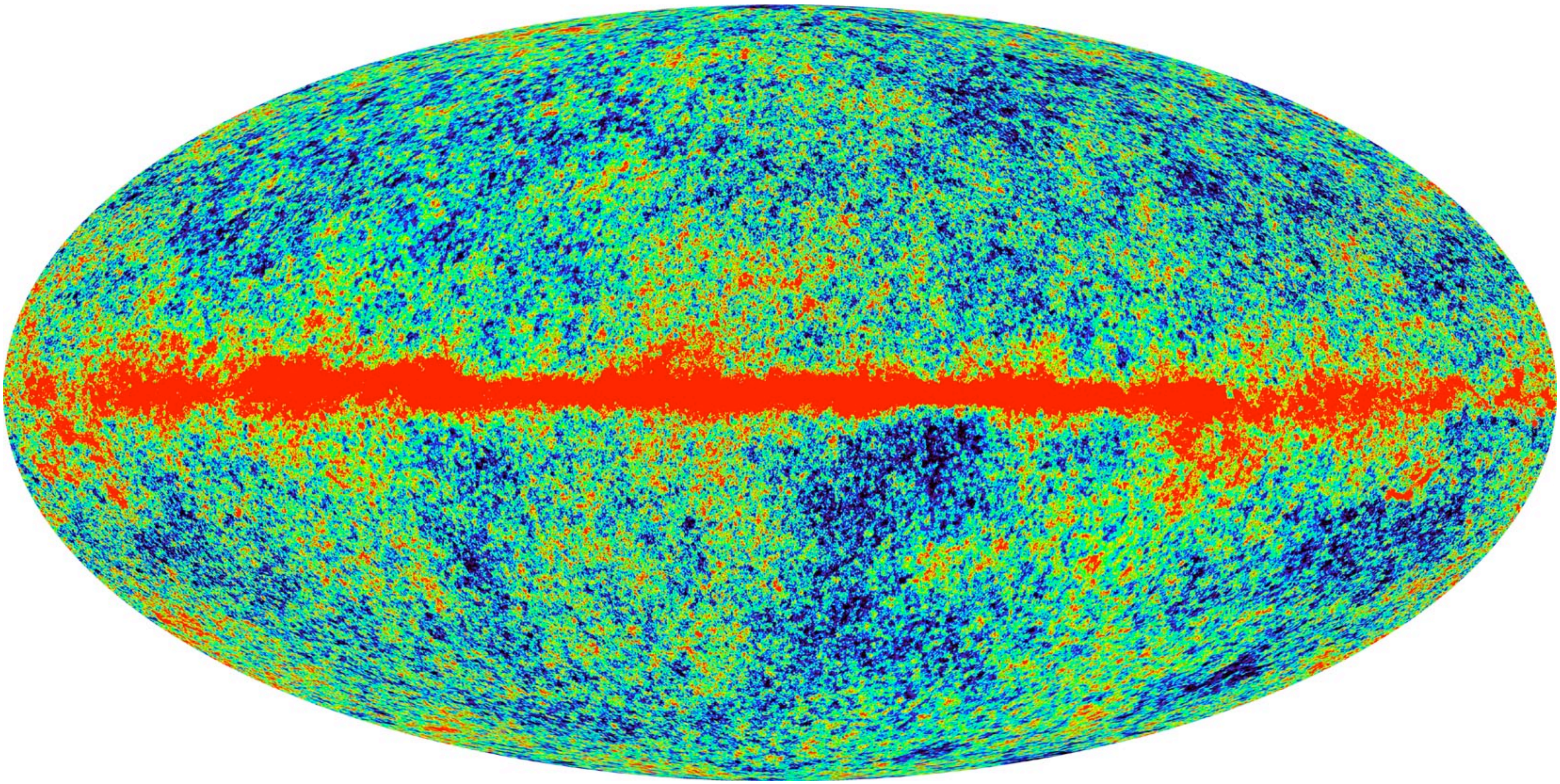
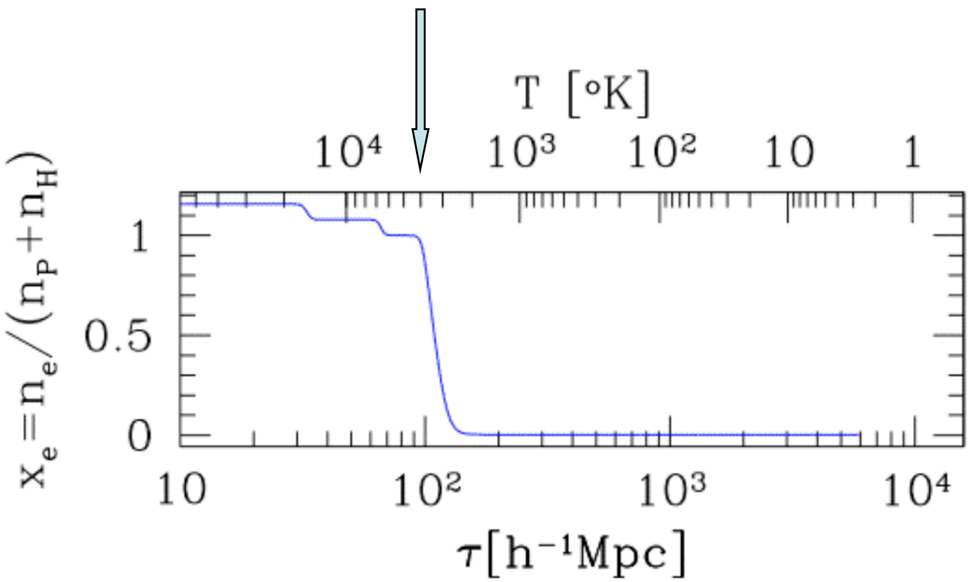
What creates the anisotropies?



