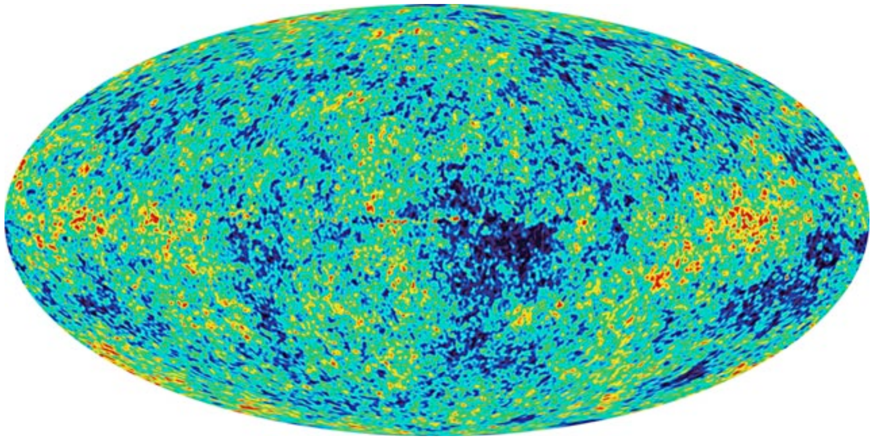
Structures et leur évolution

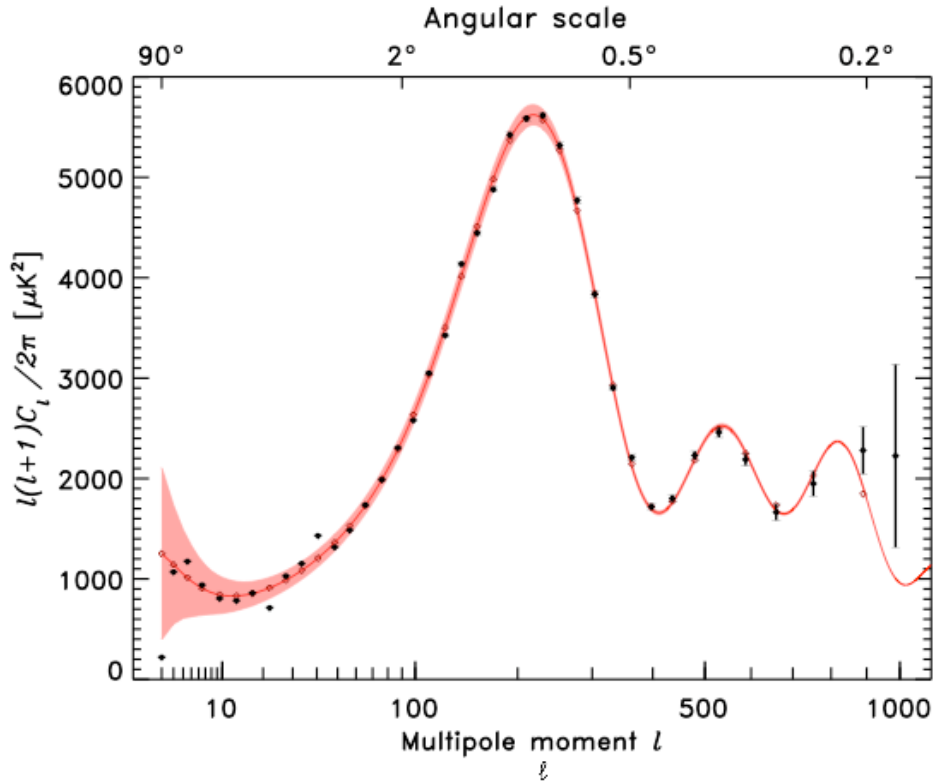
Cours 7 : Le fond cosmologique (CMB)

The Temperature Anisotropies



$$\Delta_T(\hat{n}) = \sum a_{lm} Y_{lm}(\hat{n})$$

Random variables



$$\langle a_{lm} \rangle = 0$$

$$\langle a_{lm} a^*_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

Statistical isotropy

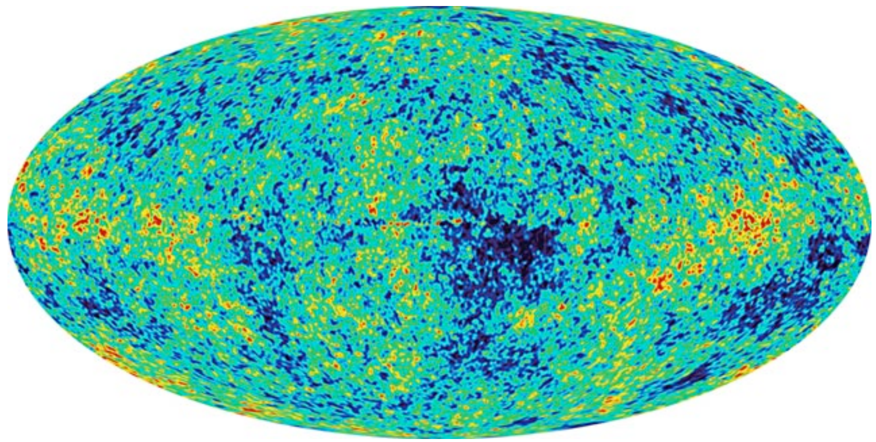
Angular power spectrum

Cosmic Variance

Given an all-sky map, we define the power spectrum estimator as:

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

We have $2l+1$ independent measurements to estimate the variance C_l at given l



- Unbiased estimator:

$$\langle \hat{C}_l \rangle = C_l$$

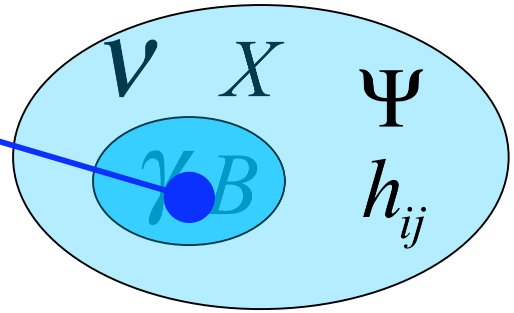
- Variance of estimator:

$$Var(\hat{C}_l) = \frac{2}{2l+1}C_l^2$$

Cosmic Variance
Intrinsic: one sky

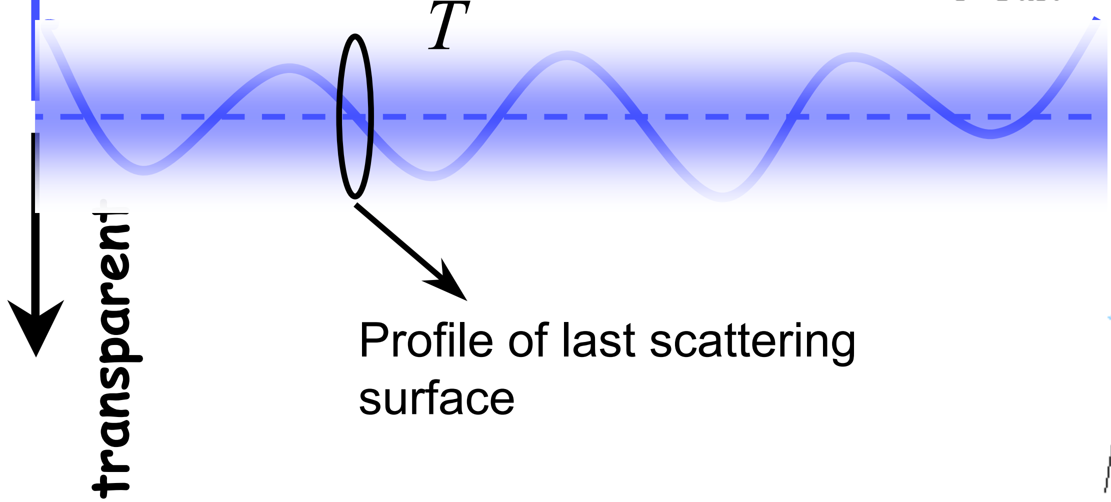
Sources of Anisotropy

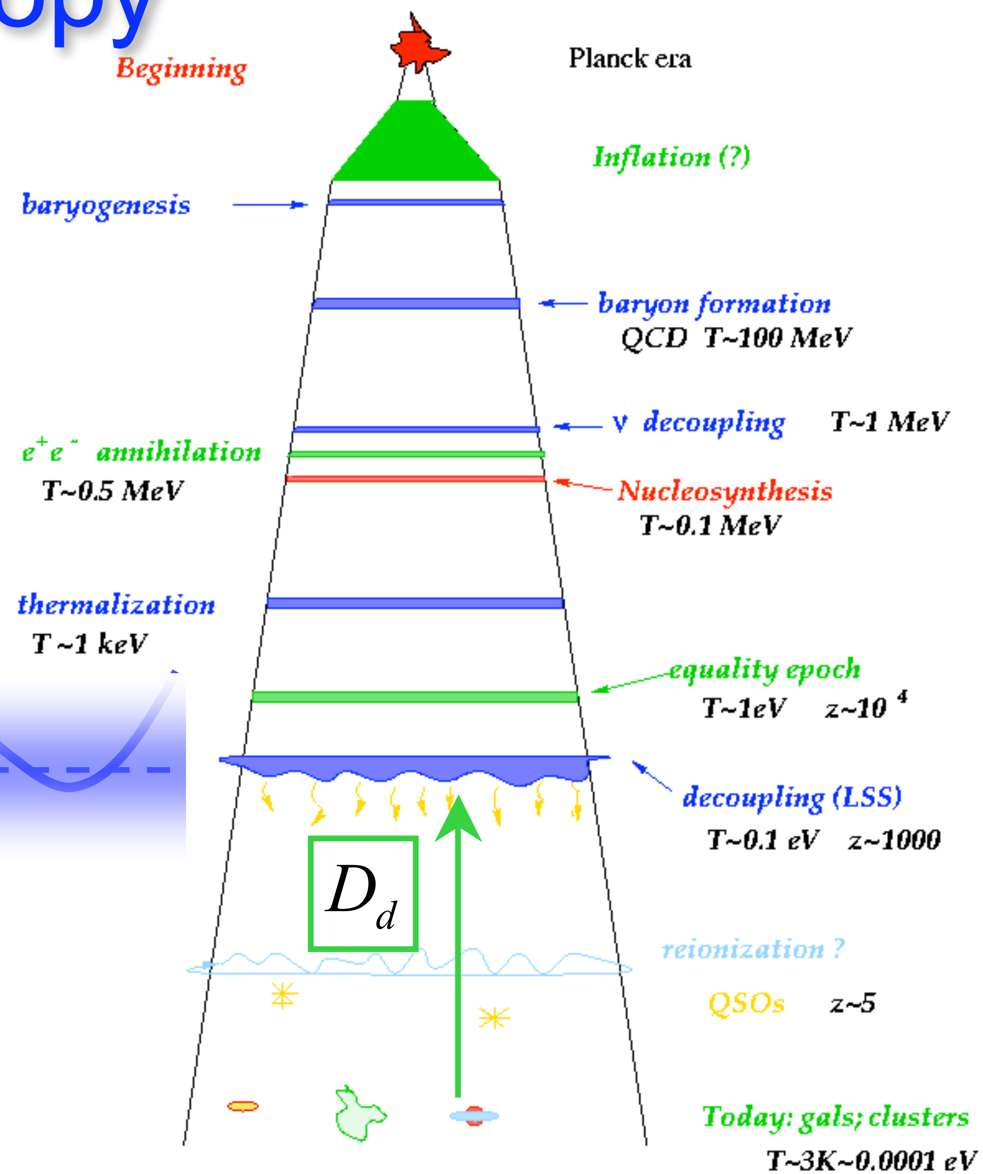
~perfect fluid:



~ density and velocity perturbations present

$$\Theta \equiv \frac{\Delta T}{T}$$





Baryon-photon fluid

$$\rho = \rho_B + \rho_\gamma$$
$$p = p_B + p_\gamma \approx \frac{1}{3}\rho_\gamma$$

Photon/pressure dominated

adiabatic

$$c_s^2 = \delta p / \delta\rho$$

$$\Theta \equiv \frac{\Delta T}{T} = \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho}$$

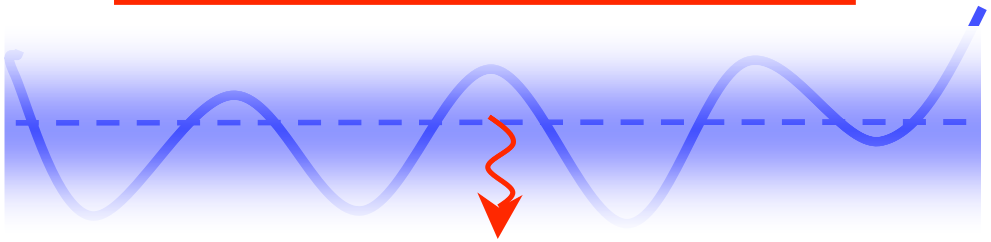
Oscillations (sound waves)

$$\boxed{\Theta(k,\tau) \approx A\cos(ks+\delta) \qquad s = \int_0^\tau d\eta\, c_s}$$

Initial conditions

$$\Theta(k,0) = -\frac{2}{3}\Psi$$
$$\dot{\Theta}(k,0) = 0$$

Curvature perturbations (scalar metric perts)

