# Probing Inflation, Neutrinos, and Dark Energy with the Cosmic Microwave Background: ACTPol and Beyond

Jeff McMahon

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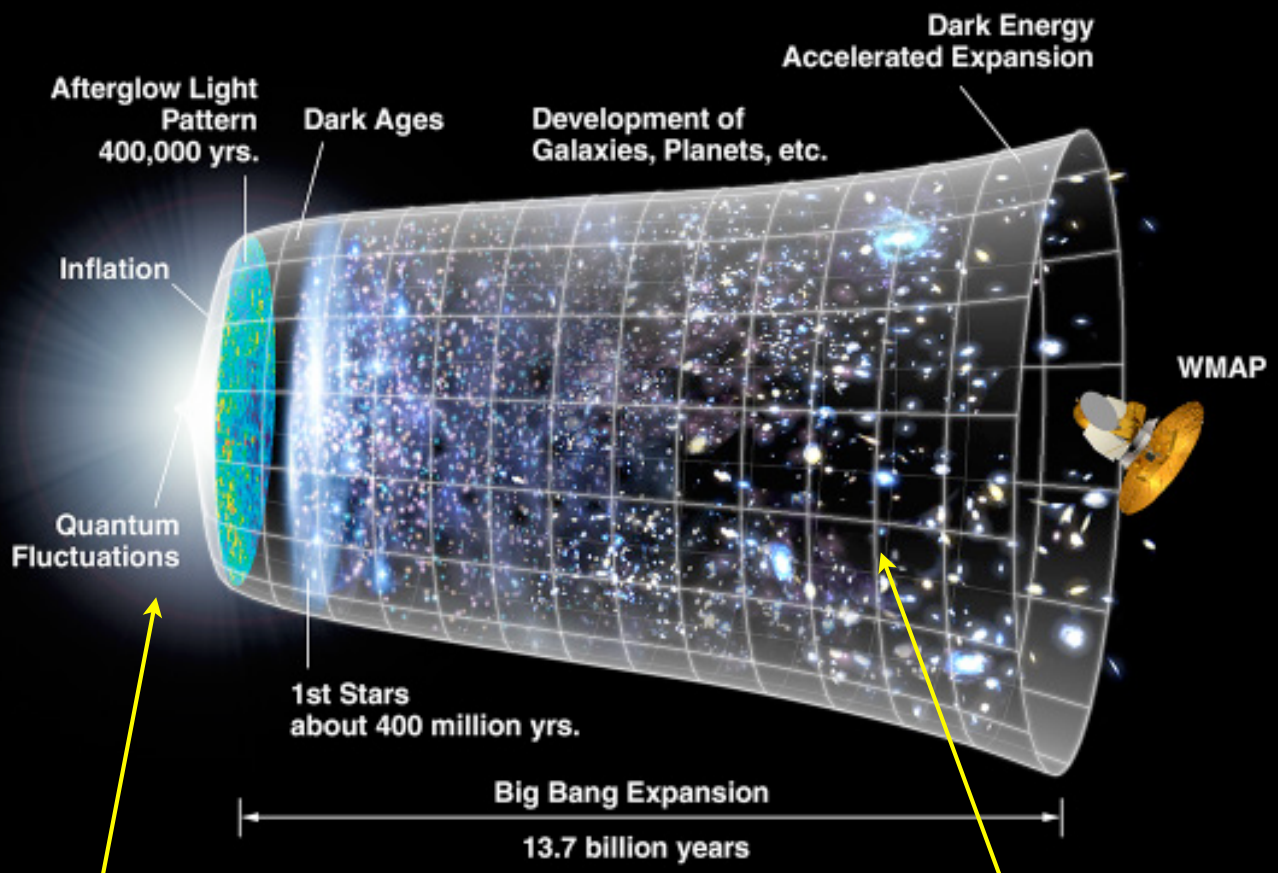
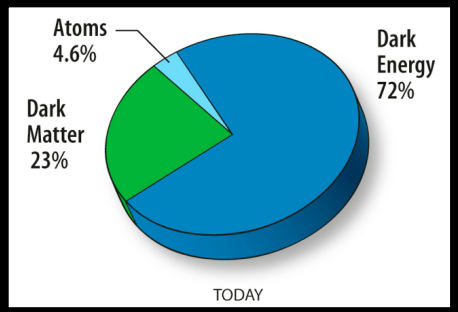
# ΛCDM: the Standard Cosmological Model




Physics at an energy scale of
$\sim 10^{16}$ GeV

Present energy density




- **6 parameters:**
  - content: $\Omega_b$, $\Omega_c$, $\Omega_\Lambda$
  - Hubble: $H$
  - reionization: $\tau$
  - inflation: $A_s$, $n_s$
- **reproduces all observations**
  - CMB
  - SN1a
  - BAO
  - BBN
- **known unknowns**
  - inflation
  - dark energy
  - dark matter
  - neutrino masses

# Inflation: conceptual summary

- Problems with the simple big bang model:
  - the relic (monopole) problem
  - flatness problem
  - horizon problem
- Solution:
  - introduce a field $\phi$ and potential $V(\phi)$ to exponentially expand the universe in the first $10^{-34}$ s

- Friedman Equation (predicts expansion of the universe)

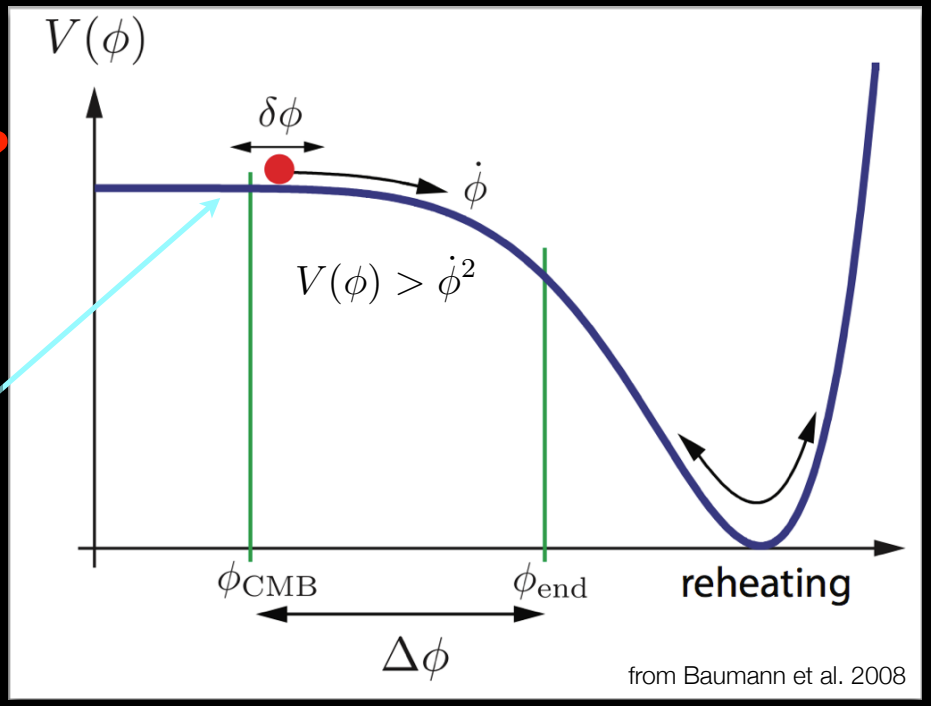
$$\frac{\ddot{a}}{a} = -\frac{1}{3M_{\text{pl}}^2}\left(\dot{\phi}^2 - V(\phi)\right)$$

- Inflation (acceleration) happens when

$$V(\phi) > \dot{\phi}^2$$

# Inflation: conceptual summary

sketch of a typical model potential




**$10^{16}$ GeV?**

quantum fluctuations generate initial perturbations

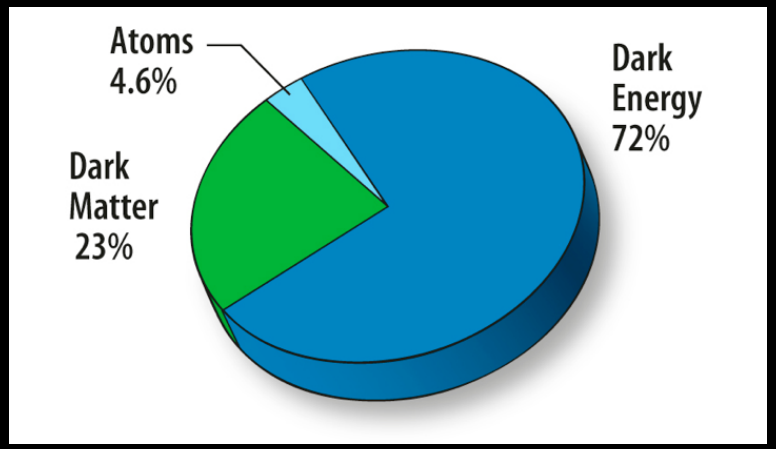
predicts initial perturbations

**density** (scalar) fluctuations: $P_s(k) = \mathbf{A_s} k^{(\mathbf{n_s}-1+\frac{1}{2}\alpha_\mathbf{s}\ln k)}$

**gravitational wave** (tensor) fluctuations: $P_t(k) = \mathbf{A_t} k^{\mathbf{n_t}}$

- Measuring inflationary parameters tests inflation
  - $A_s$ , $n_s$ , $\alpha_s$
  - $r = A_t/A_s$, $n_t$
- measuring r would determine energy scale of inflation (this is the holy grail of the CMB)
- measurements already constrain models

# Dark Energy




- Observation: present expansion rate is increasing
- Friedmann Equation

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}\left[\rho_M + \rho_D(1+3w)\right]$$

$$w = p/\rho$$

- Parameterize our ignorance:

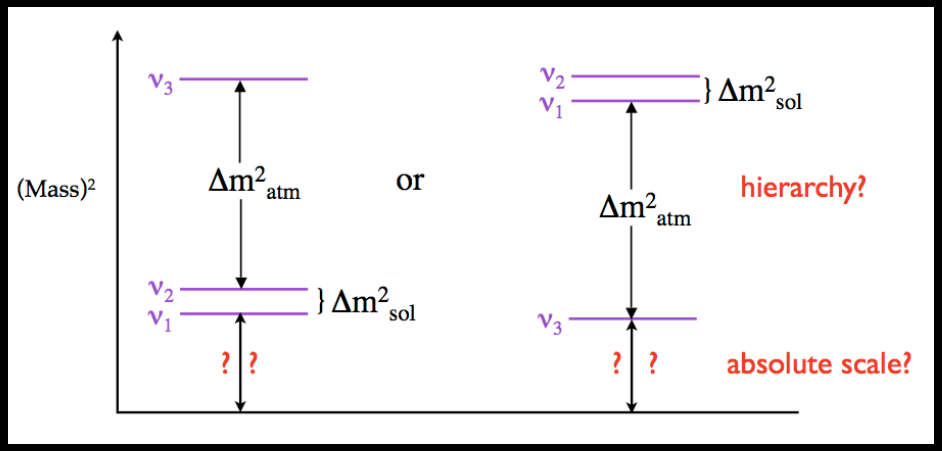
$$w(a) = w_0 + (1-a)w_a$$

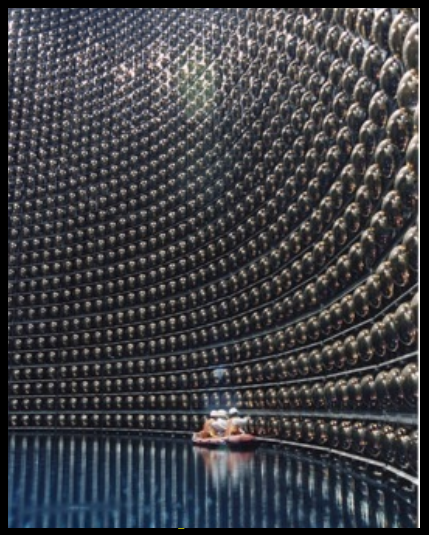
- measuring $w_0 \neq -1$ or $w_a \neq 0$ would imply dark energy is a new dynamical field

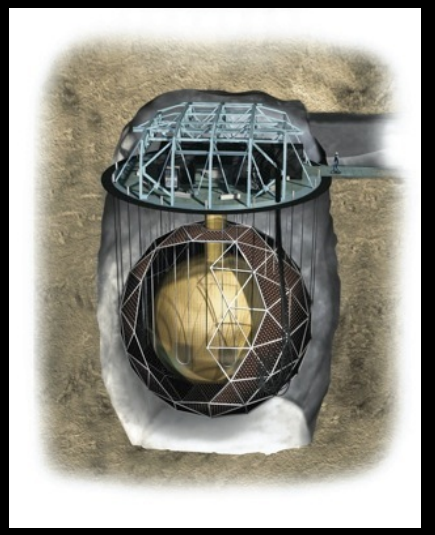
# Neutrinos

- Three flavors of neutrinos in the standard model
- Oscillation experiments measure neutrino mass differences
  - $\Delta m_{\nu 23} = 0.05$ eV
  - $\Delta m_{\nu 12} = 0.009$ eV
- Questions
  - more flavors?
  - mass scale?
  - mass hierarchy?

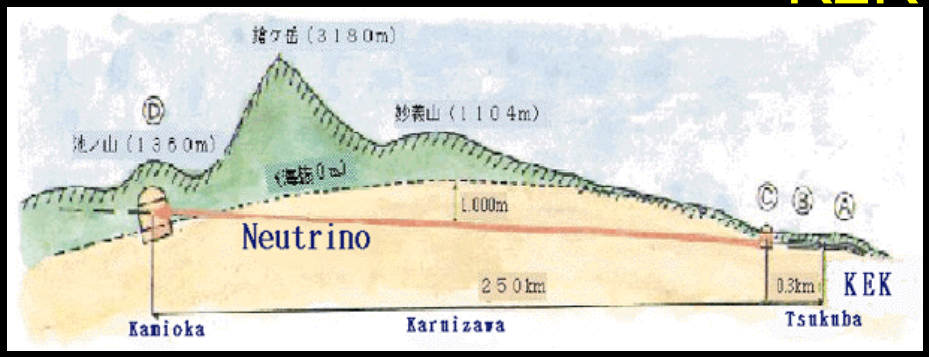
} impact cosmology



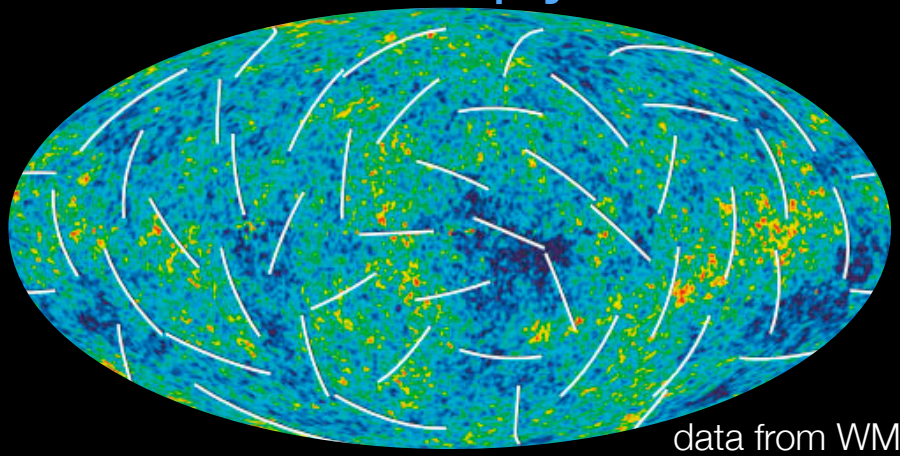


K2K



# Cosmological Measurements with the CMB

## CMB anisotropy

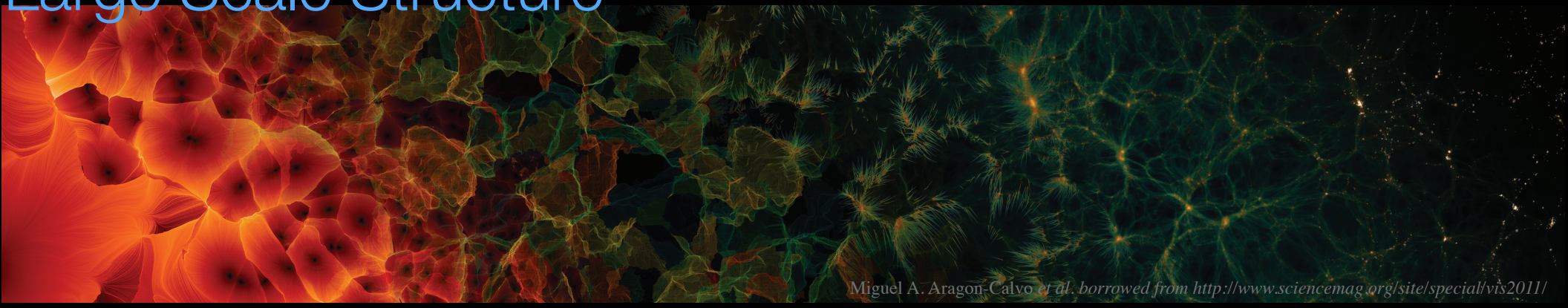


data from WMAP

## Snapshot of our universe at 380,000 years

carries the imprint of inflationary parameters, the number of neutrino species, and more

## Large Scale Structure



Miguel A. Aragon-Calvo *et al. borrowed from http://www.sciencemag.org/site/special/vis2011/*

## Probes our universe from age ~1 to ~13.8 Billion Years

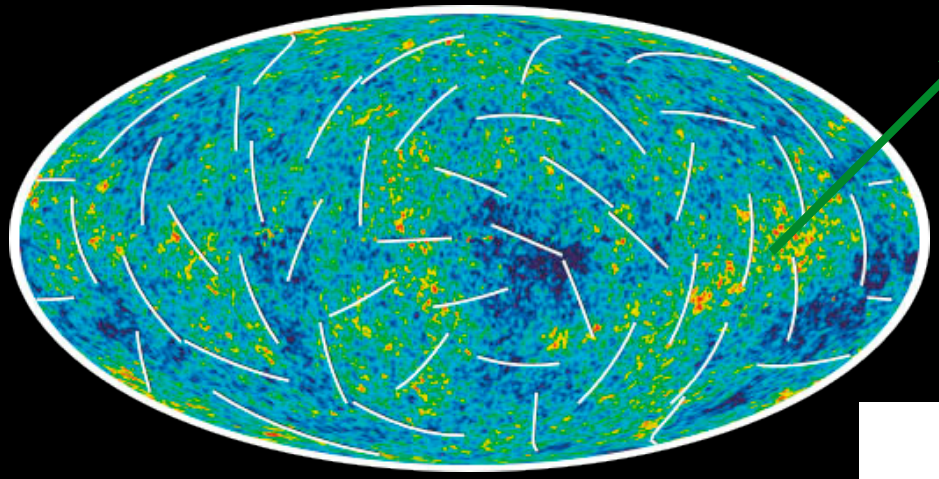
sensitive to dark energy and dark matter (neutrinos), and other parameters.

