Observational Cosmology

(C. Porciani / K. Basu)

Lecture 3

The Cosmic Microwave Background

(Spectrum and Anisotropies)

Course website:

http://www.astro.uni-bonn.de/~kbasu/astro845.html

What we will (and will not) learn

What you know (I hope!)

- ☑ Basic cosmological principles
- ☑ Parameter estimation, Bayesian methods, Fisher matrices

- ☑ How CMB is measured, from its discovery to the present
- ☑ How CMB is analyzed statistically
- ☑ How CMB is used to constrain cosmological parameters
- ☑ What are the challenges of CMB data analysis
- ☑ What the future (near and far) will bring to CMB research

- ☐ Learn about inflation
- ☐ Detailed mechanism of creation of temperature fluctuations, derivation of the relevant equations
- ☐ Explanation of how codes like CMBFAST work
- ☐ Details of CMB map making and parameter estimation methods

Outline of the CMB Lectures

Lecture 1

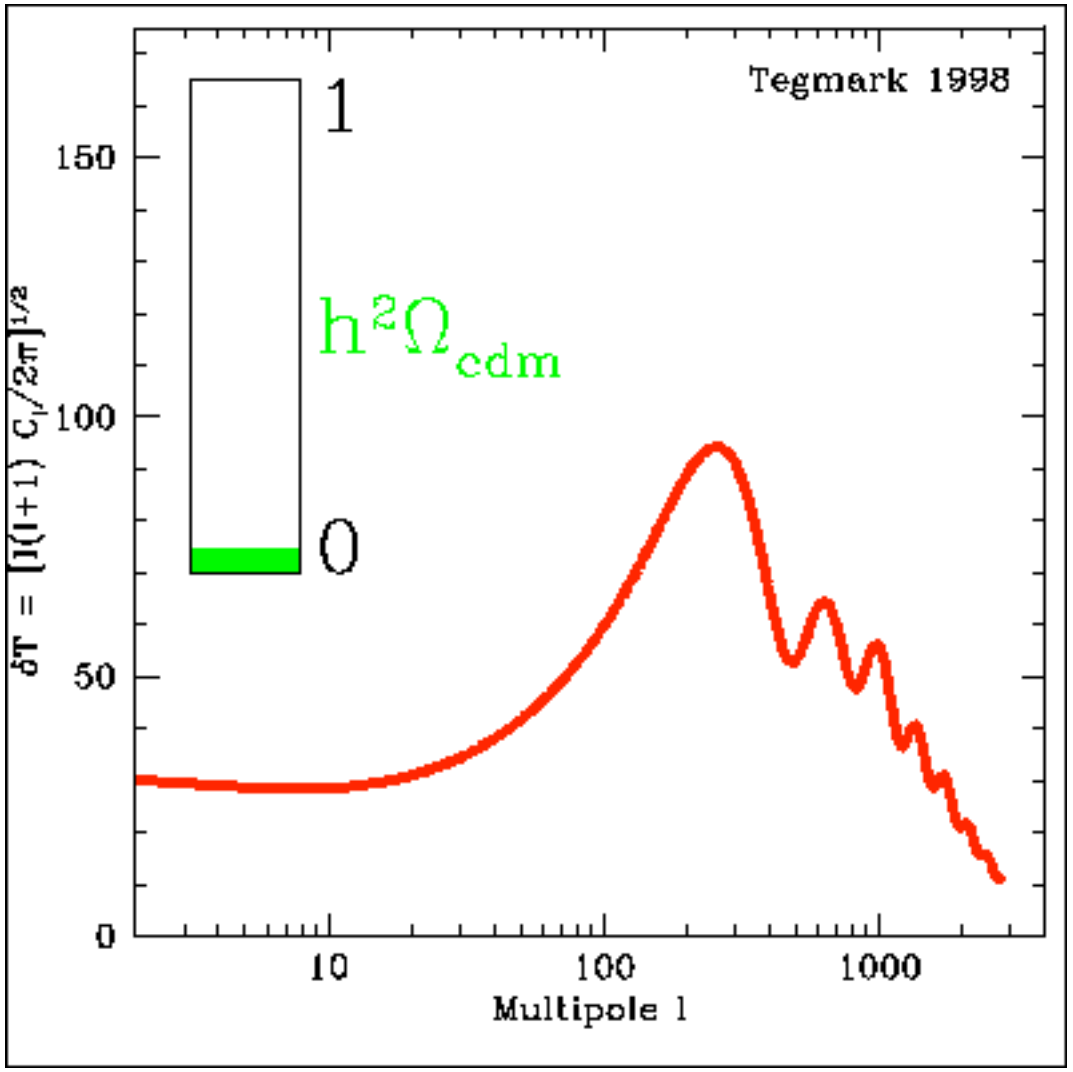
- ➡ Discovery of the CMB
- ➡ Thermal spectrum of the CMB
- ➡ Meaning of the temperature anisotropies
- ➡ CMB map making and foreground subtraction
- ➡ WMAP & PLANCK

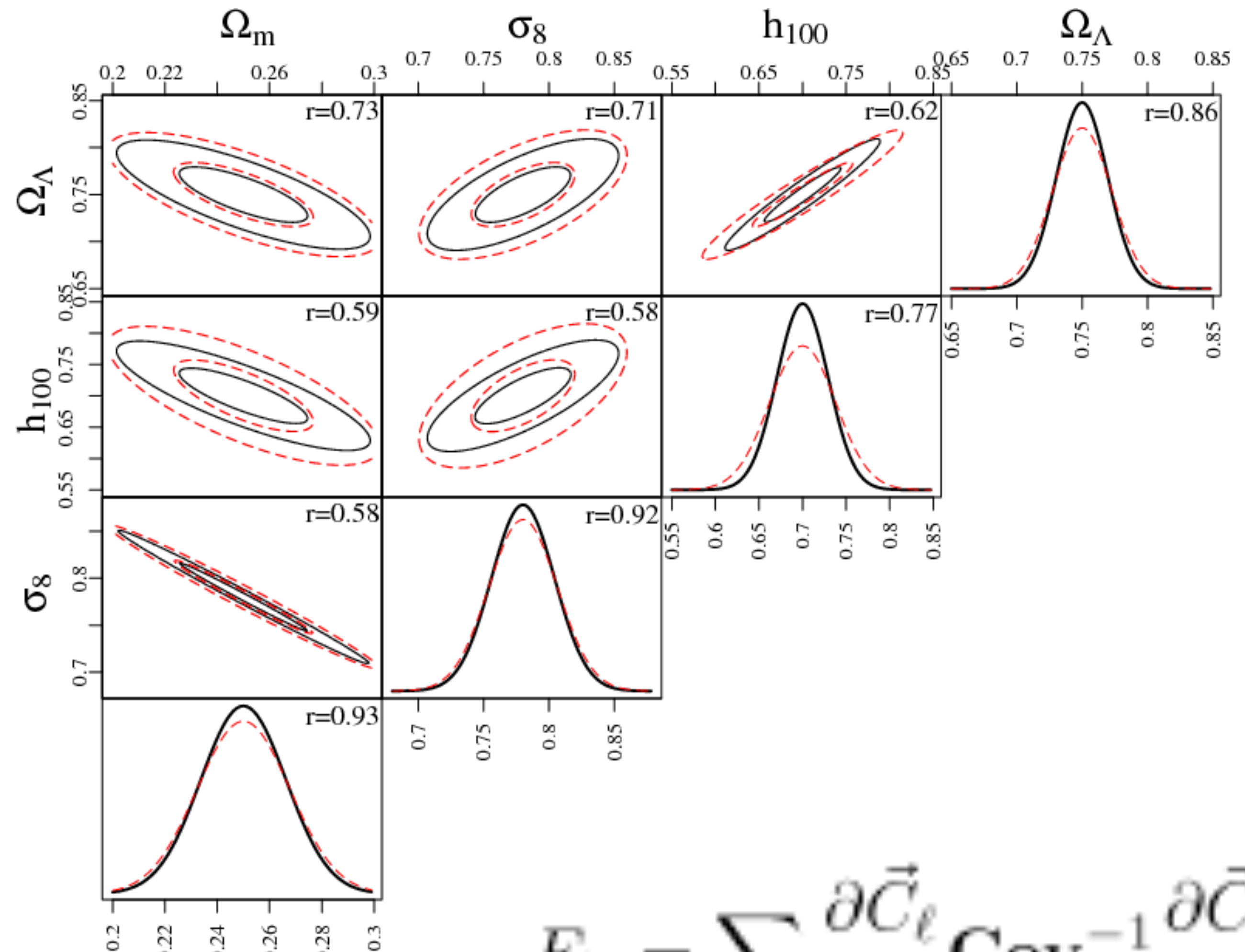
Lecture 2

- ➡ CMB secondary anisotropies
- ➡ Balloon and interferometric measurement of ΔT
- ➡ CMB Polarization and its measurement
- ➡ Big Bang Nucleosynthesis *(if time permits)*

Questions !! (and also feedback!)

Outline of the CMB exercise

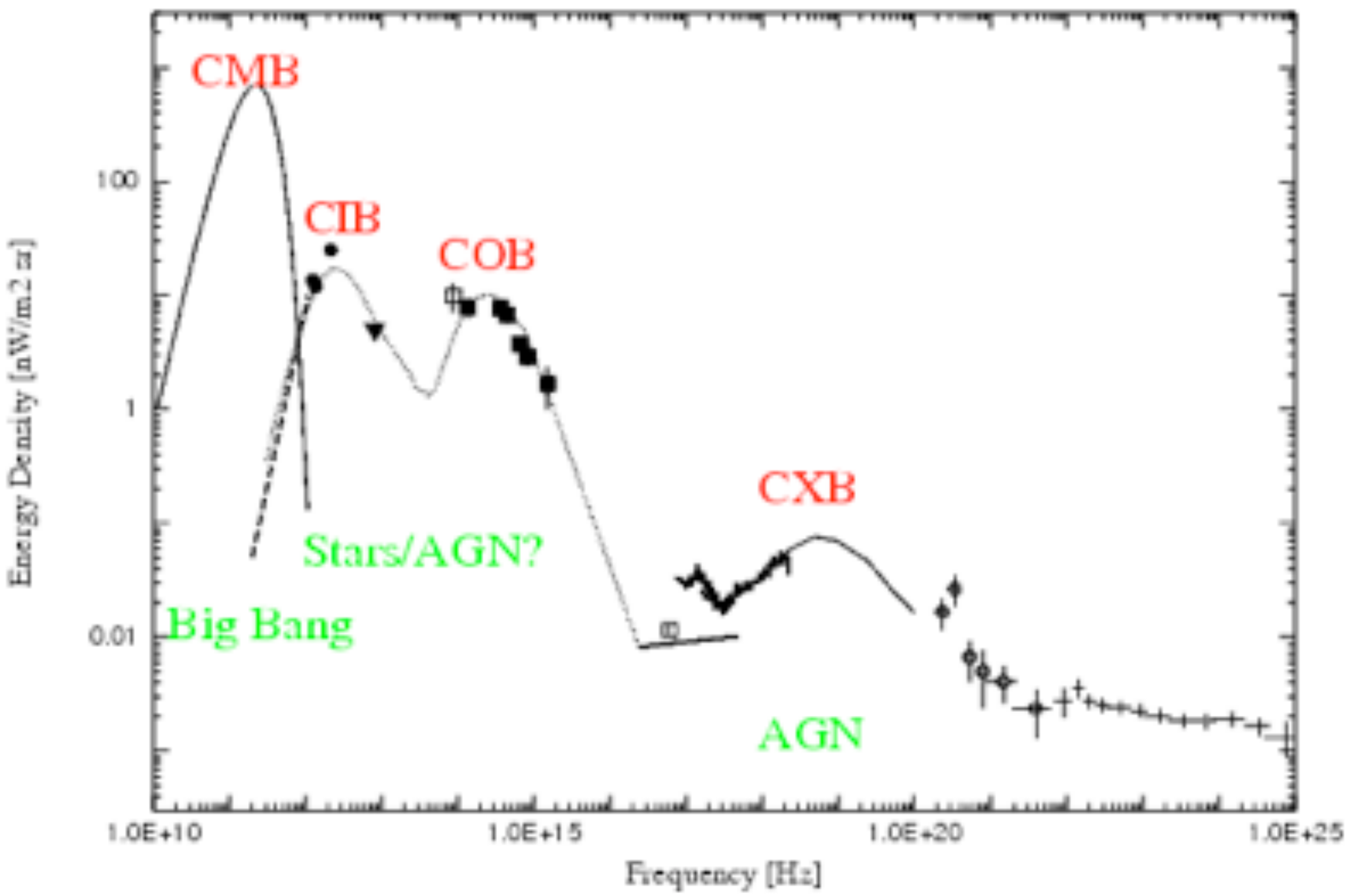


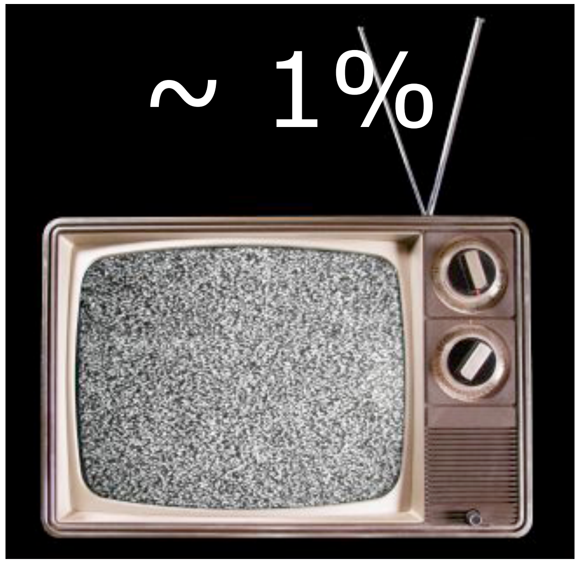


$$F_{ij} = \sum_{\ell} \frac{\partial \vec{C}_\ell}{\partial s_i} \mathbf{Cov}^{-1} \frac{\partial \vec{C}_\ell}{\partial s_j}$$

We will use online CMB tools, e.g.
http://lambda.gsfc.nasa.gov/toolbox/tb_cmbfast_form.cfm

Cosmic Microwave Background



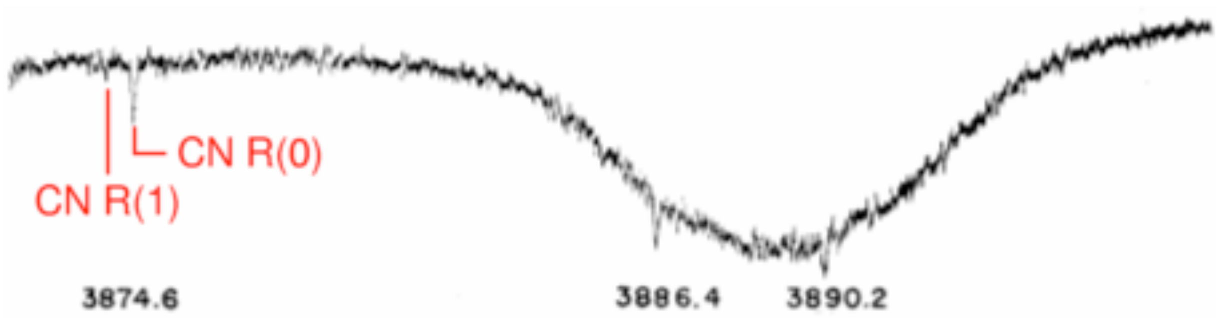


400 photons per cm^3

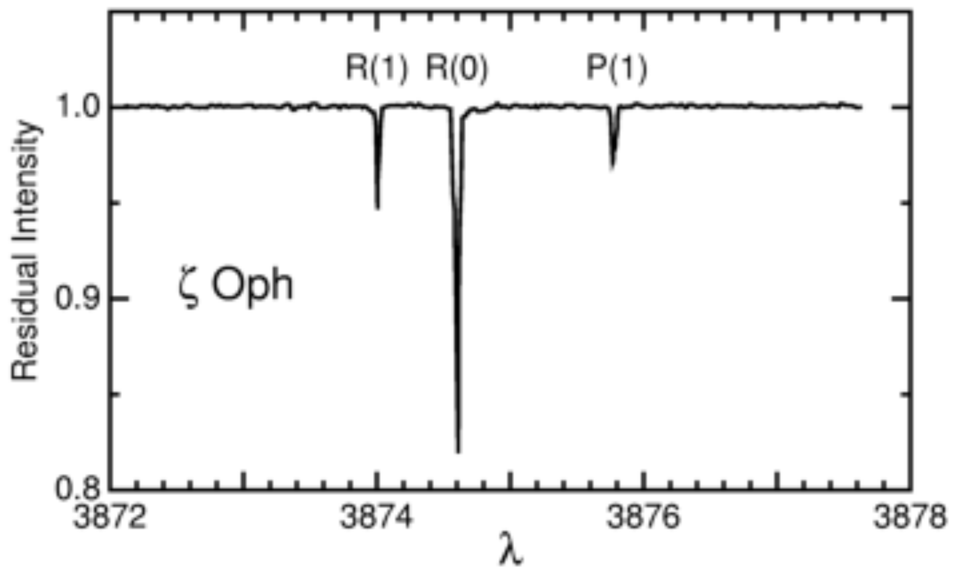
- CMB dominates the radiation content of the universe

- It contains nearly 93% of the radiation energy density and 99% of all the photons

Discovery of the CMB



McKellar (1940)



• In 1940, McKellar discovers CN molecules in interstellar space from their absorption spectra (one of the first IS-molecules)

• From the excitation ratios, he infers the “rotational temperature of interstellar space” to be 2° K (1941, PASP 53, 233)

• In his 1950 book, the Nobel prize winning spectroscopist Herzberg remarks: “From the intensity ratio of the lines with K=0 and K=1 a rotational **temperature of 2.3° K follows, which has of course only a very restricted meaning**.”

Discovery of the CMB

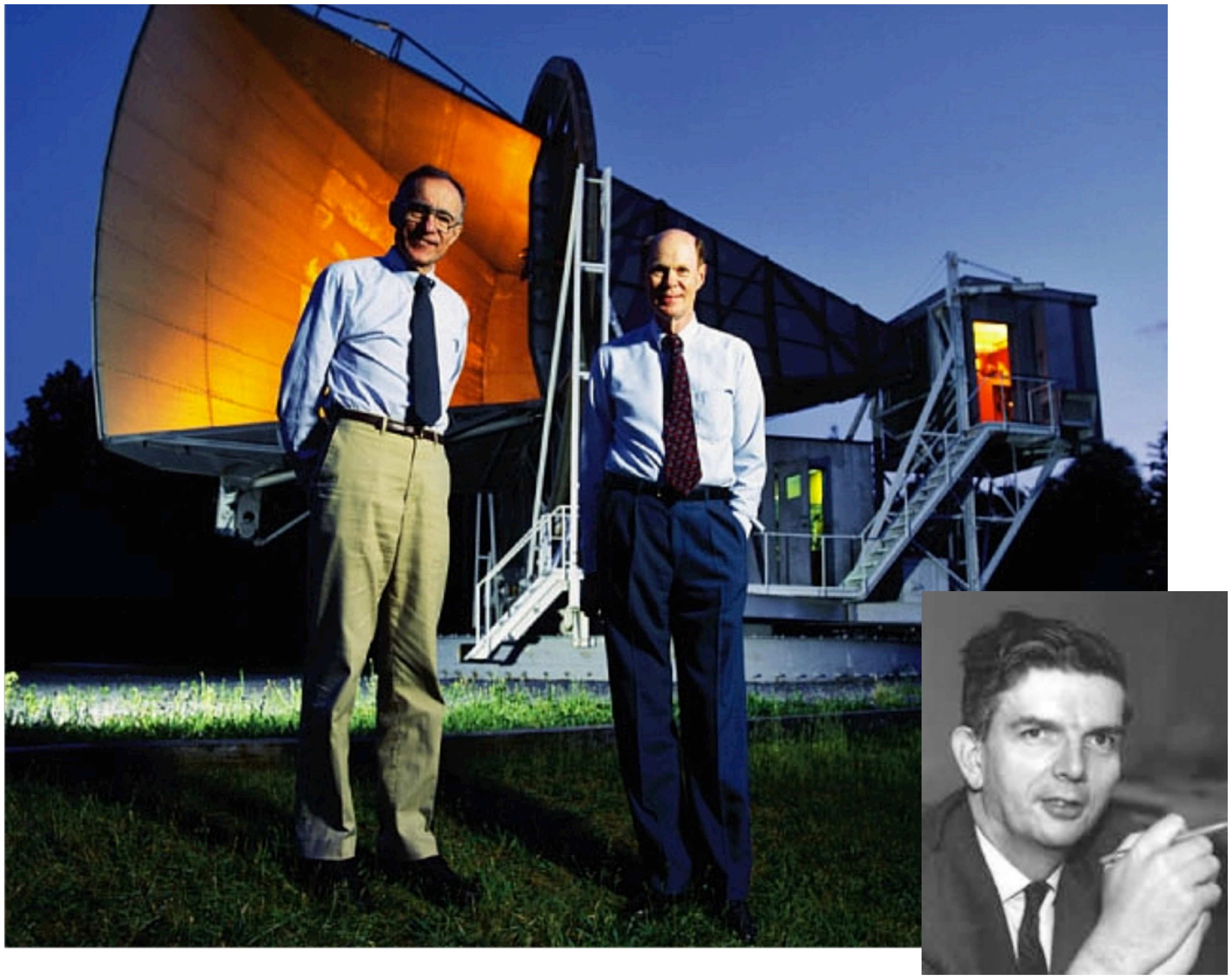
- After the “α–β–γ paper”, Alpher & Herman (1948) predict 5 K radiation background as by-product of their theory of the nucleosynthesis in the early universe (with no suggestion of its detectability).

- Shmaonov (1957) measures an uniform noise temperature of 4±3 K at λ=3.2 cm.

- Doroshkevich & Novikov (1964) emphasize the detectability of this radiation, predict that the spectrum of the relict radiation will be a blackbody, and also mention that the twenty-foot horn reflector at the Bell Laboratories will be the best instrument for detecting it!

No Nobel prize for these guys!

Discovery of the CMB



- Originally wanted to measure Galactic emission at λ=7.3 cm

- Found a direction-independent noise (3.5±1.0 K) that they could not get rid of, despite drastic measures

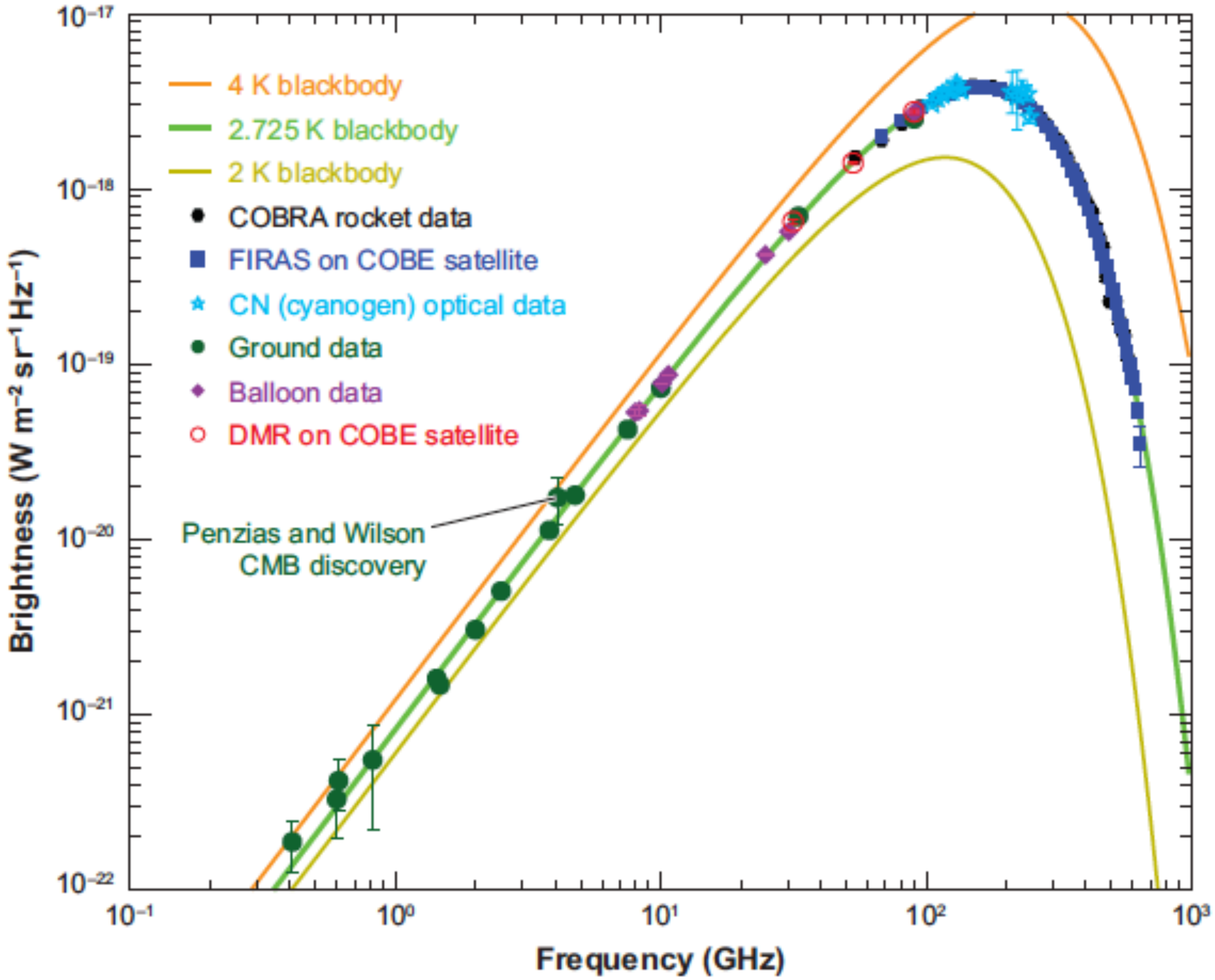
- So they talked with colleagues..

- Explanation of this “excess noise” was given in a companion paper by Robert Dicke and collaborators

(no Nobel prize for Dicke either, not to mention Gamow!)

Measurement of T_{CMB}

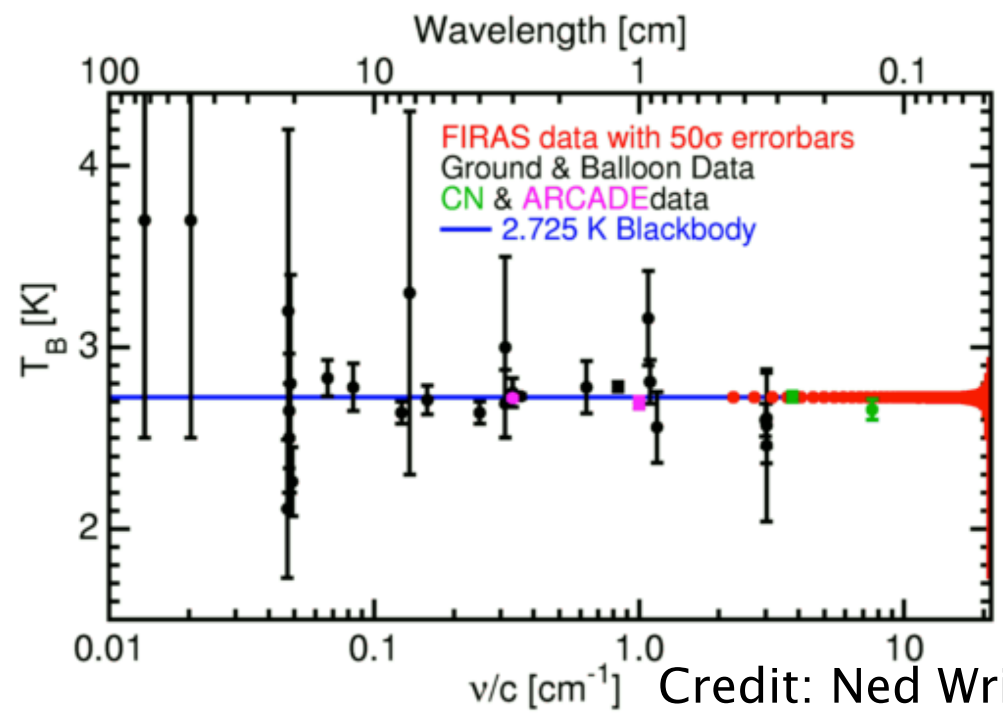
Credit: D. Samtleben



Measured blackbody spectrum of the CMB, with fit to various data

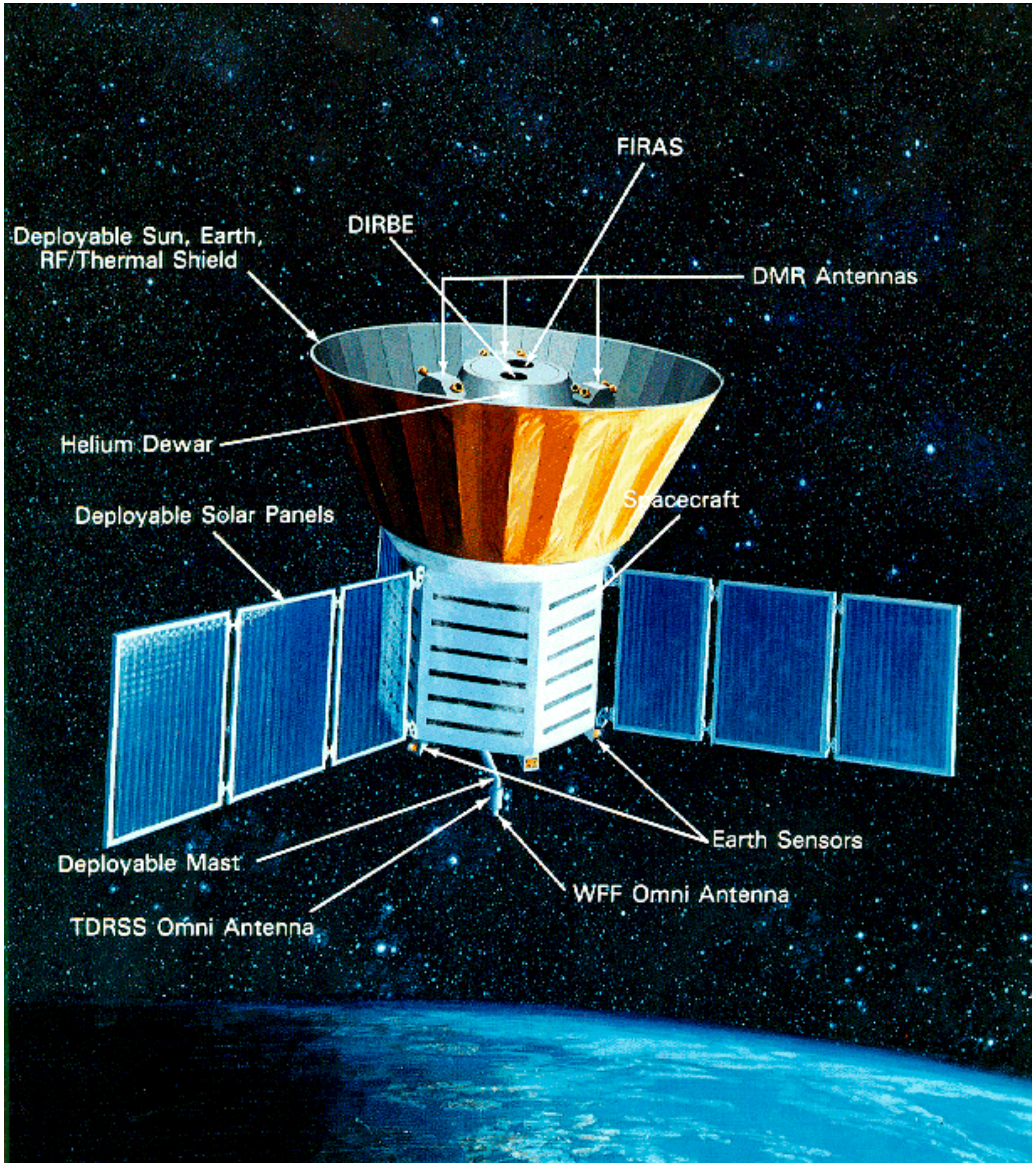
Ground- and balloon-based experiments have been measuring CMB temperature for decades with increasing precision

but it was realized that one has to go to the stable thermal environment of outer space to get a really accurate measurement.



Credit: Ned Wright

COBE



Credit: NASA

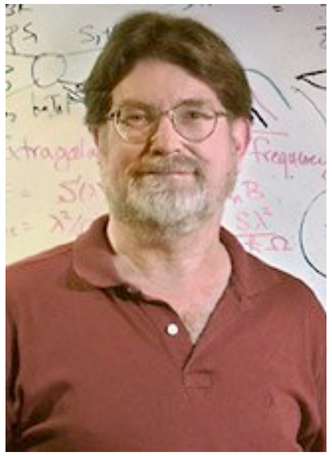
Launched on Nov. 1989 on a Delta rocket.

DIRBE: Measured the absolute sky brightness in the 1–240 μm wavelength range, to search for the Infrared Background

FIRAS: Measured the spectrum of the CMB, finding it to be an almost perfect blackbody with $T_0 = 2.725 \pm 0.002$ K

DMR: Found "anisotropies" in the CMB for the first time, at a level of 1 part in 10^5

2006 Nobel prize in physics



Thermalization of the CMB

- Compton scattering: $e + \gamma = e + \gamma$
- Bremsstrahlung: $e + Z = e + Z + \gamma$
- Inelastic (double) Compton scattering: $e + \gamma = e + \gamma + \gamma$

At an early enough epoch, timescale of thermal processes must be shorter than the expansion timescale. They are equal at $z \sim 2 \times 10^6$, or roughly two months after the big bang.

The universe reaches thermal equilibrium by this time through scattering and photon-generating processes. Thermal equilibrium generates a blackbody radiation field. Any energy injection before this time cannot leave any spectral signature on the CMB blackbody.

The universe expands adiabatically, hence a blackbody spectrum, once established, is maintained.

Limits on Spectral Distortions

- Energy added after $z \sim 2 \times 10^6$ will show up as spectral distortions. Departure from a Planck spectrum at fixed T is known as "μ distortion". μ distortion is easier to detect at wavelengths $\lambda > 10$ cm.

