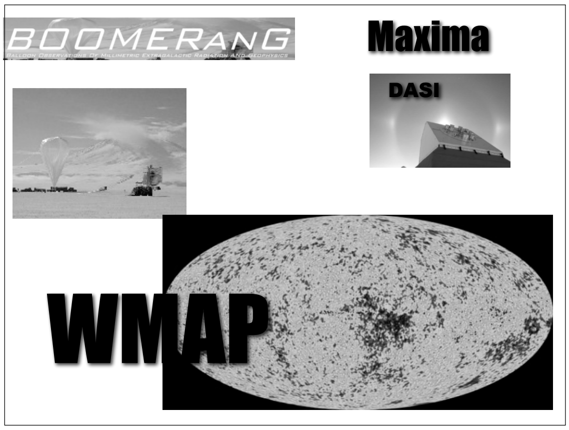
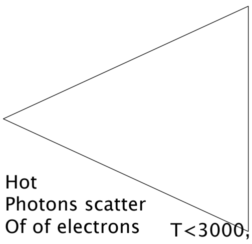
The Cosmic Microwave Background





Hot
Photons scatter
Of of electrons

T<3000, H recombines
Photons travel freely

Universe at z>1100 is hot, matter dominated, but still full of photons.

Basic paradigm assumes fluctuations are from inflation…quantum fluctuations at $t=10^{-35}$s are expanded by $\sim e^{60}$ times. The quantum fluctuations become the matter fluctuations across the entire universe…

On smaller scales, gravitational matter collapses in overdensities, but when this happens, pressure and temperature increase. Size scale is set by the speed of sound.
At any given time…speed of sound * age of Universe creates a sound-horizon, coherent scales where matter is falling in for the first time,
on smaller scales, matter has reverberated in and out…

Large Scales Fluctuations

- ***If we look at distances greater than 1.5 degrees on the sky, this material has not been in contact since the time of inflation***
- ***On these scales, then, any fluctuations we see will be the result of the primordial seeds.***

- ***Sachs-Wolf Effect***
  - ***In a potential Ψ , photons have two effects which change them.***
    - ***1) Gravitational Redshift***
    - ***2) Time dilation***

Large Scale Effects continued

$$\frac{\delta T}{T} = \frac{\Psi}{c^2} \text{ (Gravitational Redshift)}$$

$$\frac{\delta T}{T} = -\frac{da}{a} = -\frac{2}{3}\frac{dt}{t} = -\frac{2}{3}\frac{\Psi}{c^2} \text{ (Time Dilation)}$$

$$\frac{\delta T}{T} = \frac{\Psi}{c^2} - \frac{2}{3}\frac{\Psi}{c^2} = \frac{1}{3}\frac{\Psi}{c^2} \text{ (Sachs - Wolf Effect)}$$

$$a \propto t^{2/3} \text{ (Matter Dominated)}$$

$$\frac{da}{a} = \frac{2}{3}\frac{dt}{t}$$

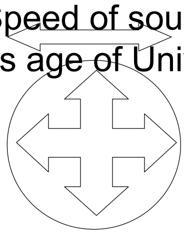
$$\frac{dt}{t} = \frac{\Psi}{c^2} \text{ (General Relativity)}$$

So any large scale perturbations in the density of the Universe, will show up as potential variations, and will lead to similar Temperature variations (1/3 strength) at sizes larger than the horizon size of the Universe.

At the largest scales - we only have a few samples of the Universe - and so there will be poisson noise here which we cannot get rid of.

Gravitational Collapse

Speed of sound
times age of Universe



Heating = Pressure

Estimate what we are going to see... How big will largest Structures be that we see in the Cosmic Microwave Background?

Ingredients:

- Recombination happens at 3000K
  - z~1100
- Age of the Universe at z~1100
  - t~370,000 years
- Speed of Sound - c/sqrt(3)
- Angular Size Distance (H_0=72, Ω_Λ=0.73, Ω_M=0.27)
  - 12.65 Mpc
- Size of sound horizon
  - ~0.6 degrees

Acoustic Basics

- Continuity Equation: (number conservation)

$$\dot{\Theta} = -\frac{1}{3} k v_\gamma$$

where $\Theta = \delta n_\gamma / 3 n_\gamma$ is the temperature fluctuation with $n_\gamma \propto T^3$

- Euler Equation: (momentum conservation)

$$\dot{v}_\gamma = k(\Theta + \Psi)$$

with force provided by pressure gradients $k\delta p_\gamma / (\rho_\gamma + p_\gamma) = k\delta\rho_\gamma / 4\rho_\gamma = k\Theta$ and potential gradients $k\Psi$.