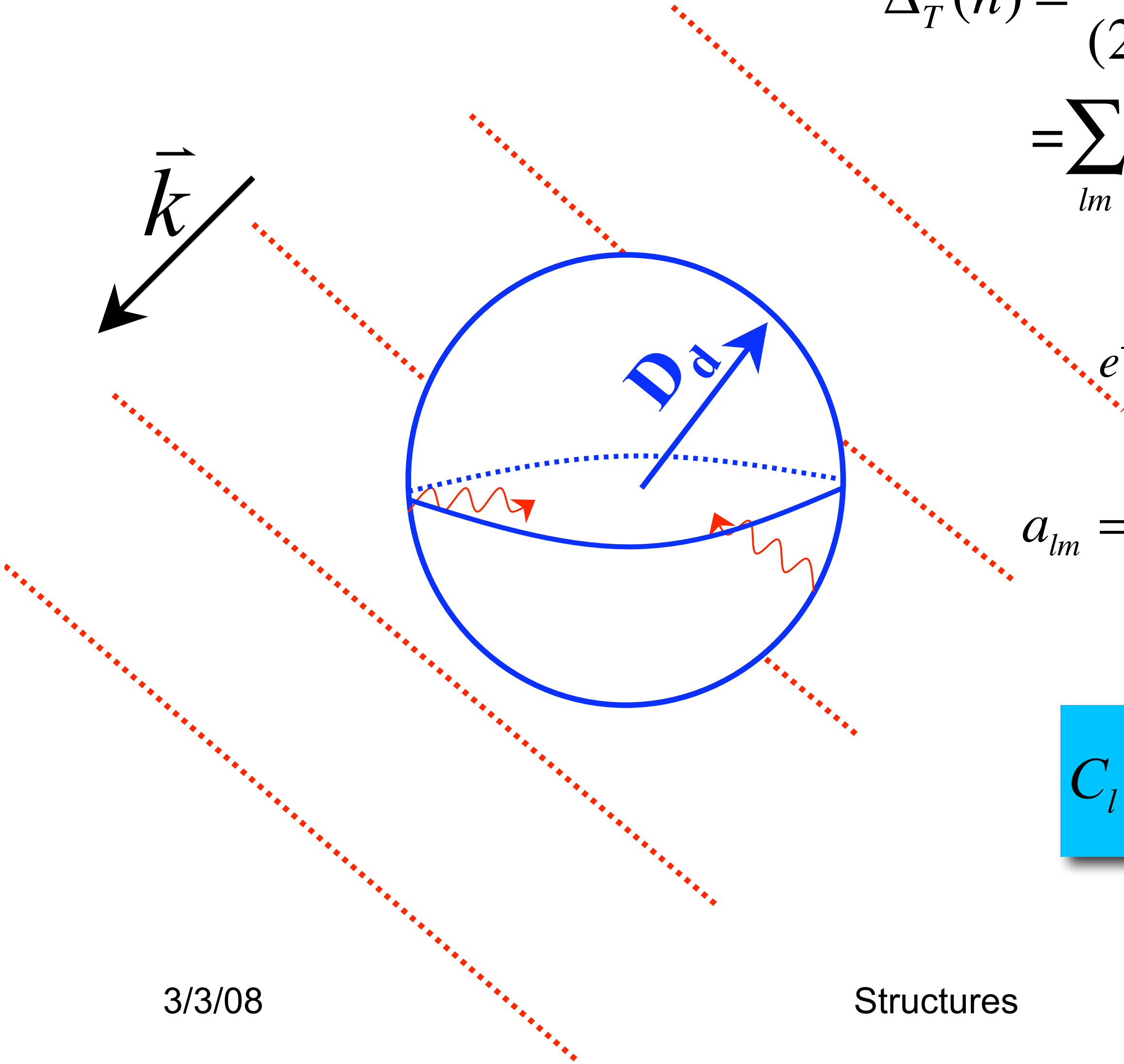


$$\boxed{\Theta + \Psi}$$

Over-dense/hot region

➔ Gravitational redshift

Projection onto the Sky



$$\Delta_T(\hat{n}) = \frac{1}{(2\pi)^3}\int d^3k\,[\Theta+\Psi](k,\tau_d)\,e^{-i\vec{k}\cdot D_d\hat{n}}$$

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

$$e^{-i\vec{k}\cdot\vec{x}} = 4\pi\sum_{lm}(-i)^l\, j_l(kx)\,Y_{lm}^*(\hat{k})\,Y_{lm}(\hat{x})$$

$$a_{lm} = \frac{i^l}{2\pi^2}\int d^3k\,[\Theta+\Psi]\,j_l(kD_d)\,Y_{lm}^*(\hat{k})$$

$$\boxed{C_l = 4\pi\int\frac{dk}{2\pi^2}\,\underbrace{j_l^2(kD_d)}\,k^2 P_\Theta(k)}$$

Peak: $l \sim kD_d$

$$\boxed{(\Psi \approx const)}$$

$$\Theta(k,\tau)+\Psi(k,0)=\Psi(k,0)\left(1-\frac{2}{3}\cos(ks)\right)$$

$$v=\frac{1}{\sqrt{3}}\Psi(k,0)\sin(ks)$$

Coherent

$$\boxed{\delta = 0 \quad \forall k}$$

$$\Theta(k,\tau_d)+\Psi \xrightarrow[ks_d \ll 1]{} \frac{1}{3}\Psi(k,0)$$

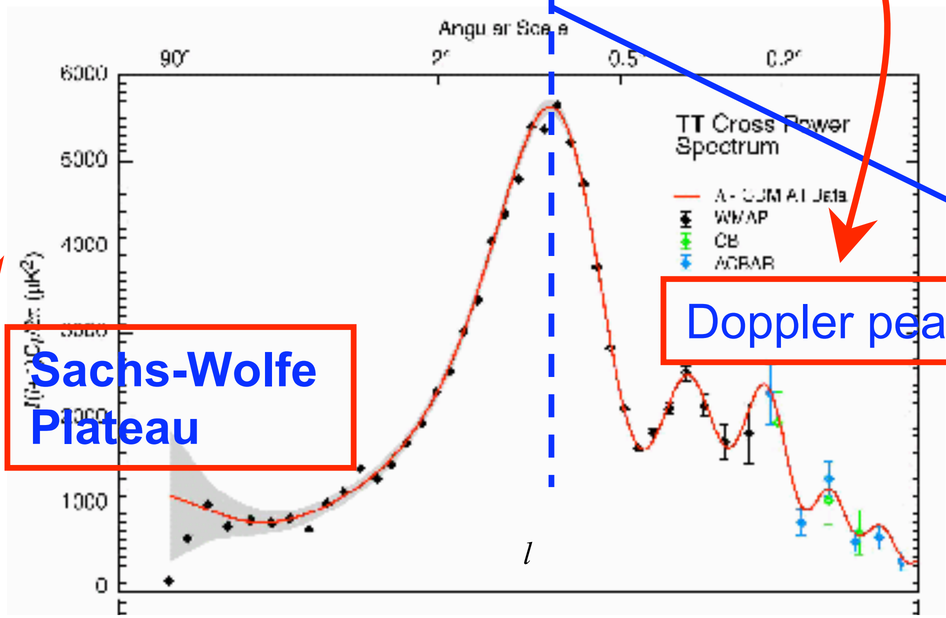
Large scales: initial conditions

$$\Theta(k,\tau_d)+\Psi \xrightarrow[ks_d \gg 1]{} \text{oscillations}$$

Small scales: sound waves

$$s_d = \int_0^{\eta_d} d\eta\, c_s$$

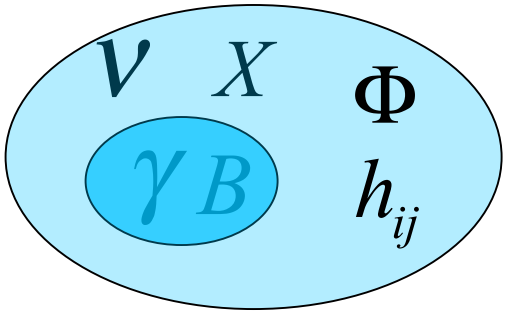
(Sound) Horizon at decoupling



Sachs-Wolfe Plateau

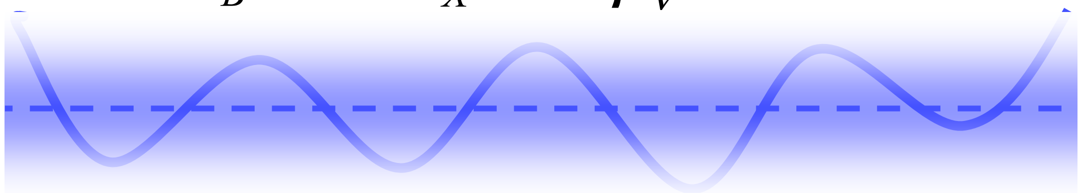
Doppler peaks

$$l_d \sim \frac{D_d(H_0,\Omega,\Lambda)}{s_d}$$



Relative heights
= fluid composition

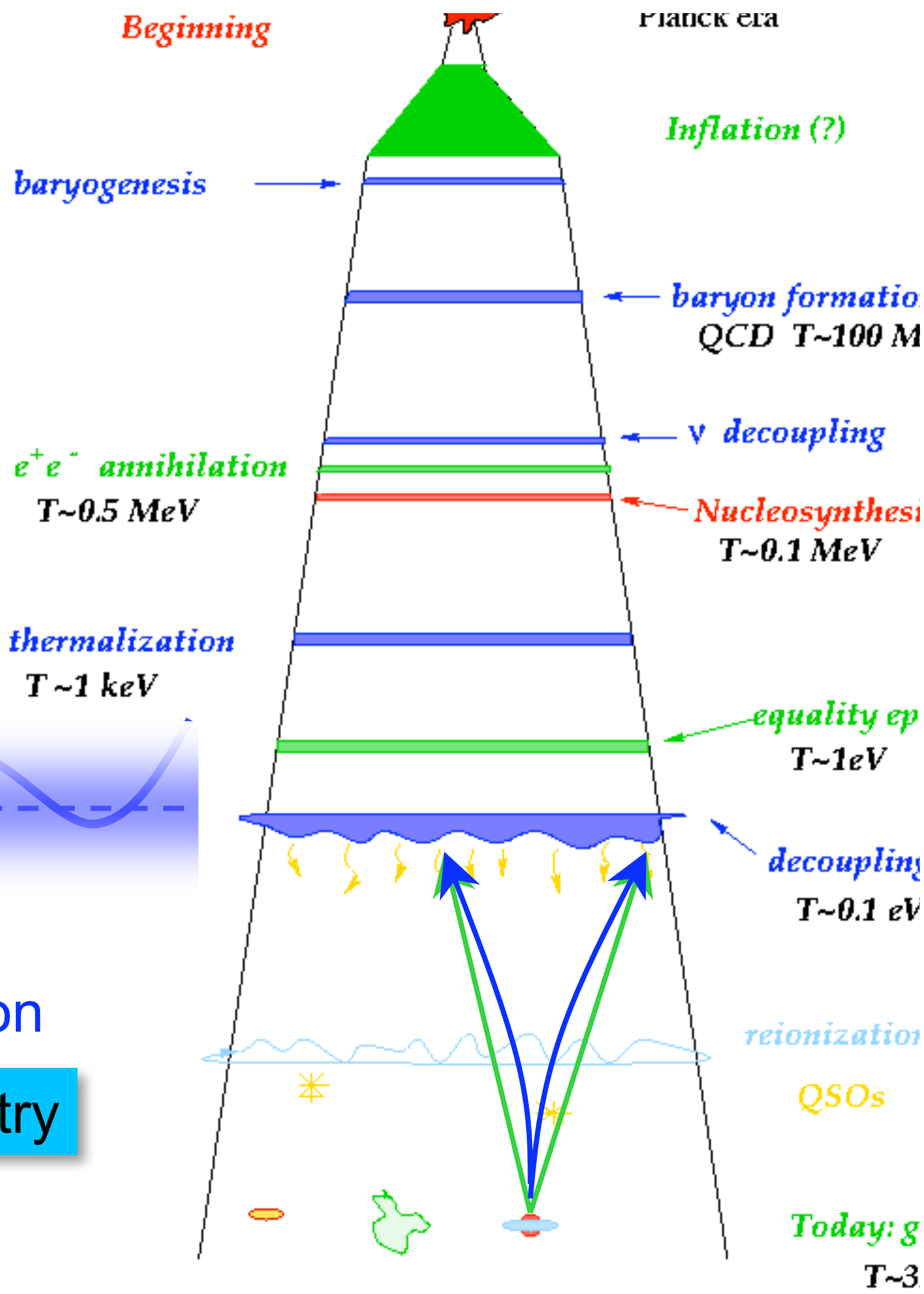
ρ_γ $\Omega_B h^2$ $\Omega_X h^2$ ρ_ν



Flat space projection

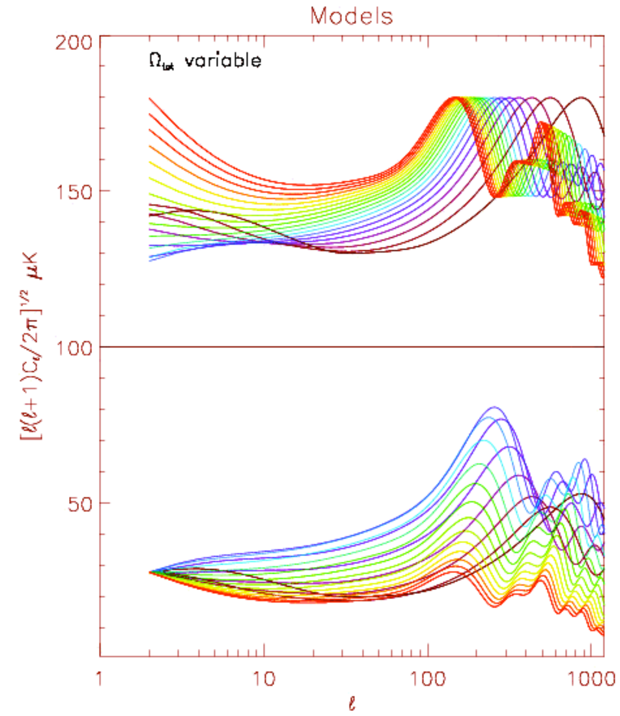
Curved space projection

Peak position ~ Geometry



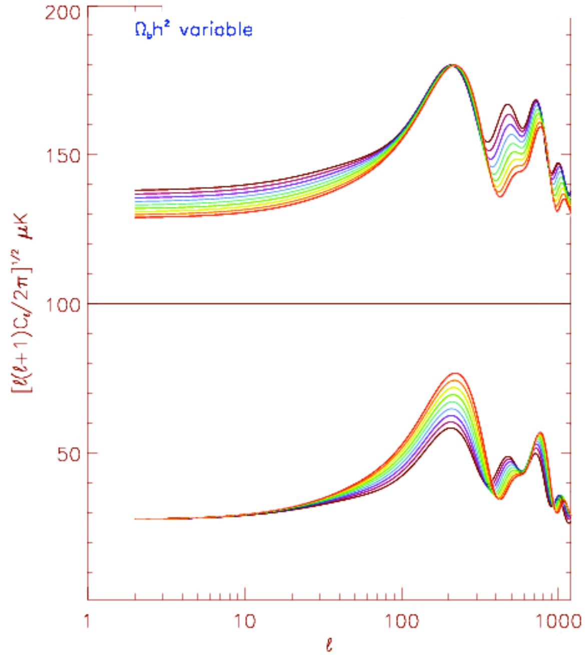
Peak position/separation

geometry



Peak *heights*

densities



(M. Douspis/
M. Le Dour)

