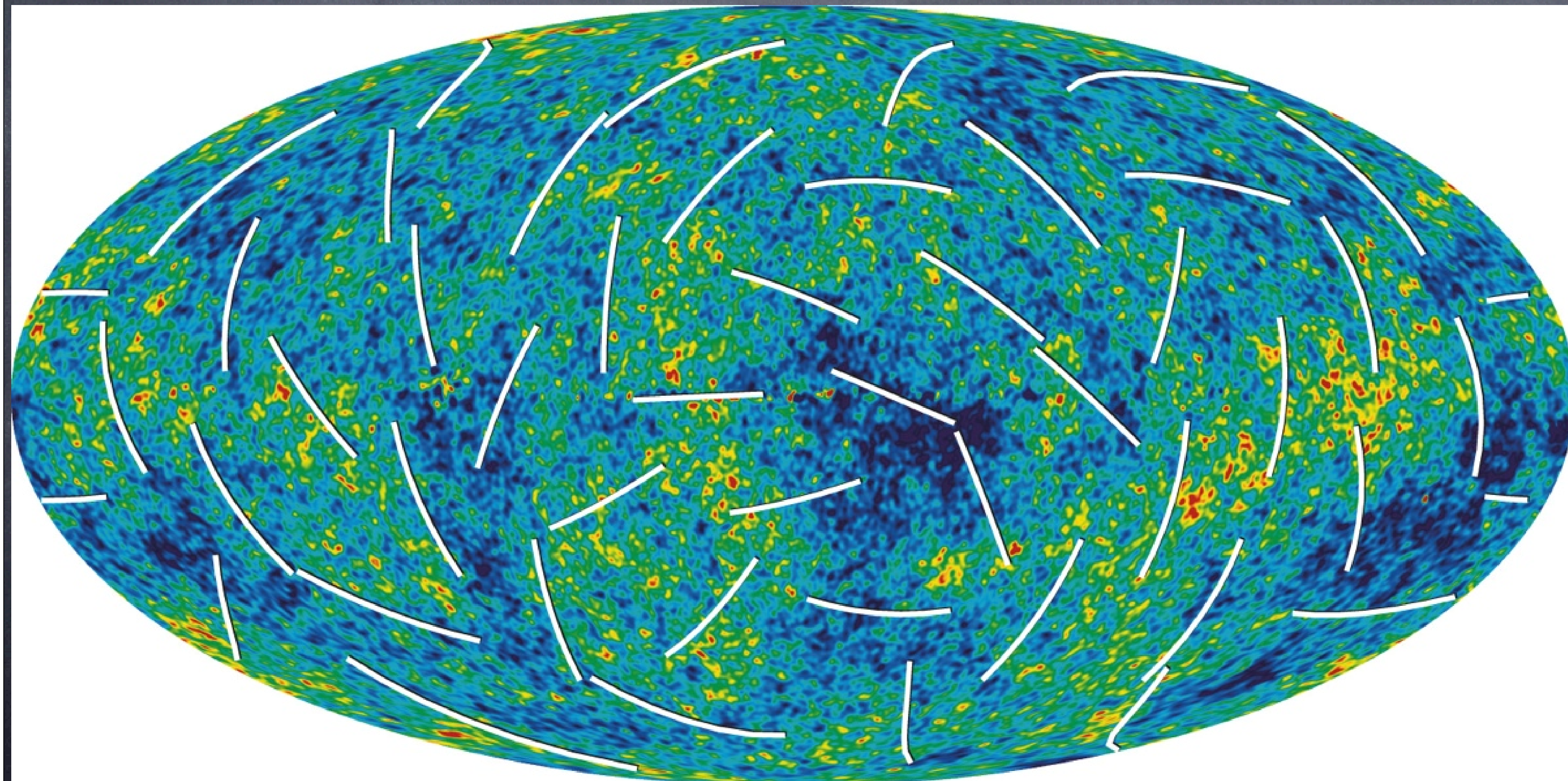
WMAP and Beyond

David Spergel



Cecilia Payne (1925) Thesis

The application of physics in the domain of astronomy constitutes a line of investigation that seems to possess almost unbounded possibilities. In the stars we examine matter in quantities and under conditions unattainable in the laboratory. The increase in scope is counterbalanced, however, by a serious limitation--the stars are not accessible to experiment, only to observation, and there is no very direct way to establish the validity of laws, deduced in the laboratory, when they are extrapolated to stellar conditions.

The verification of physical laws is not, however, the primary object of the application of physics to the stars. The astrophysicist is generally obliged to assume their validity in applying them to stellar conditions. Ultimately it may be that the consistency of the findings in different branches of astrophysics will form a basis for a more general verification of physical laws than can be attained in the laboratory; but at present, terrestrial physics must be the groundwork of the study of stellar conditions.

Requirements for Observational Physics

- Simple system
- Sensitive to Interesting Physics
- Precision Measurements of Signals

Examples: Binary Pulsar, CMB, Binary Inspiral,...

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

Science Team

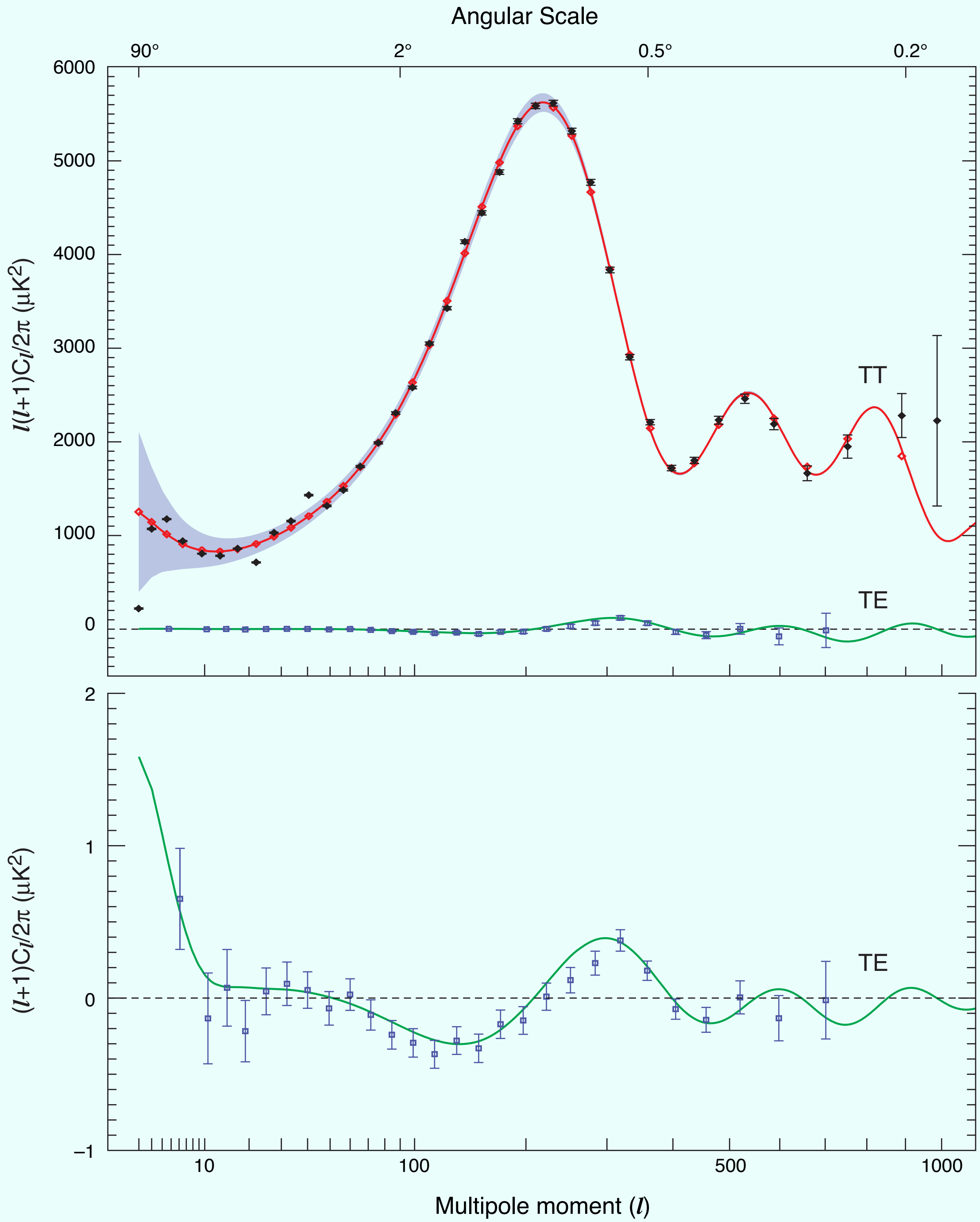
GODDARD

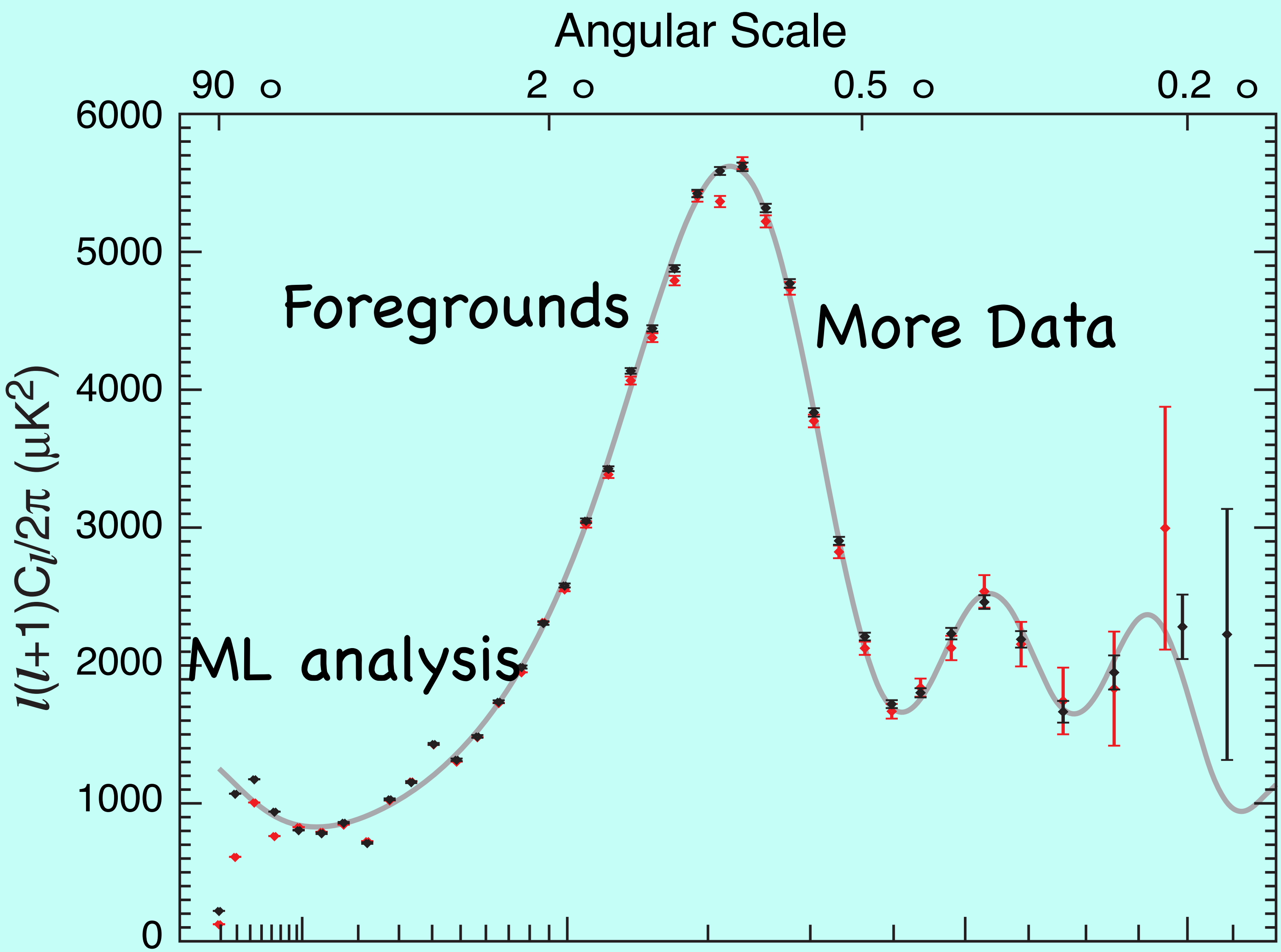
C.Bennett (JHU)
G. Hinshaw
R. Hill
A. Kogut
M. Limon
N. Odegard
J. Weiland
E. Wollack

Princeton

C. Barnes
R. Bean (Cornell)
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)


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
TT
TE
2
1
0
−1
$(l+1)C_l/2\pi$ (μK^2)
TE
10
100
500
1000
Multipole moment (l)

