Observational Cosmology

Lecture III

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AIfA, Uni-Bonn

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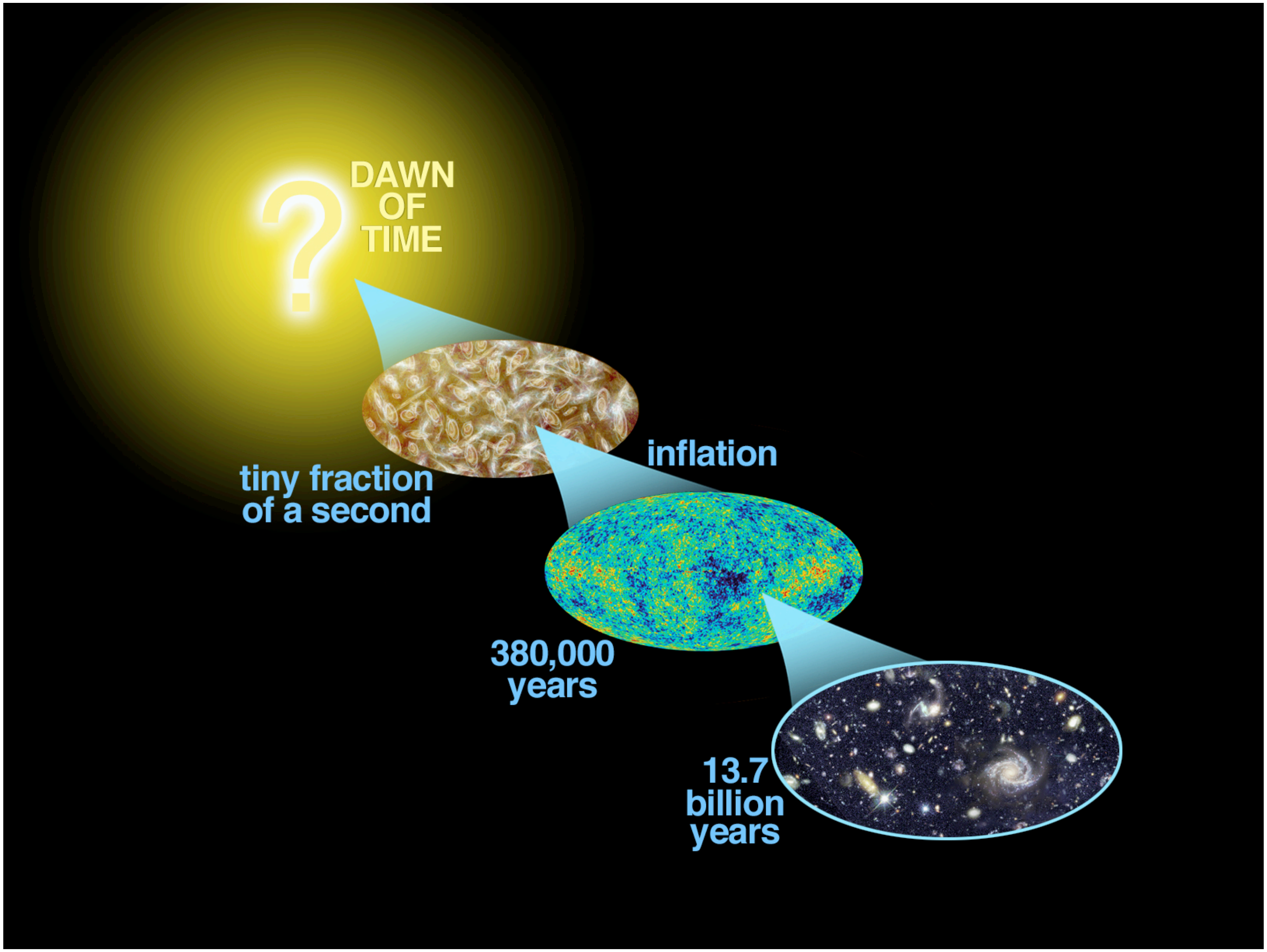
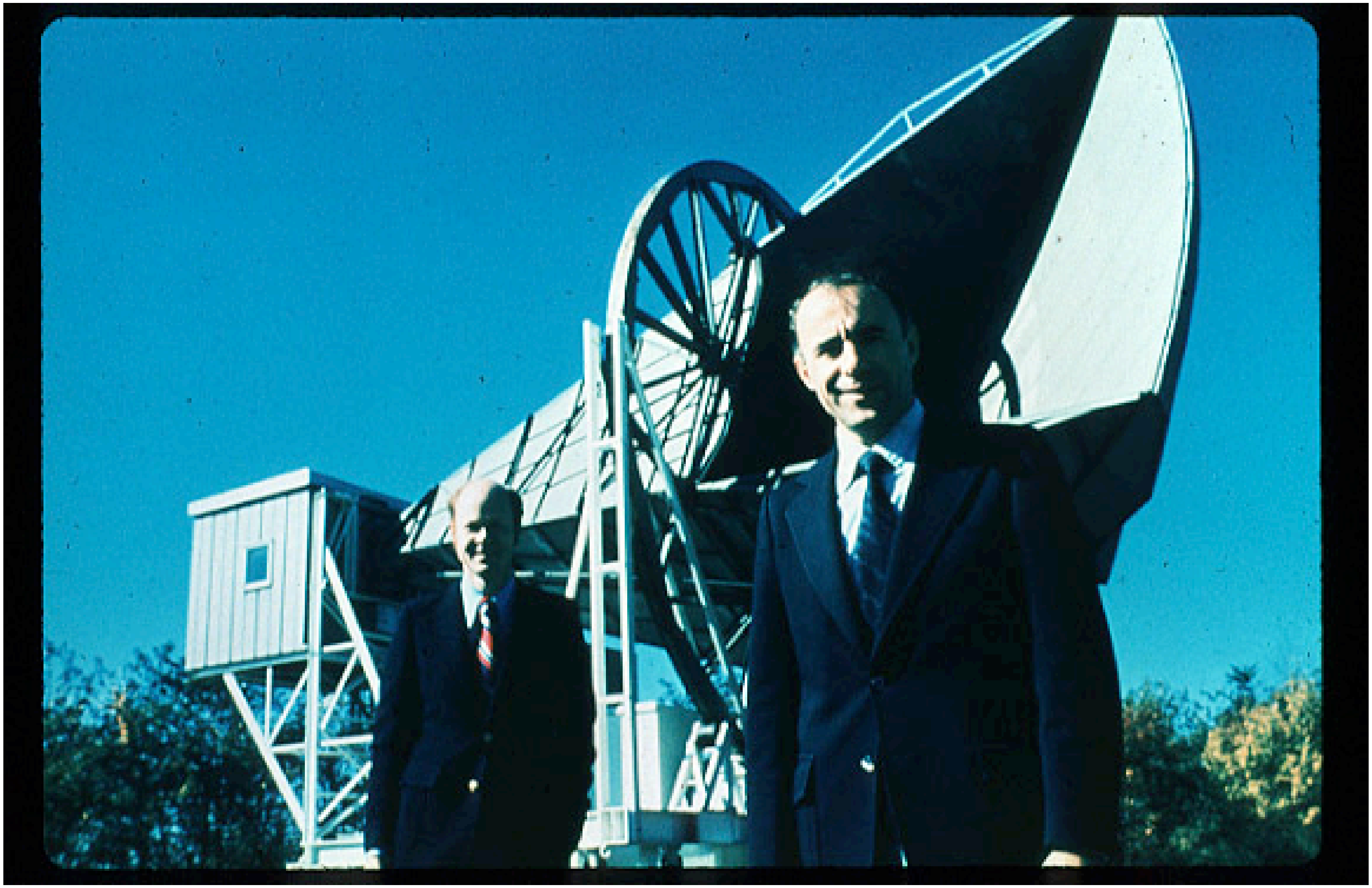
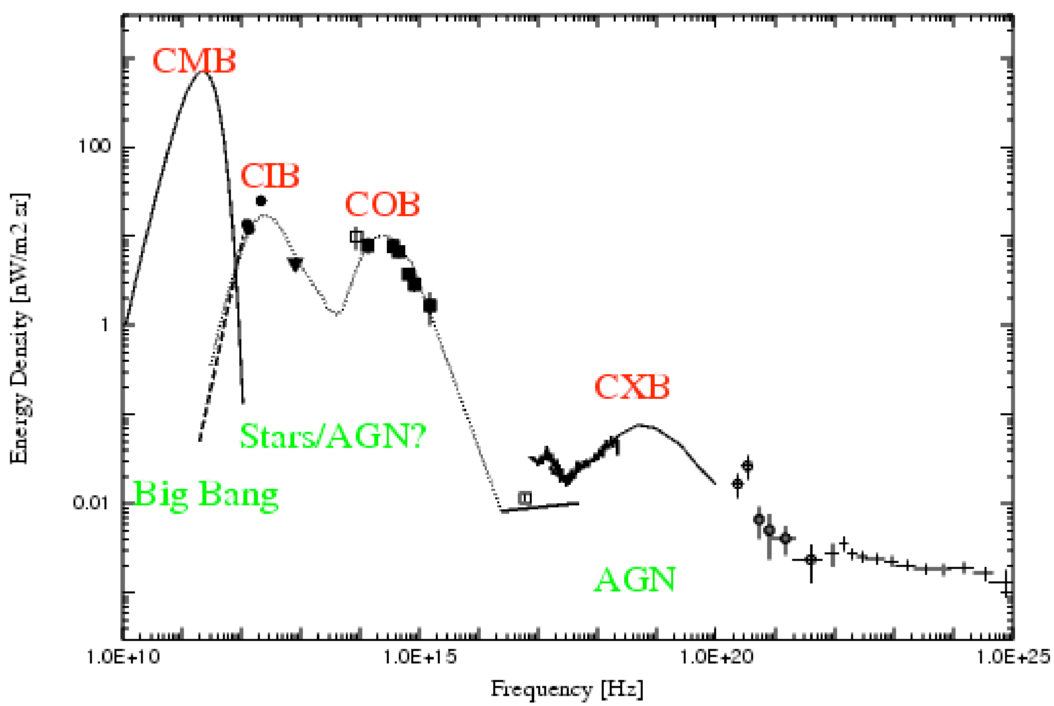
Questions?

Plan of these lectures



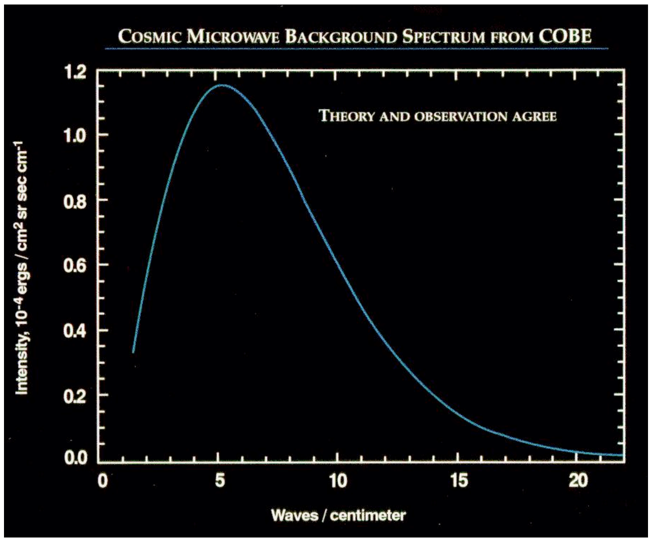


Cosmic backgrounds

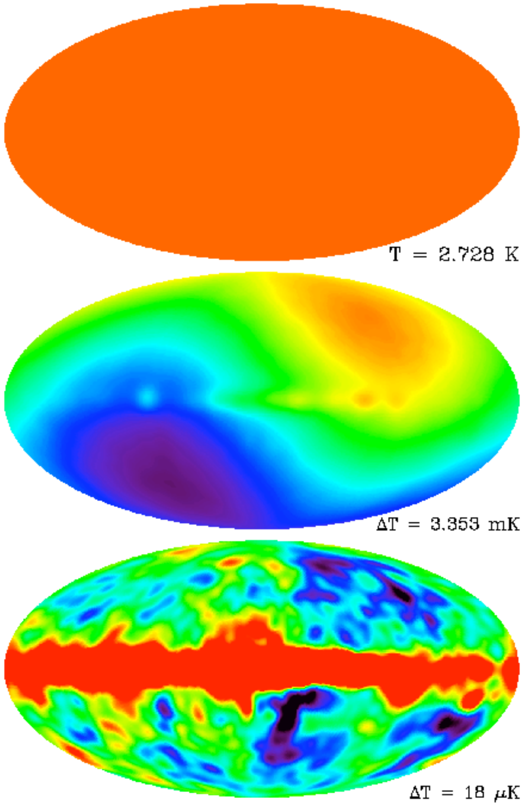


- The cosmic microwave background (CMB) dominates the radiation content of the Universe
- It has been serendipitously discovered by Penzias & Wilson in 1965
- It contains nearly 98% of the radiant energy and 99.9% of the photons!

COBE-DMR RESULTS (1992)

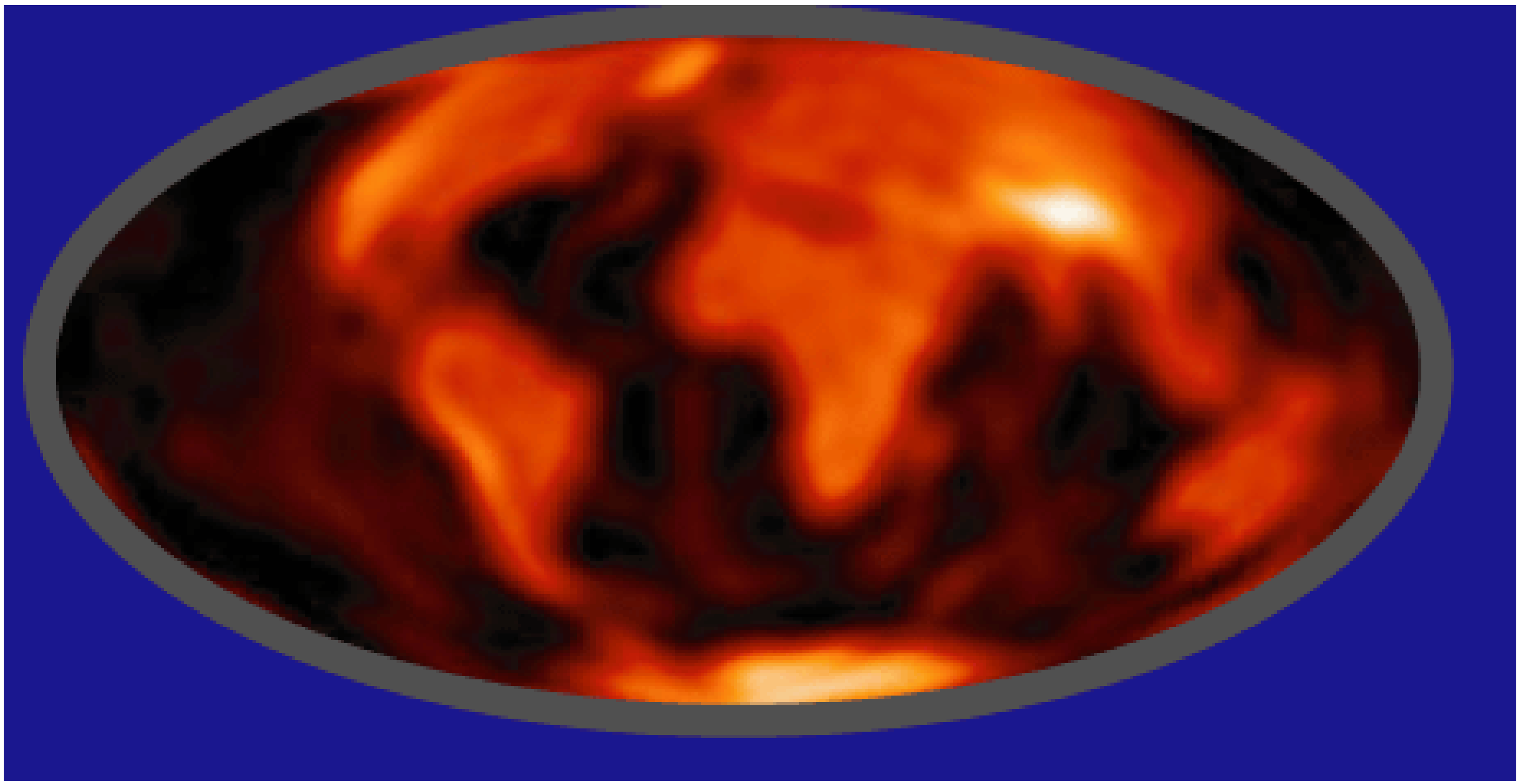


The CMB has a blackbody spectrum with T≈2.73 K



The CMB temperature is highly isotropic with intrinsic fluctuations of the order of 1 part every 10^5

Aitoff projection of the Earth



Black-body radiation

Energy per unit volume per unit frequency interval:

$$u(\nu,T) = \frac{8\pi h\nu^3}{c^3}\ \frac{1}{e^{h\nu/kT}-1} = \frac{4\pi}{c} I(\nu,T)$$

Internal energy in a volume V:

$$U = \left(\frac{8\pi^5 k^4}{15 c^3 h^3}\right) V T^4$$

Numer of photons in a volume V:

$$N = \left(\frac{16\pi k^3 \zeta(3)}{c^3 h^3}\right) V T^3$$

It corresponds to a Bose-Einstein distribution with vanishing chemical potential

Black-body radiation

At high frequencies, hν >> kT:
(Wien regime)

$$I(\nu) = \frac{2h\nu^3}{c^2} e^{-\frac{h\nu}{kT}}$$

At low frequencies, hν << kT:
(Rayleigh-Jeans regime)

$$I(\nu) = \frac{2\nu^2 kT}{c^2}.$$

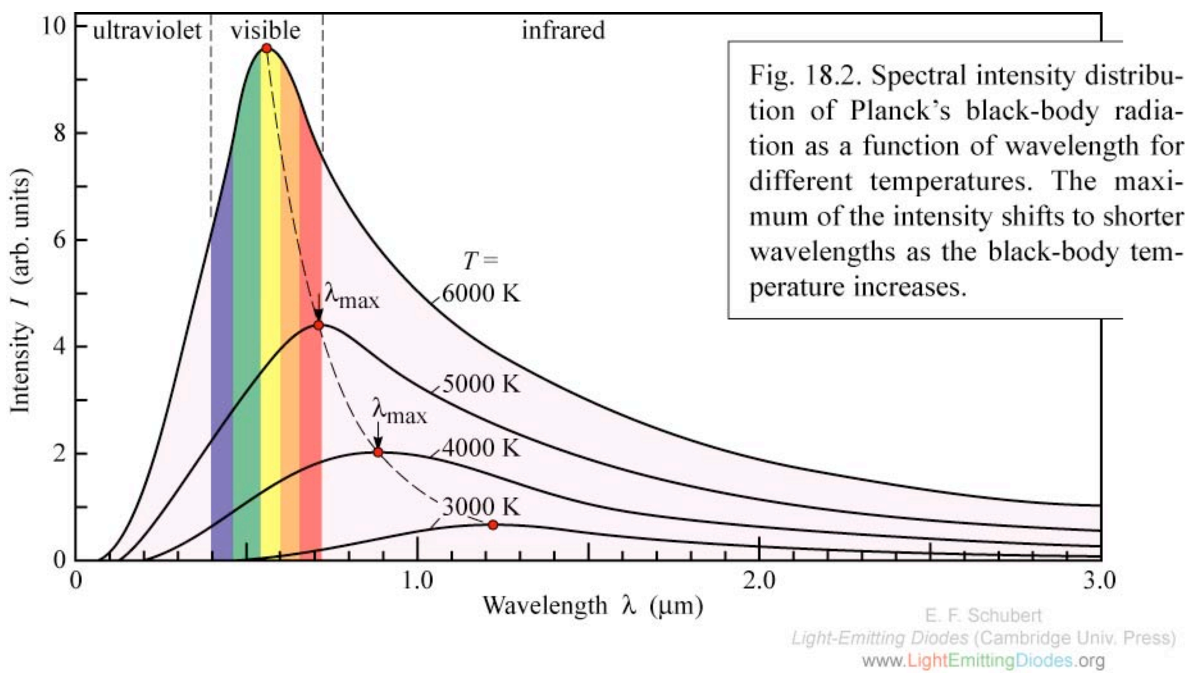
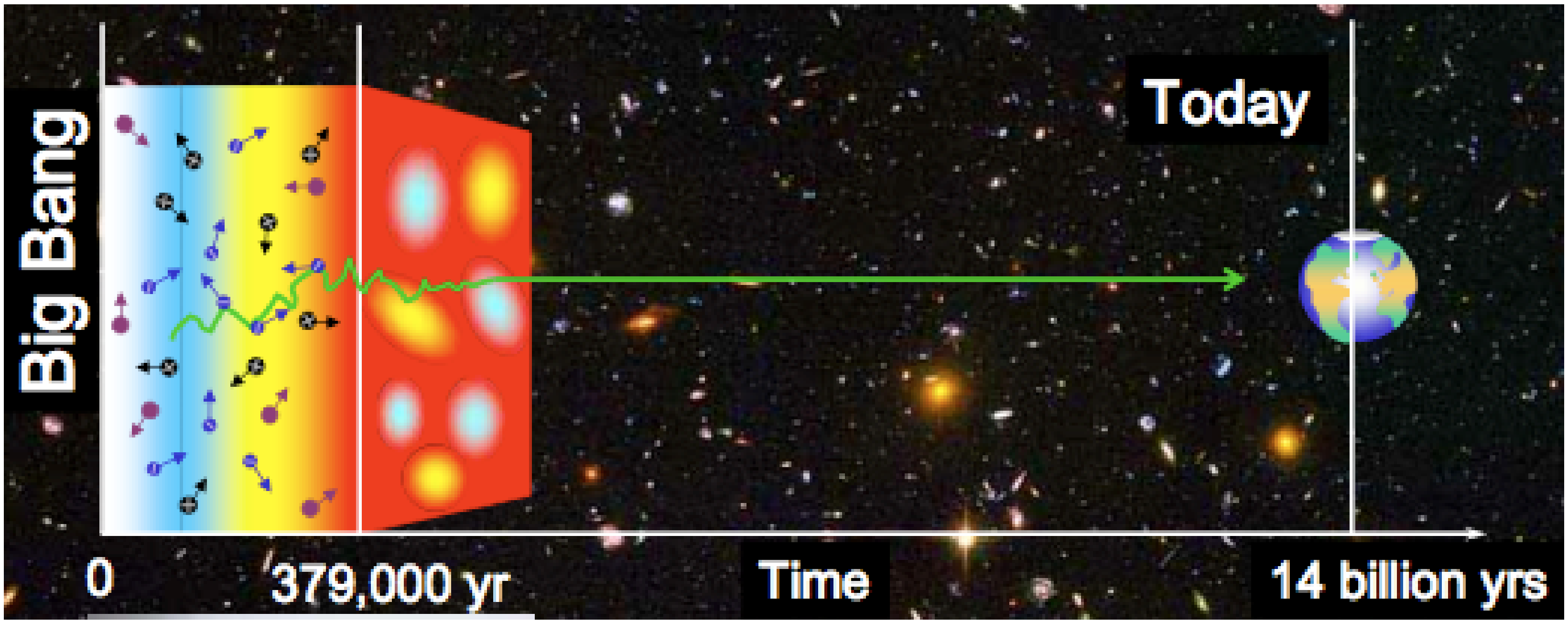


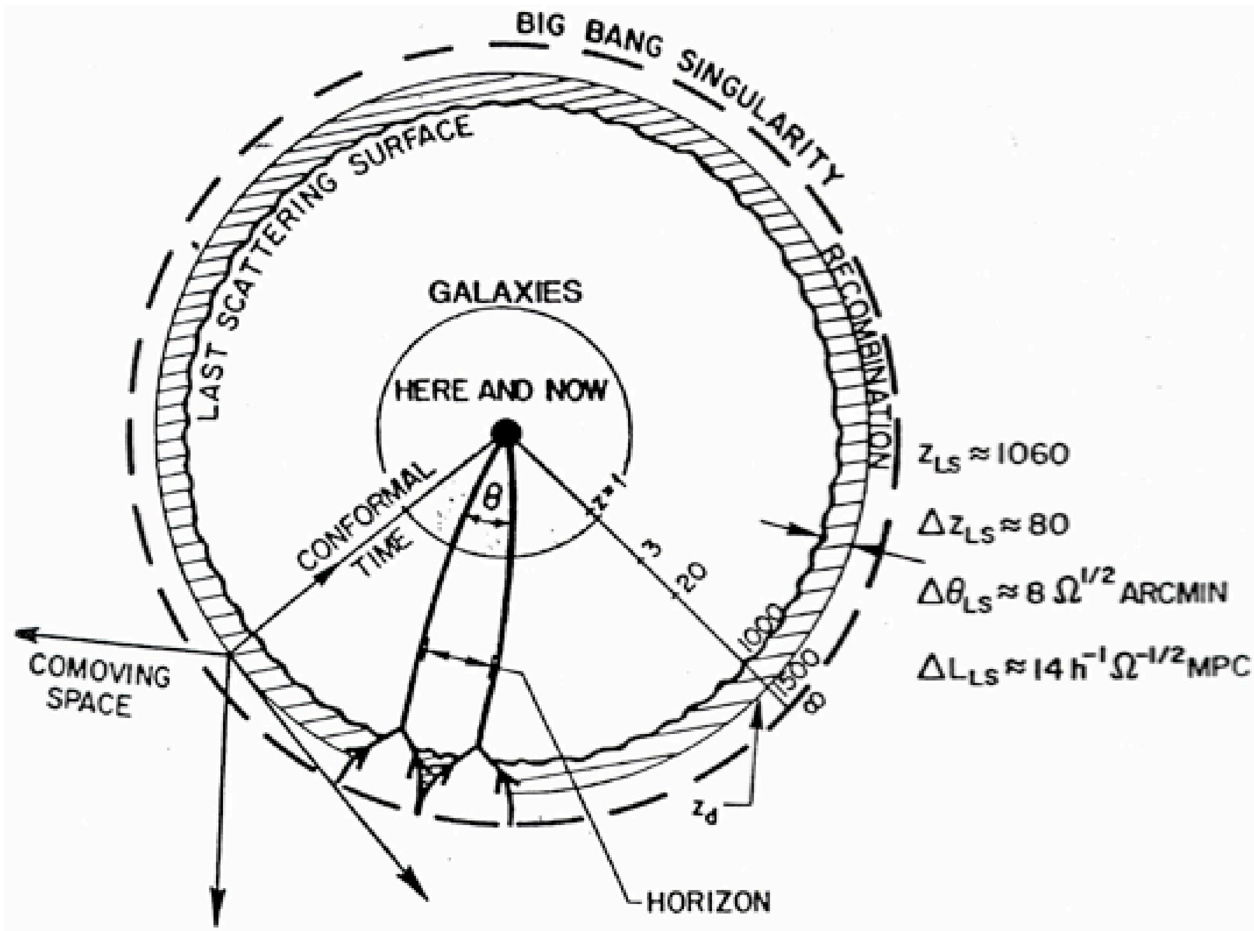
Fig. 18.2. Spectral intensity distribution of Planck's black-body radiation as a function of wavelength for different temperatures. The maximum of the intensity shifts to shorter wavelengths as the black-body temperature increases.

Origin of the CMB

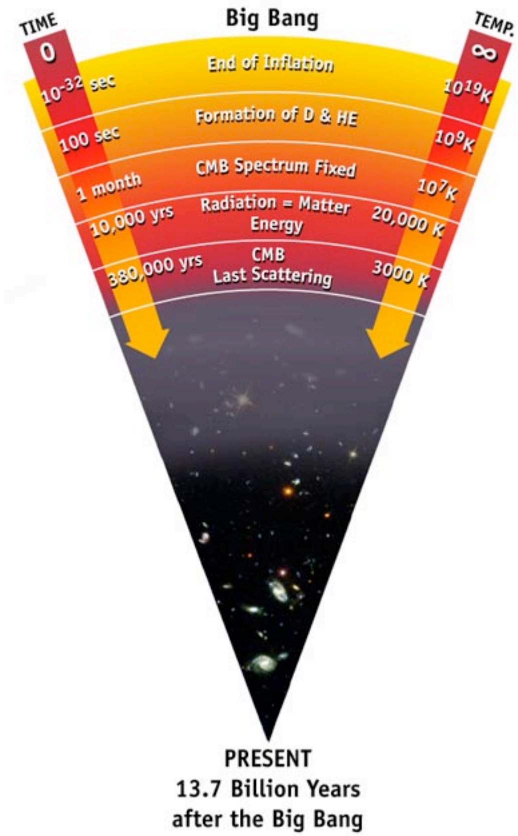
- CMB photons originated in the early Universe via matter/anti-matter annihilations and, thus, were formed as gamma-rays
- Frequent interactions with matter kept them in thermal equilibrium (non-photon conserving interactions produced a black-body energy distribution)
- CMB photons scattered off charged particles during the radiation era
- After recombination and decoupling, the CMB photons started to travel freely trough the Universe. Due to the cosmic expansion, the original gamma-ray energies of CMB photons cooled down to microwave wavelengths.
- In this sense, the CMB we see today is an echo of the Big Bang


Big Bang
Today
0
379,000 yr
Time
14 billion yrs

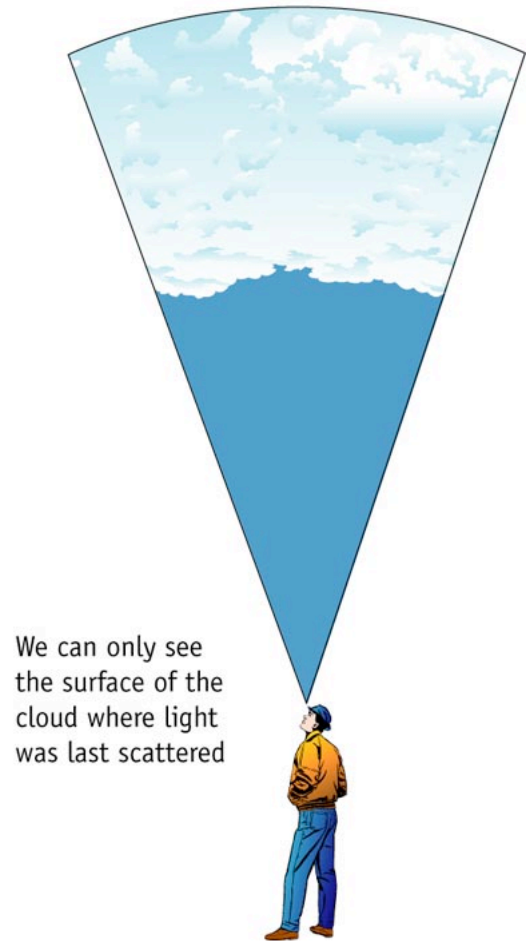
The last scattering surface



The last scattering surface



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.



