CMB: An Overview

Lloyd Knox (UC Davis)

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UC Davis

Mike Chu

Manoj Kaplinghat*

Dana Nuccitelli

Alan Peel*

Yong-Seon Song

Elsewhere

Olivier Dore (Princeton)

Zoltan Haiman (Princeton)

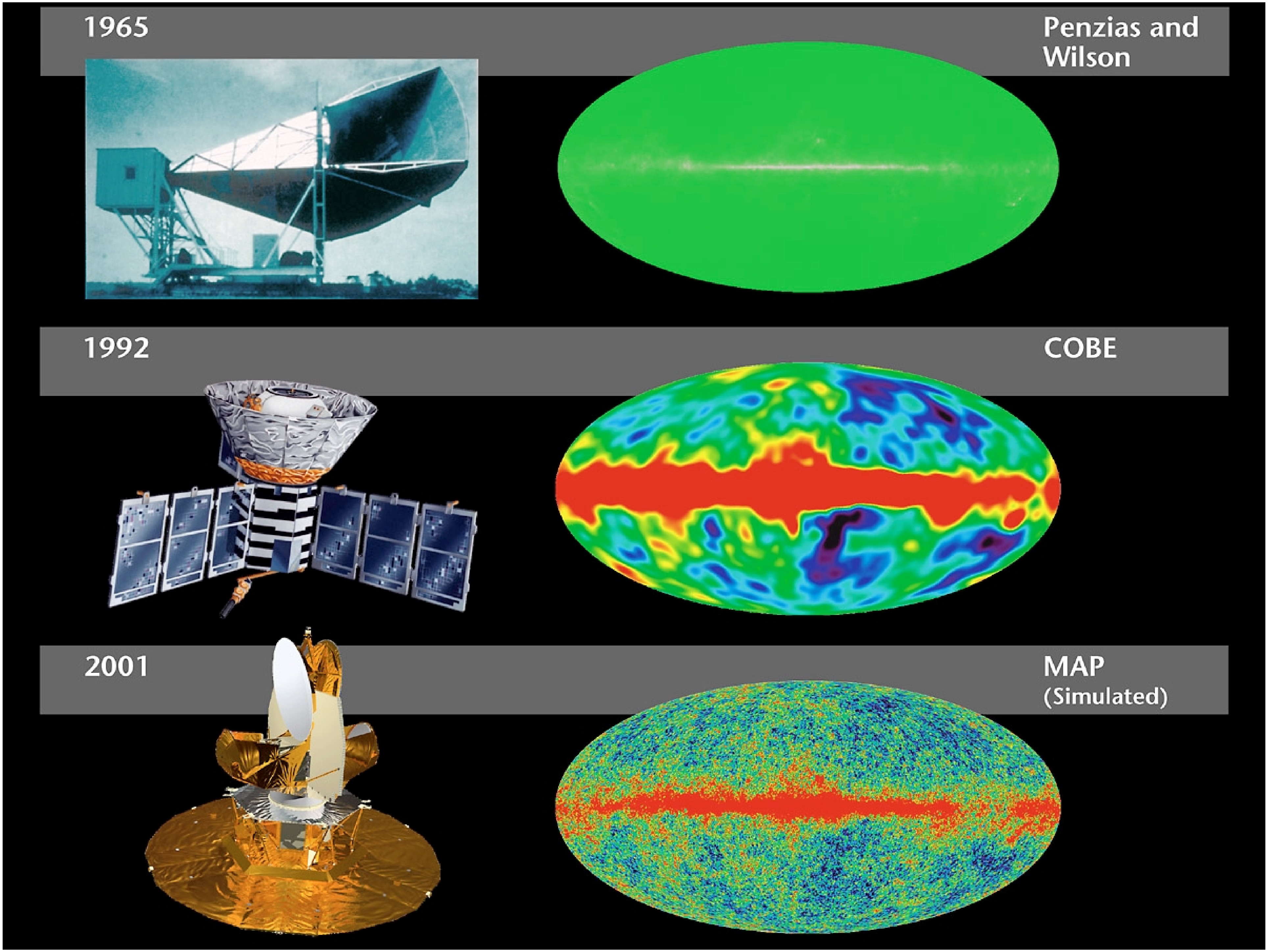
Gil Holder (IAS)

Martin White (UC Berkeley)