Recombination

$T = 0.3$ eV $\ll m_e c^2$



Hydrogen is ionized **Hydrogen is neutral**

Thomson Scattering

Orders of Magnitude:

$$\lambda_T = (a\ n_e\ \sigma_T)^{-1}$$

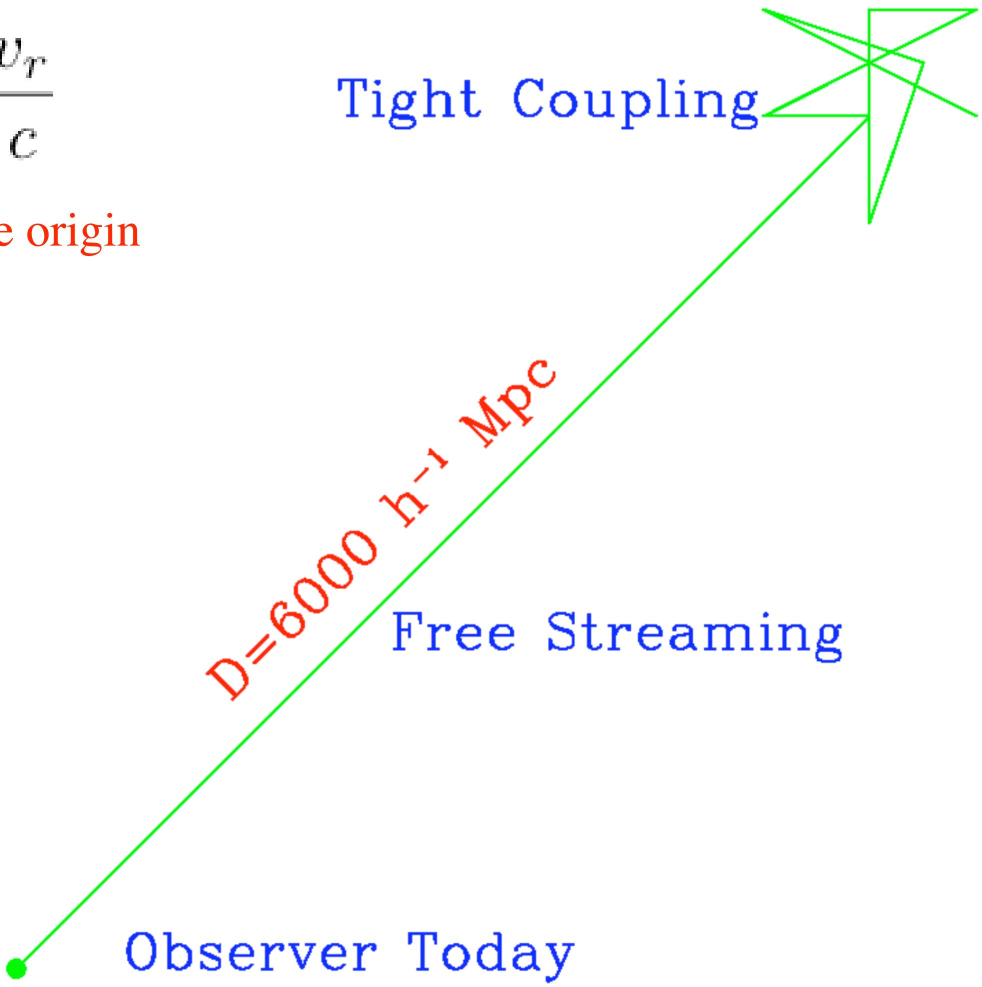
$$= 2\ \mathrm{Mpc}\ x_e^{-1}\ [(1+z)/1000]^{-2}$$

