Recent Results from the Atacama Cosmology Telescope

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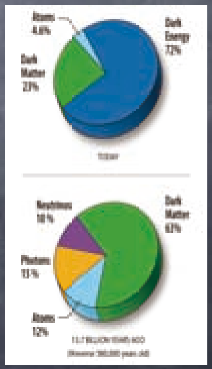
IPMU June 2011

Outline

- Cosmology Today
- ACT Results
- ACTPOL

Today's Cosmological Model

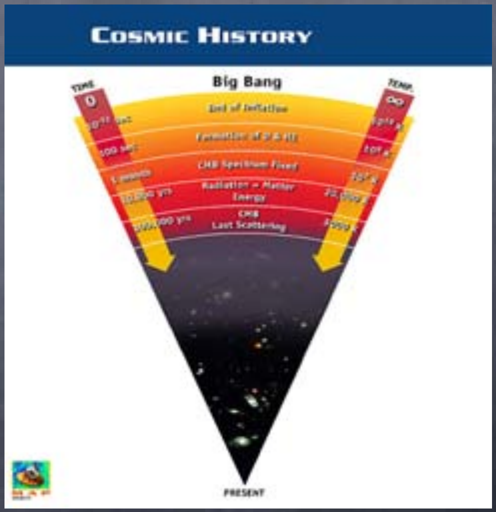
- The universe is simple. We can fit all of our observations of the universe with five numbers:
  - density of atoms
  - age of the universe
  - density of matter
  - amplitude of fluctuations
  - scale dependence of fluctuations



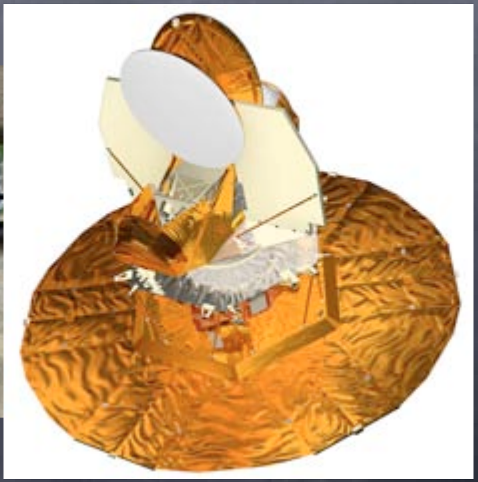
- The universe is strange

Quick History of the Universe

- Universe starts out hot, dense and filled with radiation
- As the universe expands, it cools.
  - During the first minutes, light elements form
  - After 300,000 years, atoms form
  - After 100,000,000 years, stars start to form
  - After 1 Billion years, galaxies and quasars

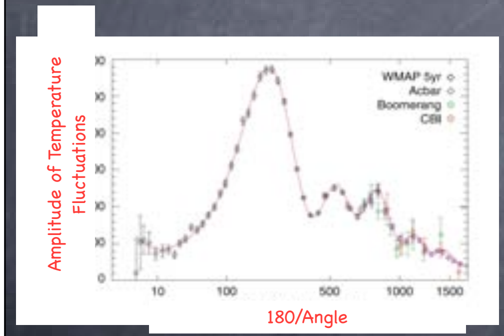


Wilkinson Microwave Anisotropy Probe (WMAP)




June 30, 2001
USAF
DELTA

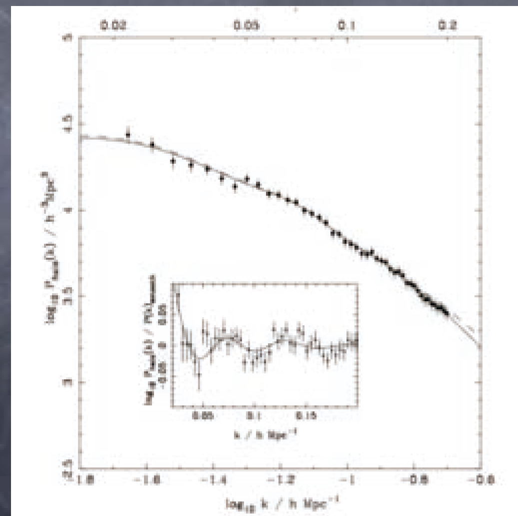
What Have We Learned?



- Simple model fits a wide range of data (only 5 numbers)
- Age of universe:13.7 Gyr
- Composition:
  - Atoms: 4%
  - Matter: 23%
  - Dark Energy: 73%
- Scale Invariant Fluctuations seed growth of galaxies
- First Stars formed ~200 Myr after the big bang

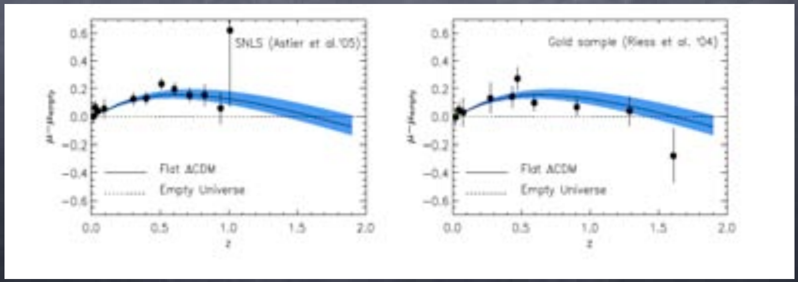
From Baby Pictures to Today's Universe

Today's Universe (Sloan Digital Sky Survey)



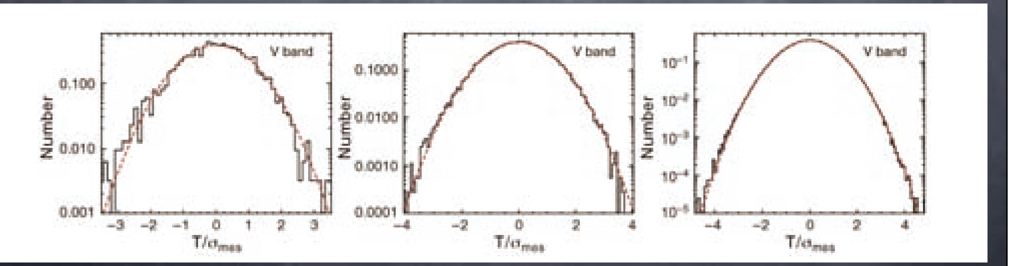
All of the pieces seem to fit....

