Cosmology in the New Millennium

David Spergel
Princeton University

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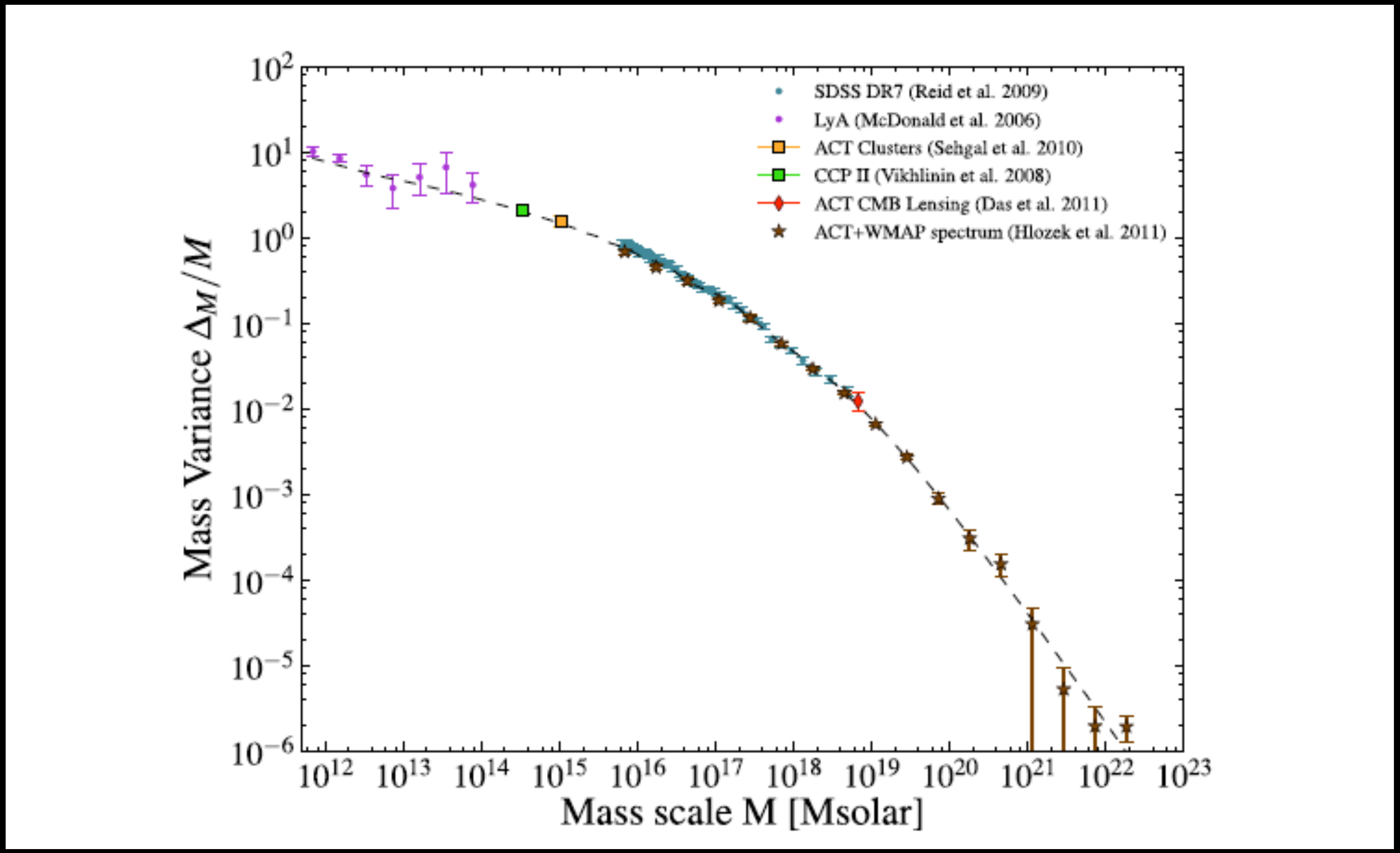
- What have we learned?
- What are the big questions?
- What does the current data tell us about these questions?

What have we learned?

- A simple model: a flat universe with nearly scale invariant adiabatic density fluctuations and composed of dark matter, dark energy, baryons, neutrinos and photons fit a host of data



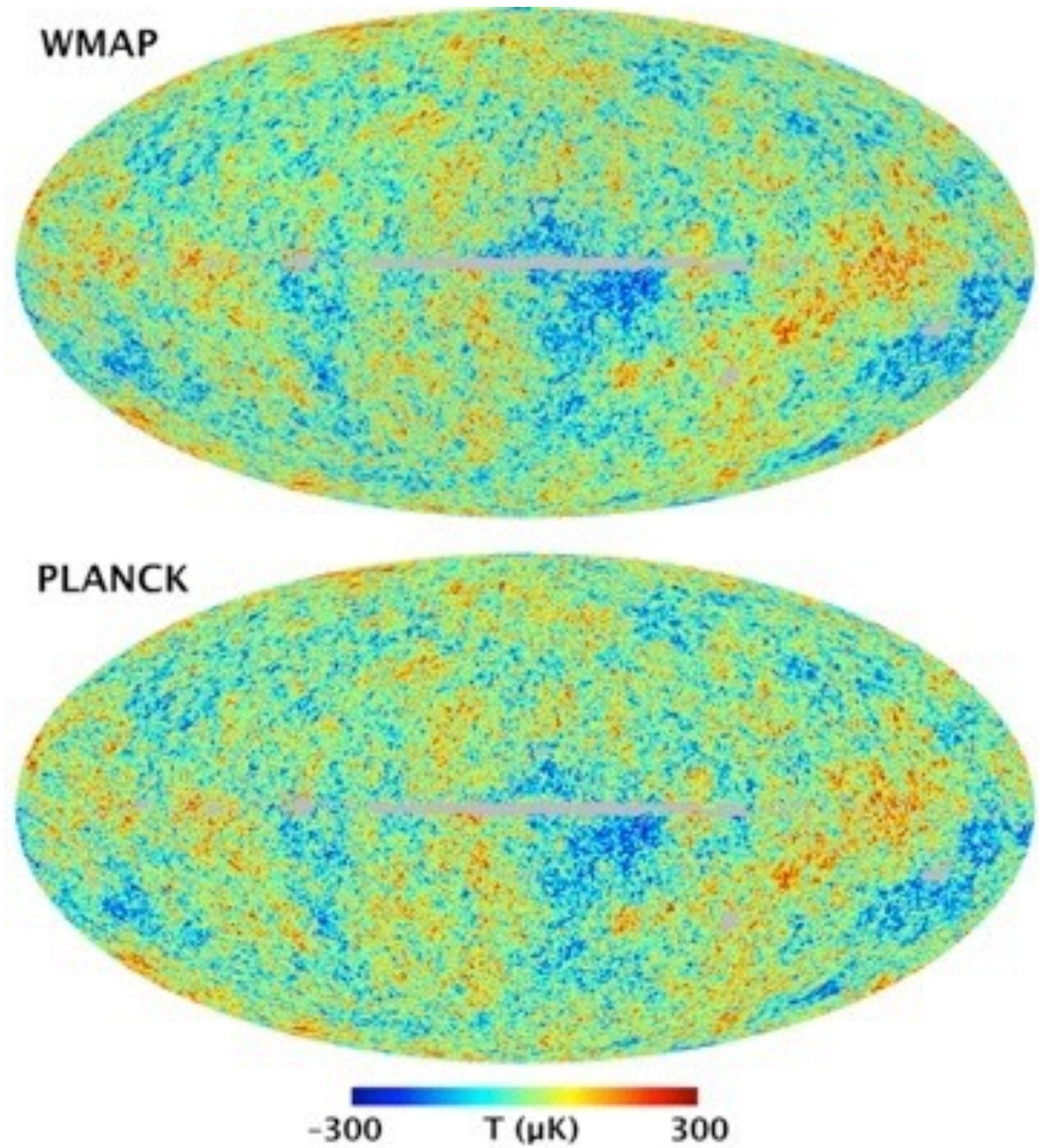
CMB Analysis

$$T(\hat{n}) = \sum a_{lm} Y_{lm}(\hat{n})$$

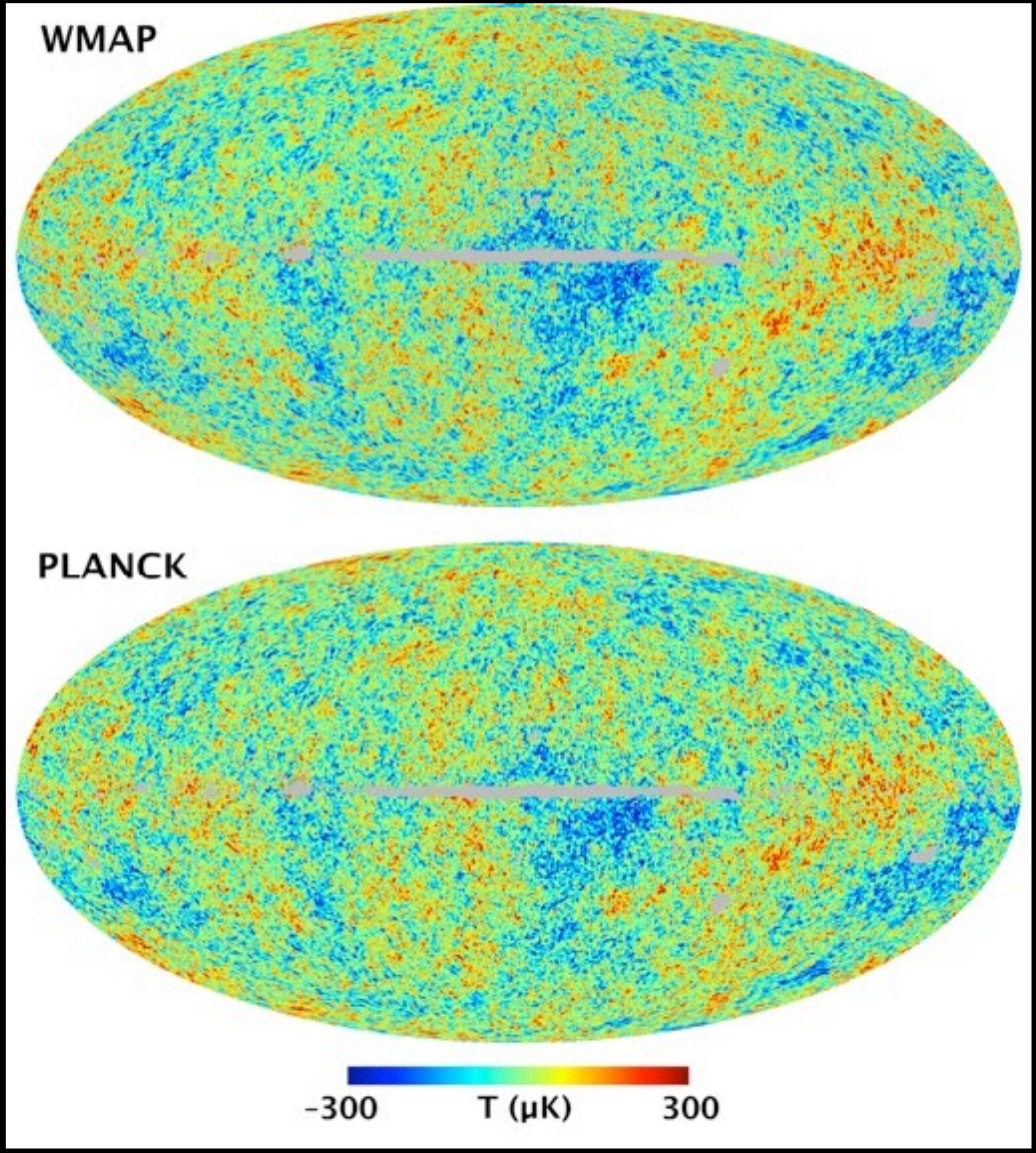
$$c_l = \frac{1}{2l+1} \sum_{m=-l}^{m=l} |a_{lm}|^2$$

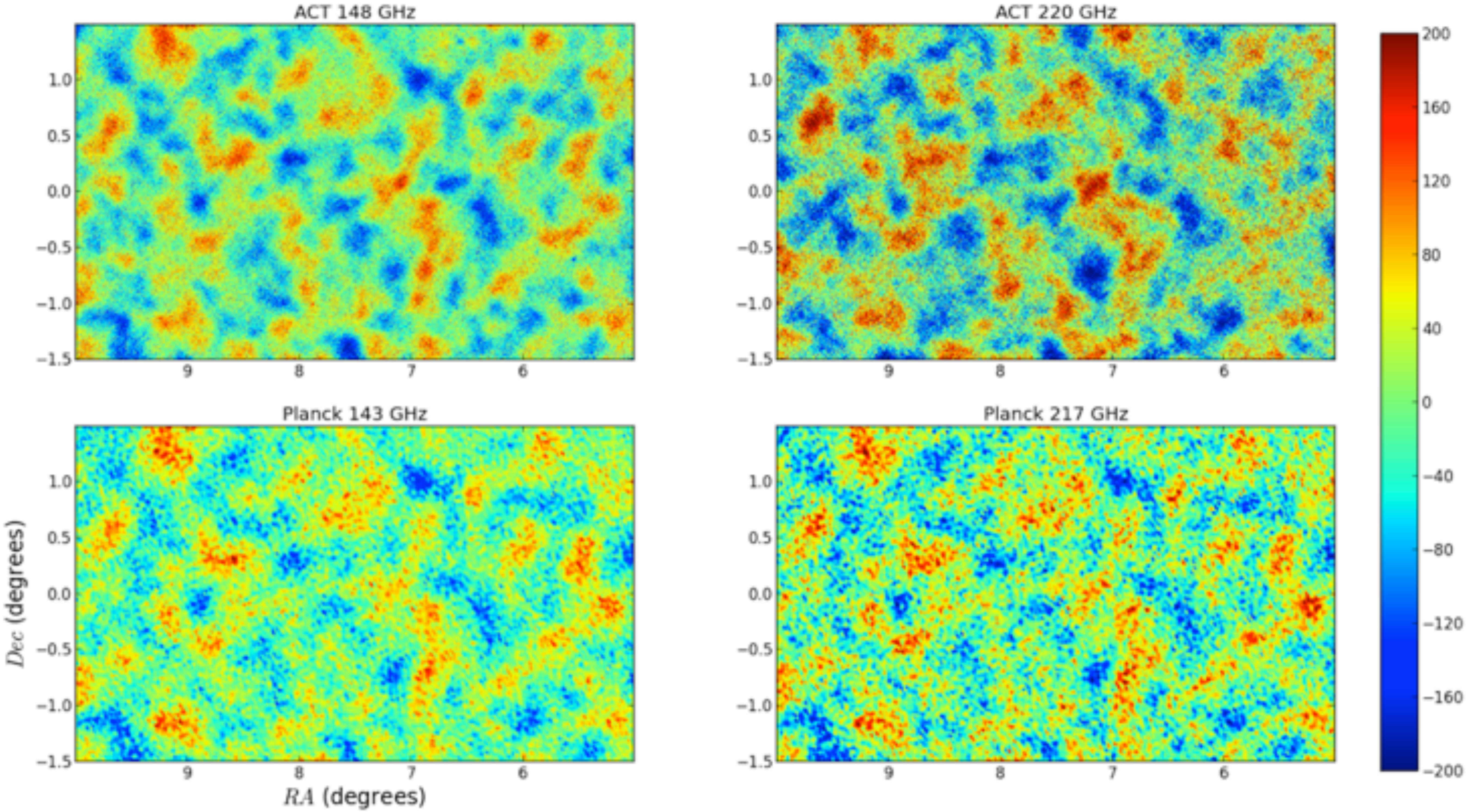
$$D_l = \frac{l(l+1)}{2\pi} c_l$$

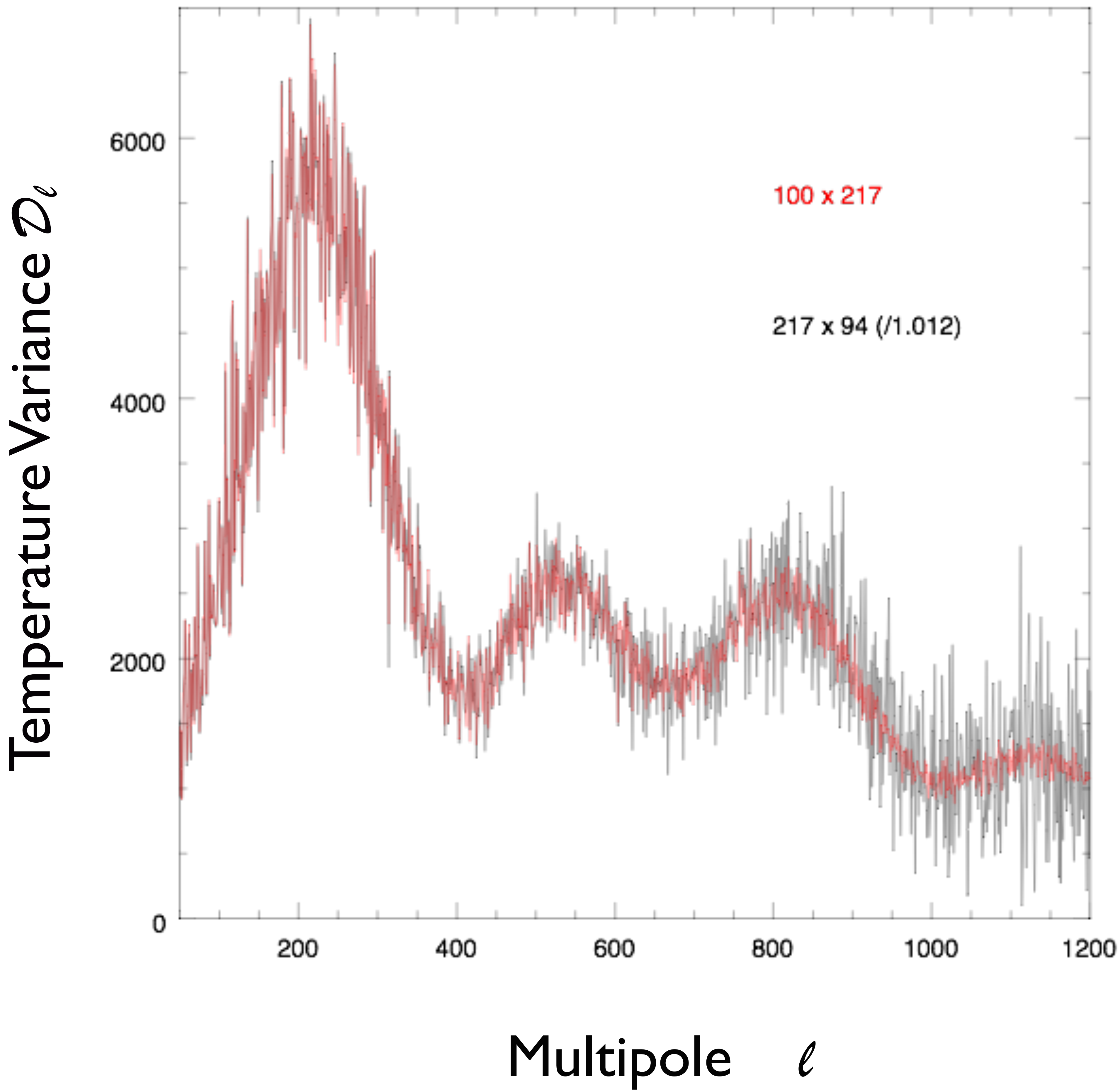
$$l \sim \frac{180^o}{\theta}$$



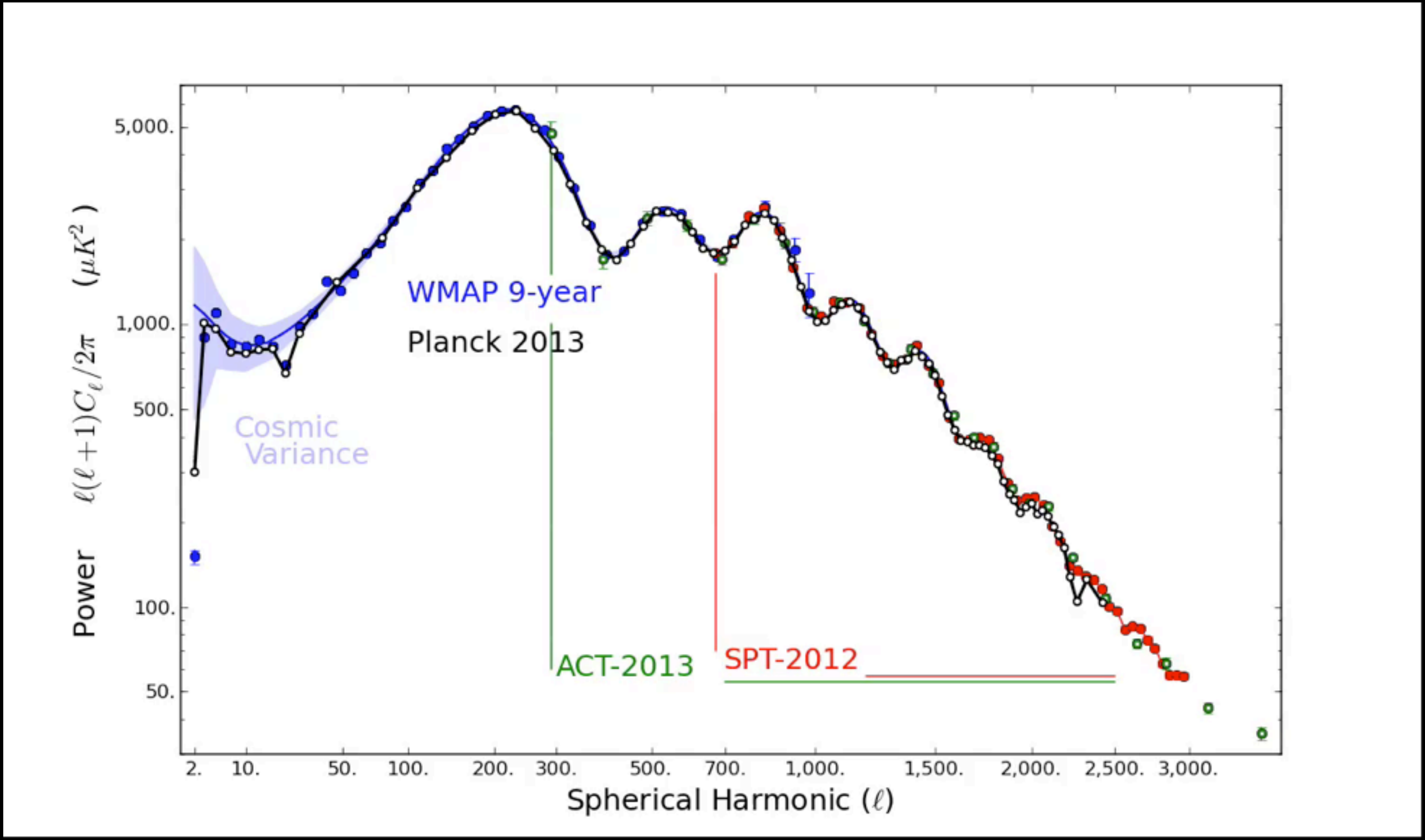
Planck and WMAP see the same sky



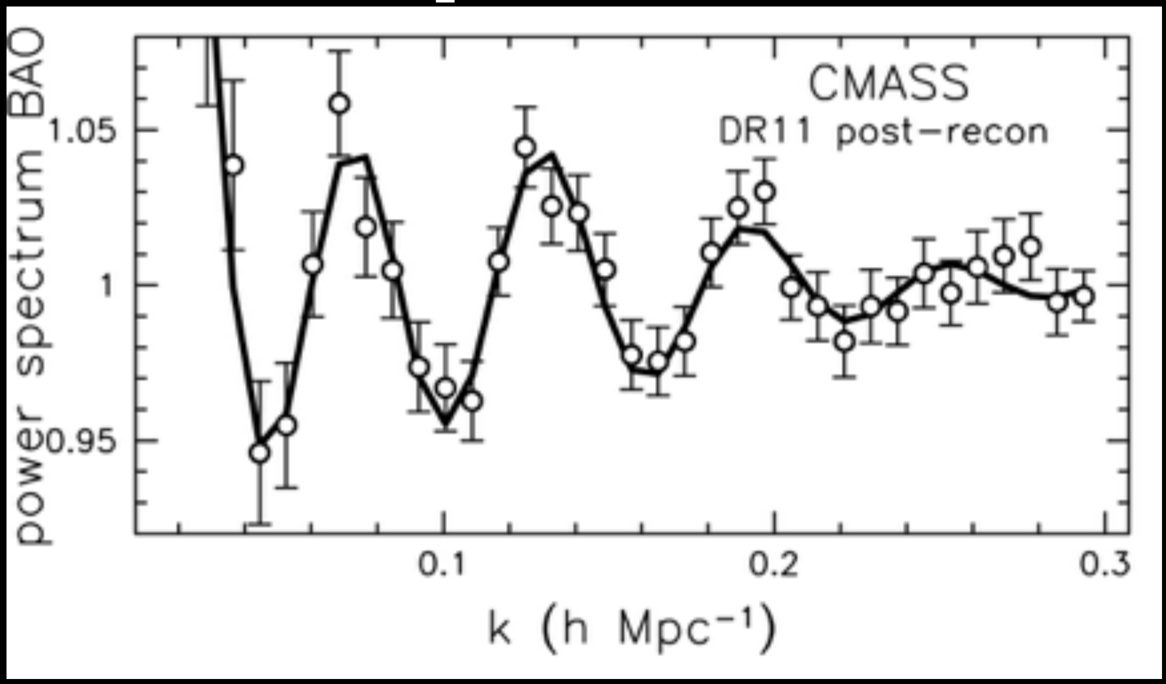

ACT 148 GHz
ACT 220 GHz
Planck 143 GHz
Planck 217 GHz
Dec (degrees)
RA (degrees)
1.0
0.5
0.0
−0.5
−1.0
−1.5
9
8
7
6
200
160
120
80
40
0
−40
−80
−120
−160
−200