$$\tau_R \approx 100\ [\Omega h^2]^{-1/2}\ \mathrm{Mpc}$$

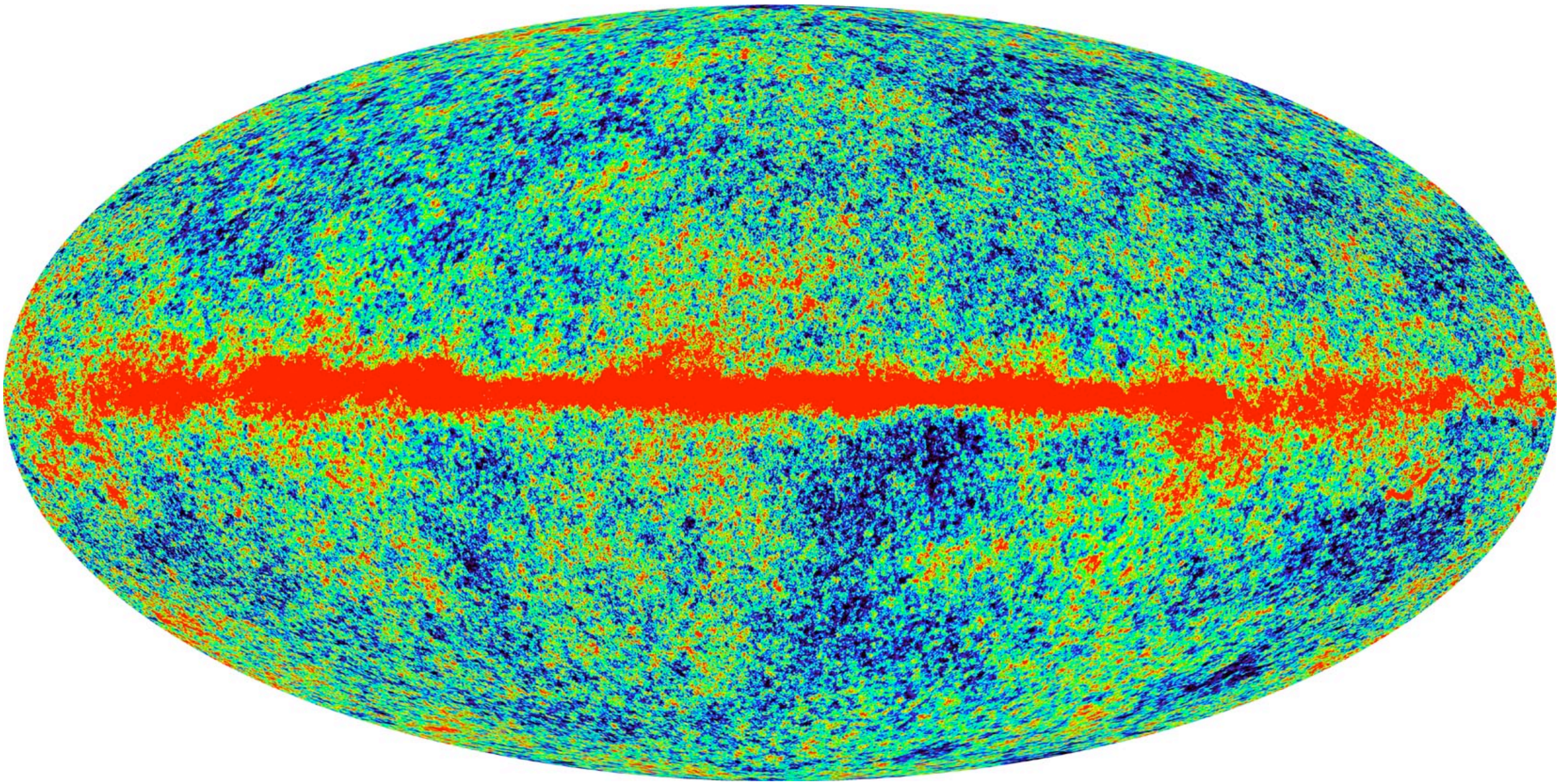
$$D = \tau_0 - \tau_R \approx 6000\ [\Omega h^2]^{-1/2}\ \mathrm{Mpc}$$