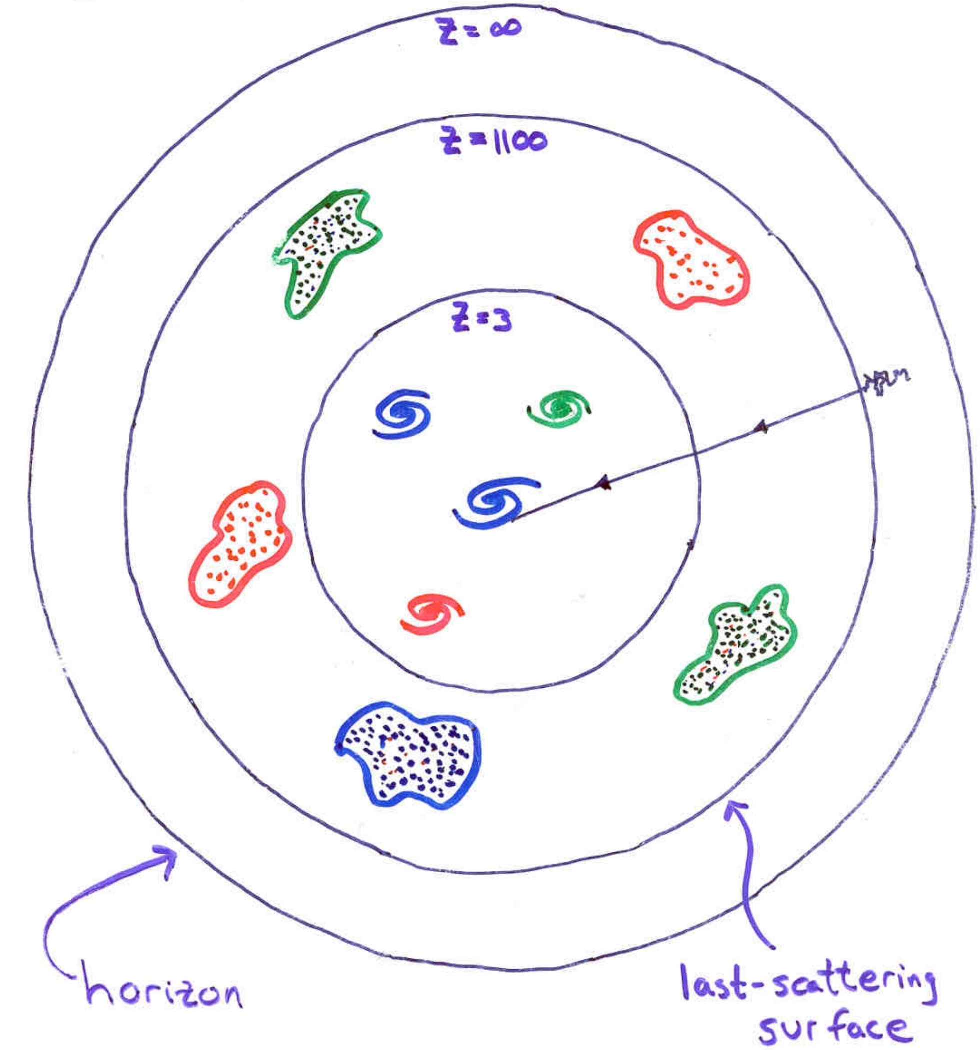
*for hire

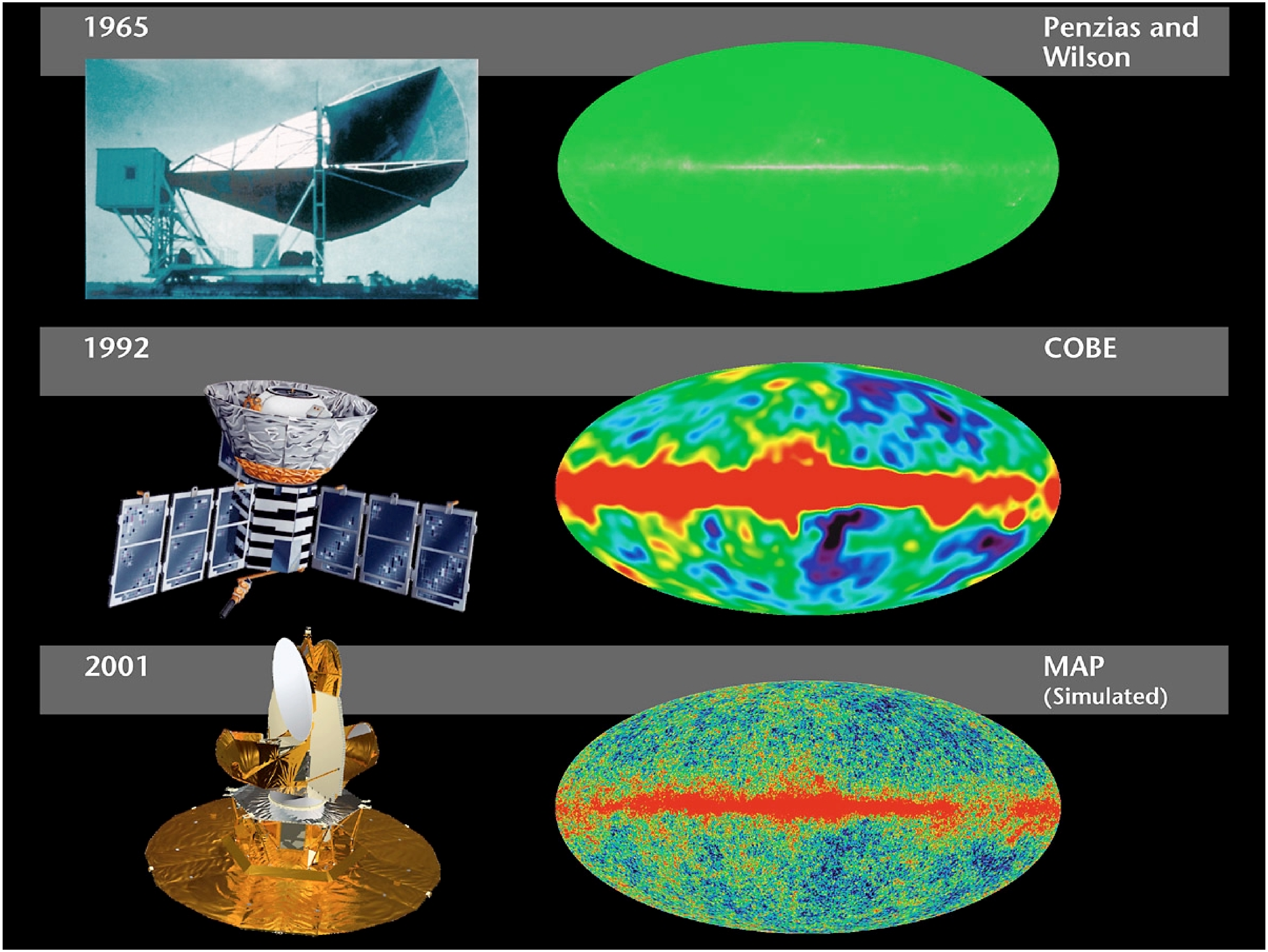
CMB: An Overview

- CMB Basics
- What we have learned already (from ΔT)
- Prospects for the future
  - Improved temperature measurements
  - Polarization measurements
  - Sunyaev—Zel'dovich Effects


1965
Penzias and Wilson
1992
COBE
2001
MAP
(Simulated)

THE HISTORY OF A SINGLE PHOTON

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Why study this power spectrum?

- Calculable --- linear perturbation theory is highly accurate.
- Rich features

peaks point to characteristic scale: angular size of sound horizon

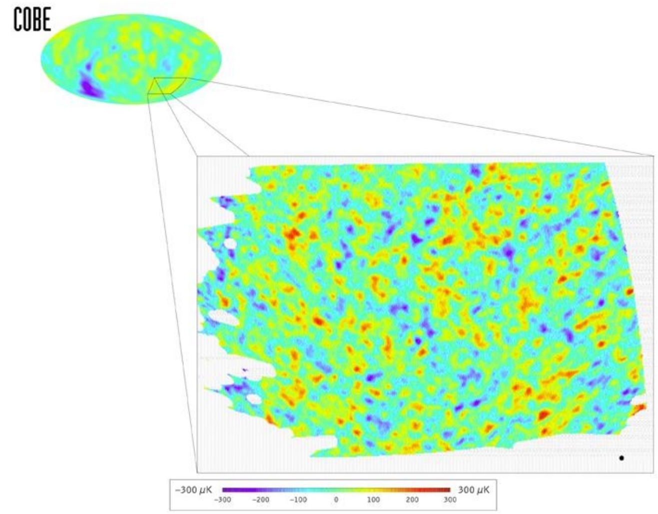
$$\theta_s = (0.6 \pm 0.01)\ \text{deg} \qquad (l \approx 180^\circ / \theta)$$

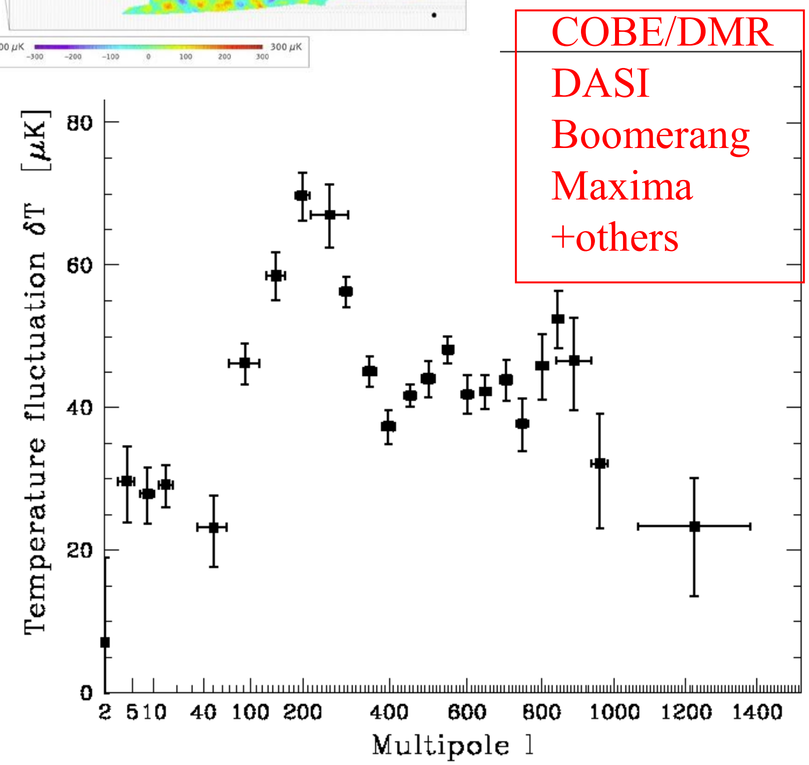
Peak morphology controlled by

1) Baryon density which affects pressure of fluid

2) Total matter density which affects gravitational driving of oscillations

➔ Excellent probe of baryon density and dark matter density





Large angular scales

small angular scales

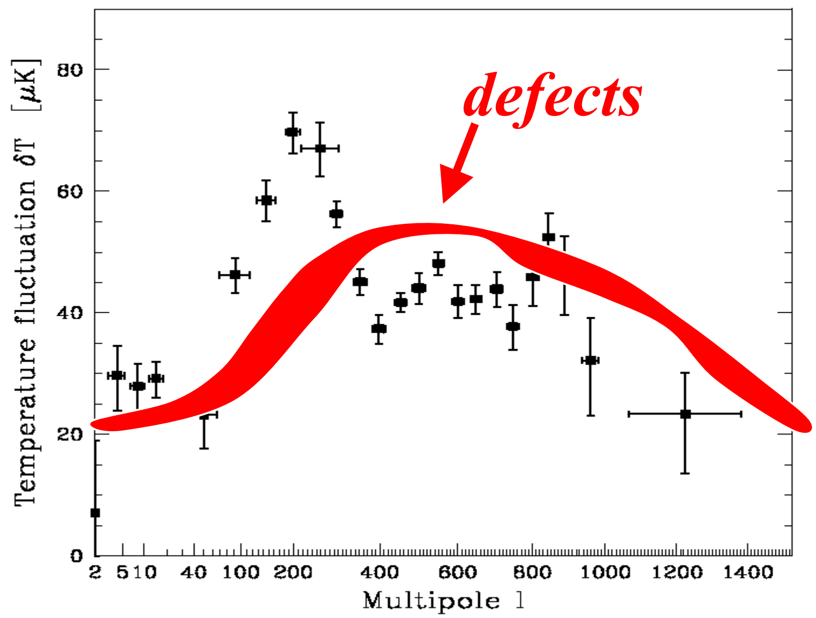
Wang, Tegmark & Zaldarriaga (2001)

What We've Learned

- Qualitative Results:
  - Structure formed from adiabatic nearly scale—invariant "initial" spectrum of fluctuations
  - Spatial geometry is flat (or at least nearly so)
  - Supernovae—independent evidence for dark energy
  - Age of Universe is 14.0 \pm 0.5 Gyrs (assuming flatness)

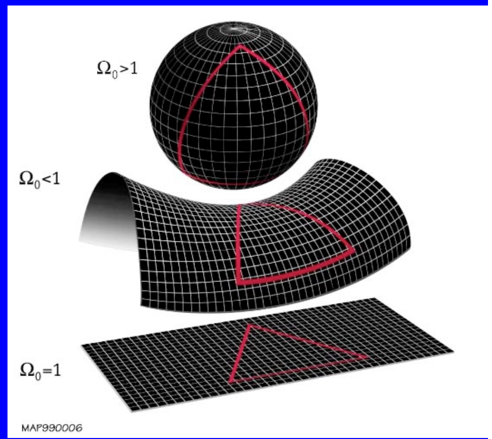
The Universe is not Defective

- Structure formed via gravitational instability
- Seed perturbations were formed early (inflation) rather than continually (topological defects)



$$ds^2 = dt^2 - a^2(t)\frac{dr^2}{1-kr^2} = a^2(t)(d\eta^2 - \frac{dr^2}{1-kr^2}) \qquad r_c \equiv \sqrt{1/|k|} = \frac{1}{H_0\sqrt{\Omega_{\rm tot} - 1}}$$