- Supernova distances
- Hubble Constant
- Age of Universe
- Cluster Properties
- Gravitational Lenses
- Nuclear Abundances
- Lyman alpha forest
- Galaxy Velocities



The Universe is Simple?

- Fluctuations are accurately as Gaussian, Random Phase
- No evidence for spatial variations in fluctuation properties
- No evidence for interaction terms
- No sign of global topology



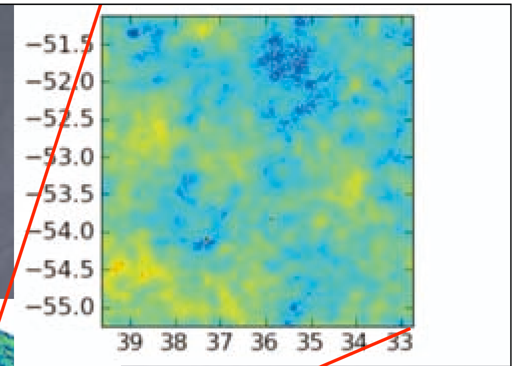
Decadal Survey Questions

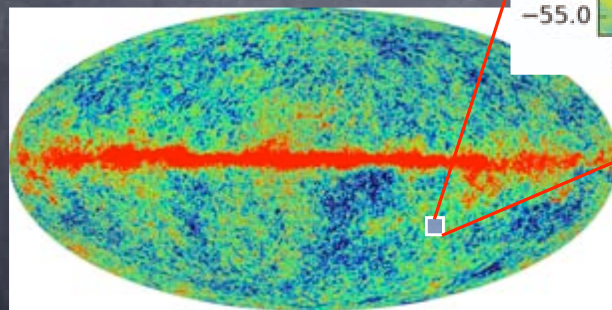
Panel	Science Questions	
Cosmology and Fundamental Physics	CFP 1	How did the universe begin?
	CFP 2	Why is the universe accelerating?
	CFP 3	What is dark matter?
	CFP 4	What are the properties of neutrinos?
Galactic Neighborhood	GAN 1	What are the flows of matter and energy in the circumgalactic medium?
	GAN 2	What controls the mass-energy-chemical cycles within galaxies?
	GAN 3	What is the fossil record of galaxy assembly from the first stars to the present?
	GAN 4	What are the connections between dark and luminous matter?
Galaxies Across Cosmic Time	GCT 1	How do cosmic structures form and evolve?
	GCT 2	How do baryons cycle in and out of galaxies, and what do they do while they are there?
	GCT 3	How do black holes grow, radiate, and influence their surroundings?
	GCT 4	What were the first objects to light up the universe, and when did they do it?

ACT

- Led by Lyman Page
- 80 scientists on 5 continents
- 6-meter telescope on Cerro Tocco (5190 m) in the Atacama Desert. Observing the sky at 128, 218 and 277 Ghz

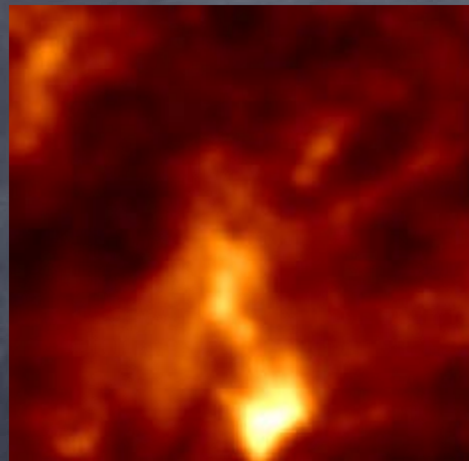
Zooming in…



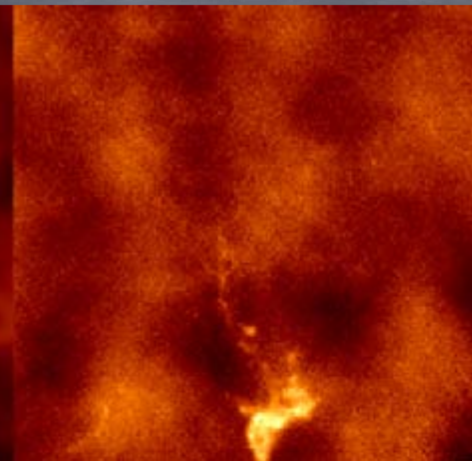


2008: 300 sq deg
2009: 600 sq deg
2010: 1500 sq deg

(4% of sky)

