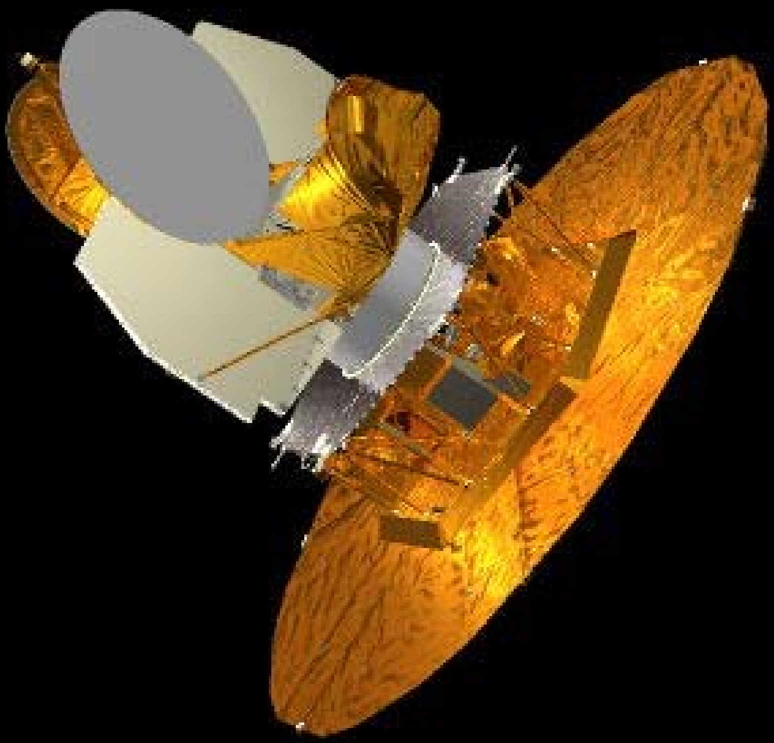
WMAP: Measuring how the universe began

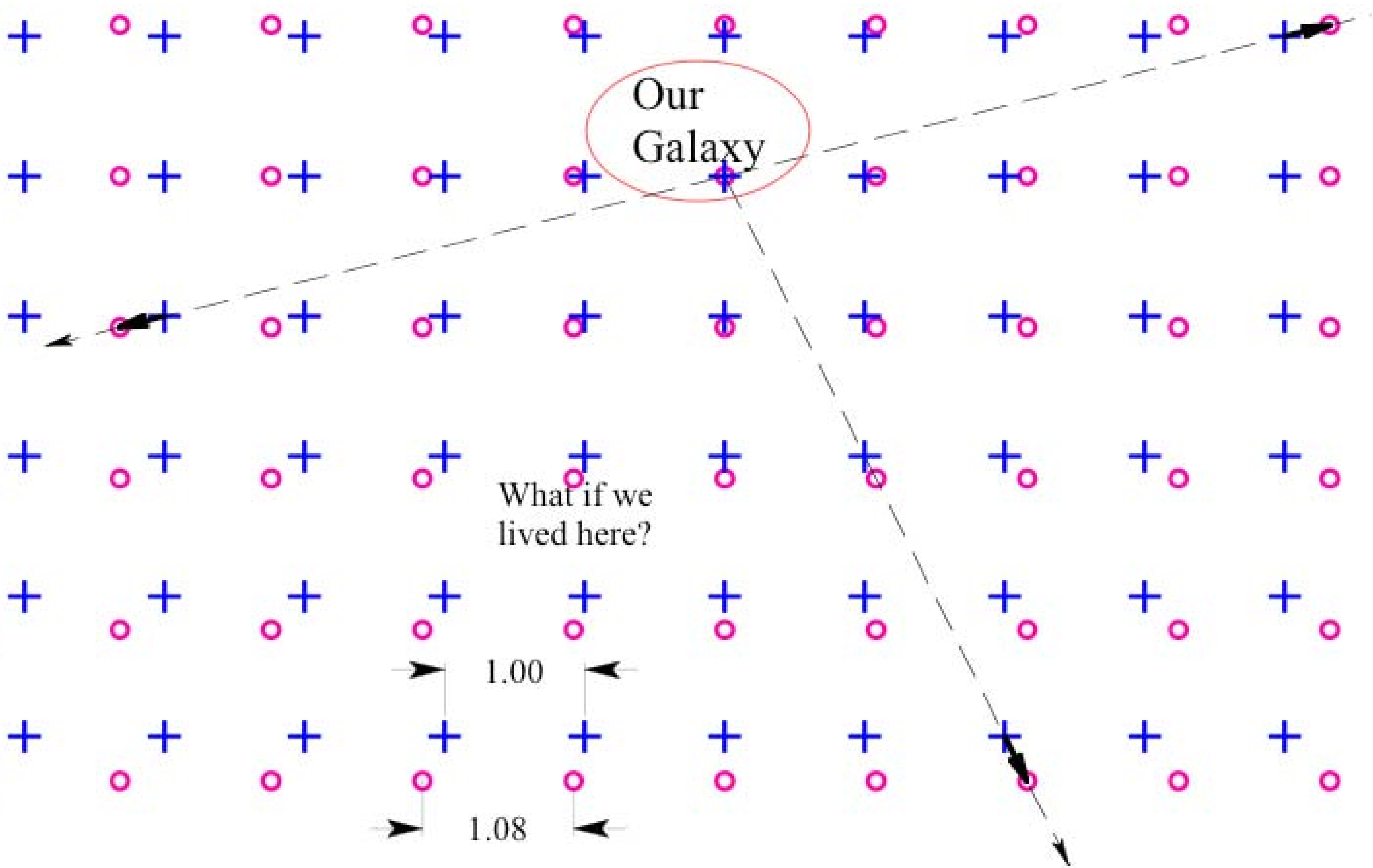
Beginning to constrain Inflation.

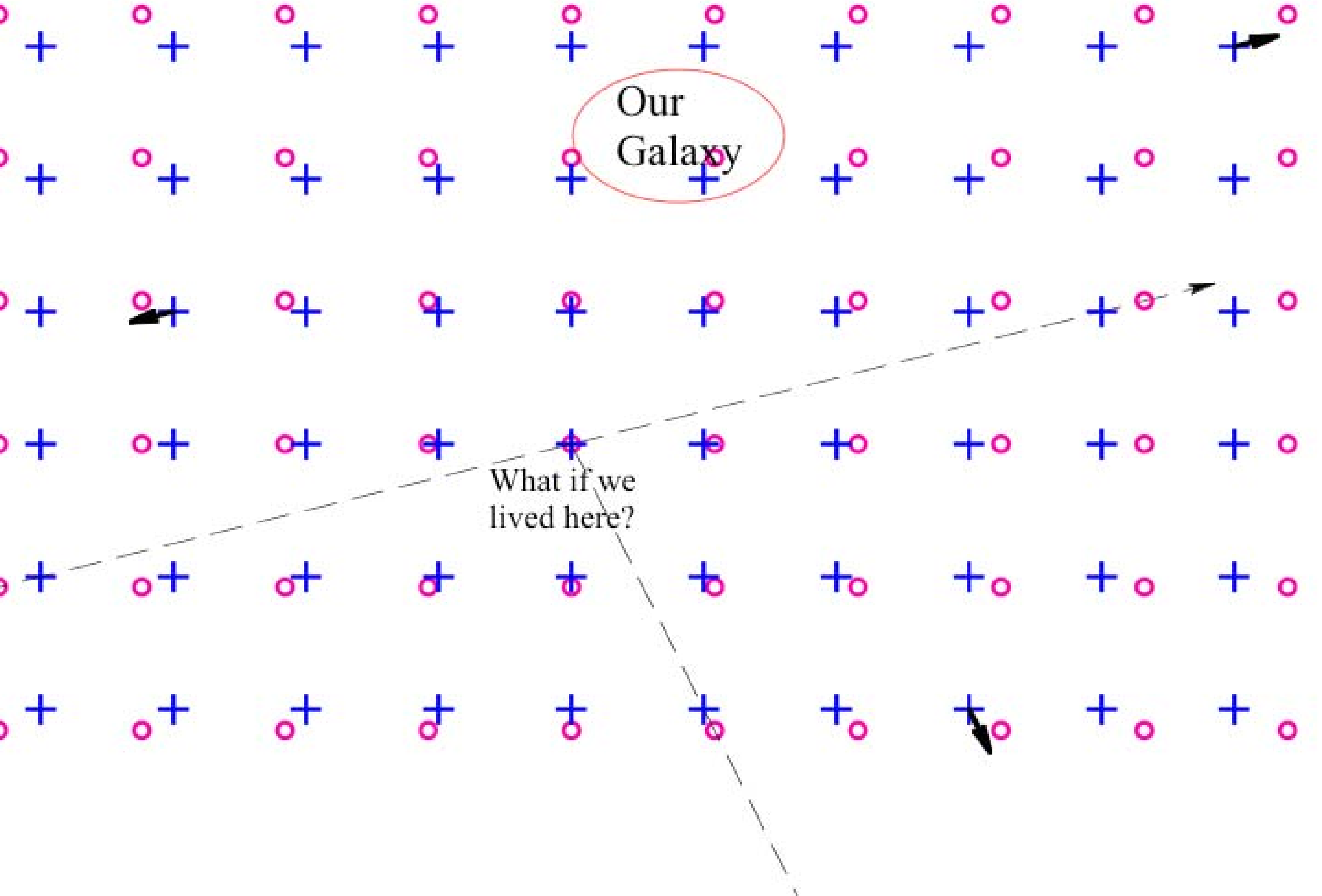
During today's talk, WMAP will survey 1/3 of the sky (again).



