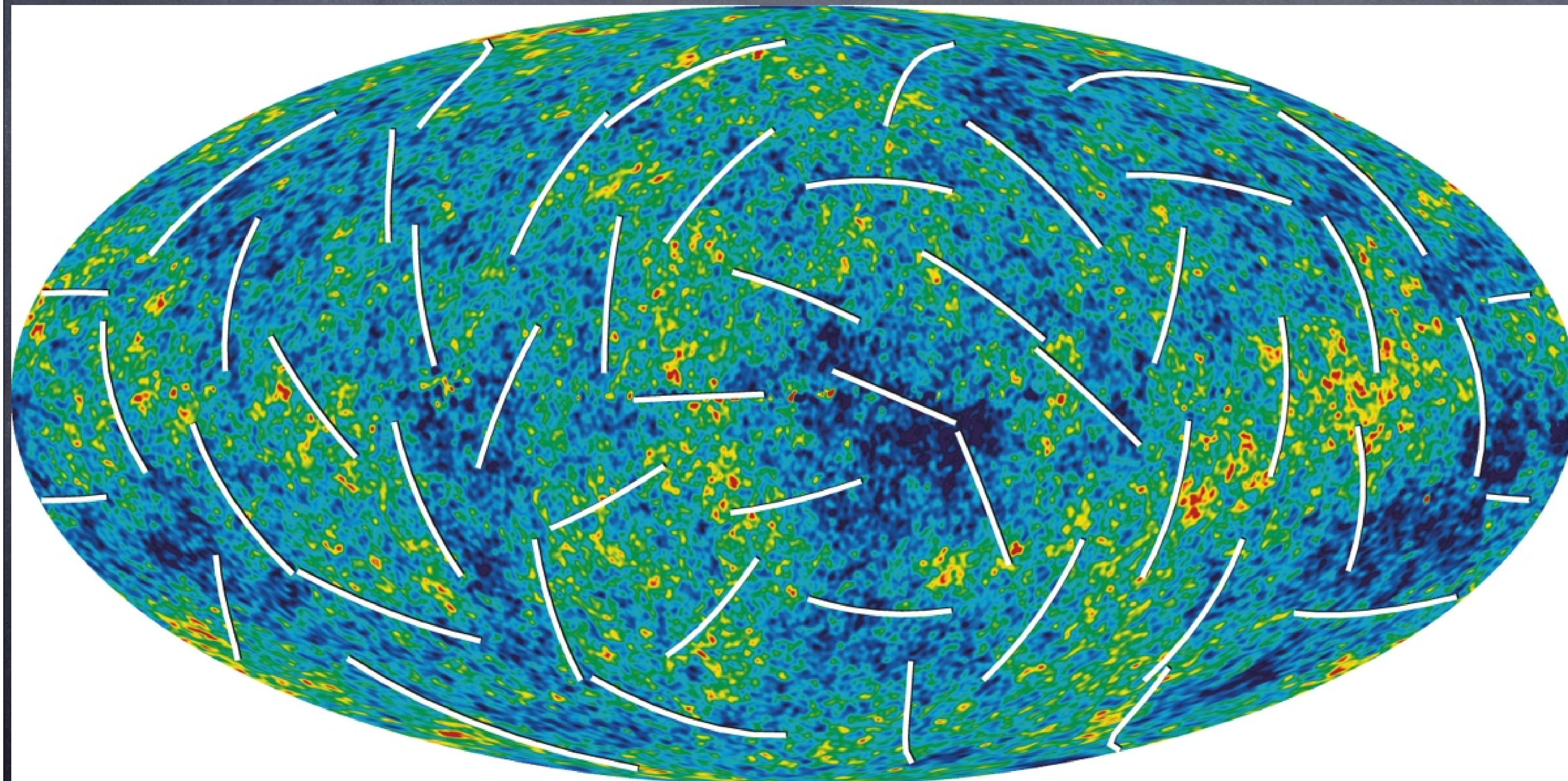
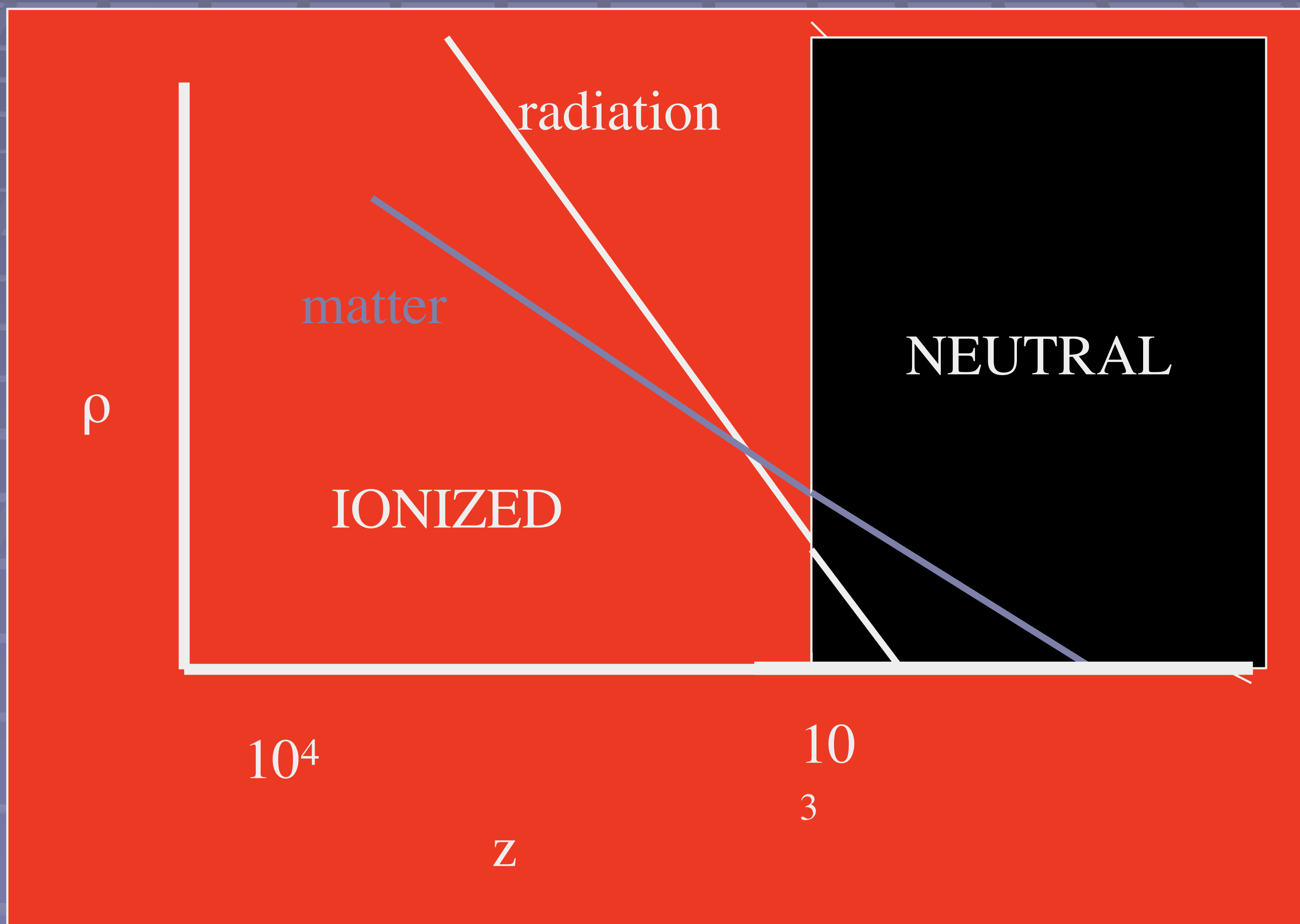
WMAP and Beyond

David Spergel

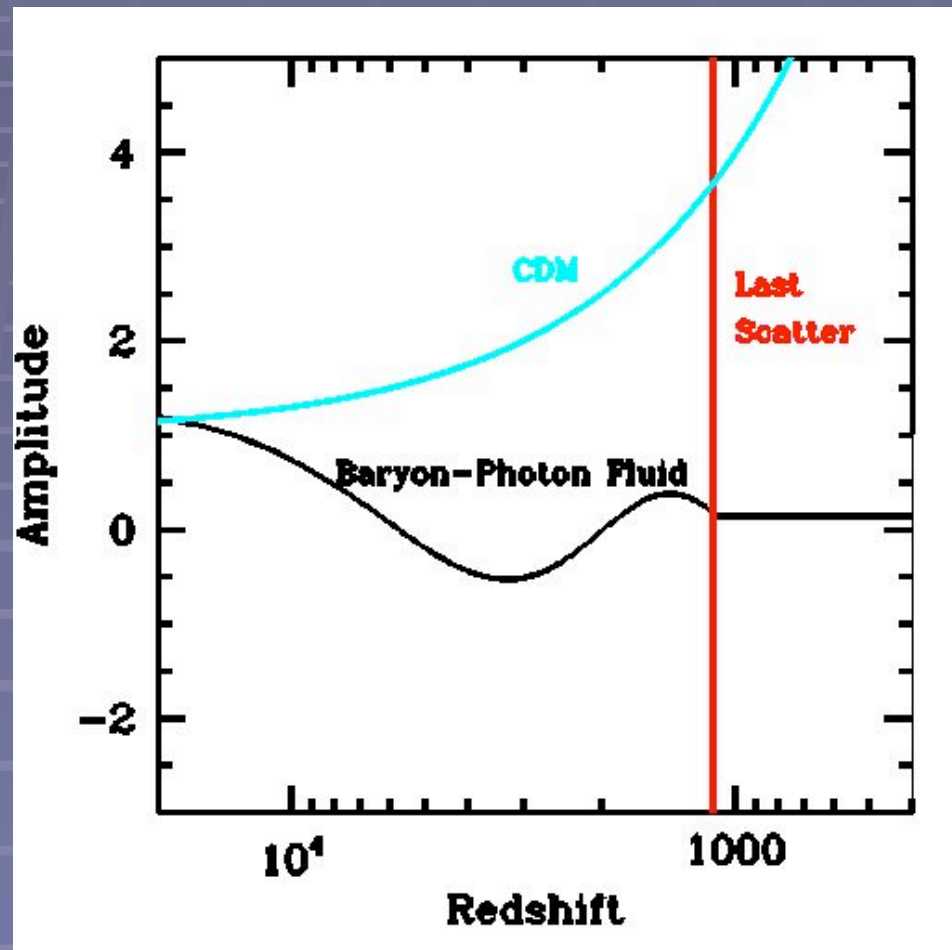


Thermal History of Universe



Growth of Fluctuations

- Linear theory
- Basic elements have been understood for 30 years (Peebles, Sunyaev & Zeldovich)
- Numerical codes agree at better than 0.1% (Seljak et al. 2003)



CMB and LSS Observations as Physics Probes

$$c_l = \int d^3k P(k) [T_l^{CMB}(k)]^2$$

Initial Conditions

$$P(k,t) = b \int d^3k P(k) [T^{LSS}(k,t)]^2$$

Composition of the Universe

CMB Overview

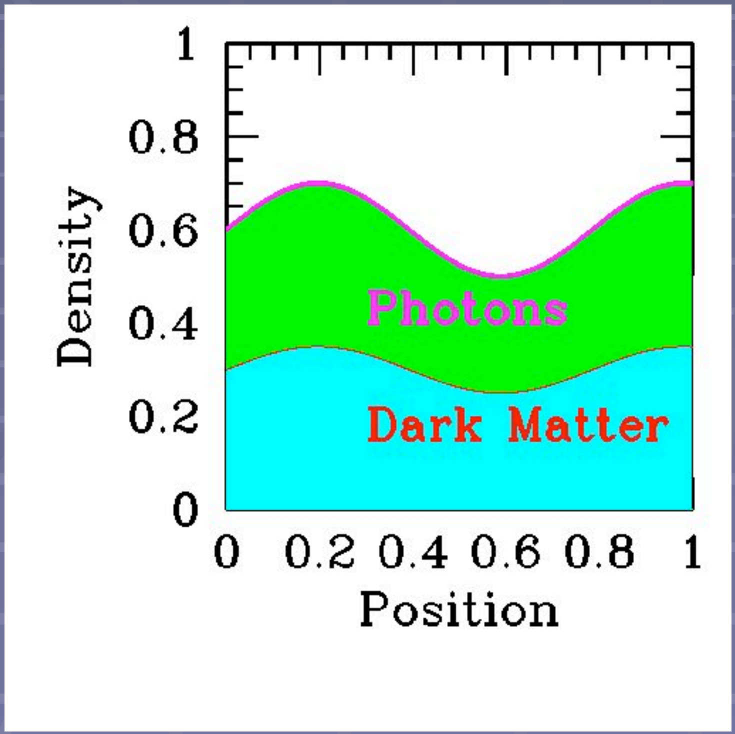
$$T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

