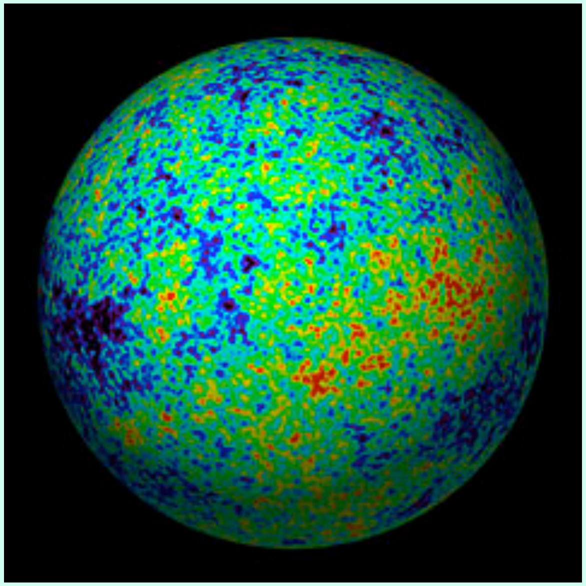
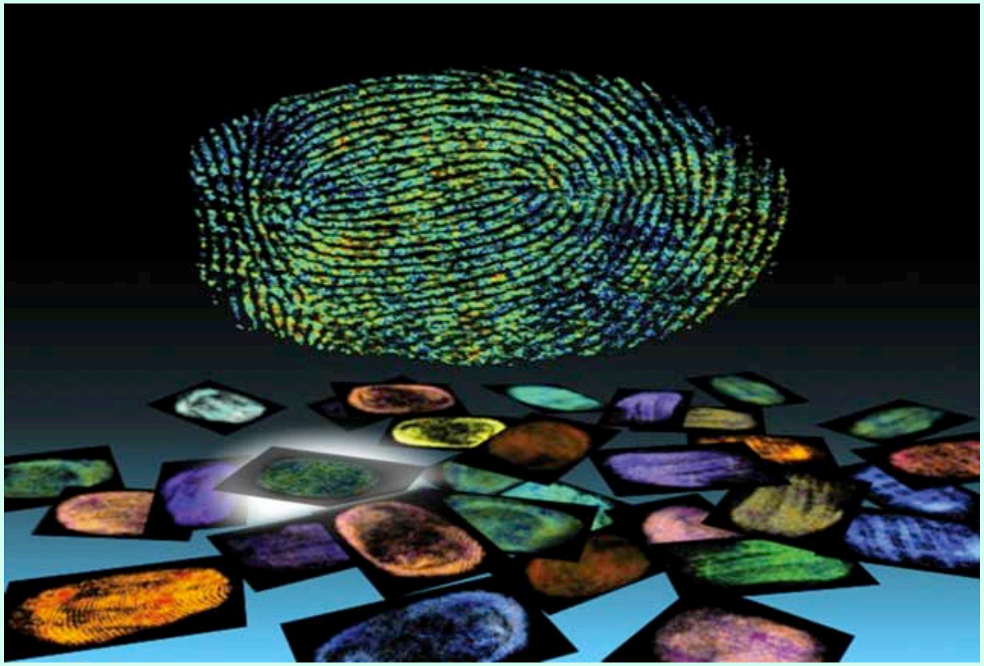
Cosmic Microwave Background



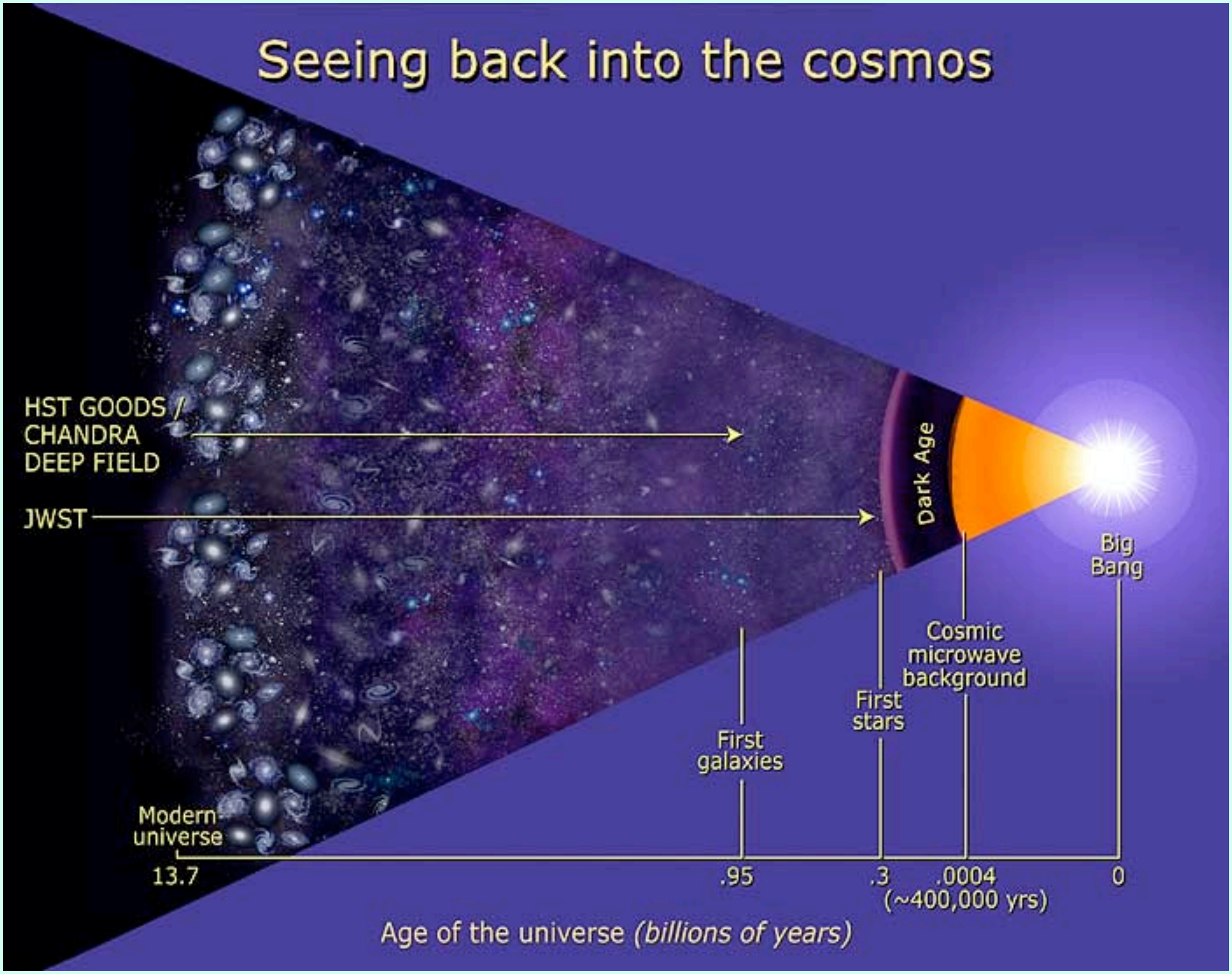
Levon Pogosian
Tufts University

Cosmology II

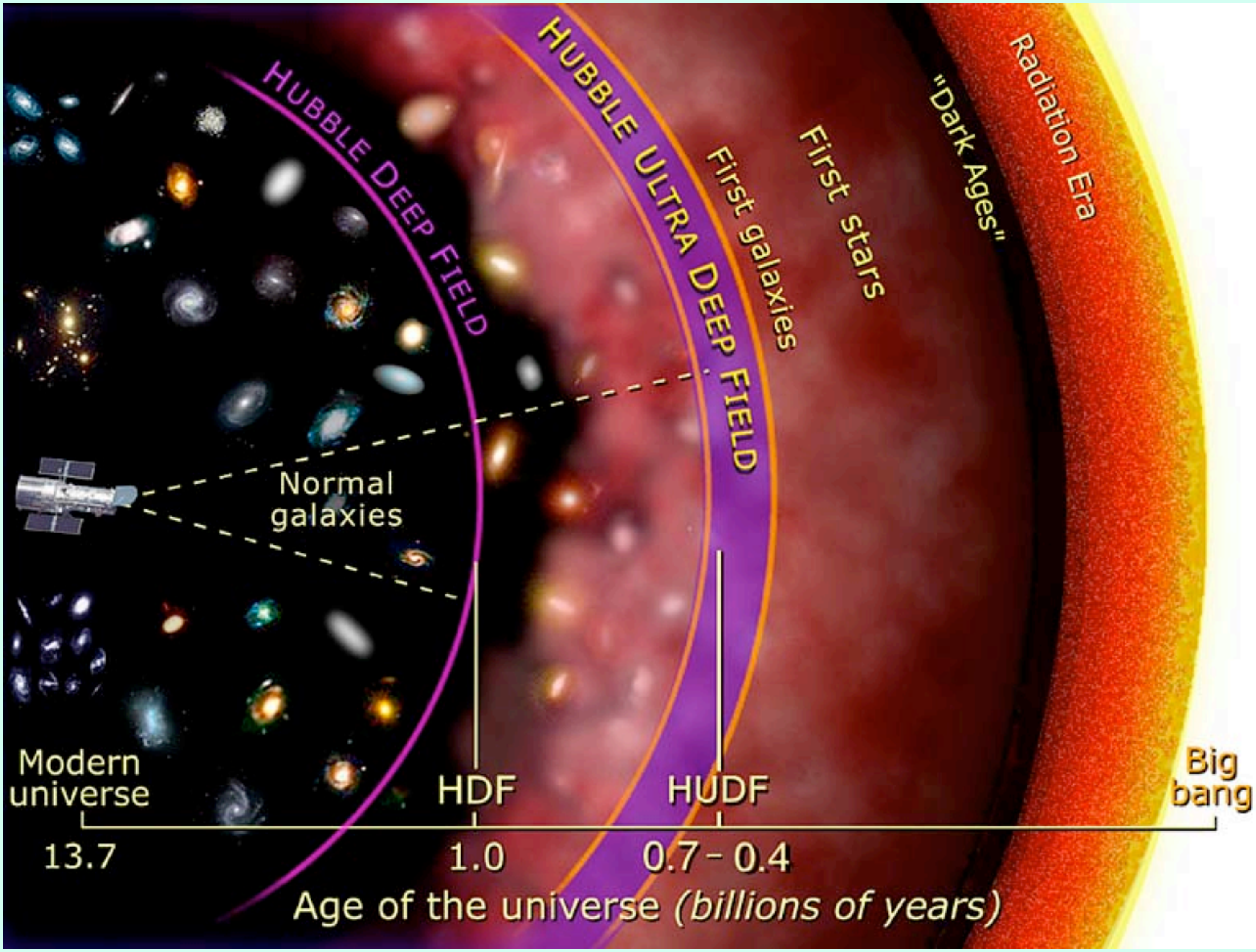


http://map.gsfc.nasa.gov/

- Basics, history, significance
- Relevant physics and tools
- Main effects and their signatures
- What we've learned already
- What else can be learned?



http://hubblesite.org/



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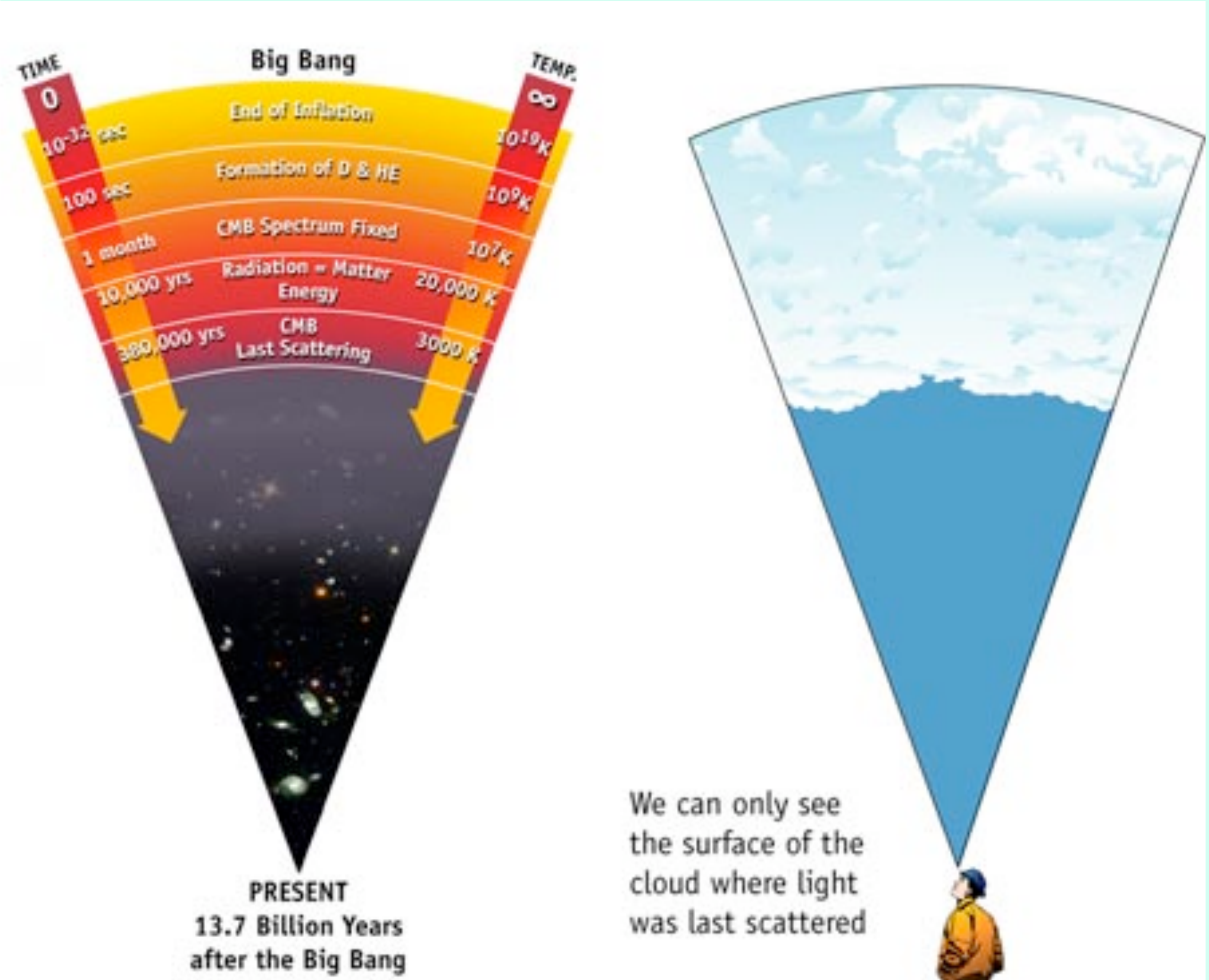