The Curvature Radius

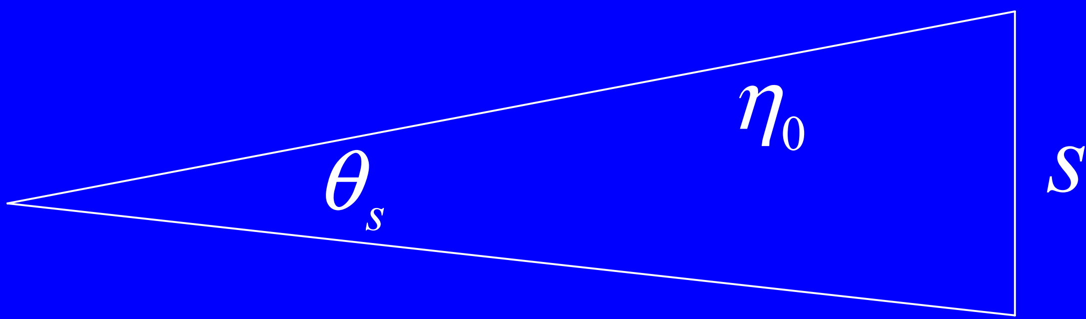


Area of sphere A =

$$4\pi\sin^2(\eta_0/r_c)r_c^2 \quad (k>0)$$

$$4\pi\sinh^2(\eta_0/r_c)r_c^2 \quad (k<0)$$

$$4\pi\eta_0^{\ 2} \quad (k=0)$$



$$r_c > 5/H_0$$

$\theta_s^{\ 2} = 4\pi s^2 / A$ where s is the comoving sound horizon

Supernovae—Independent Evidence for Dark Energy

$$r_c \equiv \sqrt{1/|k|} = \frac{1}{H_0\sqrt{\Omega_{\text{tot}} - 1}}$$

$$r_c > 5/H_0$$

➔ $\Omega_{\text{tot}} \approx 1$

And if $\Omega_m \approx 0.3$ then

$$\Omega_{somethingelse} \approx 0.7$$

Knox, Christensen and Skordis (2001)

Quantitative: Parameter Bounds

	Mean	Std. Dev.
$\Omega_b h^2$	0.021	0.002
$\Omega_m h^2$	0.15	0.02
A (arbitrary units)	6.7	0.6
n_s	0.96	0.04

	Mean	Std. Dev.
DASI calibration	1.00	0.03
BOOM calibration	1.07	0.03
Maxima calibration	1.00	0.03
BOOM fwhm	13’.9	0’.3

Also varied, but not well—constrained: Ω_Λ and z_{reion}

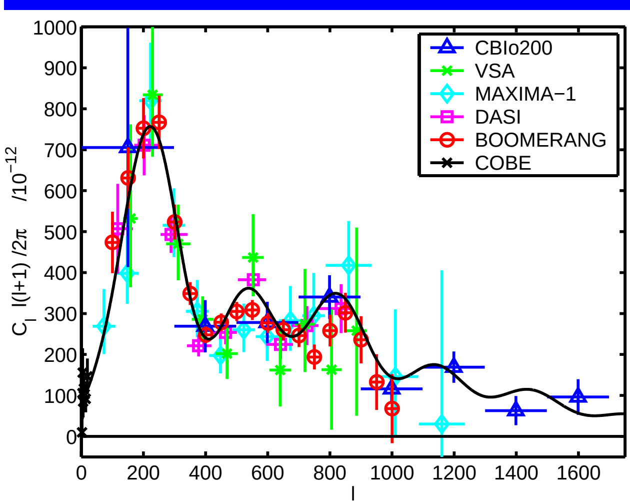
We use MCMC (Christensen et al. 2001) and DASh (Kaplinghat, LK and Skordis 2002)

Prospects for the future

- Improved temperature measurements
- Polarization measurements
  - Reionization
  - Gravity wave detection
  - Lensing potential reconstruction as dark energy probe
  - See DASI talk tomorrow
- Sunyaev—Zel’dovich Effects

Improved Temperature Measurements from MAP, ACBAR*, Planck, …

Present

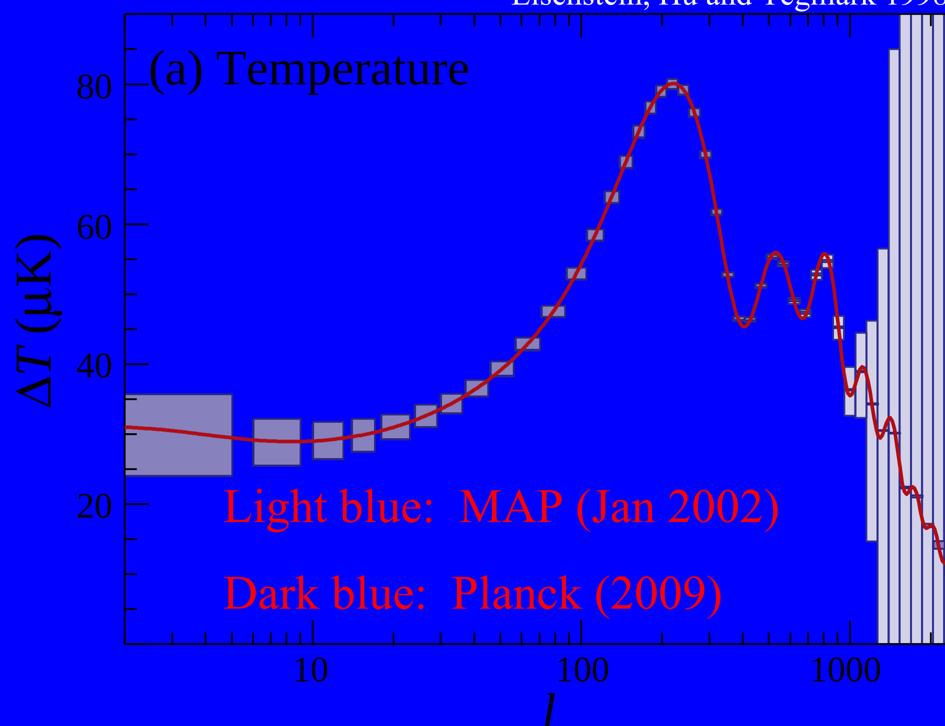


Compilation by Lewis and Bridle

Tremendous leaps in precision

Future

Eisenstein, Hu and Tegmark 1998



*Watch for ACBAR with tight high ell results this fall.

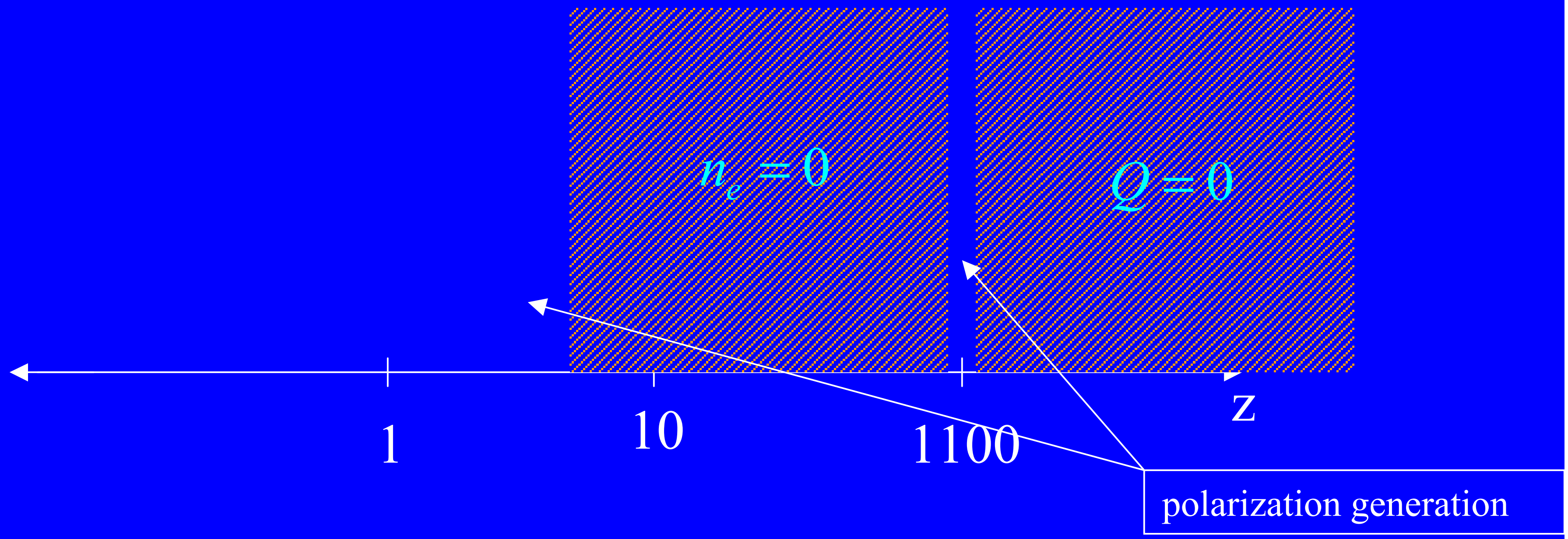
See recent Frieman et al. for one example of what to do with all this precision.