Sun shadow lines

Mark Halpern, UBC


Our Galaxy
What if we lived here?
1.00
1.08


Our
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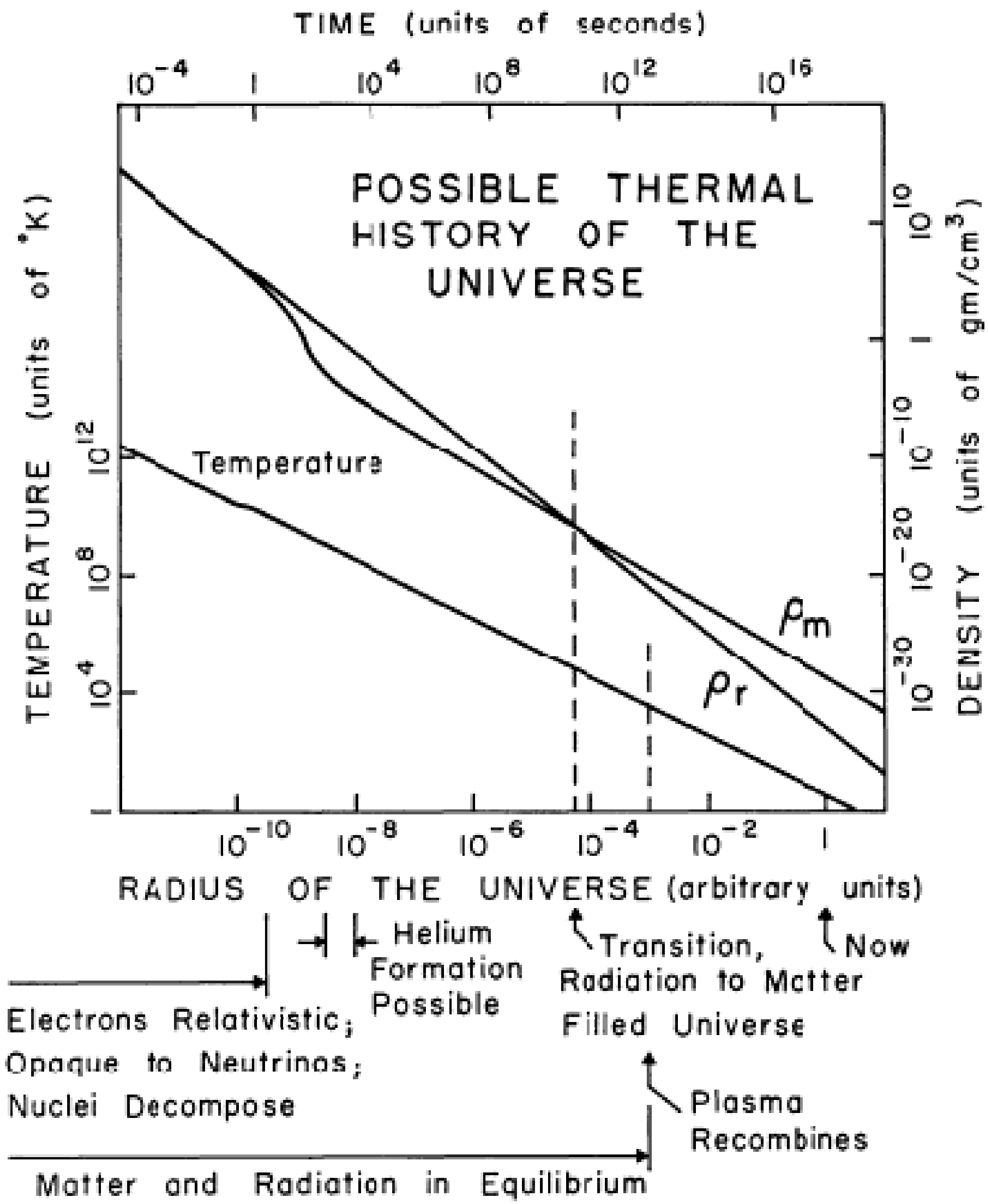
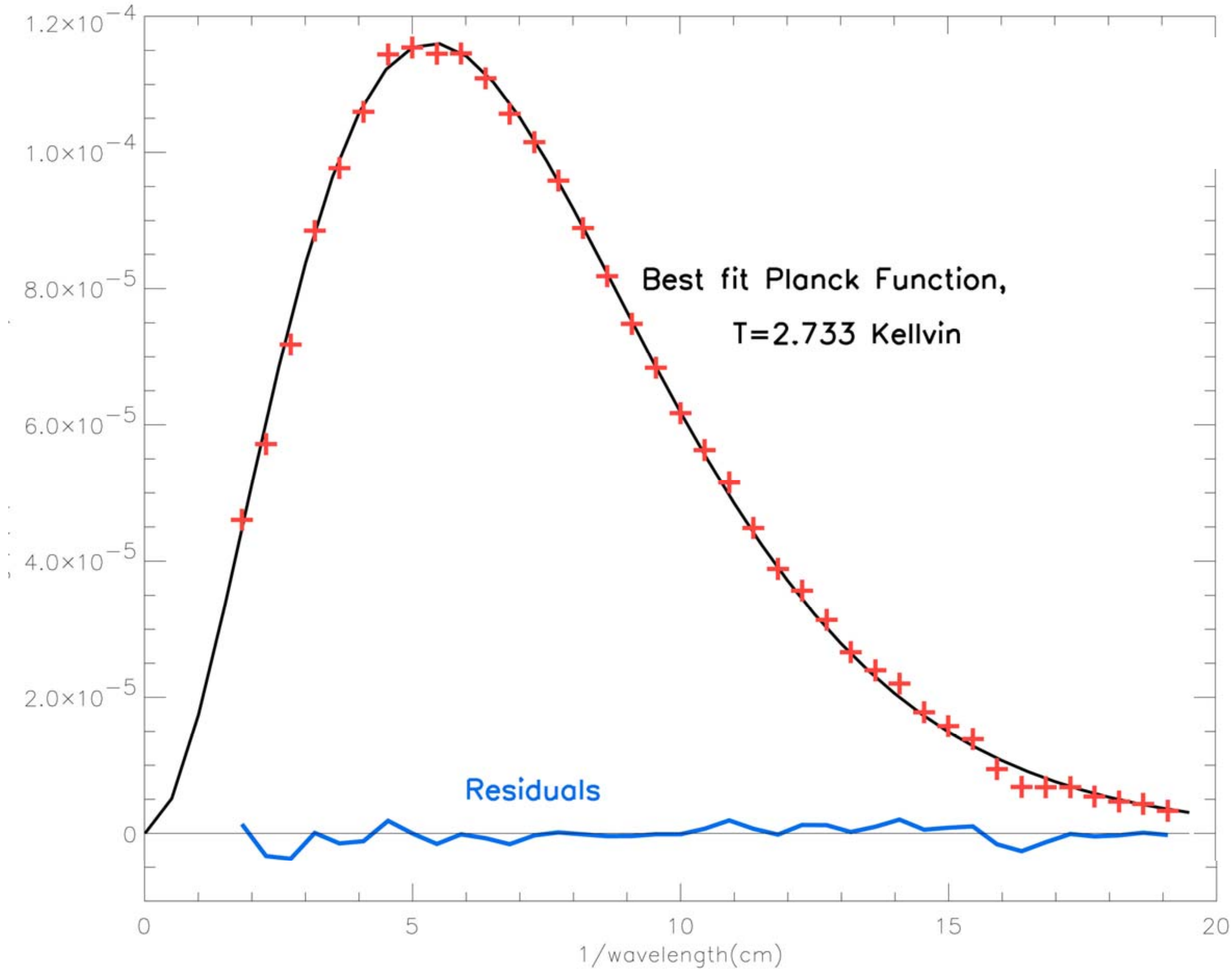


The Universe was much hotter and denser in the past.

It has been transparent since the primordial plasma became neutral, ~380,000 years after the start.

Graphics from Dicke, Peebles, Roll and Wilkinson, Ap J 142 1965.

Verification of the big bang: We see the thermal emission from the primordial plasma everywhere on the sky. It has the expected spectrum.

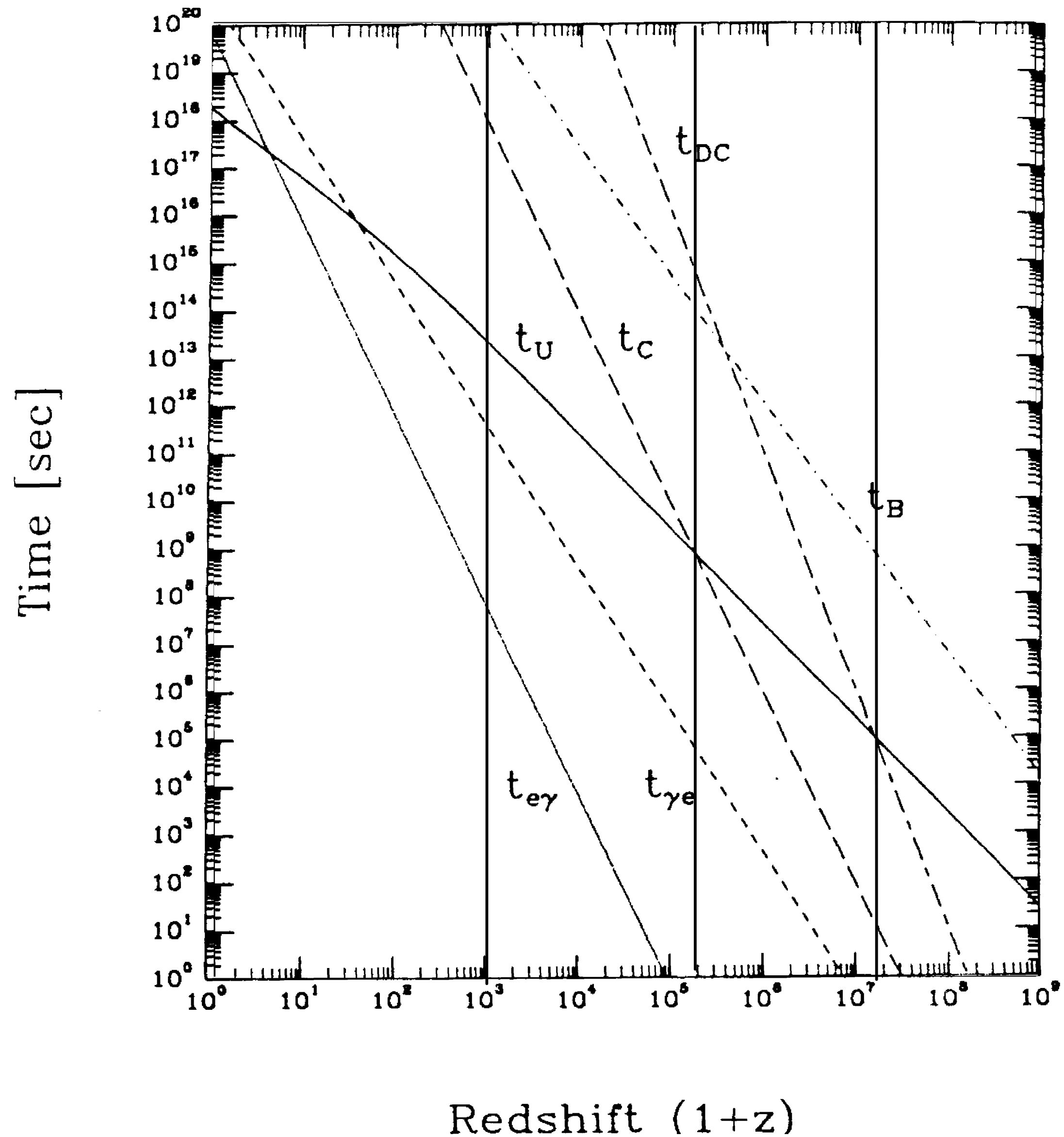


Distortion of the CMB spectrum

- Energy release at $z>10^7$ **double** Compton efficient to recreate thermal equilibrium

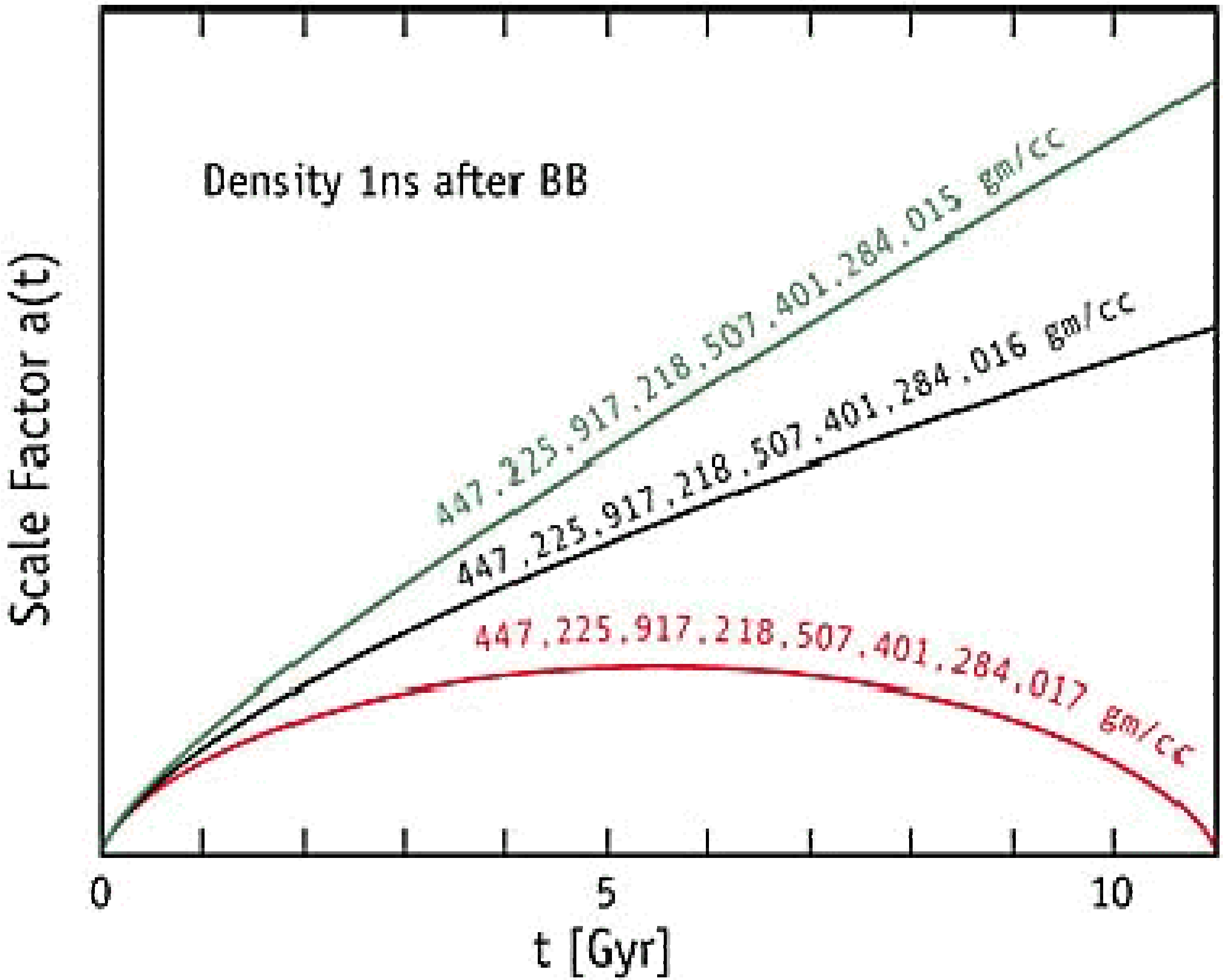
- Energy release at $10^5<z<10^7$ inverse Compton generates a Bose-Einstein distribution

- Energy release at $10^3<z<10^5$ inverse Compton effective but not toward the equilibrium