CMBFast

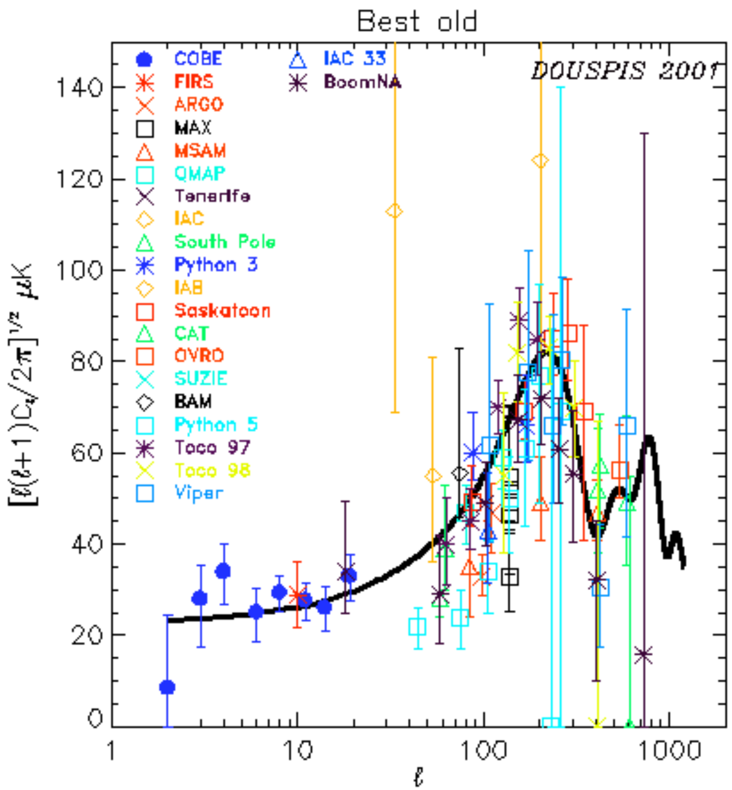
$$h^2 = \frac{\Omega_B h^2 + \Omega_X h^2}{1 - \Omega_\Lambda - \Omega_R}$$

Some Results

✸CMB anisotropies: 3 generations...

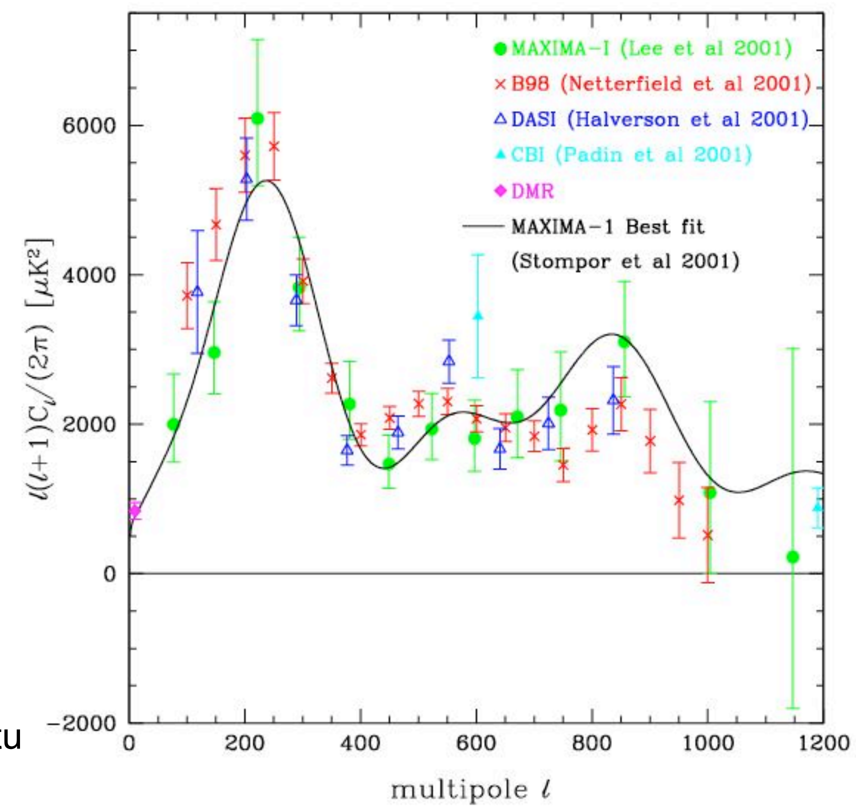
First generation

Douspis et al.
http://webast.ast.obs-mip.fr/cosmo/CMB



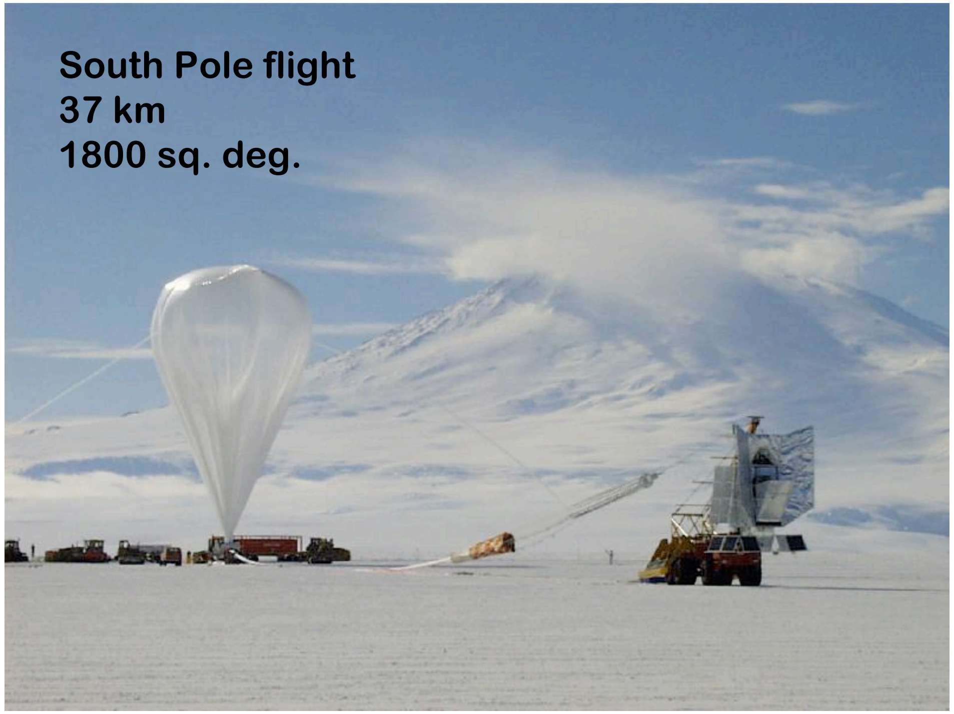
BOOMERanG/MAXIMA/
DASI

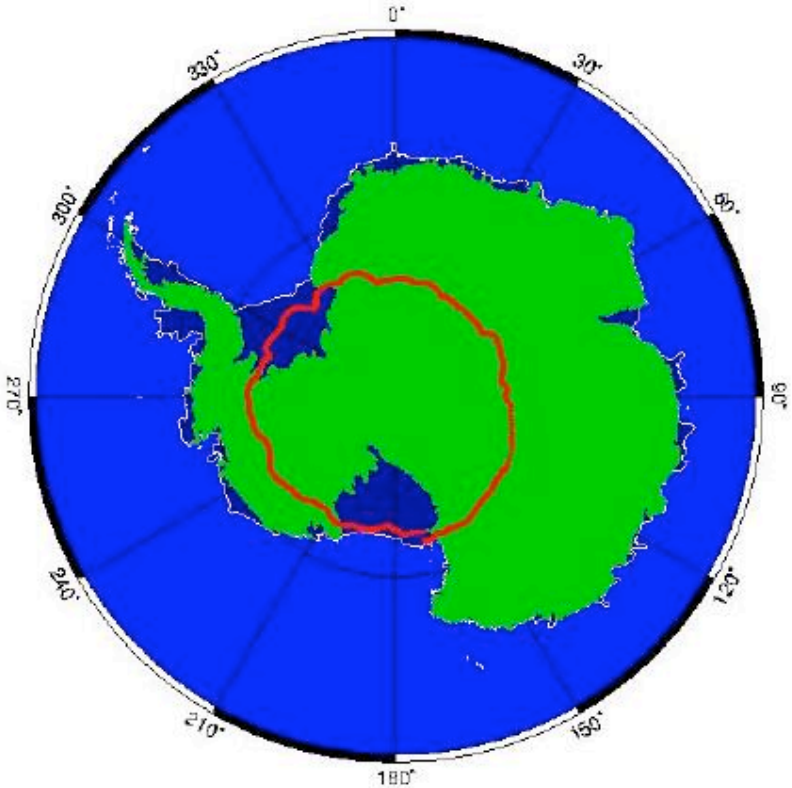
MAXIMA team (http://aether.lbl.gov/)



Structu

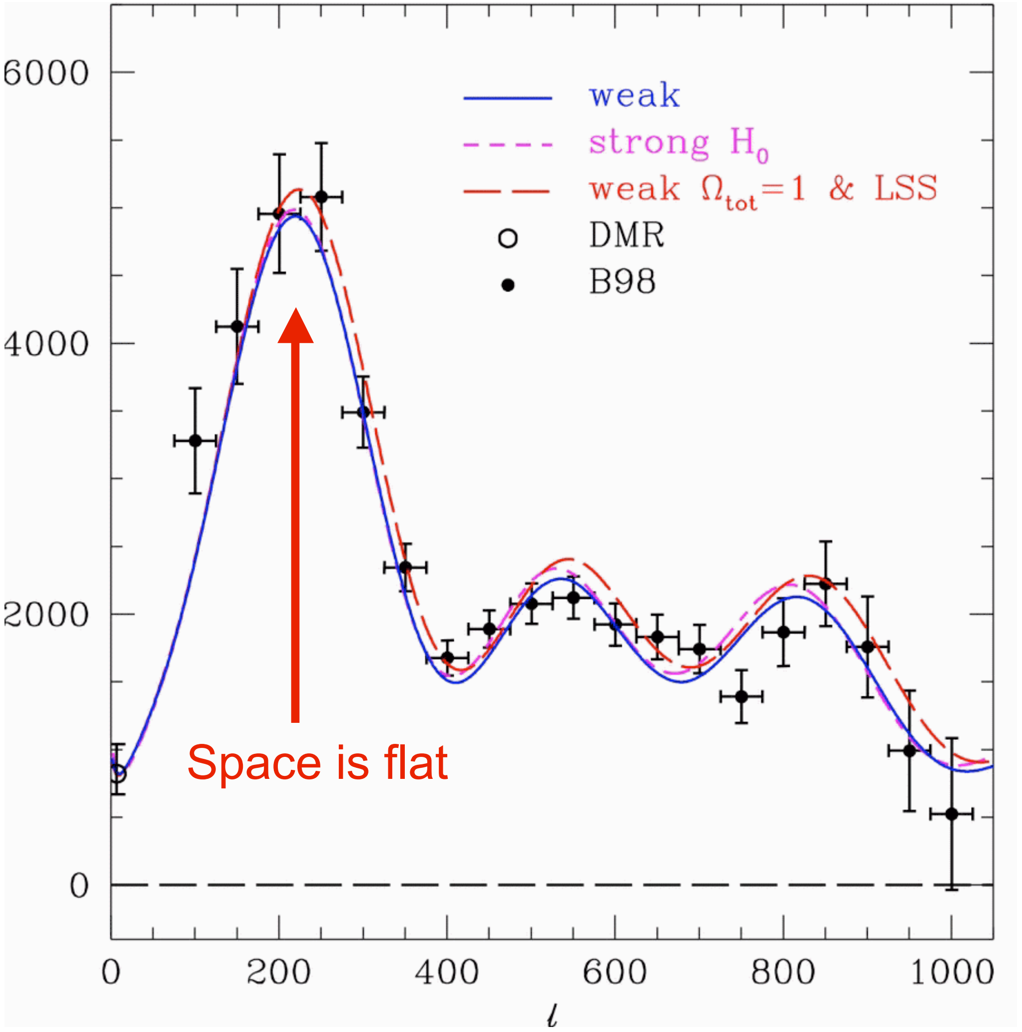
BOOMERanG:
(29 Dec 1998 - 9 Jan 1999)



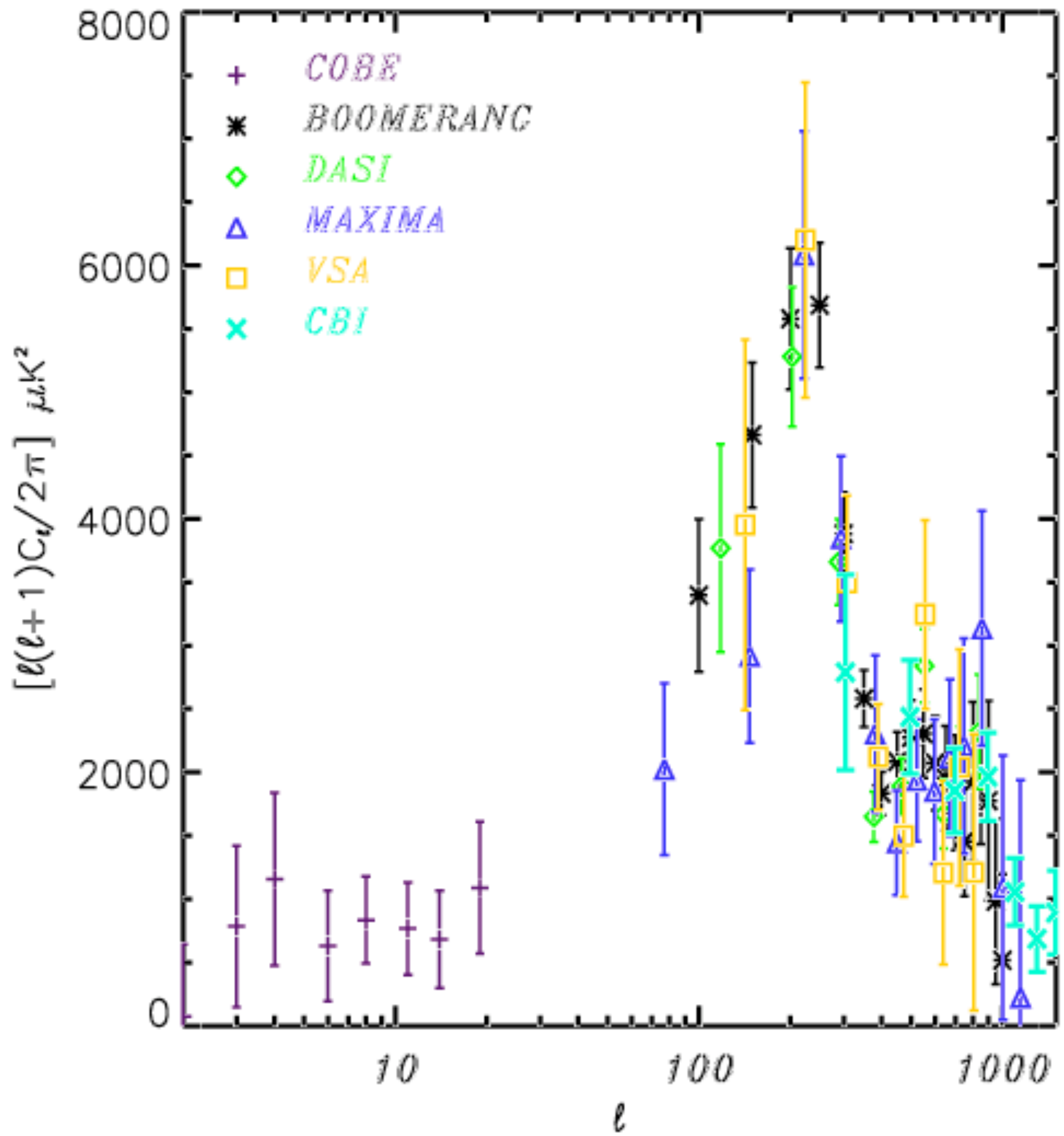


BOOMERanG (Results 2000)