  COBE measurement: $|\mu| < 9 \times 10^{-5}$ (95% CL)

- The amount of inverse Compton scattering at later epochs ($z < 10^5$) show up as "y distortion", where $y \sim \sigma_T n_e kT_e$ (e.g. the Sunyaev-Zel'dovich effect). This rules out a uniform intergalactic plasma as the source for X-ray background.

  COBE measurement: $y < 1.2 \times 10^{-5}$ (95% CL)

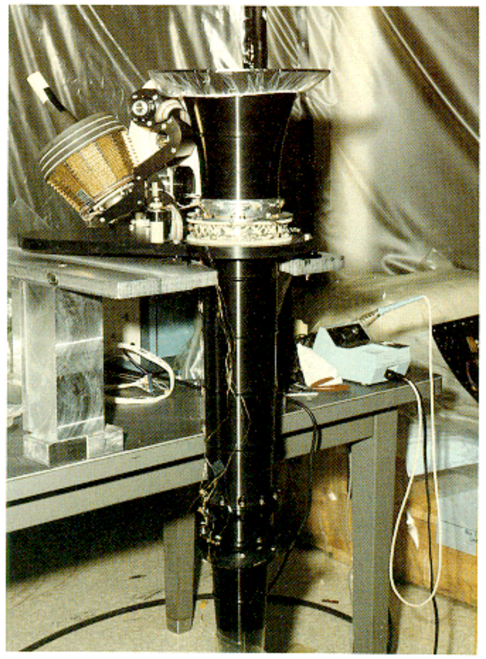
- Energy injection at much later epochs ($z << 10^5$), e.g. free-free distortions, are also tightly constrained.

  COBE measurement: $Y_{ff} < 1.9 \times 10^{-5}$ (95% CL)

FIRAS on COBE

Far Infra-Red Absolute Spectrophotometer

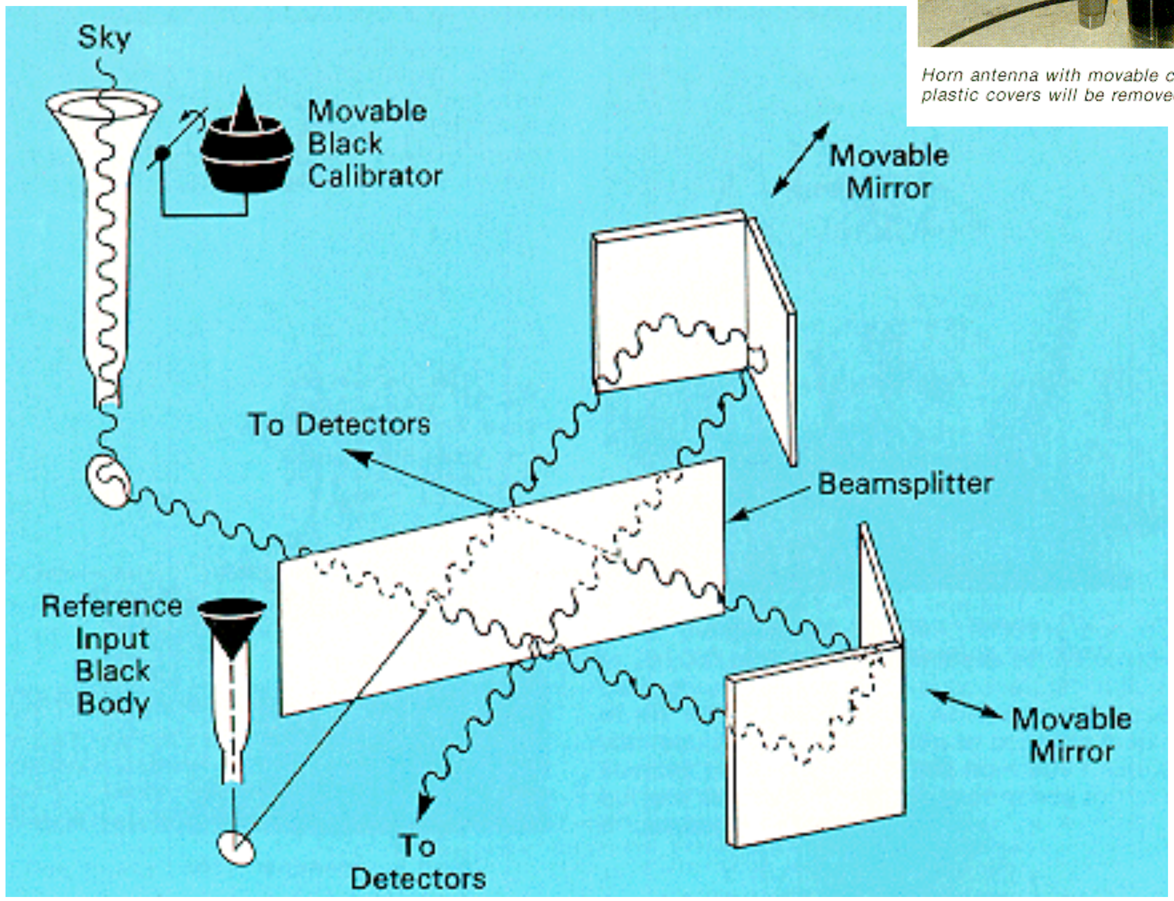
A differential polarizing Michelson interferometer

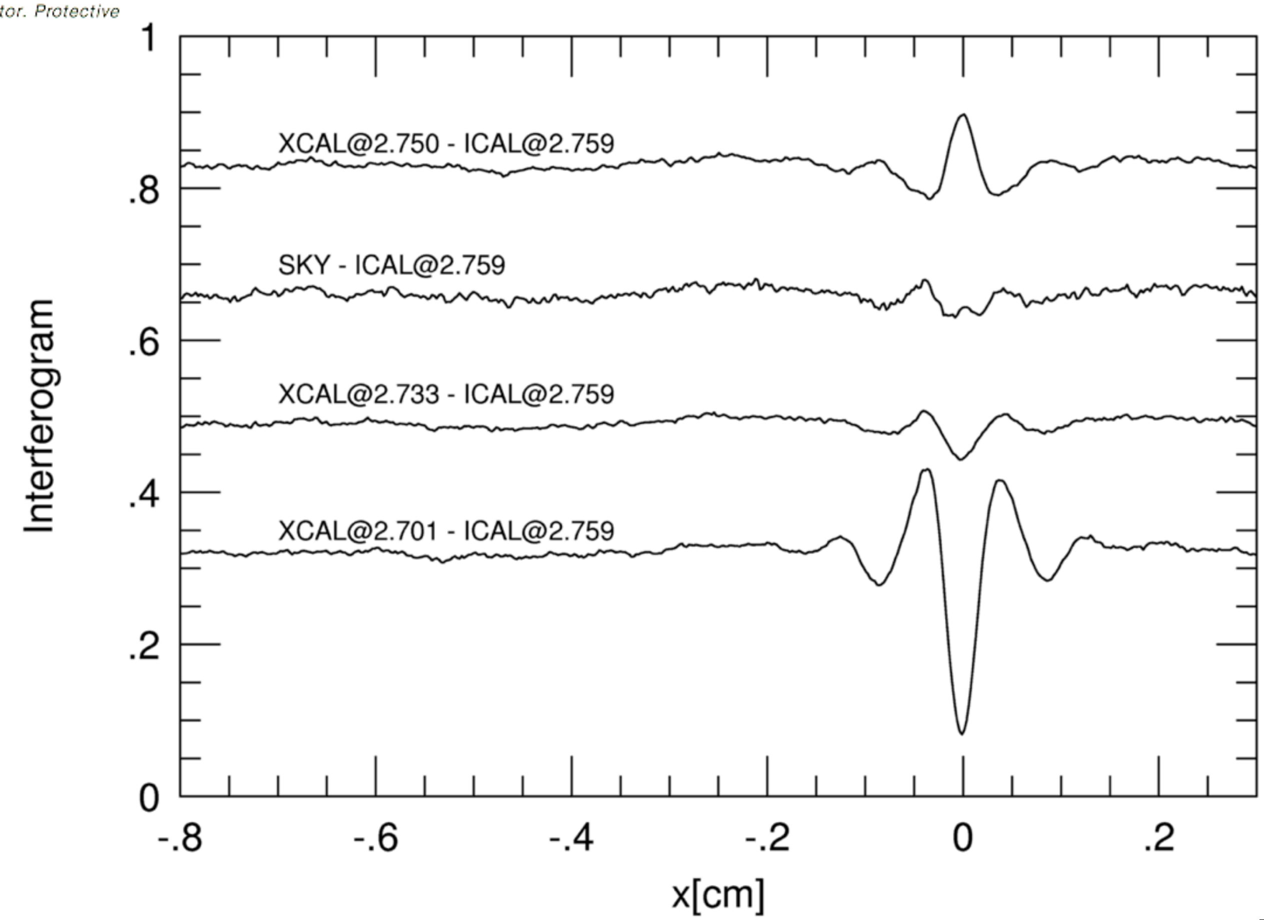


Horn antenna with movable calibrator. Protective plastic covers will be removed.

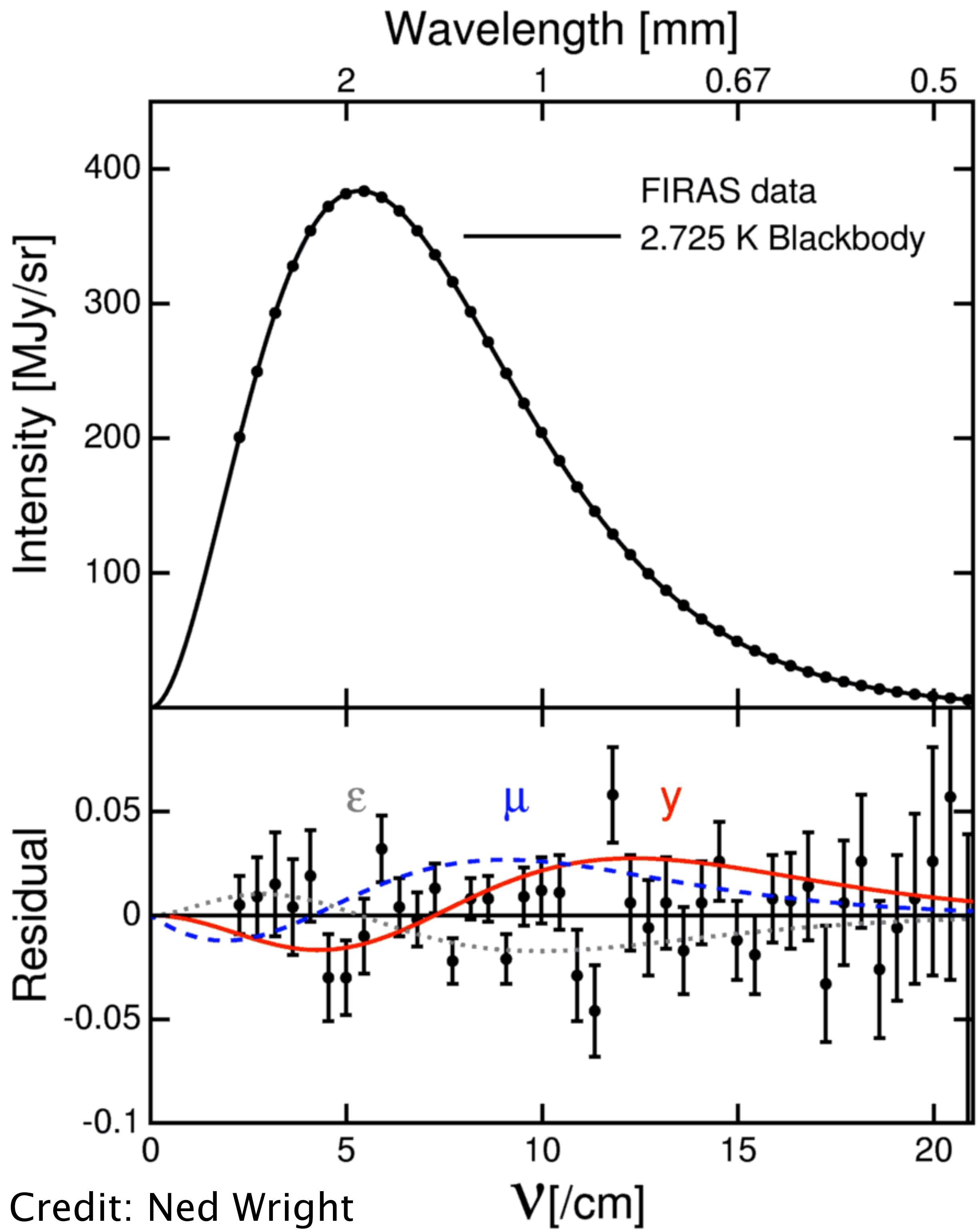
- One input is either the sky or a blackbody, other is a pretty good blackbody
- Zero output when the two inputs are equal
- Internal reference kept at T_0 (“cold load”), to minimize non-linear response of the detectors
- Residual is the measurement!

Credit: NASA





FIRAS Measurements



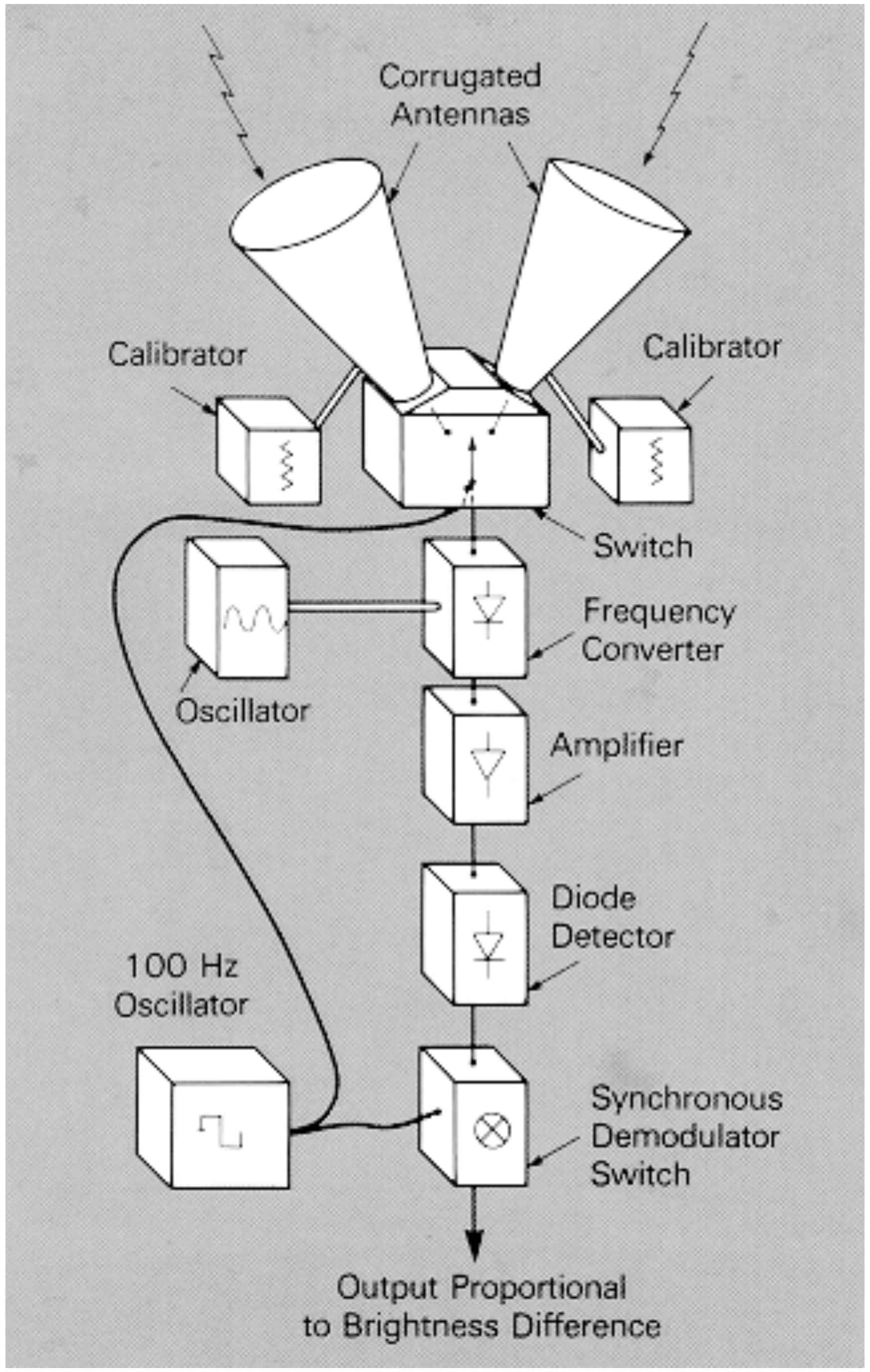
Credit: Ned Wright

Fundamental FIRAS measurement is the plot at the bottom: the difference between the CMB and the best-fitting blackbody. The top plot shows this residual added to the theoretical blackbody spectrum at the best fitting cold load temperature.

The three curves in the lower panel represents three likely non-blackbody spectra:

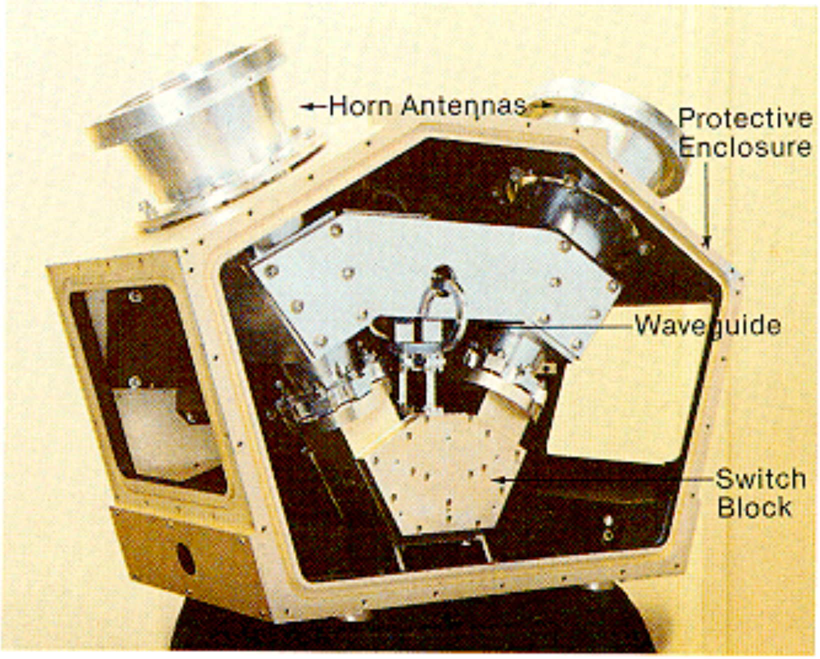
Red and blue curves show effect of hot electrons adding energy before and after recombination, the grey curve shows effect of a non-perfect blackbody as calibrator (less than 10^{-4})

DMR on COBE



Credit: NASA

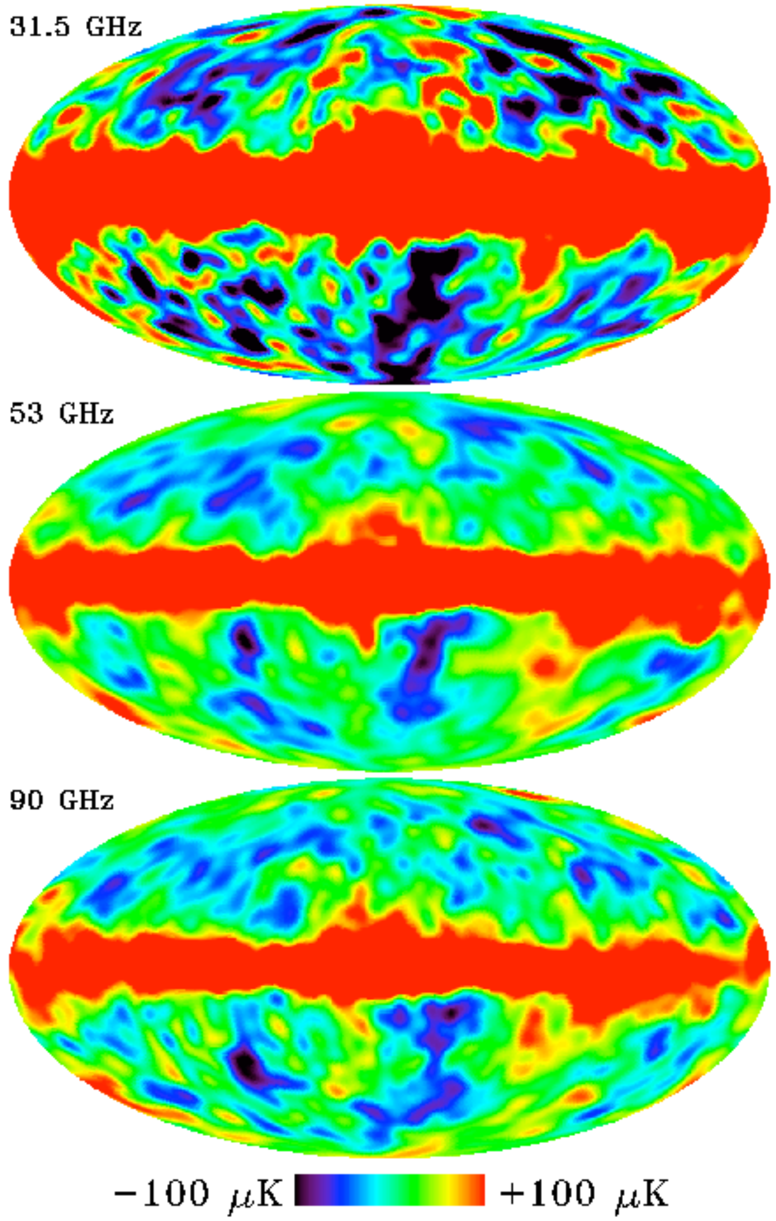
Differential Microwave Radiometer



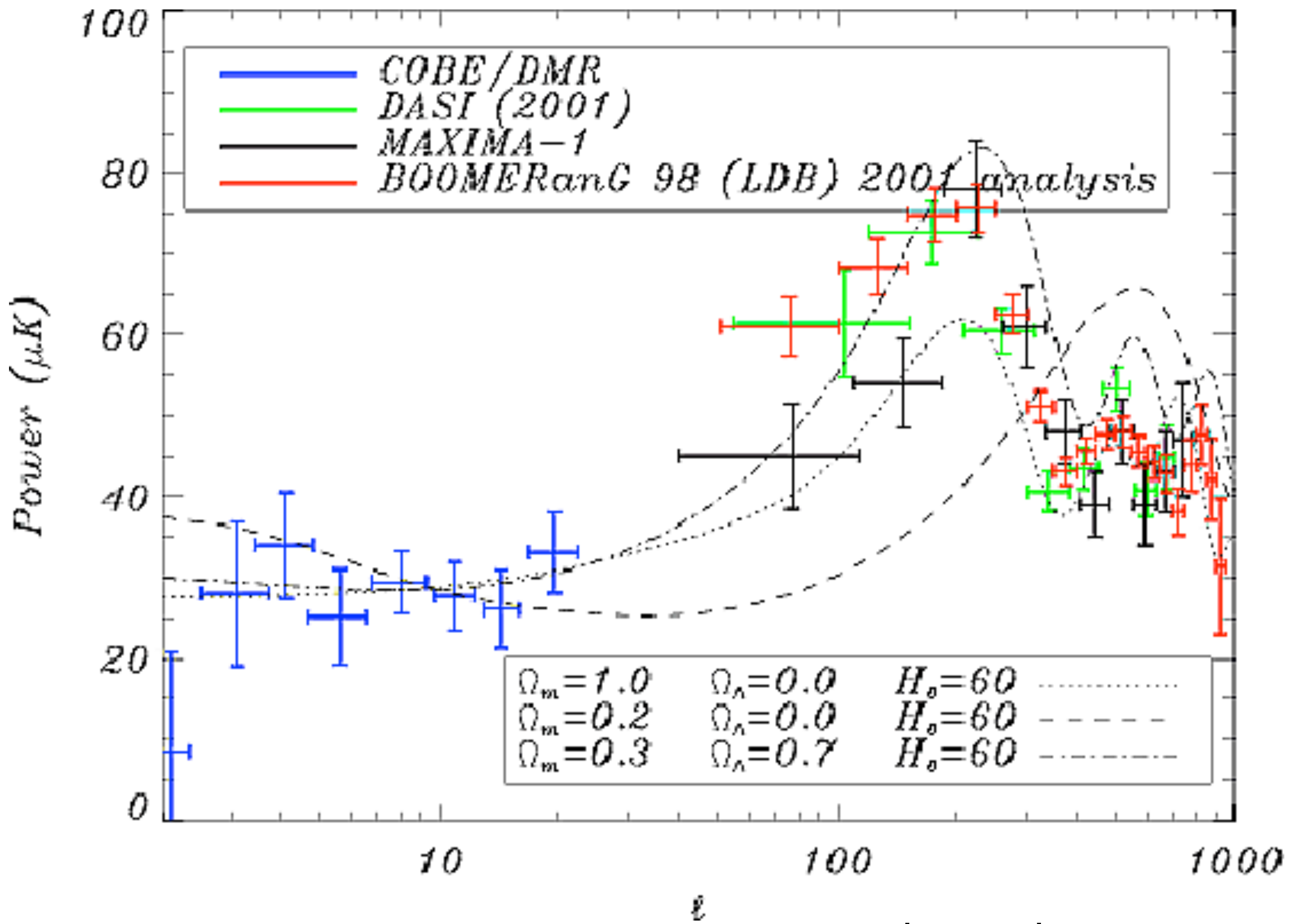
The 9.6 mm DMR receiver partially assembled. Corrugated cones are antennas.

- Differential radiometers measured at frequencies 31.5, 53 and 90 GHz, over a 4-year period
- Comparative measurements of the sky offer far greater sensitivity than absolute measurements

COBE DMR Measurements



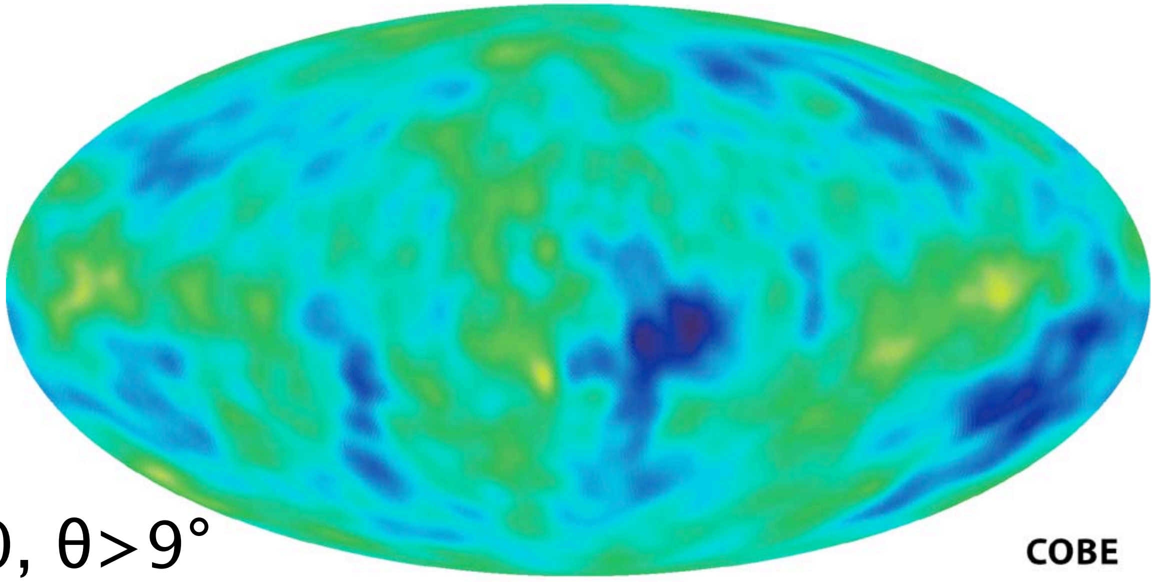
Credit: NASA



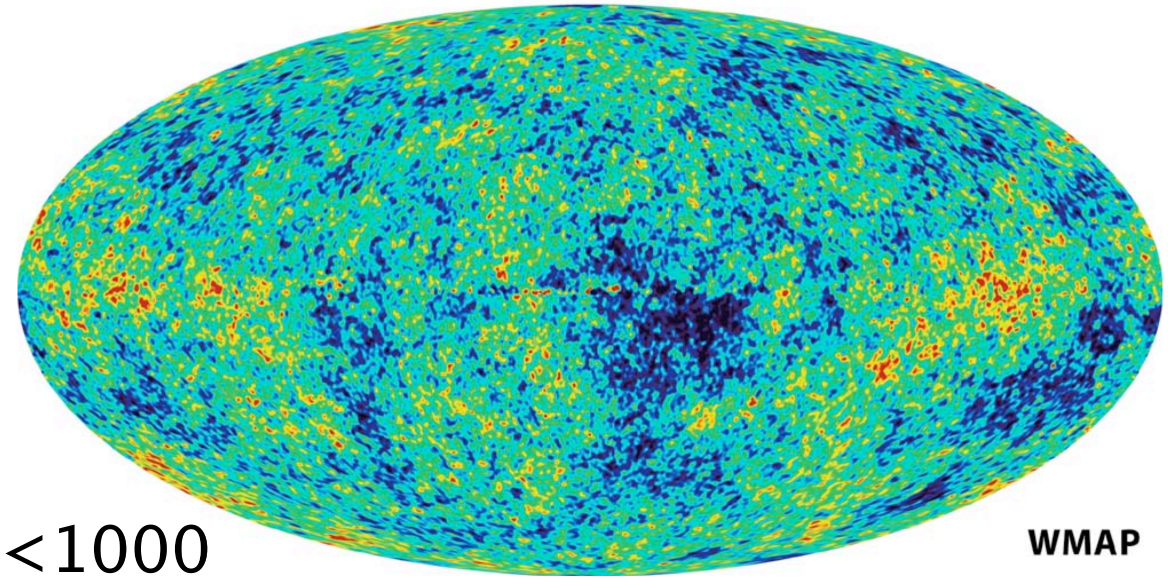
Credit: Archeops team

Today: COBE vs. WMAP

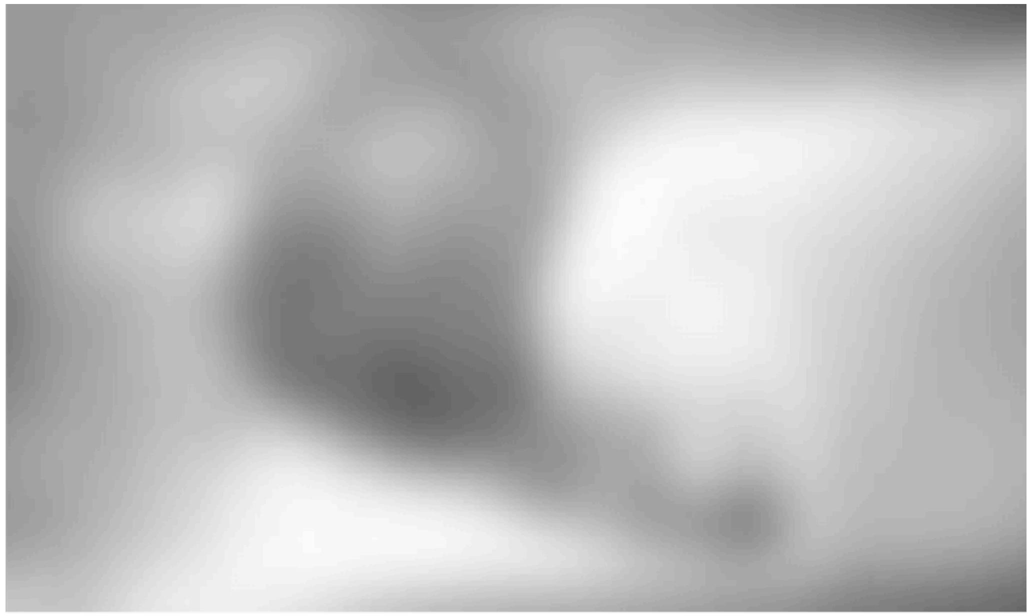
Resolution more than 20 times better with WMAP



