Lectures on Cosmic Microwave Background

Eiichiro Komatsu (Texas Cosmology Center, Univ. of Texas, Austin)
KEK Winter School, Kusatsu, February 10-12, 2009

From "Cosmic Voyage"

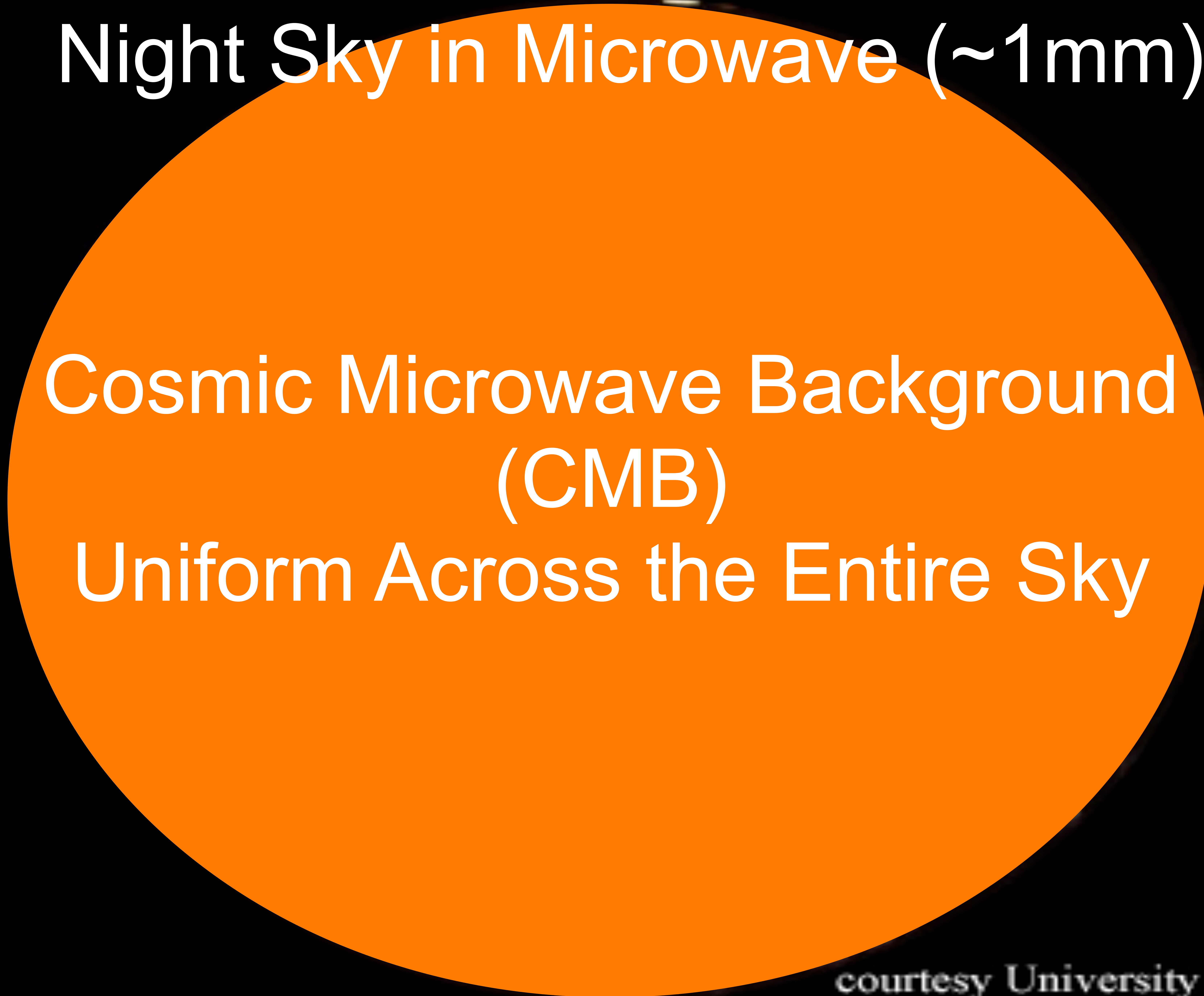
Night Sky in Optical (~500nm)

courtesy University of Arizona

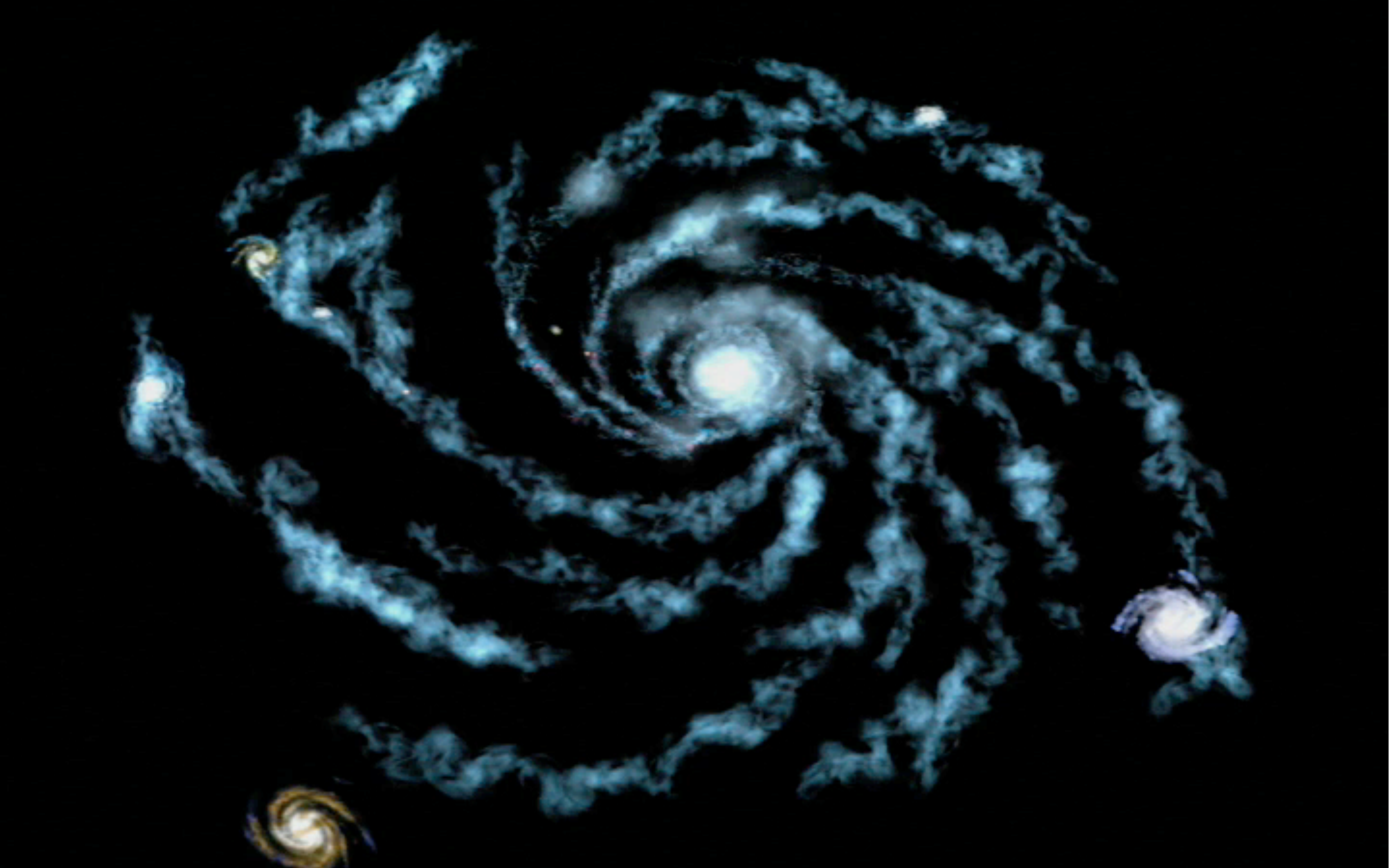
Night Sky in Microwave (~1mm)

courtesy University of Arizona

Night Sky in Microwave (~1mm)



courtesy University of Arizona



Birth of CMB

~1950

G. Gamow, 1948

The Origin of Elements and the Separation of Galaxies

G. Gamow
George Washington University, Washington, D. C.
June 21, 1948

THE successful explanation of the main features of the abundance curve of chemical elements by the hypothesis of the "unfinished building-up process,"[1,2] permits us to get certain information concerning the densities and temperatures which must have existed in the universe during the early stages of its expansion. We want to discuss here some interesting cosmogonical conclusions which can be based on these informations.

Determination of physical conditions in the early universe

The value of $\rho_{\mathrm{mat.}}{}^{\circ}$ can be estimated from the fact that during the time period Δt of about 10^2 sec. (which is set by the rate of expansion), about one-half of original particles were combined into deuterons and heavier nuclei. Thus we write:

$n+p \rightarrow D+\gamma$

$$v \Delta t n \sigma \cong 1 \tag{5}$$

where $v=5\cdot 10^8$ cm/sec. is the thermal velocity of neutrons at 10^9 °K, n is the particle density, and $\sigma \cong 10^{-29}$ cm² the capture cross section of fast neutrons in hydrogen. This gives us $n \cong 10^{18}$ cm^{-3} and $\rho_{\mathrm{mat.}}{}^{\circ} \cong 10^{-6}$ g/cm³ substantiating our previous assumption that matter density was negligibly small compared with the radiation density.

Why is it so important?

- The baryon number density was $\sim 10^{18}$ cm^{-3} when temperature was 10^9 K.
- It's $\sim 10^{-7}$ cm^{-3} now.
- Since the baryon number density scales as (radius of the universe)$^{-3}$ $\sim$(temperature)^3, we get for the present-day temperature

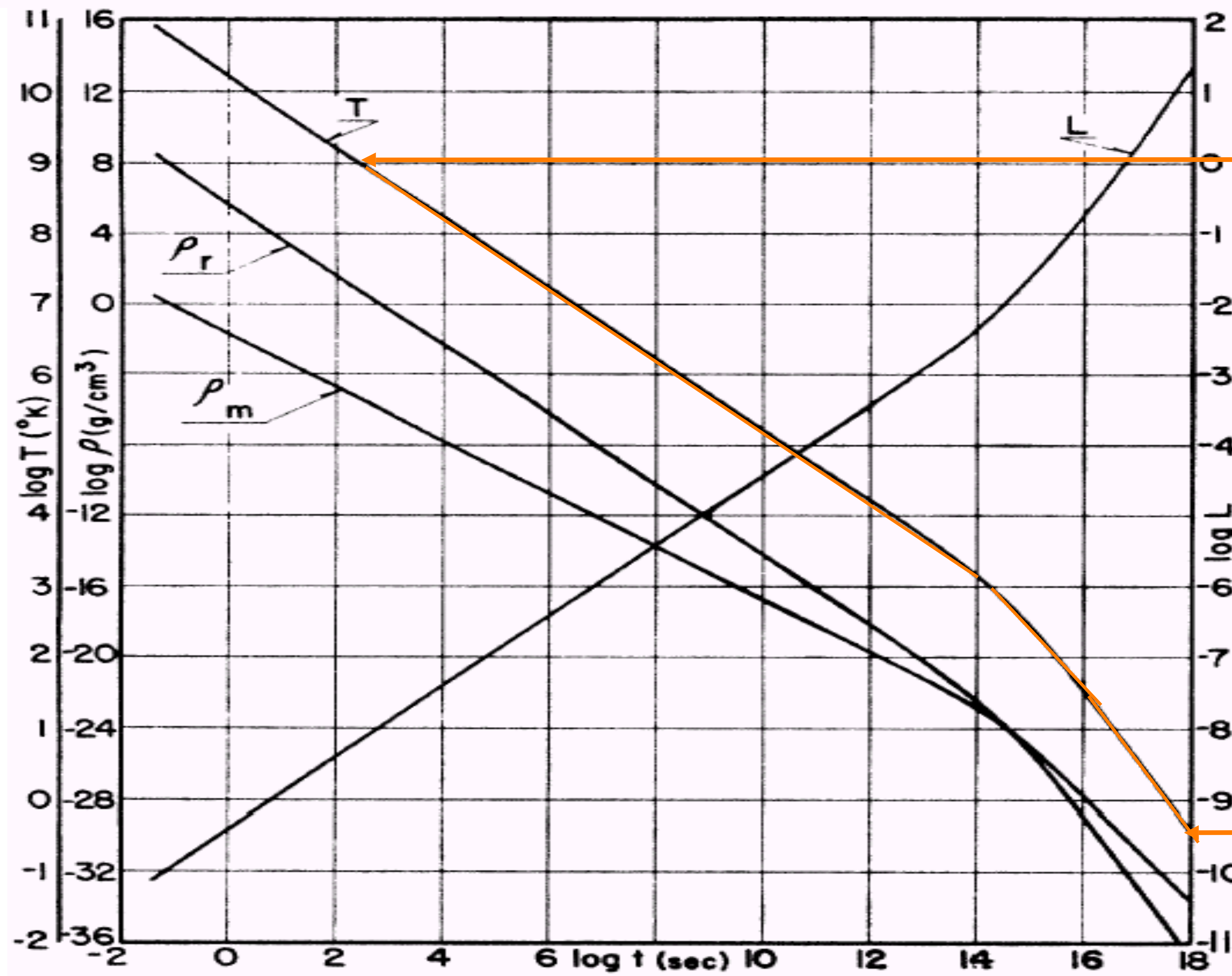
$$T_0 \sim 10^9\,\mathrm{K}\left(\frac{10^{-7}\,\mathrm{cm}^{-3}}{10^{18}\,\mathrm{cm}^{-3}}\right)^{1/3} \underline{\sim 5\mathrm{K}}$$

R. Alpher and R. Herman, 1949

Remarks on the Evolution of the Expanding Universe*, †

RALPH A. ALPHER AND ROBERT C. HERMAN
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

(Received December 27, 1948)



Log TIME (sec)

$\sim 10^9$ K
Deuterium
formation

~5K
NOW

…Then forgotten…

- Gamow has tried to synthesize ALL the elements (not only H and He) in the early Universe, which turned out to be impossible.
  - Therefore, consequences of his theory were also forgotten for many years.
- The other reason was because it seemed impossible to measure the CMB: radio astronomy was just born.

An Effort in Japan, 1951

Haruo Tanaka *et al.* (1951), at Nagoya University in Japan, using a square horn antenna at 8-cm wavelength, obtained a better constraint, that the incident radiation at zenith (including what is produced by the atmosphere) is no more than about 5 K. Tanaka (1979) offers this comment on their measurement.[43]

14 years before [Penzias and Wilson's discovery], we measured the temperature of sky at the wavelength of 8 cm, and estimated it to be between 0 and 5 K. ... The measurement [of the sky temperature at zenith] was made for an absolute calibration of the intensity of solar radio waves. ... Except for a parabolic reflector requiring accurate shaping, our instruments were all handmade: we obtained the necessary parts from the disposal goods of the army. ... Since we could not calculate a gain of the parabolic antenna, we built a pyramidal horn antenna whose length was 2 m. ... At that time A. E. Covington in Ottawa, Canada, had been observing the solar radio waves at 10.7 cm since 1947. He calibrated the solar flux using the sky temperature of 50 K. However it seemed too high for us, and we decided to measure the sky temperature by ourselves. ... I understand that 0–5 K and 3.5 ± 1 K are

completely different values and meanings. However, had someone like Gamow or Dicke notified us of the significance of our measurements, it would not have taken us 14 years [to detect the CMBR]. This is a bit of regret.

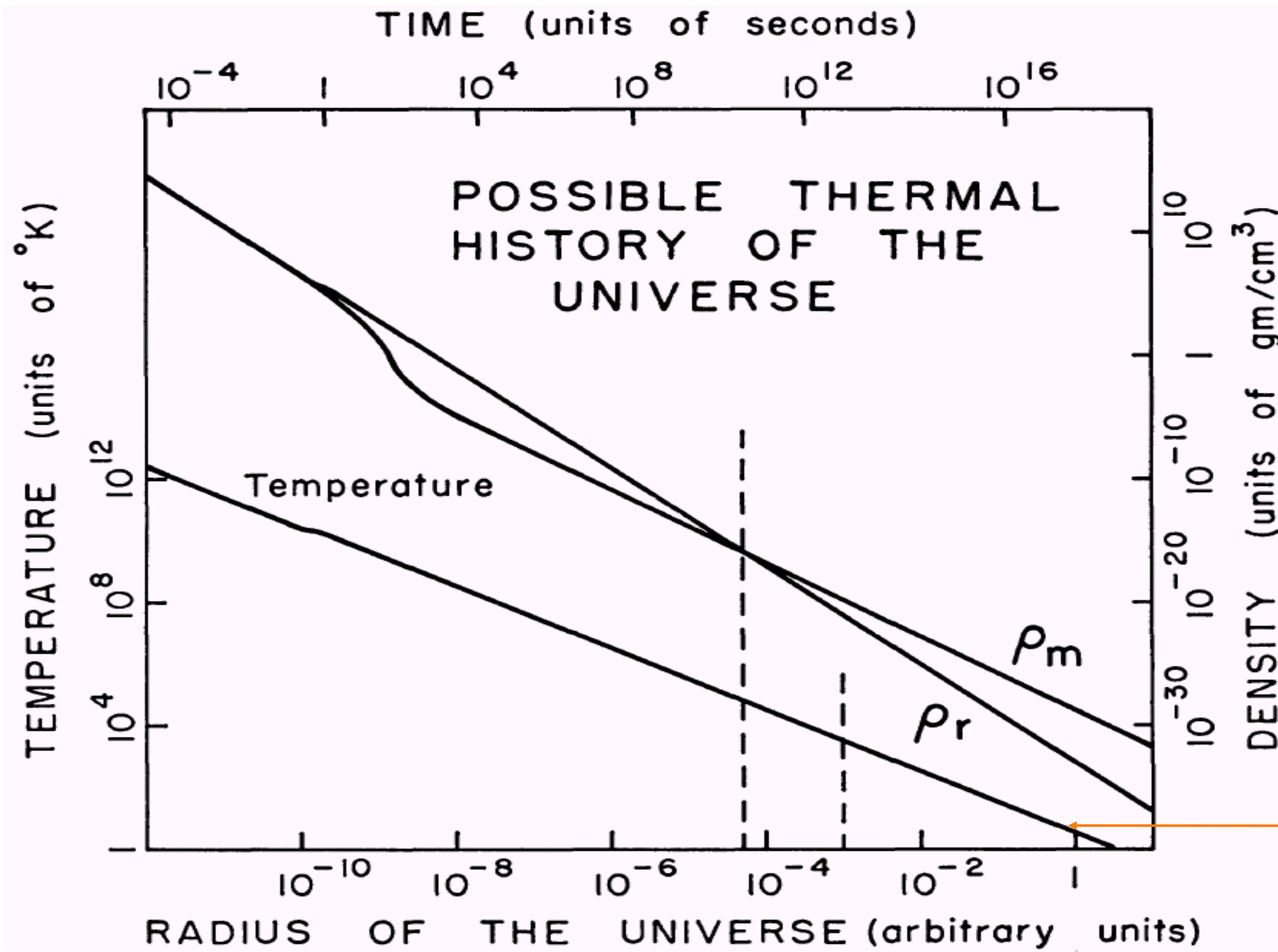
Translated from Haruo Tanaka (1979) - to be published in "*Finding the Big Bang*" edited by Jim Peebles.