- Combine these to form the simple harmonic oscillator equation

$$\ddot{\Theta} + c_s^2 k^2 \Theta = -\frac{k^2}{3}\Psi$$

where $c_s^2 \equiv \dot{p}/\dot{\rho}$ is the sound speed squared

Harmonic Peaks

- Adiabatic (Curvature) Mode Solution

$$[\Theta + \Psi](\eta) = [\Theta + \Psi](0)\,\cos(ks)$$

where the sound horizon $s \equiv \int c_s d\eta$ and $\Theta + \Psi$ is also the observed temperature fluctuation after gravitational redshift

- All modes are frozen in at recombination

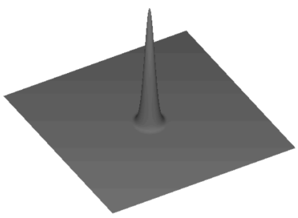
WayneHu_CMB.pdf

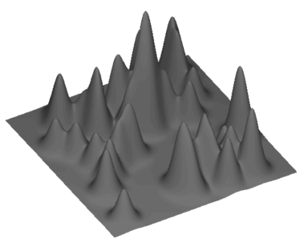
$$[\Theta + \Psi](\eta_*) = [\Theta + \Psi](0)\,\cos(ks_*)$$

- Modes caught in the extrema of their oscillation will have enhanced fluctuations

$$k_n s_* = n\pi$$

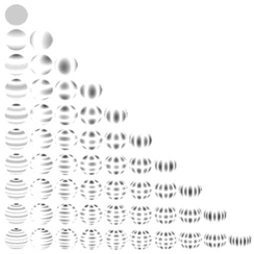
yielding a fundamental scale or frequency, related to the inverse sound horizon and series dependent on adiabatic assumption





Spherical Harmonics

- ***Cosmic Microwave Background Experiment measure temperature fluctuations on angular scales across the sky.***
- ***Want to find the average fluctuation on scales across the sky.***
- ***Use spherical Harmonics to describe the scales (dipole, quadrapole, octapole)…***
- ***Like a fourier series, the amplitude of the different scales, tells you the power (the strength) of the fluctuations on different scales.***



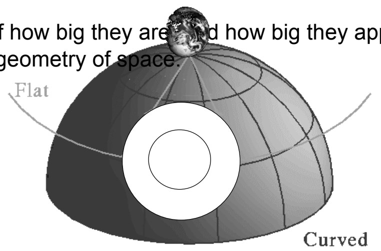
Putting it all together

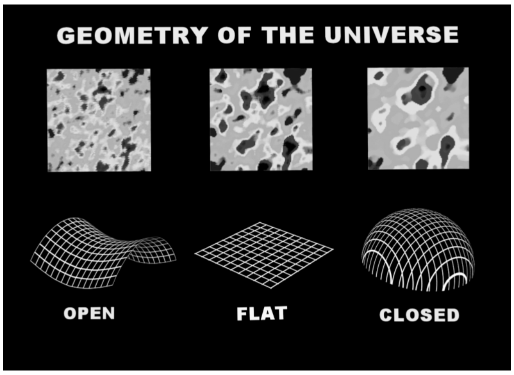
- ***Starting with gaussian scale-free perturbation spectrum, calculate how the Universe reverberates, then take a snap shot at z=1100, as the Universe suddenly becomes Transparent.***
- ***Taking into account the inherent temperature variations caused by the reverberations, and the Temperature variations caused by the Sachs-Wolf effect, calculate the variation as a function of scale, and project these onto the sky using the Angular-size distance.***
  - ***Universe doesn't become transparent instantly…Has the effect of washing out the smallest scales***

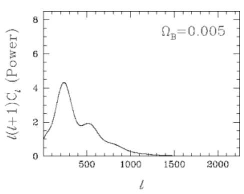
Physics how big (in meters) the blobs are in the cosmic microwave background.