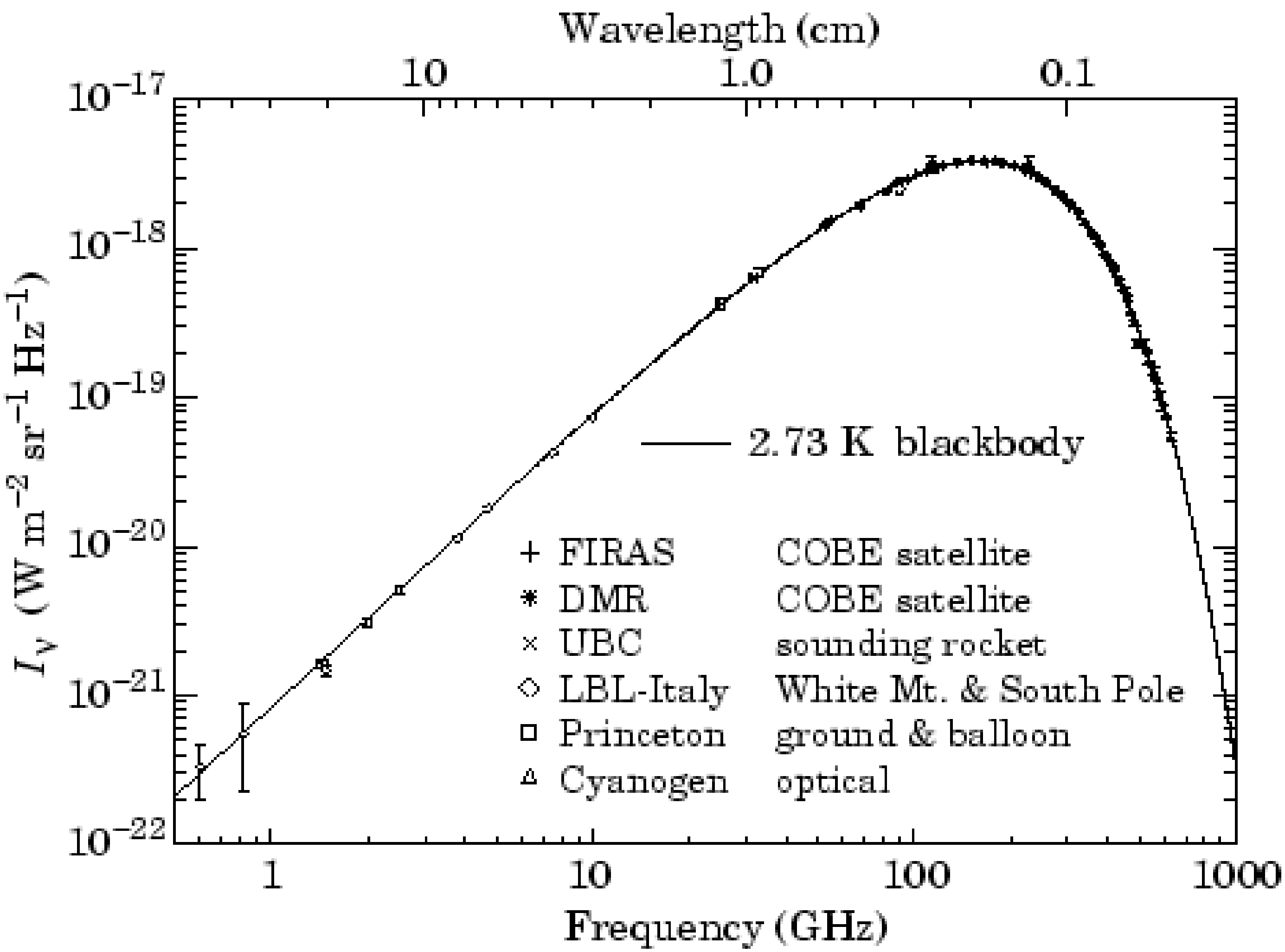
Thermalization of the CMB

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

  $e + \gamma \longrightarrow e + \gamma + \gamma$

Compton scattering conserves photon number (and, in the Thomson limit, does not transfer energy). Therefore, it can only redistribute photon energies and establish statistical equilibrium. The other two processes are essential to establish thermal equilibrium (e.g. a black-body spectrum). It can be shown that any energy injection in the plasma at redshifts $z>10^7$ (corresponding to $t\approx1$ year) cannot leave any spectral distortion in the CMB.

CMB spectral energy distribution



CMB spectral energy distribution

- Temperature: 2.728 ± 0.002 K
- Photon number density: 413 cm^{-3}
- Energy density: 4.68×10^{-34} g cm^{-3}

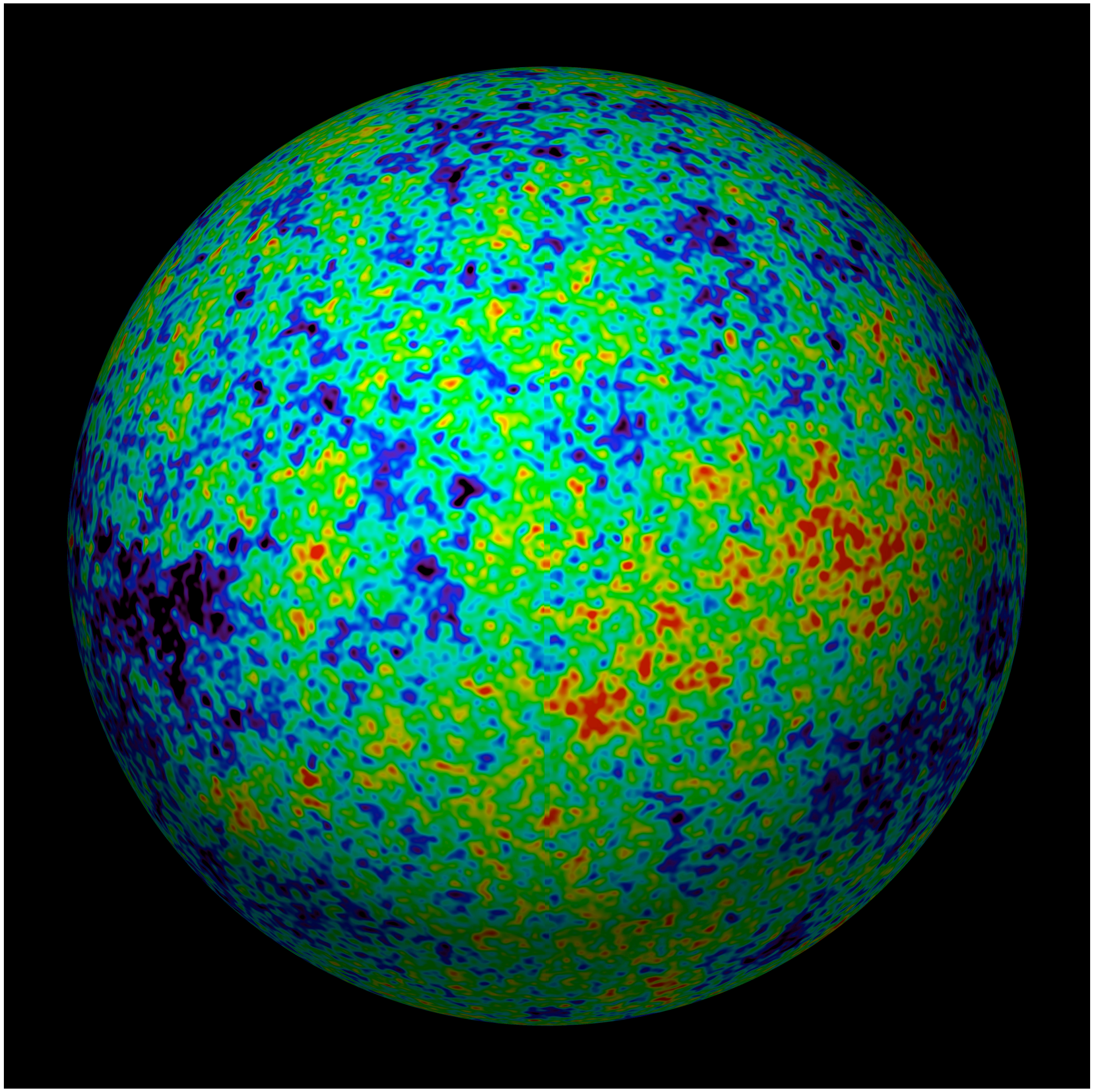
- Upper limits for the departure from a black body spectrum:

  y distortion ($z_{inj} < 10^5$): $|y| < 1.2 \times 10^{-5}$ (95% CL)

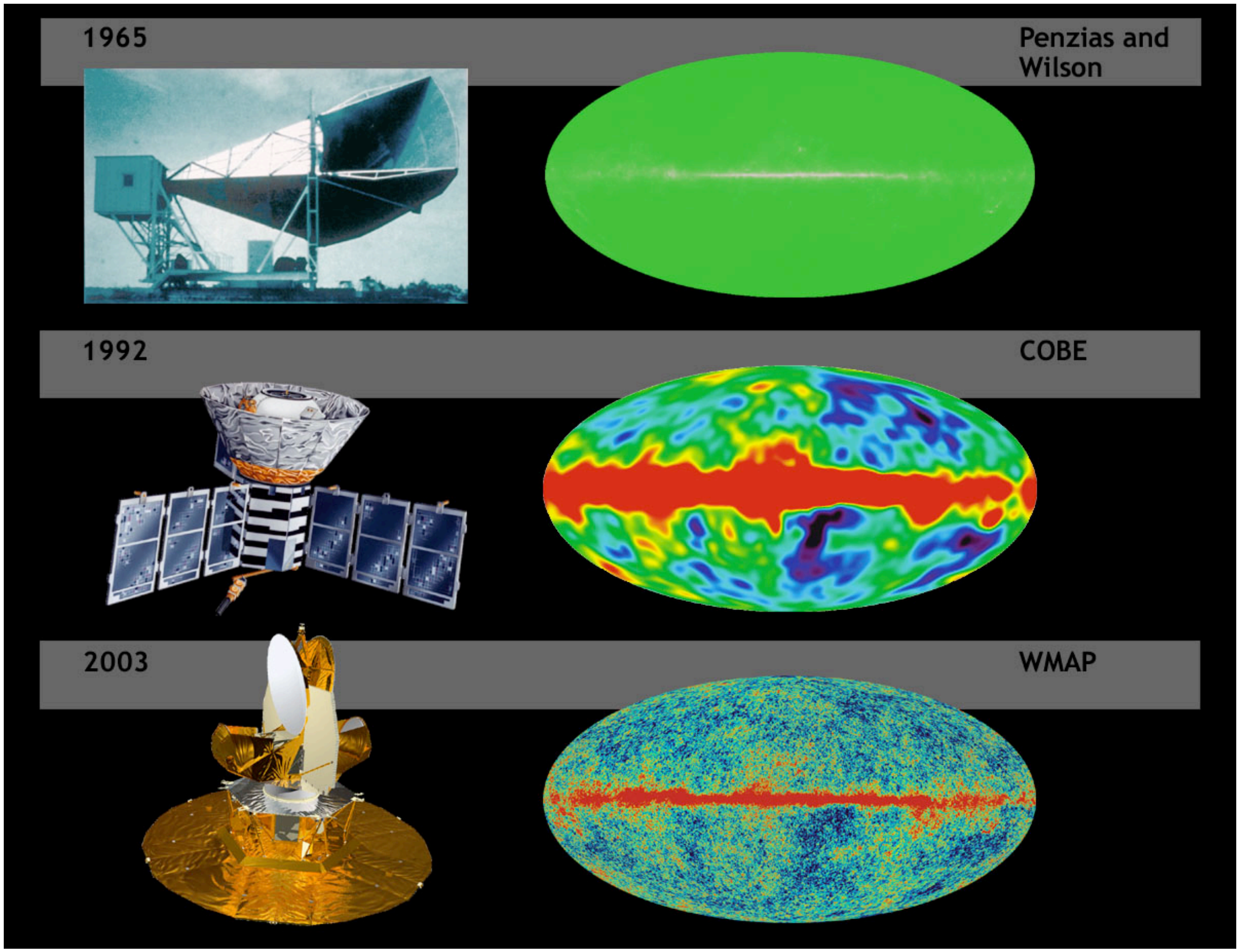
  μ distortion ($z_{inj} \approx 10^{5-7}$): $|\mu| < 9 \times 10^{-5}$ (95% CL)

  FF distortion ($z_{inj} \ll 10^3$): $|Y_{ff}| < 1.9 \times 10^{-5}$ (95% CL)

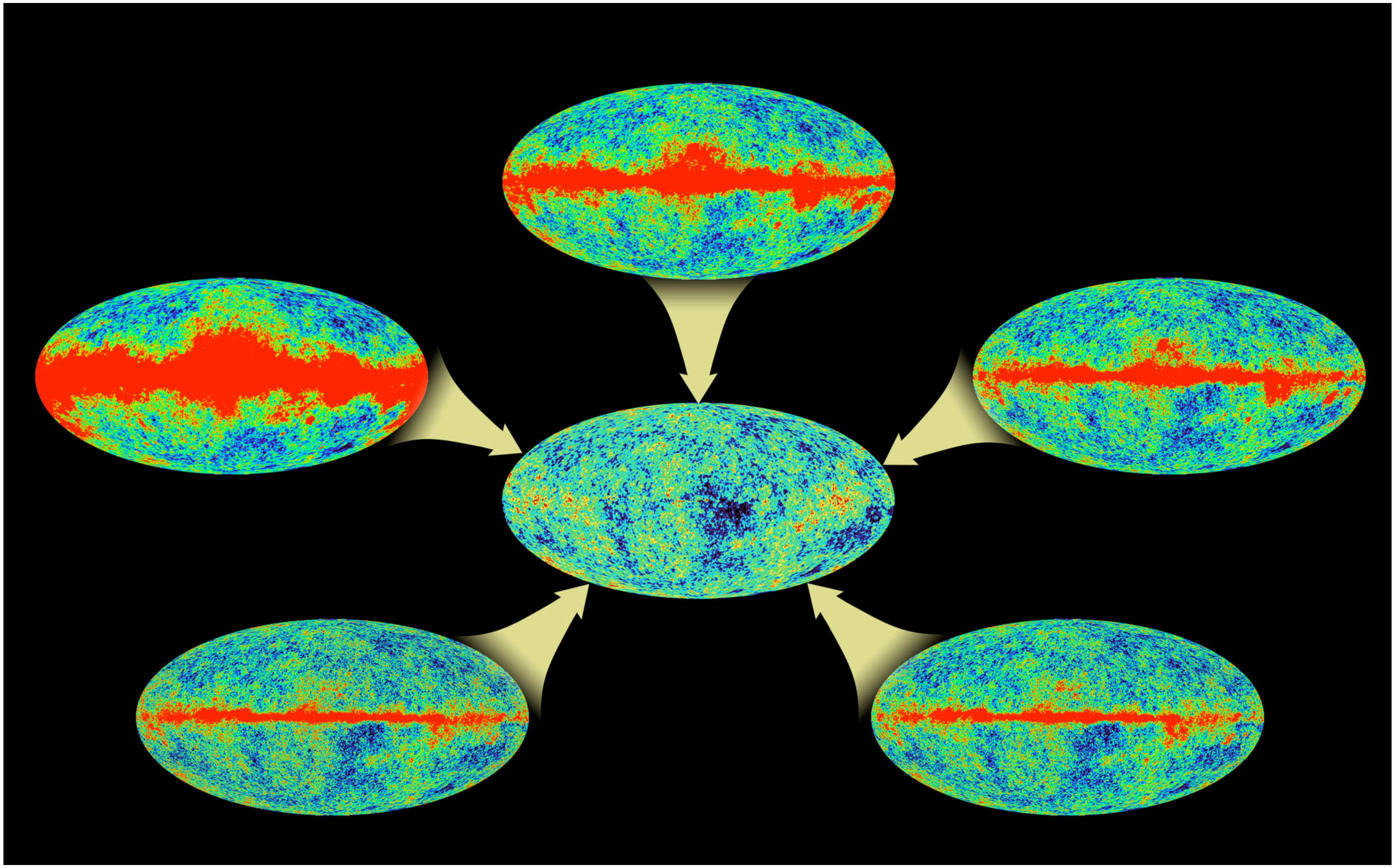
Temperature anisotropies



The detection of CMB anisotropies

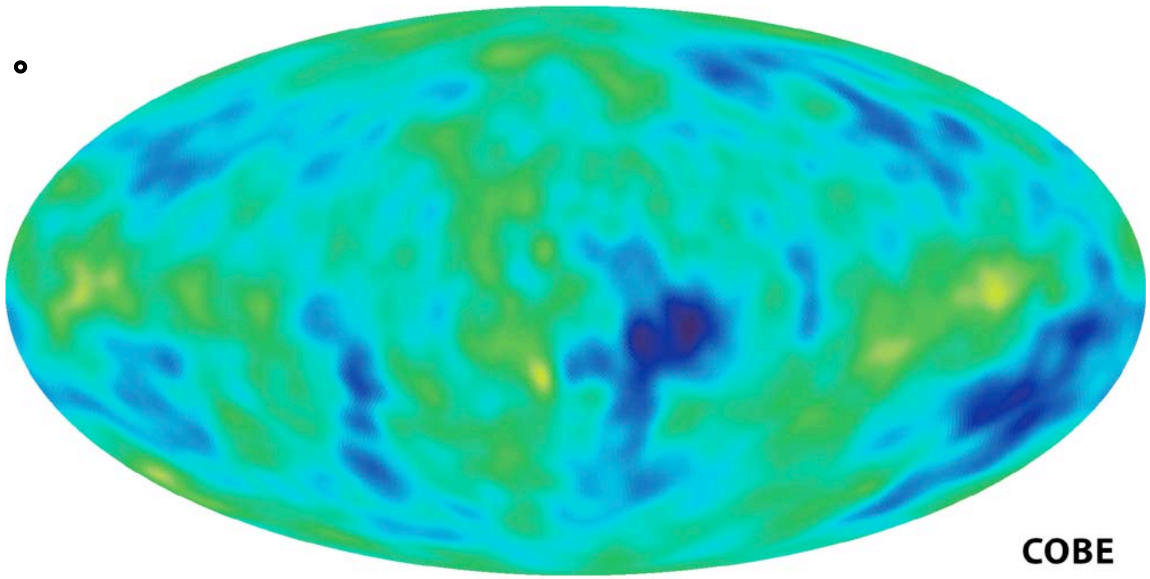


Removing the Galaxy contribution

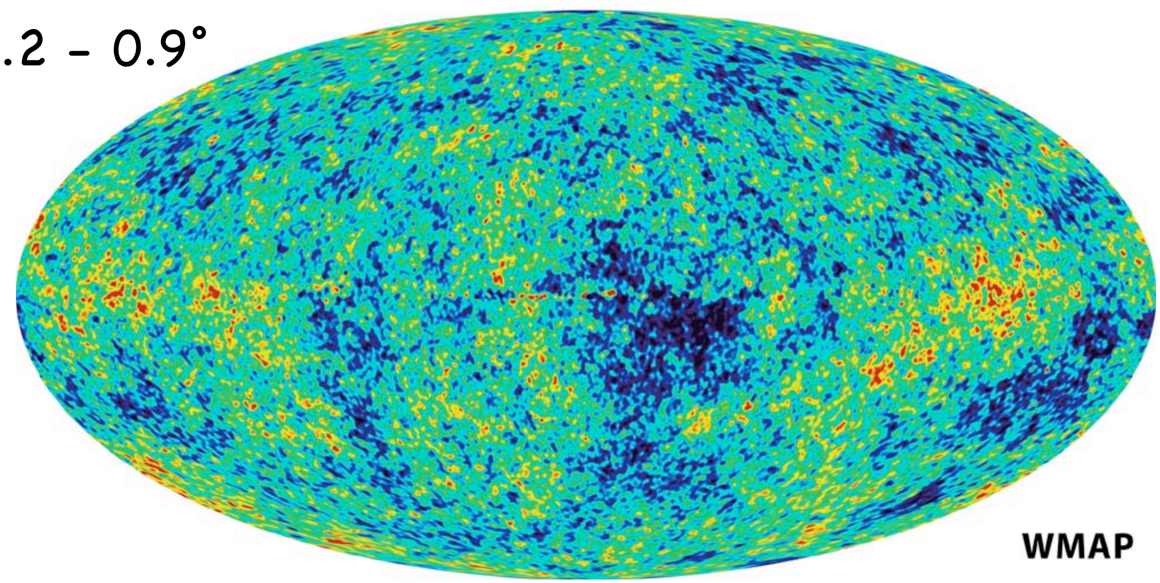


COBE vs WMAP

Resolution ≈ 7 °

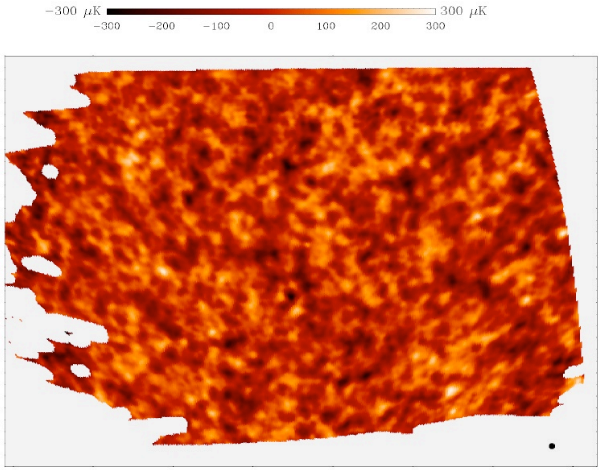


Resolution ≈ 0.2 - 0.9°

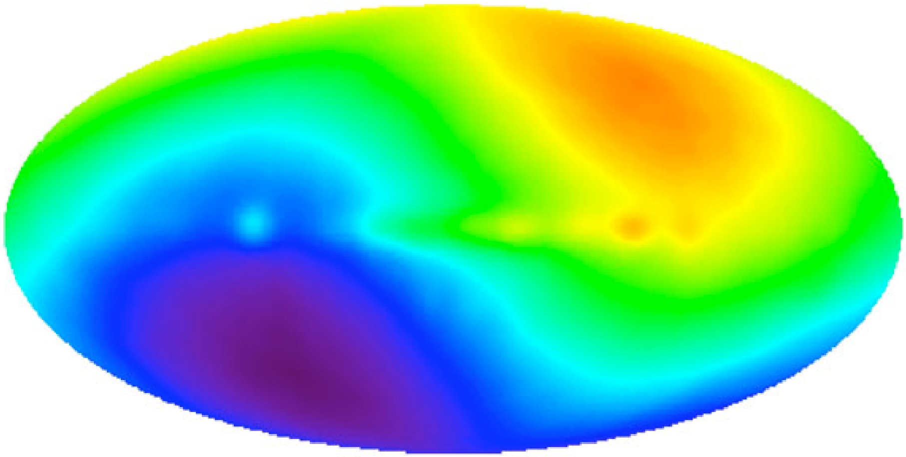


Other experiments

- A number of ground based and balloon experiments have been performed to probe small patches of the sky at very high angular resolution and at different frequencies
- For instance Boomerang and MAXIMA probed the temperature (and polarization) fluctuations down to a resolution of 0.23° while radio interferometers (CBI, DASI, VSA) could reach a resolution of 0.02° (but on a small area of the sky)



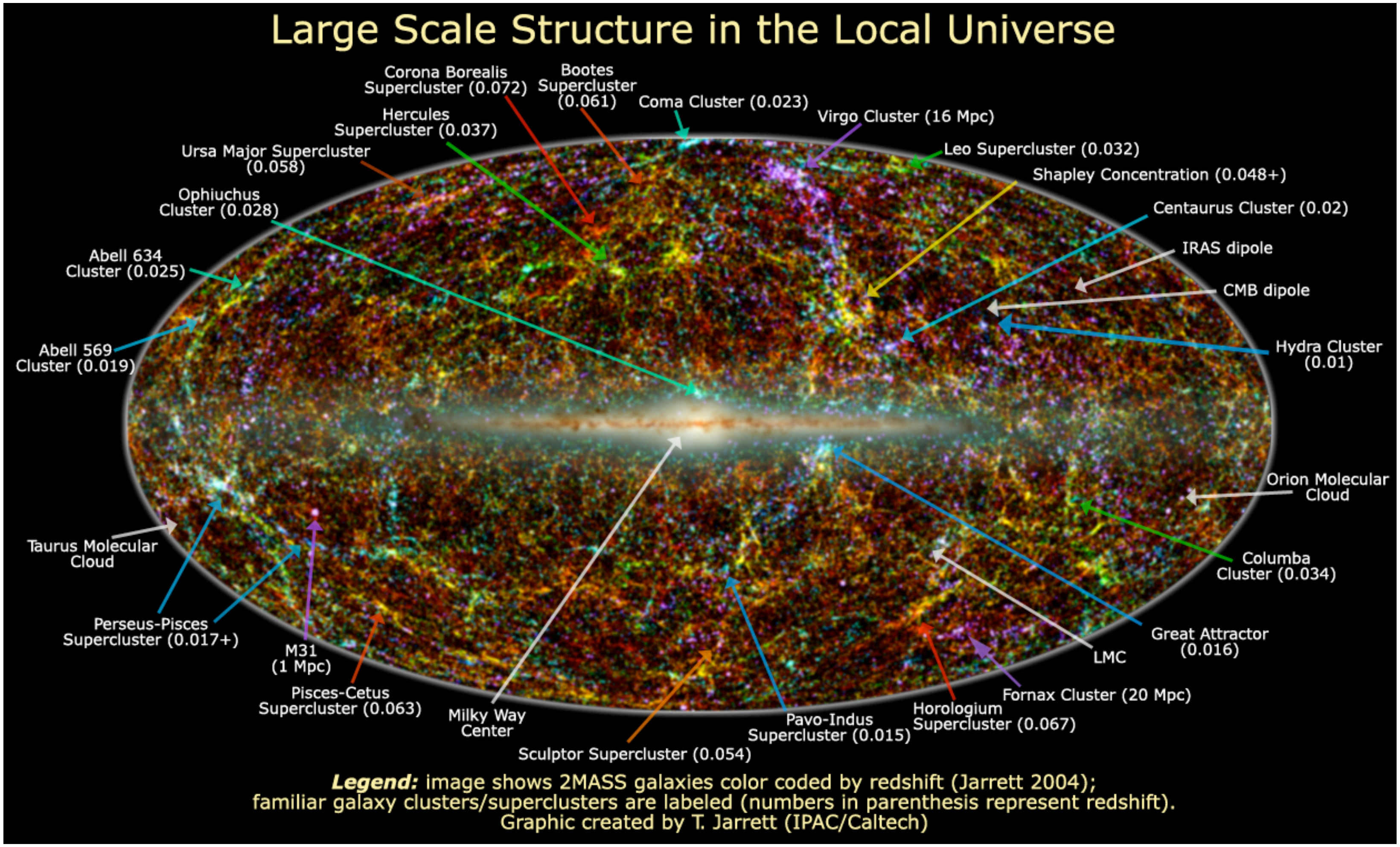
The CMB dipole



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

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 within the Local Group one finds:
$v = 627 \pm 22$ km/s
$l=276\pm3°$ $b=30\pm3°$ (towards Hydra-Centaurus)

Agreement with "light dipole" within ≈10° suggests that the acceleration vector is generated within nearly 50 Mpc


Large Scale Structure in the Local Universe
Corona Borealis Supercluster (0.072)
Bootes Supercluster (0.061)
Coma Cluster (0.023)
Virgo Cluster (16 Mpc)
Hercules Supercluster (0.037)
Ursa Major Supercluster (0.058)
Leo Supercluster (0.032)
Shapley Concentration (0.048+)
Ophiuchus Cluster (0.028)
Centaurus Cluster (0.02)
IRAS dipole
Abell 634 Cluster (0.025)
CMB dipole
Abell 569 Cluster (0.019)
Hydra Cluster (0.01)
Orion Molecular Cloud
Taurus Molecular Cloud
Columba Cluster (0.034)
Perseus-Pisces Supercluster (0.017+)
M31 (1 Mpc)
Great Attractor (0.016)
LMC
Pisces-Cetus Supercluster (0.063)
Milky Way Center
Fornax Cluster (20 Mpc)
Pavo-Indus Supercluster (0.015)
Horologium Supercluster (0.067)
Sculptor Supercluster (0.054)
Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004); familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift).
Graphic created by T. Jarrett (IPAC/Caltech)