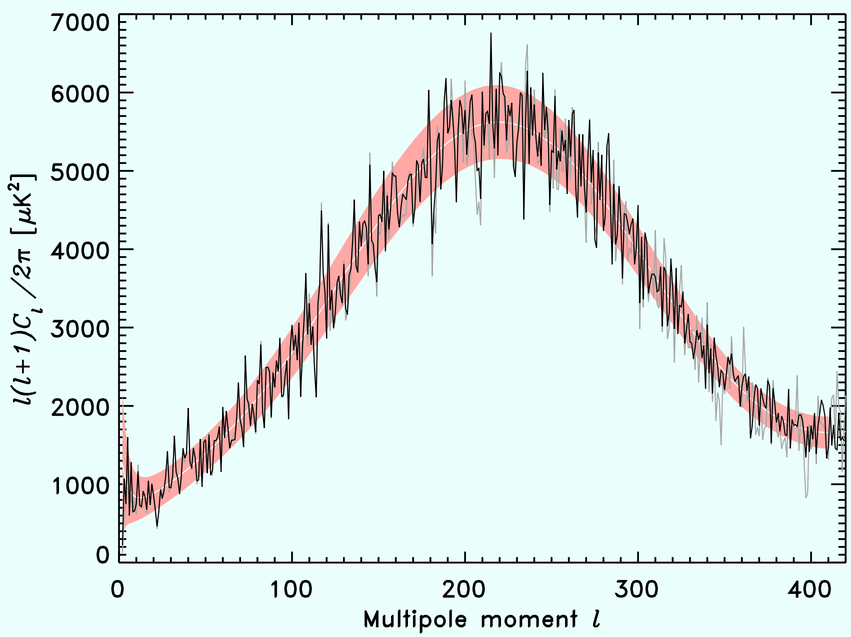


Angular Scale
90 o
2 o
0.5 o
0.2 o
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
Foregrounds
More Data
ML analysis

Model fits Data

A simple cosmological model with only 6 parameters fits the WMAP data

- At high l, errors have dropped by more than a factor of 3,   improves from 1.07/d.o.f. to 1.04/ d.o.f.
- Better beams
- Better foreground model
- Finer pixelization in map-making (0.1 -> 0.05 diameter pixels)



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

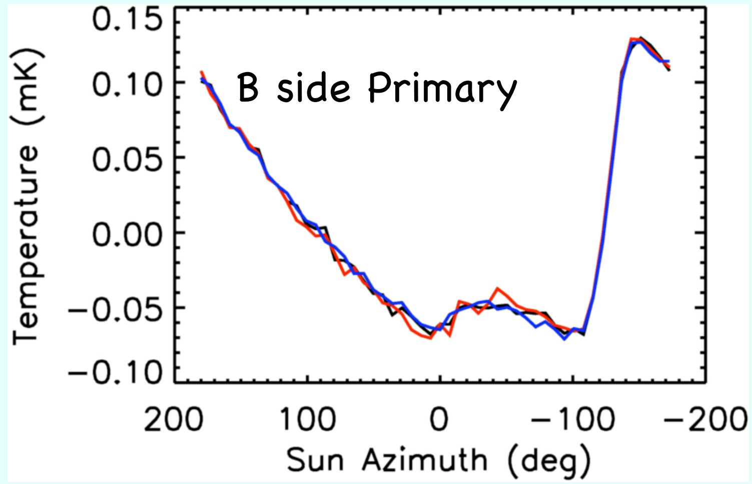
Improvements in Data Analysis

Beams

$$d(t) = G(t)M(t,p)[B(p,t) \otimes x(p)] + n(t)$$

Gain

Measurement Matrix

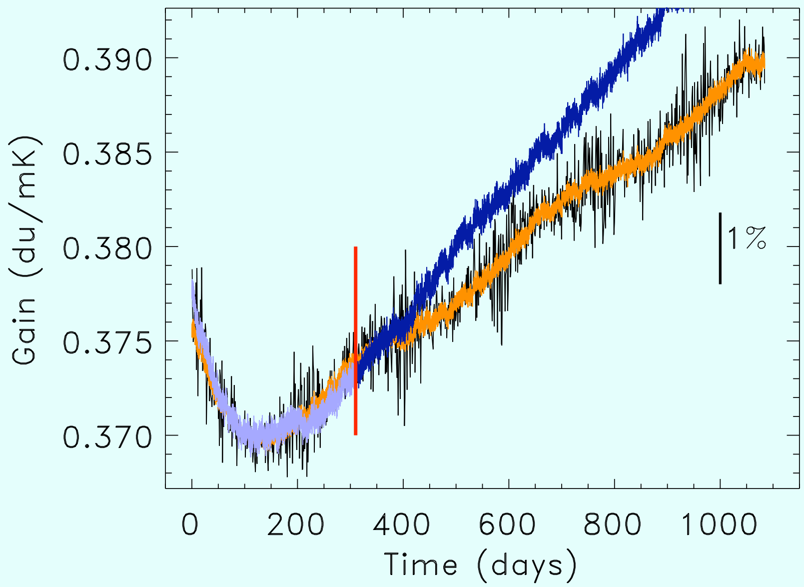


$$< n(t)n(t+\Delta t) >= N(\Delta t, t)$$

WMAP design is a success: N and B are stationary!

Gain Model

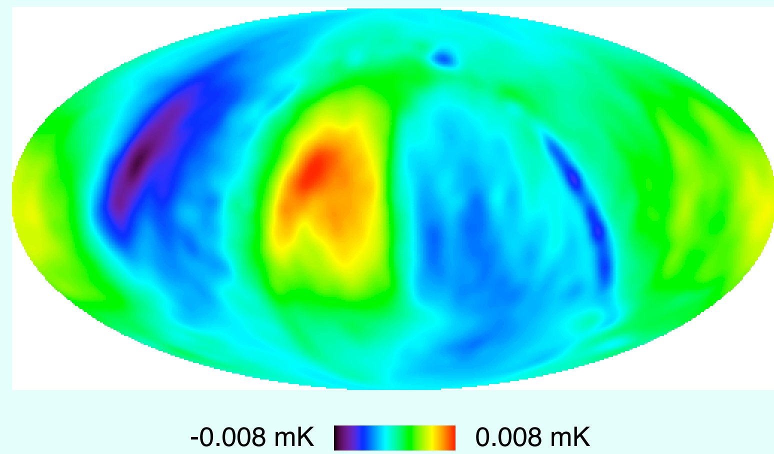
- Gain model now include RXB temperature and FPA temperature



$$G = \alpha \frac{\overline{V} - V_0 - \beta(T_{\rm RXB} - 290)}{T_{\rm FPA} - T_0},$$

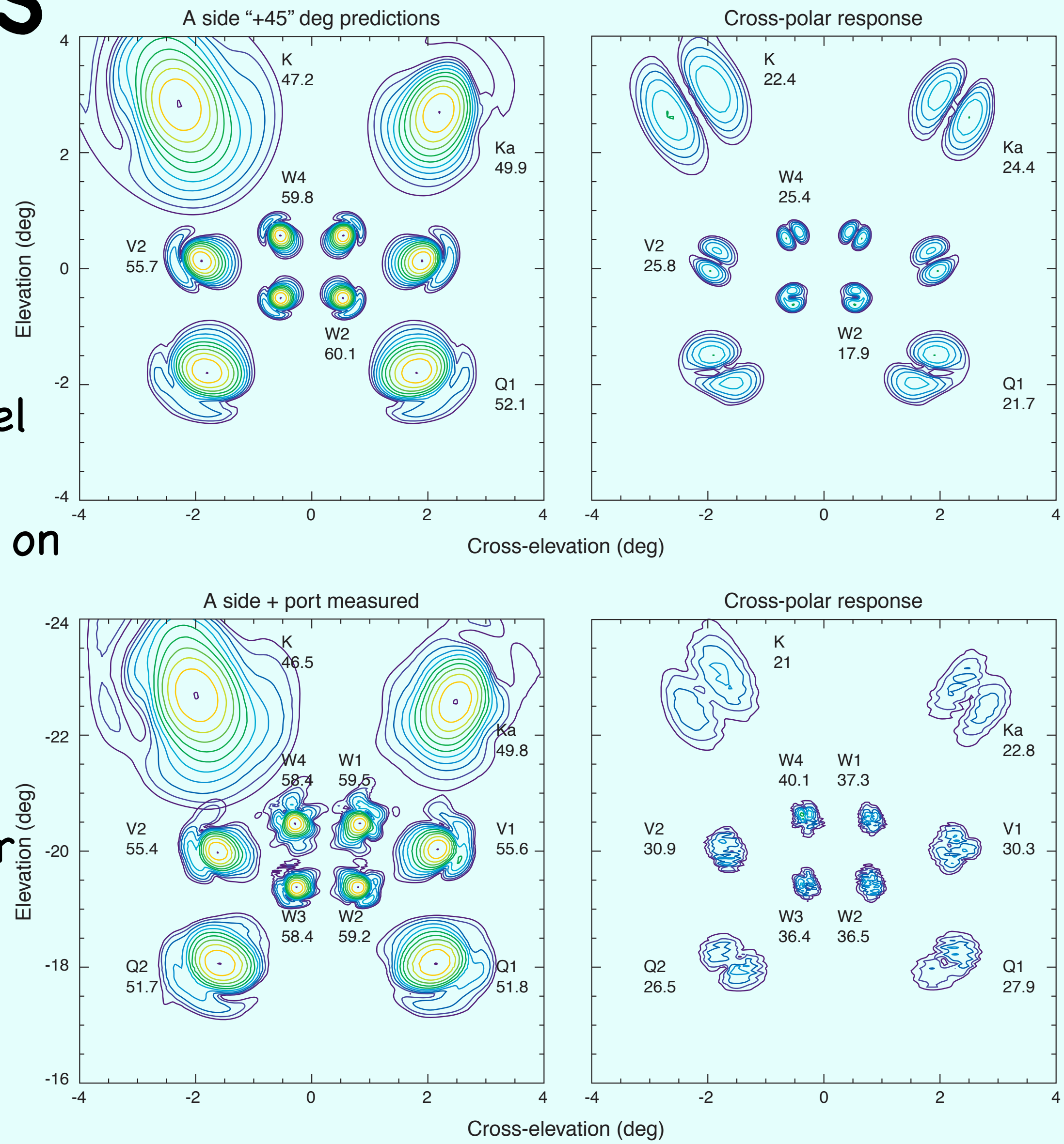
Text

Changes due to new Gain



Beams

- Determined from 6 seasons of Jupiter observations
- Full physical optics model (DADRA code) of beams using 122 fourier modes on primary and 30 fourier modes on secondary
- V and W band window functions are 1.5% lower between l=200-600



Map Making

Improved Measurement Model

$$\mathbf{d_1} = (1 + x_{\rm im})(\mathbf{i}(p_{\rm A}) + \mathbf{q}(p_{\rm A})\cos 2\gamma_{\rm A} + \mathbf{u}(p_{\rm A})\sin 2\gamma_{\rm A} + \mathbf{s}(p_{\rm A})) + (1 - x_{\rm im})(-\mathbf{i}(p_{\rm B}) - \mathbf{q}(p_{\rm B})\cos 2\gamma_{\rm B} - \mathbf{u}(p_{\rm B})\sin 2\gamma_{\rm B} - \mathbf{s}(p_{\rm B}))$$

Text

Loss Imbalance

Band Pass Mismatch

Noise Filtering

$$\tilde{\mathbf{t}}_0 = \mathbf{M}^T\mathbf{N}^{-1}\mathbf{d} = \mathbf{M}^T\mathbf{N}^{-1}\mathbf{M}\mathbf{t} = \mathbf{\Sigma}^{-1}\mathbf{t}$$

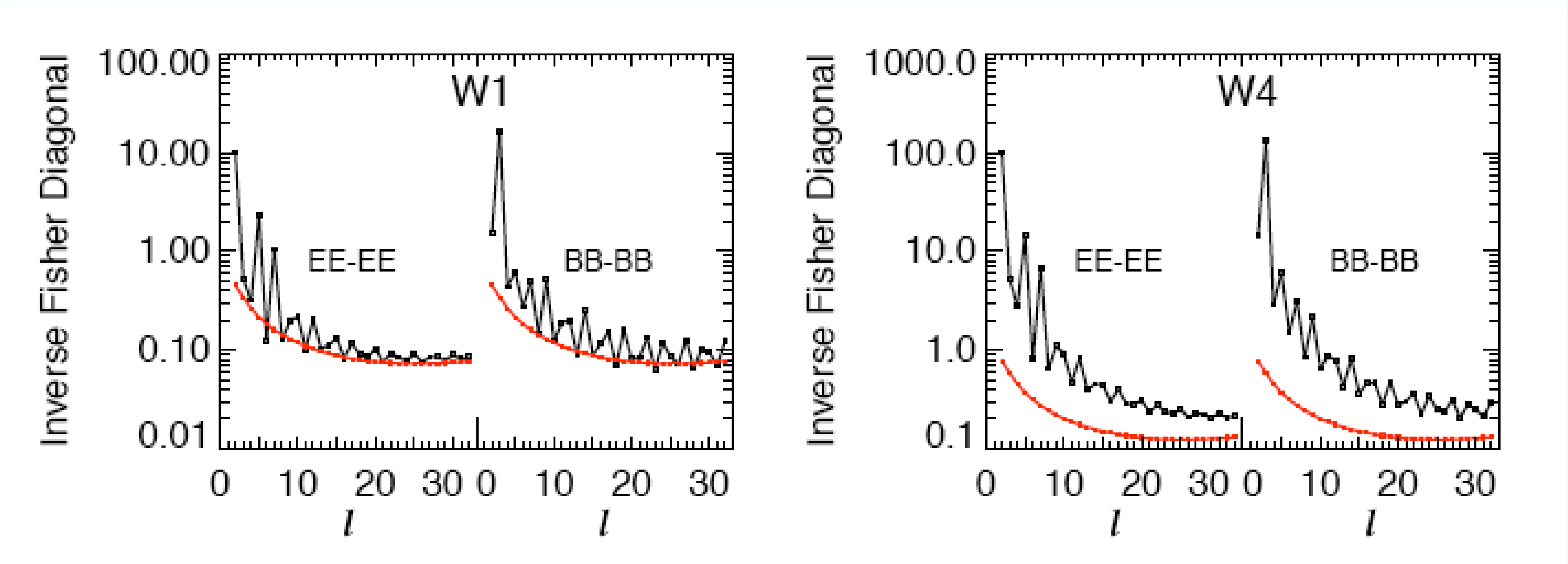
solved iterative by CG methods with preconditioner

