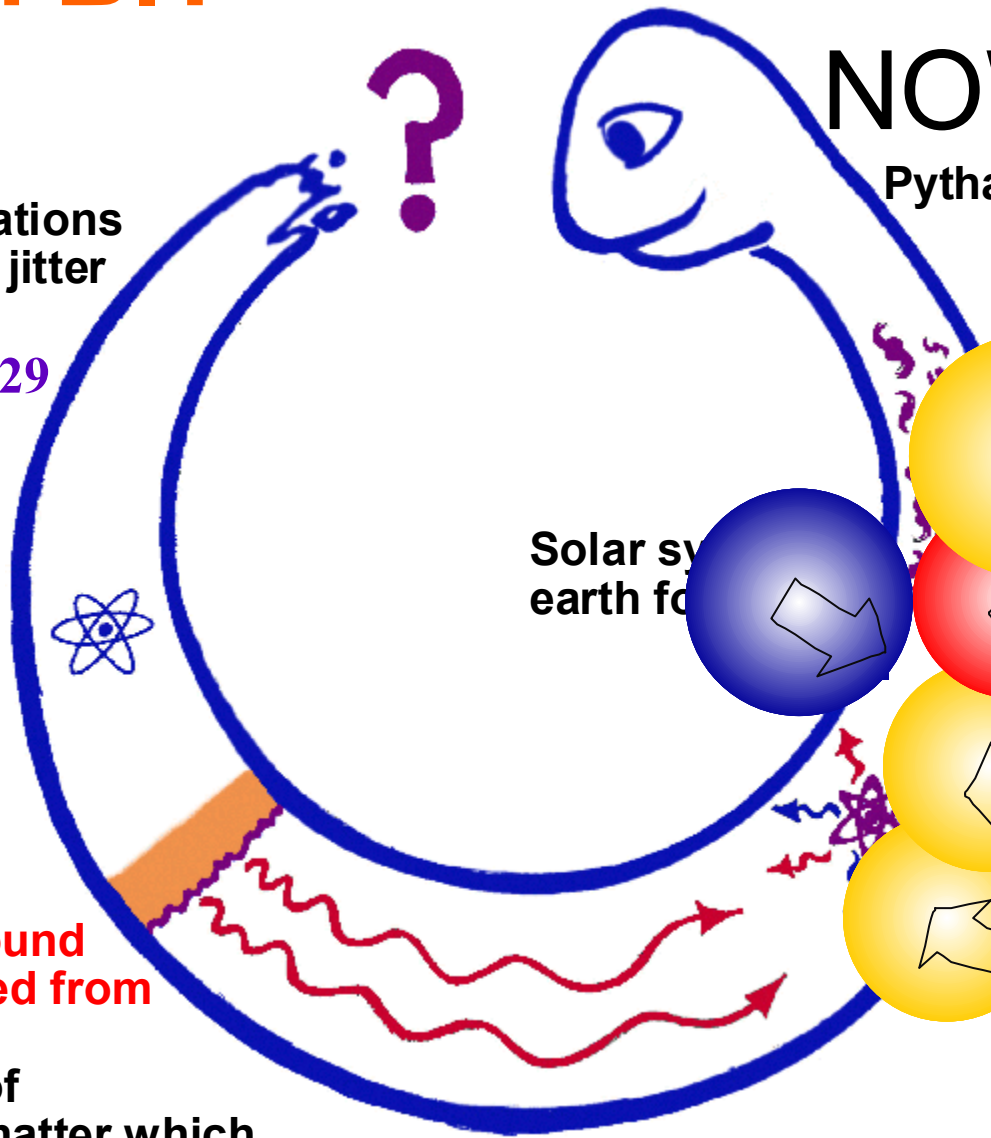
CITA ICAT Canadian Institute for Theoretical Astrophysics
L'institut canadien d'astrophysique theorique

Dick Bond

CIAR

L1: The Cosmic Microwave Background & the Thermal History of the Universe

“IT from BIT”



NOW 14 Gyr 1

Pythagoras formed

Galaxies Cluster
Cosmic “web” of vast filaments + membranes

Life forms on earth

9 Gyr 1.4

Carbon/oxygen/etc form

Galaxies form

2 Gyr 4

Inflation fluctuations form: quantum jitter

10^{-37}sec 10^{29}

Protons/Neutrons form

Helium forms

100 sec 10^{9}

Cosmic background radiation released from matter
carries imprint of fluctuations in matter which grow to generate galaxies etc.

0.4 Myr 1100

The ‘Meaning’ may change
But the facts will remain

"IT from BIT"

fate & dark energy

NOW 14 Gyr 1

Pythagoras formed

Inflation fluctuations form: quantum jitter

10^{-37}sec 10^{29}

Galaxies Cluster
Cosmic "web" of vast filaments + membranes

Protons/Neutrons form

Solar sy
earth fo

Life forms on earth

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100 sec 10^{9}

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0.4 Myr 1100

The 'Meaning' may change
But the facts will remain

EGYPT TIMES Mar 31 2006

“Canadians make it easy to say sorry”

Legislation to allow Canadians to admit mistakes without litigation

CMB/LSS Phenomenology

CITA/CIAR here

- Bond
- Contaldi
- Lewis
- Sievers
- Pen
- McDonald
- Majumdar
- Nolta
- Iliev
- Kofman
- Vaudrevange
- Shirokov
- El Zant
- Dalal
- Dore
- Kesden
- MacTavish
- Pfrommer

UofT here

- Netterfield
- MacTavish
- Carlberg
- Yee

CITA/CIAR there

- Mivelle-Deschenes (IAS)
- Pogosyan (U of Alberta)
- Prunet (IAP)
- Myers (NRAO)
- Holder (McGill)
- Hoekstra (UVictoria)
- van Waerbeke (UBC)

& Exptal/Analysis/Phenomenology Teams here & there

- Boomerang03
- Cosmic Background Imager
- Acbar
- WMAP (Nolta, Dore)
- CFHTLS – WeakLens
- CFHTLS - Supernovae
- RCS2 (RCS1: Virmos)

Parameter datasets: **CMBall_pol**

SDSS P(k), 2dF P(k)