$$\frac{\delta T}{T} = \phi + \frac{\delta_\gamma}{4} + \frac{v_r}{c}$$

All 3 effects have the same origin

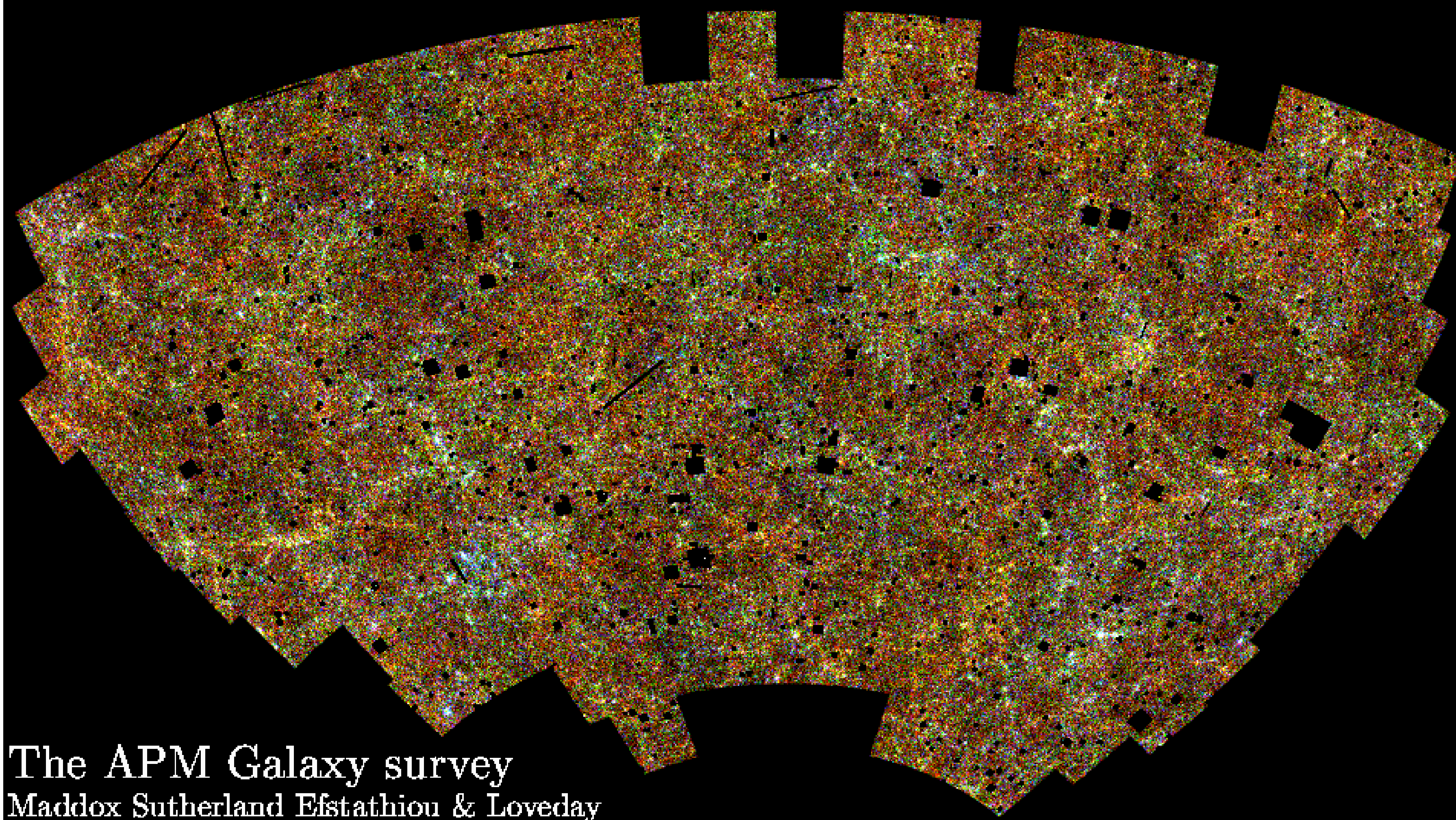


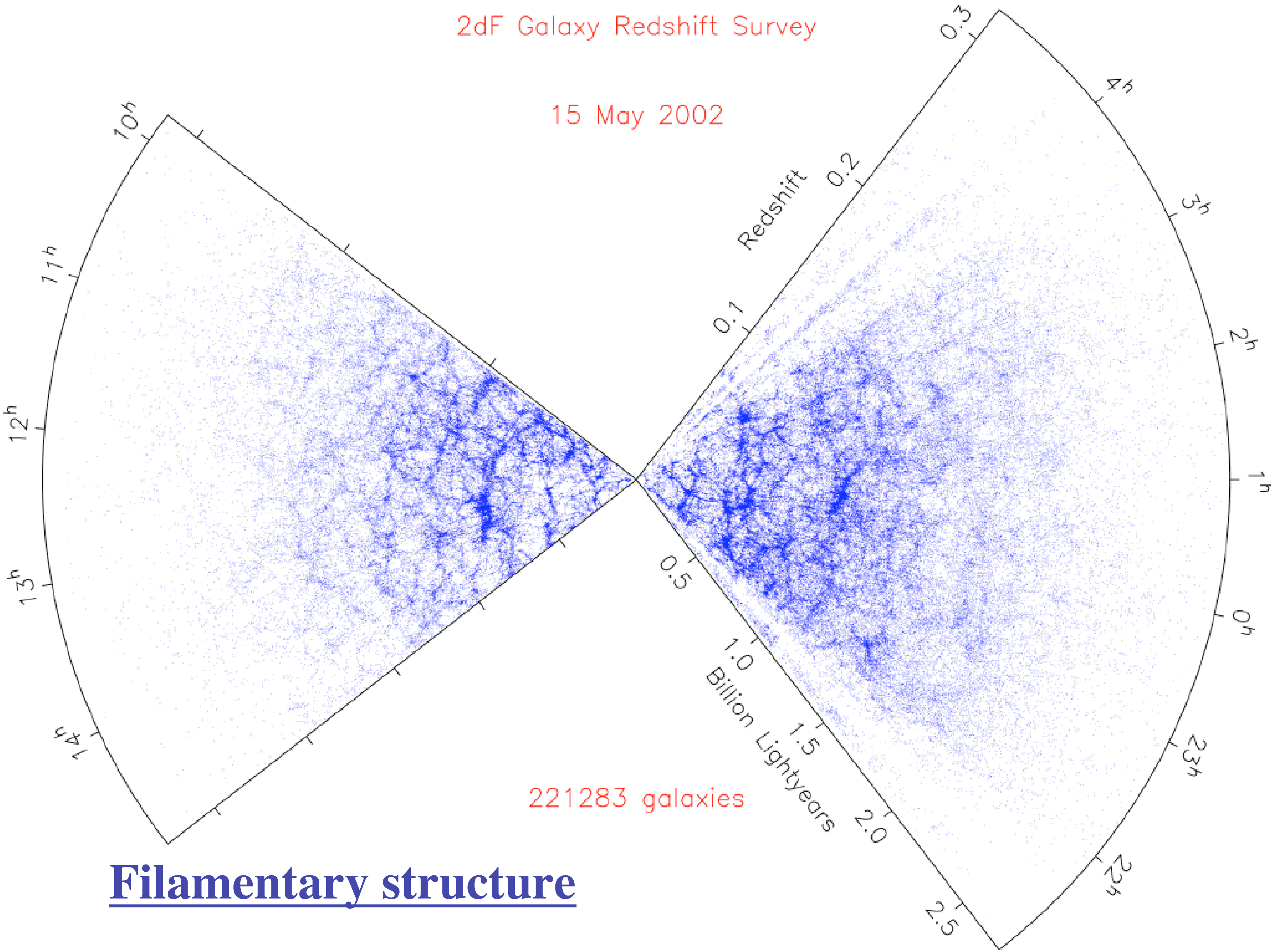
WMAP: level of structure at recombination