Measurement tells us how big the blobs appear to us now.

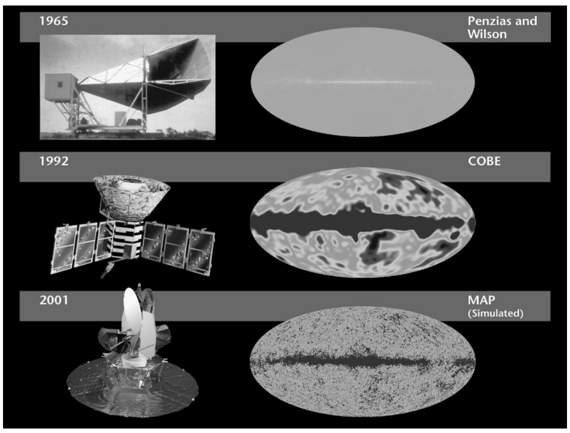
The Ratio of how big they are and how big they appear tells us the geometry of space.

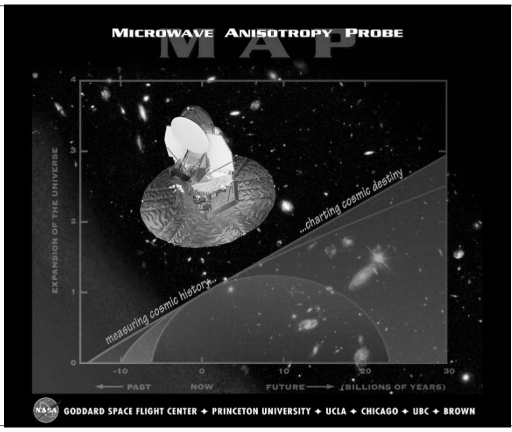


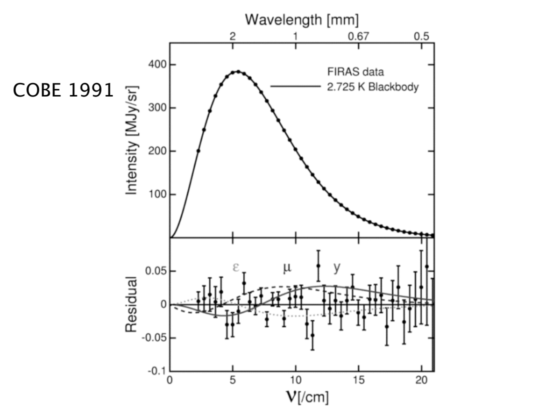


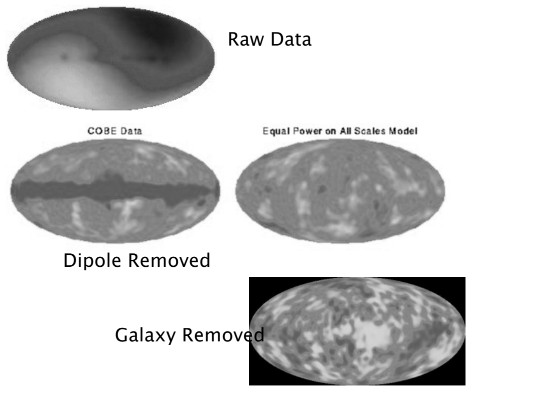


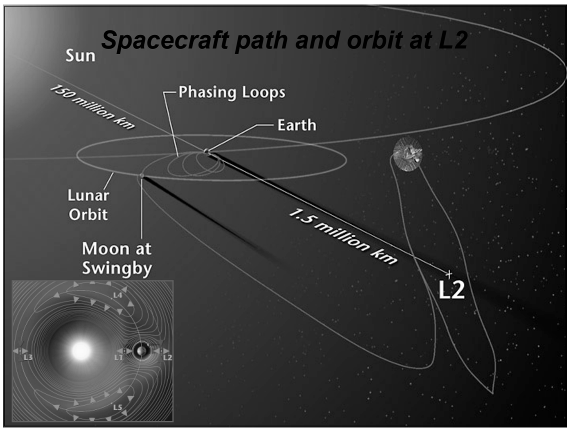
From Wayne Hu…





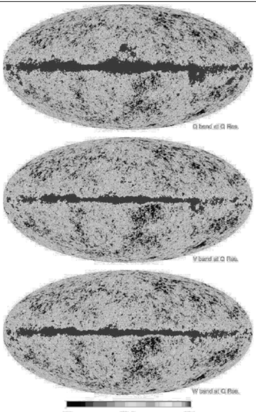






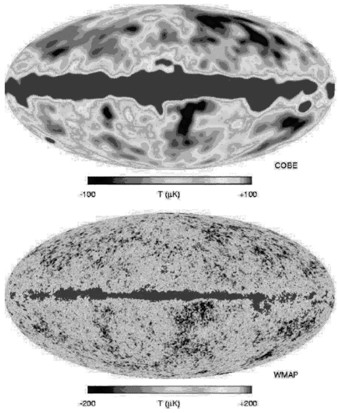
Calibrations, errors and maps

- ***WMAP team claim that systematic errors are well understood and controlled, based on multiple checks and detailed tests.***
- ***Calibration is based on the Earth-velocity modulation of the CMB dipole; claim calibration good to 0.5%.***
- ***Beam patterns are measured by observing Jupiter; the uncertainties in the beam pattern affect the window function.***



COBE vs WMAP

- ***Beamsize:***
  - ***COBE = 7°***
  - ***WMAP = 0.2°***
- ***Spectral coverage:***
  - ***COBE = 3 bands***
  - ***WMAP = 5 bands***

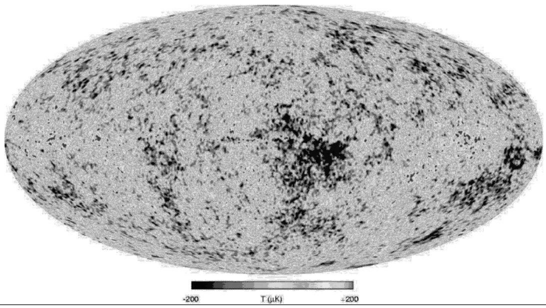


Foreground corrections

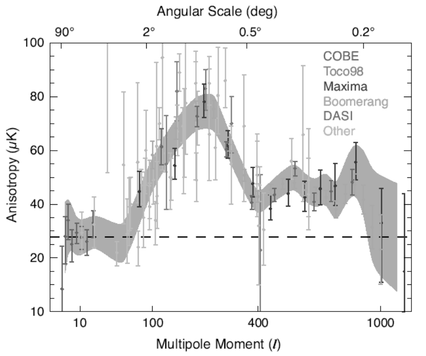