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

$$\lambda \propto a$$

$$a = \frac{1}{1+z}$$

$$T \propto \frac{1}{a} = (1+z)$$

Wed, Aug 17, 2005:

z=0, T ≈ 2.726 K

Last Scattering:

z ≈ 1090, T ≈ 3000 K

http://map.gsfc.nasa.gov/

Discovery of CMB

- 1940, **Andrew McKellar** observed excited rotational states of CN molecules in interstellar absorption lines, “temperature of space” of 2.3 K
- 1941, **Walter Adams** made similar observations

- 1948-1956, **G. Gamow, R. A. Alpher, R. C. Herman:** made estimaters of CMBR

- 1955 **Emile Le Roux**: λ=33 cm radio astronomy, isotropic emission with T=3±2 K
- 1955 **Tigran A. Shmaonov**: λ=3 cm isotropic emission with T=4±3 K

1965: A. Penzias and R. W. Wilson of Bell Labs:
T=3K antenna noise at λ=3 cm.
Explained by Dicke, Peebles, Roll and Wilkinson.

1978: Penzias and Wilson receive a **Nobel Prize**

Why is it important?

- **It exists:** confirms “Hot Big Bang” (not Steady State)

- **It has features**: provides a test for structure formation theories and a wealth of other information about the universe

Data analysis (by a theorist)

CMB is an EM wave: it **has intensity and polarization**

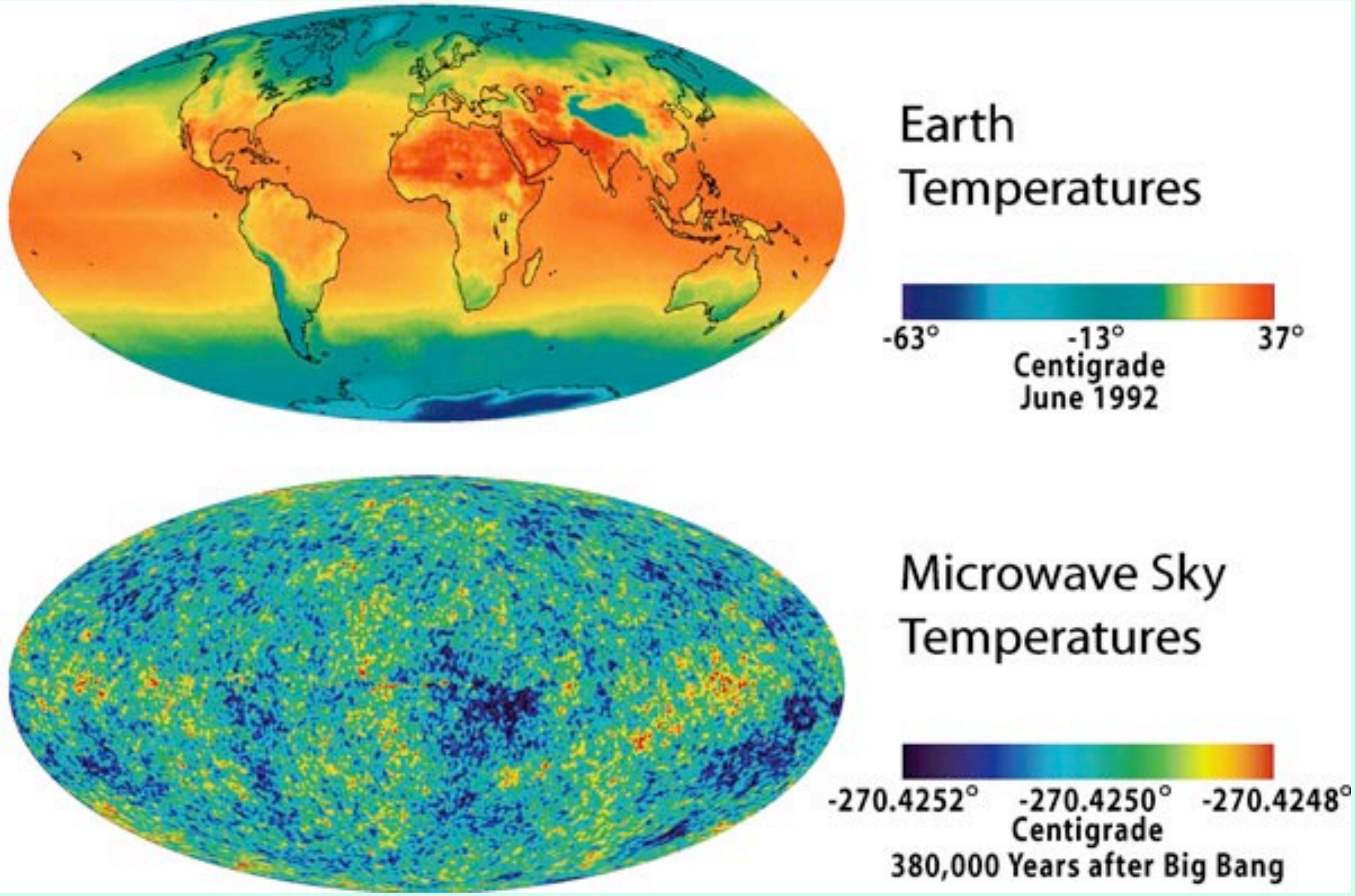
Measuring the intensity at different frequencies gives **the spectrum**, which **matches that of black body** at 2.726 K

Assuming black body and **measuring the intensity of CMB** at a fixed frequency and a given direction on the sky **gives the CMB temperature** in that direction

Make a **map** of **the CMB temperature** and study its statistical properties, e.g. the 2-point angular correlation function

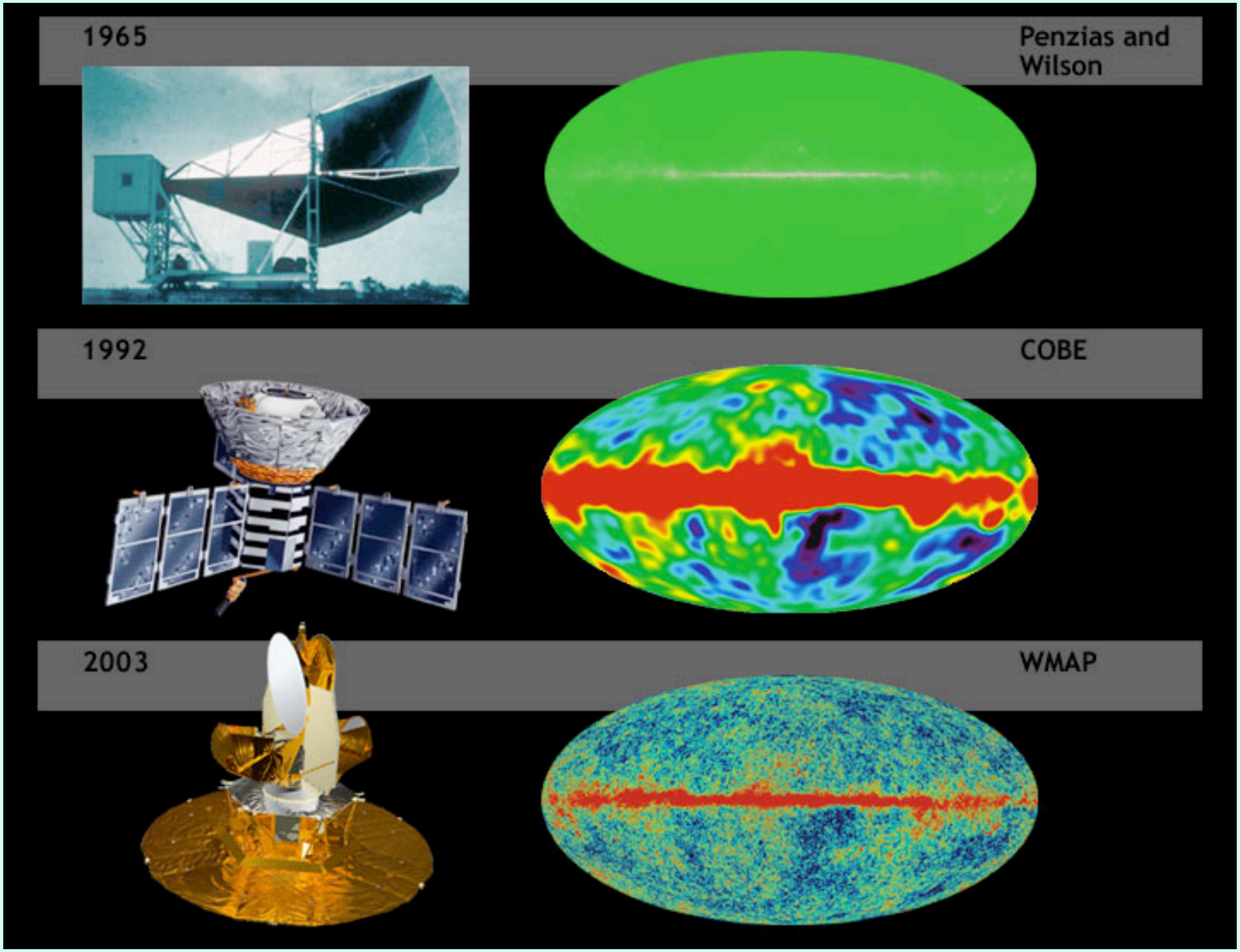
Similarly, one can make a **map** of **the CMB polarization**

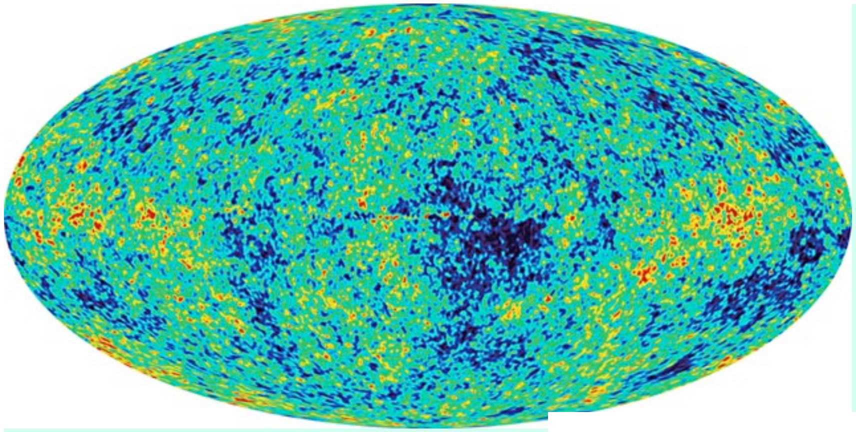
What's on the map?