$l<20$, $\theta>9°$

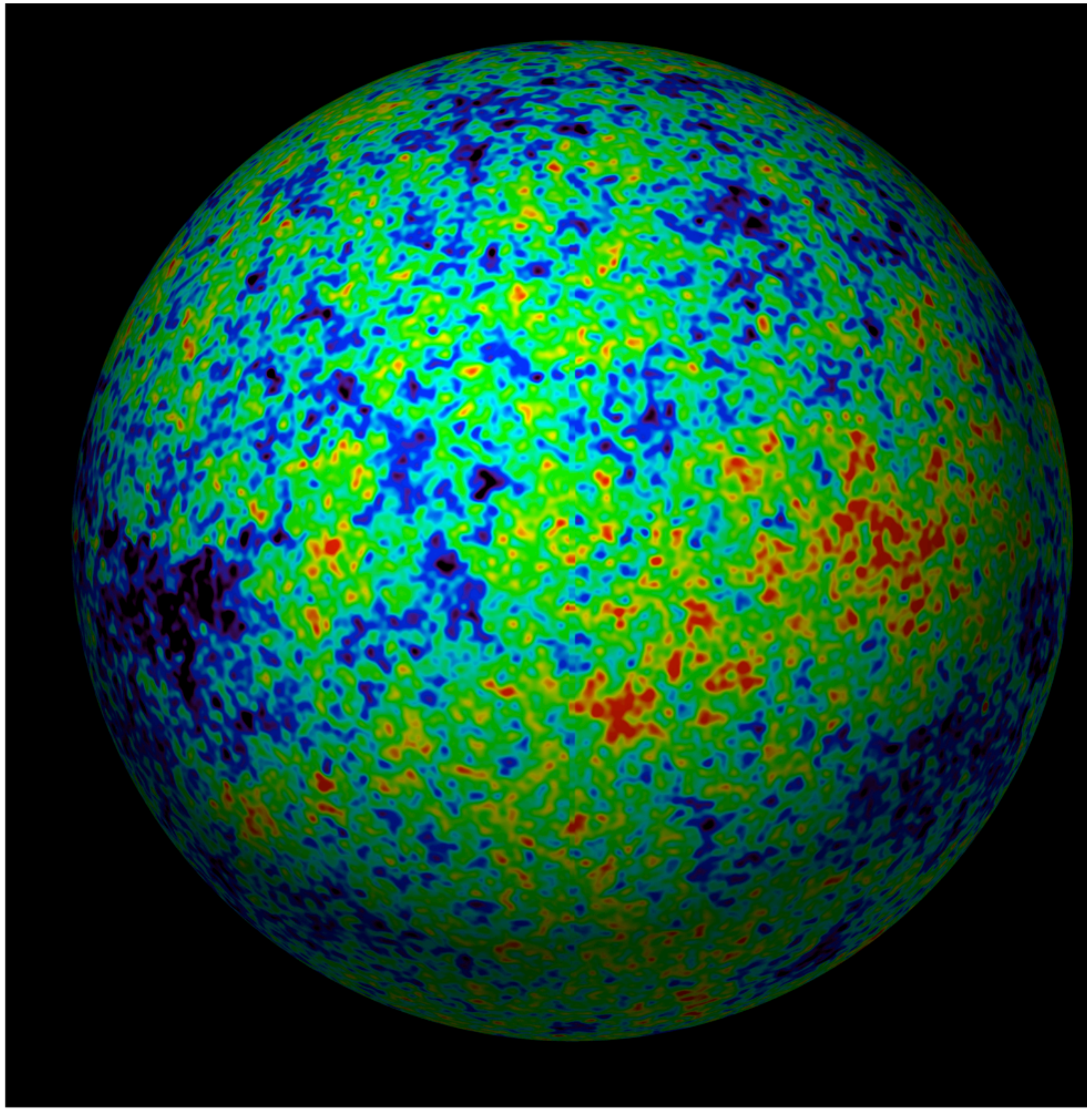


$2<l<1000$
$0.02°<\theta<90°$

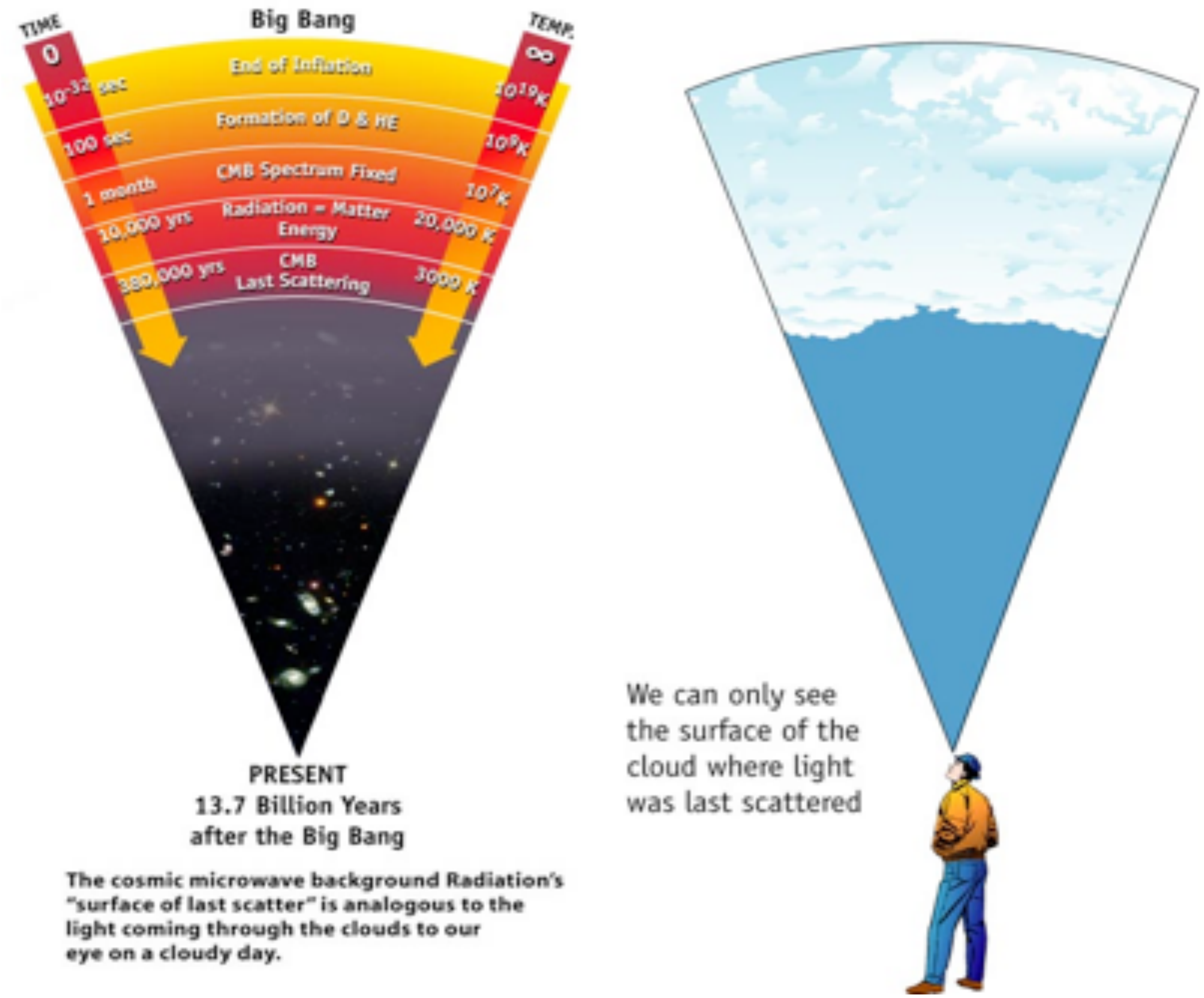


Credit: ??

Temperature anisotropies

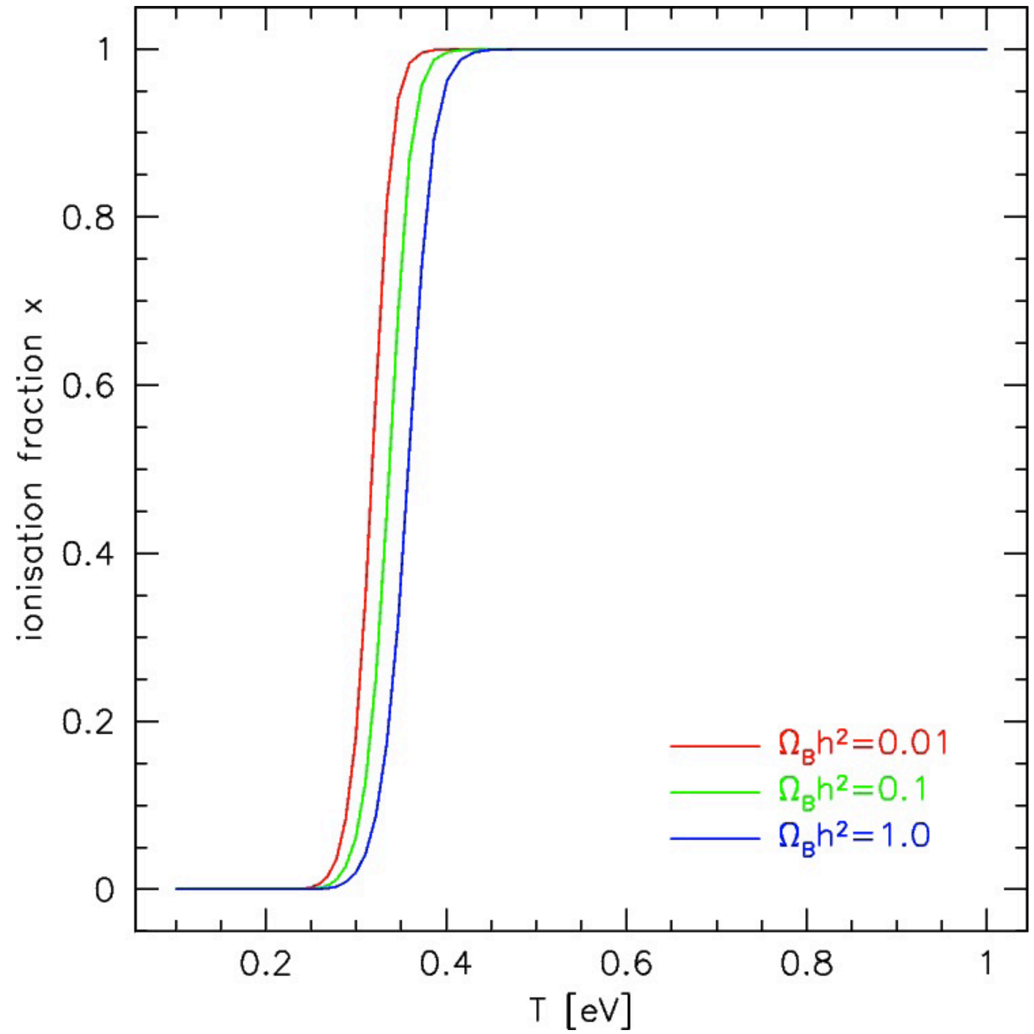


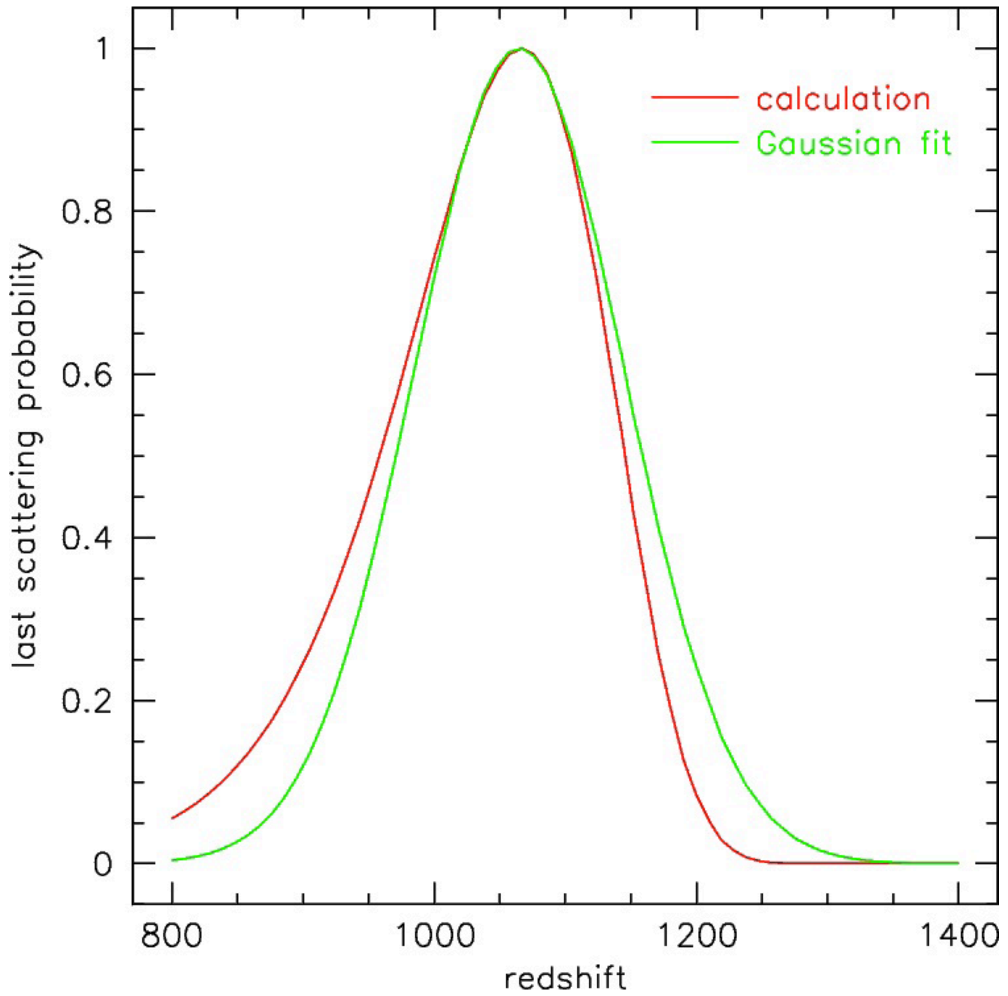
The Last Scattering Surface



All photons have travelled the same distance since recombination.
We can think of the CMB being emitted from inside of a spherical surface, we're at the center. (This surface has a thickness!)

Thickness of recombination shell



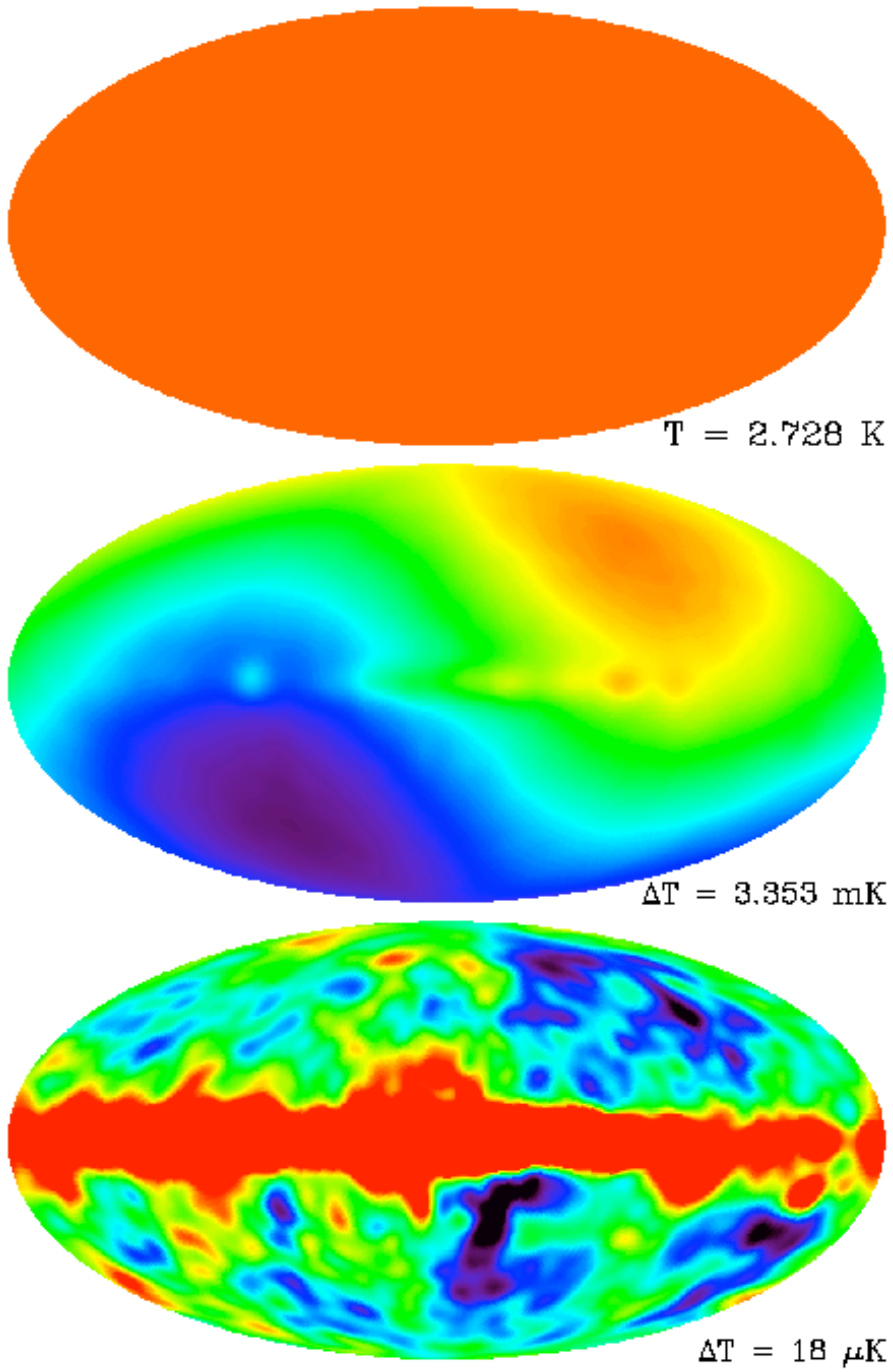


Scattering probability for photons when traveling from z to z+dz :

$$p(z)\,dz = e^{-\tau}\,(d\tau/dz)\,dz$$

Probability distribution is well described by Gaussian with mean $z \sim 1100$ and standard deviation $\delta z \sim 80$.

Amplitude of temp. anisotropies

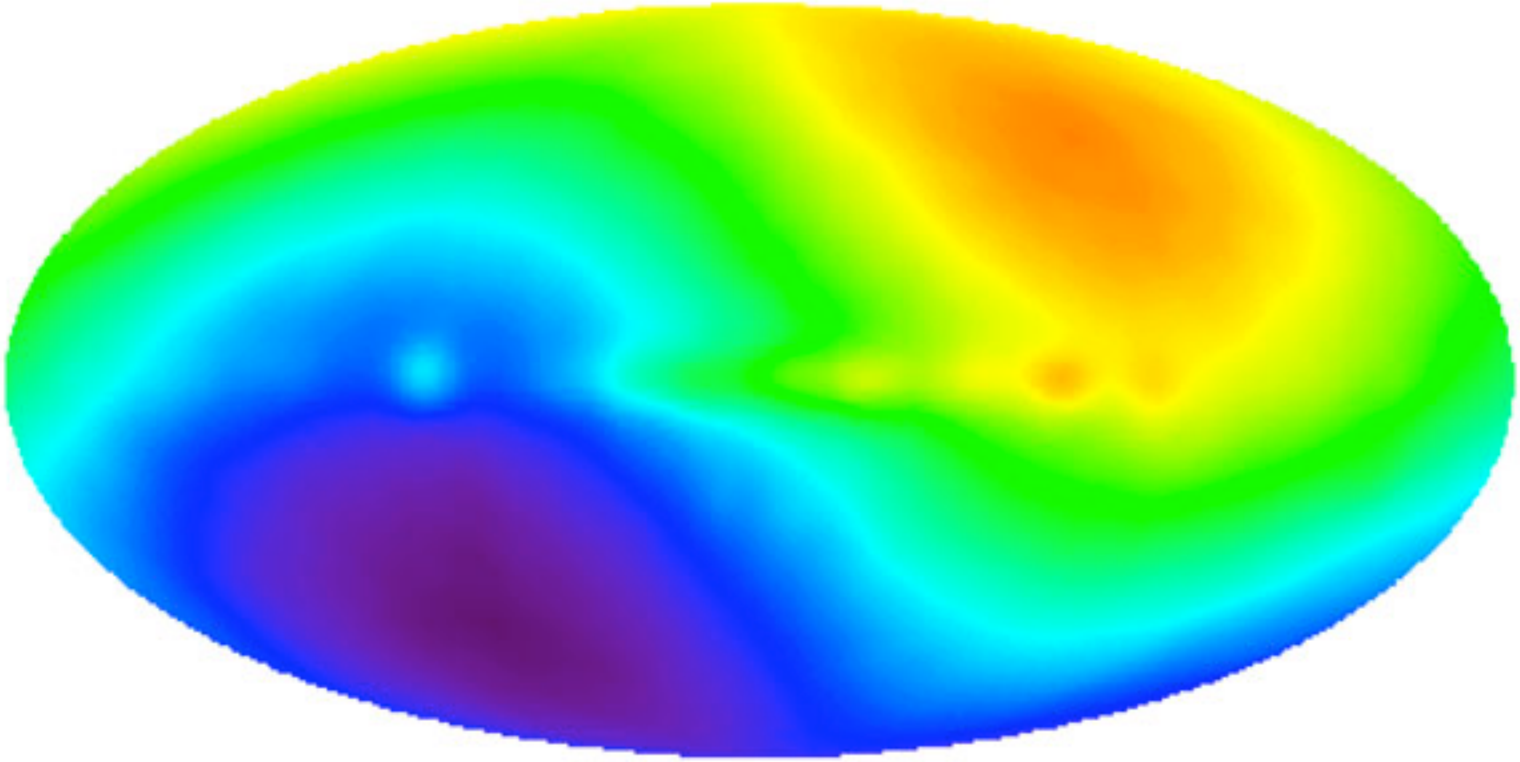


CMB is primarily a uniform glow across the sky!

Turning up the contrast, dipole pattern becomes prominent at a level of 10^{-3}. This is from the motion of the Sun relative to the CMB.

Enhancing the contrast fusther (at the level of 10^{-5}, and after subtracting the dipole, temperature anisotropies appear.

The CMB dipole

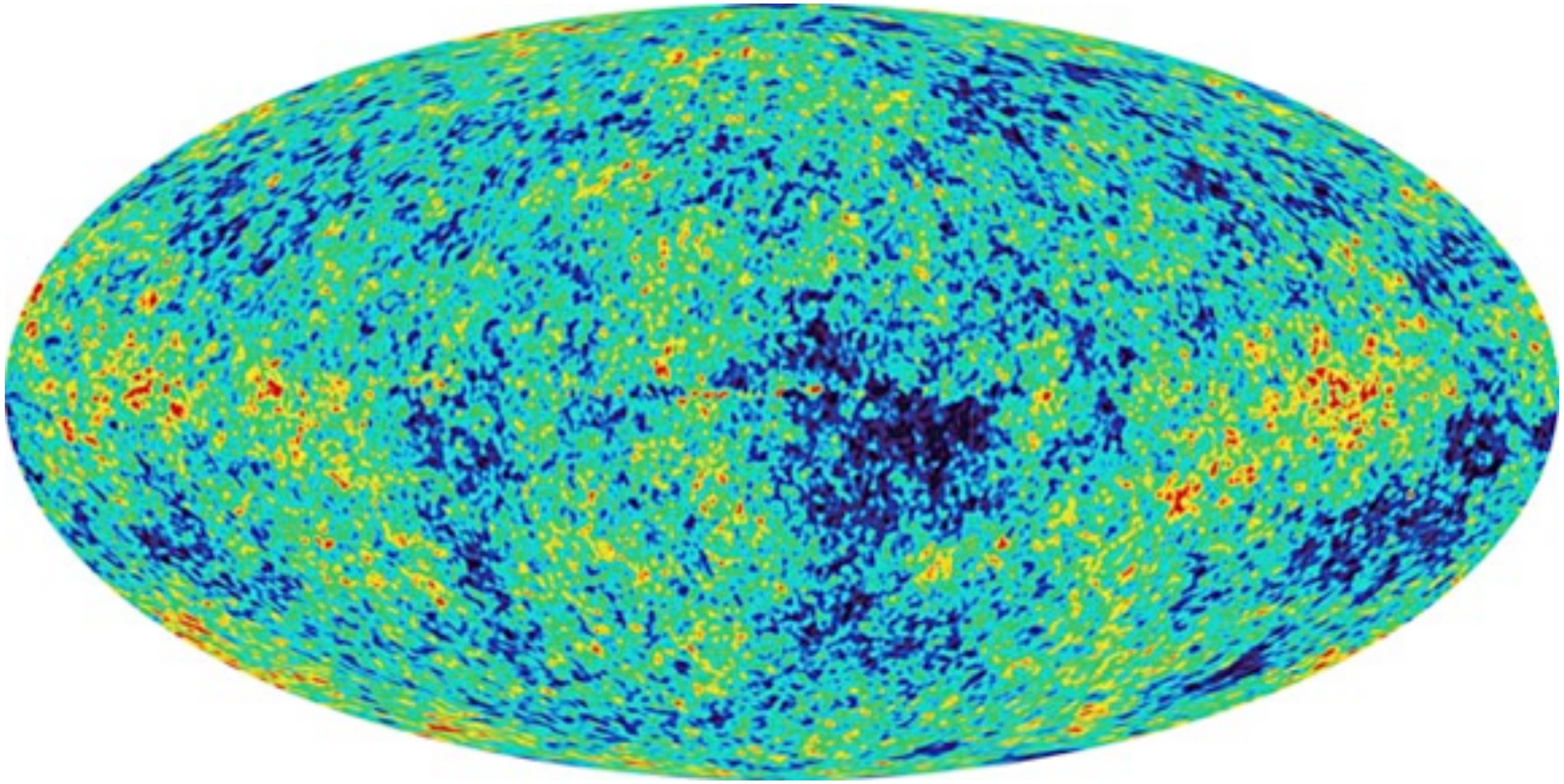


$$I'(\nu') = (1+(v/c)\cos\theta)^3\, I(\nu)$$
$$\nu' = (1+(v/c)\cos\theta)\,\nu$$
$$T(\theta) = T\,(1+(v/c)\cos\theta)$$

- Measured velocity: 390±30 km/s
- After subtracting out the rotation and revolution of the Earth, the velocity of the Sun in the Galaxy and the motion of the Milky Way in the Local Group one finds: v = 627 ± 22 km/s
- Towards Hydra-Centaurus, l=276±3° b=30±3°

Can we measure the intrinsic CMB dipole ??

Observing the CMB today



Measurement from WMAP, dipole and Galaxy subtracted.

Snapshot of the universe ages 380,000 years!

How to do science from this pretty image?

CMB temperature anisotropies

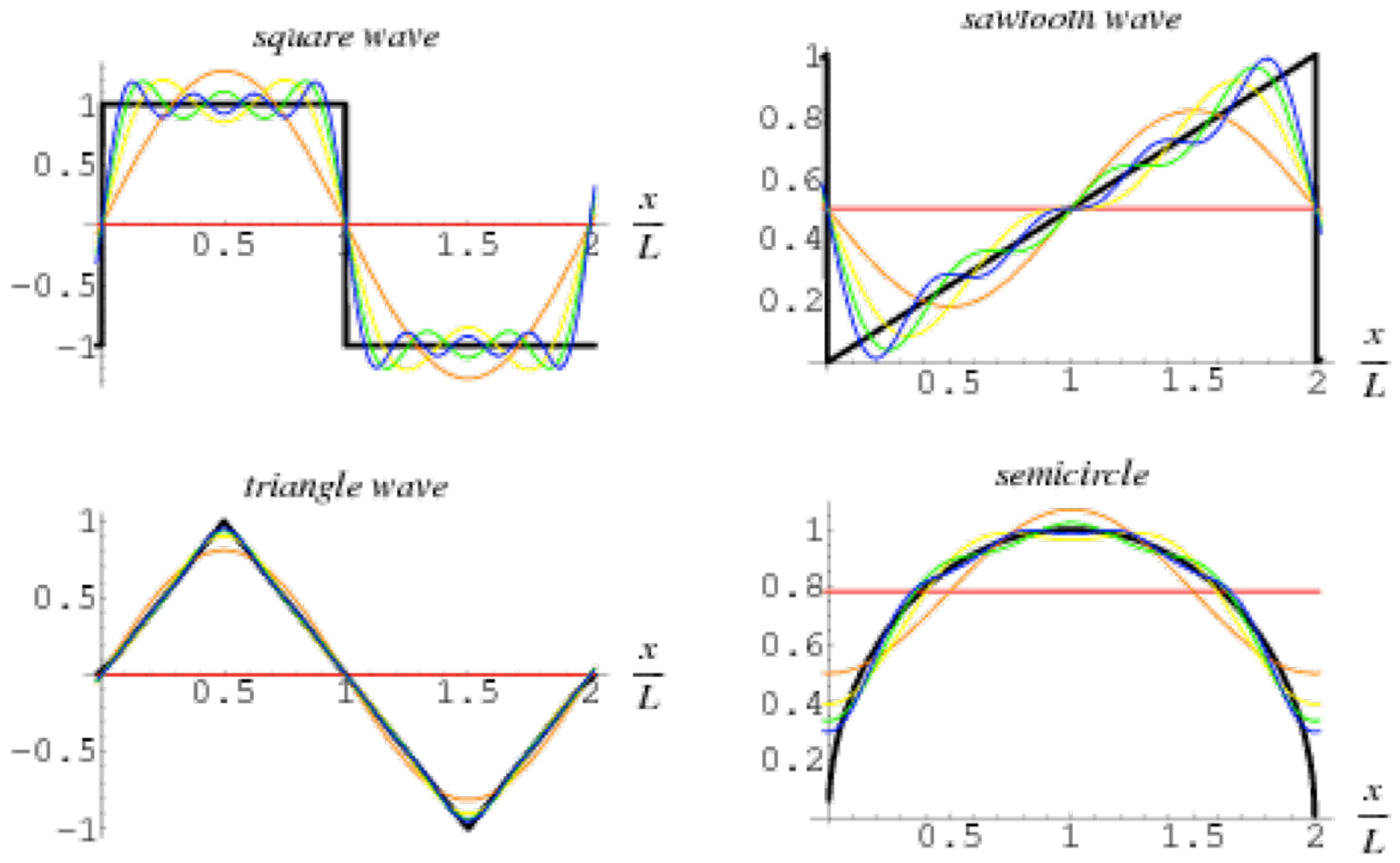
• The basic observable is the CMB intensity as a function of frequency and direction on the sky. Since the CMB spectrum is an extremely good black body with a fairly constant temperature across the sky, we generally describe this observable in terms of a temperature fluctuation

$$\frac{\Delta T}{T}(\theta,\phi) = \frac{T(\theta,\phi) - \bar{T}}{\bar{T}}$$

• The equivalent of the Fourier expansion on a sphere is achieved by expanding the temperature fluctuations in spherical harmonics

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y^{\ell}_{m}(\theta,\phi)$$

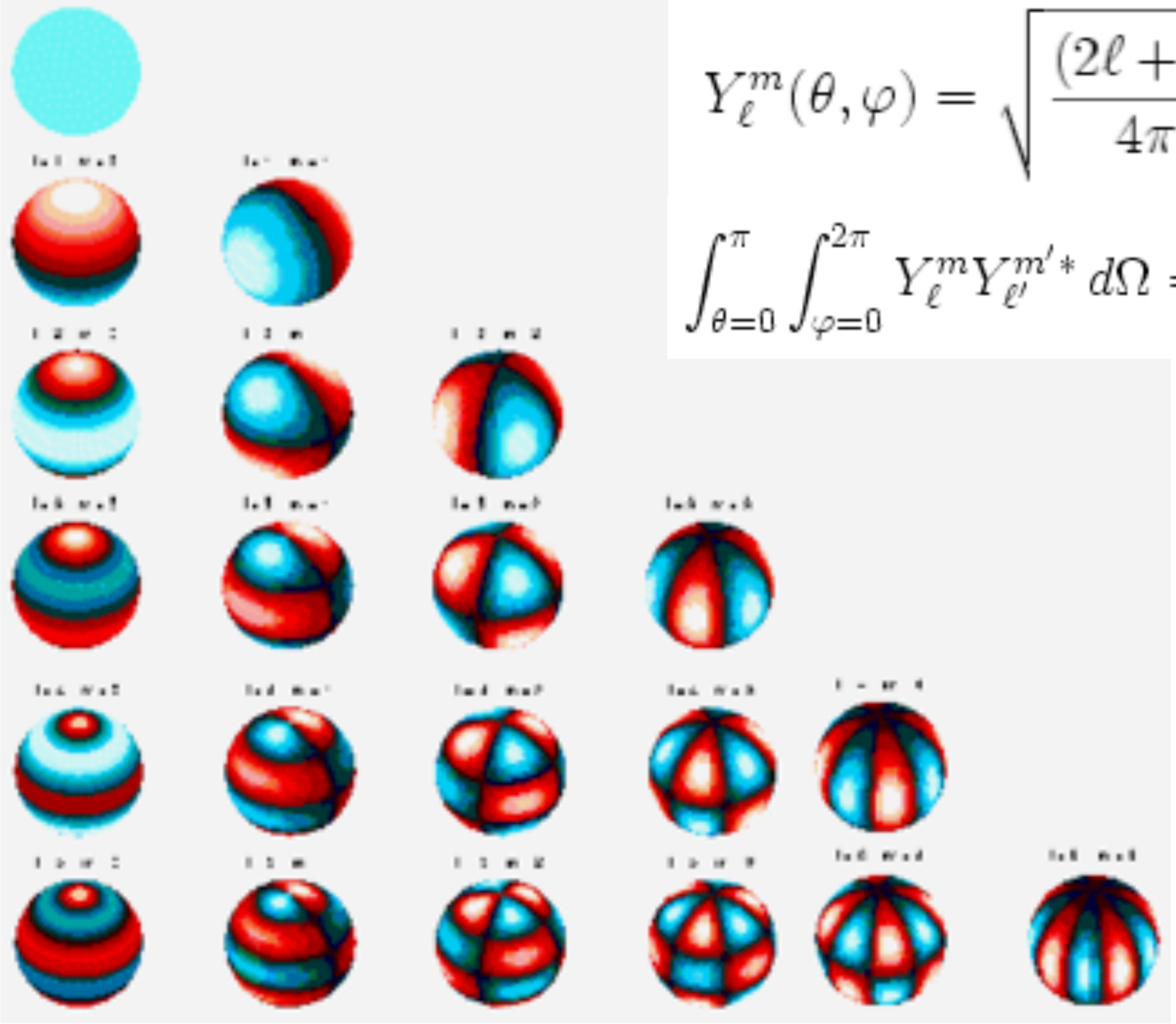
Analogy: Fourier series



Sum sine waves of different frequencies to approximate any function.

Each has a coefficient, or amplitude.