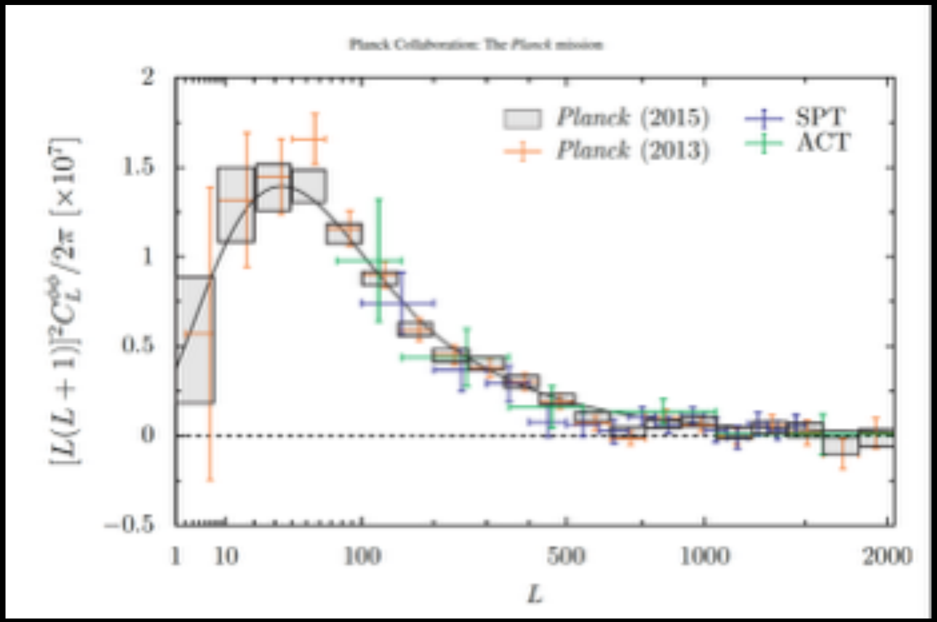

100 x 217
217 x 94 (/1.012)
0
2000
4000
6000
200
400
600
800
1000
1200
Temperature Variance $\mathcal{D}_\ell$
Multipole ℓ

LCDM Model Fits CMB

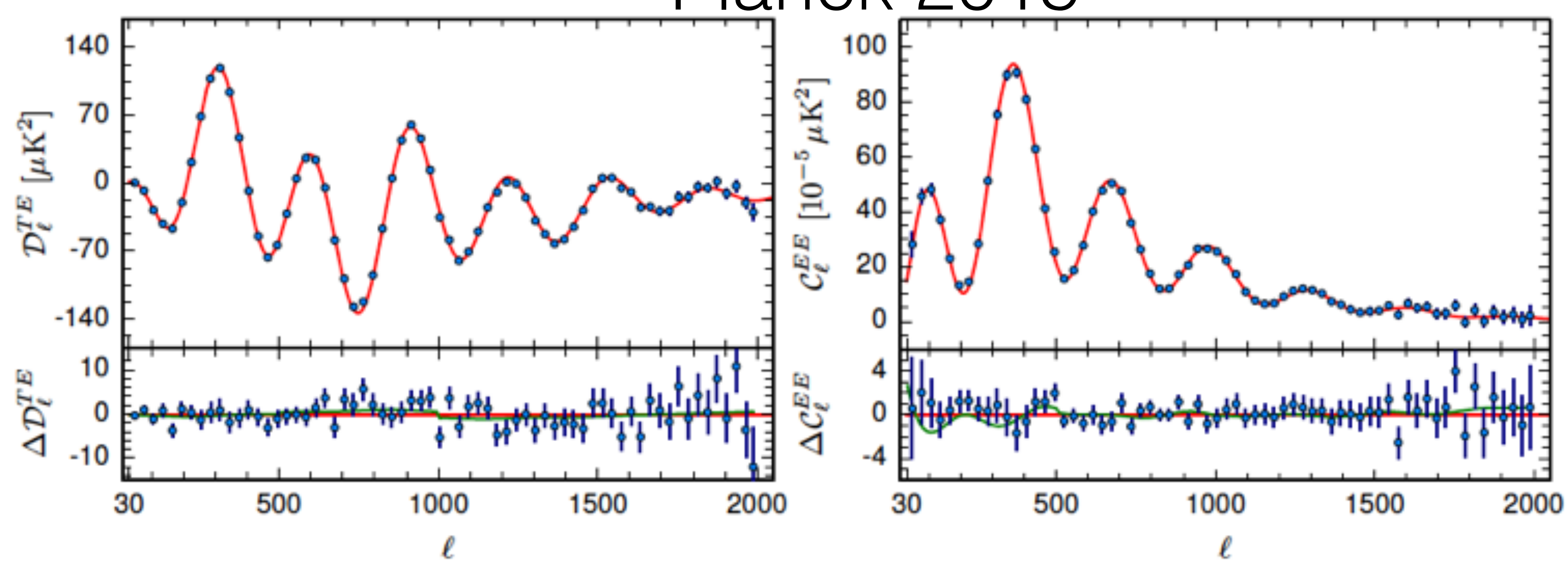


Multiple Precision Probes





Planck 2015



(Mostly) Consistent Parameters

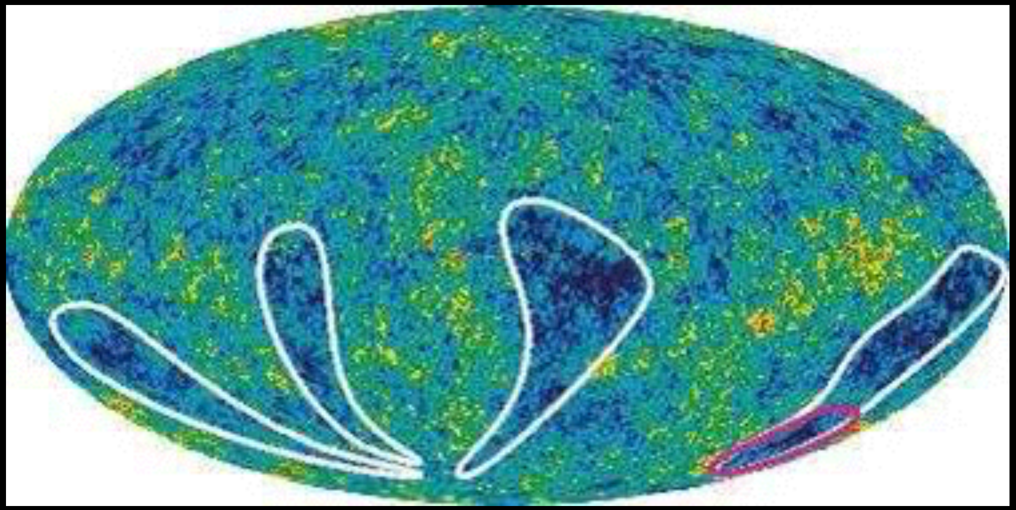
		WMAP9+ACT	PLANCK+WP
Spectral Index	n	0.973 ± 0.011	0.9603±0.0073
Matter Density	$10\ \Omega_m h^2$	1.146±0.044	1.199±0.027
Baryon Density	$100\ \Omega_b h^2$	2.260±0.040	2.205±0.028
Hubble Constant	H_0	69.7±2.0	67.3±1.2

Shift relative to WMAP+SPT parameters larger

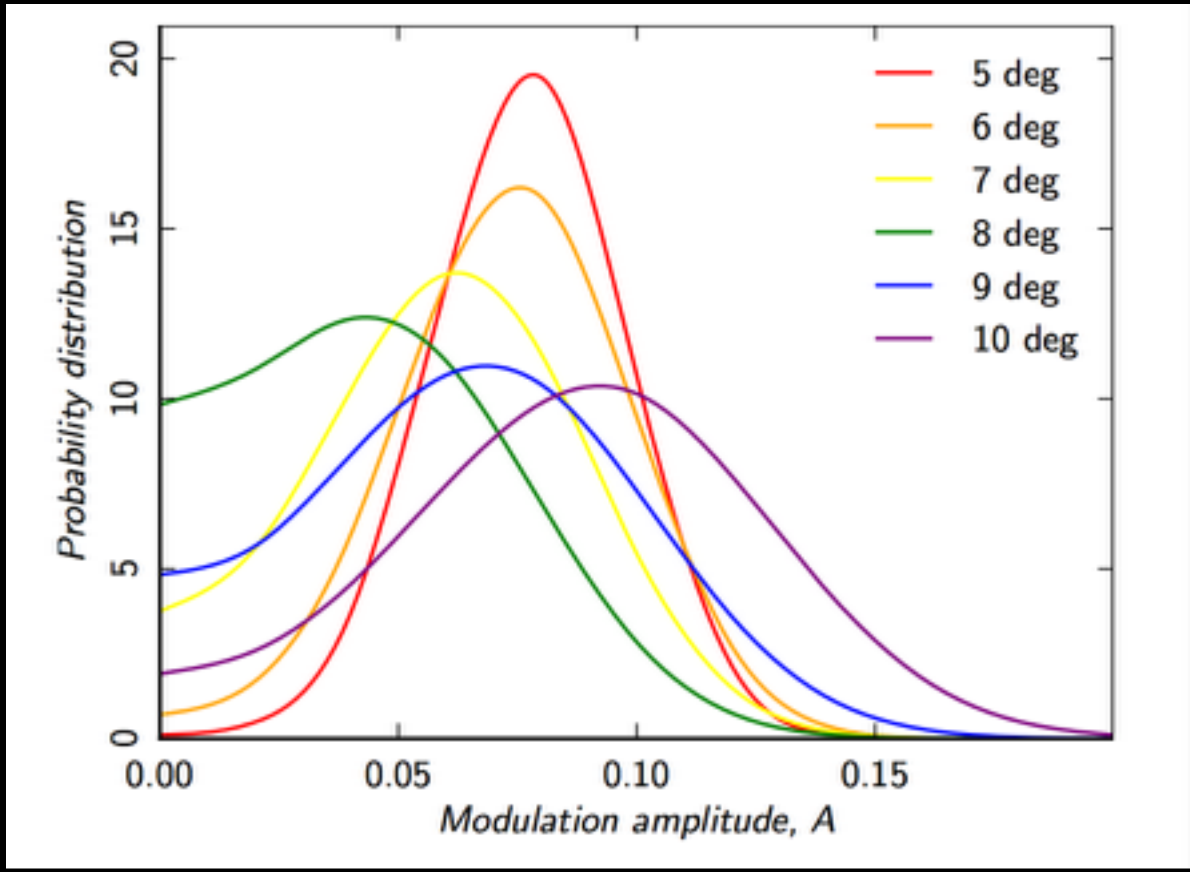
Consistent Cosmology

- Supernova data
- Large-scale structure data (galaxies, quasars, Lyman alpha forest)
- Gravitational Lensing (CMB + Optical)
- Stellar, Nucleosynthesis and Cosmology Ages
- Big Bang Nucleosynthesis
- Cluster counts

Hemispheric Asymmetries

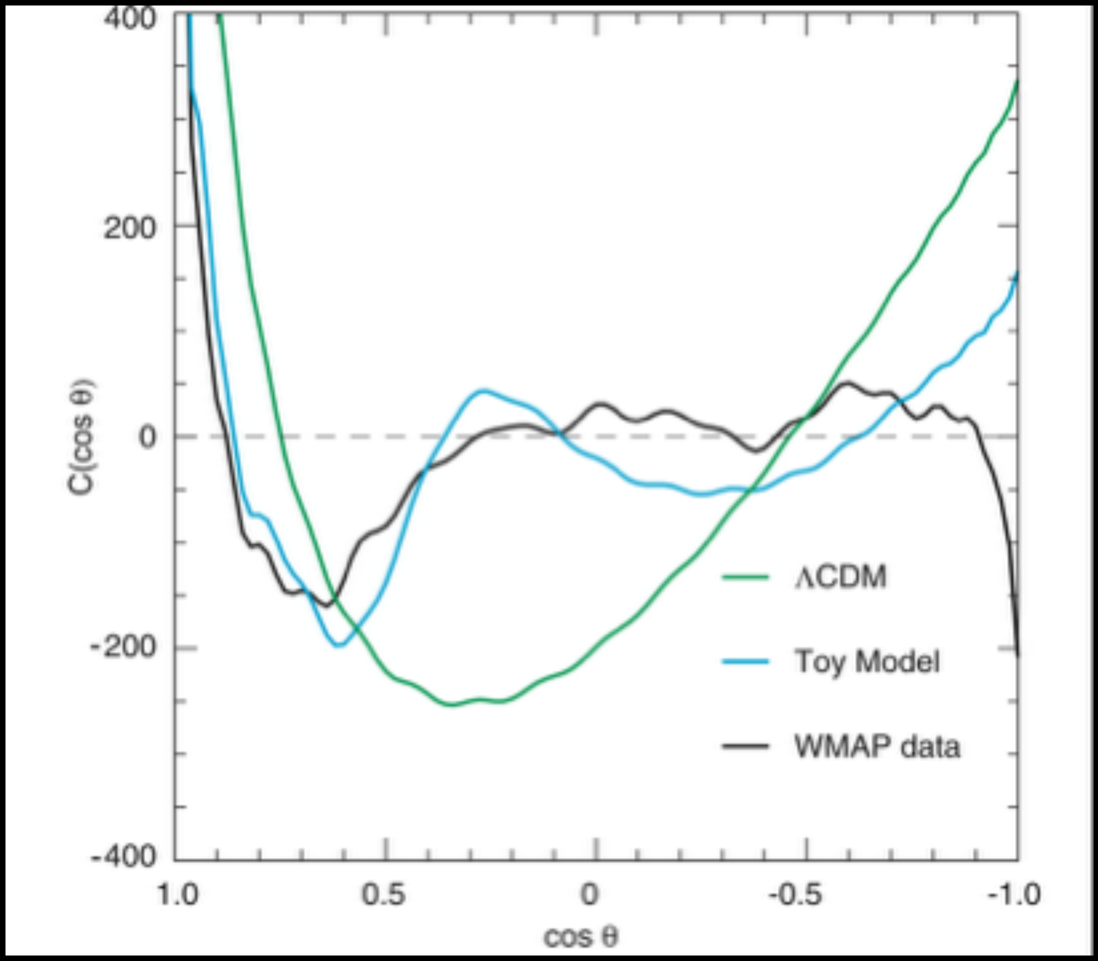


WMAP

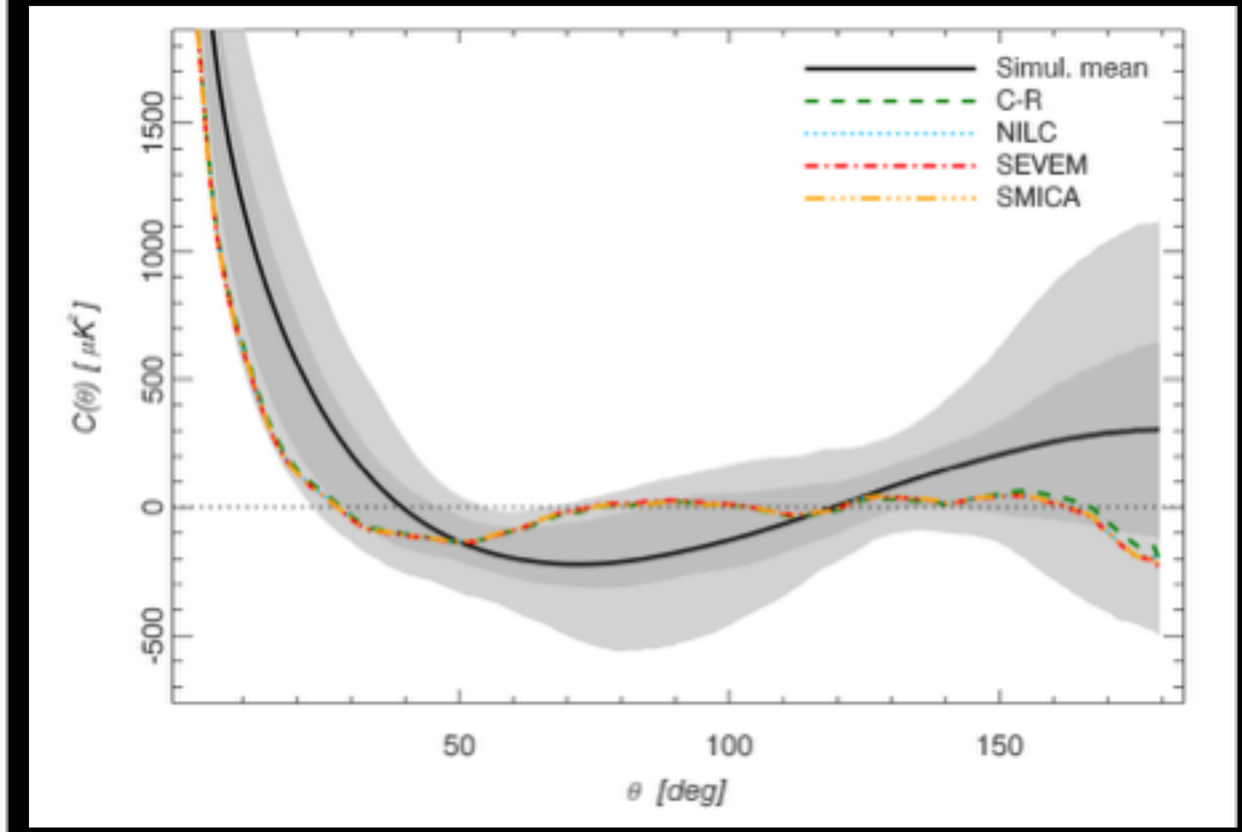


Eriksen et al. 2007 (WMAP3)
Planck 2013 XXII

Lack of Large Scale Power



Spergel et al. 2003



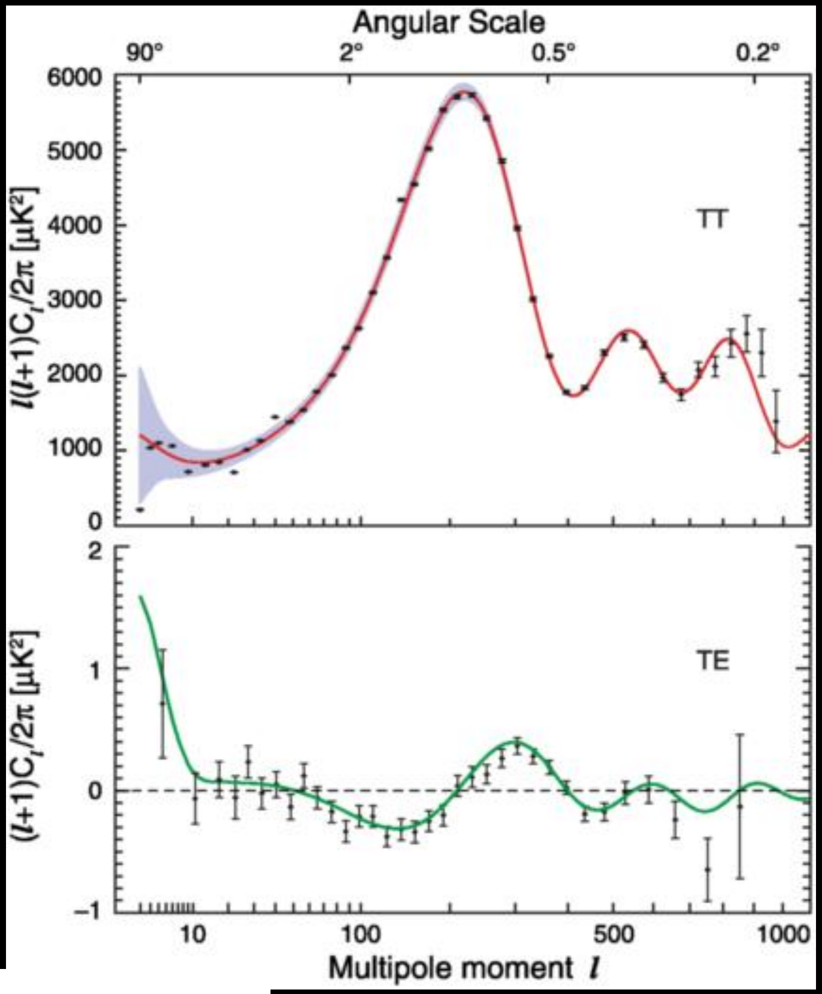
Planck 2013 XXII

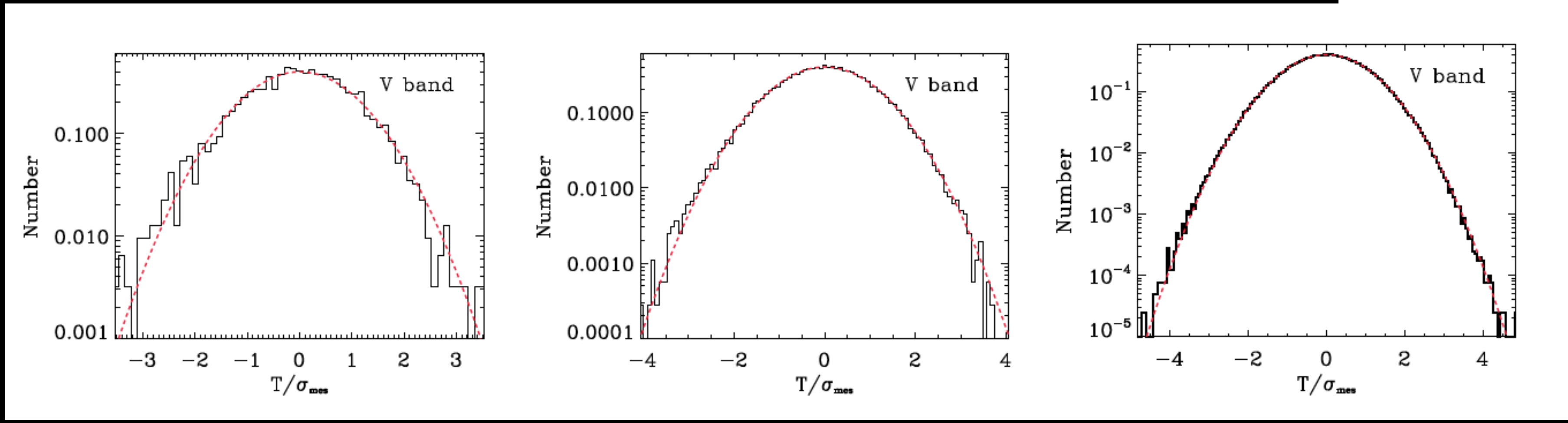
Big Questions

- What is the origin of the fluctuations that grow to form galaxies? How did the universe begin?
- Why is the universe accelerating?
- What is the dark matter?
- What is the origin of the asymmetry between baryons and anti-baryons