ACT

# CMB Power Spectra

contains most of the CMB's information

sky map from WMAP

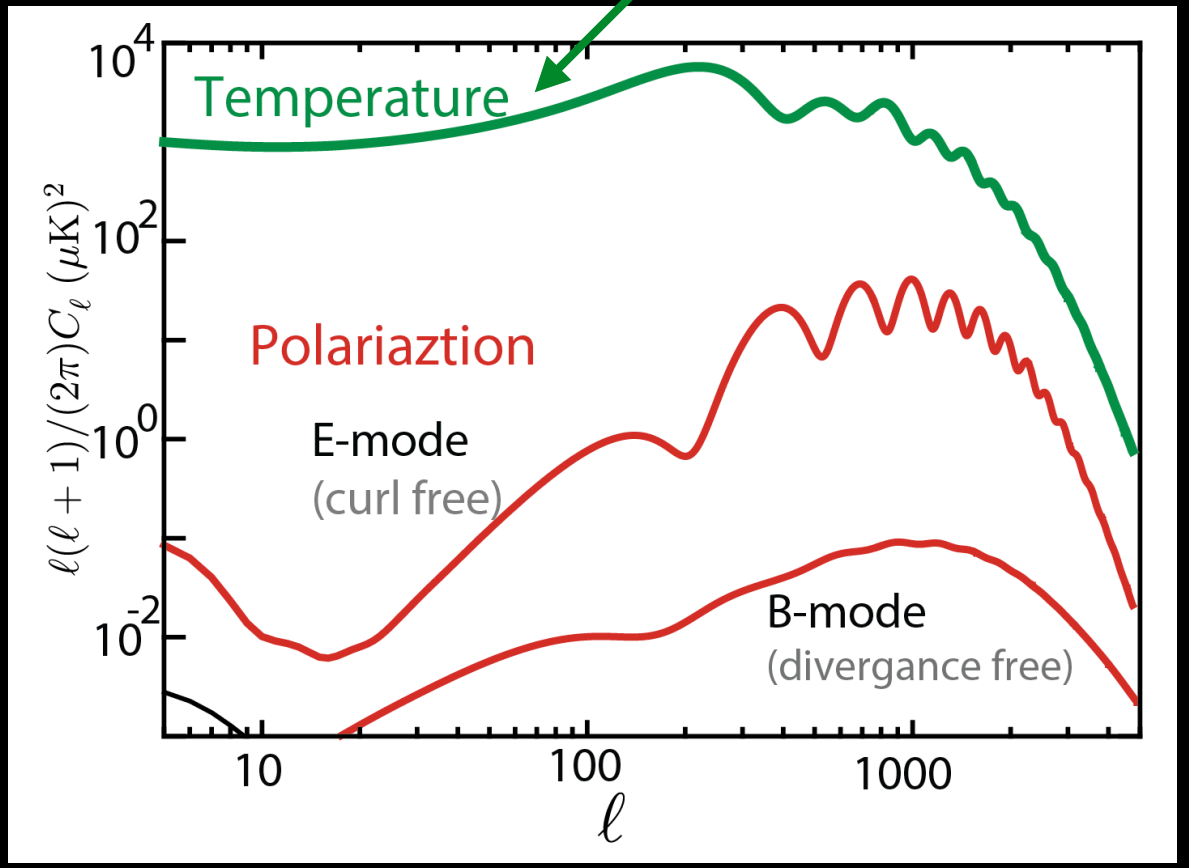


decompose

$$T(\hat{n}) = \sum_{\ell,m} a^T_{\ell m}\, Y_{\ell m}(\hat{n})$$

average

$$C_\ell = \sum_m |a_{\ell m}|^2$$



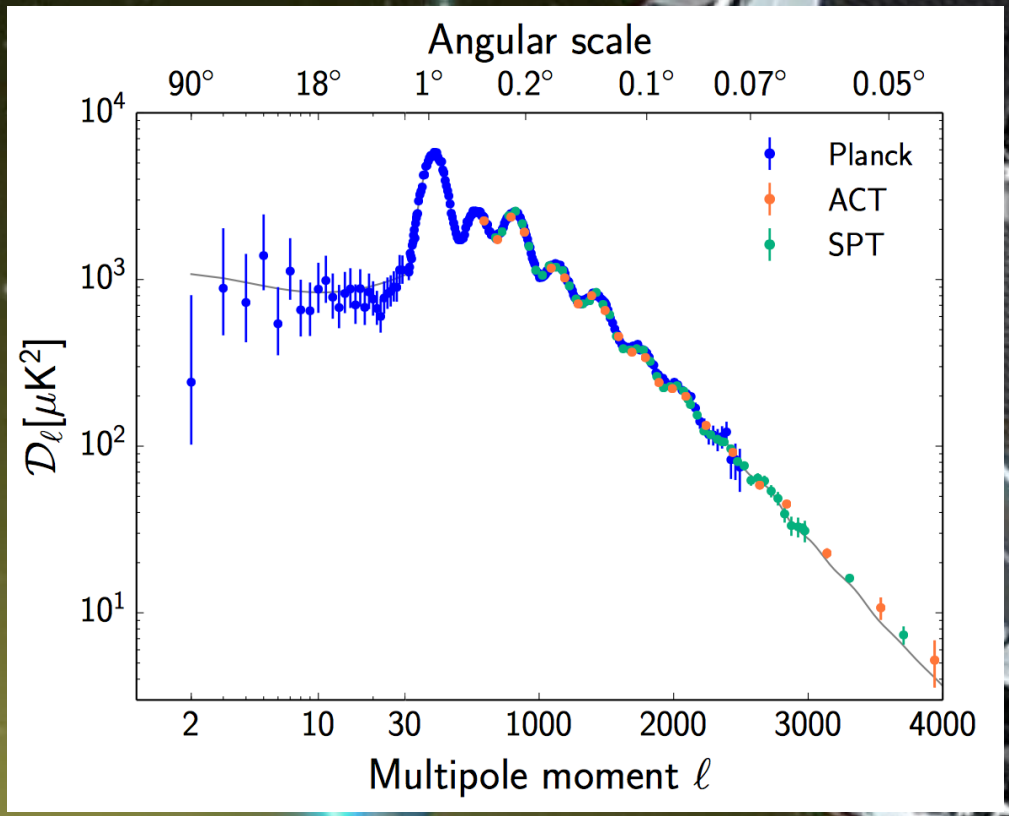

temperature fluctuations trace density perturbations

polarization generated from bulk flows and Thompson scattering

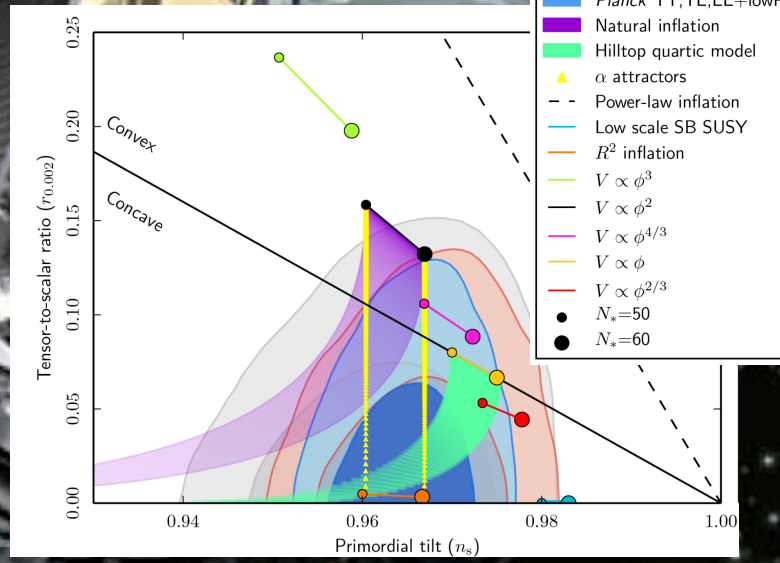
# CMB Power Spectrum

from Planck 2015 results papers XI, XII, and XX

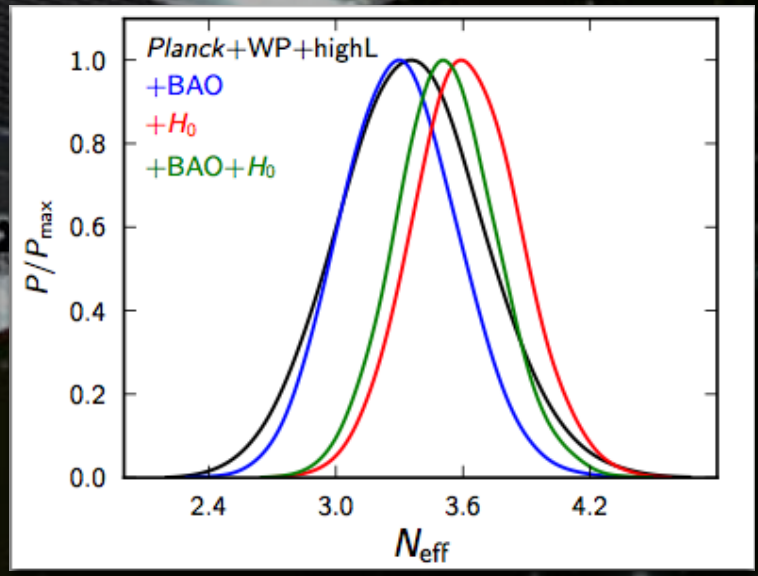
## *Temperature power spectrum*




## inflationary parameters



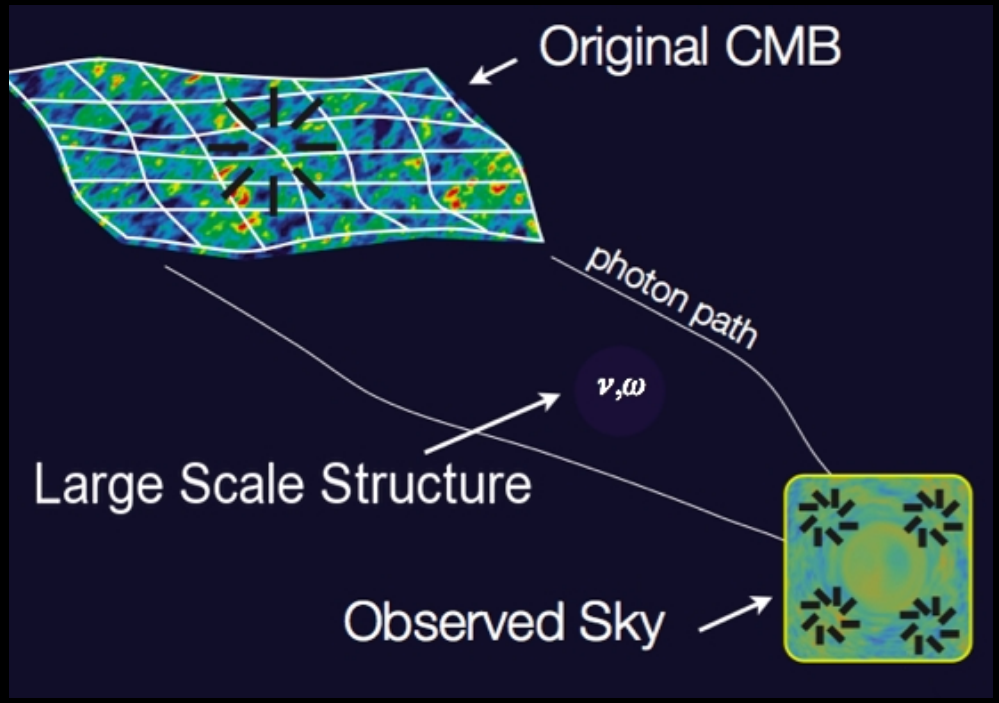

## neutrino species



# Large Scale Structure with Galaxy Clusters and Weak Lensing

Miguel A. Aragon-Calvo *et al. borrowed from http://www.scivisualmag.org/site/specialvis2011/*

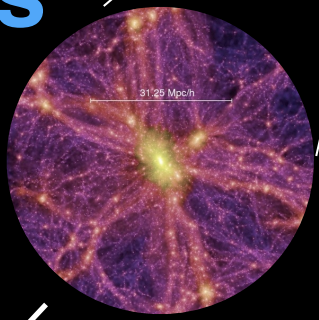
## CMB gravitational lensing




Leverage through cross-correlations with optical surveys

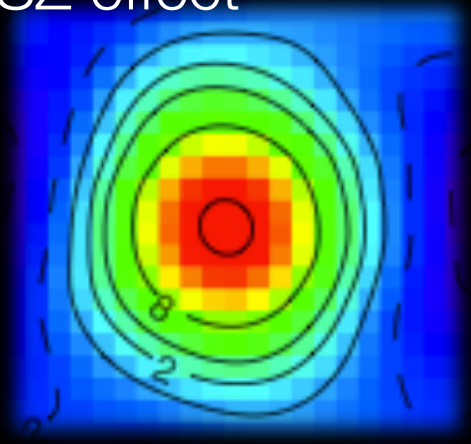
## SZ Clusters

Prediction: dark matter halos




Measurements:

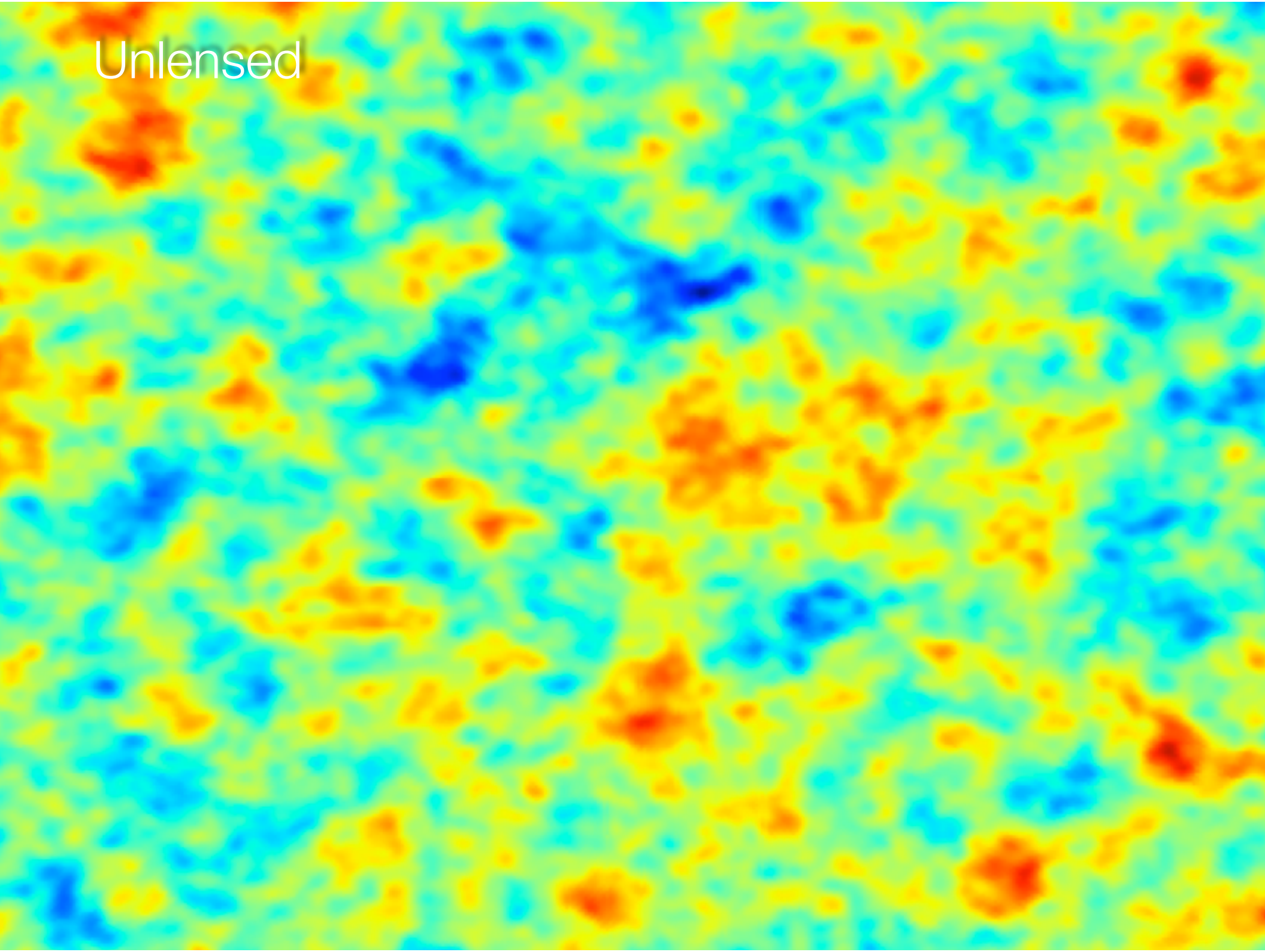
SZ effect

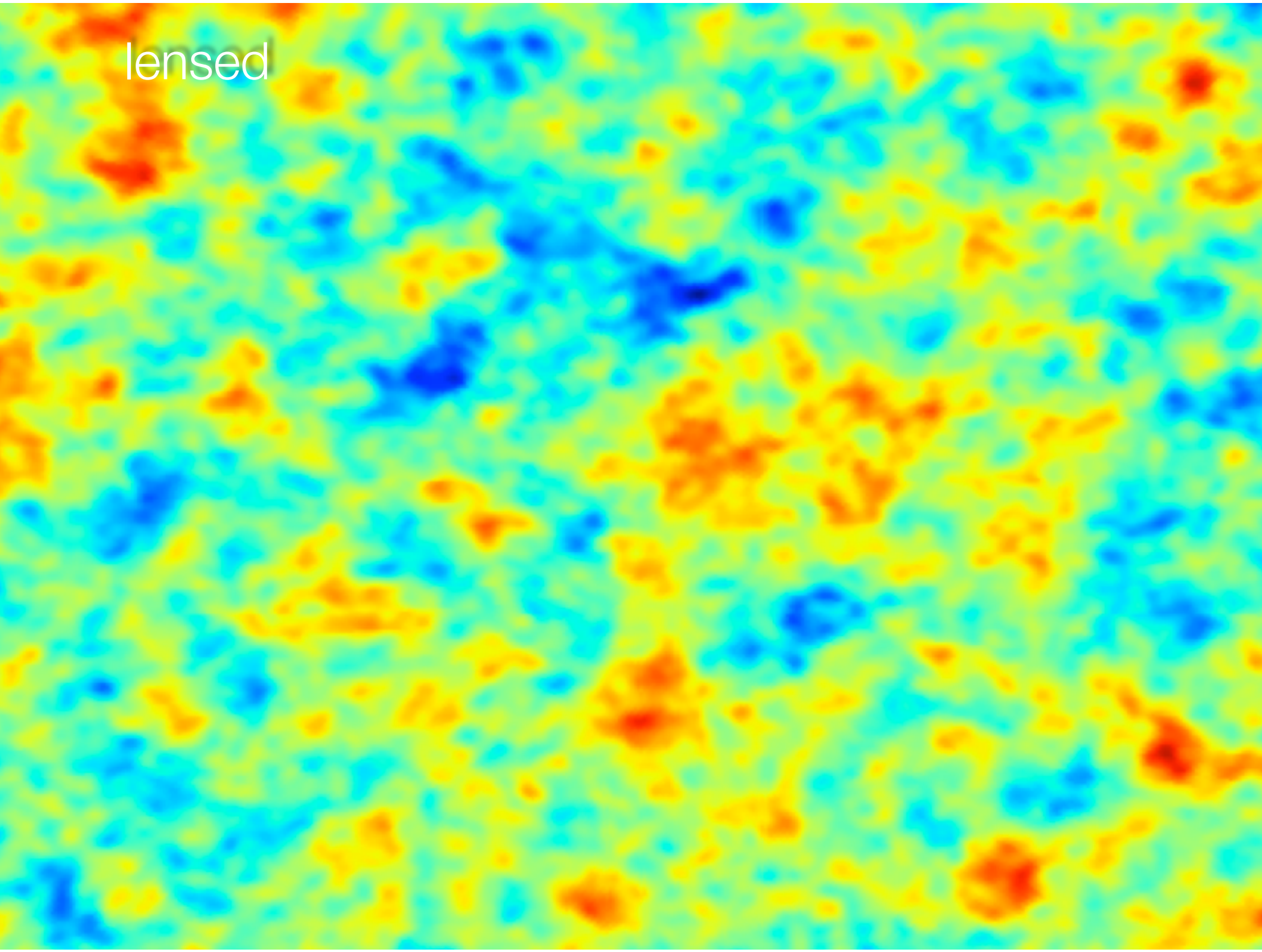


optical galaxies

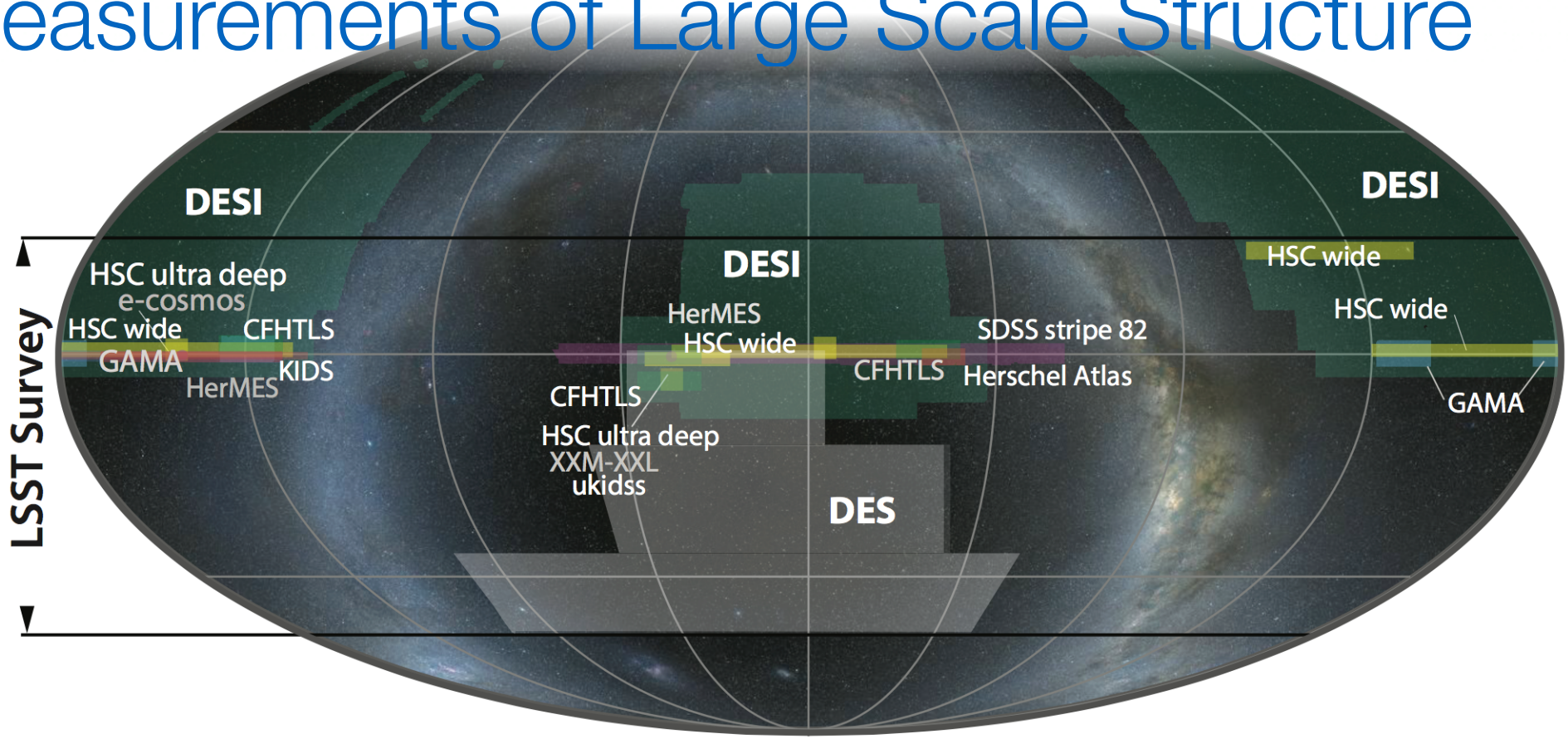
also x-ray, galaxy weak-lensing, velocity dispersion, and others

Large scale structure constrains **neutrino masses, dark energy**, and a other physics

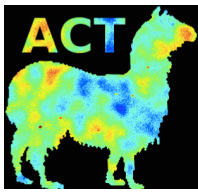

Unlensed


lensed

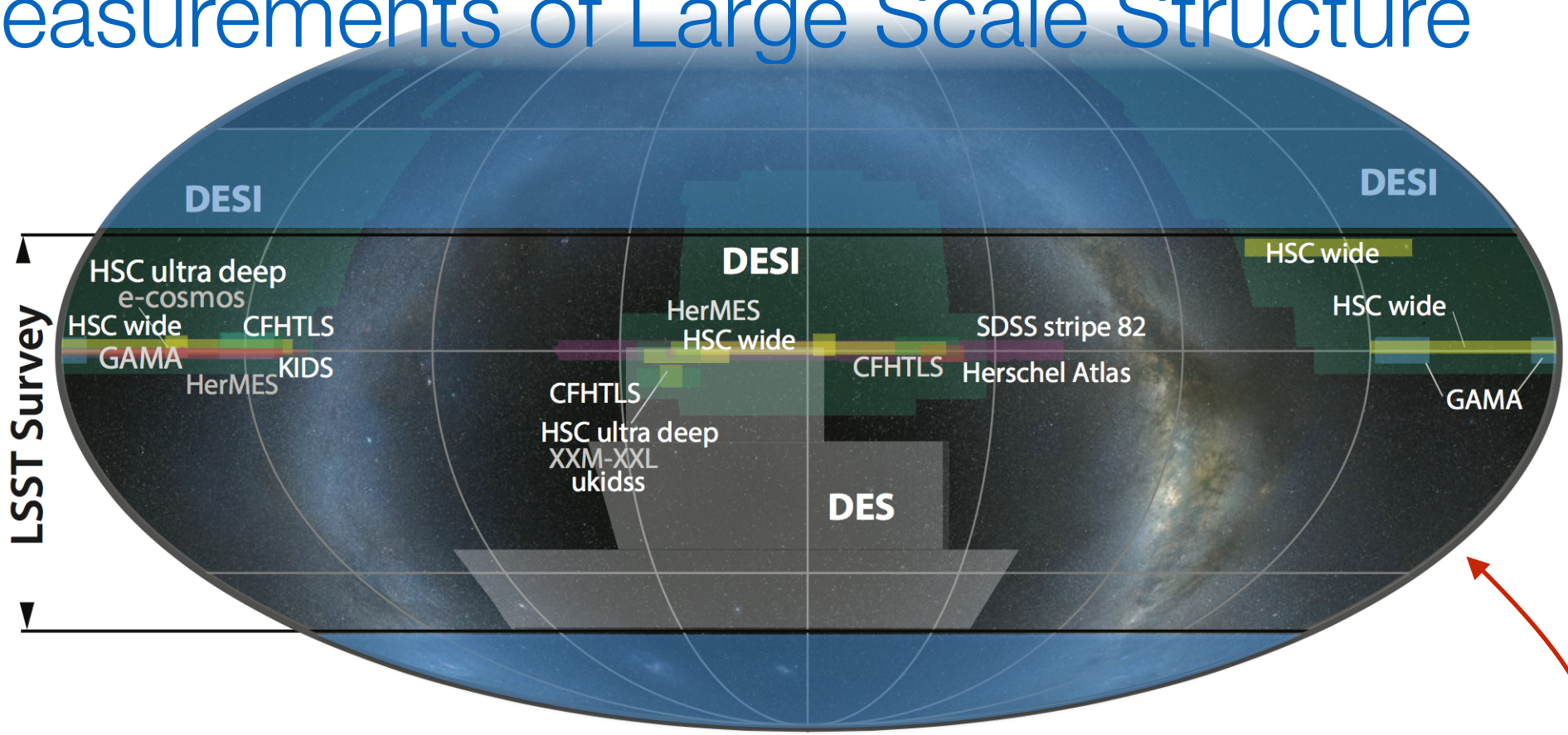
# Complementarity with optical measurements of Large Scale Structure




| survey type | measurements | complementarity |
|---|---|---|
| photometric surveys | clusters | clusters tSZ, scaling relations, mass calibraiton (CMB lensing) |
| spectroscopic surveys | mater power spectrum / BAO | velocity field (kSZ), calibration |
| galaxy shear lensing | matter power spectrum | calibration of multiplicative bias |

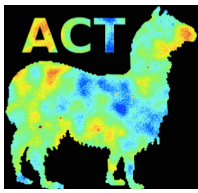


# Complementarity with optical measurements of Large Scale Structure



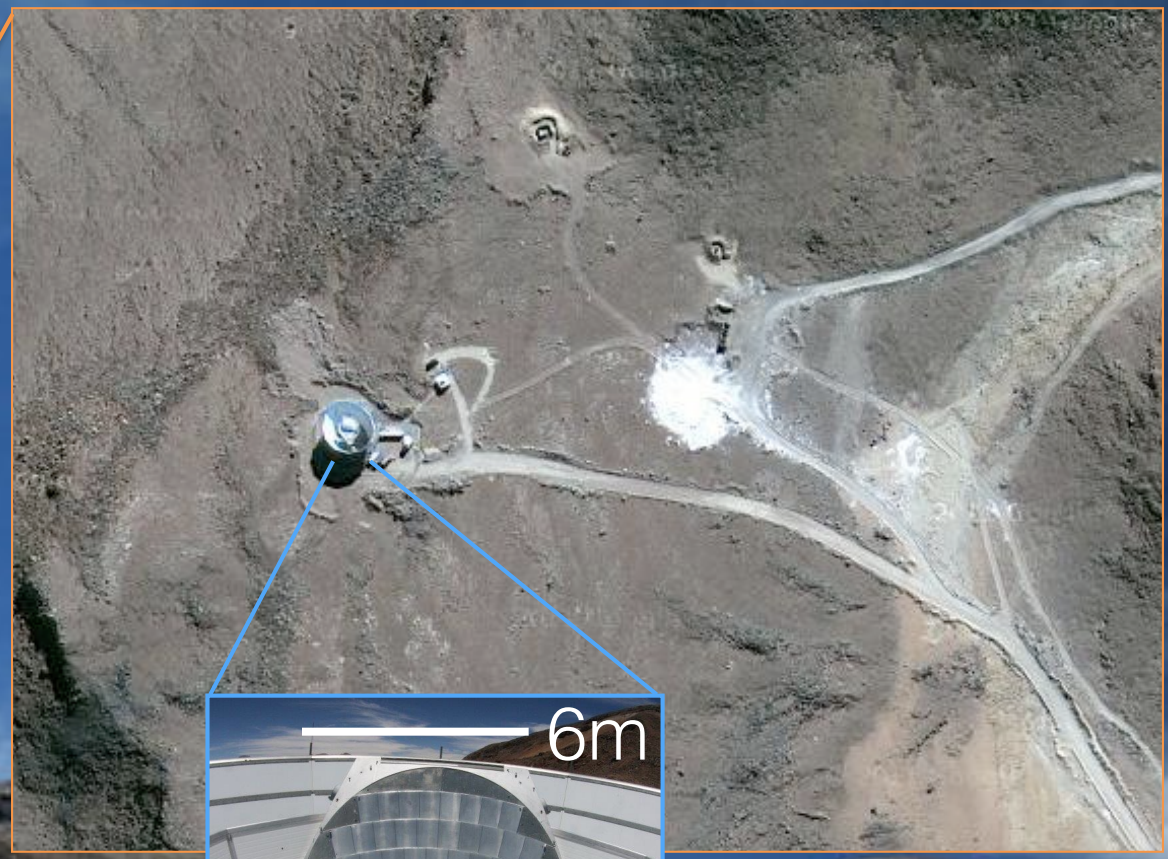

**available sky in Chile**

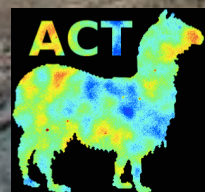
| survey type | measurements | complementarity |
|---|---|---|
| photometric surveys | clusters | clusters tSZ, scaling relations, mass calibraiton (CMB lensing) |
| spectroscopic surveys | matter power spectrum / BAO | velocity field (kSZ), calibration |
| galaxy shear lensing | matter power spectrum | calibration of multiplicative bias |