http://map.gsfc.nasa.gov/

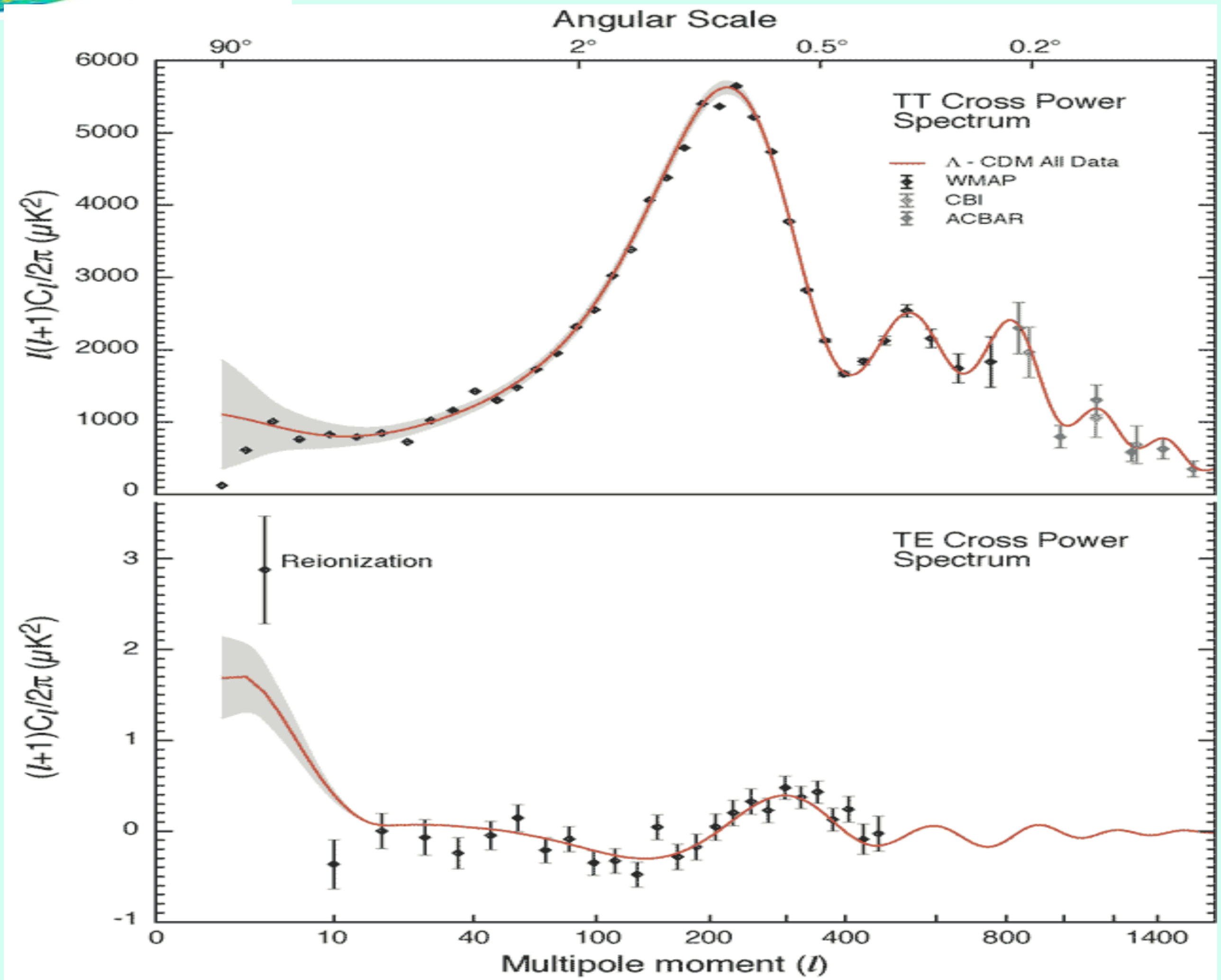
Evolution of the map



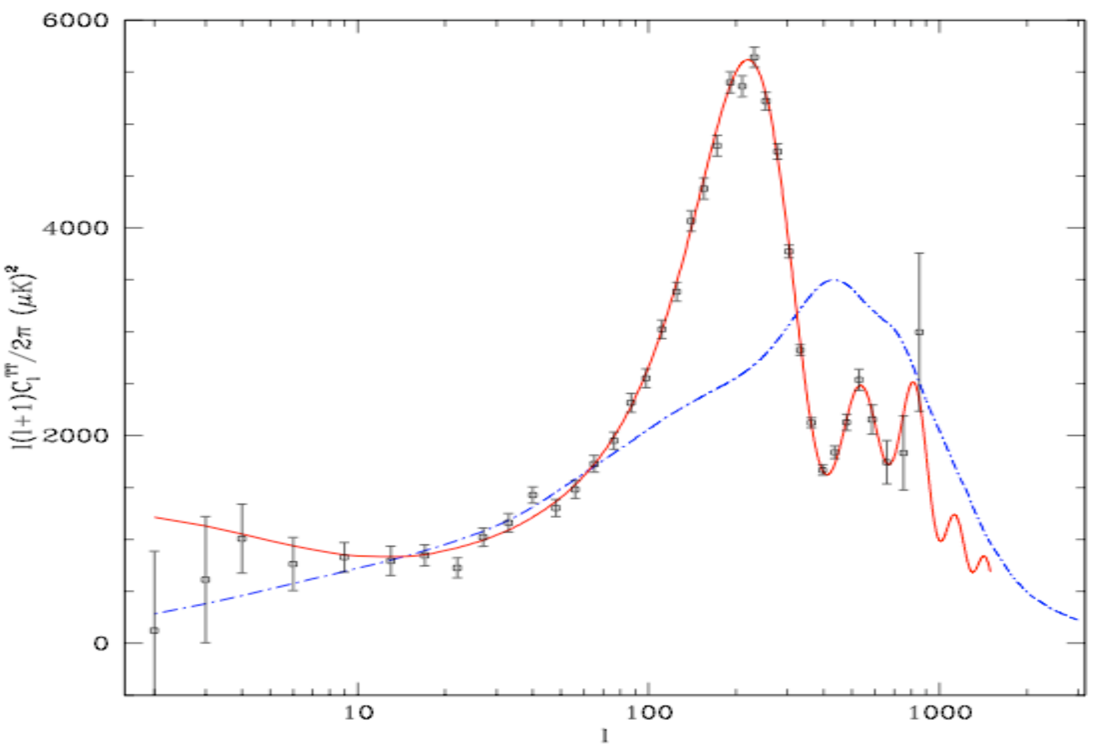


The map

The angular power spectrum



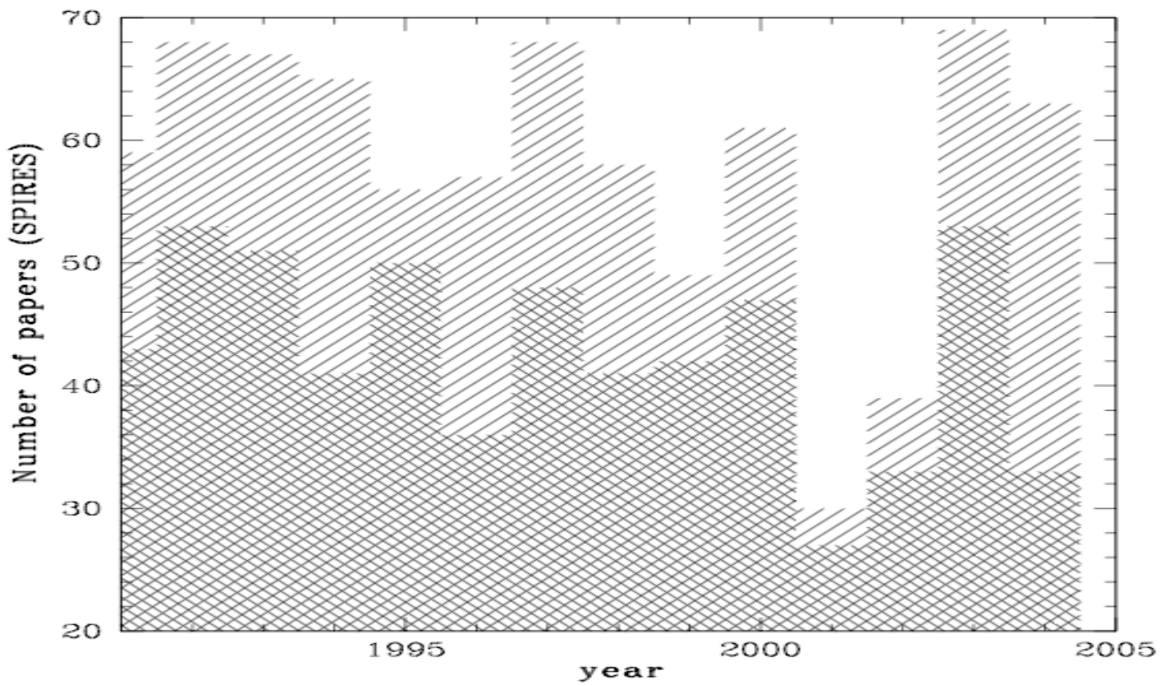
Models vs Data



- - - - - - Strings

——— Inflation

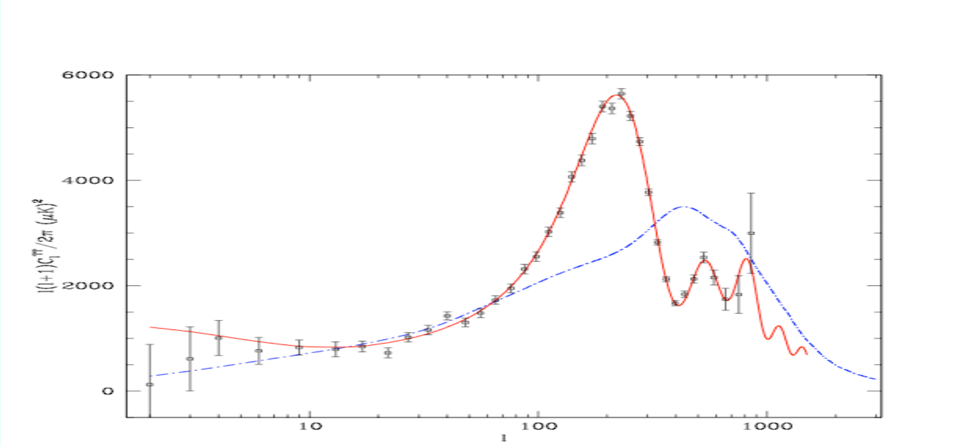
Can’t kill the strings…



What is $l(l+1)C_l$?

$$\frac{l(l+1)C_l}{2\pi} \approx \langle [\Delta T(\alpha)]^2 \rangle,$$

$$where \quad \alpha = \frac{\pi}{l}$$



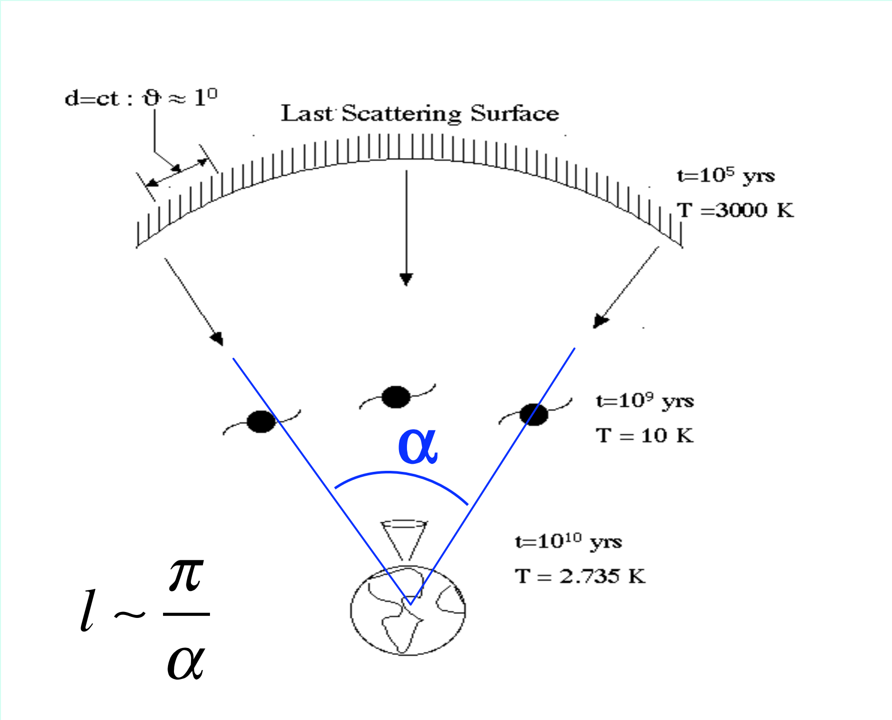
$$\Delta(\hat{n}) \equiv T(\hat{n}) - \langle T \rangle$$

$$\Delta(\hat{n}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\hat{n})$$

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} a_{lm}^{*} a_{lm}$$

$$C(\alpha) = \langle \Delta(\hat{n}) \Delta(\hat{n}') \rangle$$

$$C(\alpha) = \frac{1}{4\pi} \sum_{l=0}^{\infty} (2l+1)\ C_l\ P_l(\cos\alpha)$$



Relevant physics

Background: photons, baryons (p,He,e^-,…), neutrinos
cold dark matter (CDM)
Dark Energy (e.g. Λ)
Geometry (flat, open or closed)

Interactions: EM (**Thomson scattering**) and **Gravity**

Equations: Evolution of the metric (**Einstein eqs**)
Radiation transport (**Boltzmann eq**)
Conservation equations

Initial conditions: can be of different types, depending on the theory. **Inflation** predicts scale-invariant, adiabatic.

Background

$(\gamma, \nu, B, CDM, \Lambda \ldots)$

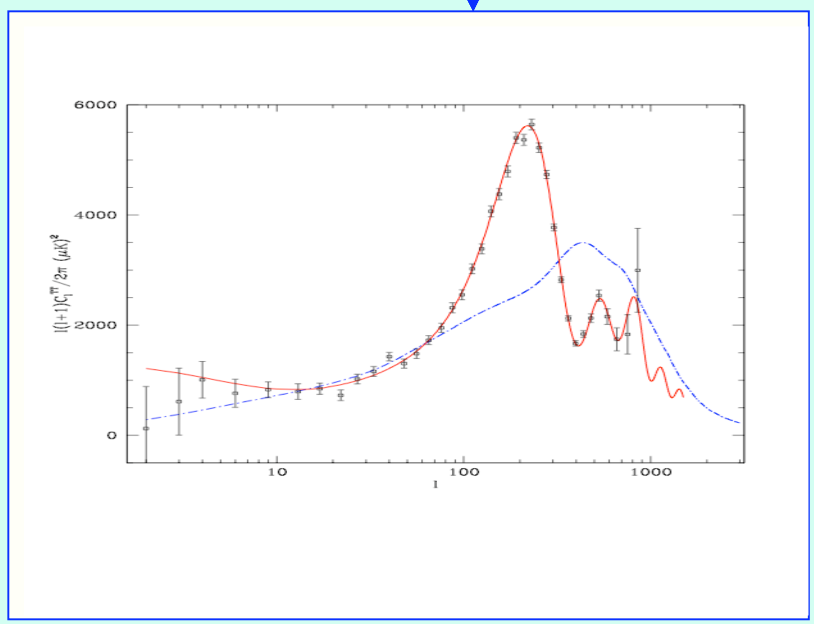
Initial conditions

Events such as reionization

Other stuff: cosmic strings?