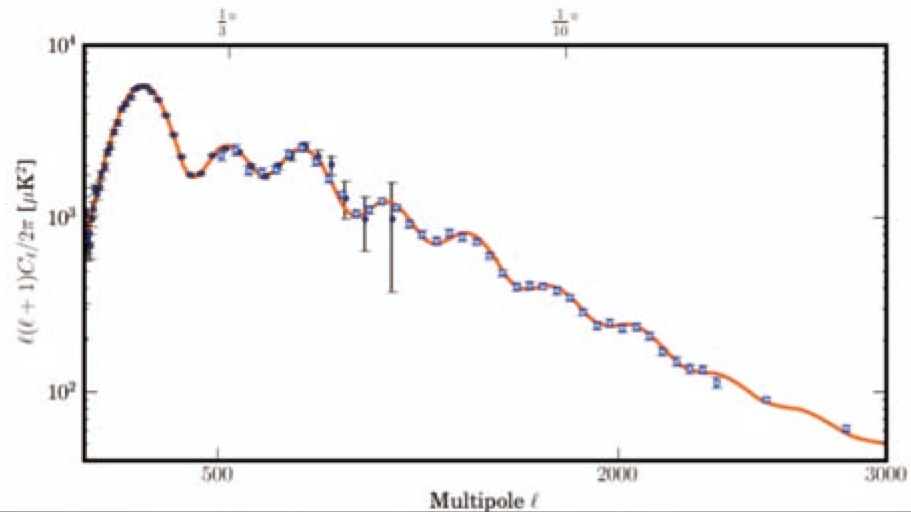


IRAS

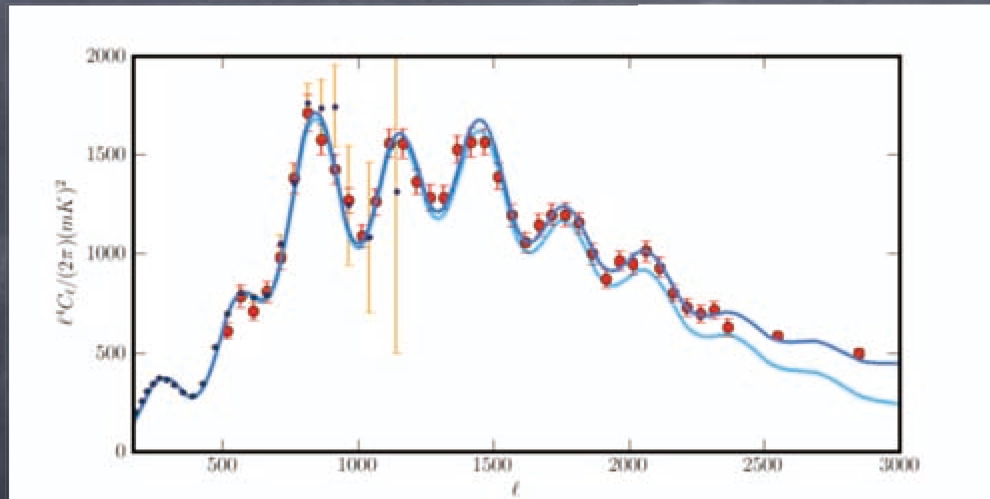


ACT 220 GHz

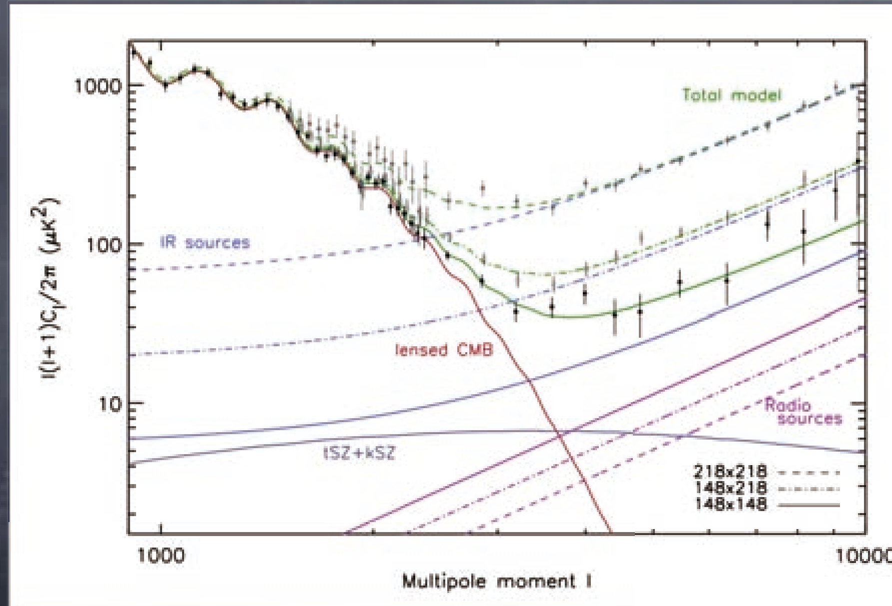
NGC 1055



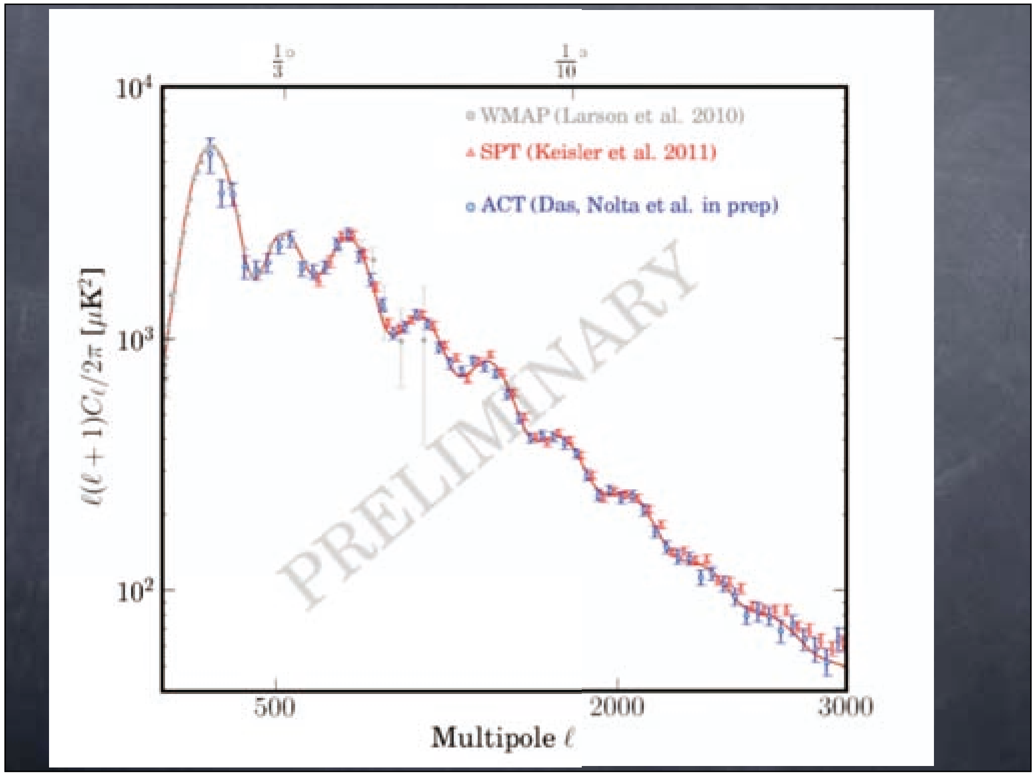
$\frac{1}{3}°$
$\frac{1}{10}°$
10^4
10^3
10^2
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
500
2000
3000
Multipole ℓ