CMB Polarization

Unpolarized radiation with a quadrupole moment scattering off of free electrons results in linearly polarized radiation.

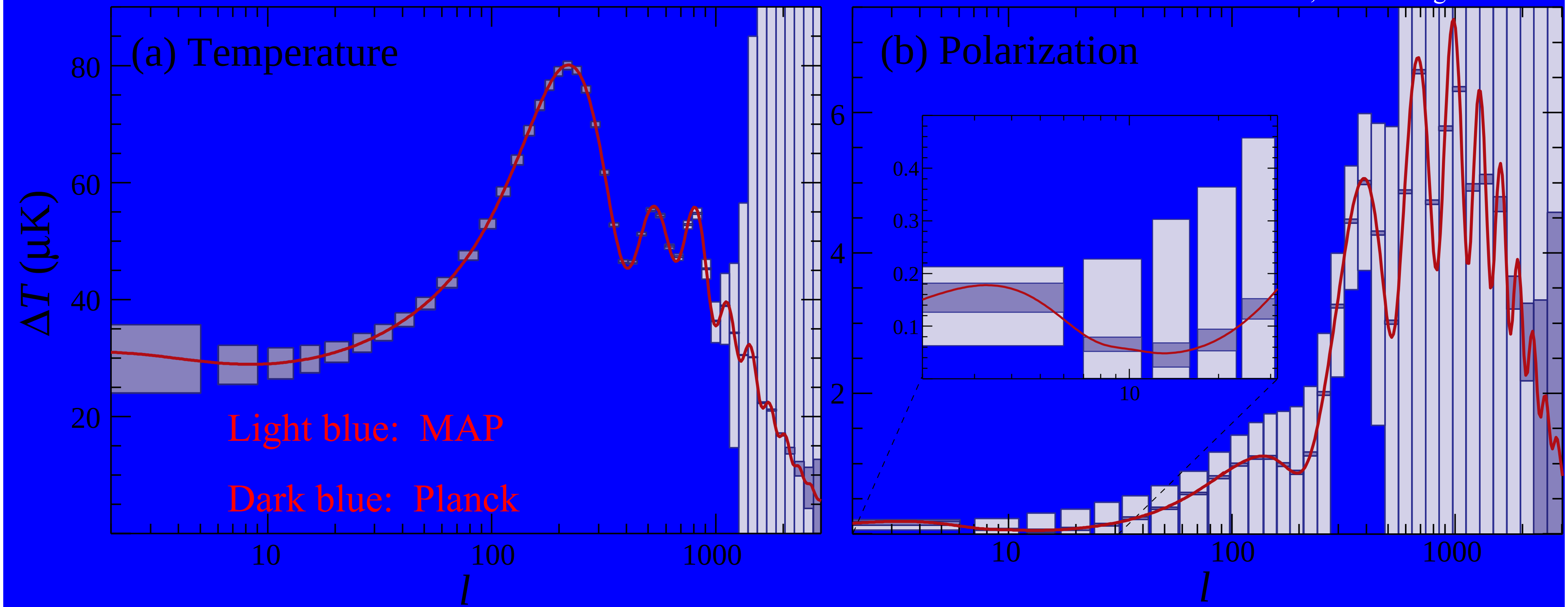
No Q at z > ~1100 (fast scattering isotropizes the radiation field)

No free electrons at ~7 < z < ~1100



Polarization

Eisenstein, Hu and Tegmark 1998



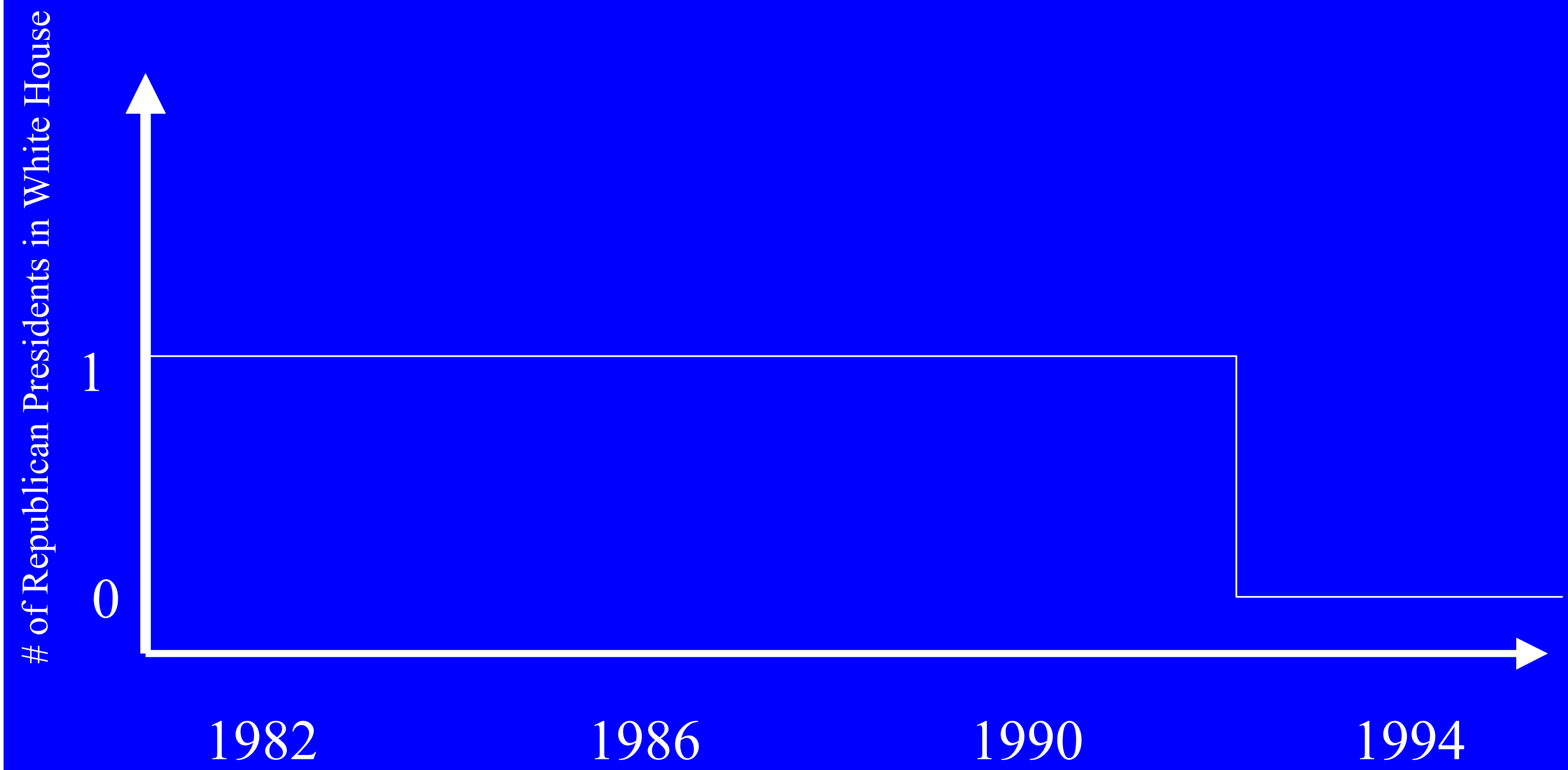
- P amplitude about 10% of T anisotropy
- l > 15 from last—scattering surface
- l < 15 from reionization

We will discuss reionization feature first.

Detecting it is important for determining amplitude of primordial fluctuations.