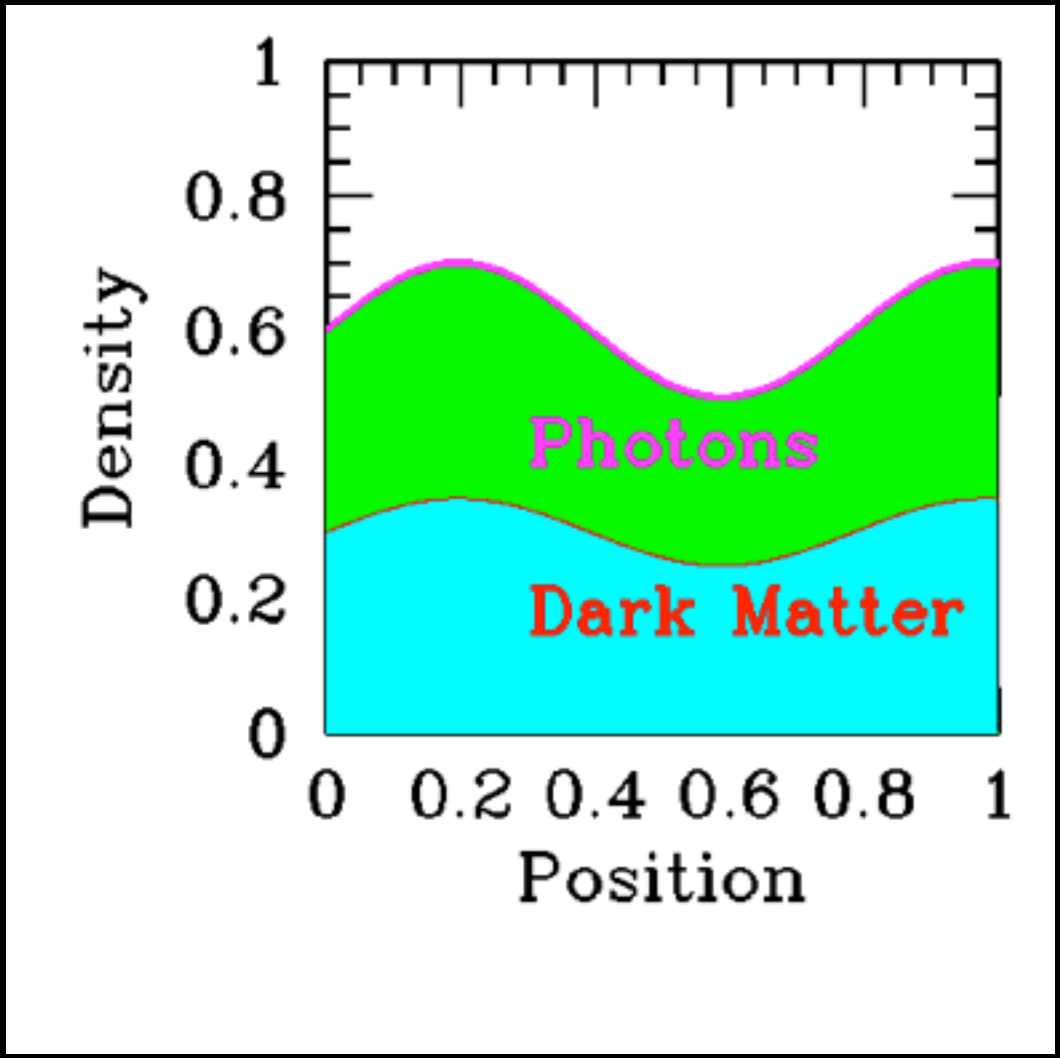
Hints from CMB on the Origin of Fluctuations

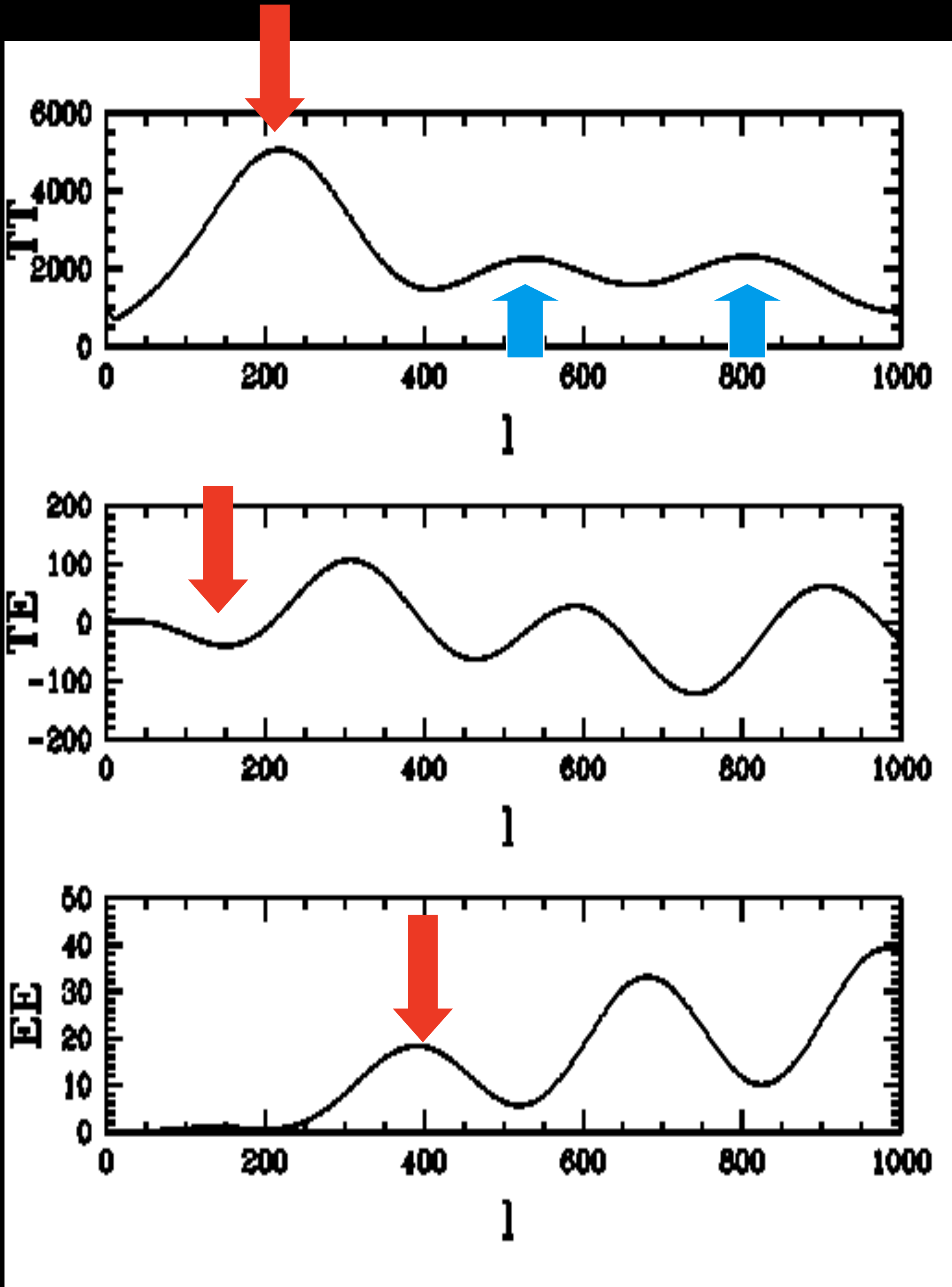
- Fluctuations are gaussian, nearly-scale invariant, adiabatic and SUPER-HORIZON
- The fluctuations were either generated in an accelerating phase or were imprinted at the big bang





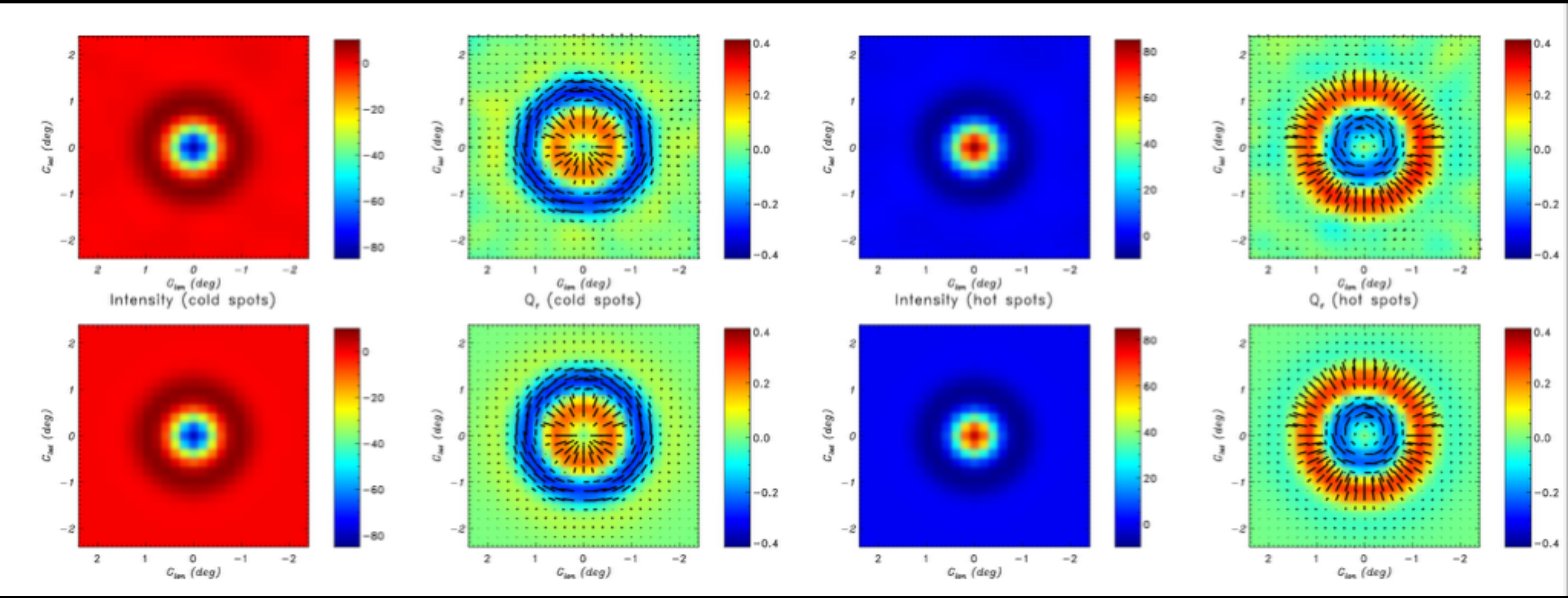
WMAP3





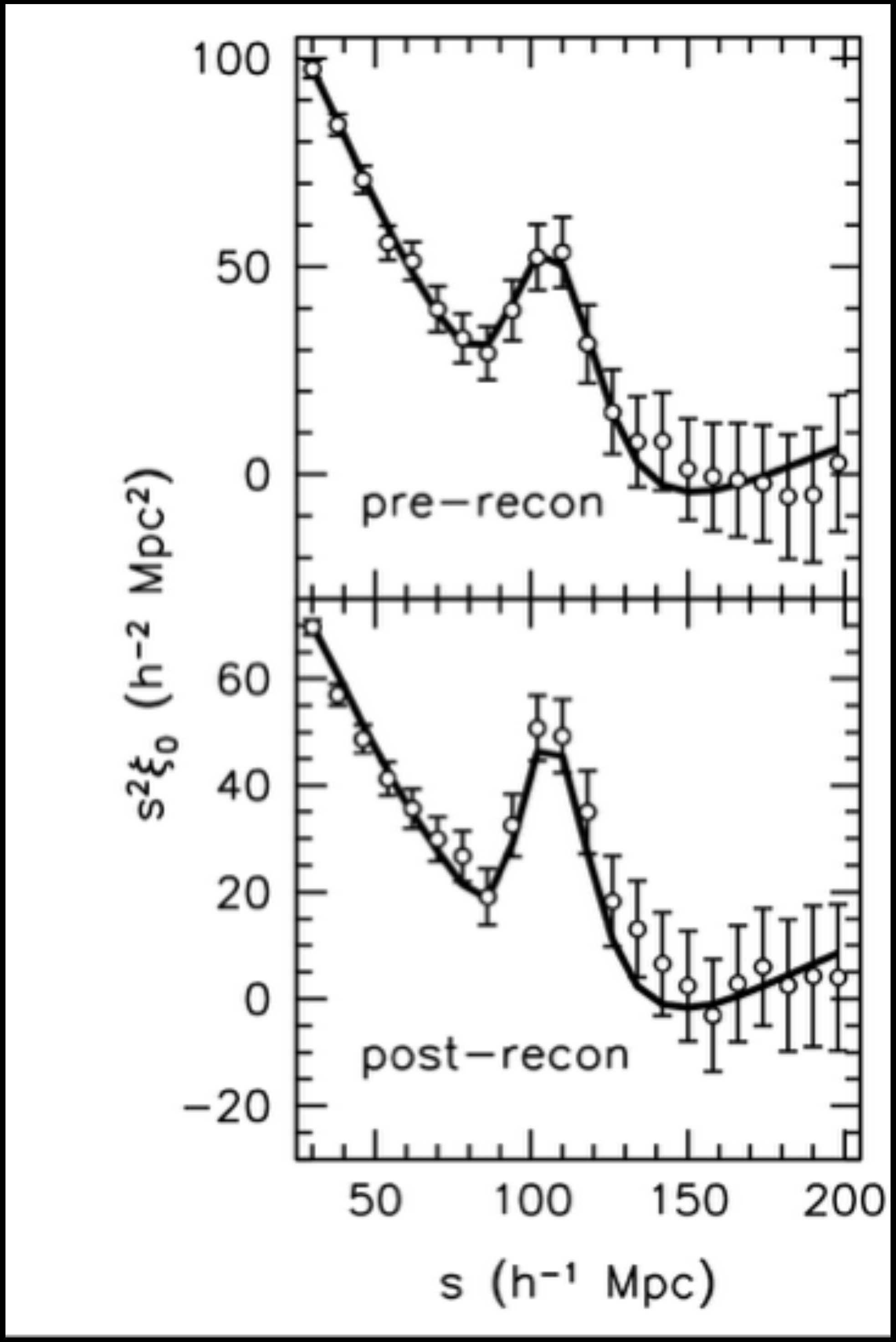
ADIABATIC DENSITY FLUCTUATIONS

Acoustic Fluctuations

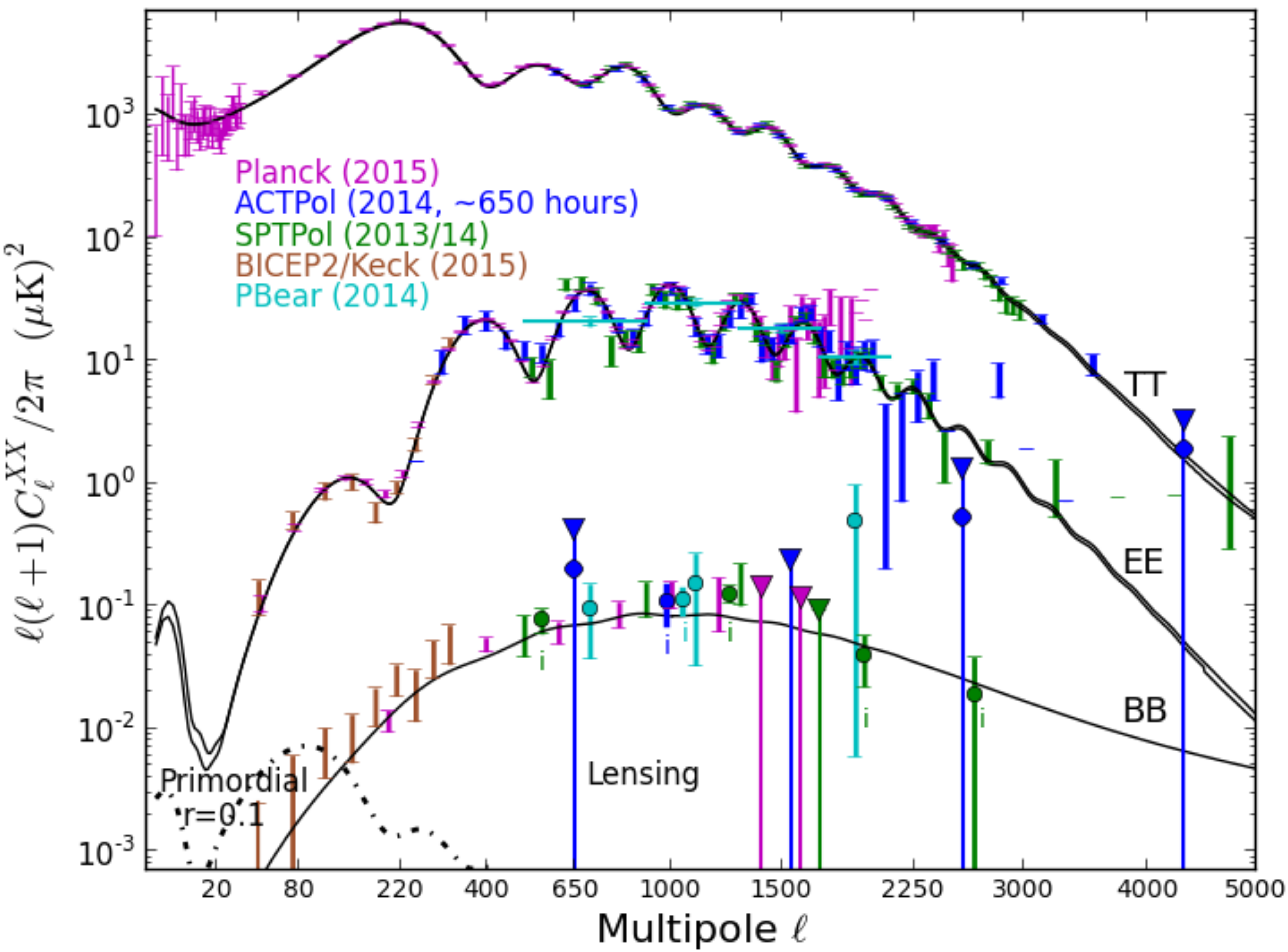


Planck Paper 1 (2013)

Sound Waves in the Sky



SDSS 3



Planck (2015)
ACTPol (2014, ~650 hours)
SPTPol (2013/14)
BICEP2/Keck (2015)
PBear (2014)
TT
EE
BB
Primordial
r=0.1
Lensing
$\ell(\ell+1)C_\ell^{XX}/2\pi\ \ (\mu K)^2$
Multipole ℓ
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
20
80
220
400
650
1000
1500
2250
3000
4000
5000

Gravitational Waves

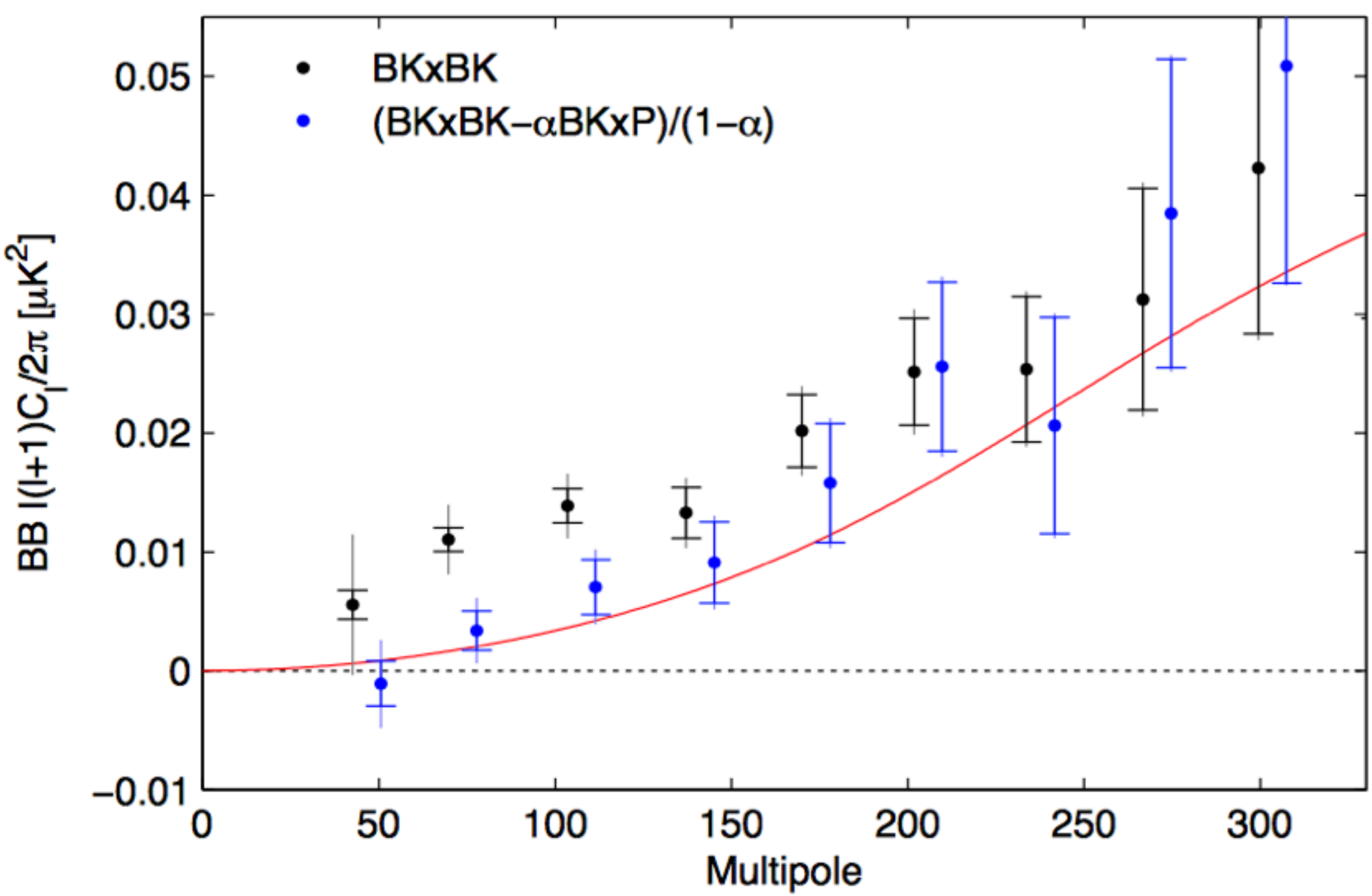
- During inflation, any massless field experiences quantum fluctuations.
- This process generates fluctuations in the gravitons at the deSitter temperature:

$$\Delta_t^2 \equiv \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}$$

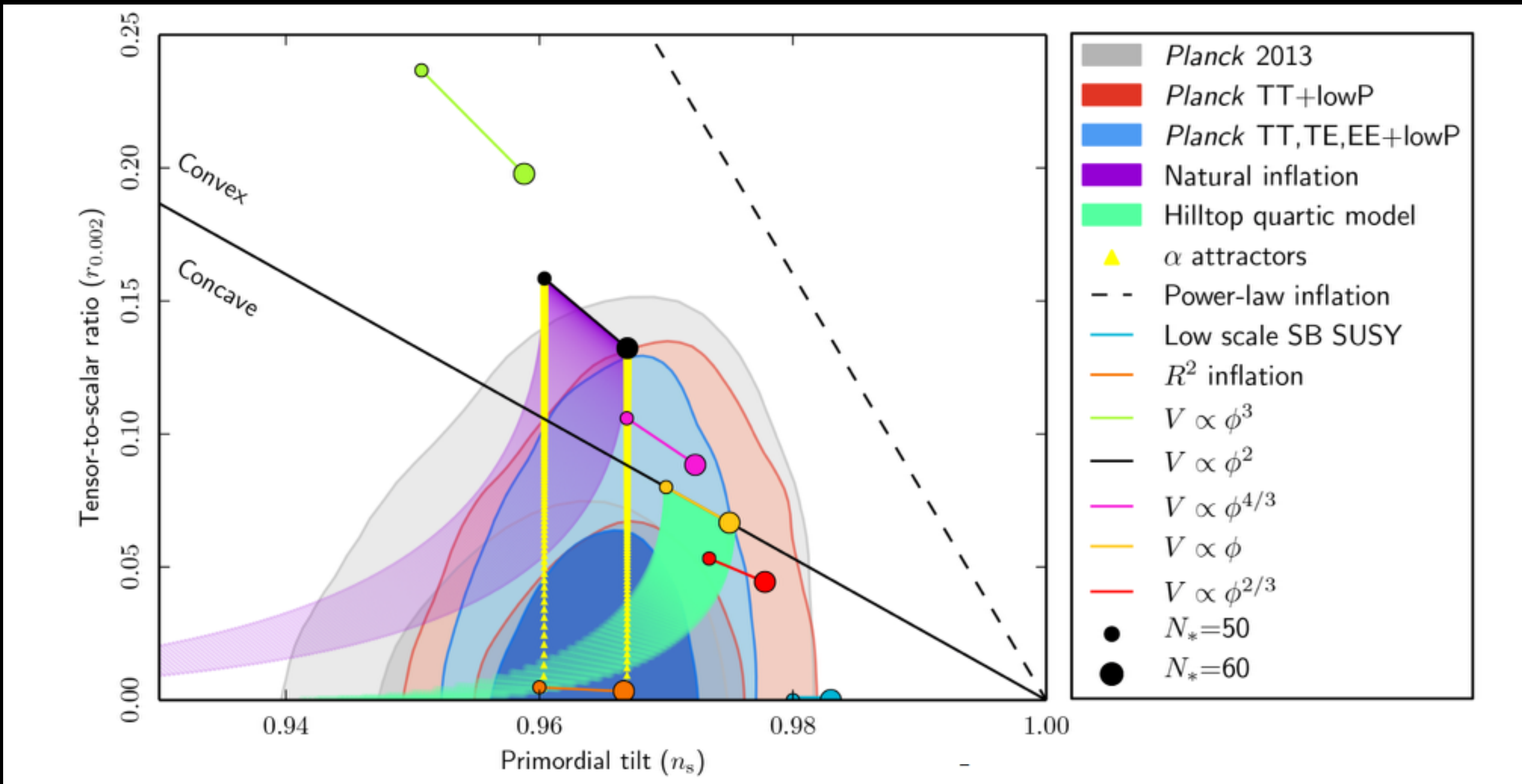
Why is this important?