2000
1500
1000
500
0
500
1000
1500
2000
2500
3000
ℓ



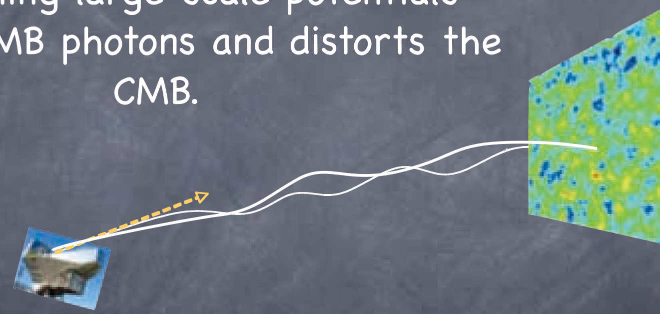
Total model
IR sources
lensed CMB
Radio sources
tSZ+kSZ
218x218
148x218
148x148
l(l+1)C_l/2π (μK^2)
Multipole moment l
1000
100
10
1000
10000



WMAP (Larson et al. 2010)
SPT (Keisler et al. 2011)
ACT (Das, Nolta et al. in prep)
PRELIMINARY
$\ell(\ell+1)C_\ell/2\pi$ [μK^2]
Multipole ℓ
10^4
10^3
10^2
500
2000
3000
$\frac{1}{3}°$
$\frac{1}{10}°$

Gravitational Lensing of the CMB

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



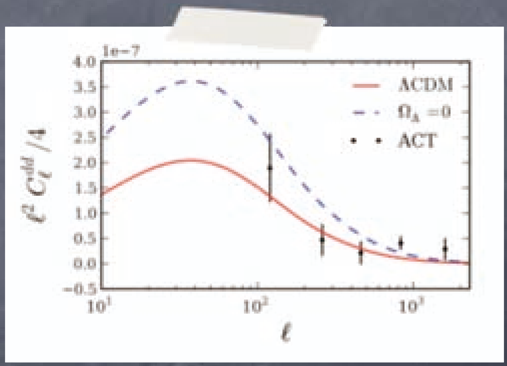
The rms deflection is about 2.7 arcmins, but the deflections are coherent on degree scales.

First Lensing Detection

- Lensing deflects photons and produce non-Gaussian signal:

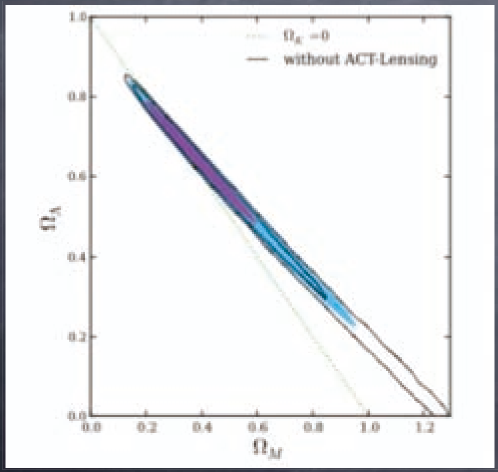
$$T_{obs}(\hat{n}) = T(\hat{n} + \nabla\phi) \simeq T(\hat{n}) + \nabla\phi \cdot \nabla T$$

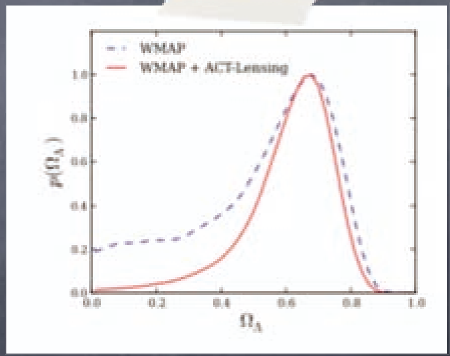
- Non-trivial 4-pt function
- Lensing power spectrum is a meausure of the amplitude of fluctuations along the line of sign