MAP will see it well enough to determine primordial amplitude to 4% (Kaplinghat et al. 2002)

Detection of a GOP Trough



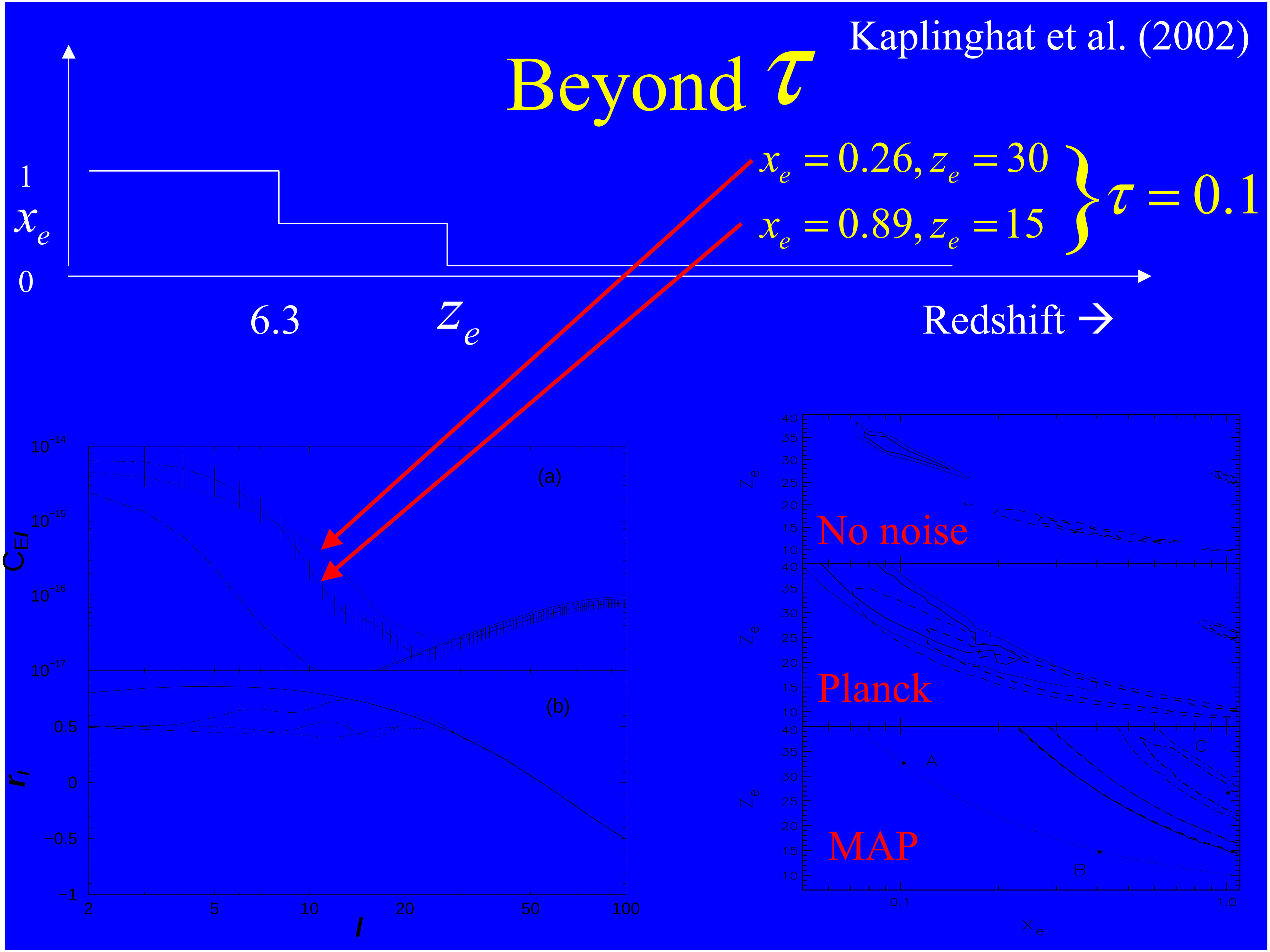
Does it signal the end of the dark ages?

Becker et al. (2001)

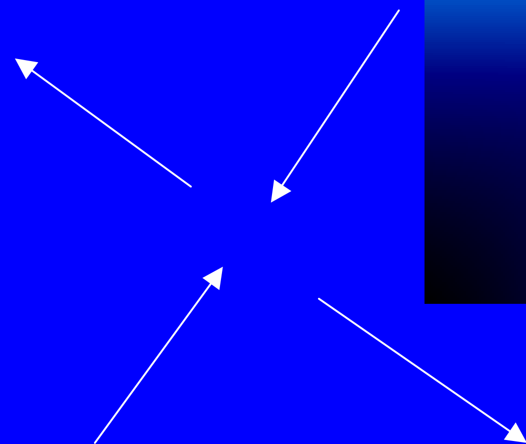
GP Trough → Detection of Dark Age? i.e., Do Quasar Spectra Really Imply Reionization at z=6.3?

- GP trough due to x_HI > 0.001 so x_e can still be quite large
- Rapid transition appears to be happening near z=6.3, but is it from x_e =0 or x_e=0.5?
- CMB polarization observations are uniquely qualified to answer these questions.

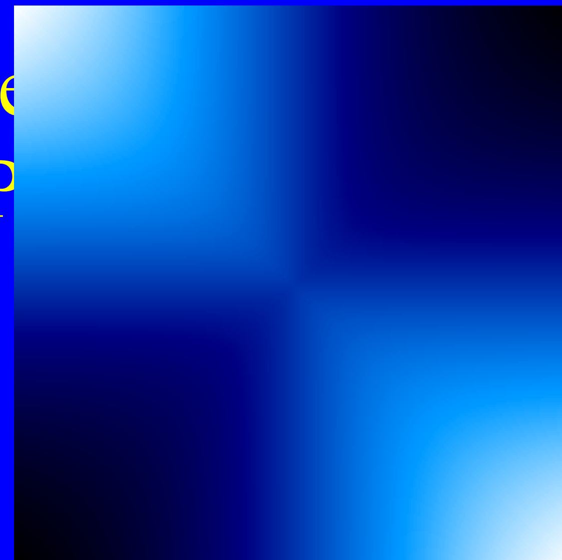
Kaplinghat, Chu, Haiman, Holder and Knox (2002)


Kaplinghat et al. (2002)
Beyond τ
1
x_e
0
6.3
z_e
Redshift →
$x_e = 0.26, z_e = 30$
$x_e = 0.89, z_e = 15$
$\tau = 0.1$
(a)
(b)
C_{El}
r_l
l
No noise
Planck
MAP
A
B
C
z_e
x_e

Gravitational Wave Gene ure Anisotropy and P



Imagine a single GW propagating out of the screen, compressing and stretching space as shown by arrows.



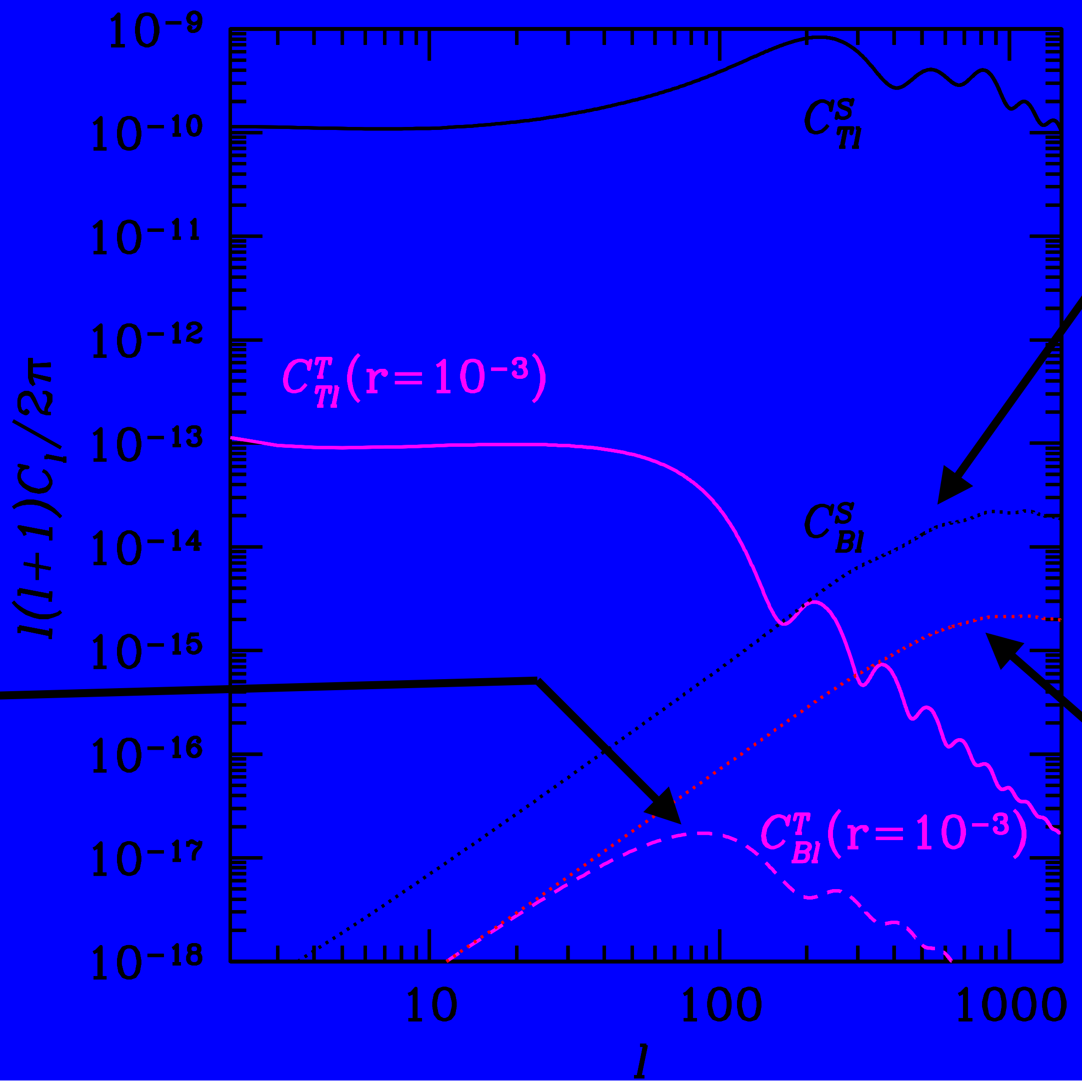
Resulting temperature pattern

Also leads to polarization since unpolarized quadrupole radiation scattered by an electron results in polarization.