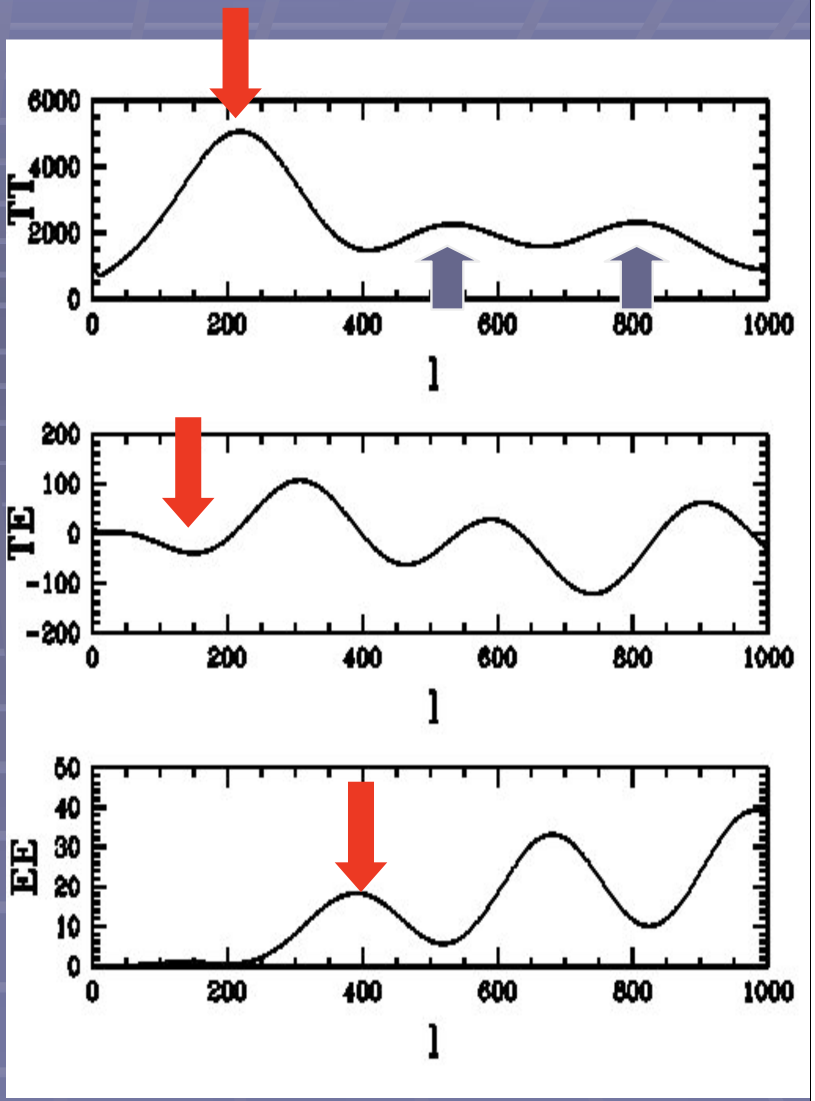
$$c_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

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

- We can detect both CMB temperature and polarization fluctuations
- Polarization Fluctuations can be decomposed into E and B modes