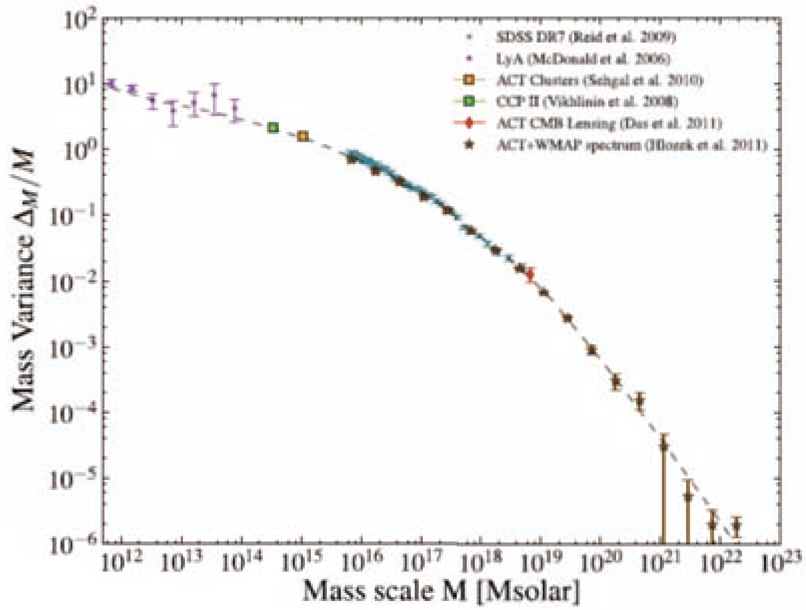


Das et al. arXiv 1103.0419

Direct Detection of Dark Energy from the CMB



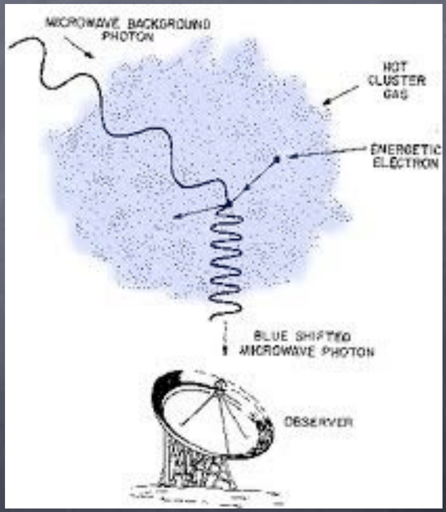


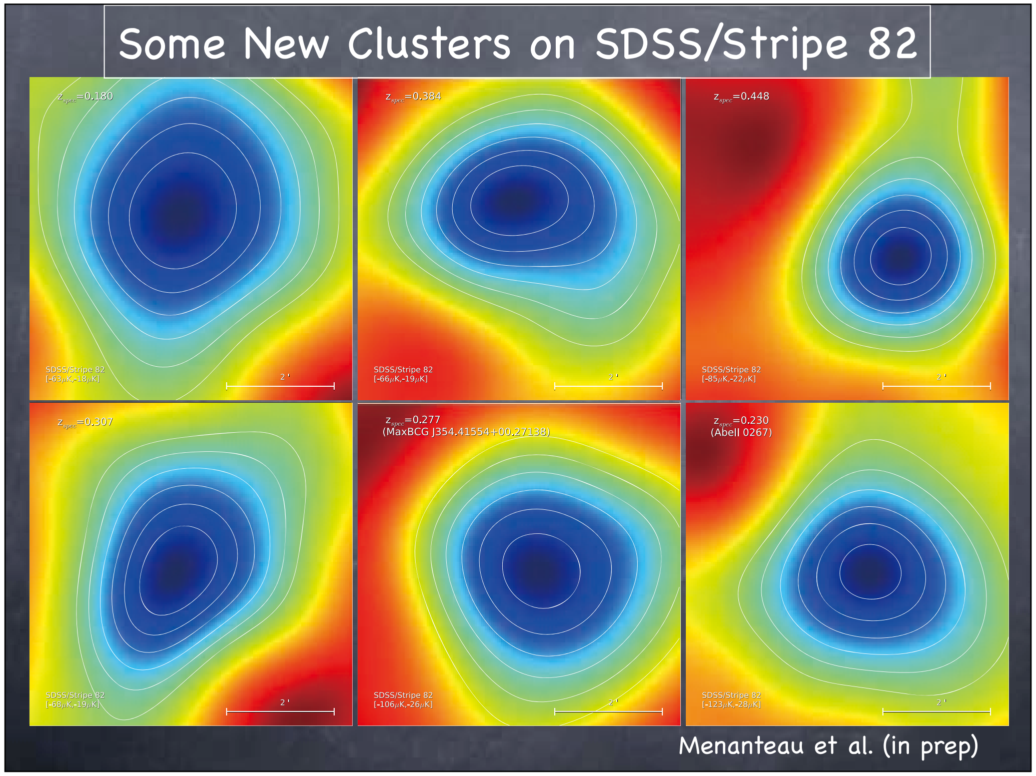


SDSS DR7 (Reid et al. 2009)
LyA (McDonald et al. 2006)
ACT Clusters (Sehgal et al. 2010)
CCP II (Vikhlinin et al. 2008)
ACT CMB Lensing (Das et al. 2011)
ACT+WMAP spectrum (Hlozek et al. 2011)
Mass Variance Δ_M/M
Mass scale M [Msolar]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}