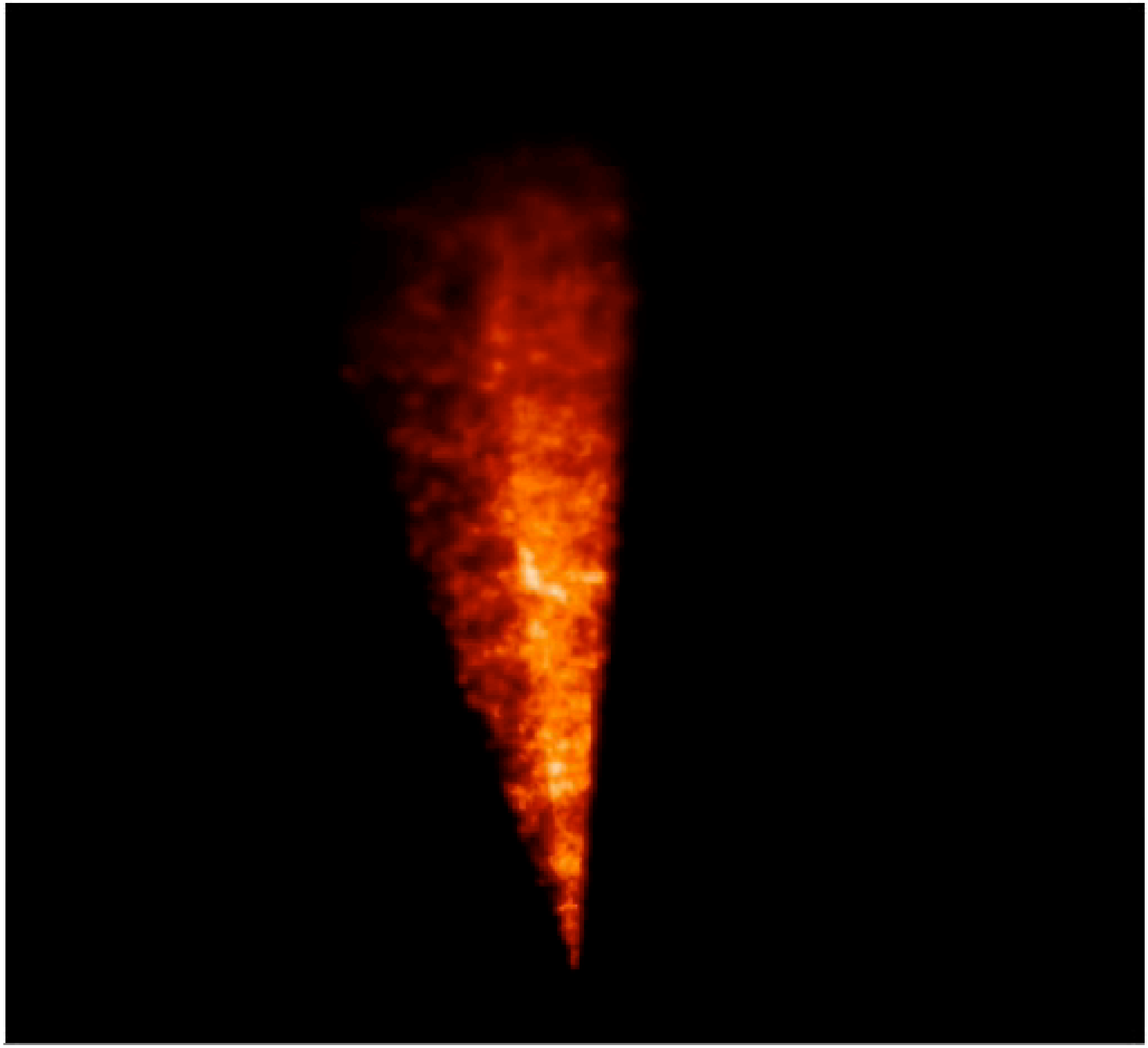
Present day structure: the distribution of galaxies

The distribution of matter as traced by galaxies





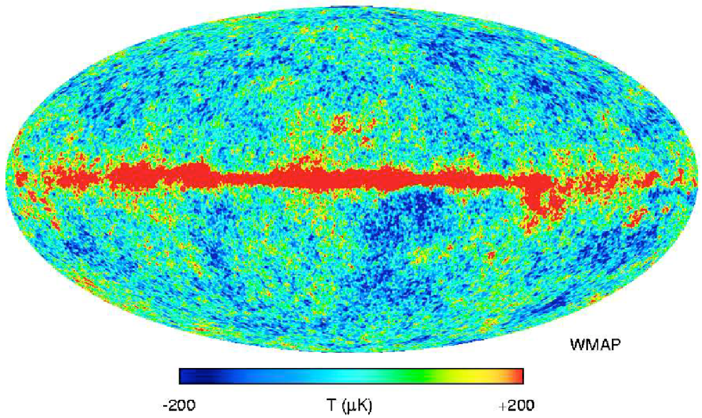
Filamentary structure



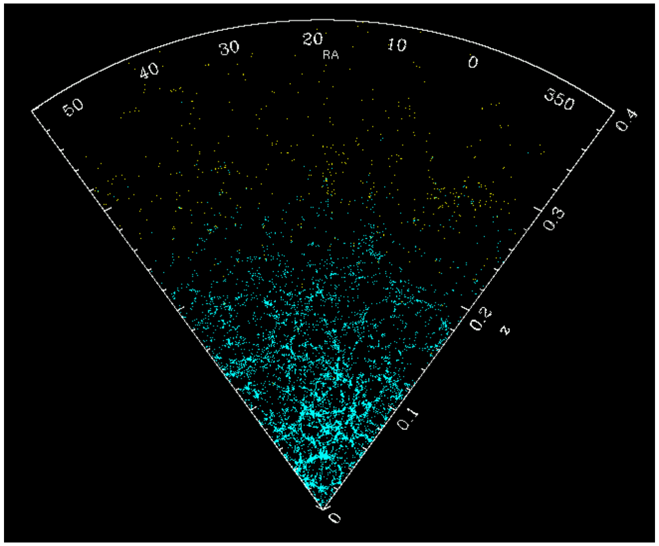
http://www.mso.anu.edu.au/2dFGRS/

Gravitational Instability

t_1



$t_2 > t_1$



$$t_g \sim (G\rho)^{-1/2}$$

Different constituents can be distinguished when studying the evolution of perturbations because of their different interactions.