$\theta \sim 180/\ell$





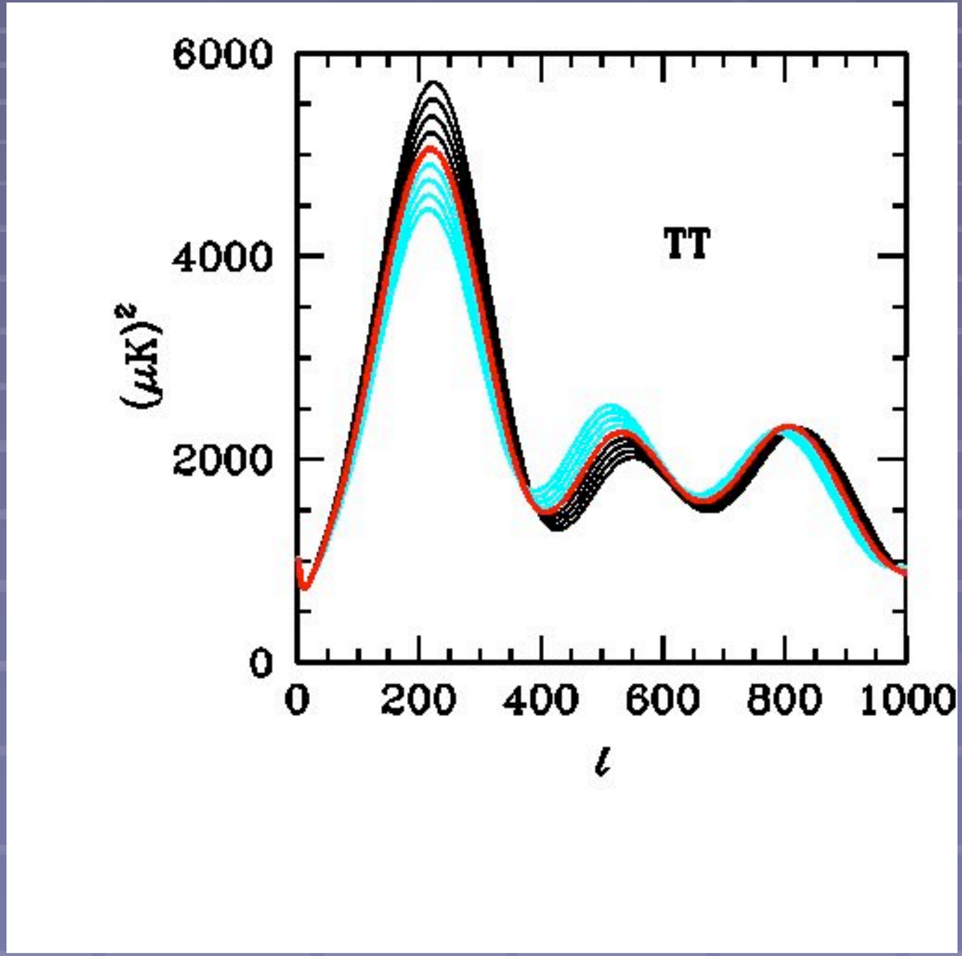
ADIABATIC DENSITY FLUCTUATIONS

Determining Basic Parameters

Baryon Density

$\Omega_b h^2 = 0.015, 0.017..0.031$

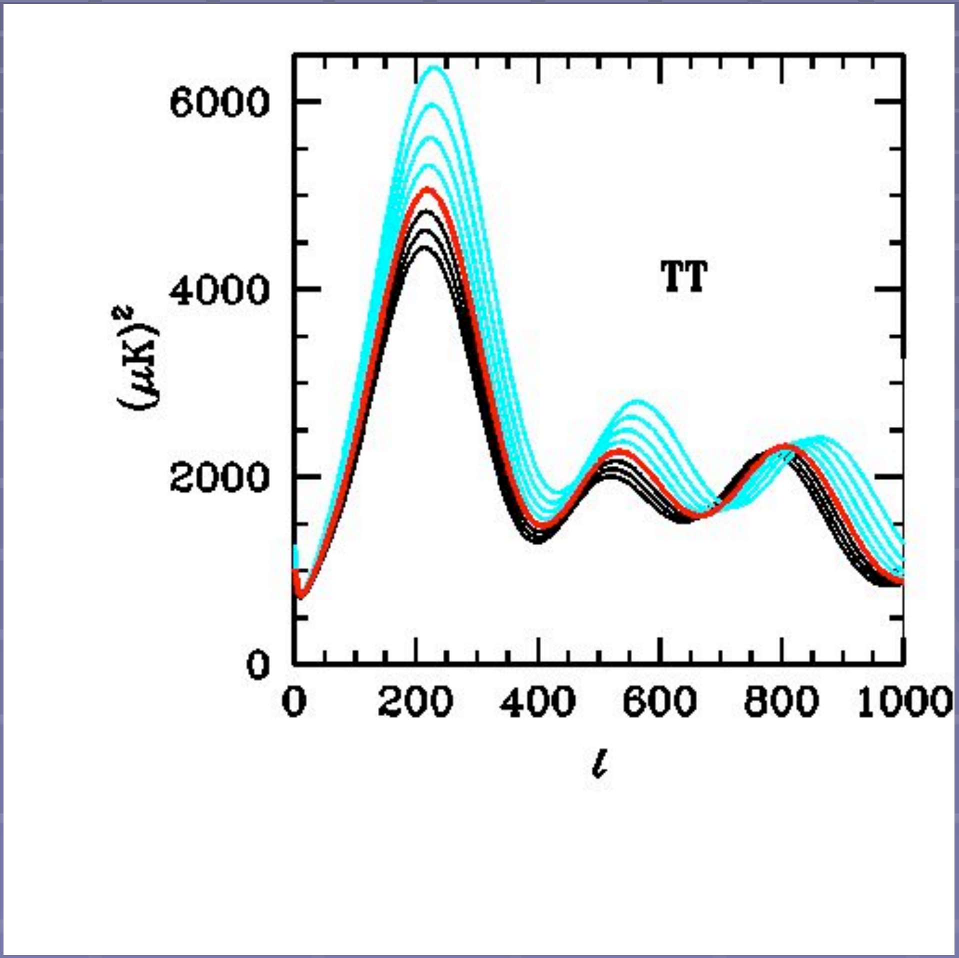
also measured through D/H

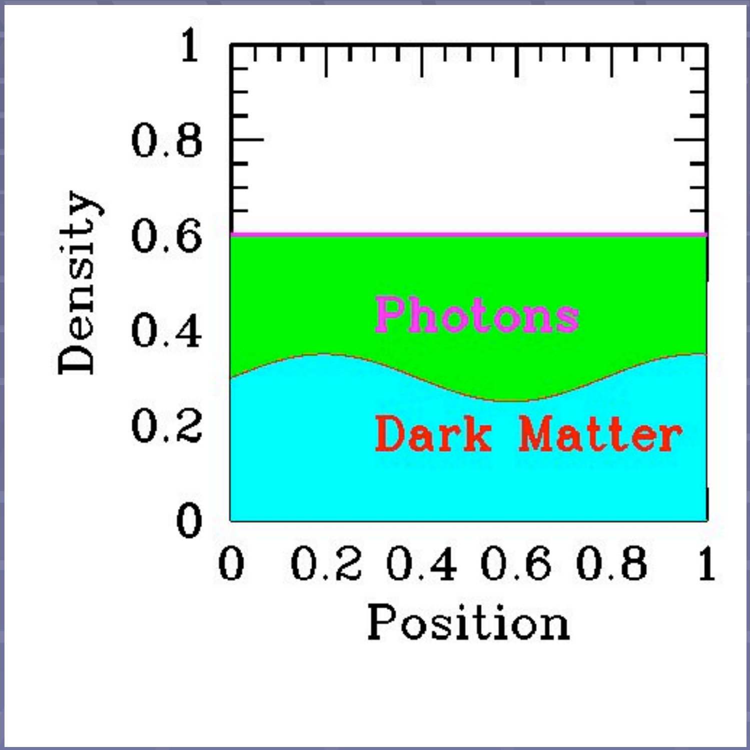


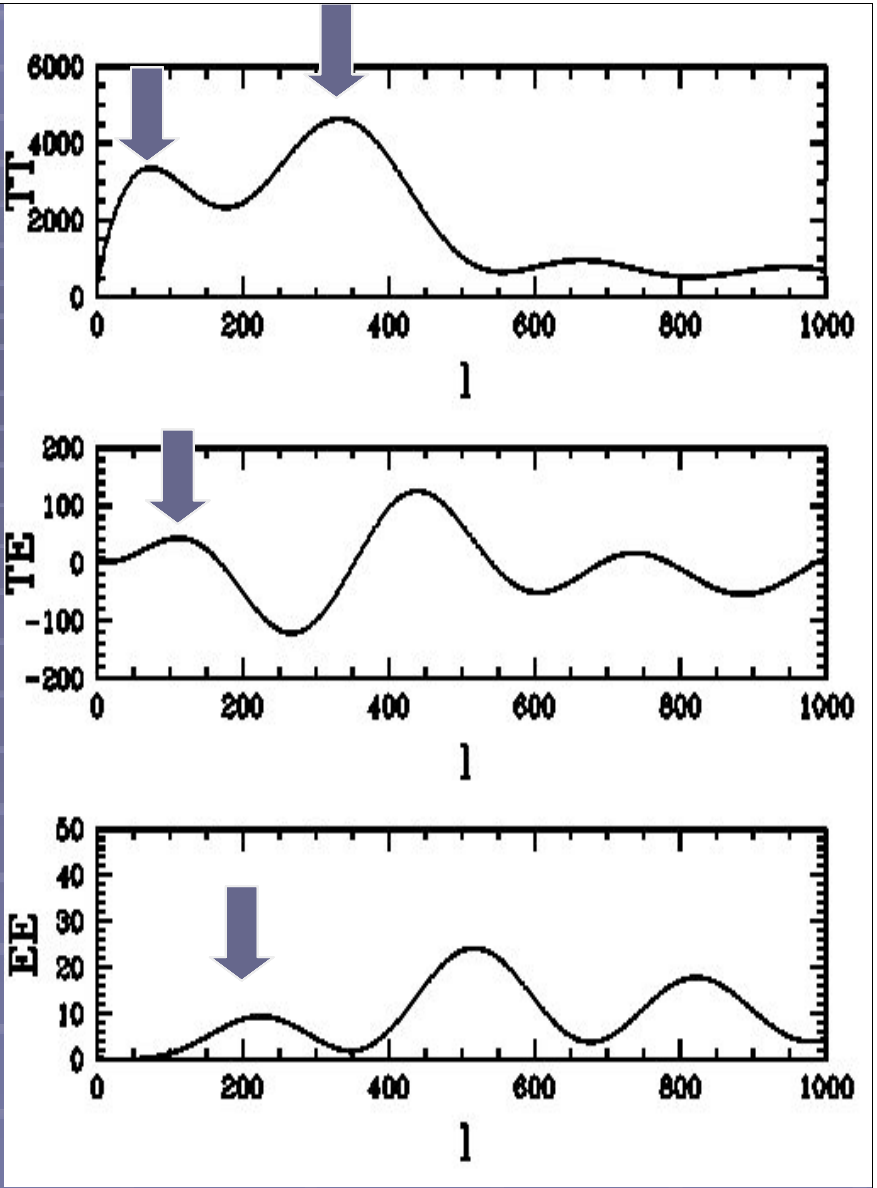
Determining Basic Parameters

Matter Density

$\Omega_m h^2 = 0.16,..,0.33$







ISOCURVATURE ENTROPY FLUCTUATIONS

Science Team

GODDARD

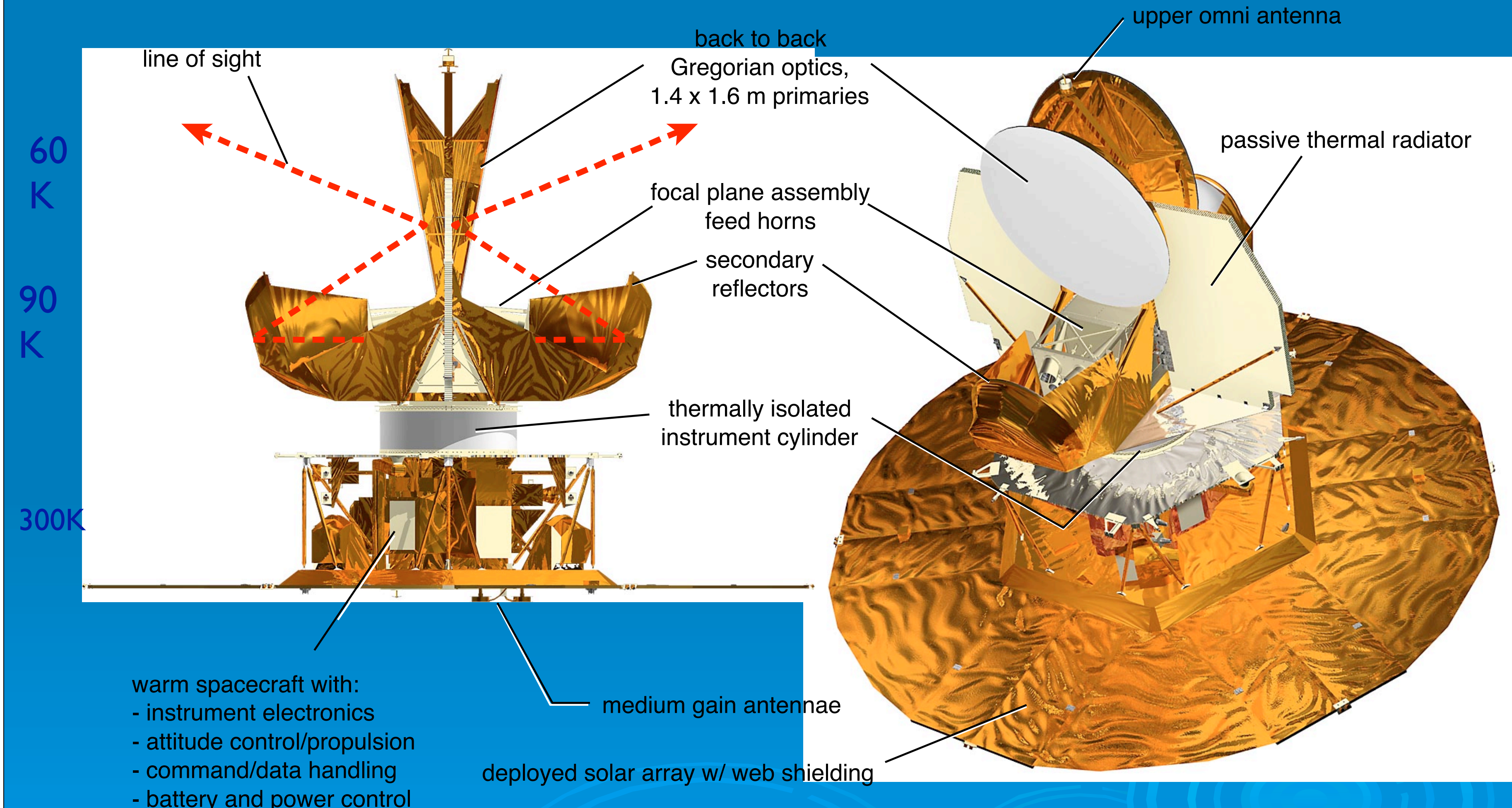
C.Bennett (JHU)
G. Hinshaw
R. Hill
A. Kogut
M. Limon
N. Odegard
J. Weiland
E. Wollack

Princeton

C. Barnes
R. Bean (Cornell)
J. Dunkley
O. Dore (CITA)
M. Nolta (CITA)
N. Jarosik
E. Komatsu (Texas)
L. Page
H. Peiris (Chicago)
L. Verde (Penn)
D. Spergel

M. Halpern (UBC)
S. Meyer (Chicago)
G. Tucker (Brown)
E. Wright (UCLA)

WMAP Spacecraft



MAP990422

What Took So Long?

- Our detected polarization signal is weak: we have errors below 200 nanoKelvin
- Making a convincing detection of large-scale polarization required understanding the experimental systematics, modeling the interplay between noise and scan strategy and understanding galactic emission

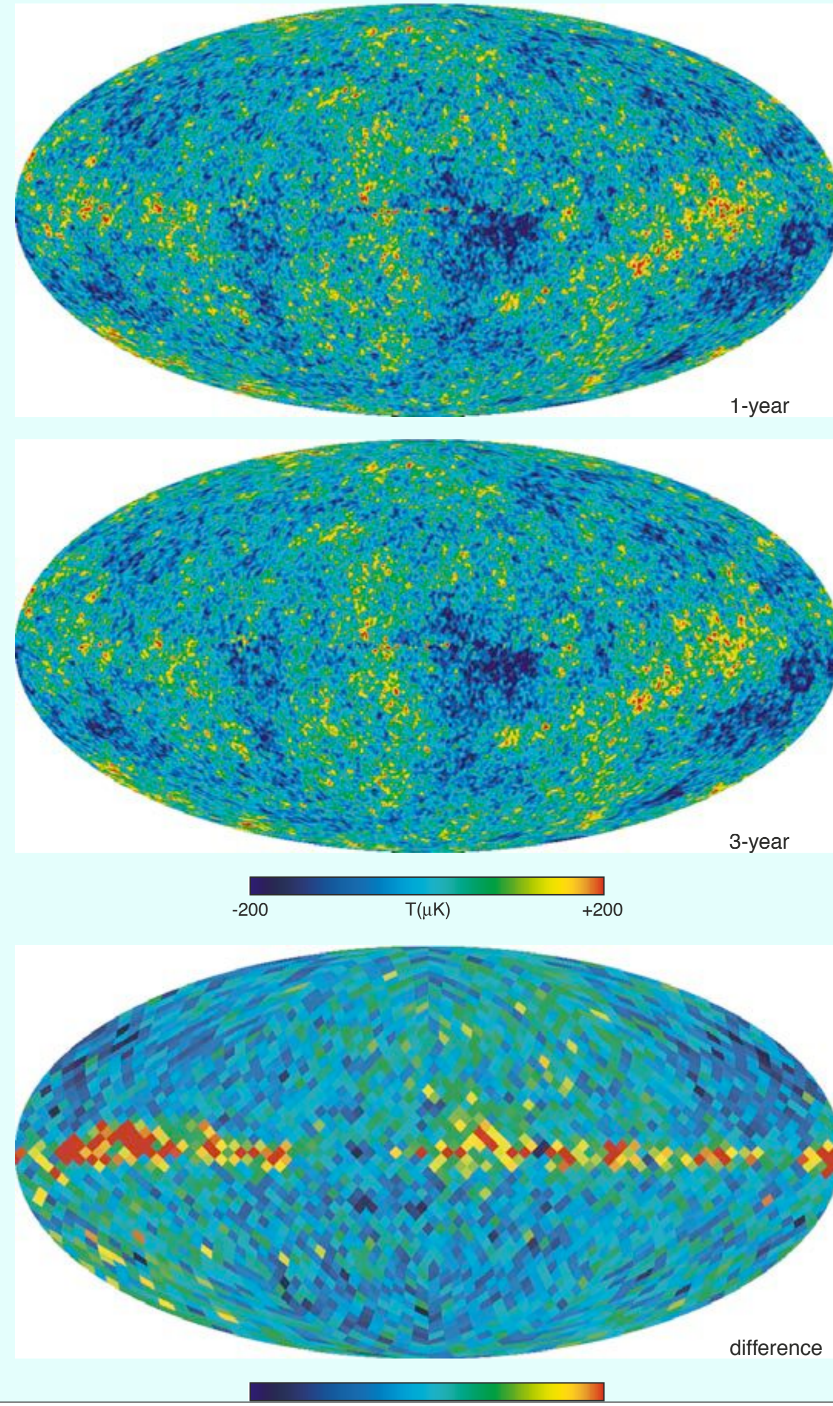
What is New?

- Improved Gain Model
- Improved Beam Model and more accurate treatment of sidelobes
- Improved Noise Model
- Improved Foreground Model
- Finer pixelization
- Exact treatment of low l likelihood for temperature and polarization

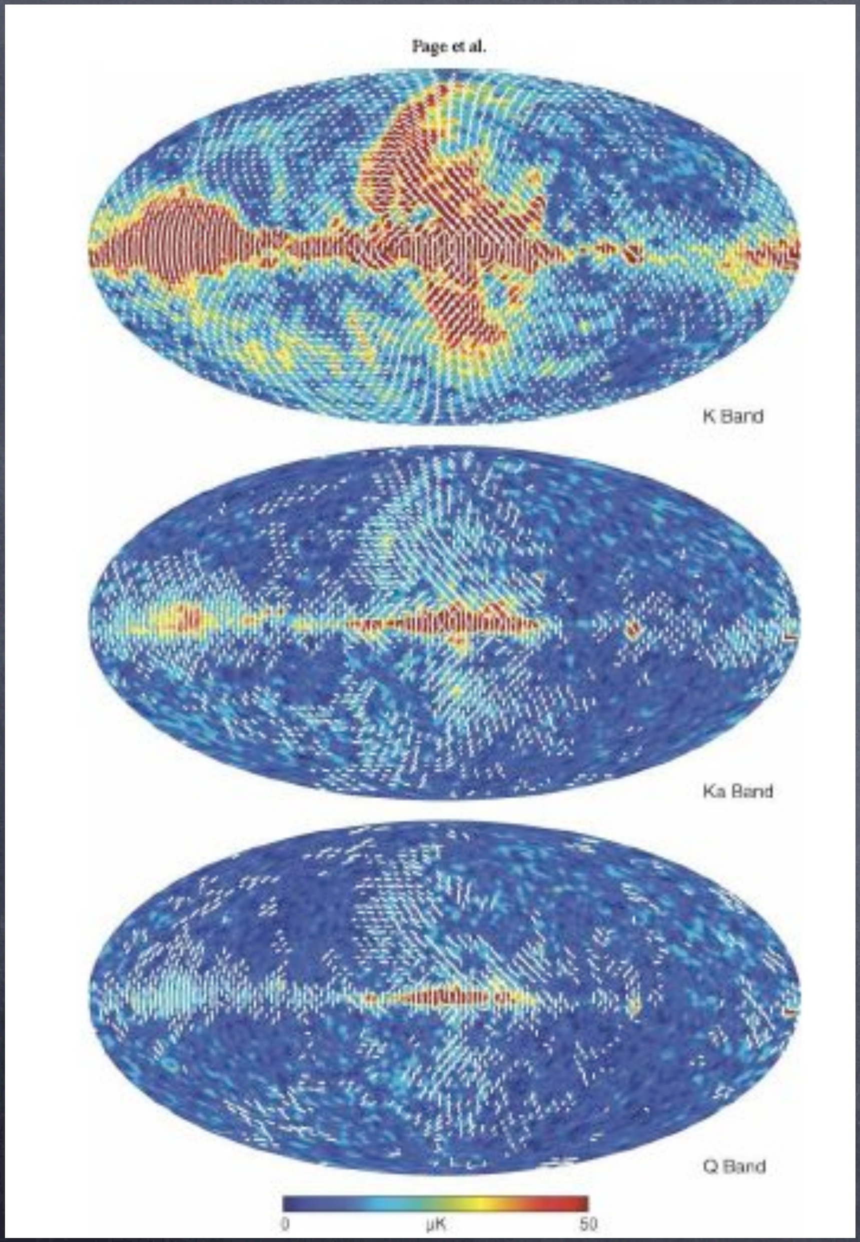
ILC Map

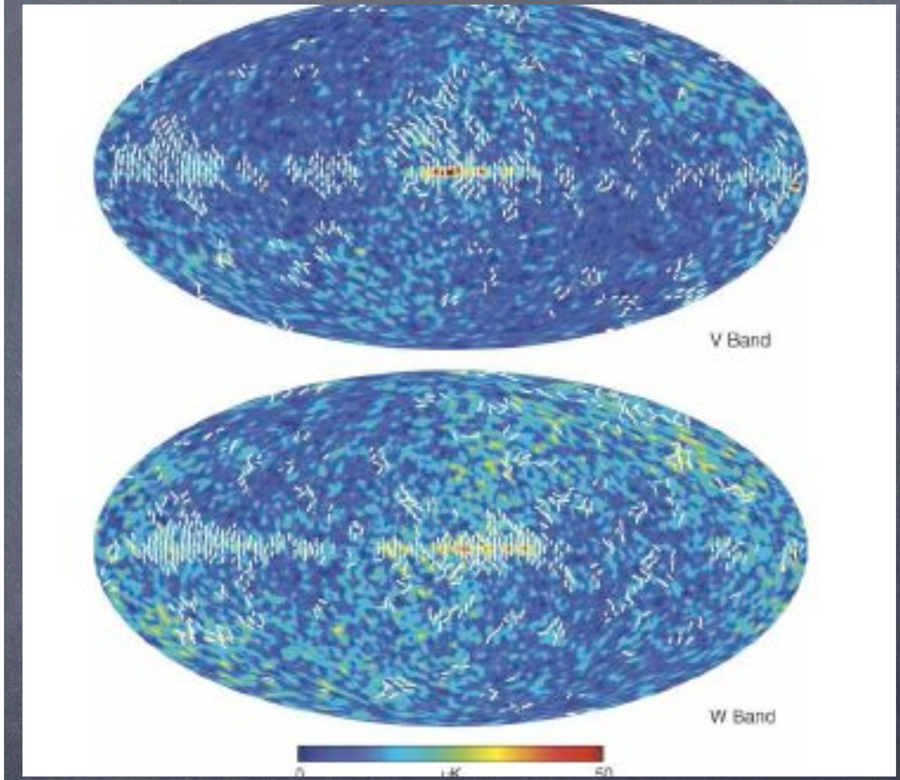
Since our 'press release" map was being used extensively for science, we have attempted to characterize the uncertainties.