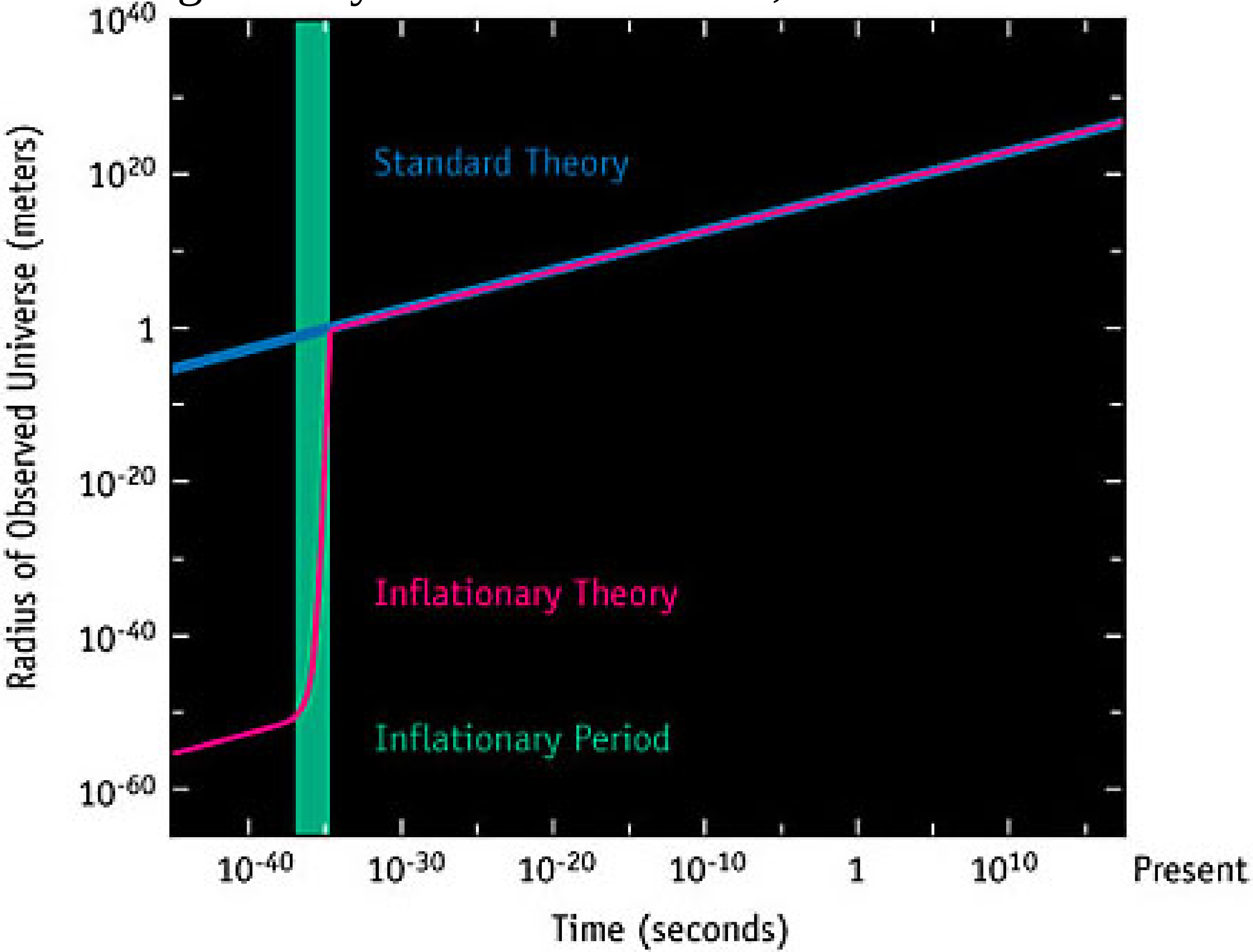


Why is the universe anywhere close to Ω_0=1 now?

Ω_0=1 is an unstable stationary point.



Inflation, an incredibly rapid early expansion, solves both the flatness and horizon problems by expanding small causally connected regions beyond their “horizons,”



Predictions of Inflation:

1. Nearly Scale Invariant spectrum; COBE
2. Nearly Flat geometry; Toco+2Df, Boomerang
3. Superhorizon scale fluctuations; WMAP-1
4. Gaussian distributed fluctuations; WMAP-1
5. Spectral index just less than 1;
6. Relic Gravitational radiation.

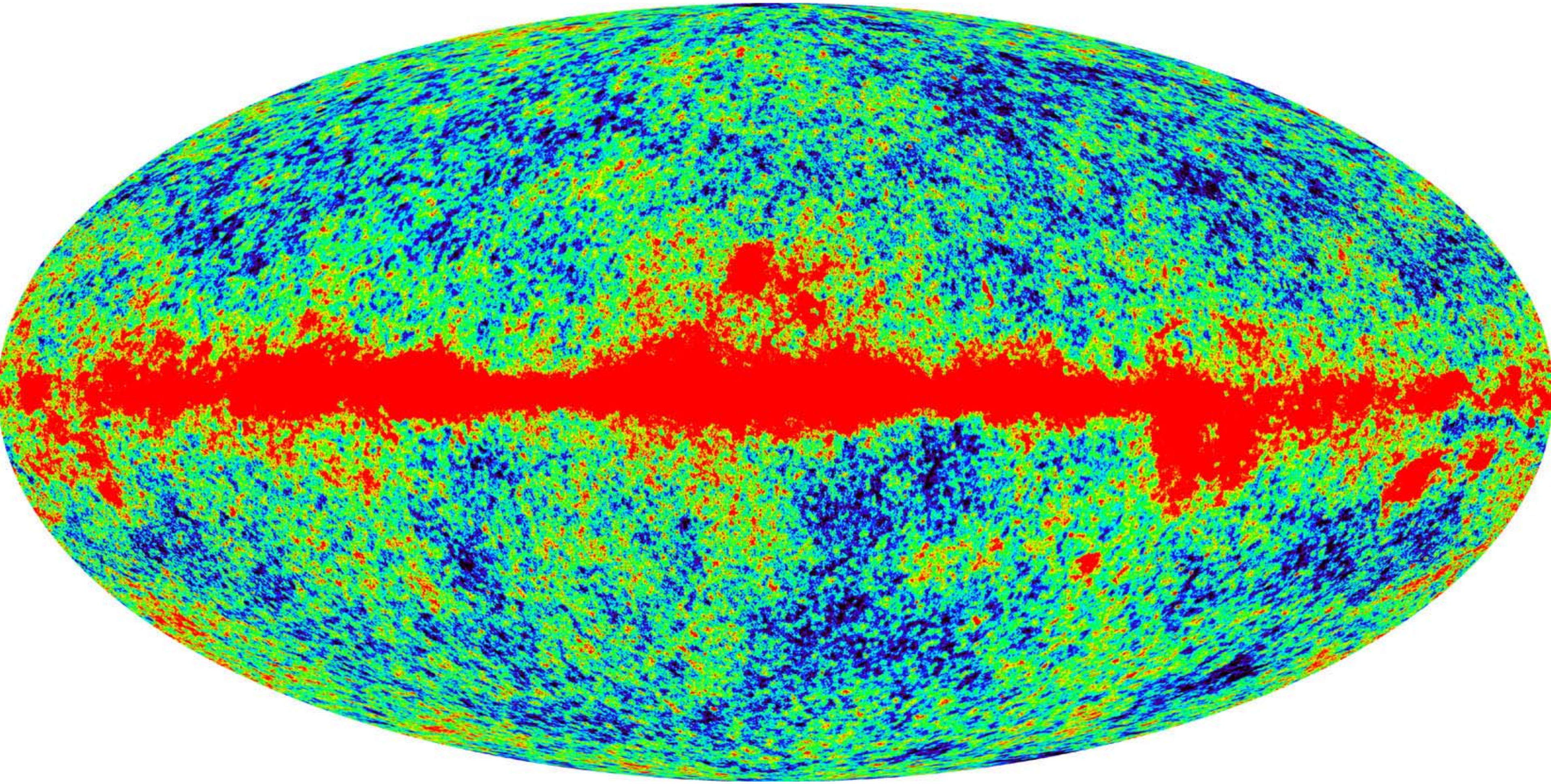
The precision of these tests are now beginning to get interesting.

Outline: Data and simple parameter fits.

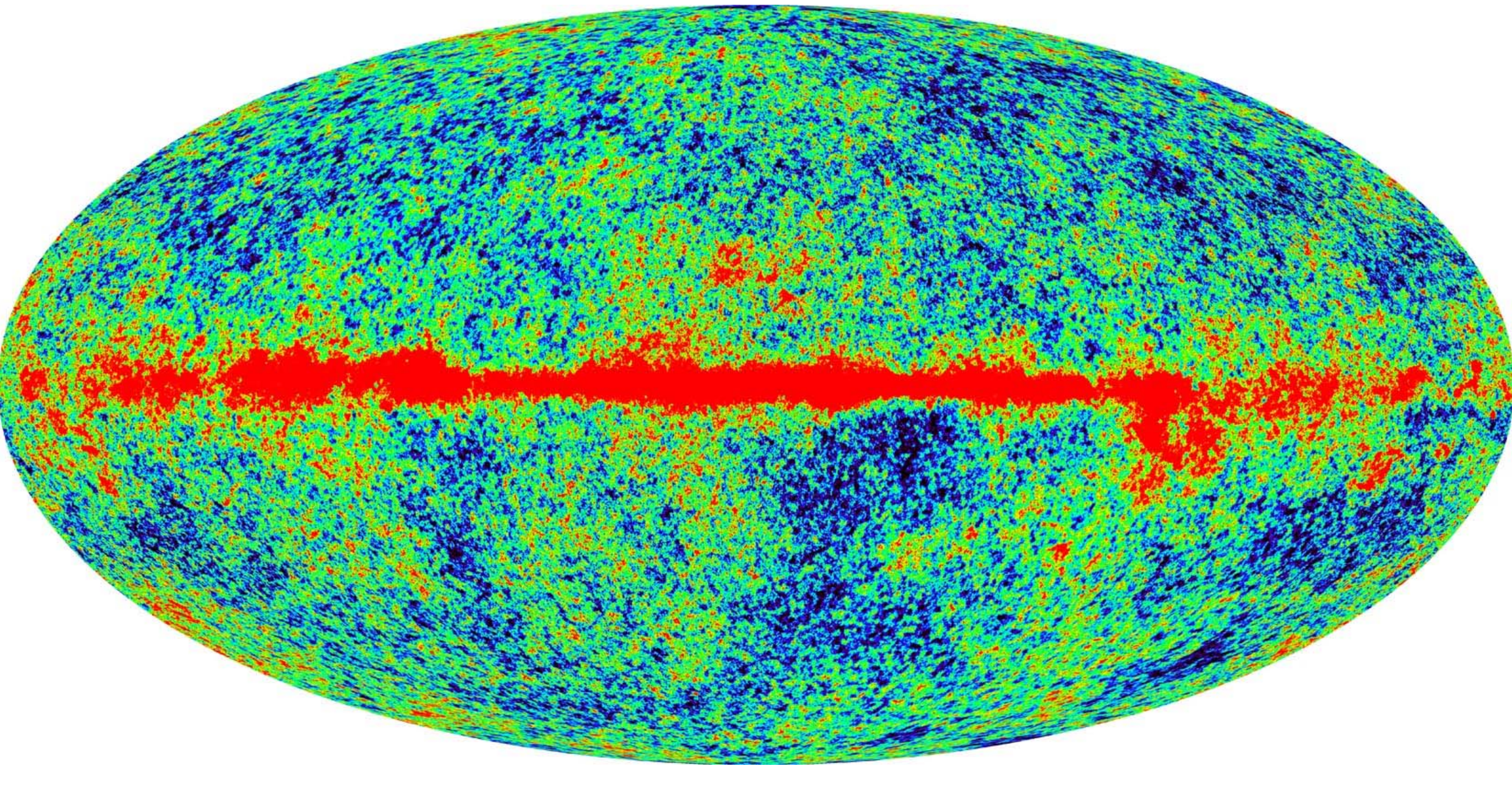
Comparison to other astronomical data.

Extensions of the model to test inflation.

