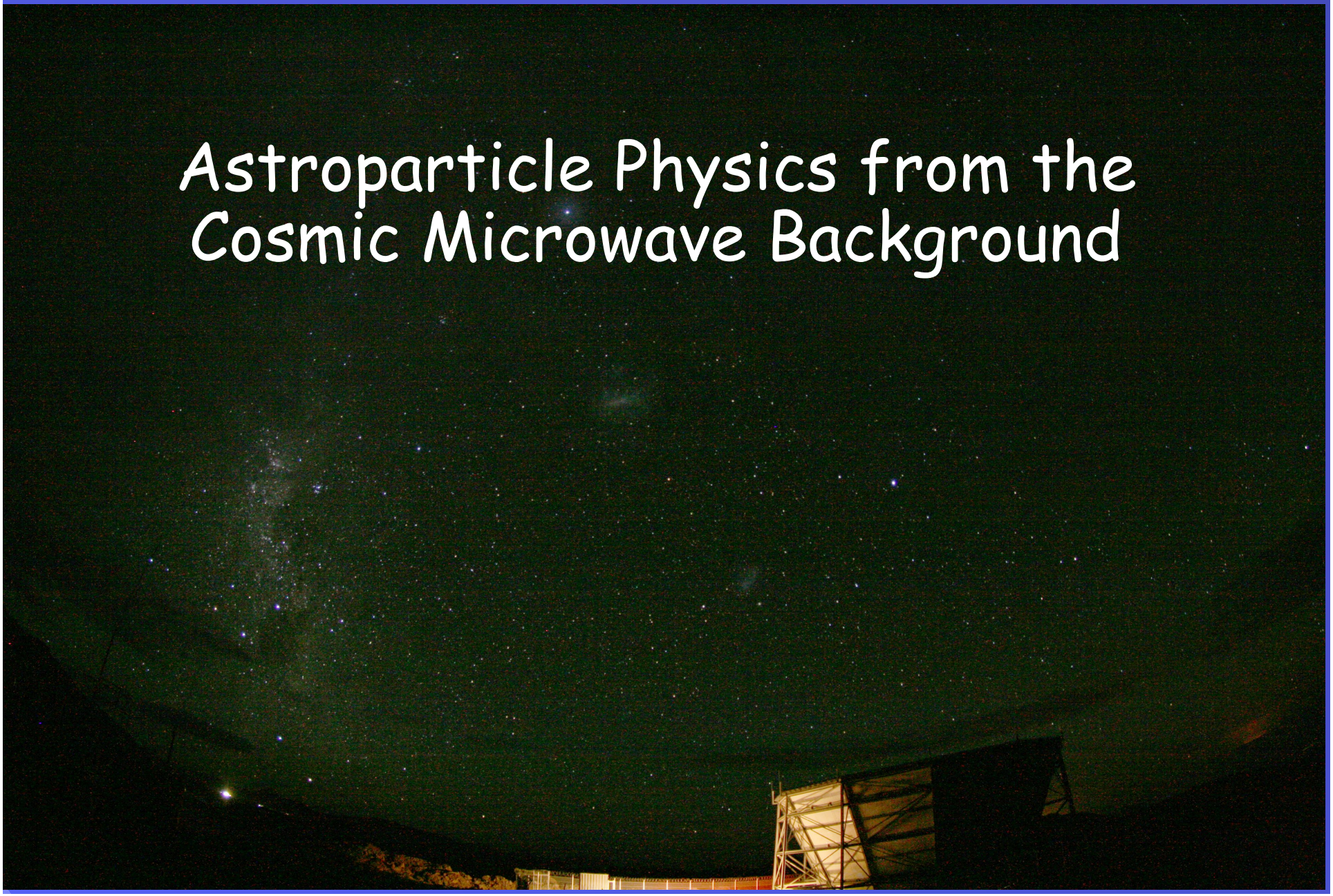
Astroparticle Physics from the Cosmic Microwave Background