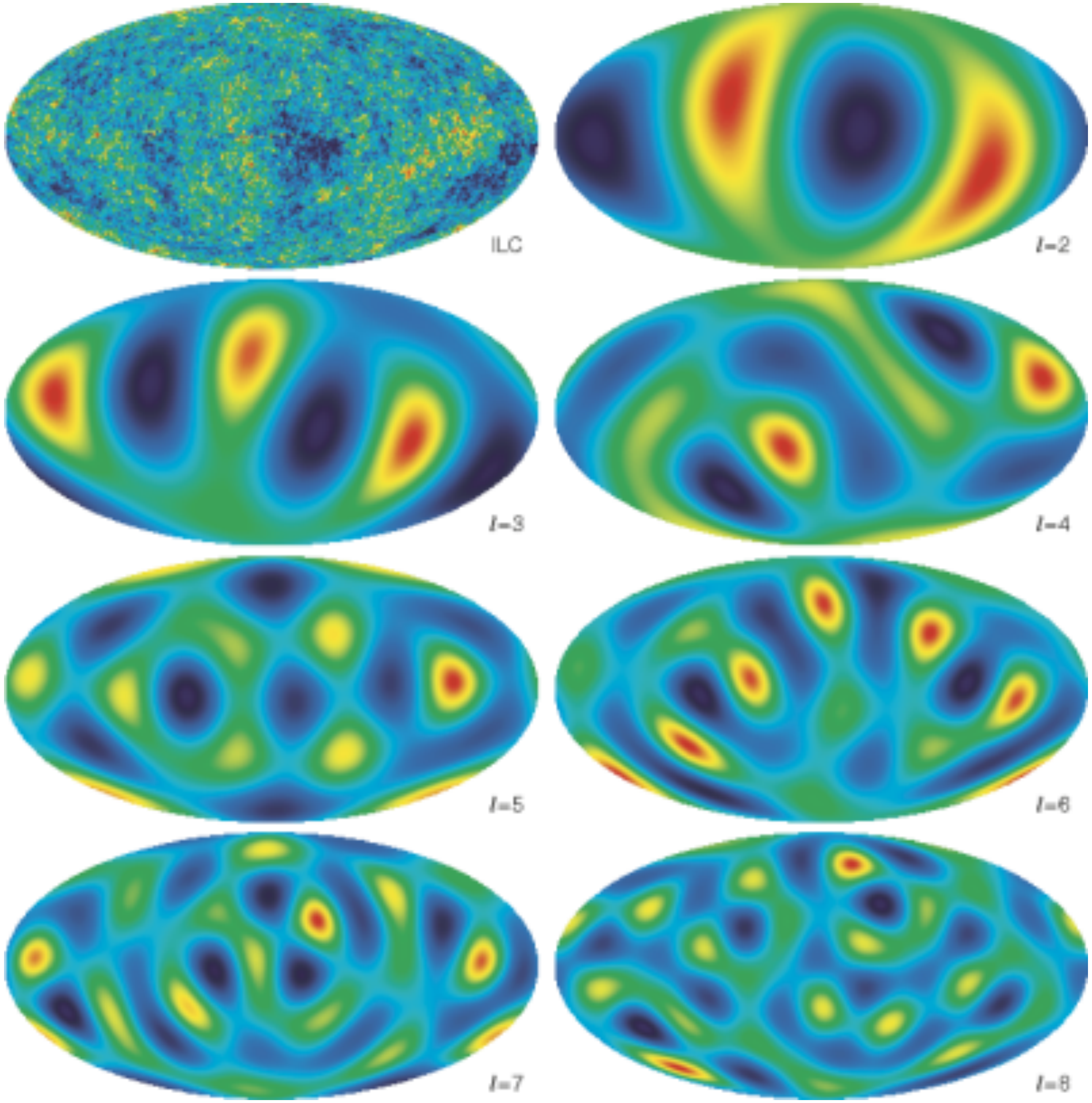
Spherical harmonics



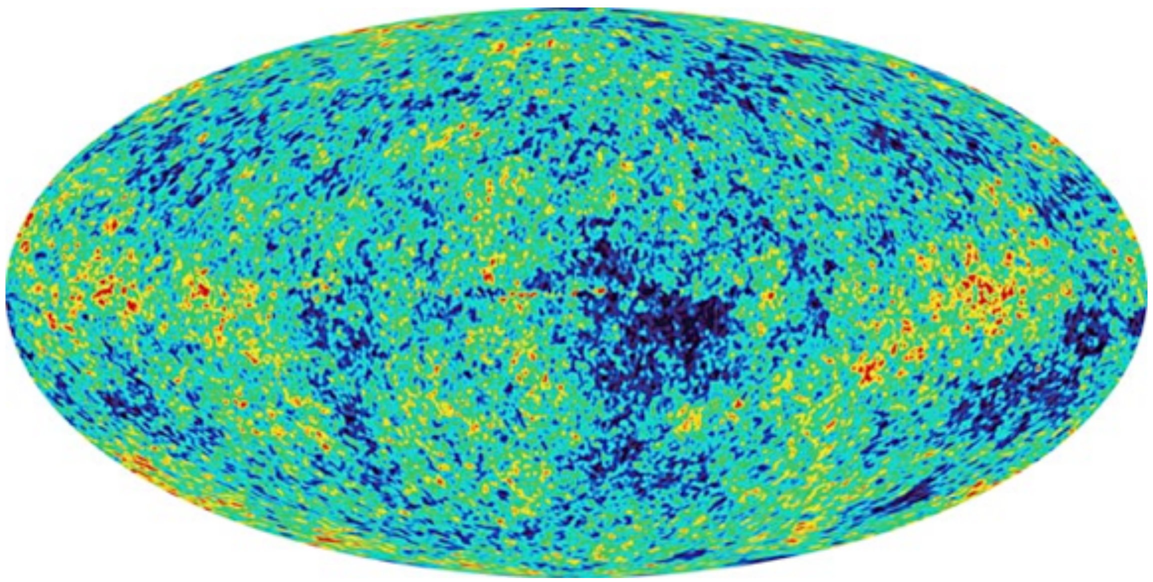
$$Y_\ell^m(\theta,\varphi) = \sqrt{\frac{(2\ell+1)}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}} \cdot e^{im\varphi} \cdot P_\ell^m(\cos\theta)$$

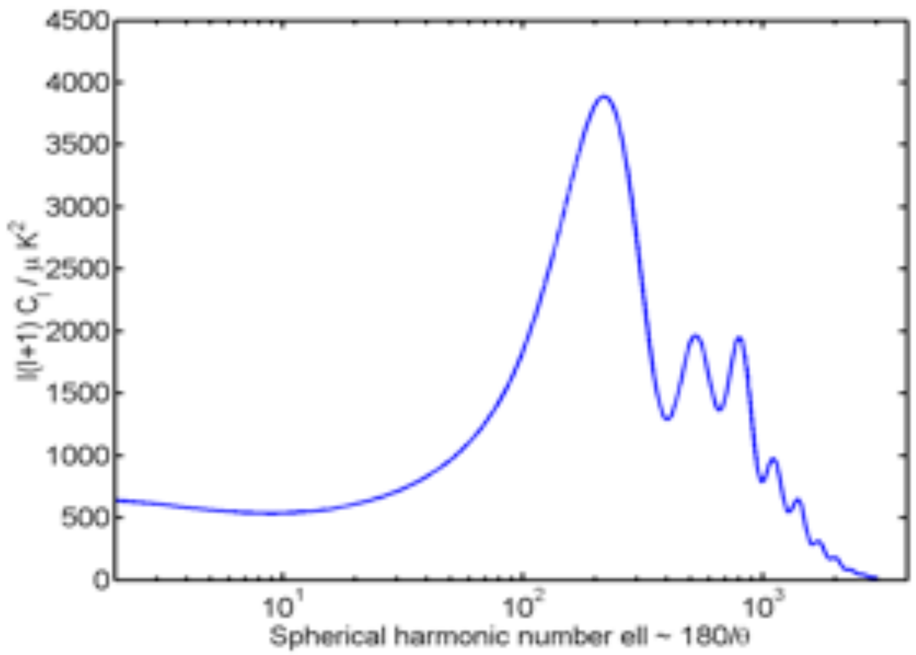
$$\int_{\theta=0}^{\pi}\int_{\varphi=0}^{2\pi} Y_\ell^m Y_{\ell'}^{m'*}\, d\Omega = \delta_{\ell\ell'}\delta_{mm'} \qquad d\Omega = \sin\theta\, d\varphi\, d\theta$$

Visualizing the multipoles



CMB power spectrum





Use spherical harmonics in place of sine waves: $$\frac{\Delta T}{T}(\theta,\phi) = \sum_{\ell=1}^{\infty}\sum_{m=-\ell}^{\ell} a_{\ell m} Y_m^{\ell}(\theta,\phi)$$

Calculate coefficients, a_{lm}, and then the statistical average: $$c_\ell = \langle |a_{\ell m}| \rangle^2$$

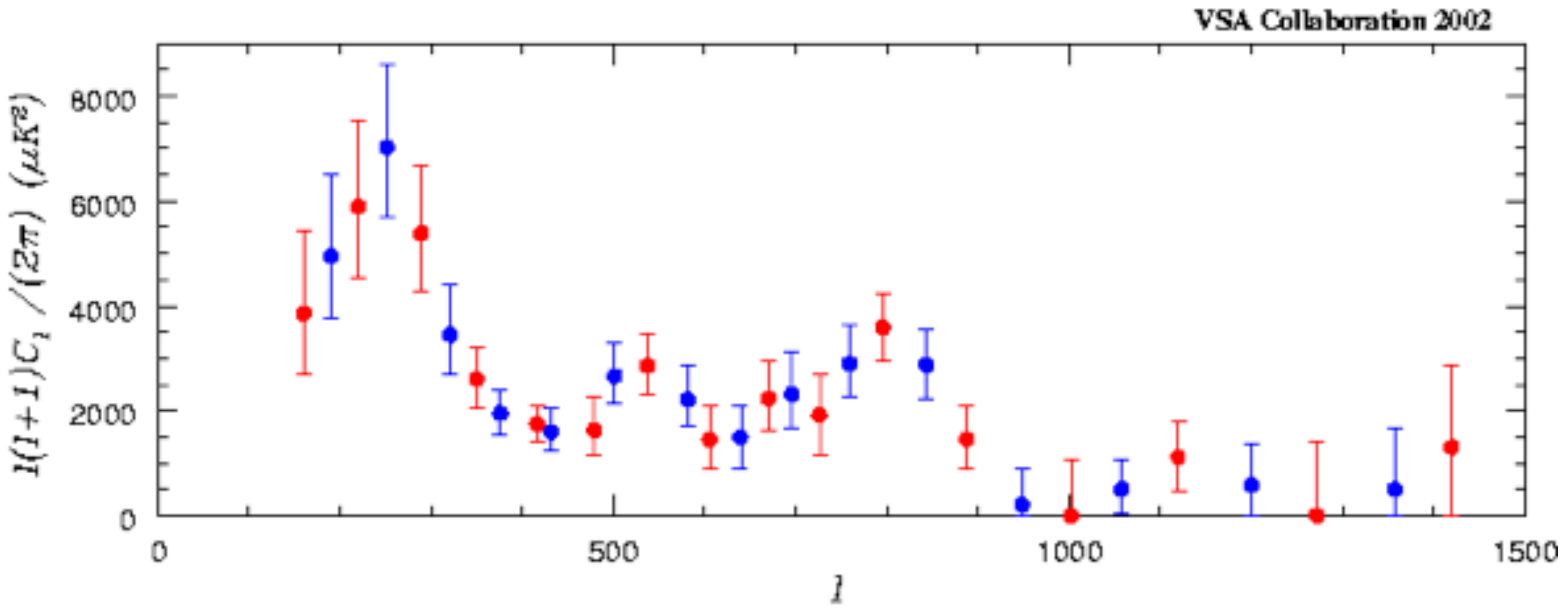
Amplitude fluctuations on each scale — that's what we plot.

Make your own CMB experiment!

- Design experiment to measure $\frac{\Delta T}{T}(\theta, \phi)$

- Find component amplitudes $a_{\ell m} = \int_{\Omega} \frac{\Delta T}{T}(\theta, \phi) Y^{*}_{\ell m}(\theta, \phi) d\Omega$

- Plot $c_\ell = \langle |a_{\ell m}| \rangle^2$ against l (where l is inverse of angular scale, $l \sim \pi / \theta$)



Generating theoretical C_l

INPUT

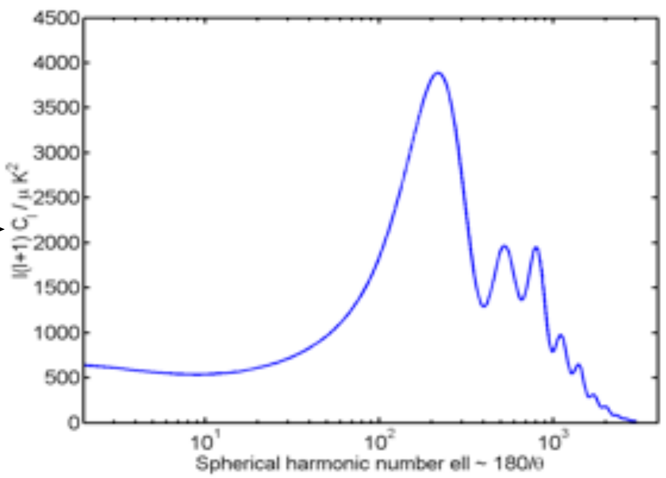
Favorite cosmological model:
Ω_m, Ω_Λ, σ_8, H_0, ..

<u>Physics</u>

powerful cosmological codes (CMBFast or CAMB)

??

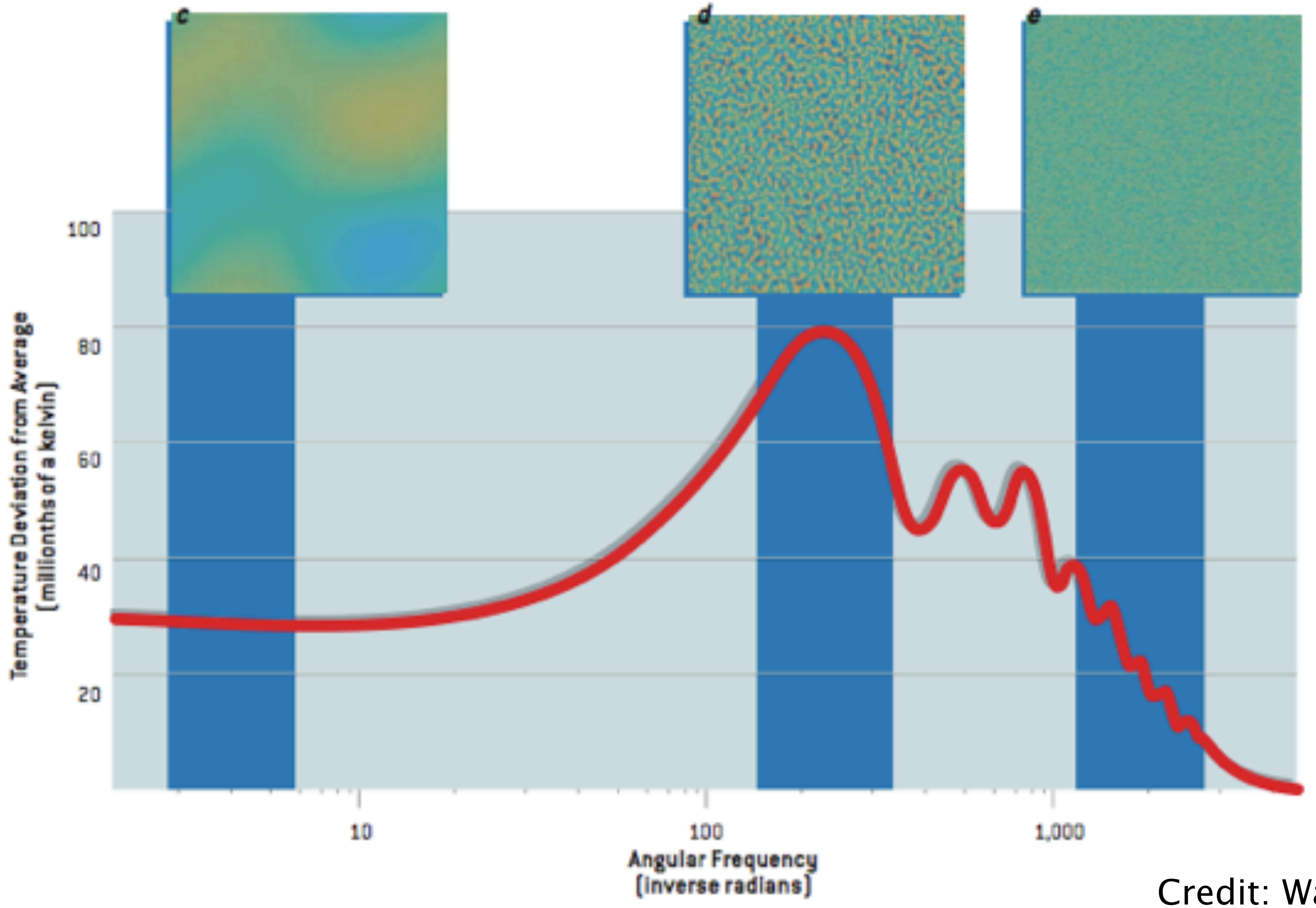
OUTPUT



Fit to data

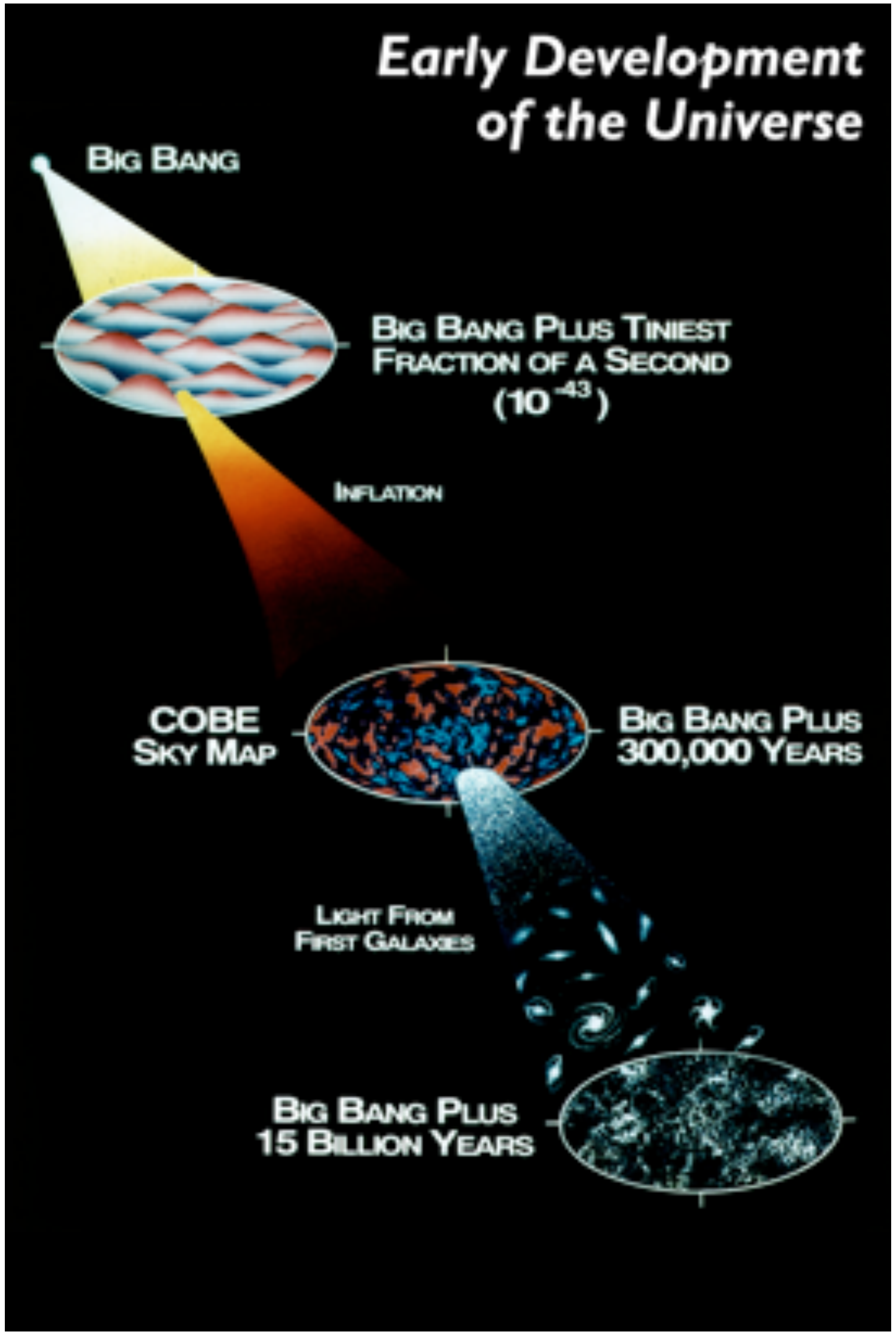
Power at different scales

What does it mean for cosmology?



Credit: Wayne Hu

Primordial temp. anisotropies



At recombination, when the CMB was released, structure had started to form

This created the "hot" and "cold" spots in the CMB

These were the seeds of structure we see today

Please don't confuse between the "creation" of the CMB photons, and their "release" from the last scattering surface!

CMB photons are created at much earlier epoch through matter/anti-matter annihilation, and thus, were formed as gamma rays (now cooled down to microwave)

Sources of primary anisotropies

Quantum density fluctuations in the dark matter were amplified by inflation.
Gravitational potential wells (or “hills”) developed, baryons fell in (or moved away).

Various related physical processes affected the CMB photons:

- **Perturbations in the gravitational potential (Sachs-Wolfe effect):** photons that last scattered within high-density regions have to climb out of potential wells and are thus redshifted

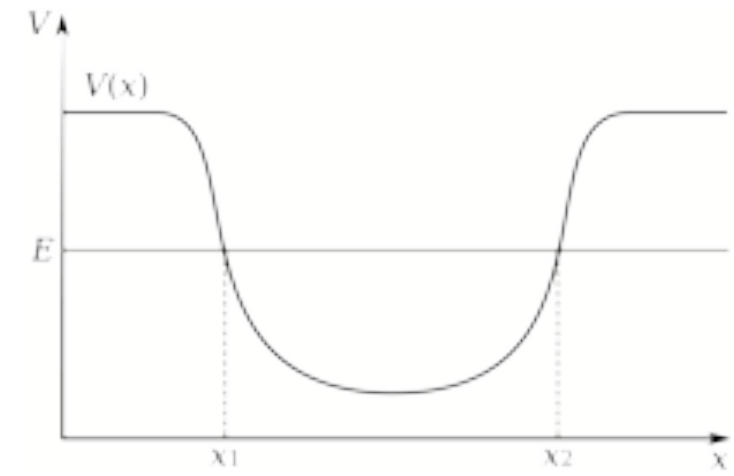
- **Intrinsic adiabatic perturbations:** in high-density regions, the coupling of matter and radiation will also compress the radiation, giving a higher temperature

- **Velocity (Doppler) perturbations:** photons last-scattered by matter with a non-zero velocity along the line-of-sight will receive a Doppler shift

Sachs-Wolfe effect

Gravitational potential well:
photon falls in, gains energy
photon climbs out, loses energy

No net change in energy, unless the potential changes while the photon is inside (ISW).



$$\Delta\nu/\nu \sim \Delta T/T \sim \Phi/c^2$$

Additional effect of time dilation while potential evolves (full GR):

$$\frac{\Delta T}{T} \sim \frac{1}{3}\frac{\Delta\Phi}{c^2}$$

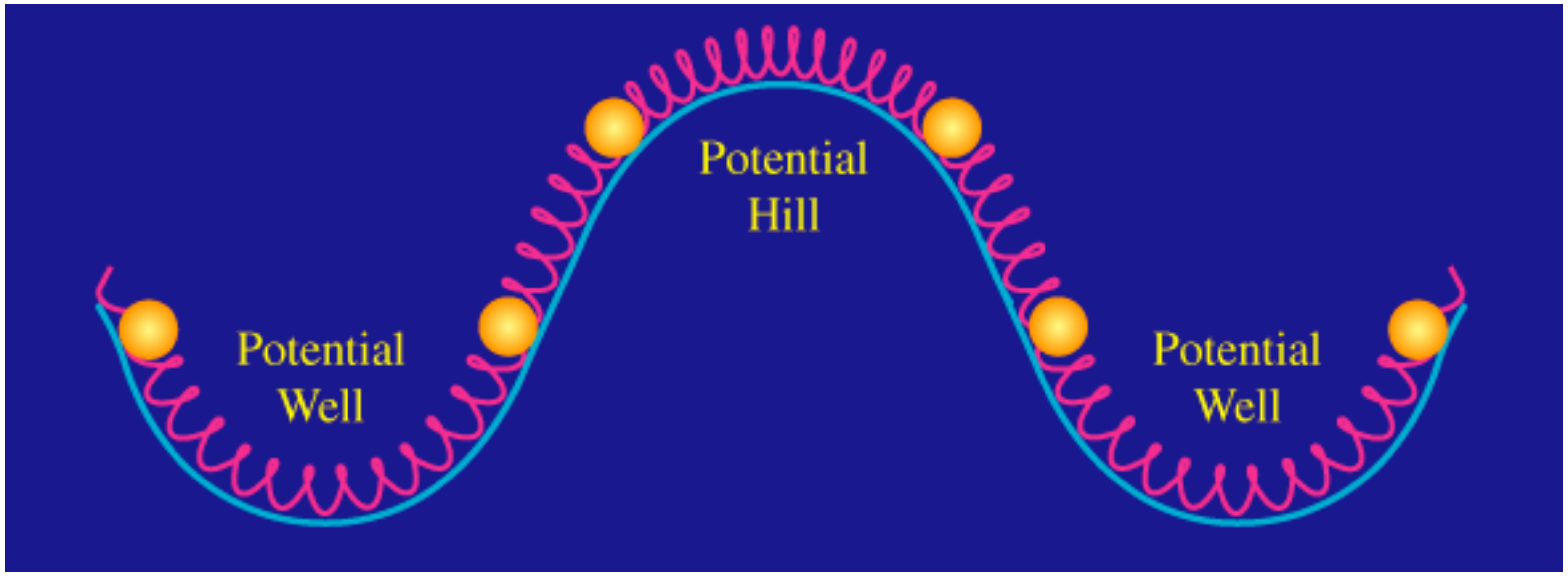
For power-law index of primary density perturbations ($n_s=1$, Harrison-Zel'dovich spectrum), the Sachs-Wolfe effect produces a flat power spectrum: $C_l^{SW} \sim 1/l(l+1)$

Acoustic oscillations

- Baryons fall into dark matter potential wells: Photon baryon fluid heats up
- Radiation pressure from photons resists collapse, overcomes gravity, expands: Photon-baryon fluid cools down
- Oscillating cycle on on scales. Sound waves stop oscillating at recombination when photons and baryons decouple.

Credit: Wayne Hu

Springs: photon pressure



Balls: baryon mass

Acoustic peaks

Oscillations took place on all scales. We see temperature features from modes which had reached the extrema

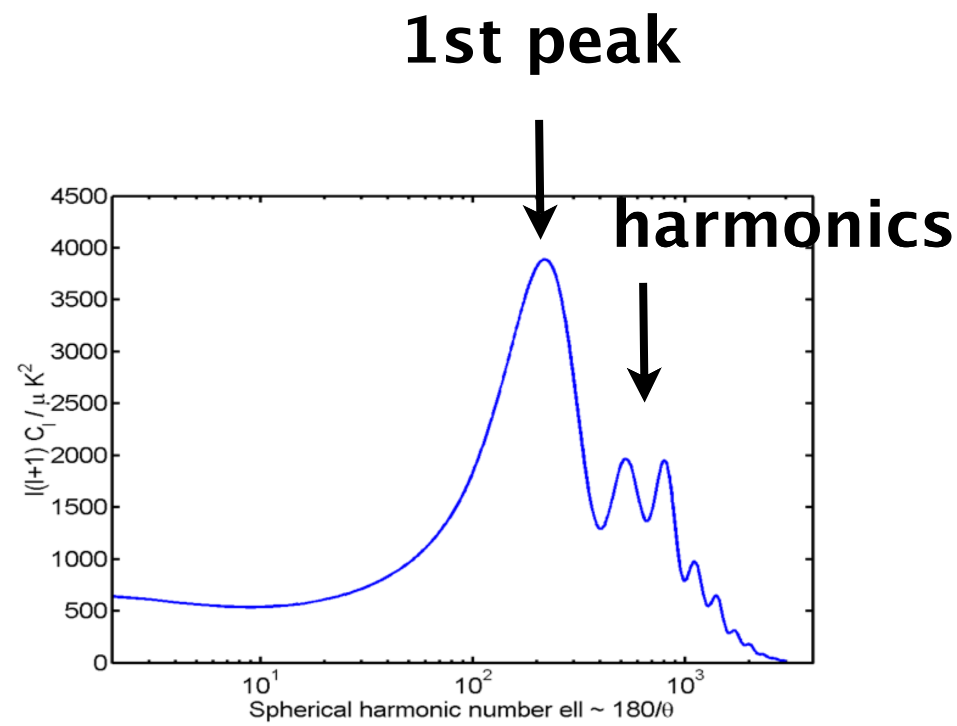
- Maximally compressed regions were hotter than the average
  Recombination happened later, corresponding photons experience less red-shifting by Hubble expansion: HOT SPOT

- Maximally rarified regions were cooler than the average
  Recombination happened earlier, corresponding photons experience more red-shifting by Hubble expansion: COLD SPOT

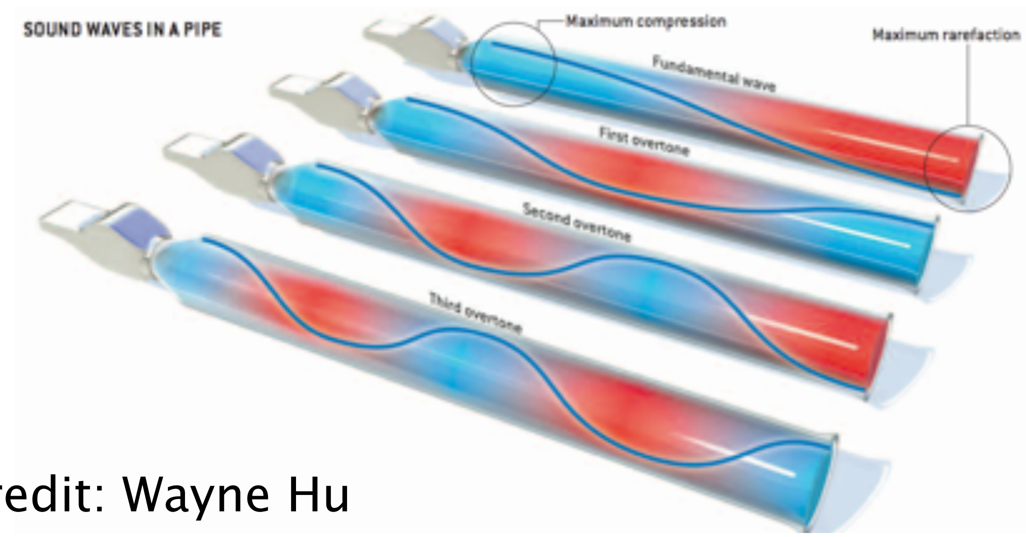
Harmonic sequence, like waves in pipes or strings:

2nd harmonic: mode compresses and rarifies by recombination
3rd harmonic: mode compresses, rarifies, compresses

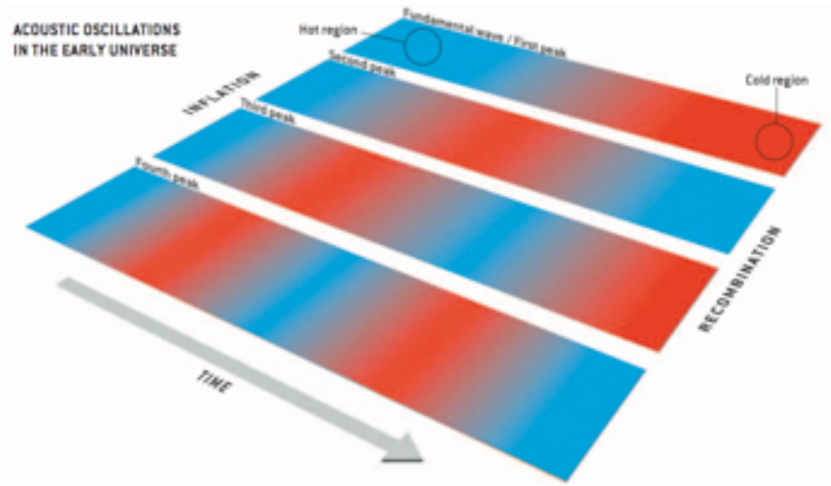
➡ 2nd, 3rd, .. peaks

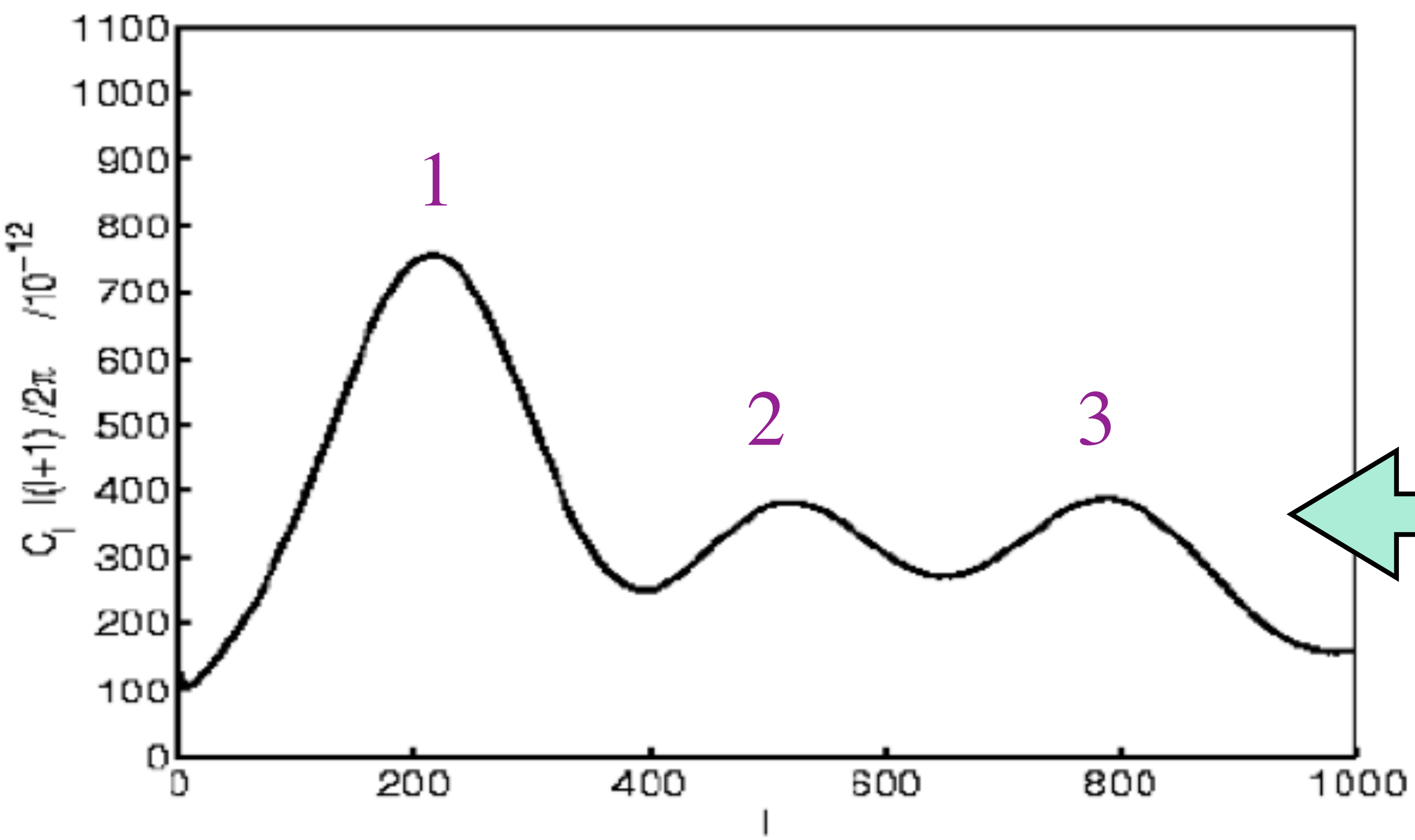


Harmonic sequence



Credit: Wayne Hu





Modes with half the wavelengths osccilate twice as fast ($\nu = c/\lambda$).