South Pole flight



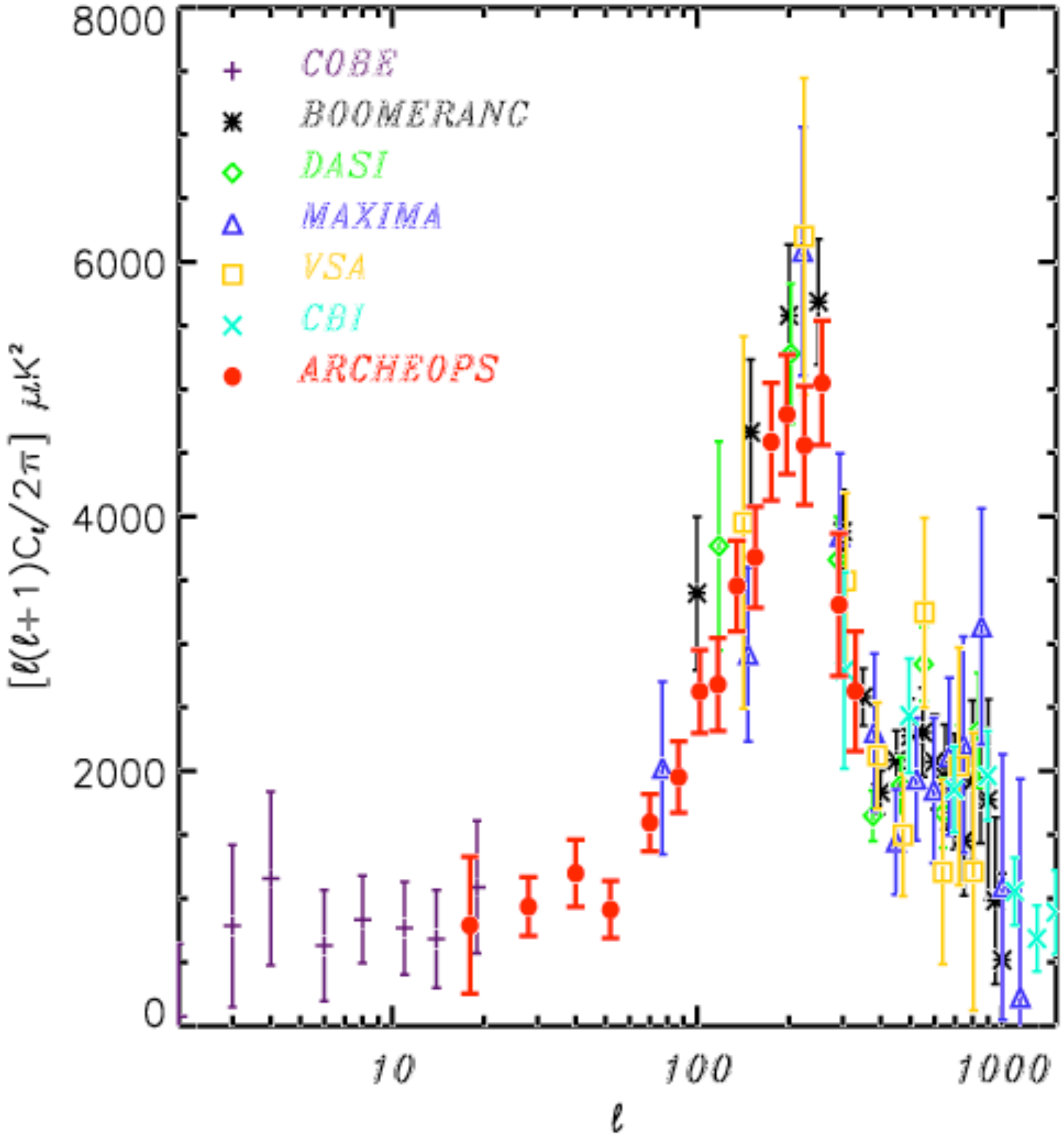
Before Archeops



Archeops

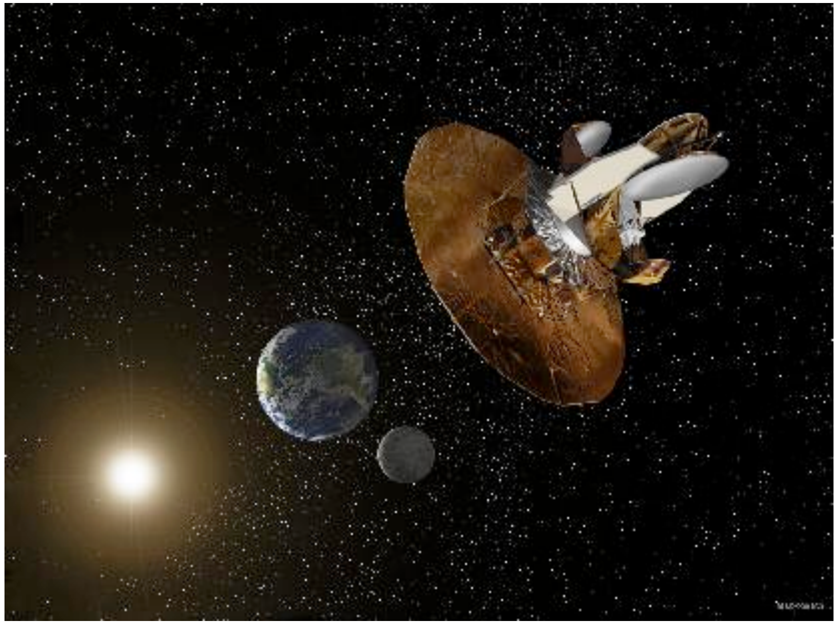
Une seul expérience couvre des échelles de COBE au premier pic acoustique

Benoît et al. 2003



Wilkinson Microwave Anisotropy Probe (WMAP)

- Launch: June 30, 2001
- Orbit at L2
- All-sky observations
- First-year data release: 2/2003
- Three-year data release: 3/2006
  - Polarization data
- Five-year data release: 3/2008

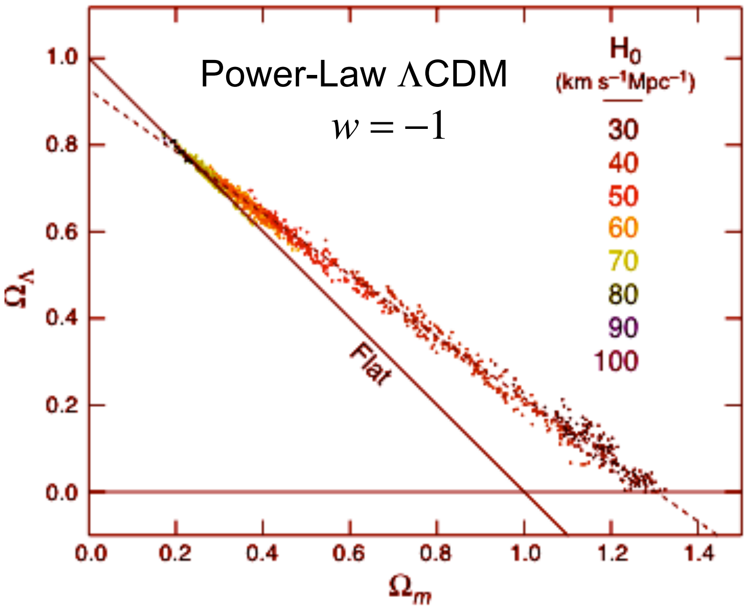


Space is Flat

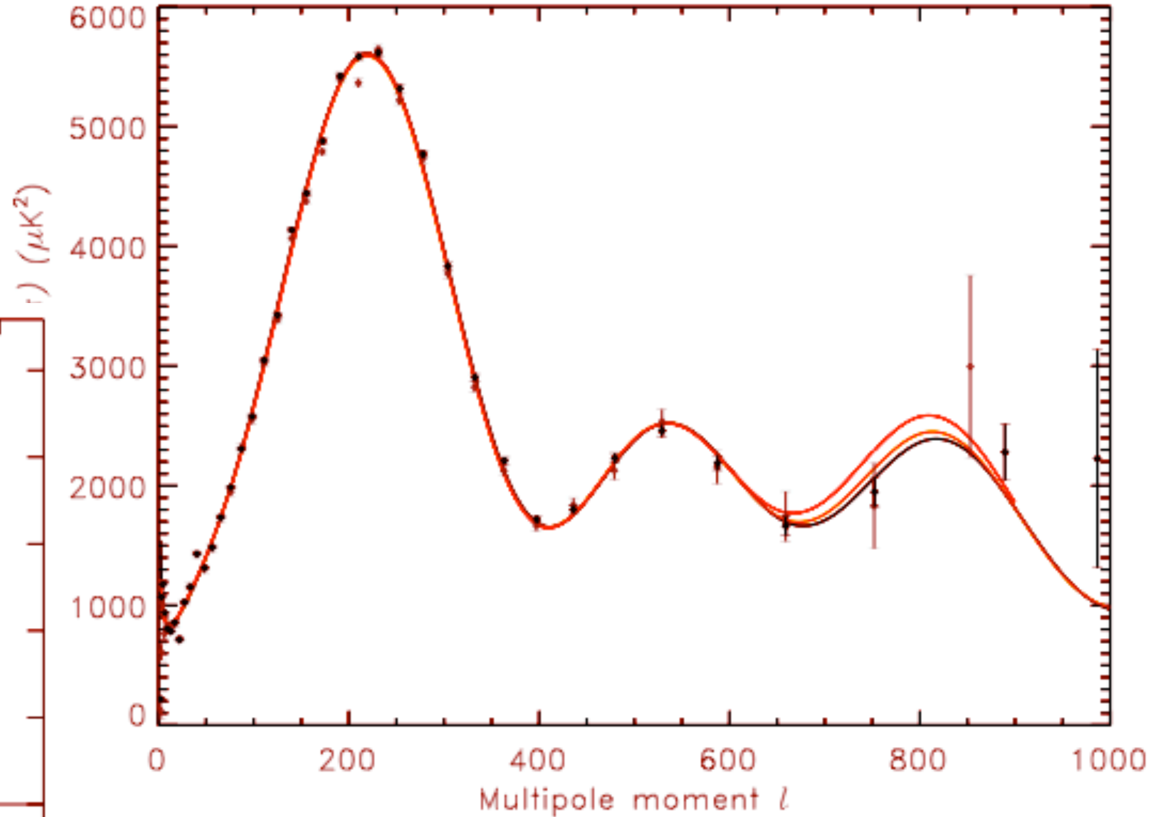
WMAP 3
+ HST: $h = 0.72 \pm 0.08$
(Freedman et al. 2001, ApJ 553, 47)