CMB temperature fluctuations

- 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

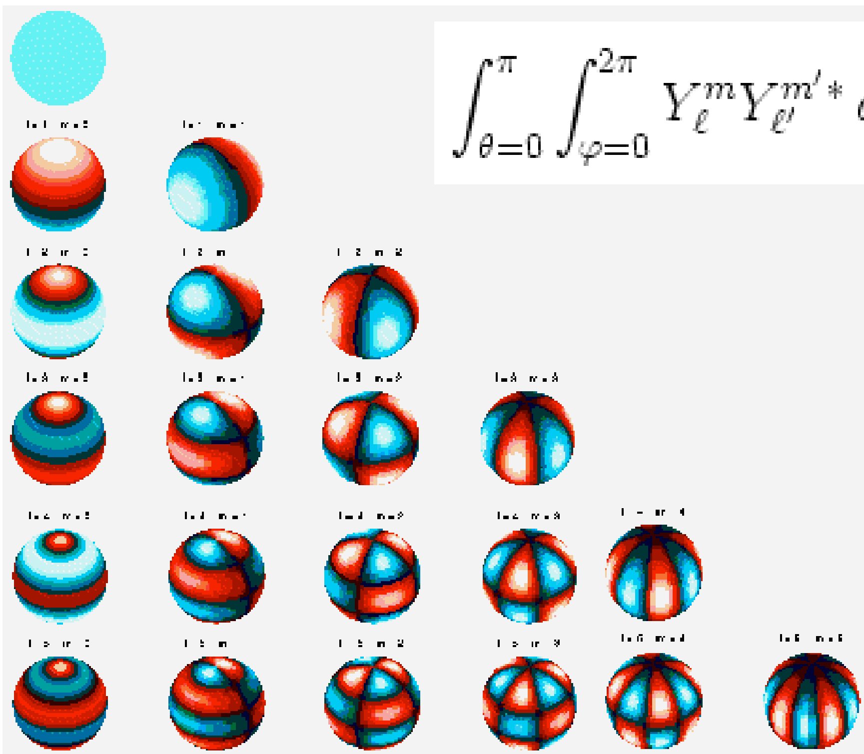
$$\Theta(\hat{\mathbf{n}}) = \Delta T / T$$

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

$$\Theta_{\ell m} = \int d\hat{\mathbf{n}} Y^*_{\ell m}(\hat{\mathbf{n}})\Theta(\hat{\mathbf{n}})$$

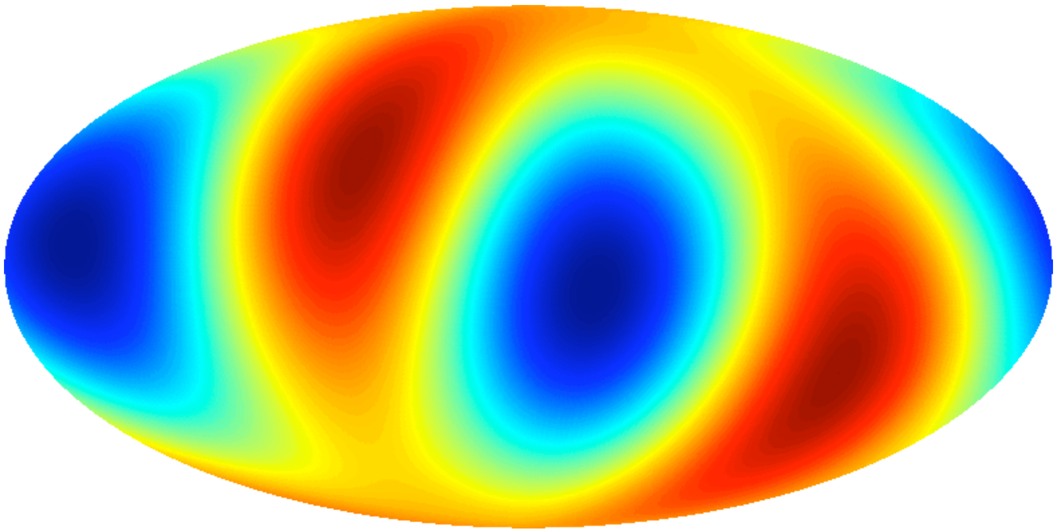
Spherical harmonics

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

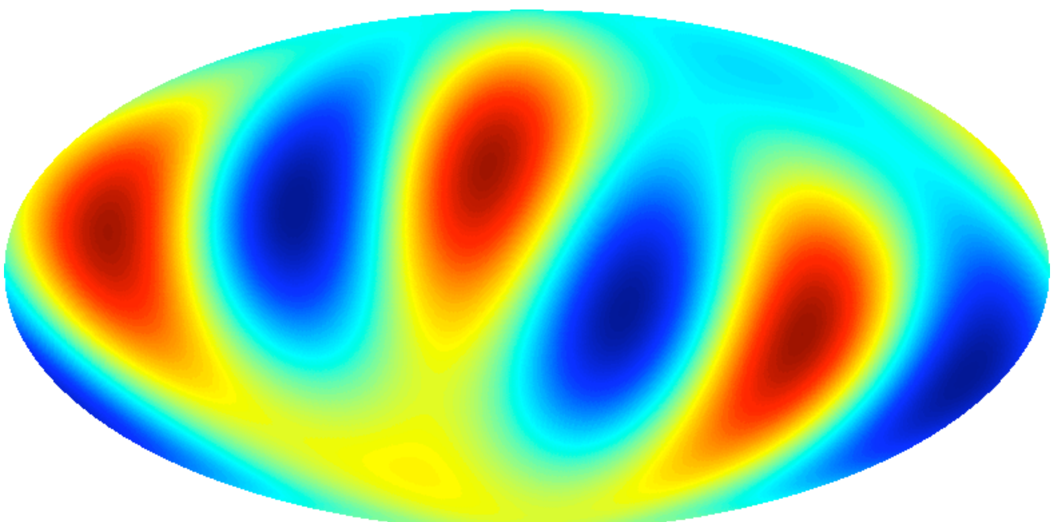


$$\int_{\theta=0}^{\pi}\int_{\varphi=0}^{2\pi} Y_\ell^m Y_{\ell'}^{m'*}\, d\Omega = \delta_{\ell\ell'}\delta_{mm'} \qquad d\Omega = \sin\theta\, d\varphi\, d\theta$$

Example: low multipoles from WMAP



Quadrupole (l=2)



Octupole (l=3)

CMB temperature fluctuations

- The power spectrum is then defined as

$$\langle \Theta^*_{\ell m} \Theta_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell$$

- The contribution to the variance per logarithmic interval (for l>> 1) is

$$\Delta_T^2 \equiv \frac{\ell(\ell+1)}{2\pi} C_\ell T^2$$

This is the quantity usually plotted to represent experimental data

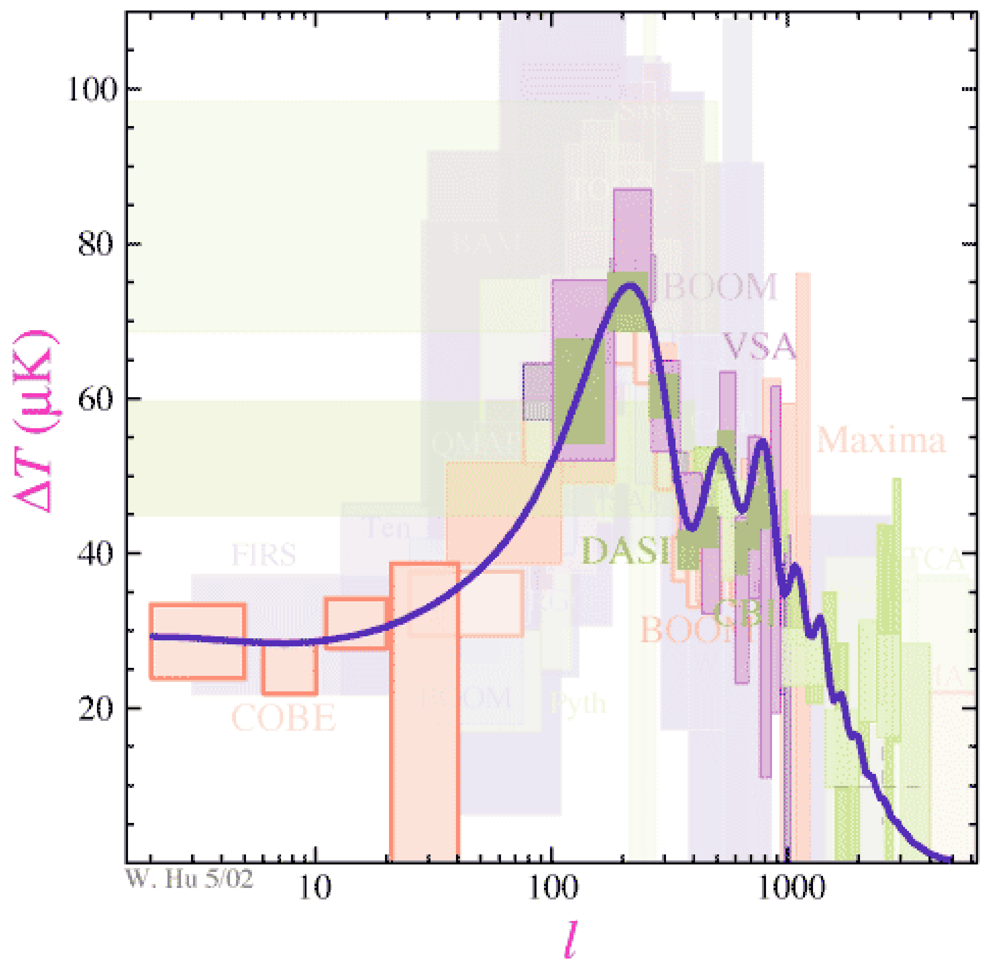
Cosmic and sample variance

- The predicted power spectrum is the average power we would see in an ensemble of universes. However, a real observer is limited to one Universe and one sky with its own set of spherical harmonics (2l+1 for each l).
- This leads to an inevitable error (cosmic variance)

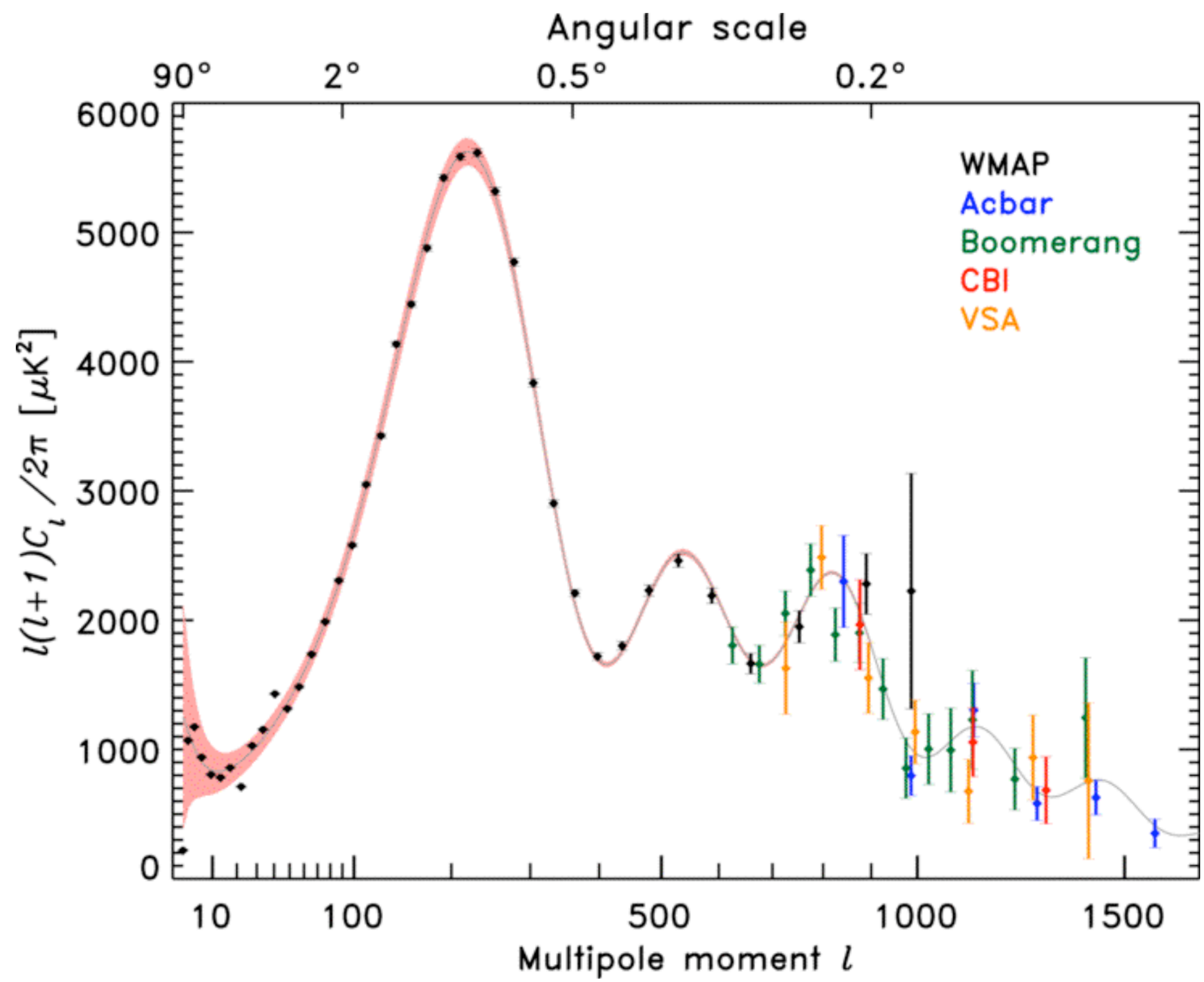
$$\Delta C_\ell = \sqrt{\frac{2}{2\ell+1}} C_\ell$$

- Allowing for further averaging over l in bands of $\Delta l \approx l$ makes the errors 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 planned Planck satellite)

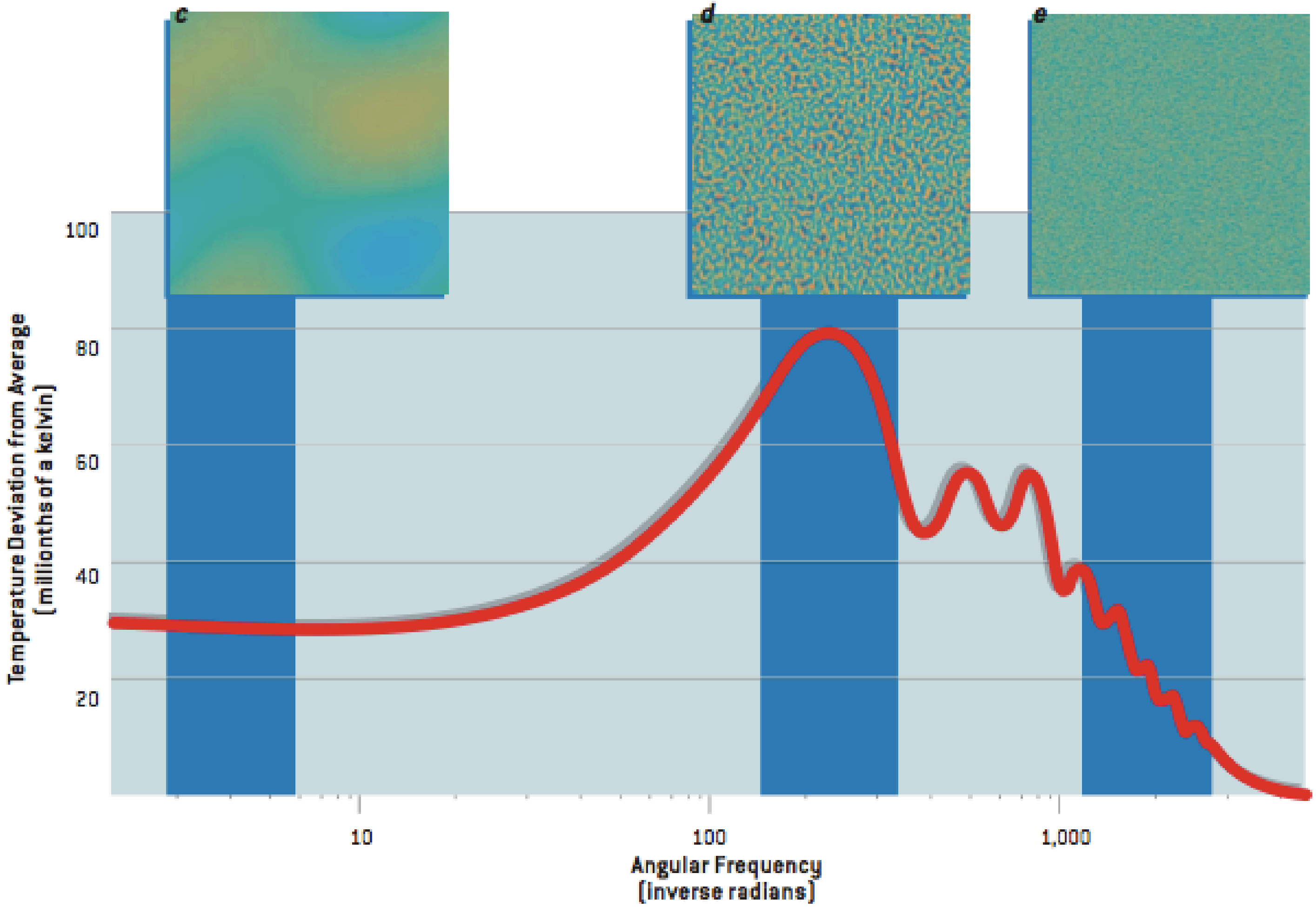
Temperature power spectrum (pre-WMAP)



Temperature power spectrum



What does this mean?



Sources of primary anisotropy

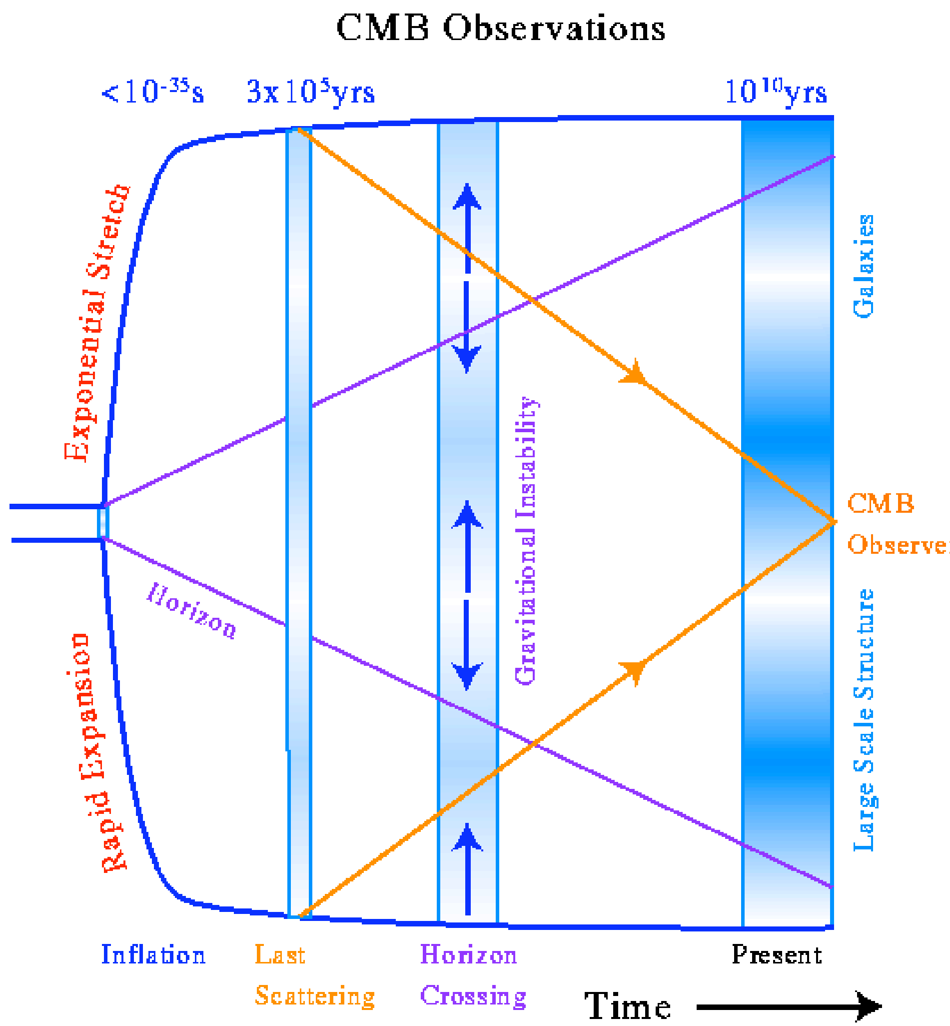
- Perturbations in the gravitational potential (Sachs-Wolfe effect): photons that last scattered within high-density regions have to climb out of potential wells and are thus redshifted
- Intrinsic adiabatic perturbations: in high-density regions, the coupling of matter and radiation can compress the radiation also, giving a higher T
- Velocity (Doppler) perturbations: photons last-scattered by matter with a non-zero velocity along the line-of-sight will receive a Doppler shift

$$\Delta T/T\,(\mathbf{r}/|\mathbf{r}|) = \delta\varphi(\,\mathbf{r}\,)/c^2 - \mathbf{r}\cdot\mathbf{v}(\,\mathbf{r}\,)/\,(c\,|\mathbf{r}|) + \delta(\,\mathbf{r}\,)\,/\,3$$

where $|\mathbf{r}|$ is the comoving distance to the surface of last scattering and all the fields are evaluated at the time of last scattering

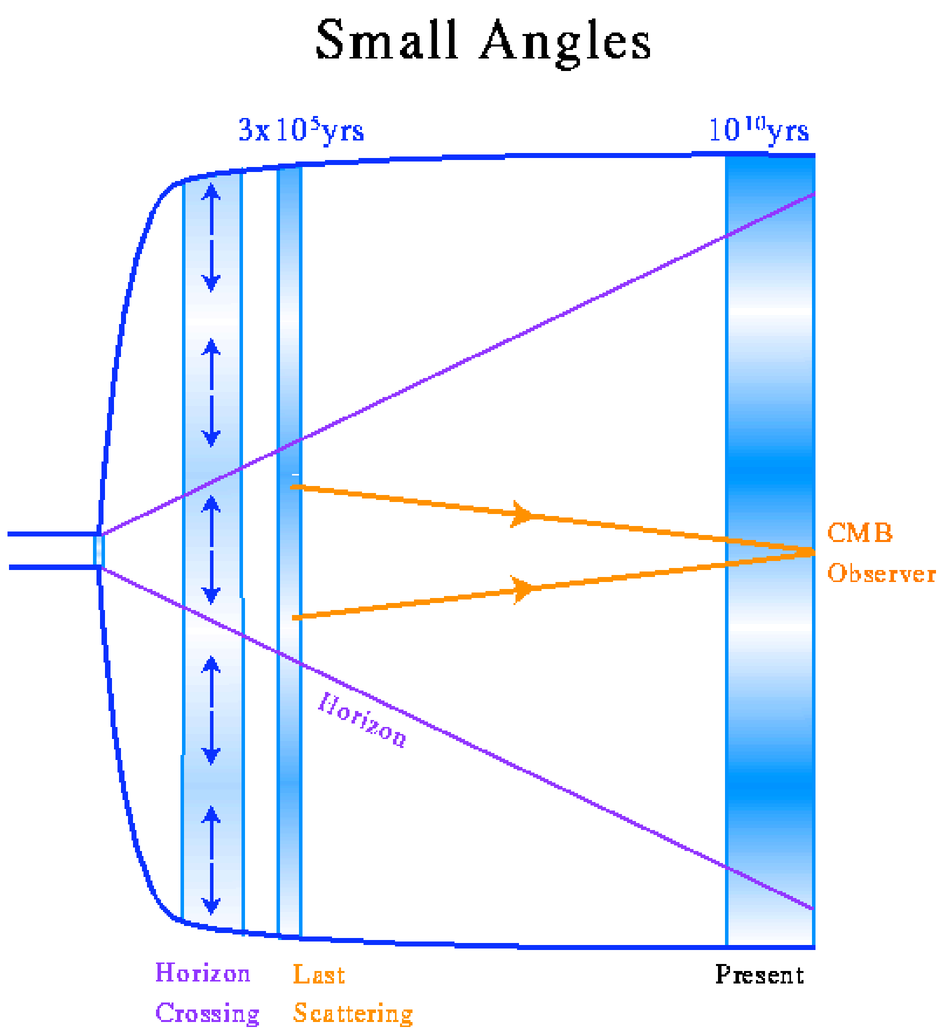
CMB fluctuations: large scales (θ>1°)

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



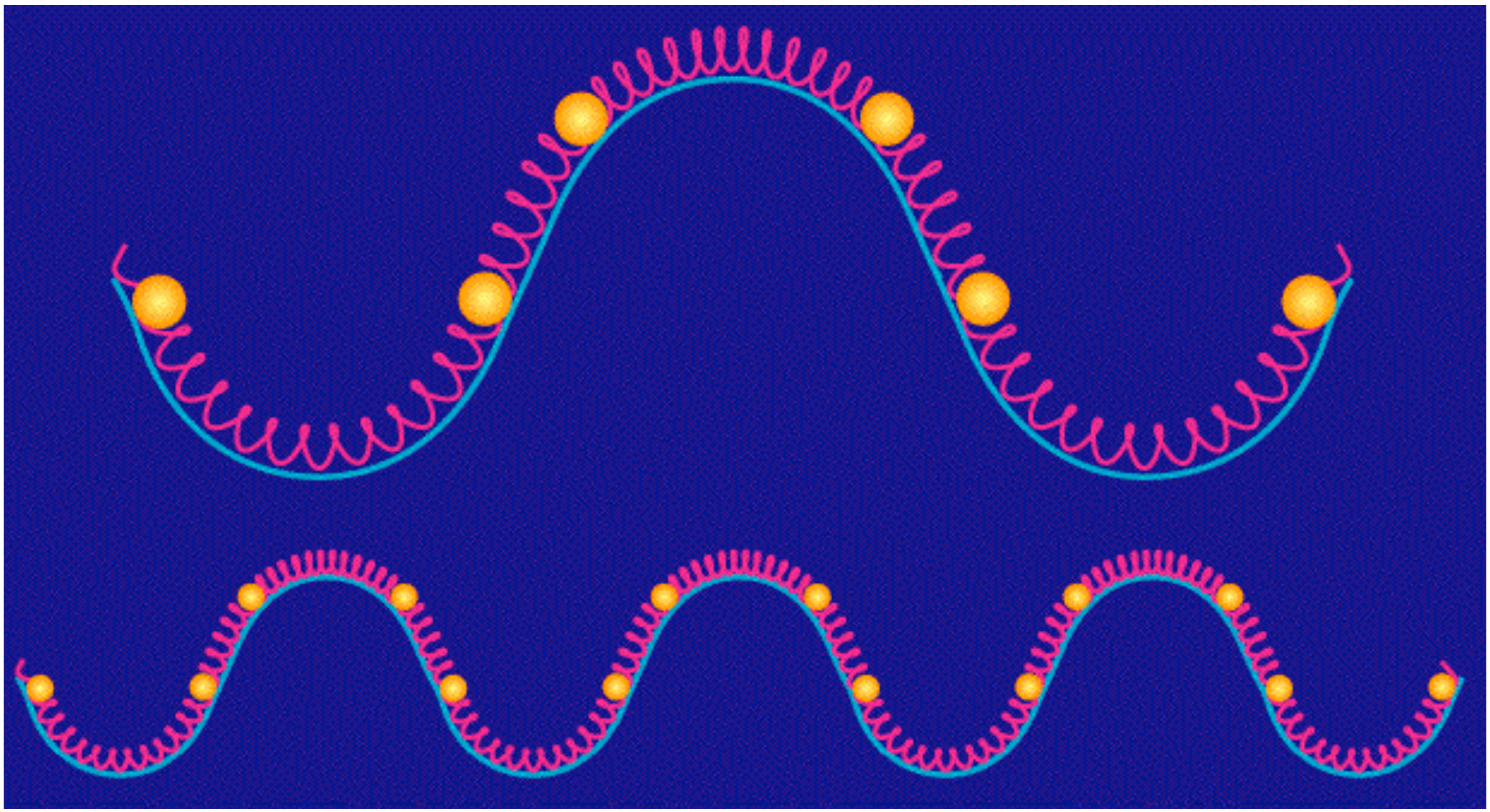
CMB fluctuations

All the effects contribute

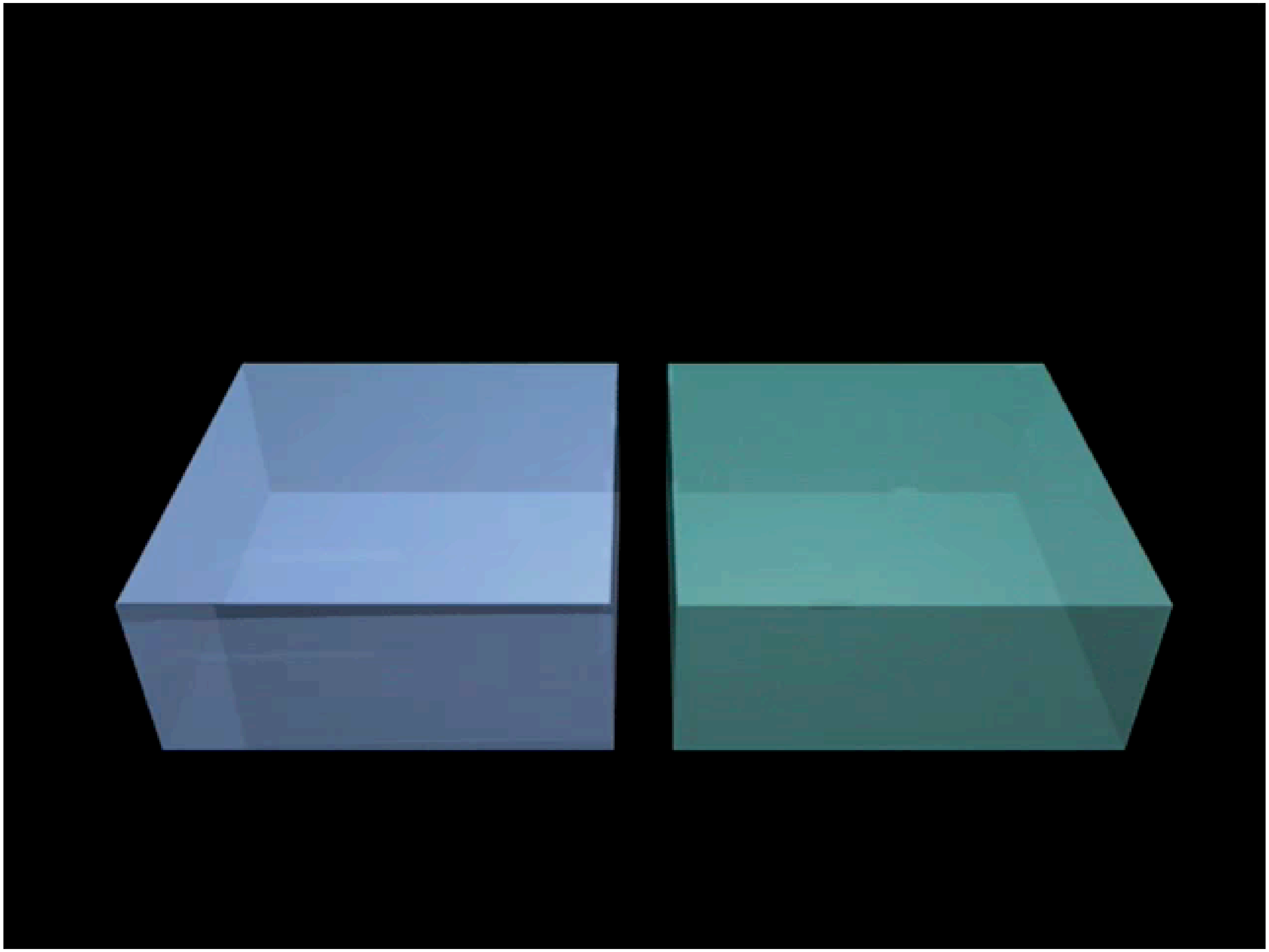


Baryon-photon oscillations

Gravitational compression of the coupled baryon-photon plasma into potential wells is counteracted by radiation pressure