Pixel Noise Matrix

$$\mathbf{\Sigma}^{-1} = \mathbf{M}^T\mathbf{N}^{-1}\mathbf{M} = \Sigma^{-1}(p_1,p_2) = \sum_{t_1,t_2} M(t_1,p_1)N^{-1}(t_1-t_2)M(t_2,p_2),$$

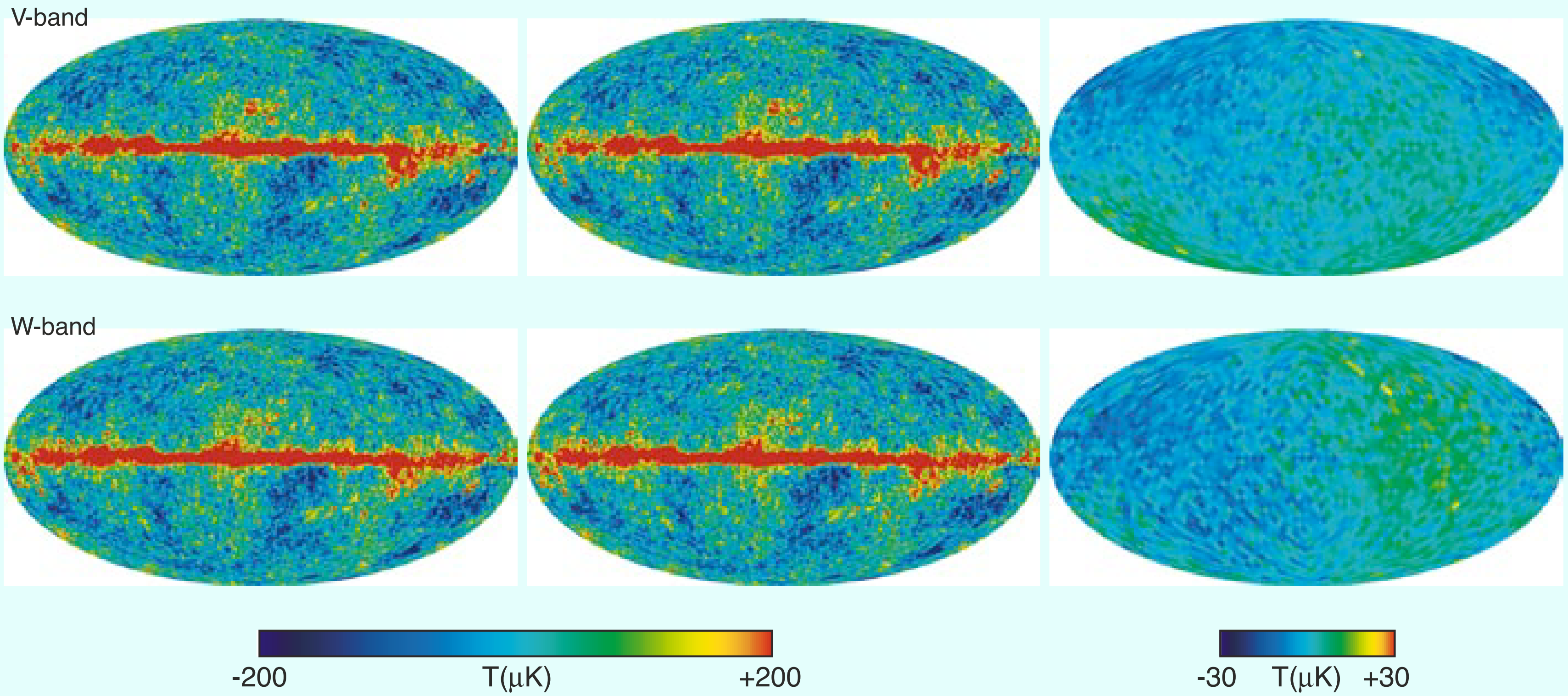
Projecting Loss Imbalance:

$$\widetilde{\mathbf{\Sigma}}^{-1} = \mathbf{\Sigma}^{-1} - \frac{\mathbf{\Sigma}^{-1}\mathbf{v}\otimes\mathbf{\Sigma}^{-1}\mathbf{v}}{\mathbf{v}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{v}},$$



Note l=2 EE and l=3 BB errors are large!

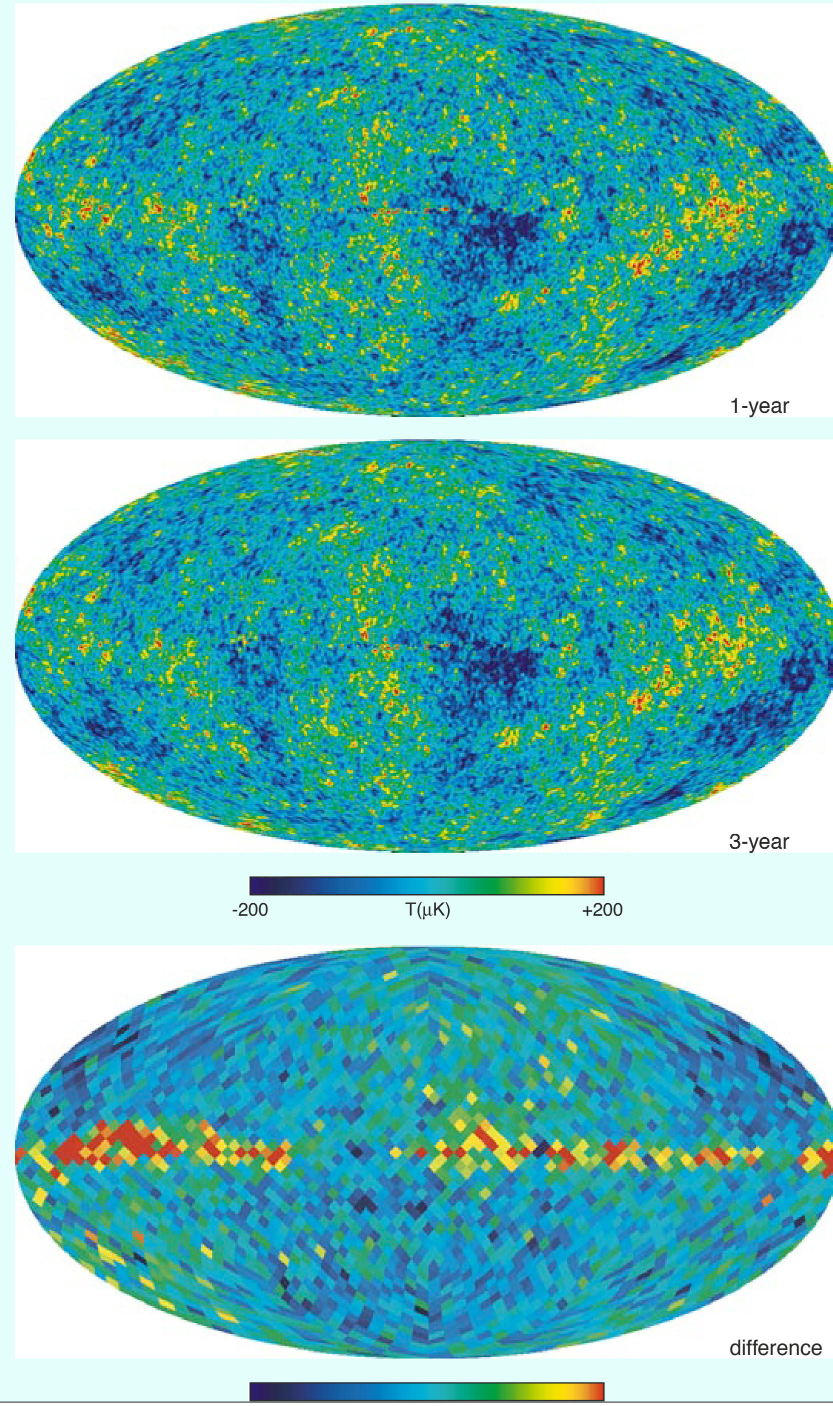
Temperature Maps



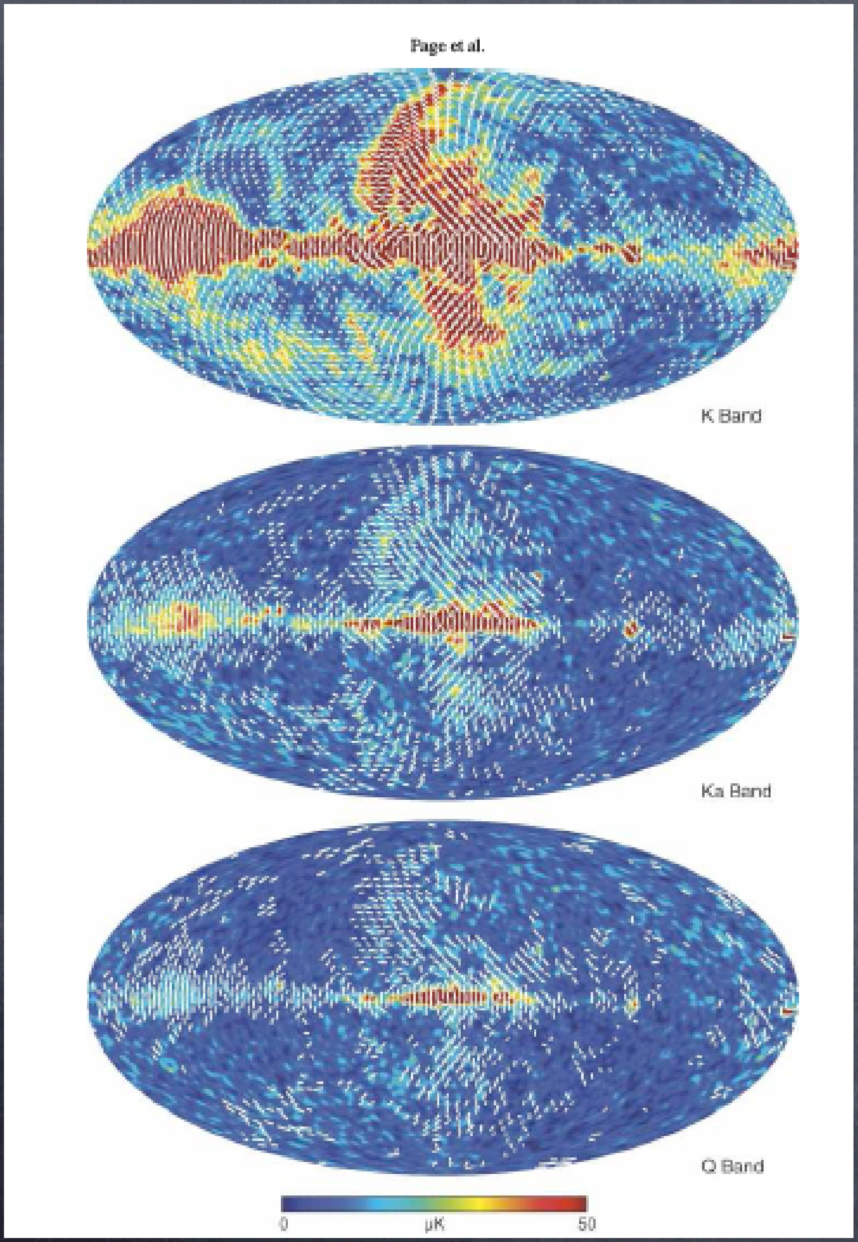
ILC Map

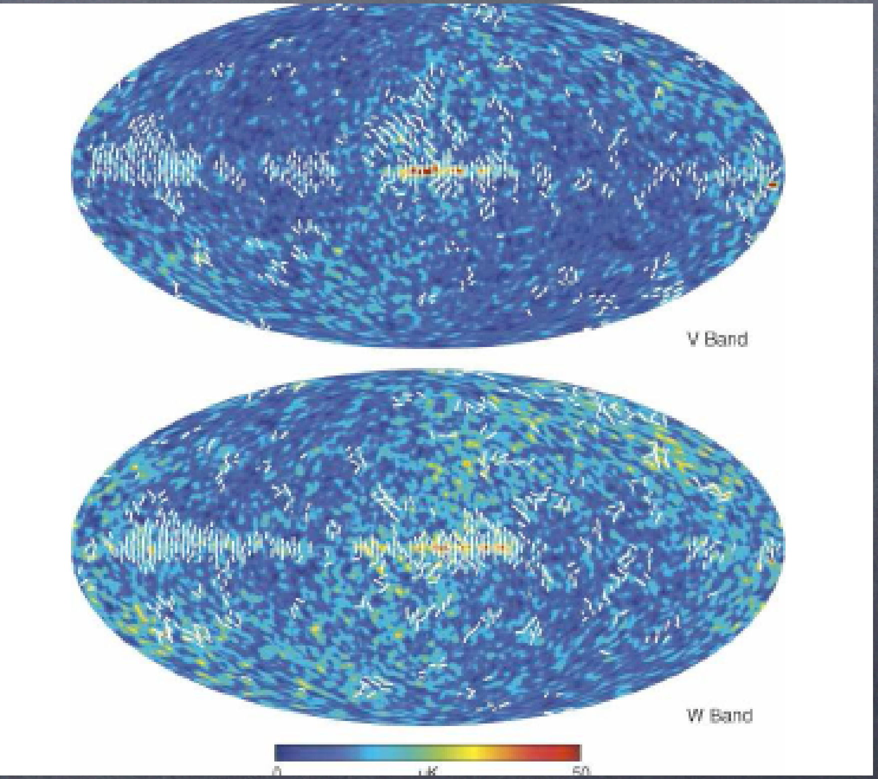
Since our 'press release" map was being used extensively for science, we have attempted to characterize the uncertainties.