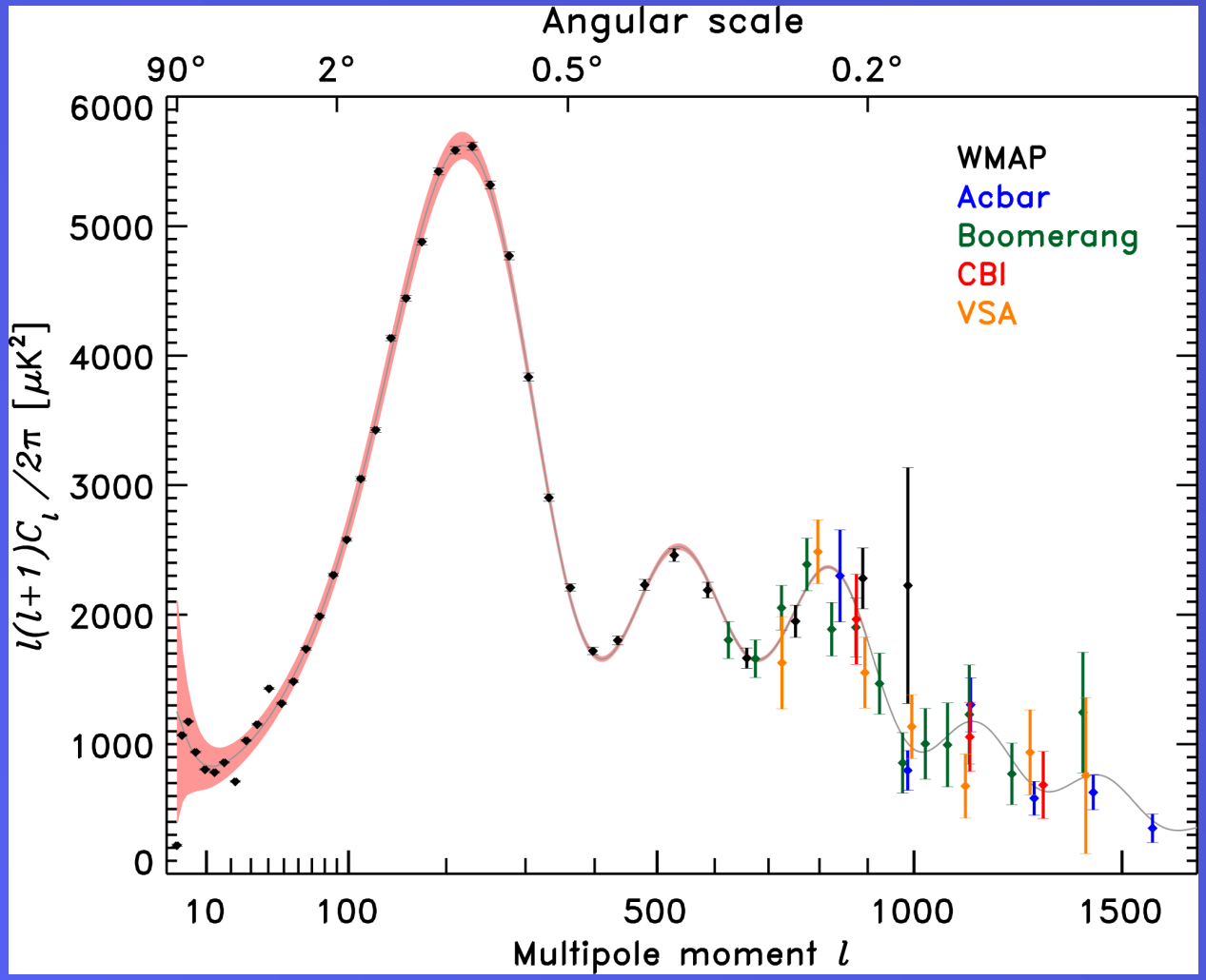


Astroparticles

as extracted from the cosmic microwave background (CMB) anisotropies

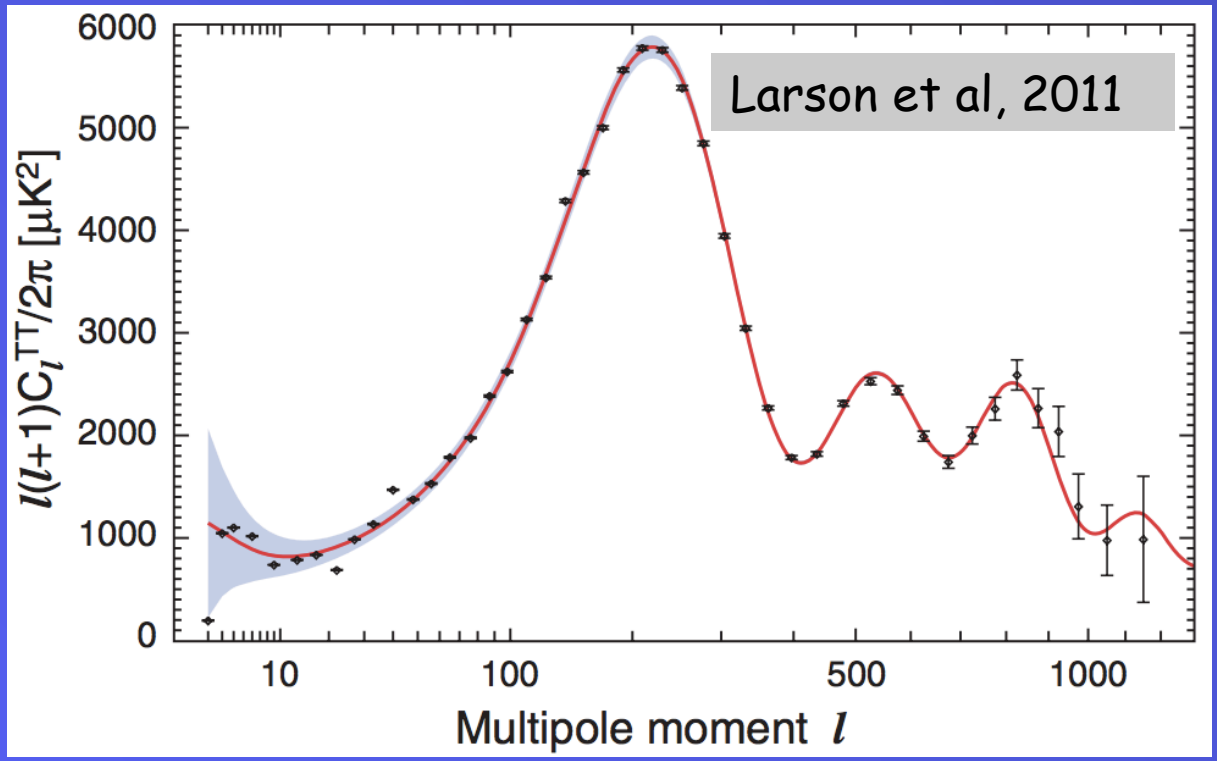
- Baryons (cosmic density, dearth of antibaryons)
- Dark matter (cosmic density, clustering)
- Dark energy (cosmic density, history)
- Neutrinos (how many, mass effects)
- Gravity waves (inflaton field)
- Other (cosmic strings, axions, etc)