Peaks are equally spaced in ℓ

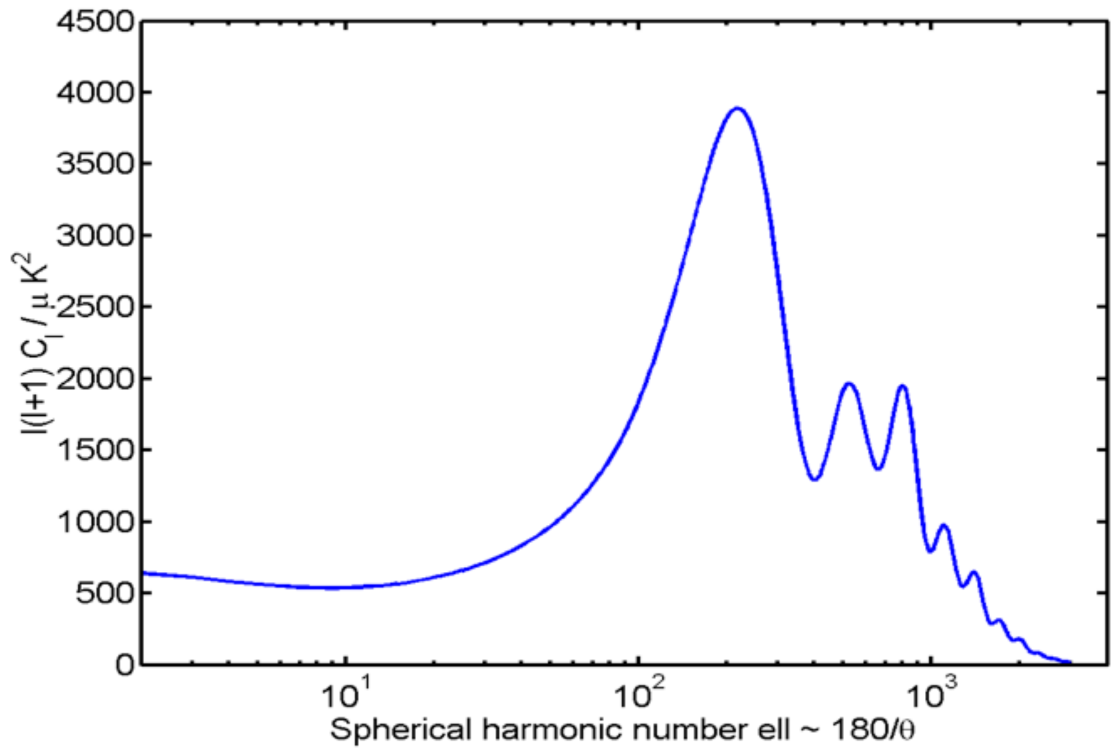
Doppler shifts

Times in between maximum compression/rarefaction, modes reached maximum velocity

This produced temperature enhancements via the Doppler effect (non-zero velocity along the line of sight)

This contributes power in between the peaks

➡ **Power spectrum does not go to zero**

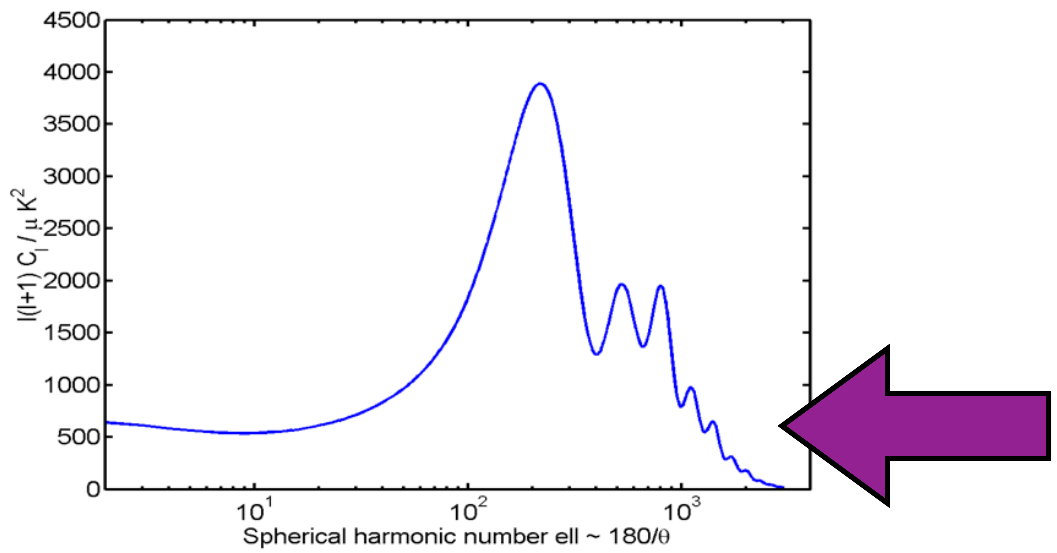


Damping and diffusion

- Photon diffusion (Silk damping) suppresses fluctuations in the baryon-photon plasma

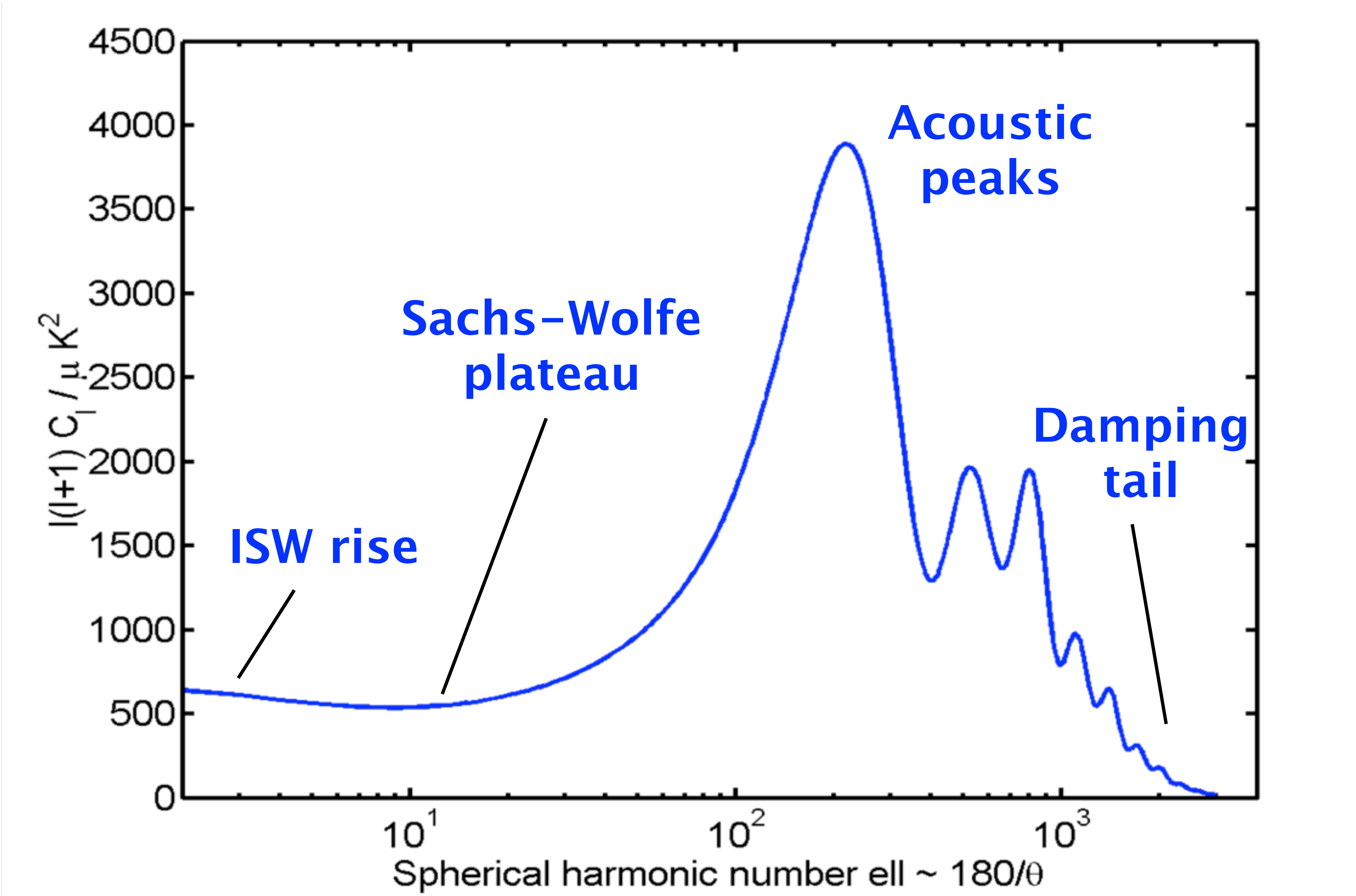
- Recombination does not happen instantaneously and photons execute a random walk during it. Perturbations with wavelengths which are shorter than the photon mean free path are damped (the hot and cold parts mix up)

When we measure the temperature in a given direction in the sky, we are averaging photons that last scattered near the front and near the back of the last scattering surface. This projection effect washes out fluctuations on scales smaller than the thickness of the last scattering surface (l≈1000, ≈0.1°).

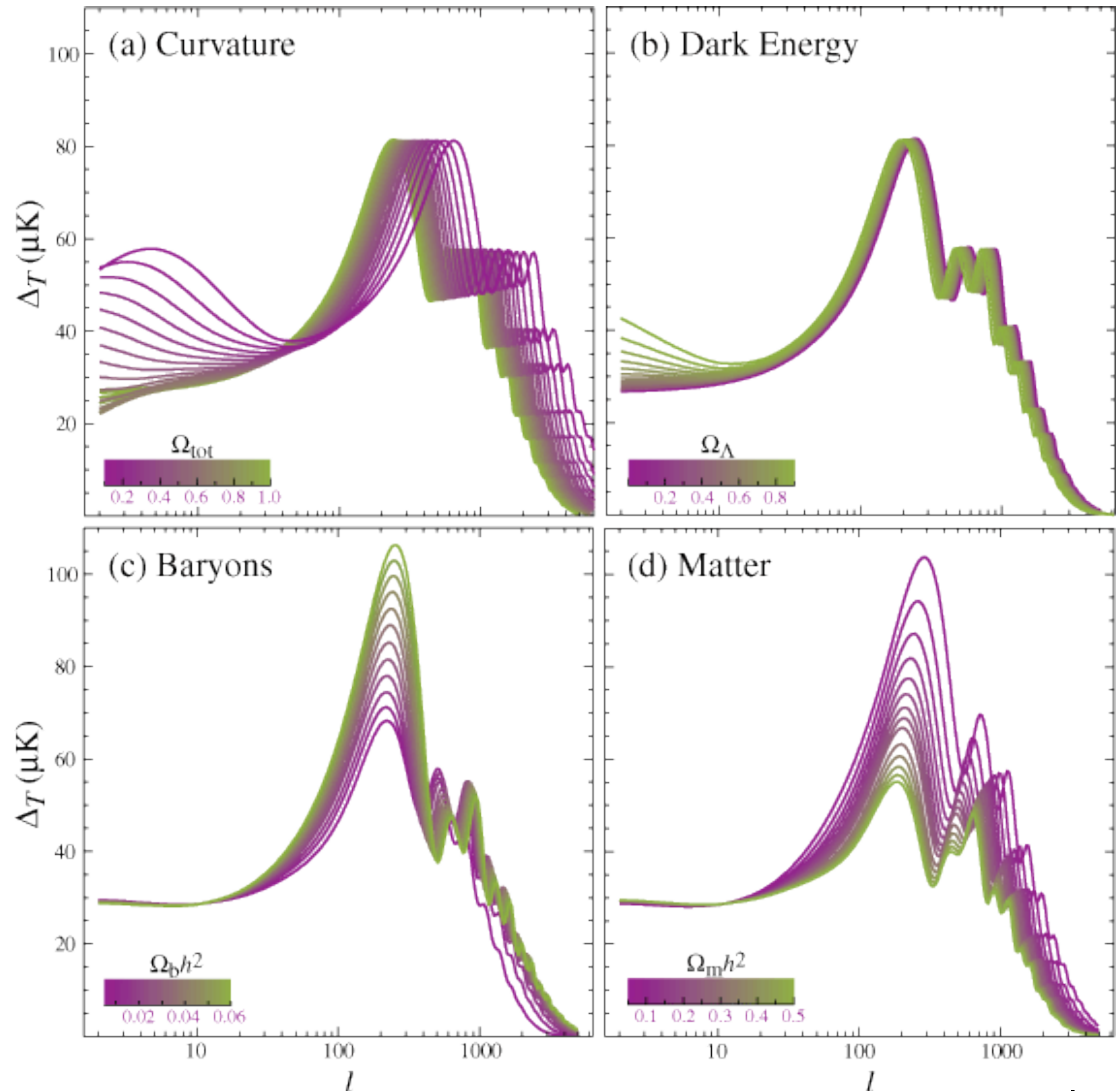


Power falls off

Power spectrum summary



Which way the peaks move?



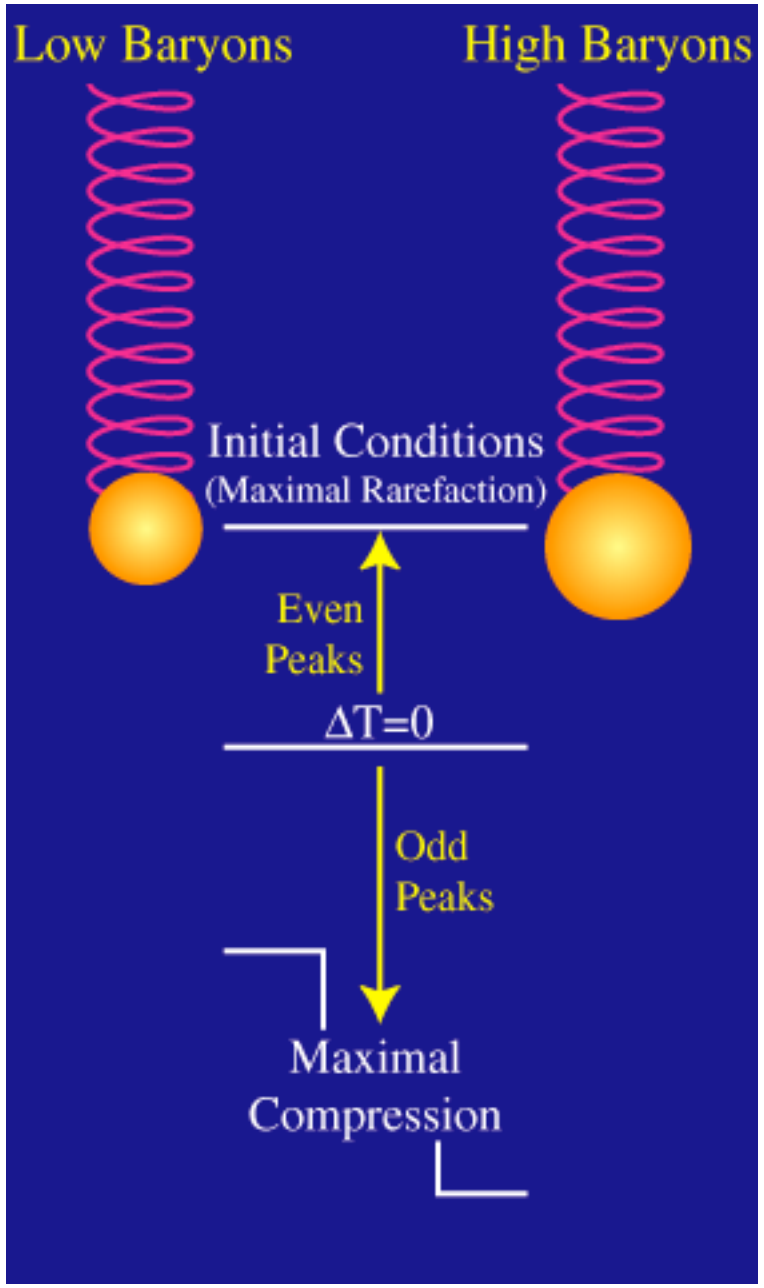
Credit: Wayne Hu

Baryon loading

The presence of more baryons increases the amplitude of the oscillations (makes gravity more efficient).

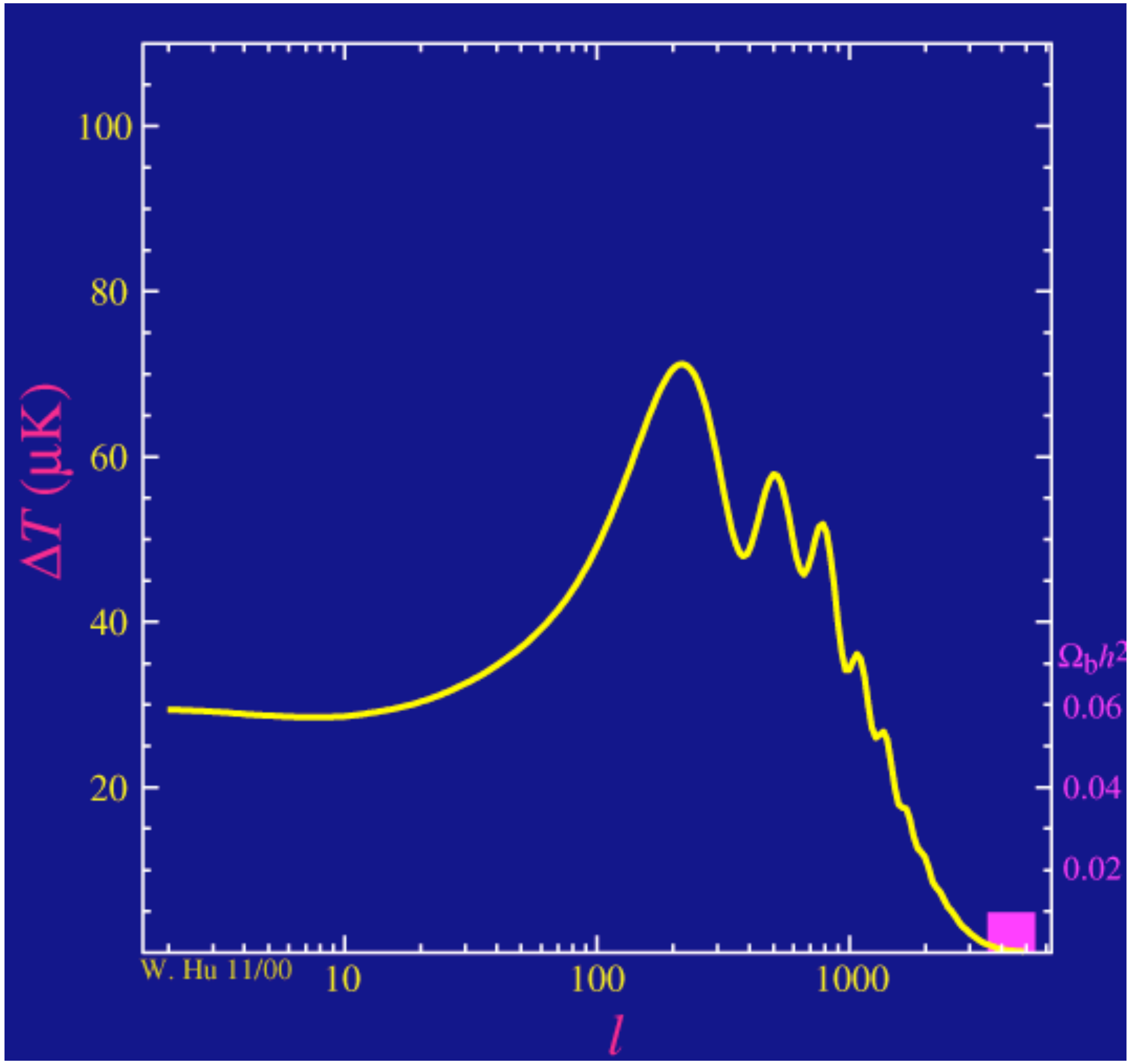
Perturbations are then compressed more before radiation pressure can revert the motion.

This causes an alternation in the odd and even peak heights that can be used to measure the abundance of cosmic baryons.



Credit: Wayne Hu

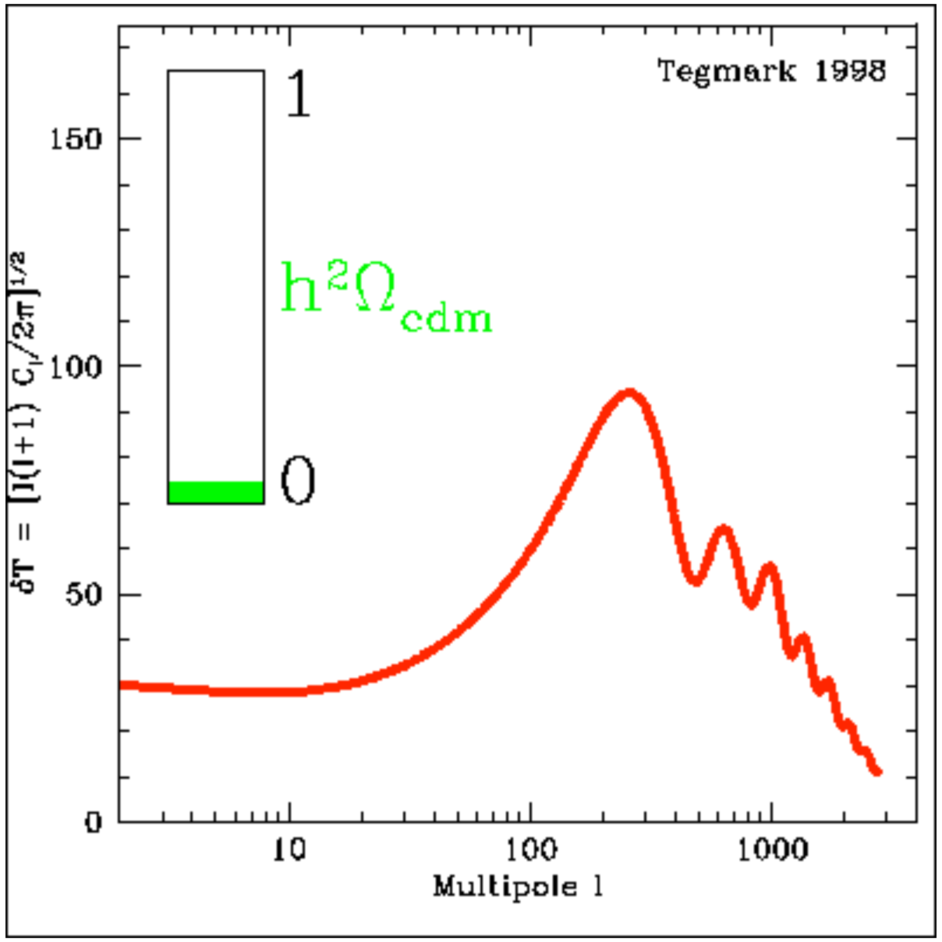
Baryons in the power spectrum

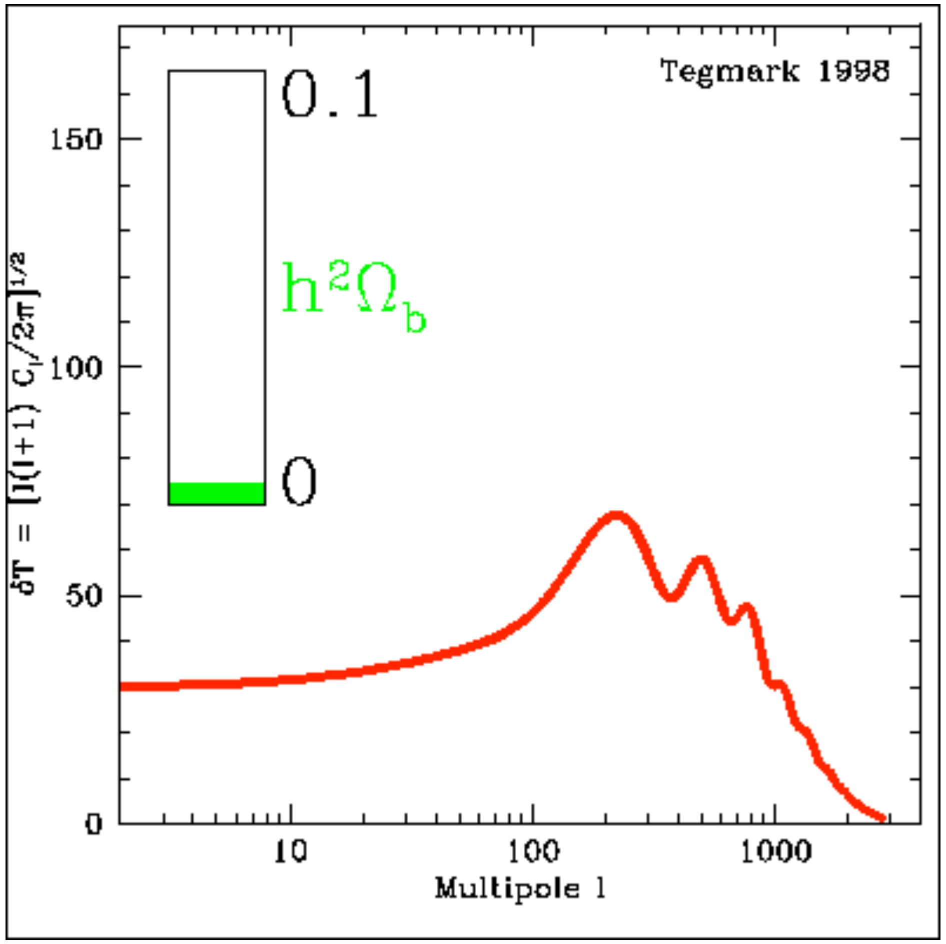


Credit: Wayne Hu

Power spectrum shows baryon enhance every other peak, which helps to distinguish baryons from cold dark matter

DM in the power spectrum



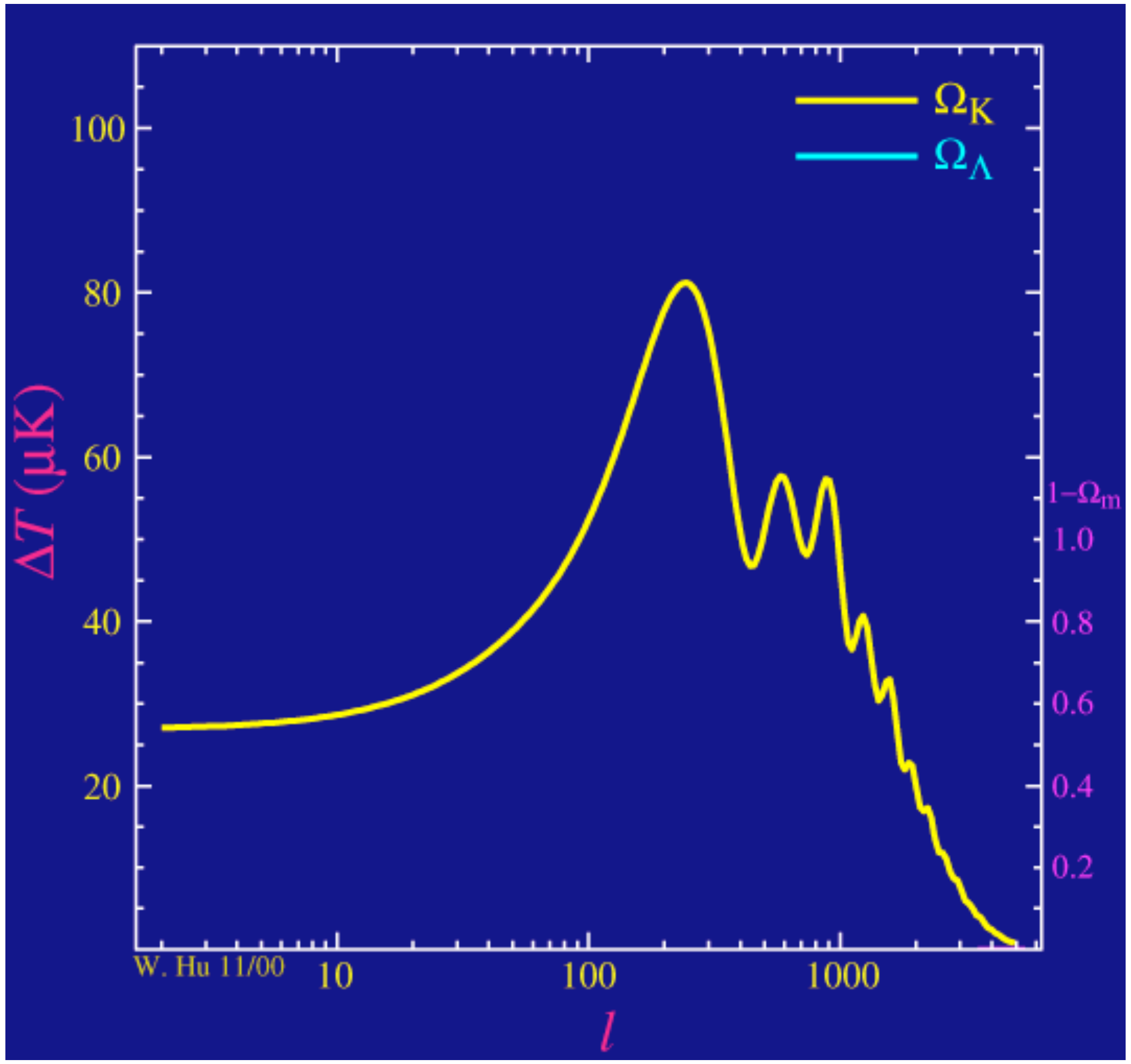


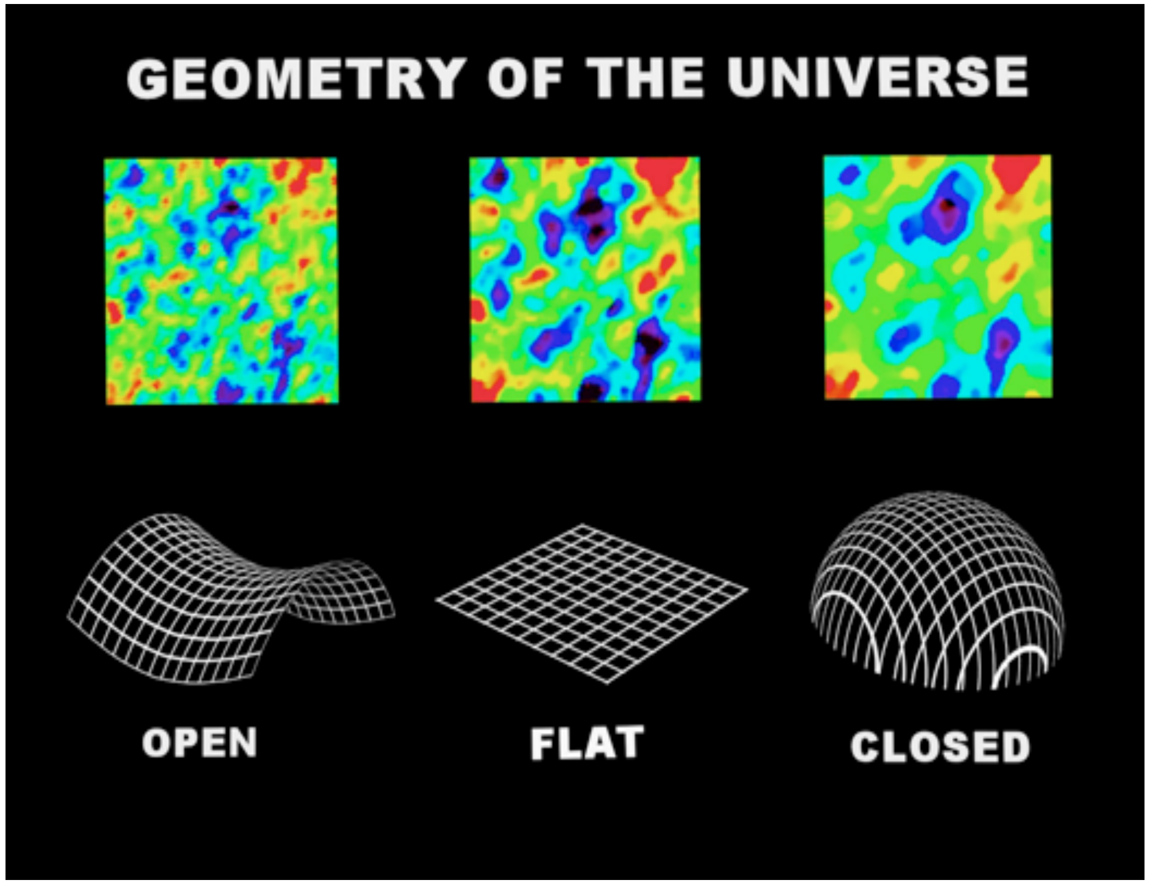
Cold dark matter

Baryons

Credit: Max Tegmark

Effect of curvature

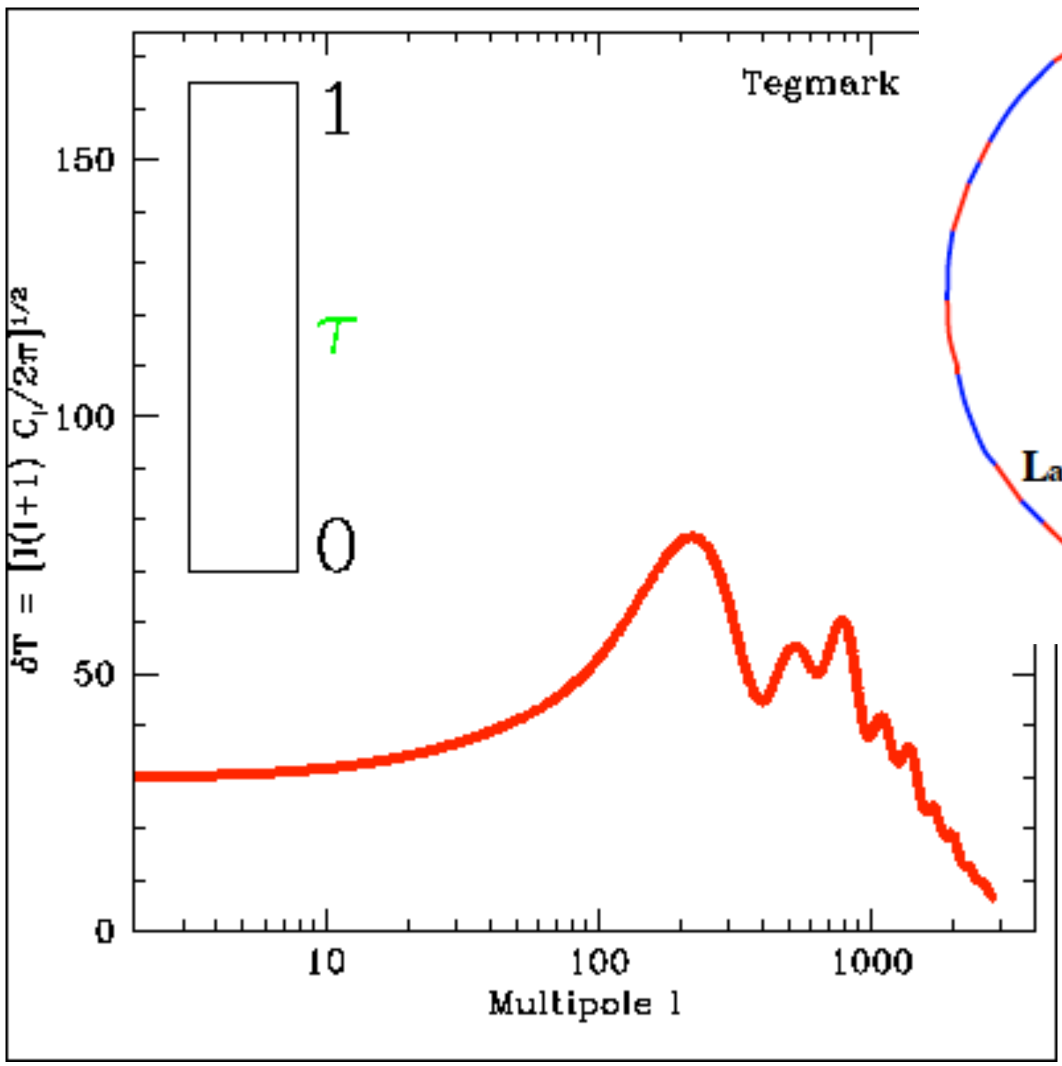


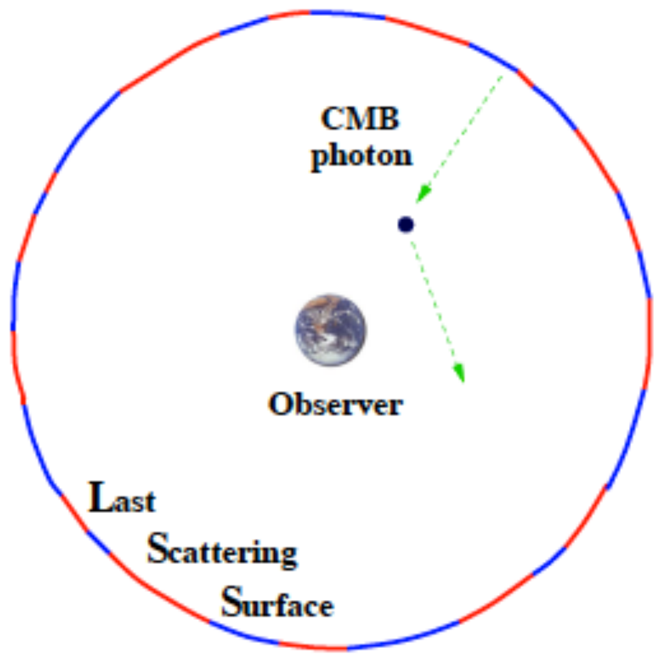


Ω_k does not change the amplitude of the power spectrum, rather it shifts the peaks sideways. This follows from the conversion of the physical scales (on the LSS) to angular scales (that we observe), which depends on the geometry.