# The Atacama Cosmology Telescope

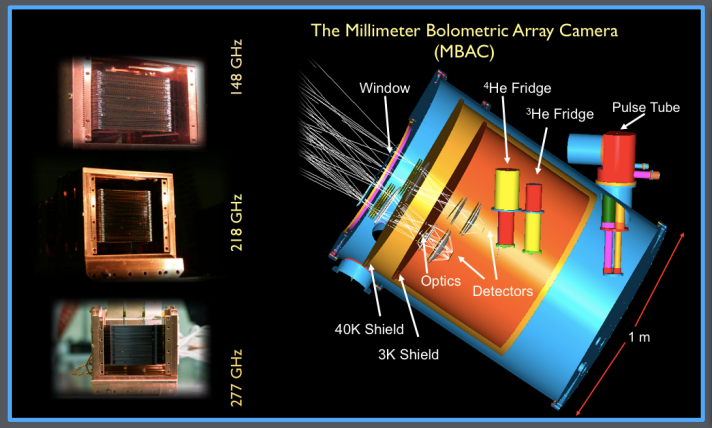

- 5200 m (high)
- Desert (dry)
- Latitude -23°

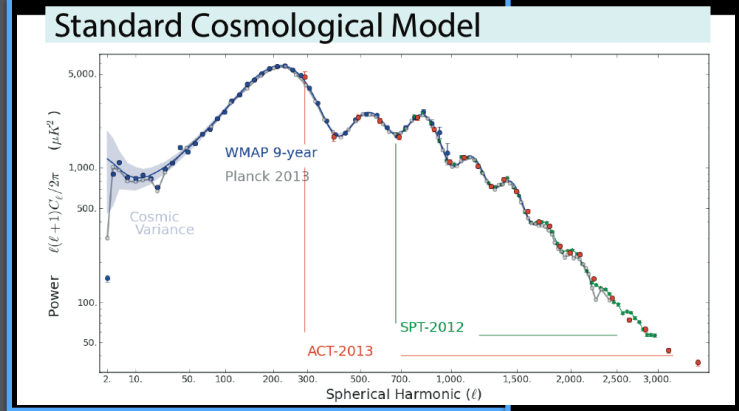


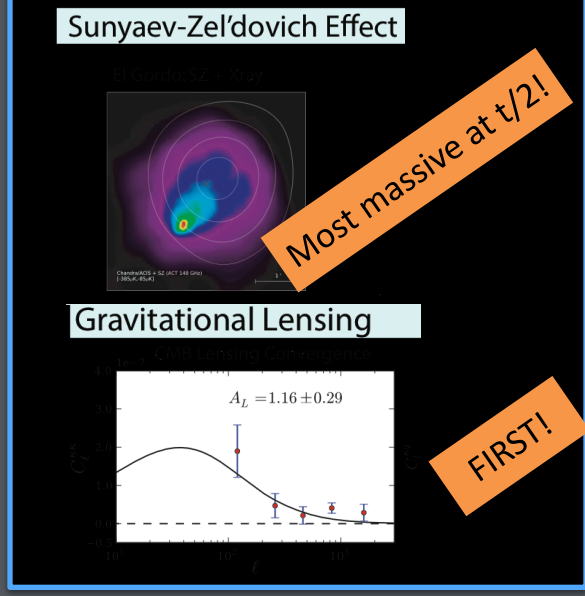
# Three Cameras and ACT

The Past:
2007-2010
**MBAC**

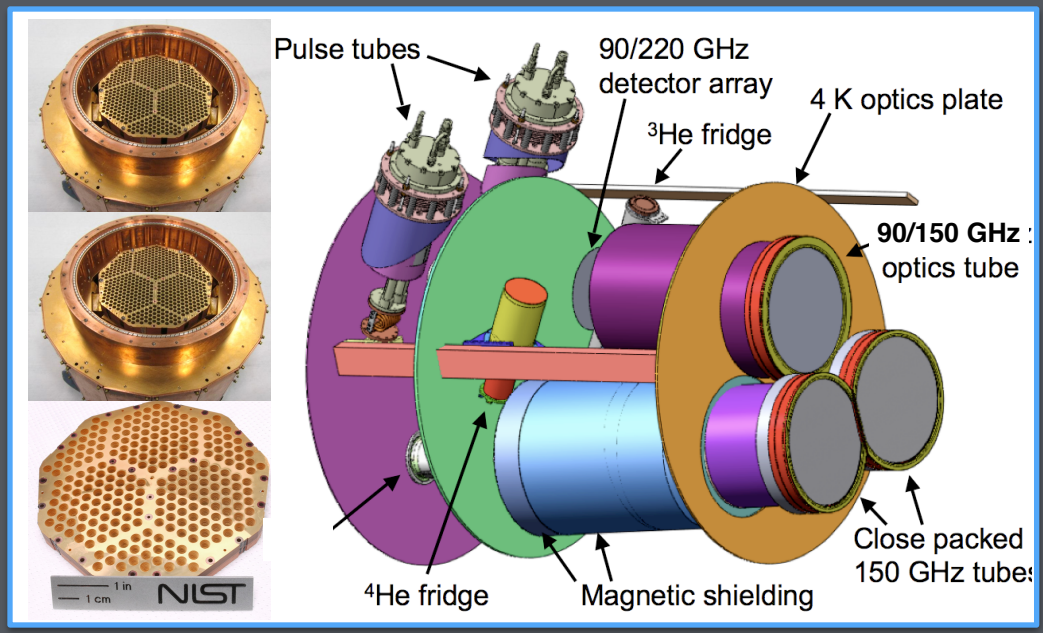



**ACT discovery highlights**



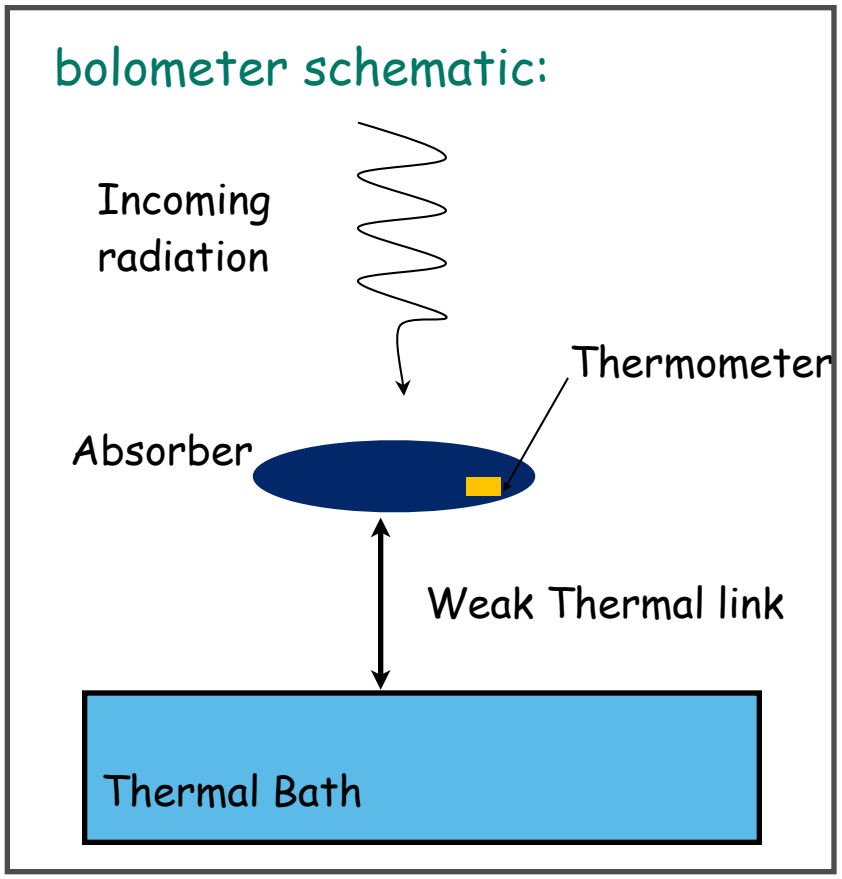

The Present:
2012-2015
**ACTPol**

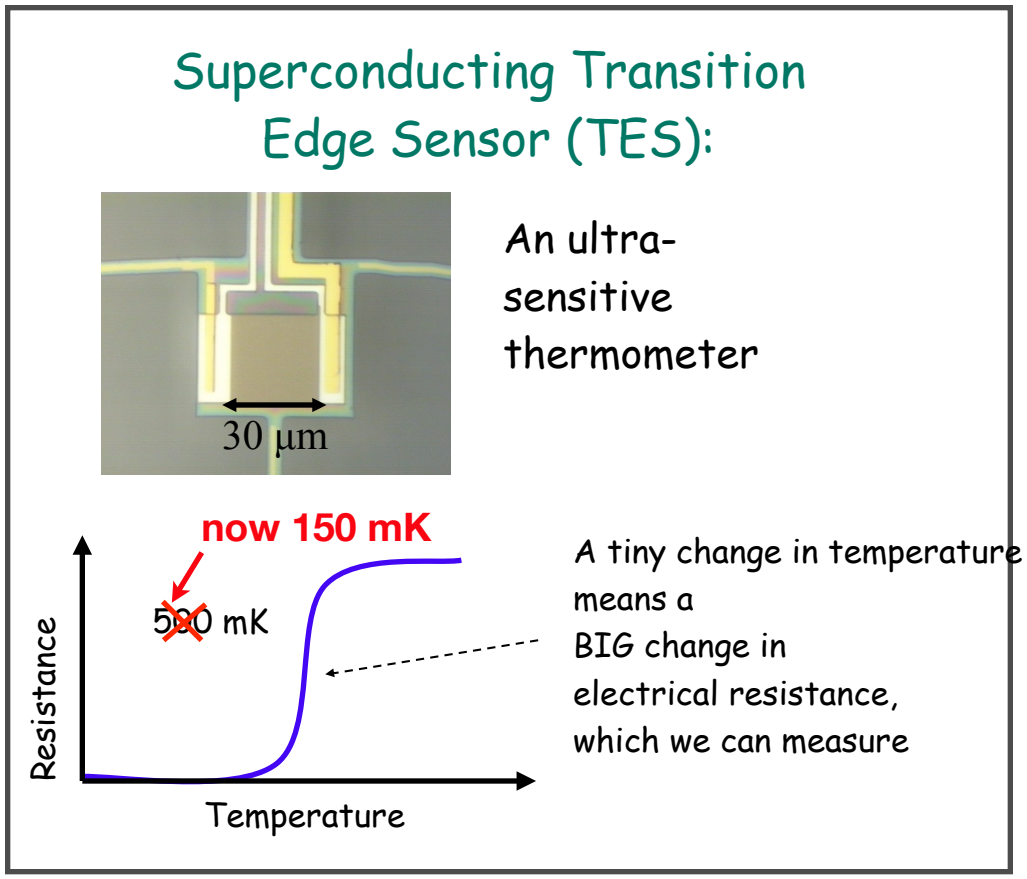



The Future:
2016-2019 **Advanced ACTPol (AdvACT)**

2020 and beyond
# CMB-S4

# **TES basics** overview and sensitivity

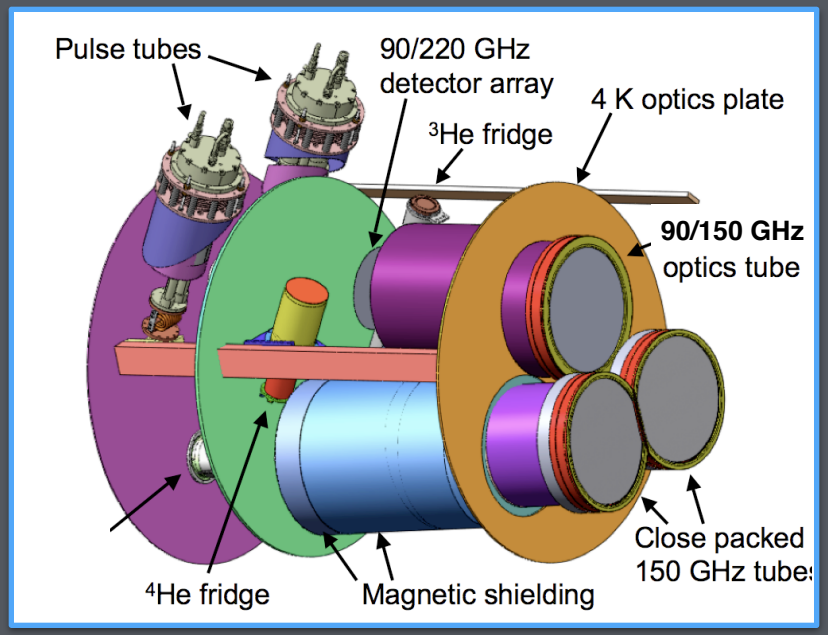



- **Noise contributions**
  - photons
  - phonons

- **Maximizing sensitivity**
  - lower all sources of noise
    - phonons
    - radiation
  - arrays of detectors to boost sensitivity

# the **ACTPol** Receiver




## 3 optics tubes

- 2 @ 150 GHz arrays
- 1 @ 90/150 multichroic

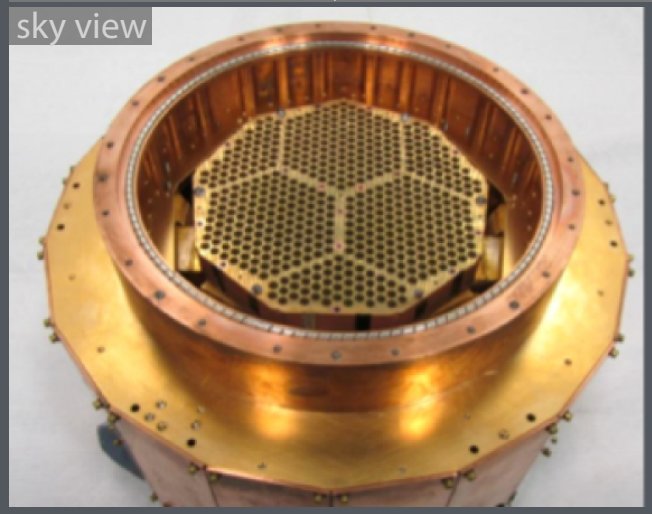
## Metamaterial AR silicon lenses

-low reflectance
-low dielectric loss

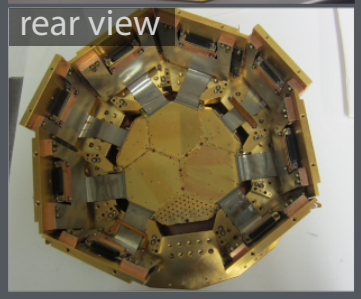
## Dilution refrigerator

- 90 mK base
- continous operation

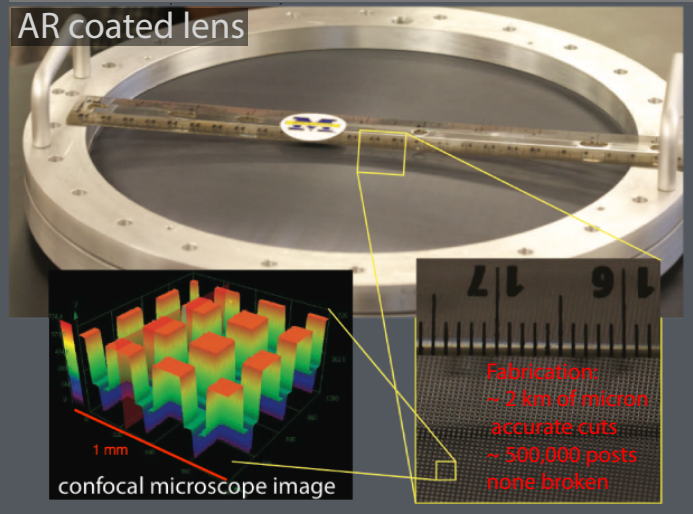
## Detector Arrays



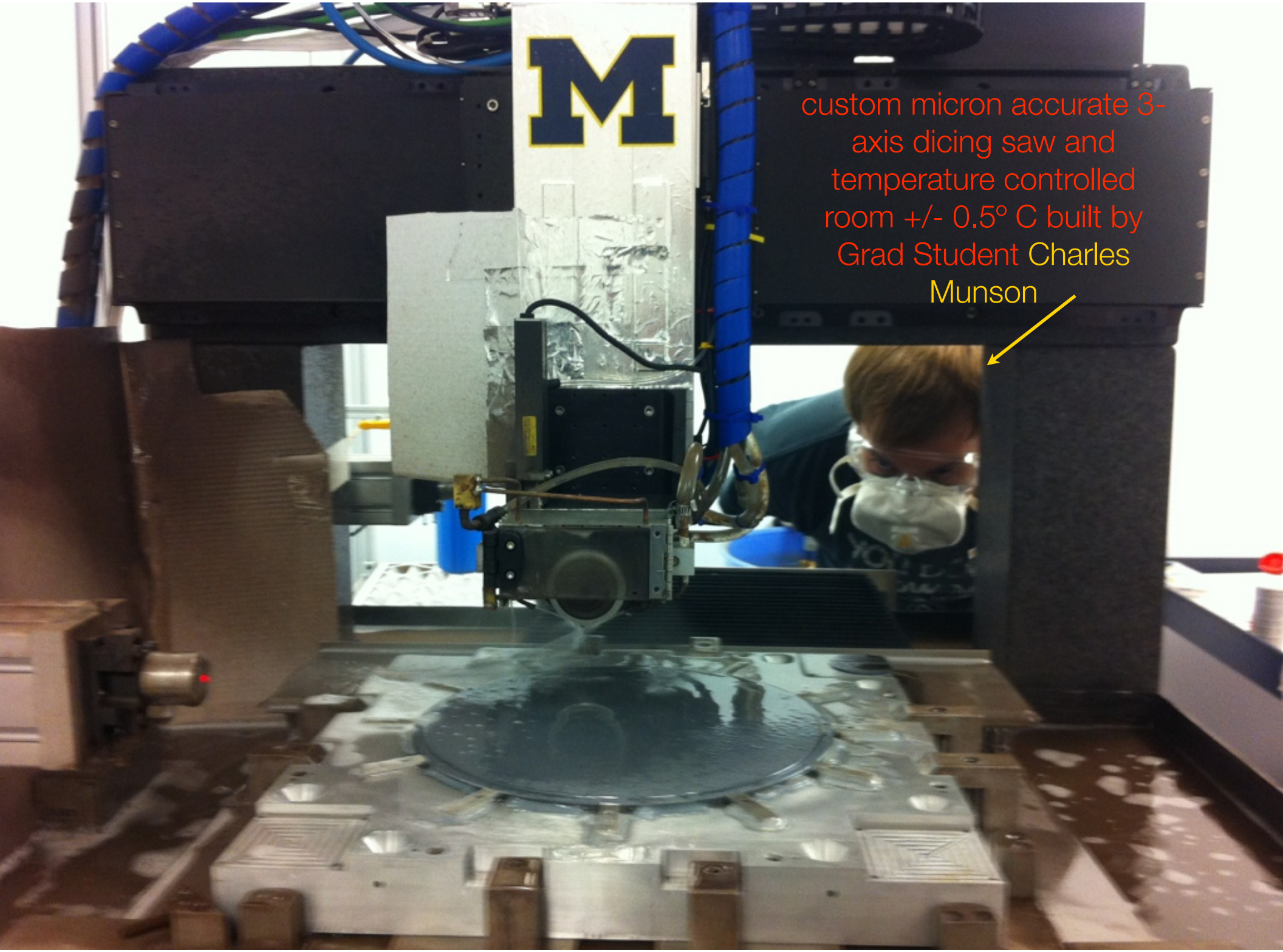




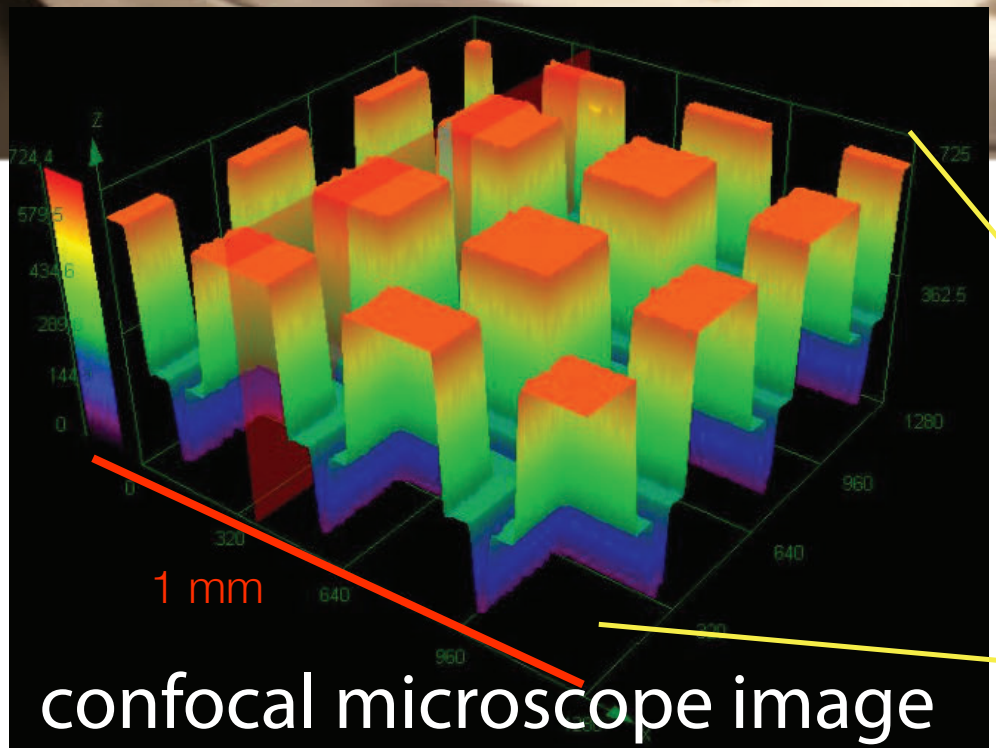

## Metamaterial AR Coated Silicon Lenses

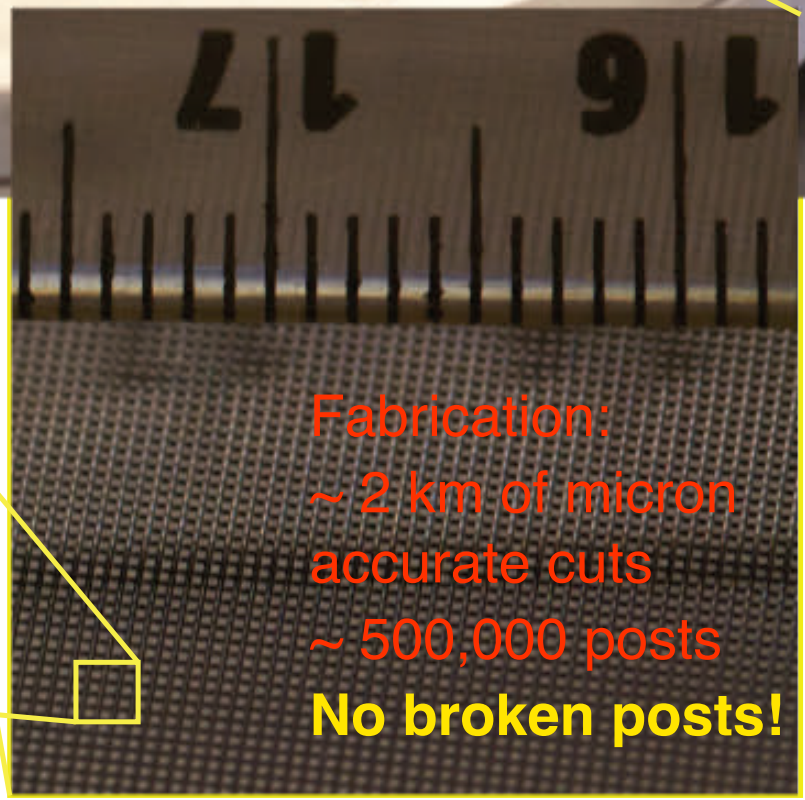





custom micron accurate 3-axis dicing saw and temperature controlled room +/- 0.5° C built by Grad Student Charles Munson

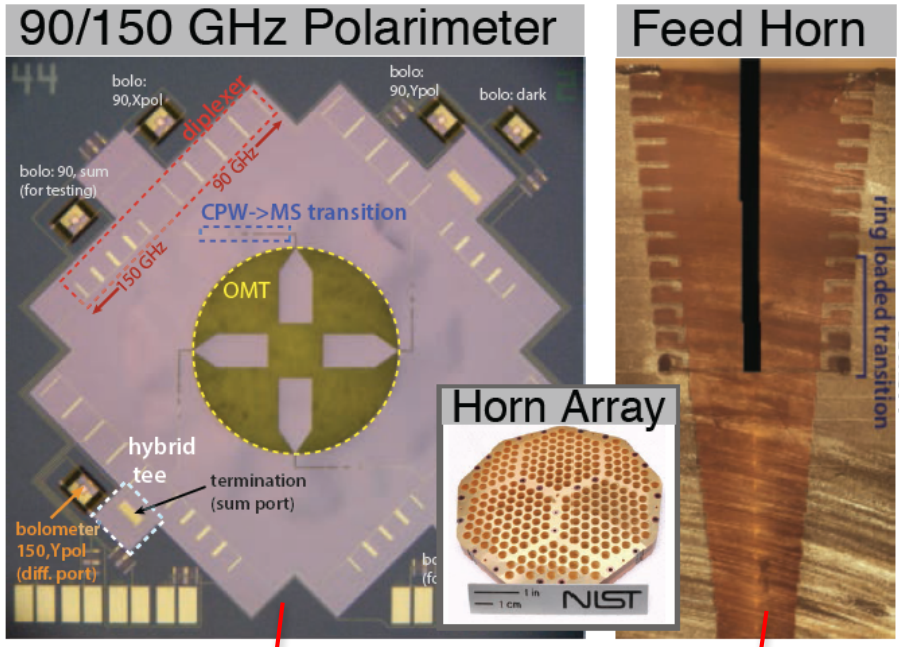
# An ACTPol lens



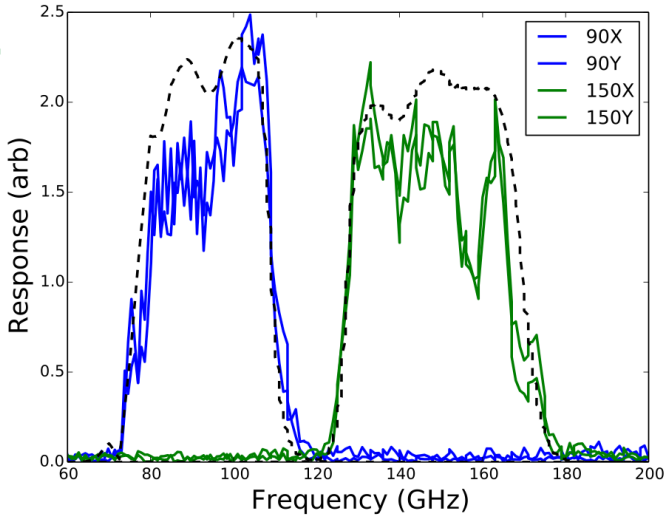



# ACTPol Multichroic Polarimeter Array

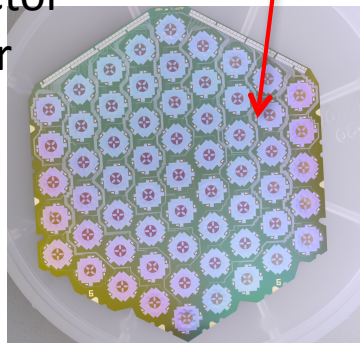
- New dichroic polarimeters
- Datta et al., JLTP (2014)