The CMB Power Spectrum
circa 2007



- Primordial density fluctuations stretched by inflation outside horizon;
- Begin collapsing upon entering horizon;
- Oscillate under influence of radiation pressure and gravity;
- Captured in the snapshot of last scattering.

The WMAP7 CMB TT Spectrum



Matter density: $\Omega_m h^2$

Baryon density: $\Omega_b h^2$

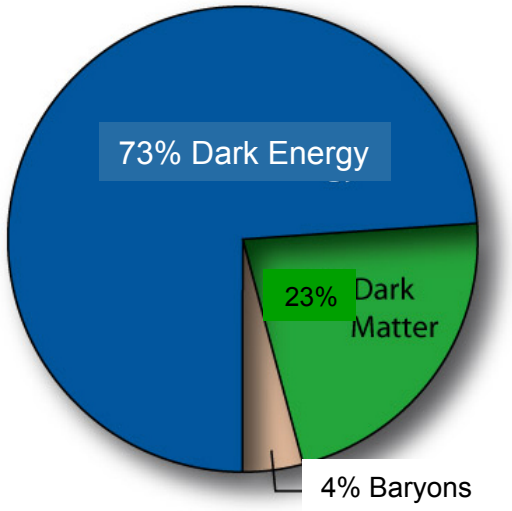
Dark energy: Ω_Λ

Optical depth: τ

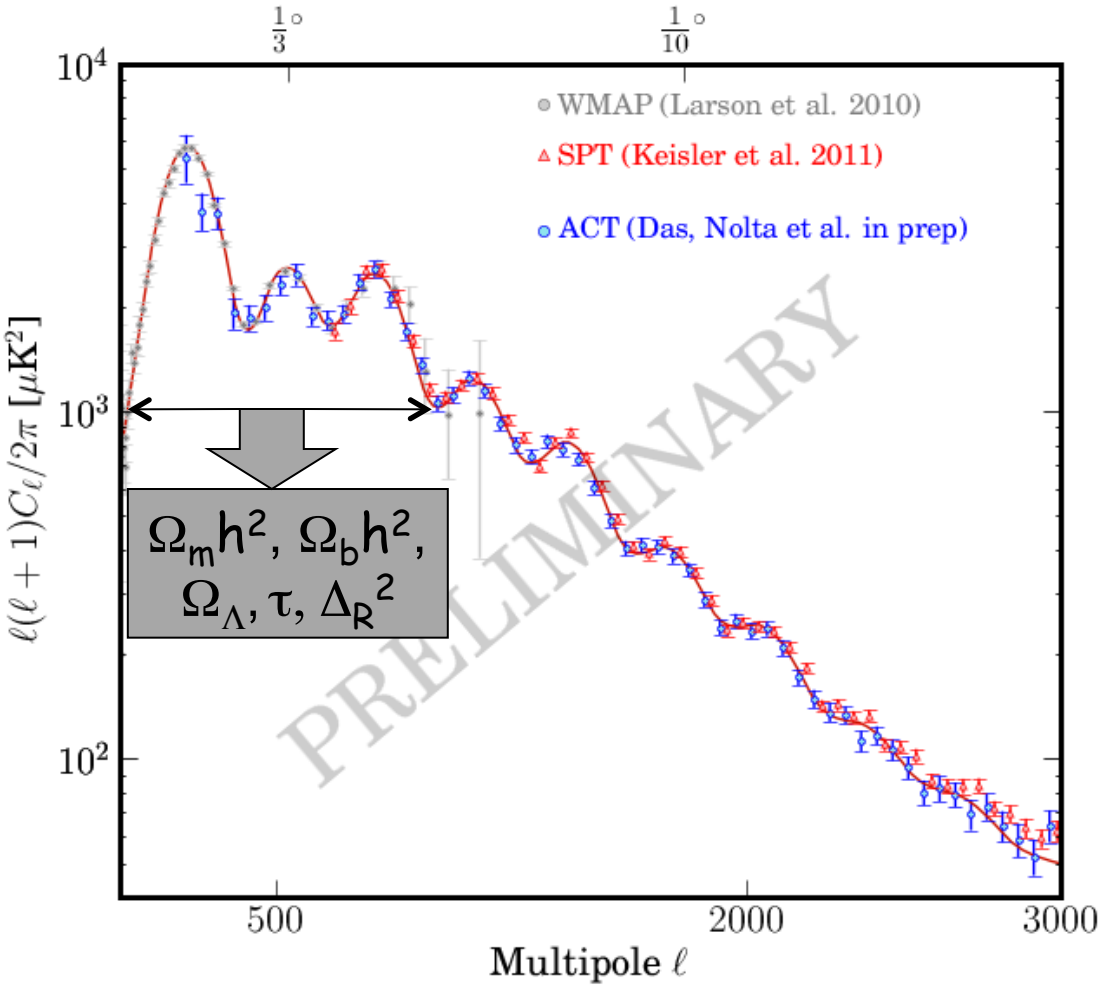
Spectral index: n_s

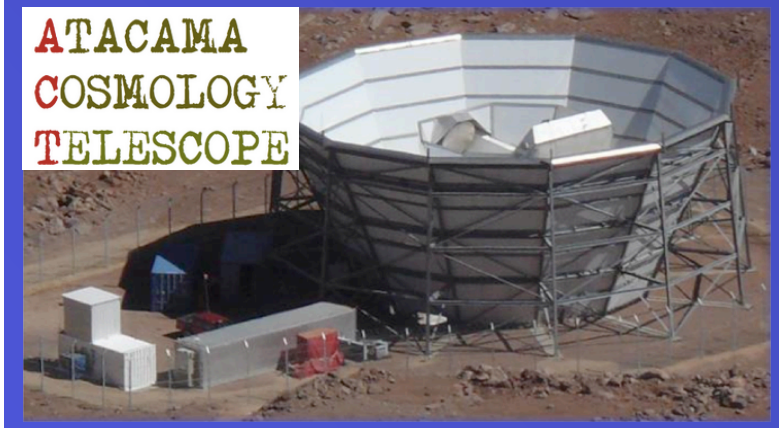