There remains large uncertainties in the plane where there is significant foreground removal

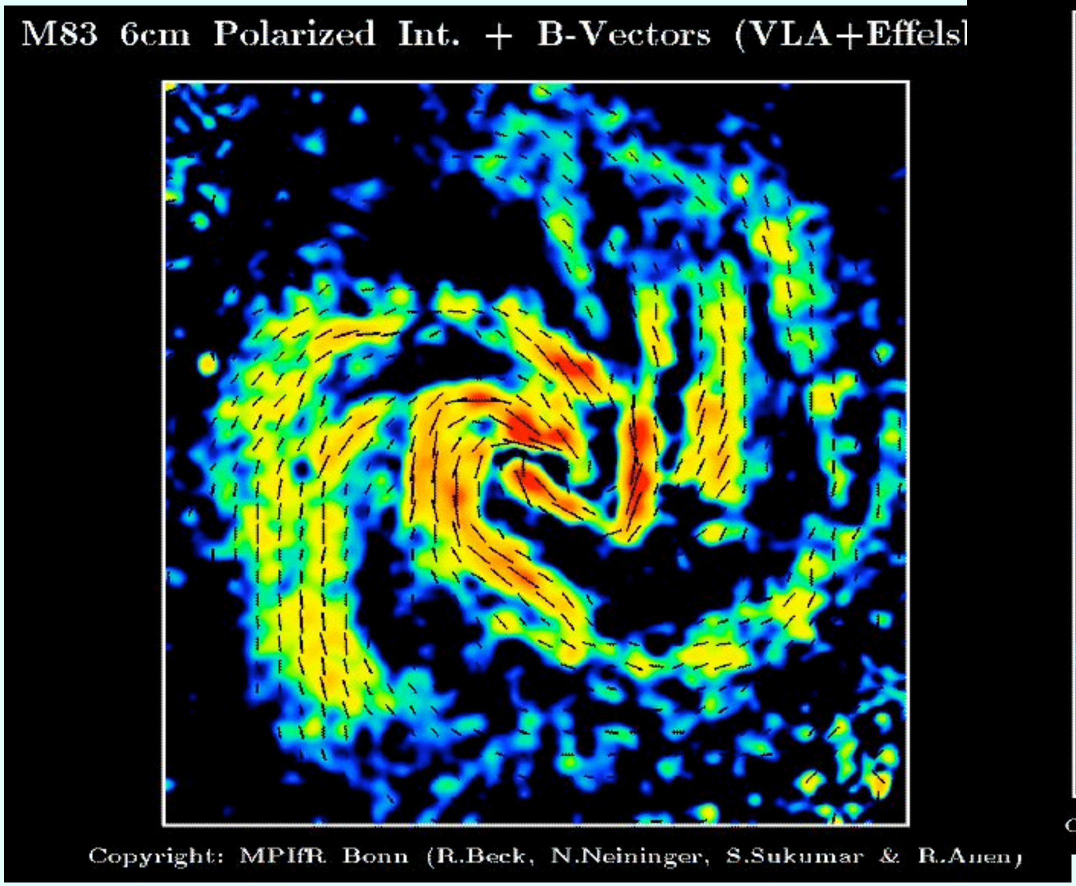


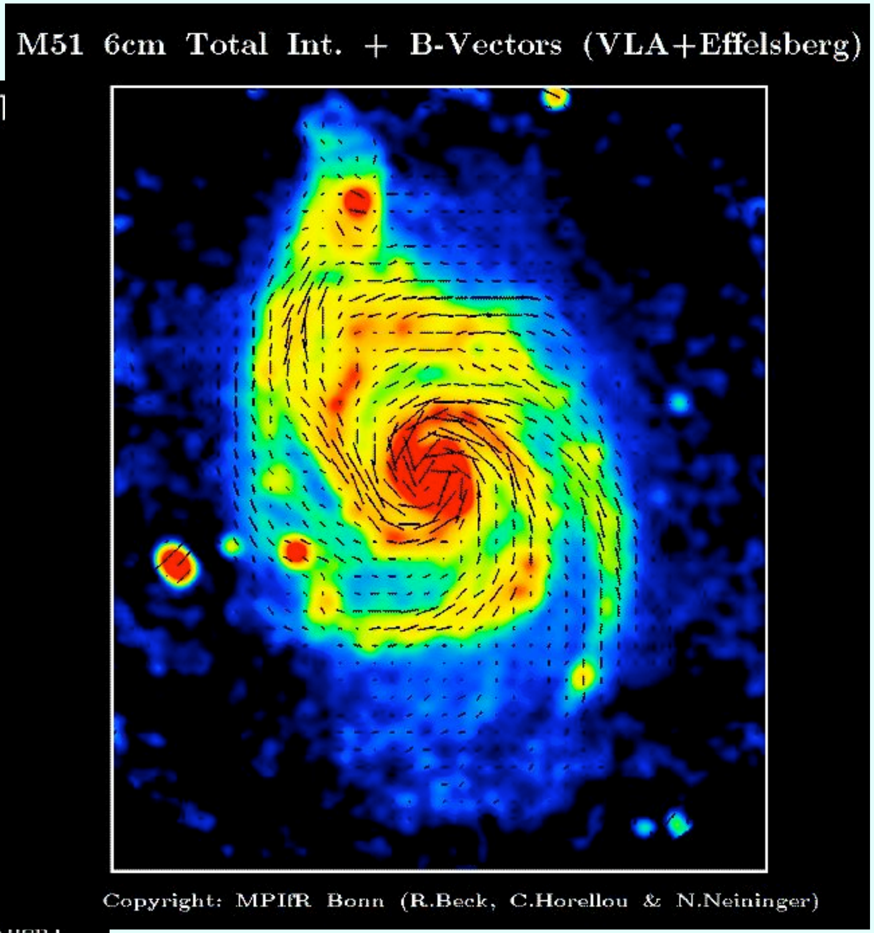
Polarization Maps



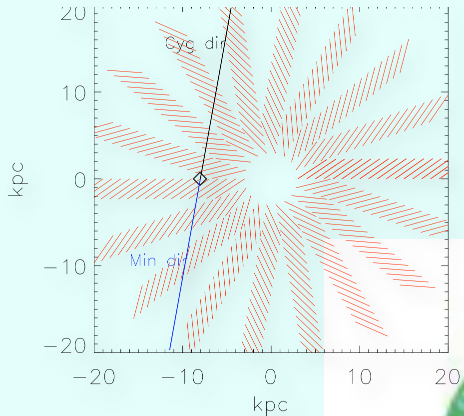


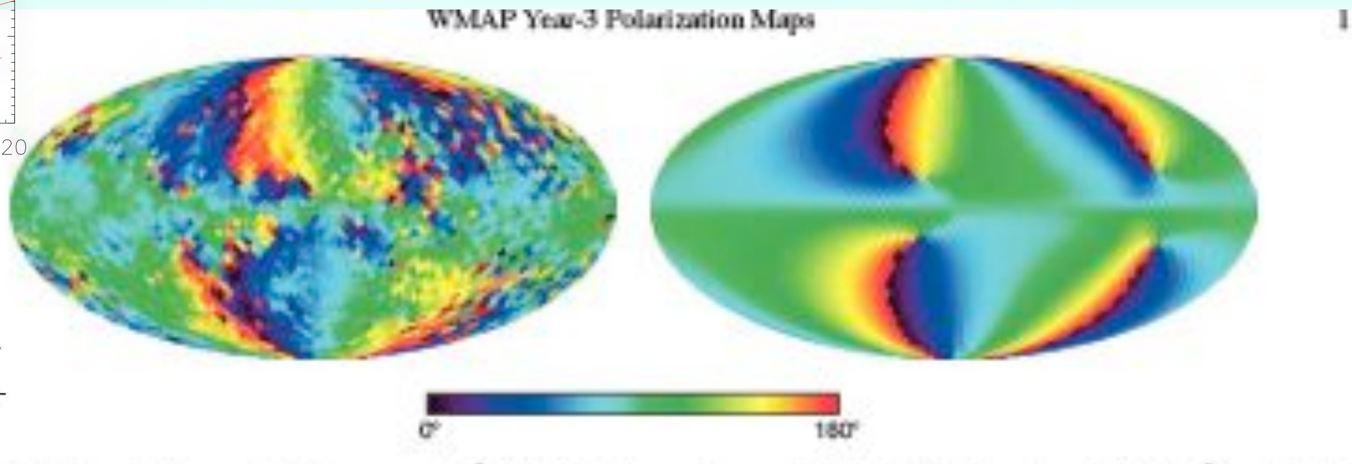
Magnetic Field Structure in external galaxies exhibit spiral structure





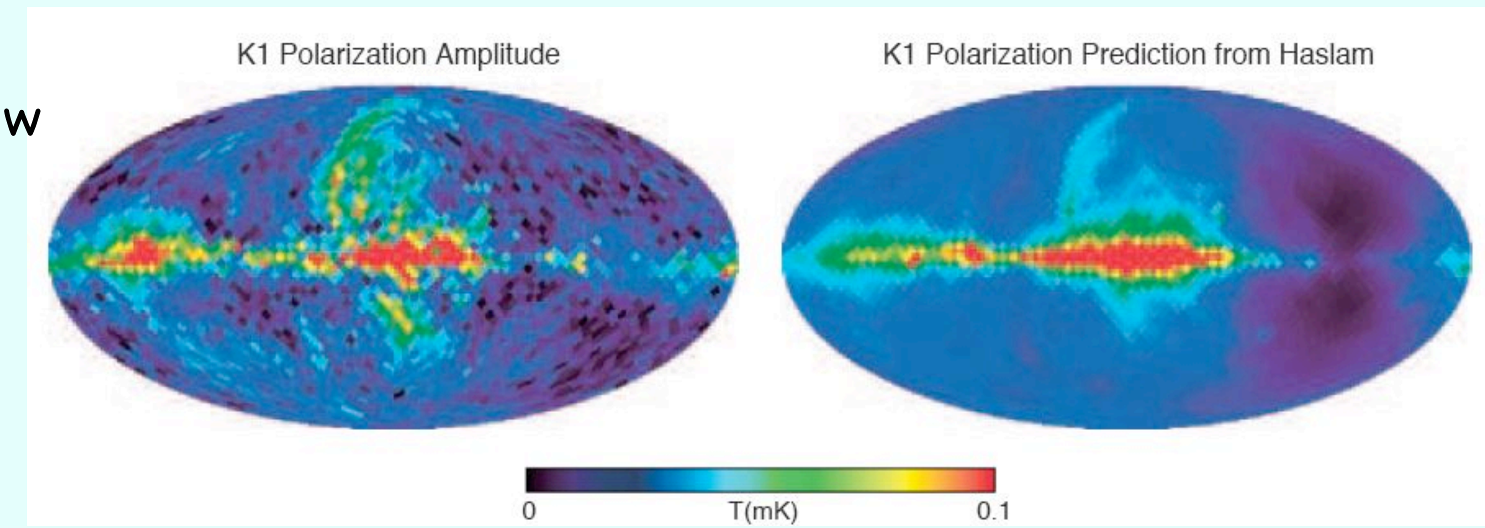
Same bisymmetric spiral pattern is a good global fit to the field structure





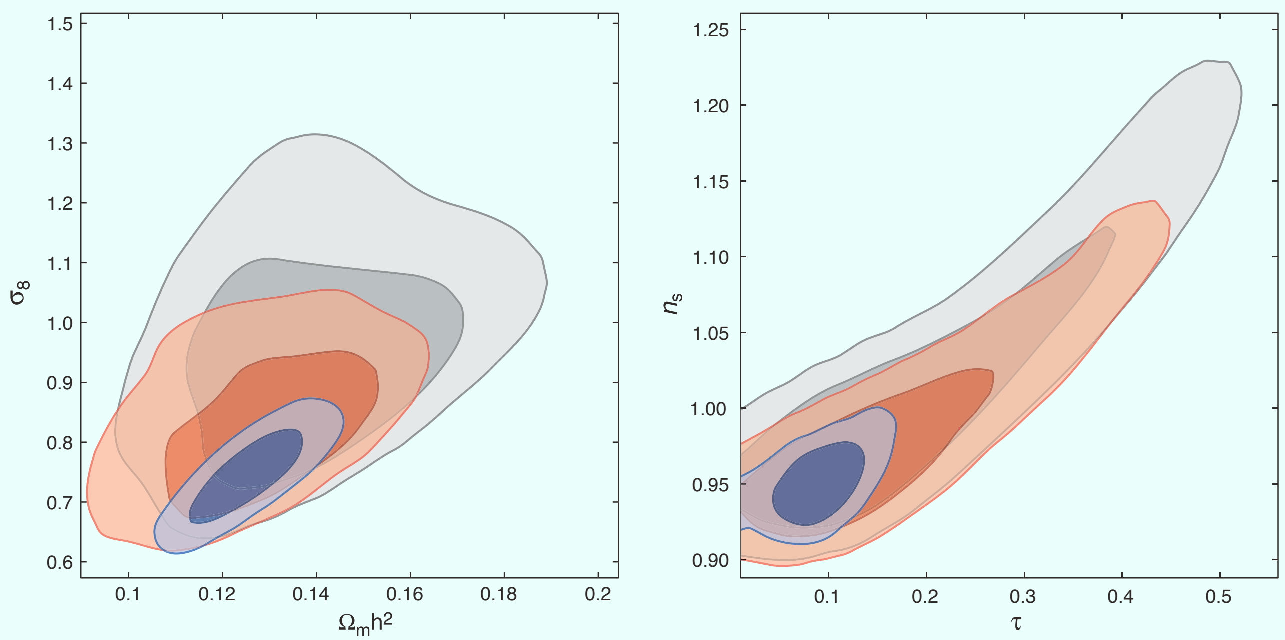
$$
\begin{aligned}
\mathbf{B}(r,\phi,z) = B_0[& \cos\psi(r)\cos\chi(z)\hat{r} + \\
& \sin\psi(r)\cos\chi(z)\hat{\phi} + \\
& \sin\chi(z)\hat{z}]
\end{aligned}
$$