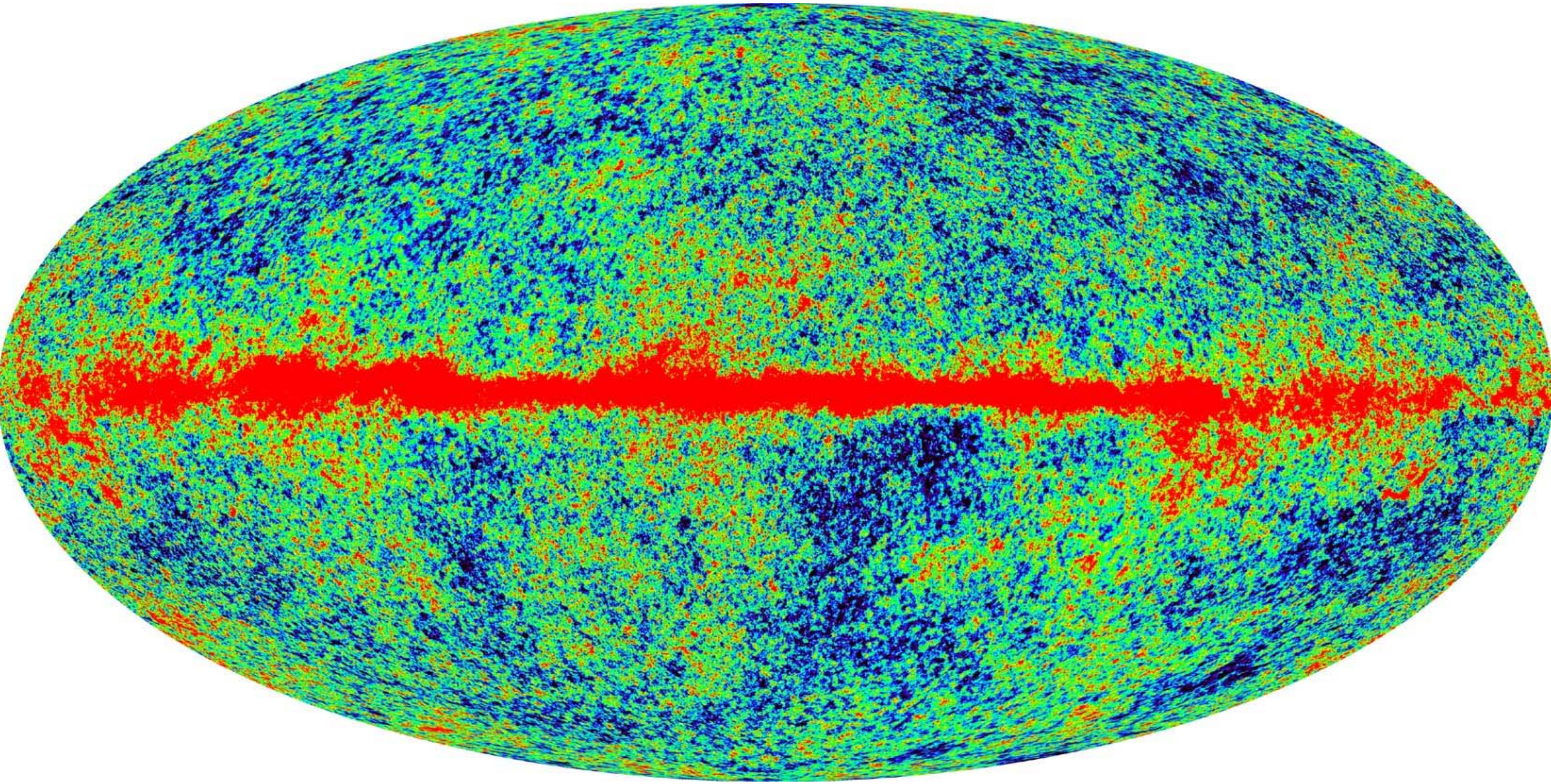
Q-Band 41 GHz 30’ FWHM



V-Band 61 GHz 19’ FWHM



W-Band 94 GHz 12’ FWHM

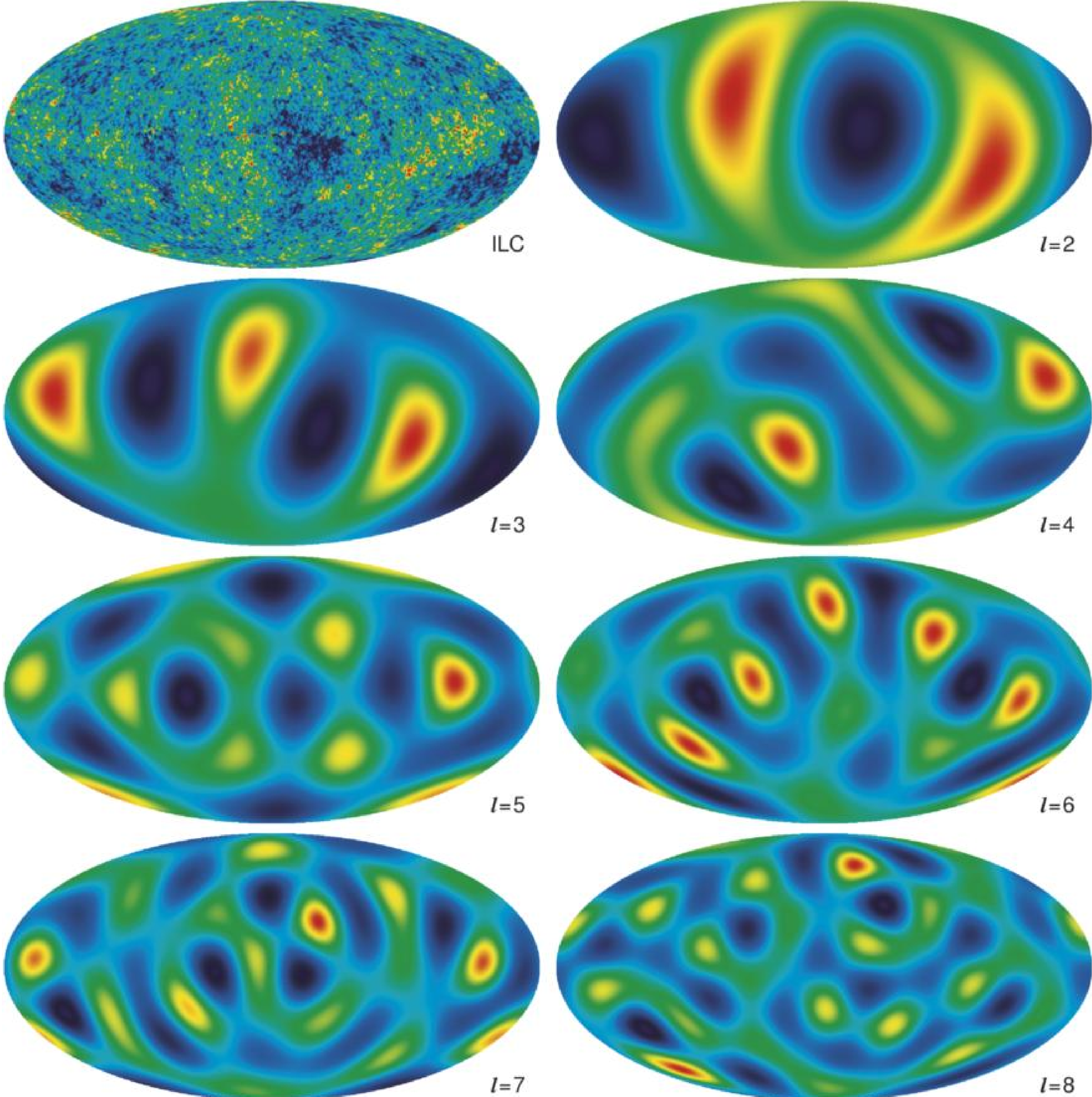


Fluctuation Spectrum:

The lowest few terms in the spherical harmonic expansion of the temperature are fit explicitly by maximum likelihood in pixel space.

At higher *l* we use power spectrum estimation like a fourier transform.

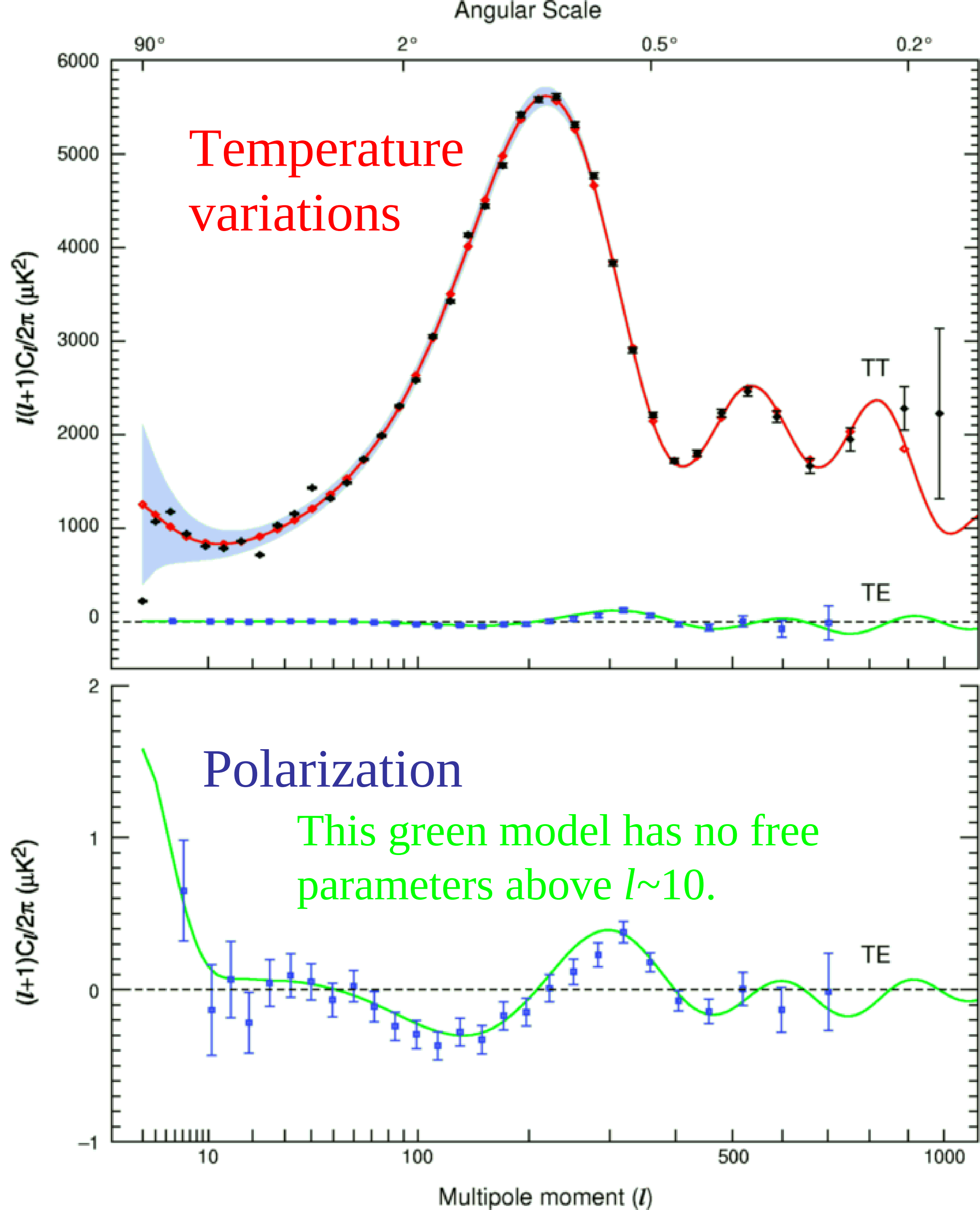
These images are the decomposition of the ILC map into low l modes and are NOT used in power spectrum estimation.