Primordial amplitude at k_0=0.002 Mpc^{-1}: Δ_R^2

- Six parameters. (Zero curvature favored/assumed.)
- Need H_0 = h (100 km/s/Mpc) from elsewhere + another angular diameter distance (eg BAO).
- Nota bene: h = 0.74 → h^2 ~1/2
- Critical density ~ 5 protons/m^3.



The CMB TT Power Spectrum
circa 2012



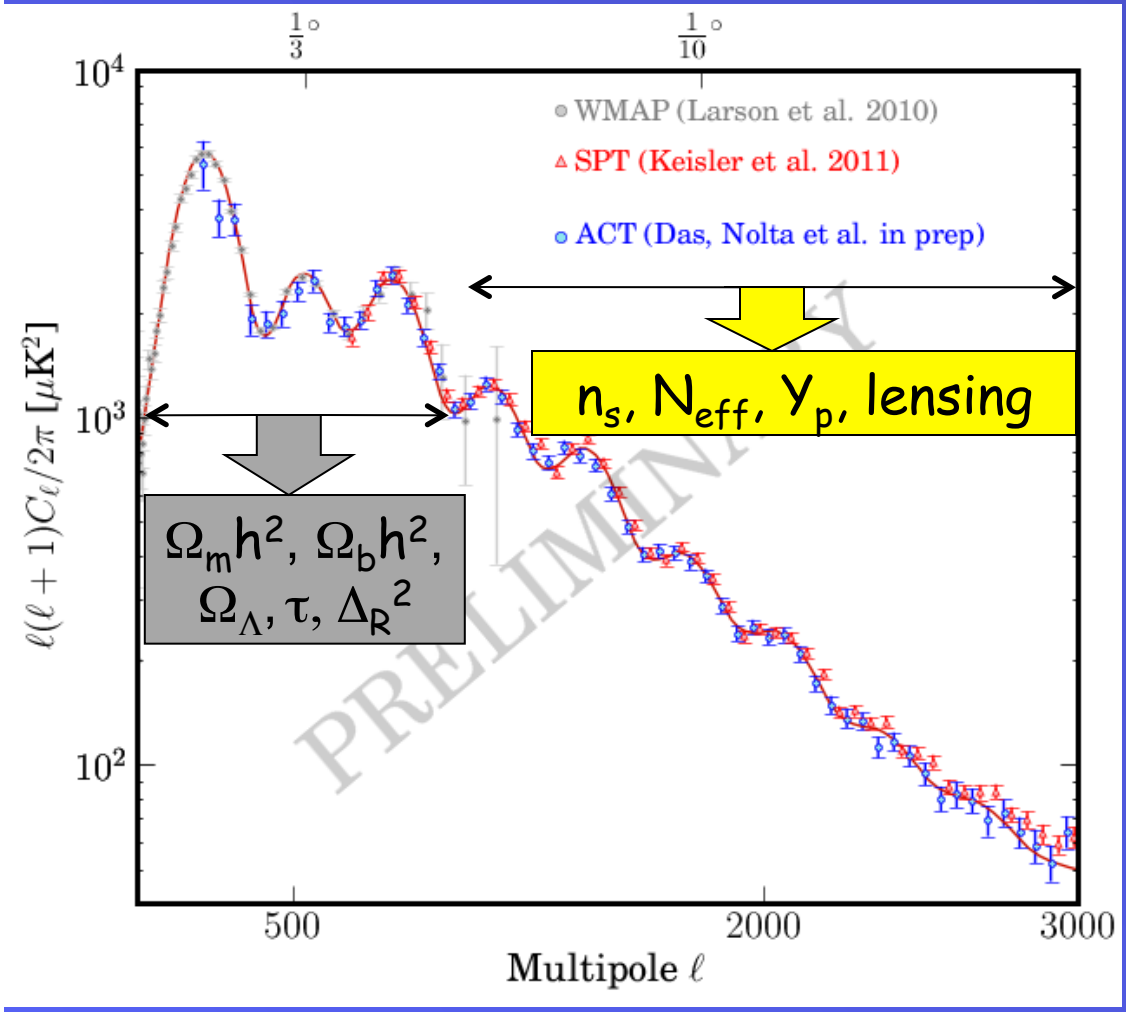


- Located at 5200 m (0.5 mm PWV)
- 3 arrays of 1024 TES bolometers each
- 148 GHz, 218 GHz, 277 GHz
- 18 institutions, 4 continents, PI = Lyman Page