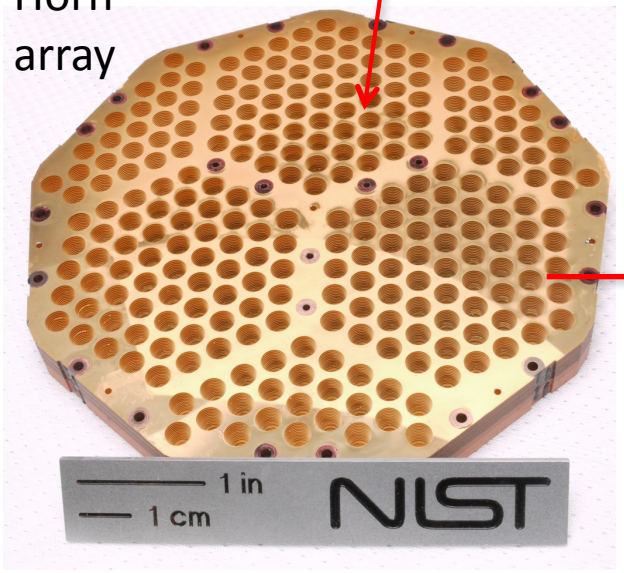

**sensitive to the 90 GHz and 146 GHz CMB bands in each pixel**



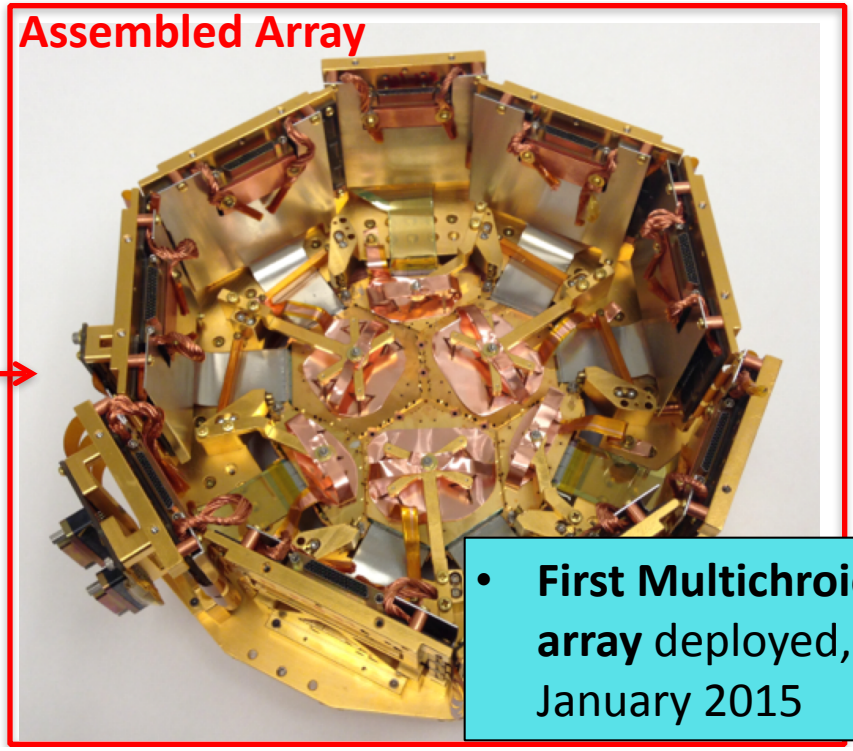

Detector wafer



Horn array




**Assembled Array**



- **First Multichroic array** deployed, January 2015

# ACTPOL STATUS


2013: First array (all 146 GHz)

- background limited
- consistent with proposed sensitivity
- first results published

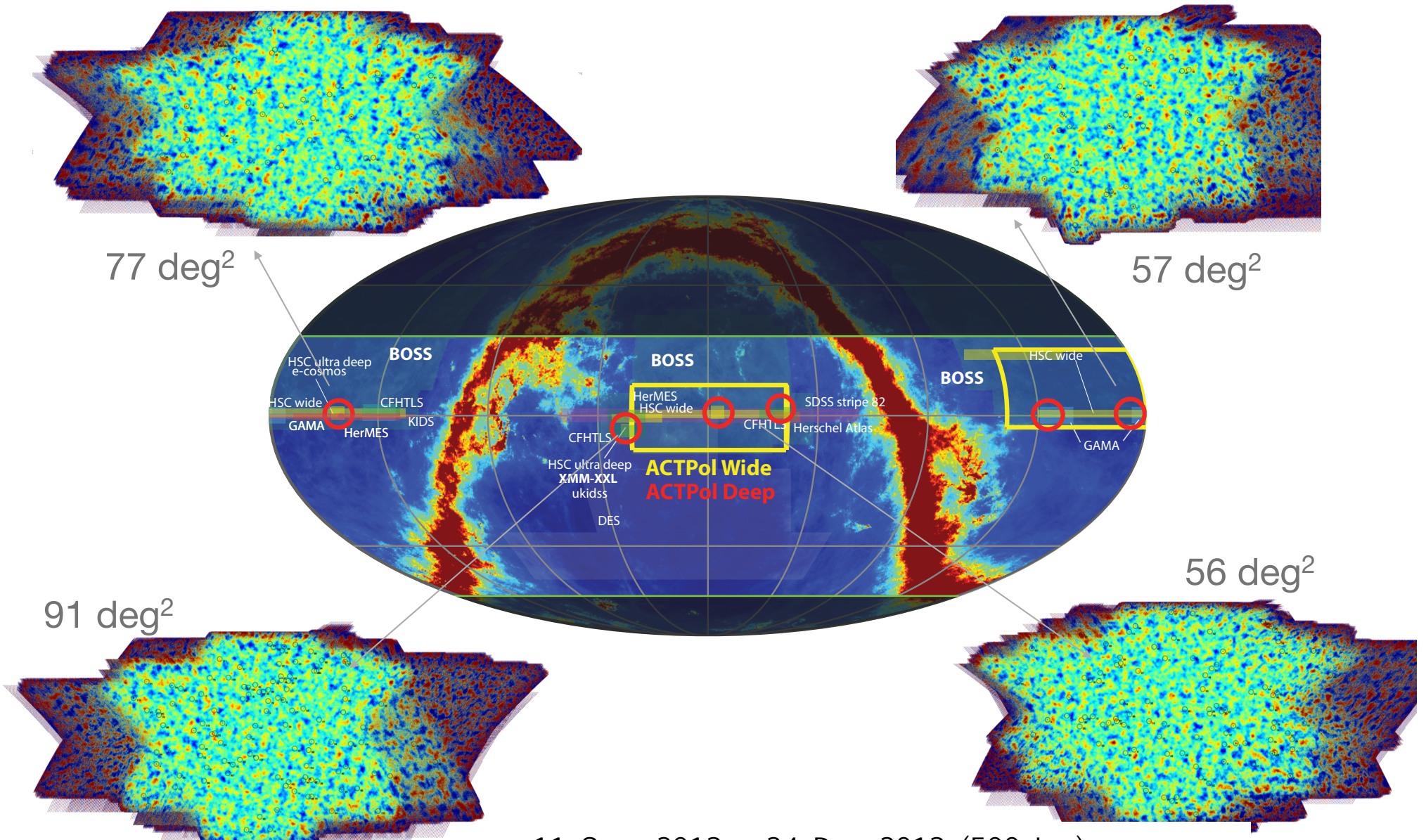
2014: Two arrays (all 146 GHz)

- analysis underway

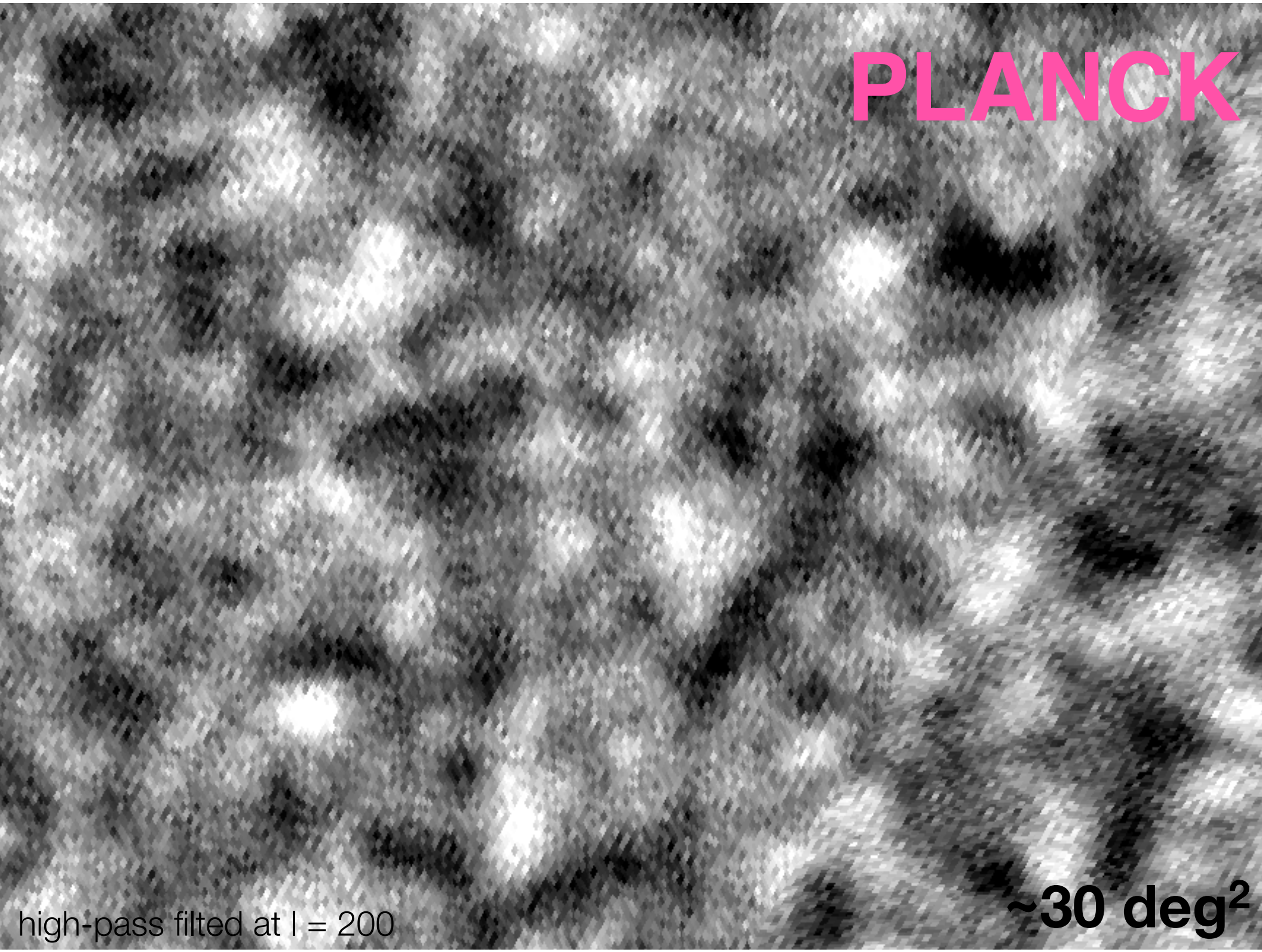
2015: Multichroic 90/146 GHz

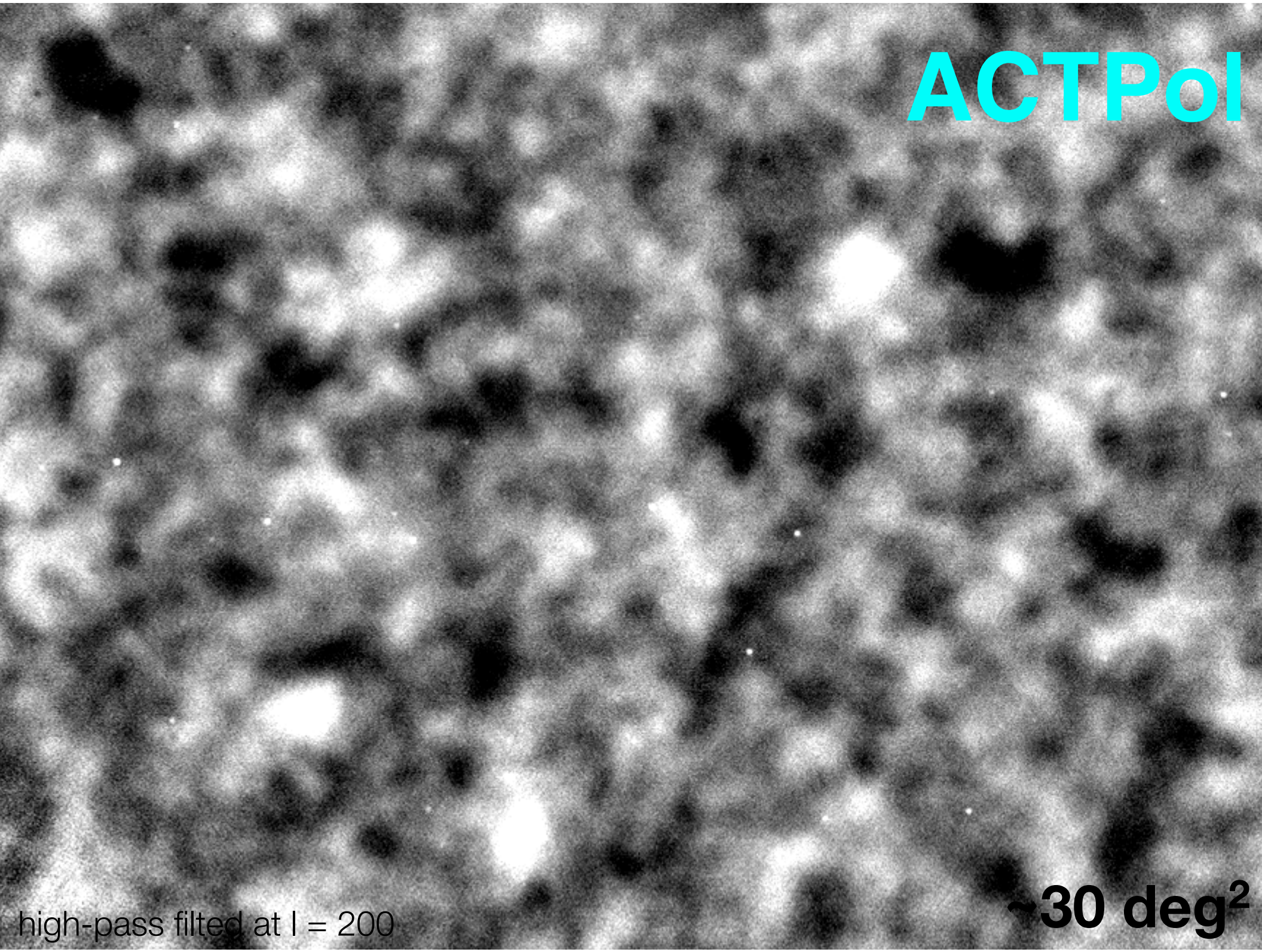
- First light Feb 2015
- First fielded multichroic polarimeter array

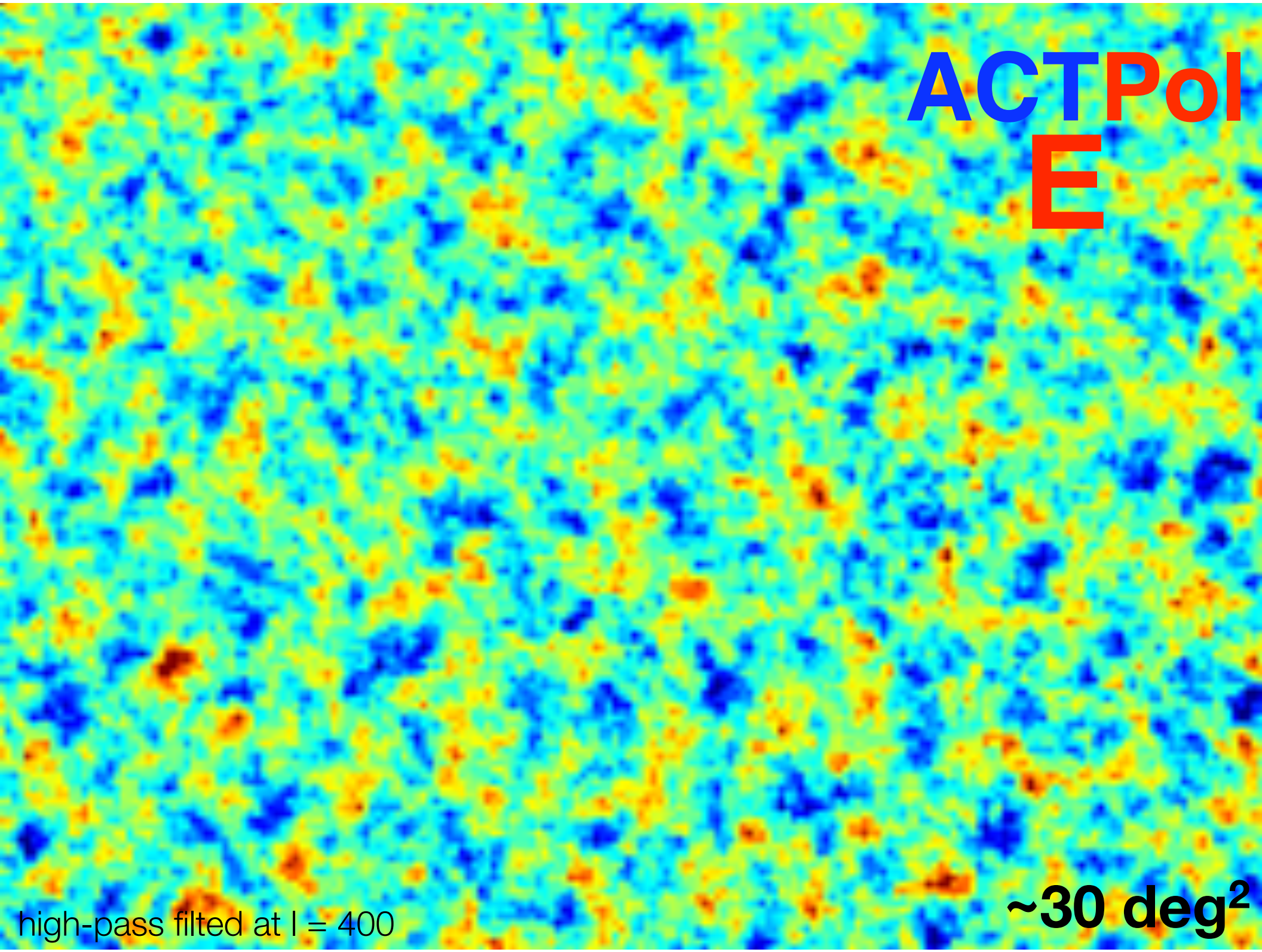

# ACTPol Survey 2013

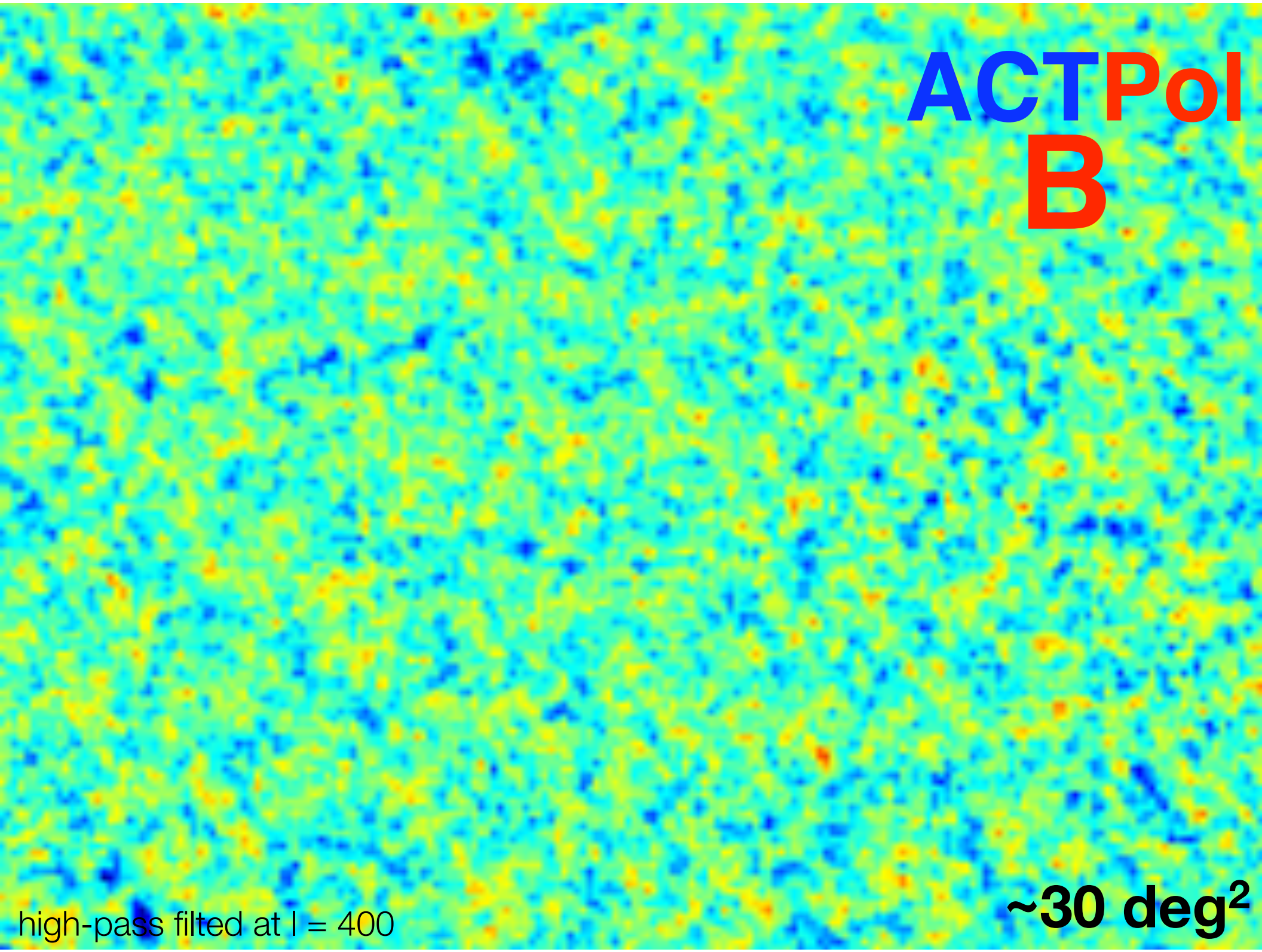



- 11 Sept 2013 – 24 Dec 2013 (500 hrs)
- Only one 150 GHz array installed then
- Four ~ 70 deg$^2$ patches