CMBfast (F77, Seljak & Zaldarriaga)
CAMB (F90, Challinor & Lewis)
CMBeasy (C++, Doran)

(can be treated as a black box but it is not really black)



What does CMB stand for?
(compiled by Douglas Scott)

* Call Me Back
* Canadian Mathematics Bulletin
* Capacity Management Branch (of the US IRS)
* Caparo Merchant Bar PLC (steel company)
* Carbolic Methylene Blue
* Cash Money Boys (band)
* Cash Money Brothers (band)
* Casa da Moeda do Brasil
* Cellular and Molecular Biology
* Central Maritimes Basin (of Atlantic Canada)
* Central Massachusetts Bandits
* Central Medical Board (of the canadian DCIEM)
* Centrale Medische Bibliotheek (eg in Groningen)
* Centre for Mathematical Biology (Oxford University)
* Centro Medico Barrashopping (Brazilian hospital)
* Center for Mechanistic Biology and Biotechnology (Argonne NL)
* Chadwick Martin Bailey (management consultants)
* Chase-Manhattan Bank
* Chelsea Market Baskets (purveyors of distictive gift baskets)
* China Motor Bus (Hong Kong)
* Christian Music Bulletin
* Circus Model Builder

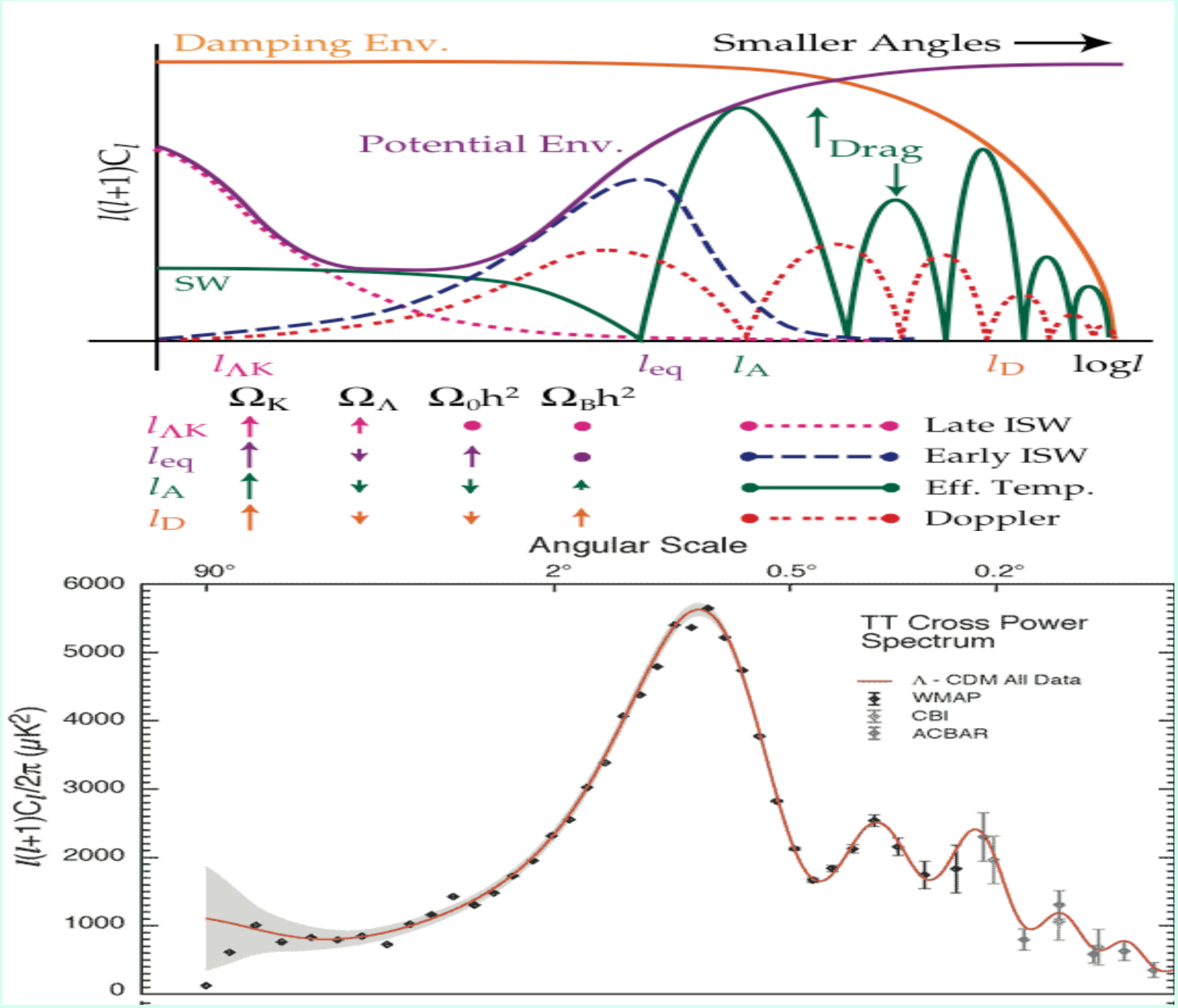
Sources of CMB anisotropy

Primary (at last scattering):

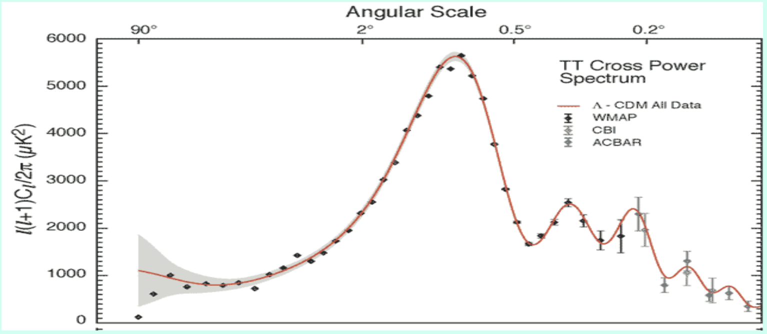
- fluctuations in the gravitational potential (**Sachs-Wolfe** (SW) effect)
- higher (lower) T in over(under)-dense regions (Density or **Intrinsic** fluctuations)
- peculiar velocity of matter (**Doppler** effect)
- **Damping** of small scale fluctuations due to the finite thickness of the LSS

Secondary (after last scattering):

- **Integrated Sachs-Wolfe** (ISW) effect
- Global **reionization**
- scattering by ionized matter in clusters (**Sunyaev-Zeldovich** effect)
- Weak **gravitational lensing** by matter along the line of sight



Wayne Hu's website: *http://background.uchicago.edu/*



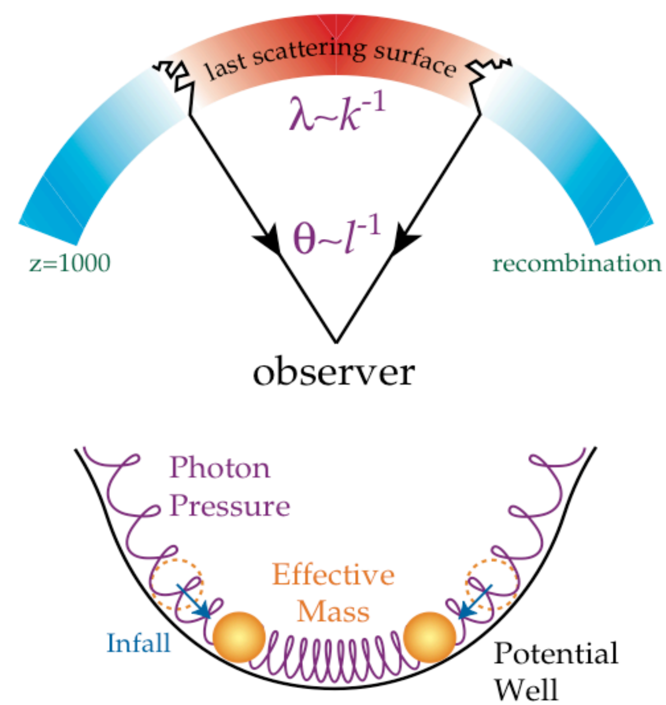
Why oscillations?

Before decoupling **photons and baryons are tightly coupled** into a single fluid

This **fluid has mass and pressure** and responds to gravitational potentials very much **like a** (damped) **harmonic oscillator.**

The space-time is **perturbed on all scales** (wavelengths), and the fluid responds on all (sub-horizon) scales.

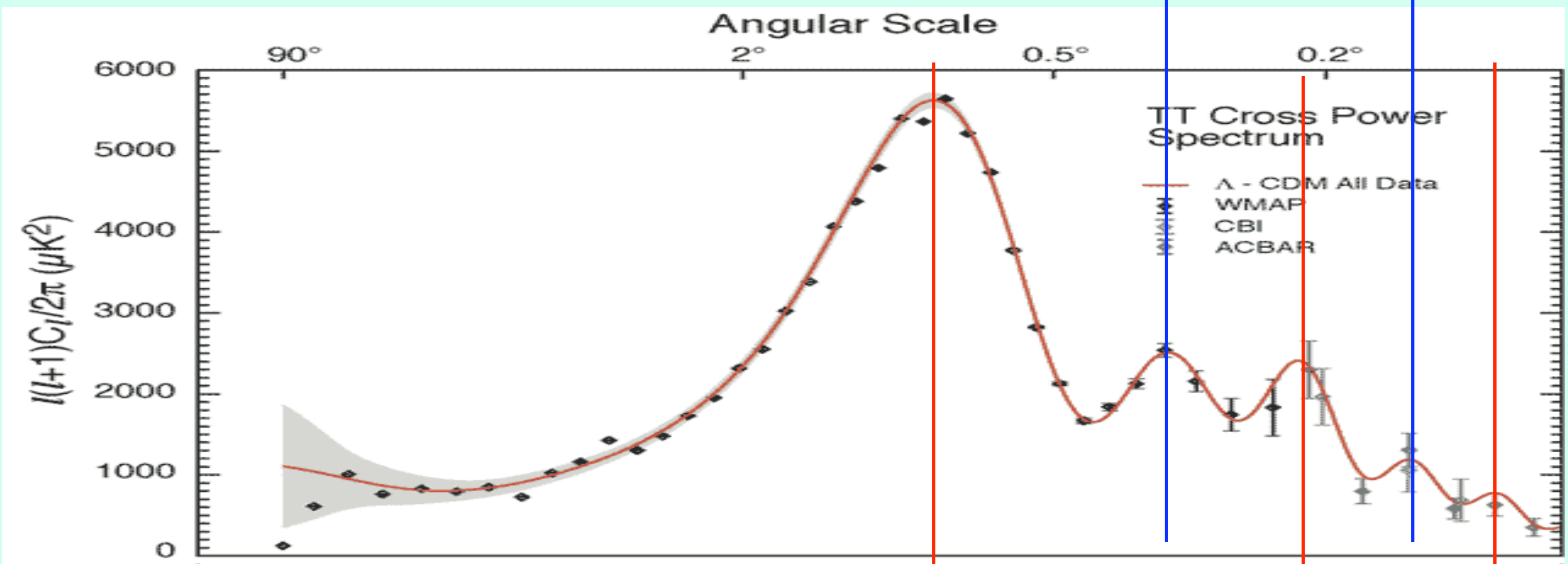
A snapshot of the **oscillations in time** of all the different modes **appears as oscillations in** Fourier space (or ***l*-space**)



From Wayne Hu's website

Angular scale corresponding to the largest wavelength mode fully **stretched** at t_{dec}

Angular scale corresponding to the 2nd largest wavelength mode fully **stretched** at t_{dec}