- WMAP (1.4 m): 3 peaks
- ACT (6m) & SPT (10m): **9 PEAKS & COUNTING**

(Note WMAP measures polarization also.)

The CMB Damping Tail
circa 2012



- INFLATION PROPERTIES:

Primordial scalar index: n_s

Running of n_s: $d\ln n_s / d\ln k$

- NEUTRINOS:

relativistic species: N_{eff}

Primordial He abundance: Y_p

Gravitational lensing: A_L

- DARK MATTER:

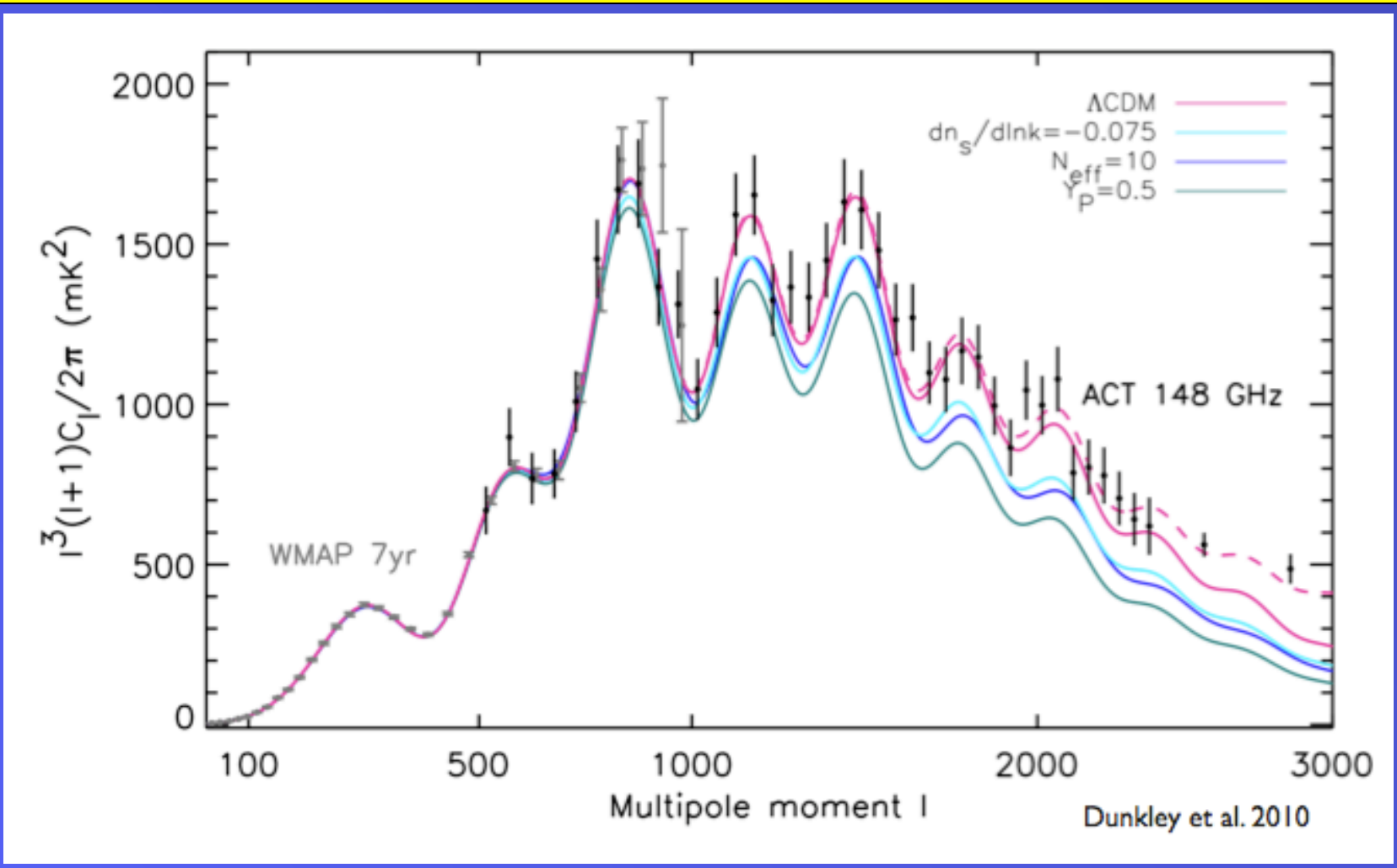
Clusters (SZ: σ_8)

- POINT SOURCES:

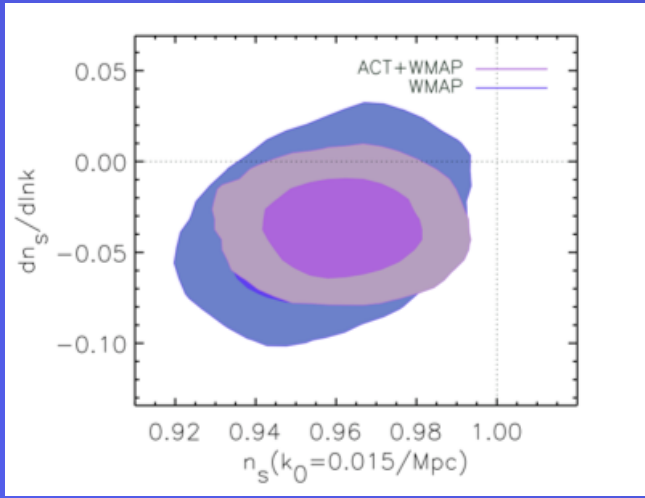
radio, IR, clustered and Poisson

The Damping Tail of the CMB Power Spectrum

Running of n_s: $d\ln n_s / d\ln k$; # Relativistic species: N_{eff}; Primordial He abundance: Y_p



Testing Inflation with the Power Spectra



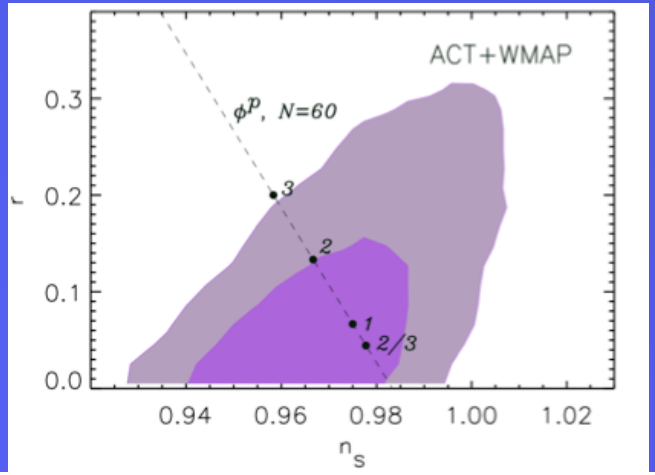
Primordial power spectrum P(k) described as power law in the wavevector k.

Canonical values shown as crosshairs:
n_s=1 (flat spectrum), $dn_s/d \ln k = 0$

n_s = 0.962 +- 0.013 → 3σ different from 1 (ACT +WMAP)

$dn_s/d\ln k = -0.034 \pm 0.018$ (ACT+WMAP)

$dn_s/d\ln k = -0.024 \pm 0.015$ (ACT+WMAP+BAO+H0)



Ratio of tensor to scalar fluctuation amplitudes, r, varies with the inflation energy scale

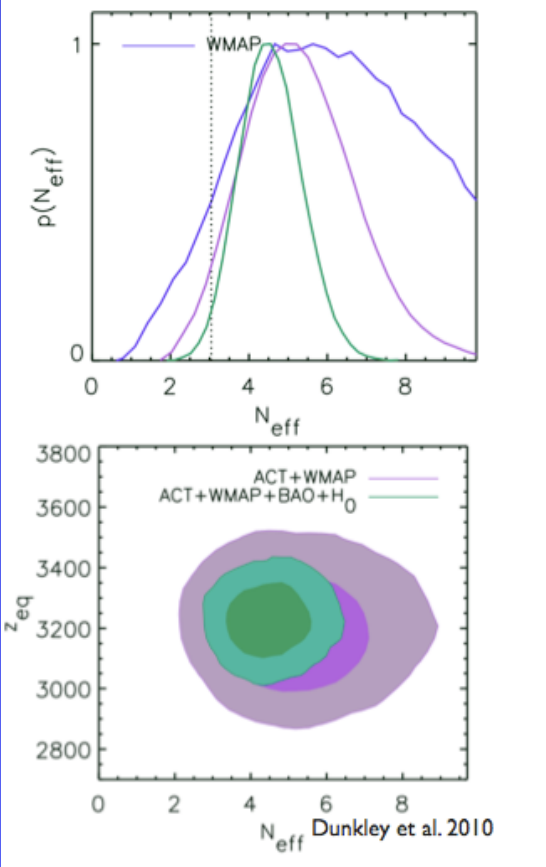
$r < 0.25$ (95% CL,ACT+WMAP)

$r < 0.19$ (95% CL,ACT+WMAP +BAO+H0)

Polarization B-modes will constrain r better soon!

Particle Physics in the Power Spectra

•The 2.984 +- 0.008 neutrino species measured from the width of the Z boson contribute 11% of the energy density at the time of last scattering!