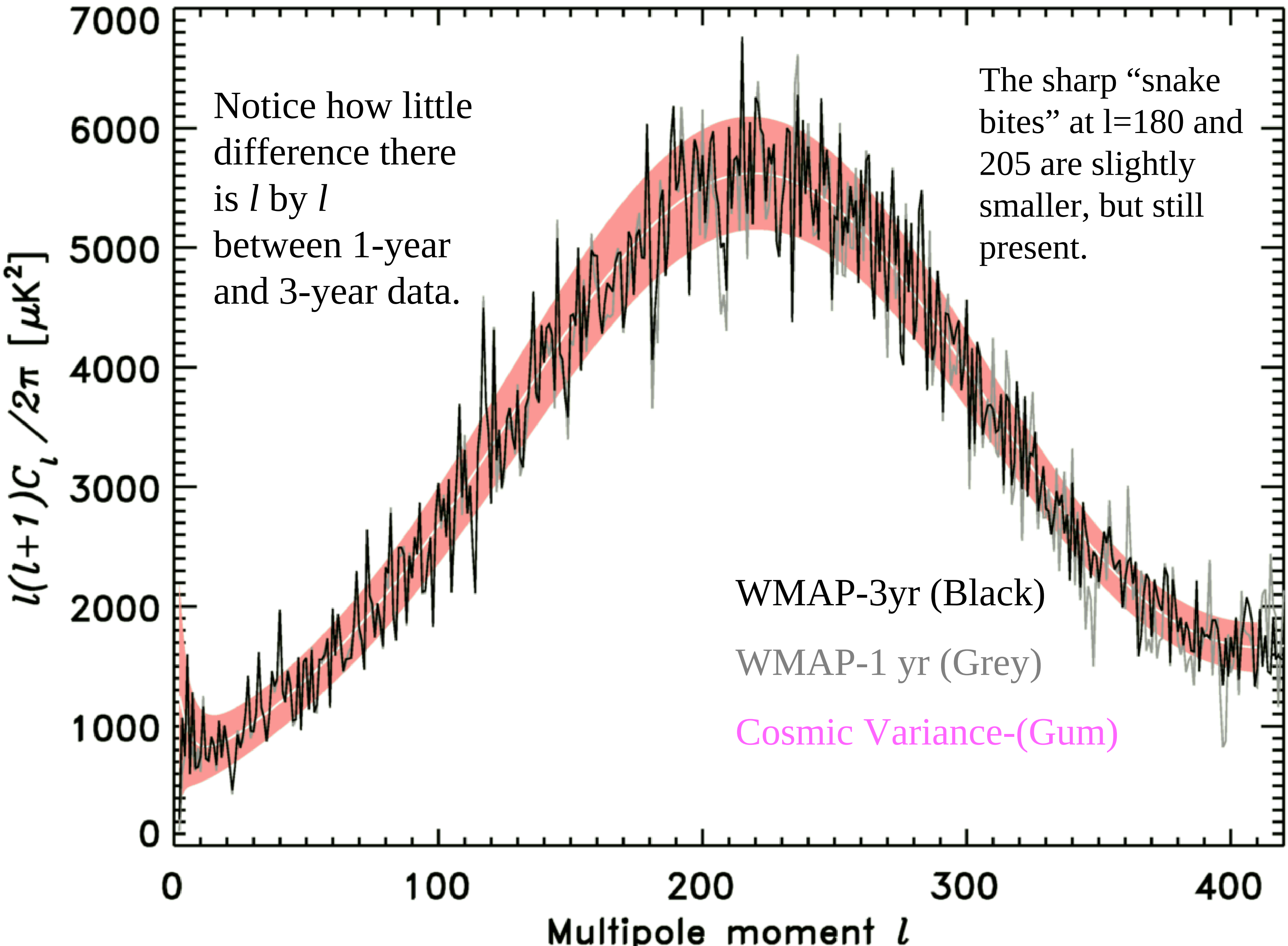
The ripples in the power spectrum--called acoustic peaks--confirm a generic prediction of any big bang model

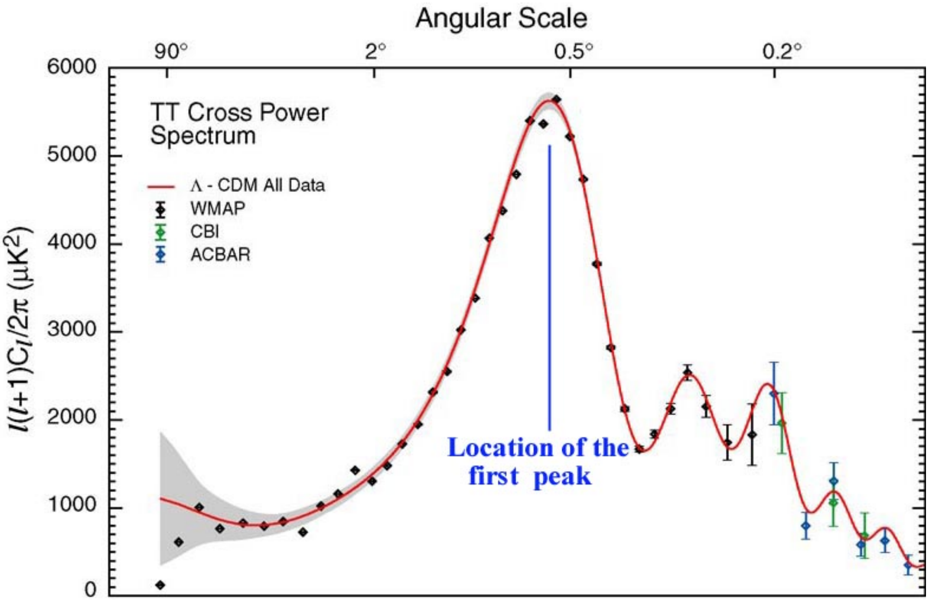
Above l=10 the TE cross-power spectrum is derived from the TT spectrum with no ambiguity; motion giving rise to the acoustic peaks gives rise to a correlated polarized signal.

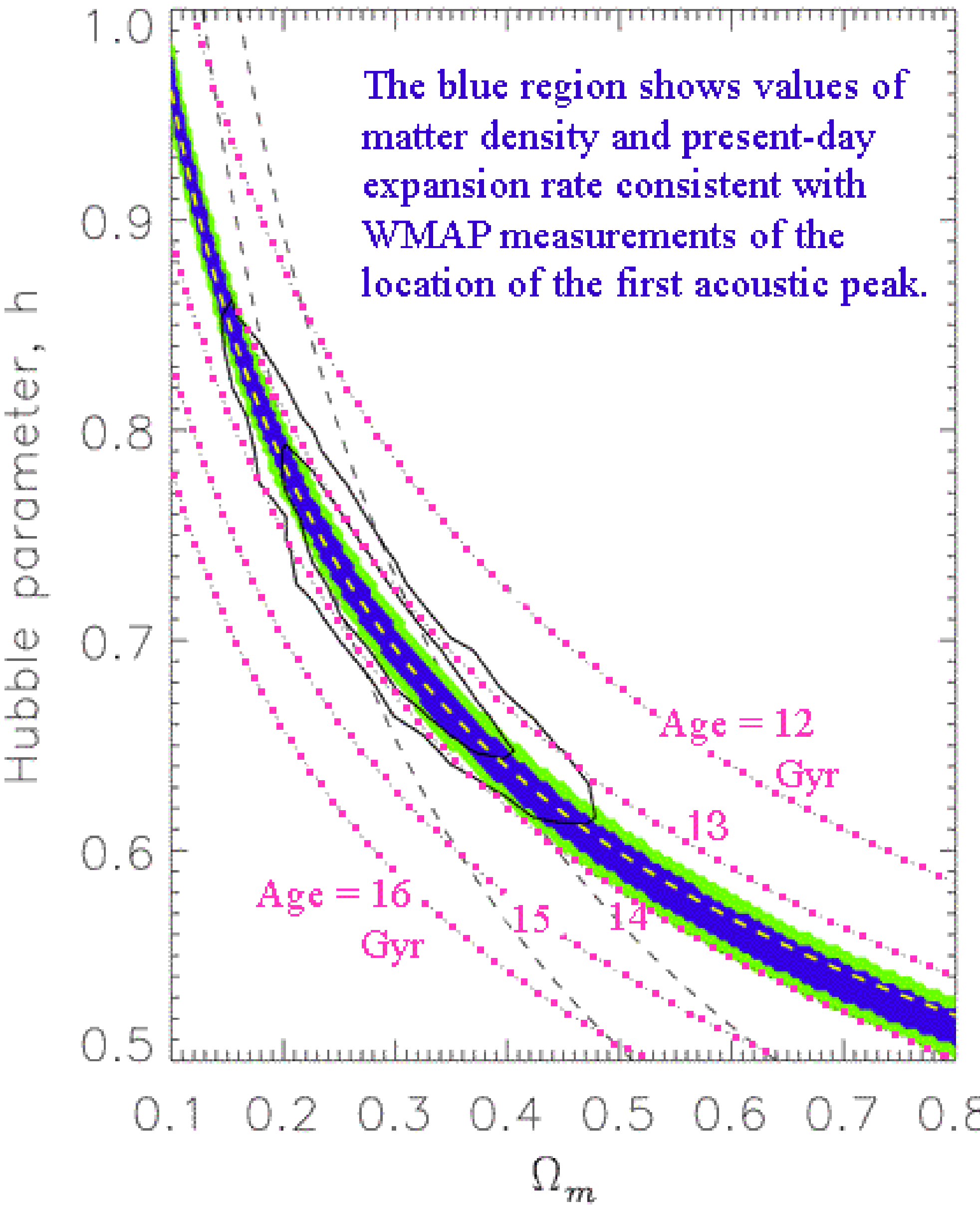
The motion below l~200 is taking place on scales larger than the horizon at the time of the motion.



The TT power spectrum is now cosmic-variance limited out to l =400.



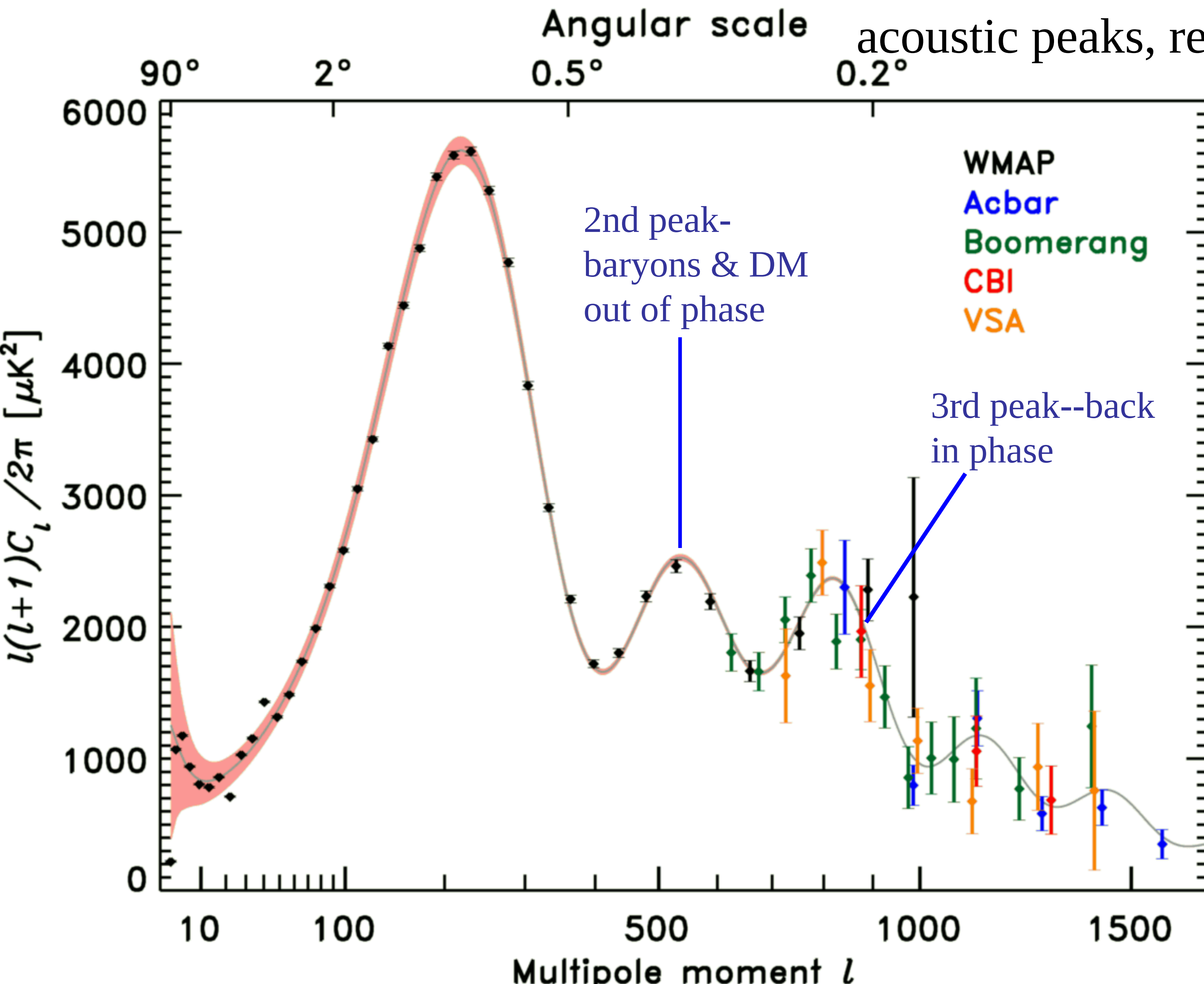




In a flat universe, the angular scale of the first acoustic peak tells us the age of the universe.

Baryon density and Dark Matter density

are constrained by the heights of the second and third acoustic peaks, respectively.