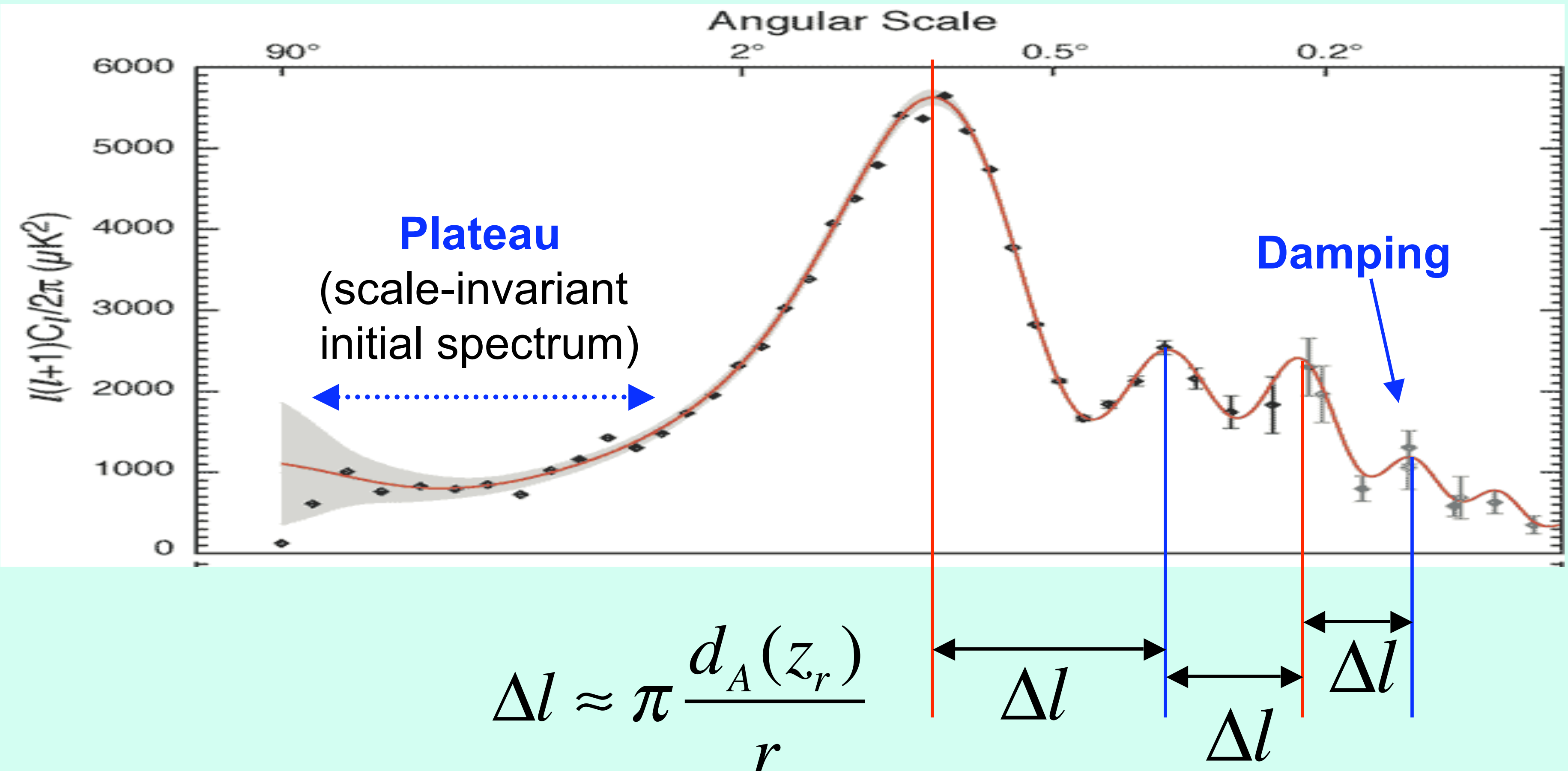


Angular scale corresponding to the largest wavelength mode fully **compressed** at t_{dec}

…

Angular scale corresponding to the 2nd largest wavelength mode fully **compressed** at t_{dec}

A few features:



$$\Delta l \approx \pi \frac{d_A(z_r)}{r_s}$$

Initial conditions

what is the initial amplitude of a given wave-mode?

it's a random number

Inflation predicts that **amplitudes are Gaussian** distributed and specifies the variance.

Inflation also predicts that all wave-modes are created equal, or **there is no preferred scale**

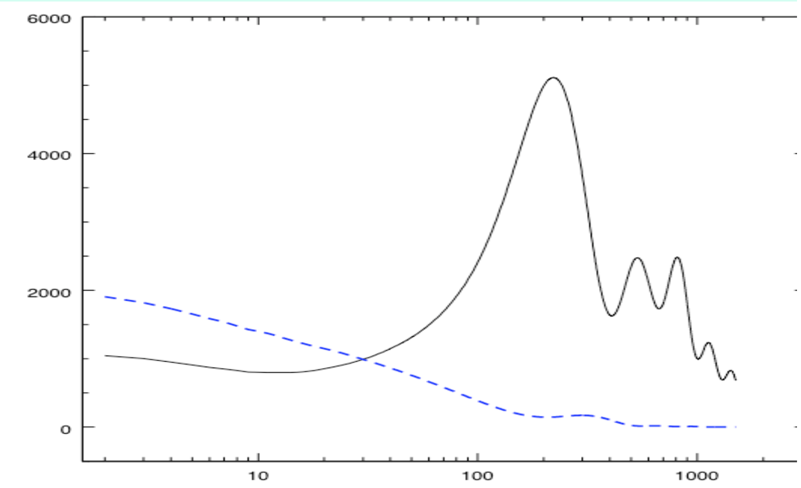
For density fluctuations, $\delta \equiv \delta\rho/\rho$, **this implies**

$$\left\langle \left|\delta(k)\right|^2 \right\rangle = P(k) = A\ k^{n_s}$$

with

$$n_s \approx 1$$

Initial conditions (cont'd)



Adiabatic:

$$\frac{\delta n_\gamma}{n_\gamma} = \frac{\delta n_\nu}{n_\nu} = \frac{\delta n_B}{n_B} = \frac{\delta n_{CDM}}{n_{CDM}}$$

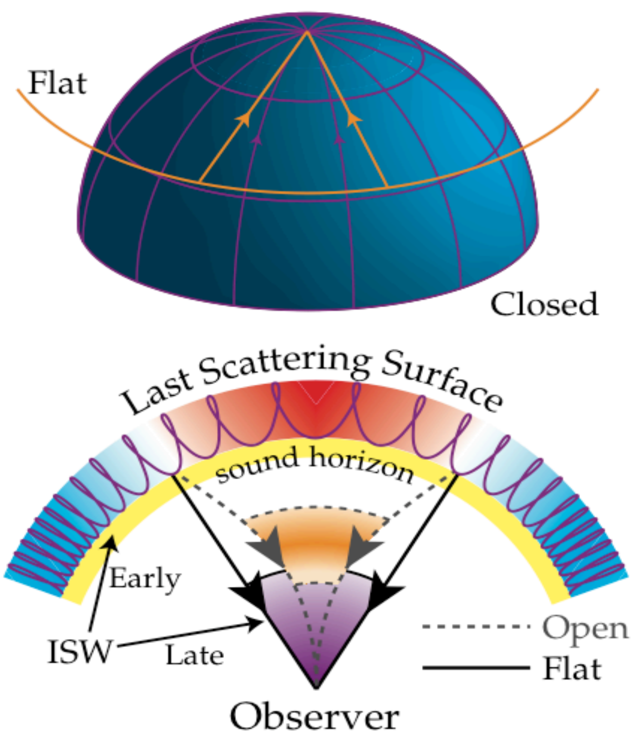
at any point in space, the relative change in the number density is the same for all species (**constant entropy**). This is the case if all perturbations are set by fluctuations in the curvature of space-time. The simplest inflation models provide such intitial conditions.

Isocurvature:

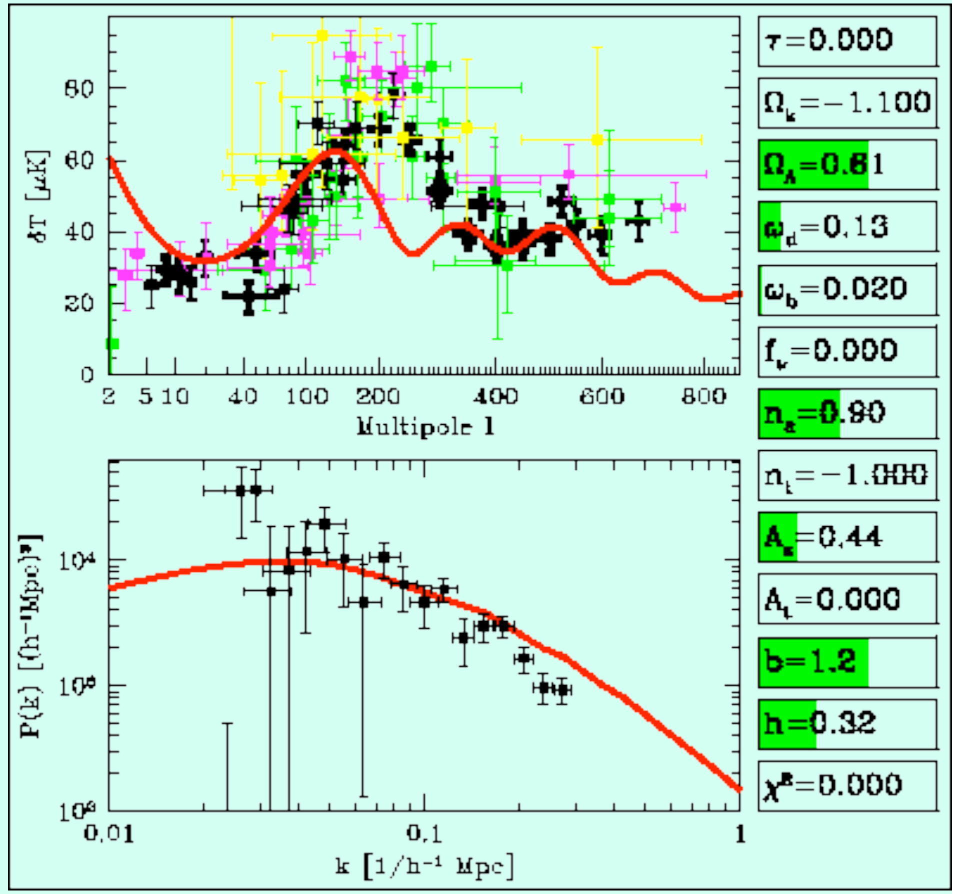
$$\delta\rho_\gamma + \delta\rho_\nu + \delta\rho_B + \delta\rho_{CDM} = 0$$

Individual components are perturbed but the total density is not (**constant curvature**). Several possibilities, many theories.

Geometry



From Wayne Hu's website



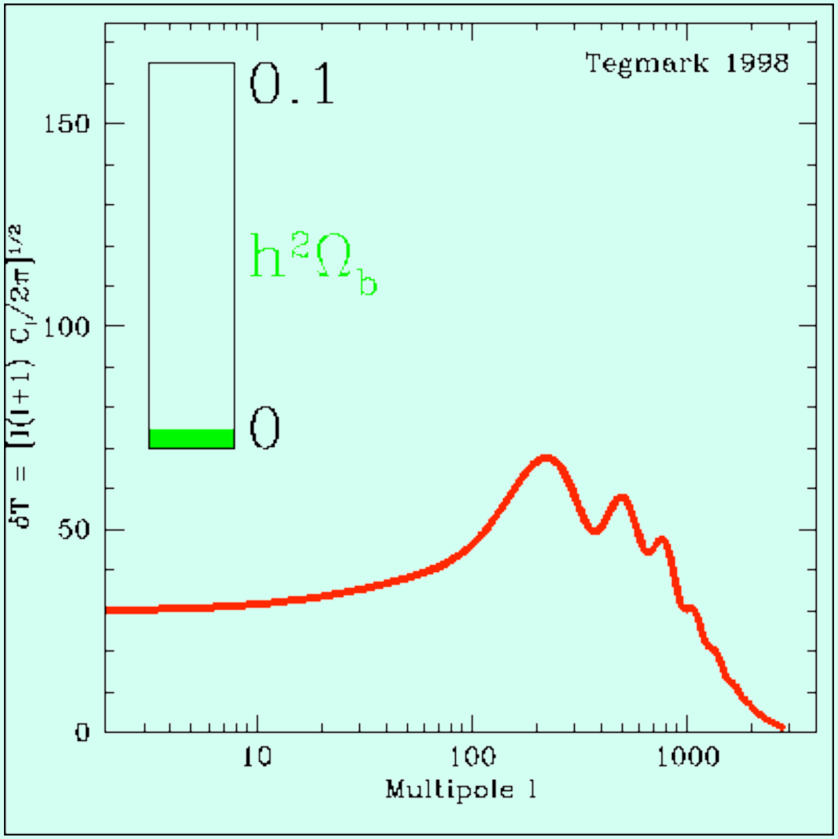
From Max Tegmark's website

The baryon fraction

Baryons **enhance** compression of oscillating photon-baryon fluid (**odd** numbered **peaks**)

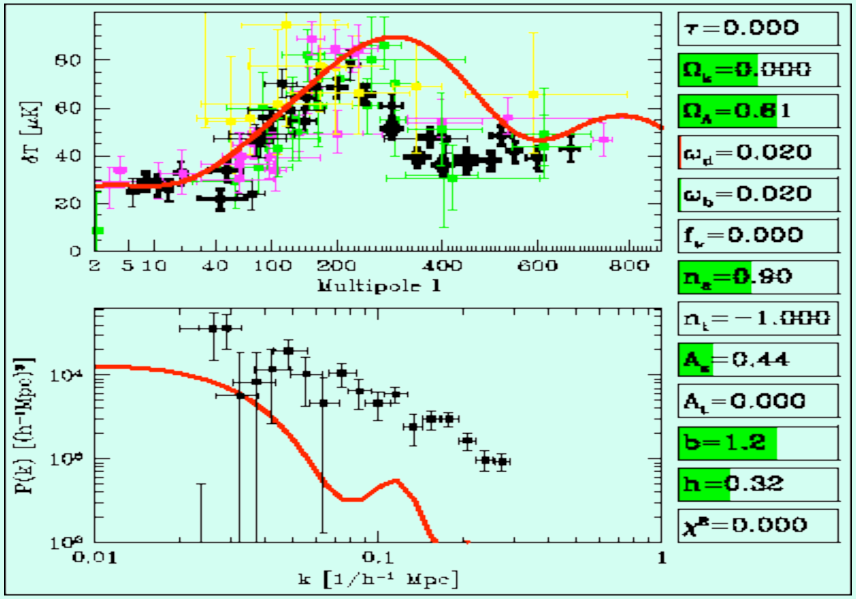
and

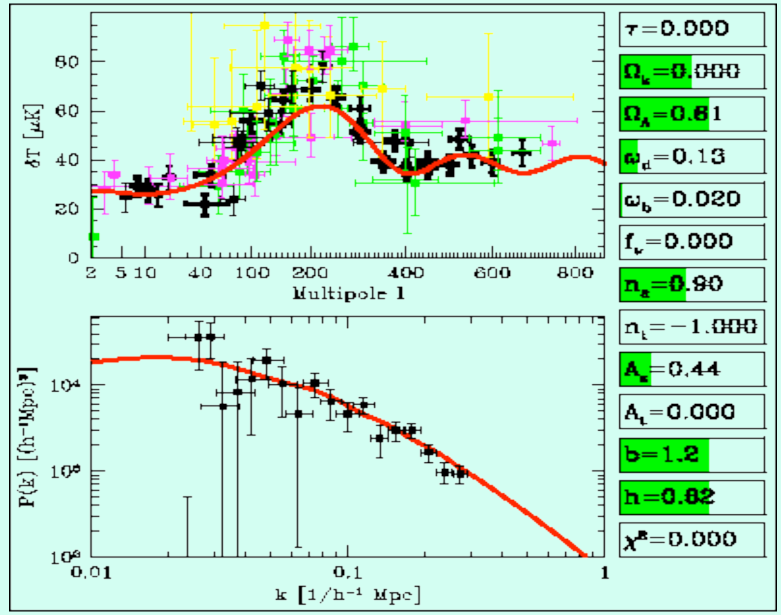
degrade rarefaction (**even** numbered **peaks**).