Rebirth and Discovery

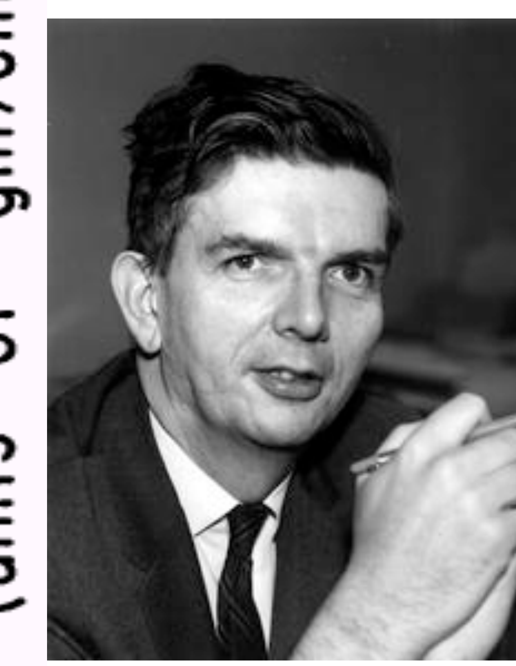
1965

R. Dicke and J. Peebles, 1965

COSMIC BLACK-BODY RADIATION*



R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson



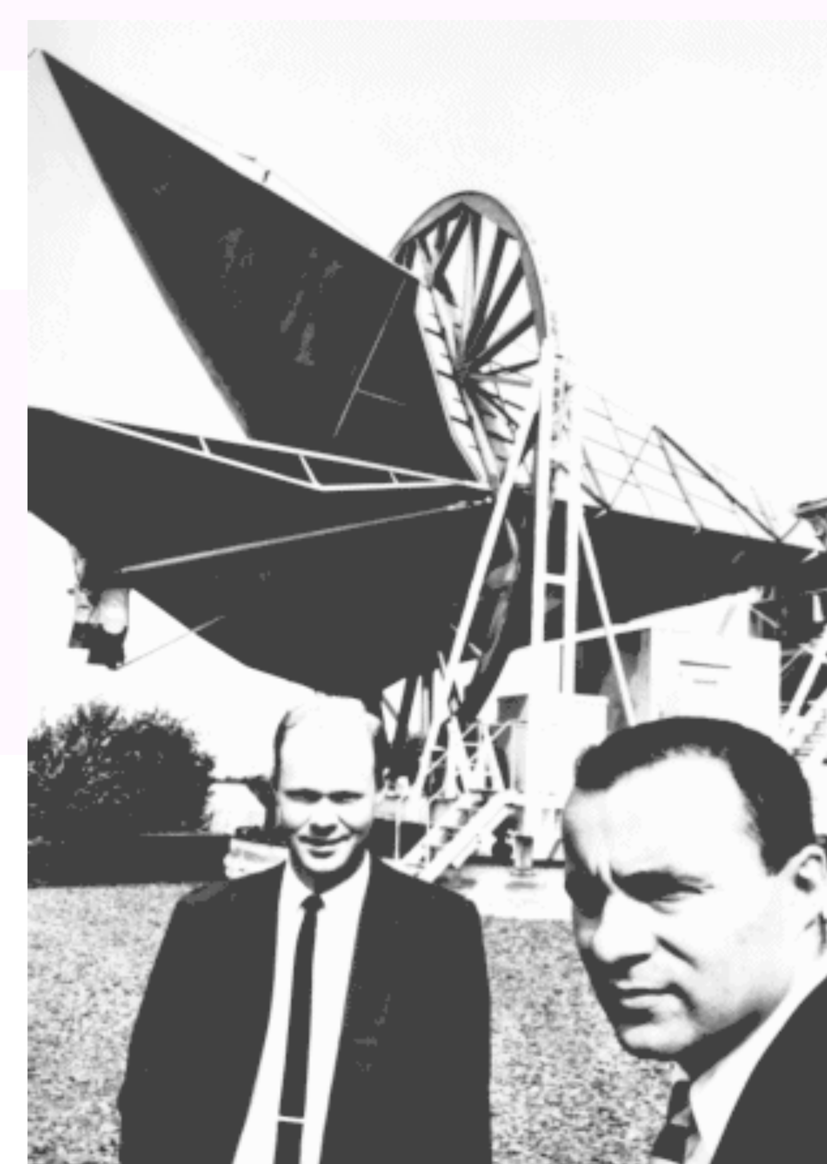
May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

3.5K
NOW

A. Penzias & R. Wilson, 1965

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.



- Isotropic
- Unpolarized

A. A. PENZIAS
R. W. WILSON

May 13, 1965
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

COSMIC BLACK-BODY RADIATION*

Is the measured signal thermal?

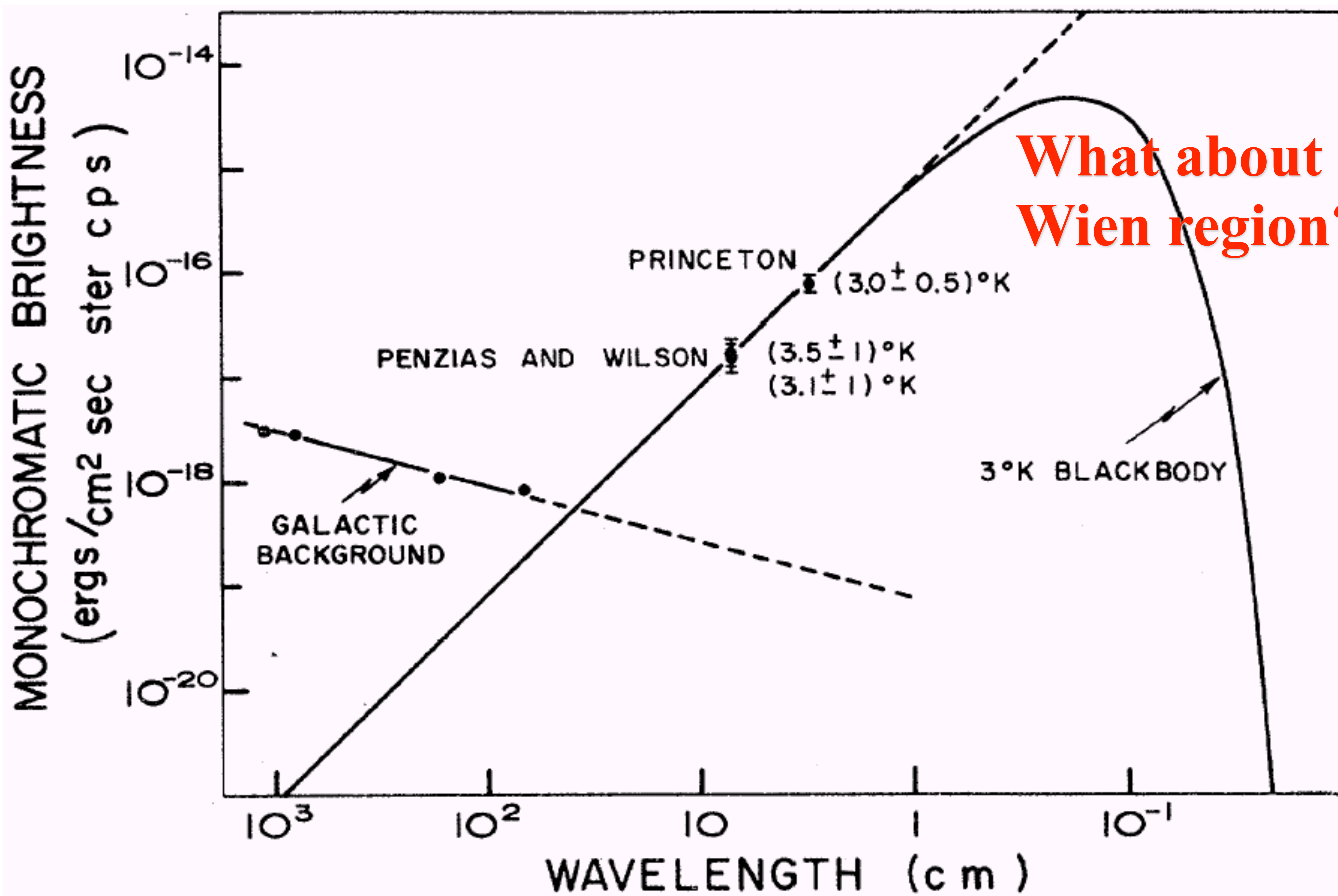
P. Roll and D. Wilkinson, 1966

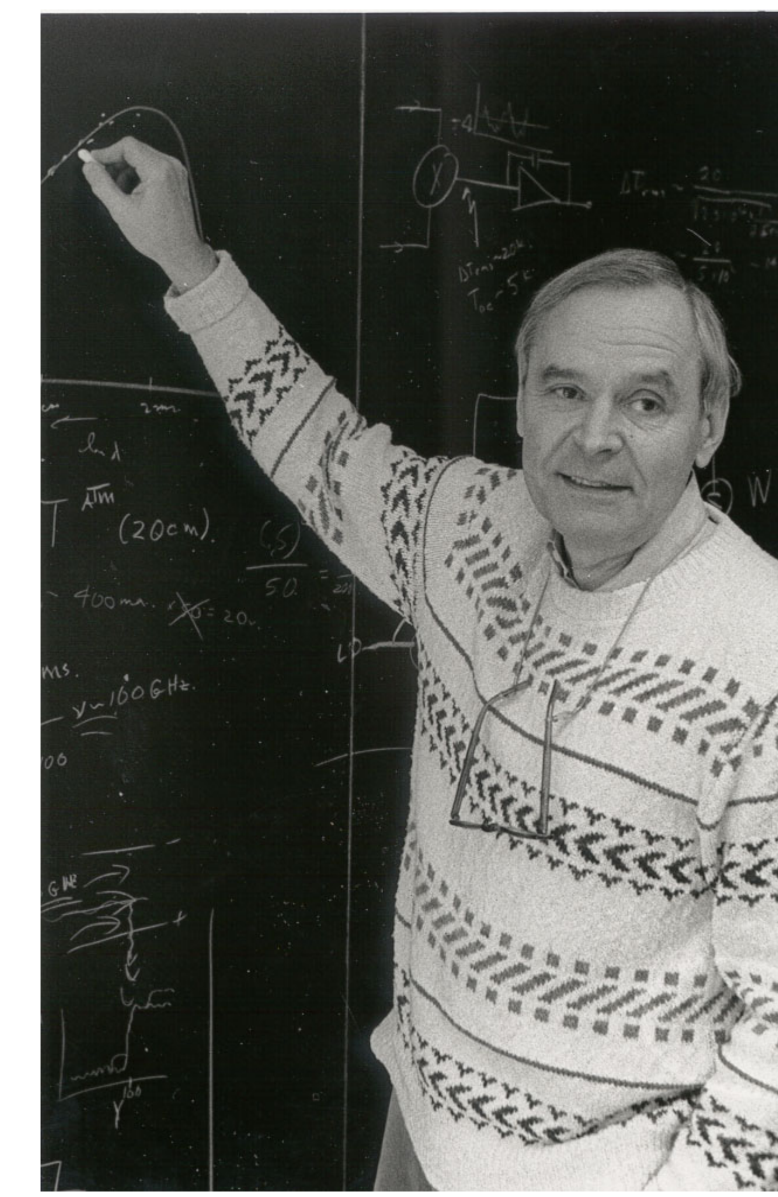
COSMIC BACKGROUND RADIATION AT 3.2 cm—SUPPORT FOR COSMIC BLACK-BODY RADIATION*

P. G. Roll† and David T. Wilkinson

Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received 27 January 1966)





D.Wilkinson

(W of WMAP)

Ya. Zel'dovich and R. Sunyaev, 1969

THE INTERACTION OF MATTER AND RADIATION IN A HOT-MODEL UNIVERSE*

YA. B. ZELDOVICH and R. A. SUNYAEV

Institute of Applied Mathematics, U.S.S.R. Academy of Sciences, Moscow, U.S.S.R.

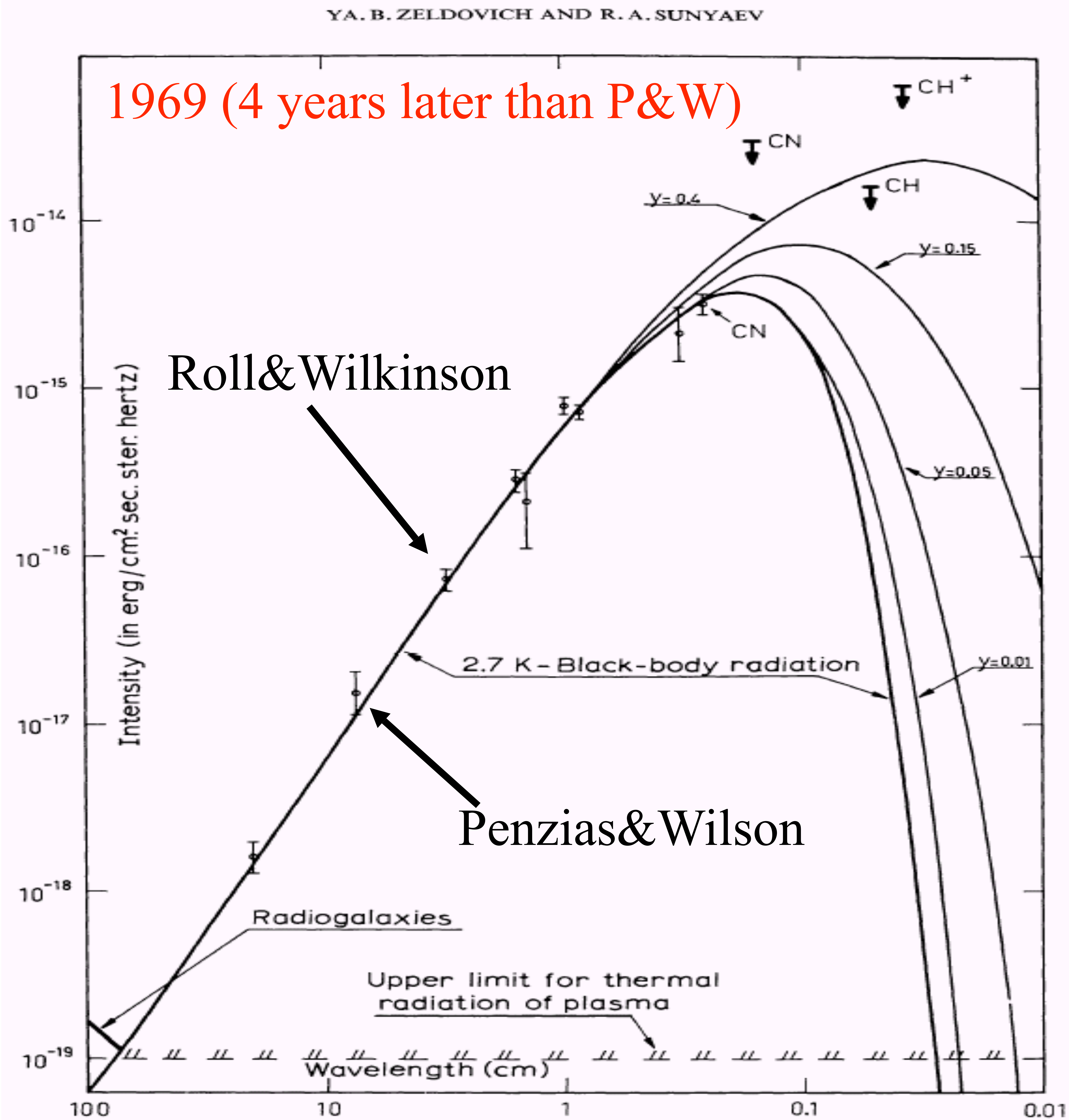
(Received 30 December, 1968)

Abstract. In this paper we continue the investigation initiated by Weymann as to the reason why the spectrum of the residual radiation deviates from a Planck curve. We shall consider the distortions of the spectrum resulting from radiation during the recombination of a primeval plasma. Analytical expressions are obtained for the deviation from an equilibrium spectrum due to Compton scattering by hot electrons. On the basis of the observational data it is concluded that a period of neutral hydrogen in the evolution of the universe is unavoidable. It is shown that any injection of energy at $t > 10^{10}$ sec (red shift $z < 10^5$) leads to deviation from an equilibrium spectrum.