WMAP data are fit to 6 parameters:

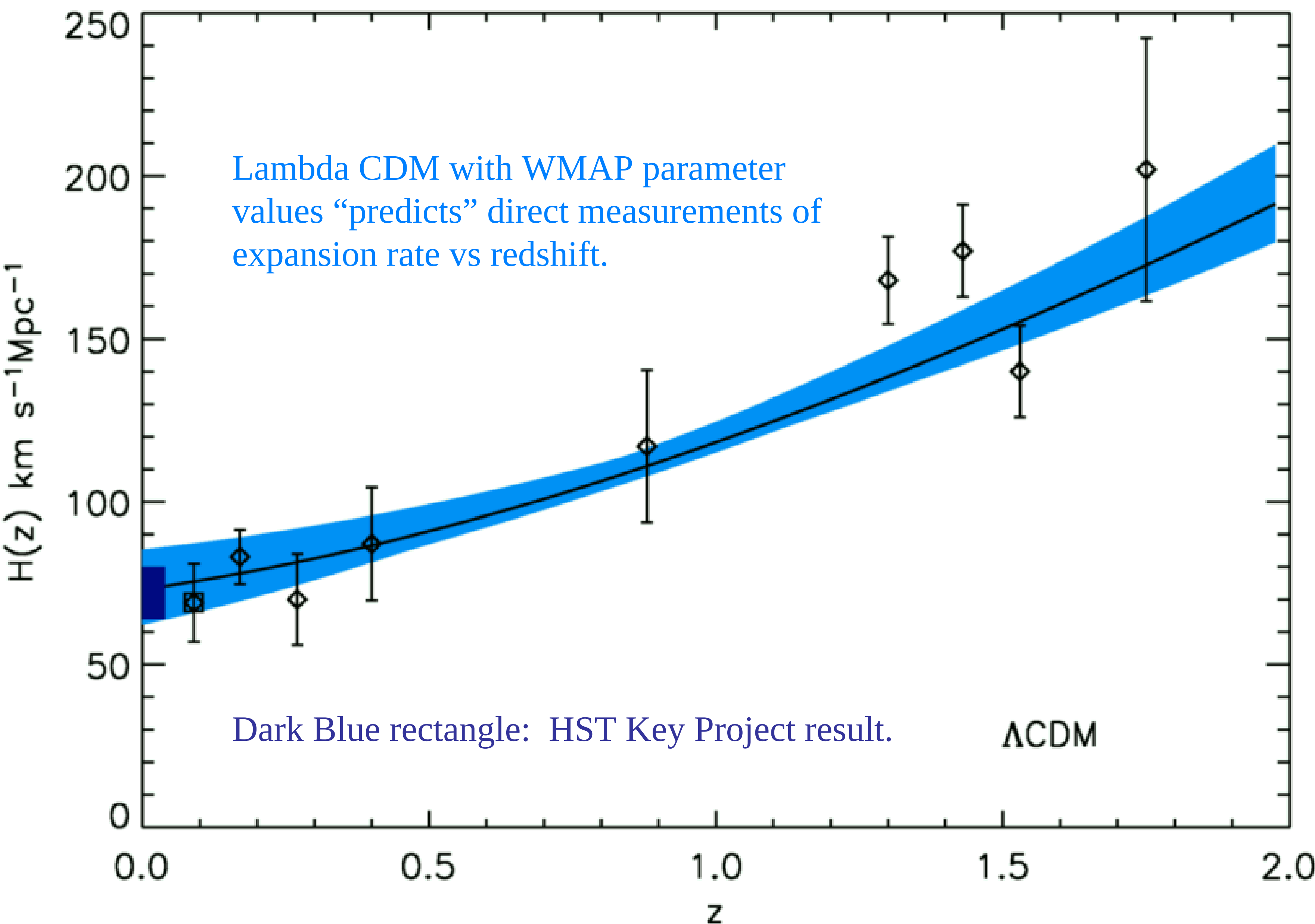
Baryon density, Total matter density, Current expansion rate, Optical depth to the CMB, Slope of the fluctuation spectrum, Amplitude of the fluctuation spectrum.

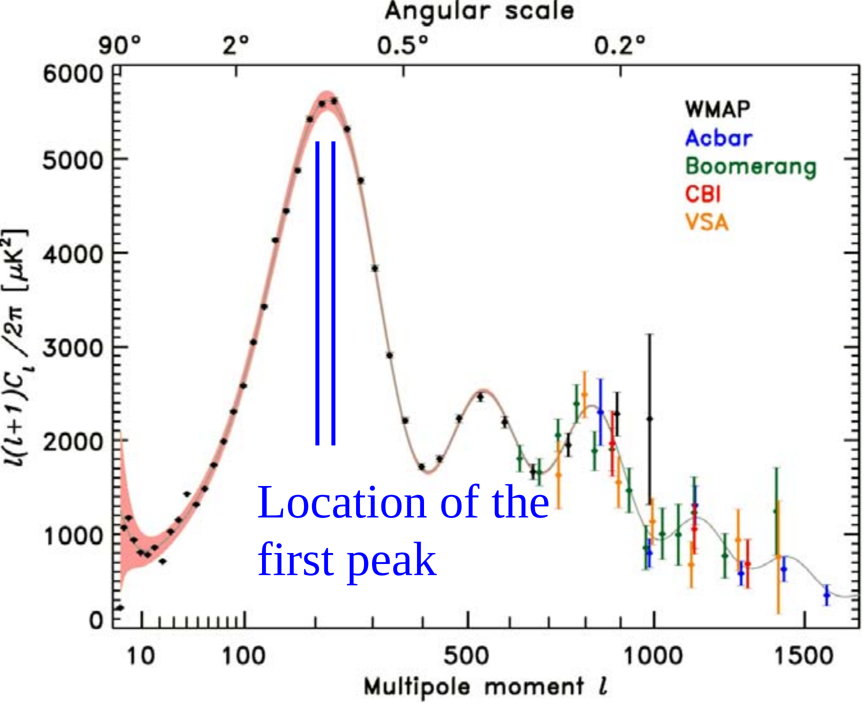
In the simplest fits we assume Flat, do not fit for Λ, age or w.

Parameter	First Year Mean	WMAPext Mean	Three Year Mean
$100\Omega_b h^2$	$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08
$\Omega_m h^2$	$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009
H_0	72^{+5}_{-5}	73^{+3}_{-3}	74^{+3}_{-3}
τ	$0.17^{+0.08}_{-0.07}$	$0.15^{+0.07}_{-0.07}$	0.093 ± 0.029
n_s	$0.99^{+0.04}_{-0.04}$	$0.98^{+0.03}_{-0.03}$	0.961 ± 0.017
Ω_m	$0.29^{+0.07}_{-0.07}$	$0.25^{+0.03}_{-0.03}$	0.234 ± 0.035
σ_8	$0.92^{+0.1}_{-0.1}$	$0.84^{+0.06}_{-0.06}$	0.76 ± 0.05

Chi-squared is 1.041 for ~4000 DoF

Comparison to direct measurements of expansion, H(z)



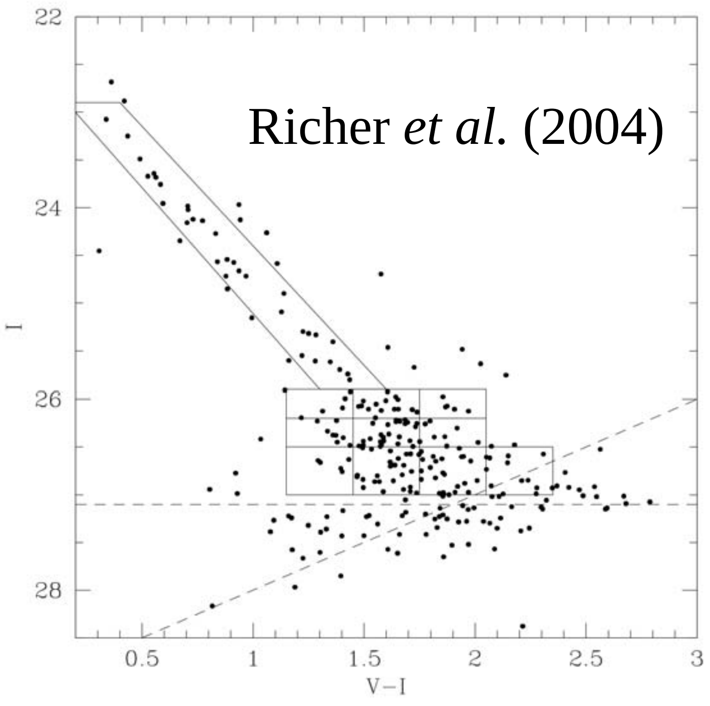


The Universe is older than the stuff in it is.

In a flat universe the location of the first acoustic peak tells us the age of the universe.

In the end, we calculate t from the results of the full 6-D fit.

WMAP Age :13.73 +0.13 -0.17 Gyr



Fits to white dwarf cooling curves give an age estimate for the globular cluster they live in:

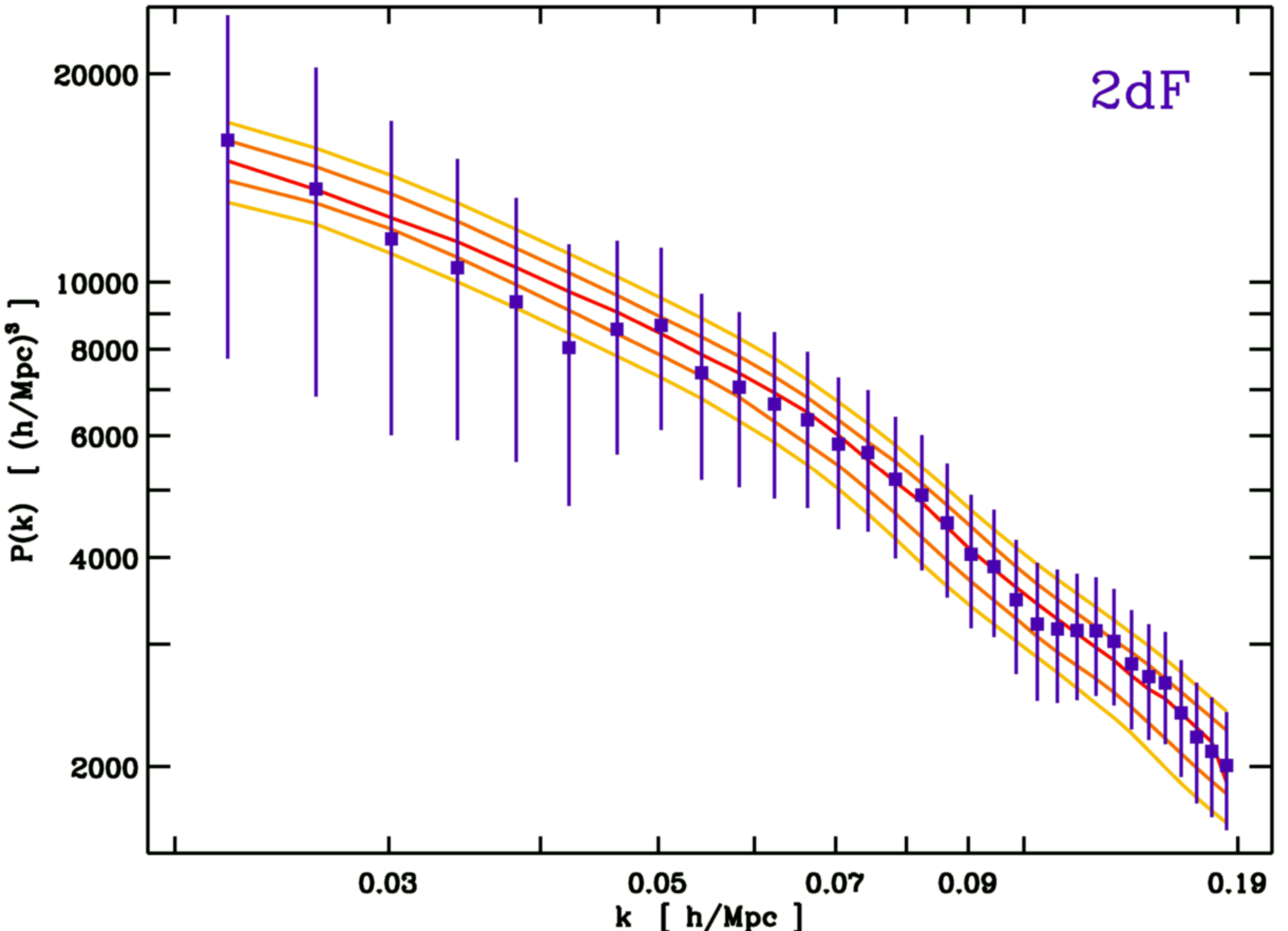
WD Age: 12.1 Gyr

Add to this an estimate for globular cluster formation and star ignition.