- Glimpse into the universe in its first 10^{-30} s
- Probe of physics near the Planck Scale
- Direct evidence for gravitons and quantum nature of gravitational field
- Open up a new area of cosmology
- Potentially, most important new physics results of this century!

Joint Bicep/Keck/Planck Analysis

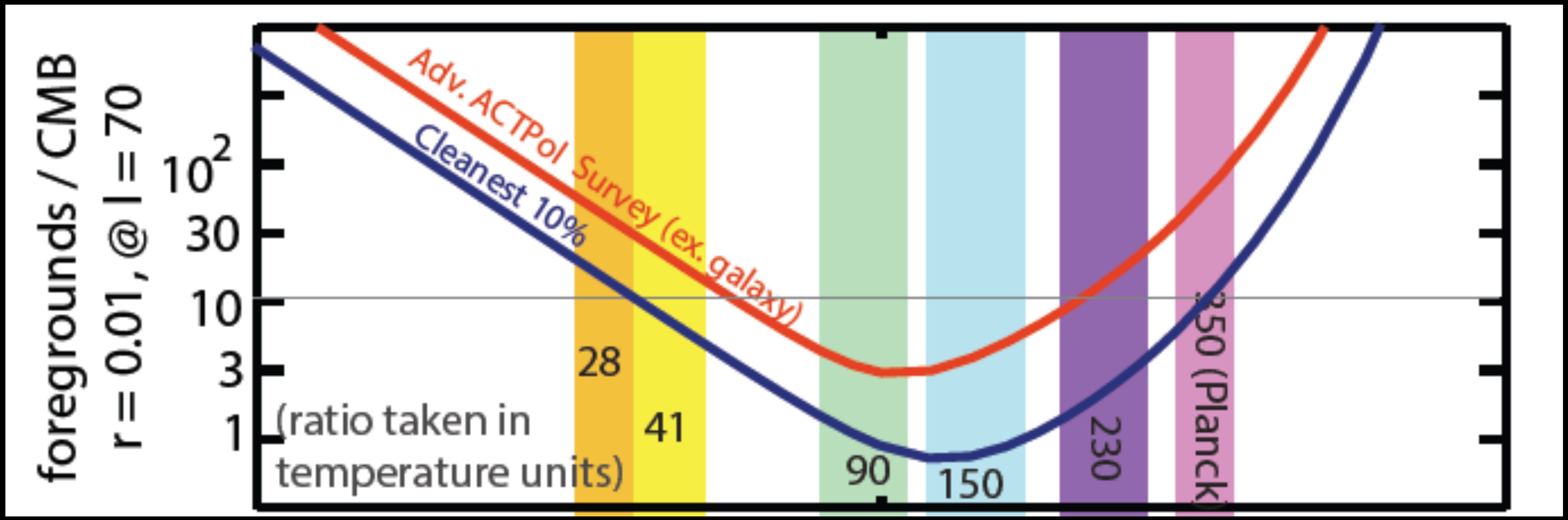


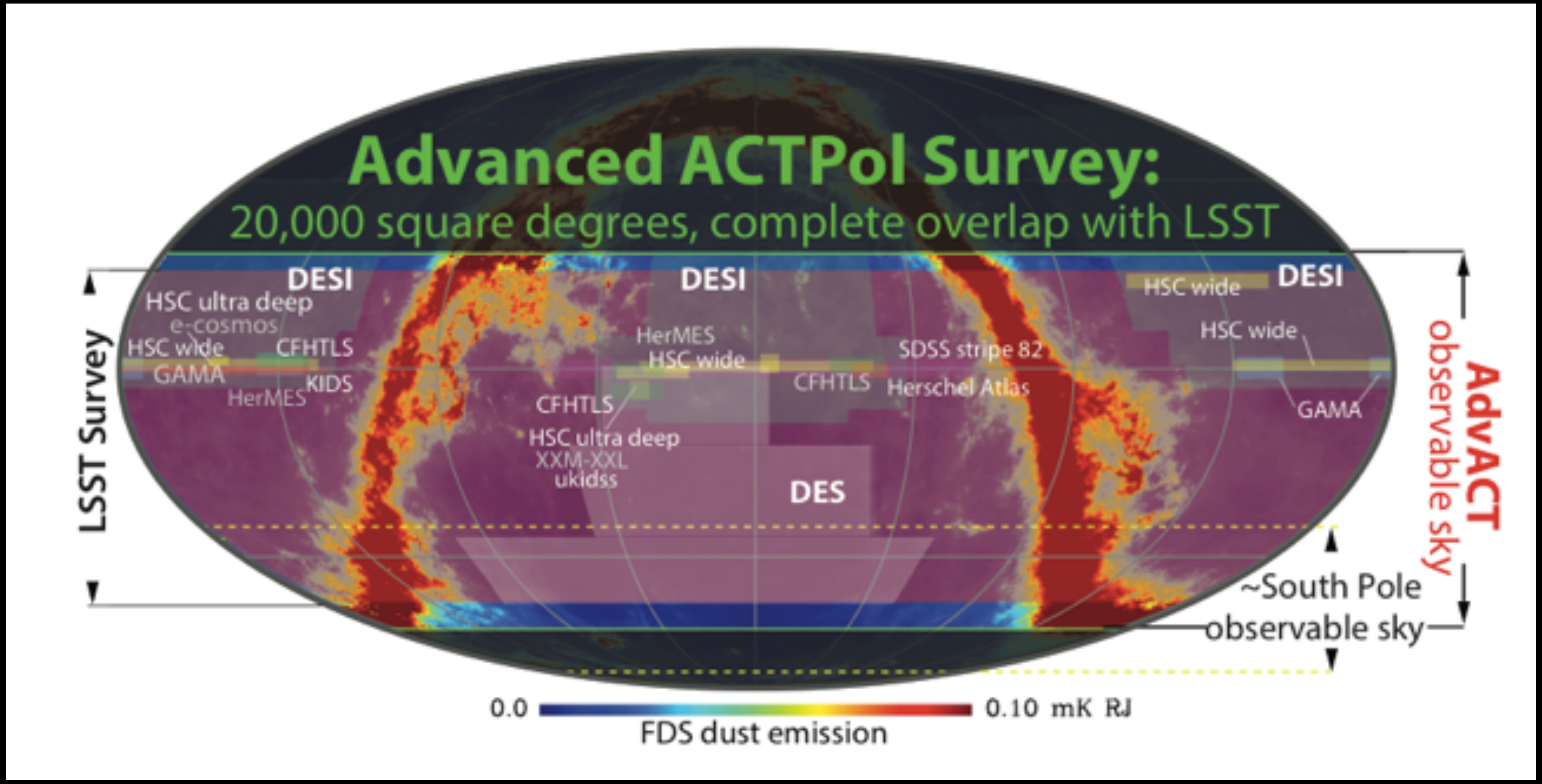
Current Limits (Planck 2015 XX)



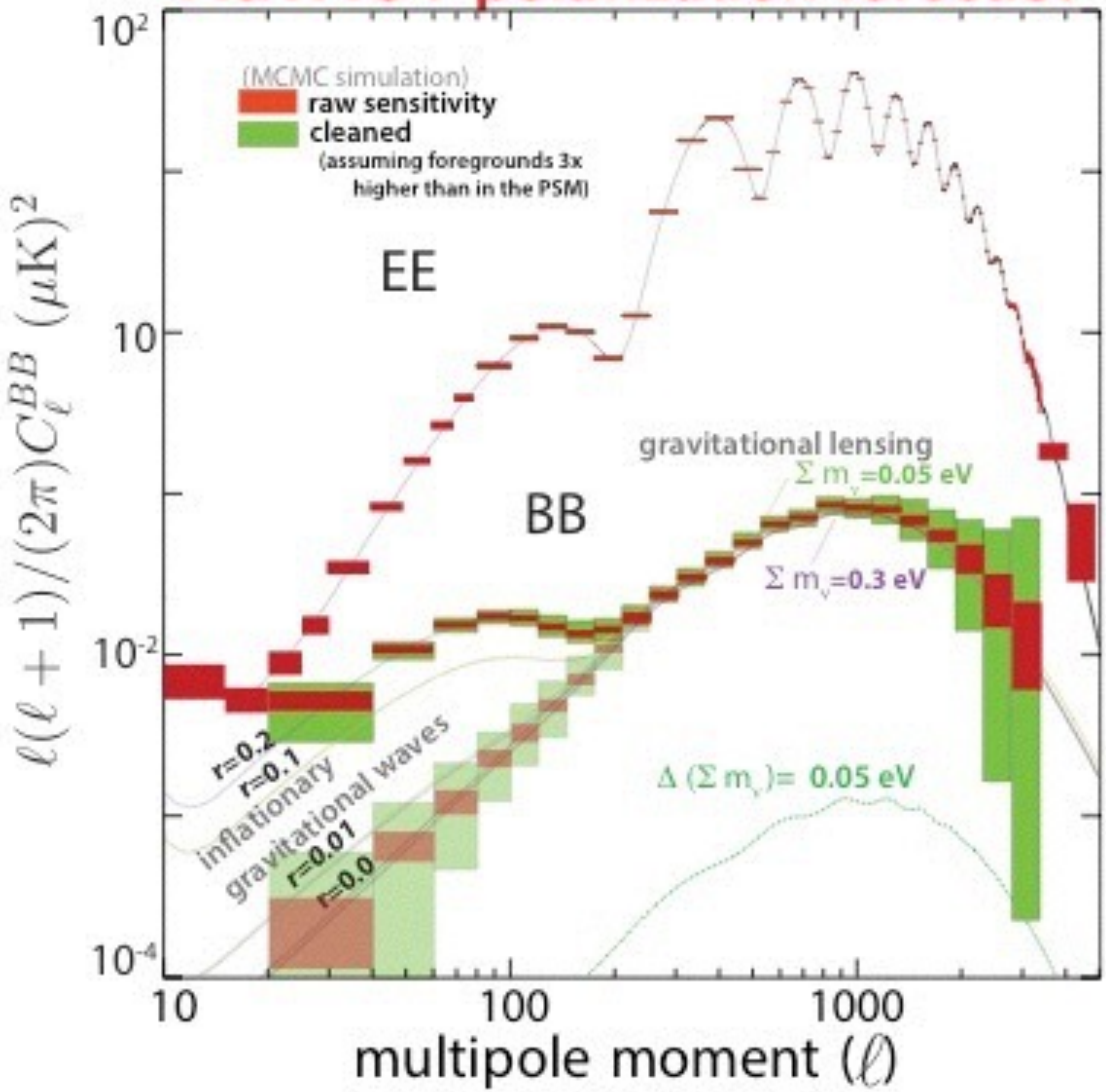
$$H_{\rm inf} \simeq 8.5 \times 10^{13}\ {\rm GeV} \left(\frac{r}{0.11}\right)^{1/2}.$$

Deep Wide and Multi-frequency





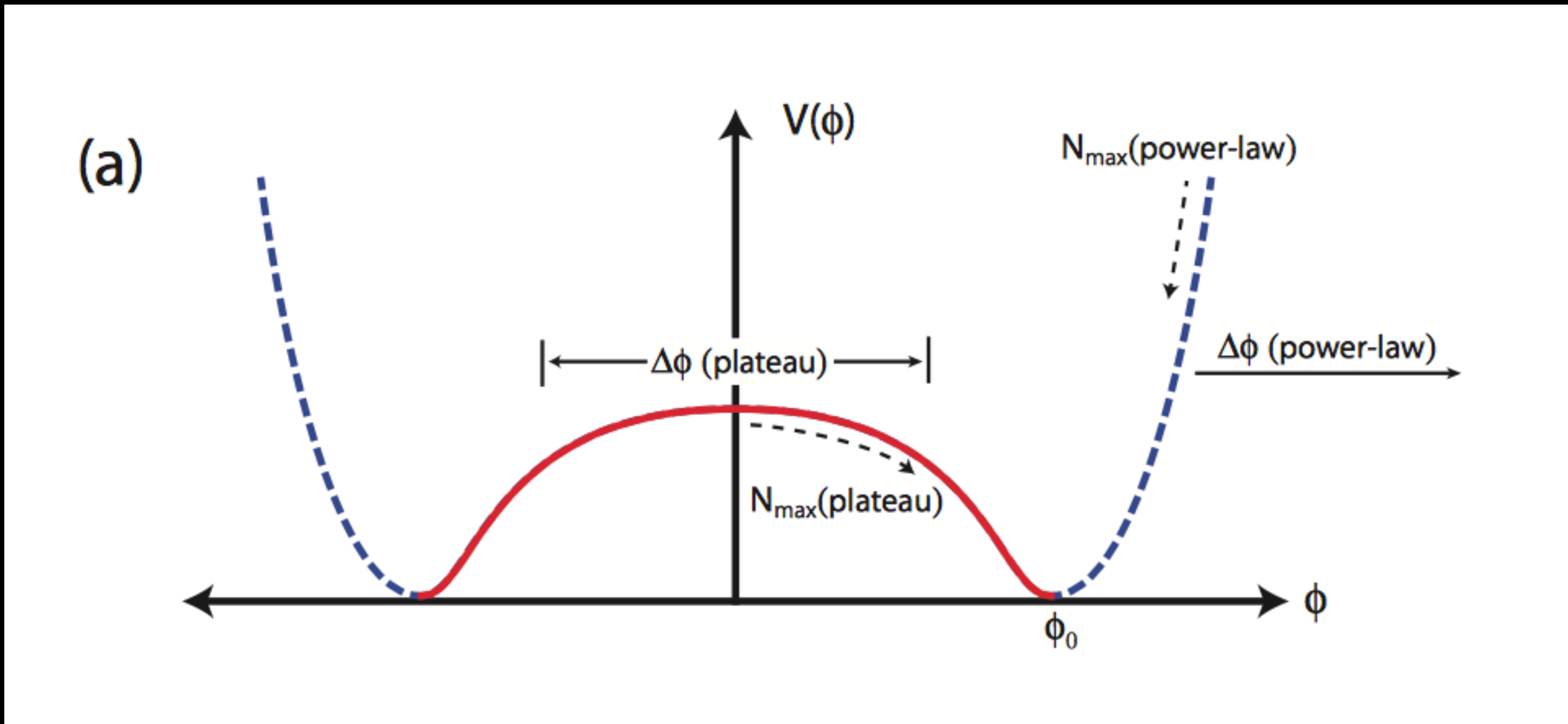
AdvACT polarization forecast



NOTES:

1) "raw" projections based on 20,000 square degrees, 5 μK-arcmin
2) "cleaned", based on 12 μK-arcmin which is Jo's estimate for the residual after removing foregrounds 3x larger than in the PSM
3) the solid boxes are simulated on r = 0.2
4) the semi-transparent boxes have r = 0.0
5) we still get over 1 sigma on r = 0.01 for the 3x plank cleaning
6) the high ell cleaned error bars are probably pessimistic at high ell— a more thorough analysis should reduce these since the foregrounds don't dominate at high ell range.

If limits continue to improve, plateau-like (small field inflation models) will be favored

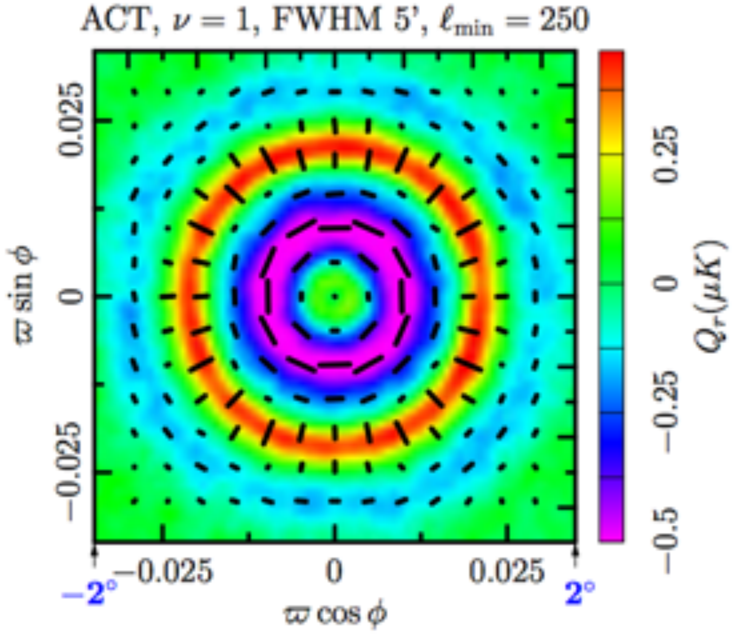


Ijjas, Steinhardt and Loeb 2013,2014

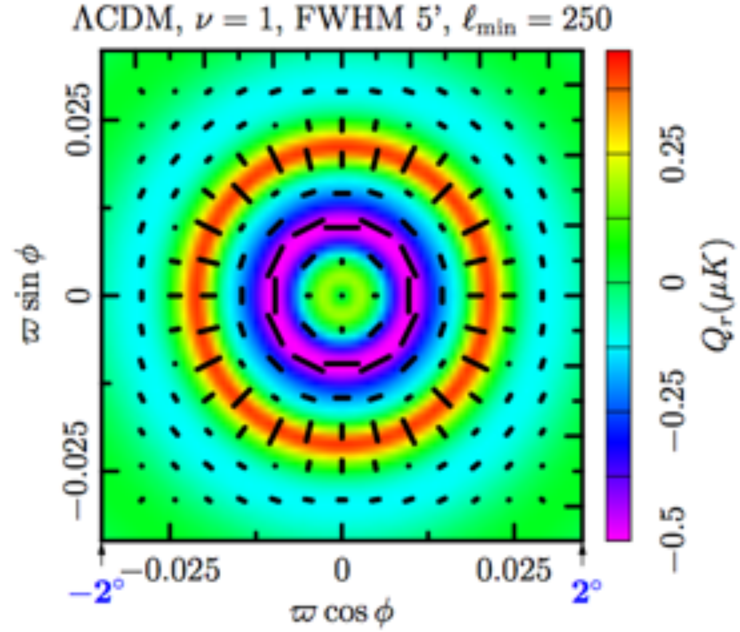
What is the Dark Matter?