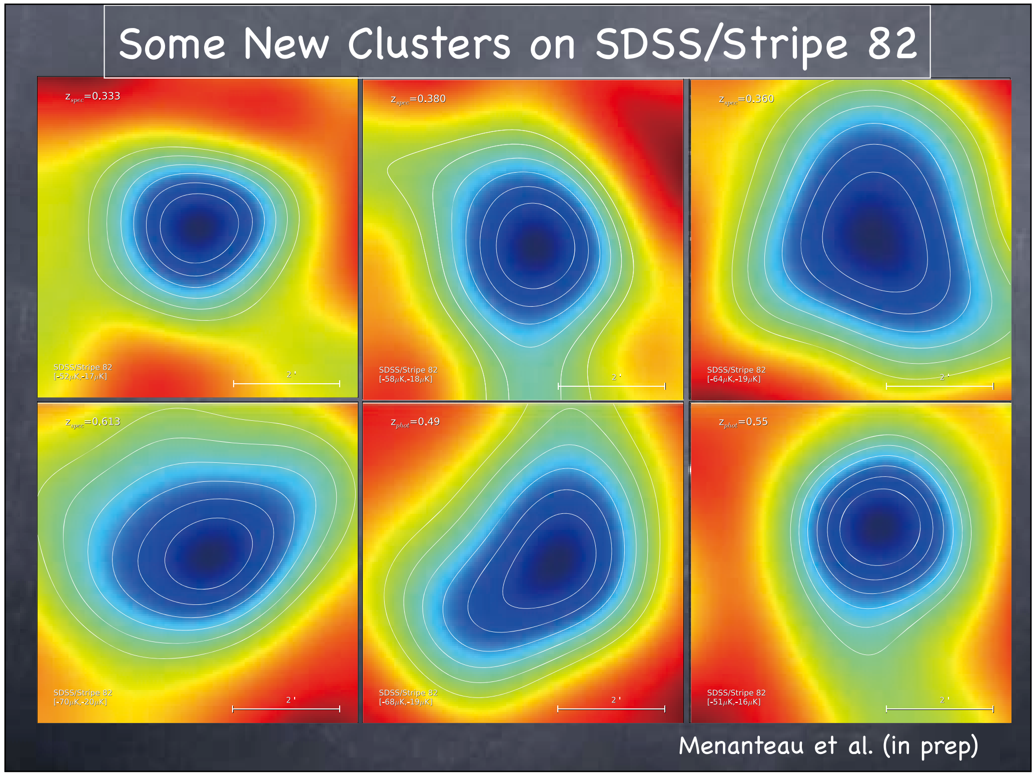
CMB As a Backlight

- CMB Lensing: Mass
- Thermal SZ: Pressure
- Kinematic SZ: Momentum

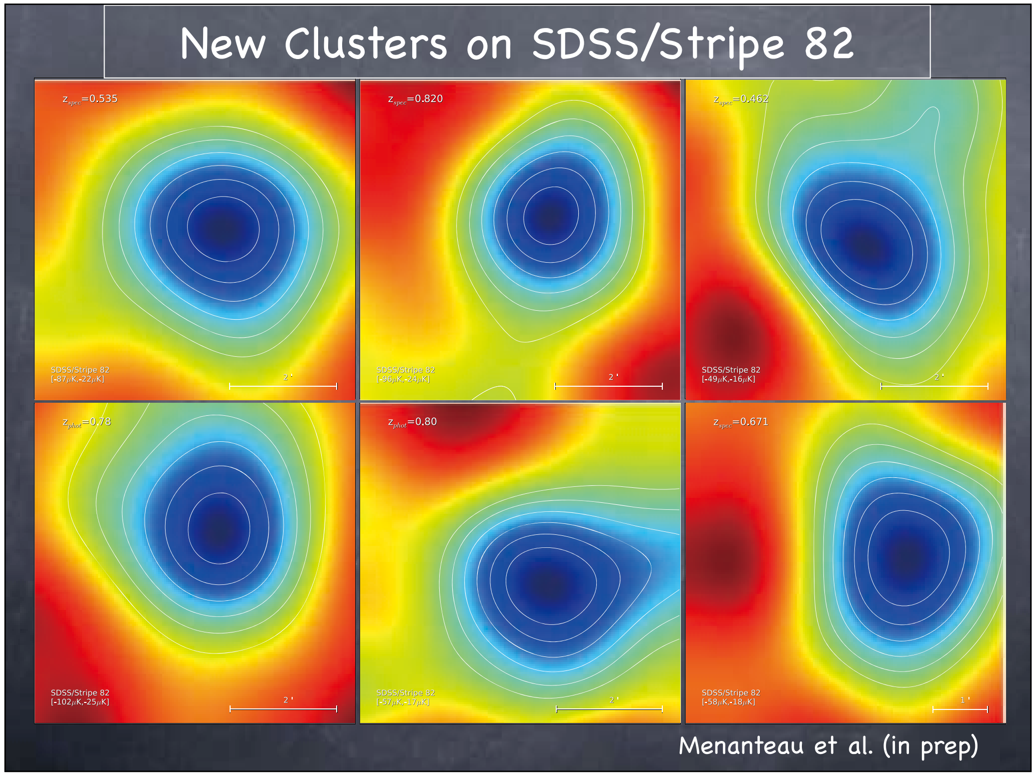




- Includes 148GHz transition



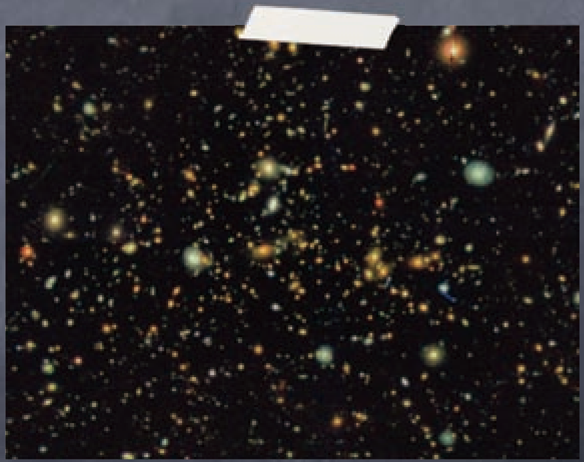
- Includes 148GHz transition



- Includes 148GHz transition

Clusters as Cosmological Probes

- SZ signal measures integrated pressure in cluster
- SZ signal is redshift-independent, so an SZ-selected cluster sample should be a mass-selected sample.
- Potentially, number counts could be an important dark energy probe.
- Key step: lensing calibration



Subaru Image: Takada, Miyatake, et al.

Next Step: ACTPOL

- Funded by NSF for 2011-2016
- Camera now under construction... 25 times faster survey speed and polarization sensitivity
- First light in 2012
- Wide survey (~4000 sq. degrees)
- Deep survey (5 25 sq degree fields)

E + B modes

- Scalar fluctuations generate E-modes. They produce TT, TE and EE correlations
- Tensor fluctuations generate equal amounts of E and B modes. They produce TT, EE and BB correlations
- Gravitational lensing rotate polarization and converts E modes into B modes.

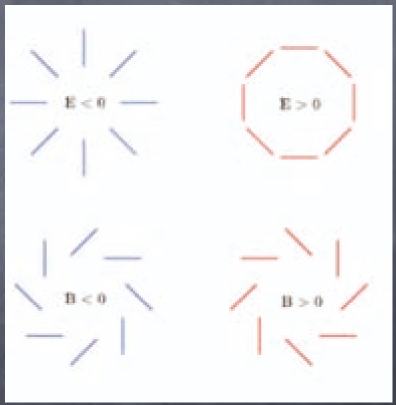
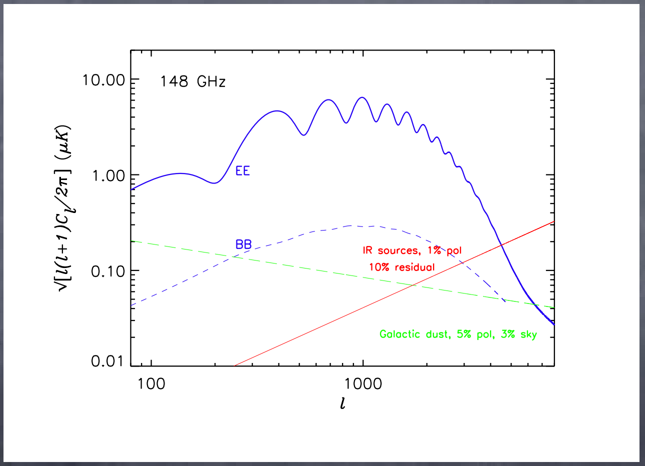


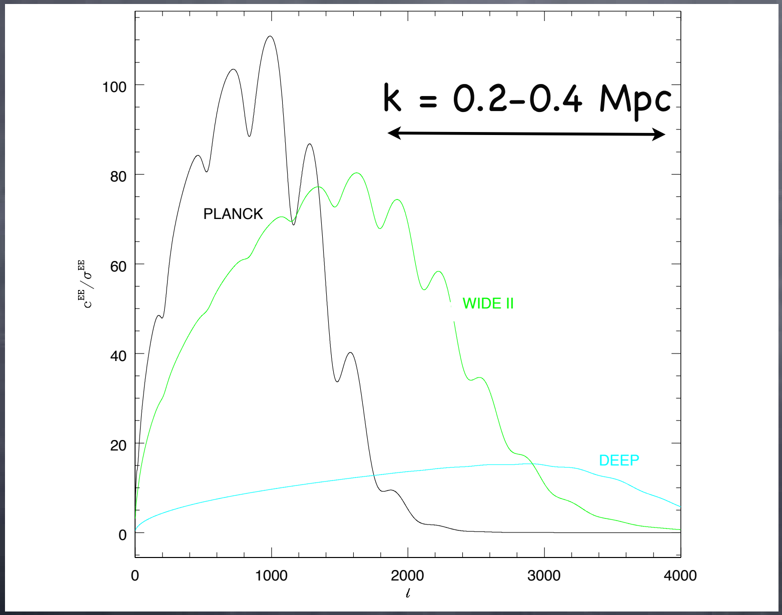
Figure from Dodelson et al. NAS White Paper astro-ph/0902.3796