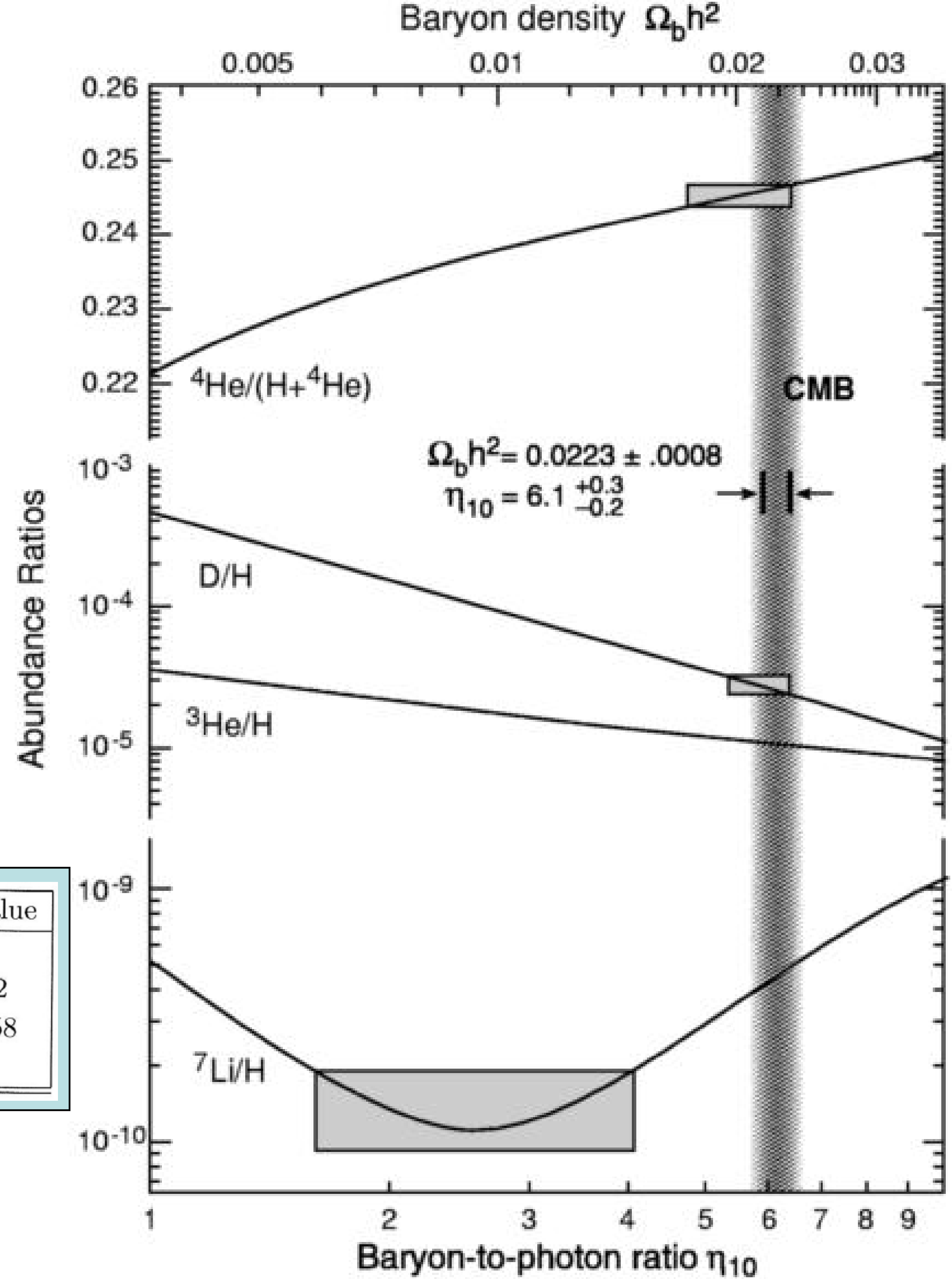
WMAP data alone "predict" the amplitude and shape of the power spectrum probed at much smaller physical scales by 3D surveys of the distribution of galaxies in redshift space.

The data here in red and orange are the WMAP 1σ and 2σ predictions.

The bars in purple are from the 2 Degree Field redshift survey. (Adjacent bars are correlated.)

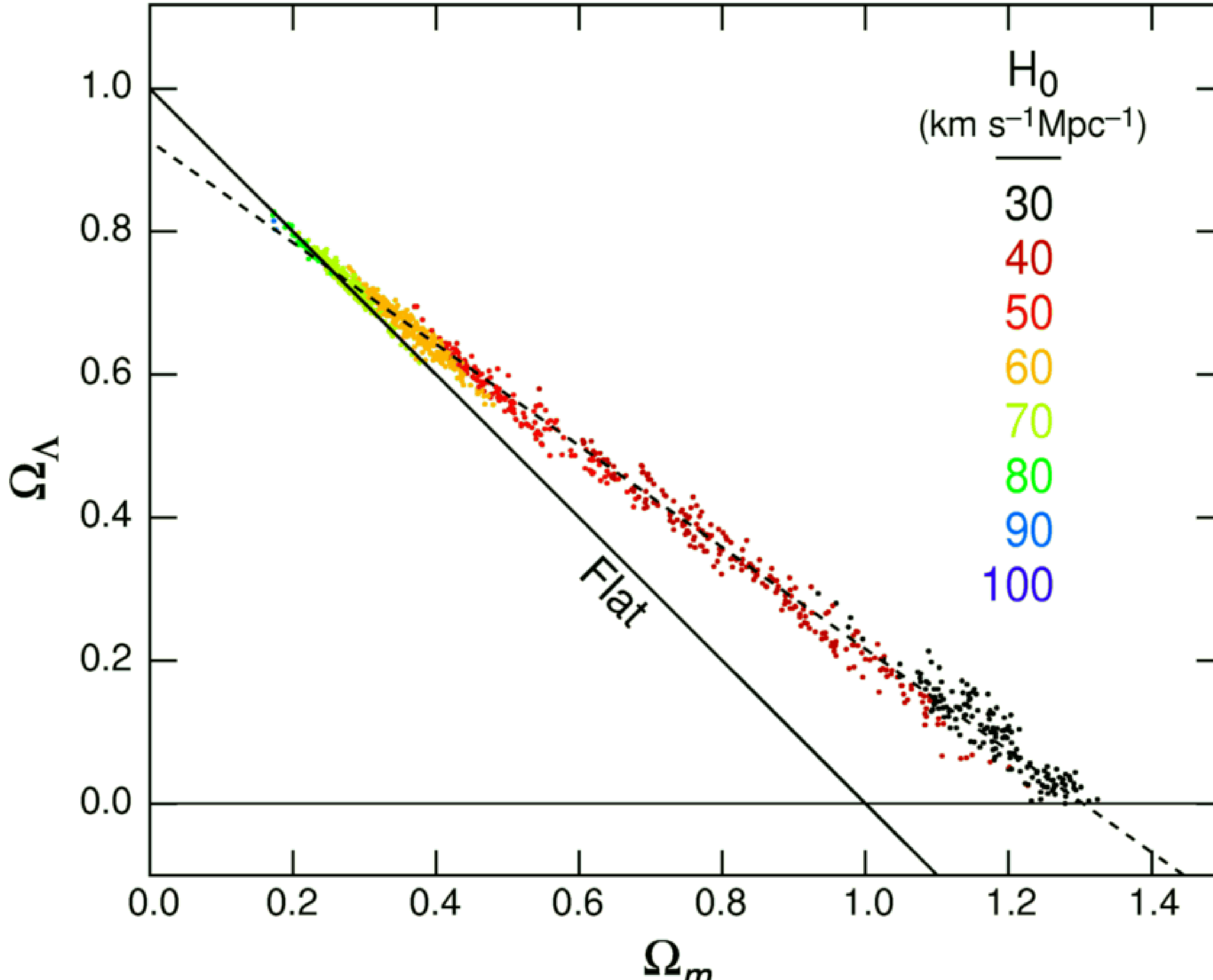


The baryon-to-photon ratio is the only free parameter in calculating nuclear fusion models of the first few minutes. The WMAP constraint agrees with direct measurements of primordial abundance (if you ignore lithium).



	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

If we do not assume flatness a variety of fits become acceptable to WMAP alone.

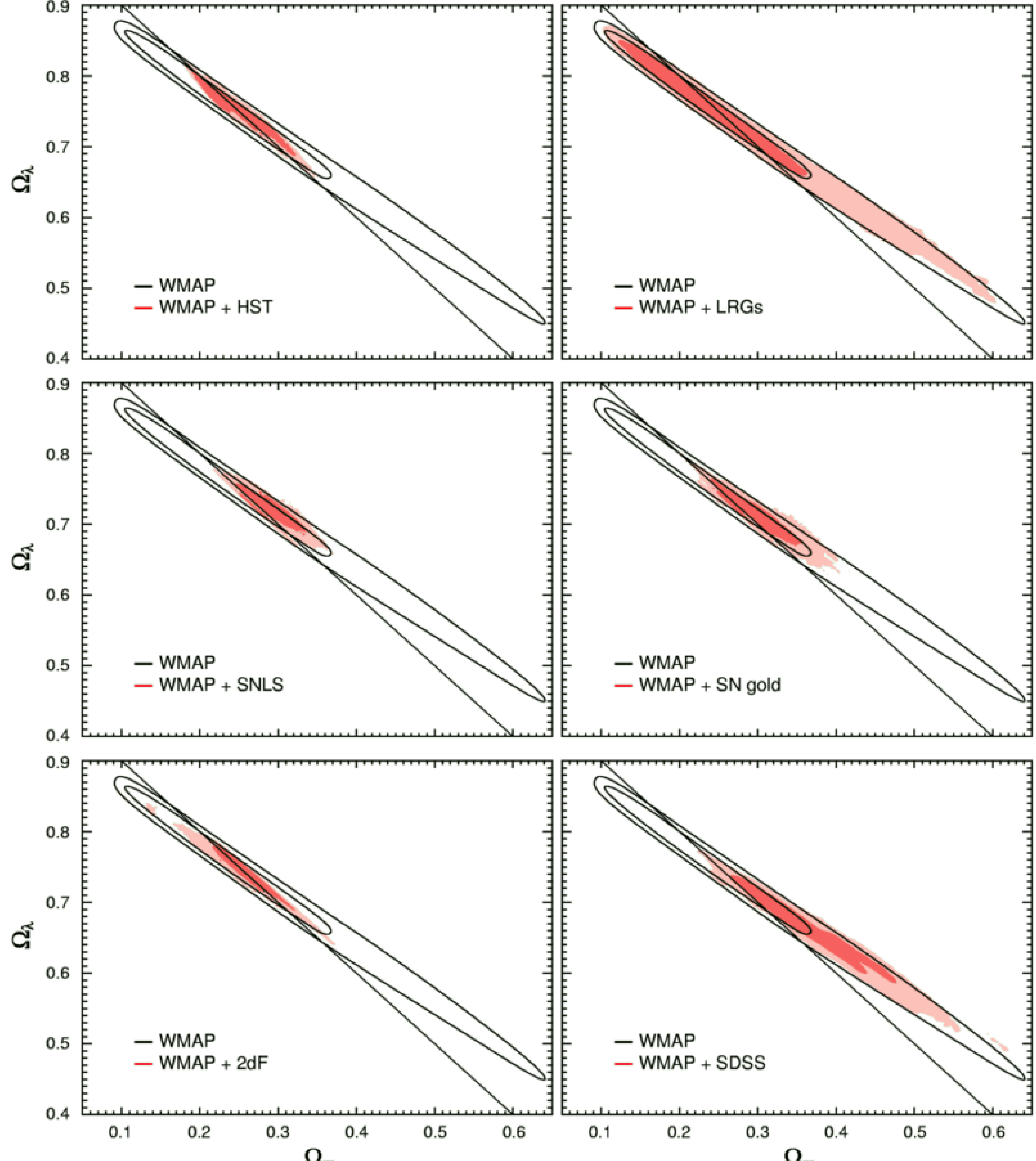


Inclusion of any one of a number of other astronomical measurements restricts the allowed region to be very close to flat.

Supernavae measure a distance to z~1.

Baryon Acoustic oscillations measure a distance to z~0.35.

Either of these in combination with the CMB distance to z=1035. Constrains geometry.



In addition to the six parameters some others are held at “obvious” values of 1 or 0.

For example, flat means

$\Omega b + \Omega m + \Lambda = 1$

so we do not need to fit for all 3.

First, lets see how the six parameter model does against other data.