Curvature (cosmological constant, Ω_Λ) also causes ISW effect on large scales, by altering the growth of structures in the path of CMB photons.

Effect of reionization





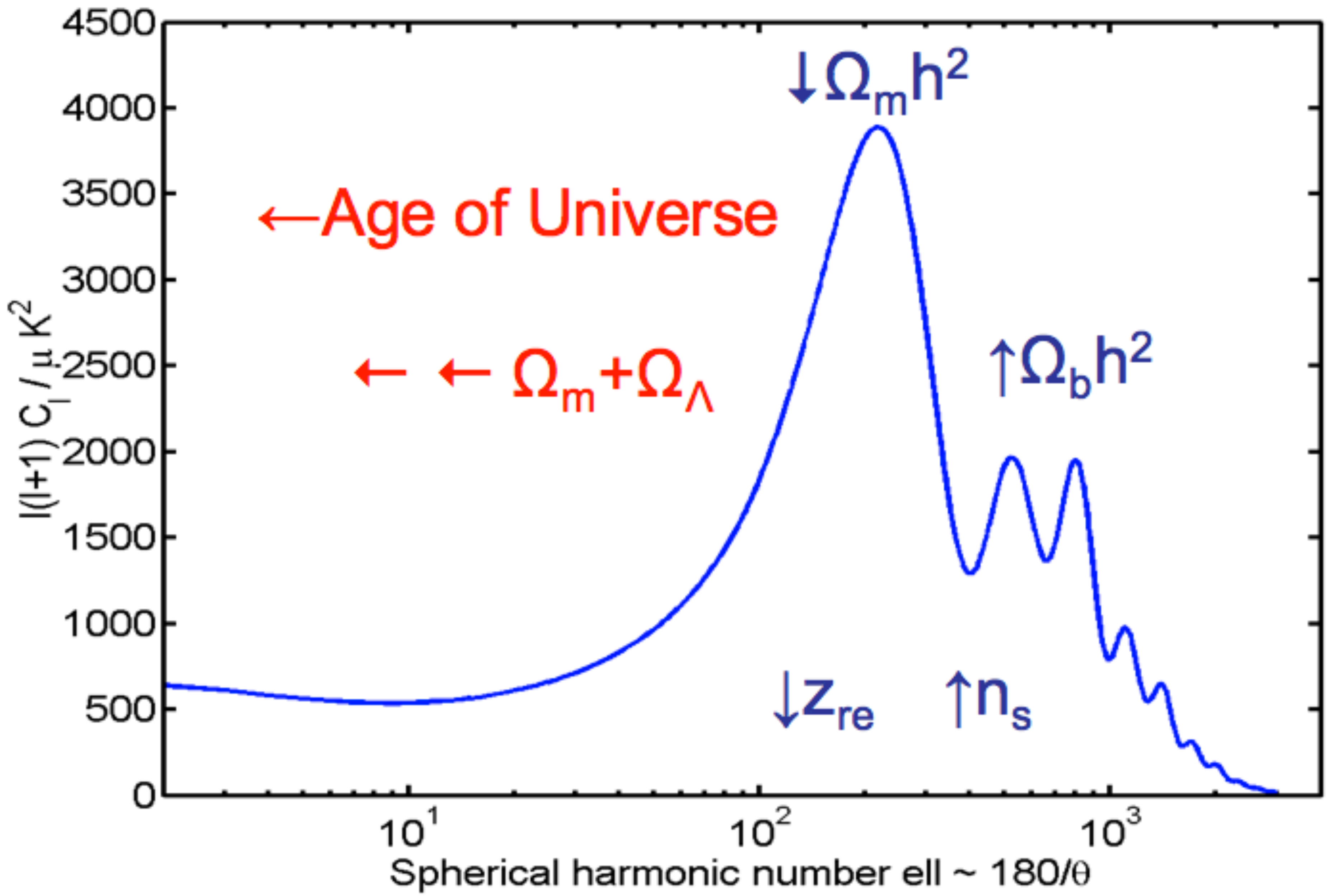
$$\frac{\Delta T}{T_0}(\theta) = e^{-\tau_\nu}\,\frac{\Delta T}{T_0}(\theta)\Big|_{orig.} + \frac{\Delta T}{T_0}(\theta)\Big|_{new}$$

"suppression (blurring)" & "generation"

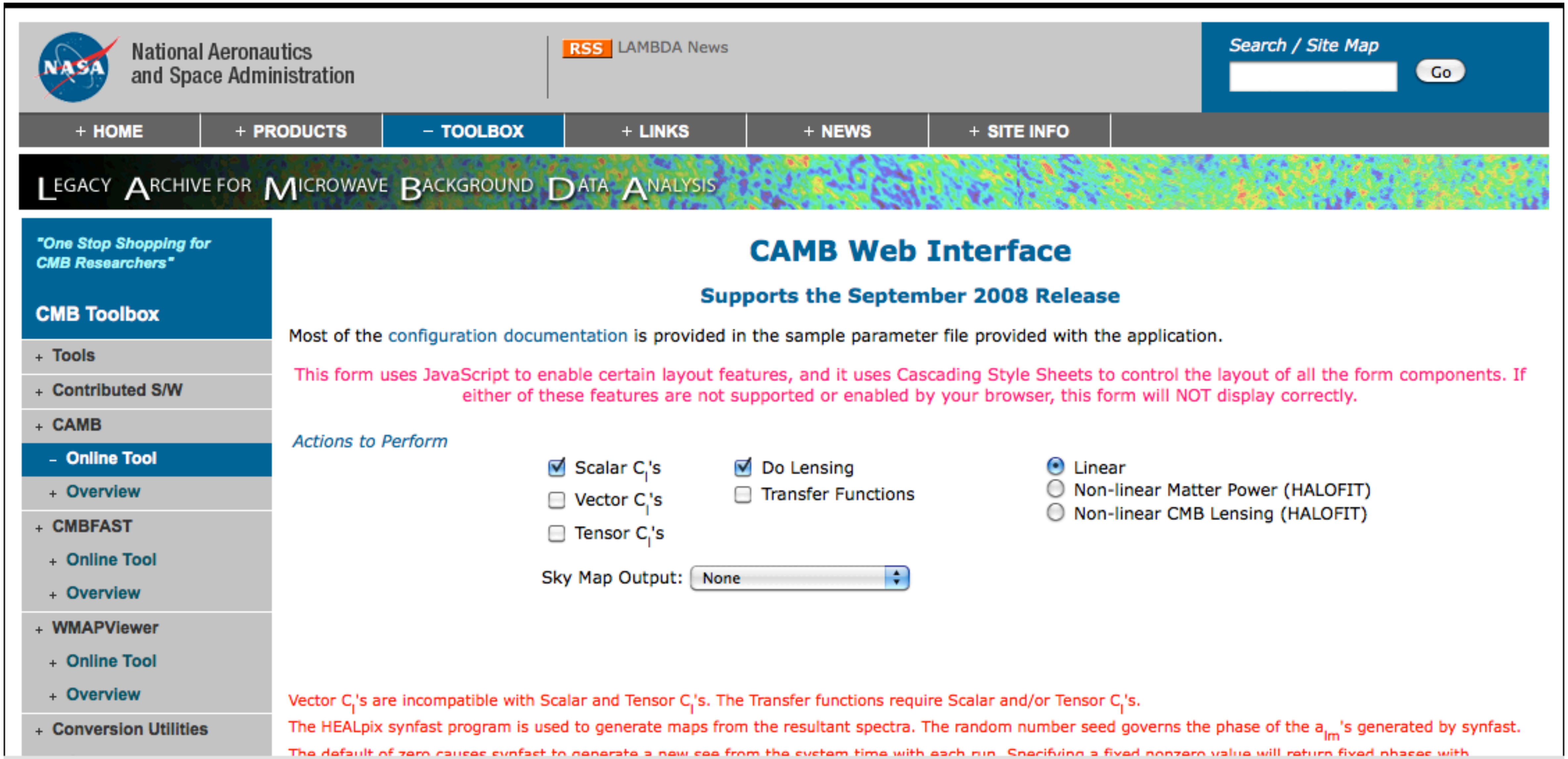
Thomson scattering smears-out the features in the power spectrum, causing peaks at all scales by a constant factor $e^{-\tau}$

(it also generates new anisotropies due to Doppler motion and the Ostriker-Vishniac effect – next lecture!)

CMB parameter cheat sheet



Online C_l calculators



CMB Toolbox: http://lambda.gsfc.nasa.gov/toolbox/

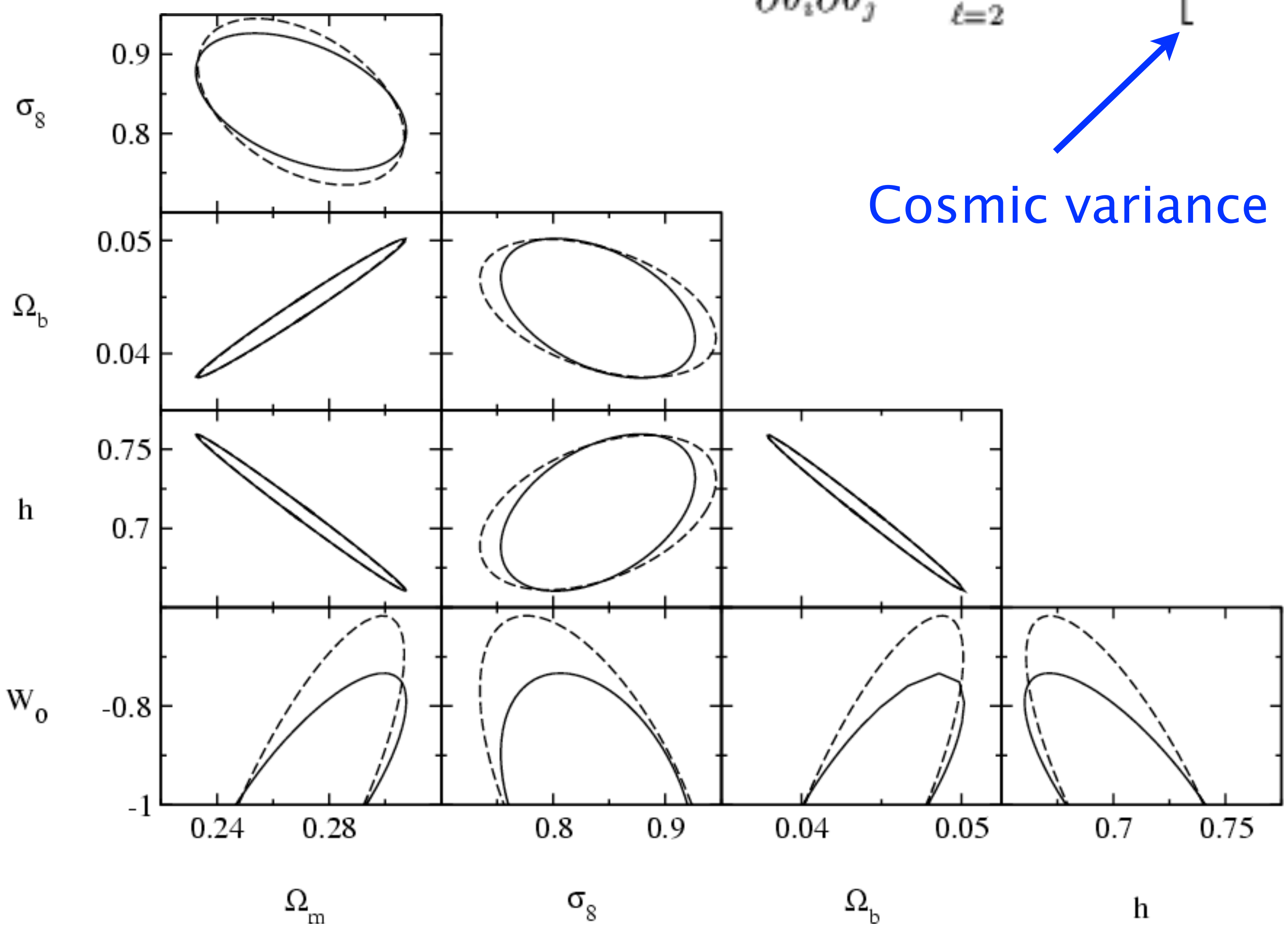
CAMB website: http://camb.info/
CMBFast website: http://www.cmbfast.org/

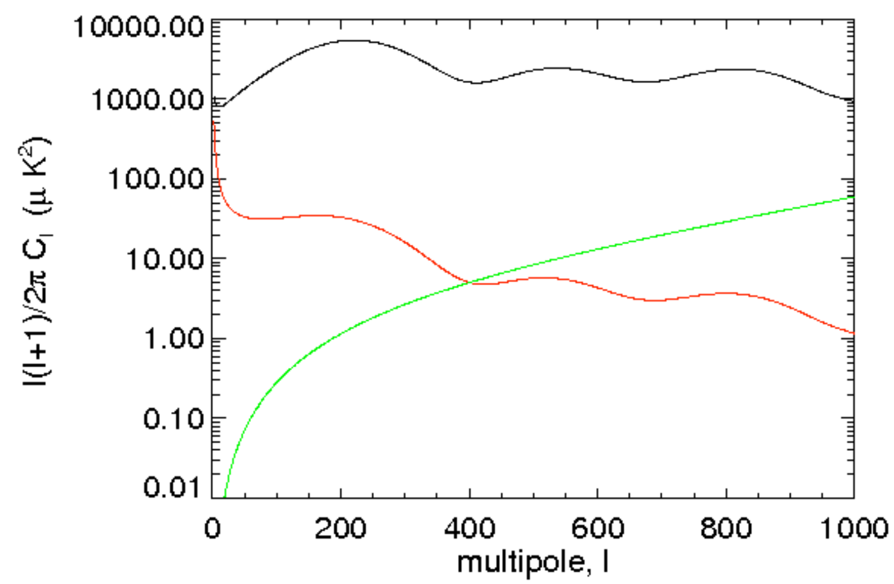
Parameter estimation (Exercise!)

$$I_{ij} \equiv \frac{\partial^2 \mathcal{L}}{\partial\theta_i \partial\theta_j} = \sum_{\ell=2}^{\ell_{\max}} (2\ell+1) \left[C_\ell + \frac{4\pi\sigma^2}{N} e^{\theta_b^2 \ell(\ell+1)} \right]^{-2} \left(\frac{\partial C_\ell}{\partial\theta_i} \right) \left(\frac{\partial C_\ell}{\partial\theta_j} \right).$$

Cosmic variance

Noise per beam



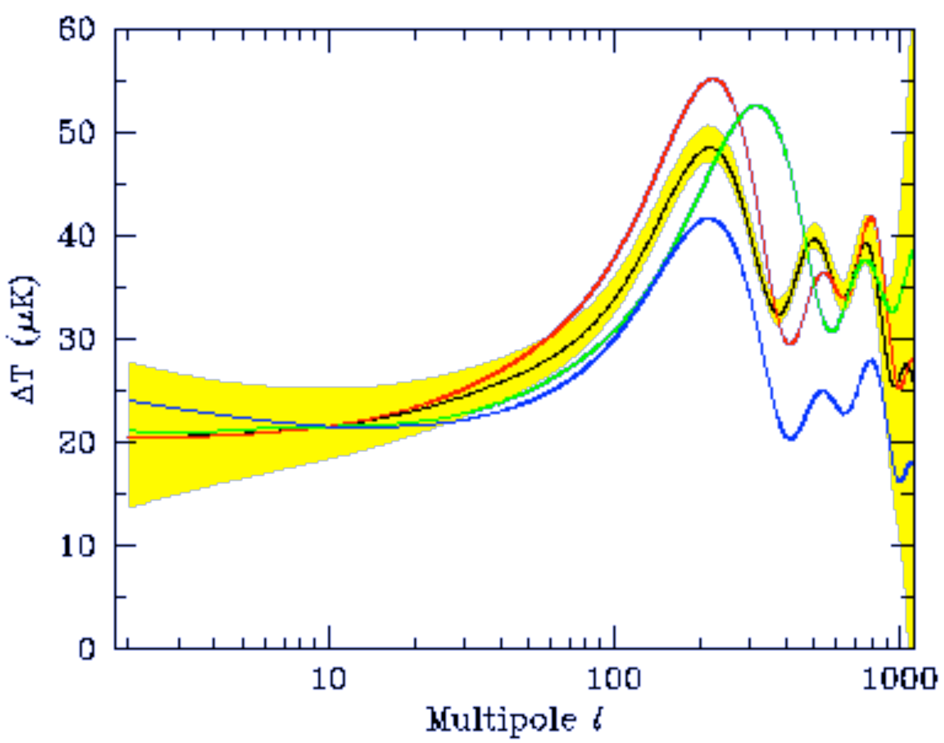


Plot your own power spectra (two for each parameter), and sum up the terms!

Power at low multipoles *($l \leq 100$)*

The horizon scale at the surface of last scattering ($z \sim 1100$) corresponds roughly to 2°. At scales larger than this ($l \geq 100$), we thus see the power spectrum imprinted during the inflationary epoch, unaffected by later, causal, physical processes.

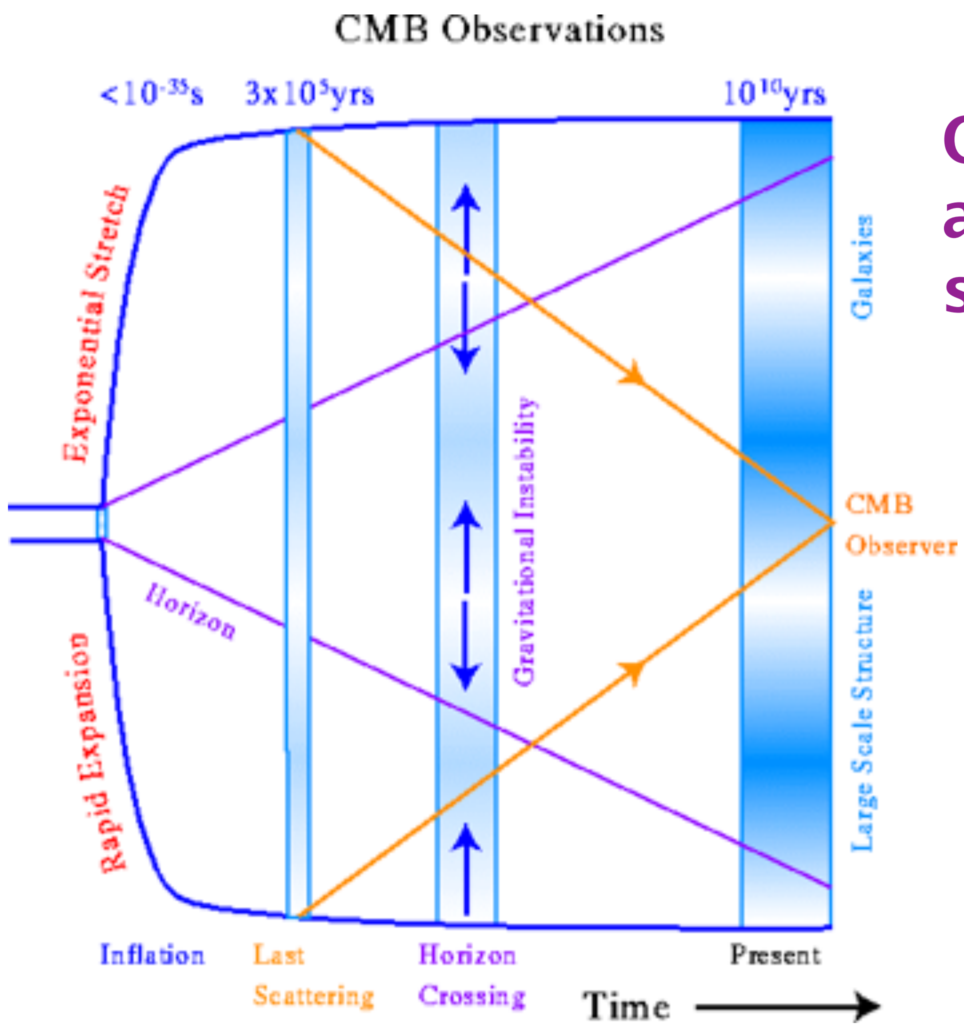
For power-law index of primary density perturbations ($n_s=1$, Harrison-Zel'dovich spectrum), the Sachs-Wolfe effect produces a flat power spectrum: $C_l^{SW} \sim 1/l(l+1)$.



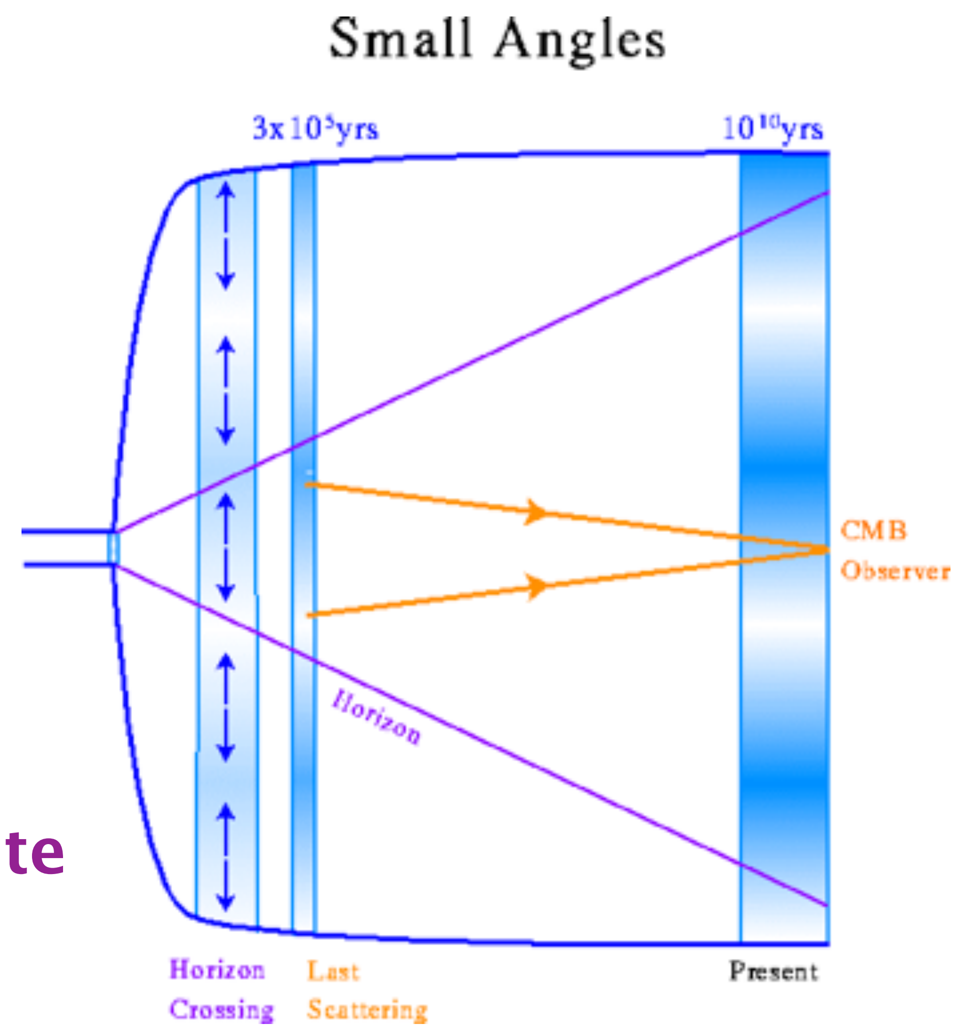
At low multipoles, we also need to consider the cosmic variance: only one sky, limited independent modes.

(Strictly speaking, the variance is not in the cosmos but in the models!)

ΔT at large and small scales



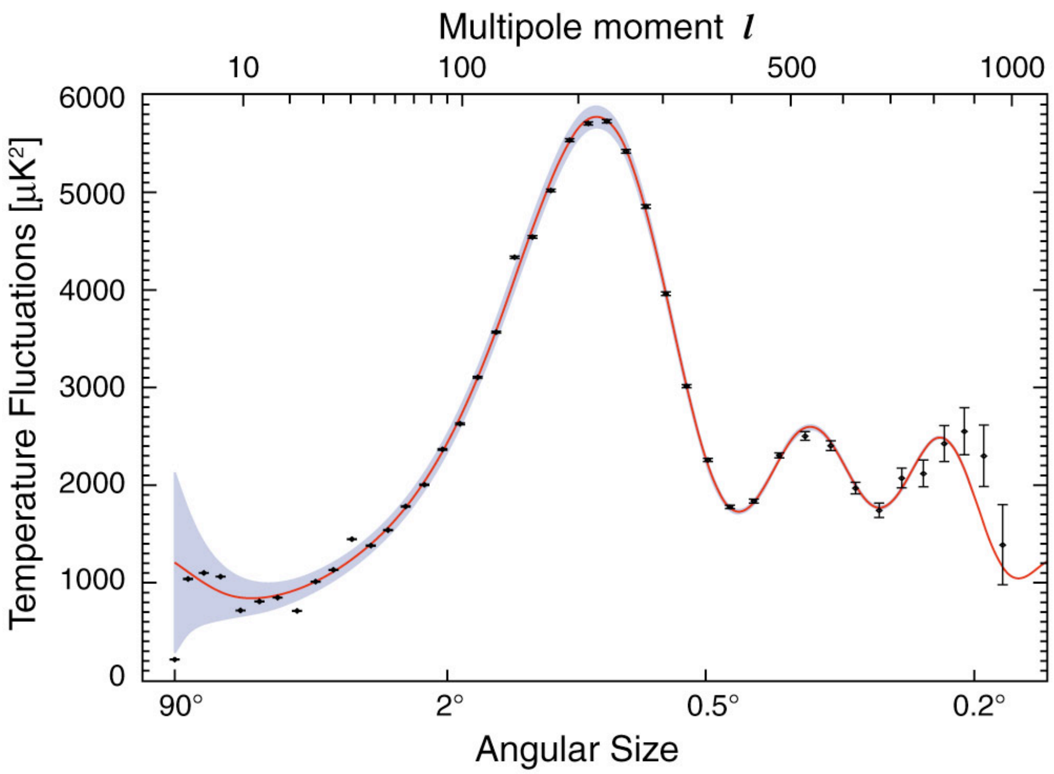
Only the Sachs-Wolfe effect contributes and gives rise to the flat part of the power spectrum at small l.