CMB fluctuations and sound waves



Sub-horizon perturbations

- During radiation domination, adiabatic perturbations with wavenumber k drive a cosine oscillation (η here is the time variable), i.e. a sound wave with velocity $v_s \approx c/3$

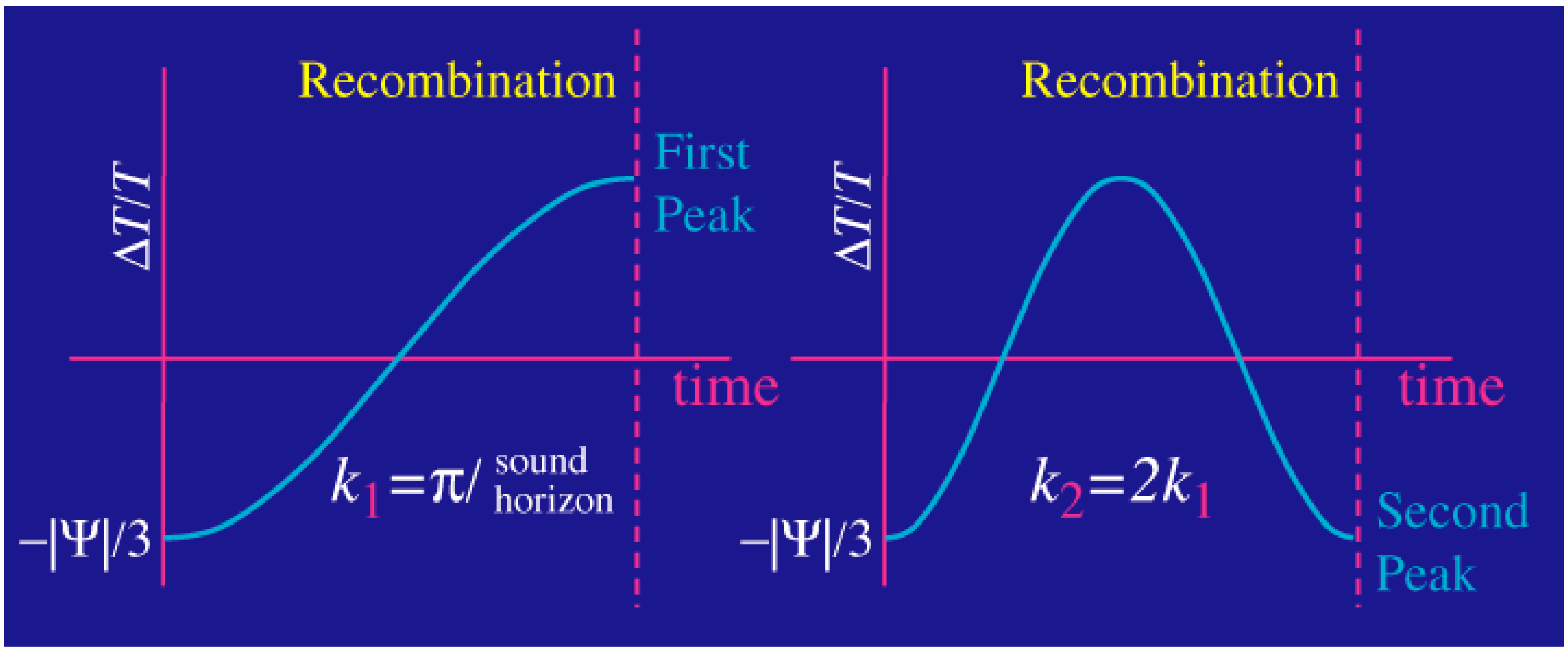
$$\hat{\Theta}(\eta) = \frac{\hat{\phi}}{3}\cos(v_s k \eta) - \hat{\phi}$$

- On average the temp zero. Rather, the relevant quantity for our purposes are the variances which give the power. Thus the contribution

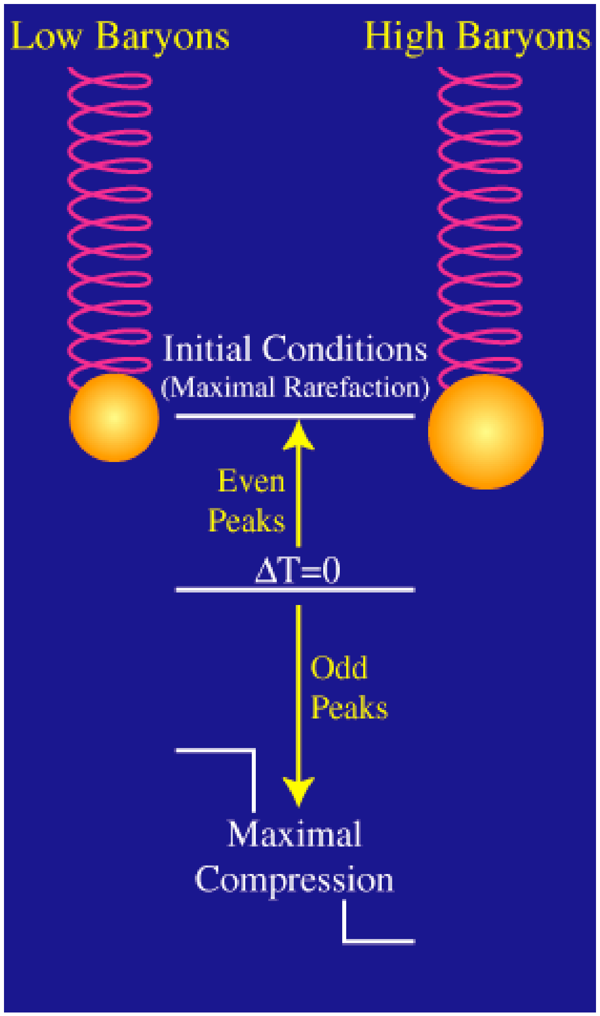
$$V\left[\hat{\phi} + \hat{\Theta}\right] \equiv \left\langle \left|\hat{\phi} + \hat{\Theta}\right|^2 \right\rangle = \frac{1}{9} V[\hat{\phi}] \cos^2(v_s k \eta).$$

- Sound waves stop the baryons release the photons. Thus, although we originally thought of the equation above as an oscillating function of time, with k a mere constant, we now think of it as a function of k instead, with time held fixed. This is why the power-spectrum exhibits oscillating behaviour with respect to l

Acoustic peaks



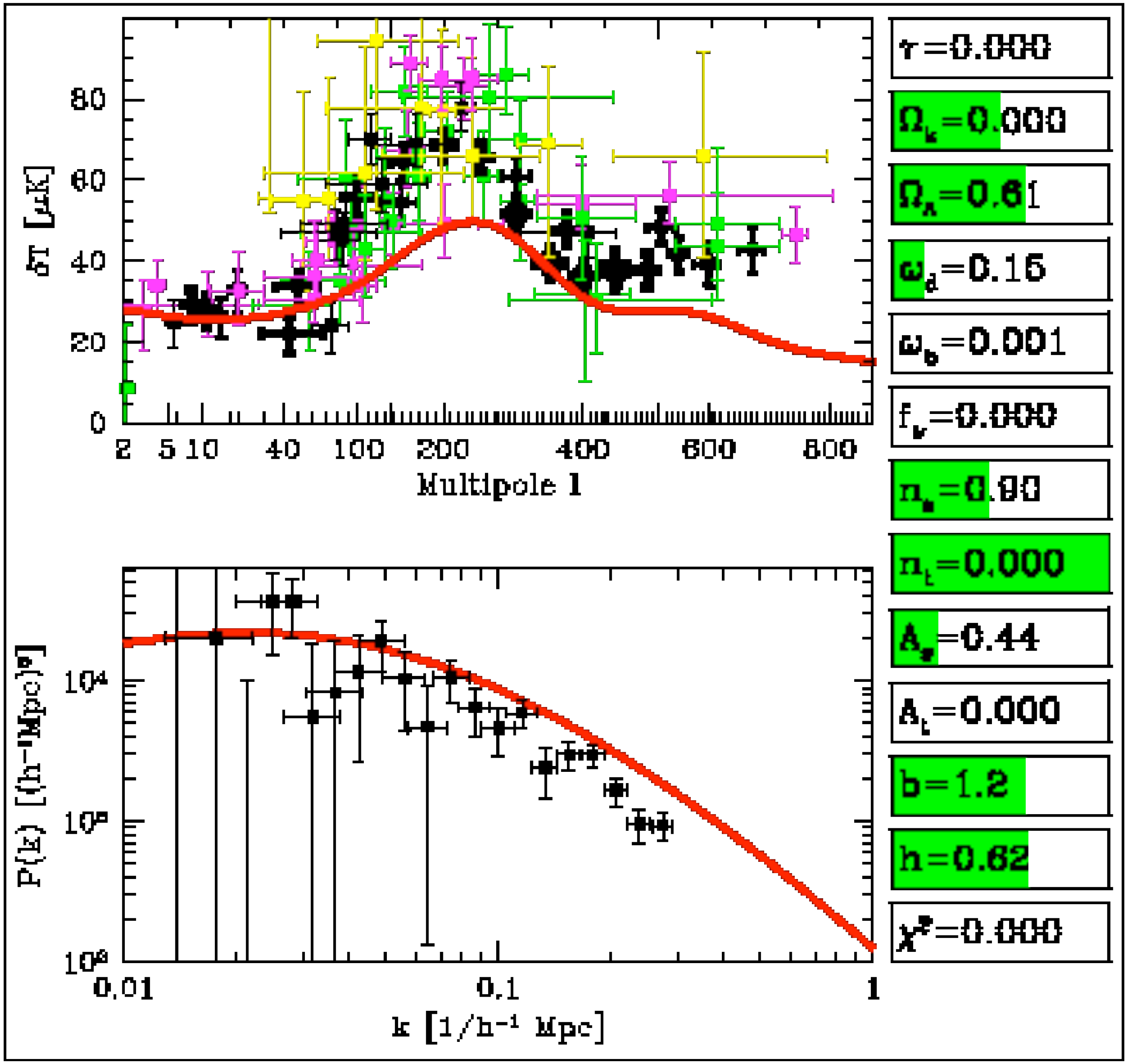
Baryon loading



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.



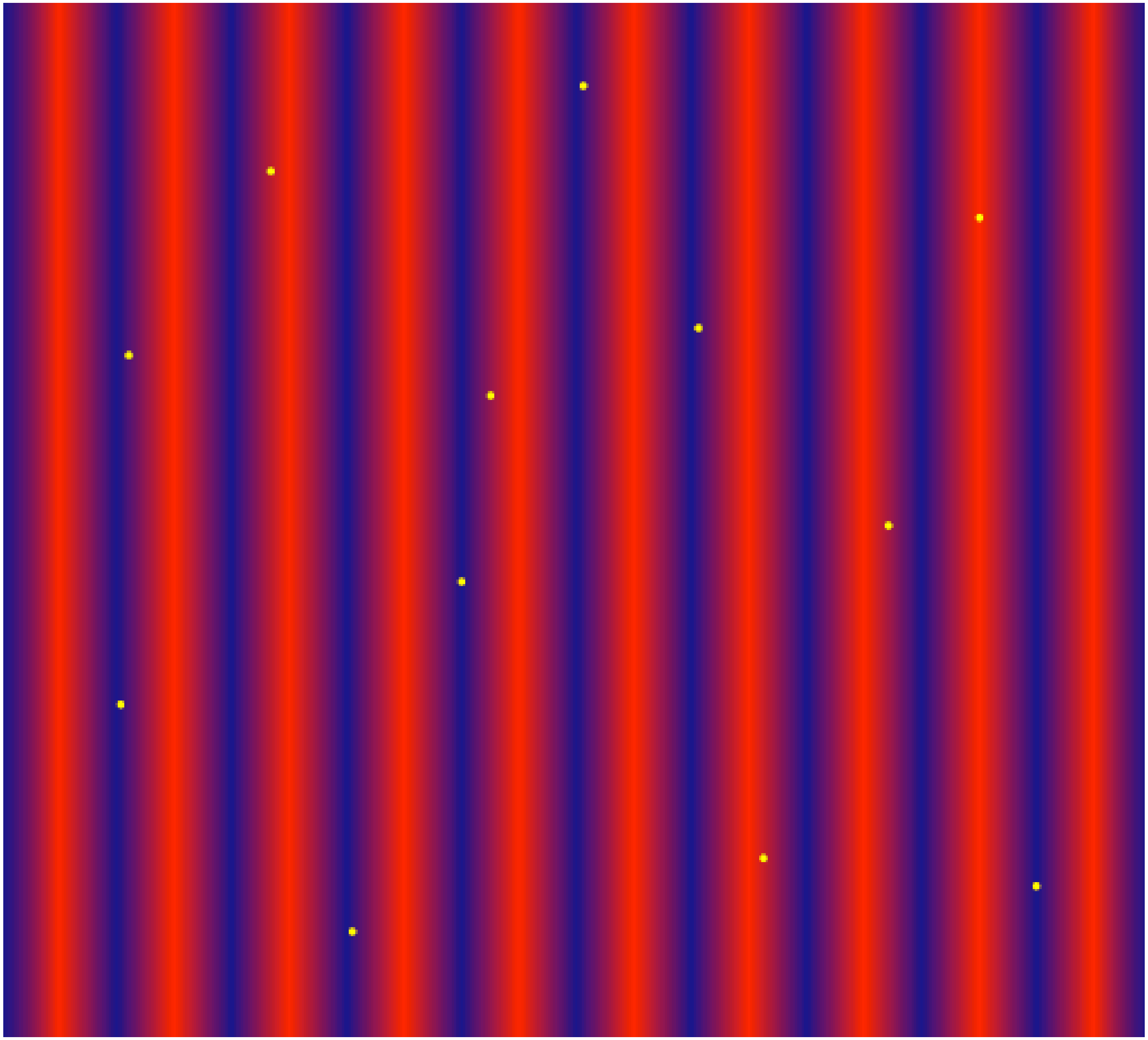
δT [μK]
0
20
40
60
80
2
5 10
40
100
200
400
600
800
Multipole l
P(k) [(h⁻¹Mpc)³]
0.01
0.1
1
k [1/h⁻¹ Mpc]
τ=0.000
Ω_k=0.000
Ω_Λ=0.61
ω_d=0.15
ω_b=0.001
f_ν=0.000
n_s=0.90
n_t=0.000
A_s=0.44
A_t=0.000
b=1.2
h=0.62
χ²=0.000

Damping and diffusion

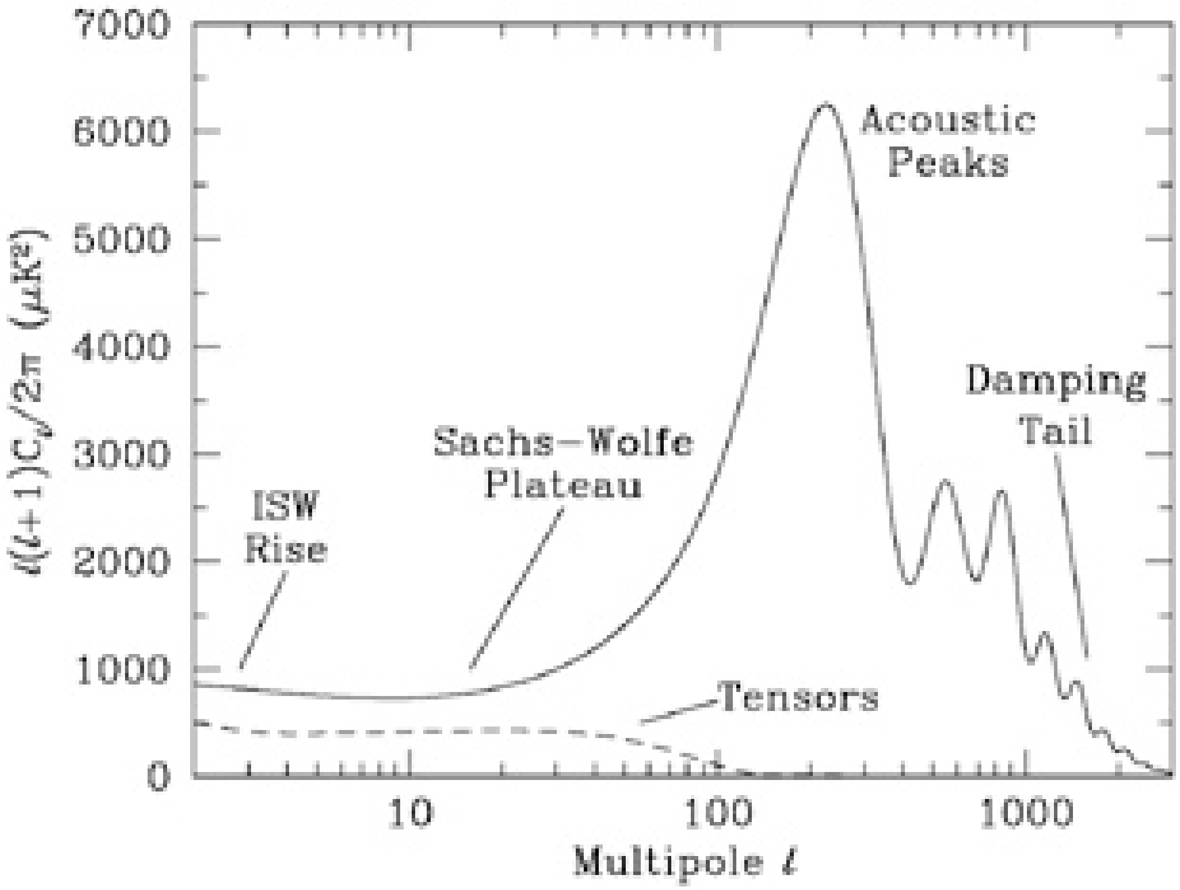
- Photon diffusion (Silk damping) suppresses fluctuations in the baryon-photon plasma

- 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 ($l \approx 1000$, $\theta \approx 0.1°$).



Summary

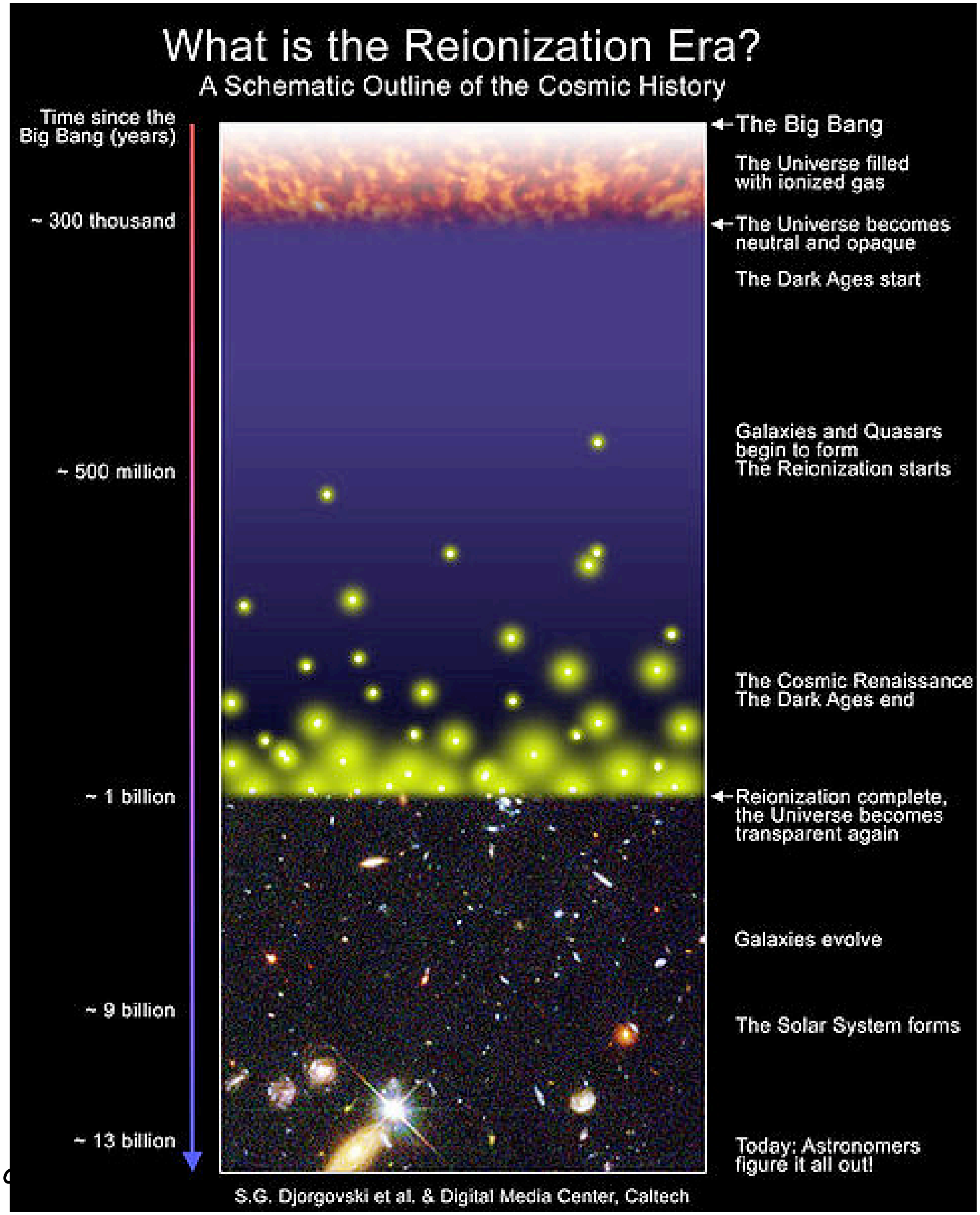


7000
6000
5000
4000
3000
2000
1000
0
10
100
1000
Multipole ℓ
ℓ(ℓ+1)C_ℓ/2π (μK²)
ISW
Rise
Sachs–Wolfe
Plateau
Acoustic
Peaks
Damping
Tail
Tensors

Sources of secondary anisotropies

- Gravitational effects (late and early integrated Sachs-Wolfe and Rees-Sciama effects): if a photon flies through a potential well the blueshift it acquires when falling in will be exactly cancelled by its redshift from climbing out. If the potential well evolves while the photon is in it (for instance in the presence of dark energy), the cancellation will no longer be perfect.
- Reionization: when the Universe is reionized, Thomson scatter off free electrons becomes efficient and the temperature we see in a given direction of the sky is really the weighted average of the temperature of part of the last scattering surface
- The Sunyaev-Zel'dovich effect: when CMB photons cross the potential well of a cluster of galaxies, they can be scattered by free electrons in the hot intra-cluster gas. The motion of the cluster gives rise to a Doppler shift known as kinematic SZ effect, while the high-temperature of the electrons distorts the CMB spectrum by depopulating the low-frequency tail and overpopulating the high-frequency tail

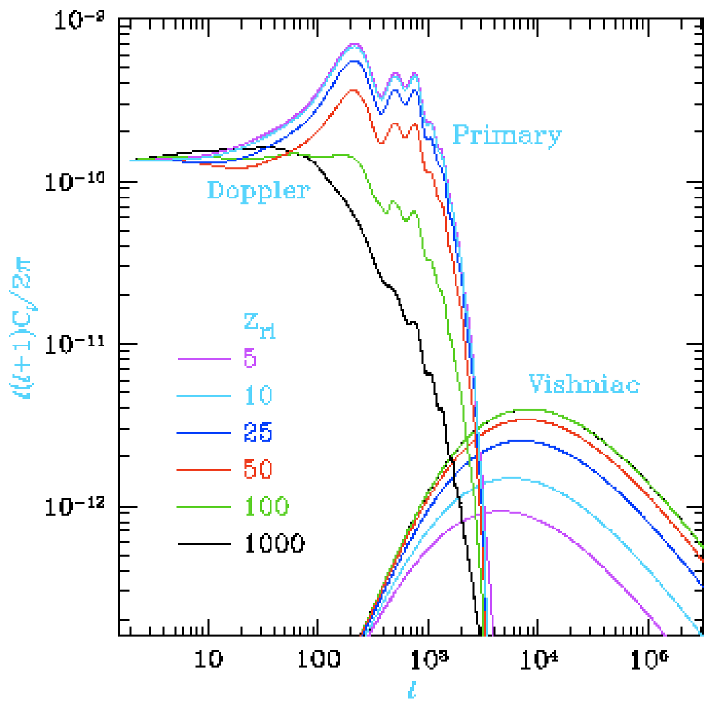
With time souces become more and more abundant. Random points in the IGM start receiving UV photons by more than one source.