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

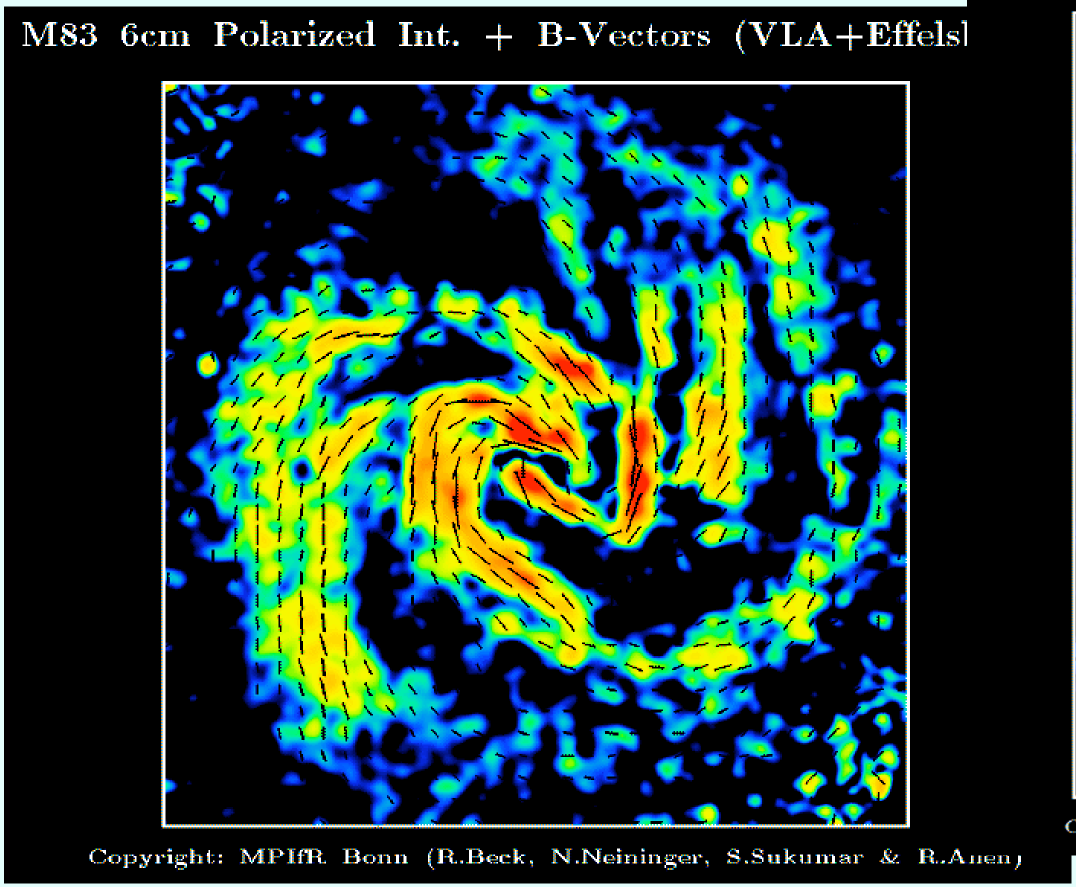


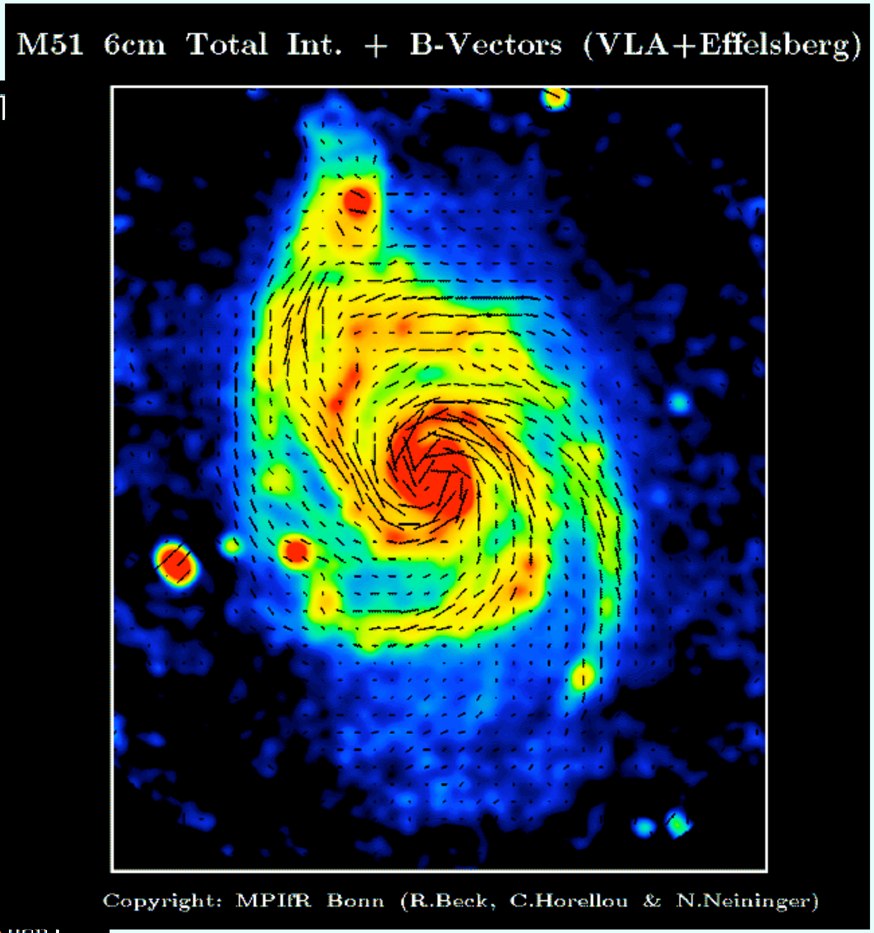
Polarization Maps



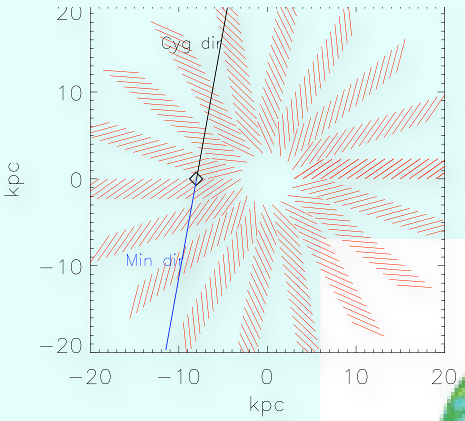


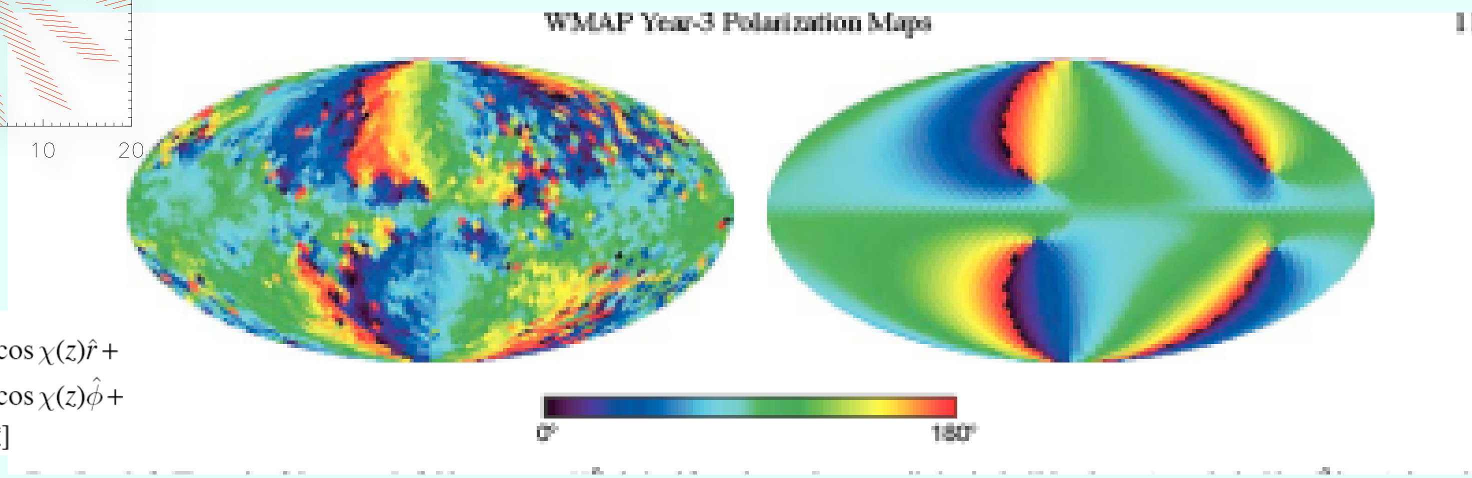
Magnetic Field Structure in external galaxies exhibit spiral structure