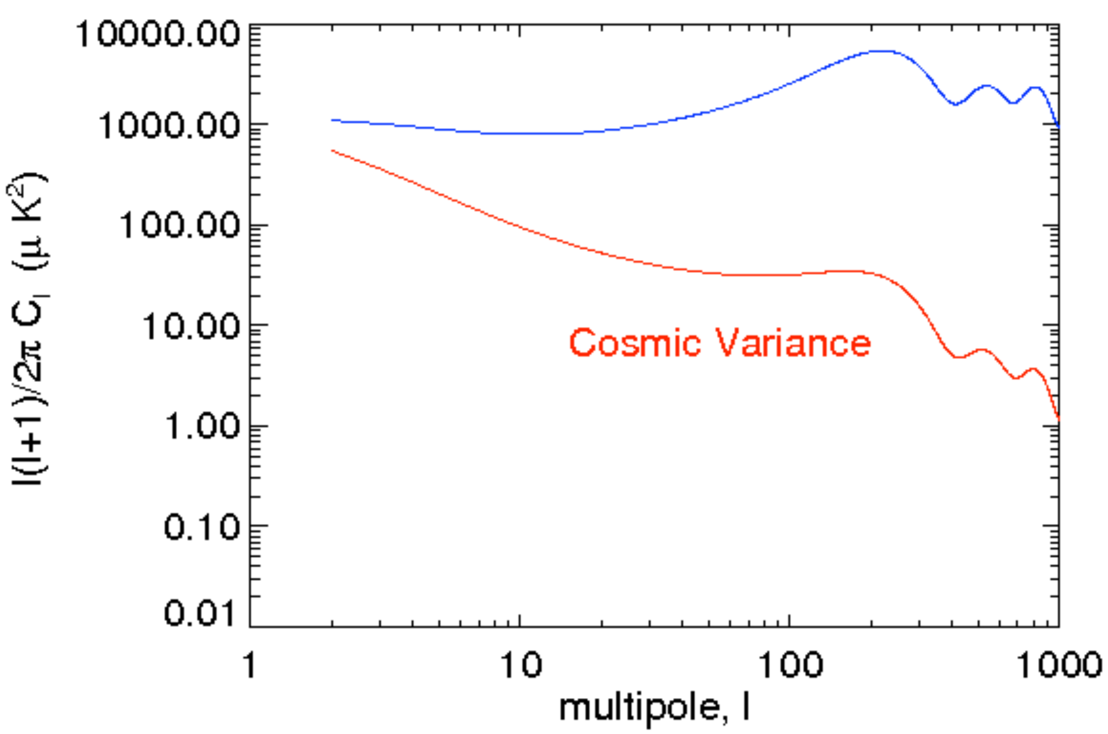


At small scales, all other effects contribute

Credit: Wayne Hu

Cosmic and sample variance





- **Cosmic variance**: on scale l, there are only $\sim l(l+1)$ independent modes (only one sky!)

$$\Delta C_\ell = \sqrt{\frac{2}{2\ell+1}} C_\ell$$

- This leads to an inevitable error, in the predicted amplitudes at low l, even for very specific cosmological models

- Averaging over l in bands of $\Delta l \approx l$ makes the error scale as l^{-1}

- If the fraction of sky covered is f, then the errors increase by a factor $f^{-1/2}$ and the resulting variance is called **sample variance** (f=0.65 for the PLANCK satellite)

Sources of ΔT

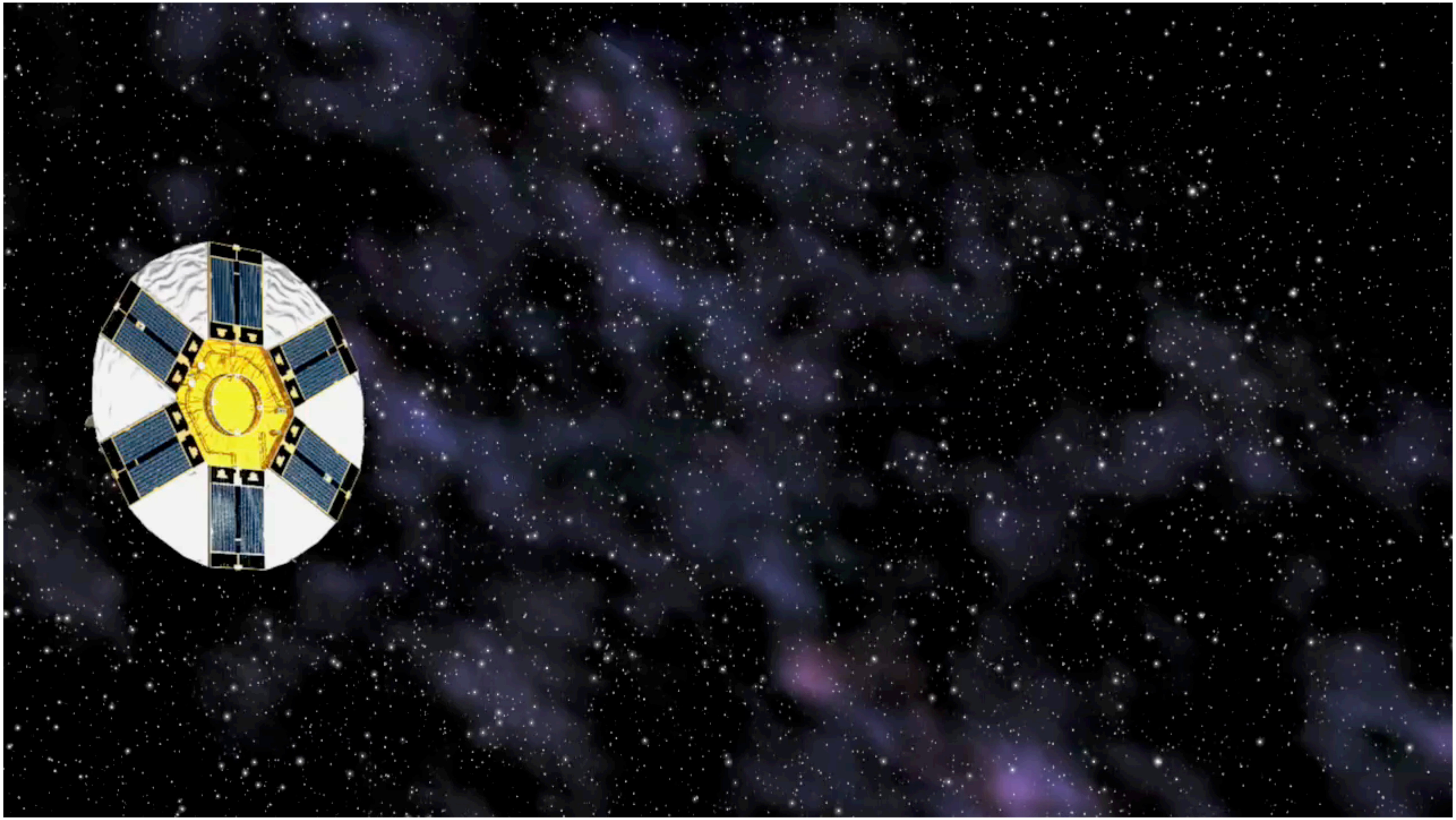
(you'll have to come to Lecture 2 !)

Table 1. Sources of temperature fluctuations.

PRIMARY	Gravity	
	Doppler	
	Density fluctuations	
	Damping	
	Defects	Strings
		Textures
SECONDARY	Gravity	Early ISW
		Late ISW
		Rees-Sciama
		Lensing
	Local reionization	Thermal SZ
		Kinematic SZ
	Global reionization	Suppression
		New Doppler
		Vishniac
"TERTIARY"	Extragalactic	Radio point sources
		IR point sources
(foregrounds & headaches)	Galactic	Dust
		Free-free
		Synchrotron
	Local	Solar system
		Atmosphere
		Noise, *etc.*

Max Tegmark (astro-ph/9511148)

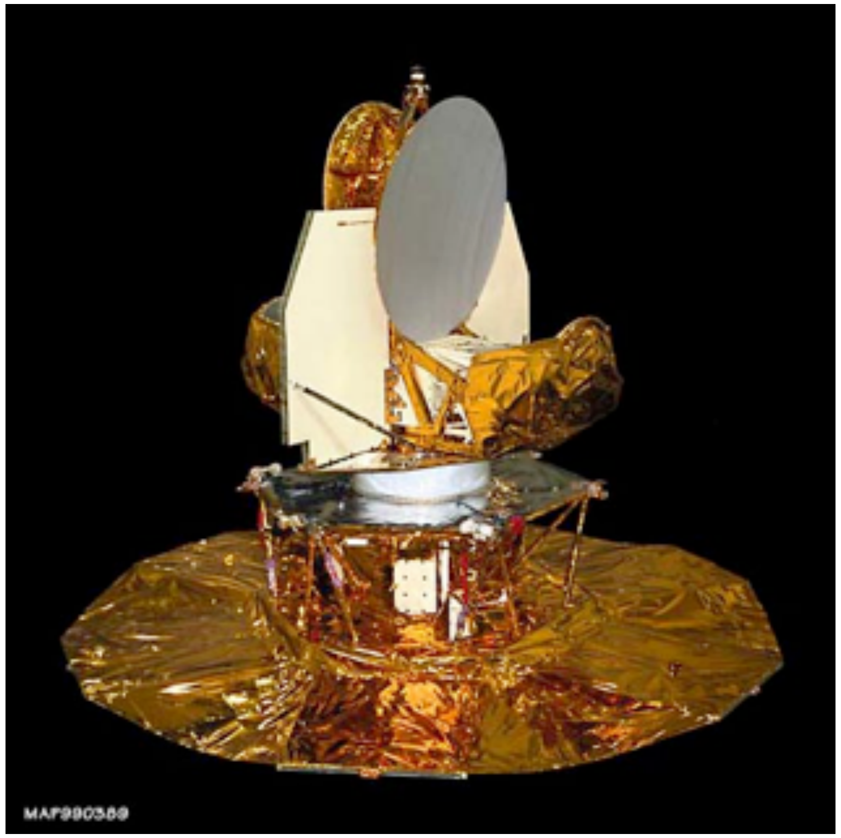
CMB cosmology today: WMAP



Credit: NASA

WMAP launched June 2001

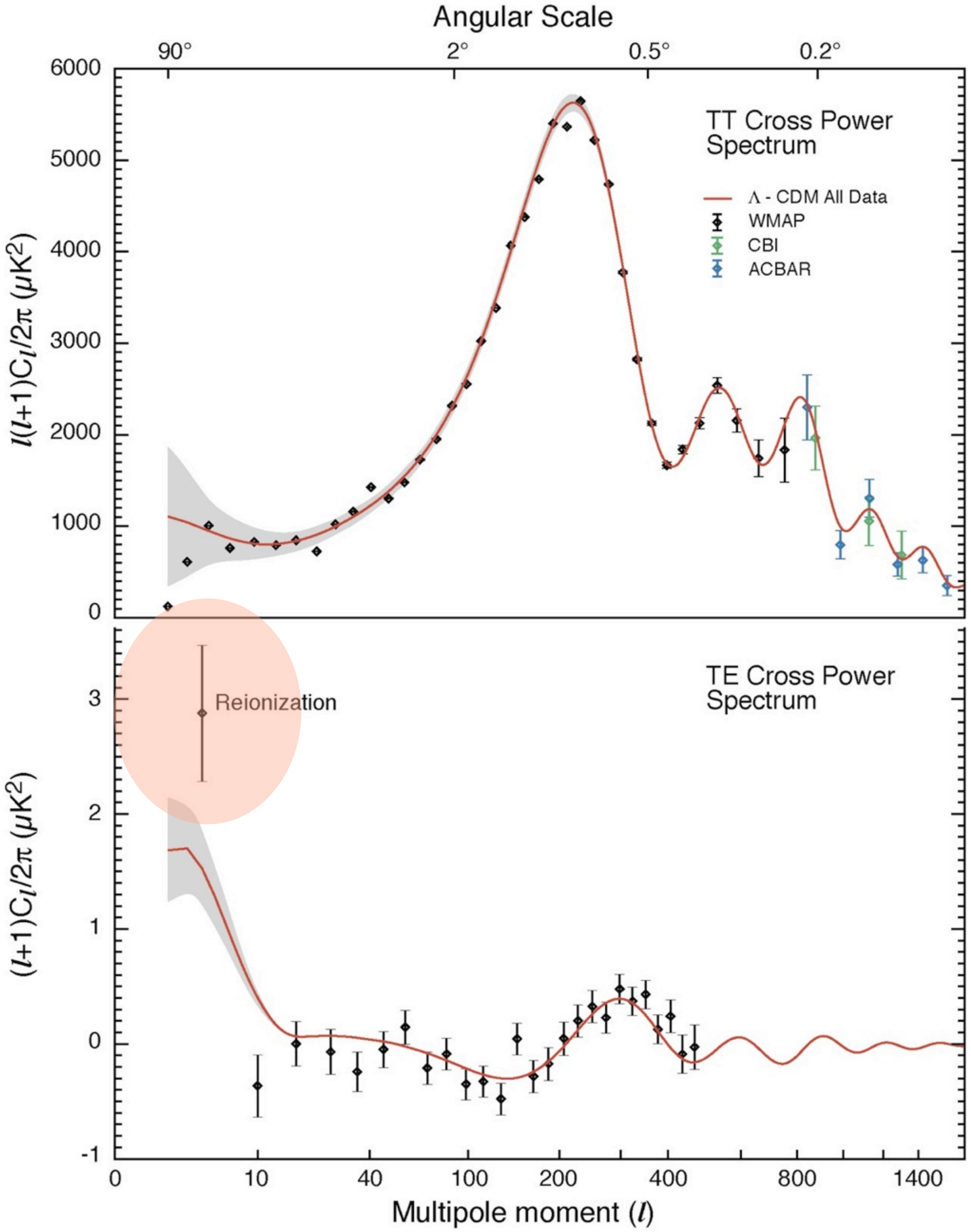
Credit: NASA



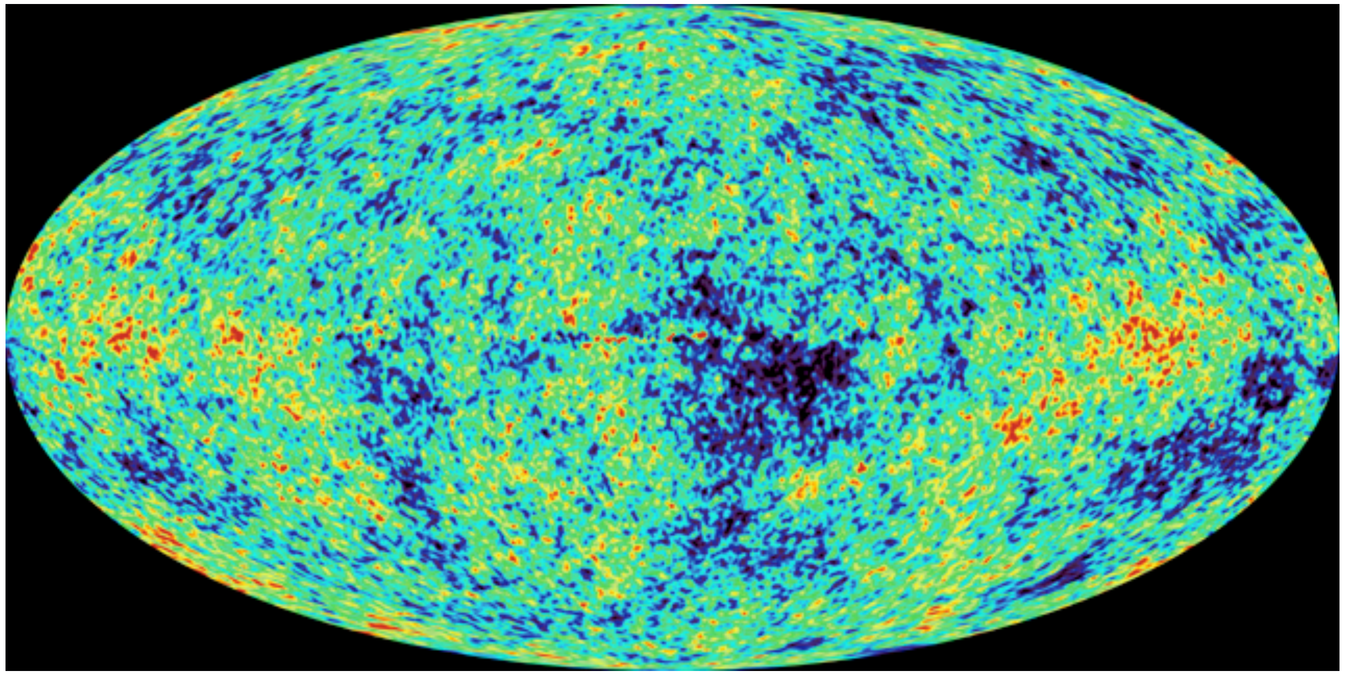
Note the same dual receivers as COBE! This design, added with the very stable conditions at the L2, minimizes the "1/f noise" in amplifiers and receivers.

Thus after 7 years, the data can still be added and noise lowered!

WMAP results after 1st year



(Credit: WMAP Science Team)

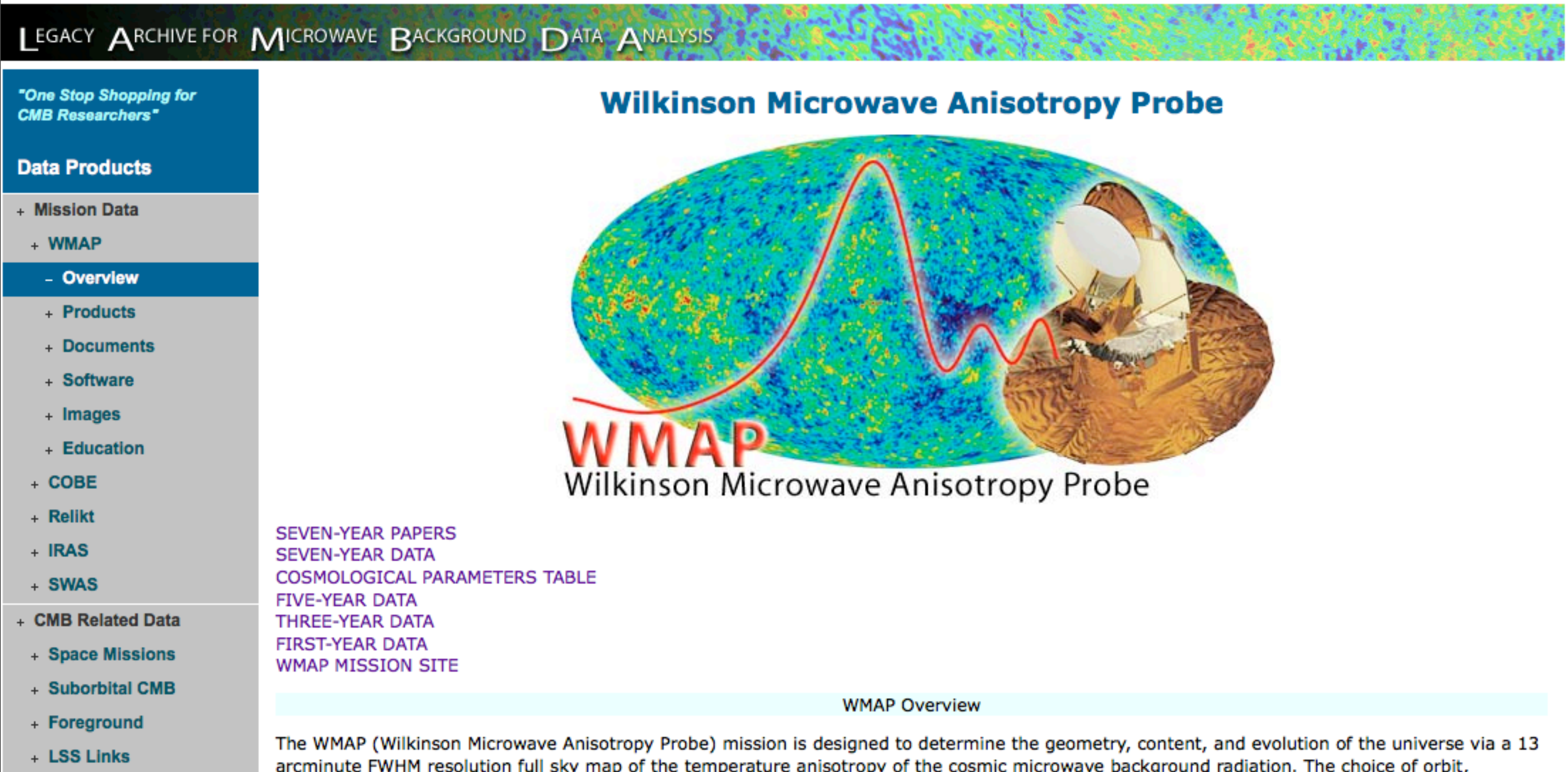


Internal Linear Combination map

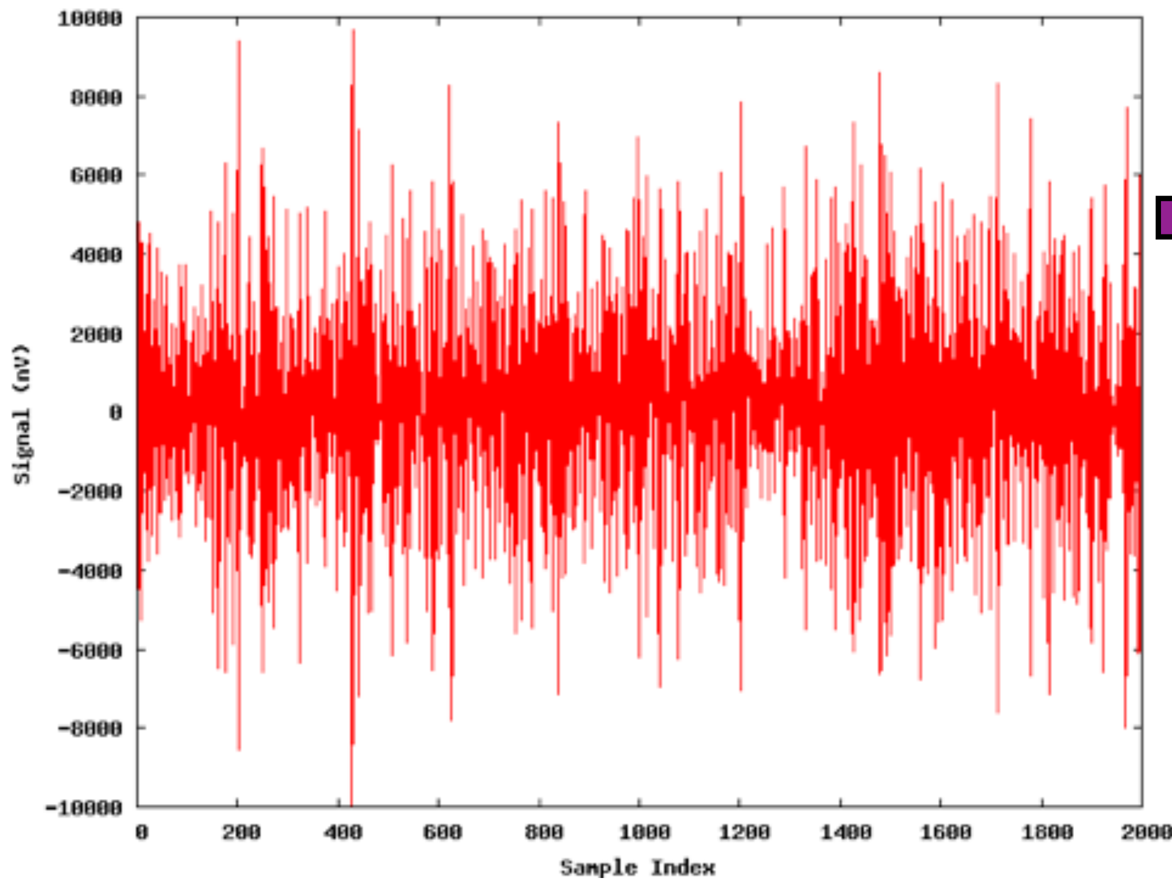
Cosmology from WMAP after 7 yr

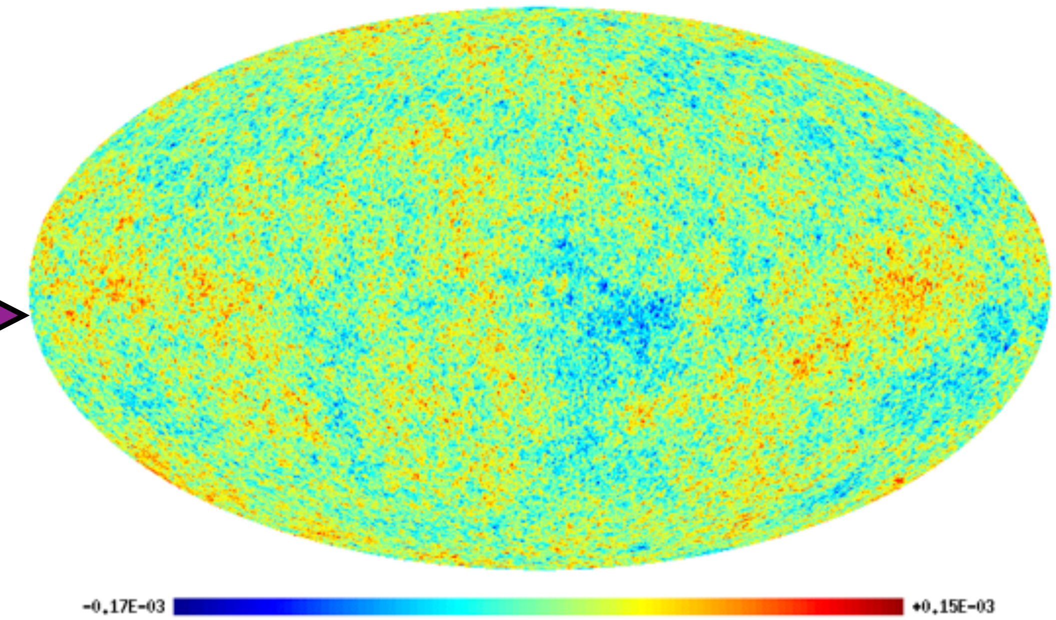
WMAP Cosmological Parameters Model: lcdm+sz+lens Data: wmap7			
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	$1 - n_s$	0.037 ± 0.014
$1 - n_s$	$0.0079 < 1 - n_s < 0.0642$ (95% CL)	$A_{\rm BAO}(z = 0.35)$	$0.463^{+0.021}_{-0.020}$
C_{220}	5763^{+38}_{-40}	$d_A(z_{\rm eq})$	14281^{+158}_{-161} Mpc
$d_A(z_*)$	14116^{+160}_{-163} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$
h	0.710 ± 0.025	H_0	71.0 ± 2.5 km/s/Mpc
$k_{\rm eq}$	$0.00974^{+0.00041}_{-0.00040}$	$\ell_{\rm eq}$	137.5 ± 4.3
ℓ_*	302.44 ± 0.80	n_s	0.963 ± 0.014
Ω_b	0.0449 ± 0.0028	$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$
Ω_c	0.222 ± 0.026	$\Omega_c h^2$	0.1109 ± 0.0056
Ω_Λ	0.734 ± 0.029	Ω_m	0.266 ± 0.029
$\Omega_m h^2$	$0.1334^{+0.0056}_{-0.0055}$	$r_{\rm hor}(z_{\rm dec})$	285.5 ± 3.0 Mpc
$r_s(z_d)$	153.2 ± 1.7 Mpc	$r_s(z_d)/D_v(z = 0.2)$	$0.1922^{+0.0072}_{-0.0073}$
$r_s(z_d)/D_v(z = 0.35)$	$0.1153^{+0.0038}_{-0.0039}$	$r_s(z_*)$	$146.6^{+1.5}_{-1.6}$ Mpc
R	1.719 ± 0.019	σ_8	0.801 ± 0.030
$A_{\rm SZ}$	$0.97^{+0.68}_{-0.97}$	t_0	13.75 ± 0.13 Gyr
τ	0.088 ± 0.015	θ_*	0.010388 ± 0.000027
θ_*	$0.5952 \pm 0.0016\ ^\circ$	t_*	379164^{+5187}_{-5243} yr
$z_{\rm dec}$	1088.2 ± 1.2	z_d	1020.3 ± 1.4
$z_{\rm eq}$	3196^{+134}_{-133}	$z_{\rm reion}$	10.5 ± 1.2
z_*	$1090.79^{+0.94}_{-0.92}$		

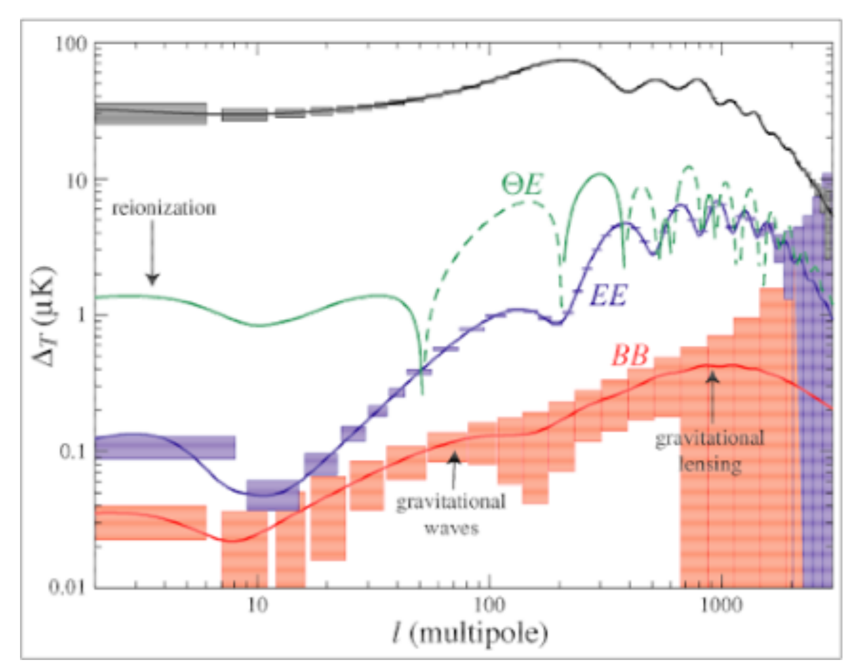
Check the WMAP website



CMB Data Analysis

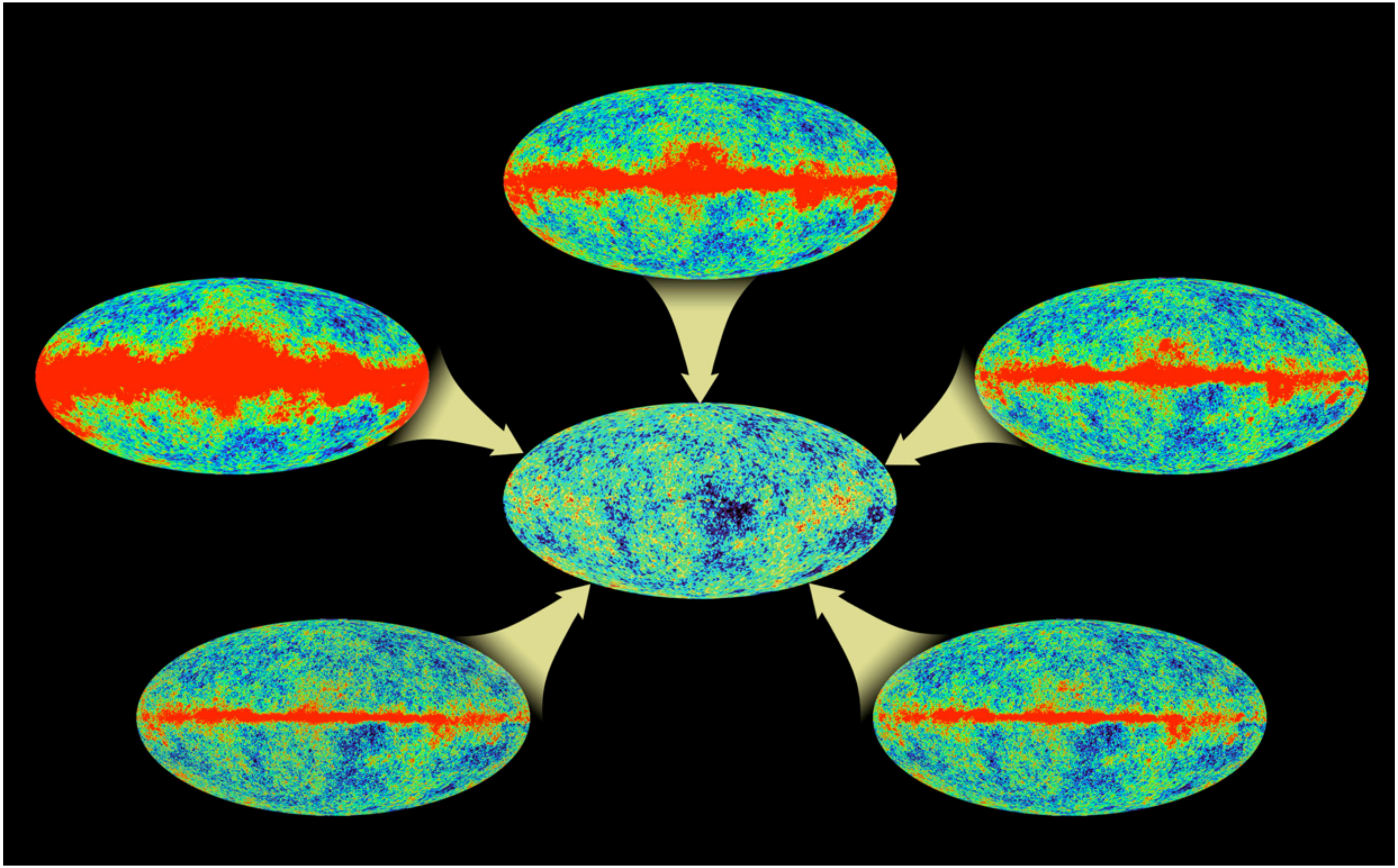




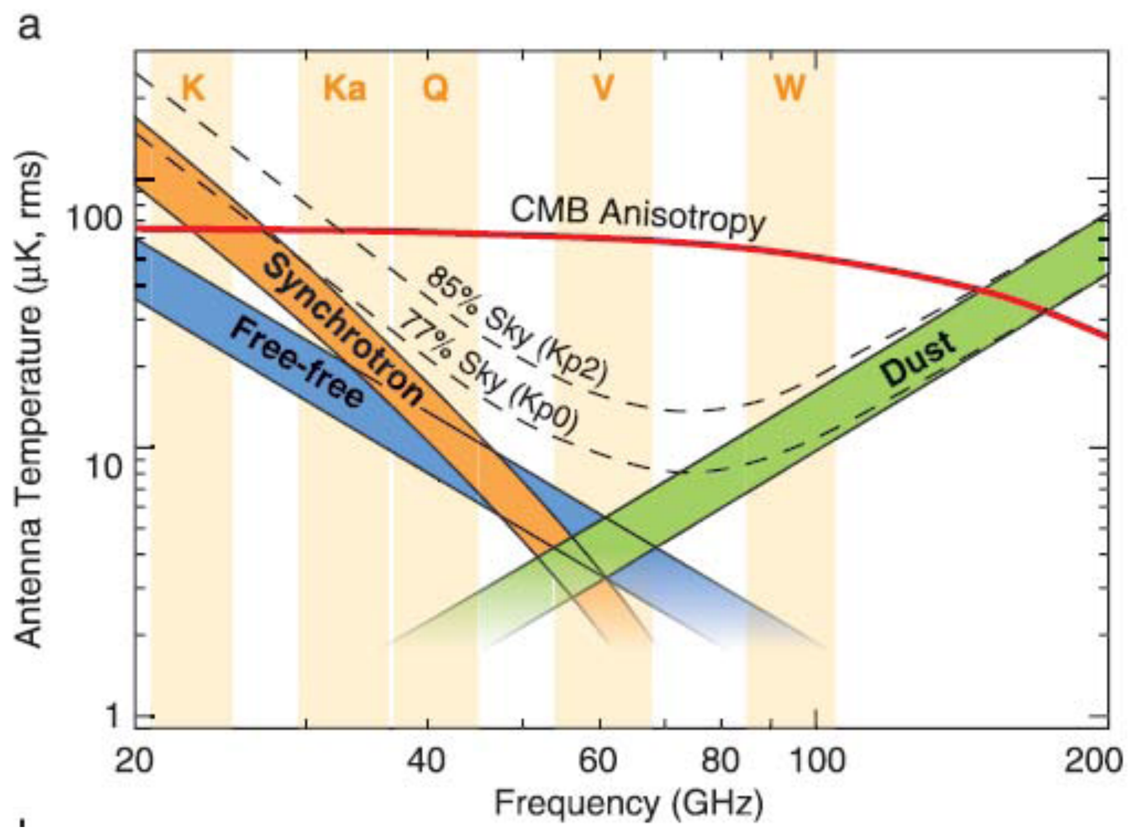


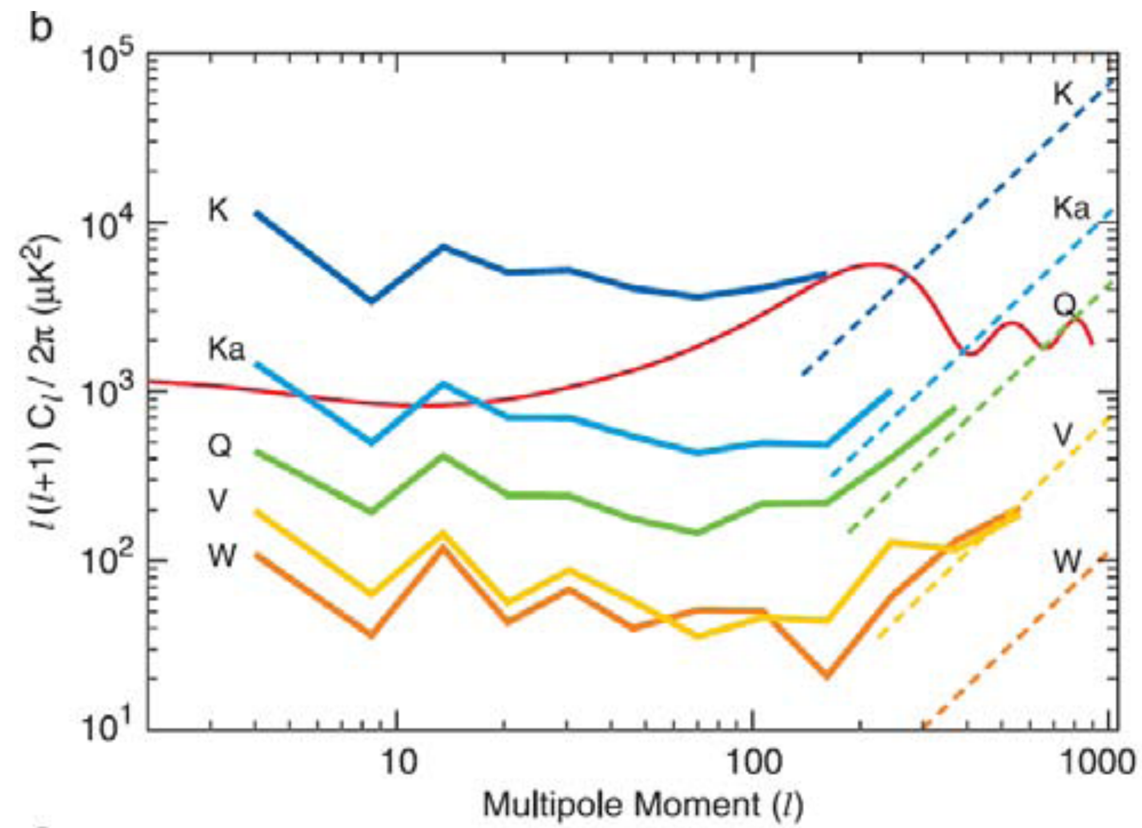
Data time-stream

Removing the Galaxy



Galaxy dominates!