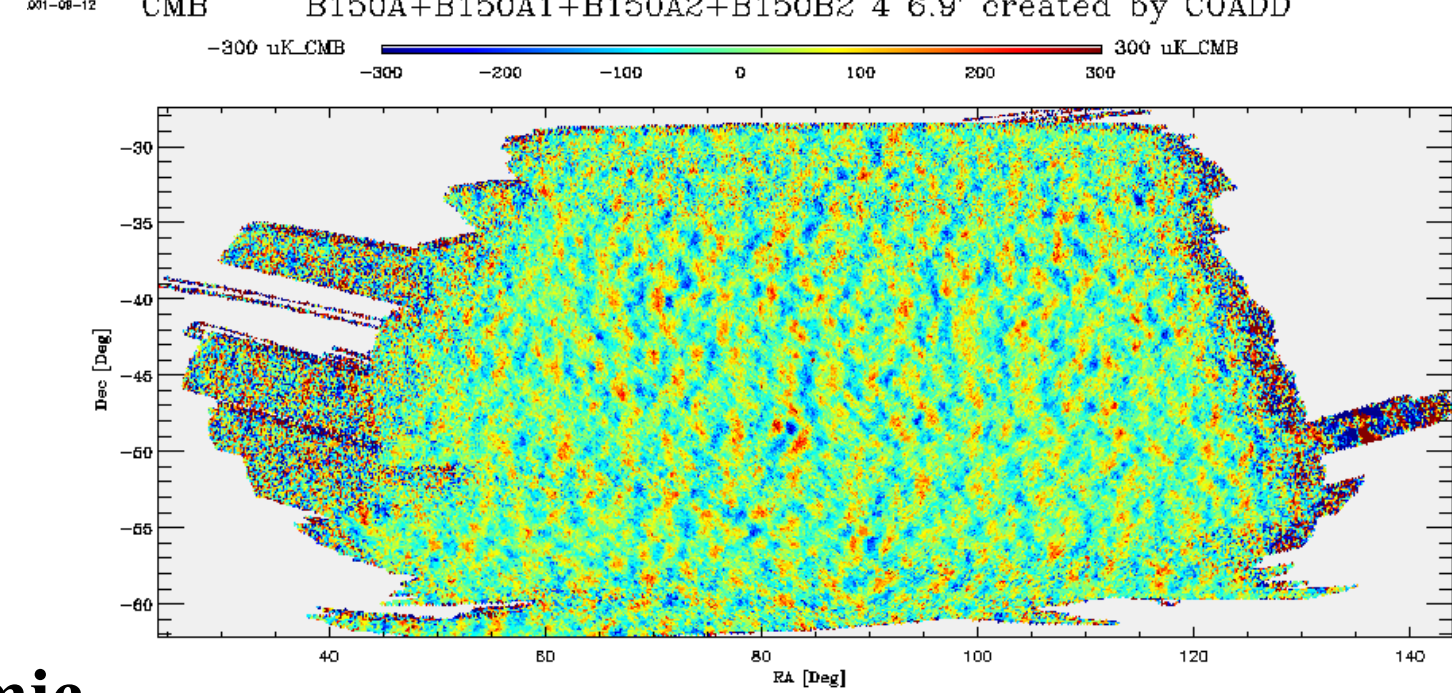
Weak lens (Virmos/RCS1; CFHTLS, RCS2)

Lya forest (SDSS)

SN1a “gold” (157, 9 z>1), CFHT

futures: SZ/opt, 21(1+z)cm

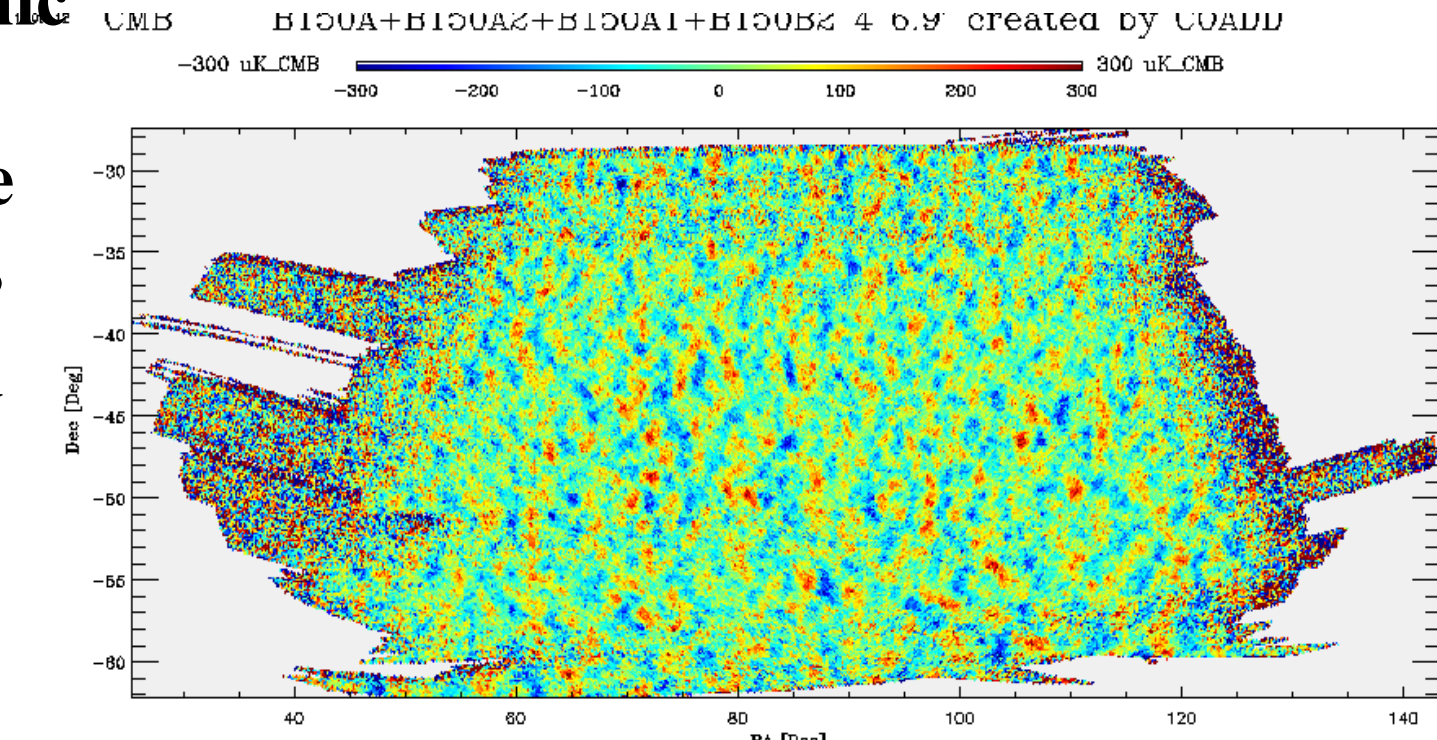
Boomerang @150GHz is (nearly) Gaussian: Simulated *vs* Real