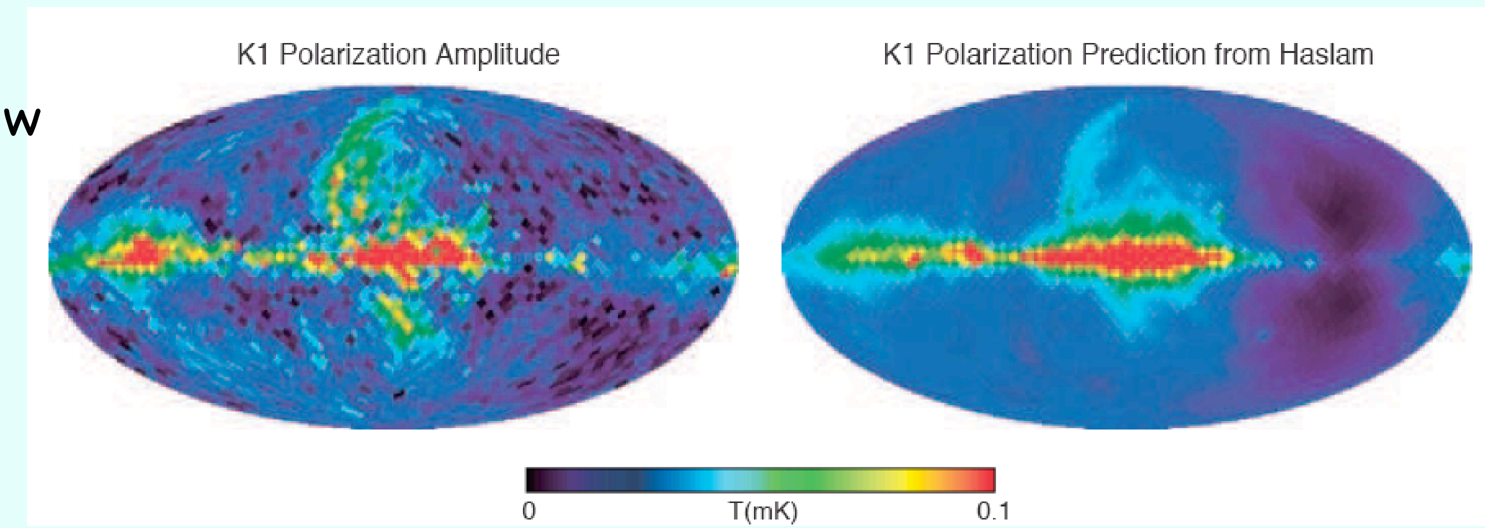


Same bisymmetric spiral pattern is a good global fit to the field structure

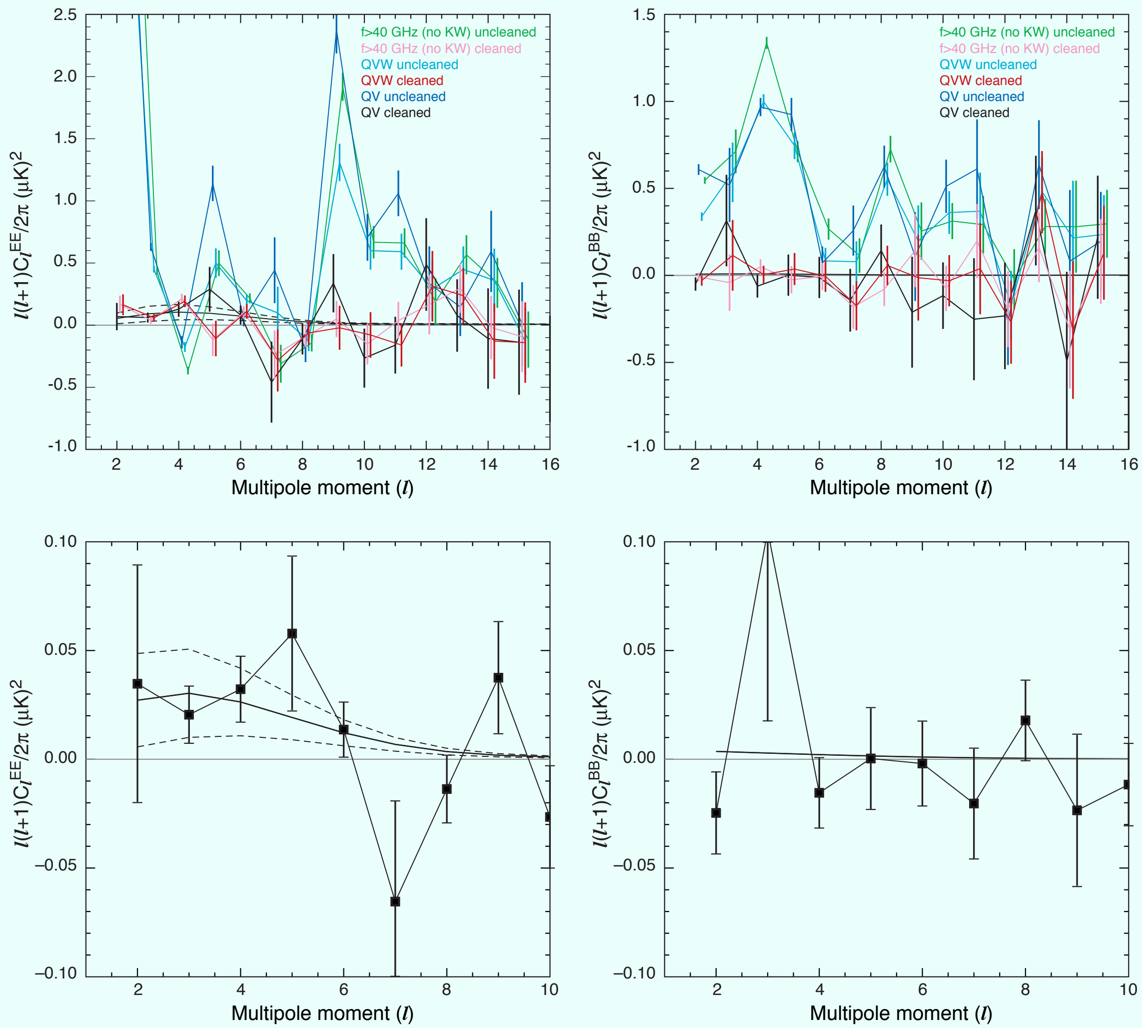




$$\mathbf{B}(r,\phi,z) = B_0[\cos\psi(r)\cos\chi(z)\hat{r} + \sin\psi(r)\cos\chi(z)\hat{\phi} + \sin\chi(z)\hat{z}]$$



Deviations show regions with shallower spectra


f>40 GHz (no KW) uncleaned
f>40 GHz (no KW) cleaned
QVW uncleaned
QVW cleaned
QV uncleaned
QV cleaned
l(l+1)C_l^EE/2π (μK)^2
l(l+1)C_l^BB/2π (μK)^2
Multipole moment (l)

Optical Depth Measurement is Robust

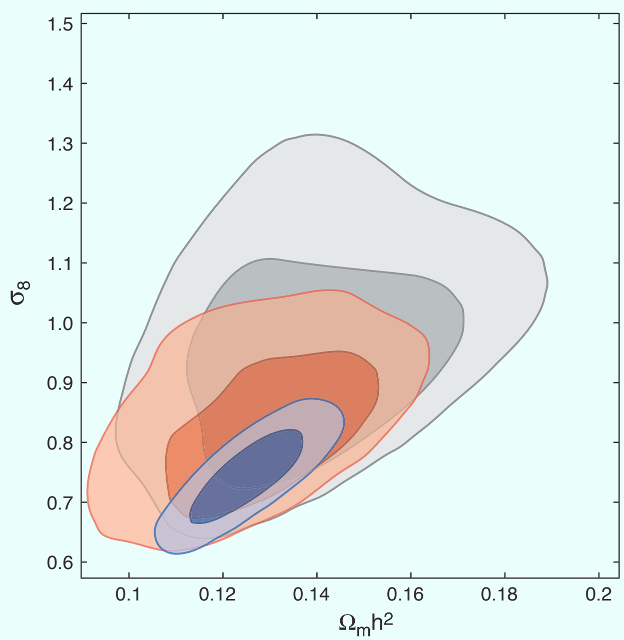
TABLE 9
OPTICAL DEPTH VS. DATA SELECTION

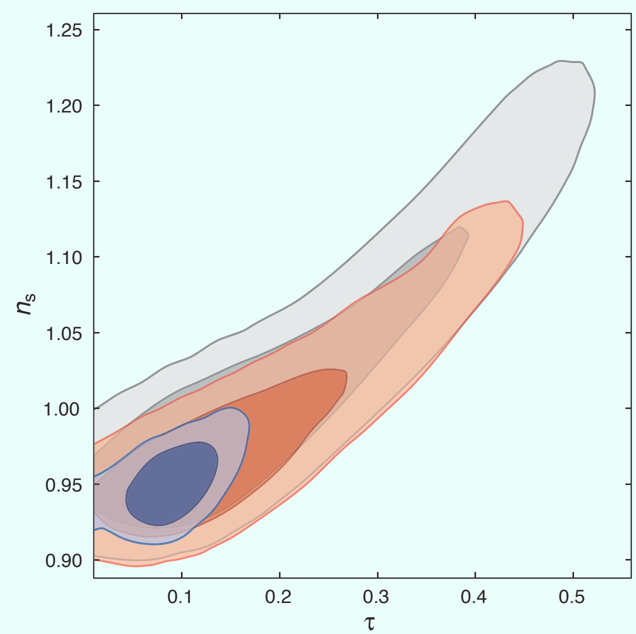
Combination	Exact EE Only	Exact EE & TE	Simple tau EE	Simple tau, no $\ell = 5, 7$
KaQV	0.111 ± 0.022	0.111 ± 0.022	...	...
Q	0.100 ± 0.044	0.082 ± 0.043	0.08 ± 0.03	0.085 ± 0.03
QV	0.100 ± 0.029	0.092 ± 0.029	0.110 ± 0.027	$0.085^{+0.045}_{-0.015}$
QV+VV	...	...	0.145 ± 0.03	$0.14^{+0.02}_{-0.06}$
V	0.089 ± 0.048	0.094 ± 0.043	$0.09^{+0.03}_{-0.07}$	$0.10^{+0.03}_{-0.07}$
QVW	0.110 ± 0.021	0.101 ± 0.023	0.090 ± 0.012	0.090 ± 0.015
KaQVW	0.107 ± 0.018	0.106 ± 0.019	0.095 ± 0.015	0.095 ± 0.015

We find the same optical depth value regardless of frequency choice. We use QV for the parameter estimation

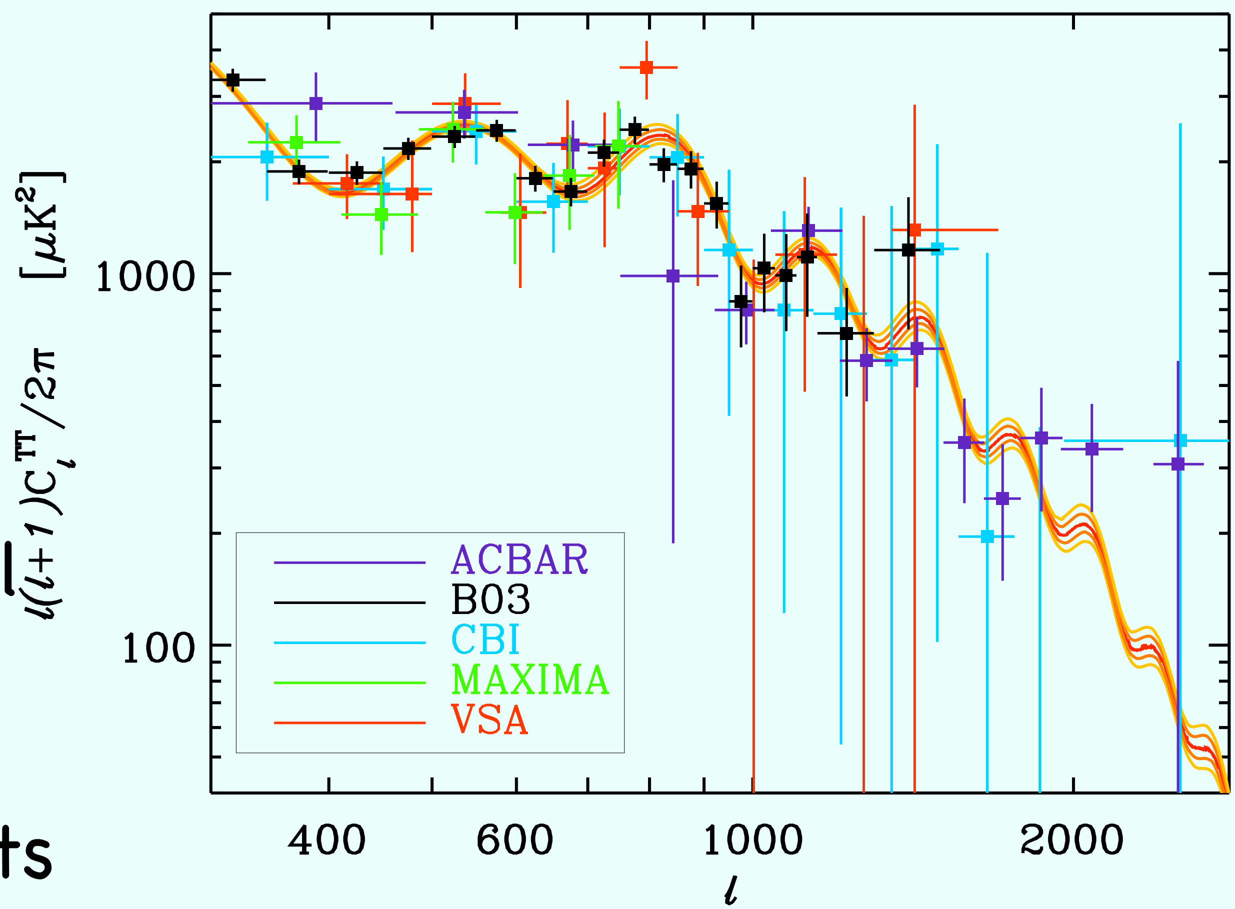
Improvement in Parameters

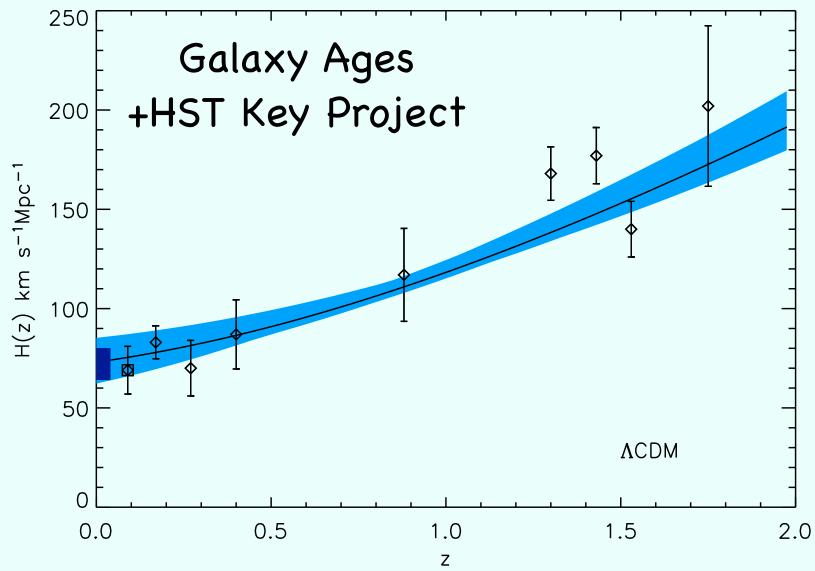
Parameter	First Year Mean	WMAPext Mean	Three Year Mean	First Year ML	WMAPext ML	Three Year ML
$100\Omega_b h^2$	$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08	2.30	2.21	2.22
$\Omega_m h^2$	$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009	0.145	0.138	0.128
H_0	72^{+5}_{-5}	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





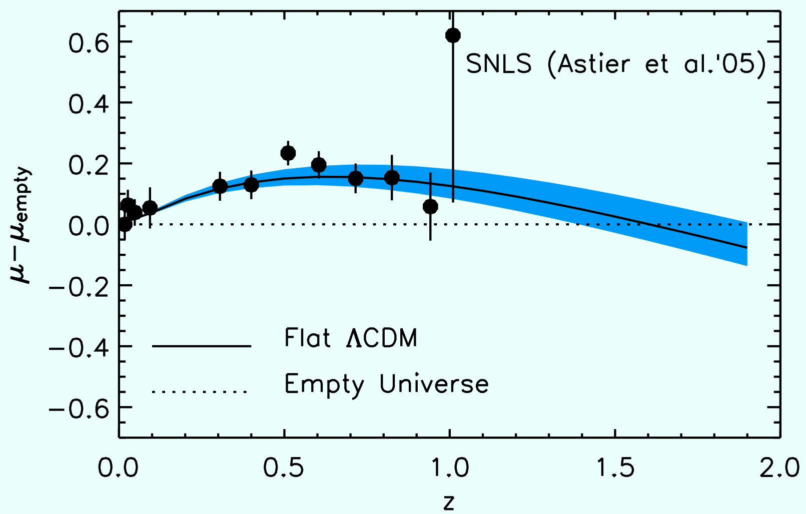
Same Model fits small scale CMB measurements