Deviations show regions with shallower spectra

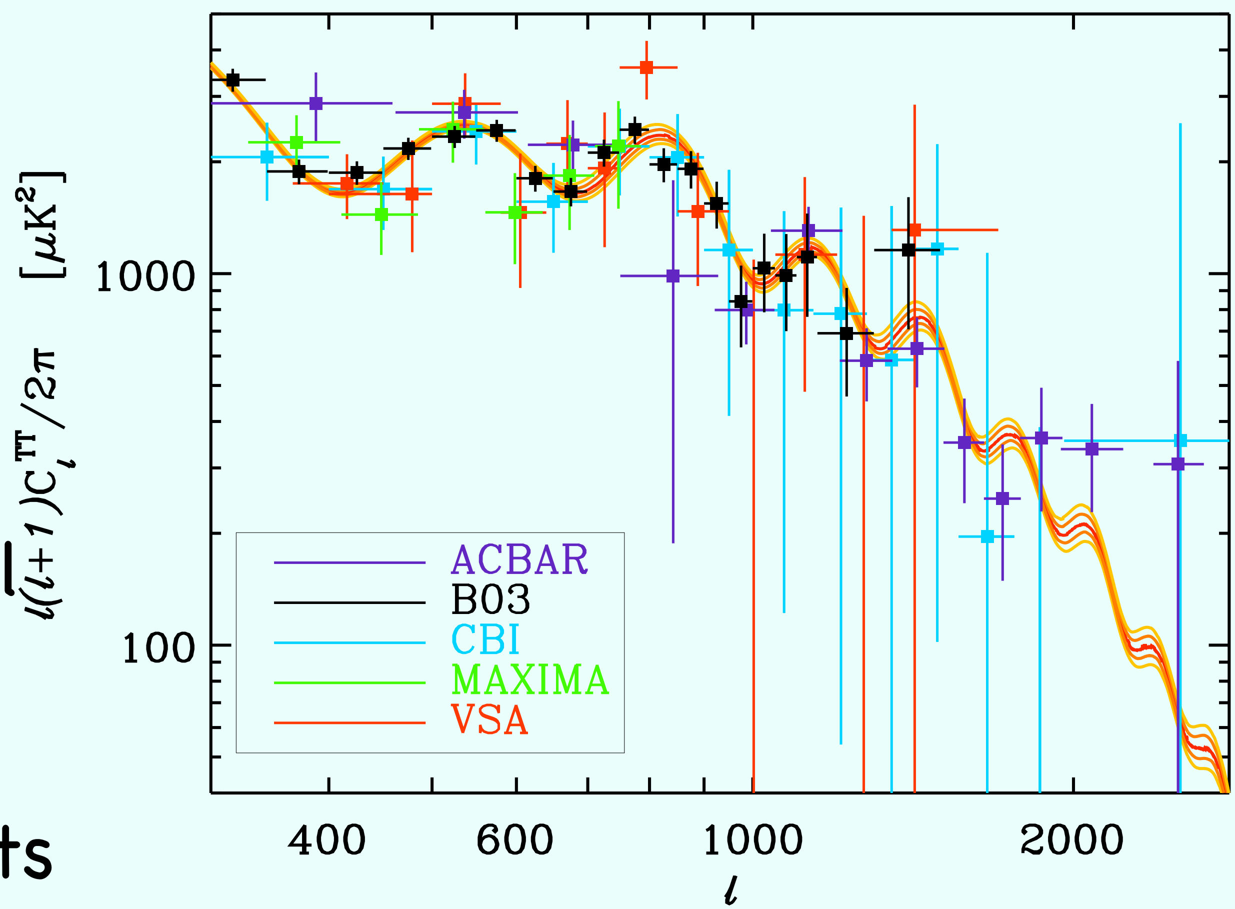


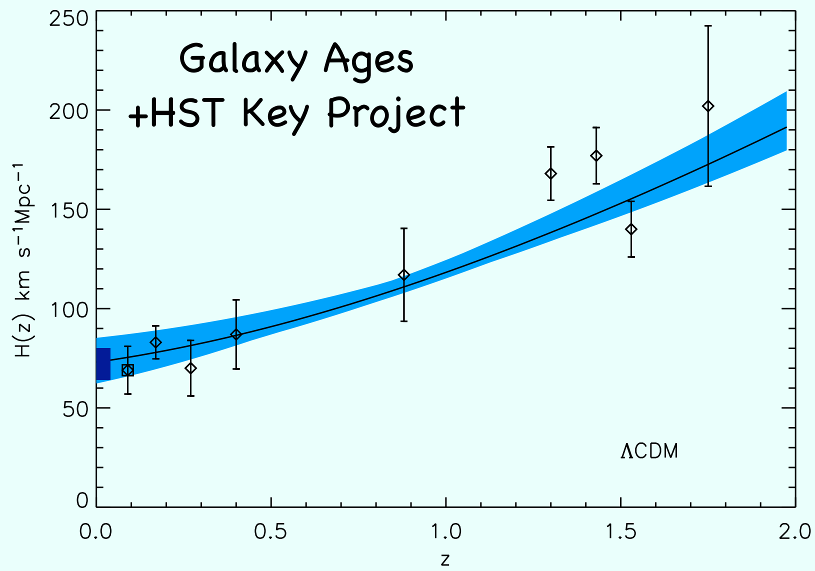
Improvement in Parameters

Parameter	First Year Mean	WMAPext Mean	Three Year Mean	First Year ML	WMAPext ML	Three Year ML
$100\Omega_b h^2$	$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08	2.30	2.21	2.22
$\Omega_m h^2$	$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009	0.145	0.138	0.128
H_0	72^{+5}_{-5}	73^{+3}_{-3}	74^{+3}_{-3}	68	71	73
τ	$0.17^{+0.08}_{-0.07}$	$0.15^{+0.07}_{-0.07}$	0.093 ± 0.029	0.10	0.10	0.092
n_s	$0.99^{+0.04}_{-0.04}$	$0.98^{+0.03}_{-0.03}$	0.961 ± 0.017	0.97	0.96	0.958
Ω_m	$0.29^{+0.07}_{-0.07}$	$0.25^{+0.03}_{-0.03}$	0.234 ± 0.035	0.32	0.27	0.24
σ_8	$0.92^{+0.1}_{-0.1}$	$0.84^{+0.06}_{-0.06}$	0.76 ± 0.05	0.88	0.82	0.77



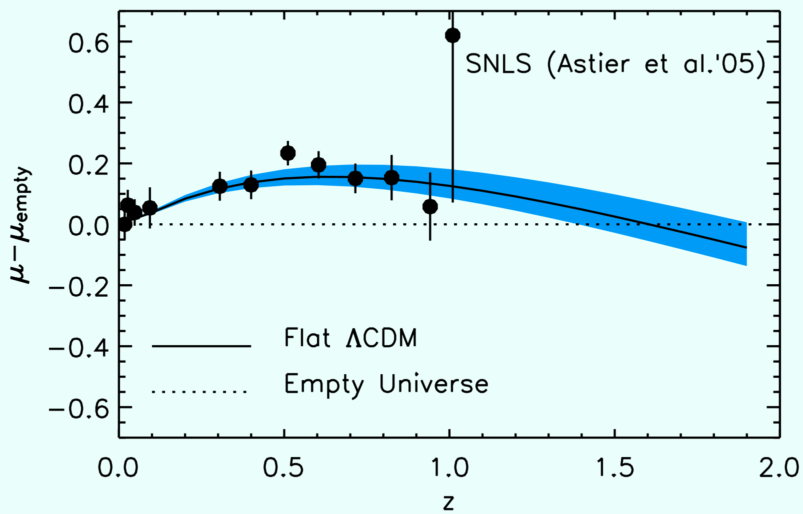
Same Model fits small scale CMB measurements

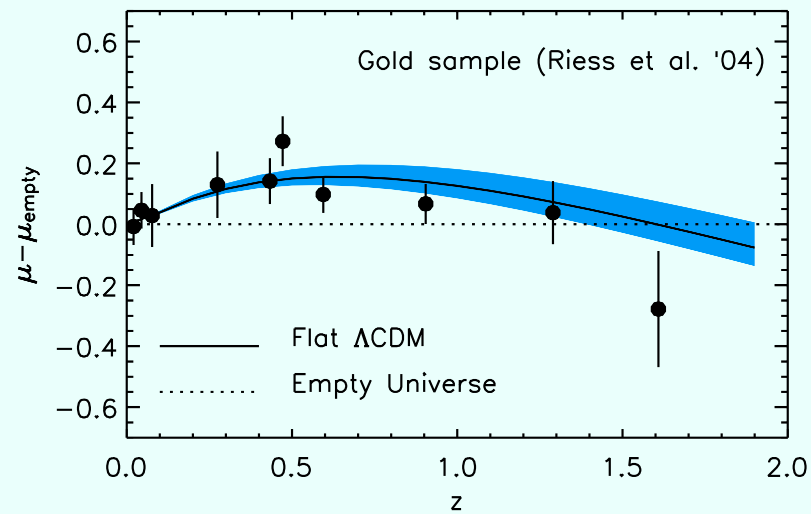




WMAP fits predict H(z)