thermodynamic CMB temperature fluctuations

2.9% of sky

~ 30 ppm



Sorry CITAzens: real seems to be simulated

Boomerang, Cosmic Background Imager, WMAP3, …

No wonder the LCDM concordance model looks so good

Real is a mock: march 29, 2006

a BLACK DAY for some CITAzens

new deeply embedded analysis march 31, 2006

The wrinkled lightcone may not be LCDM

but a statistically anisotropic but well-known shape

The anisotropic lightcone led to a new model for the power defining the current universe

Pyramid power

Acknowledgment: realization

Occurred at Khufu's place in Giza, the chamber in the centre of the great pyramid

March 31, 2006

But new realization now I am on Egyptian time and APRIL FOOL's ends at noon April 1

real is in fact real, for

Boomerang, Cosmic Background Imager, WMAP3, …

the LCDM concordance model does indeed look good

& the structure of the universe seems to be understandable in terms of a handful of basic cosmological parameters,

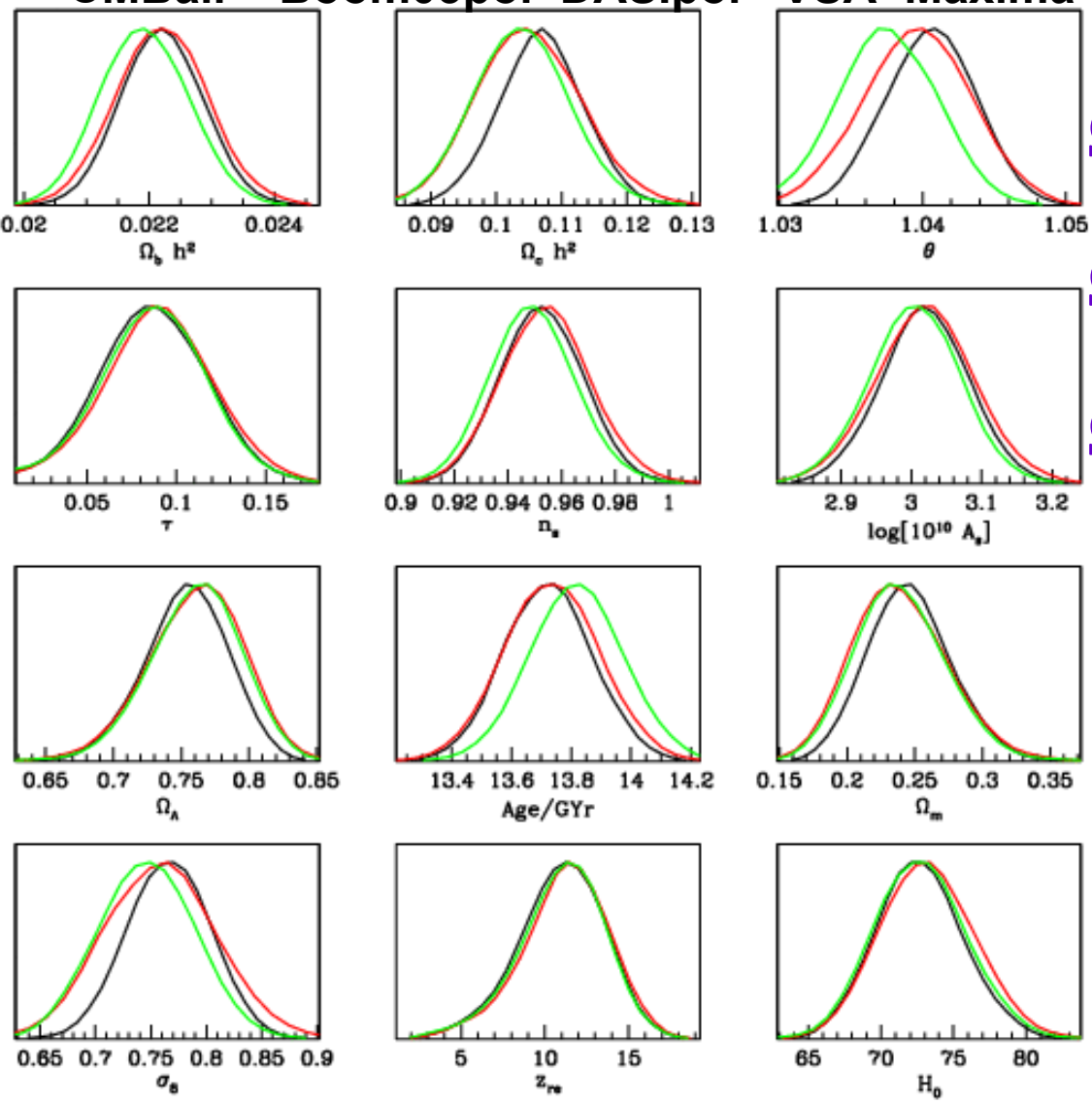
Baryon, dark matter, dark energy densities

Power spectra for primordial fluctuations

The Parameters of Cosmic Structure Formation

WMAP3 WMAP3+CBIcombinedTT+CBIpol

CMBall = Boom03pol+DASIpol +VSA+Maxima+WMAP3+CBIcombinedTT+CBIpol



$\Omega_b h^2 = .0222 +- .0007$

$\Omega_c h^2 = .107 +- .007$

$\Omega_\Lambda = .75 +- .03$

Parameters of Cosmic Structure Formation

Period of inflationary expansion, quantum noise → metric perturb.