•N_{eff} = number of relativistic particle species,

•N_{eff} affects when matter density begins to dominate energy budget and thus changes expansion history

•Early decoupling of neutrinos results in an anisotropic stress contribution to the governing gravitational potential, also impact the CMB peak heights and positions slightly

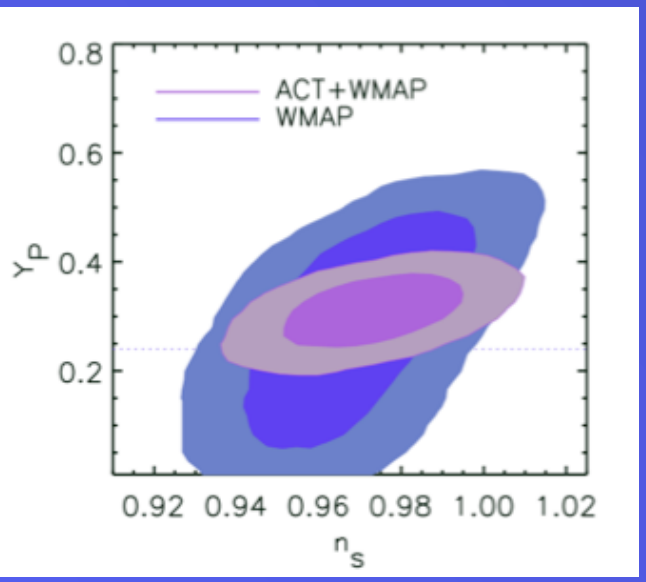
• Data consistent with standard decoupling & # of neutrinos

•CMB data alone now bound N_{eff} from above!

•Recent measurements:

- •N_{eff} = 5.3 +- 1.3 (ACT +WMAP)
- •N_{eff} = 4.56 +- 0.75 (ACT +WMAP + BAO + H_0)
- •N_{eff} = 3.85 +-0.62 (SPT +WMAP – Keisler et al 2011)
- •N_{eff}= 4.34+-0.86 (WMAP + BAO + H_0, Komatsu et al 2011)

Nuclear Physics in the Power Spectra



$Y_p = 0.313 \pm 0.044$ (68% CL, ACT+WMAP)

- Y_p = fraction of primordial helium
- BBN prediction as dotted line
- More helium --> smaller electron density --> more Silk damping
- No-helium universe ruled out at 6σ --> independent confirmation of BBN!

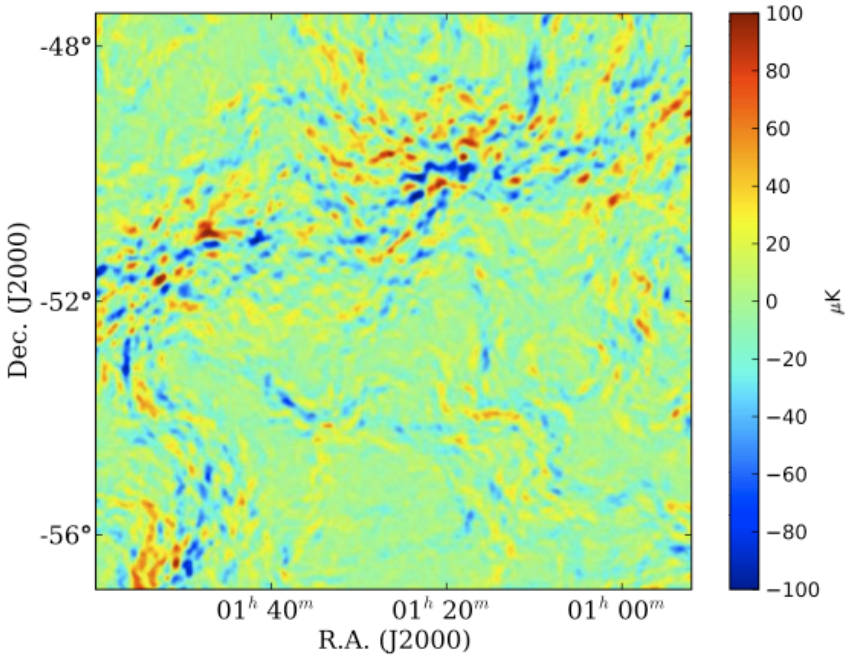
Note – delicate timing of BBN veru sensitive to ratios of radiation and matter density → turn this confirmation into probe of N_{eff} → agreement.

Note – more primordial Helium decreases the number of electrons at recombination, increasing the photon diffusion length → more damping.

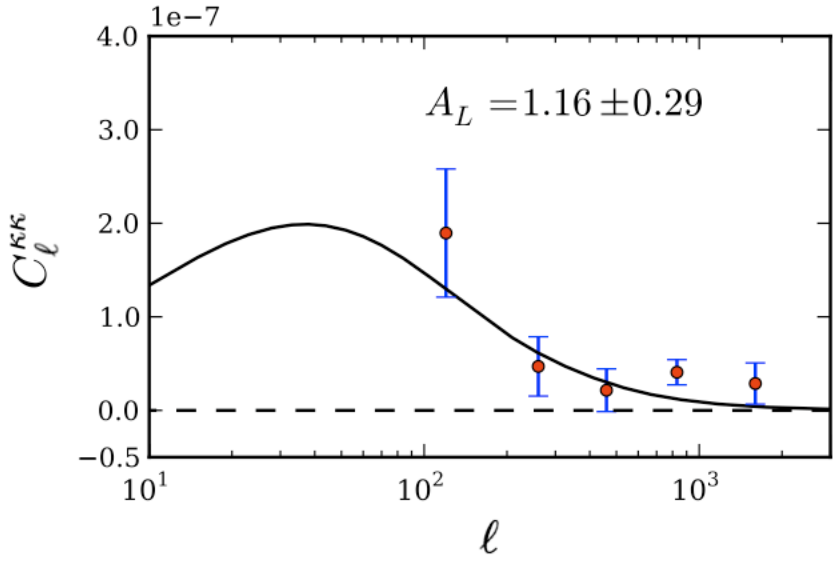
Beyond the Power Spectrum:
First Detection of Gravitational Lensing from the CMB Alone