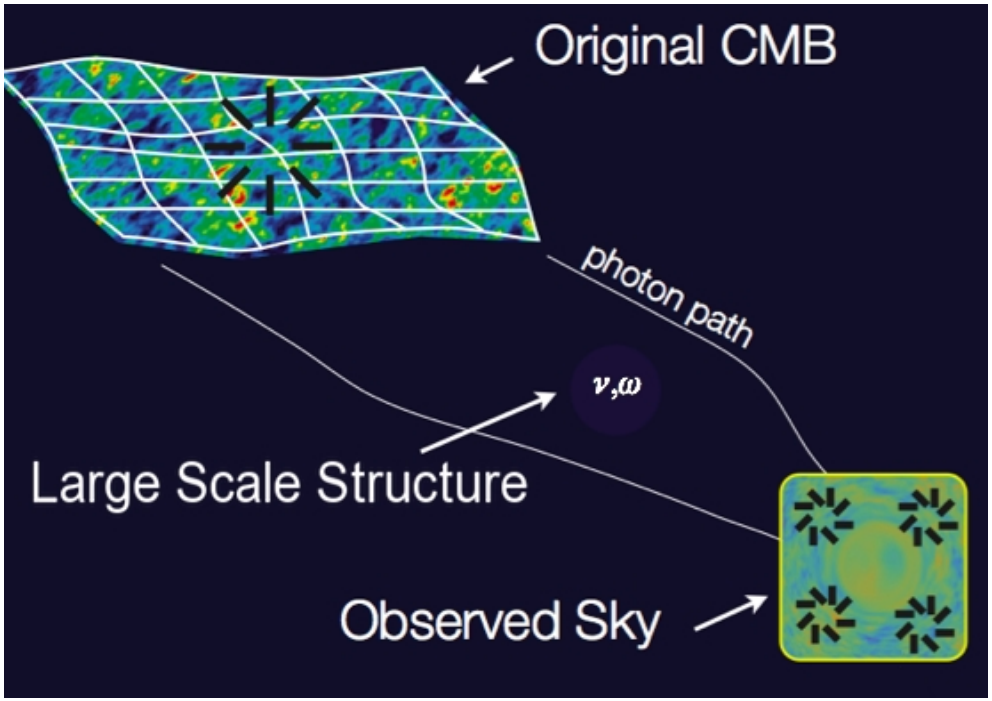

PLANCK
high-pass filted at l = 200
~30 deg²


ACTPol
~30 deg²
high-pass filted at l = 200

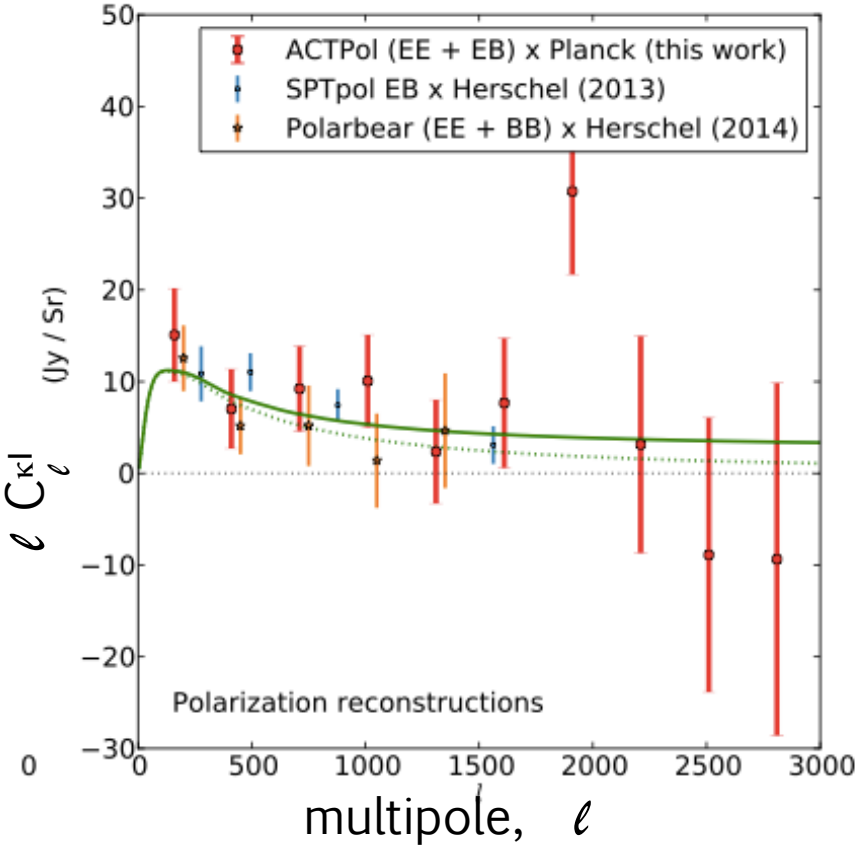

ACTPol
E
high-pass filted at l = 400
~30 deg²


ACTPol
B
high-pass filted at l = 400
~30 deg²

# POLARIZATION Lensing (cross-correlation)




Deflection x CIB Cross Spectrum

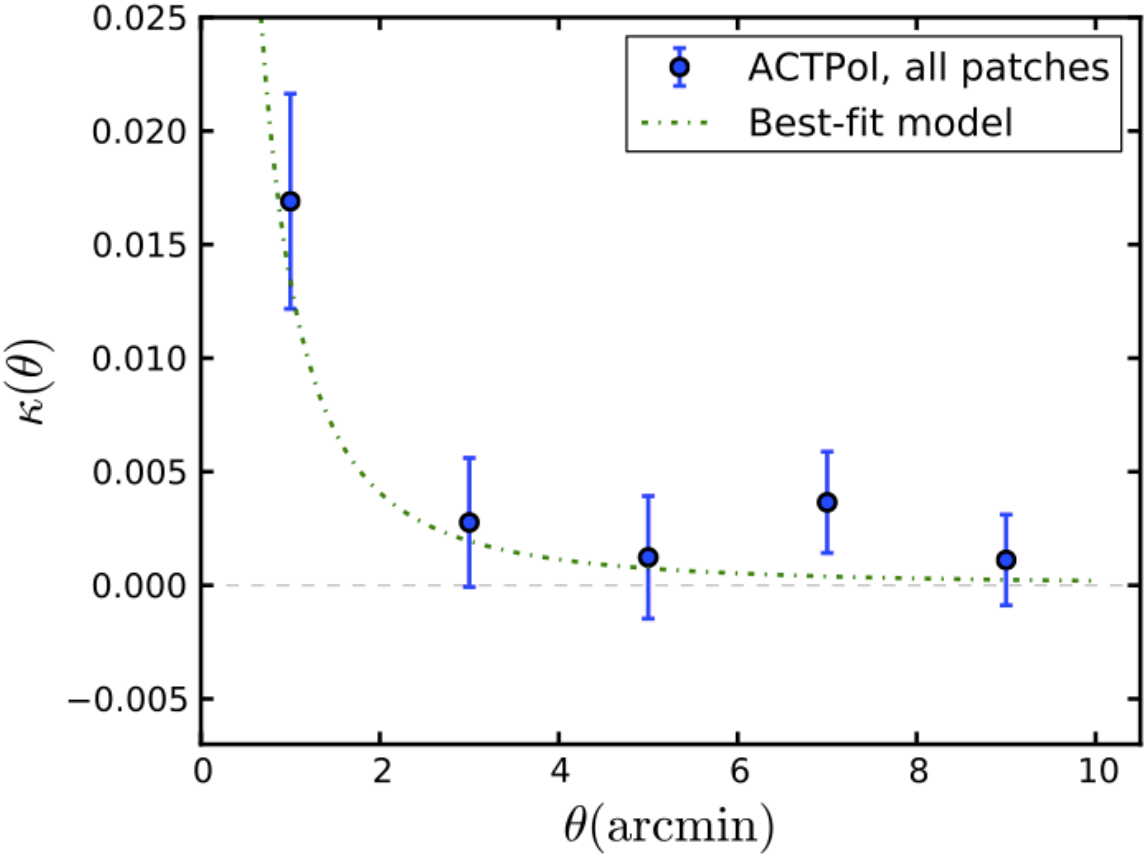


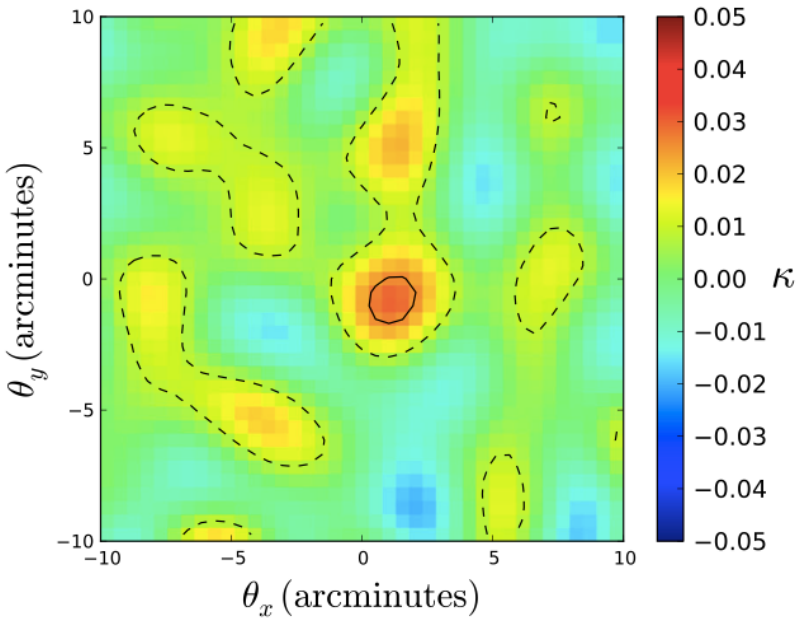

small scale CMB lensing BB revealed via cross-correlation to CIB.

Van Engelen et al 2014 (ACTPol), Hanson et al 2013 (SPT), POLARBEAR Collaboration 2013, 2014, see also BICEP2, 2014 & BICEP2/Keck/Planck 2015

# CLUSTERS LENSING the CMB

3.2σ; stack of 12,000 CMASS galaxies (SDSS/BOSS)

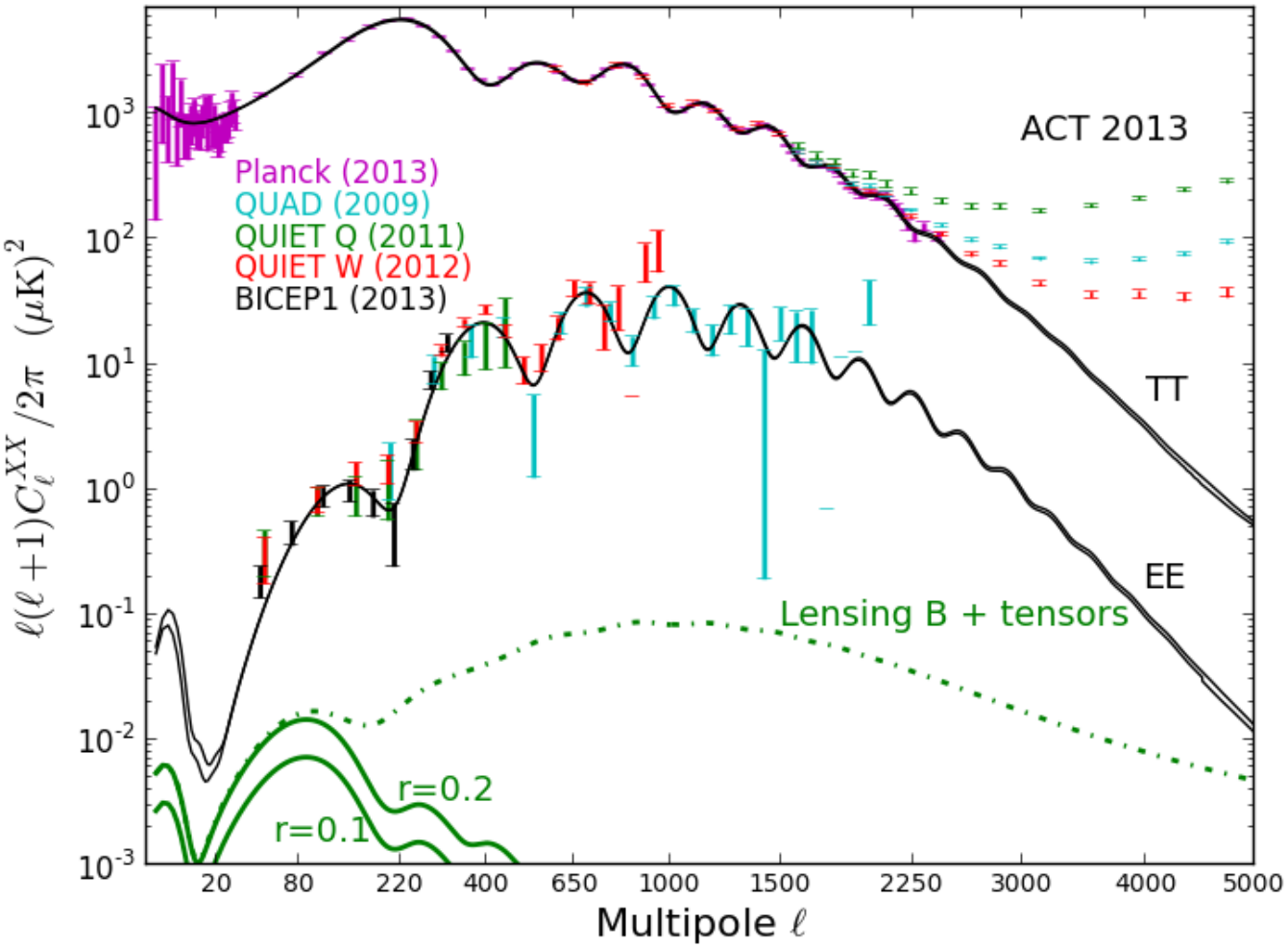



Madhavacheril et al – PRL 114, 151302, 2015. (ACTPol 2014 D1, D5, D6 fields.)

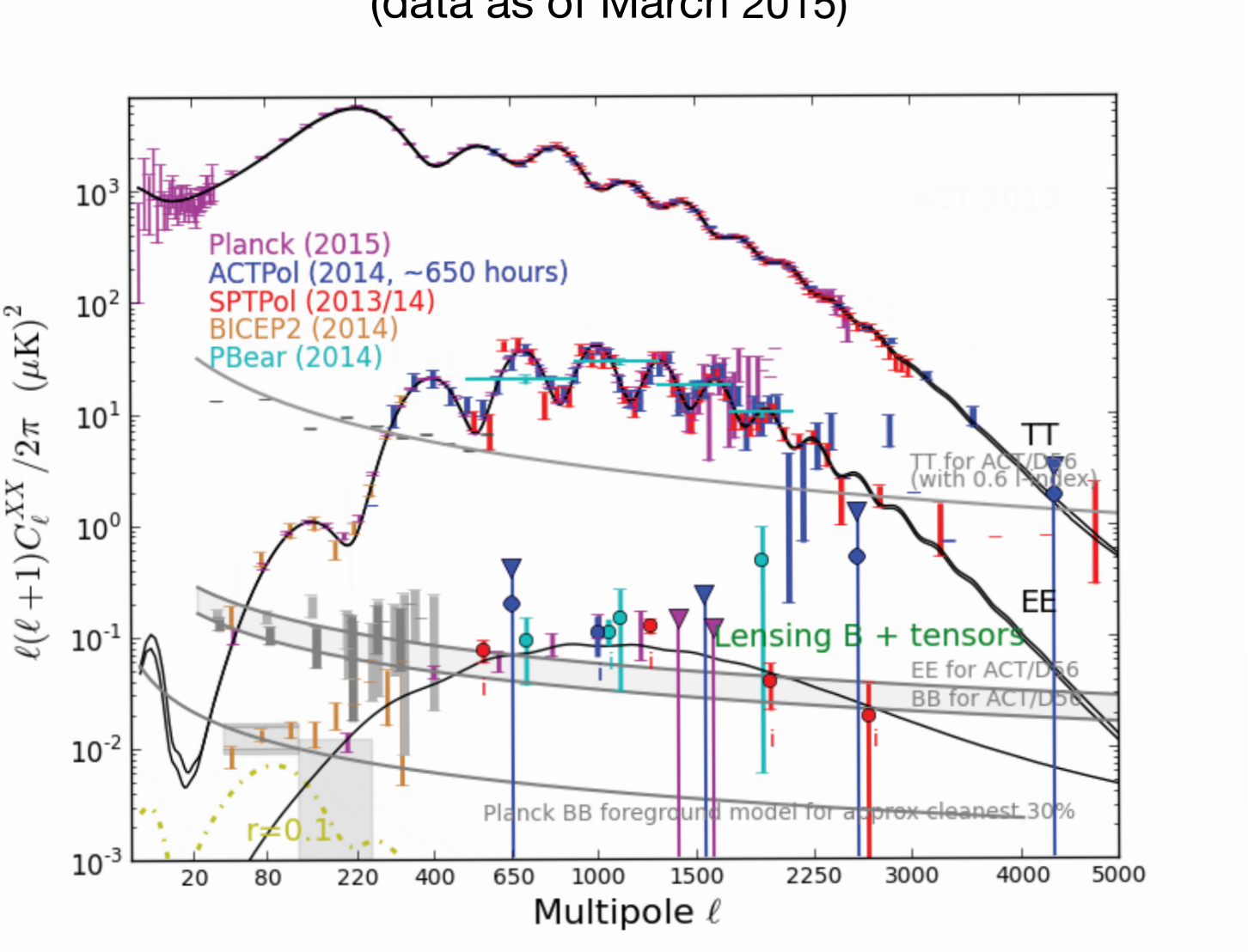
# CMB Status and Next Steps

(data as of 2013)