Sunyaev-Zel'dovich effect

- Additional energy injection in the early universe would create energetic electrons.
- The hot electrons scatter background photons, giving their energy to the photons.
  - –The thermal spectrum distorted (non-equilibrium)
  - –The amplitude of distortion parameterized by ***y***:

$$\frac{\Delta T}{T} = g(\nu) \times y = g(\nu) \int \sigma_T n_e \frac{k(T_e - T)}{m_e c^2} dl$$

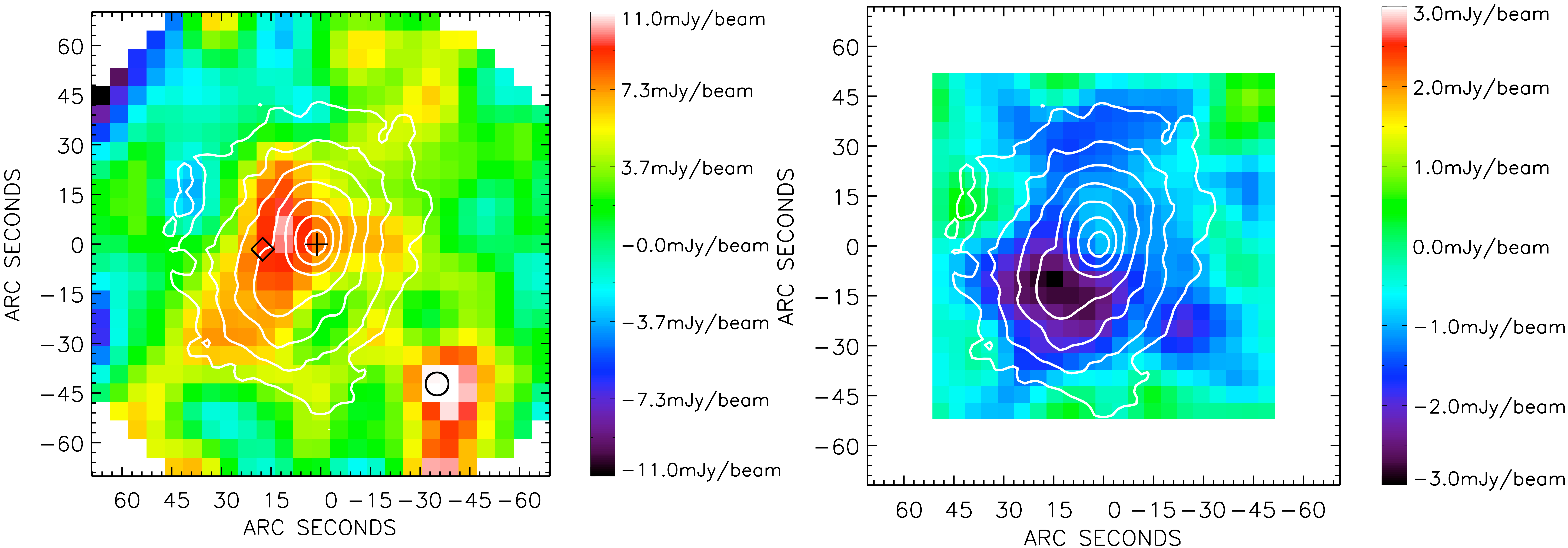


Wien region of the spectrum is very sensitive to the thermal history of the Universe.

In the limit of $T_e >> T$,

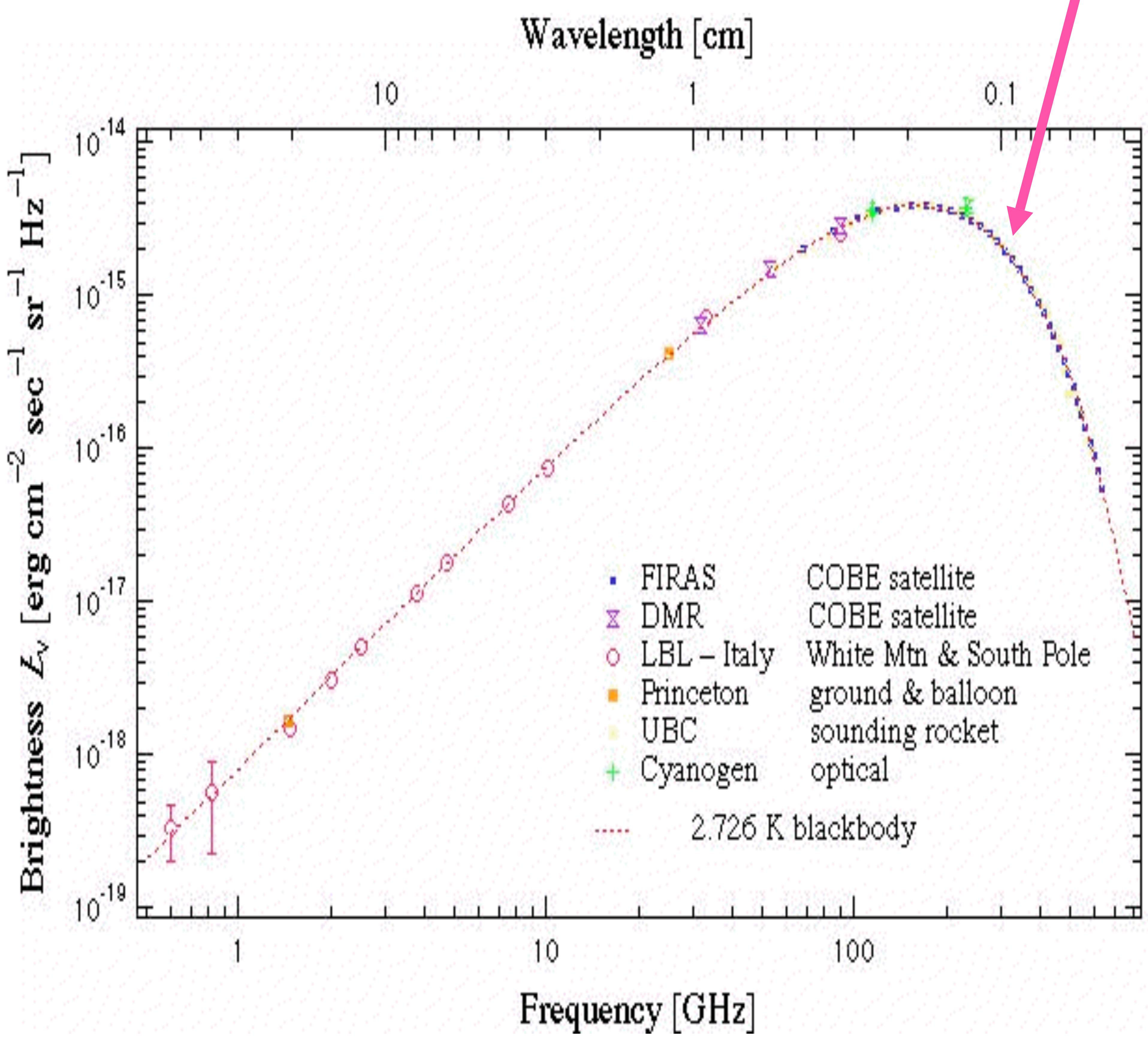
$$y \propto \int p_e dl$$

S-Z Effect Toward Individual Clusters



- RXJ1347-1145
- Left, SZ increment (350GHz)
- Right, SZ decrement (150GHz)

COBE/FIRAS, 1990



Perfect blackbody = Thermal equilibrium = Big Bang proved

No y distortion = No energy injection = Silent universe

Temperature fluctuations

Radiation transport in a perturbed universe

(perturbations are small $\sim 10^{-5}$)

R. Sachs and A. Wolfe, 1967

PERTURBATIONS OF A COSMOLOGICAL MODEL AND ANGULAR VARIATIONS OF THE MICROWAVE BACKGROUND

R. K. SACHS AND A. M. WOLFE
Relativity Center, The University of Texas, Austin, Texas
Received May 13, 1966

- **SOLVE GENERAL RELATIVISTIC BOLTZMANN EQUATIONS TO THE FIRST ORDER IN PERTURBATIONS**

$$\frac{Df}{D\lambda} \equiv \frac{dx^\mu}{d\lambda}\frac{\partial f}{\partial x^\mu}\bigg|_p + \frac{dp^\mu}{d\lambda}\frac{\partial f}{\partial p^\mu}\bigg|_x = p^0 C[f]$$

$$\frac{dx^\mu}{d\lambda} = p^\mu \ , \qquad \frac{dp^\mu}{d\lambda} = -\Gamma^\mu_{\alpha\beta}p^\alpha p^\beta$$

Introduce temperature fluctuations, Θ=ΔT/T:

$$\Delta f_t \equiv f_t - \bar{f}_t \approx \bar{T}\frac{\partial \bar{f}_t}{\partial \bar{T}}\Theta$$

Expand the Boltzmann equation to the first order:

$$\dot{\Theta} + \frac{p^k}{p^0}\frac{\partial \Theta}{\partial x^k} = \mathcal{G}_{SW} + \mathcal{G}_C$$

where

$$\mathcal{G}_{SW} = \frac{1}{\bar{a}p}\frac{d(\bar{a}p)}{d\tau}$$

describes the Sachs-Wolfe effect: purely GR-induced fluctuations.

For metric perturbations in the form of:

$$ds^2 = a^2\left[\left(-1 + h_{00}\right)d\tau^2 + \left(\delta_{ij} + h_{ij}\right)dx^i dx^j\right]$$

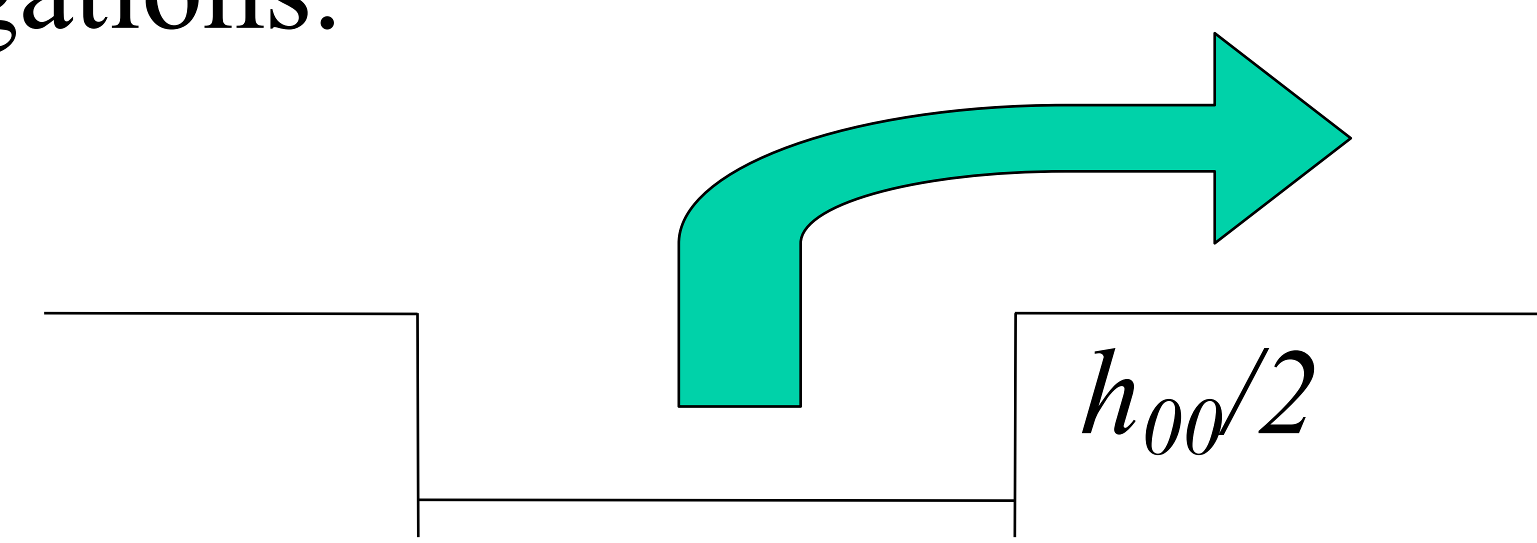
Newtonian potential

Curvature perturbations

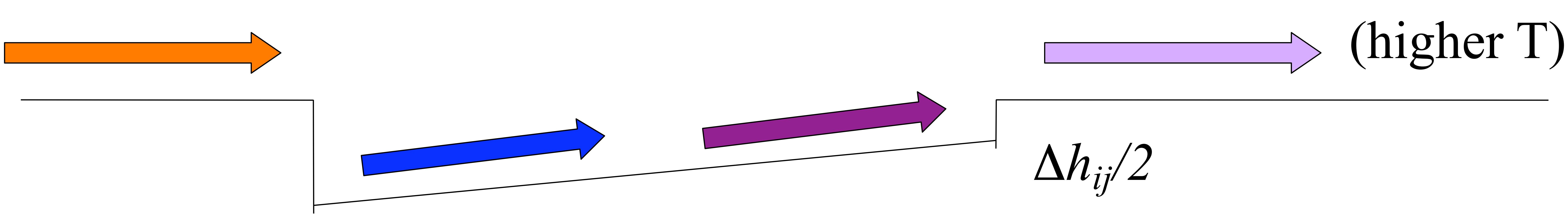
the Sachs-Wolfe terms are given by

$$\mathcal{G}^n_{SW} = \frac{1}{2} h_{00|k}\bar{\gamma}^k - \frac{1}{2}\dot{h}_{kl}\bar{\gamma}^k\bar{\gamma}^l$$

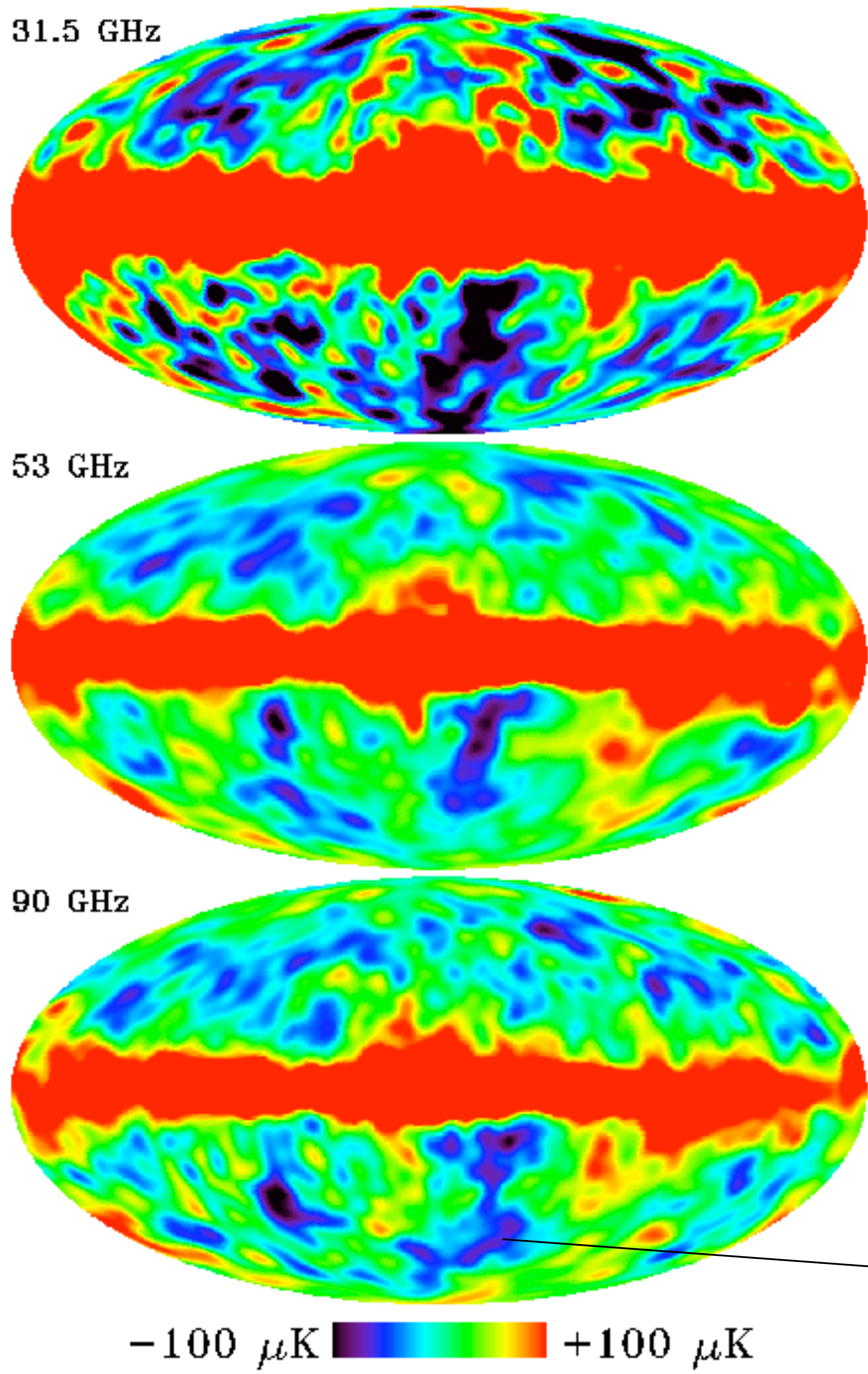
where γ is the directional cosine of photon propagations.