Ω_k $\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ τ_c n_s n_t $A_s \sim \sigma_8$ A_t

Wha… Densi… Sp… Optical Depth to … litude

curvatu… interac… pr… Last Scattering … ions

M… (… Surface … es)

$\Omega_k > 0$

$\Omega_k = 0$ flat … s

$\Omega_k < 0$ open … n_t

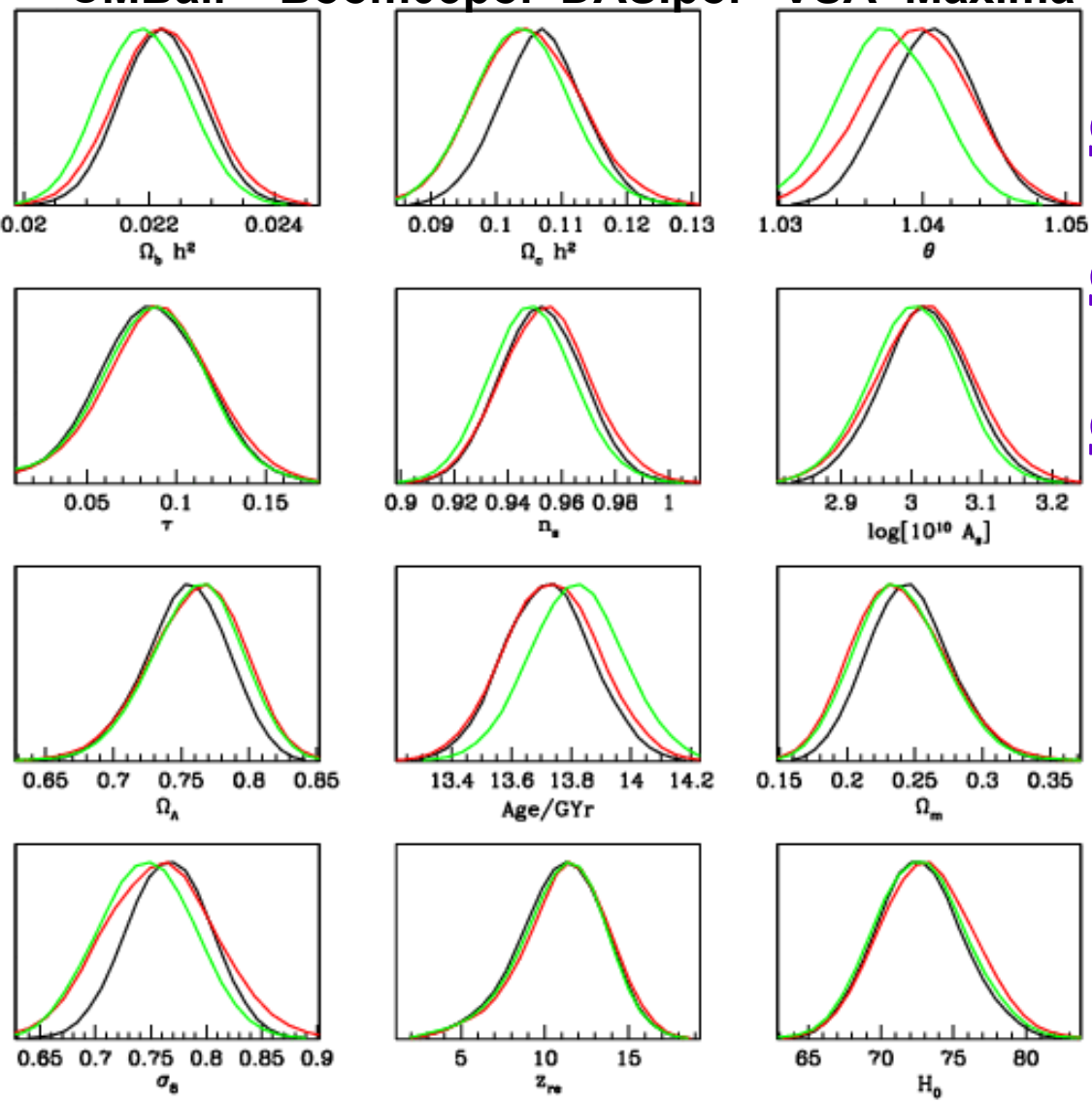
When did stars reionize the universe? … S

- Inflation → predicts nearly scale i… and background of gravitational wa…
- Passive/adiabatic/coherent/gaussia…
- Nice linear regime
- Boltzman equation + Einstein equ…