- ***Essential to correct for Galactic emission and extragalactic point sources. The CMB is separated from the foregrounds using the spectral information in the five WMAP bands.***
- ***Sky regions with bright foreground emission are masked.***
- ***Low-level diffuse emission removed by forming a map based on a MEM linear combination of the five bands - but this map has complex error properties and is not used in the analysis.***
- ***Cosmological parameters are derived from a map based on masking bright sources and subtracting foregrounds based on spectral templates for the various components (IRAS $\Rightarrow$ dust, 408MHz $\Rightarrow$ synchrotron radiation, Hα $\Rightarrow$ free-free ionized gas).***
- ***This method leaves rms foreground contaminations of <7μK in the Q-band and <3μK in the V and W bands for ℓ <15.***

WMAP's CMB anisotropy map

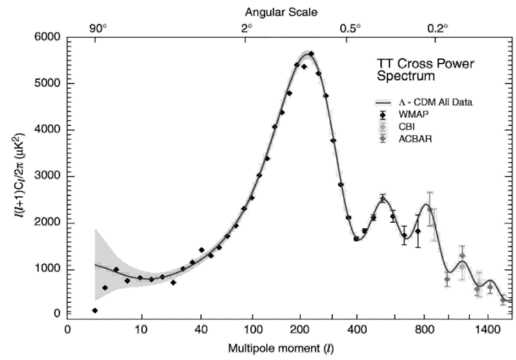
- ***'Best-buy' linear combination of the maps in the different bands, optimized to remove the foregrounds - but errors are complex, so not actually used in fitting cosmological models.***