$$\Omega_K = -0.003 \pm^{0.013}_{0.017}$$

$$\Omega_\Lambda = 0.758 \pm^{0.035}_{0.058}$$



WMAP 3 year data results: *Spergel et al. 2006*



WMAP3 Constraints

Spergel et al. 2007

$\boxed{\text{Power-law } \Lambda\text{CDM}}$

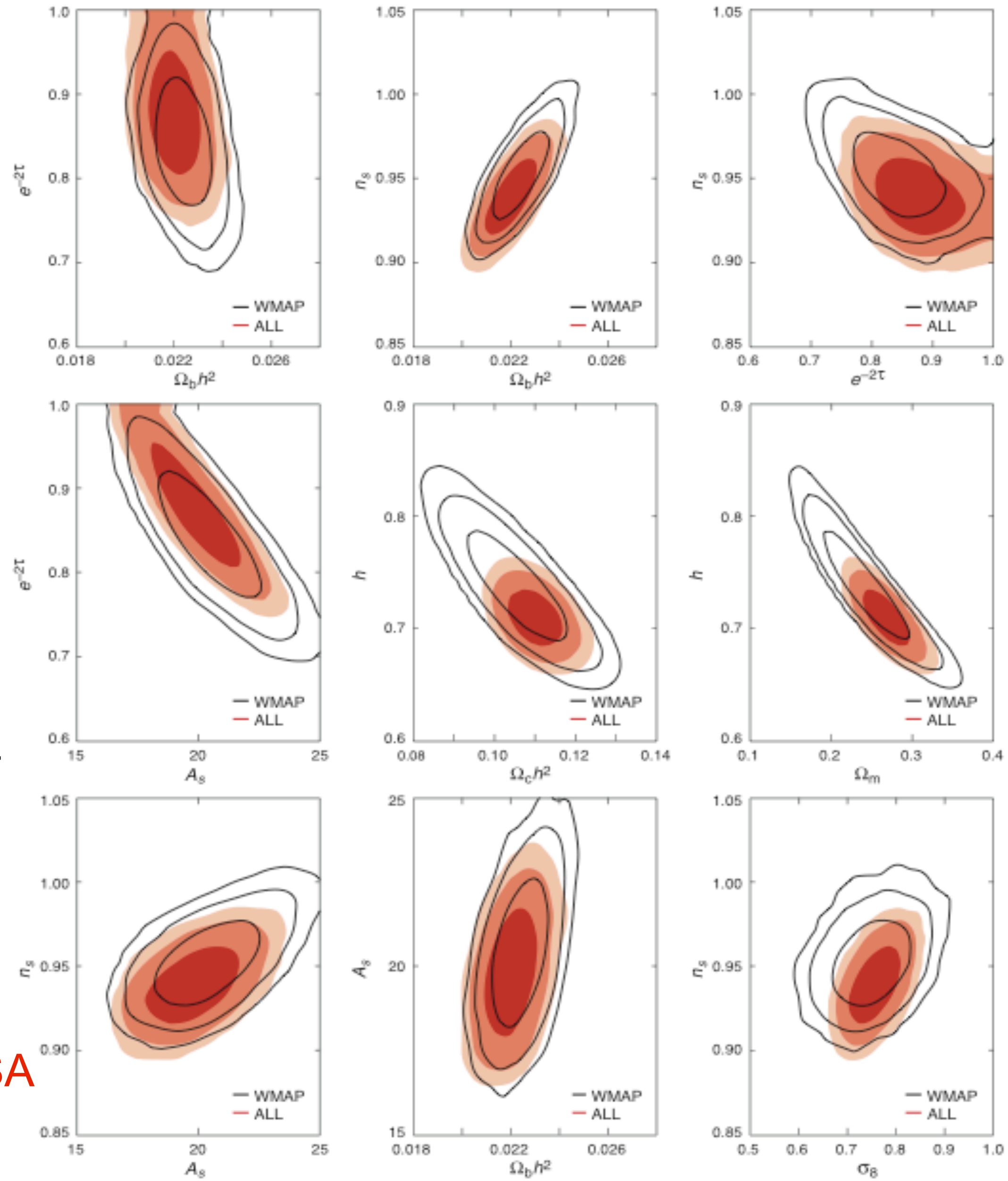
$$\Omega_M h^2 = 0.127 \pm^{0.007}_{0.013}$$

$$\Omega_B h^2 = 0.0223 \pm^{0.0007}_{0.0009}$$

$h = 0.73 \pm^{0.03}_{0.03}$ Consistent with HST

$$n_s = 0.951 \pm^{0.015}_{0.019} \quad (<1 @ 3\sigma)$$

ALL = WMAP+2dFGRS+SDSS
+ACBAR+BOOMERanG+CBI+VSA
+SN(HST/GOODS)+SN(SNLS)



CMB: WMAP 3 Year Results

Assuming flat ΛCDM:

$\Omega_B h^2 = 0.022 \pm^{0.072}_{0.091}$ =BBN

$\Omega_M h^2 = 0.1268 \pm^{0.0073}_{0.0128}$ $> \Omega_B h^2$

With h from HST: $\Omega_M \simeq 0.25$

$\sigma_8 = 0.744 \pm^{0.050}_{0.060}$

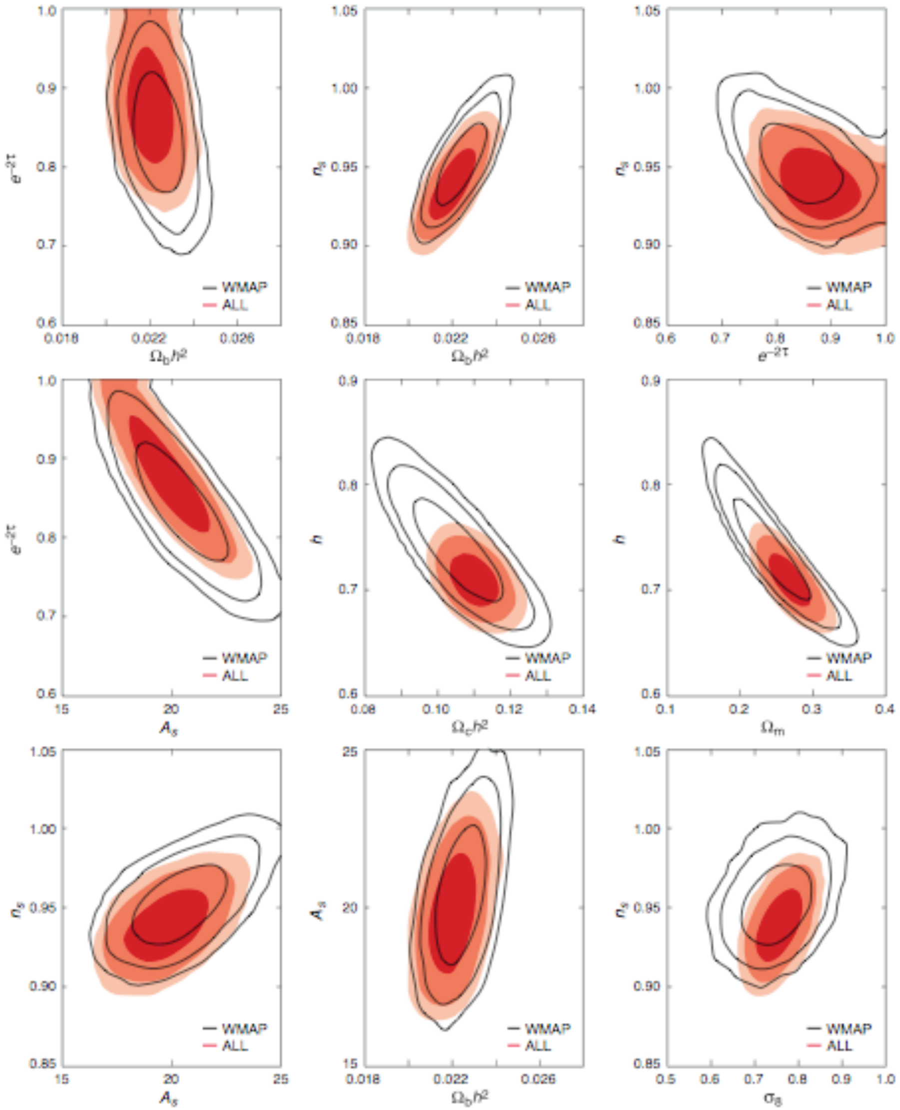
$n_s = 0.951 \pm^{0.015}_{0.019}$ $< 1\ldots$

$\tau = 0.088 \pm^{0.028}_{0.034}$

General ΛCDM + HST:

$\Omega_K = -0.003 \pm^{0.013}_{0.017}$

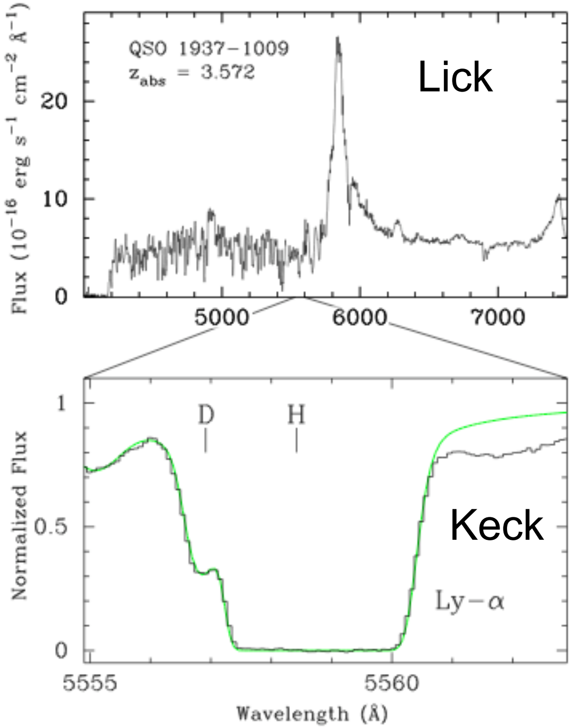
$\Rightarrow \Omega_\Lambda \simeq 0.75$

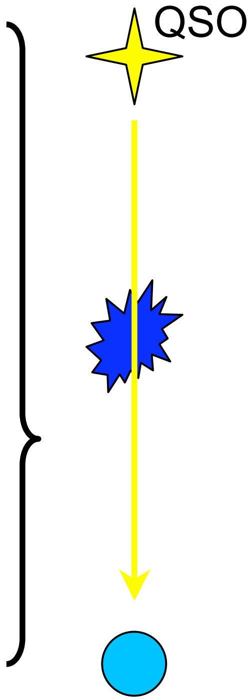


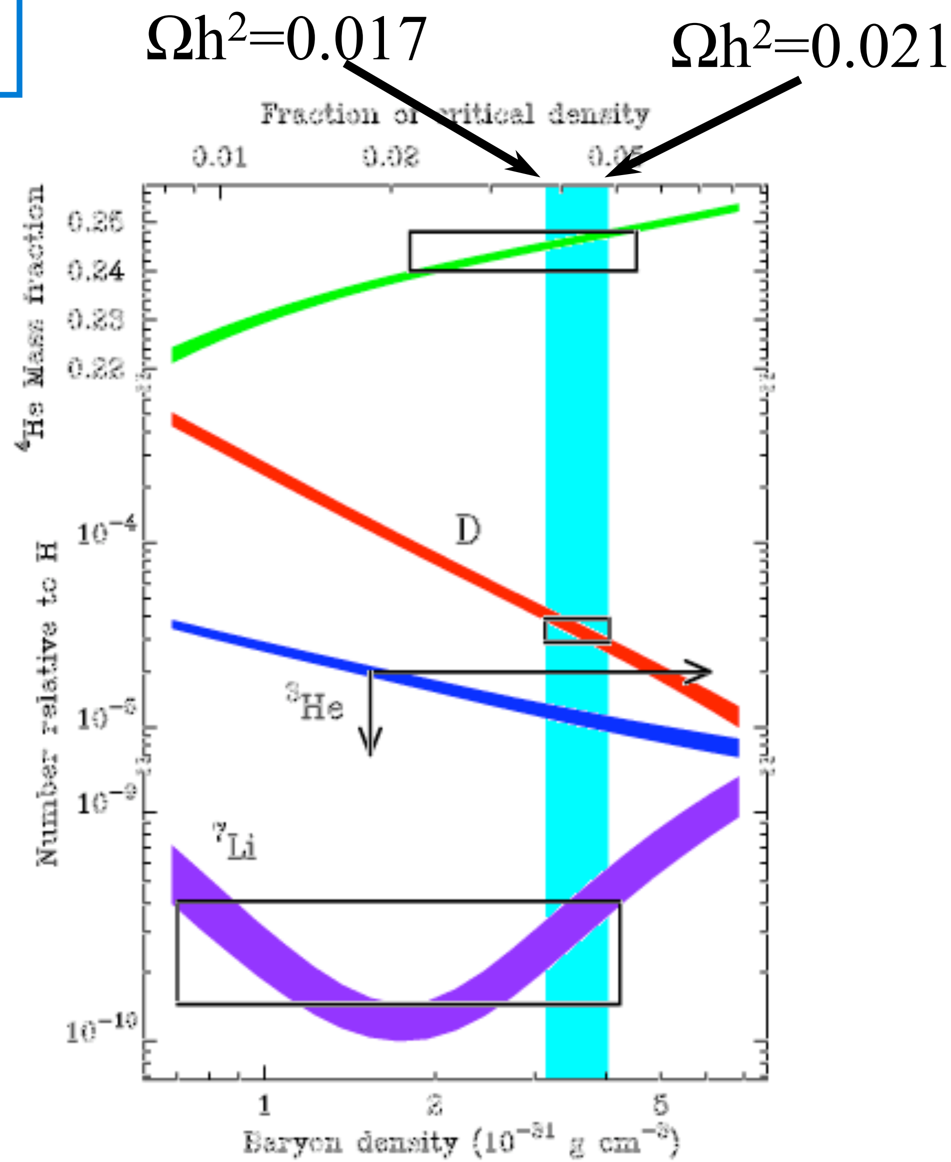
Tytler et al. 2001, astro-ph/0001318
(physical scripta T85, 12)

Primordial D measured in Intergalactic clouds (Ly α forest)

High resolution spectra: **Keck**



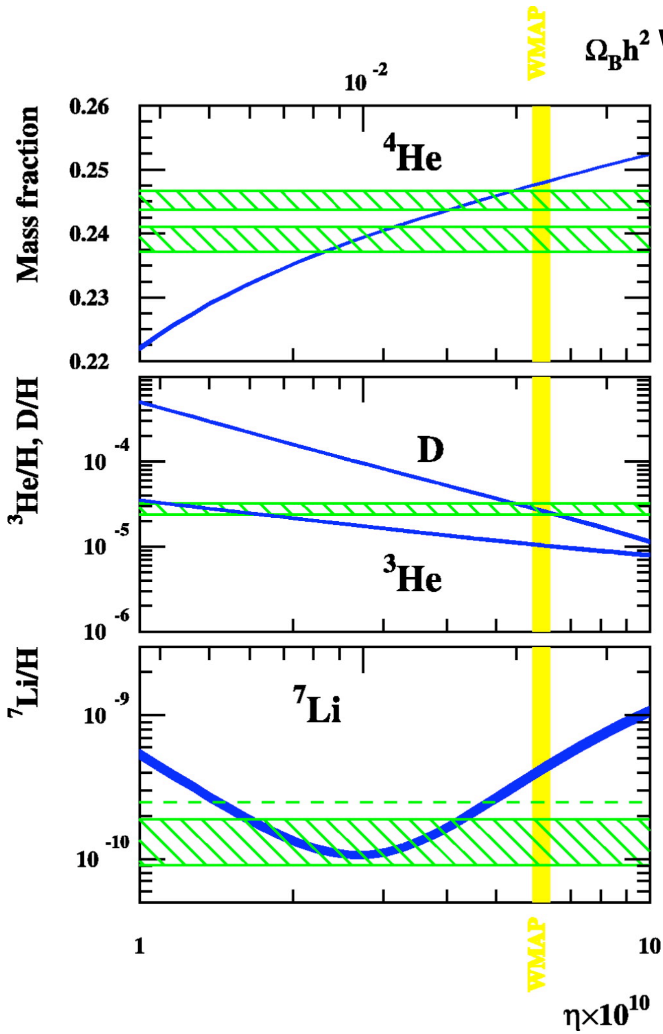




Comparison BBN/CMB: Coc et al. 2004, ApJ 600,544

WMAP1: $\Omega_B h^2 = 0.024 \pm 0.001$

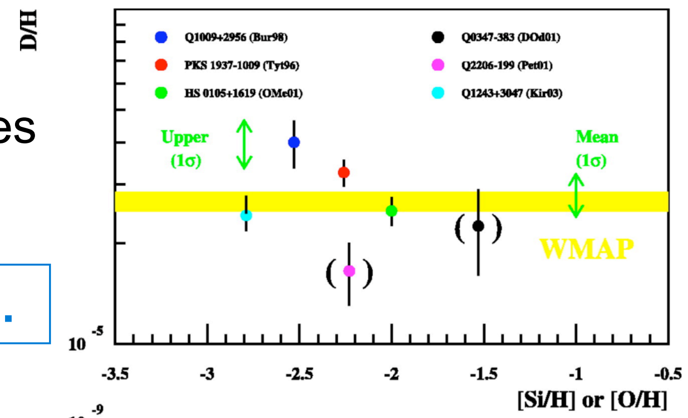
(WMAP3 $\Omega_B h^2 = 0.0223 \pm^{0.0007}_{0.0009}$)