The Parameters of Cosmic Structure Formation

WMAP3 WMAP3+CBIcombinedTT+CBIpol

CMBall = Boom03pol+DASIpol +VSA+Maxima+WMAP3+CBIcombinedTT+CBIpol



$\Omega_b h^2 = .0222 +- .0007$

$\Omega_c h^2 = .107 +- .007$

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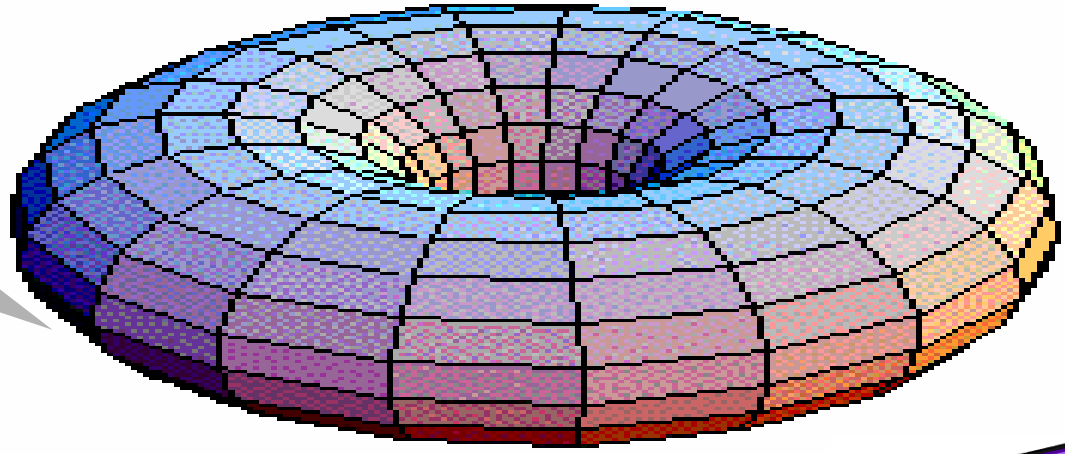
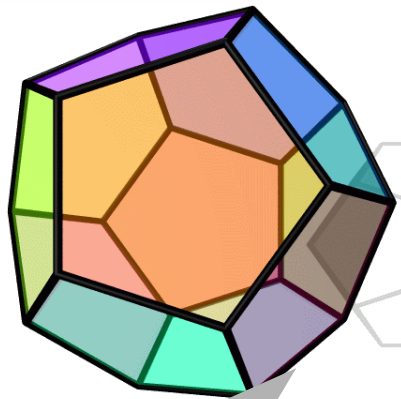
Simple Torus
(Euclidean)

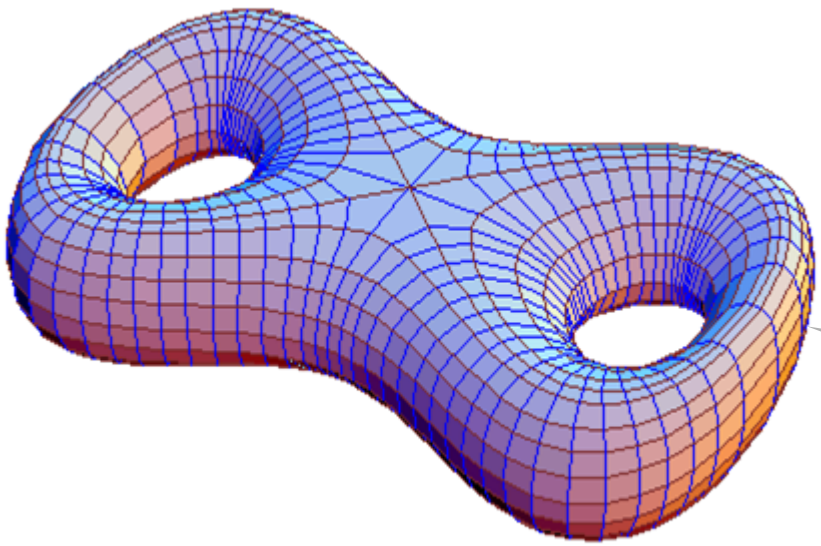


Cosmic topology

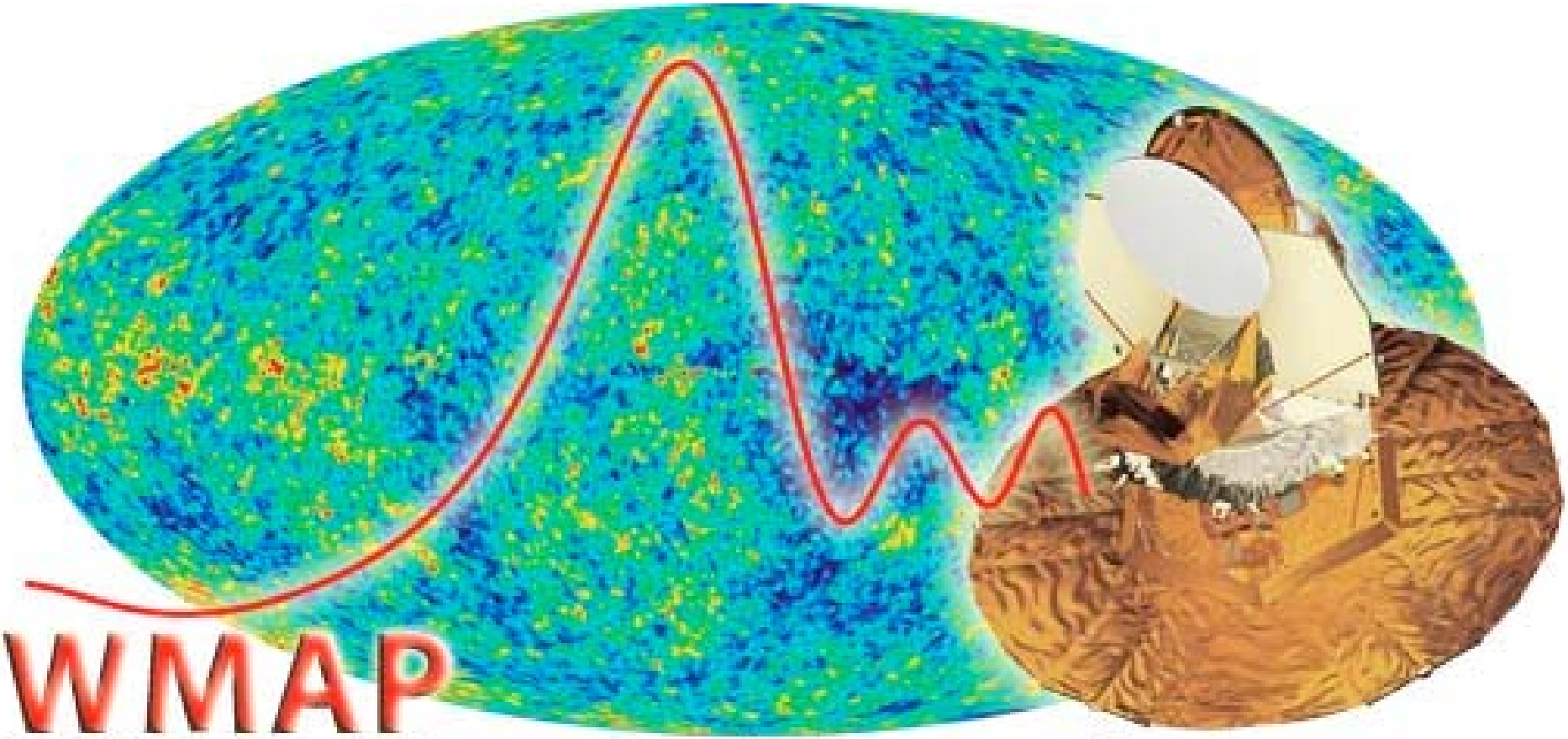
Multiply connected universe ?