The first UV sources start ionizing gas in their neighbourhood

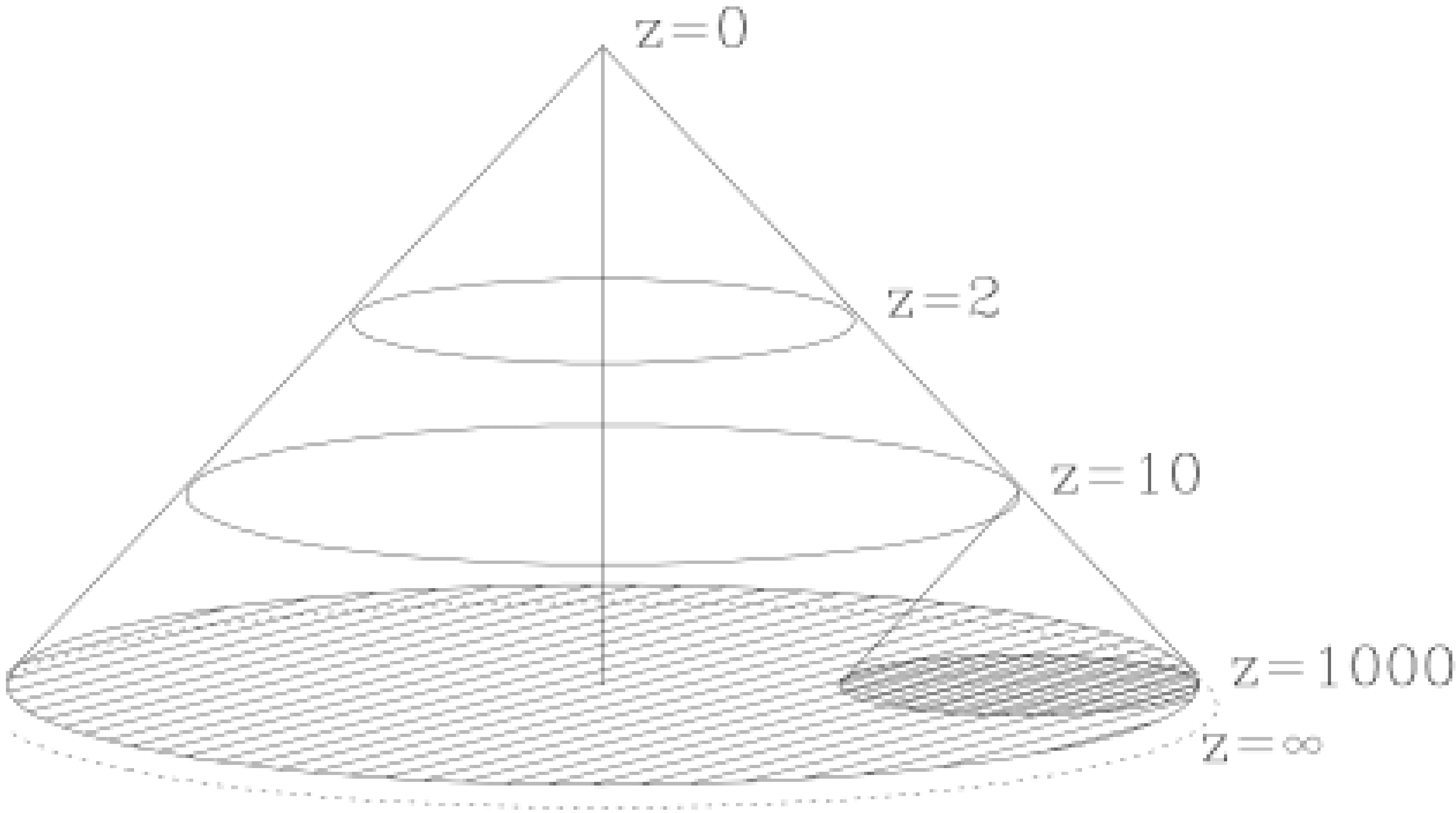
Finally, the bubbles cover the whole volume. This is known as percolation (or bubble-overlap) phase.

CMB and reionization

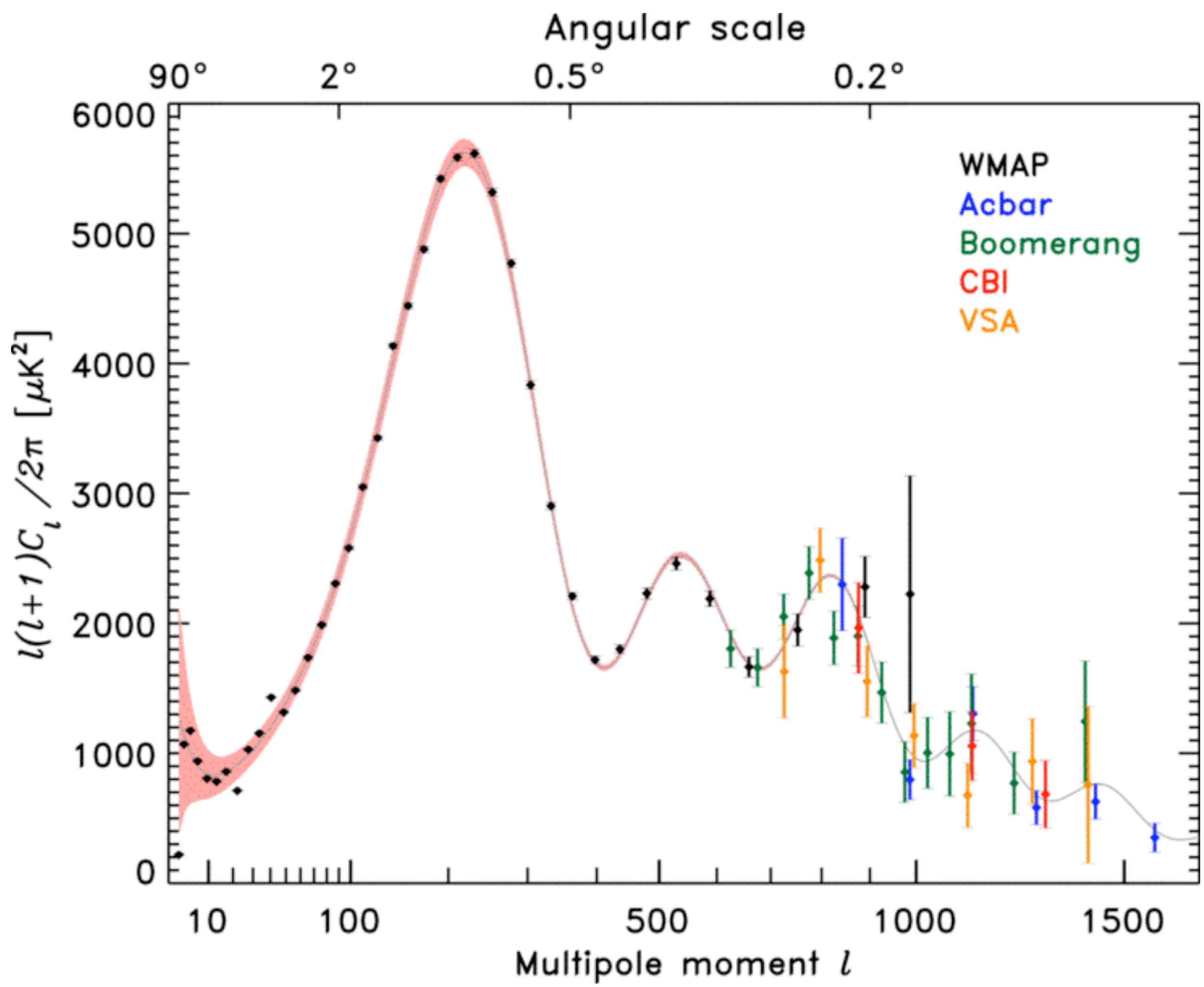


- Rescattering of CMB photons damps fluctuations as $e^{-\tau}$, with τ the optical depth to Thomson scattering
- New perturbations are generated on small scales due to the bulk motion of electrons in overdense regions (Ostriker-Vishniac effect)

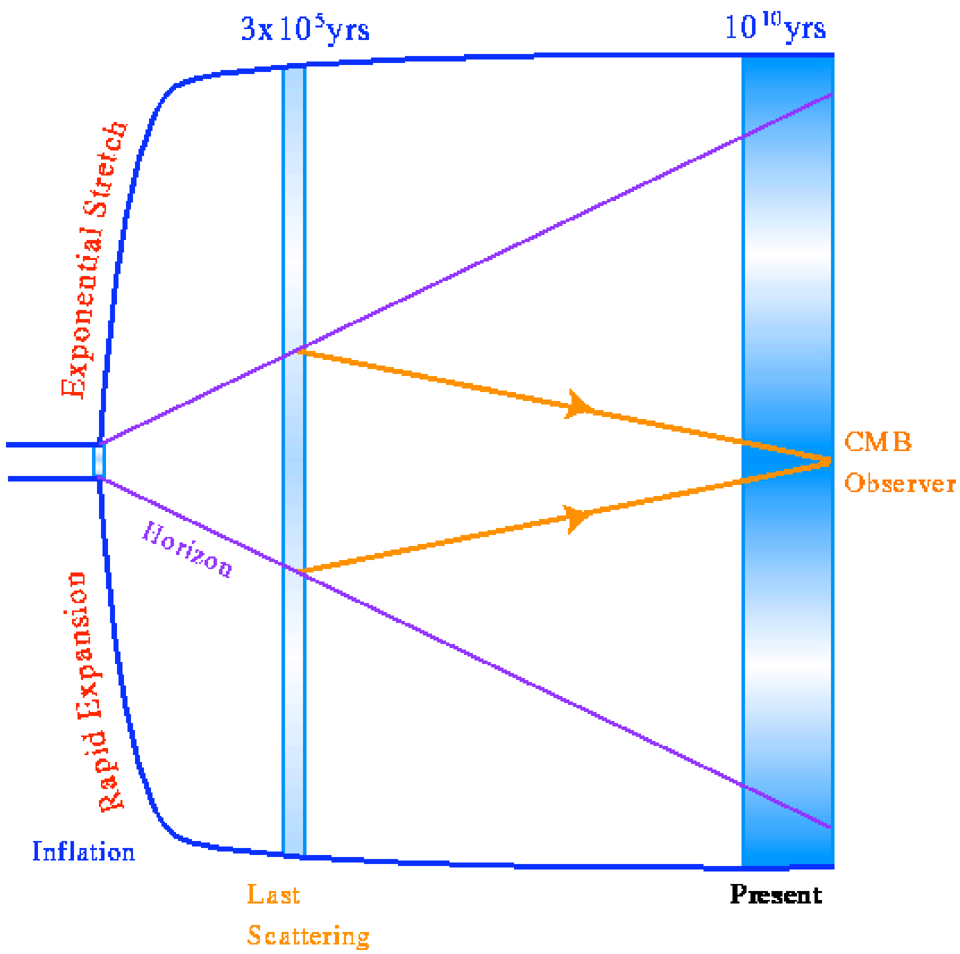
Reionization



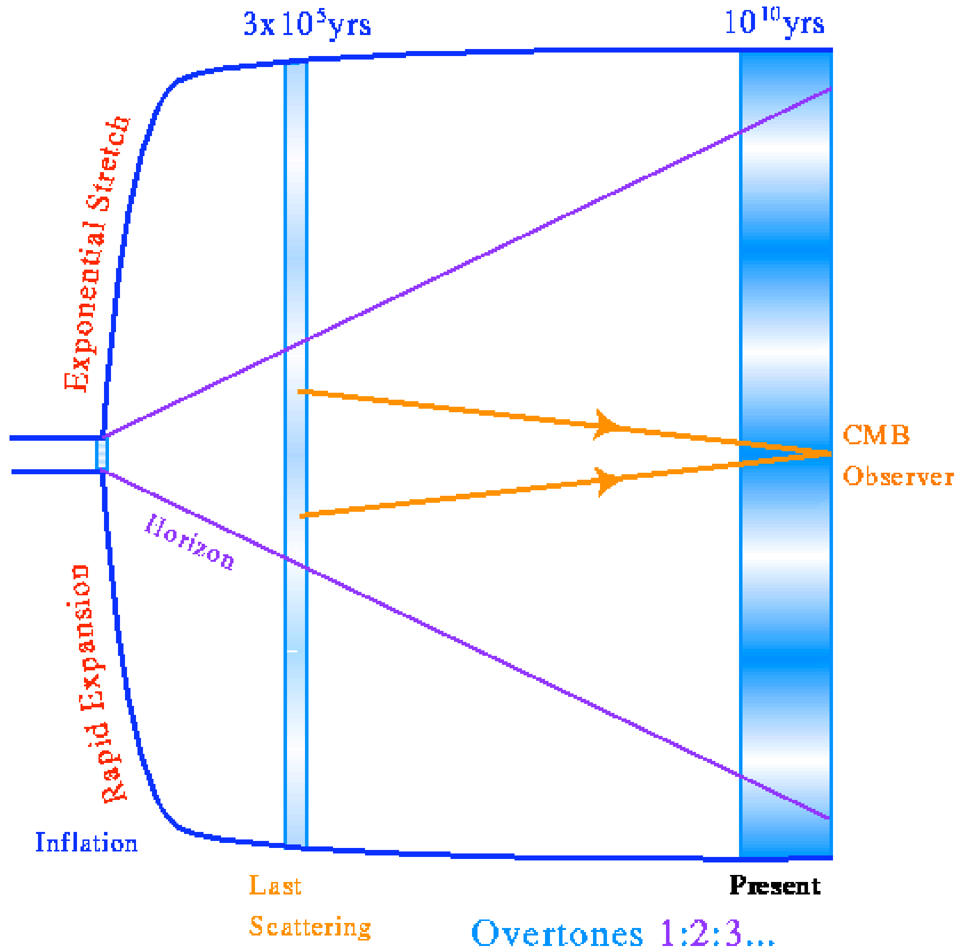
Retrieving information from CMB spectra



Fundamental Mode



Overtone



$3x10^5$yrs
10^{10}yrs
Exponential Stretch
Rapid Expansion
Horizon
CMB
Observer
Inflation
Last
Scattering
Present
Overtones 1:2:3...

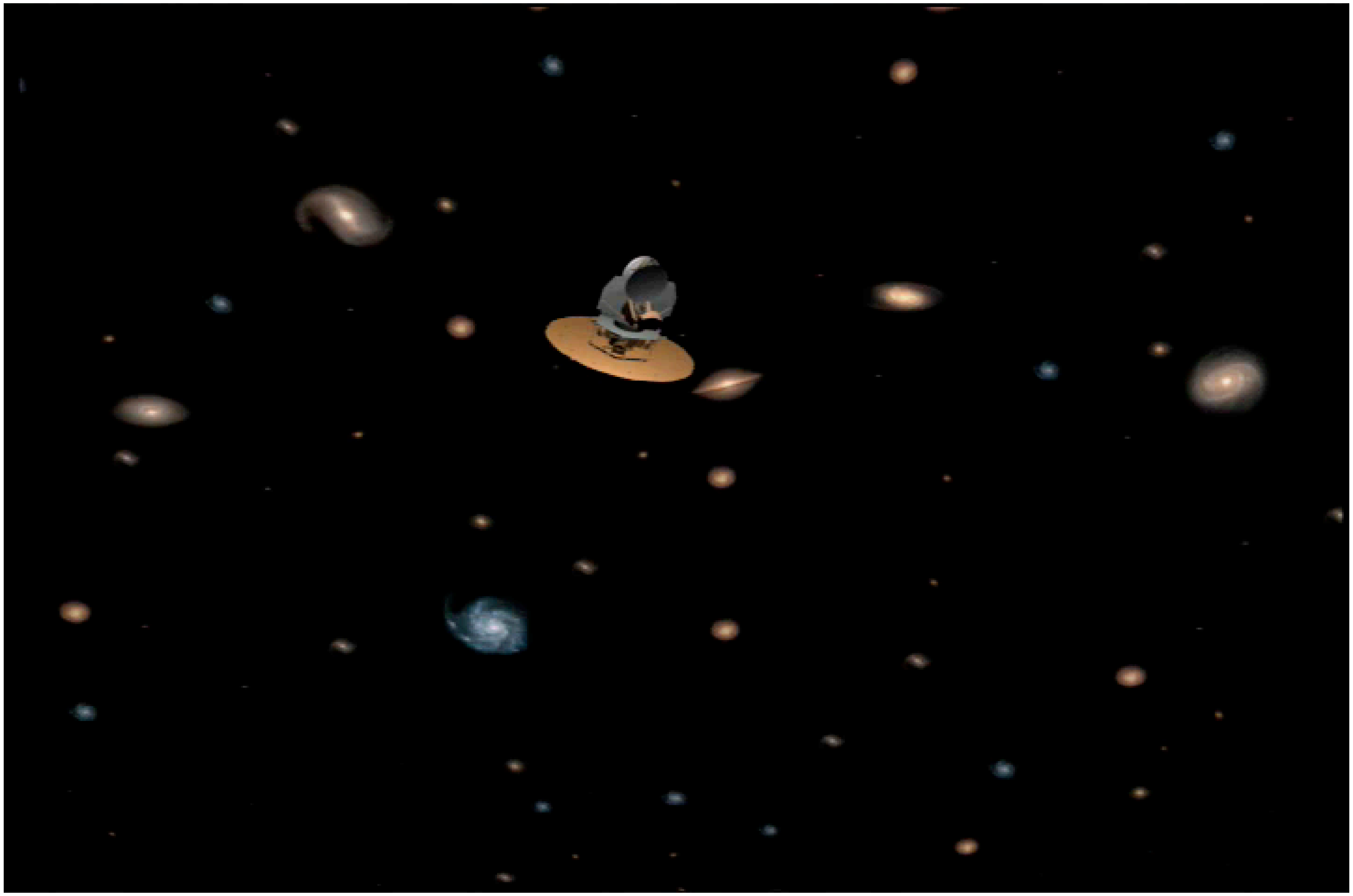
Curvature and projection effects

- A spherical harmonic is a weighted average of the 3D fluctuations on many different scales. Although, for a given multipole l, the weights tend to peak at a characteristic wavenumber $k \propto l$, they do not vanish for a wide range of k.

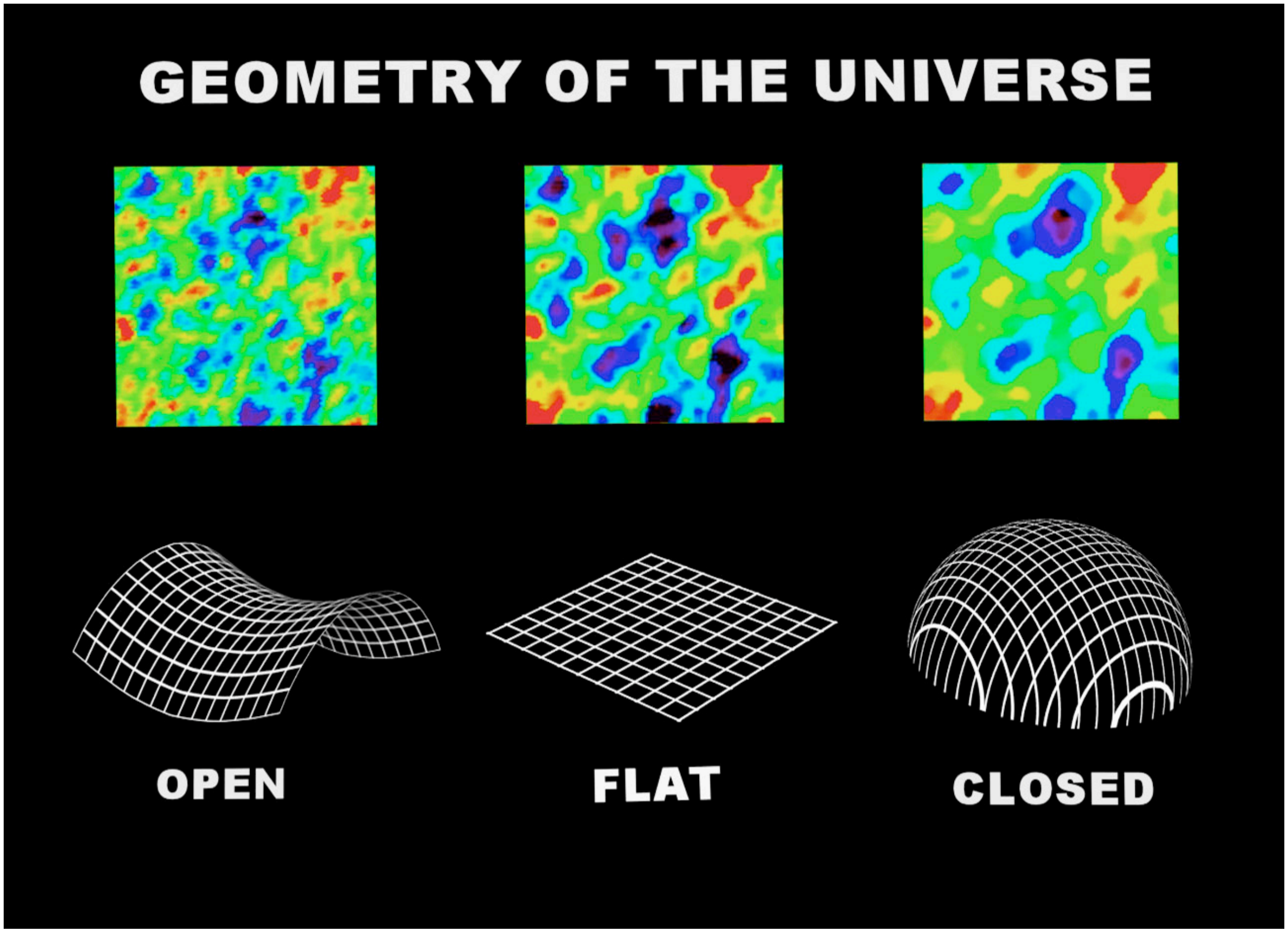
- The net effect is that the angular power spectrum is a smeared out version of the 3D power spectrum, with all features slightly softened.

- The constant of proportionality between k and l depends on the curvature of the space, increasing with Ω_0 (roughly $l \propto \Omega_0^{-1/2}$).

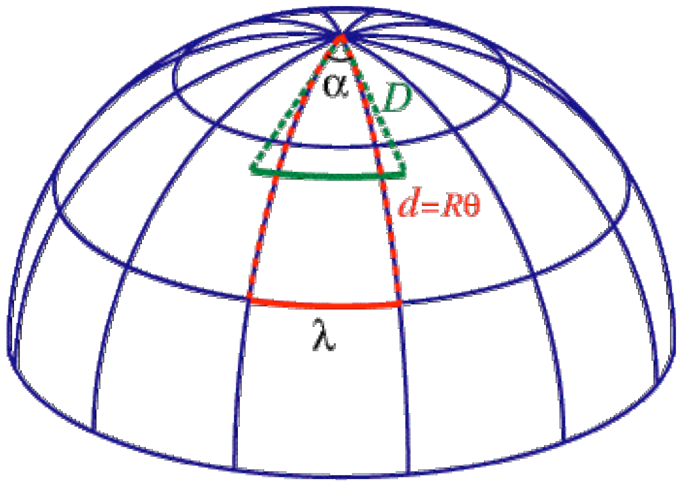
Curvature



Curvature



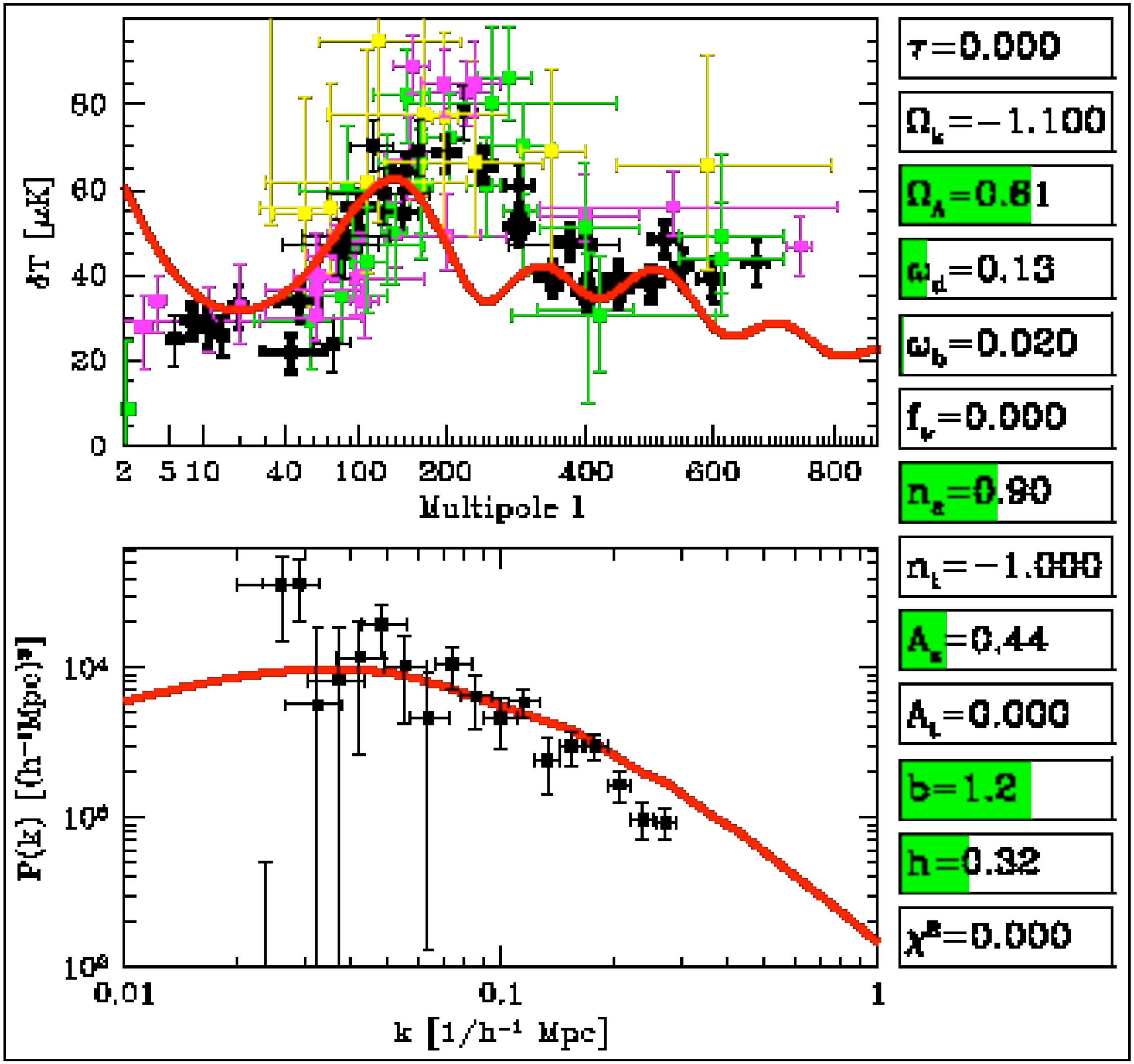
Effect of curvature



$\theta_H \approx 0.87° \, \Omega_0^{1/2} (1100/z_{dec})^{1/2}$ $1° = 2\pi/360 = 0.01745$ rad $l_H \approx 2/\theta_H(\text{rad})$

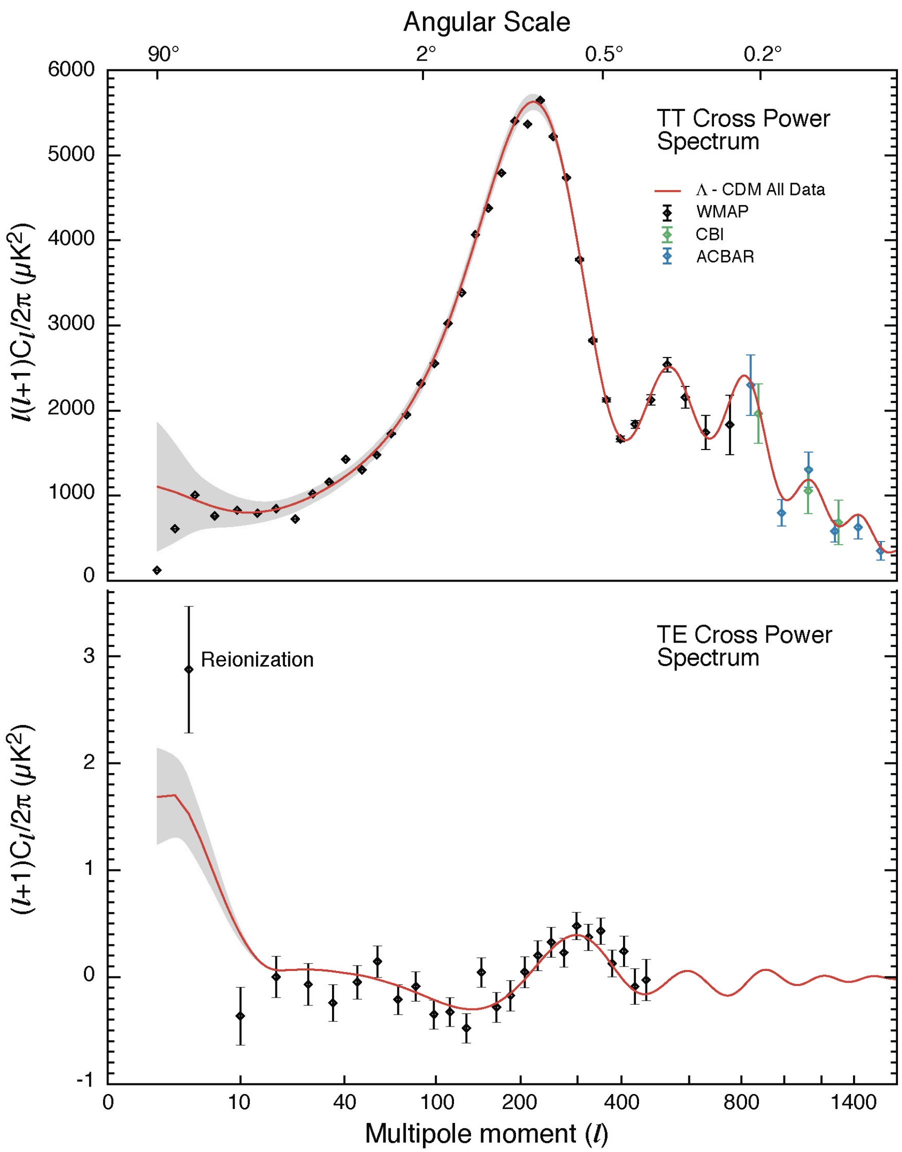
$l_H \approx 132 \, \Omega_0^{-1/2} (z_{dec}/1100)^{1/2}$