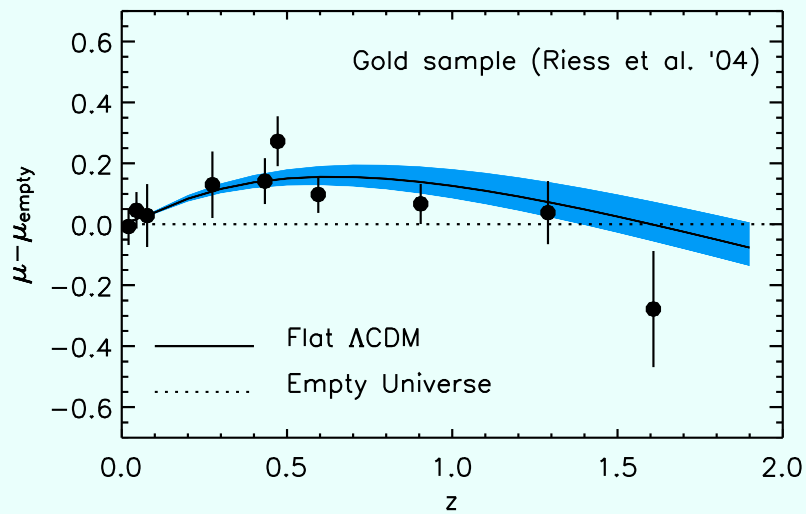




WMAP fits predict H(z)

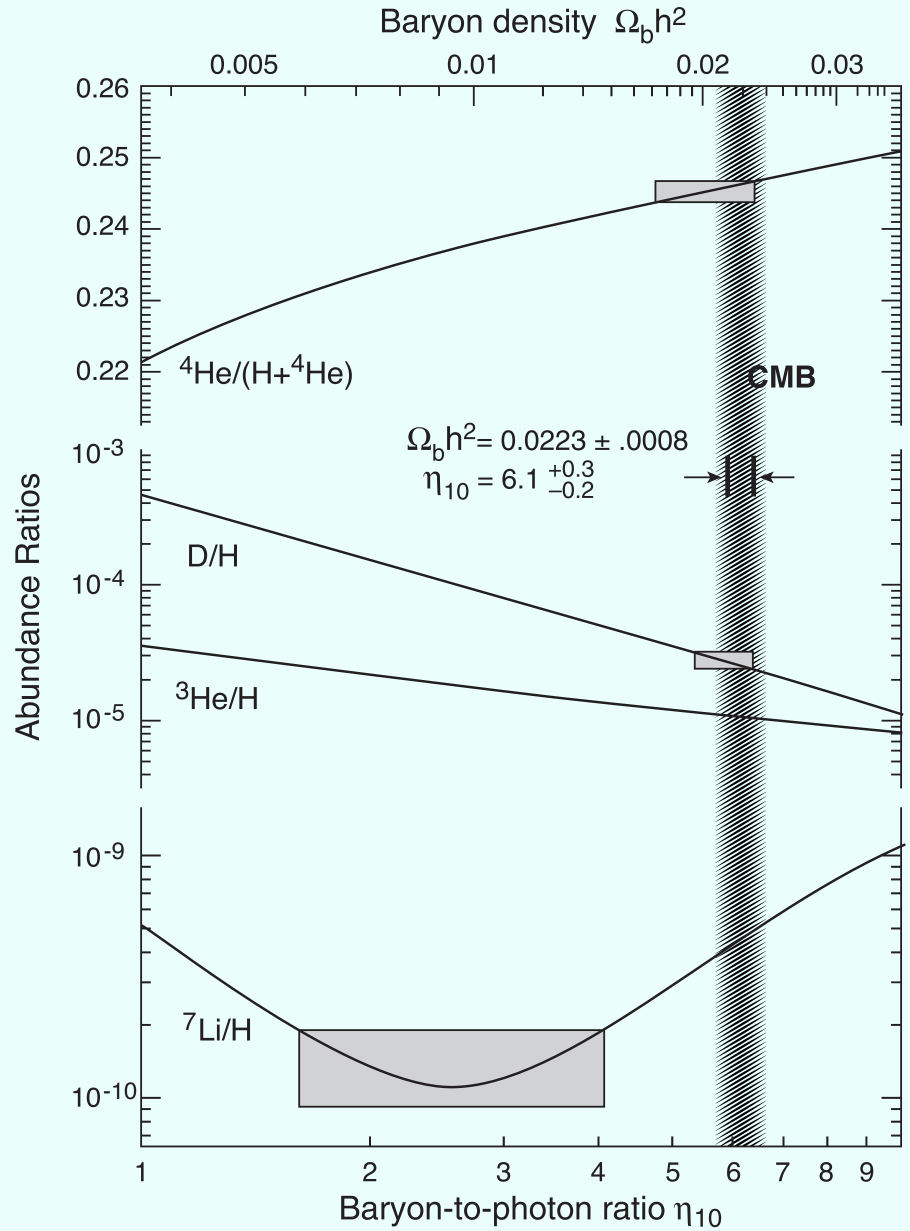
Supernovae

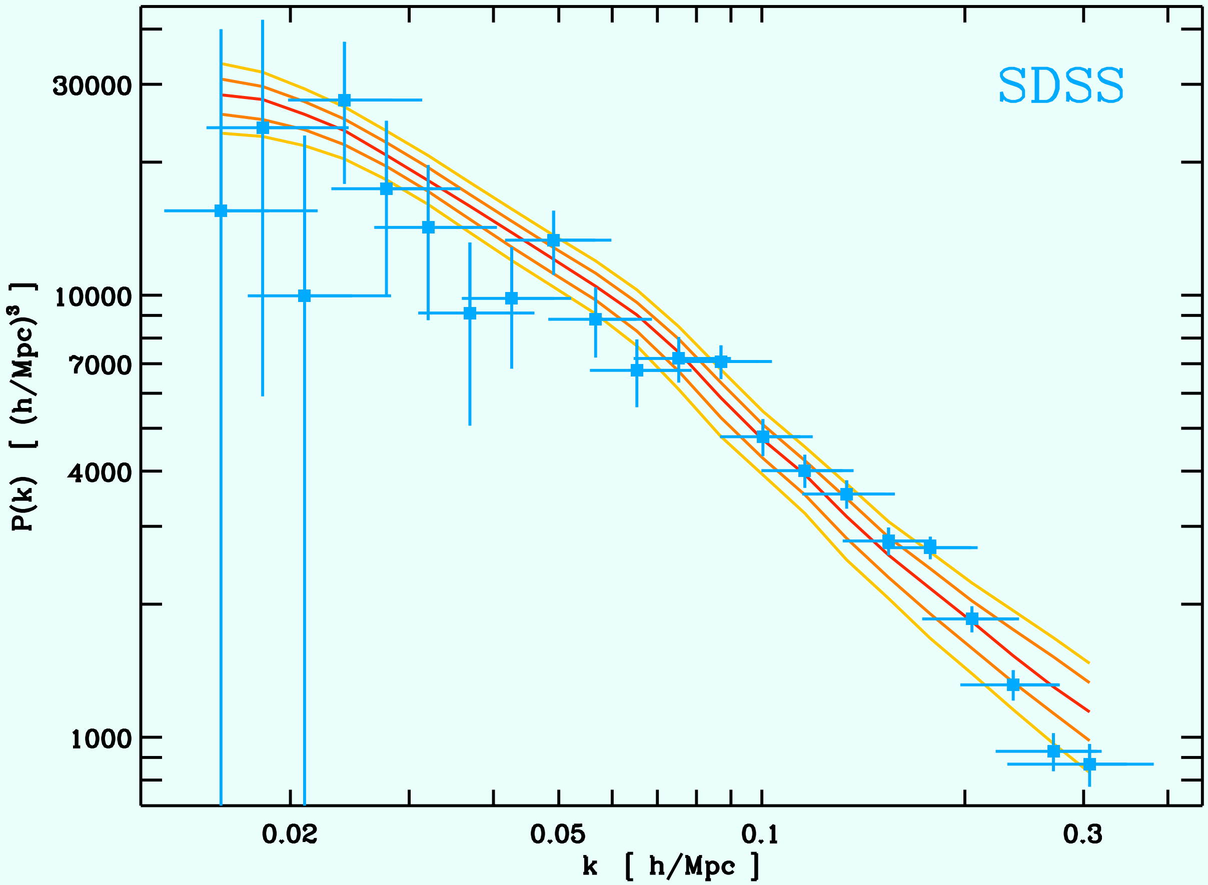




	CMB-based BBN prediction	Observed Value
$10^5 y_D^{FIT}$	$2.58^{+0.14}_{-0.13}$	1.6 - 4.0
$10^5 y_3$	$1.05 \pm 0.03 \pm 0.03$ (syst.)	$< 1.1 \pm 0.2$
Y_P	$0.24815 \pm 0.00033 \pm 0.0006$(syst.)	0.232 - 0.258
[Li]	2.64 ± 0.03	2.2 - 2.4

WMAP fits predict abundances





WMAP fits predict galaxy and mass distribution

Simple Model Fits!

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

New Questions

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

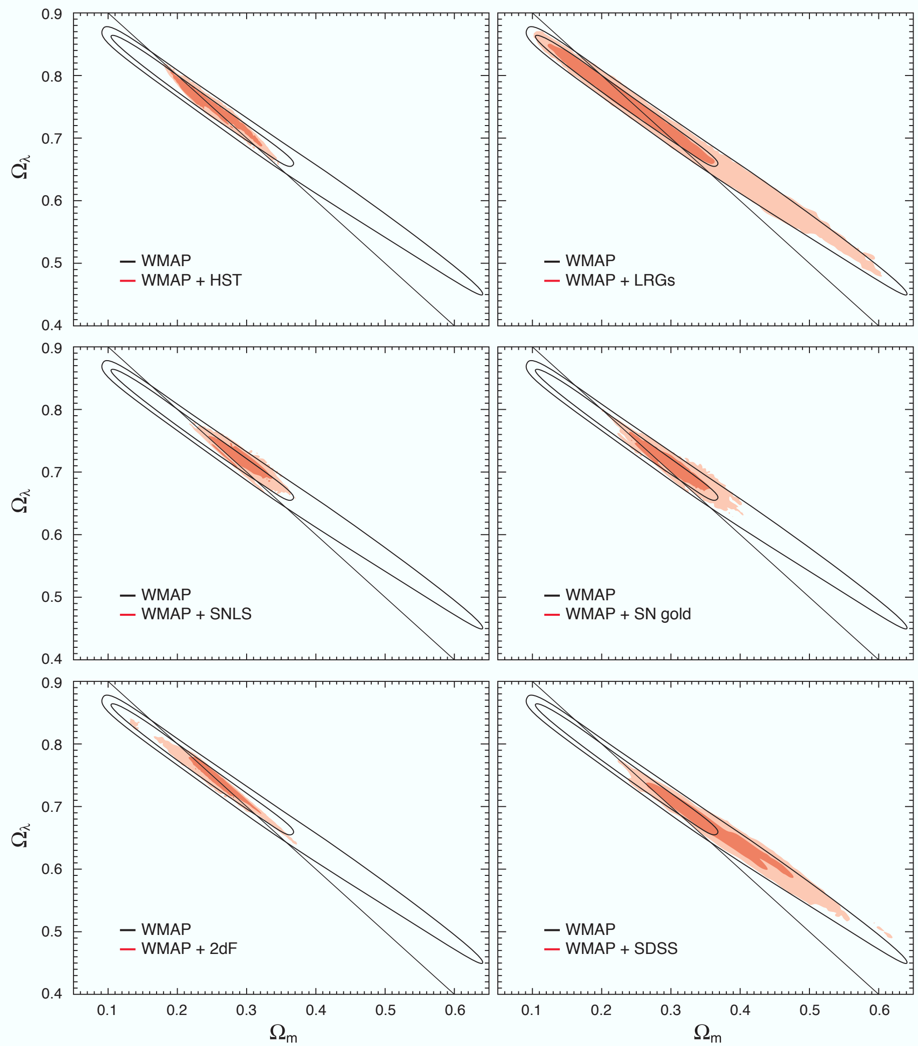
Inflationary Paradigm

- 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

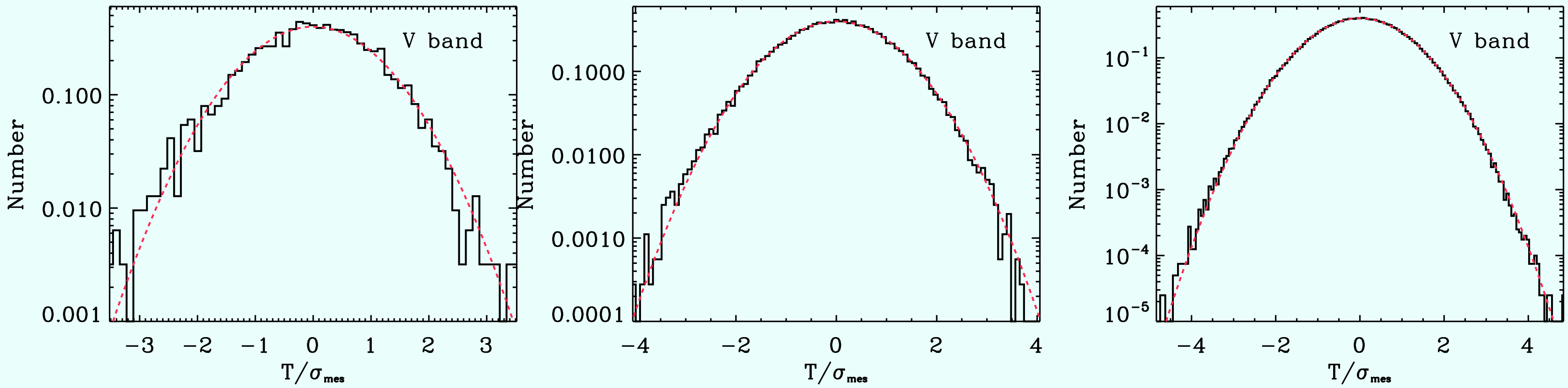
Inflationary Predictions

- 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)