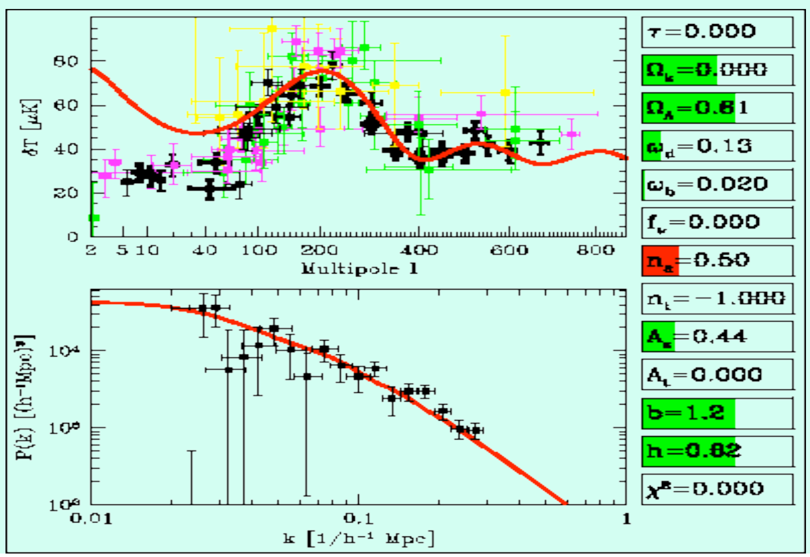


Other stuff: CDM, initial spectrum, reionization,…

From Max Tegmark's website:
http://space.mit.edu/home/tegmark/cmb/movies.html







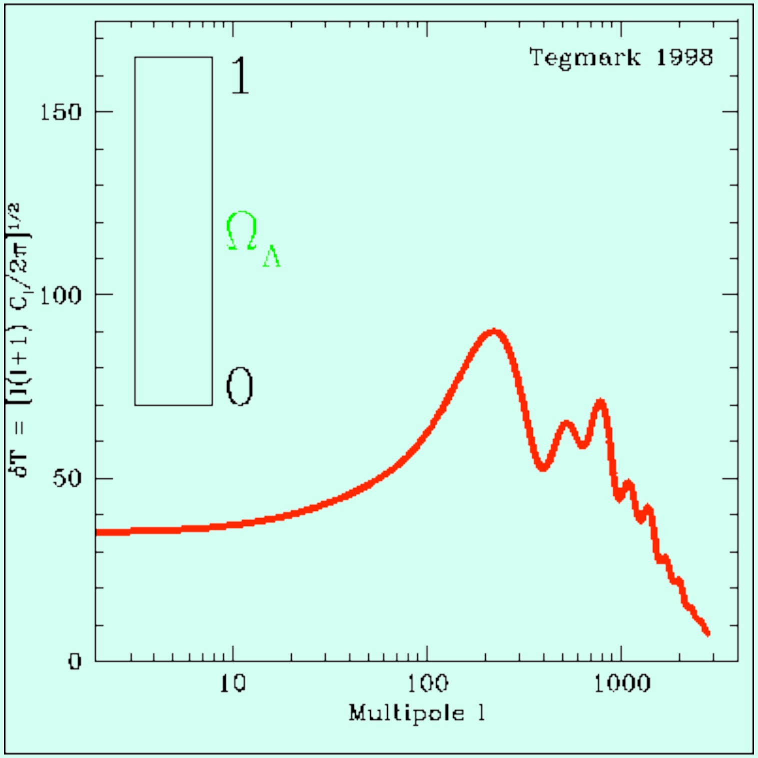
What does CMB stand for? (compiled by Douglas Scott)

* City of Miama Beach
* Climate Modeling Branch (of EMC/NCEP/NWS/NOAA)
* Coleman Building (Silver Spring, MD)
* College of Management and Business (eg at NLU)
* Coalition of Minnesota Businesses Inc.
* Collection Management Branch (various government agencies)
* Colombo, Katunayake International, Sri Lanka (airport code)
* Color Me Badd (pop group)
* Color me Beautiful (dutch image consultants)
* Columbia College, California (Seismograph Network Station)
* Combat Maneuver Battalion
* Combat Medical Badge (US military)
* Combat Mobility Branch
* Community Mail Bag (Australia Post)
* Compagnie des Machines Bull (computer company)
* Comparative Medicine Branch (of NIEHS)
* Computational Molecular Biology
* Computer Modern Bold (font)
* Concours Mondial de Bruxelles (wine contest)
* Configuration Management Board (Department of the Army)

Effects of Dark Energy on CMB…

1. DE affects the expansion history of the universe and, hence, the **distance to** the surface of **last scattering**. This **shifts** positions of **the peaks**.

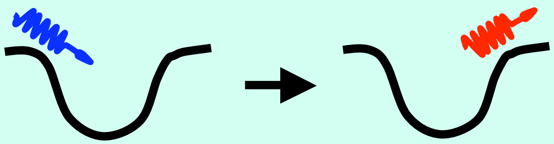
2. Results in additional anisotropy on large scales because of the **Integrated Sachs-Wolfe effect**



… are very weak

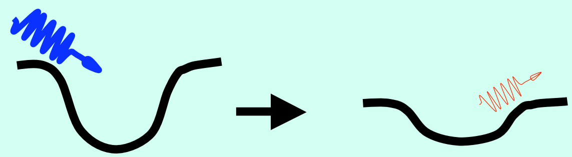
Integrated Sachs-Wolfe effect

$\Omega_M = 1$

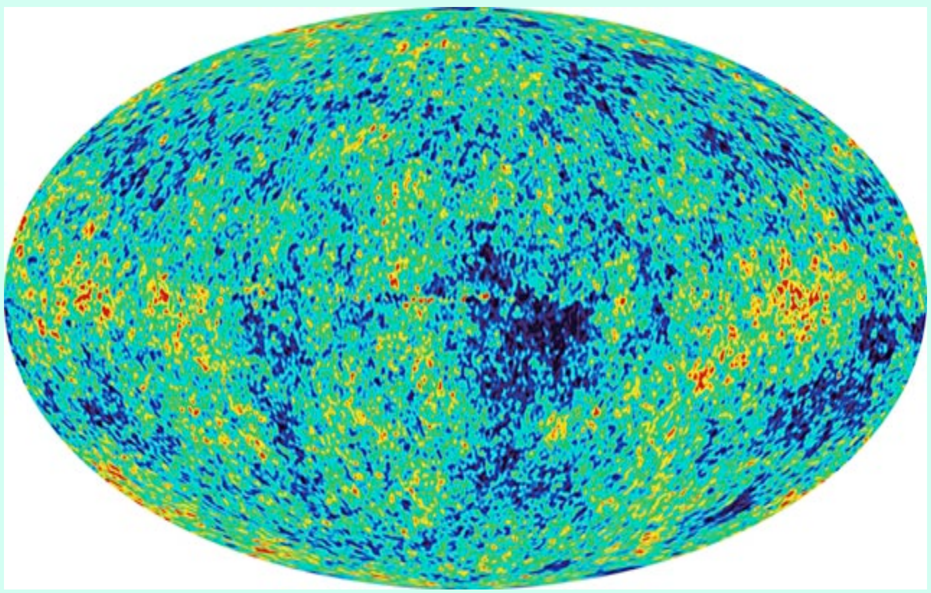


blueshift = redshift

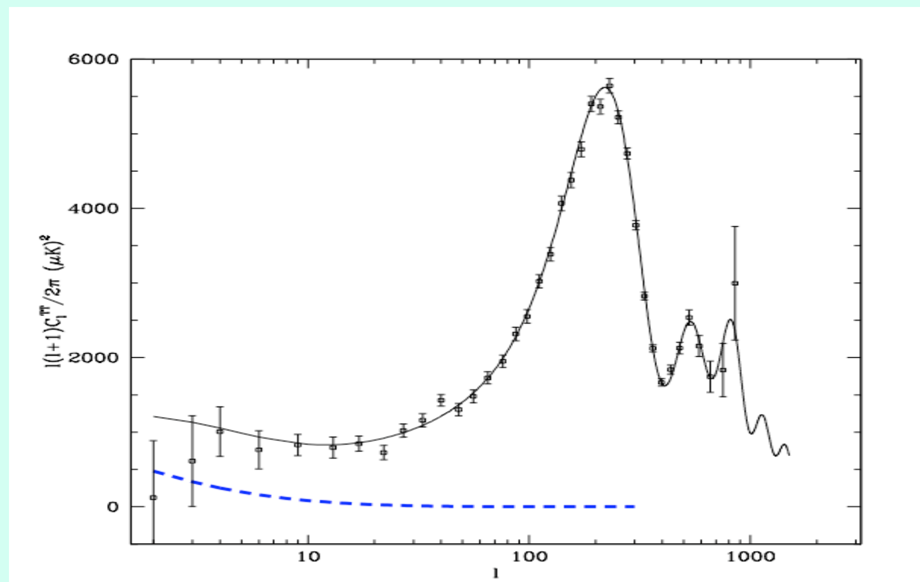
$\Omega_M \neq 1$



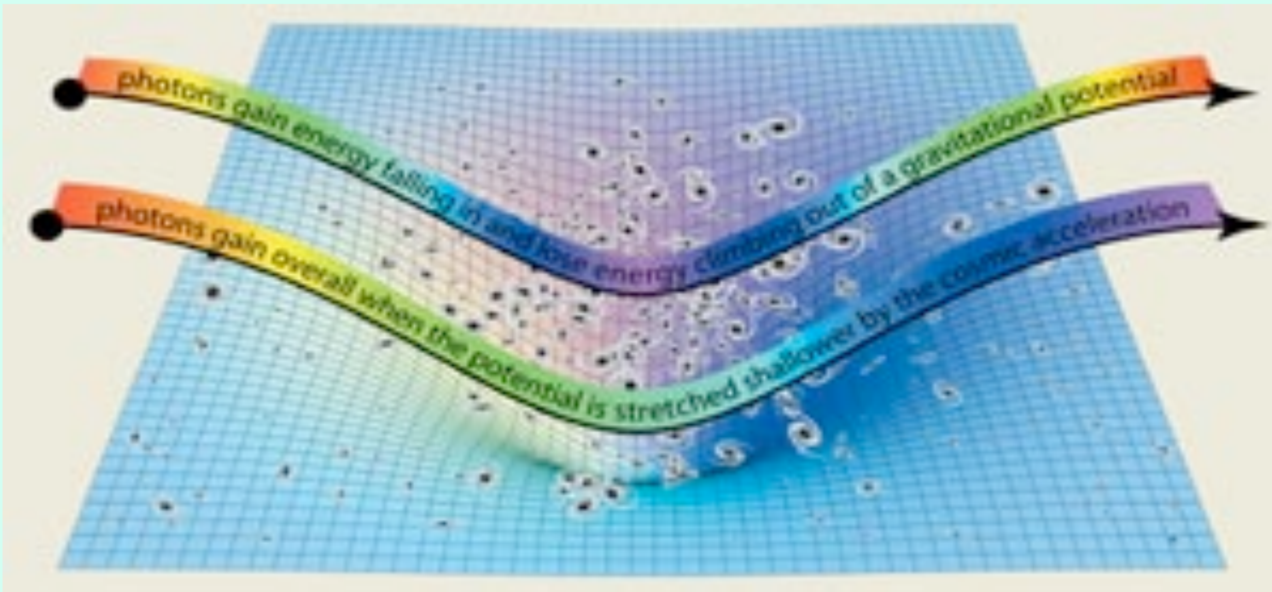
blueshift ≠ redshift



WMAP



LSS and ISW are correlated



From http://physicsweb.org/

ISW$\neq$0 $\rightarrow$ CMB/LSS correlation

R. Crittenden and **N. Turok,** Phys Rev Lett (1996)

Current status of ISW

• Boughn and Crittenden, astro-ph/0305001, Nature
WMAP / HEAO-1 X-ray, 2.5-3σ detection
WMAP / NVSS radio, 2.5σ detection