1. The 1st term = gravitational redshift
2. The 2nd term = integrated Sachs-Wolfe effect



COBE/DMR, 1992



- Fluctuations are due to the Sachs-Wolfe effect!
- Gravity is stronger in colder spots (i.e. $\Delta T/T \sim \Phi$)

Why Sachs-Wolfe Only?

- DMR's angular resolution (7 degrees) corresponds to $1300h^{-1}$Mpc at z~1100 (the surface of the last scatter, where CMB photons come from).
- The horizon radius at z~1100 is only about $280h^{-1}$Mpc.
- Therefore, collision terms in the Boltzmann equation must not have any effects on temperature fluctuations (it violates causality otherwise!).
- The collision terms become important on scales smaller than the "sound crossing scales"~horizon/sqrt(3), which subtends ~ 1 degree on the sky.

GO TO SMALL SCALES

PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

P. J. E. PEEBLES†
Joseph Henry Laboratories, Princeton University

AND

J. T. YU‡
Goddard Institute for Space Studies, NASA, New York

Received 1970 January 5; revised 1970 April 1

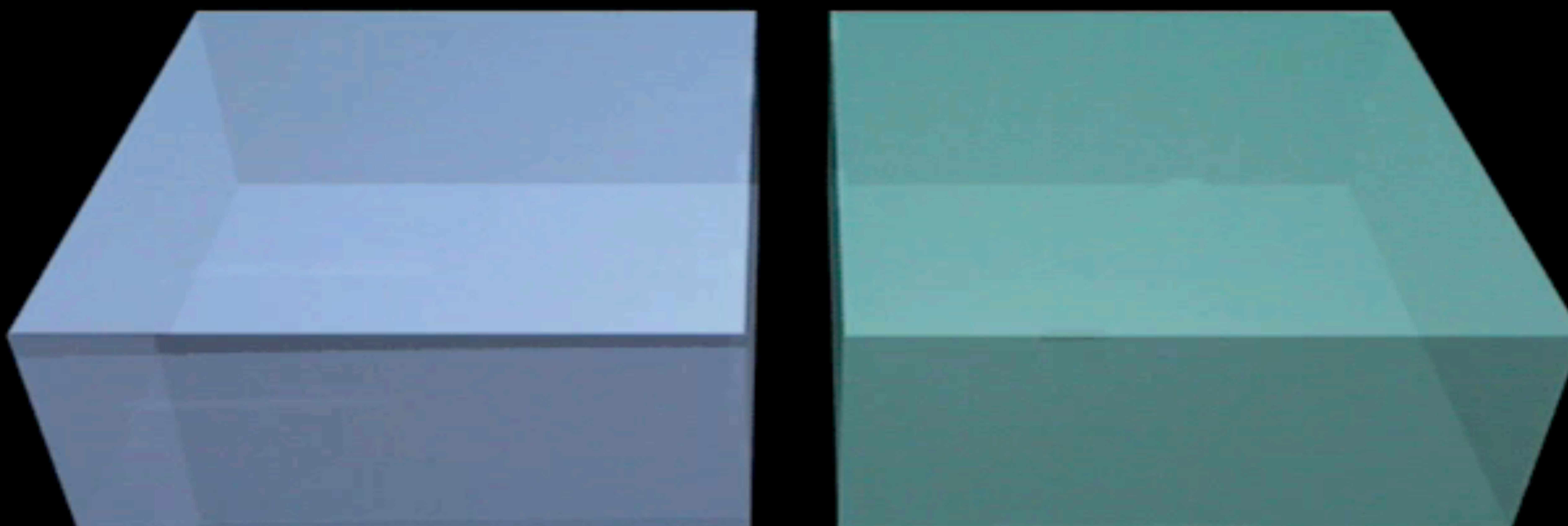
Small scales: Hydrodynamic perturbations

$$\dot{\Theta} + \frac{p^k}{p^0}\frac{\partial \Theta}{\partial x^k} = \mathcal{G}_{SW} + \mathcal{G}_C$$

Collision term describing coupling between photons and baryons via electron scattering.

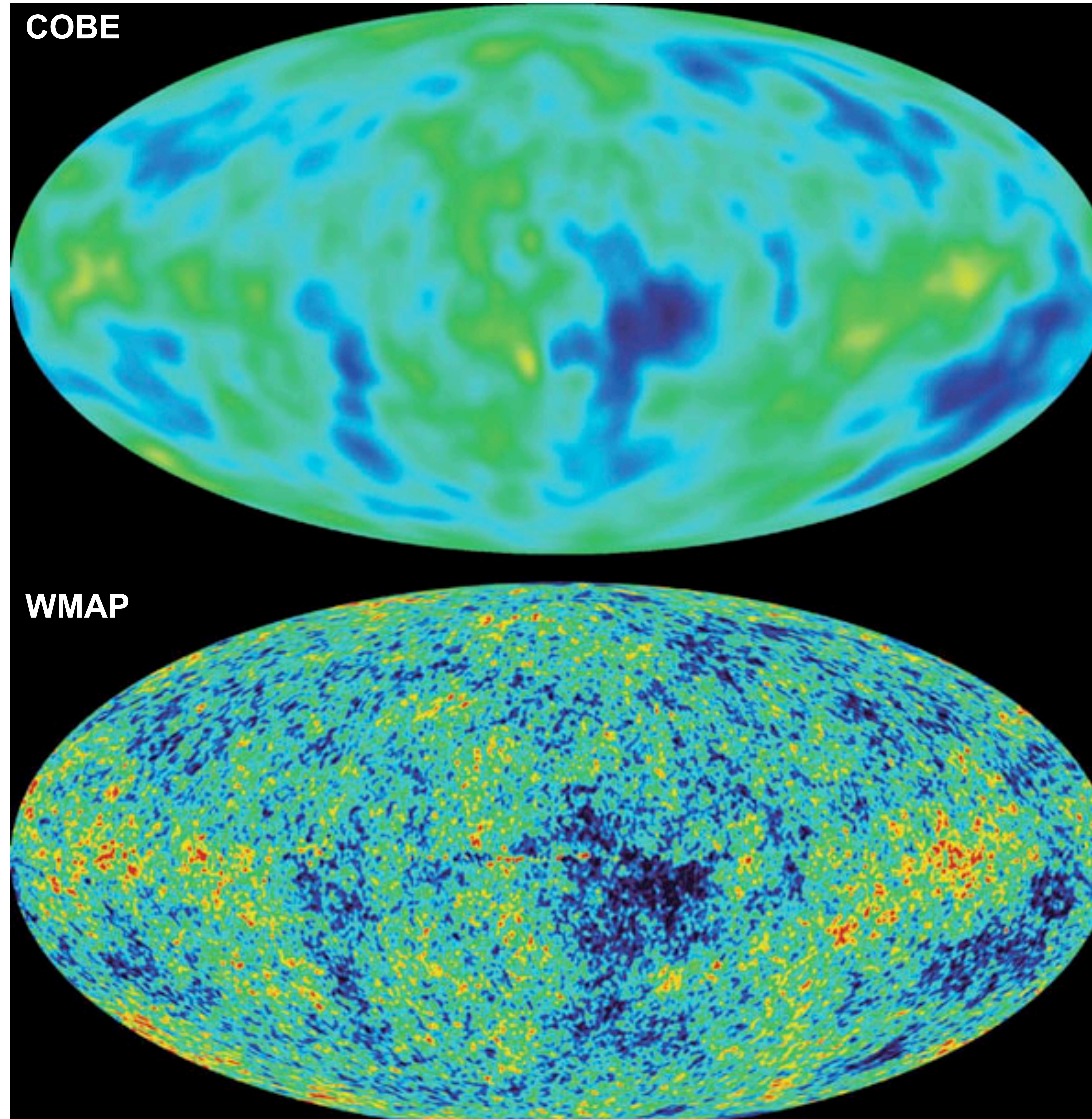
- When coupling is strong, photons and baryons move together and behave as a *single fluid*.
- When coupling becomes less strong, they behave as *two fluids with viscosity*.
- So, the problem can be formulated as "hydrodynamics". (cf S-W effect was pure GR.)

The Cosmic Sound Wave



COBE to WMAP (x35 better resolution)

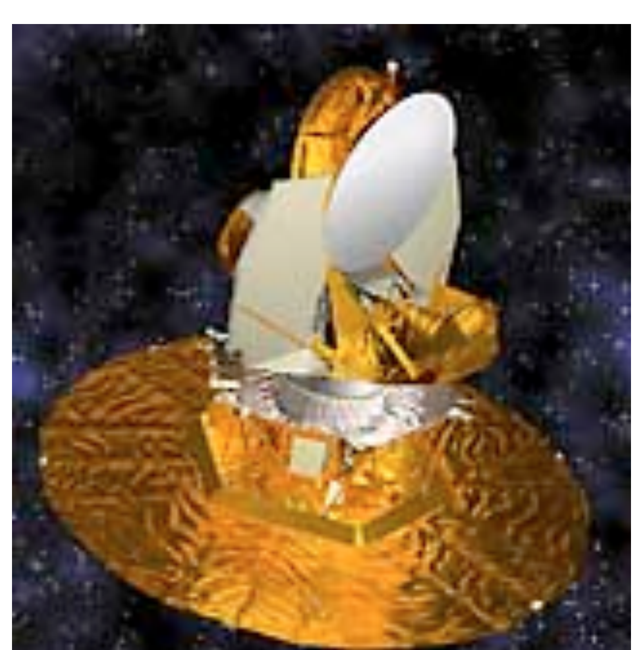
COBE
1989



Press Release from the Nobel Foundation

[COBE's] measurements also marked the inception of cosmology as a precise science. It was not long before **it was followed up,** for instance **by the WMAP satellite, which yielded even clearer images of the background radiation**.

WMAP
2001



How to see the sound waves

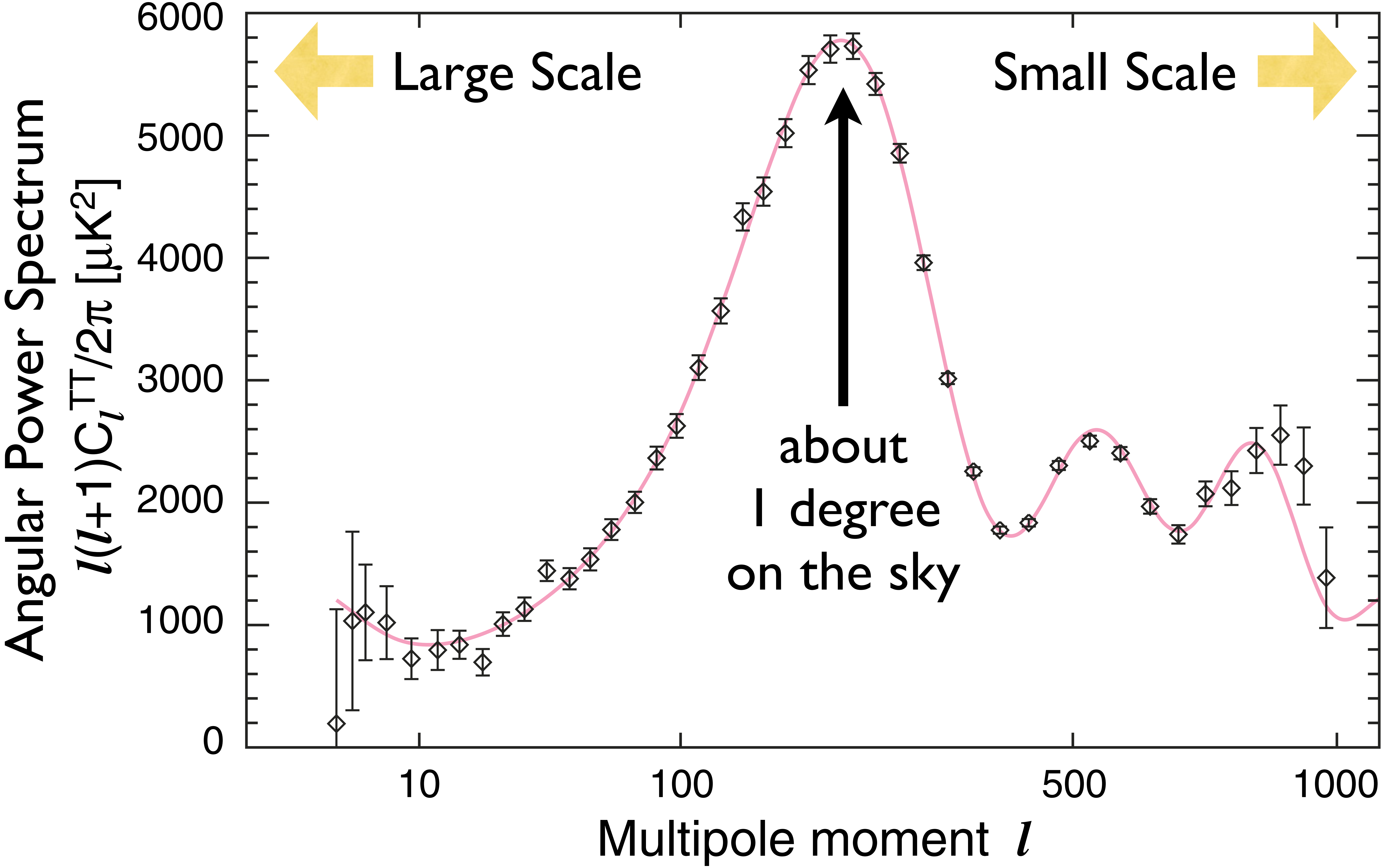
- The angular power spectrum, C_l
  - C_l measures the amplitude of temperature fluctuations at a given angular scale:

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

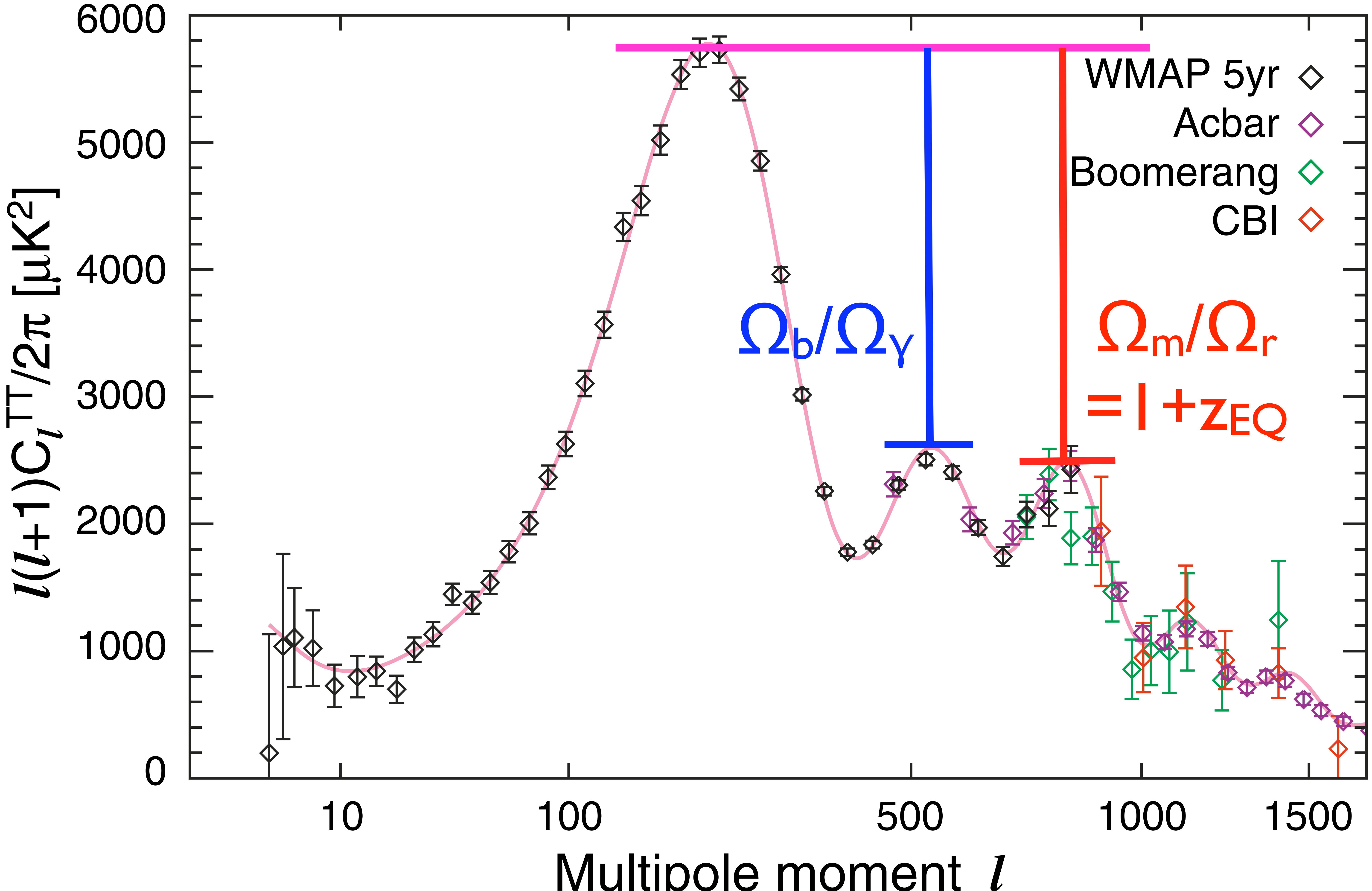
where

$$a_{lm} = \int \frac{\Delta T}{T} Y_{lm}^*(\hat{n}) d\hat{n}$$

The Spectral Analysis



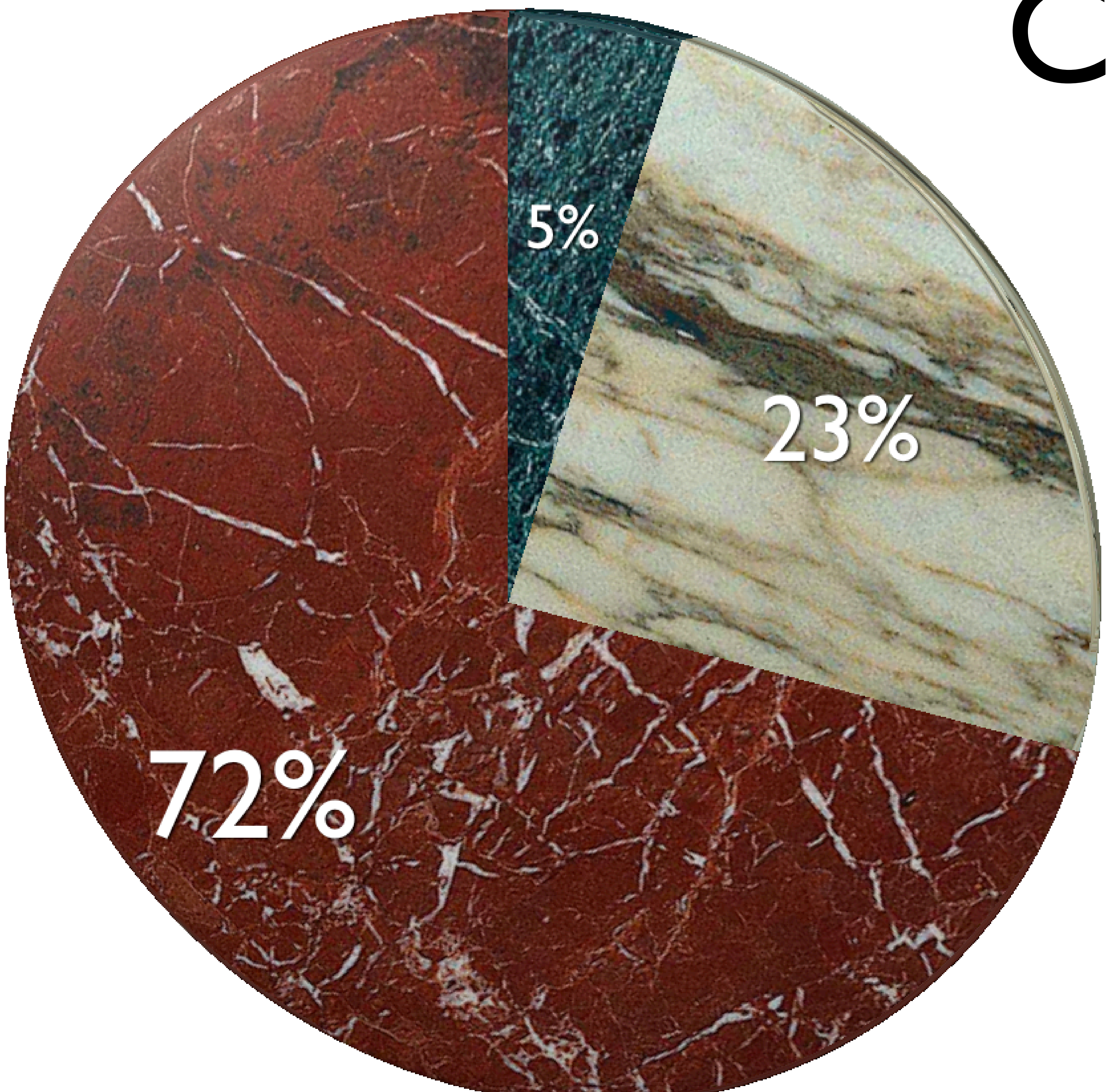
CMB to $\Omega_b h^2$ & $\Omega_m h^2$



- 1-to-2: baryon-to-photon; 1-to-3: matter-to-radiation ratio
- $\Omega_\gamma=2.47\times10^{-5}h^{-2}$ & $\Omega_r=\Omega_\gamma+\Omega_\nu=1.69\Omega_\gamma=4.17\times10^{-5}h^{-2}$

Composition of the Universe

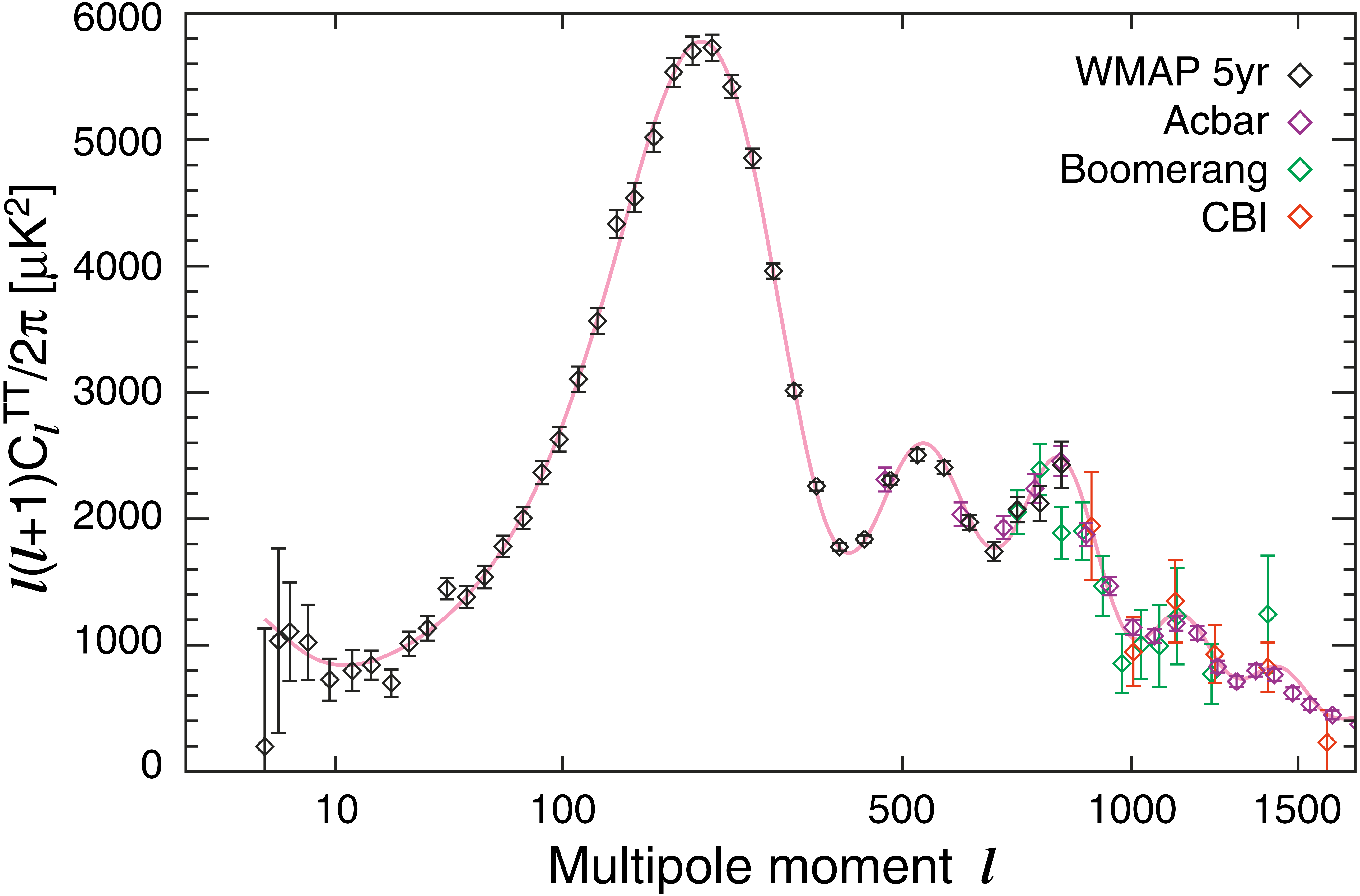
Cosmic Pie Chart



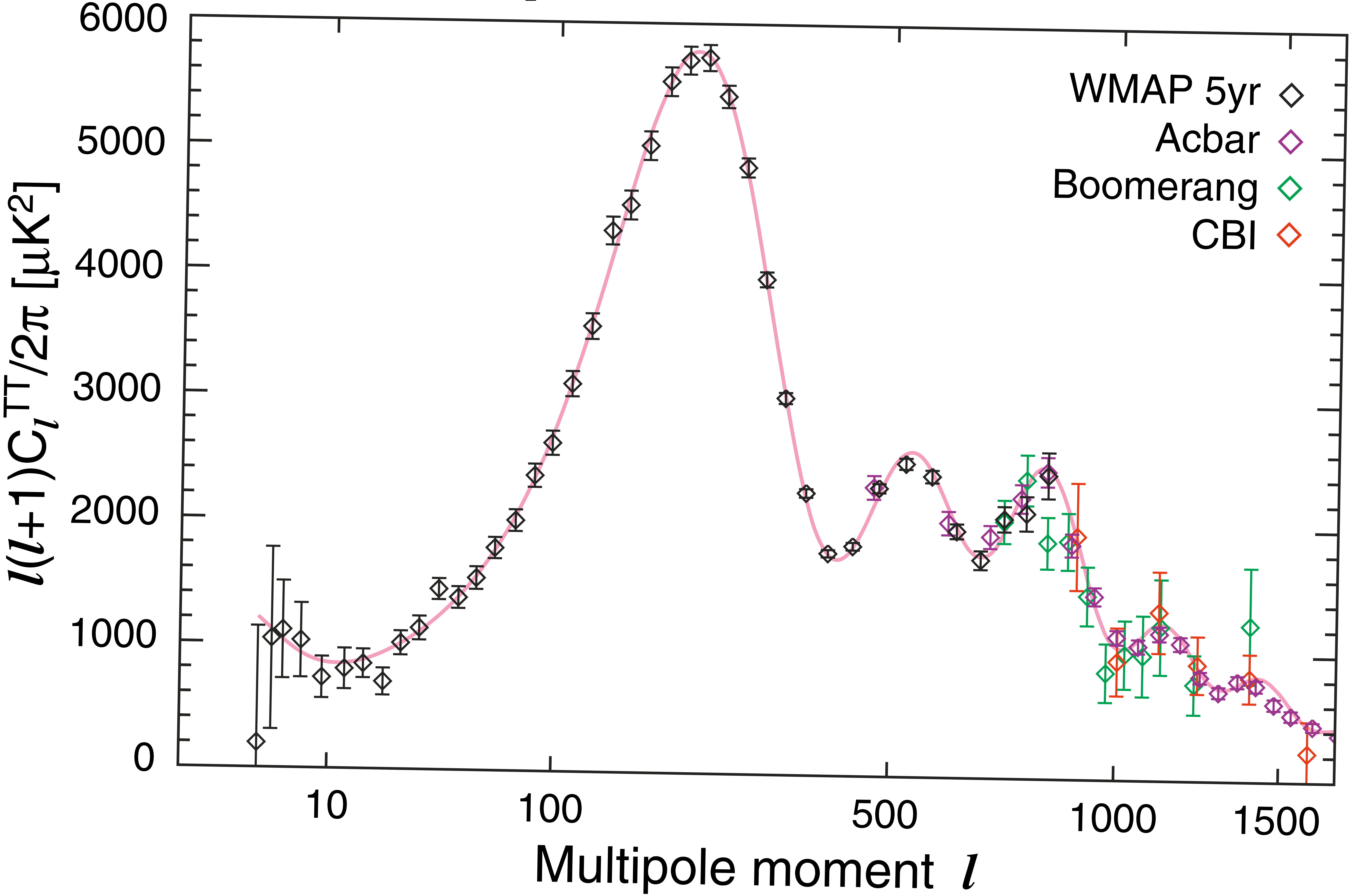
- Cosmological observations (CMB, galaxies, supernovae) over the last decade told us that **we don’t understand much of the Universe**.