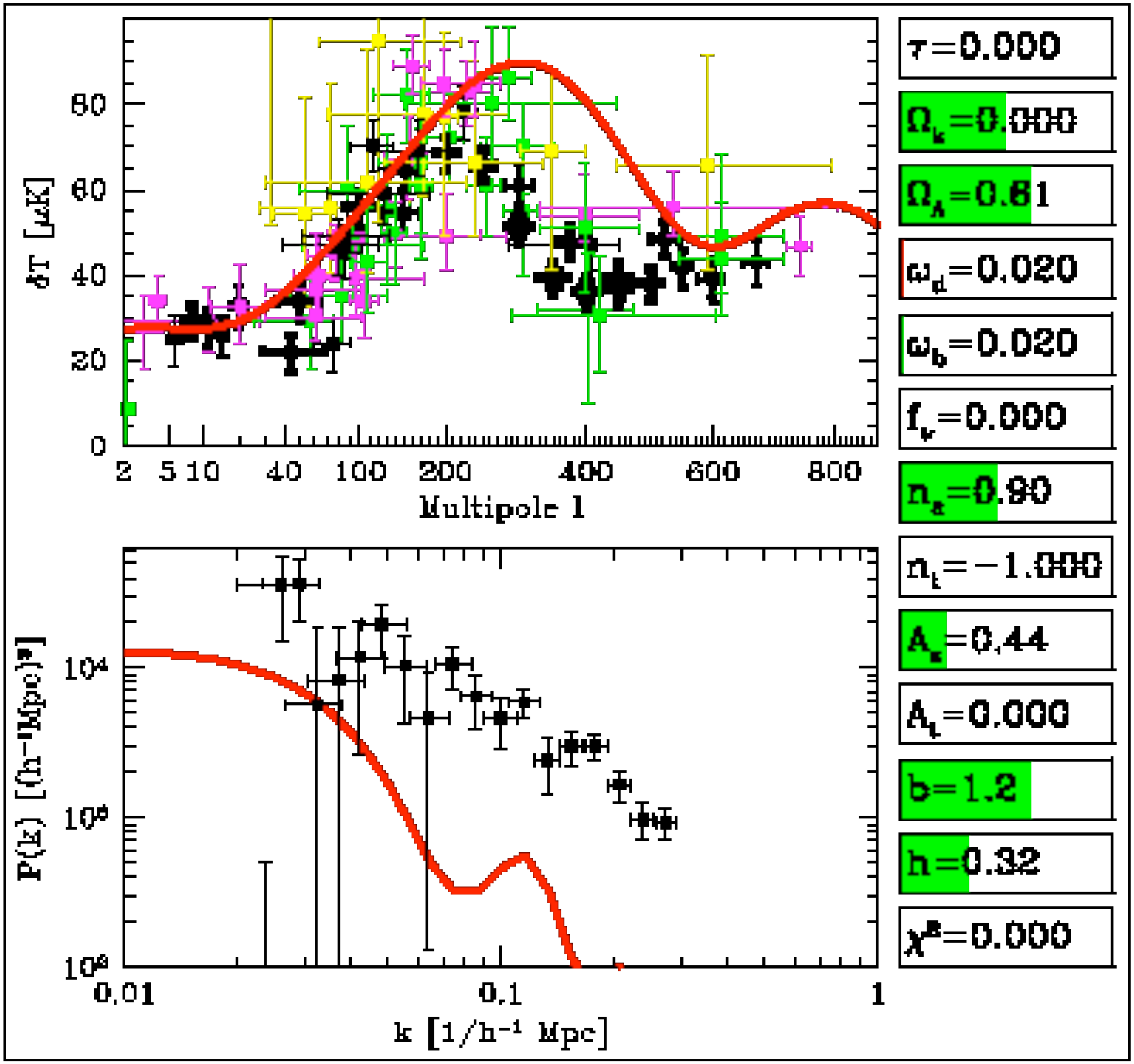
WMAP data indicate that $\Omega_0 = 1.02 \pm 0.02$



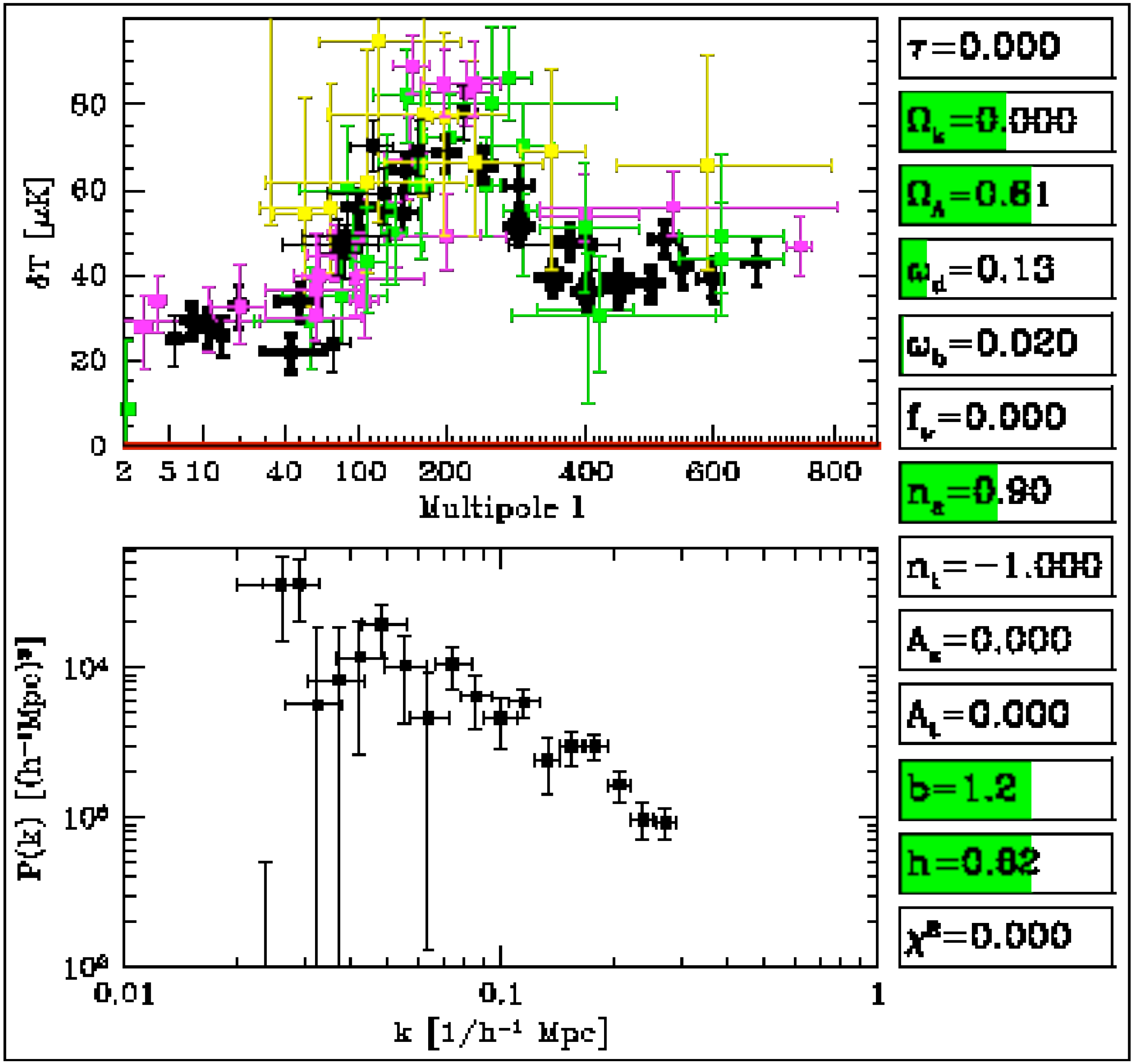
τ=0.000
Ω_k=−1.100
Ω_Λ=0.81
ω_d=0.13
ω_b=0.020
f_ν=0.000
n_s=0.90
n_t=−1.000
A_s=0.44
A_t=0.000
b=1.2
h=0.32
χ²=0.000
δT [μK]
Multipole l
P(k) [(h⁻¹Mpc)³]
k [1/h⁻¹ Mpc]

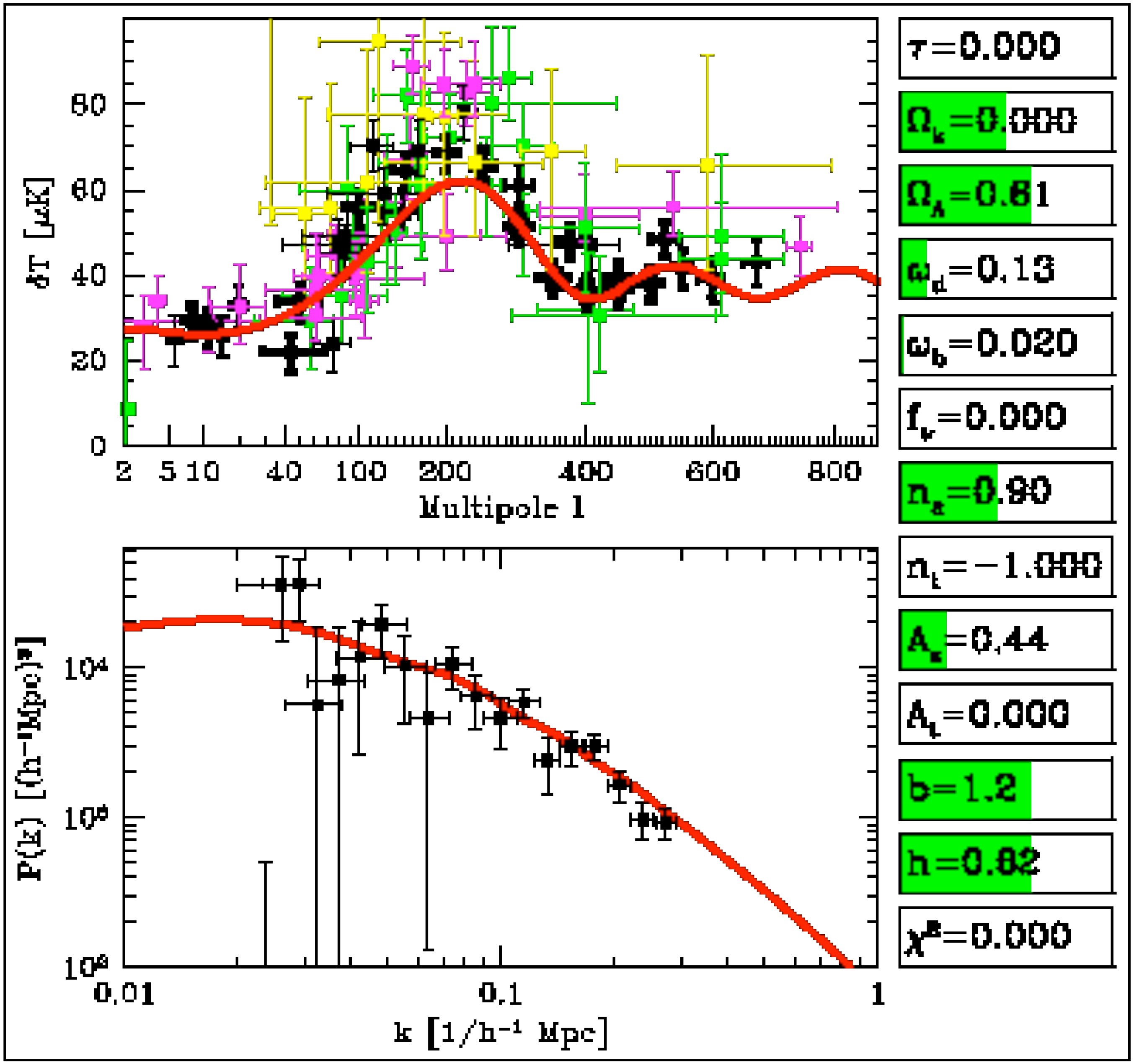
Results from WMAP



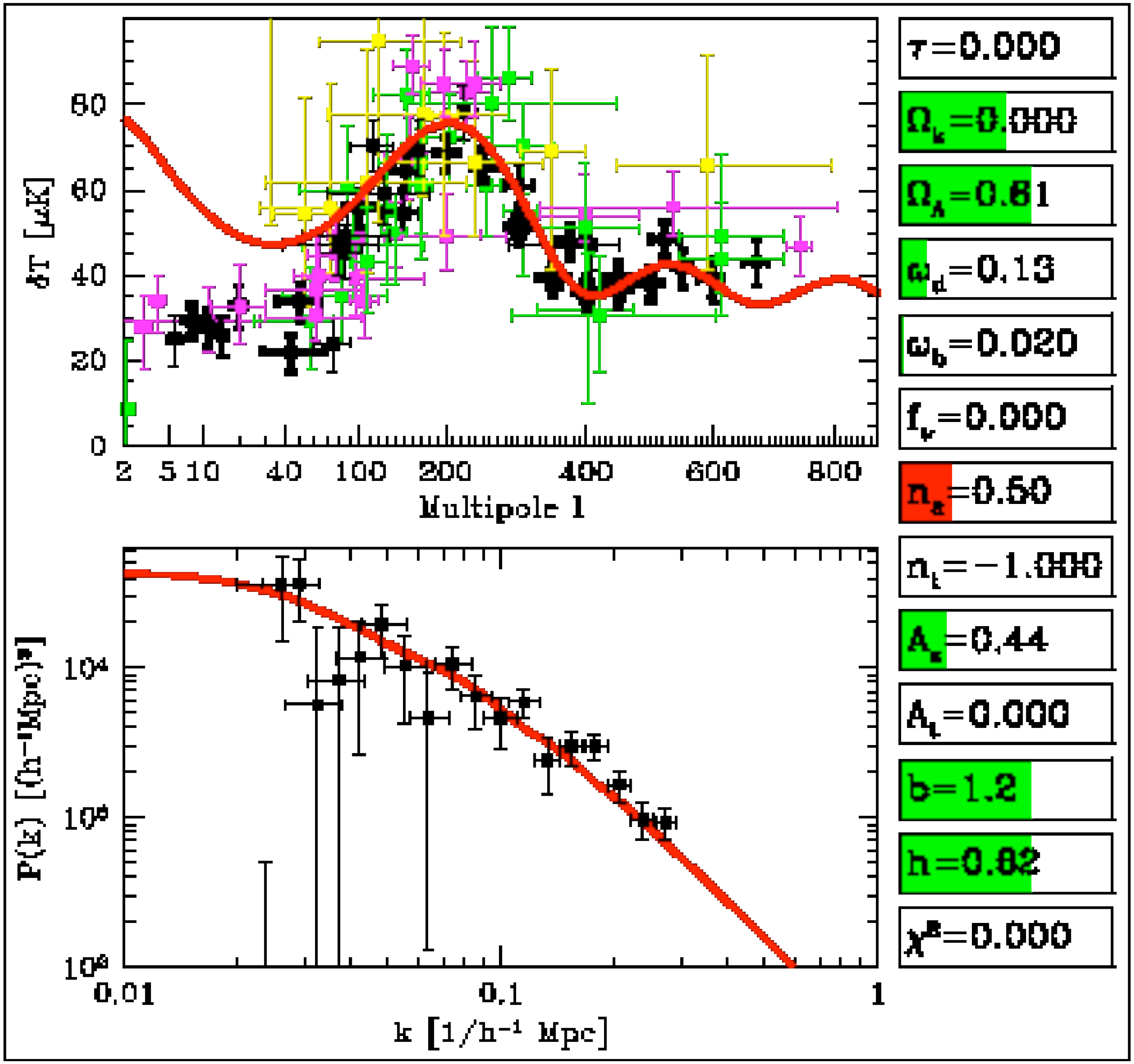


δT [μK]
Multipole l
P(k) [(h⁻¹Mpc)³]
k [1/h⁻¹ Mpc]
τ=0.000
Ωk=0.000
ΩΛ=0.61
ωd=0.020
ωb=0.020
fν=0.000
ns=0.90
nt=−1.000
As=0.44
At=0.000
b=1.2
h=0.32
χ²=0.000


δT [μK]
Multipole l
2 5 10 40 100 200 400 600 800
0 20 40 60 80
P(k) [(h⁻¹Mpc)³]
k [1/h⁻¹ Mpc]
0.01 0.1 1
τ=0.000
Ωk=0.000
ΩΛ=0.81
ωd=0.13
ωb=0.020
fν=0.000
ns=0.90
nt=−1.000
As=0.000
At=0.000
b=1.2
h=0.82
χ²=0.000

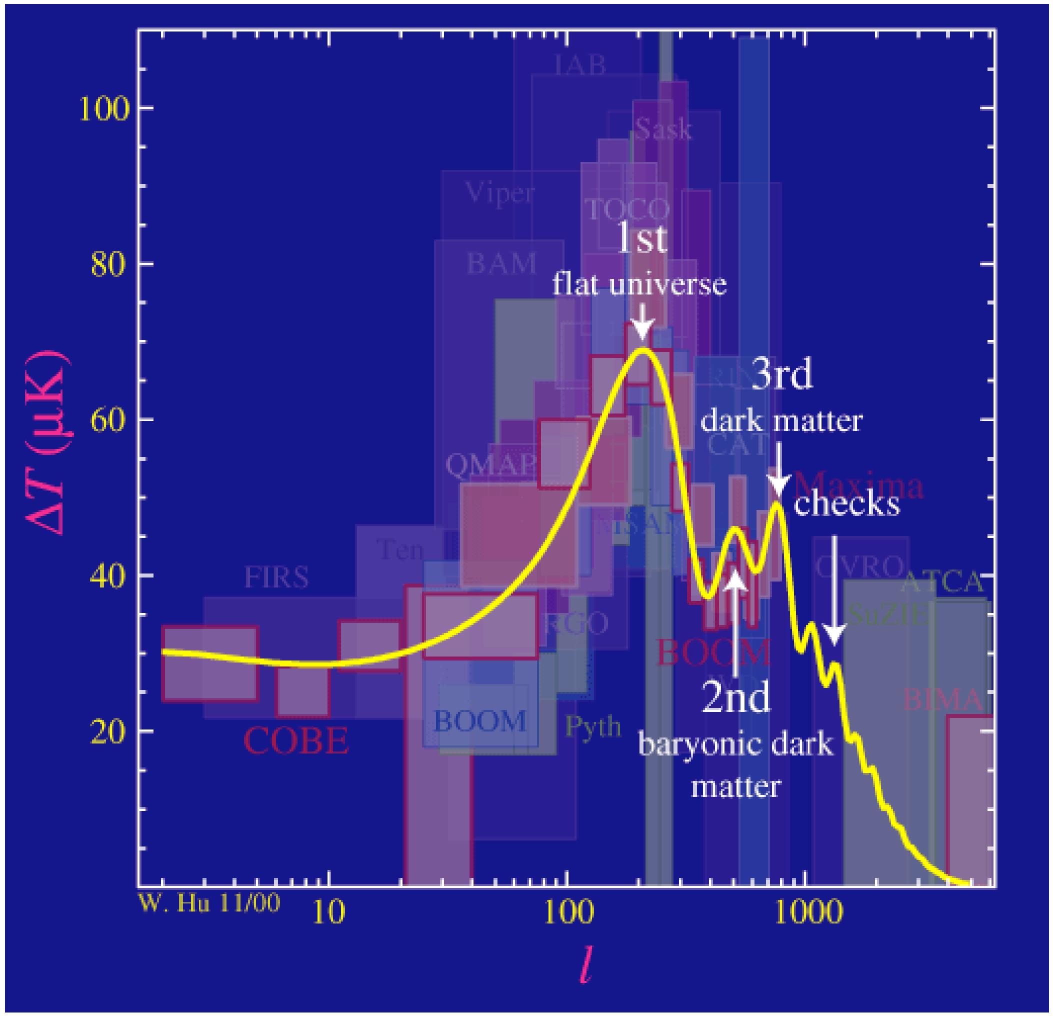


δT [μK]
Multipole l
P(k) [(h⁻¹Mpc)³]
k [1/h⁻¹ Mpc]
τ=0.000
Ω_k=0.000
Ω_Λ=0.81
ω_d=0.13
ω_b=0.020
f_ν=0.000
n_s=0.90
n_t=−1.000
A_s=0.44
A_t=0.000
b=1.2
h=0.82
χ²=0.000



δT [μK]
0
20
40
60
80
2 5 10 40 100 200 400 600 800
Multipole l
P(k) [(h⁻¹Mpc)³]
0.01
0.1
1
k [1/h⁻¹ Mpc]
τ=0.000
Ωk=0.000
ΩΛ=0.81
ωd=0.13
ωb=0.020
fν=0.000
ns=0.50
nt=−1.000
As=0.44
At=0.000
b=1.2
h=0.82
χ²=0.000

Summary



100
80
60
40
20
ΔT (μK)
W. Hu 11/00
10
100
1000
l
1st
flat universe
3rd
dark matter
checks
2nd
baryonic dark
matter
IAB
Sask
Viper
TOCO
BAM
QMAP
CAT
Maxima
FIRS
Ten
COBE
BOOM
Pyth
RGO
OVRO
ATCA
SuZIE
BIMA

What have we learned from WMAP?

1. NASA's Wilkinson Microwave Anisotropy Probe (WMAP) has mapped the Cosmic Microwave Background (CMB) radiation (the oldest light in the universe) and produced the first fine-resolution (0.2 degree) full-sky map of the microwave sky
2. WMAP definitively determined the age of the universe to be 13.73 billion years old to within 1% (0.12 billion years) -as recognized in the Guinness Book of World Records!
3. WMAP nailed down the curvature of space to within 1% of "flat" Euclidean, improving on the precision of previous award-winning measurements by over an order of magnitude
4. The CMB became the "premier baryometer" of the universe with WMAP's precision determination that ordinary atoms (also called baryons) make up only 4.6% of the universe (to within 0.1%)
5. WMAP's complete census of the universe finds that dark matter (not made up of atoms) make up 23.3% (to within 1.3%)

Three acoustic-peak observables:

A) angular scale,

B) photon-to-baryon ratio,

C) radiation-to matter ratio,

plus information about the shape of the initial power spectrum

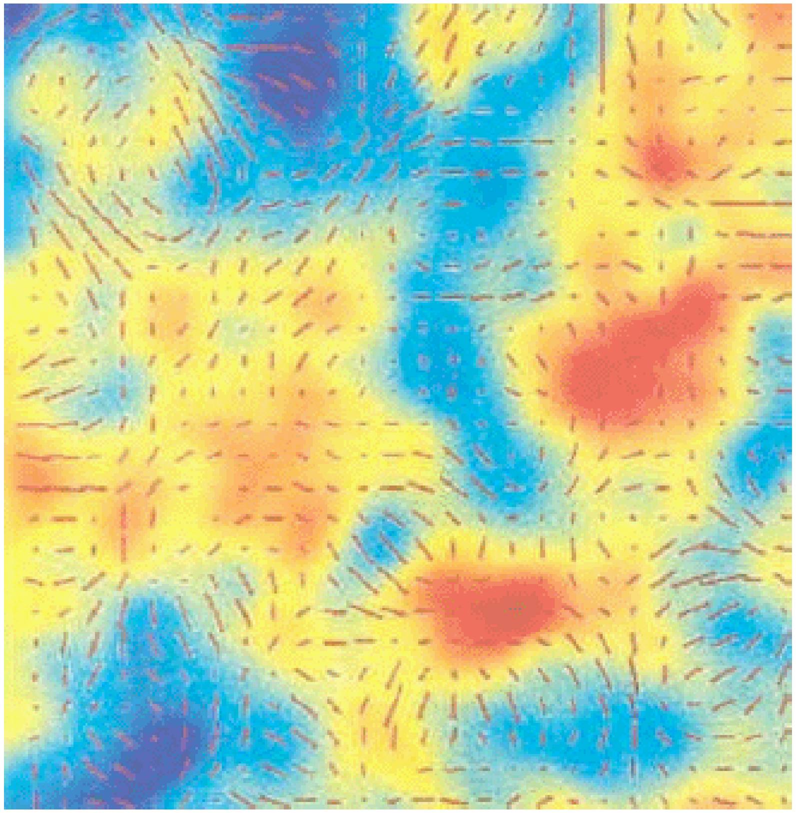
CMB polarization

- Imagine to look at a single point in the CMB sky. What you see is a train of electromagnetic waves that is travelling towards you. Their wavevectors would look like a point since you are viewing them head on.

- The electric and magnetic fields of the waves are perpendicular to each other and are also perpendicular to the wavevector.

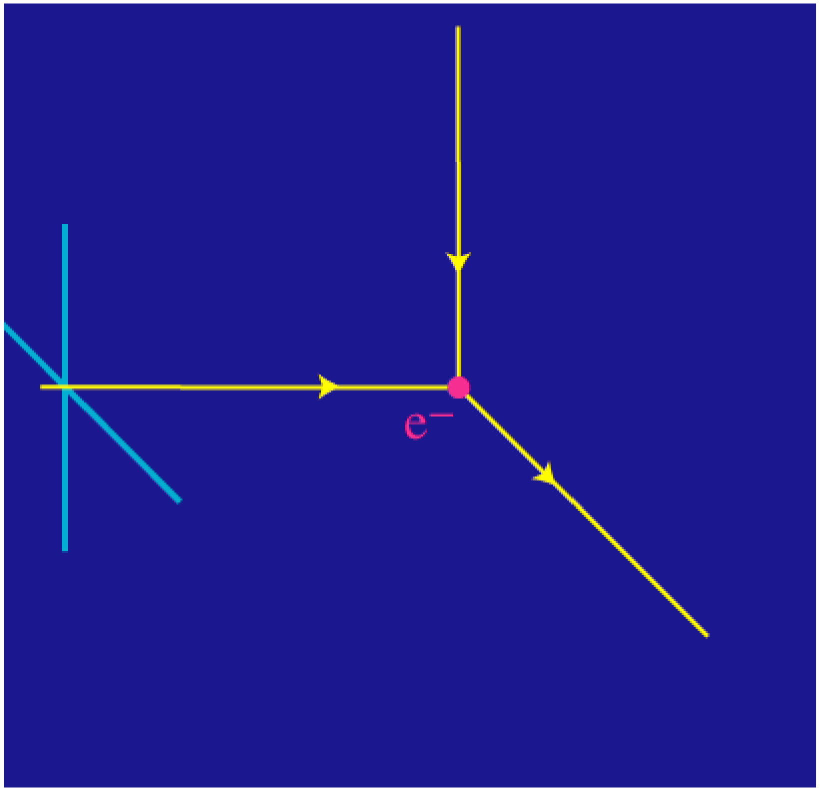
- Let us focus on the electric field. If we sum up over all the incident waves, it will have roughly the same intensity in each direction. However, there will be a direction that has a slightly greater magnitude of E than the other directions. This is the direction of the polarization. This line however is not a vector because we have no meaningful way to say which way this line "points". It only takes a rotation of 180 degrees to come around to the same orientation (as opposed to 360 for a vector), therefore it a spin-2 field on the sphere.