The New Frontier



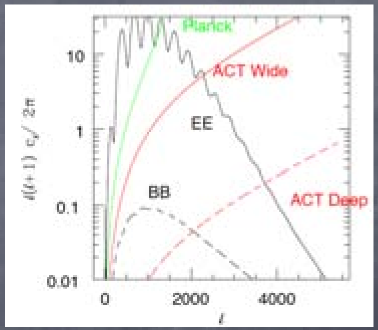
Full sky polarization survey to l = 5000 would have 6 times the number of modes as

ACTPol's Discovery Space

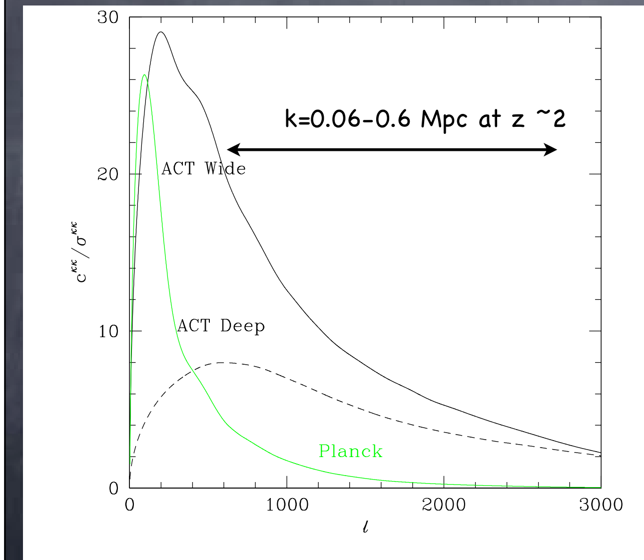


Small-scale BB

- Gravitational Lensing rotates E modes into B modes. Measurements of B modes can be used to construct the convergence field.
- Amplitude of convergence field measure mass fluctuations at z ~ 1-2



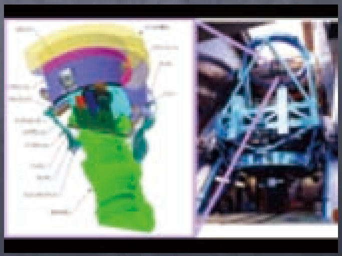
ACTPol & Matter Distribution



2% measurement of amplitude of mass fluctuations at z~2

ACT Wide

- Survey 4000 sq degrees with sensitivity of 28 microK/arcmin (polarization) and 20 microK/arcmin (temperature)
- Overlap SDSS III spectroscopy and imaging (600,000 LRGs, 80,000 quasar spectra)
- SUMIRE program: HSC imaging (under construction) + PFS (under review)
- Science goals:
  - EE power spectrum out to l ~2000
  - CMB lensing (and cross-correlations with low z surveys)
  - Clusters
  - Missing Baryons
  - Dark energy (calibrate BAOs; measure power spectrum at z ~ 1-2)



ACT Deep

- Deep observing program:
    - 5 2x15 degree regions. Plan to target regions with extensive deep data
    - 4 uK/arcmin in polarization
- Science goals:
    - high l EE tail
    - stacking of astronomical objects
    - characterization of foregrounds
    - delensing gravity wave B-mode (see Smith et al. astro-ph0811.3916)

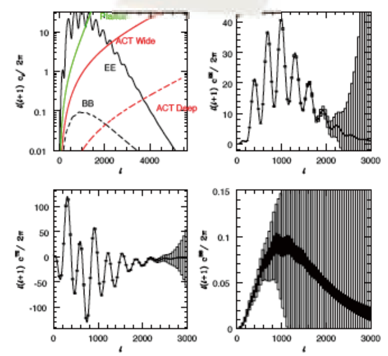
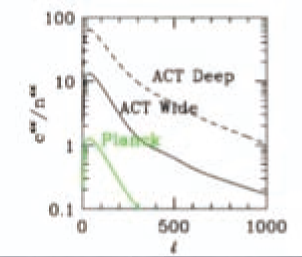
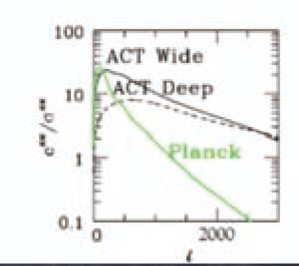


Figure 5. The upper left panel shows the noise per multipole for Planck, ACT Wide and ACT Deep and the predicted EE and BB power spectrum. The other three panels show the EE, BB and TE spectrum with anticipated ACT (filled boxes, at places small on a linear scale, see Figure 2) and Planck errors (open boxes). When the Planck errors are smaller, only they (open boxes) are shown. The deep field errors are shown by the grey boxes and are only shown when they are smaller than the wide field errors. The other three panels shows the expected signal/noise for the EE, TE and BB angular power spectra binned with $\Delta l = 50$.

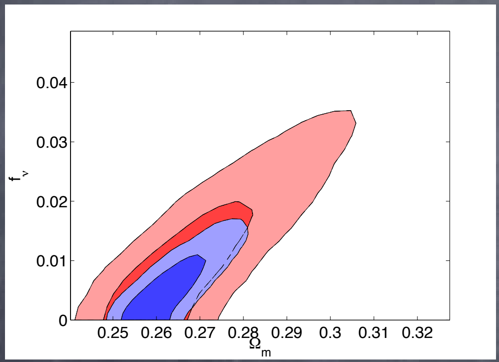
ACT + HSC Deep

- ACTPOL should get first light in late spring 2012 and being surveying in fall 2012.
- The first target field is XMM-LSS field
  - Herschel: 17 sq. deg
  - XMM: 25 sq. deg
  - UKIRT: J+K
  - SWIRE
  - VIPERS
  - 2 uK-arcmin sensitivity