Summary of previous CMB power spectra

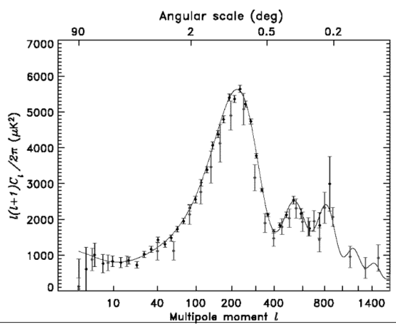


The CMB power spectrum from WMAP

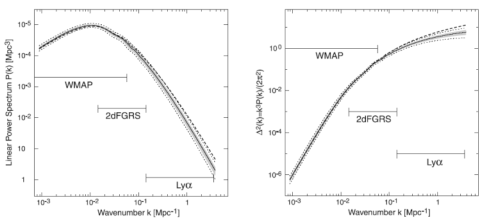


Comparison to previous CMB results

- ***The WMAP power spectrum is normalized ~10% higher at large multipoles compared to previous CMB results. (Why?)***



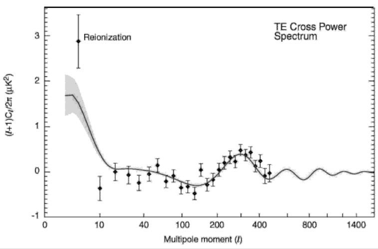
The Power Spectrum from all sources



Spergel et al. 2003

CMB polarization cross-correlated with temperature

- ***Use measurements of Stokes I parameter***
- ***The temperature-polarization (TE) cross-power spectrum shows:***
  - ***correlations on large scales (low l) due to re-ionization***
  - ***correlations on small scales from adiabatic fluctuations***



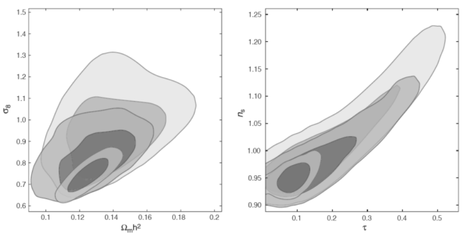
Draft: March 17, 2006

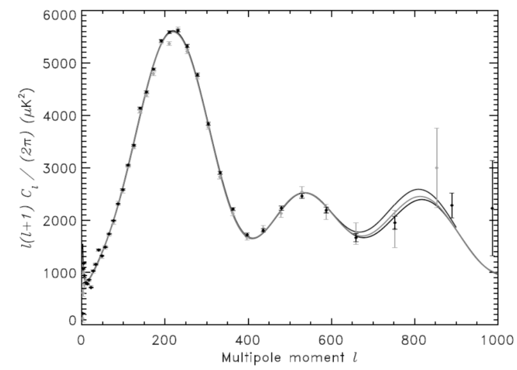
Wilkinson Microwave Anisotropy Probe (WMAP) Three Year Results: Implications for Cosmology

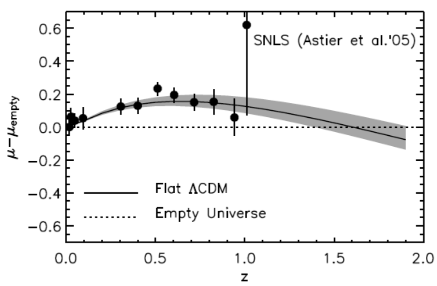
D. N. Spergel[1,2], R. Bean[1,3], O. Doré[1,4], M. R. Nolta [4,5], C. L. Bennett[6,7], G. Hinshaw[6], N. Jarosik [5], E. Komatsu [1,8], L. Page[5], H. V. Peiris [1,9,10], L. Verde [1,11], C. Barnes[5], M. Halpern [12], R. S. Hill[6,15], A. Kogut [6], M. Limon [6], S. S. Meyer [9], N. Odegard [6,15], G. S. Tucker [13], J. L. Weiland[6,15], E. Wollack [6], E. L. Wright [14]