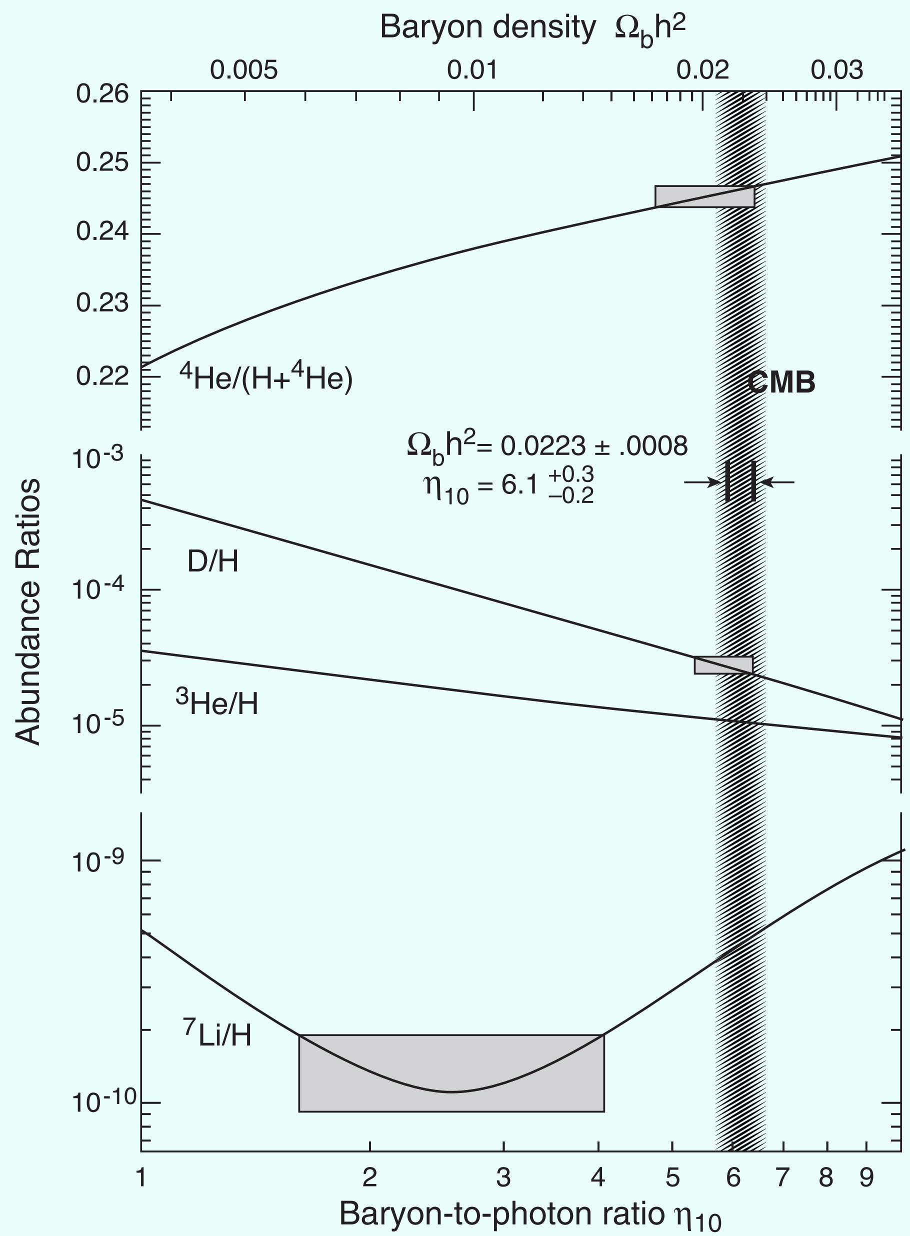
Supernovae

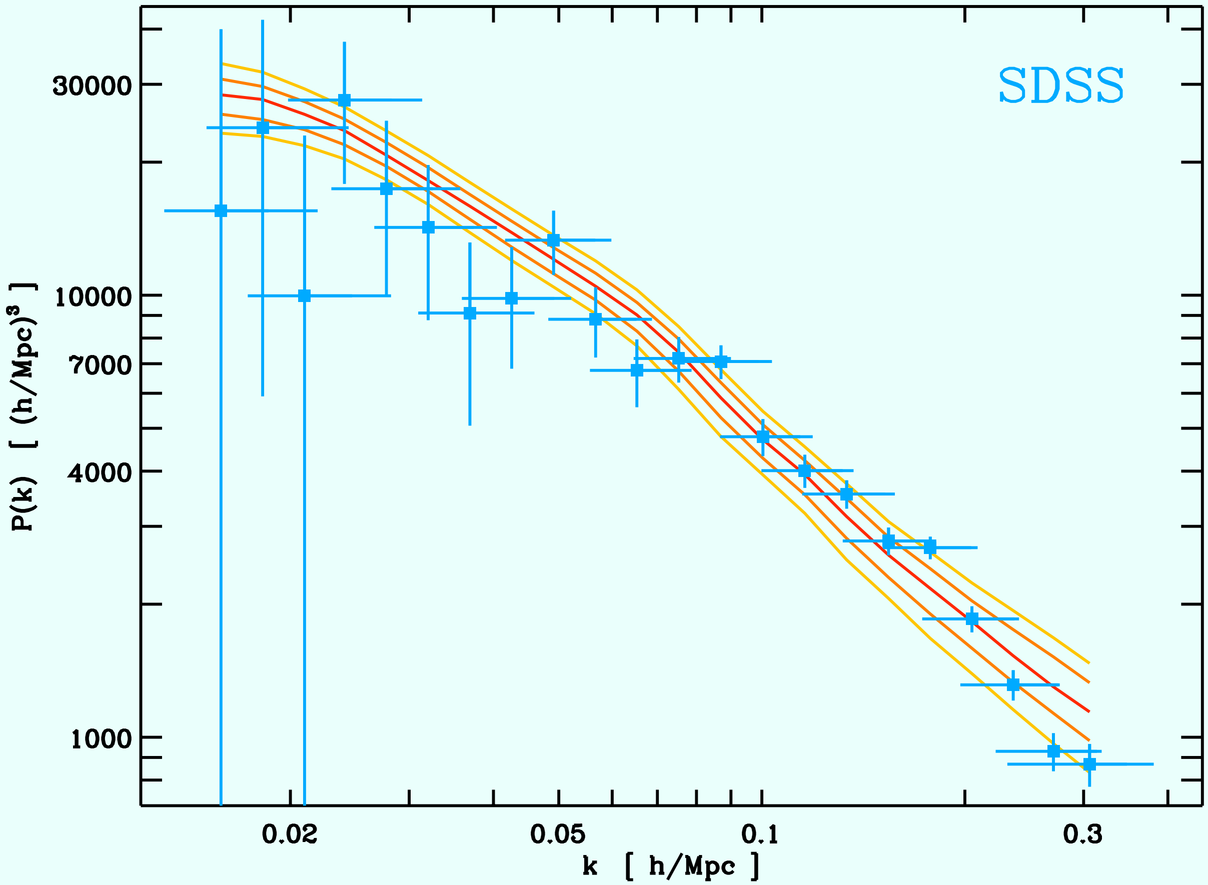




	CMB-based BBN prediction	Observed Value
$10^5 y_D^{FIT}$	$2.58^{+0.14}_{-0.13}$	1.6 - 4.0
$10^5 y_3$	$1.05 \pm 0.03 \pm 0.03$ (syst.)	$< 1.1 \pm 0.2$
Y_P	$0.24815 \pm 0.00033 \pm 0.0006$(syst.)	0.232 - 0.258
[Li]	2.64 ± 0.03	2.2 - 2.4

WMAP fits predict abundances





WMAP fits predict galaxy and mass distribution

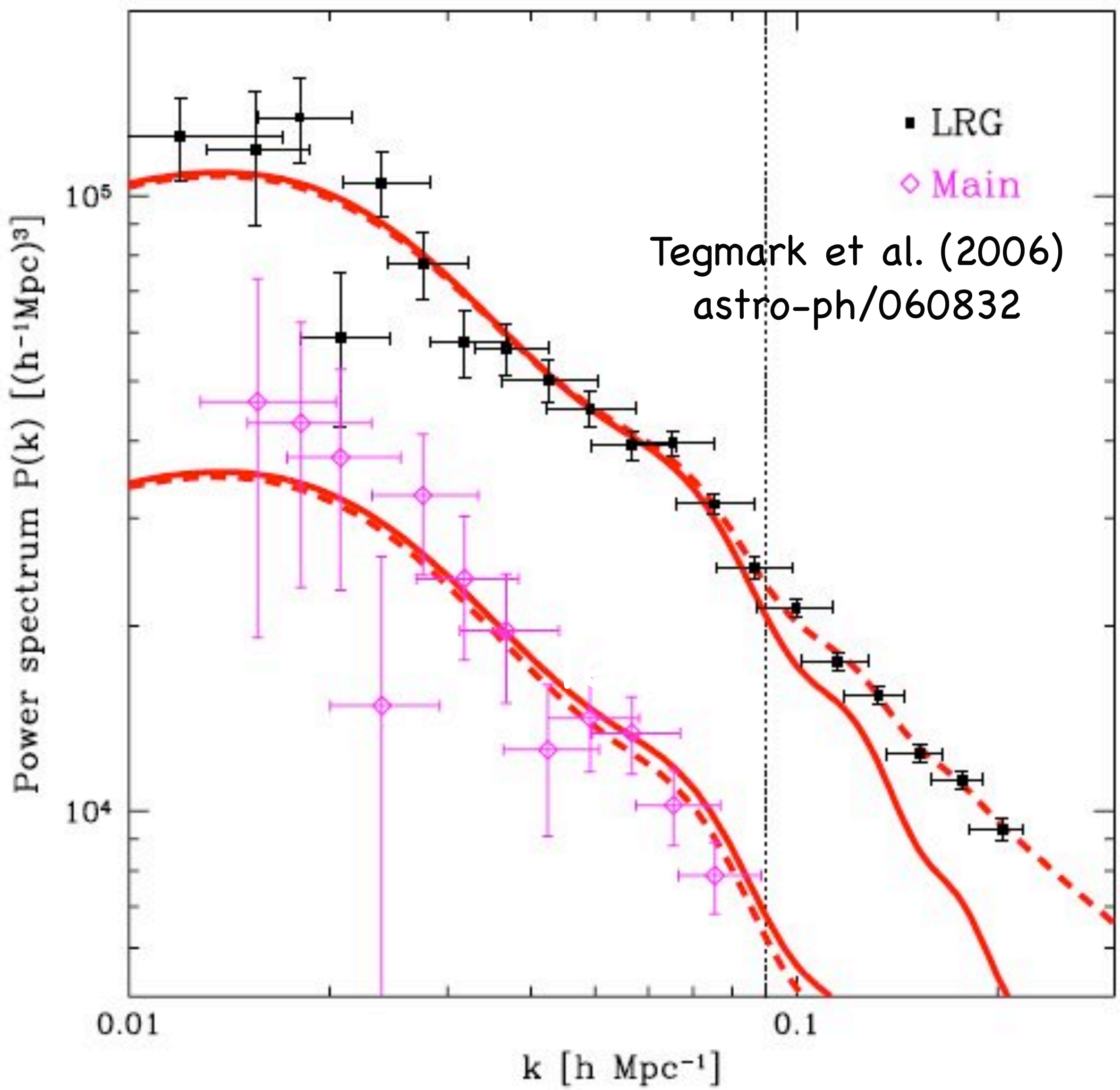


FIG. 4: Measured power spectra for the full LRG and main galaxy samples. Errors are uncorrelated and full window functions are shown in Figure 5. The solid curves correspond to the linear theory ΛCDM fits to WMAP3 alone from Table 5 of [7], normalized to galaxy bias $b = 1.9$ (top) and $b = 1.1$ (bottom) relative to the $z = 0$ matter power. The dashed curves include the nonlinear correction of [29] for $A = 1.4$, with $Q_{nl} = 30$ for the LRGs and $Q_{nl} = 4.6$ for the main galaxies; see equation (4). The onset of nonlinear corrections is clearly visible for $k \gtrsim 0.09h$/Mpc (vertical line).

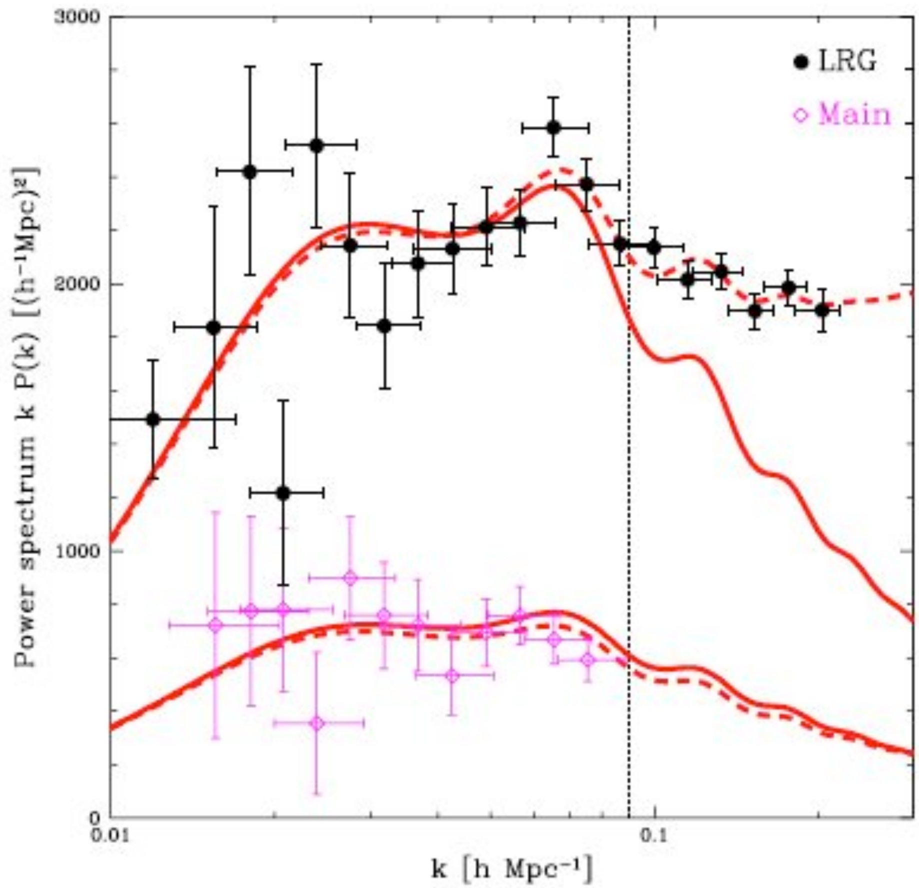


FIG. 7: Same as Figure 4, but multiplied by k and plotted with a linear vertical axis to more clearly illustrate departures from a simple power law.

Simple Model Fits!

- Age
- CMB Observations
- Hubble Constant
- Element Abundances
- Cluster abundances
- Lensing (Weak and Strong)
- Galaxy Clustering & Galaxy Properties

Lots of new data ... No New Epicycles

New Questions

- What is the dark energy?
- What is the dark matter?
- How did the universe begin?

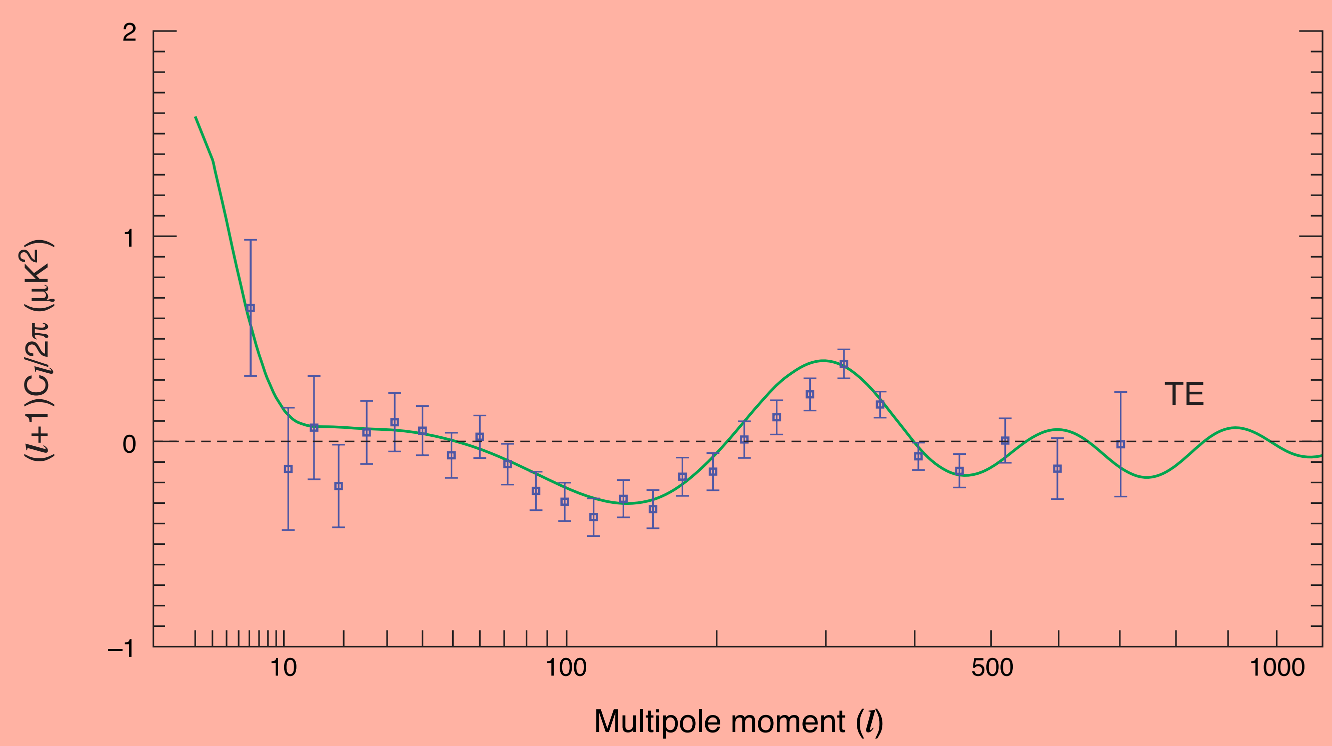
Inflationary Paradigm

- Developed in 1980s by Guth, Linde, Steinhardt, ...
- Motivated by recognition that the universe has gone through a series of phase transition
- During its first moments, universe gets trapped in a false vacuum state, drives exponential expansion