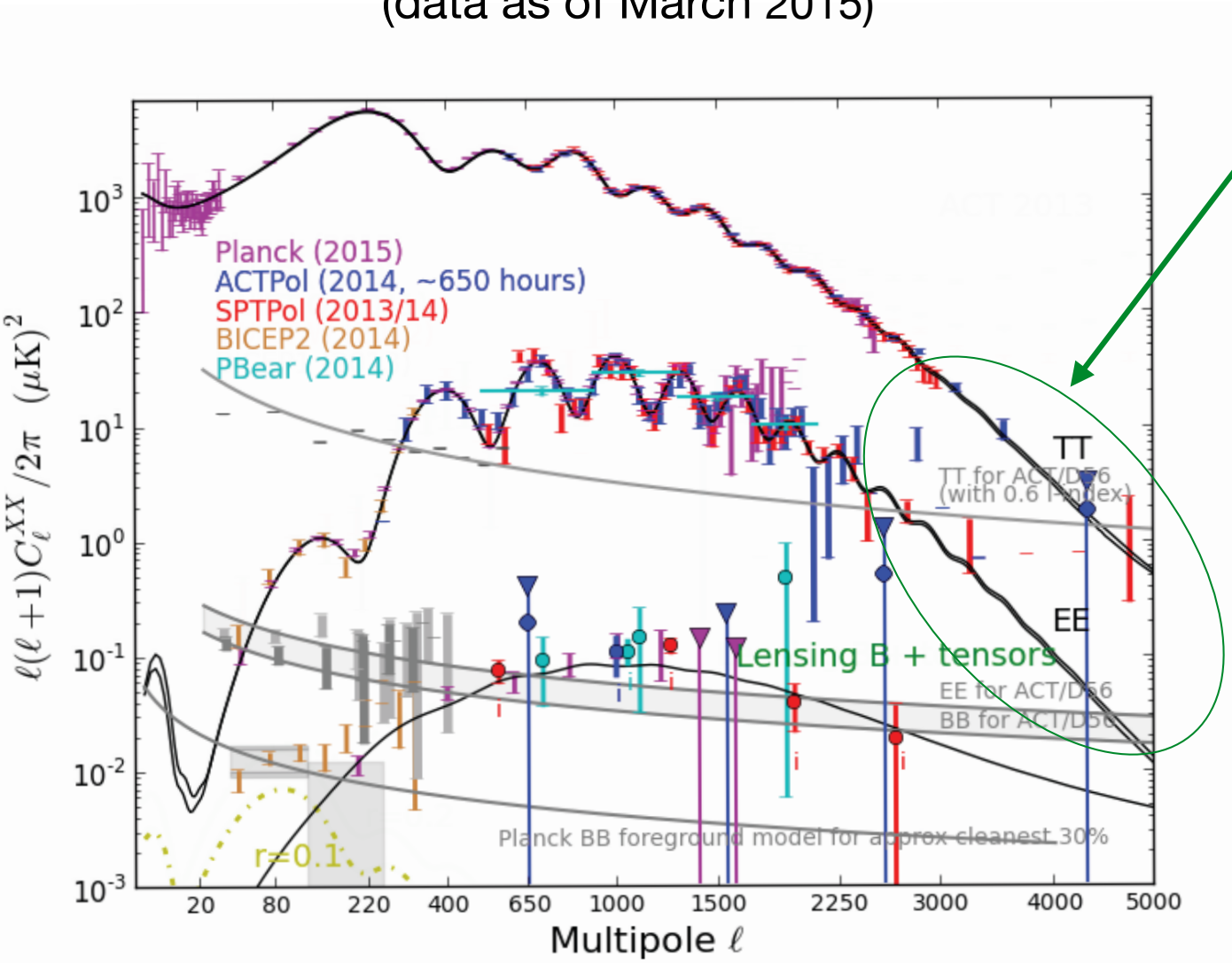
# CMB Status and Next Steps

(data as of March 2015)



# CMB Status and Next Steps

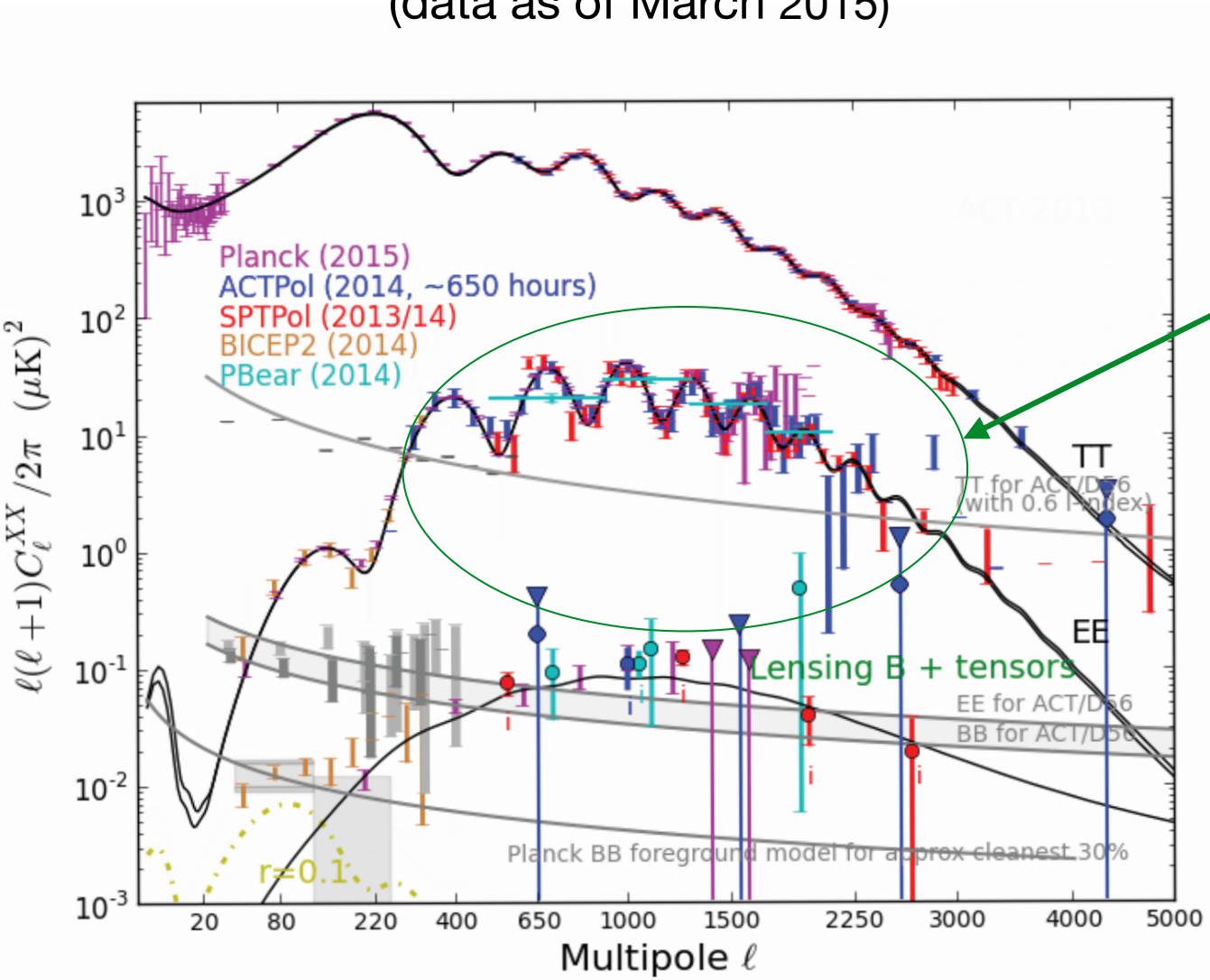
(data as of March 2015)




- **damping tale**
  - $N_{eff}$, $n_s$, $Y_{He}$
- **EE spectrum**
  - improved standard cosmology
- **Lensing**
  - $\sum m_\nu$, dark energy, dark matter
- **Large Scale B**
  - r

# CMB Status and Next Steps

(data as of March 2015)

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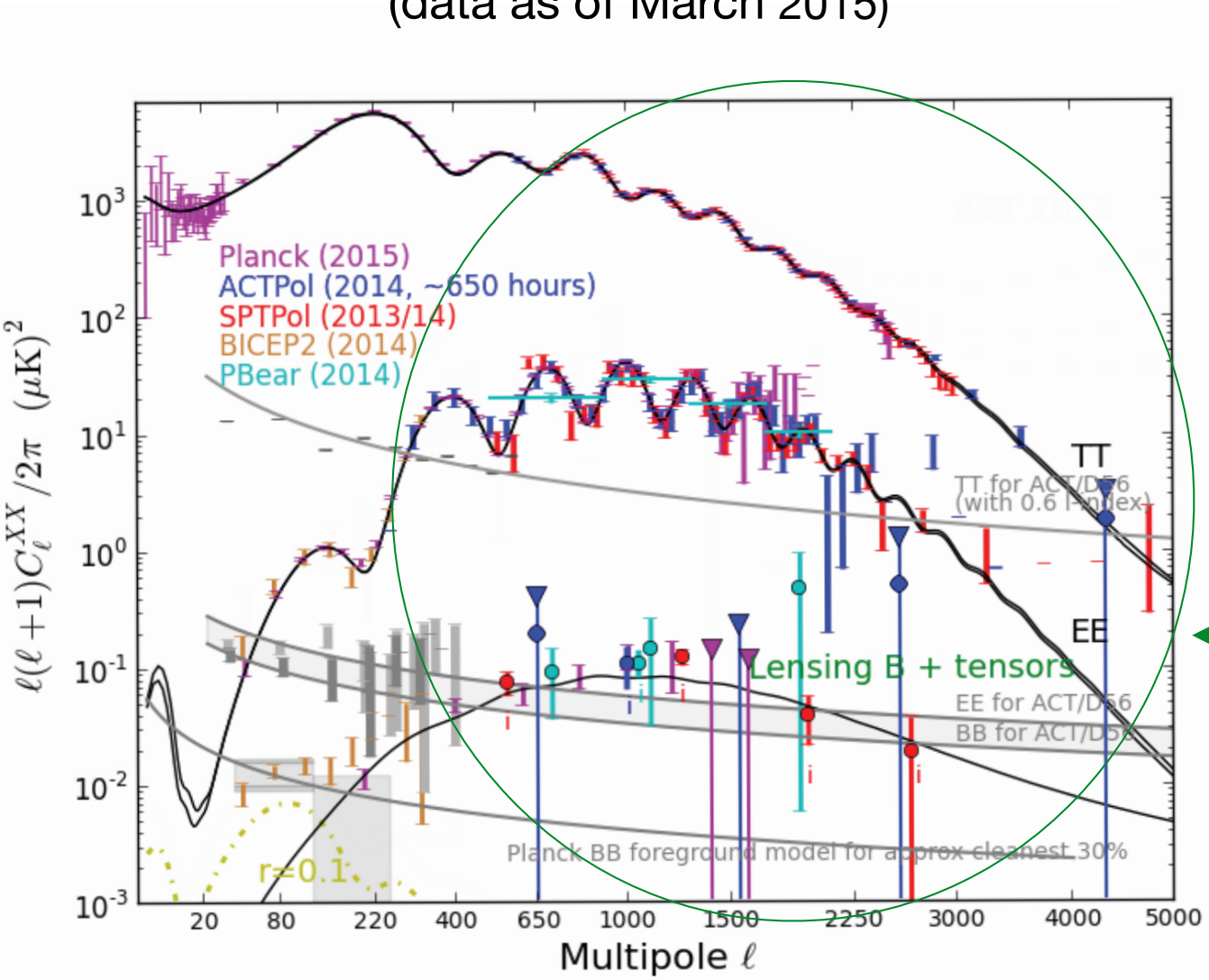
  - r

# CMB Status and Next Steps

(data as of March 2015)

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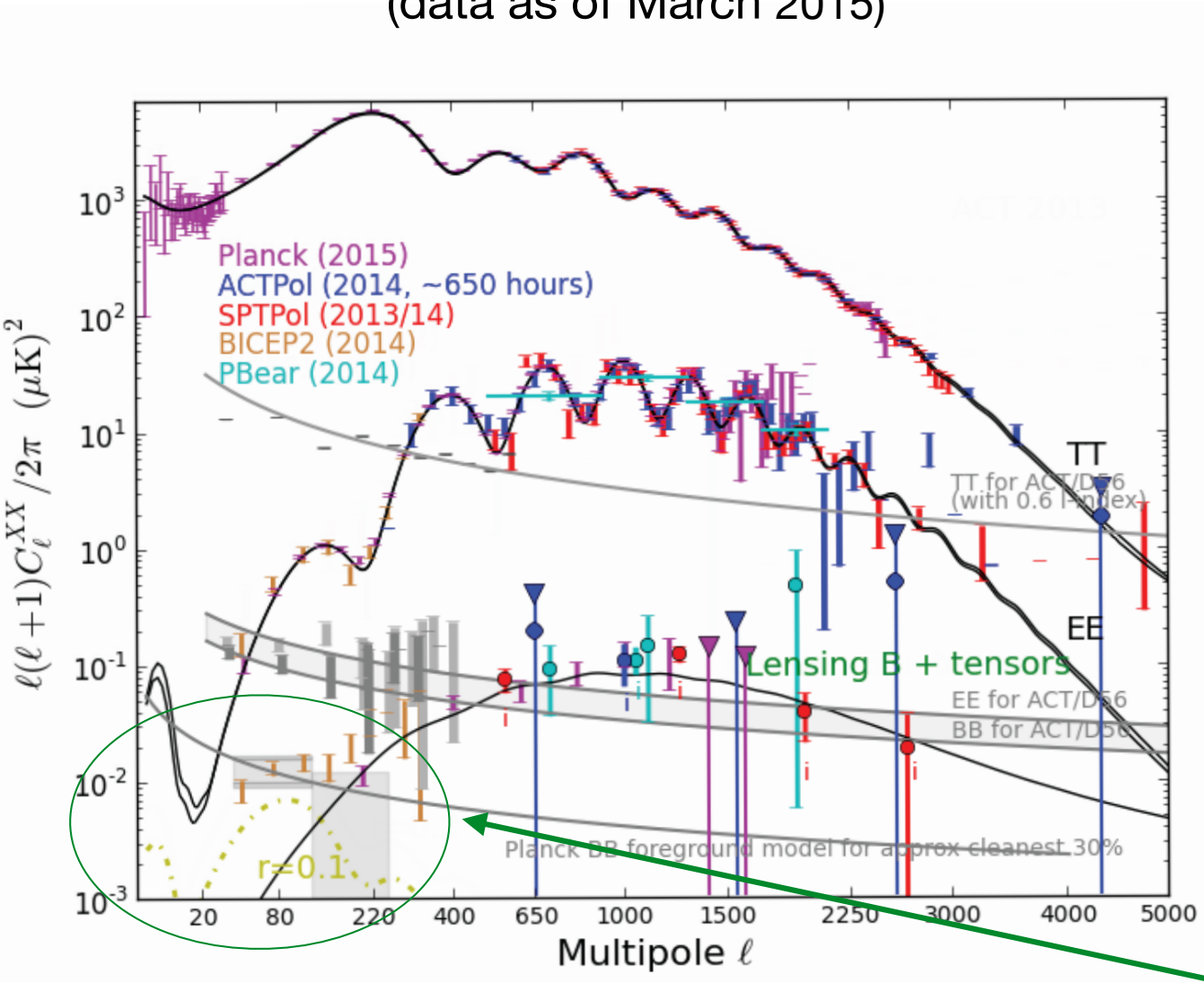
# CMB Status and Next Steps

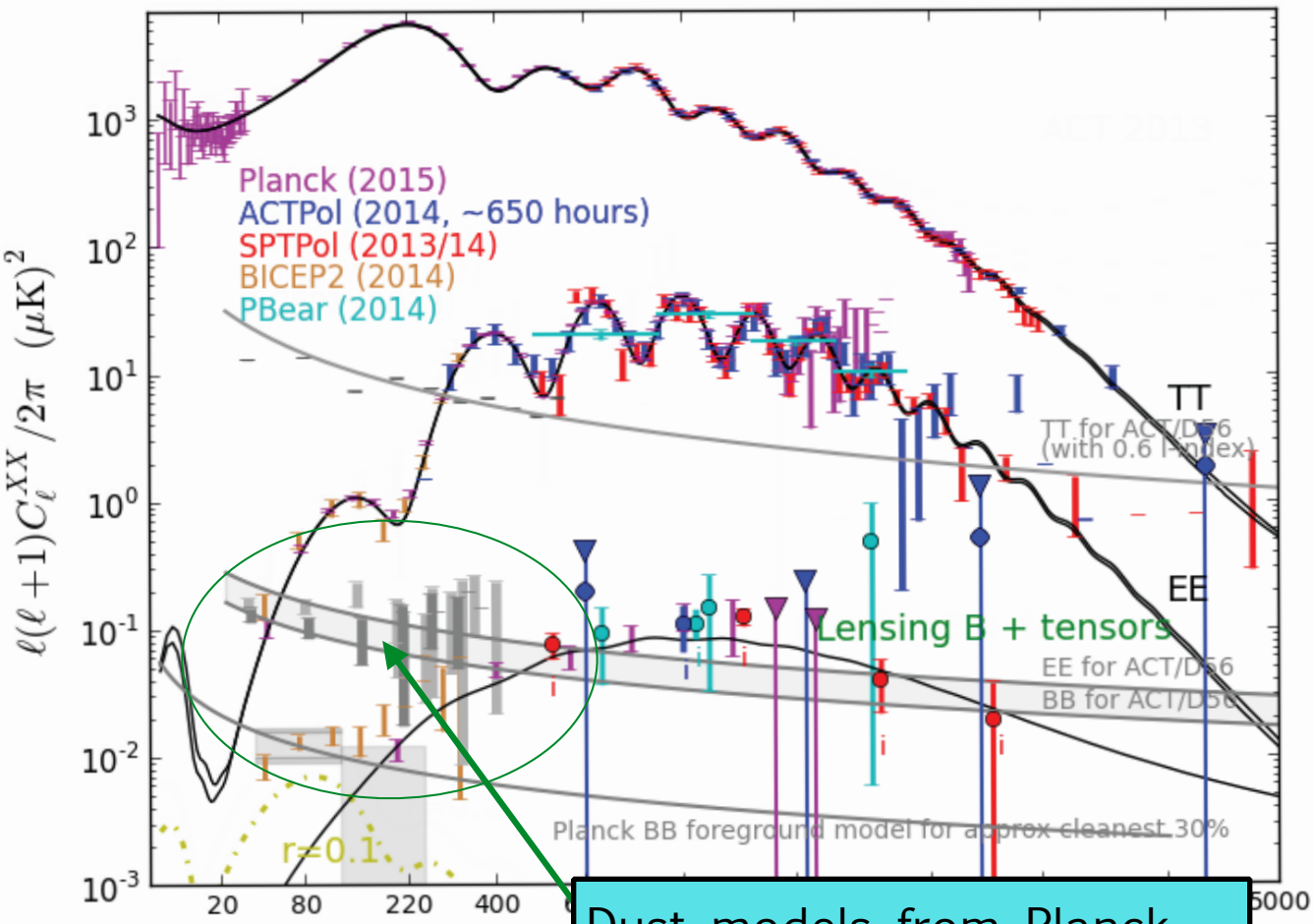
(data as of March 2015)




- **damping tale**
  - $N_{eff}$, $n_s$, $Y_{He}$
- **EE spectrum**
  - improved standard cosmology
- **Lensing**
  - $\sum m_\nu$, dark energy, dark matter
- **Large Scale B**
  - r

# CMB Status and Next Steps

(data as of March 2015)



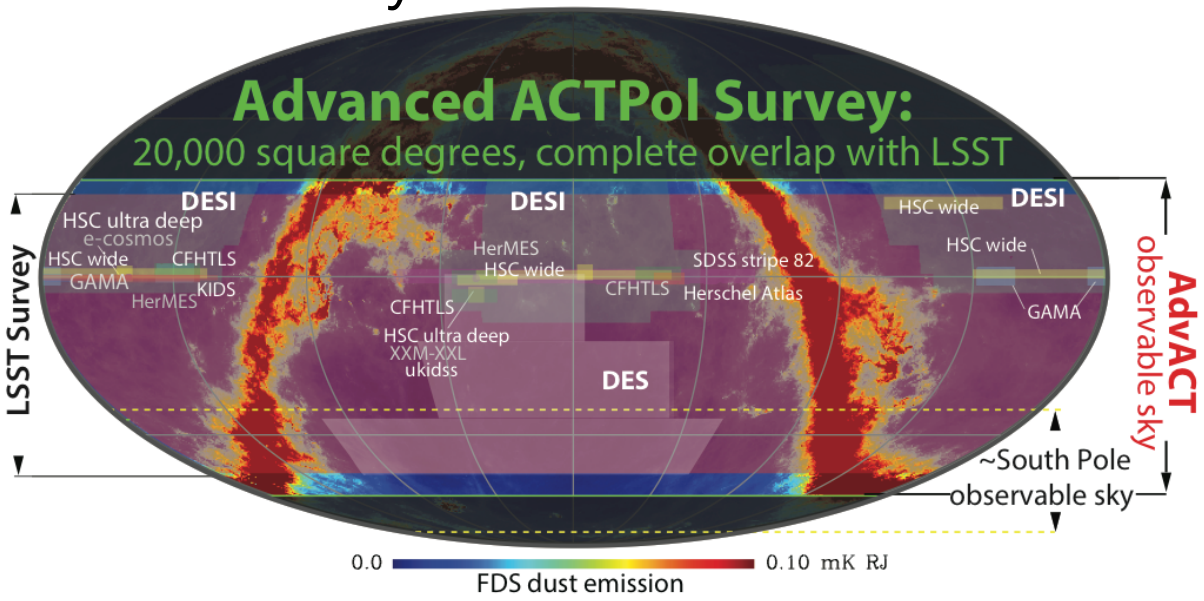

Dust models from Planck Paper XXX (1409.5378)

Polarized dust mandates multi-frequency data and internal consistency checks.