- Acoustic waves imply two distinct fluids:
  - CMB constraints on DM abundance
  - DM is non-baryonic and has interacts very weakly with photons, electrons, neutrinos, and baryons (CMB acoustic peaks)
- DM has weak self-interactions (cluster shapes) and is cold (or at least luke warm)
- DM searches place increasingly strong constraints on DM-nucleon interactions

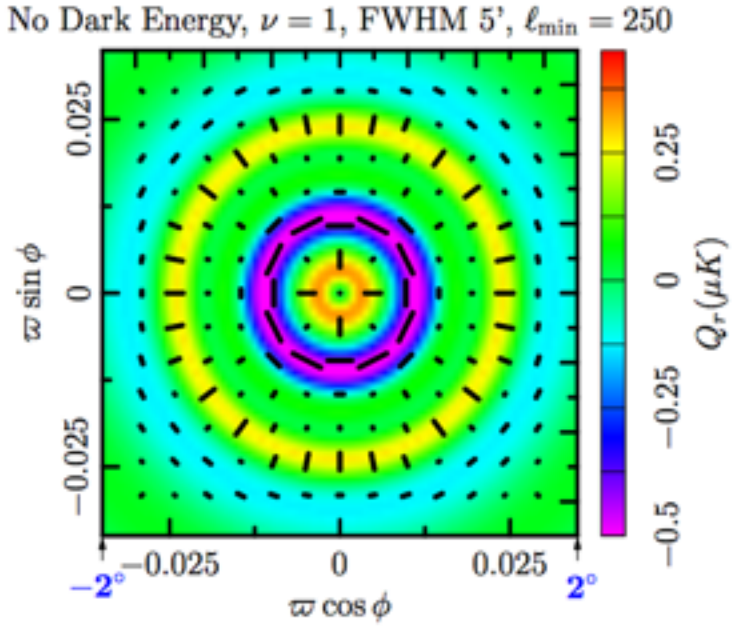
ACT data



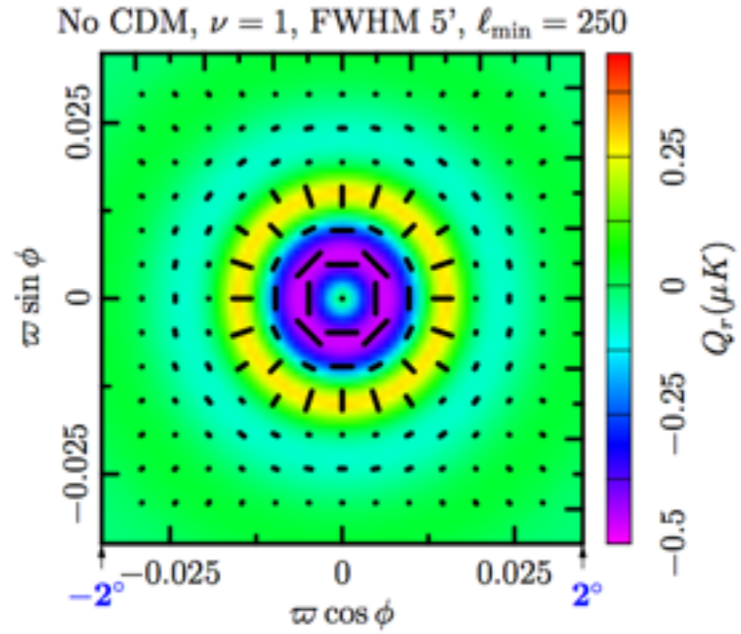
ΛCDM



No DE



No CDM

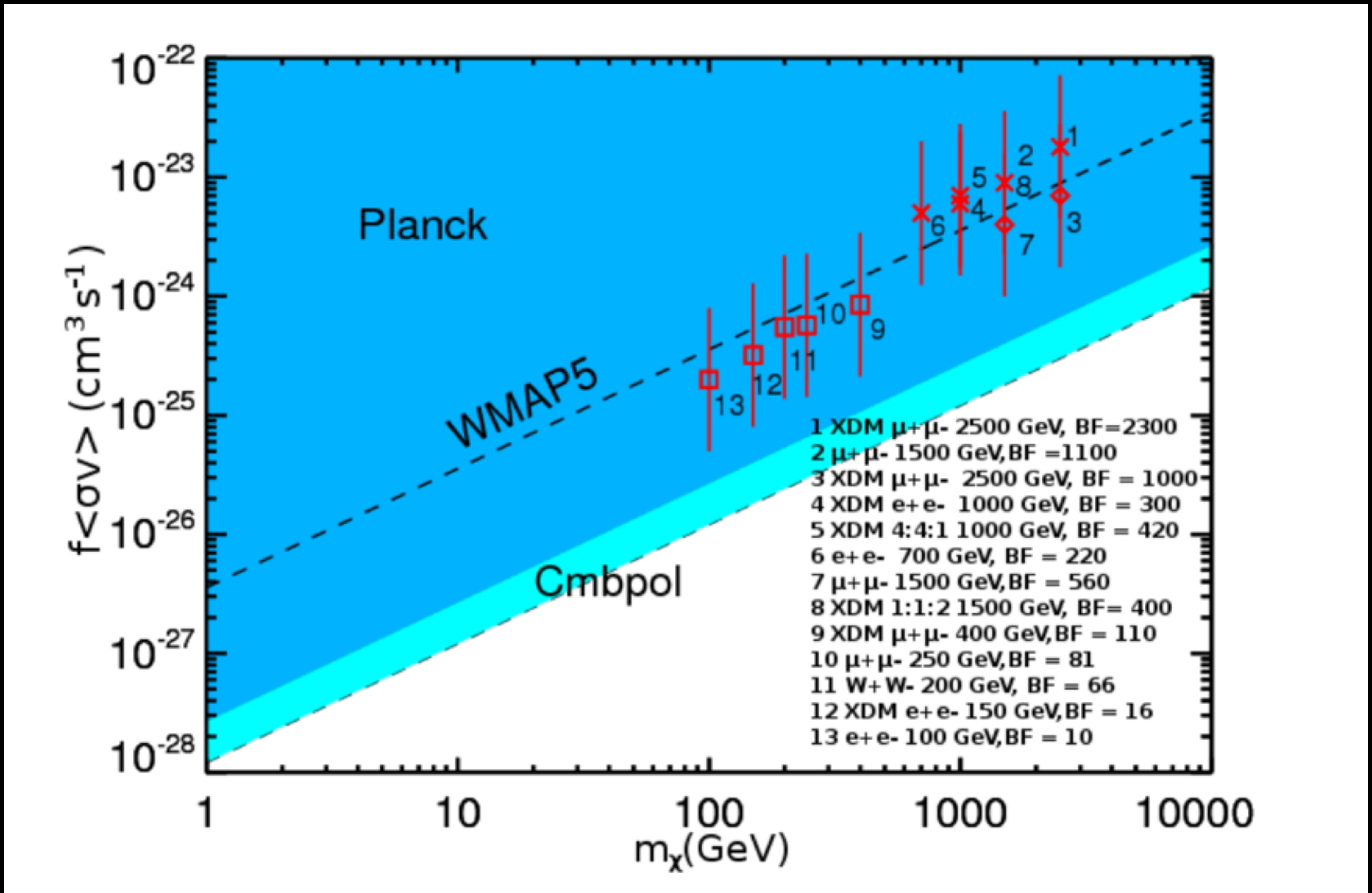


ACT Map Stacking (1.5% sky)

On Planck T hot pixels (reduce systematics)
No DE: $\Omega_\Lambda = 0$, $\Omega_c = 1 - \Omega_b - \Omega_\nu$.
No CDM: $\Omega_c = 0$, $\Omega_\Lambda = 1 - \Omega_b - \Omega_\nu$.

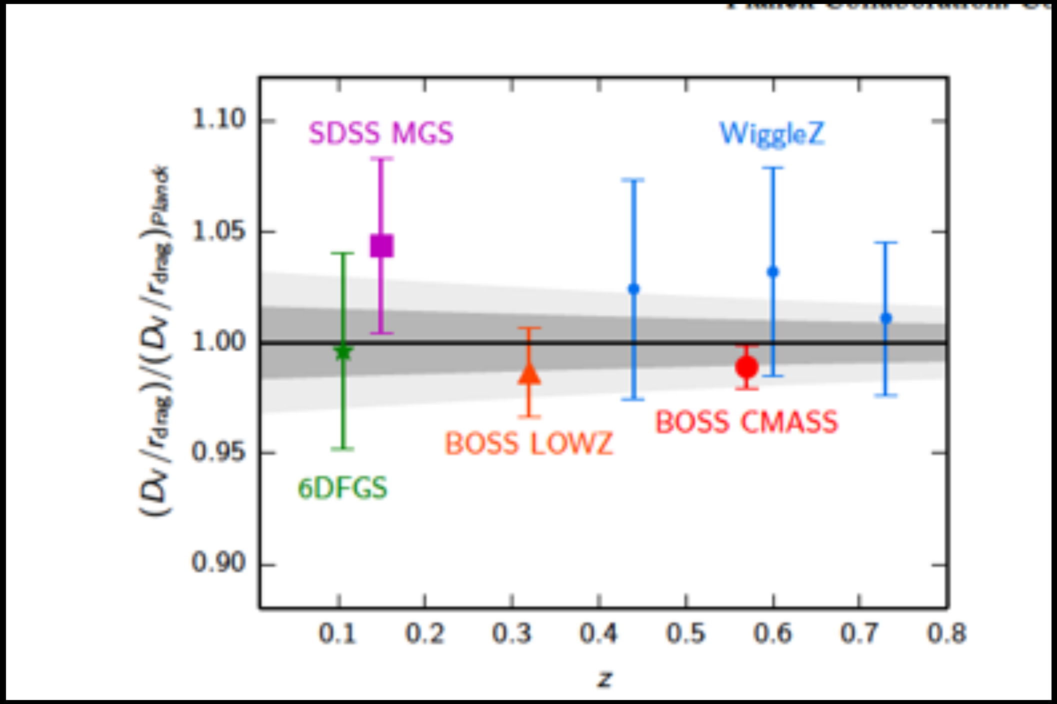
$\langle \Delta T^2 \rangle$ normalized by adjusting A_s.

Dark matter constraints



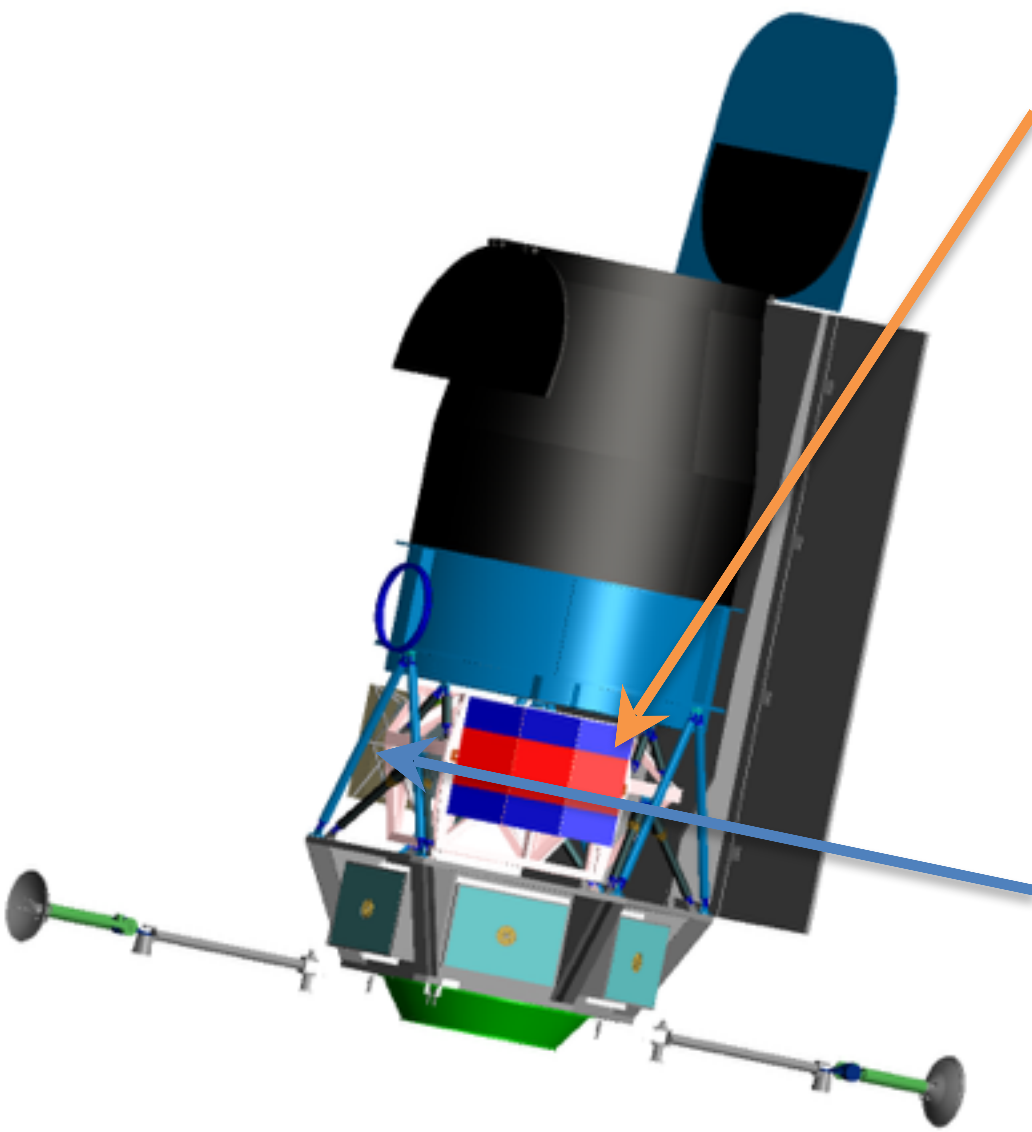
What is dark energy?

- Vacuum energy?
- Quintessence?
- Break-down of General Relativity



Need to measure both distance and growth rate of structure

WFIRST-AFTA Instruments



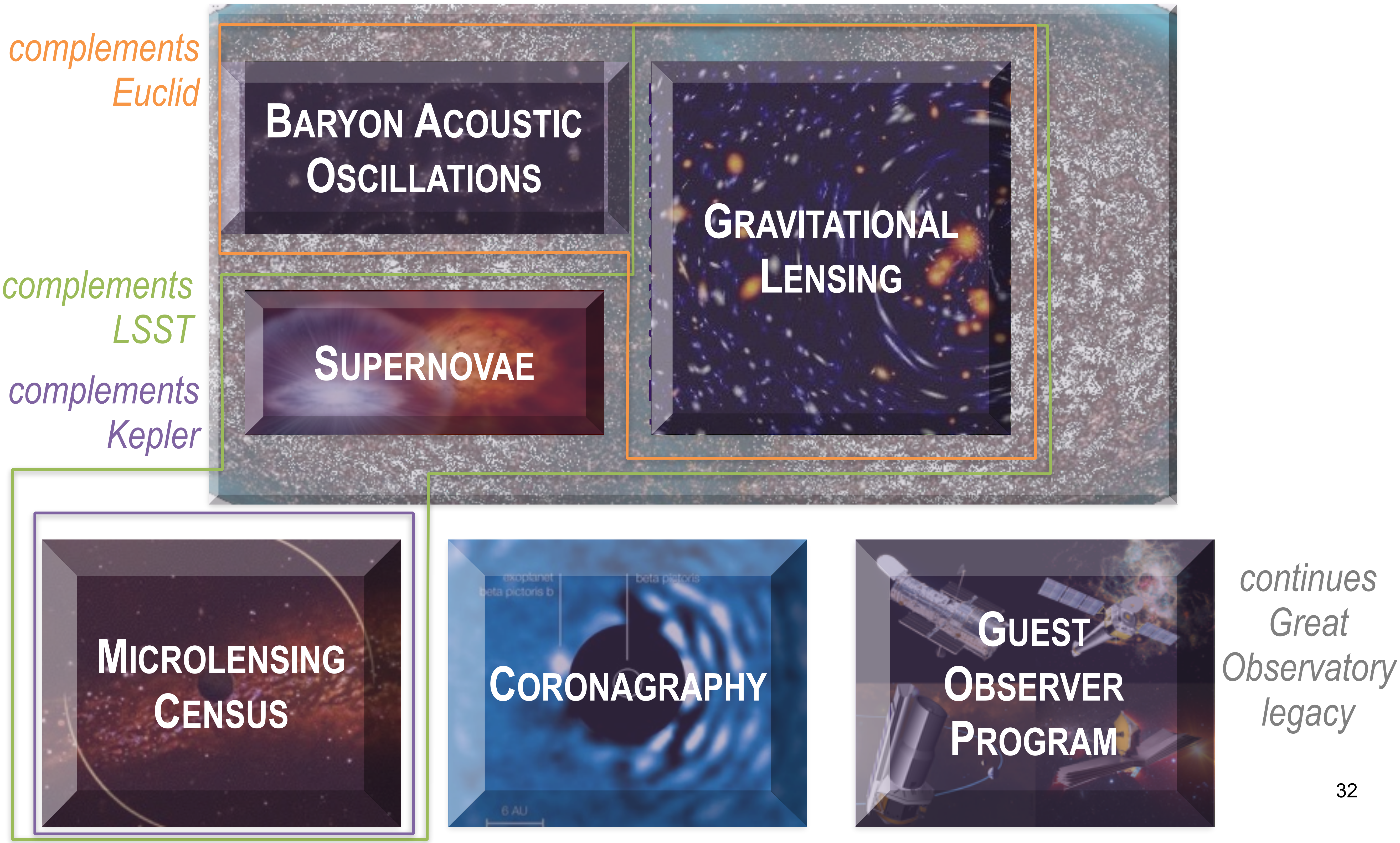
Wide-Field Instrument

- *Imaging & spectroscopy over 1000s of sq. deg.*
- *Monitoring of SN and microlensing fields*
- 0.7 – 2.0 μm (imaging) & 1.35-1.89 μm (spec.)
- 0.28 deg^2 FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 6 filter imaging, grism + IFU spectroscopy

Coronagraph

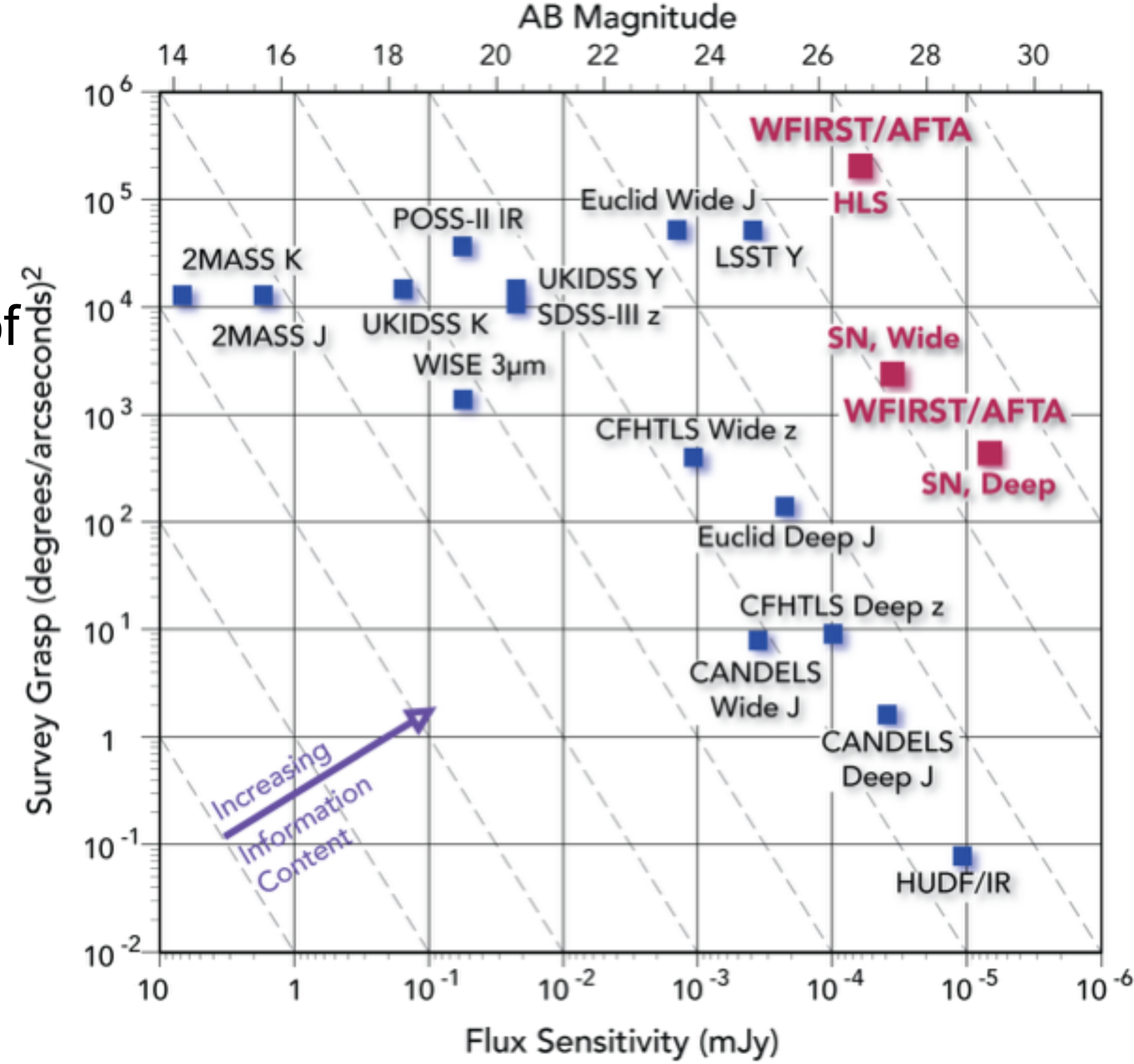
- *Image and spectra of exoplanets from super-Earths to giants*
- *Images of debris disks*
- 430 – 970 nm (imaging) & 600 – 970 nm (spec.)
- Final contrast of 10^{-9} or better
- Exoplanet images from 0.1 to 1.0 arcsec

WFIRST-AFTA Science



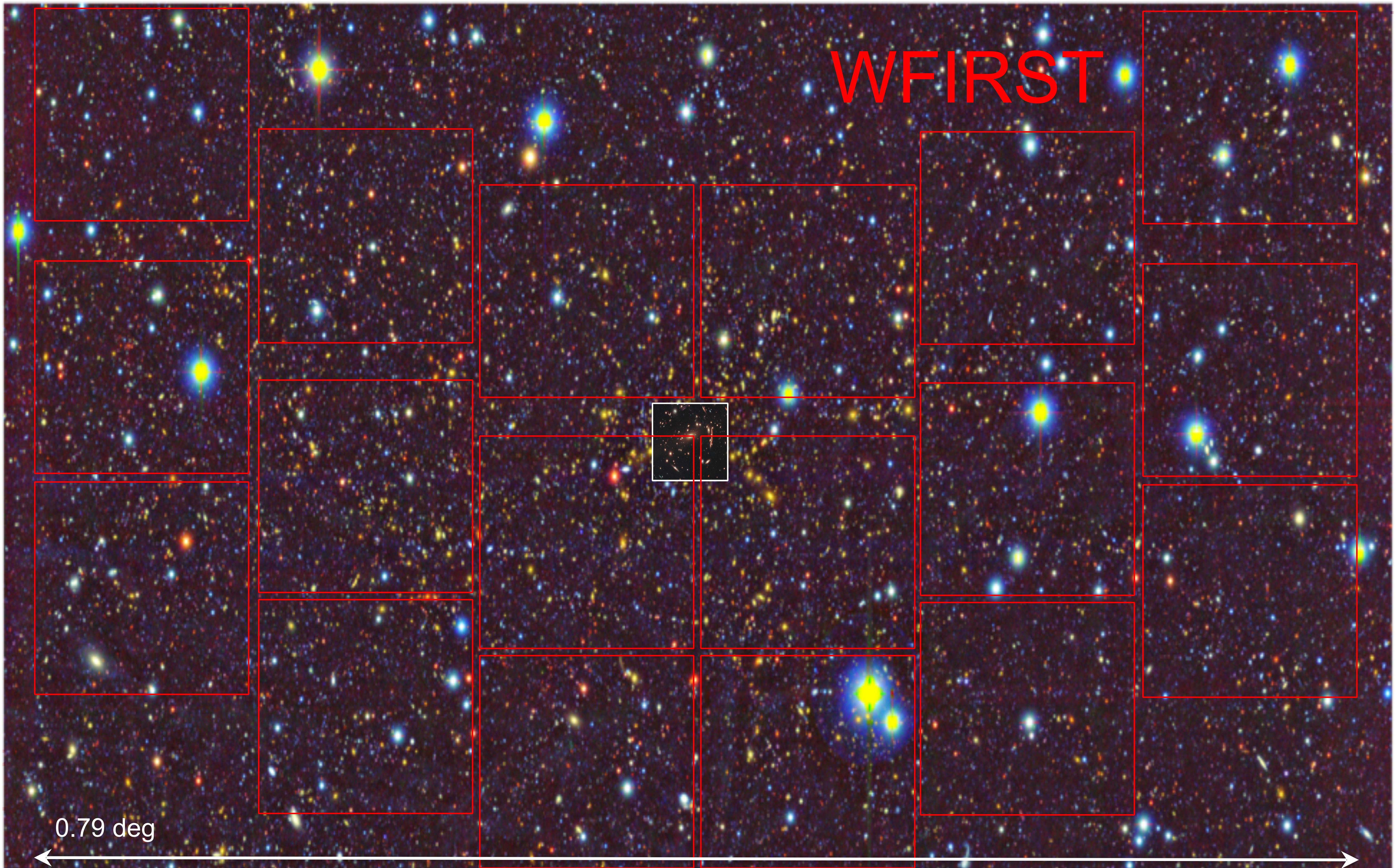
WFIRST-AFTA Surveys

- Multiple surveys:
  - High-Latitude Survey
    - Imaging, spectroscopy, supernova monitoring
  - Repeated Observations of Bulge Fields for microlensing
  - 25% Guest Observer Program
  - Coronagraph Observations
- Flexibility to choose optimal approach