$E_{\text{infl}} > 2\times10^{15}$ GeV Knox & Song, PRL (2002) ; Kesden et al. PRL (2002)

Detecting Gravitational Waves

Hu and Okamoto, 2002 lensing potential reconstruction



Lensing—induced scalar B mode

The "B mode" polarization pattern is not generated by scalar perturbations in linear perturbation theory.

Residual scalar B mode power

Lensing

$$I(\vec{\theta}) = \tilde{I}(\vec{\theta} + \vec{d}) \qquad \mathrm{Q}(\vec{\theta}) = \tilde{Q}(\vec{\theta} + \vec{d}) \qquad U(\vec{\theta}) = \tilde{U}(\vec{\theta} + \vec{d})$$

$$\vec{d} = \vec{\nabla}\phi \qquad \phi = 2\int dr \frac{r - r_s}{r r_s}\Phi(r)$$

Harmonic effects of lensing:

1) creates B out of E (and vice—versa)

2) leads to correlation between $a_{\vec{l}}$ and $a_{\vec{l}'}$ proportional to $\varphi_{\vec{l}-\vec{l}'}$

Use to build estimator for ϕ

Hu (2001), Hu and Okamoto (2002)

Power Spectrum of the Lensing Potential

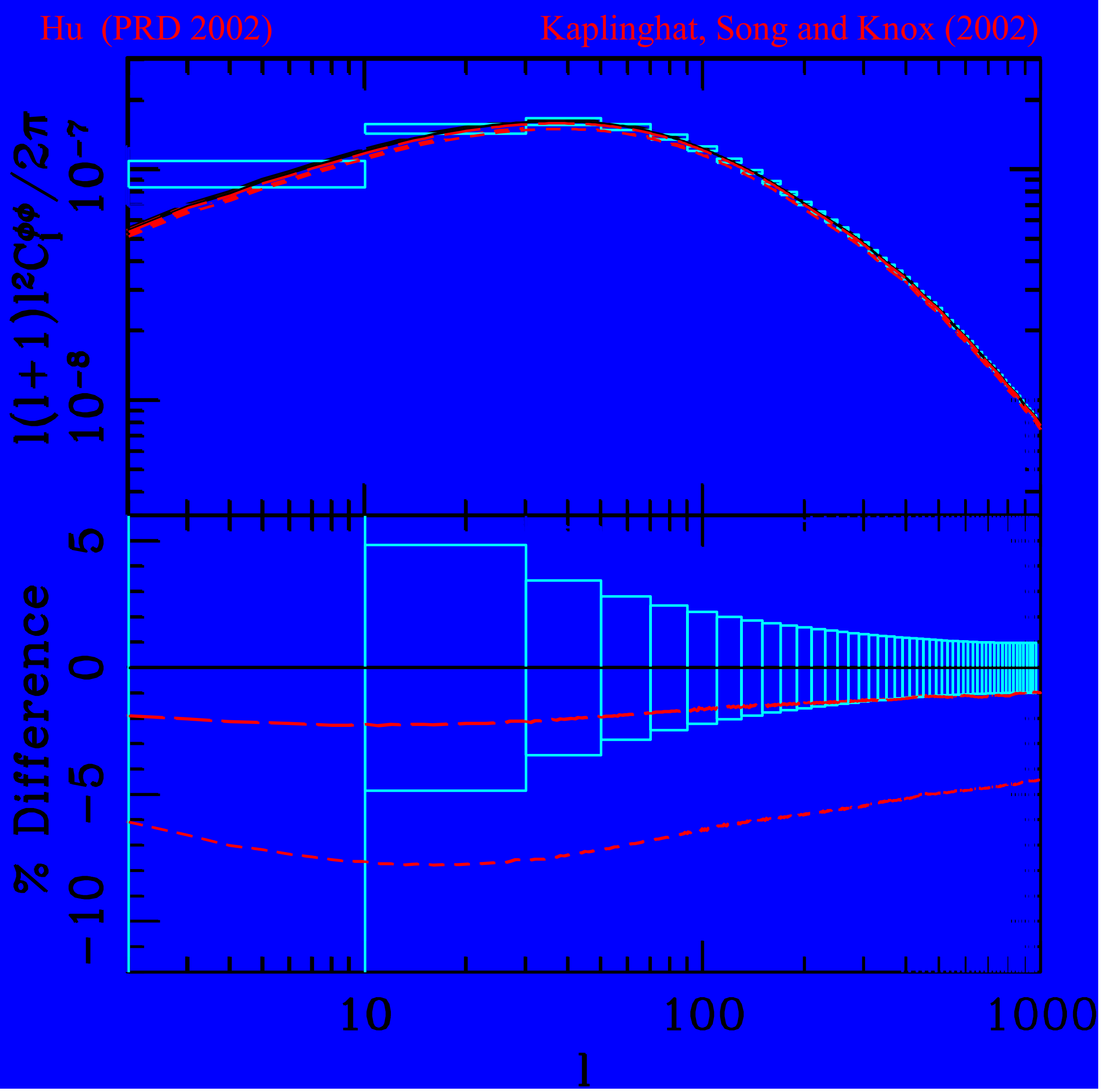
w=-1