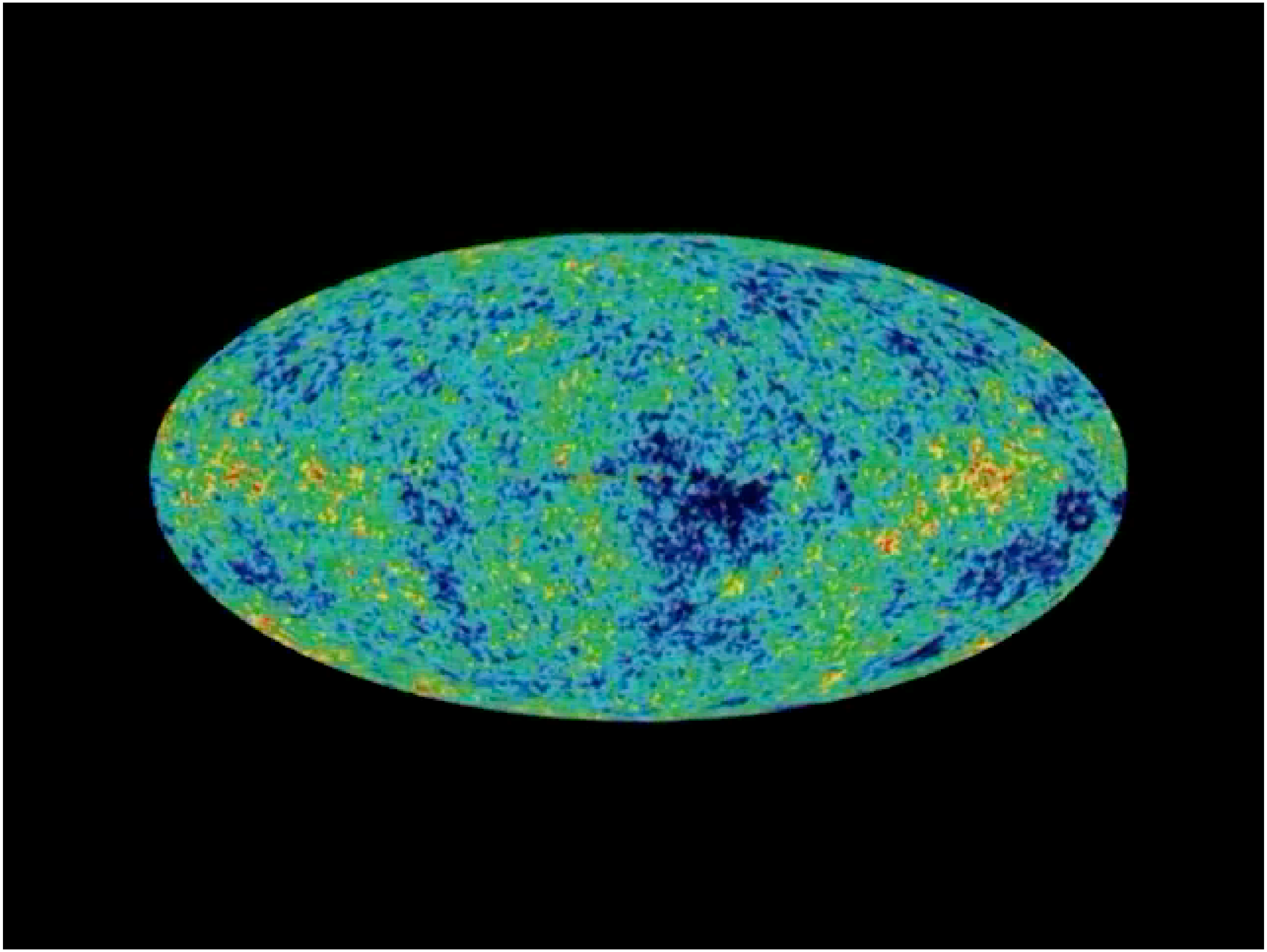
Baryons are coupled to the CMB before recombination.

CDM only interacts with the rest through gravity but can cluster.

A cosmological constant is spatially constant so it only affects the evolution of the expansion factor.

“Best” Cosmological Parameters:
Table 3 from ***Wilkinson Microwave Anisotropy Probe (WMAP)* Observations: Preliminary Maps and Basic Results**,
C. L. Bennett et al. (2003), accepted by the *Astrophysical Journal*;
available at `http://lambda.gsfc.nasa.gov/`

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 $k_0 = 0.05\ \mathrm{Mpc}^{-1}$)[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05\ \mathrm{Mpc}^{-1}$)[c]	n_s	0.93	0.03	0.03
Running index slope (at $k_0 = 0.05\ \mathrm{Mpc}^{-1}$)[c]	$dn_s/d\ln k$	-0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002\ \mathrm{Mpc}^{-1}$)	r	< 0.90	95% CL	—



http://lambda.gsfc.nasa.gov/

Gravitational instability amplifies fluctuations but it does not create them.