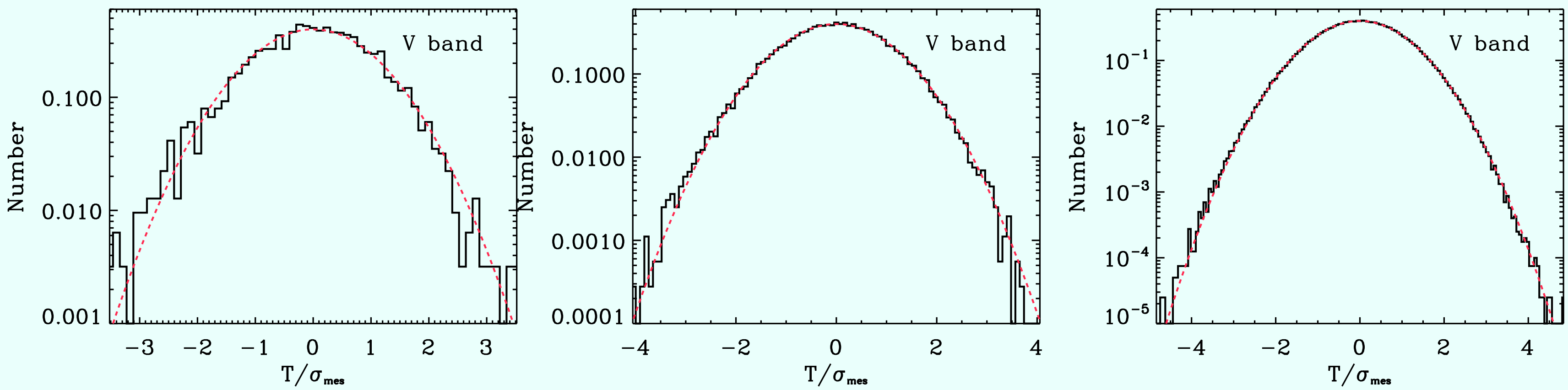
Inflationary Predictions

- Nearly Scale Invariant Fluctuations (COBE)
- Flat (TOCO, Boomerang, CBI,...,WMAP)
- Adiabatic (Boomerang, CBI, ...,WMAP I)
- Superhorizon Fluctuations (WMAP I)
- Gaussian (WMAP I, WMAP II)
- $n < 1$ (WMAP II)
- Gravitational Waves (TBD)

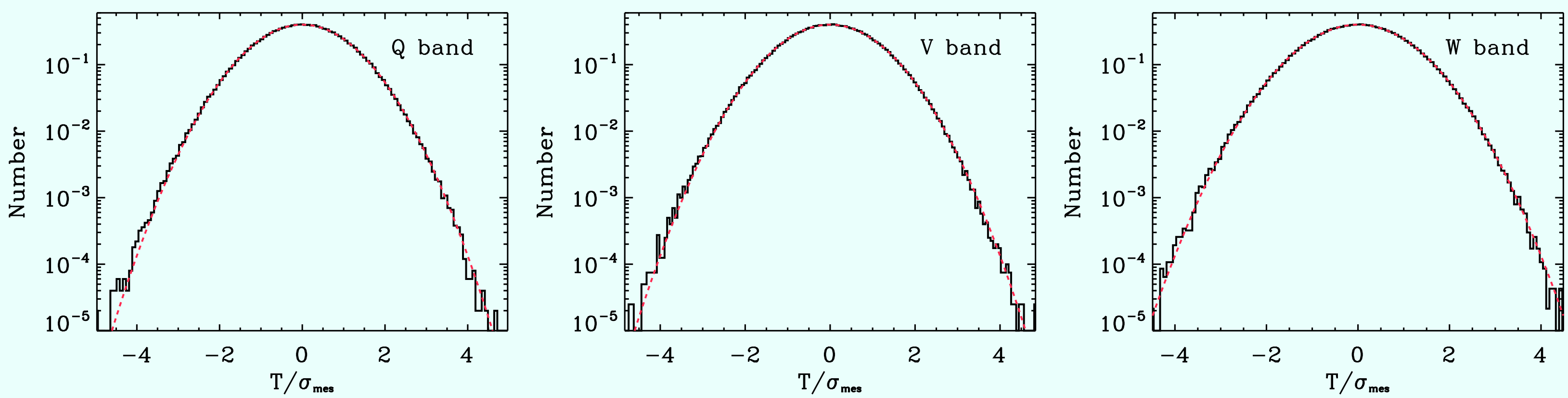
Superhorizon Fluctuations



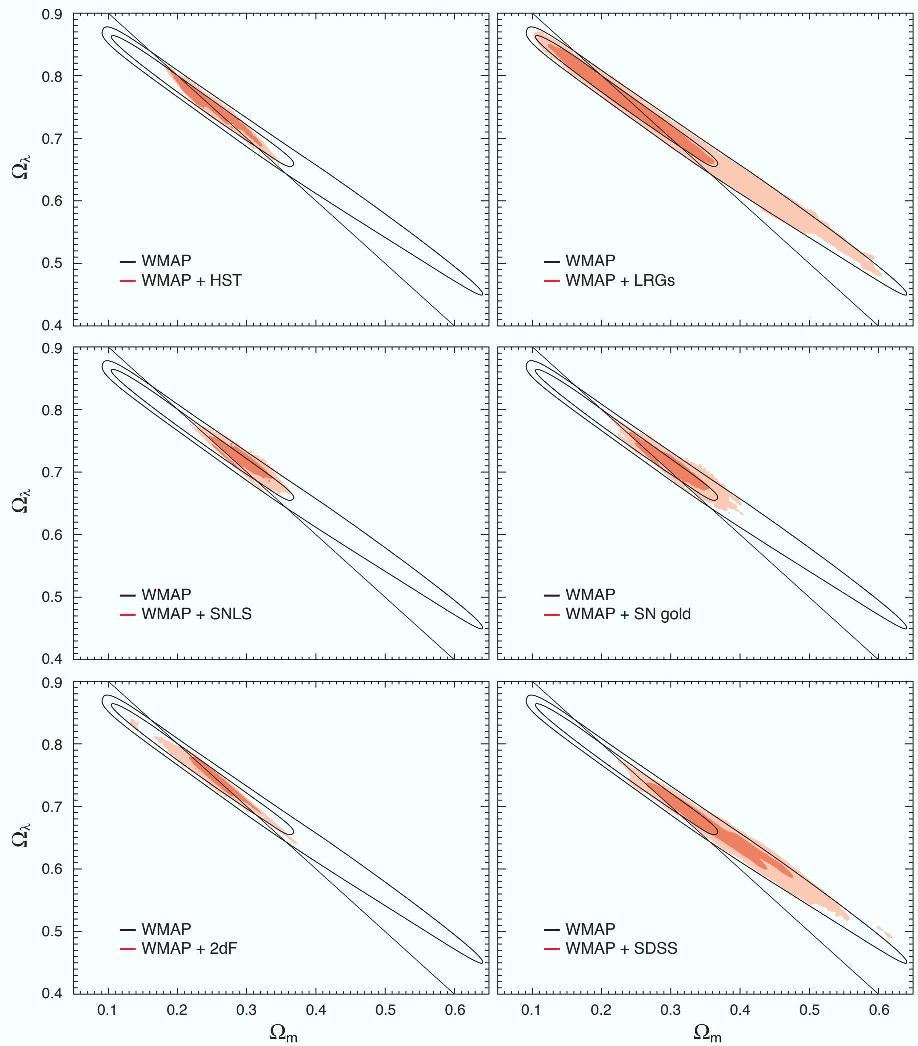
Looking Pretty Gaussian....



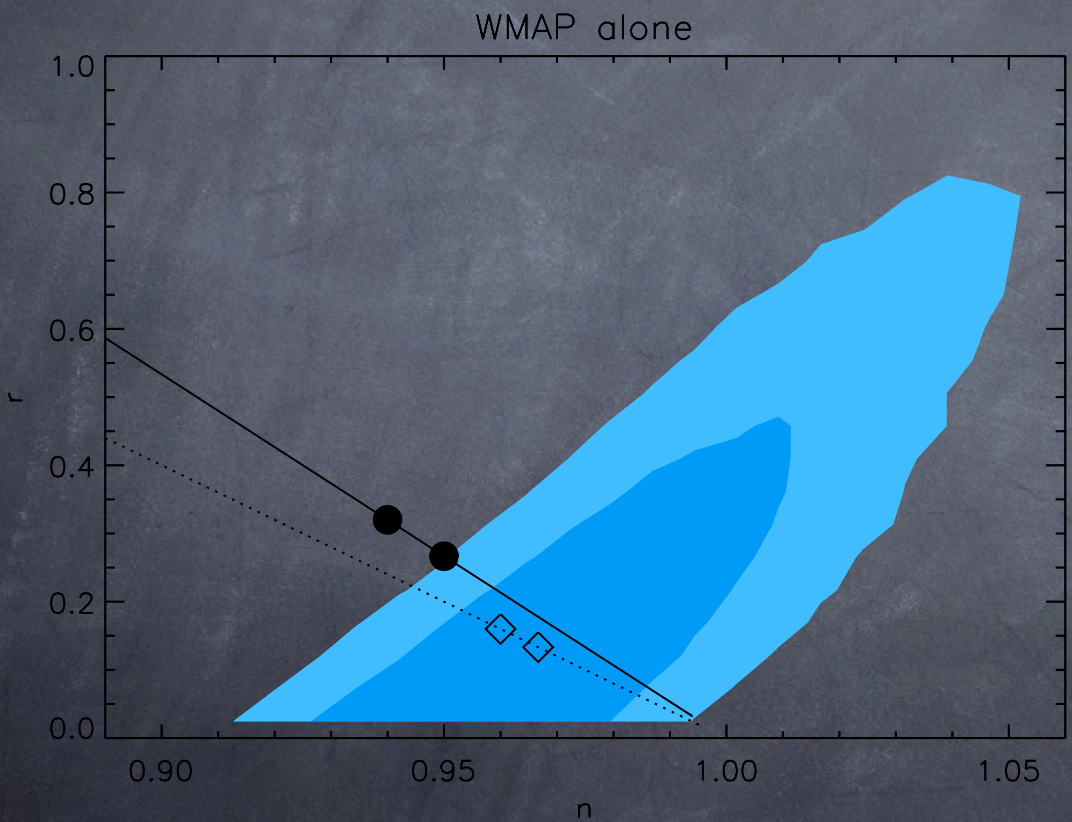
Nside = 16, 64, 256

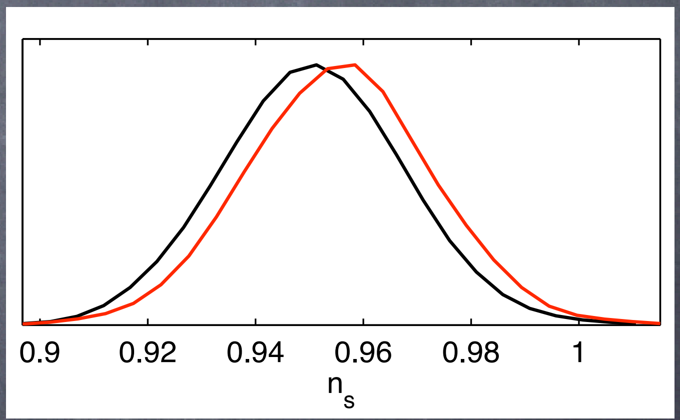


Looking Flat...