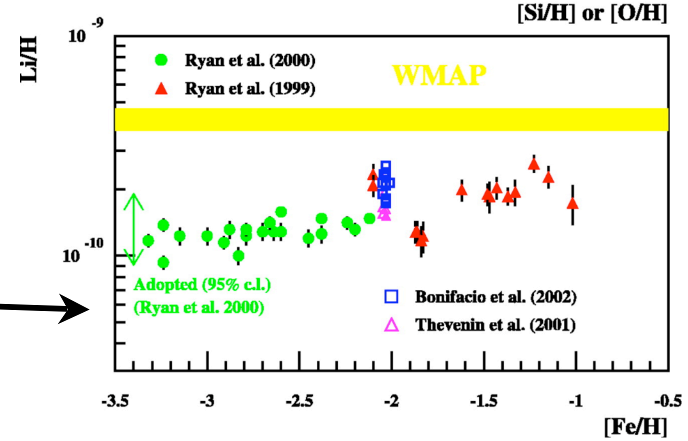


Primordial ⇔
Measured abundances
Chemical evolution

D seems cleanest…

Li problem ?

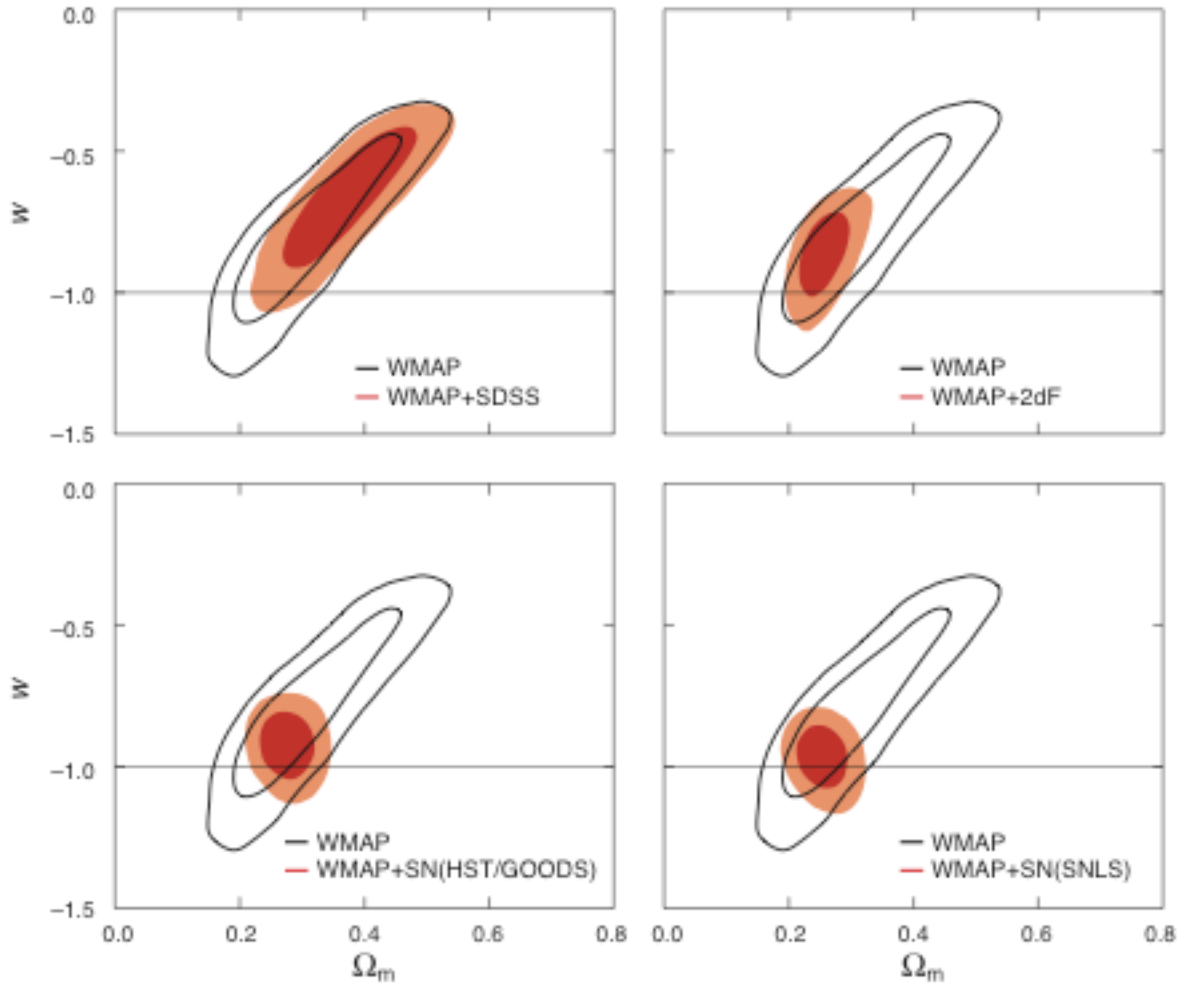




WMAP3 Constraints: w

Spergel et al. 2007

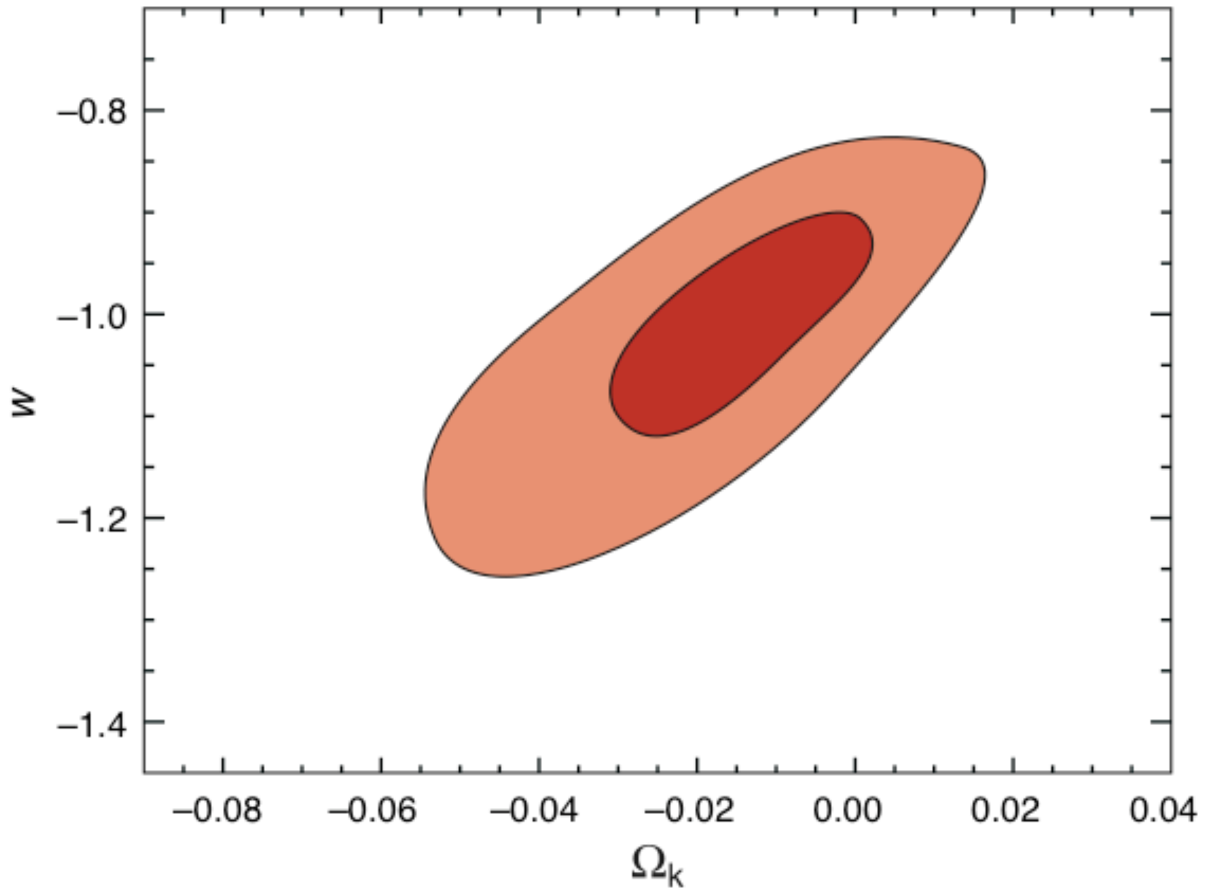
Flat models



WMAP3 Constraints: w & curvature

Spergel et al. 2007

$$\Omega_K = -0.024 \pm^{0.016}_{0.013}$$
$$w = -1.062 \pm^{0.128}_{0.079}$$



WMAP3 Constraints: w & neutrino mass

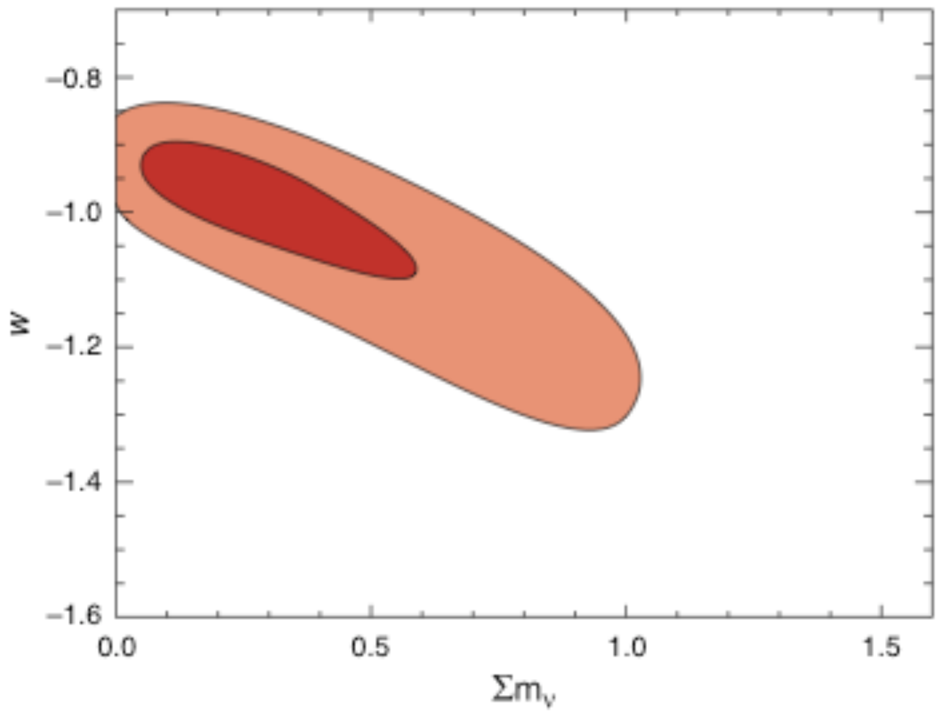
Spergel et al. 2007

Flat Models

CMB+2dFGRS
+SDSS+supernova

$$\sum m_\nu < 1eV \ (95\%)$$

$$w = -1.06 \pm^{0.13}_{0.10}$$



Next Mission: Planck

Launch: October 31, 2008!

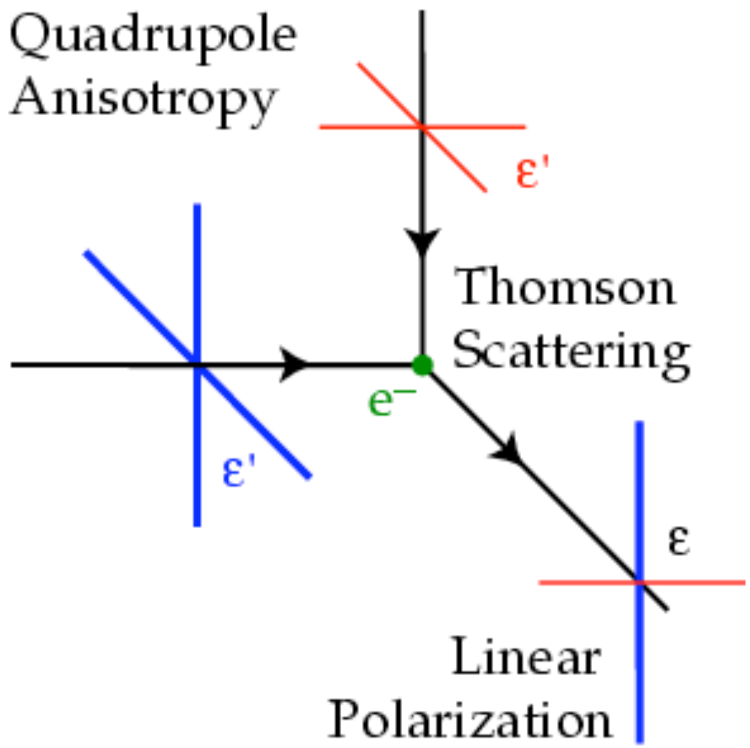
The Future: *Polarization*

CMB Polarization Anisotropies

Thompson scattering in the plasma

$$\frac{d\sigma}{d\Omega} = \frac{3}{8\pi}\sigma_T |\varepsilon \cdot \varepsilon'|^2$$