Hydrogen & Helium
Dark Matter
Dark Energy

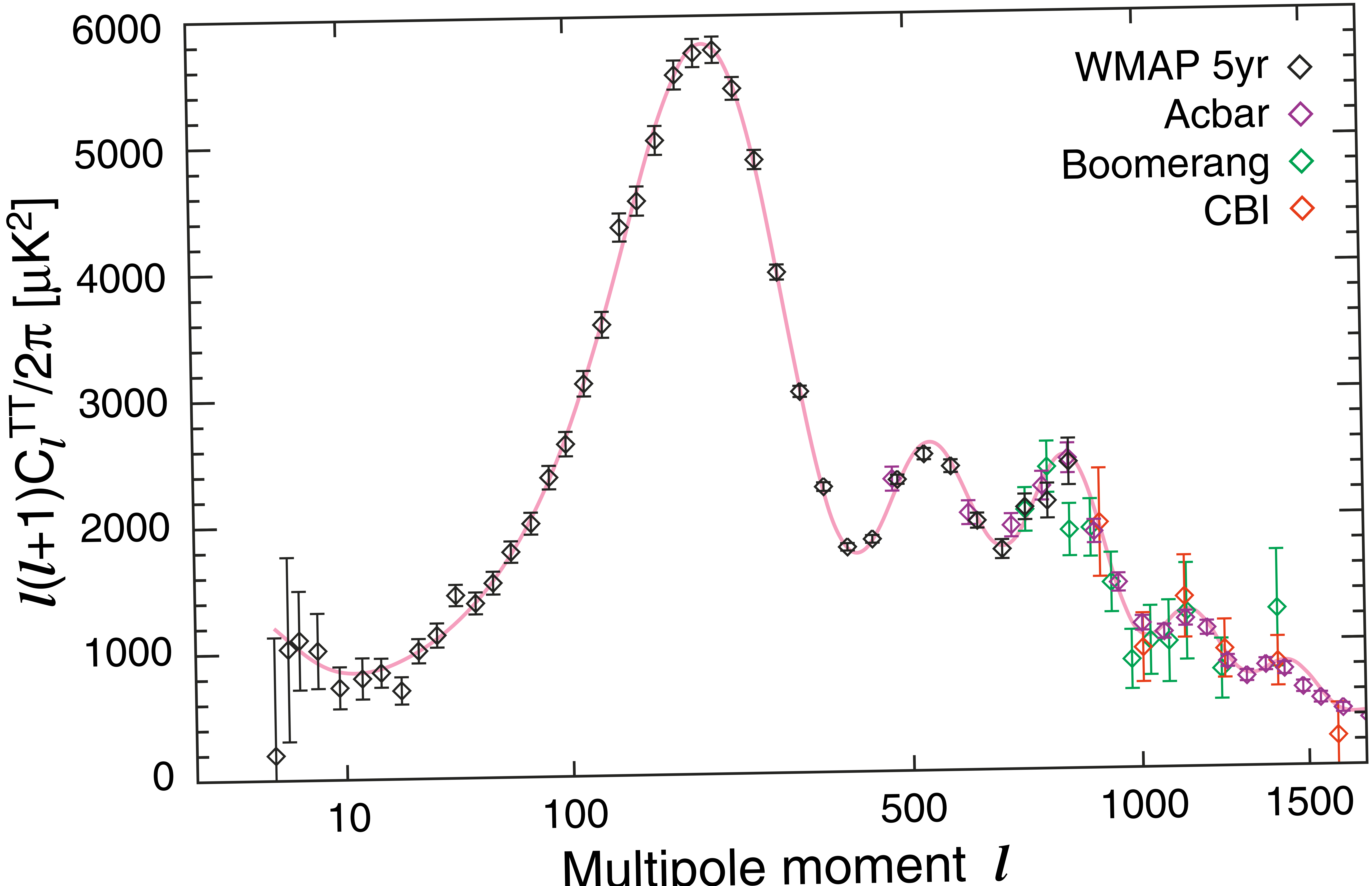
Tilting=Primordial Shape->Inflation



"Red" Spectrum: $n_s < 1$



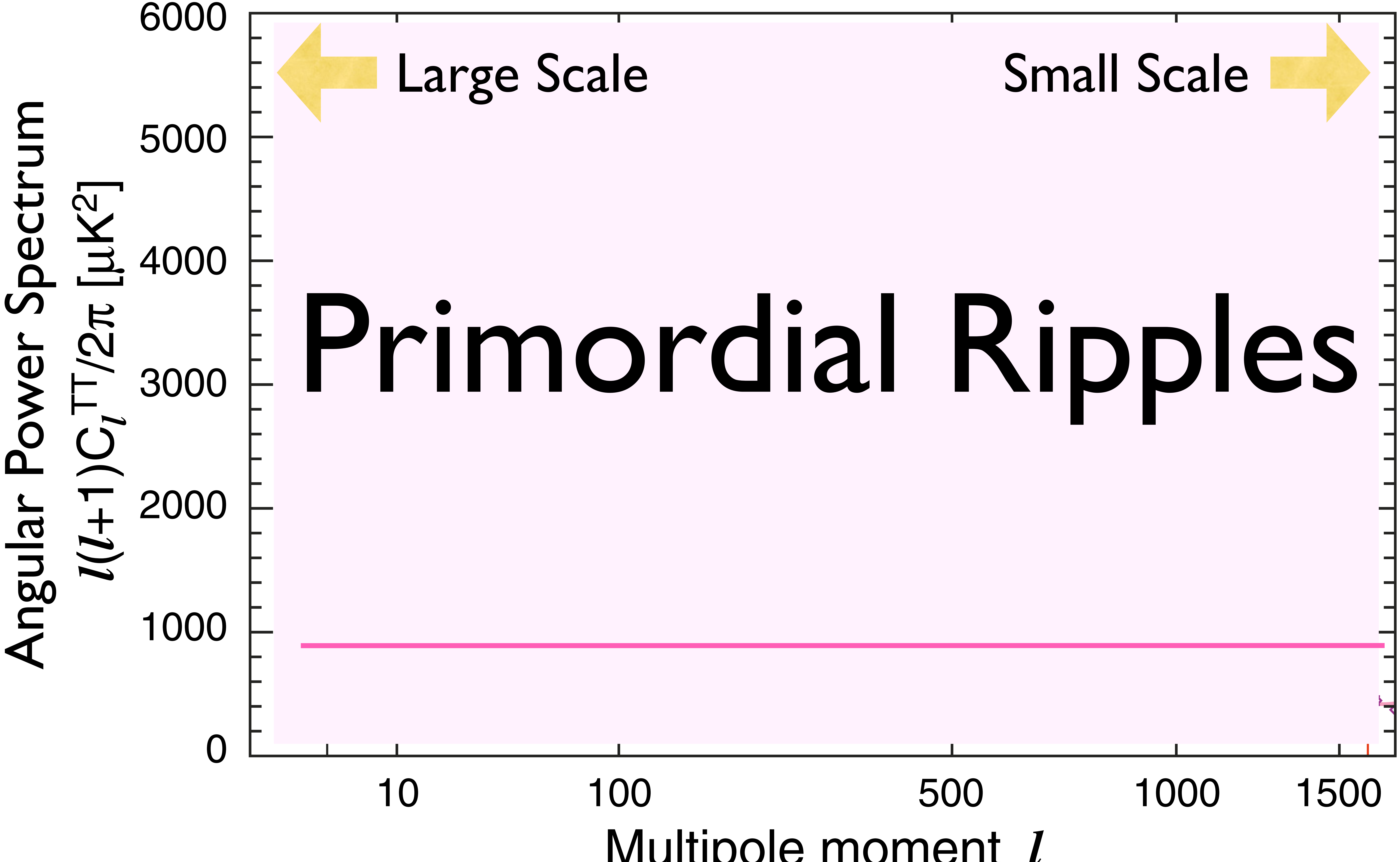
“Blue” Spectrum: $n_s > 1$



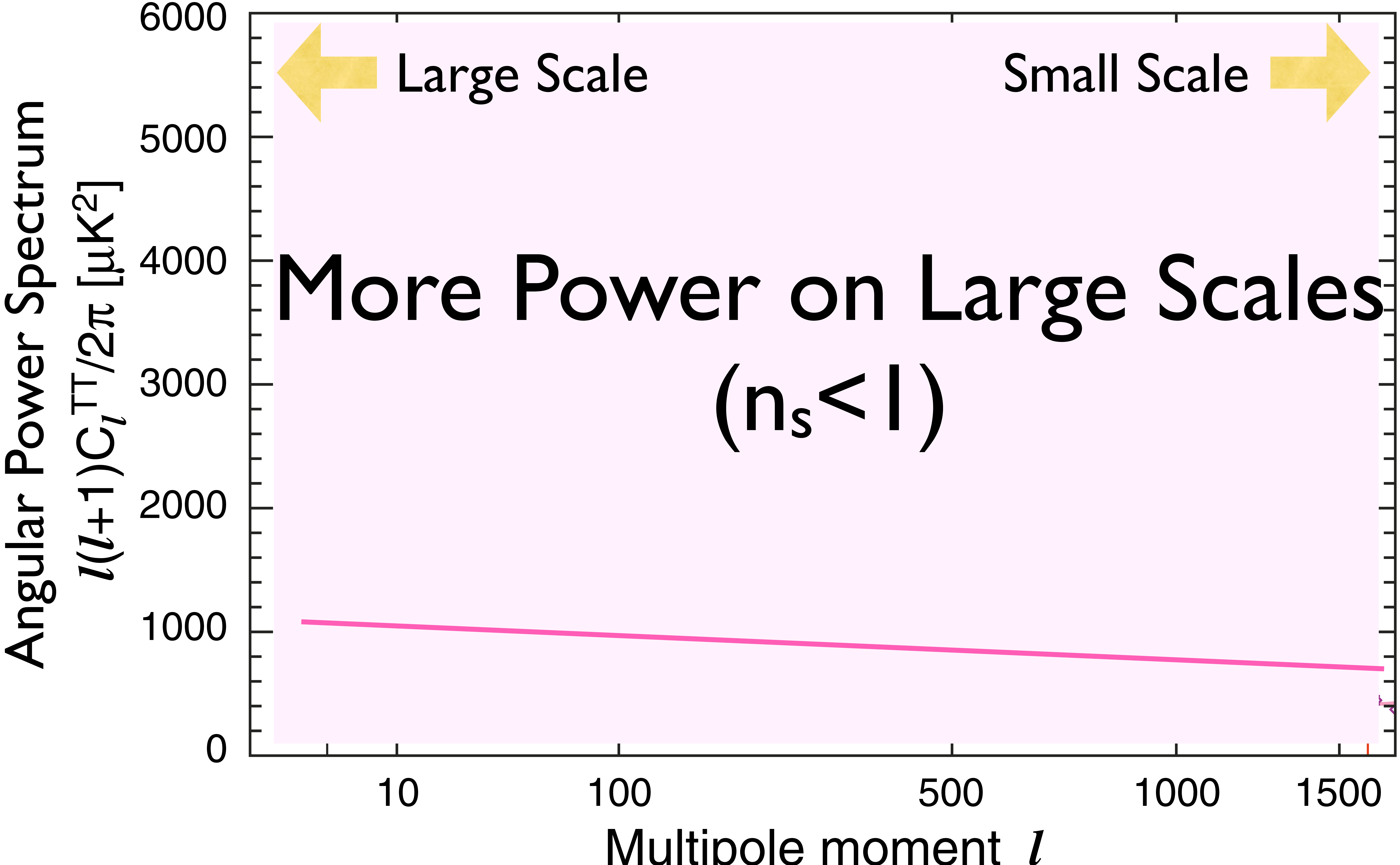
Expectations From 1970's: n_s=1

- Metric perturbations in g_{ij} (let's call that "curvature perturbations" Φ) is related to δ via
  - $k^2\Phi(k)=4\pi G\rho a^2\delta(k)$
- Variance of $\Phi(x)$ in position space is given by
  - $<\Phi^2(x)>=\int \ln k\ \mathbf{k^3|\Phi(k)|^2}$
  - In order to avoid the situation in which curvature (geometry) diverges on small or large scales, a "scale-invariant spectrum" was proposed: $\mathbf{k^3|\Phi(k)|^2 = const.}$
  - This leads to the expectation: $\mathbf{P(k)}=|\delta(k)|^2\mathbf{=k}$ $\mathbf{(n_s=1)}$
    - *Harrison 1970; Zel'dovich 1972; Peebles&Yu 1970*

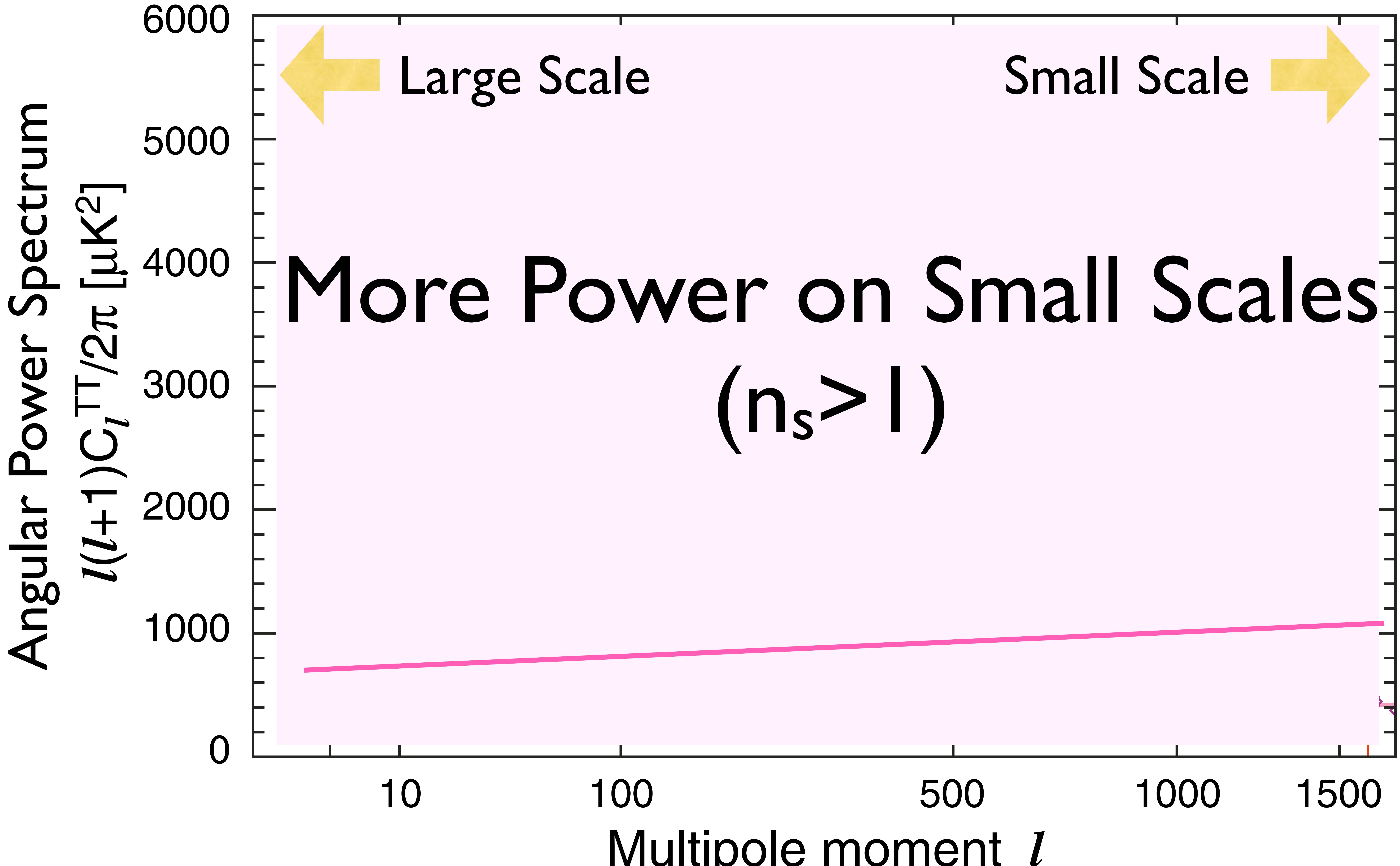
Getting rid of the Sound Waves



The Early Universe Could Have Done This Instead



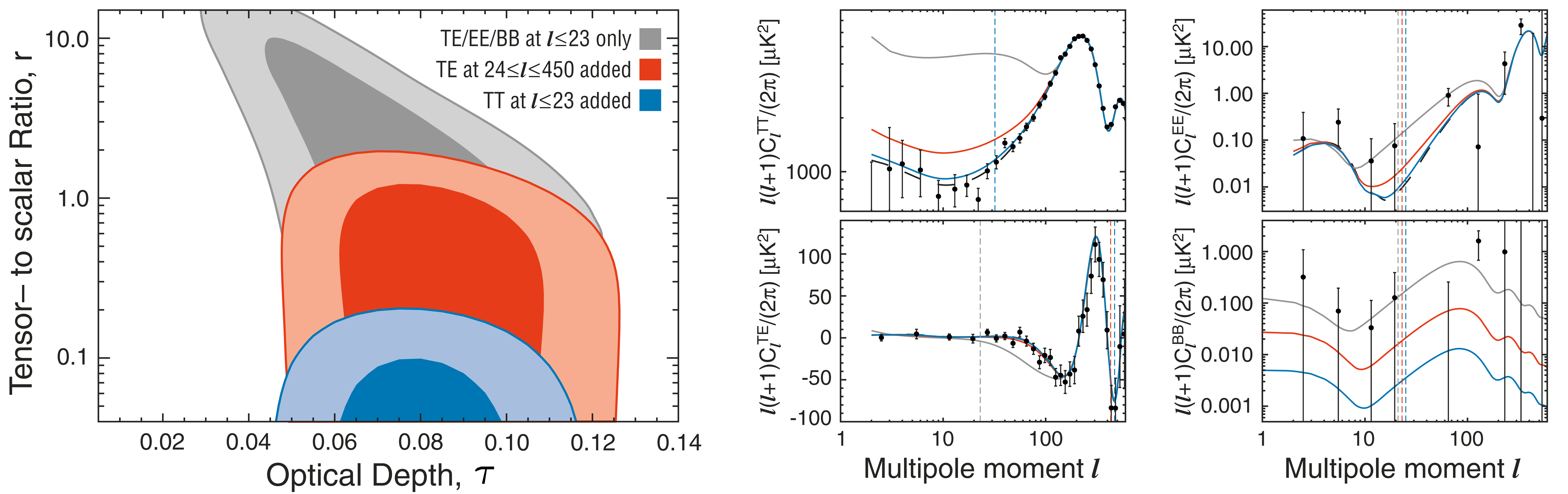
...or, This.



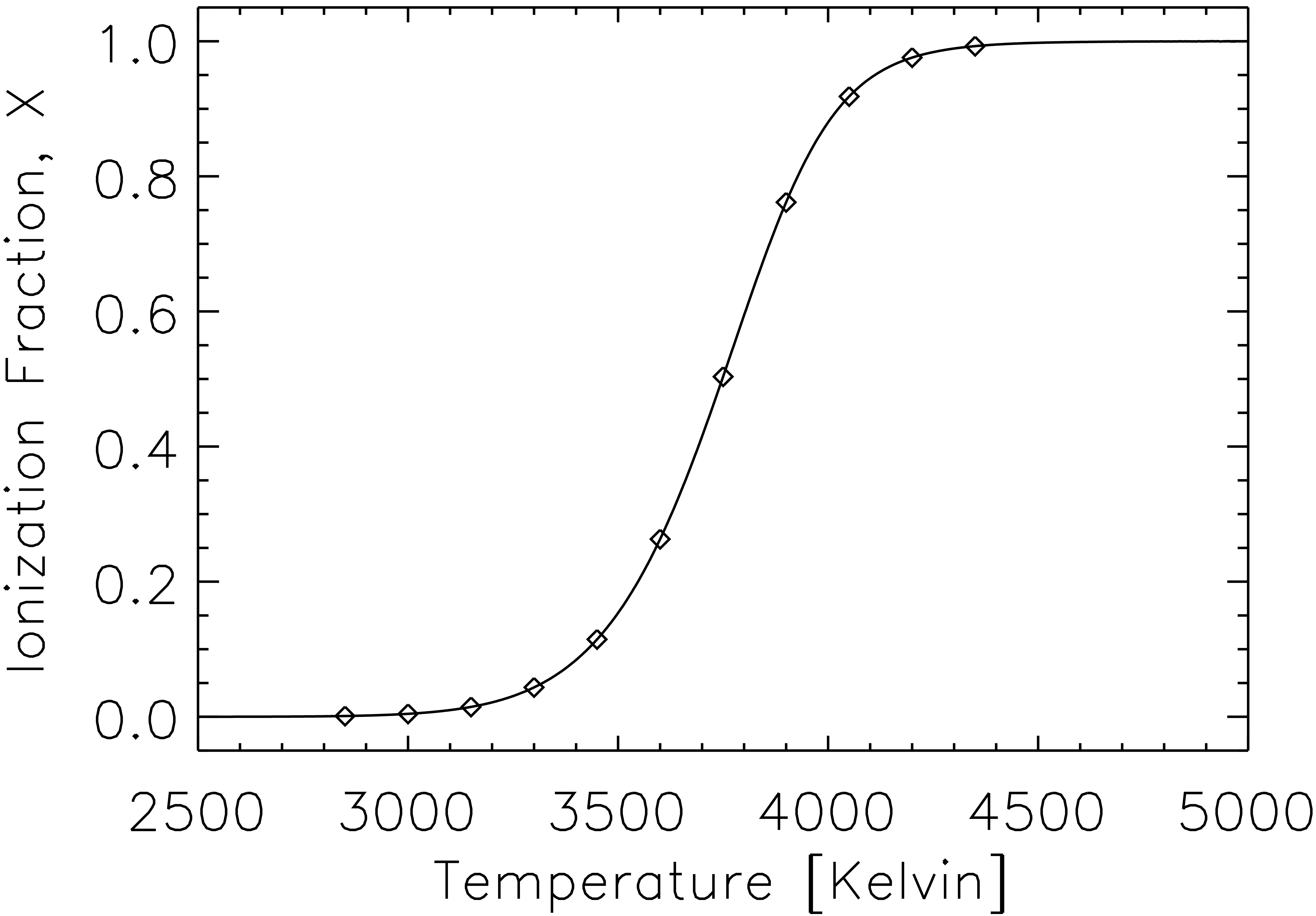
Large Scale
Small Scale
More Power on Small Scales
(n_s>1)
Angular Power Spectrum
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l