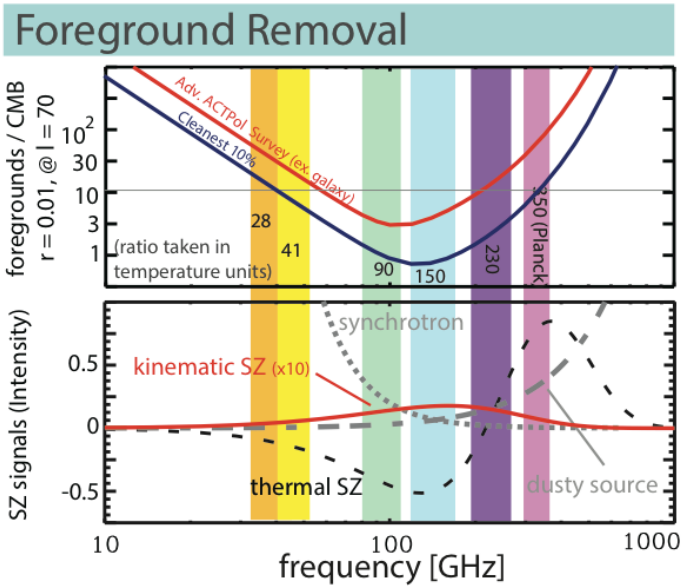
- **damping tale**
  - $N_{eff}$, $n_s$, $Y_{He}$
- **EE spectrum**
  - improved standard cosmology
- **Lensing**
  - $\sum m_\nu$, dark energy, dark matter
- **Large Scale B**
  - r

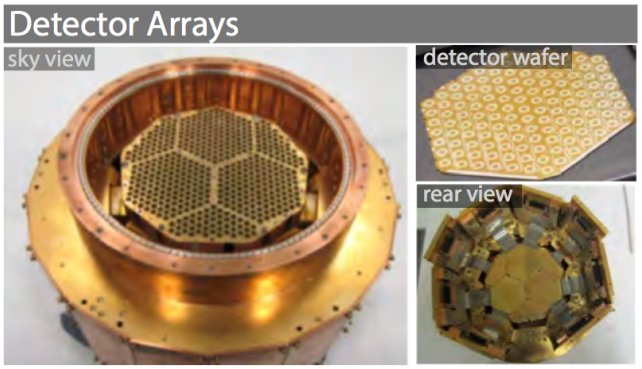
# Advanced ACTPol

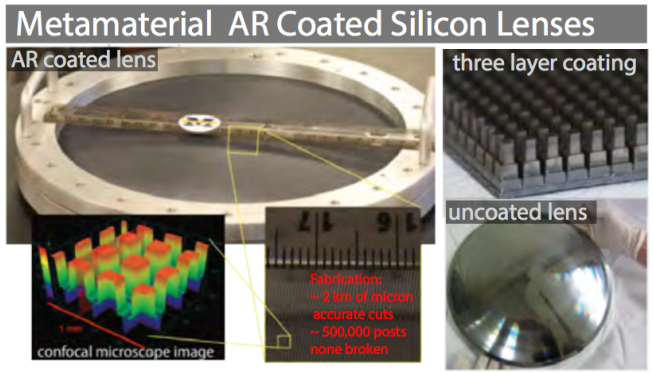
~ half the sky




5 frequency bands

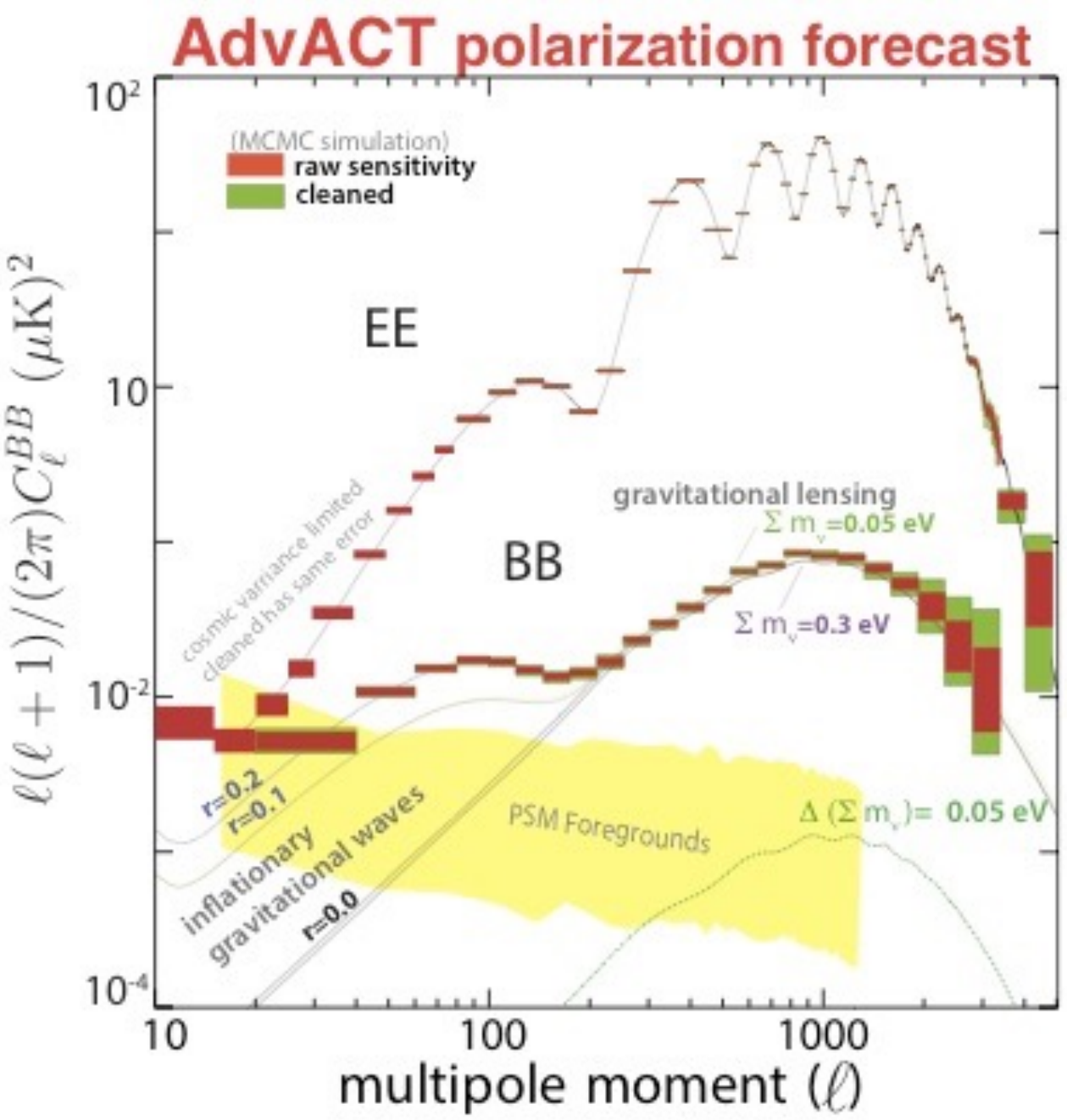


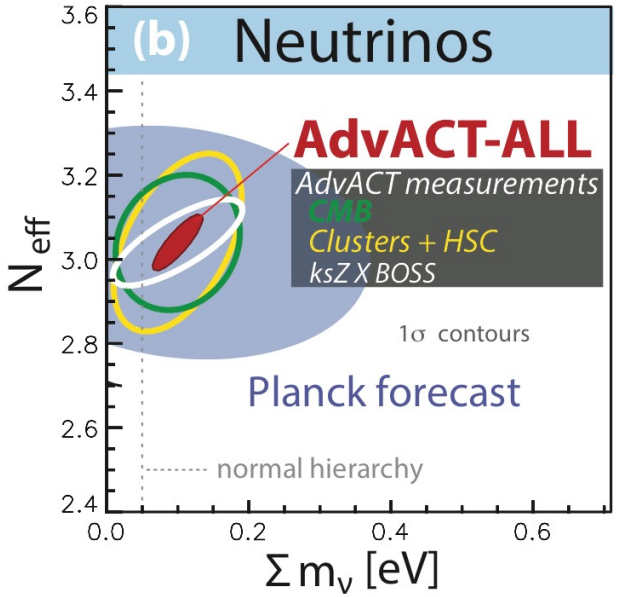




+ metamaterial Half Wave Plate

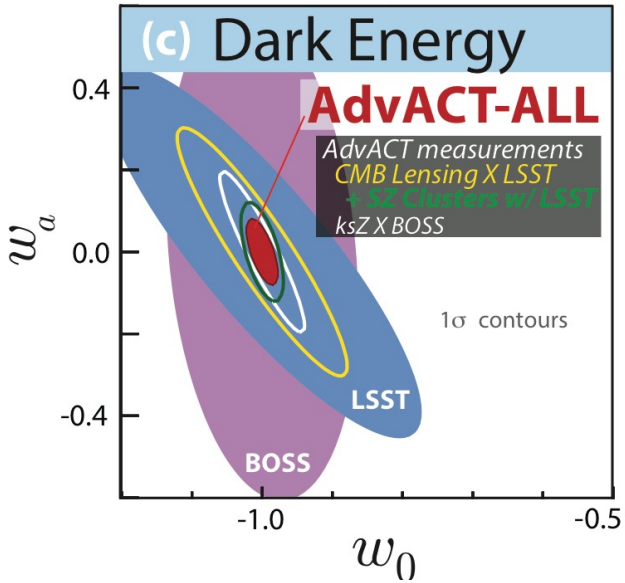
three scaled multichroic arrays to cover the 5 frequency bands




Projected to improve Planck limit on $\Sigma m_\nu$ by 10x!



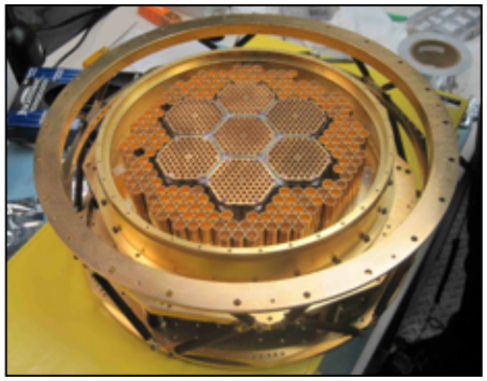

Projected to improve LSST's DE FOM by 20x!



***Maintaining Moore's Law: focal planes are saturated so must use parallel processing and multiple telescopes.***

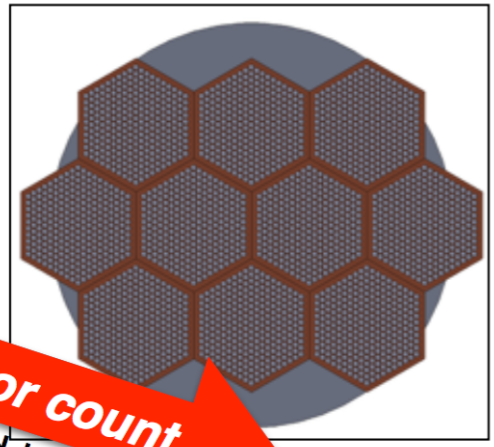
Stage II
**Now**
~1000 detectors

**ACTPol**

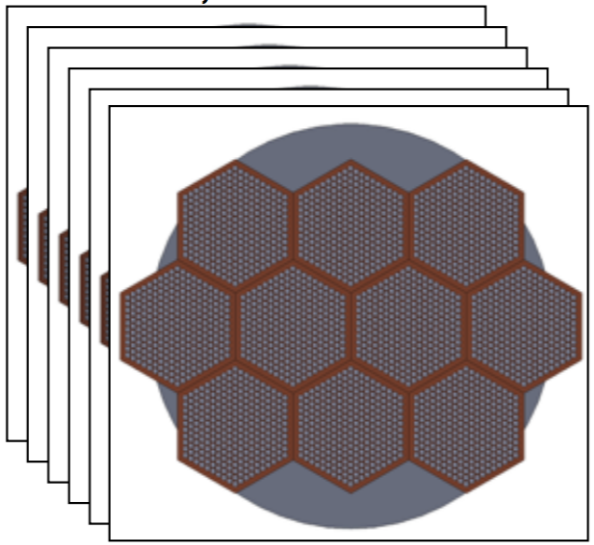


Stage III
**ramping up**
~10,000 detectors

**Advanced ACTPol**



Stage IV
**~2020 - CMB-S4**
~500,000 detectors



***increasing detector count***
(the trend being followed by all CMB projects, not just SPT)

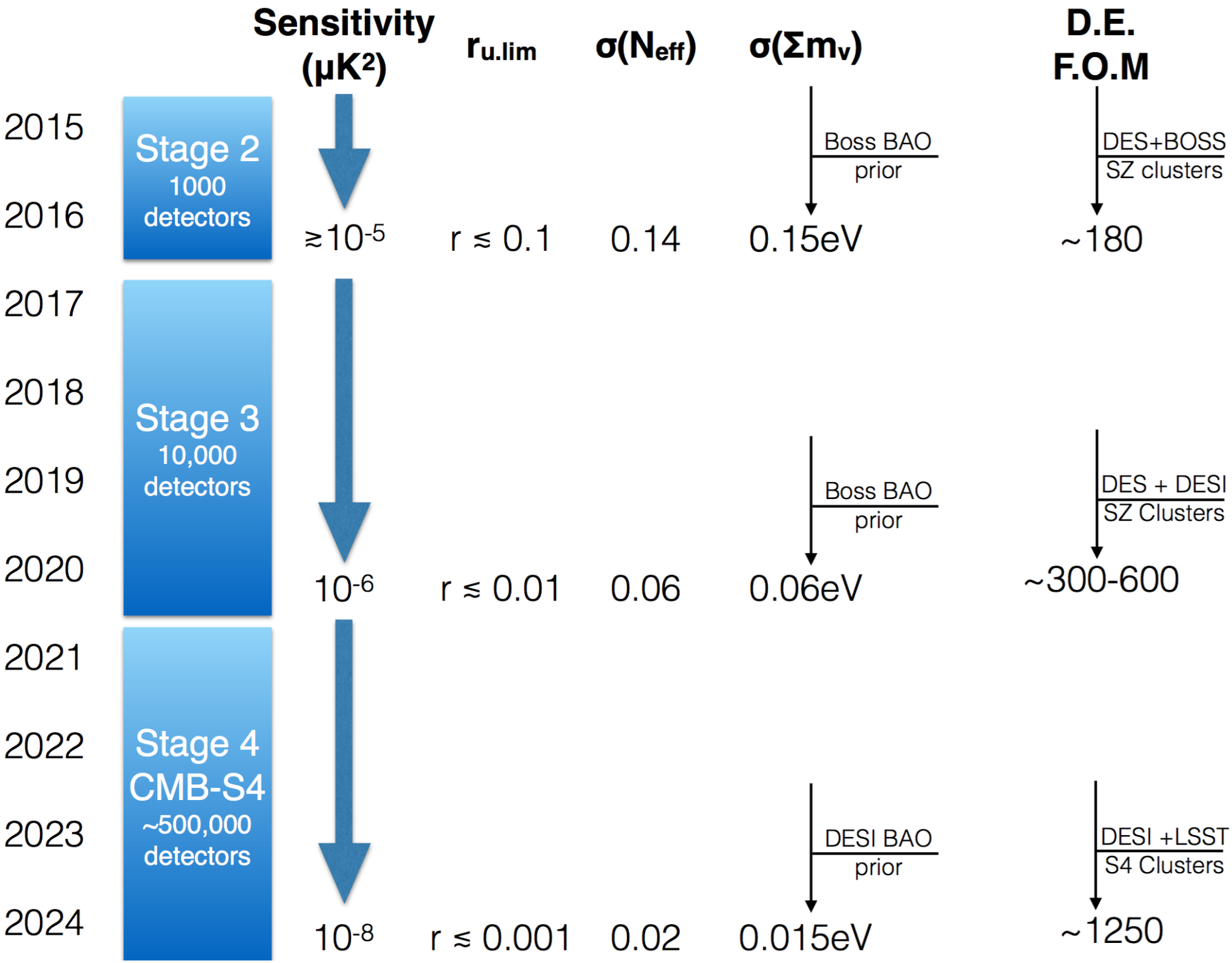
**CMB-S4: A program to put *O*(500,000) detectors spanning 30 - 300 GHz using multiple telescopes and sites to map ≳70% of sky.**


P5's timelines

CMB-S4 ramps up as LSST ramps down

| Project | 2015 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|
| Currently operating | | | | | |
| **Large Projects** | | | | | |
| Mu2e | | | | | |
| LHC: Phase 1 upgrade | | | | | |
| HL-LHC | | | | | |
| LBNF | | | | | |
| ILC | | | | | |
| **Medium and Small Projects** | | | | | |
| LSST | | | | | |
| DESI | | | | | |
| DM G2 | | | | | |
| DM G3 | | | | | |
| CMB S4 | | | | | |

# First CMB-S4 Community Meeting (two weeks ago) at the University of Michigan


Sensitivity (μK²)
r u.lim
σ(N eff)
σ(Σm ν)
D.E. F.O.M
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
Stage 2
1000 detectors
Stage 3
10,000 detectors
Stage 4
CMB-S4
~500,000 detectors
Boss BAO prior
DES+BOSS SZ clusters
≳10-5
r ≲ 0.1
0.14
0.15eV
~180
Boss BAO prior
DES + DESI SZ Clusters
10-6
r ≲ 0.01
0.06
0.06eV
~300-600
DESI BAO prior
DESI +LSST S4 Clusters
10-8
r ≲ 0.001
0.02
0.015eV
~1250

# The ACT Collaboration

# THANKS!