• Nolta et al, astro-ph/0305097, ApJ
WMAP / NVSS radio, 2σ detection

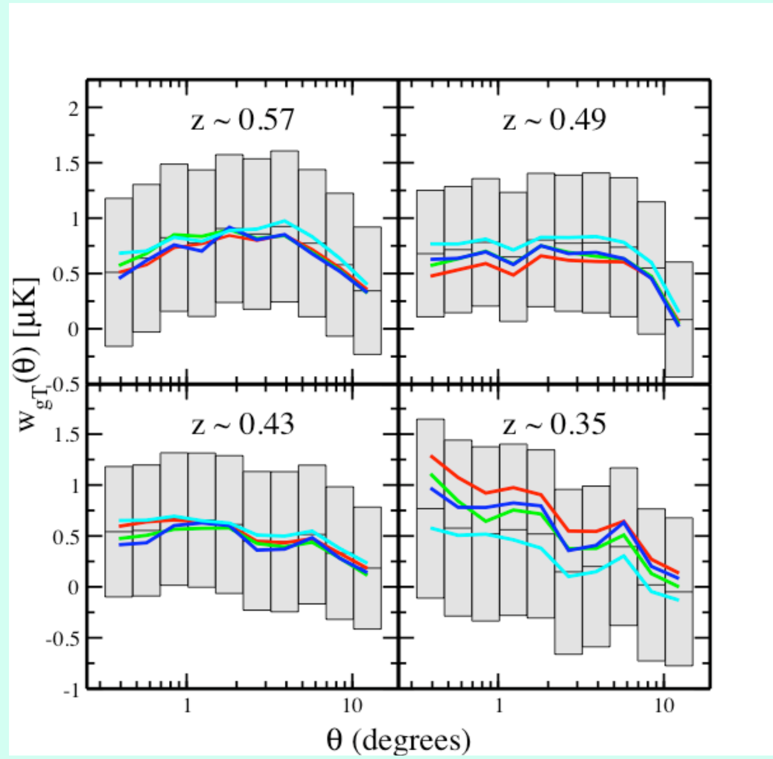
• Fosalba and Gaztanaga, astro-ph/0305468, MNRAS
WMAP / APN galaxies, 2.5σ detection

• Fosalba et al, astro-ph/0307249, ApJ
WMAP / SDSS galaxies, 3σ detection

• Afshordi, Loh and Strauss, astro-ph/0308260, PRD
WMAP / 2MASS galaxies, 2.5σ detection

• Vielva et al, astro-ph/0408252
WMAP / NVSS radio, 3.7σ detection

• N. Padmanabhan et al, astro-ph/0410360
WMAP / SDSS LRG galaxies, 2.5σ detection



From Scranton et al, astro-ph/0307335
WMAP / SDSS LRG

What we have learned from CMB by now

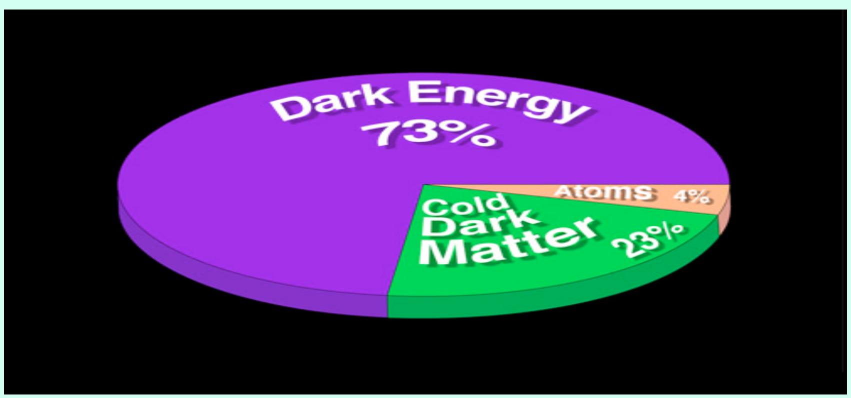
1. **The seeds** for cosmic structure **are** (mostly) **passive** and not active like cosmic strings. Otherwise, we would not see acoustic peaks.

2 . **The initial spectrum** of the density fluctuations **is** (close to) **scale-invariant.** Otherwise, the plateau would be tilted and the spacing between the peaks would not be (so close to) constant.

3. **The initial conditions are** (predominantly) **adiabatic**. Otherwise, the peak pattern would be quite difficult to fit. Also supported by the existing CMB polarization data.

4. **The universe is** (nearly) **fla**t, as follows from the positions of the peaks

5. CMB (especially when combined with other probes) favors a universe made of

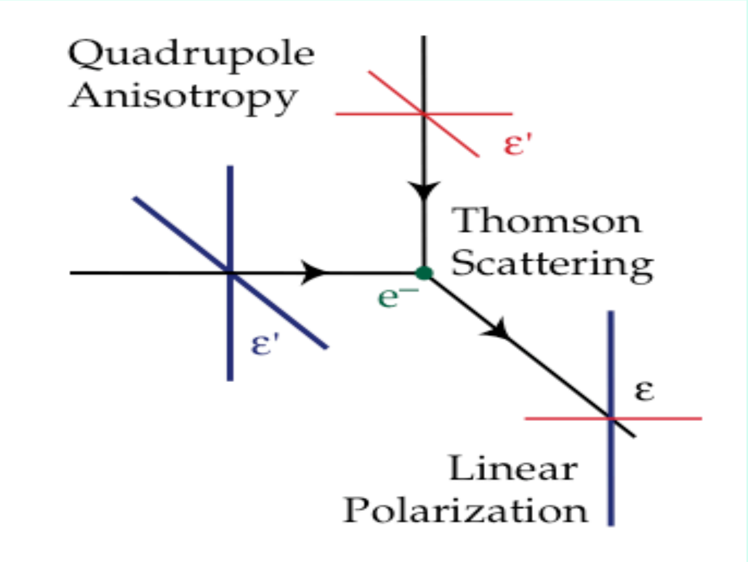


Friday talk by **Chris Stubbs** is about the **dark stuff**

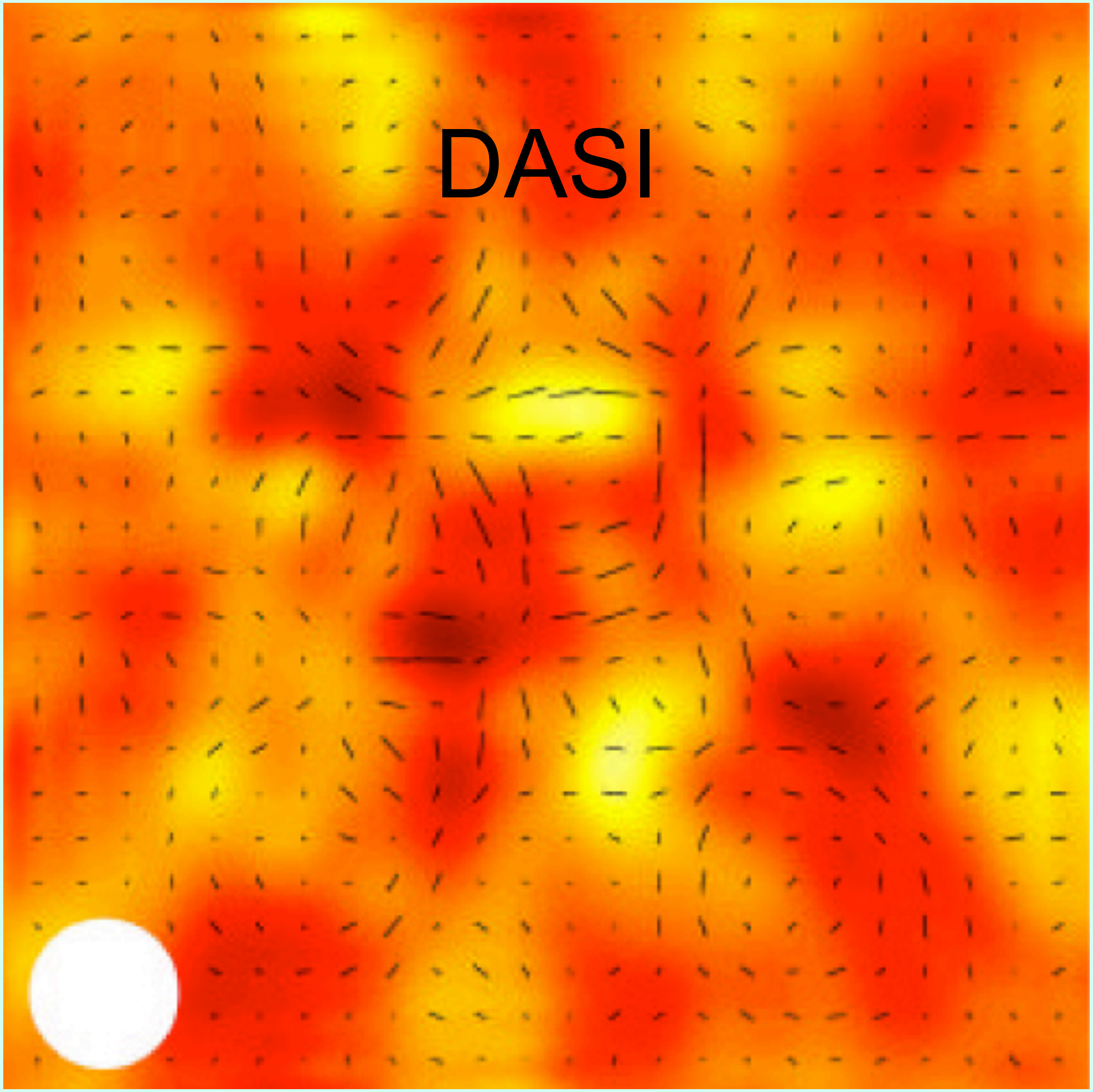
CMB polarization

How is it produced? Unpolarized incoming radiation is Thomson scattered into linearly polarized radiation if the intensity of the incoming radiation has a **quadrupolar** directional dependence.

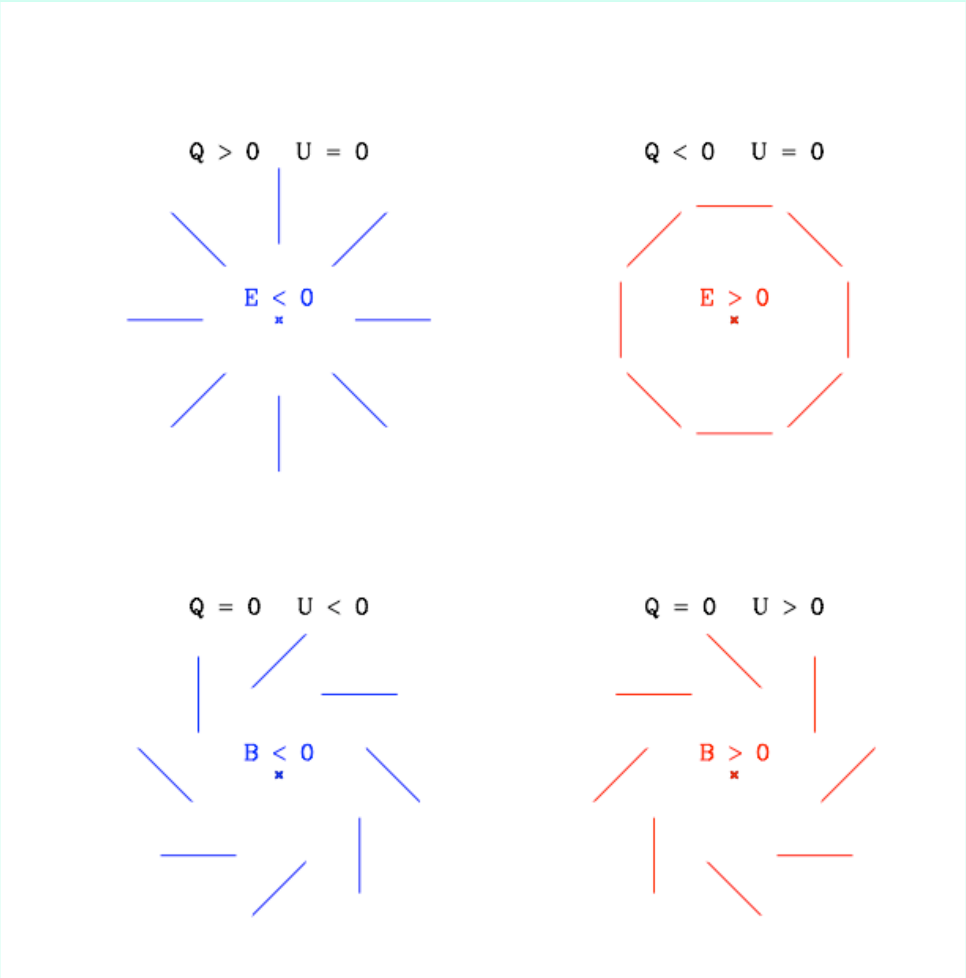
$$\frac{d\sigma}{d\Omega} \propto \sigma_T \left| \hat{\varepsilon}' \cdot \hat{\varepsilon} \right|^2$$