Current Limit on n_s

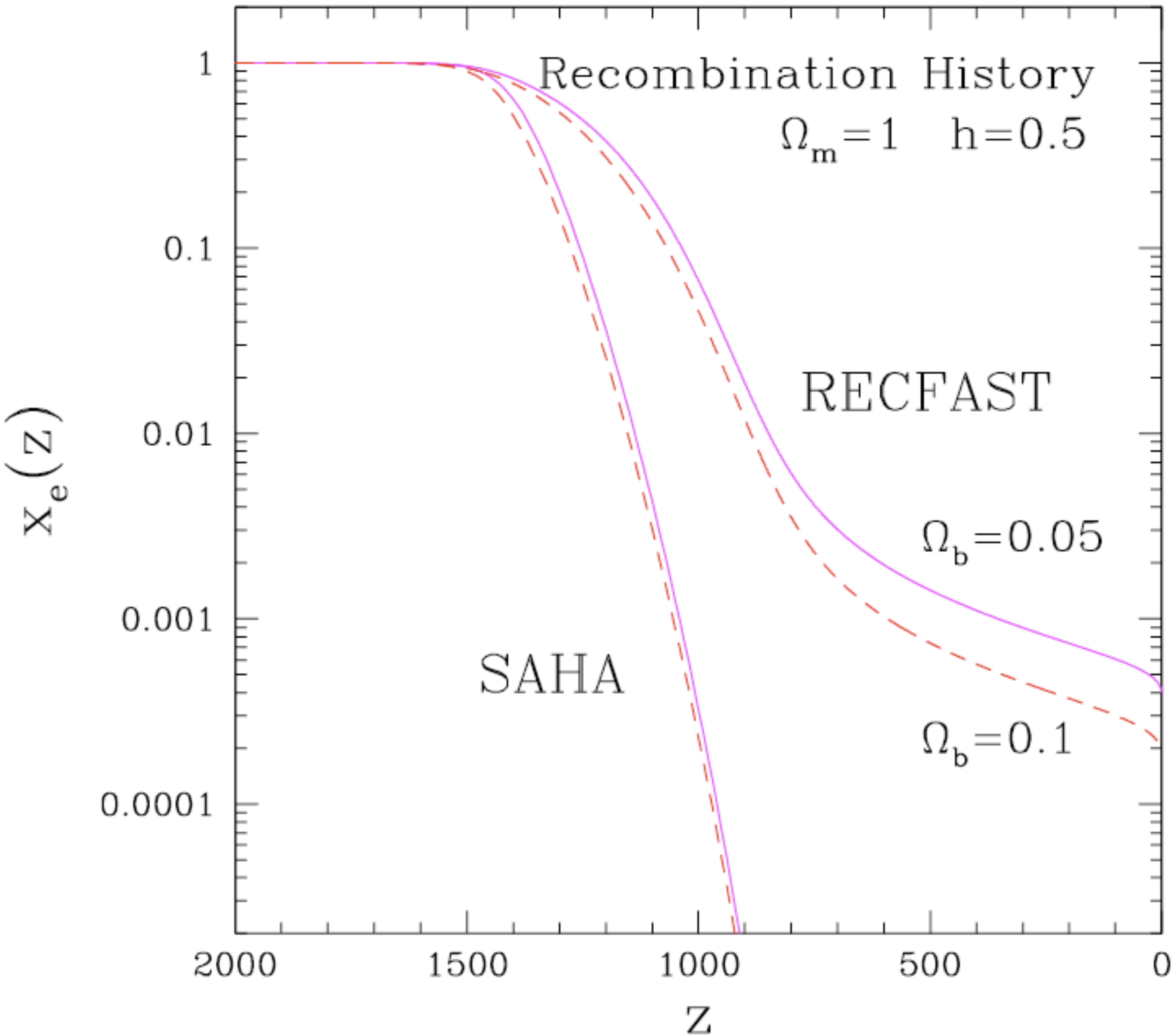
- $n_s = 0.960 \pm 0.013$
  - Gravitational waves were ignored.
- $n_s = 0.970 \pm 0.015$
  - Gravitational waves were included



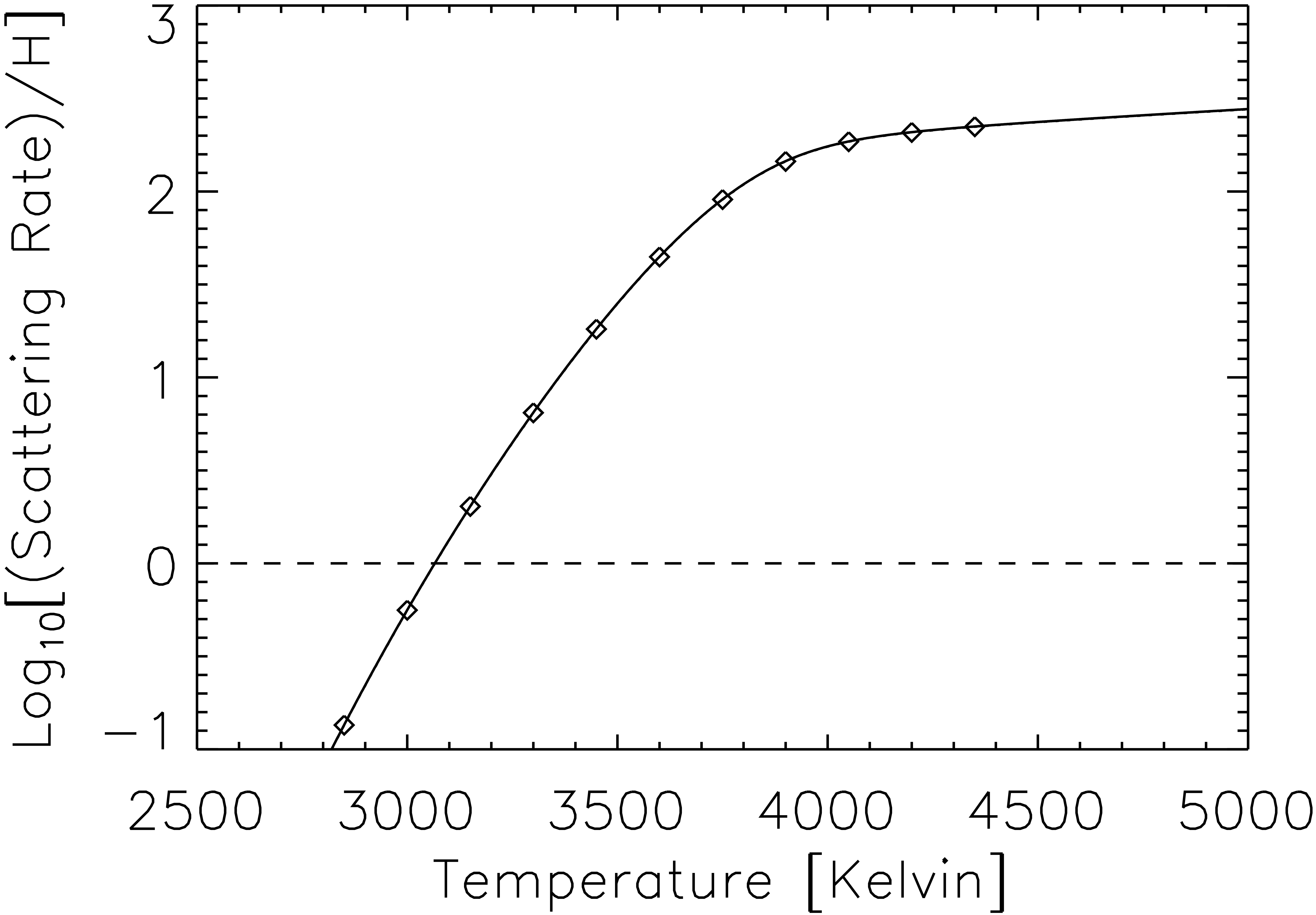
- Low-l polarization data (TE/EE/BB at l<23) only: r<20
  - BB data only with tau=0.10 (fixed): r<4.5
- High-l TE data included: r<2
- Low-l temperature data included: r<0.2



Ionization Fraction, X
1.0
0.8
0.6
0.4
0.2
0.0
2500
3000
3500
4000
4500
5000
Temperature [Kelvin]

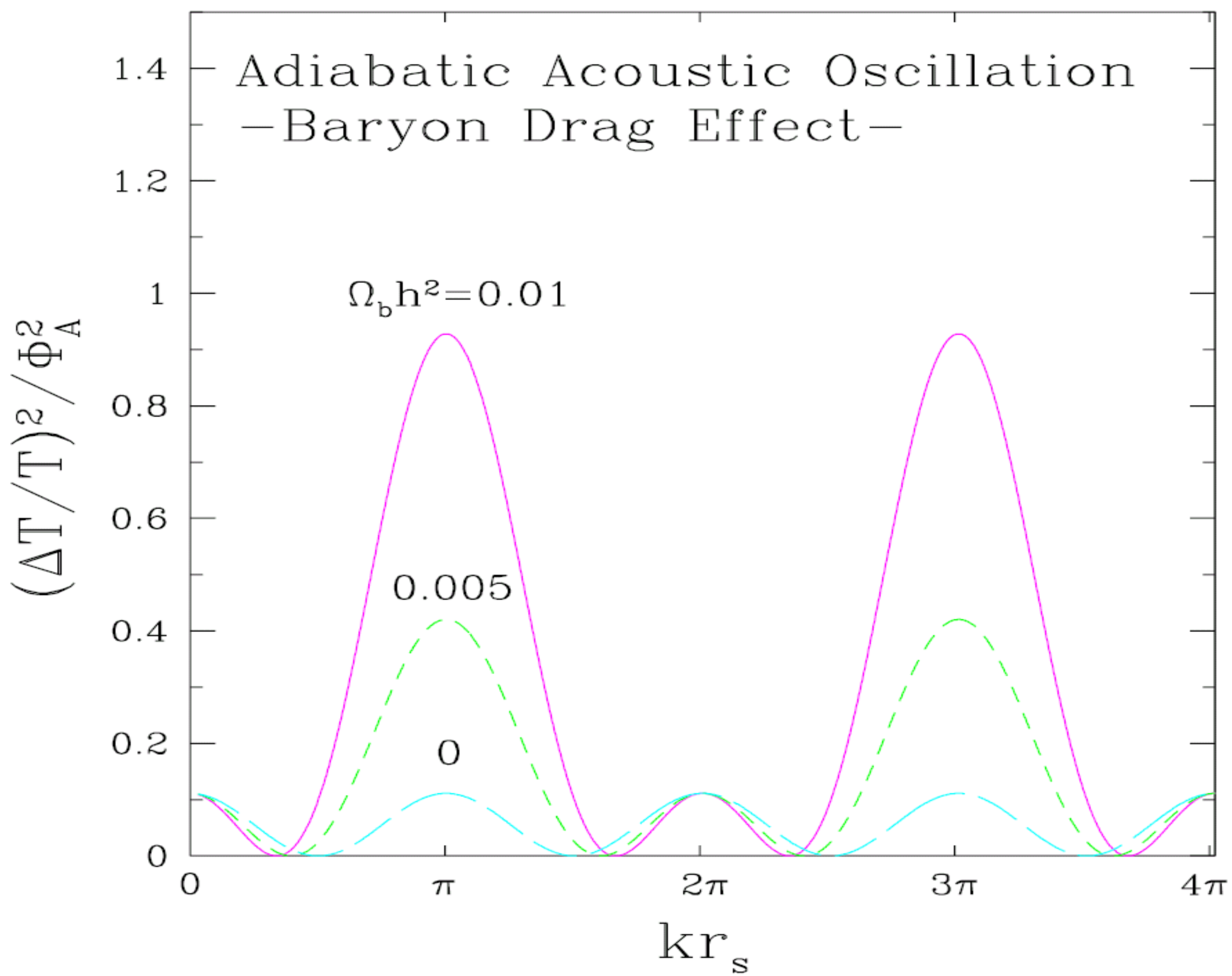


Recombination History
Ωm=1 h=0.5
RECFAST
Ωb=0.05
Ωb=0.1
SAHA
Xe(z)
z
1
0.1
0.01
0.001
0.0001
2000
1500
1000
500
0



Log_{10}[(Scattering Rate)/H]
3
2
1
0
−1
2500
3000
3500
4000
4500
5000
Temperature [Kelvin]

Wave Form and Cosmological Parameters (Example)