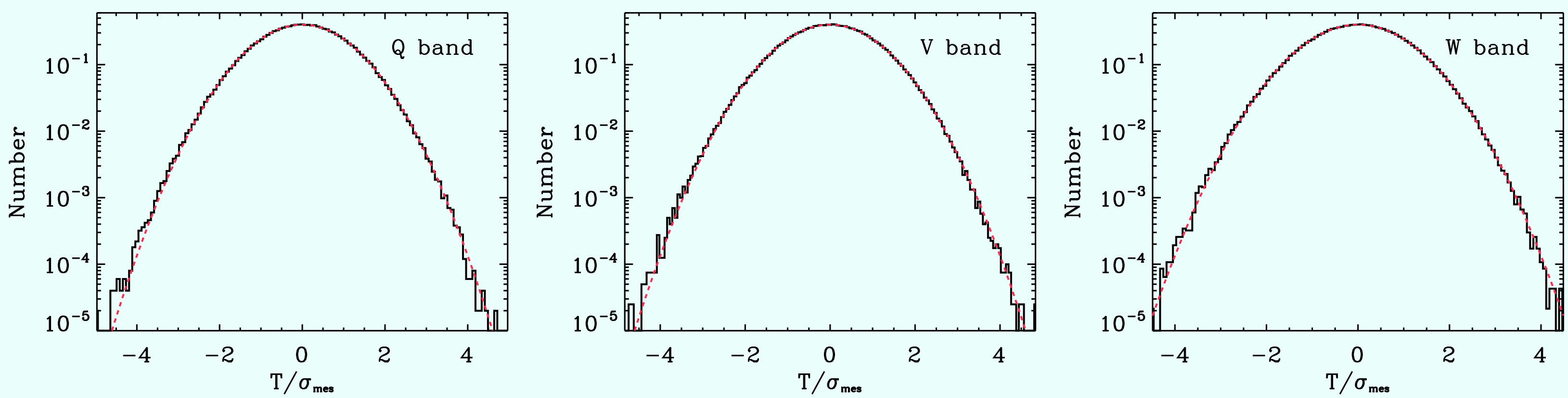
Looking Flat...



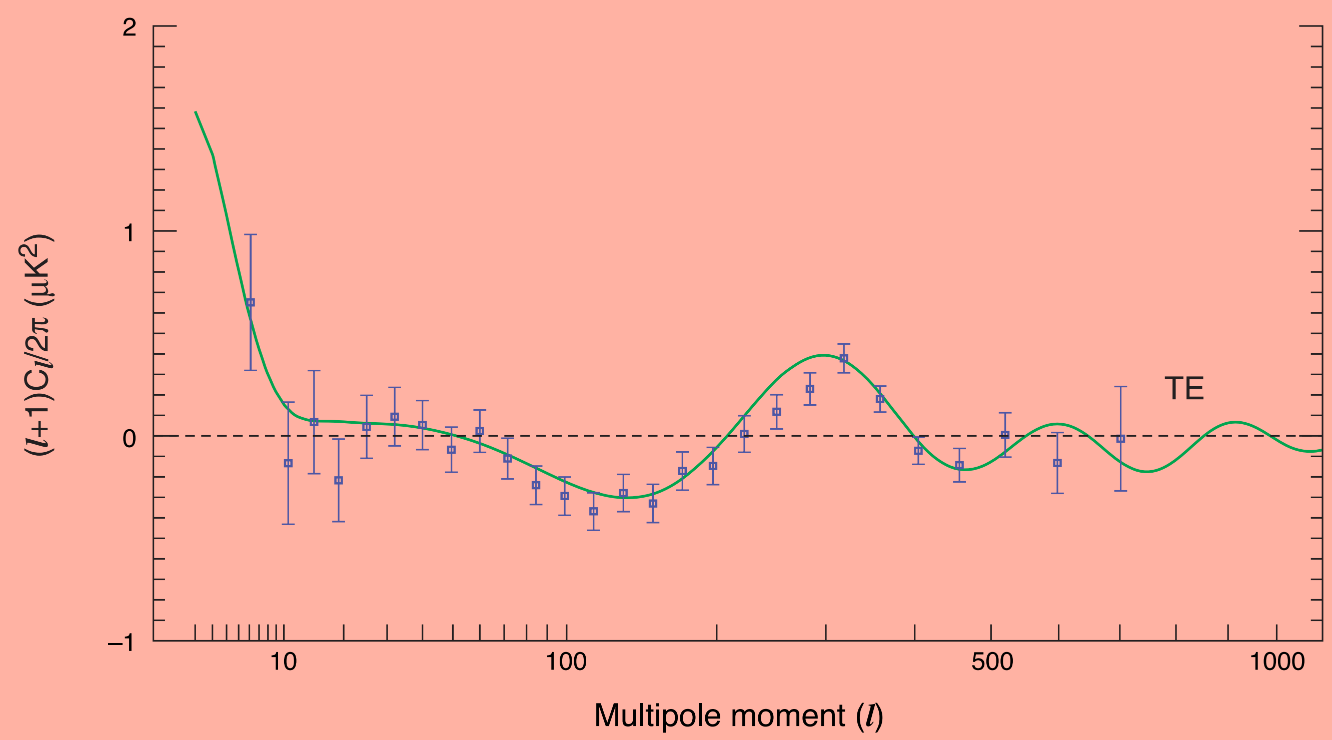
Looking Pretty Gaussian....