CMB polarization



- We can represent polarization as a line in the direction of the largest E and with length proportional to the excess magnitude of the electric field.
- Here you can see how the polarization pattern might look like on a small patch of the CMB (the colors indicate temperature fluctuations)

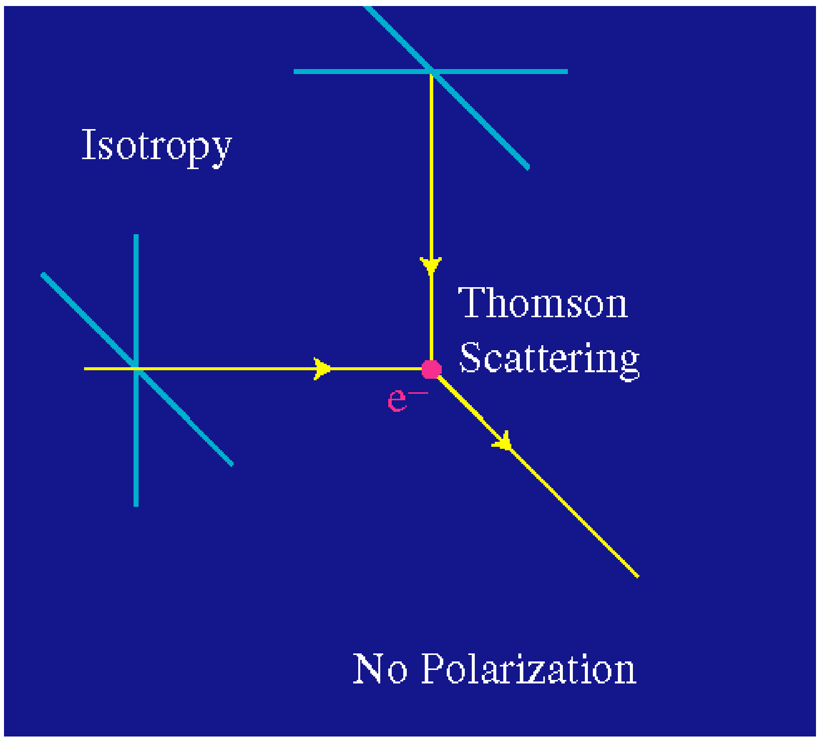
Thomson scattering



$$\frac{d\sigma}{d\Omega} = \left(\frac{e^2}{4\pi mc^2}\right)^2 |\hat{\epsilon} \cdot \hat{\epsilon}'|^2$$

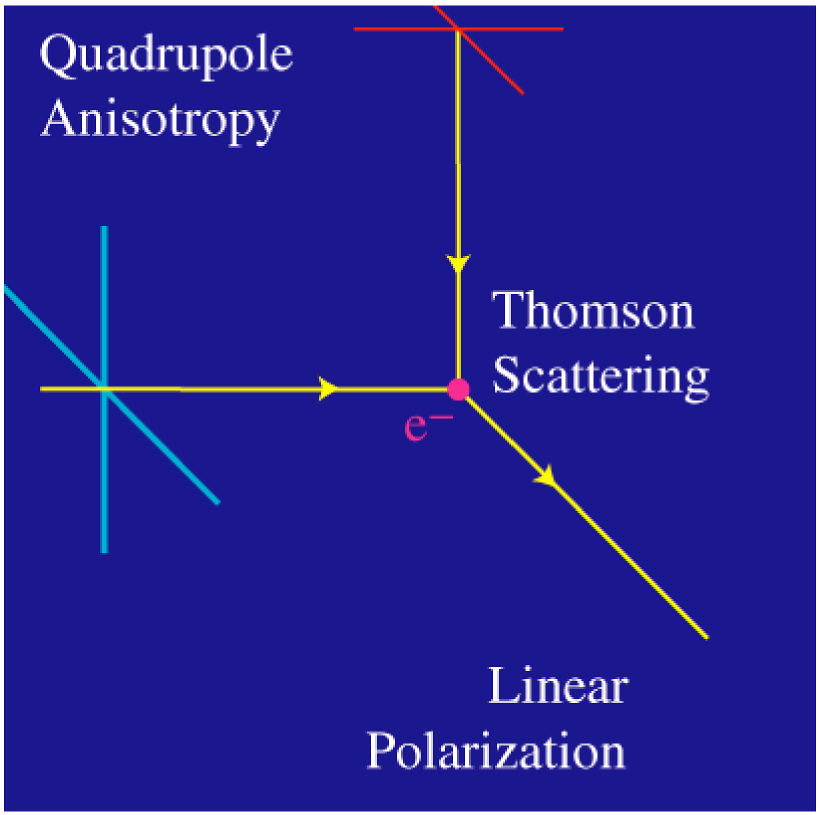
- The differential cross-section for Thomson scattering, $d\sigma/d\Omega$, depends on the initial and final linear polarization states of the photon
- Consider an electron, and incoming radiation from the left with no net polarization
- We are interested in radiation scattered by 90 degrees out of the screen
- Since electromagnetic waves are transverse (i.e. cannot be polarized along the direction of propagation), only one linear polarization is possible

Thomson scattering II

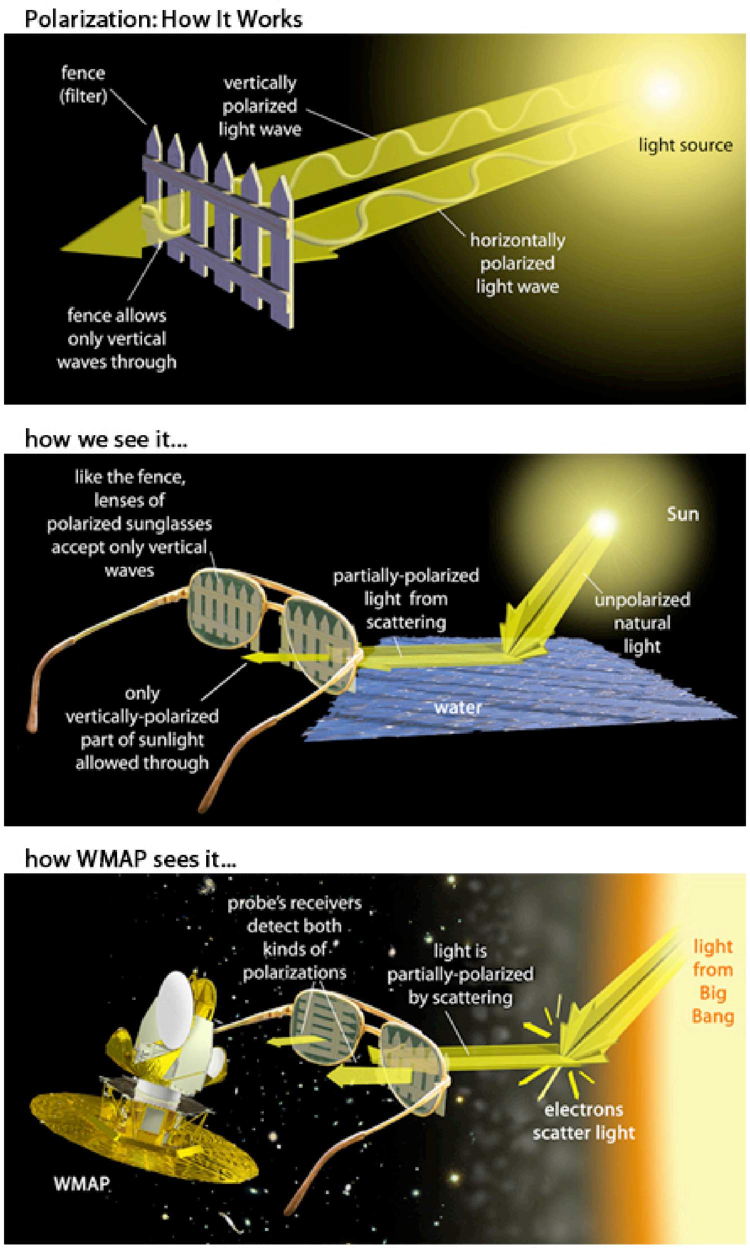


- An electron near the last-scattering surface, however, sees radiation coming from every direction
- Consider now radiation coming both from the left and from the top with equal intensity
- The result is no net polarization in the outgoing direction

Thomson scattering III

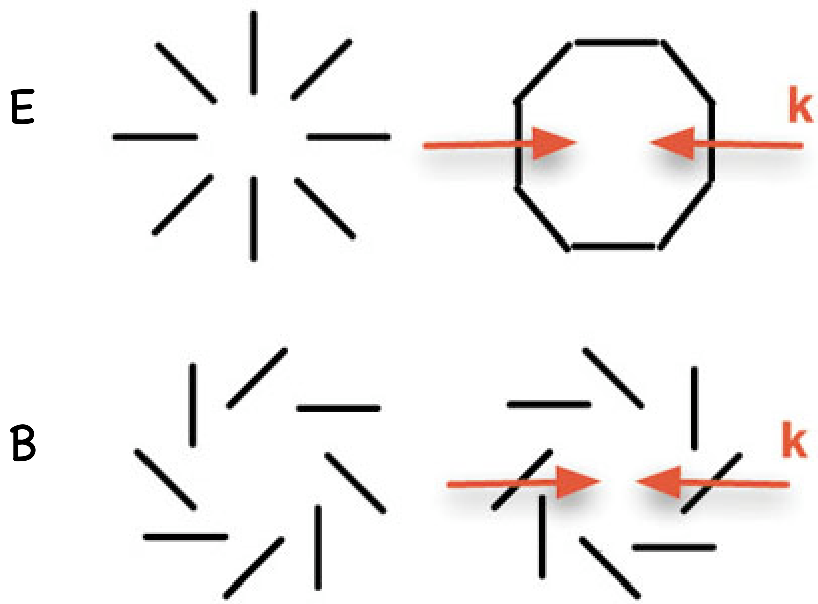


- Only if the angular distribution of radiation (as seen by the electron) has a quadrupole pattern (i.e. the intensity varies between directions at 90 degrees) then a net linear polarization results
- In particular the polarization is aligned with the cold (red) axis of the quadrupole anisotropy



The only epochs in cosmic history that provide the appropriate conditions for significant CMB polarization are recombination and reionization.

E-B decomposition



Parity: $(-1)^l$ for E and $(-1)^{l+1}$ for B

E-modes: $\Pi_{ab} = \left(\nabla_a \nabla_b - \frac{1}{2}\delta_{ab}\nabla^2\right)\phi.$

B-modes: $\Pi_{ab} = \left(\frac{1}{2}\epsilon_a{}^c \nabla_b \nabla_c + \frac{1}{2}\epsilon_b{}^c \nabla_a \nabla_c\right)\phi.$

- We can break down the polarization field into two components which we call E and B modes. This is the spin-2 analog of the gradient/curl decomposition of a vector field.
- E modes are generated by density (scalar) perturbations via Thomson scattering.
- B modes are generated by gravity waves (tensor perturbations) at last scattering or by gravitational lensing (which transforms E modes into B modes along the line of sight to us) later on

Power spectra

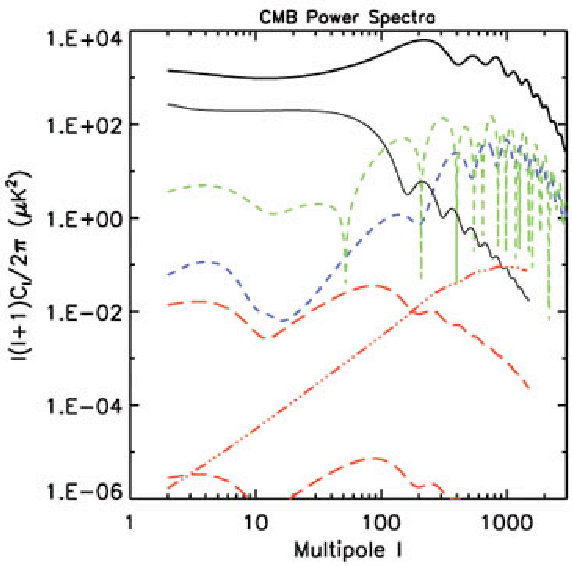
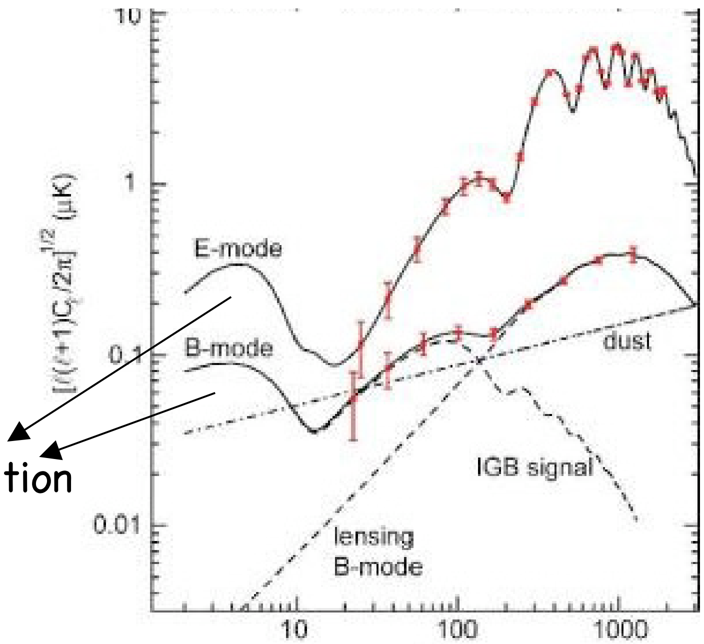


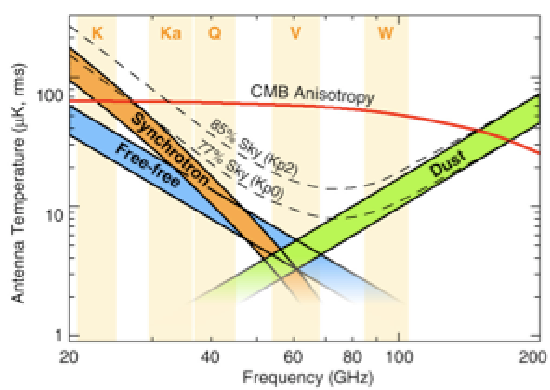
FIG. 2: Angular power spectra. The bold solid black line shows the temperature power spectrum from scalar perturbations in the standard flat model (WMAP 3–year values were adopted: $(\Omega_M h^2, \Omega_B h^2, h, n_s, \tau, \sigma_8) = (0.127, 0.0223, 0.73, 0.951, 0.09, 0.74)$ [15]), while the thin black line gives the temperature perturbations from tensor perturbations when $r = 0.5$. The green (upper) and blue (lower) short dashed curves are, respectively, the scalar TE (absolute value shown) and EE power spectra for the standard model; the former is well measured on large scales by WMAP [26]. The red long dashed lines indicate the tensor B–mode power for $r = 0.5$ (upper) and $r = 10^{-4}$ (lower). Gravitational lensing produces the B–mode power shown as the red 3–dot–dashed curve peaking at $l \sim 1000$.

- The temperature fluctuations (T) and the E and B modes of the polarization can be combined into 6 different angular power spectra: C^{TT}, C^{TE}, C^{TB}, C^{EE}, C^{EB}, C^{BB}.
- Since we do not think that primordial perturbations have a preferred parity, C^{TB} and C^{EB} are expected to vanish.
- We are therefore left with 4 fundamental observables

The polarization power spectrum



reionization

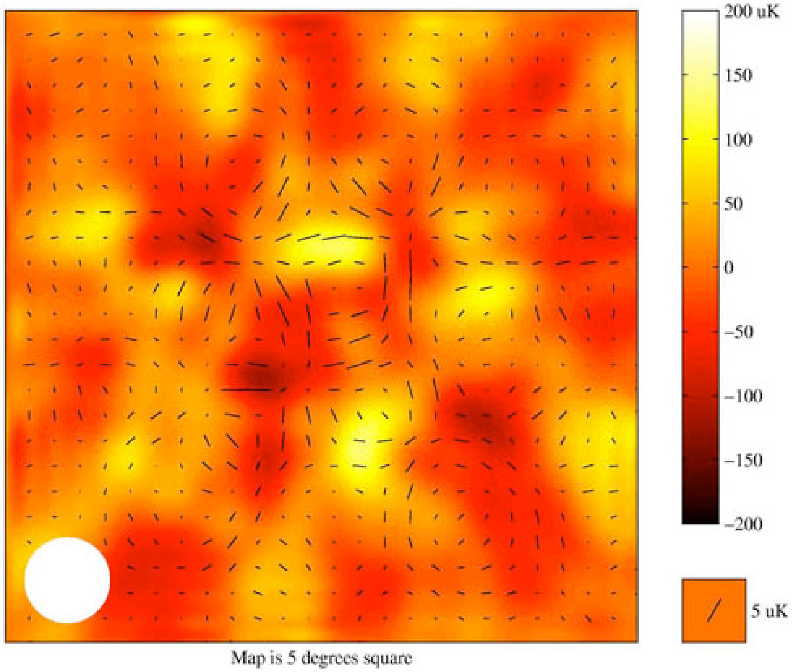


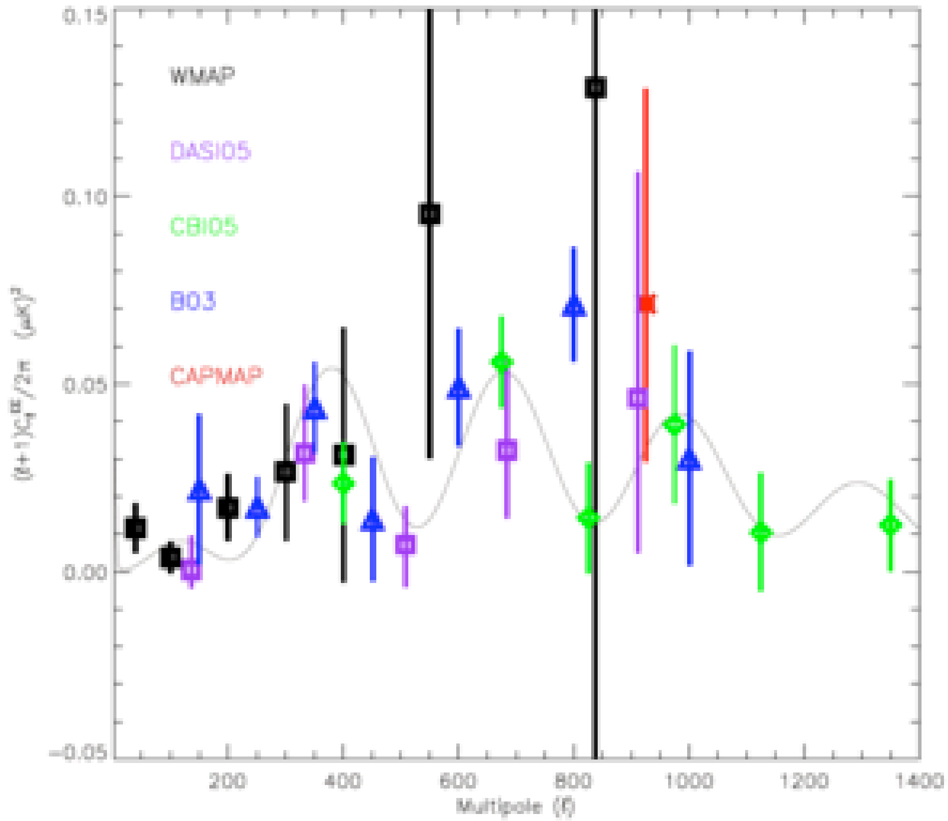
- The primordial B-mode signal (due to a stochastic background of gravitational waves) dominates only at intermediate angular scales
- On very large scales, the polarization signal is dominated by secondary fluctuations imprinted by reionization
- The lens-generated signal grows at smaller scales
- Dust will be a prominent foreground contaminant for B-mode detection

Current data

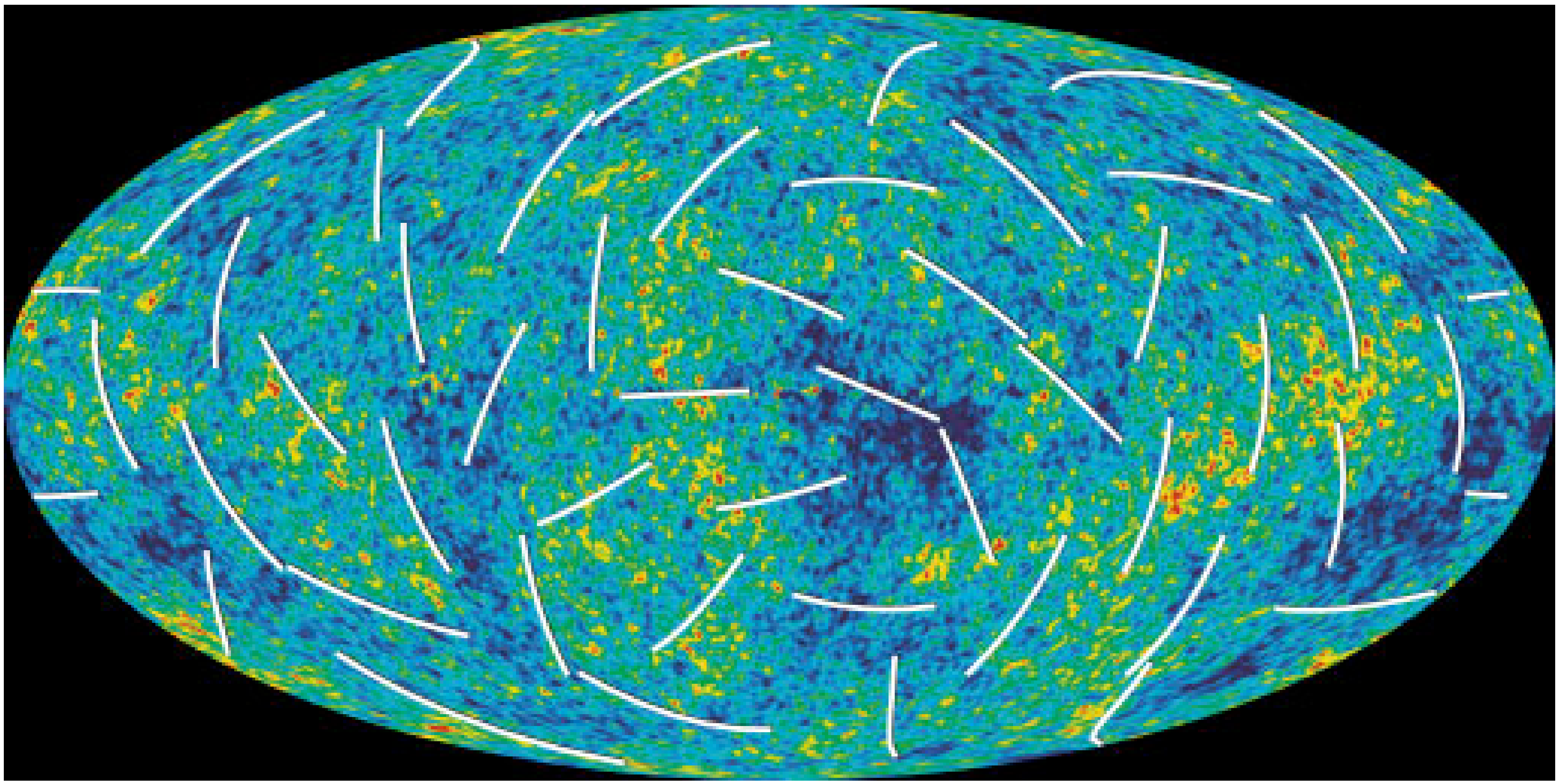
- The DASI experiment at the South Pole was the first to detect E-mode CMB polarization
- It was followed by WMAP's measurement of $C^{TE}(l)$ for $l<500$
- Both the BOOMERANG and the CBI experiments have reported measurements of C^{TT}, C^{TE} , C^{EE} and a non-detection of B modes
- E-mode has also been measured by CAPMAP and Maxipol
- B-mode polarization has not been detected yet (current noise level is 50 μK at the arcmin scale, future ground-based experiment will go down to 5 μK)

DASI 2002

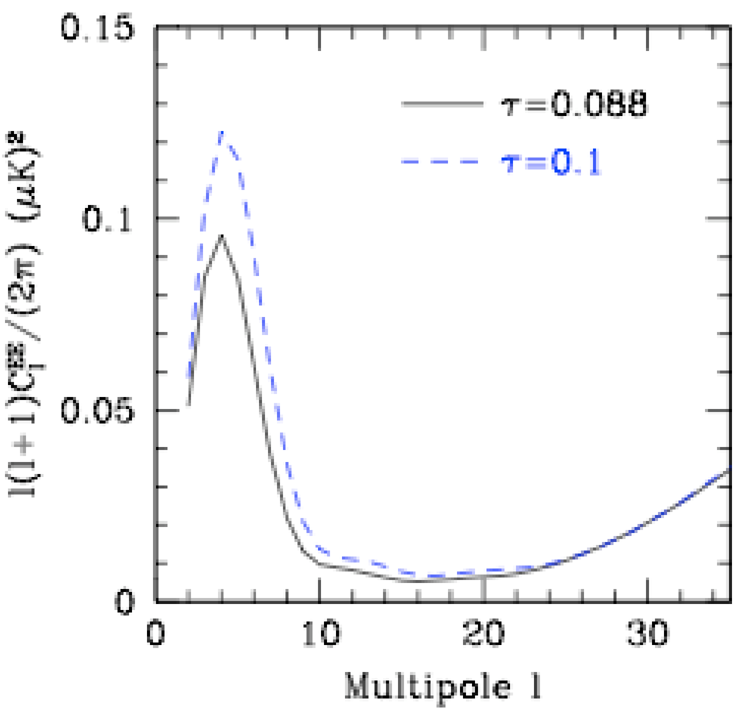



WMAP
DASI05
CBI05
B03
CAPMAP
0.15
0.10
0.05
0.00
−0.05
200
400
600
800
1000
1200
1400
Multipole (ℓ)

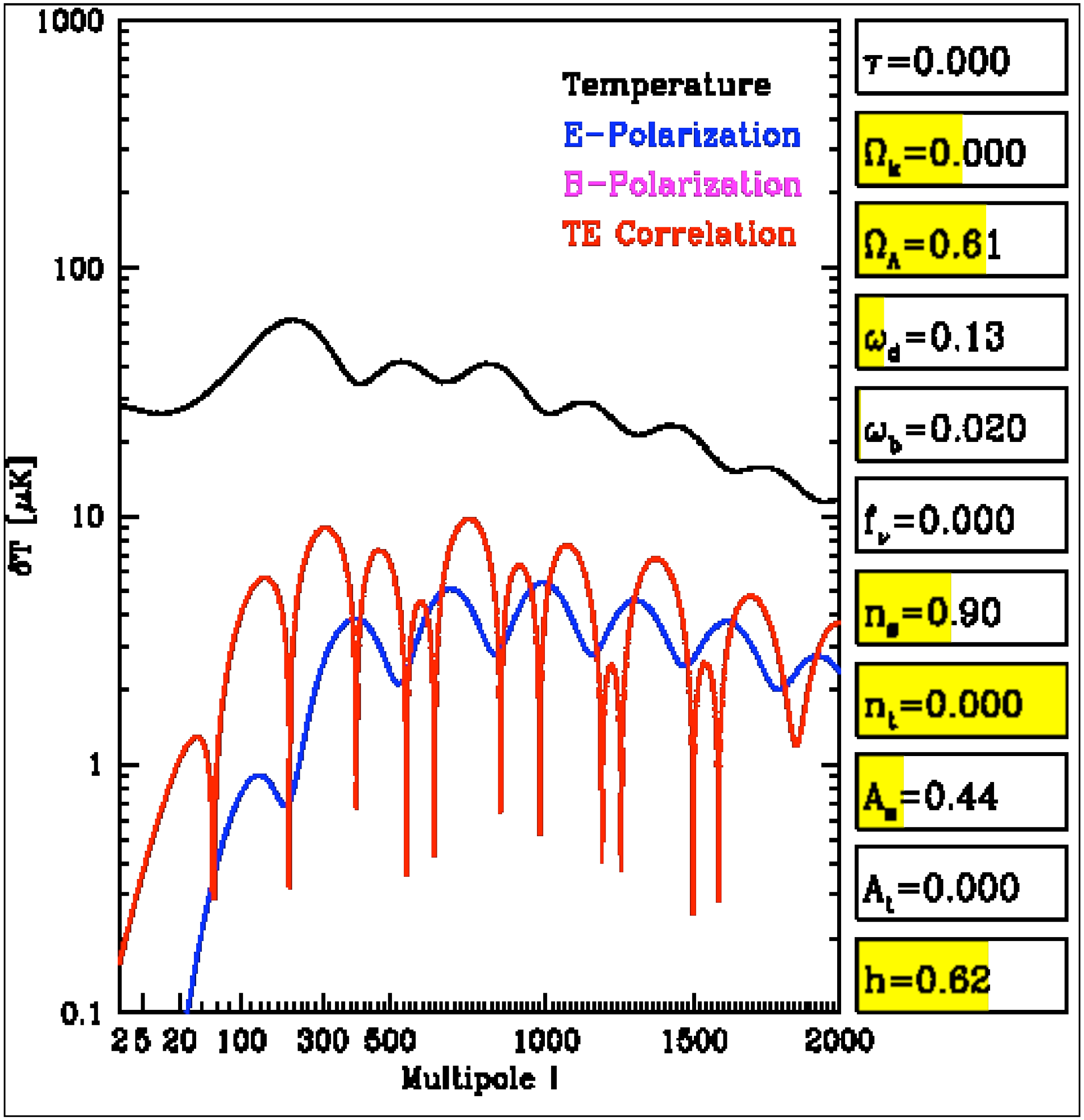
The WMAP measurement



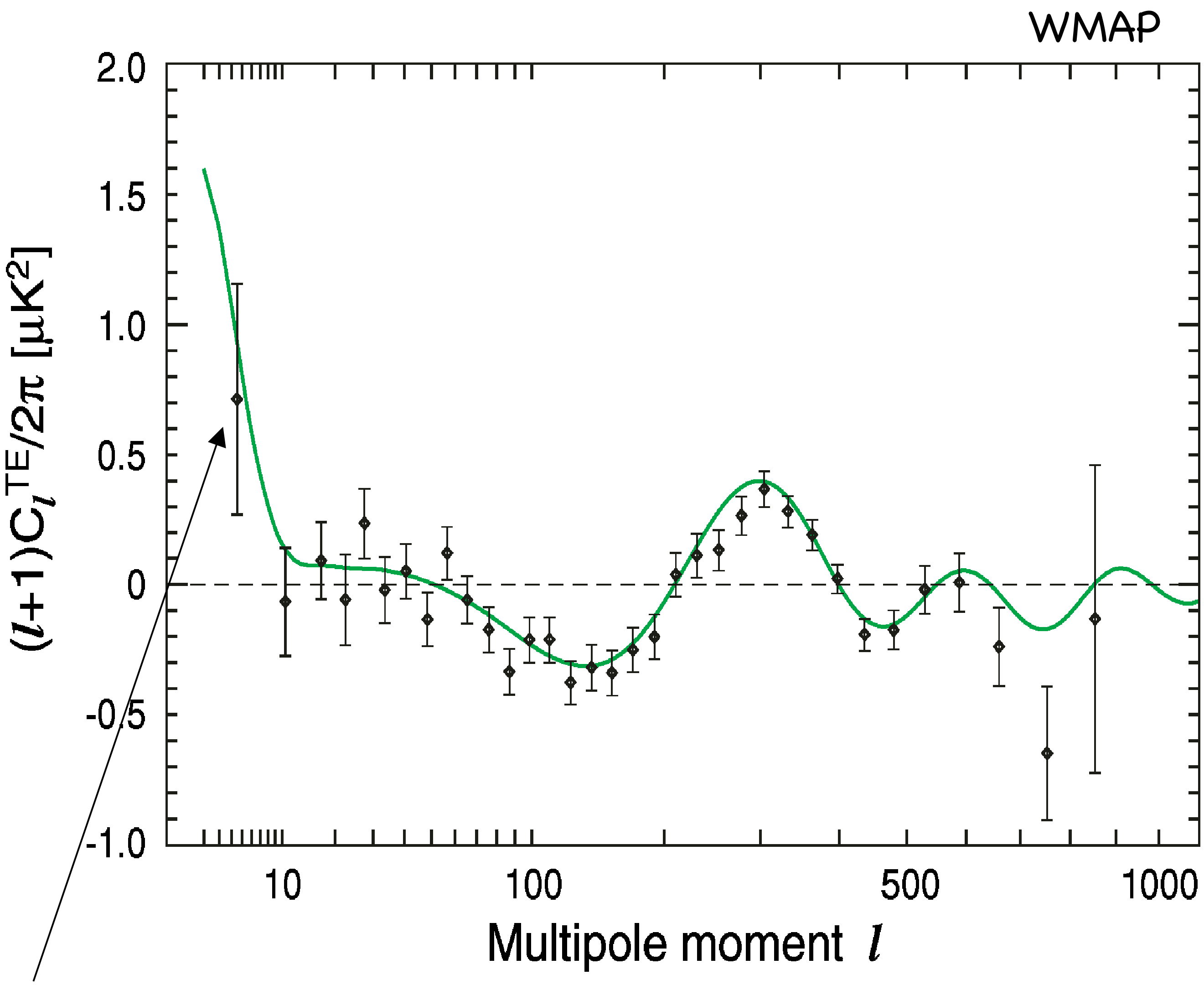
Polarization and reionization



- The spectrum of temperature anisotropies is nearly perfectly degenerate in the amplitude of primordial fluctuations, A, and the reionization optical depth, τ
- The amplitude scales as A $e^{-2\tau}$ (photons are scattered off the line of sight by free electrons)
- Low multipoles in C^{EE} measure τ and break the degeneracy



Temperature
E-Polarization
B-Polarization
TE Correlation
δT [μK]
1000
100
10
1
0.1
2 5 20 100 300 500 1000 1500 2000
Multipole l
τ=0.000
Ω_k=0.000
Ω_Λ=0.61
ω_d=0.13
ω_b=0.020
f_ν=0.000
n_s=0.90
n_t=0.000
A_s=0.44
A_t=0.000
h=0.62



Re-scattering of CMB photons during and after reionization added to the polarization spectrum at small angular scales.