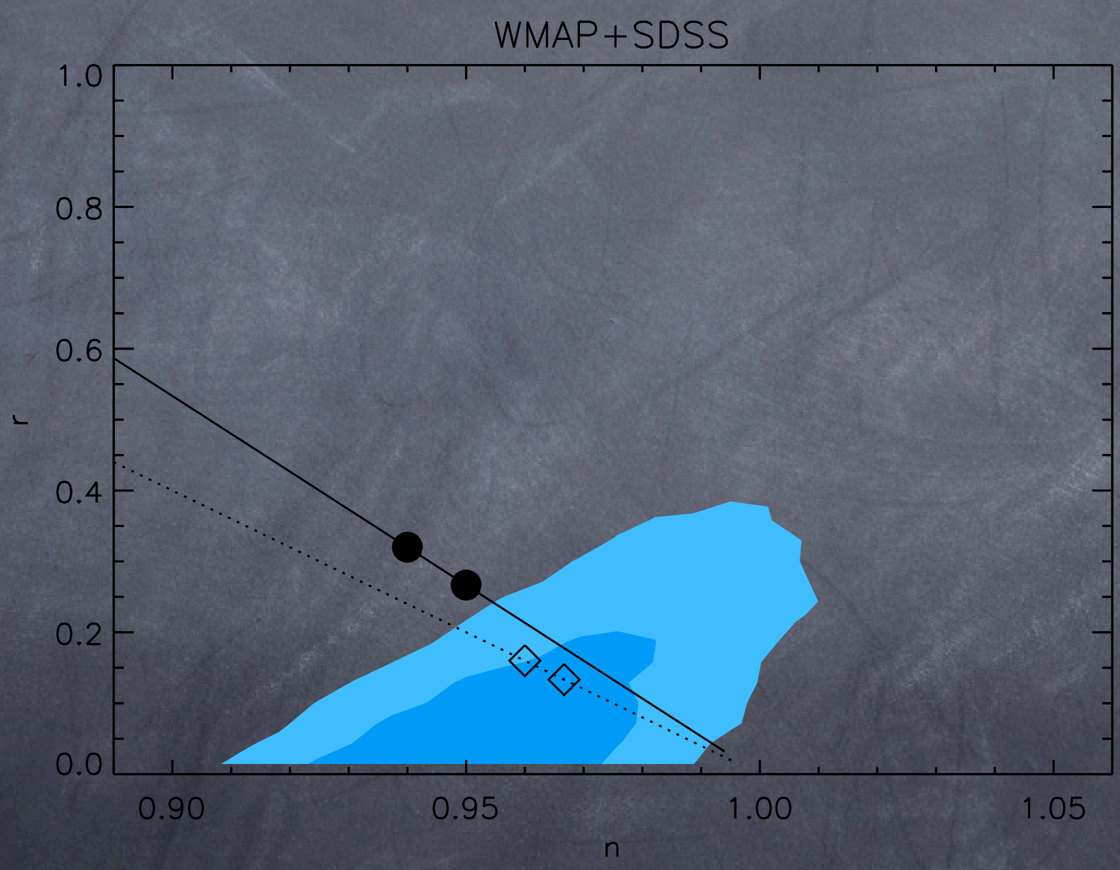


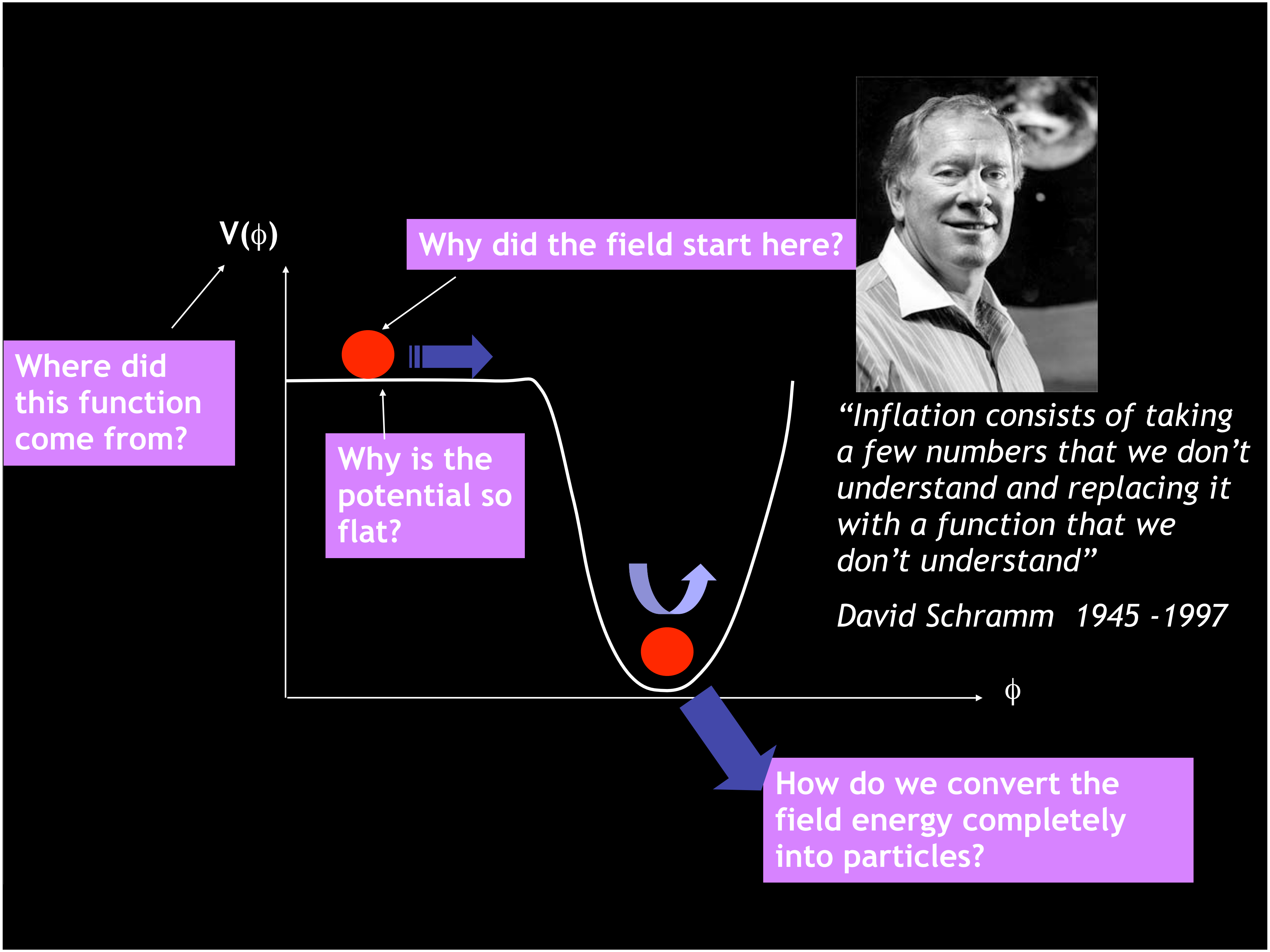
Deviations from Scale Invariance



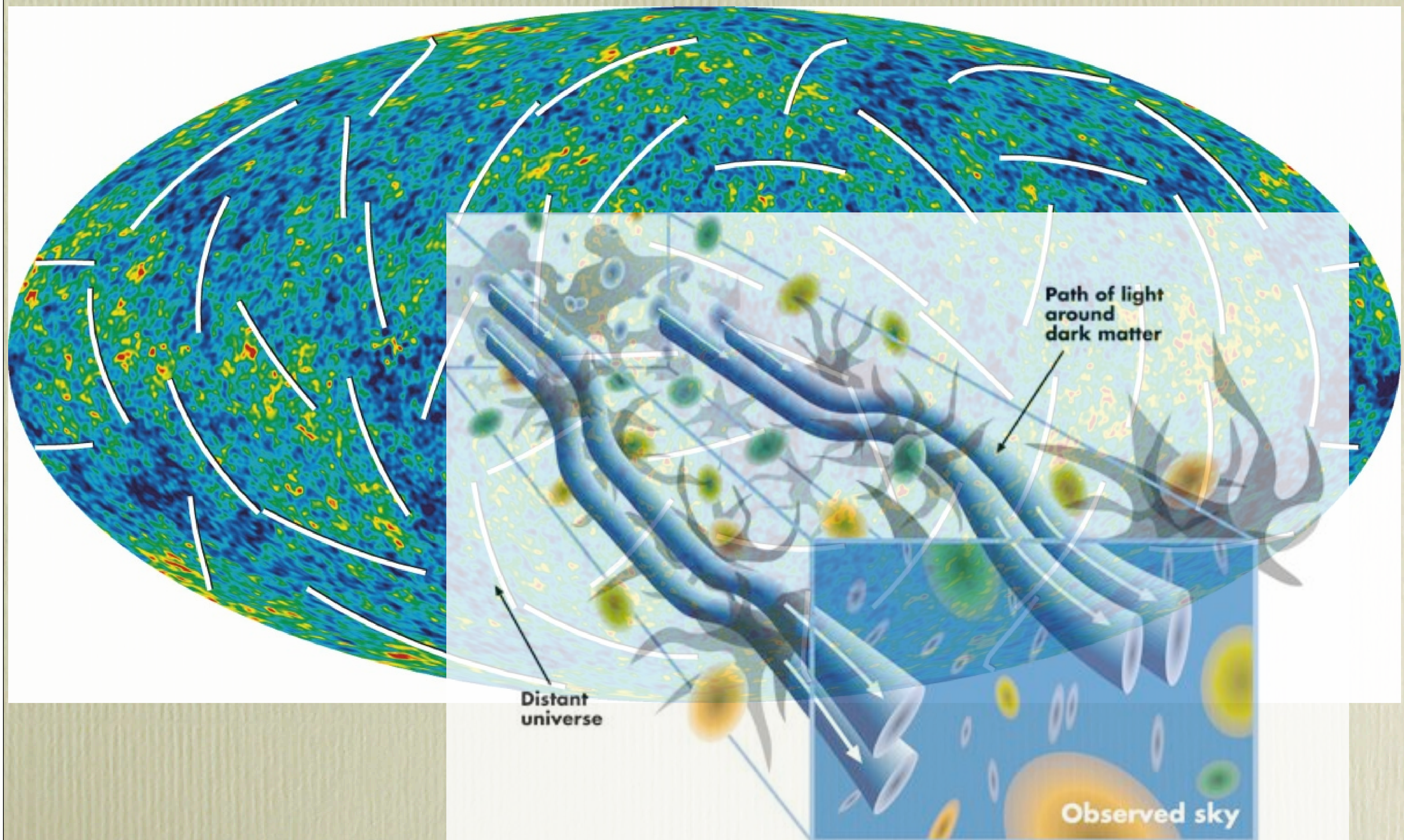


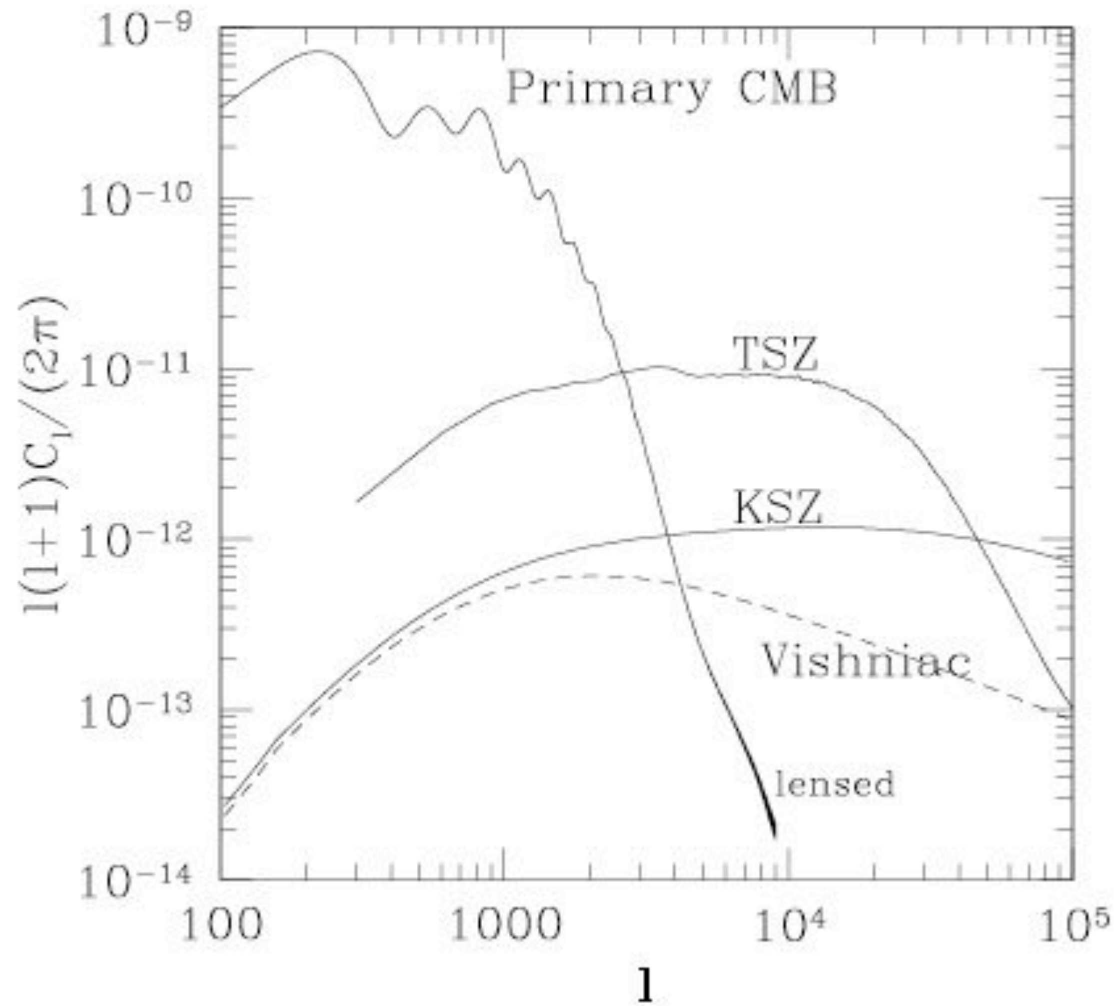
WMAP + LSS




V(ϕ)
Why did the field start here?
Where did this function come from?
Why is the potential so flat?
ϕ
How do we convert the field energy completely into particles?
"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand"
David Schramm 1945 -1997

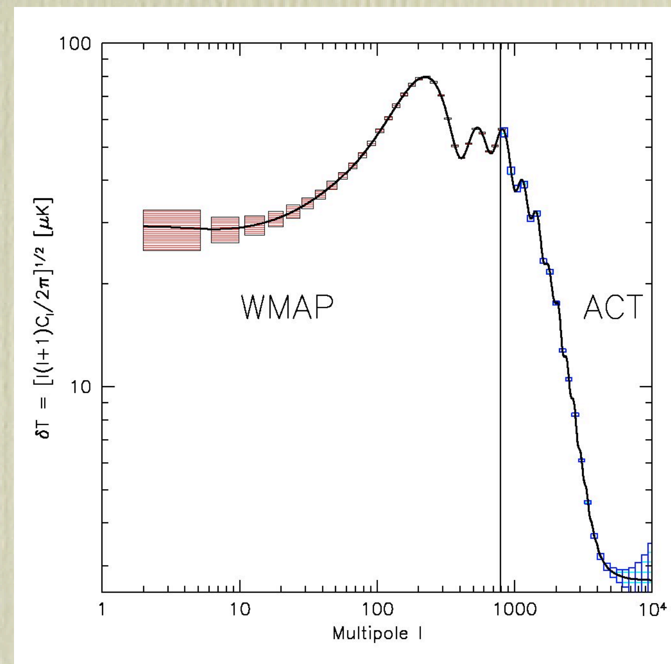
New Approach: CMB as a back light





Primary CMB
TSZ
KSZ
Vishniac
lensed
$l(l+1)C_l/(2\pi)$
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
100
1000
10^4
10^5
l

Atacama Cosmology Telescope



Conclusions

- CMB observations provide a "clean observational laboratory" for studying both the early universe and the basic properties of the universe today.
- Current data consistent with a simple cosmological model
- CMB a powerful tool for addressing fundamental questions in cosmology and physics