w=-0.8

w=-0.5

Planck: dark blue error boxes

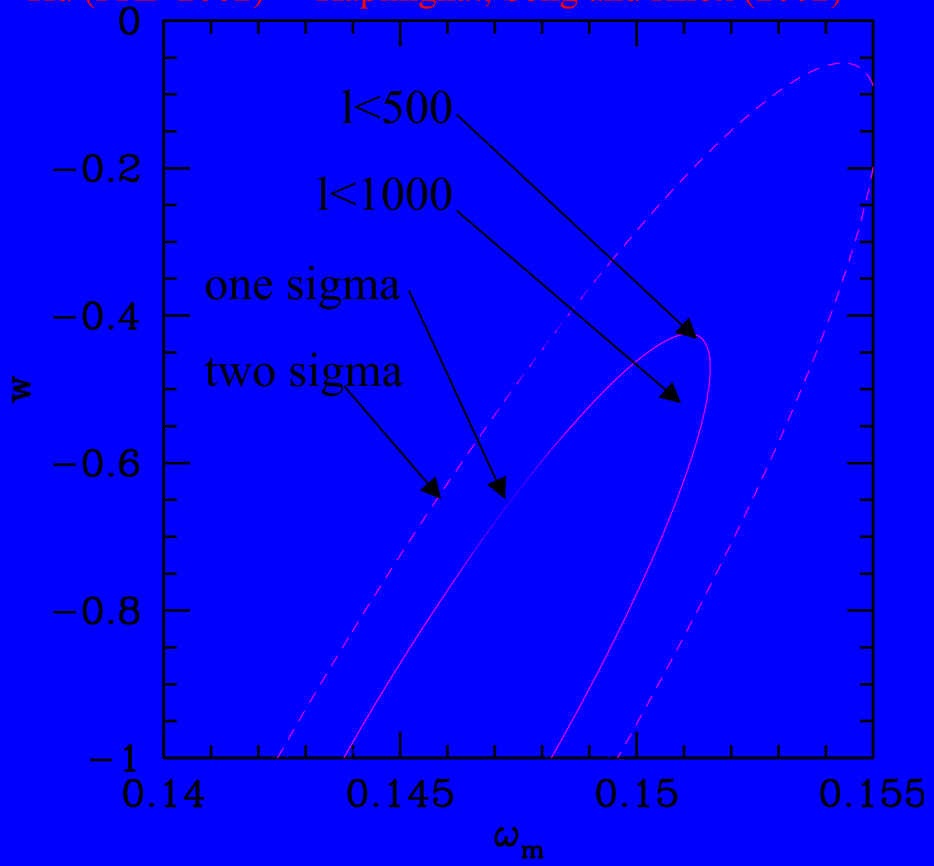
No noise: light blue error boxes



Dark Energy Constraints from CMB Lensing

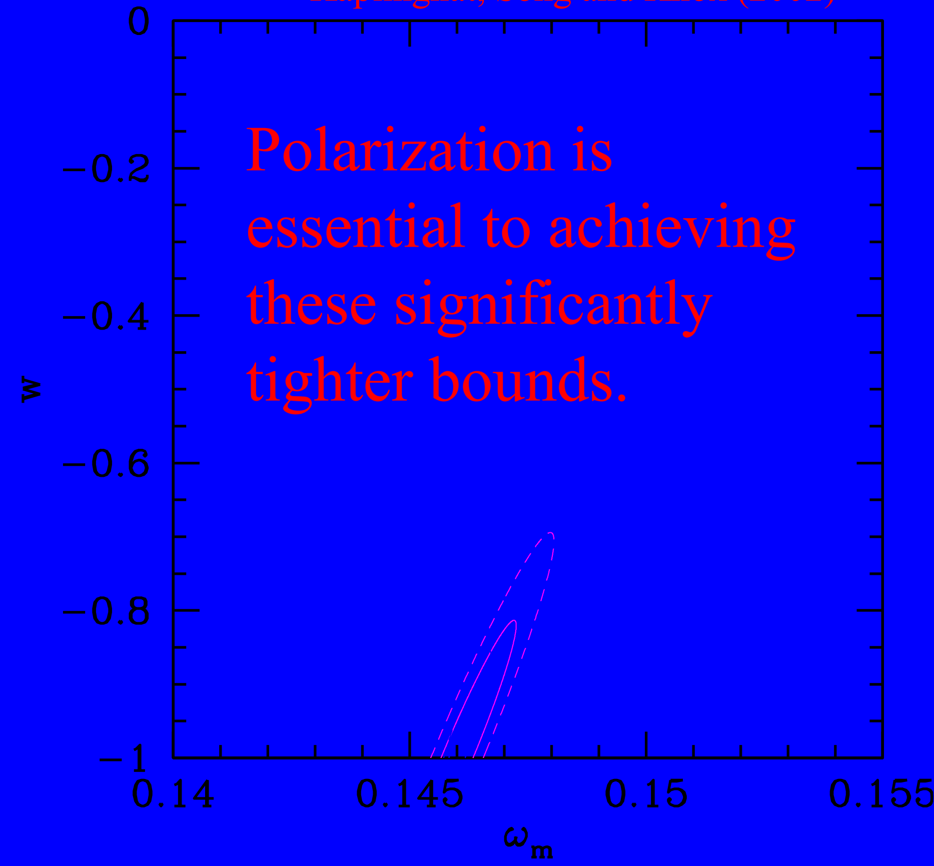
Planck

Hu (PRD 2002) Kaplinghat, Song and Knox (2002)



No Noise

Kaplinghat, Song and Knox (2002)

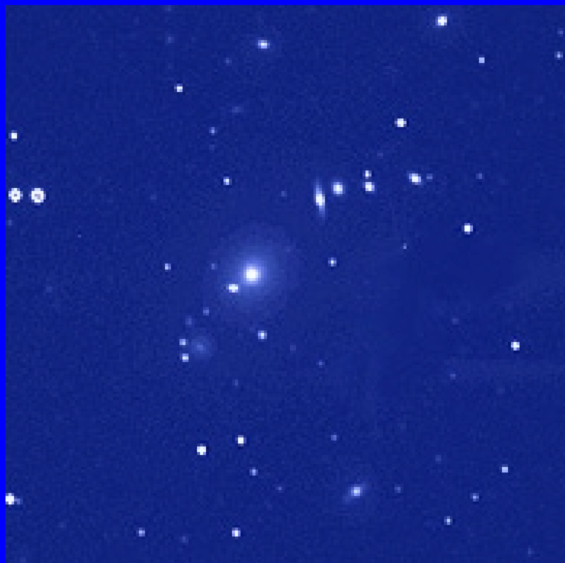


One Final Note on Polarization:

Go see the DASI talk tomorrow!

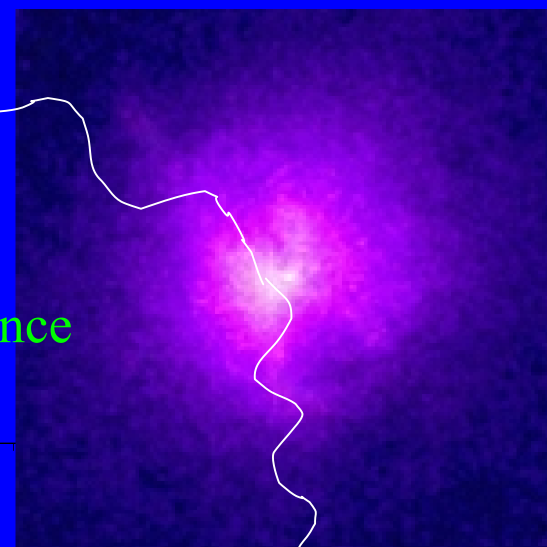
Sunyaev—Zeldovich Effects

LK+Dore, Nuccitelli, Peel & White

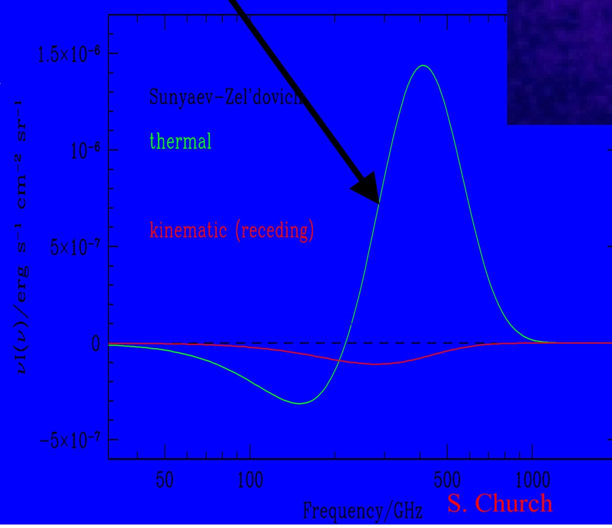


Optical image of Hydra A from La Palma and B. McNamara

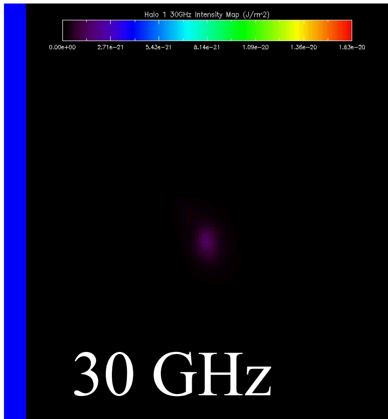
Chandra image of Hydra A

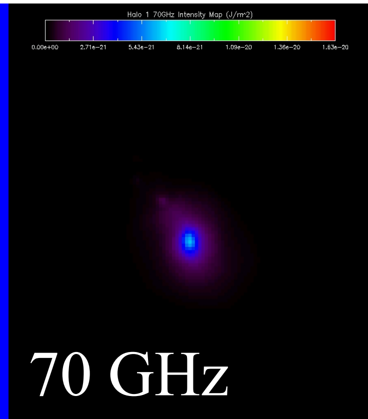


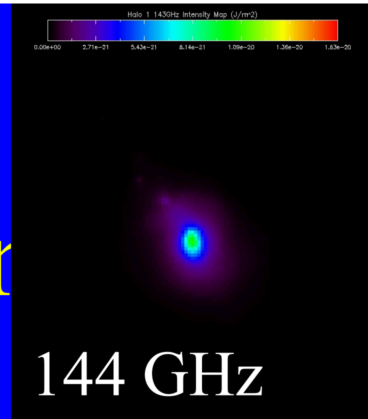
Thermal SZ difference from Planck law

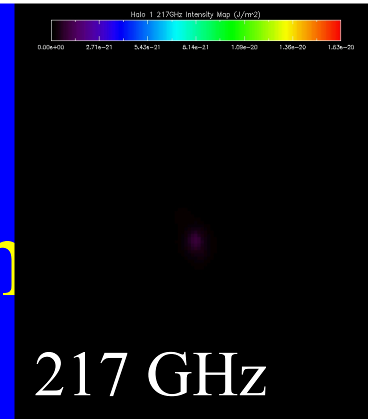


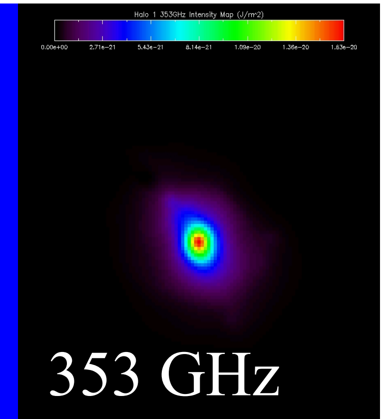
Thermal SZ effect is a spectral distortion proportional to τT_e