MC spherical space
("soccer ball")



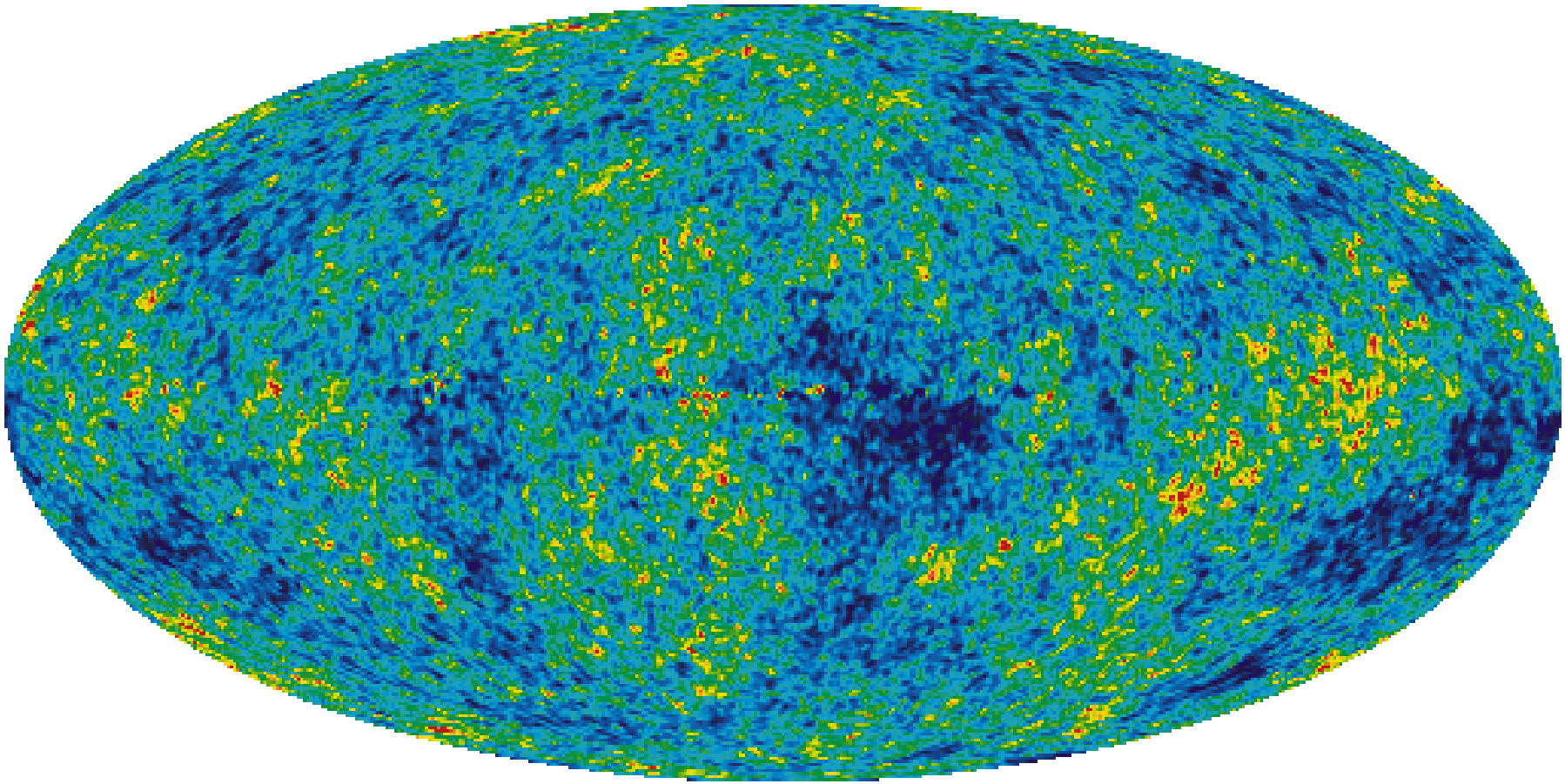
Compact hyperbolic
space



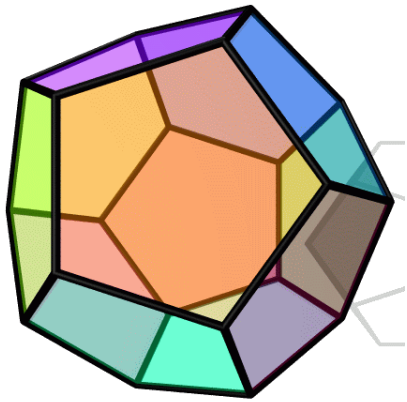
WMAP

Wilkinson Microwave Anisotropy Probe

WMAP3 thermodynamic CMB temperature fluctuations



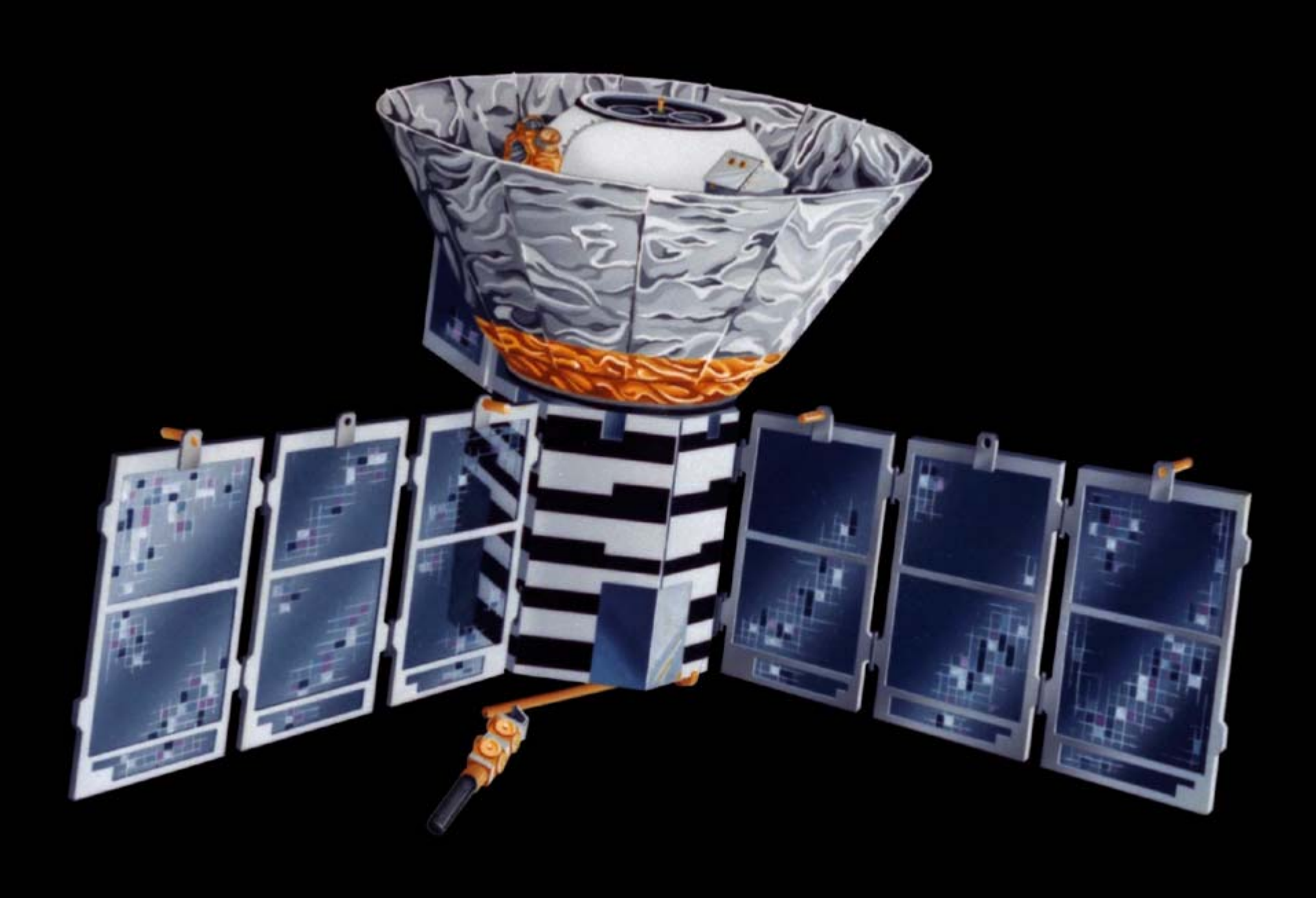
Co(s)mic Topology



Non april fool

Is the universe like a soccer ball?

The CMB data decides:

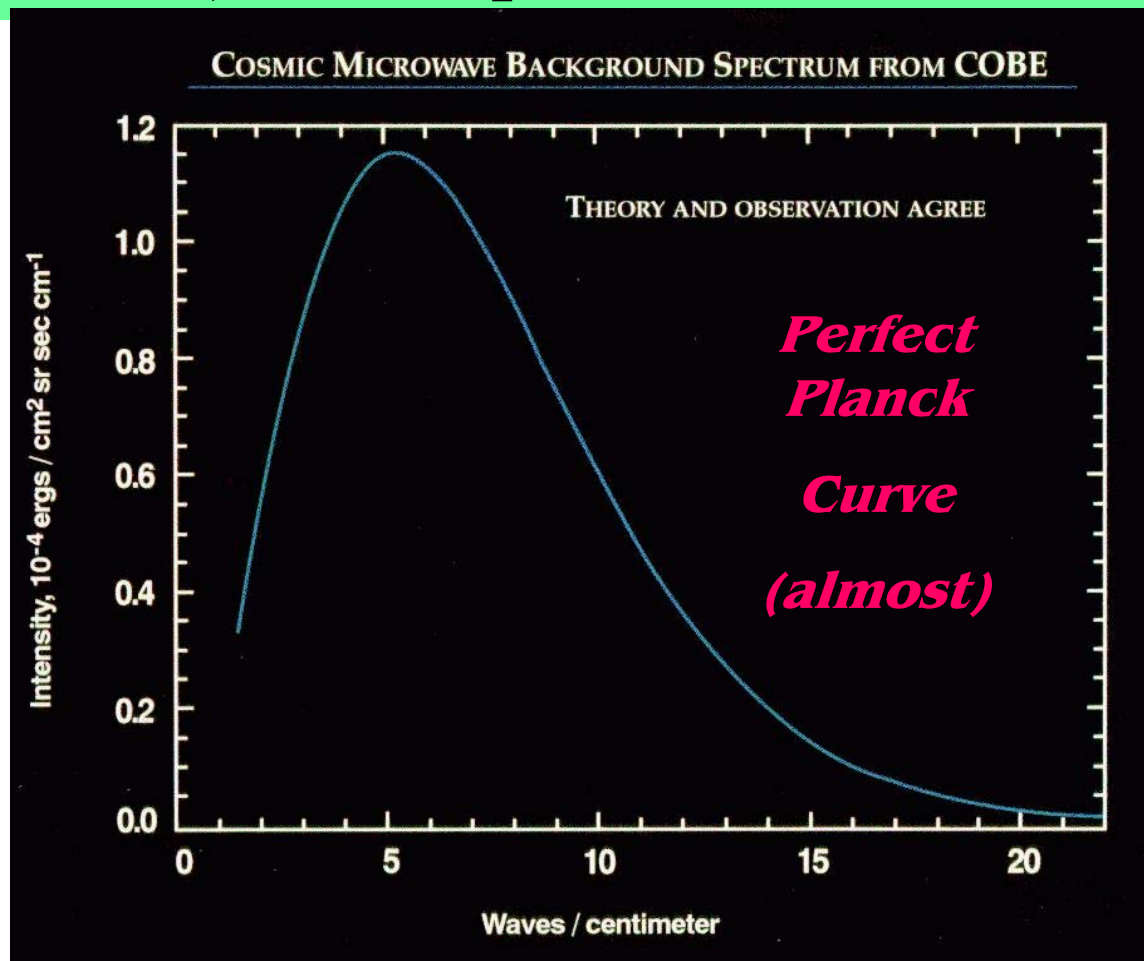


COBE satellite 1989-1994

Hot Big Bang

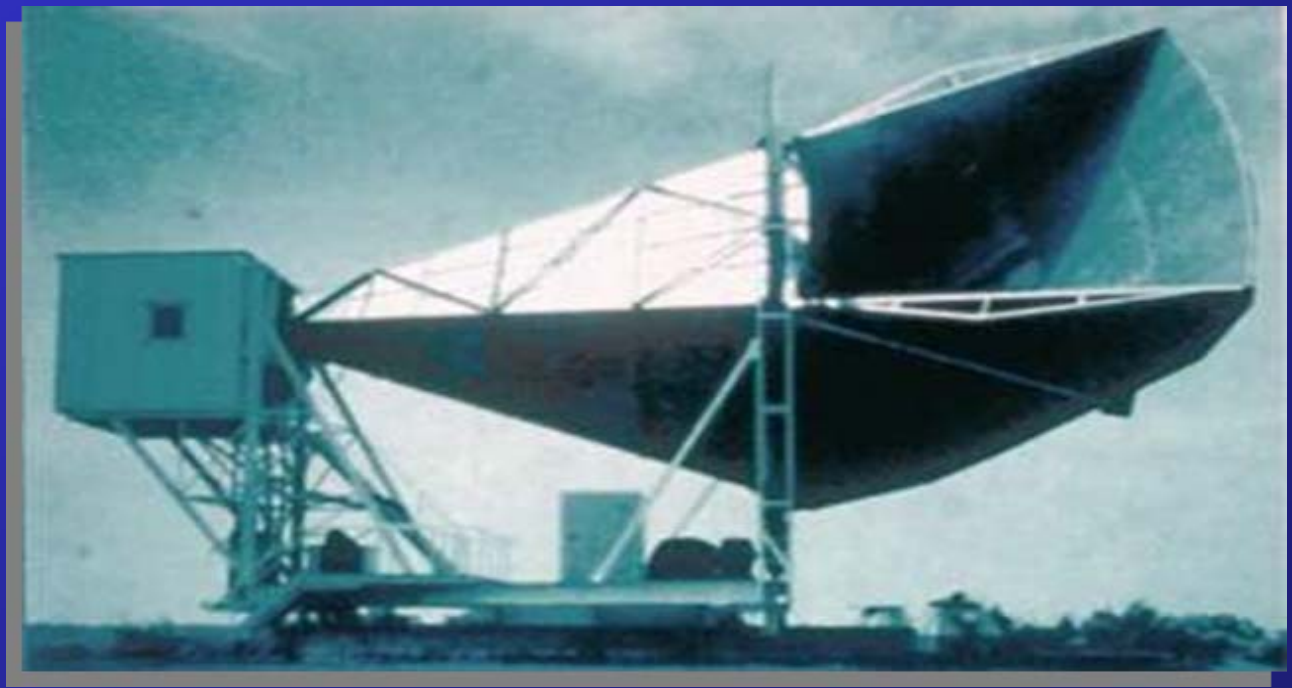
- Picked up as TV ‘snow’ - a few %
- 2.725 ±.001 degrees above absolute zero
- 410 photons per cubic centimetre
- Isotropic (smooth) to one part in 100,000

released as red light 400,000 yrs after the Big Bang, expansion of space stretched the wavelengths to microwave



Discovery of the Microwave Background

- Discovered accidentally as a source of noise in a radio receiver
- 1965 Bell Telephone Laboratories
- Penzias and Wilson share Nobel prize in 1978



$$qc = \frac{2\pi\hbar c}{\lambda} = \bar{a}(t)\omega = \bar{a}(t)\frac{2\pi\hbar c}{\lambda_e}$$

Planck distribution function

f = 1/(exp[q/(aT)] -1)

Thermodynamic temperature T(q) from f(q)

d Number of photons = f d Phase Space Volume

$= f\ 2\ d^3q/(2\pi)^3\ d^3x$

$d\ E/V = f\ q^3/\pi^2\ dq$ Planck energy curve

$$\left.\frac{\partial f_k}{\partial \tau}\right|_q + \hat{q}\cdot\nabla f_k = \bar{a}\,S[f_k]$$

Time derivative along the photon direction