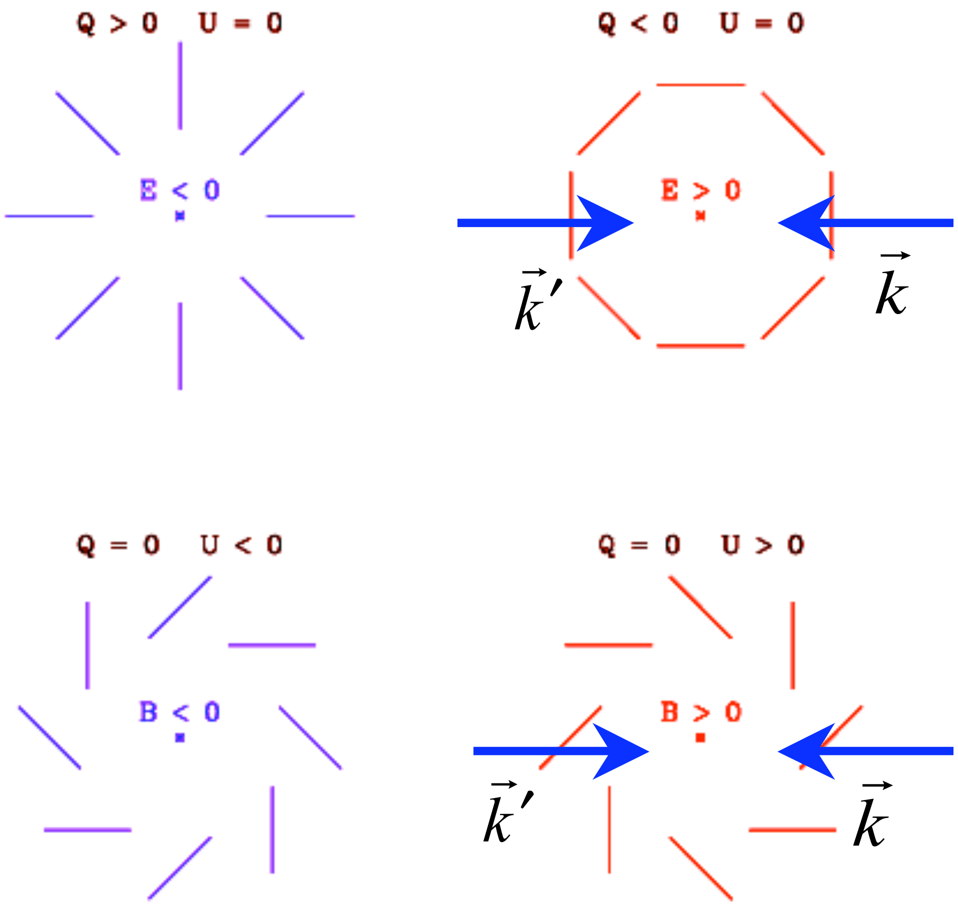
Hu & White 97



- Linear polarization
- Local quadrupole anisotropy
- Finite optical depth

Generated by local anisotropy

Two Kinds of Spatial Patterns



E-modes (even parity)

B-modes (odd parity)

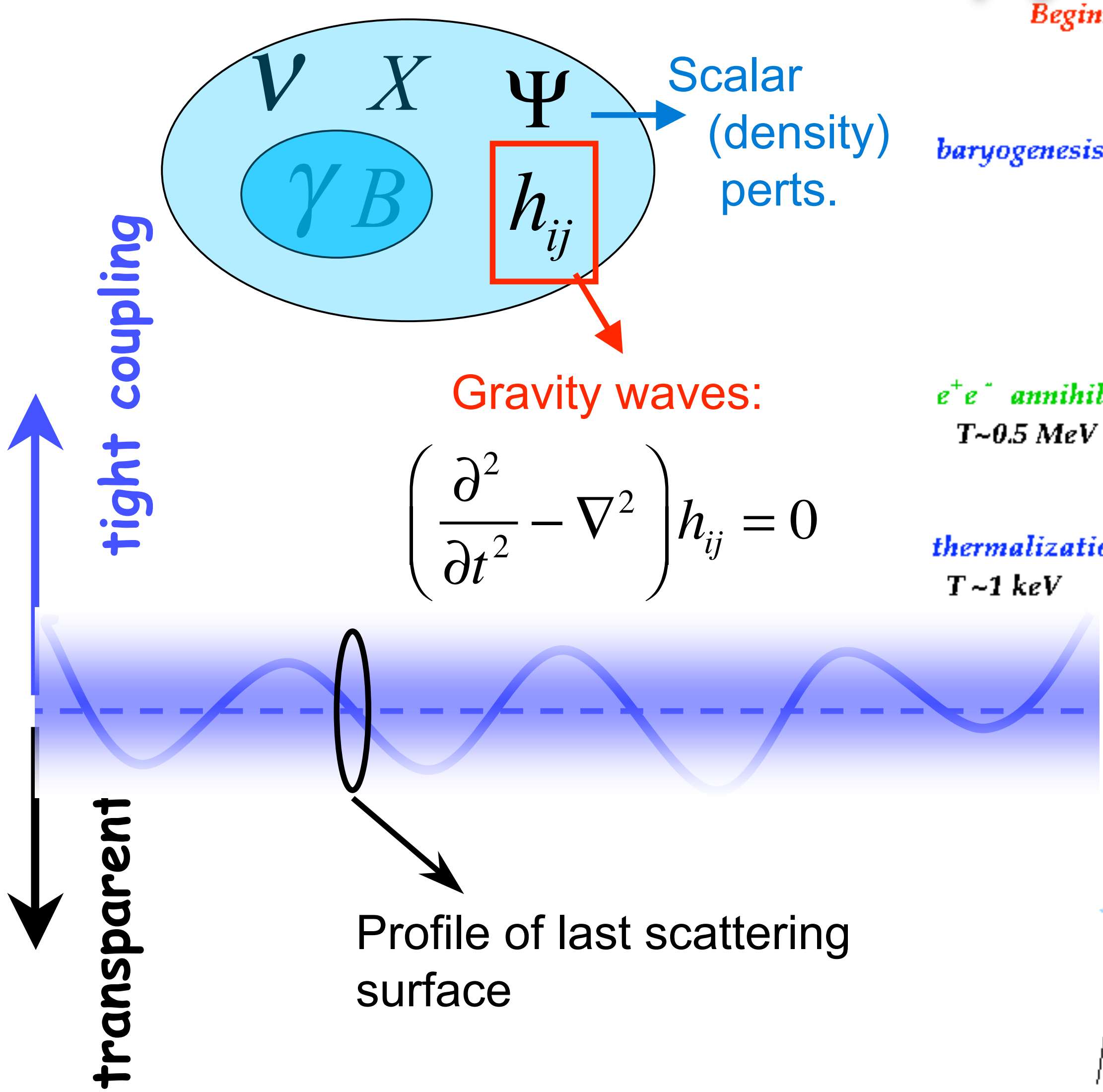
Zaldarriaga

Importance of decomposition

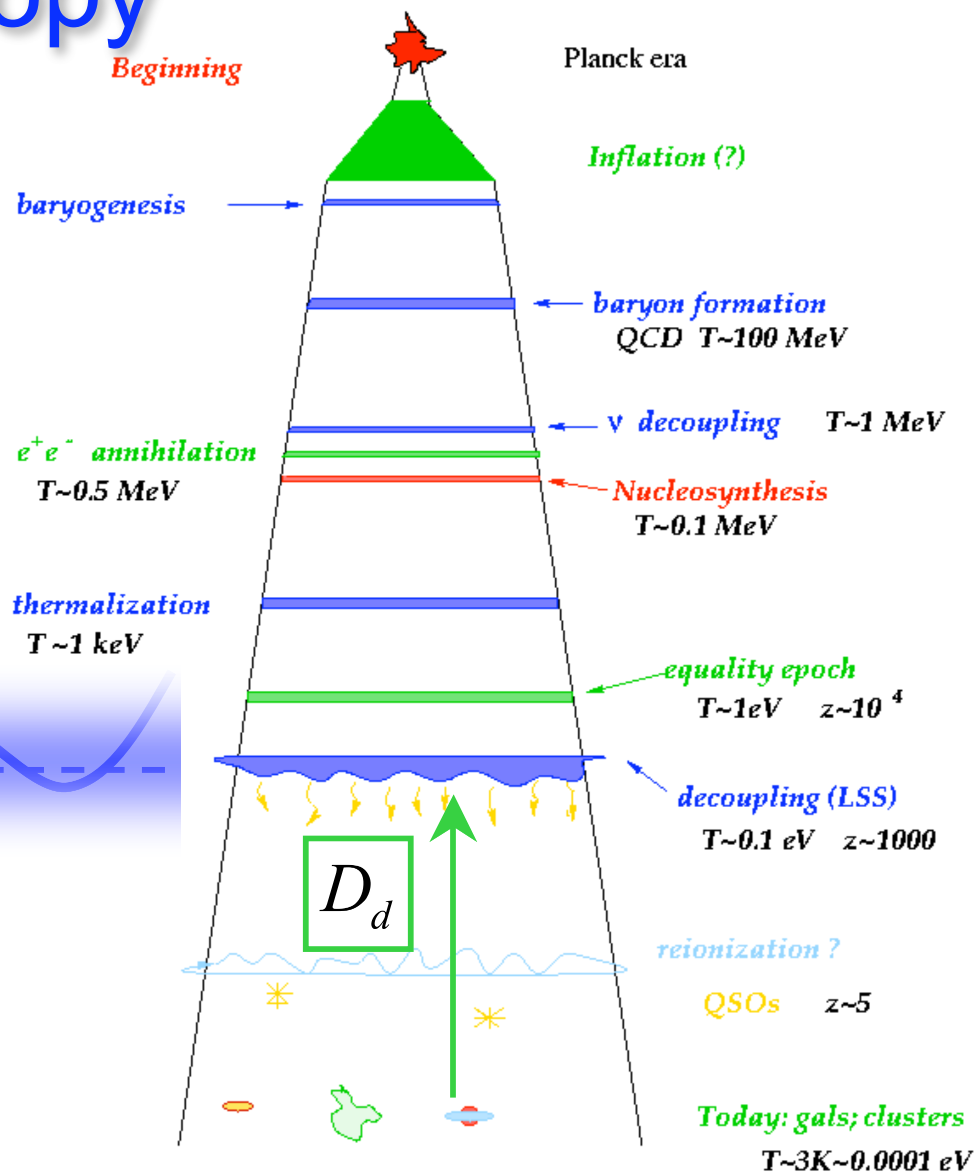
- T (intensity), E & B call all be measured separately
- They isolate different physical processes

T spectrum	E spectrum	Cross TE spectrum	B spectrum
C_l^{TT}	C_l^{EE}	C_l^{TE}	C_l^{BB}