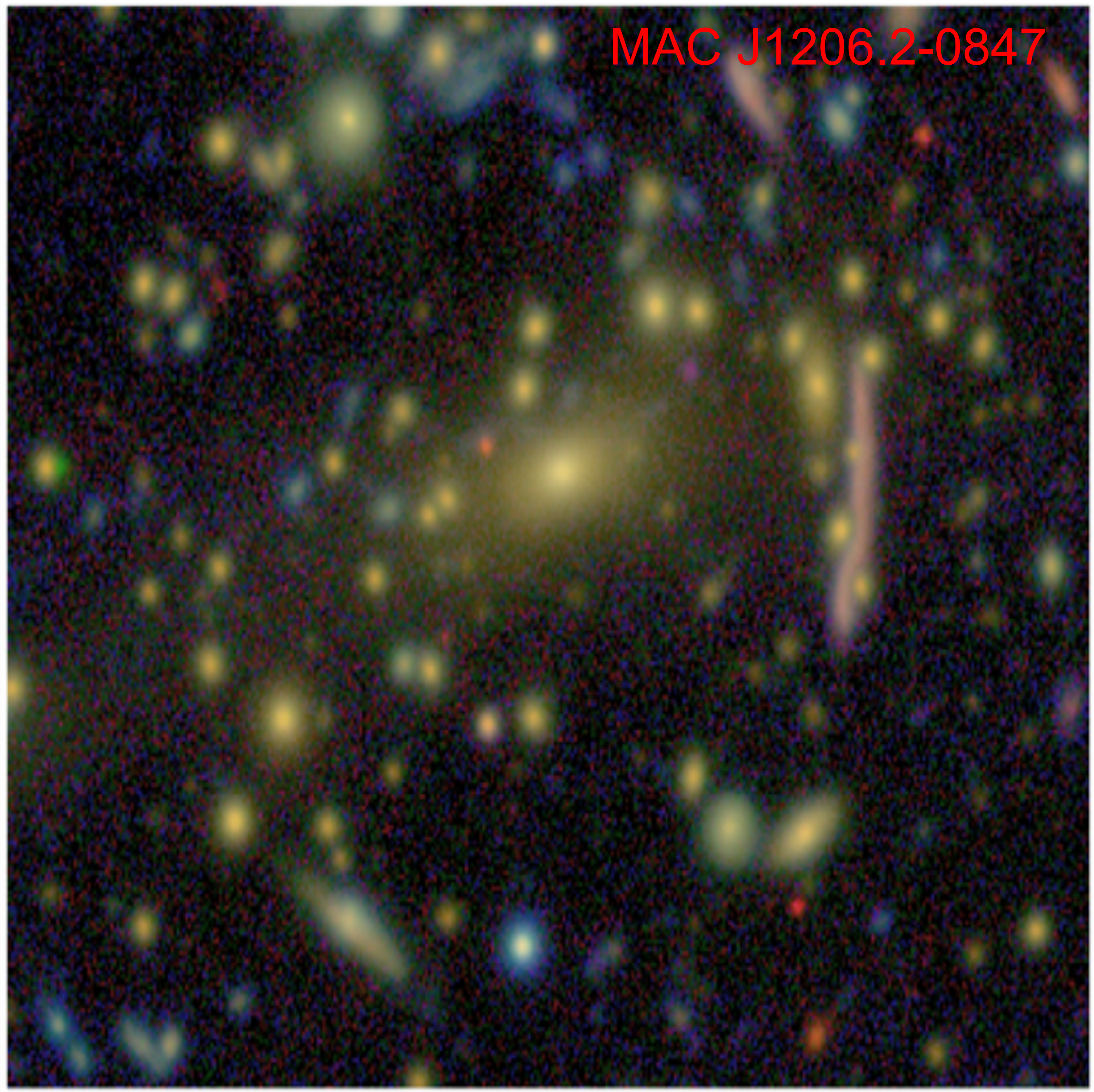


Near Infrared Surveys

Gravitational Lensing



Gravitational Lensing

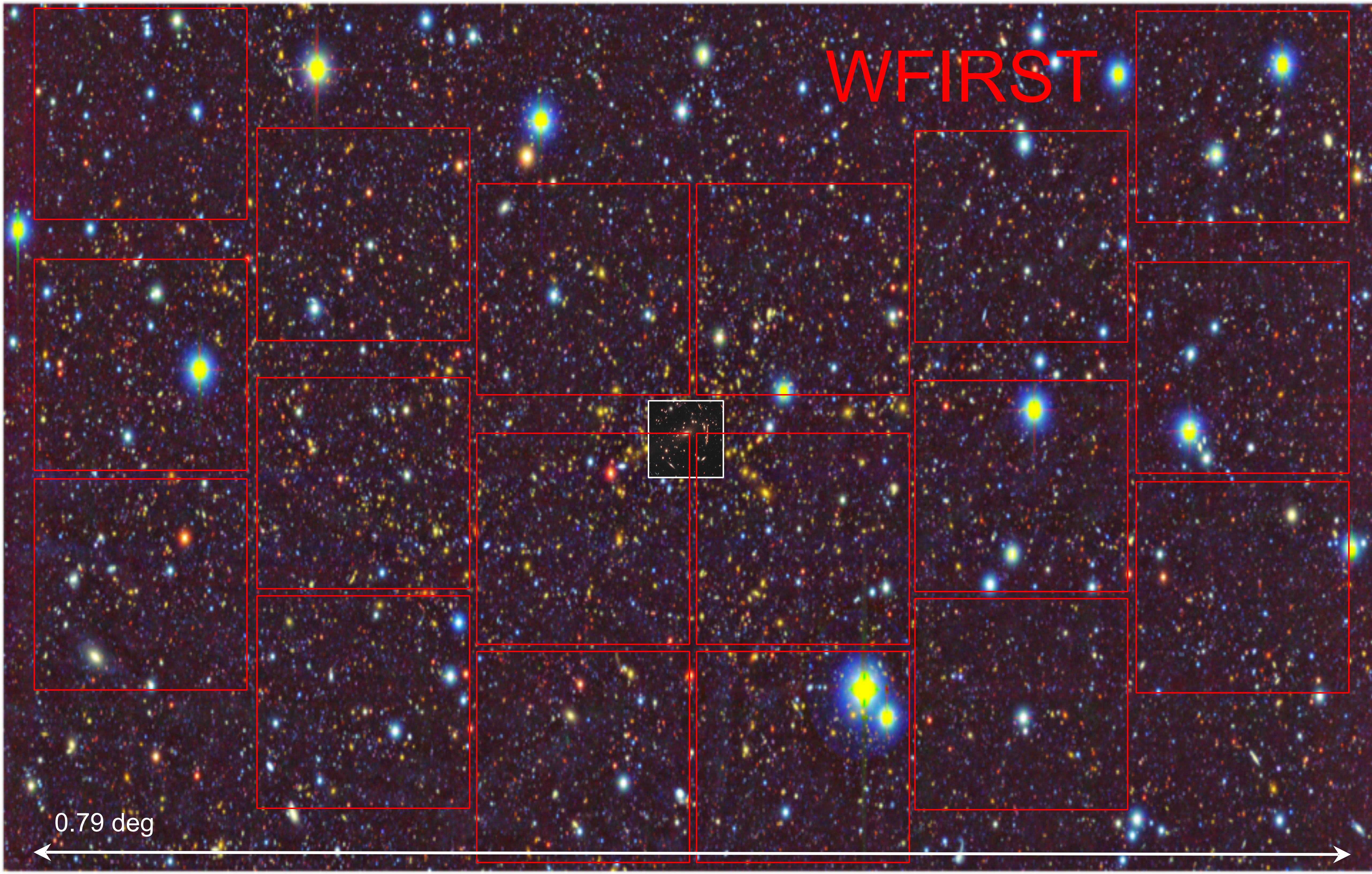


Postman
HST

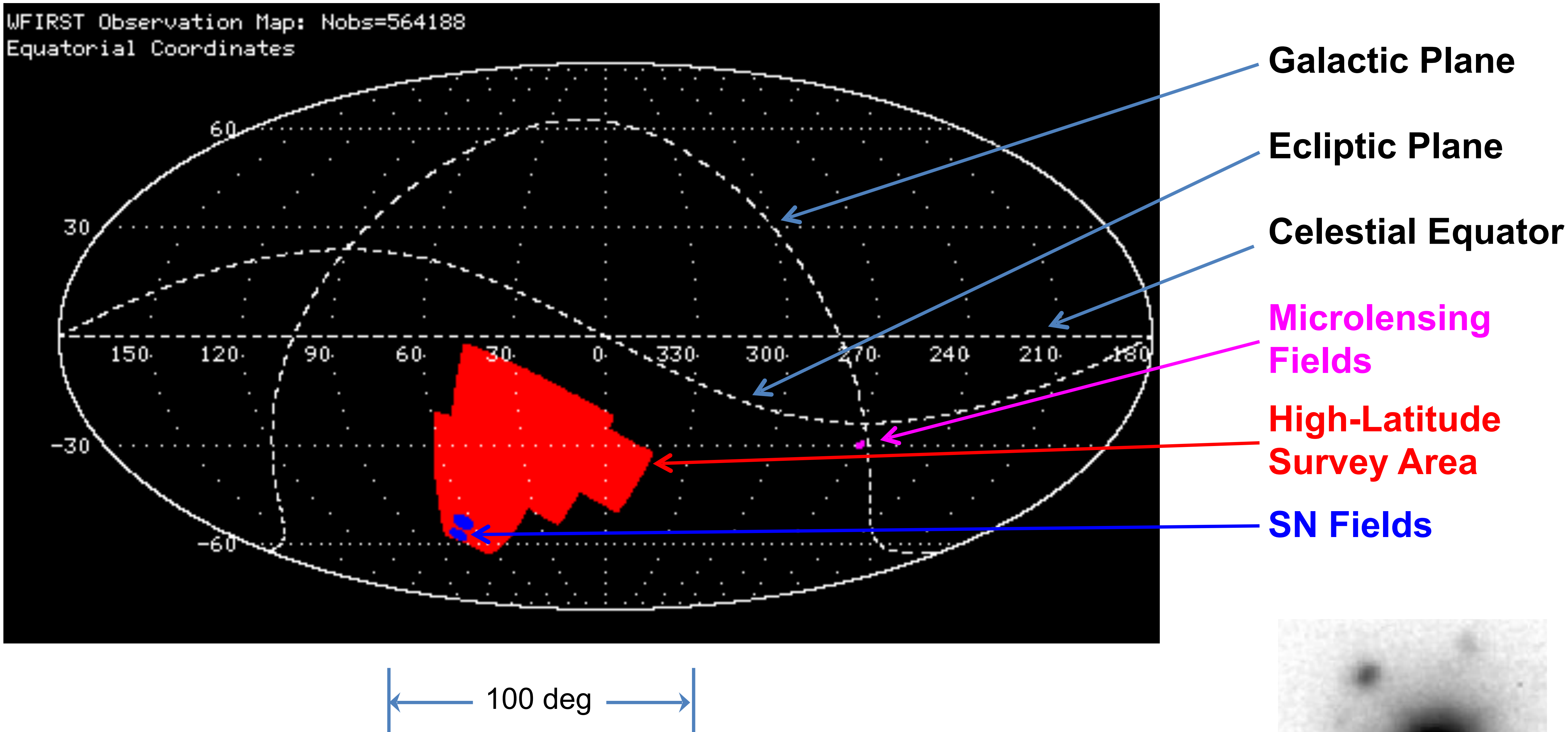
Gravitational Lensing

Postman
HST

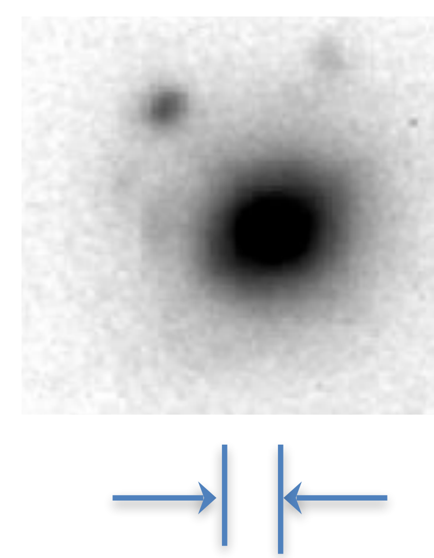
Gravitational Lensing



Huge Dynamic Range



~10^6 dynamic range in size
~$2x10^{12}$ resolution elements in HLS



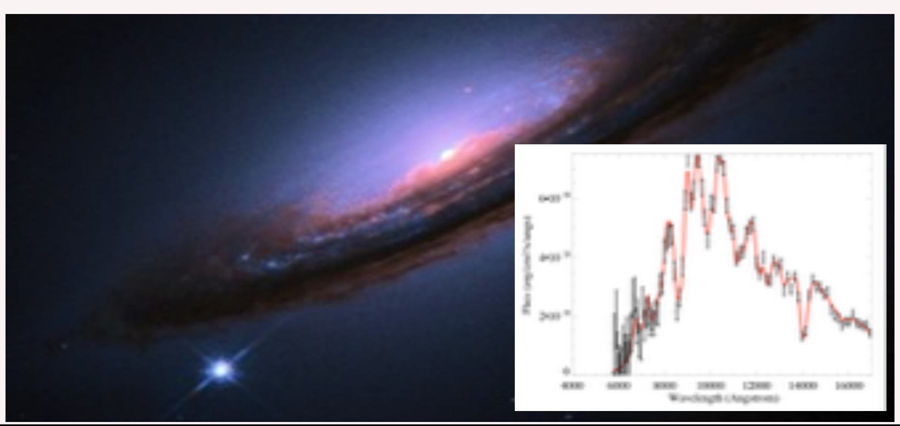
WFIRST-AFTA Dark Energy Roadmap

Supernova Survey

wide, medium, & deep imaging
+
IFU spectroscopy

2700 type Ia supernovae
z = 0.1–1.7

standard candle distances
z < 1 to 0.20% and z > 1 to 0.34%



High Latitude Survey

spectroscopic: galaxy redshifts

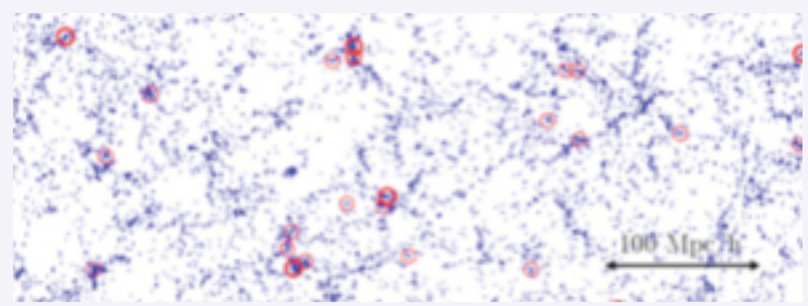
16 million Hα galaxies, z = 1–2
1.4 million [OIII] galaxies, z = 2–3

imaging: weak lensing shapes

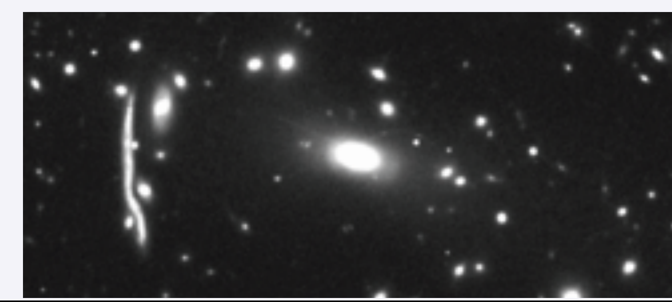
380 million lensed galaxies
40,000 massive clusters

standard ruler

distances	expansion rate
z = 1–2 to 0.5%	z = 1–2 to 0.9%
z = 2–3 to 1.3%	z = 2–3 to 2.1%

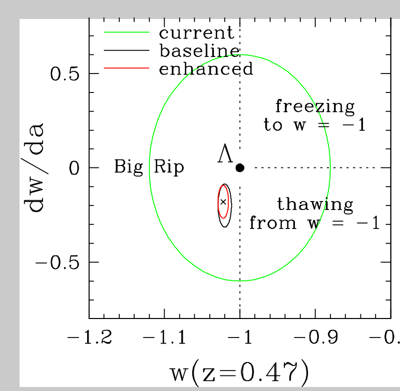


dark matter clustering
z < 1 to 0.21% (WL); 0.24% (CL)
z > 1 to 0.78% (WL); 0.88% (CL)
1.1% (RSD)



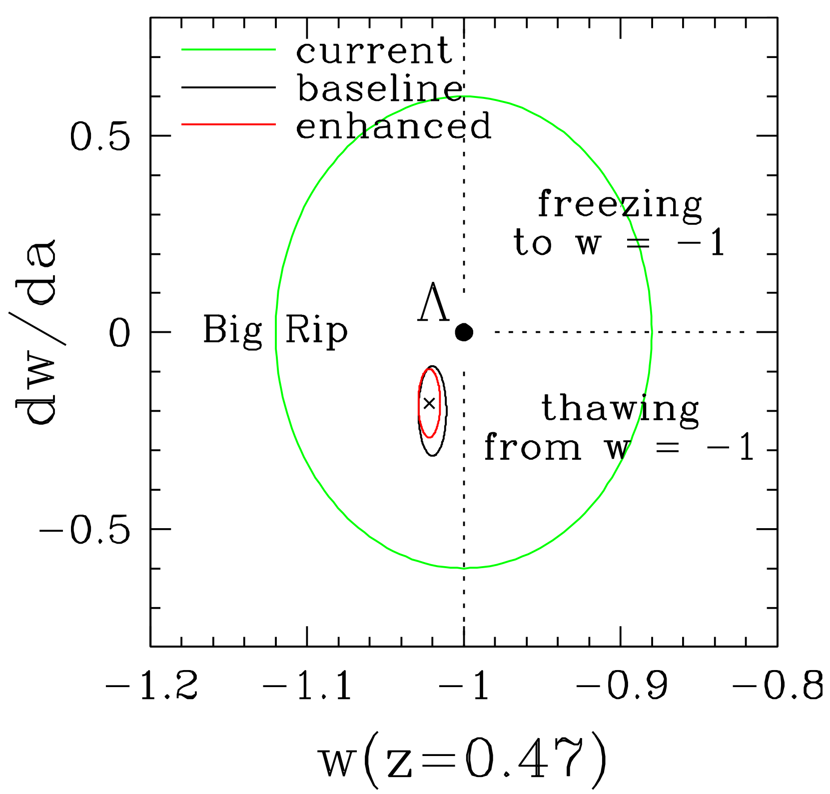
history of dark energy
+
deviations from GR

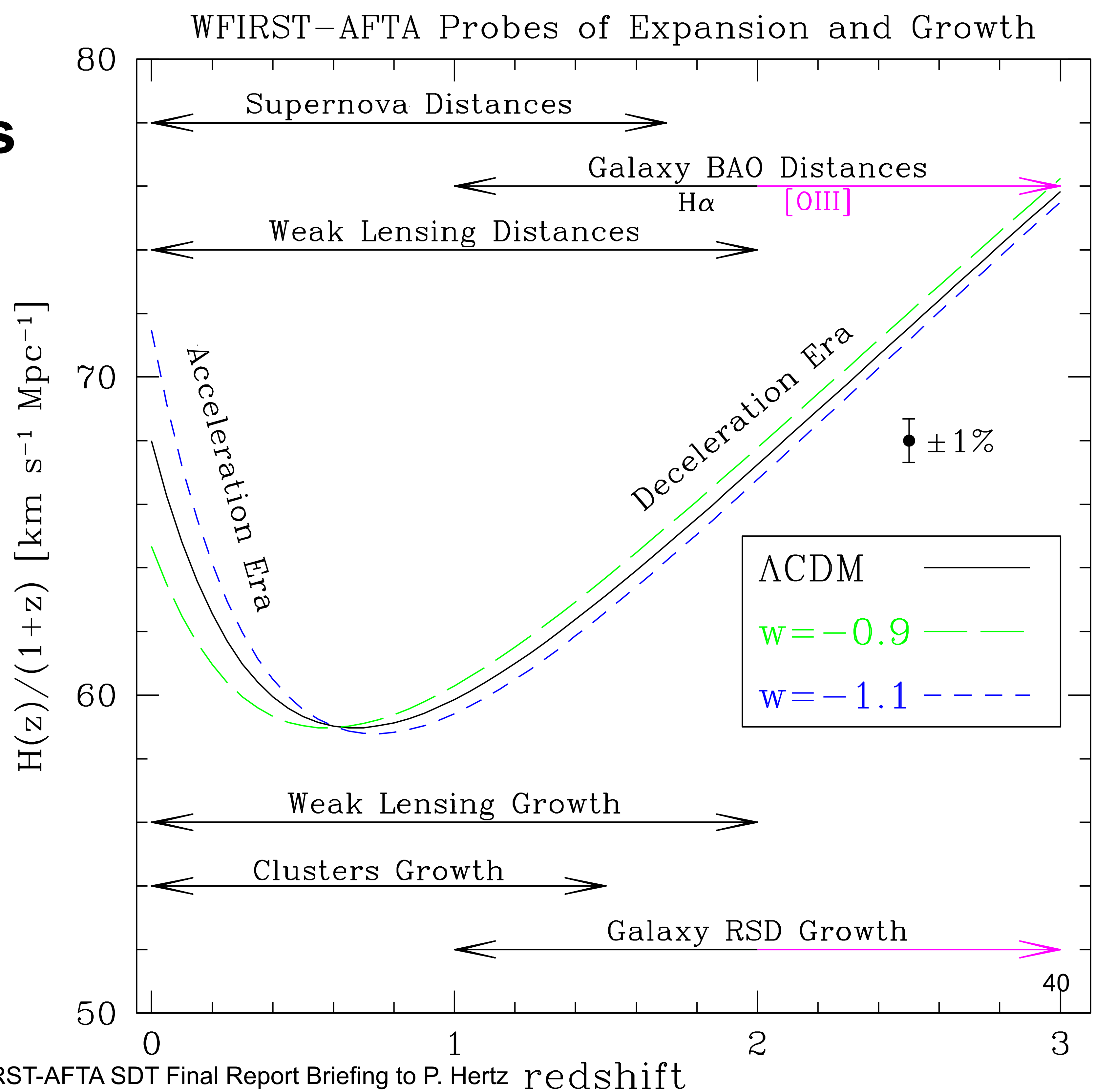
w(z), ΔG(z), Φ_{REL}/Φ_{NREL}



Dark Energy Program

Multiple DE techniques to measure
- expansion history
- growth of structure



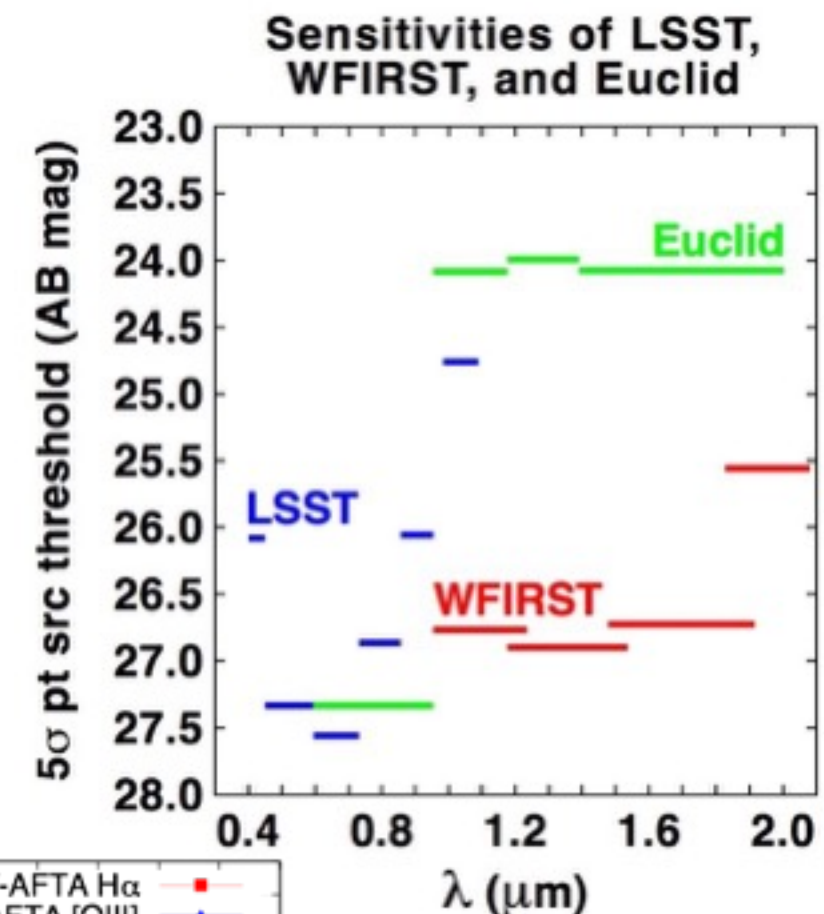


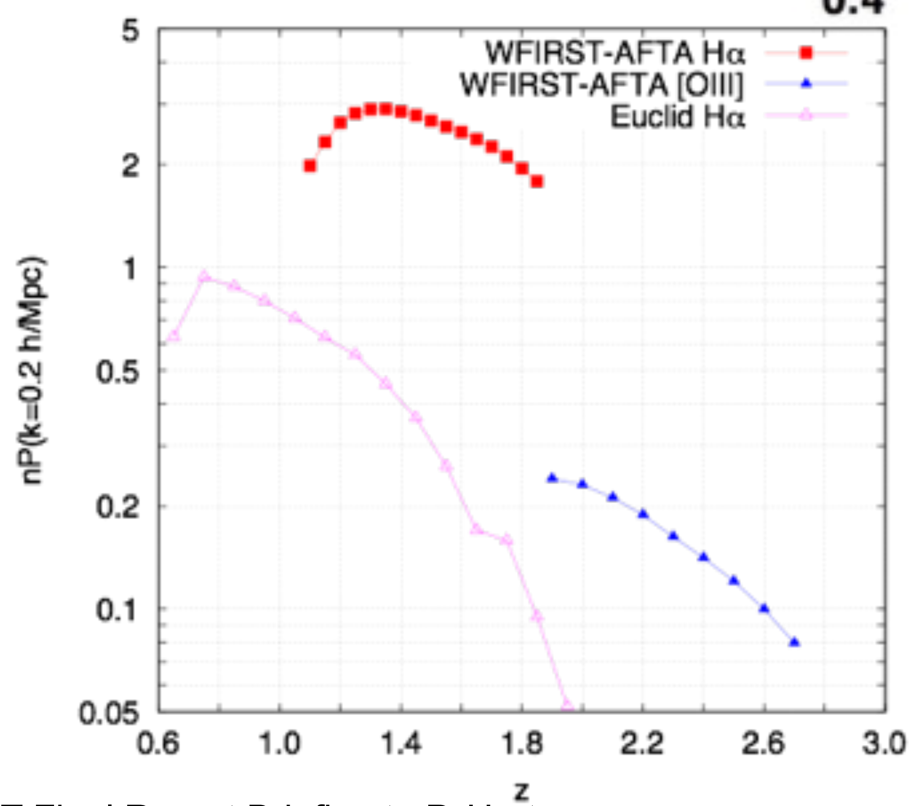
WFIRST-AFTA Dark Energy

Weak Lensing (2200 deg^2)
- High angular resolution
- Galaxy shapes in IR
- 380 million galaxies
- Photo-z redshifts
- 4 imaging filters