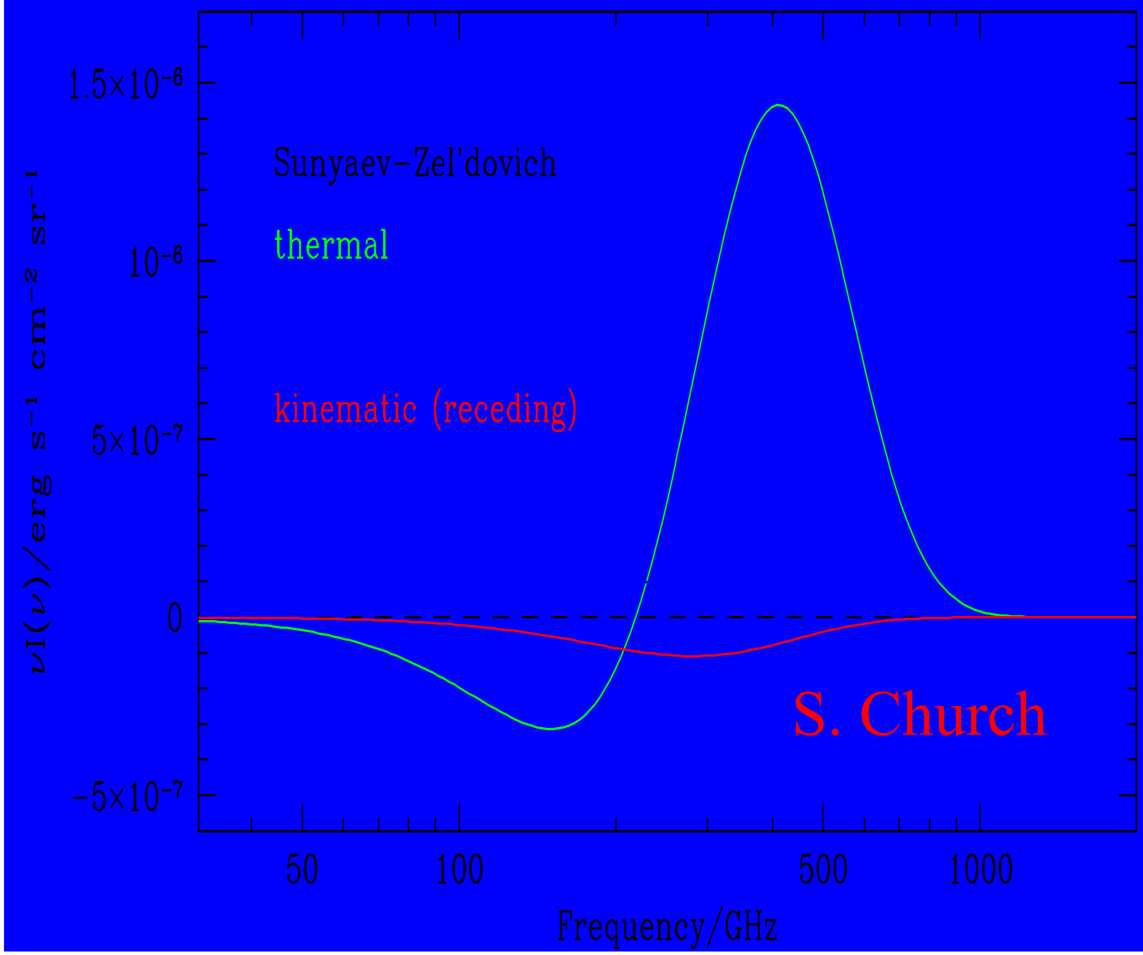


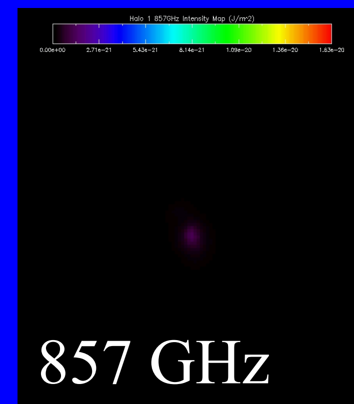












Peel, Nuccitelli, LK, White (2002)

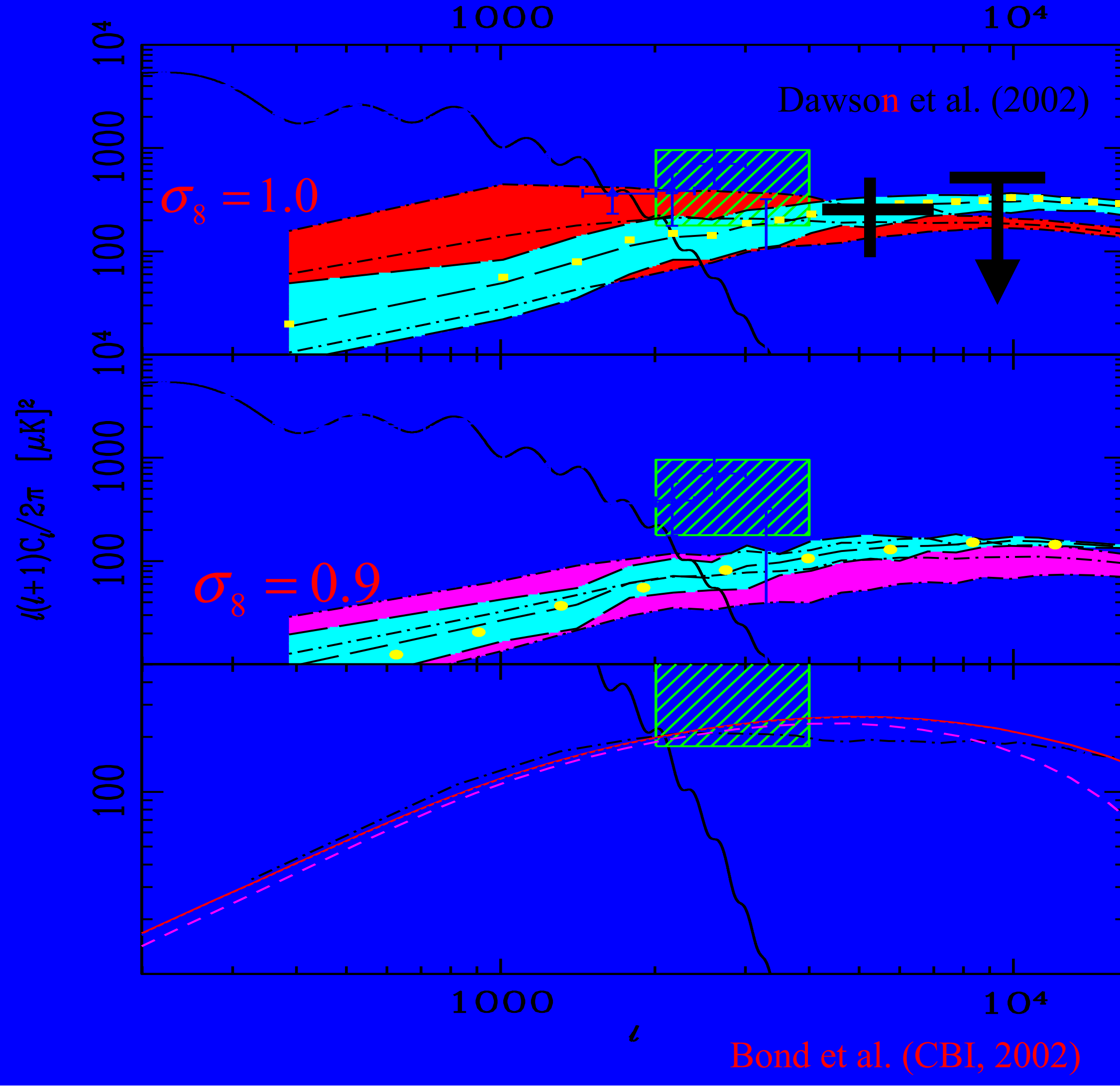
Applications of SZ Effects

- Angular diameter distance → $H_0, \Omega_{D.E.}$ Reese et al. (2002)
- One-point function and two-point function as functions of z → $\sigma_8, \Omega_{D.E.}, w$ Haiman et al. (2000), Holder et al. (2001)
- Radial peculiar velocities
  - 3 D gravitational potential reconstruction Dore, Knox and Peel (2002)
  - Two-point function → Ω_m Peel and Knox (2002)

Note: using clusters for precision cosmology will require X-ray, weak lensing and optical input as well.

SZ Science Already Being Done

- At BIMA
- With SuzIE
- With CBI



…also Planck!

Planned SZ Experiments

Experiment	Channels	fwhm	Sensitivity (uK)	Sky coverage	First light
SZA	26-36 GHz	~1’		12 sq. deg.	
SuZIE III	150 220 270 350	64” 43” 35” 27”	5 9 22 110	~100 clusters	Early 2004
ACT	150 GHz 220 GHz 250 GHz	1.7’ 1.1’ 0.9’	2 2 2	400 sq. deg. at high gal. latitude	
APEX	150 GHz 220 GHz (?)	~1’ ~45”	10	250 sq. deg.	Early 2004
SPT	150 GHz	~1’	8	4,000 sq. deg.	2007

Summary and Conclusions

- Applicability of linear theory ➔ CMB is our cleanest cosmological probe
- Rich features in C_l ➔ a powerful probe
- We have learned much already
  - Structure formed from adiabatic nearly scale—invariant “initial” spectrum of fluctuations
  - Spatial geometry is flat (or at least nearly so)
  - Supernovae—independent evidence for dark energy
  - Age of Universe is 14.0 \pm 0.5 Gyrs (assuming flatness)
- There is still much more to come