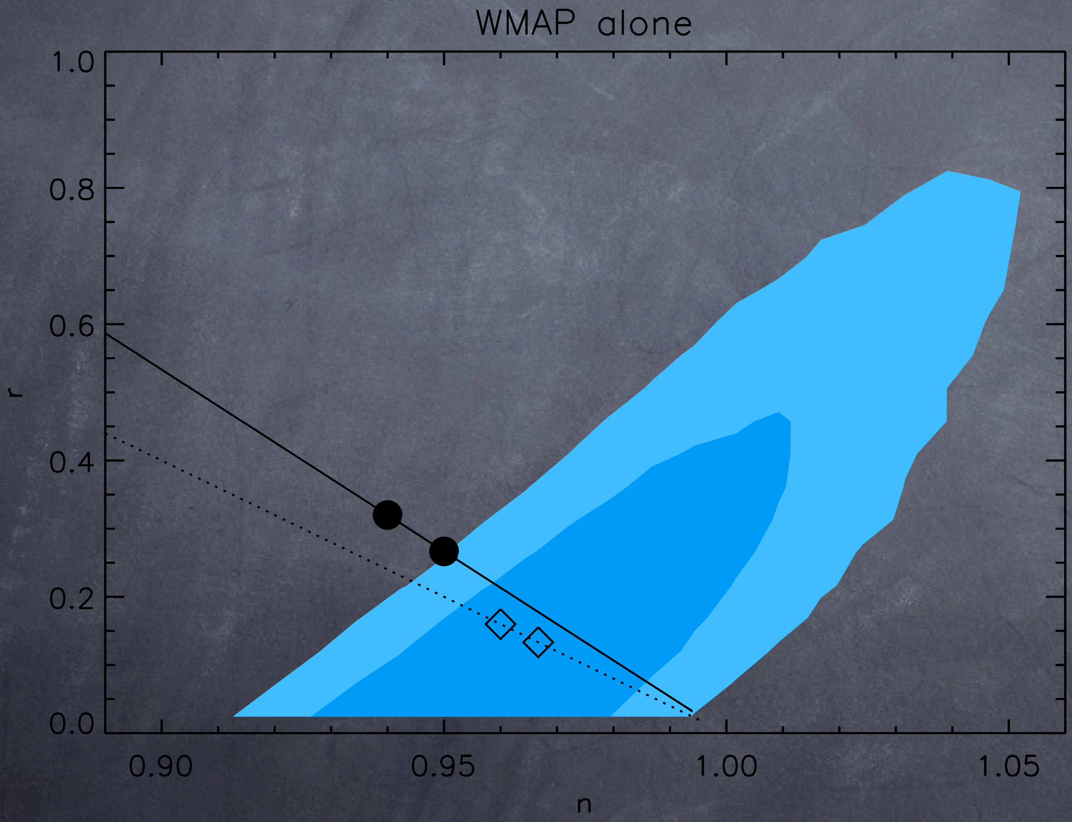
Nside = 16, 64, 256

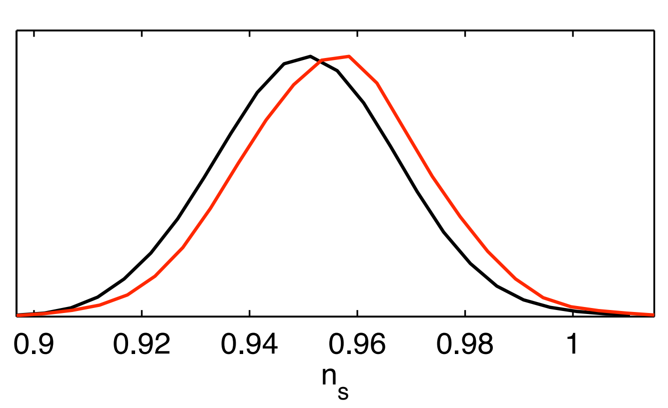


Superhorizon Fluctuations

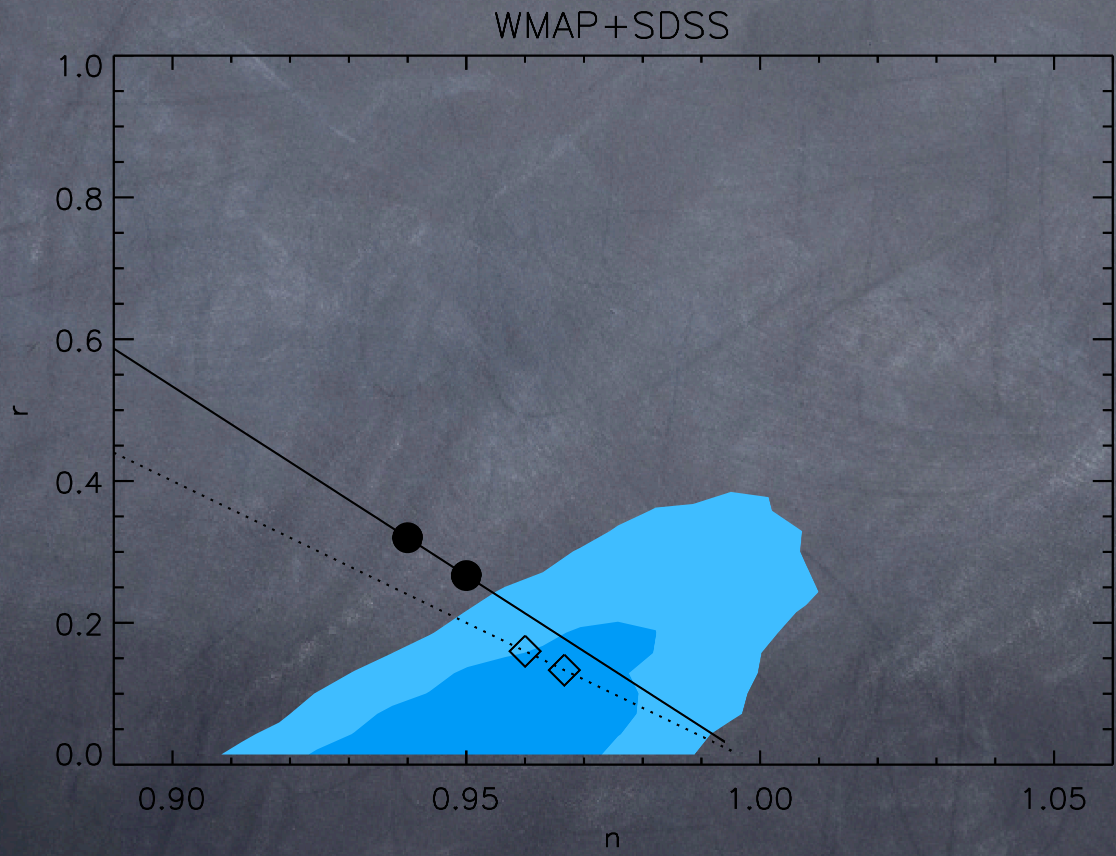


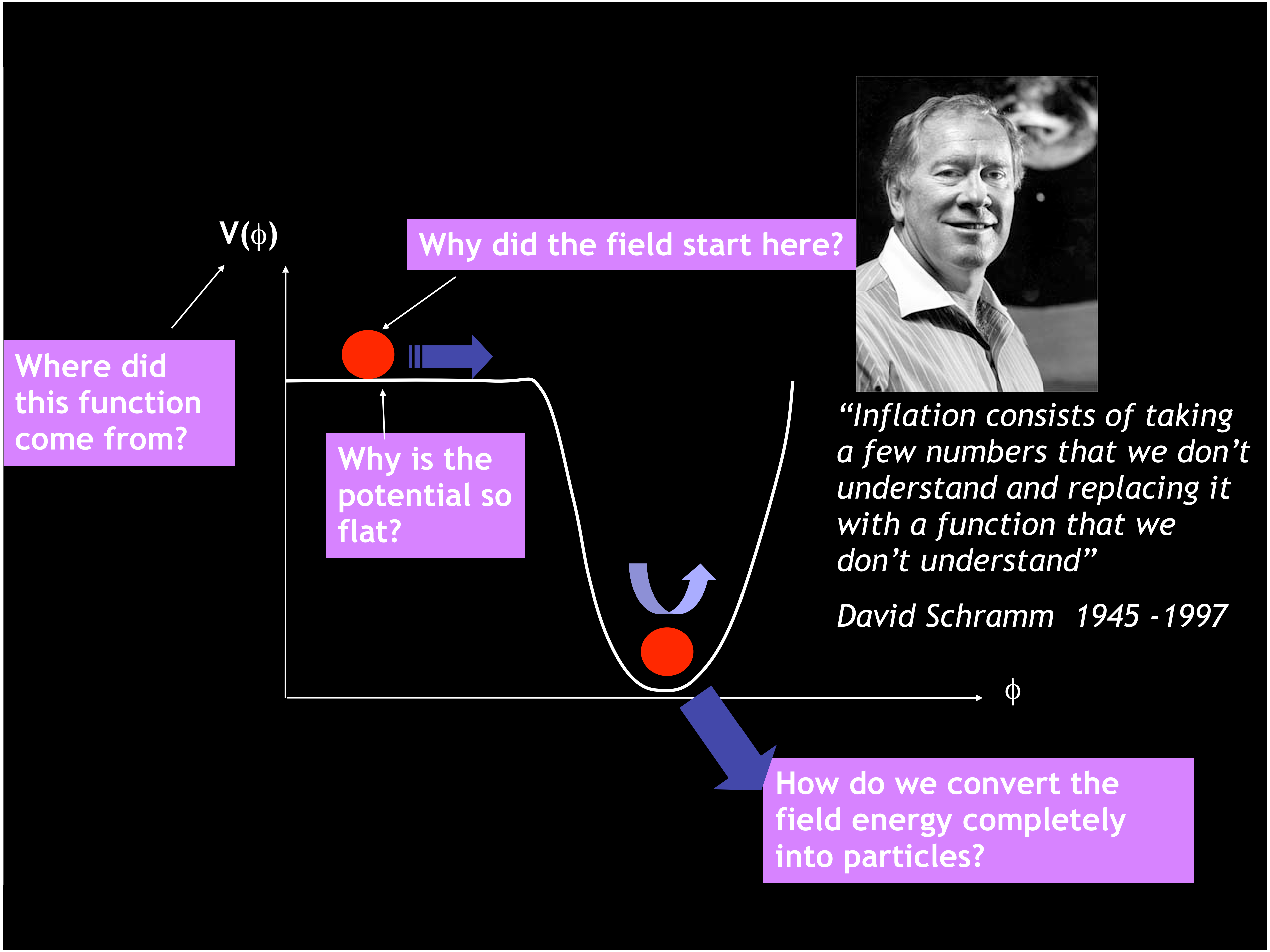
Deviations from Scale Invariance





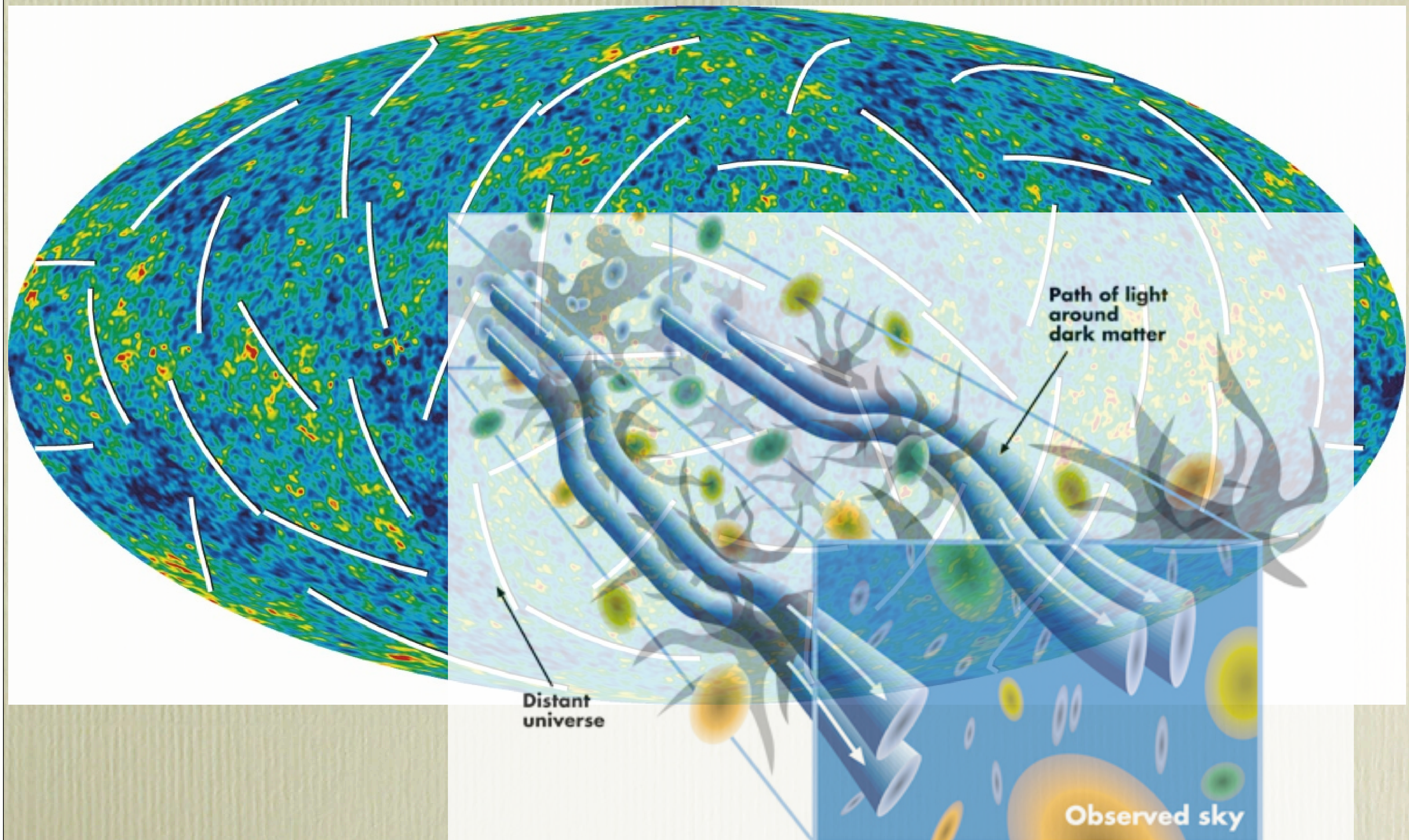
WMAP + LSS

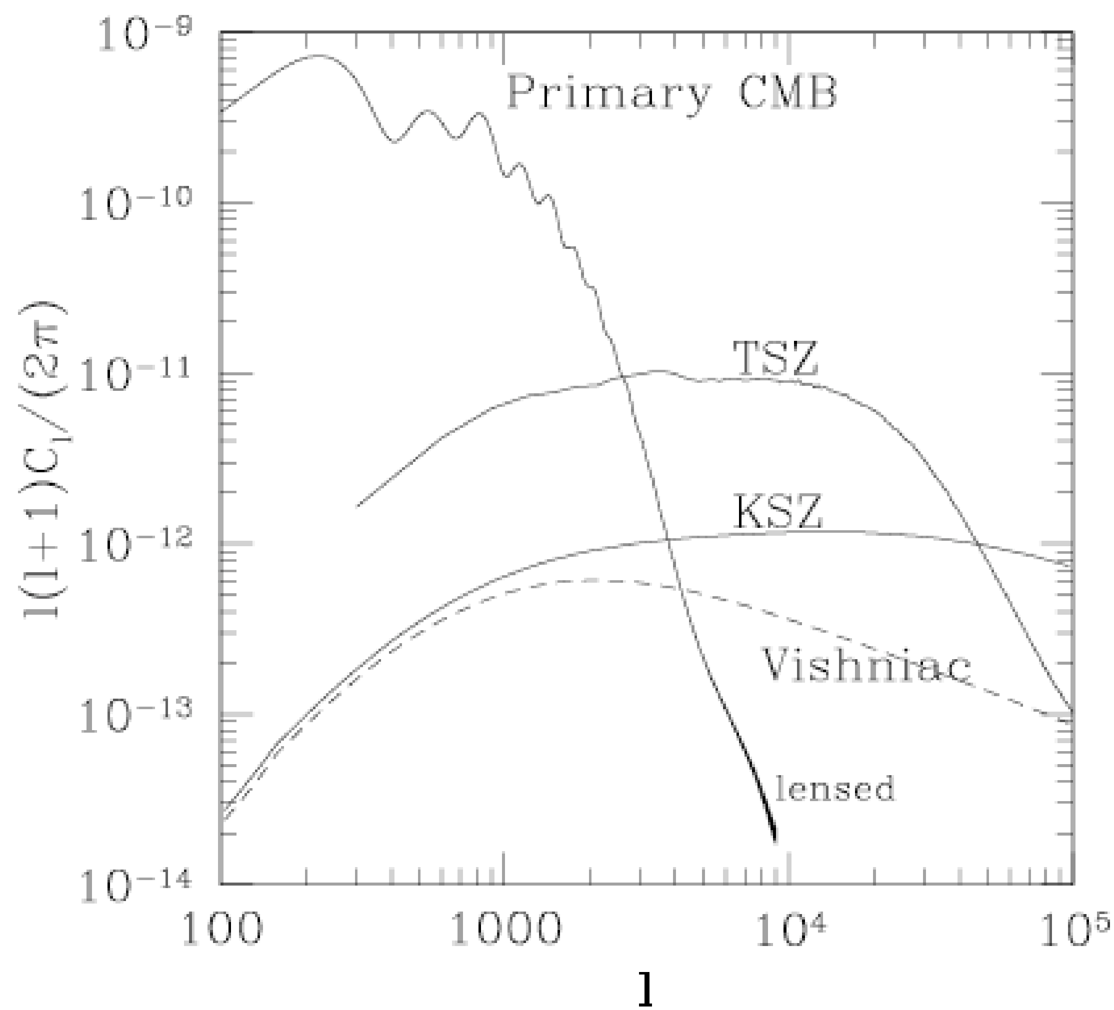




V(ϕ)
Why did the field start here?
Where did this function come from?
Why is the potential so flat?
ϕ
How do we convert the field energy completely into particles?
“Inflation consists of taking a few numbers that we don’t understand and replacing it with a function that we don’t understand”
David Schramm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

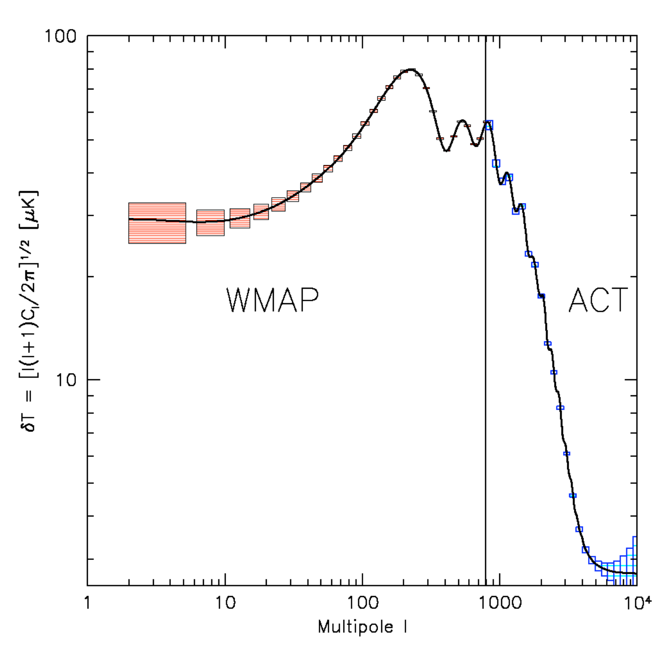
New Approach: CMB as a back light





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

Be careful of a posteori patterns...

ABRAHAM LINCOLN WAS ELECTED TO CONGRESS IN 1846.
JOHN F. KENNEDY WAS ELECTED TO CONGRESS IN 1946.

ABRAHAM LINCOLN WAS ELECTED PRESIDENT IN 1860.
JOHN F. KENNEDY WAS ELECTED PRESIDENT IN 1960.

ANDREW JOHNSON, WHO SUCCEEDED LINCOLN, WAS BORN IN 1808.
LYNDON JOHNSON, WHO SUCCEEDED KENNEDY, WAS BORN IN 1908.

JOHN WILKES BOOTH, REPORTEDLY ASSASSINATED LINCOLN.
LEE HARVEY OSWALD, REPORTEDLY ASSASSINATED KENNEDY.
BOTH ASSASSINS WERE KNOWN BY THREE NAMES.
BOTH NAMES CONTAINED FIFTEEN LETTERS.

BOOTH AND OSWALD WERE ASSASSINATED BEFORE THEIR TRIALS.