Supernovae
- High quality IFU spectra
- 5 day sampling of light curves
- 2700 SNe

Redshift survey (2200 deg^2)
- BAO & Redshift Space Distortions
- High number density of galaxies
- 16 million galaxies





WFIRST-AFTA Significantly Expands the Population of Characterized Planets

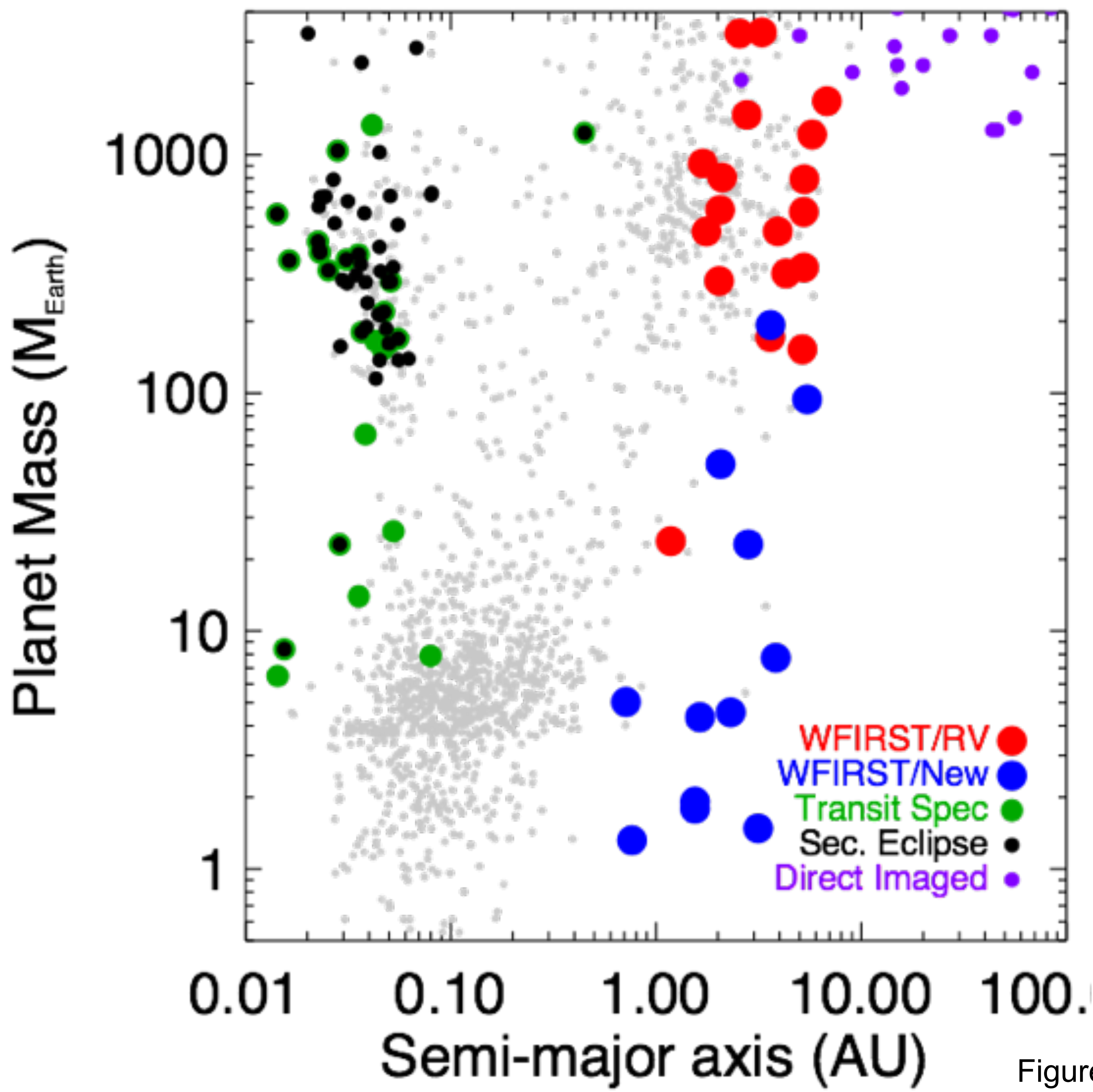
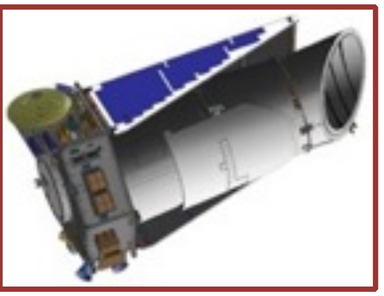
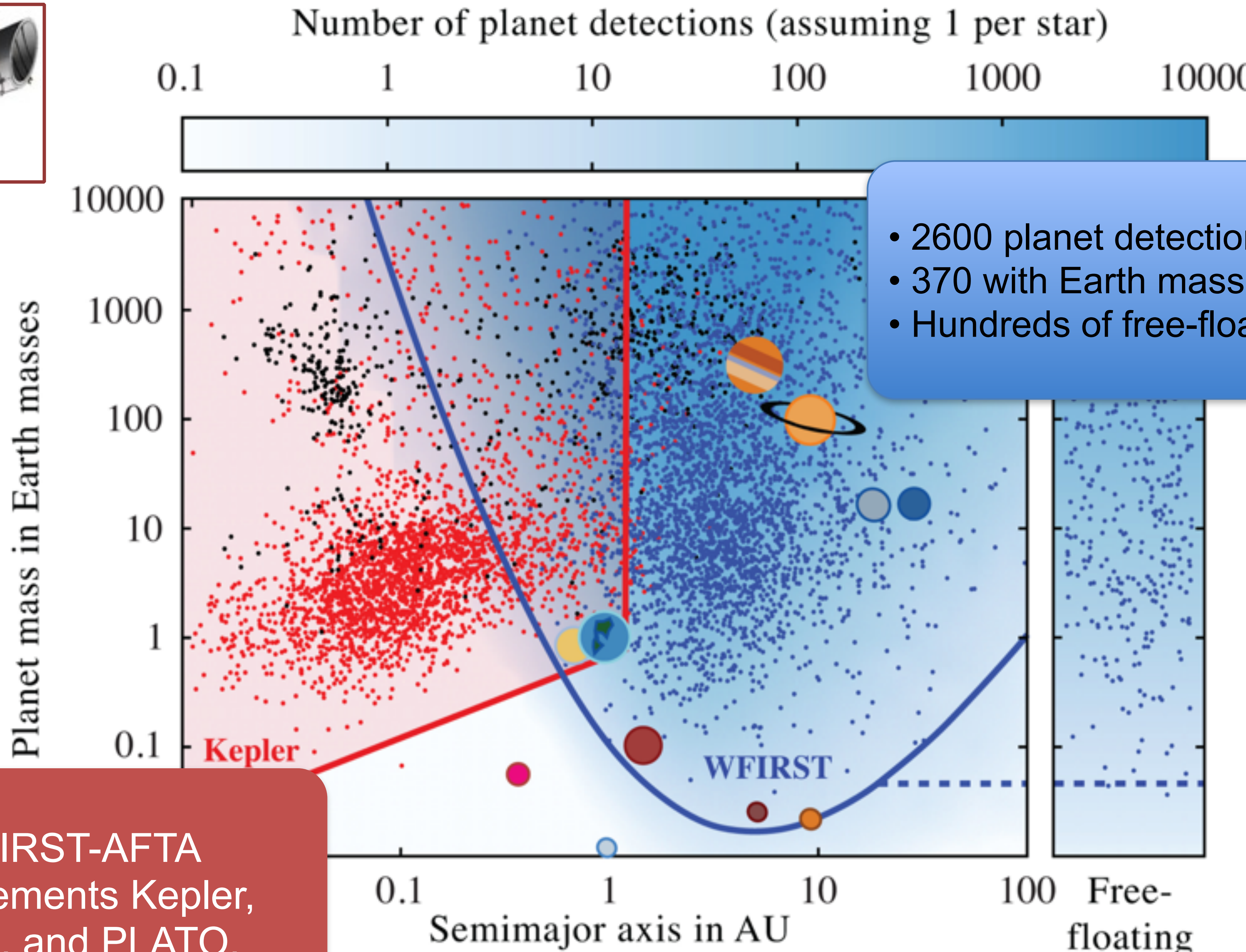


Figure credit Eric Nielsen

Exoplanet Surveys
Kepler & WFIRST





- 2600 planet detections.
- 370 with Earth mass and below.
- Hundreds of free-floating planets.

WFIRST-AFTA complements Kepler, TESS, and PLATO.

M. Penny (OSU)

Conclusions

- The start of the millenium has been an exciting time for cosmology
  - The last millenium ended with the discovery of dark energy and the new one began with precision CMB measurements
  - Next steps: discover the nature of dark energy and dark matter, understand the origin of the universe!

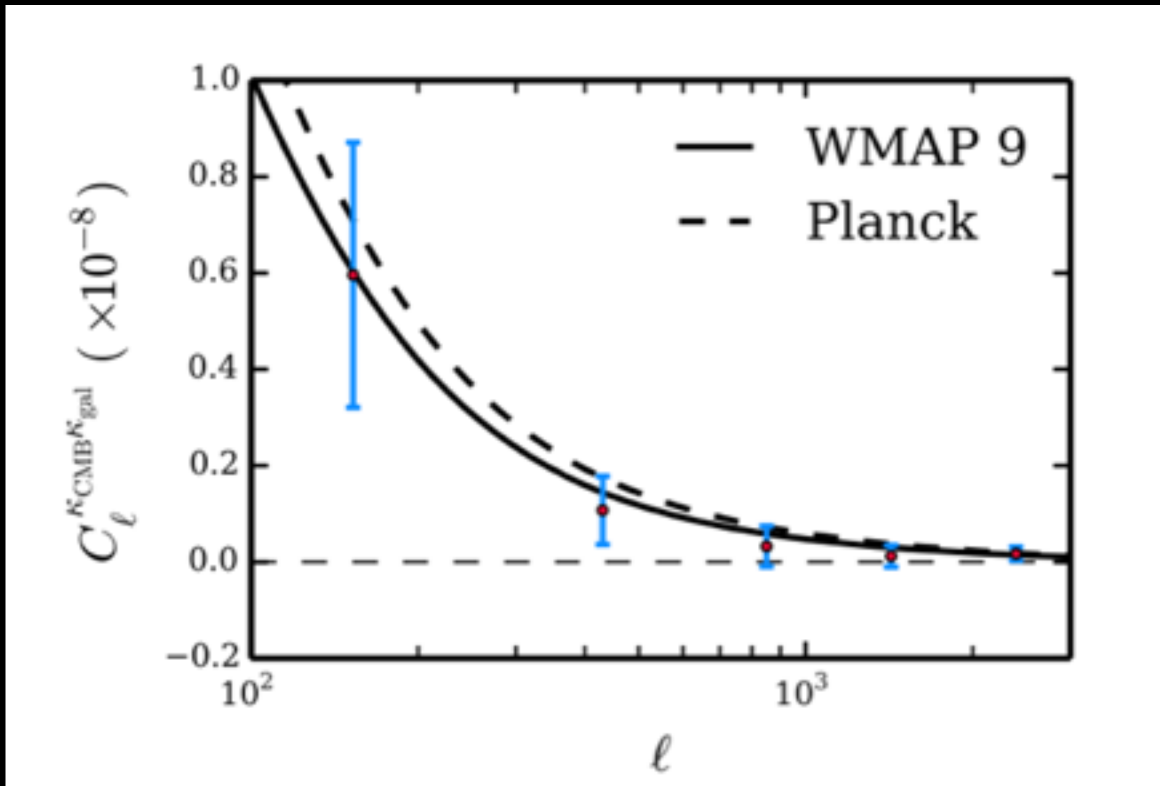
Gravitational Lensing of the CMB

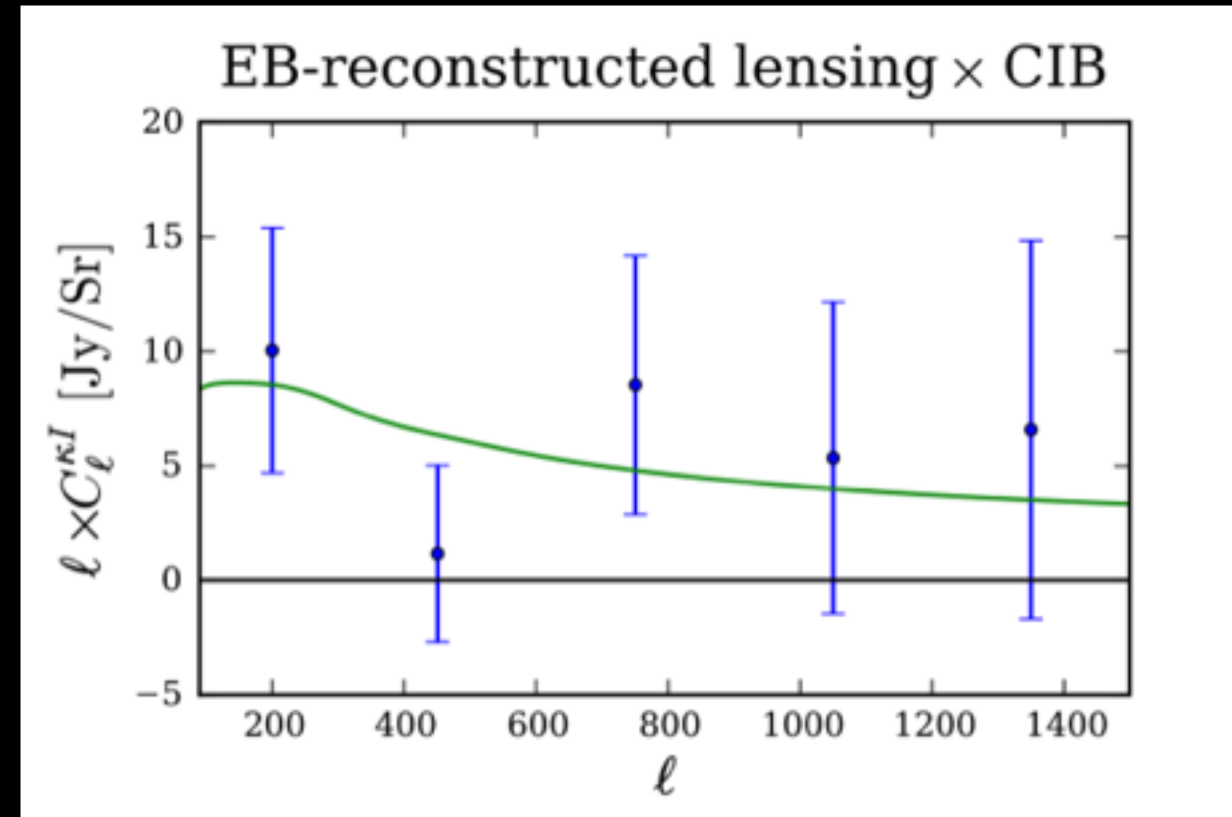
Intervening large-scale potentials deflect CMB photons and distorts the CMB.

The rms deflection is about 2.7 arcmins, but the deflections are coherent on degree scales.

CMB Lensing is different...

- Measure deflection rather than shear (more signal on large-scale; less on small scale)
- Well understood source plane at known conformal distance
- Behind everything
- Single source plane- Very poor resolution