We need some “seeds”

↓

Inflation

Summary of model parameters

1. Dark matter density
2. Baryon density
3. Radiation density
4. Neutrino fraction

} Matter budget: affects the physics of perturbations

5. Curvature
6. Cosmological "constant"

} Affect the evolution of a(t)

7. Initial spectrum of scalar perturbations
8. Initial spectrum of gravity waves

} Properties of the initial seeds

↑

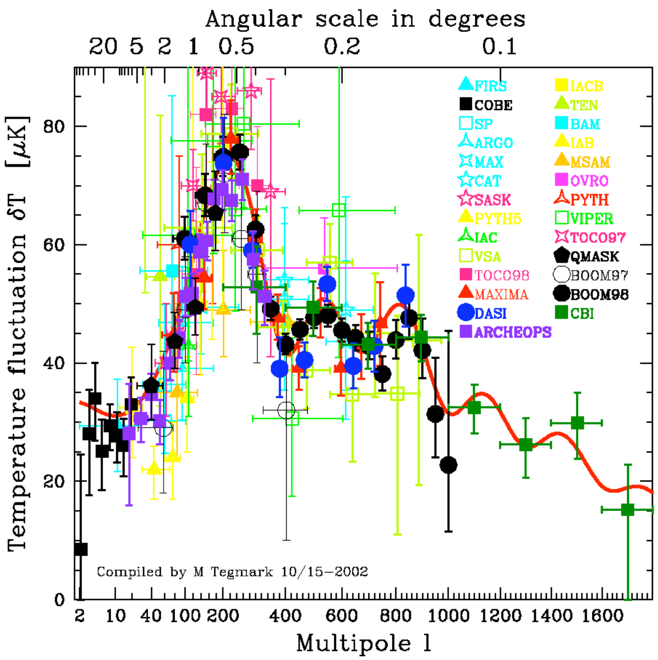
Objective: Invert the physics of the perturbations to get at properties of the seeds and hopefully to the mechanism that created the seeds

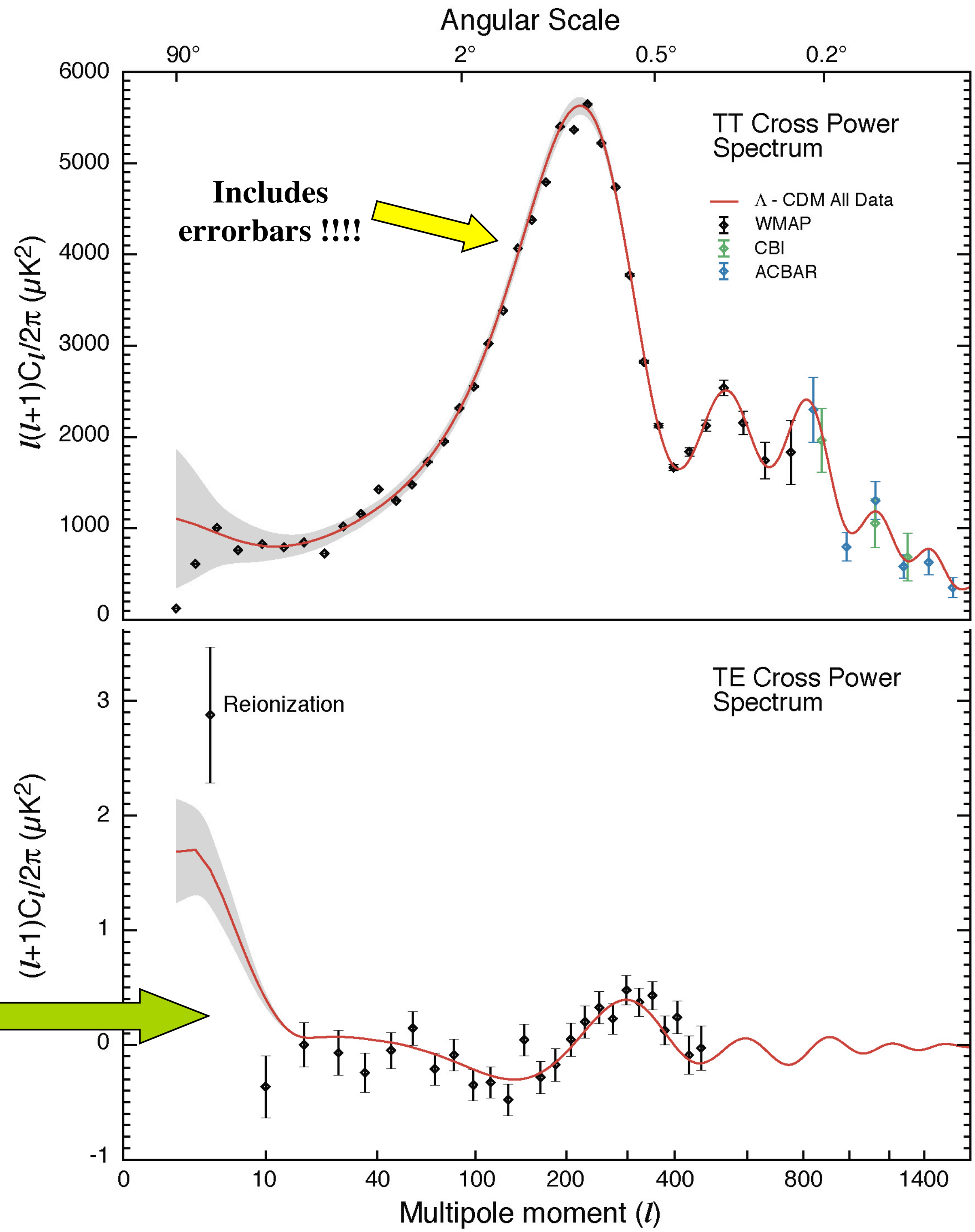
Anisotropies in the CMB Temperature

Outline

- Basic equations
- Solution under some simplifying assumption
- Basic parameter dependences
- Some effects left out