From Wayne Hu's website


DASI

E (gradient) **and B** (curl) **modes**

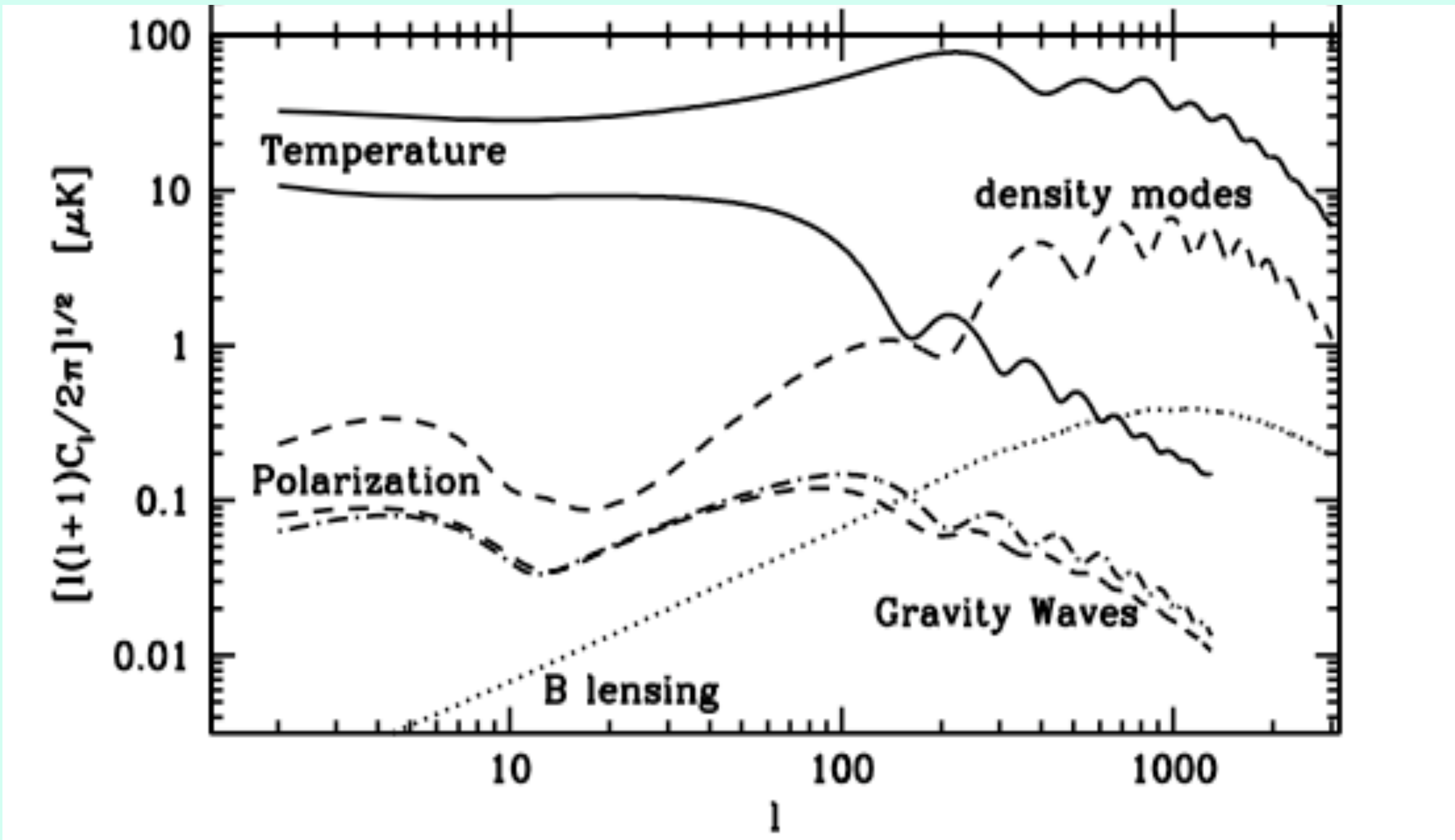


Polarization **E-mode** is due to **density gradients**

B-mode could be **produced by gravity waves** generated during Inflation. Its detection would be an important test of the paradigm

From M. Zaldariaga, astro-ph/0305272

Beyond the temperature spectrum



From M. Zaldariaga, astro-ph/0305272

What does CMB stand for?
(compiled by Douglas Scott)

* Consolidated Materials Brokers (steel mill waste recyclers)
* Contact Memory Button
* Contracts Management Branch (of NINDS)
* Controlled Metal Build Up
* Cooper Medical Buildings Inc. (design and construction company)
* Cooperativa Muratori e Braccianti di Carpi S.r.l. (construction company)
* Core-Mantle Boundary (geology)
* Creative Music for Business (internet audio company)
* Credit Mutuel de Bretagne
* Critical Mass Balance
* CMB Systems (computer company)
* CMB Technologies, Inc. (information technology company)

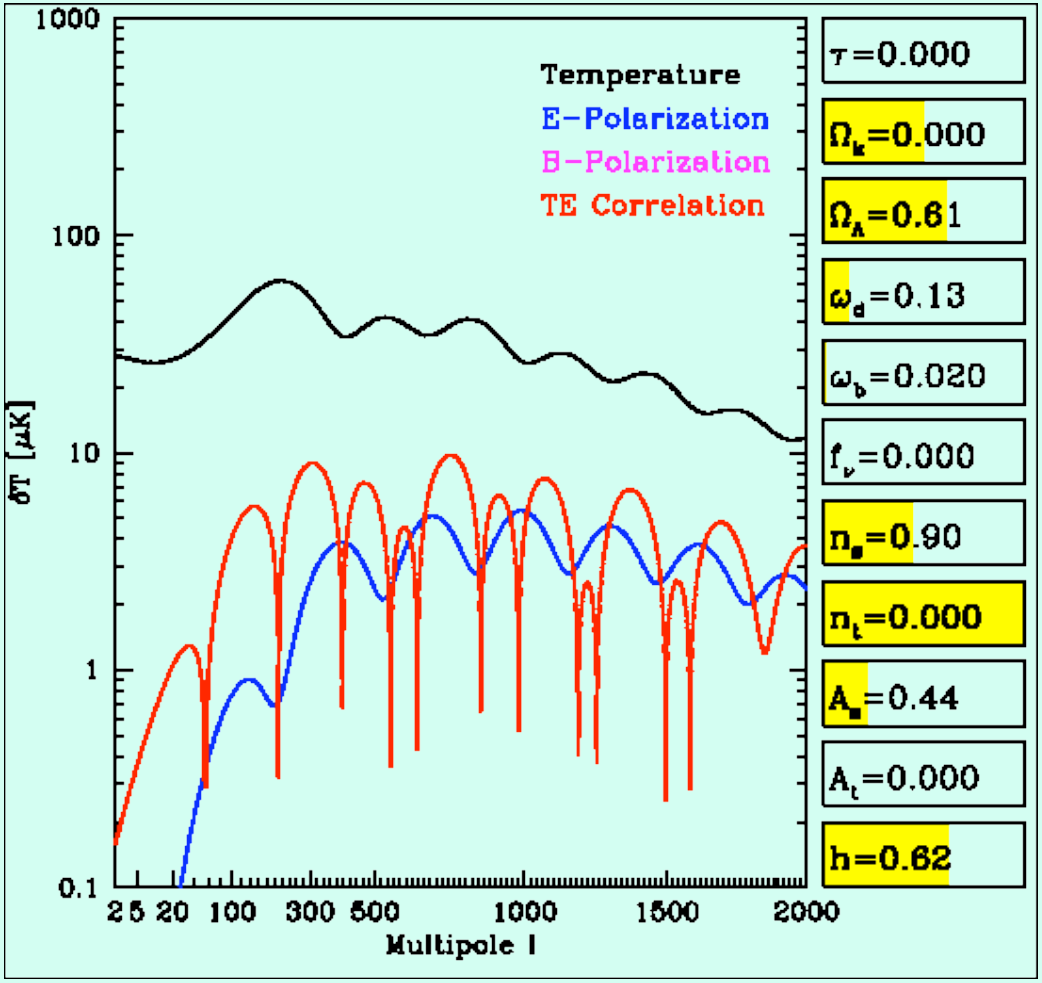
Reionization

After recombination **the universe was neutral**.

Then, after a while, first **stars began to form**. Nuclear fusion in **stars** releases ~7 MeV per hydrogen atom: enough to **ionize** many hydrogen atoms in **the surrounding space**.

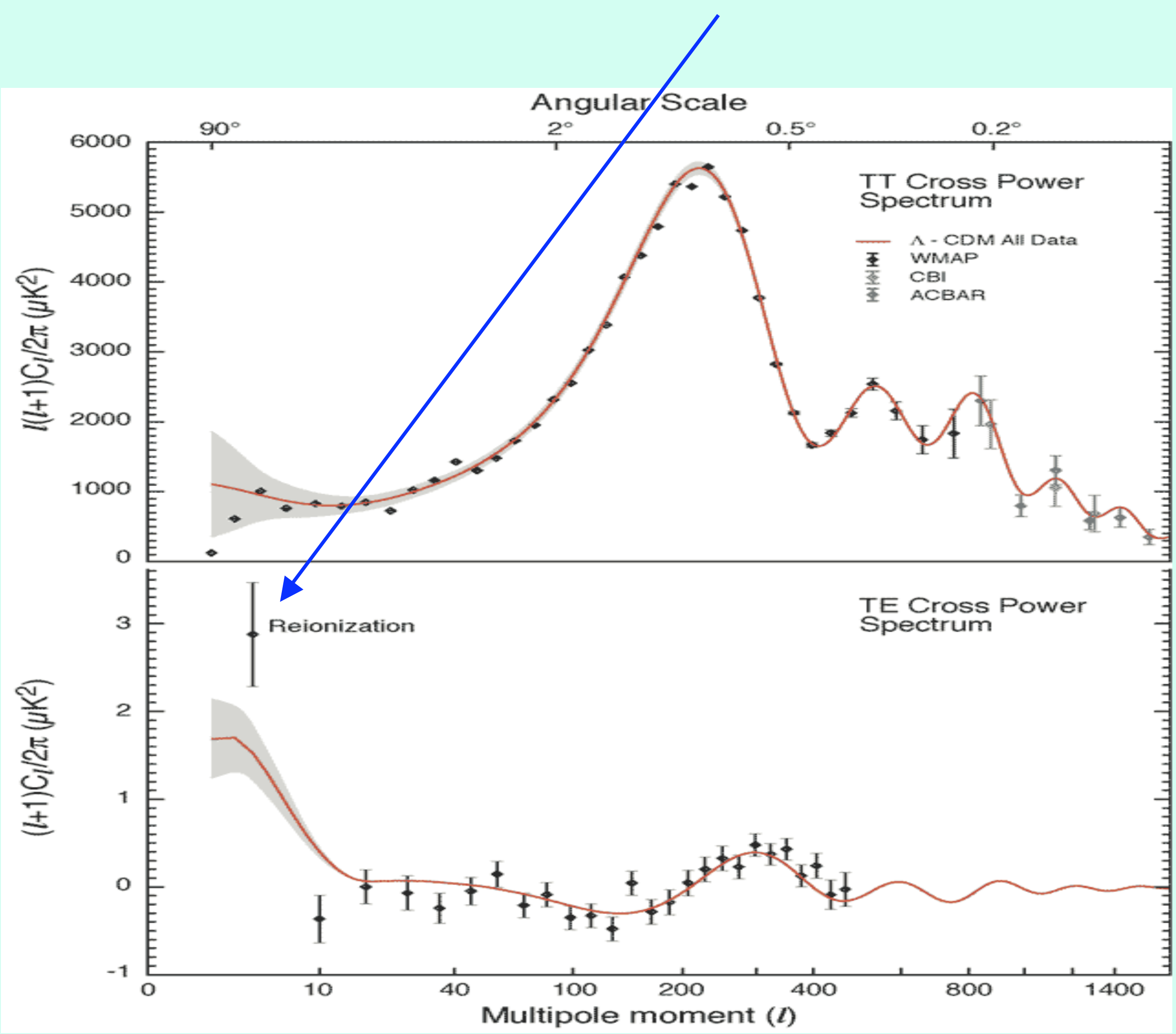
Reionization has an observable effect on the CMB temperature and polarization. Re-scattering by ionized gas **washes out** some of the **temperature anisotropy and generates** new **polarization** fluctuations on large scales.

Reionization effects



Agelica de Oliveira-Costa's website:
http://www.hep.upenn.edu/~angelica/

WMAP and reionization



A puzzle

WMAP: reionization happened between z = 11 and 30

z=11(30) is roughly 400 (100) million years after the Big Bang

Spectra of galaxies at z~6-7 show Lyman-α absorption, i.e. there was a significant amount of neutral hydrogen long after z=11.

z=6 corresponds to about 1billion years after the Big Bang

Double reionization?
Is our theory of structure formation complete?

Current state:

waiting for WMAP's next data release, which is supposed to include the **E-polarization spectum**.
(E-mode was first detected by DASI in 2002)

waiting for Planck to go up in 2007

planning dedicated experiments **to measure the B-mode** (e.g. CLOVER in Antarctica)

going after secondaries: **CMB on smaller scales** affected by lensing and scattering by hot gas in galaxy clusters

combining CMB **with** other tests (**SNIa, lensing, galaxies**,…)
to test the nature of **Dark Energy**

In conclusion:

http://background.uchicago.edu/ (Wayne Hu)
http://space.mit.edu/home/tegmark/ (Max Tegmark)
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