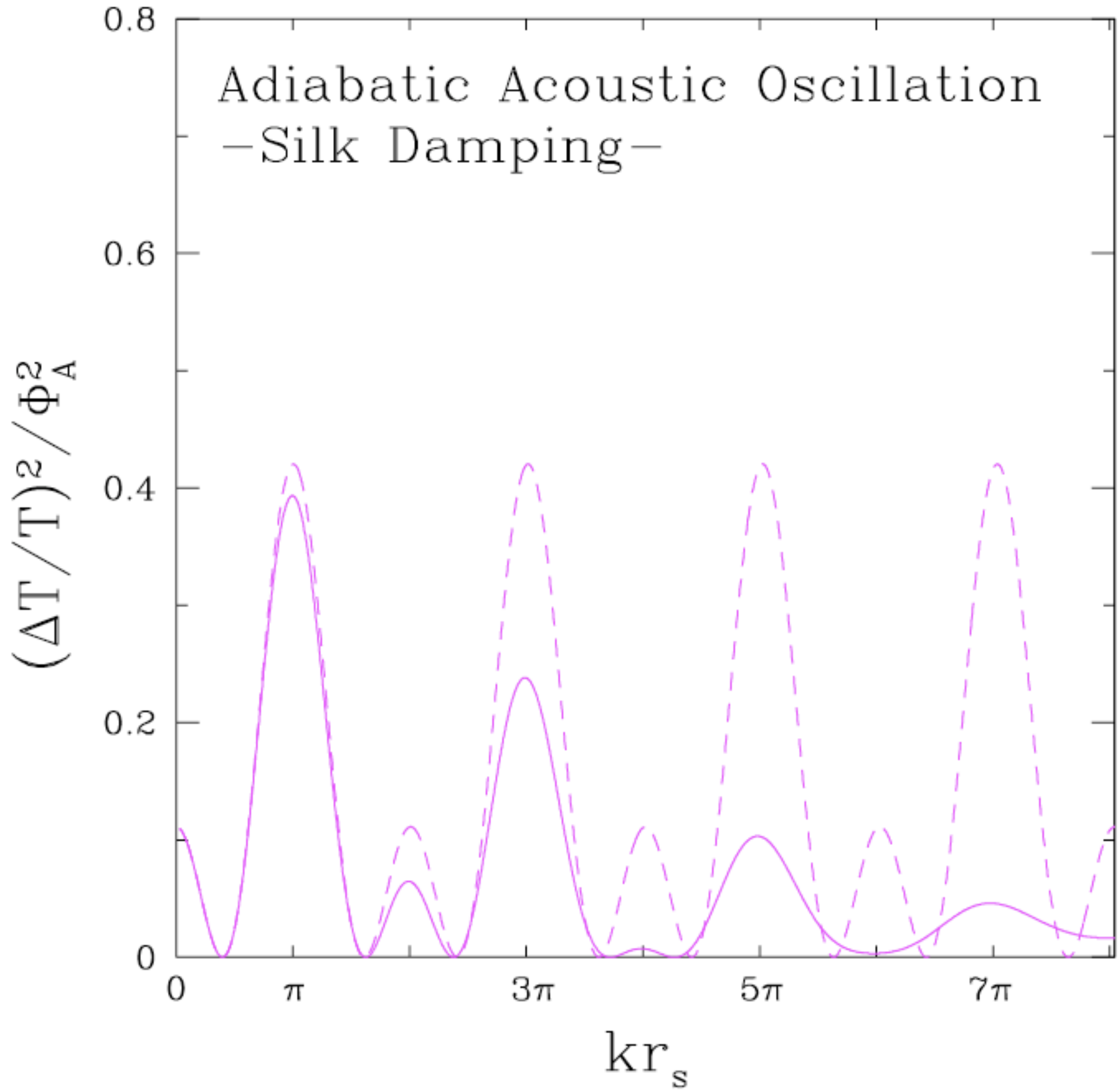


Higher baryon density

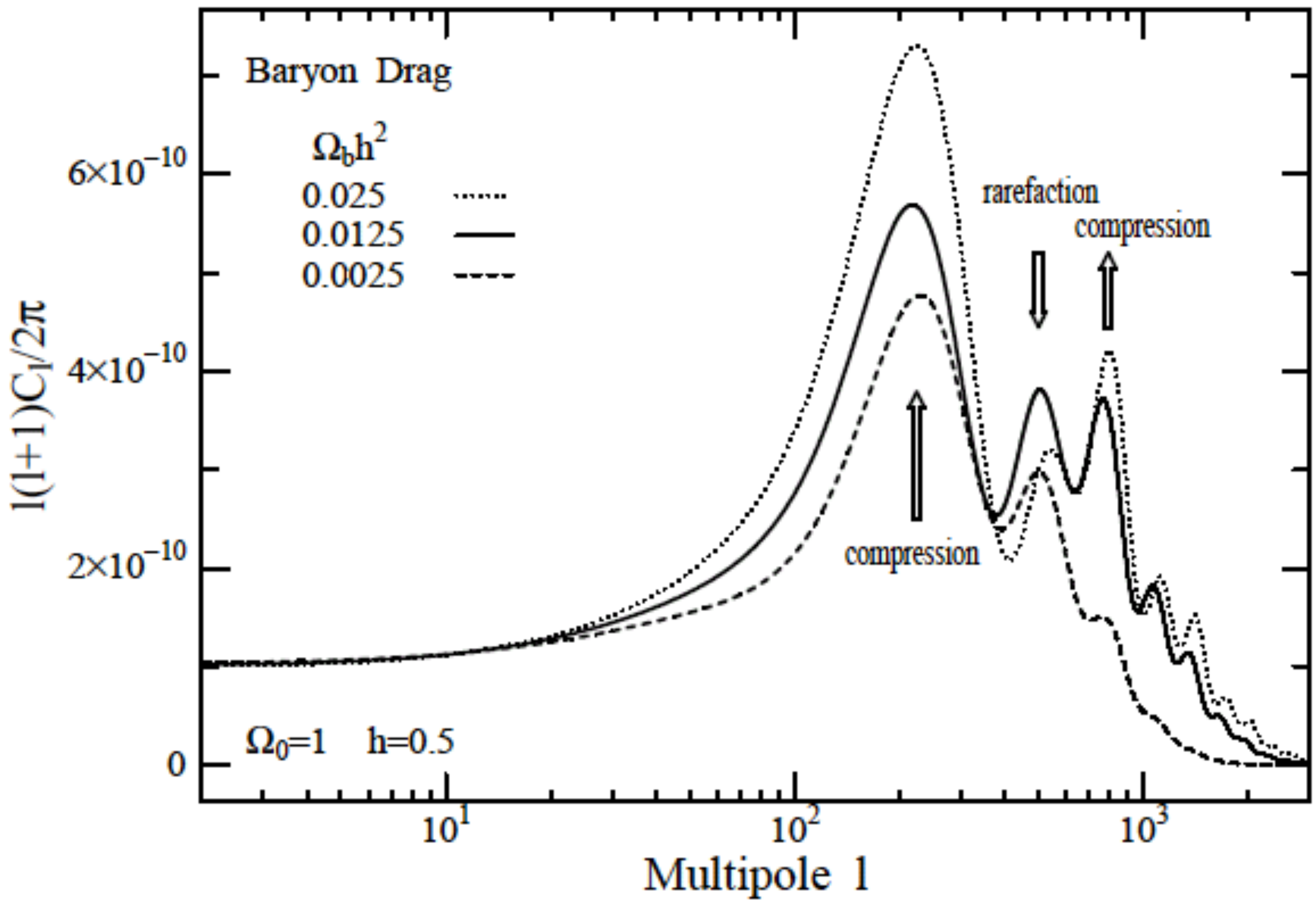
→Lower sound speed

→Compress more

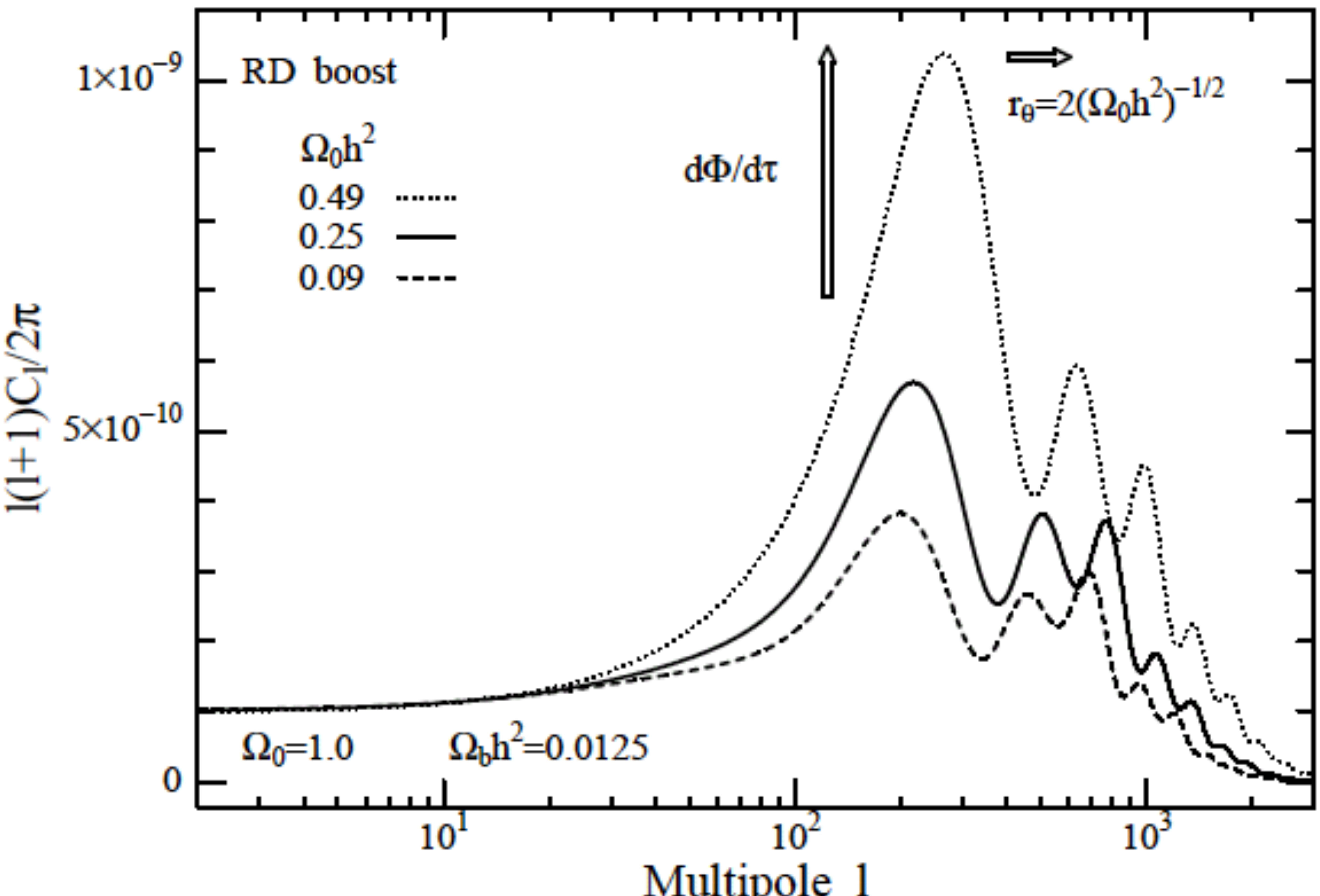
→Higher peaks at compression phase (even peaks)


Adiabatic Acoustic Oscillation
–Silk Damping–
0.8
0.6
0.4
0.2
0
$(\Delta T/T)^2/\Phi_A^2$
0
π
3π
5π
7π
kr_s

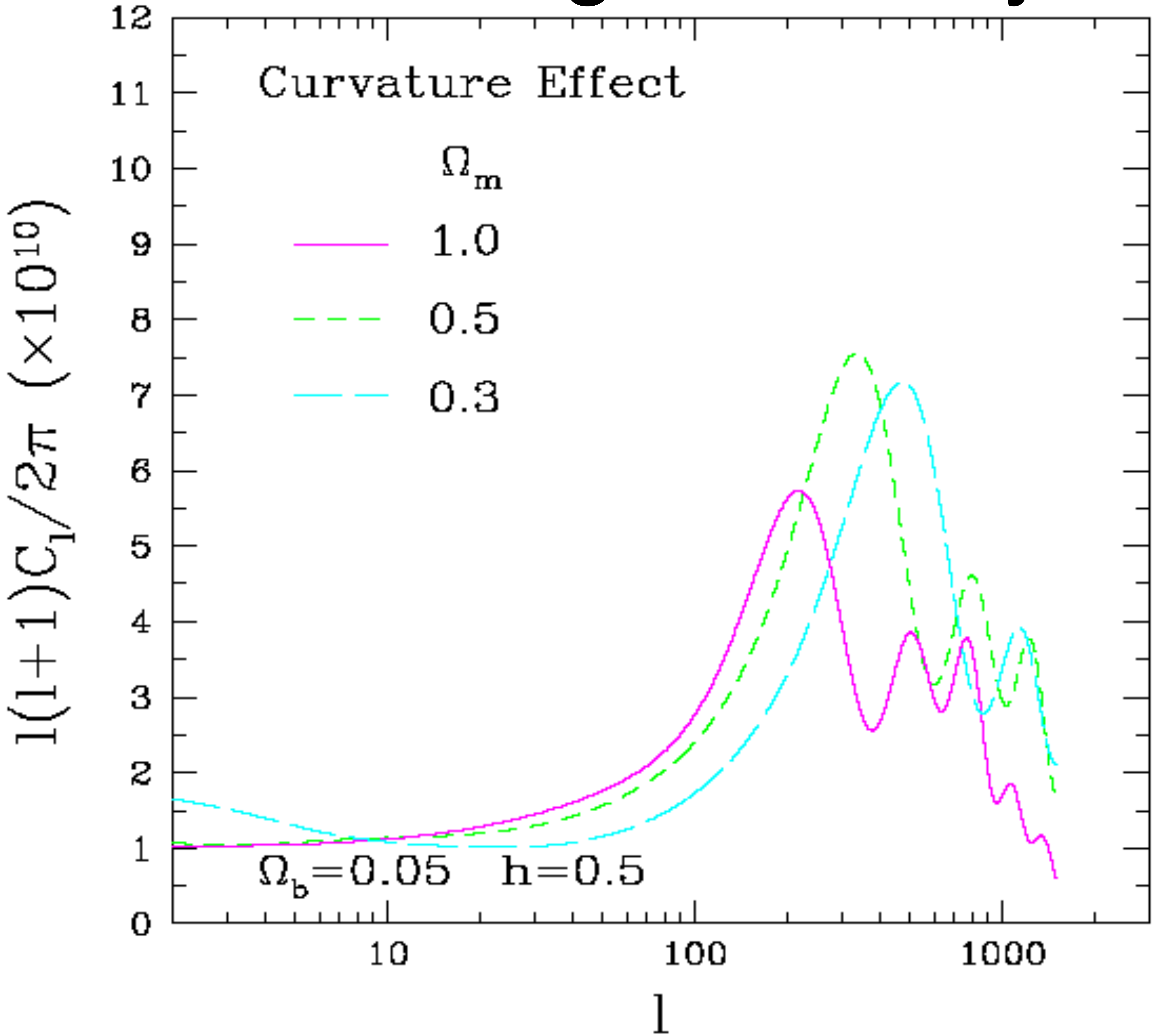
Determining Baryon Density



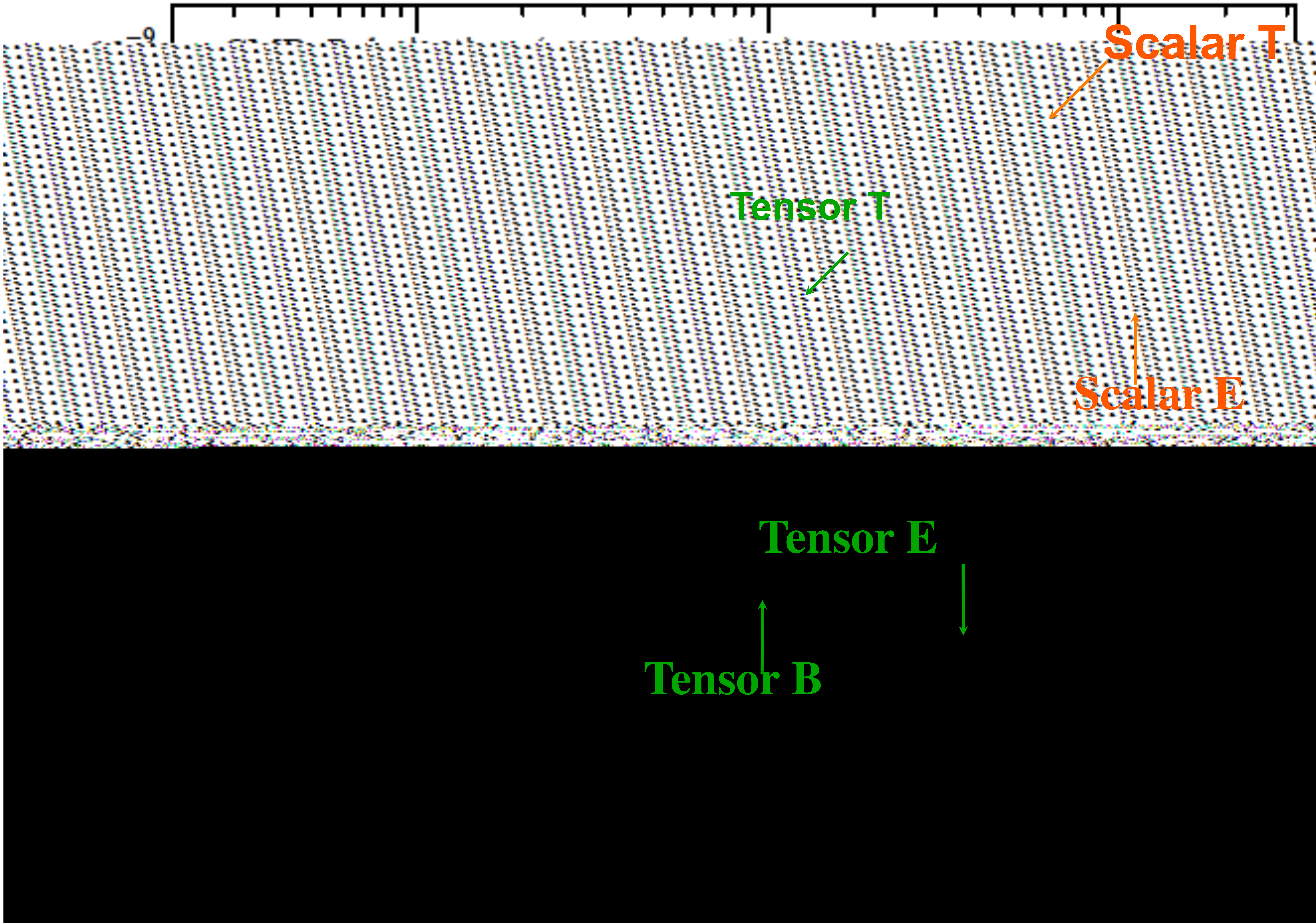
Determining Dark Matter Density



Measuring Geometry



Power Spectrum



Measuring Optical Depth

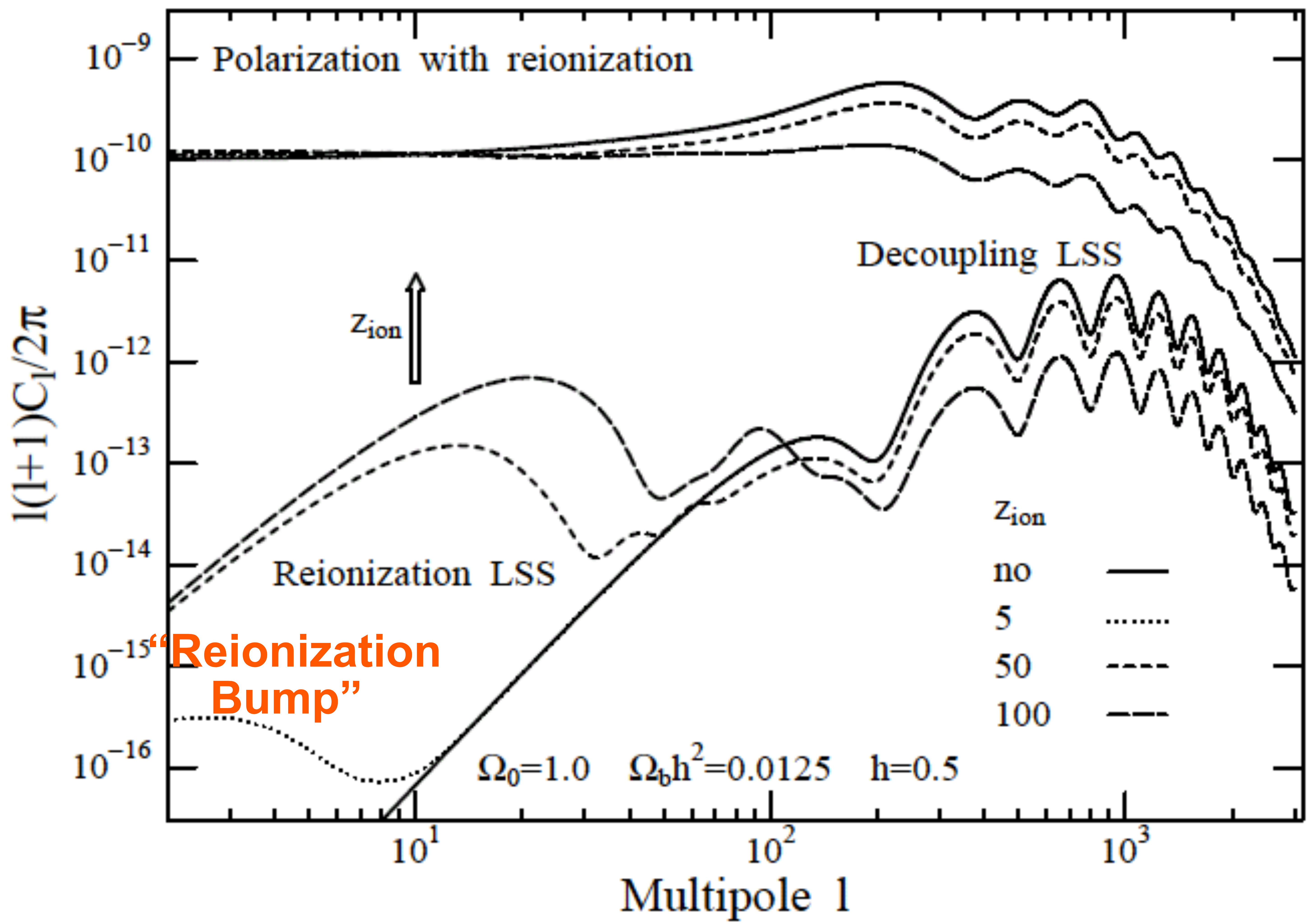
- Since polarization is generated by scattering, the amplitude is given by the number of scattering, or optical depth of Thomson scattering:

$$\tau(z) = \sigma_T n_{e0} \int_0^z dz' \frac{cdt}{dz'} x_e(z')(1+z')^3$$

which is related to the electron column number density as

$$\tau / \sigma_T = 1.5 \times 10^{23} (\tau / 0.1)\ \mathrm{cm}^{-2}$$

Polarization from Reioniazation



WMAP 3-Year Power Spectra