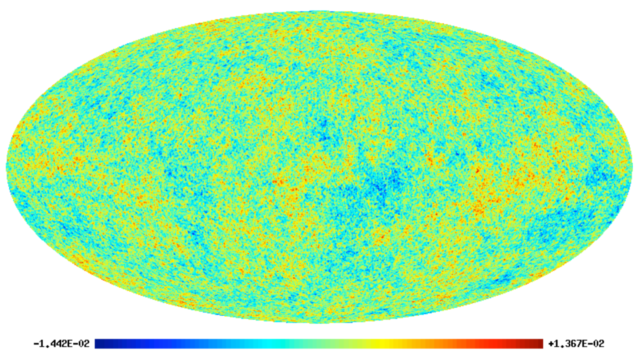
CMB vs. foreground anisotropies (Bennett et al. 2003, WMAP 1st year)

Left: Spectrum of the CMB and foreground emissions (models). WMAP frequencies were chosen such CMB mostly dominates.

Right: Foreground power spectra for each WMAP band. The dashed lines at the right are estimated point source contributions.

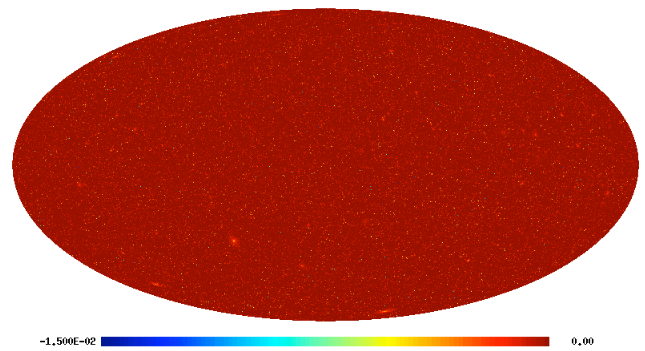
CMB Foregrounds

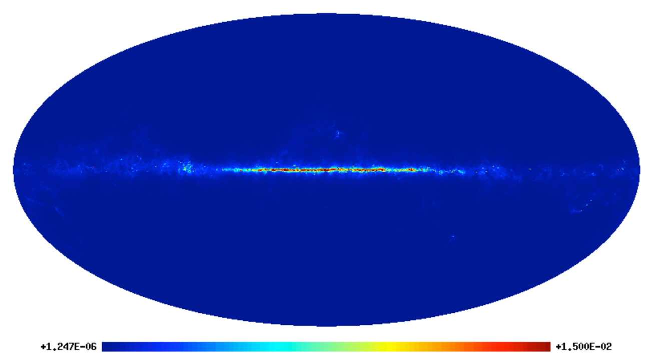
CMB

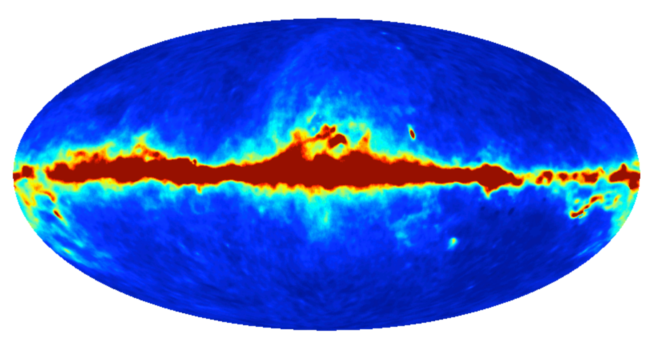


+

Foregrounds

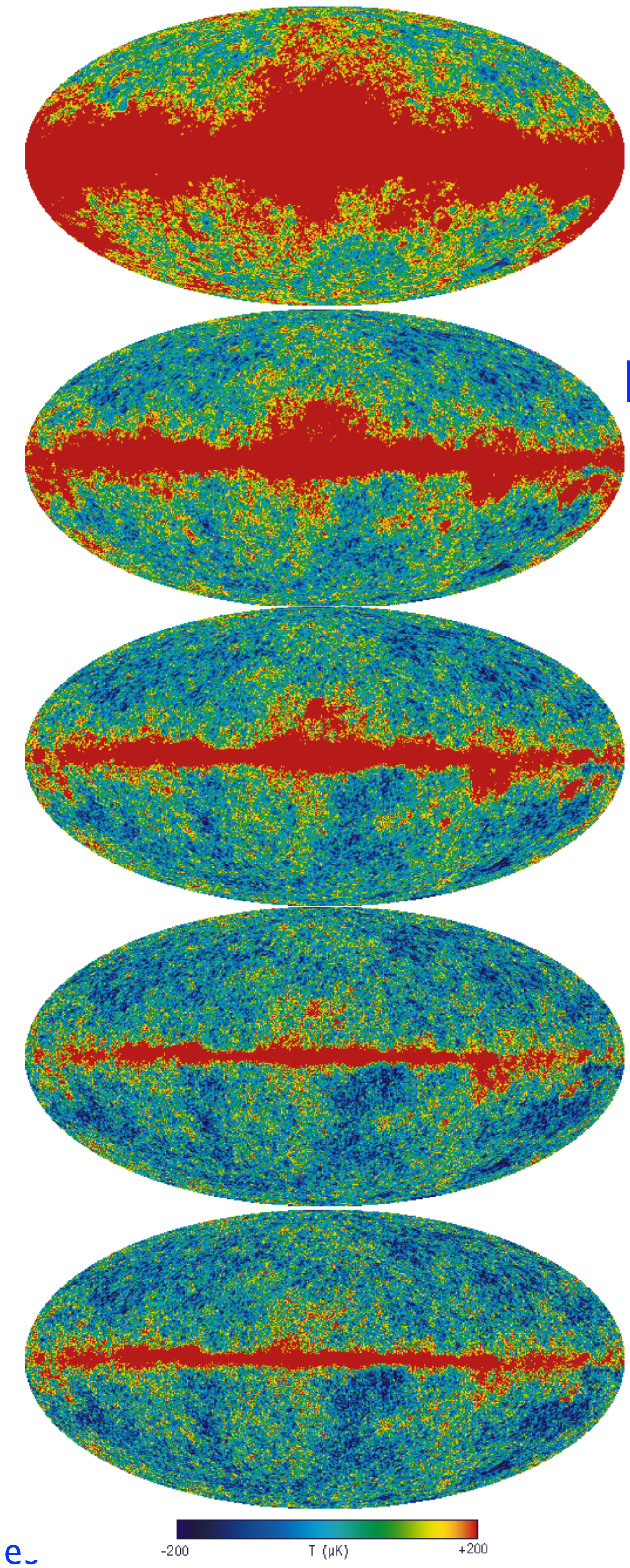






=

Observation



K band
23 GHz

Ka band
33 GHz

Q band
41 GHz

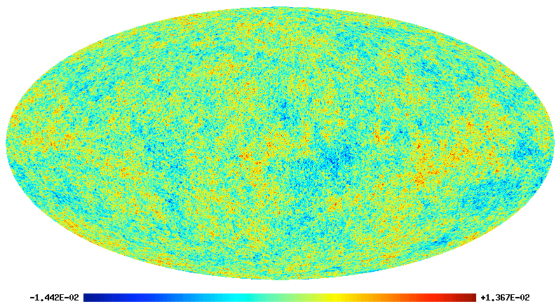
V band
61 GHz

W band
94 GHz

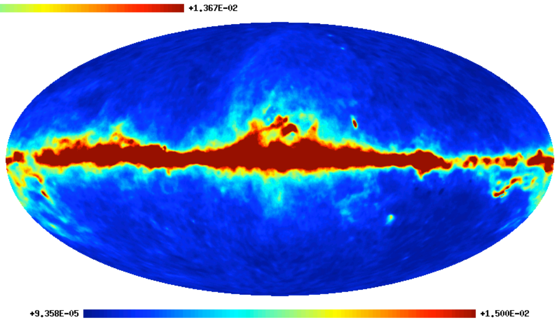
Credit: L. Colombo

Component Separation

Two observing frequencies: ν_1, ν_2

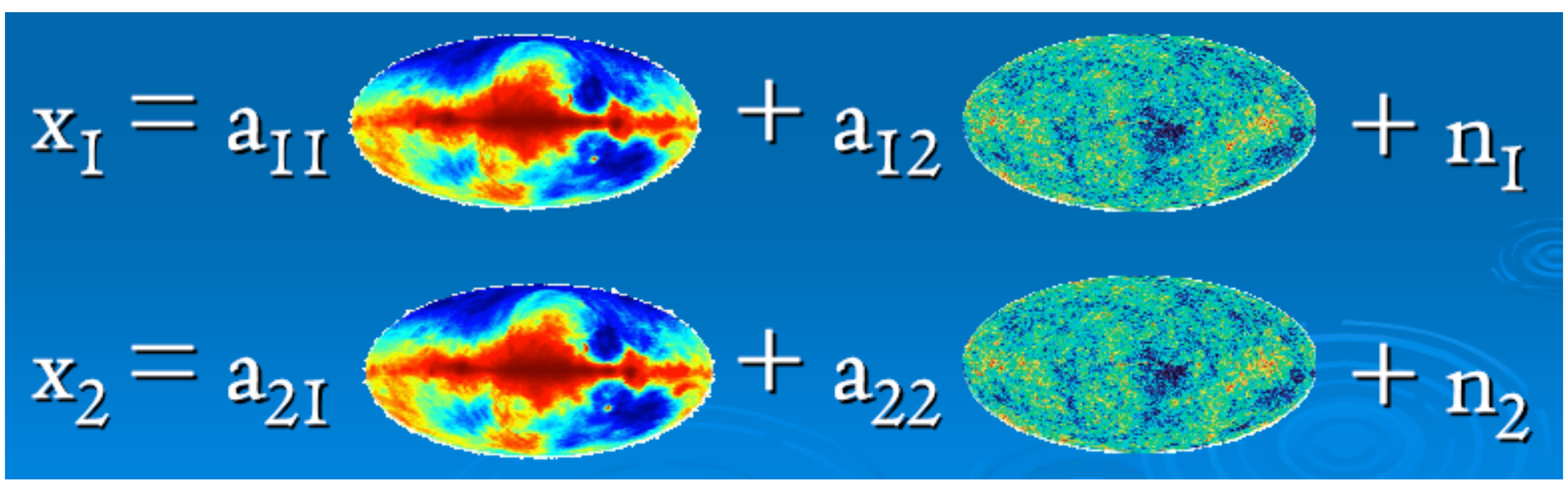


S_1



S_2

$$x_1 = a_{11}\, s_1 + a_{12}\, s_2 + n_1$$
$$x_2 = a_{21}\, s_1 + a_{22}\, s_2 + n_2$$



$\mathbf{x} = \mathbf{A}\mathbf{s} + \mathbf{n}$

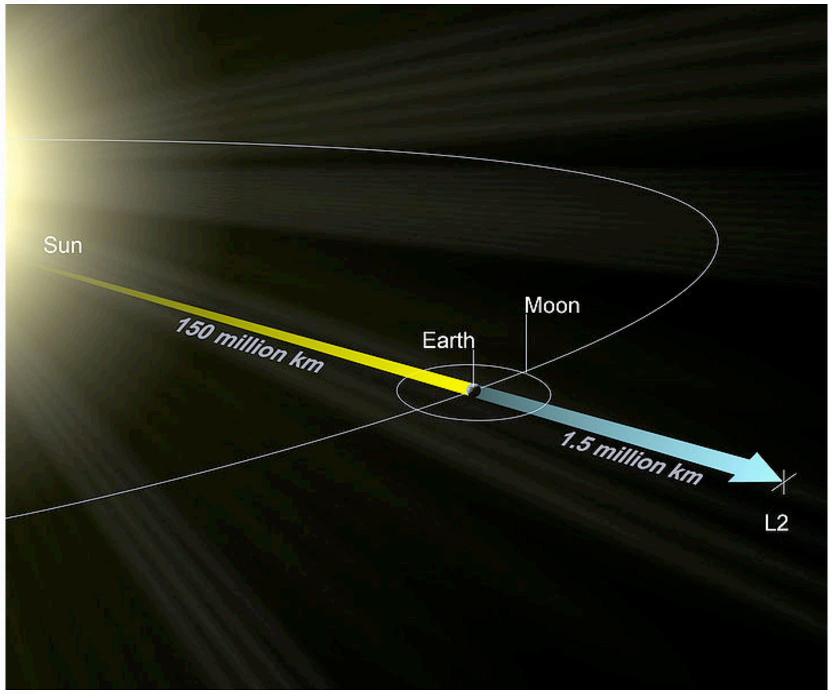
Invert for $\mathbf{s}$

The future is now! PLANCK

Credit: ESA

PLANCK launch May 2009

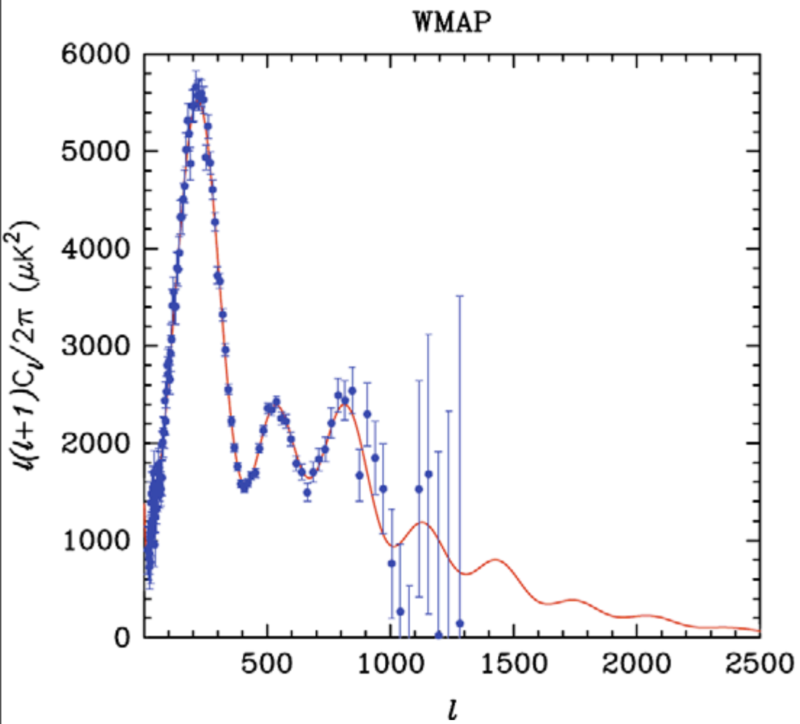
Credit: ESA

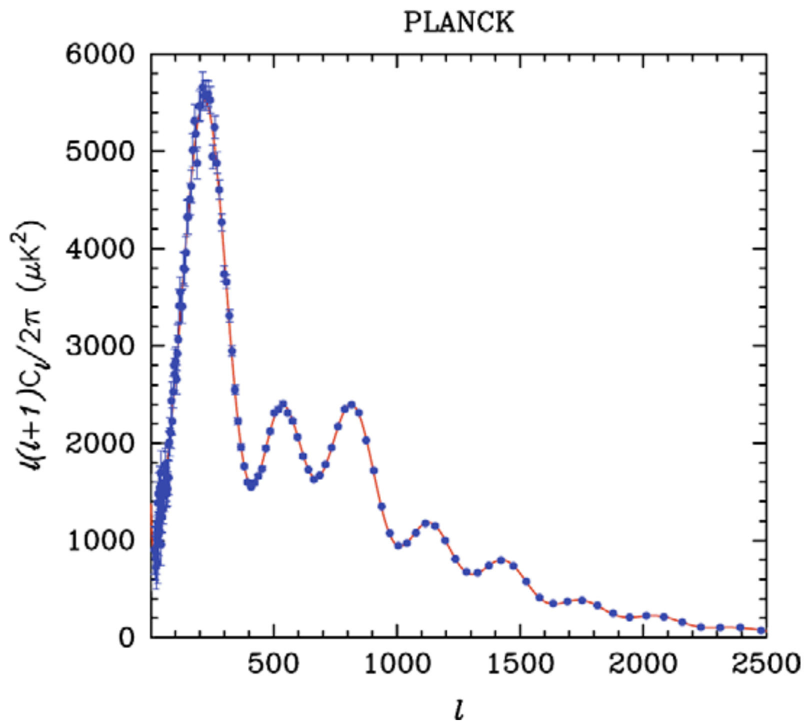


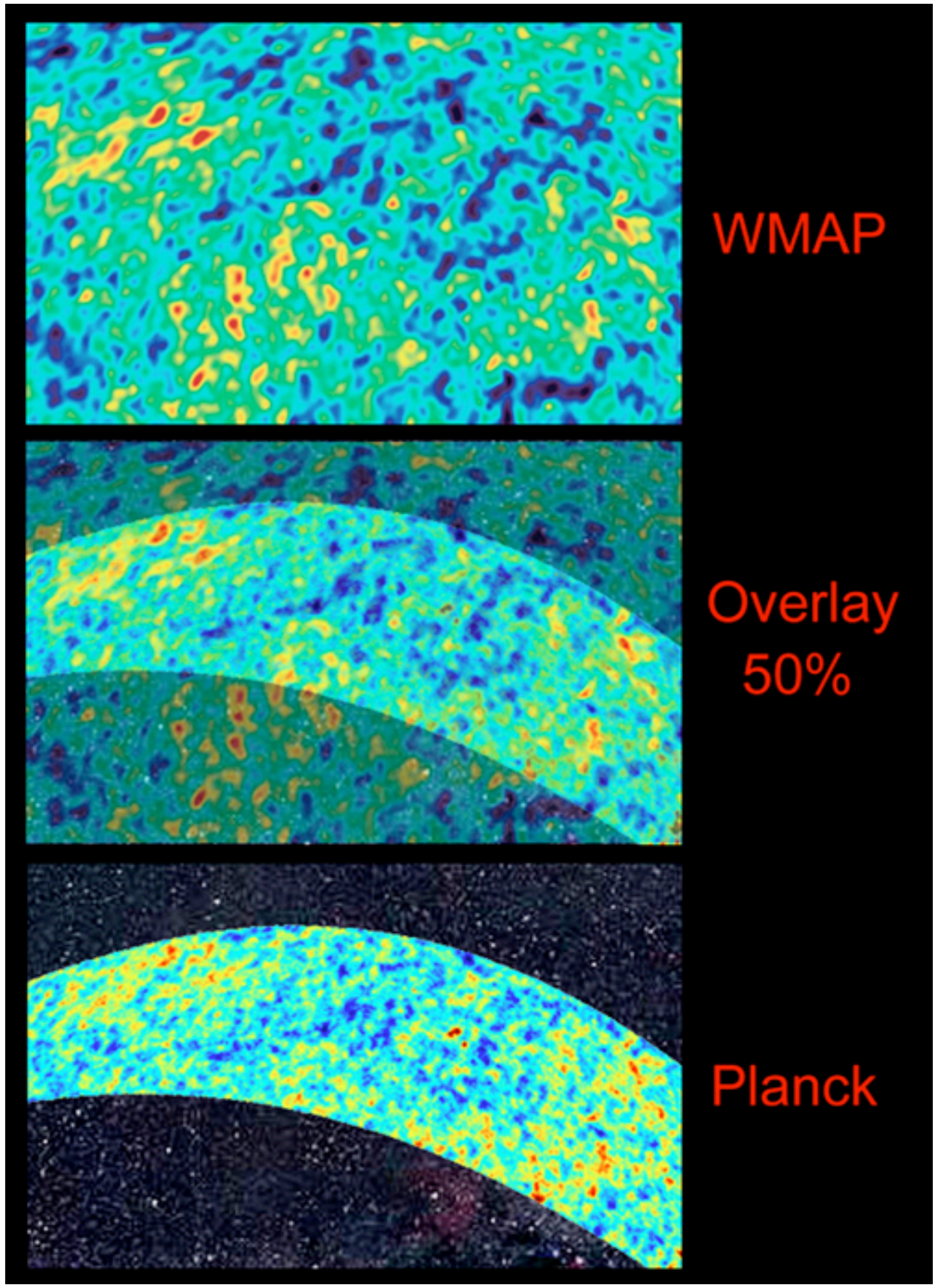
Destination L2: the second Lagrangian point

(getting crowded there!)

Precision cosmology with PLANCK







- Much better resolution (5′ compared to 14′ for WMAP), combined with μK sensitivity (about an order of magnitude lower than WMAP at 100 GHz)

- Much wider frequency coverage (30-857 GHz) - better foreground removal

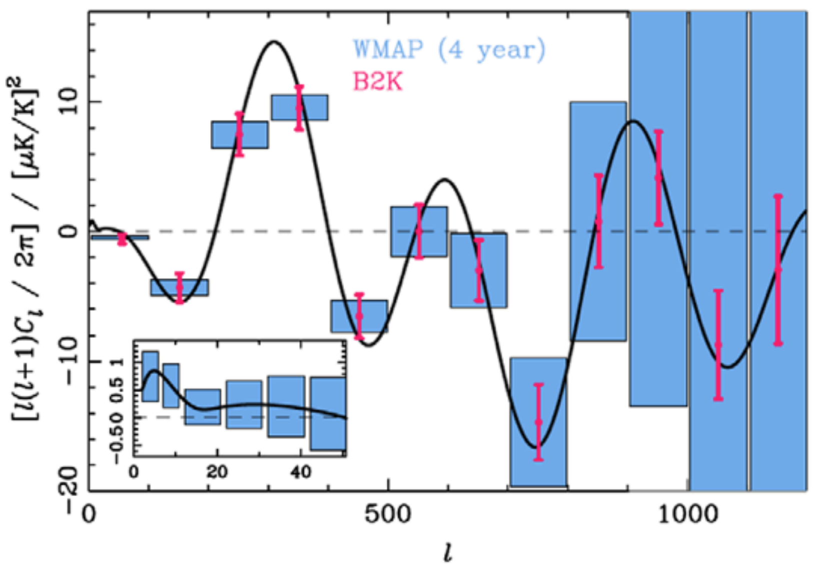
- By-product: all-sky cluster catalogue (lecture 7 on galaxy clusters)

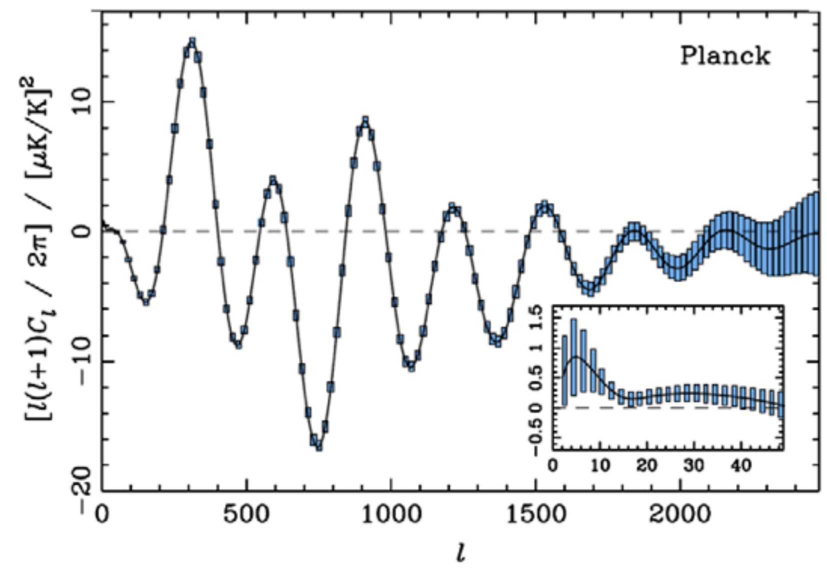
Credit: I. Morison

Measurement of EE and BB modes

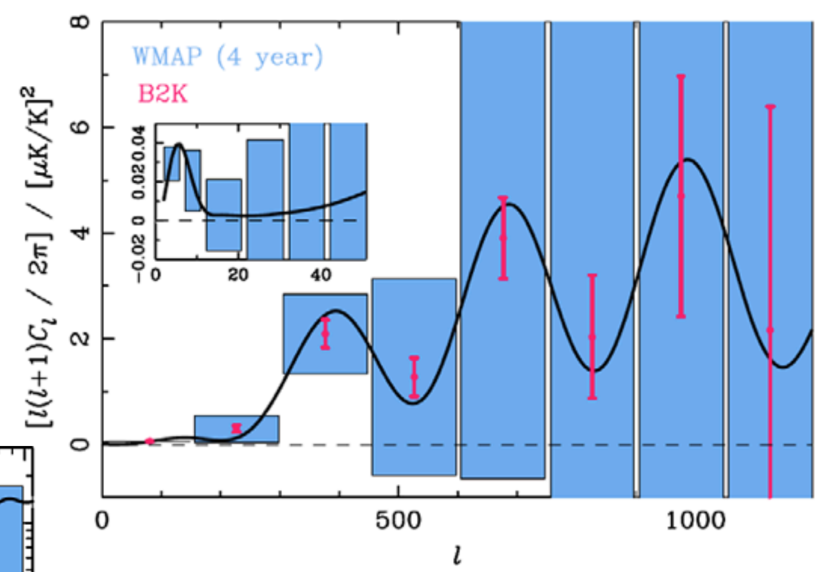
Polarization measure-ment is PLANCK's holy grail (next lecture!)

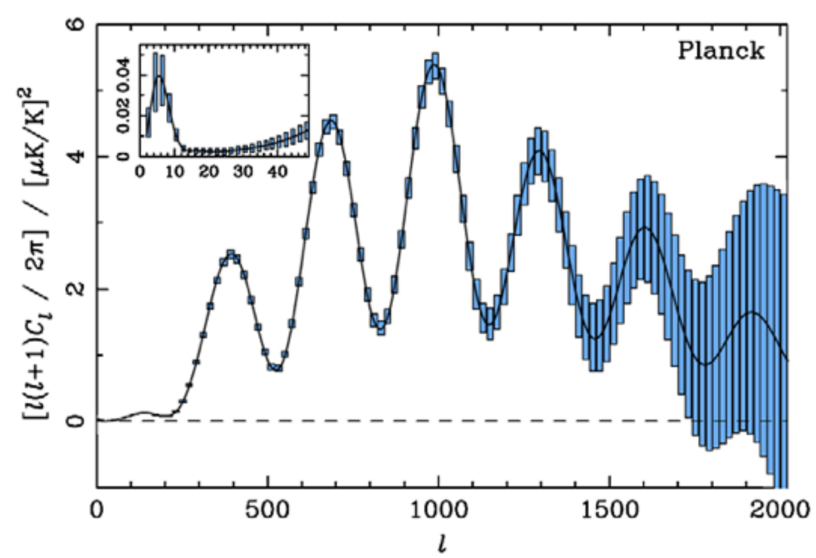
TE power



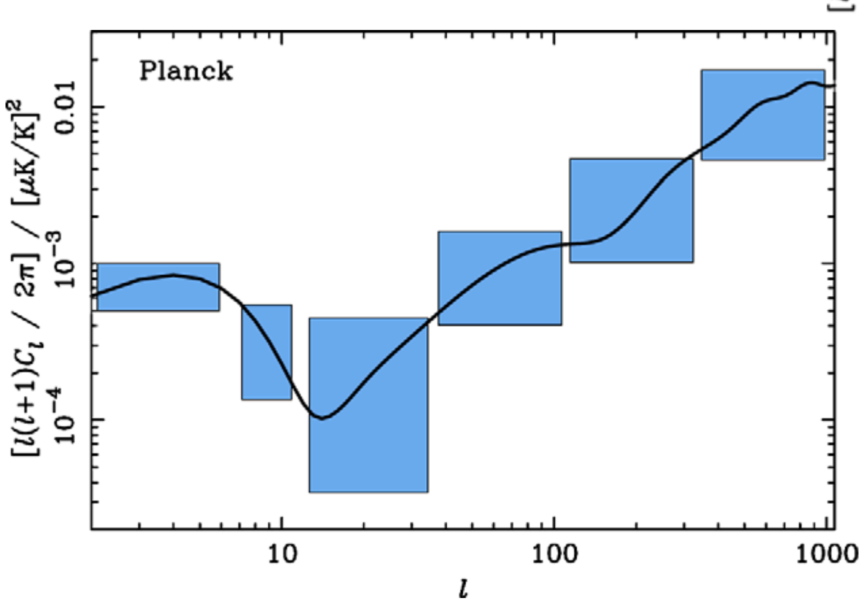


EE power





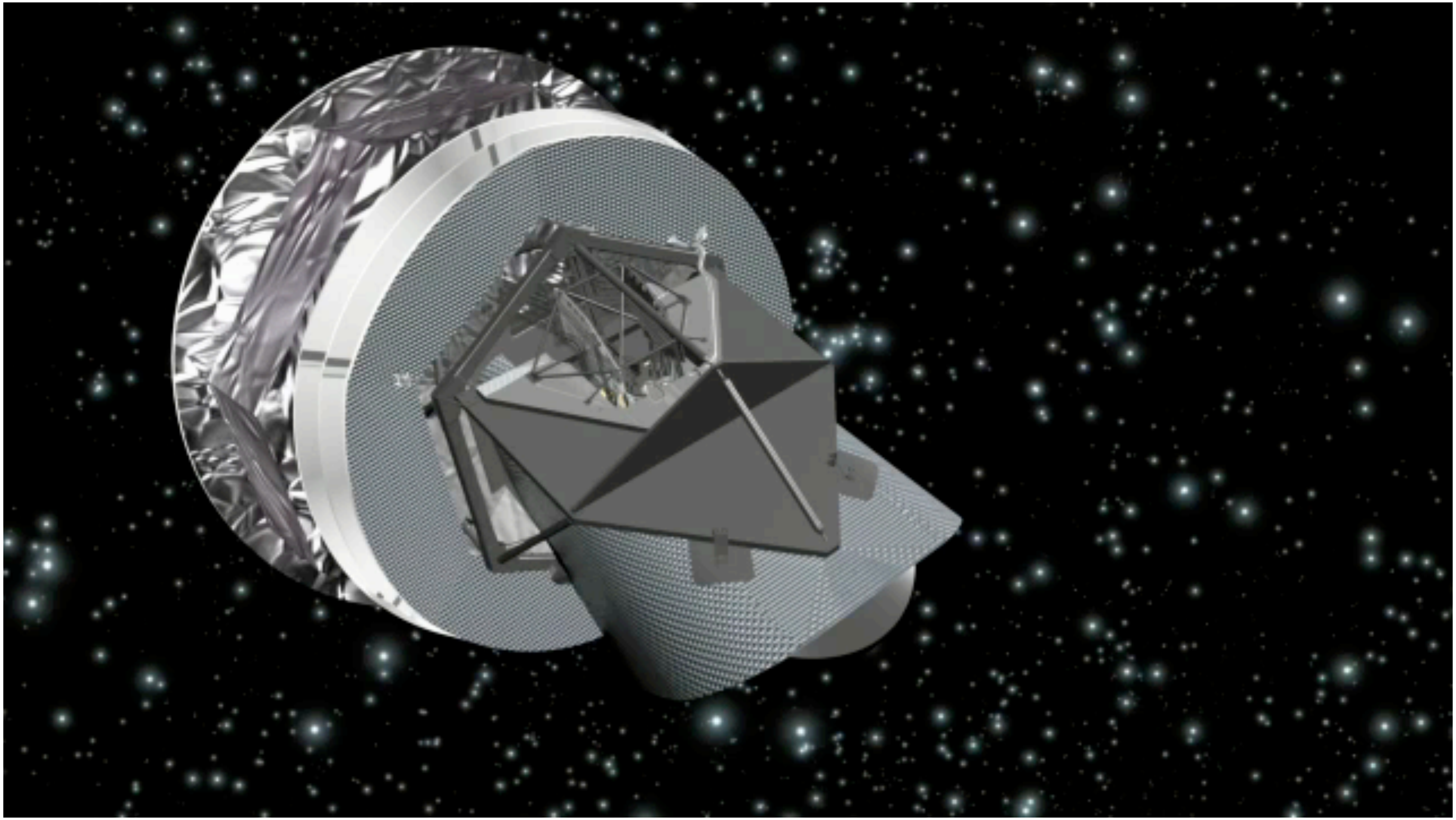
WMAP **PLANCK**



Measurement of the BB power spectrum!

Credit: Planck bluebook

PLANCK scanning the sky!



Credit: ESA

See you next week!