Typical 3' shift, but convergence spectrum peaks at l = 50: large & small scales coupled (non

Simulated difference between lensed and unlensed CMB in 10°x10° patch



Data from ACT 4pt function



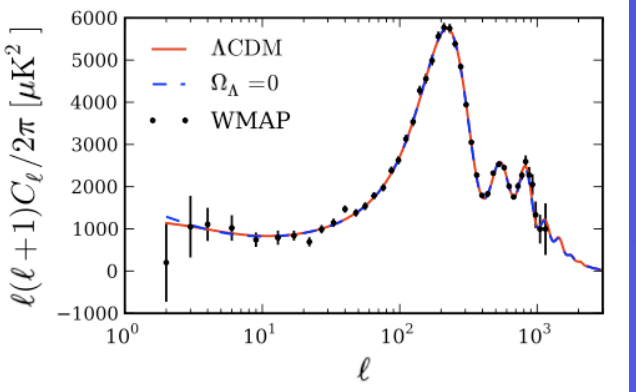
Das et al, 2011, 1103.2124 (PRL 107, 021301.)

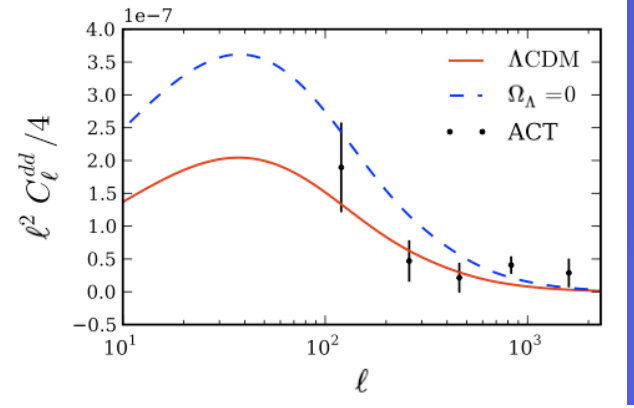
Beyond the Power Spectrum:
Dark Matter, Neutrinos, Growth Rate of Structure

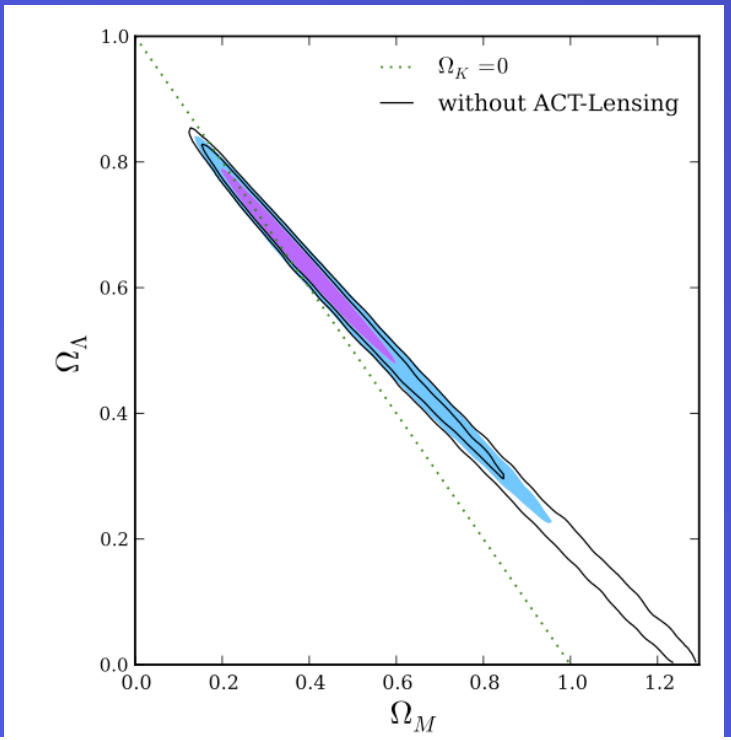
- CMB lensing measures the integrated gravitational effects along the line of sight back to z = 1090
- Probes dark matter distribution
- The growth rate of structure probes the expansion history for z~ 1-3
- Sensitive to the sum of the neutrino masses!
- Clusters of galaxies are detected in blind surveys by ACT and SPT via the Sunyaev Zeldovich effect and also probe dark matter clustering, and the expansion history

Extending the Power Spectrum:
Dark Energy from the CMB Alone

The lensing probes the universe at z~0.2, breaking the dark energy/matter/curvature degeneracy in the CMB power spectrum alone.







Sherwin et al, 2011, 1105.0419 (PRL 107, 021302)

The Very Near Future

ACT and SPT will have polarization power spectra soon → greatly enhances the gravitational lensing measurements

ACTPol (4x more sensitive than ACT + has polarization sensitivity now) will also overlap BOSS survey regions; lensing cross-correlations improve on the neutrino mass even more.

THE END