Current results

- The combined analysis of the WMAP 5-yr data (temperature and polarization) gives $\tau = 0.087 \pm 0.017$.
- This means that nearly 9% of the CMB photons have been re-scattered by free electrons produced by the reionization process.
- Assuming that the universe was reionized instantaneously, this gives $z_{reion} = 11.0 \pm 1.4$
- This is only an indicative result as reionization is likely to have been extended in time.

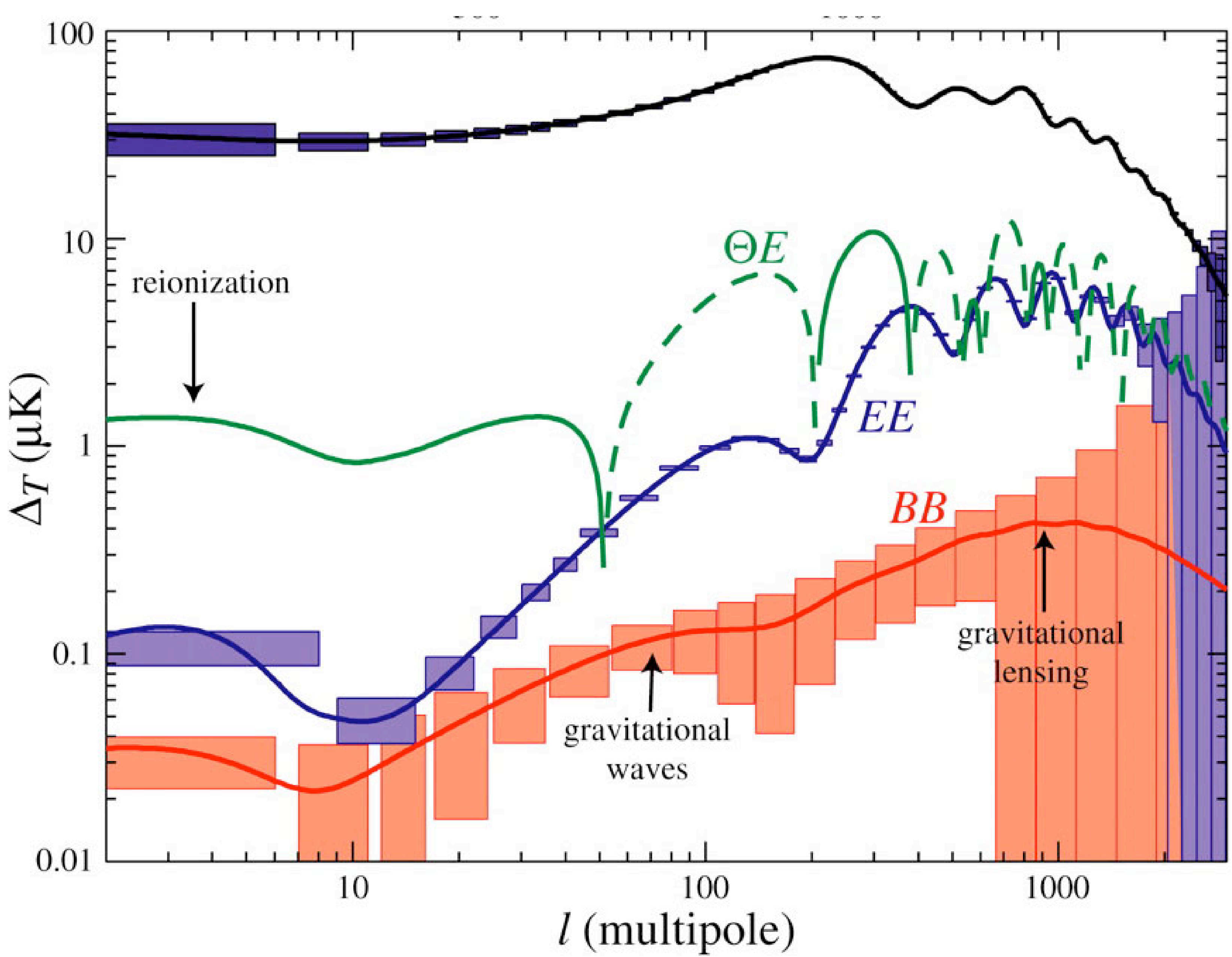
Why measuring polarization?

- Differentiating between scalar (density fluctuations) and tensor (gravity waves) modes

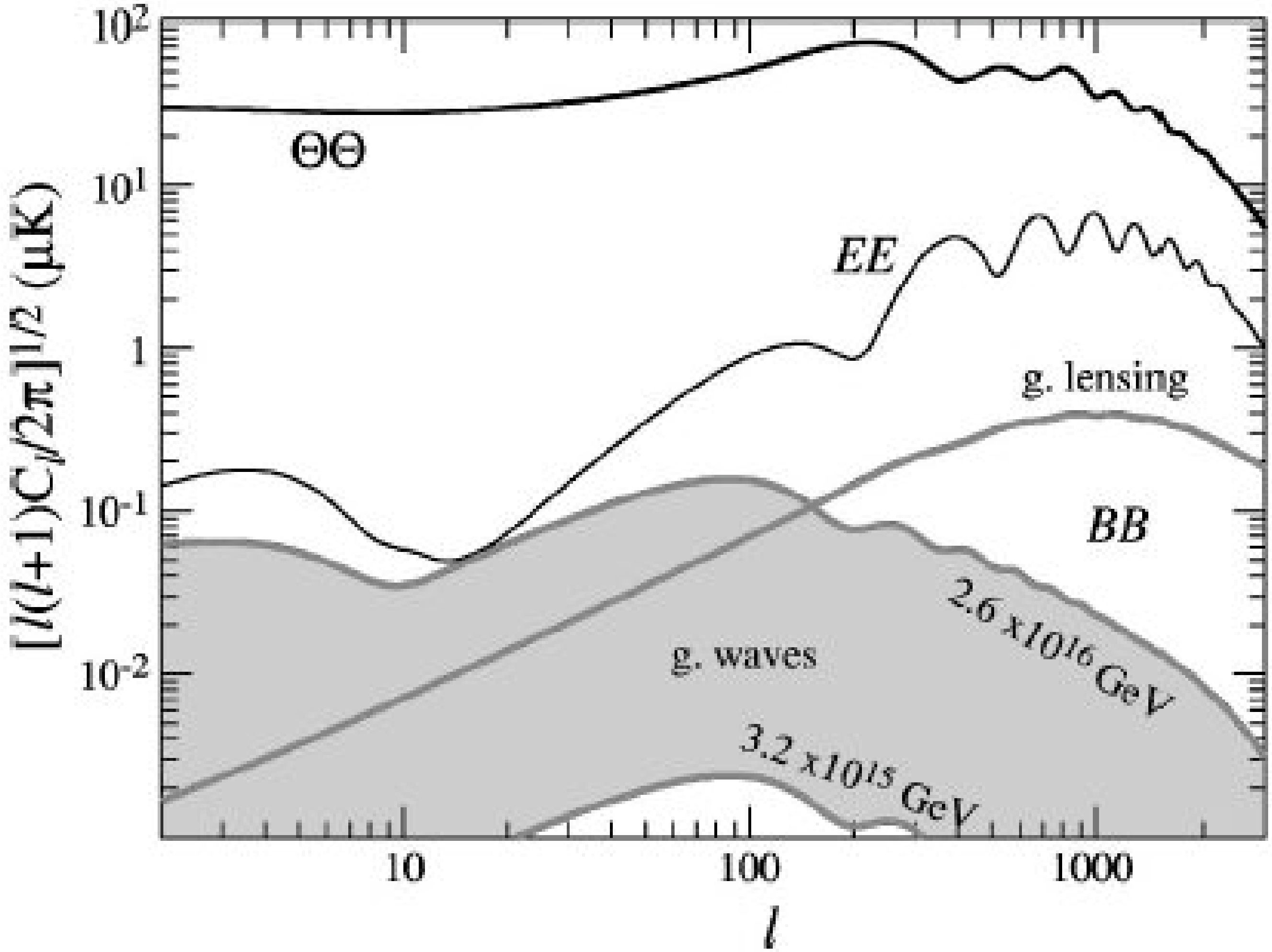
- Consistency checks for the cosmological parameters estimated from temperature fluctuations (and also removal of degeneracies between some parameters)

- Constrain the redshift of reionization

- Constrain the amplitude of the power spectrum of density fluctuations through the gravitational lensing effect


100
10
1
0.1
0.01
Δ_T (μK)
10
100
1000
l (multipole)
reionization
ΘE
EE
BB
gravitational lensing
gravitational waves

Can we detect gravitational waves?



The future: the Planck satellite

- Medium-Sized Mission (M3) part of ESA's Cosmic Vision Programme
- Planned to launch on May 14 2009 on an Arianne 5 from Kourou (French Guyana)
- Much better sensitivity, angular resolution and frequency range than previous experiments
- A complete science case can be downloaded from www.rssd.esa/SA/PLANCK/docs/Bluebook-ESA-SCI(2005)1_V2.pdf
- The total cost of the Planck mission is about 700 MEUR

The Planck satellite

- Planck is 4.2m high and has a similar maximum diameter
- It carries a telescope with an effective aperture of 1.5m that feeds microwave radiation to two instruments:
- The Low Frequency Instrument (LFI) is an array of 22 radio receivers that will image the sky at 3 frequencies between 30 and 70 GHz
- The High Frequency Instrument (HFI) is an array of 52 bolometers that will image the sky at 6 frequencies between 100 GHZ and 857 GHz

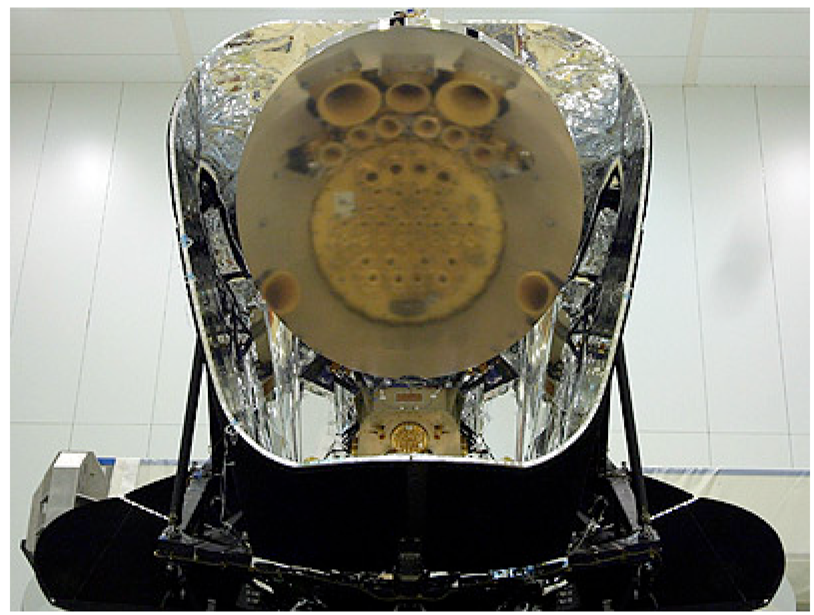


Photo: ESA

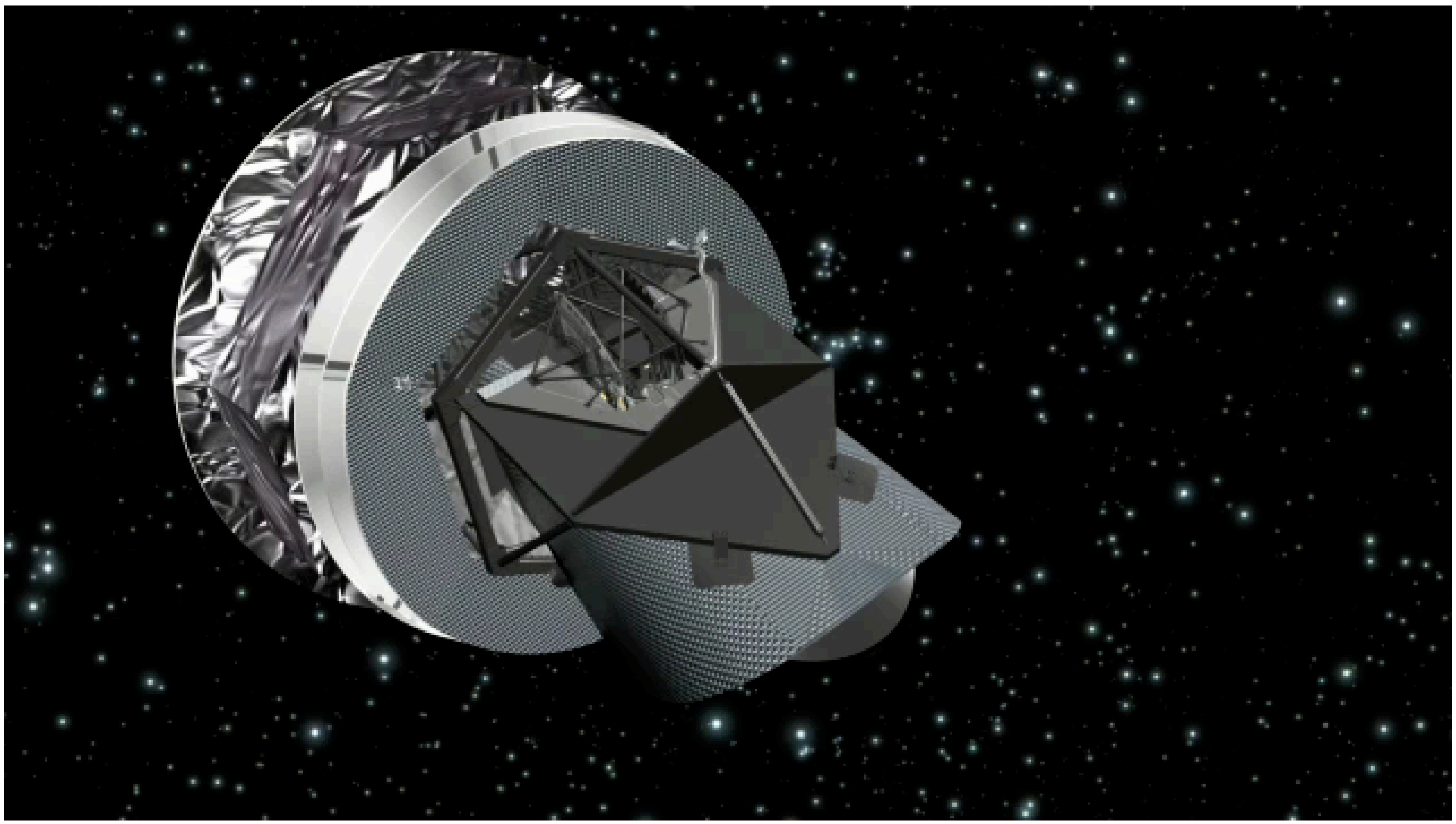
The Planck mission

Photo: ESA

- Planck will enter its operational L2 orbit (1.5 Mkm from Earth) two months after launch
- It will start scientific observations one month later
- The science observation will last 15 months allowing 2 sky surveys
- The mission could be further extended by one year depending on the resources still available for cooling the instruments

The Planck mission

Movie: ESA



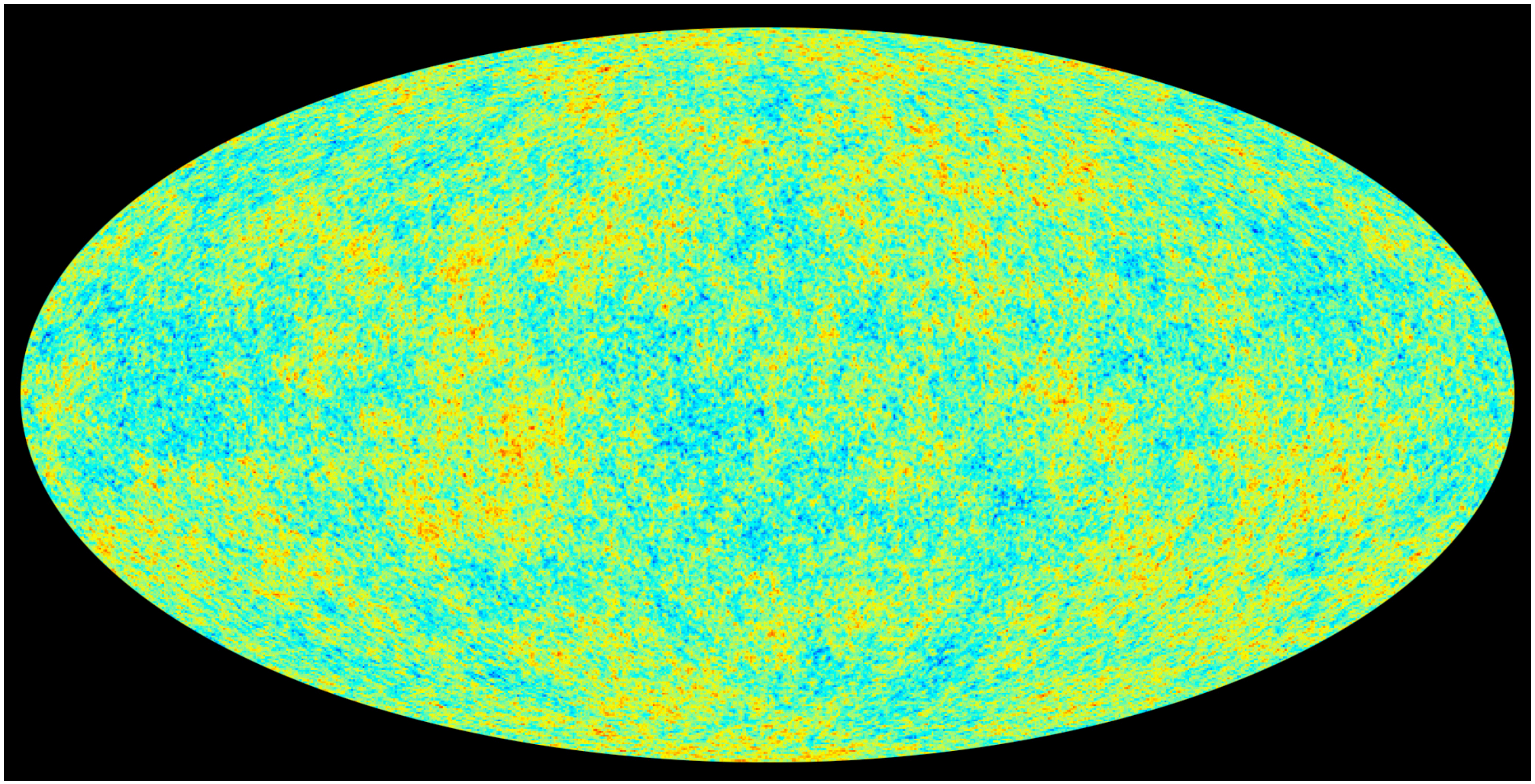
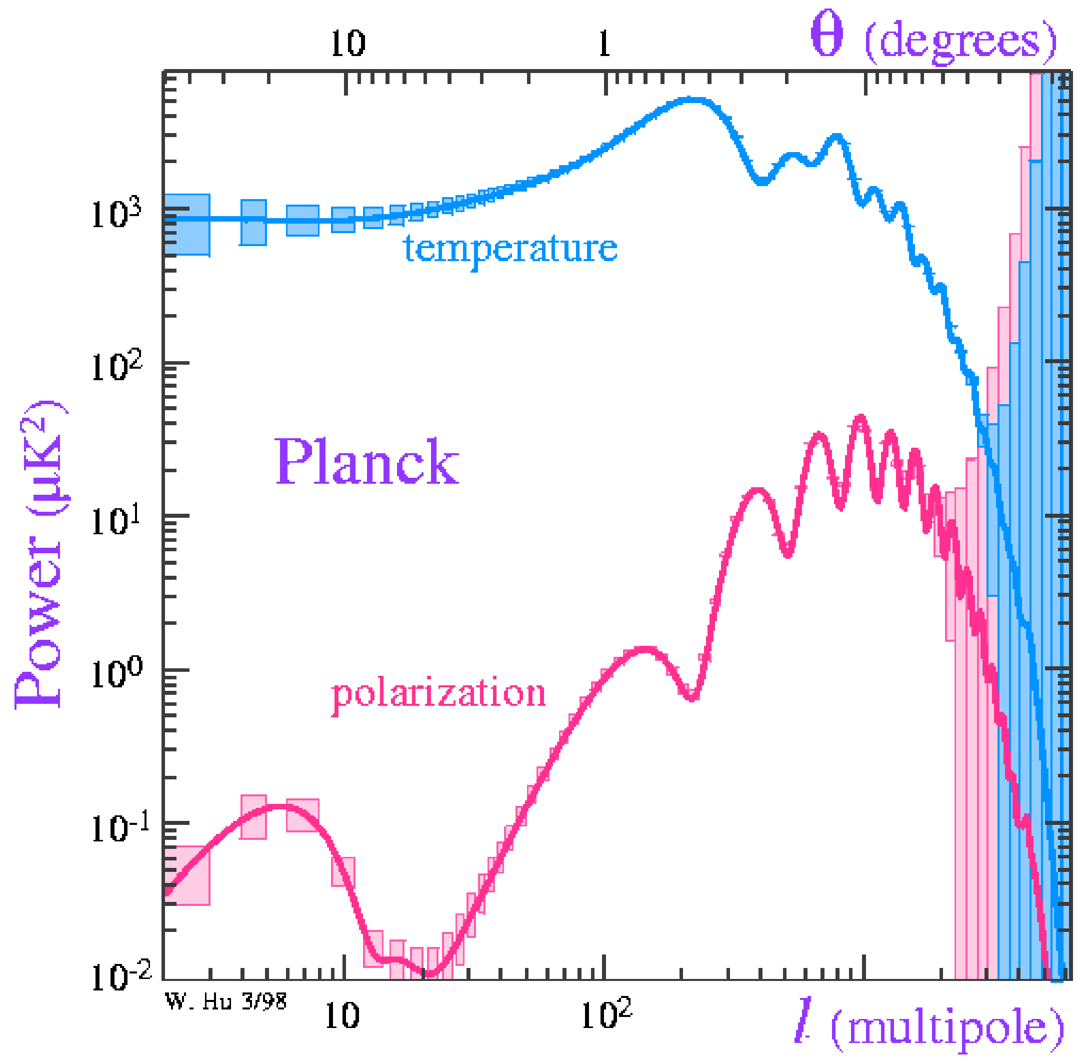
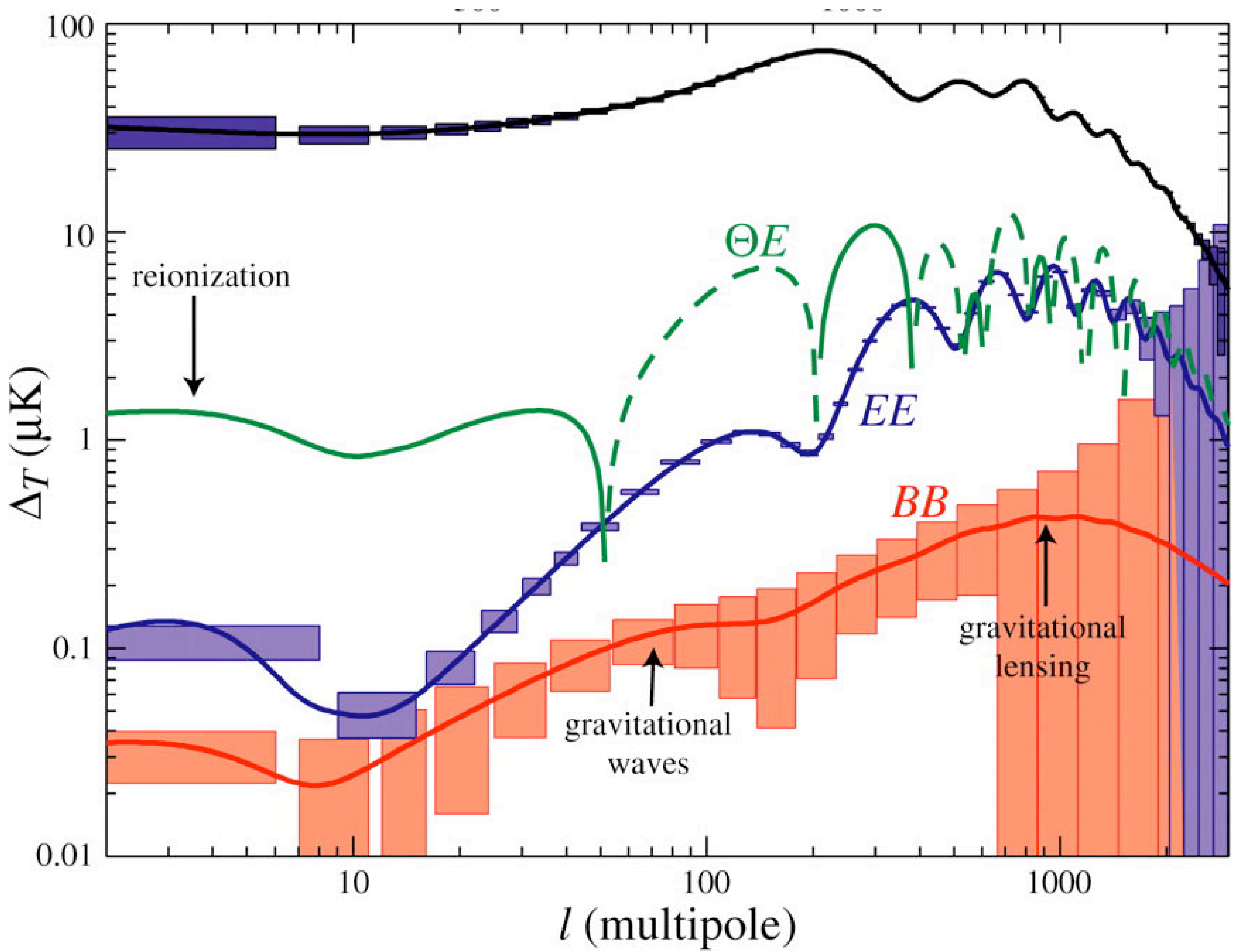


Photo: ESA

Forecast of Planck spectra




100
10
1
0.1
0.01
10
100
1000
Δ_T (μK)
l (multipole)
reionization
ΘE
EE
BB
gravitational waves
gravitational lensing

The future is bright

- The Planck satellite will greatly advance our knowledge of CMB polarization by providing foreground/cosmic variance-limited measurements of C^{TE} and C^{EE} (and C^{TT}) out beyond $l \sim 1000$. We also expect to detect the lensing signal, although with relatively low precision, and could see gravity waves at a level of $r \sim 0.1$.

- A leap in instrument sensitivity is required in order to go beyond Planck and get at the B-modes from lensing and gravity waves. This important science goal is motivating a vast effort world wide at developing a new generation of instruments based on large detector arrays. Numerous ground-based and ballon-borne experiments are actually observing or being prepared.

- In the longer term future, both NASA (Beyond Einstein) and ESA (Cosmic Vision) have listed a dedicated CMB polarization mission as a priority in the time frame 2015-2020. Such a mission could reach the cosmic variance limit on the lensing power spectrum to measure the neutrino mass scale and perhaps detect primordial gravity waves from inflation near the GUT scale.