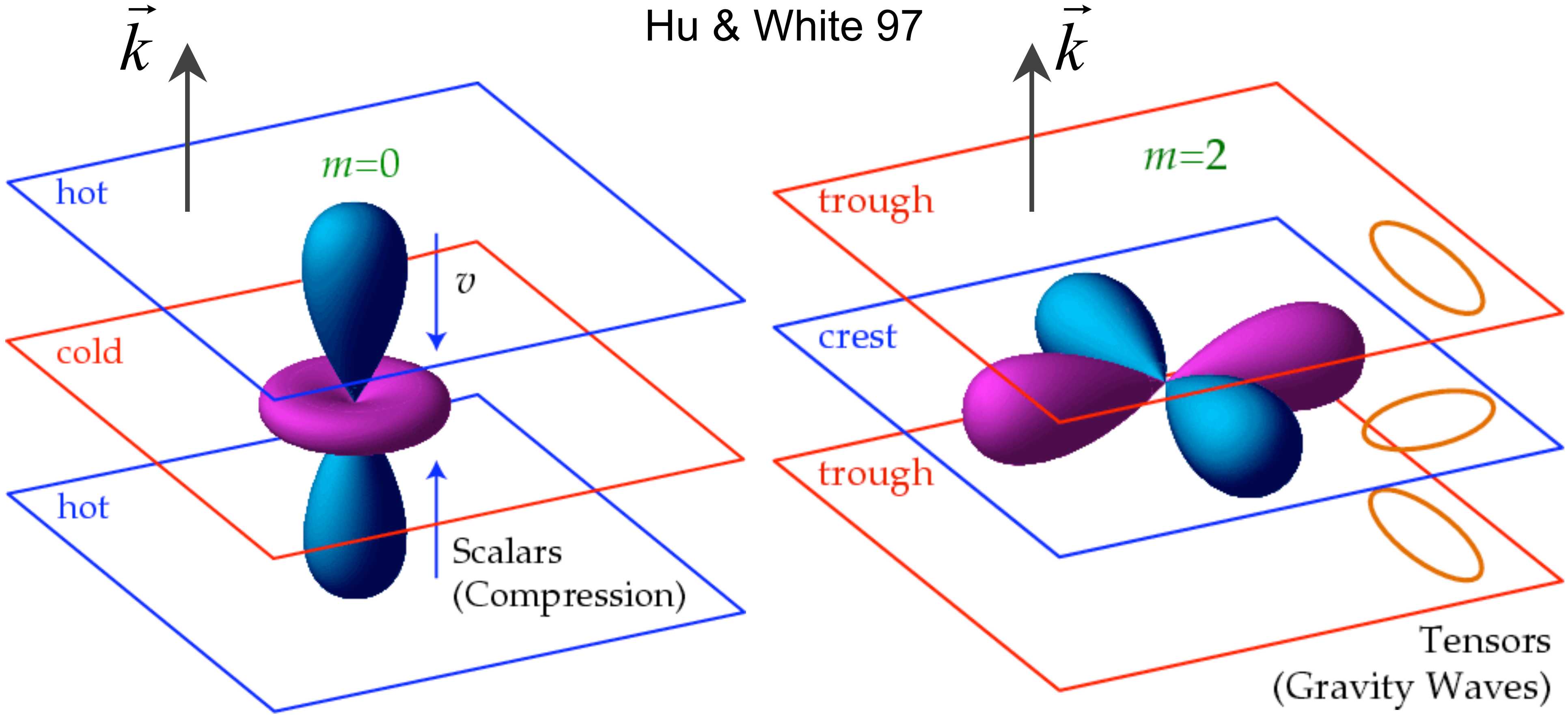
Sources of Anisotropy



$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2 \right) h_{ij} = 0$$



Hu & White 97



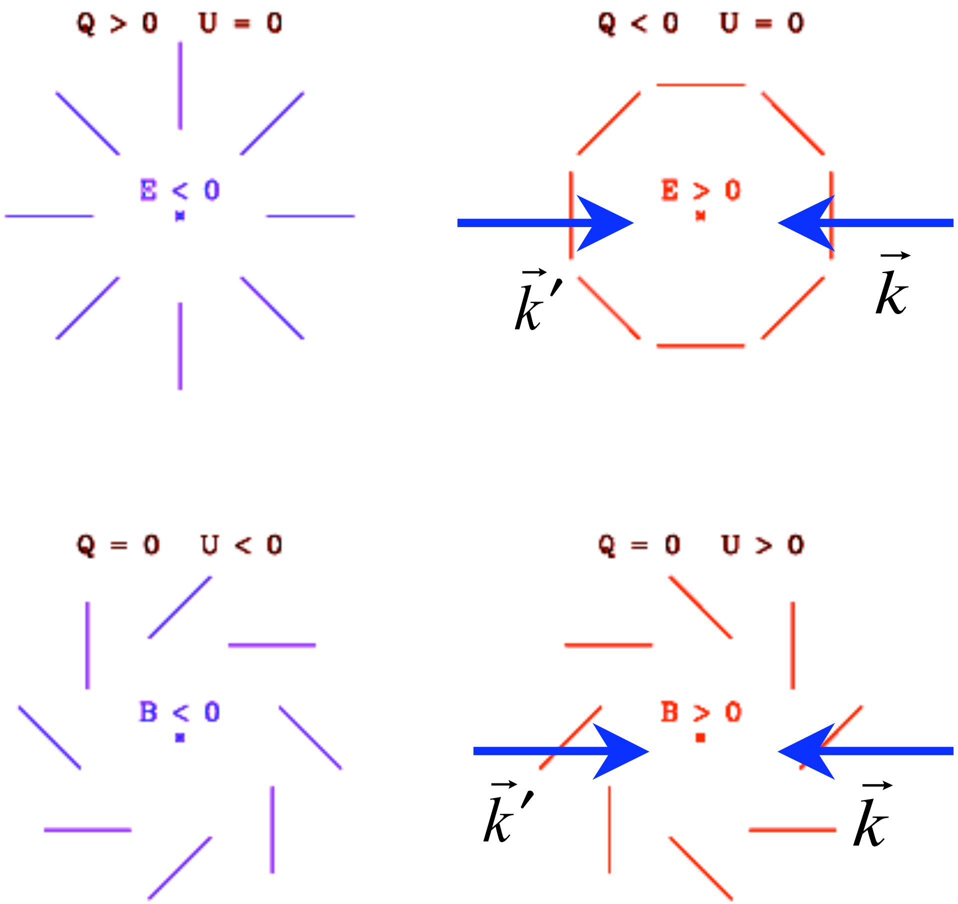
Axial symmetry around wavevector

Even parity ⇒ **E mode**

Loss of axial symmetry around wavevector

No parity ⇒ **E & B modes**

Two Kinds of Spatial Patterns



Zaldarriaga

E-modes (even parity)

Density perturbations

Gravity waves

B-modes (odd parity)

Gravity waves

Gravitational lensing

Gravity Waves

Produced with CAMB

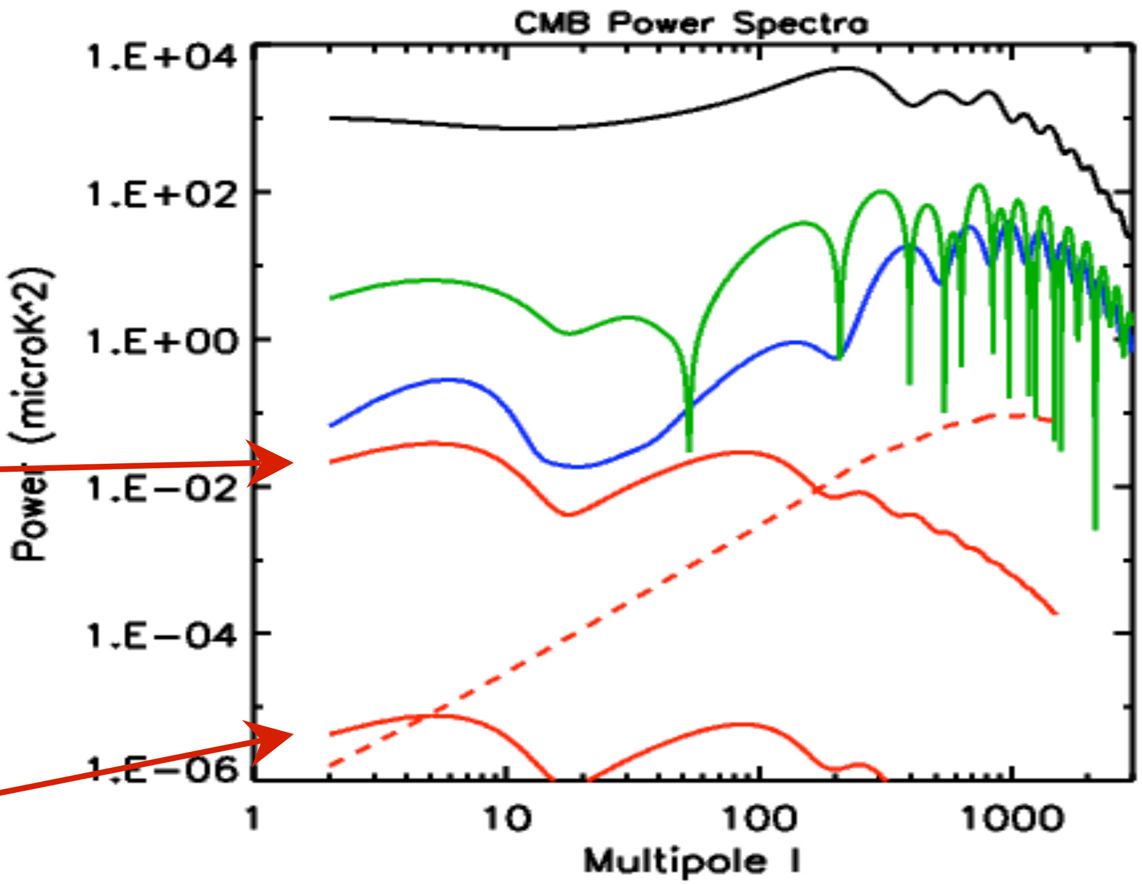
$$r \equiv \frac{T^2}{S^2} \propto \left(\frac{E_I}{M_{pl}}\right)^4$$

$r = 0.5$

$E_I \sim 3\times10^{16}\,GeV$

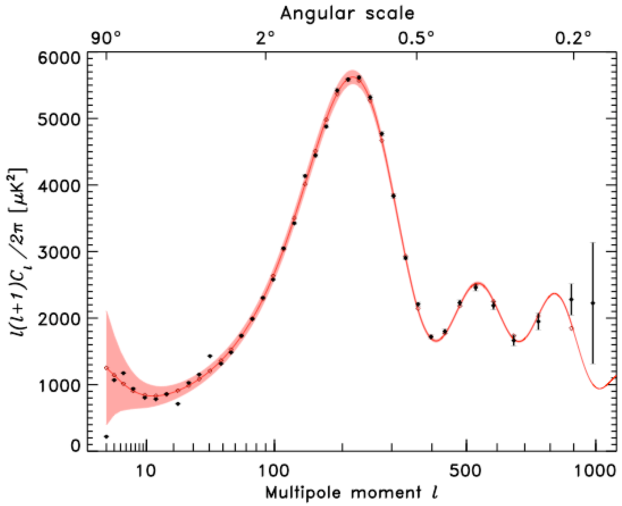
$r = 10^{-4}$

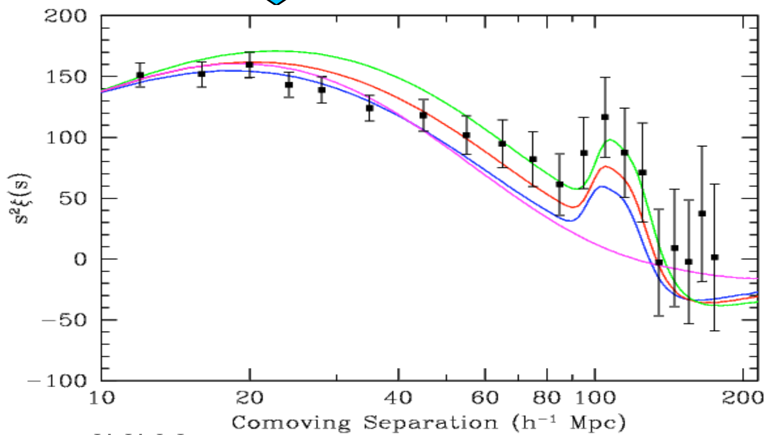
$E_I \sim 3.6\times10^{15}\,GeV$



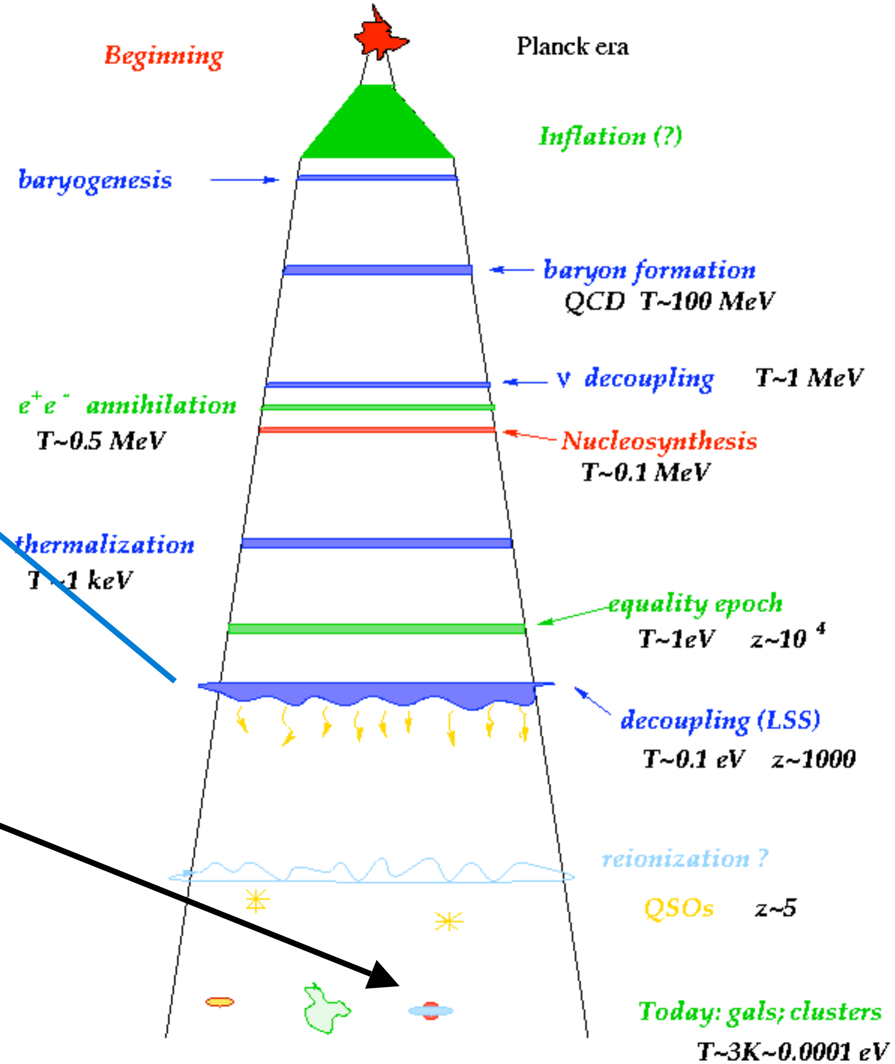
Fiducial WMAP-1 Model $(\tau = 0.17)$

Baryon Acoustic Oscillations





Str



Baryon Acoustic Peak

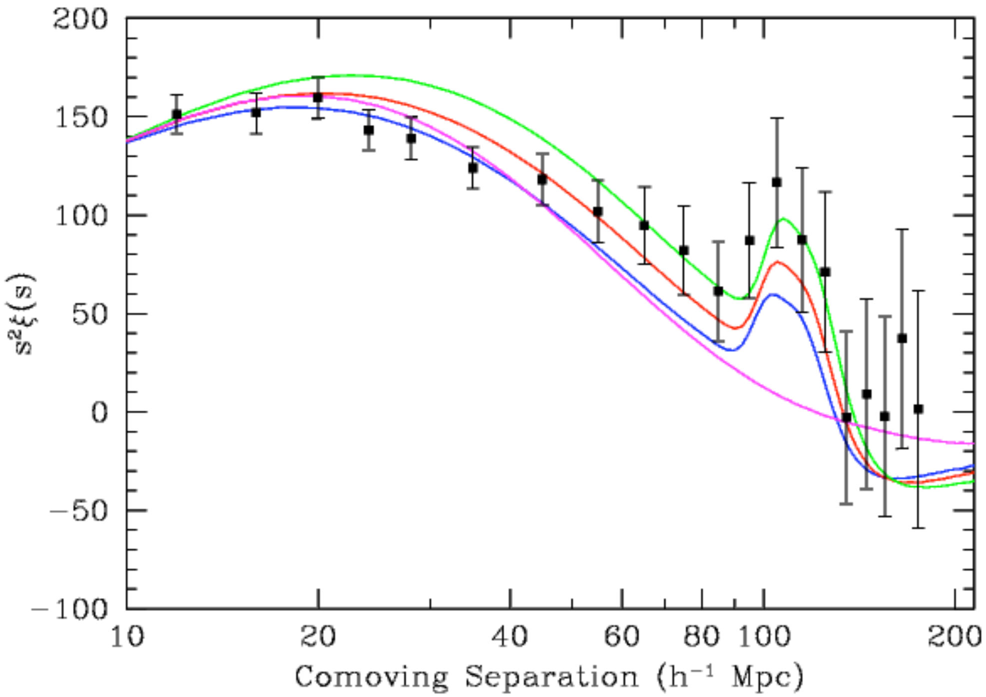
Eisenstein et al. 2005, ApJ 633, 560

•Correlation function for the Luminous Red Galaxy (LRG) sample from SDSS.

•46,748 galaxies with $0.16<z<0.47$

•Peak is the same acoustic signature seen in CMB

•Effectively measures $D_{ang}(z=0.35)$



CMB (WMAP1)+SDSS

$$\Omega_R = -0.010 \pm 0.009$$

i.e., SN, HST