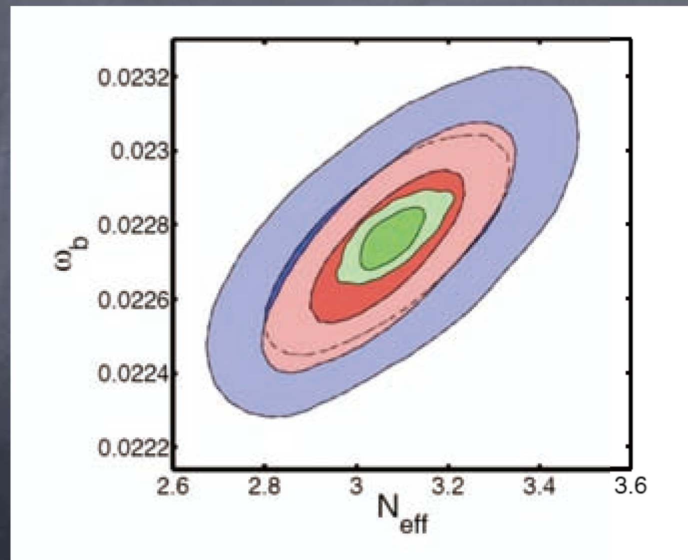
Neutrinos



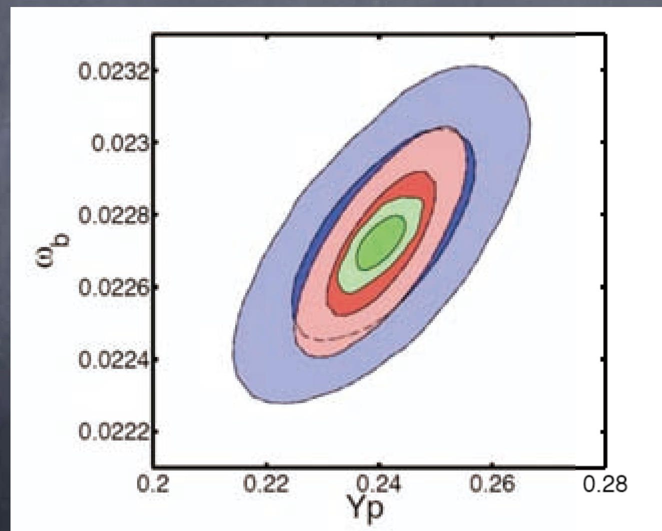
ACTPol should be able to distinguish between inverted and normal mass spectra by constraining neutrino mass to 0.05 eV

Thanks to Sylvia Galli, A. Melchiorri and L. Pugano

Neutrino Number



Helium

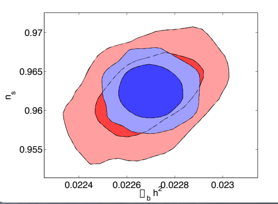


0.0232
0.023
0.0228
0.0226
0.0224
0.0222
ω_b
0.2
0.22
0.24
0.26
0.28
Yp

Initial Conditions

	WMAP5	WMAP5+ACT	[illegible]	PLANCK	PLANCK + ACTPol
$\Omega_b h^2$	6×10^{-4}	5×10^{-4}	1.9×10^{-4}	2×10^{-4}	1.3×10^{-4}
$\Omega_m h^2$	6×10^{-3}	7×10^{-3}	3.7×10^{-3}	2.2×10^{-3}	1.7×10^{-3}
n_s	0.014	0.015	0.008	0.007	0.006
$\ln \theta_A$	3×10^{-3}	1.2×10^{-3}	4×10^{-4}	5×10^{-4}	3×10^{-4}
m_ν	-	0.3	0.15	0.1	0.06
τ	0.017	0.011	0.010	0.004	0.004
Y_{He}	-	0.017	0.007	0.01	0.005

Table 1. This table compares the expected constraints in an 8 parameter model (baryon density, matter density, slope, H_0, neutrino mass, optical depth, Helium abundance, amplitude) with the current constraints from WMAP5 and a 6 parameter model. Note that the WMAP5+ACT wide field I limits on certain parameters in an 8 parameter model are worse than limits in a 6 parameter model for WMAP alone.

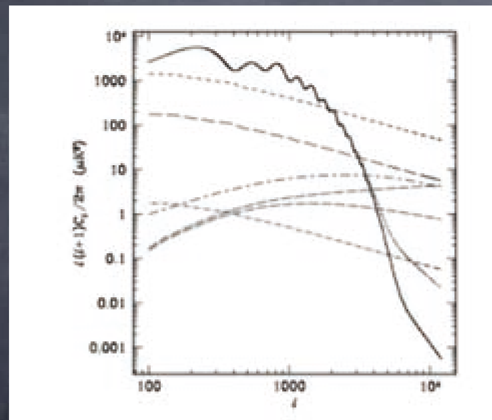


- EE measurements unique window into small scale fluctuations
- Parameter estimates:
  - Estimates do not include beam uncertainties and foreground contamination
  - Data sets are complementary
  - Big gains on parameters that affect high l

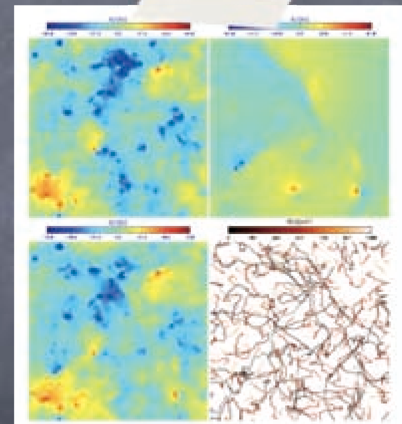
Non-Gaussianity

- Sensitive to number of modes measured on the sky.
  - WMAP: 2e5 modes in TT
  - Planck: 3e6 modes in TT, 7.5e5 in EE
  - Polarization (to l = 5000): 2.5e7 modes available.
- Polarization measurements have the potential to measure modes out to l~4000, a 4 fold increase in the number of modes over PLANCK. ACTPol is a step in this direction
- ACTPol will be sensitive to small scale primordial non-Gaussianities (particularly cosmic strings)

Cosmic Strings



Polarization limits on strings



Fraisse et al. astro-ph/0708.1162

Conclusions

- Data continues to improve... the simple but strange model still fits
- Small scale CMB measurements enable observations of mass (through lensing), pressure (through SZ) and momentum (through kSZ). New tool to study evolution of the universe
- Beginning of multi-wavelength CMB astronomy