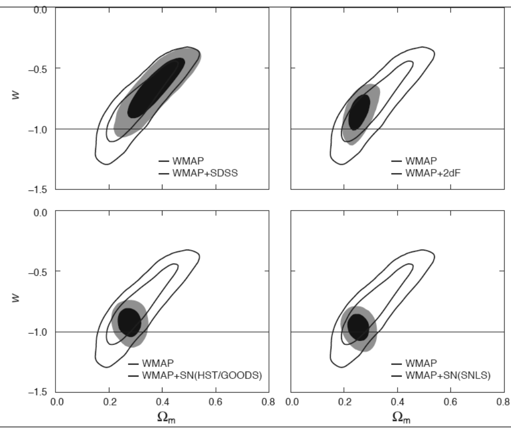
dns@astro.princeton.edu

Cosmology



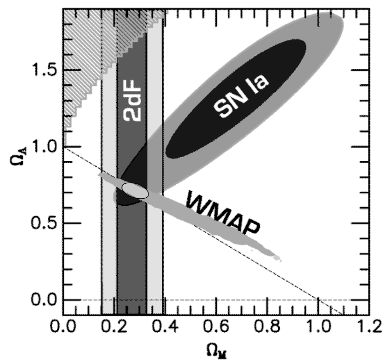






The Cosmic Timeline

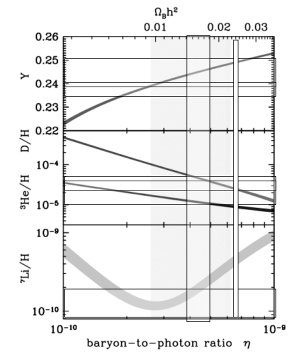
- ***CMB last scattering surface: (WMAP)***
  t_{dec} = 379 ± 8 kyr
  (z_{dec} = 1089 ± 1)
- ***Epoch of re-ionization?: WMAP and QSOs seem to disagree a bit –***
  t_r = 300 - 1000 Myr
- ***Age of the universe today: SN +WMAP agree very well***
  t_0 = 13.7 ± 0.2 Gyr
- ***Hubble constant: (CMB+2dF, or Cepheids + SN Ia)***
  H_0 = 71 ± 4 km/s/Mpc



The 'Concordance model'

(WMAP + 2dFGRS + SN Ia + HST KP)

Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< −0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	T_{cmb}	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.5}$	0.44	0.04	0.05
Power spectrum normalization (at k_0 = 0.05 Mpc^{-1})[c]	A	0.833	0.086	0.083
Scalar spectral index (at k_0 = 0.05 Mpc^{-1})[c]	n_s	0.93	0.03	0.03
Running index slope (at k_0 = 0.05 Mpc^{-1})[c]	$dn_s/d\ln k$	−0.031	0.016	0.018
Tensor-to-scalar ratio (at k_0 = 0.002 Mpc^{-1})	r	< 0.71	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	195	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2
Age at decoupling (kyr)	t_{dec}	379	8	7
Age at reionization (Myr, 95% CL))	t_r	180	220	80
Decoupling time interval (kyr)	Δt_{dec}	118	3	2
Redshift of matter-energy equality	z_{eq}	3233	194	210
Reionization optical depth	τ	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_r	20	10	9
Sound horizon at decoupling (°)	θ_A	0.598	0.002	0.002
Angular diameter distance to decoupling (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale[d]	ℓ_A	301	1	1
Sound horizon at decoupling (Mpc)[d]	r_s	147	2	2

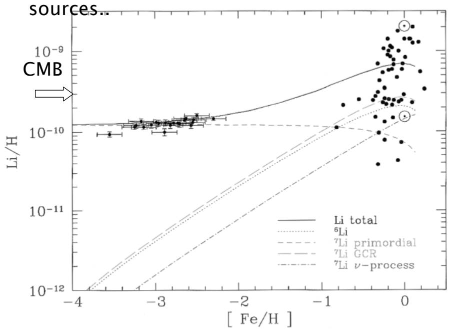


OK

OK

Yuk!

Lithium does evolve slowly due to SN? Or other sources..



Choose stars without convective envelopes…Measure…