Then let’s see about other parameters, relaxing flatness, exploring non-Λ cosmologies, adding gravitational radiation…

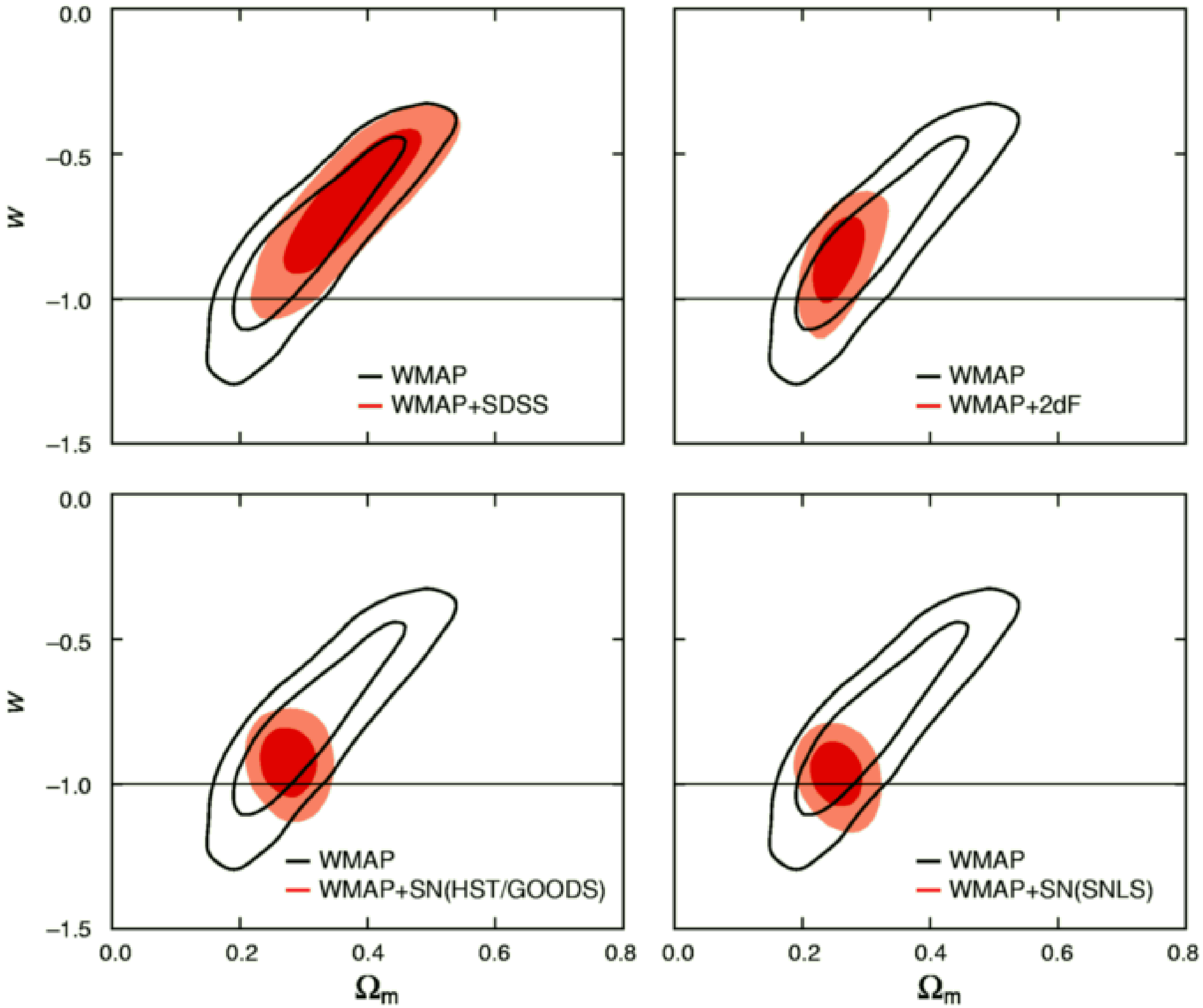
Relaxing the model I:

Do not insist on Lambda. Let the ratio of pressure to density be a free parameter.

$w = P/\rho$

$w = -1$ for a simple cosmological constant.

WMAP alone allows a range for w, but the constraints become pretty good when supernovae data are added.



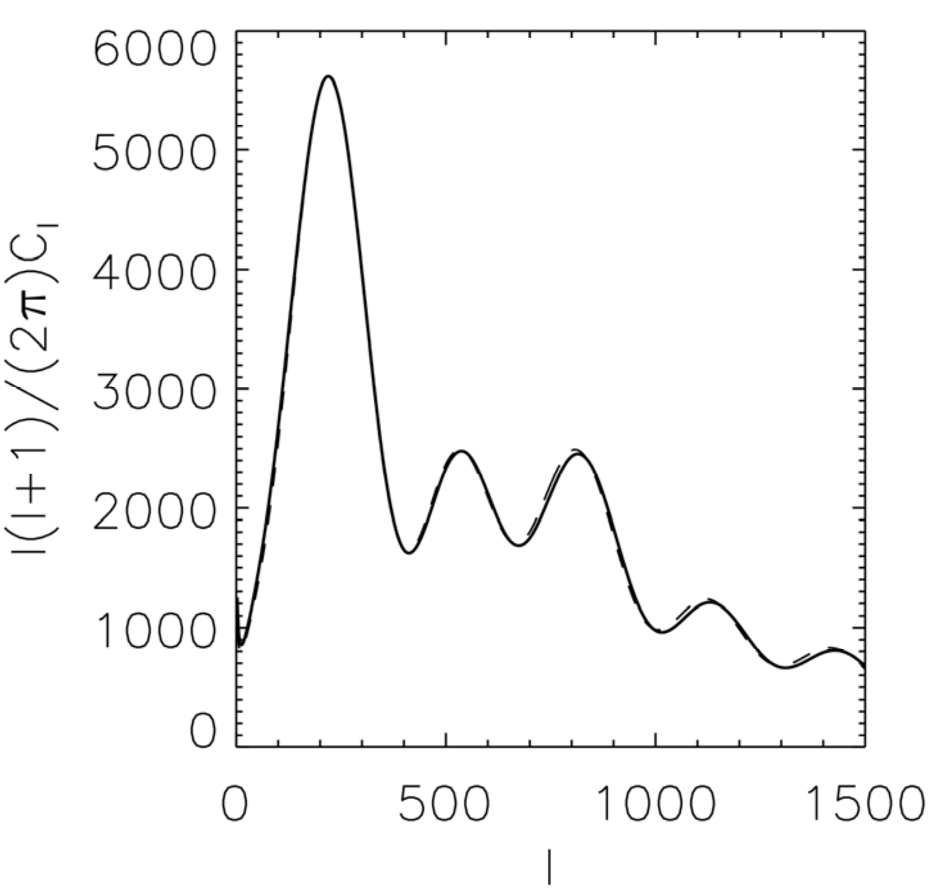
Relaxing the model II:

The comparison of WMAP to 2dF constrains the neutrino mass.

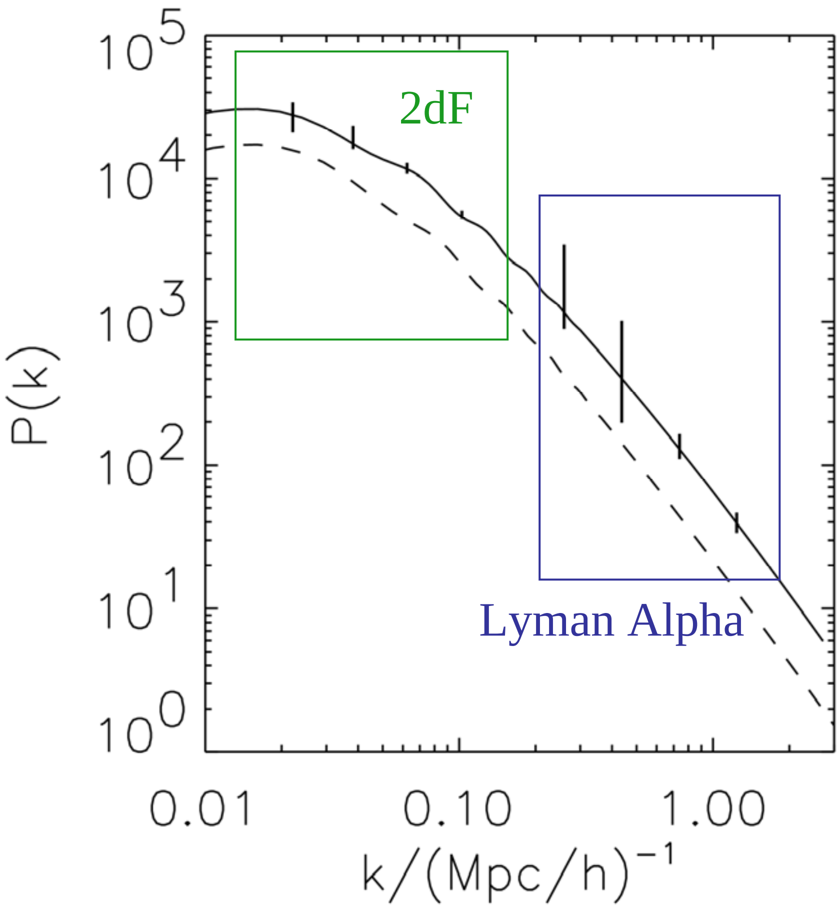
Massive neutrinos can hide in the CMB…

Solid: h=0.71 neutrino density=0

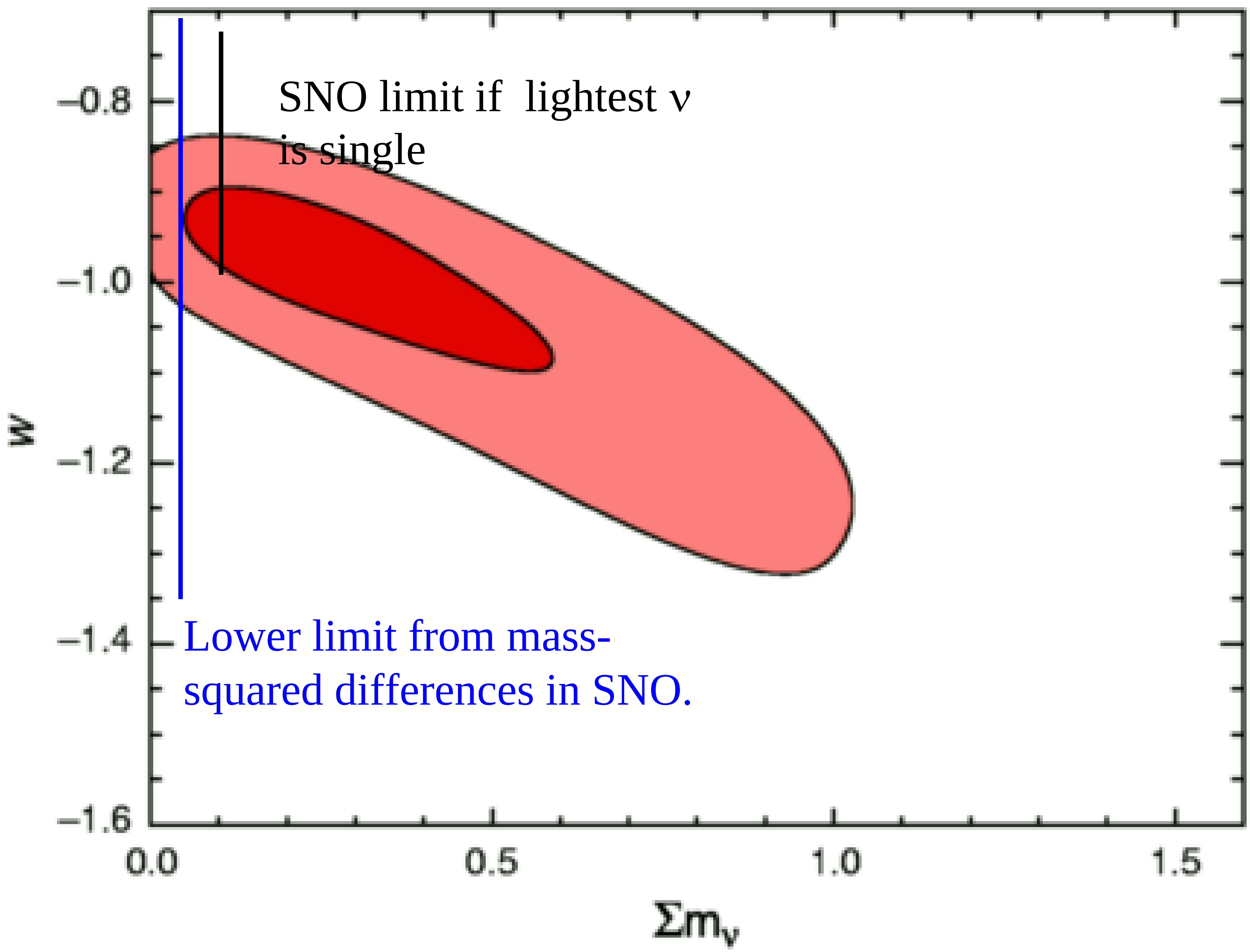
Dashed: h=0.60 neutrino density=0.02



... but at low redshift they are no longer relativistic and have a big effect on galaxy clustering.



We are moving toward a level of precision where we might usefully fit neutrino mass and w simultaneously. (We do still need a factor of 10!)



Relaxing III: Constraints on Inflation:

In monotonic inflationary potentials such as

$$V(\phi) \propto \phi^{\alpha}.$$

after N e-foldings, we expect the tensor/scalar ratio and spectral index to obey

$$r = 16\epsilon_1 \simeq \frac{4\alpha}{N}$$

$$1 - n_s = 2\epsilon_1 + \epsilon_2 \simeq \frac{\alpha + 2}{2N}$$

Inflationary expansion simultaneously drives the amplitude of fluctuations, and therefore Gravitational radiation, to zero and also drives towards a scale invariant spectrum, n=1.