WMAP Spectra

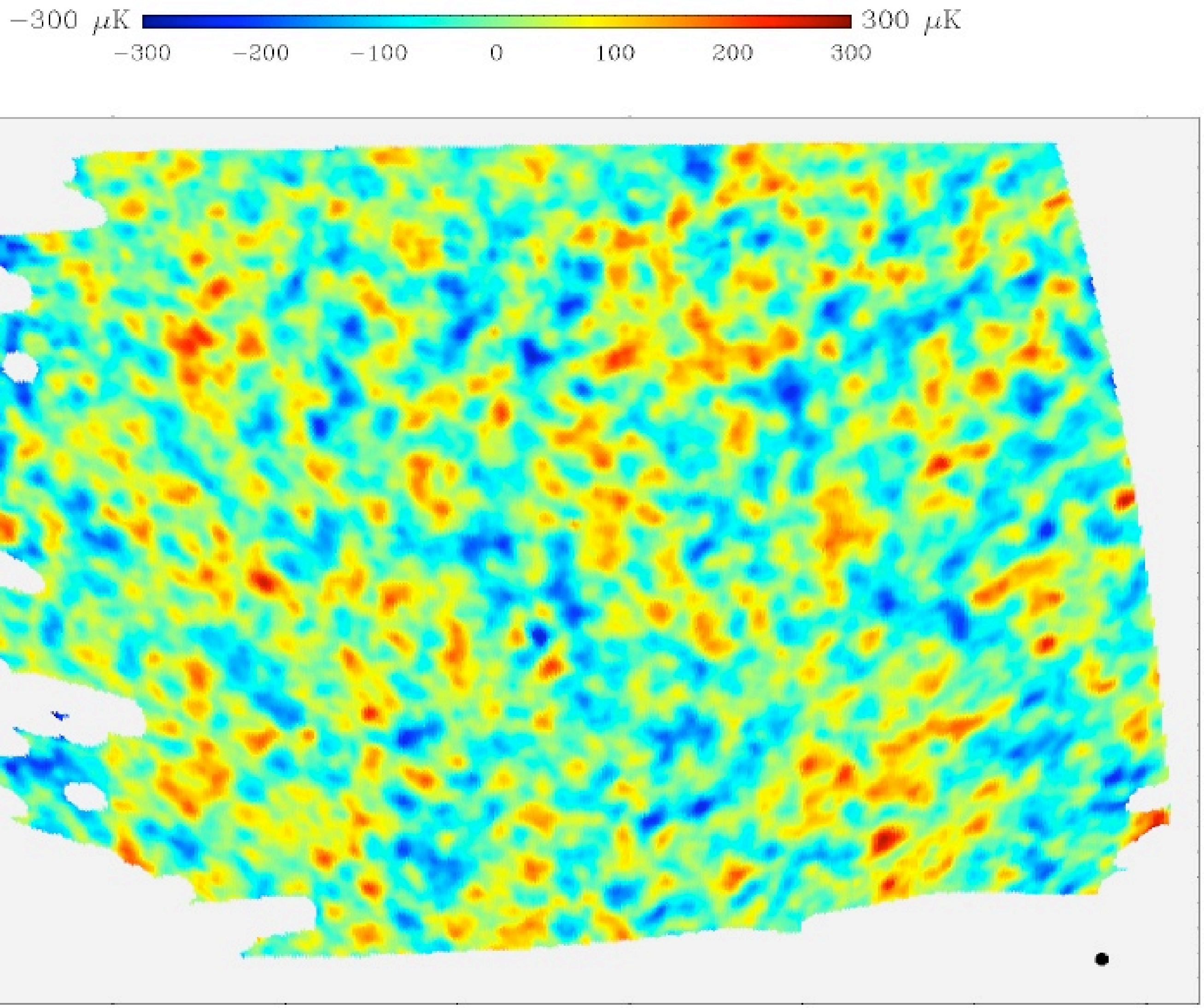




Temperature and polarization patterns are correlated

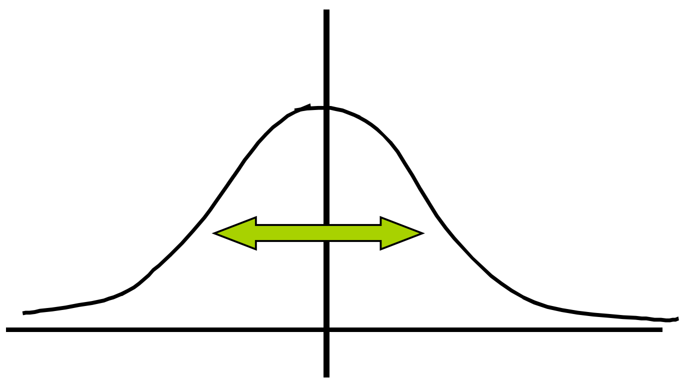
Anisotropies as seen by Boomerang

Flight: 10 days
1800 deg^2
3 % of the Sky
Resolution 0.2^o



Definition of C_l

a_{lm} ← Gaussian Random Variable



$$\langle a^*_{lm} \, a_{lm} \rangle = C_l$$

There are only (2l+1) multipoles of a given l on the sky → COSMIC VARIANCE

WMAP Spectra

Fluctuations are small of order 10^{-5}

We can use linear theory