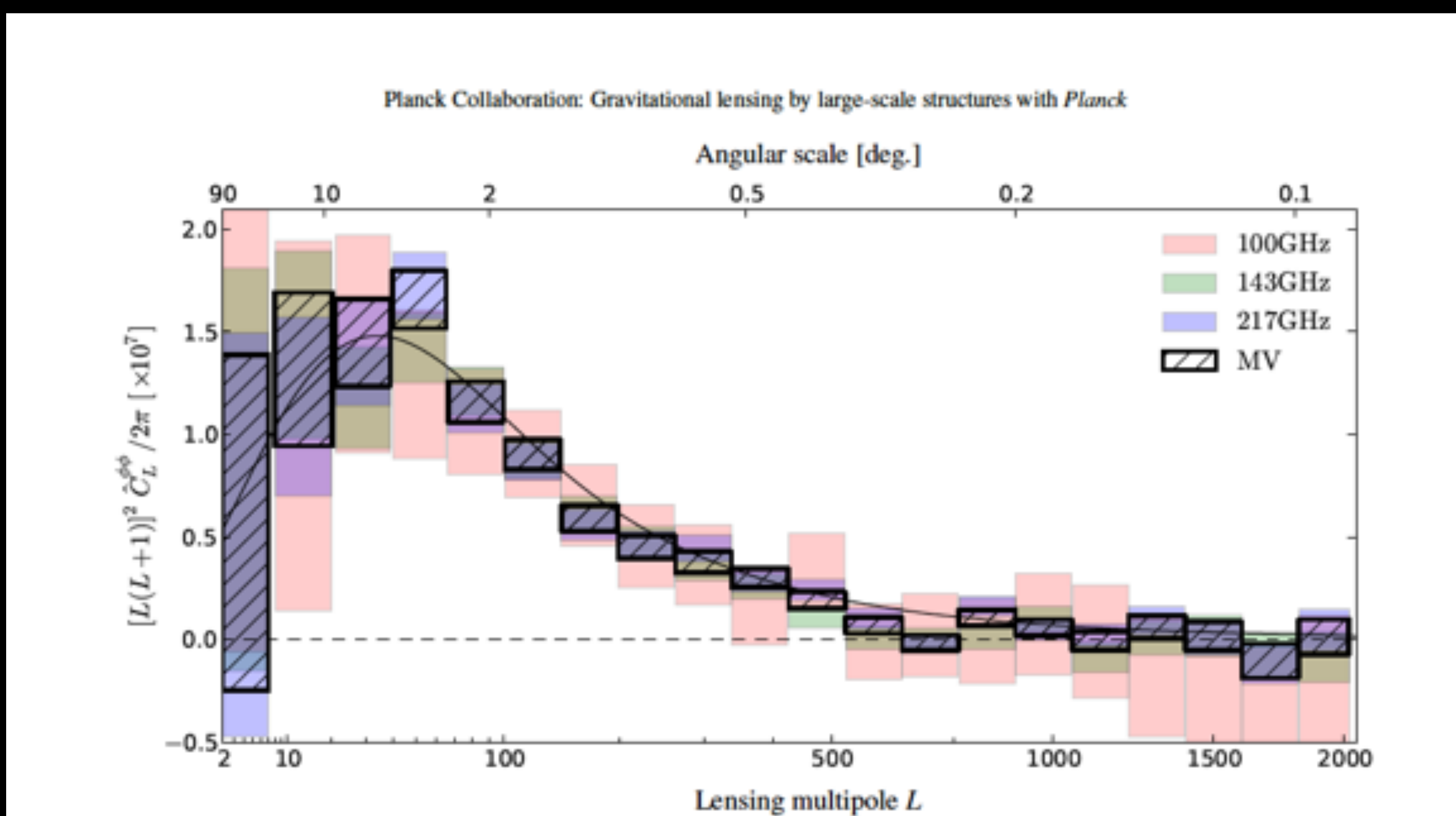
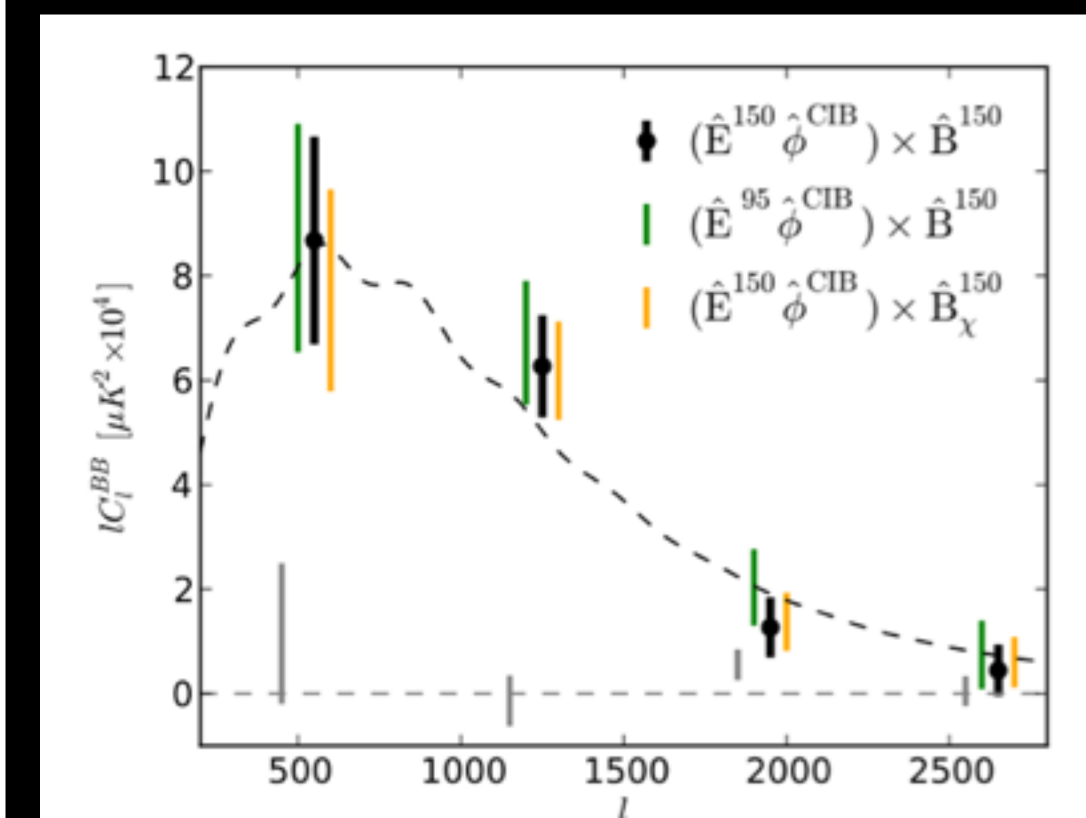
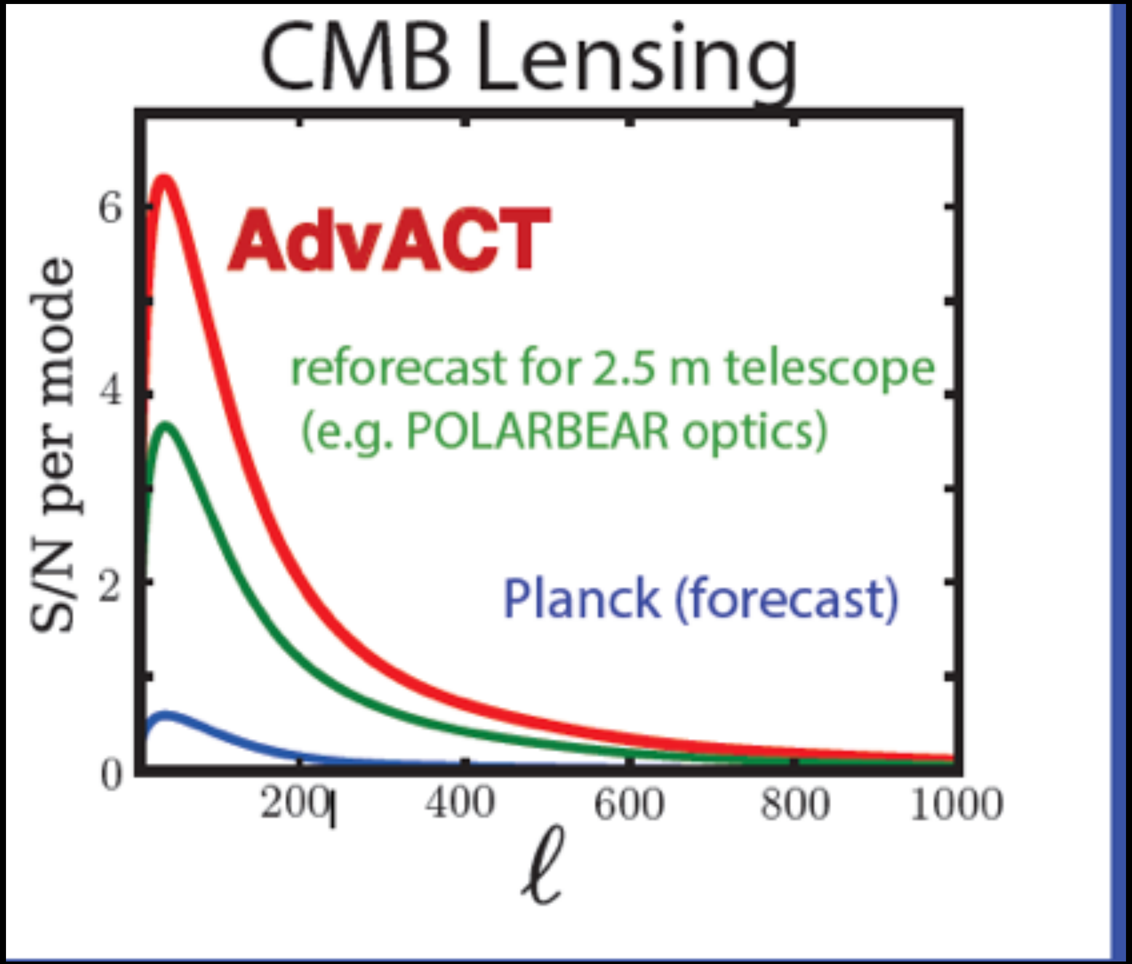
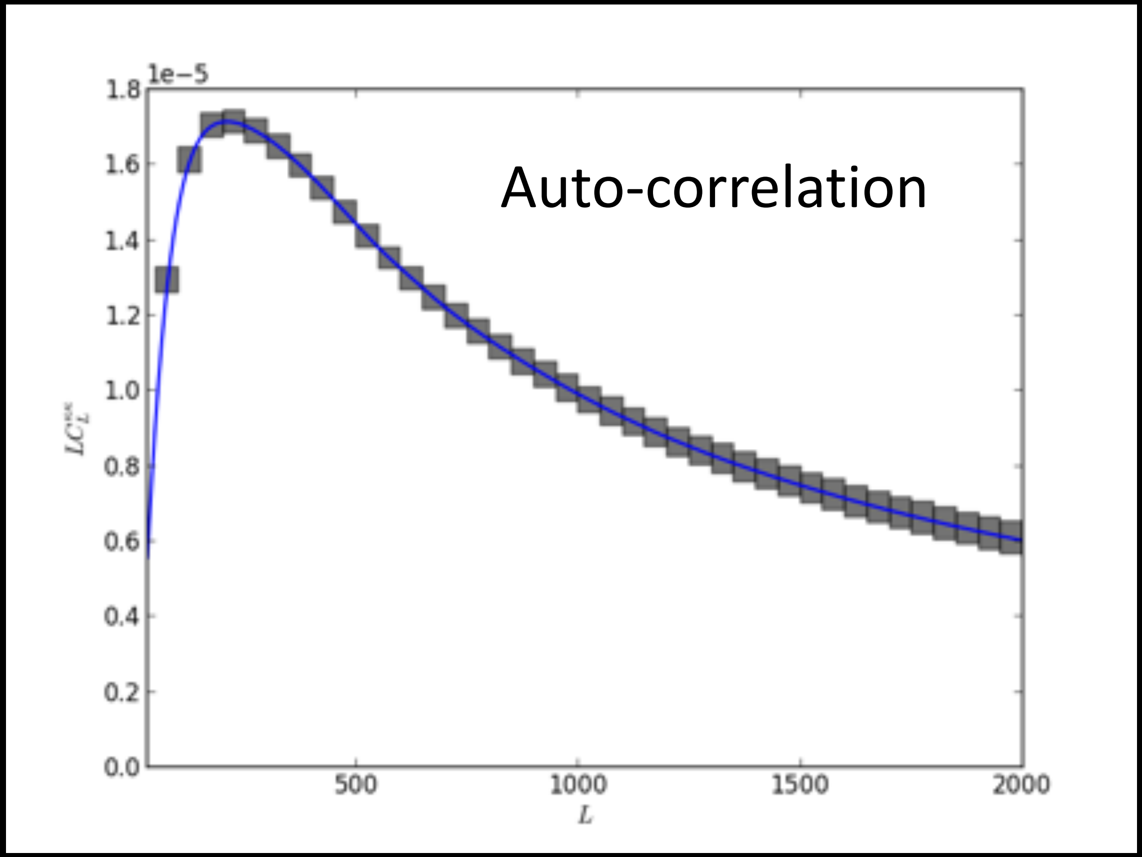


Fig. 10. Lensing potential power spectrum estimates based on the individual 100, 143, and 217 GHz sky maps, as well our fiducial minimum-variance (MV) reconstruction which forms the basis for the *Planck* lensing likelihood. The black line is for the best-fit ΛCDM model of Planck Collaboration XVI (2014).



CMB Lensing

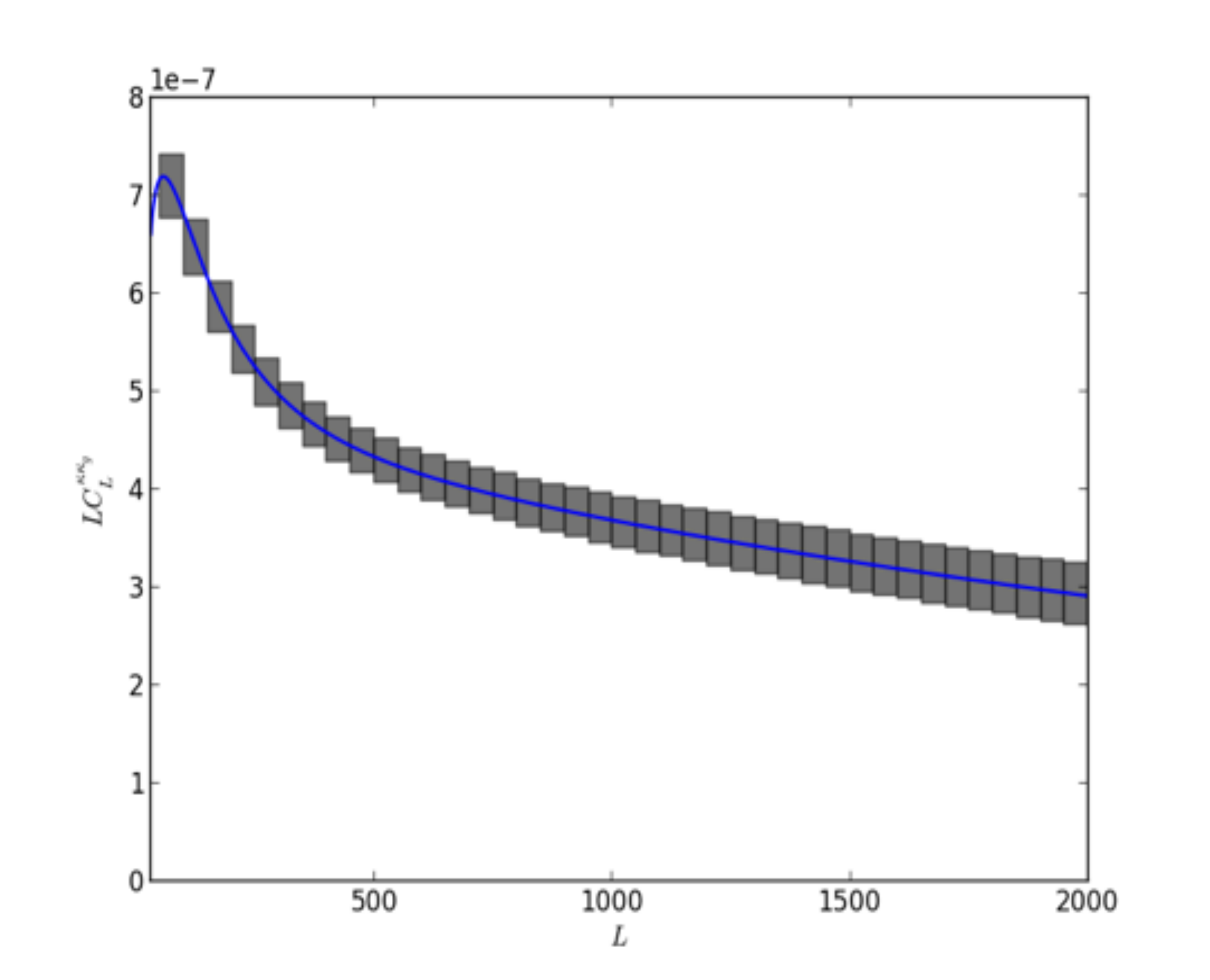




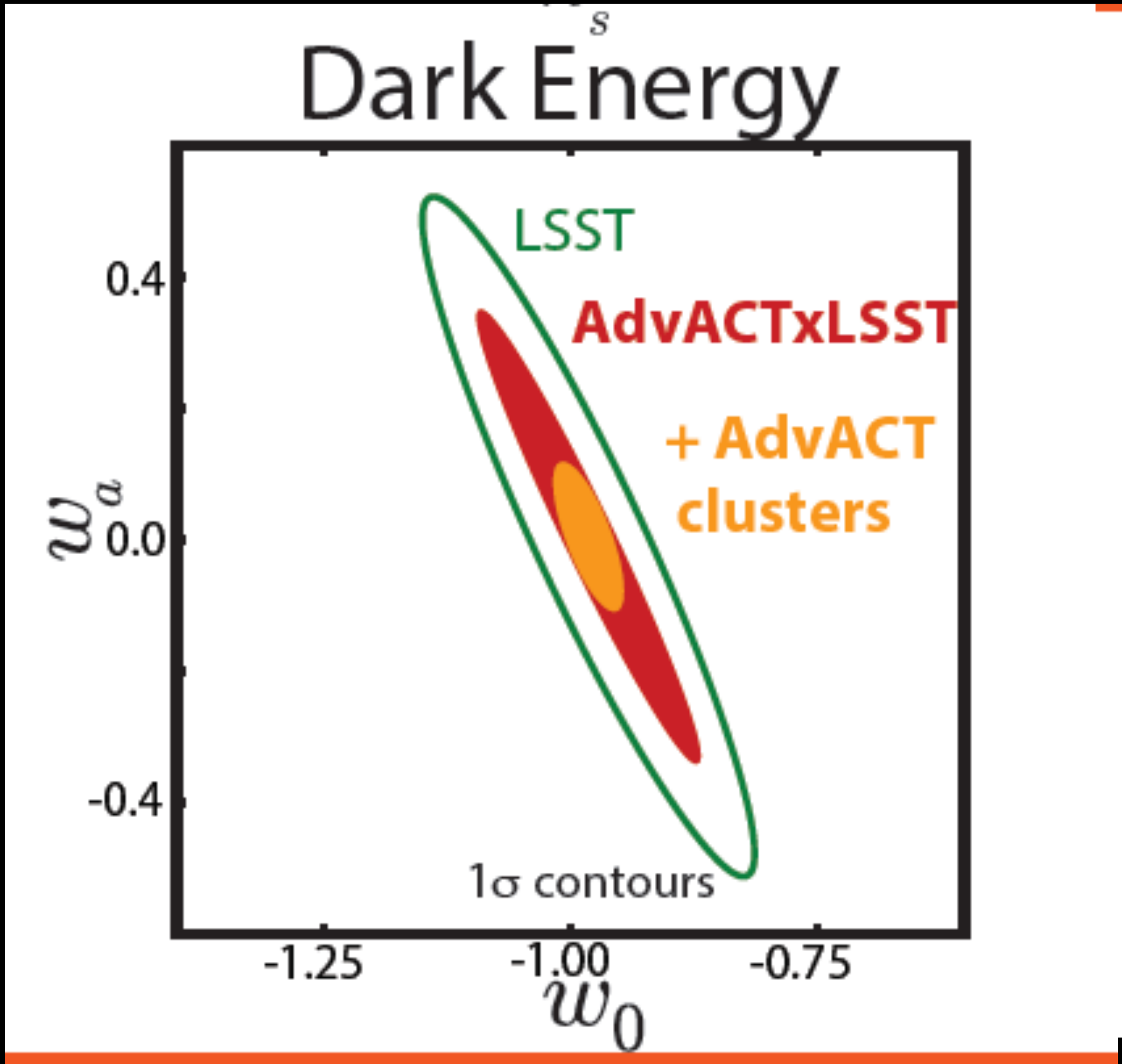
AdvACT will make a precise map of the projected mass distribution with angular resolution of 0.5 degrees

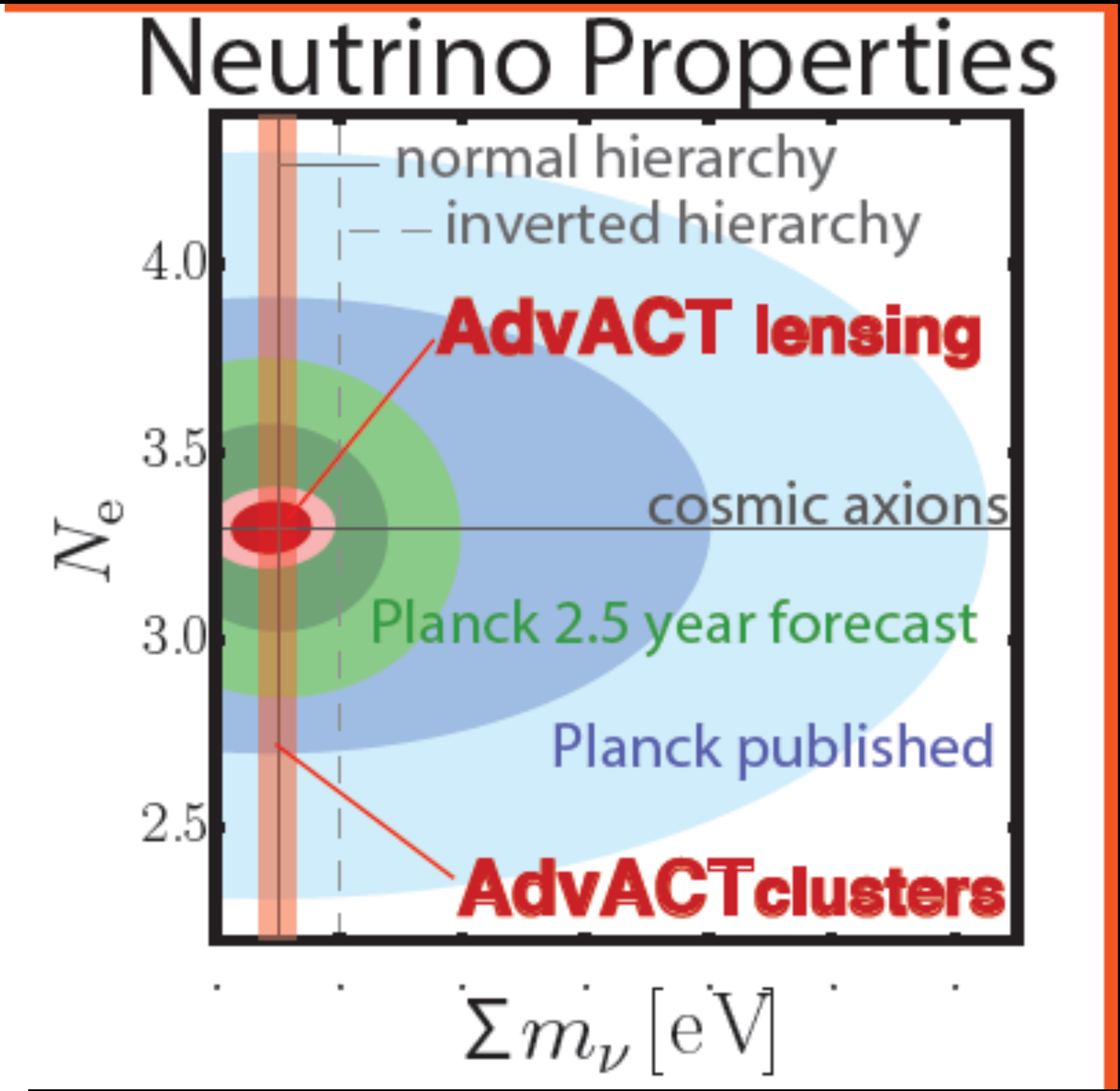
CMB x LSST Lensing

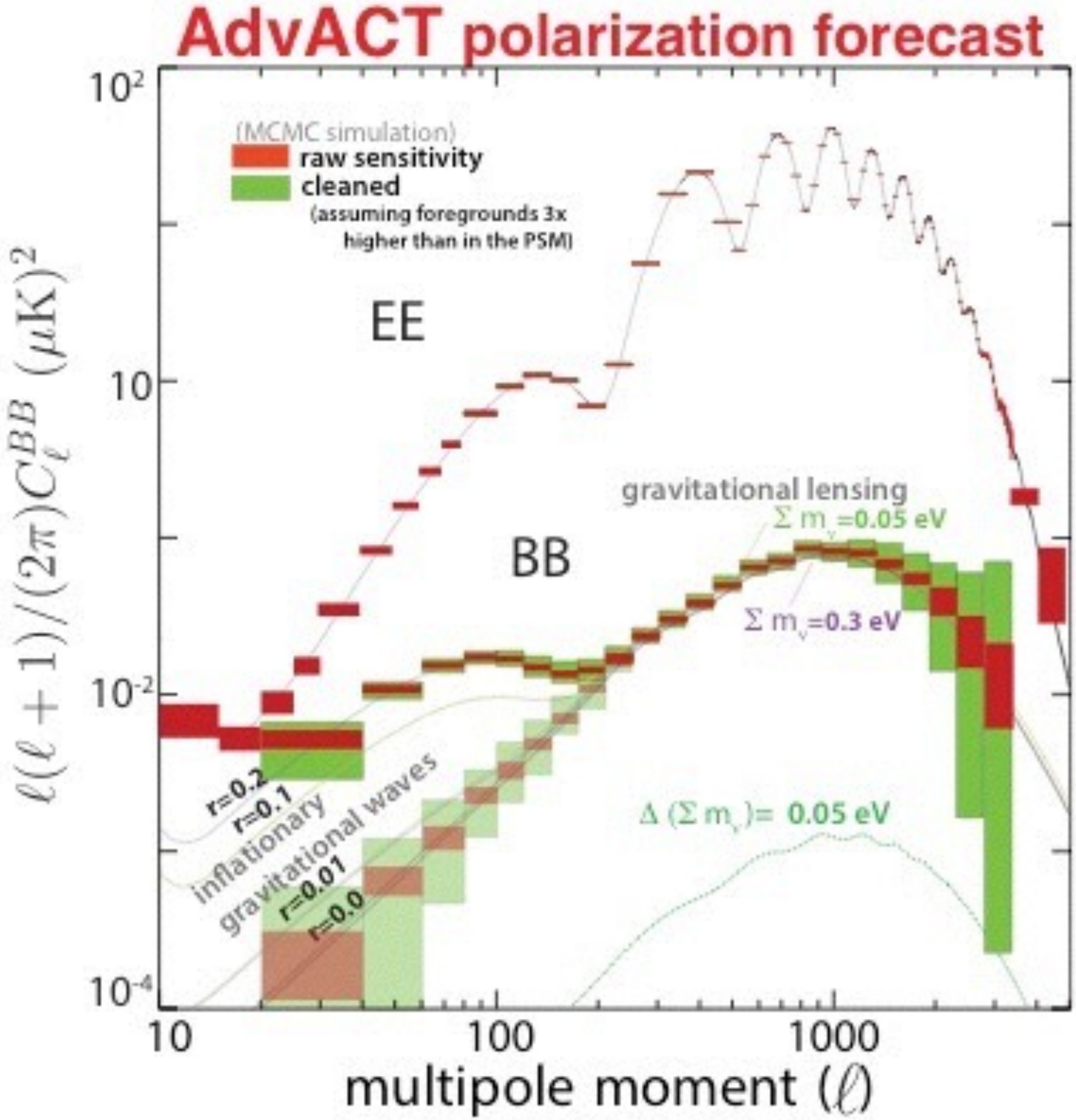
- High redshift lens plane extends LSST measurements (> 90 σ correlation)
- Reduce systematics
- Determine multiplicative bias
- Cross-correlate with galaxies and quasars as well
- Weigh clusters with multiple lens sheets



Parameter Constraints







NOTES:

1) “raw” projections based on 20,000 square degrees, 5 μK-arcmin

2) “cleaned”, based on 12 μK-arcmin which is Jo’s estimate for the residual after removing foregrounds 3x larger than in the PSM

3) the solid boxes are simulated on r = 0.2

4) the semi-transparent boxes have r = 0.0

5) we still get over 1 sigma on r = 0.01 for the 3x plank cleaning

6) the high ell cleaned error bars are probably pessimistic at high ell— a more thorough analysis should reduce these since the foregrounds don’t dominate at high ell range.