Sources, sinks, scattering processes

$$n_{\gamma *} = \frac{2\zeta(3)}{\pi^2} T_{\gamma *}^3, \quad \rho_{\gamma *} = \frac{3}{4} s_{\gamma *} T_\gamma \approx 2.7 n_{\gamma *} T_\gamma, \quad p_\gamma = \frac{1}{3} \rho_\gamma \approx 0.9 n_\gamma T_\gamma,$$

$n_{\gamma *} = 410/cc,$

$\rho_{\gamma *} = 0.26$ ev/cc

$1+(7/8)(4/11)N_\nu^{4/3}$ x 1.04]

total energy

when was the entropy generated in the U?

$$dE + p\,dV = T\,dS \qquad (-\Sigma\,\mu\,d\,N)$$

$$s_{\gamma *} = \frac{4\pi^2}{45}(\bar{a}T_\gamma)^3 \left[\frac{k_B}{\hbar c}\right]^3 = 1.48 \times 10^3\ cm^{-3}$$

$\Omega_{\gamma *} h^2 = 2.45 \times 10^{-5}$

Lev Kofman lectures

Answer: earlier than redshift $z \sim 10^{6.8}$ or distortions in the CMB spectrum

(when was the baryon number generated? dB=0 after)

$s_{\gamma *} / n_{b *} = 0.65 \times 10^{10}\ (.02/\Omega_b h^2)$

$[1+(7/8)(4/11)N_\nu \times 1.04]$ total entropy

cf. entropy per baryon in the centre of the sun ~19

In a pre-supernova core about to implode ~1

Thermodynamic temperature T(q)

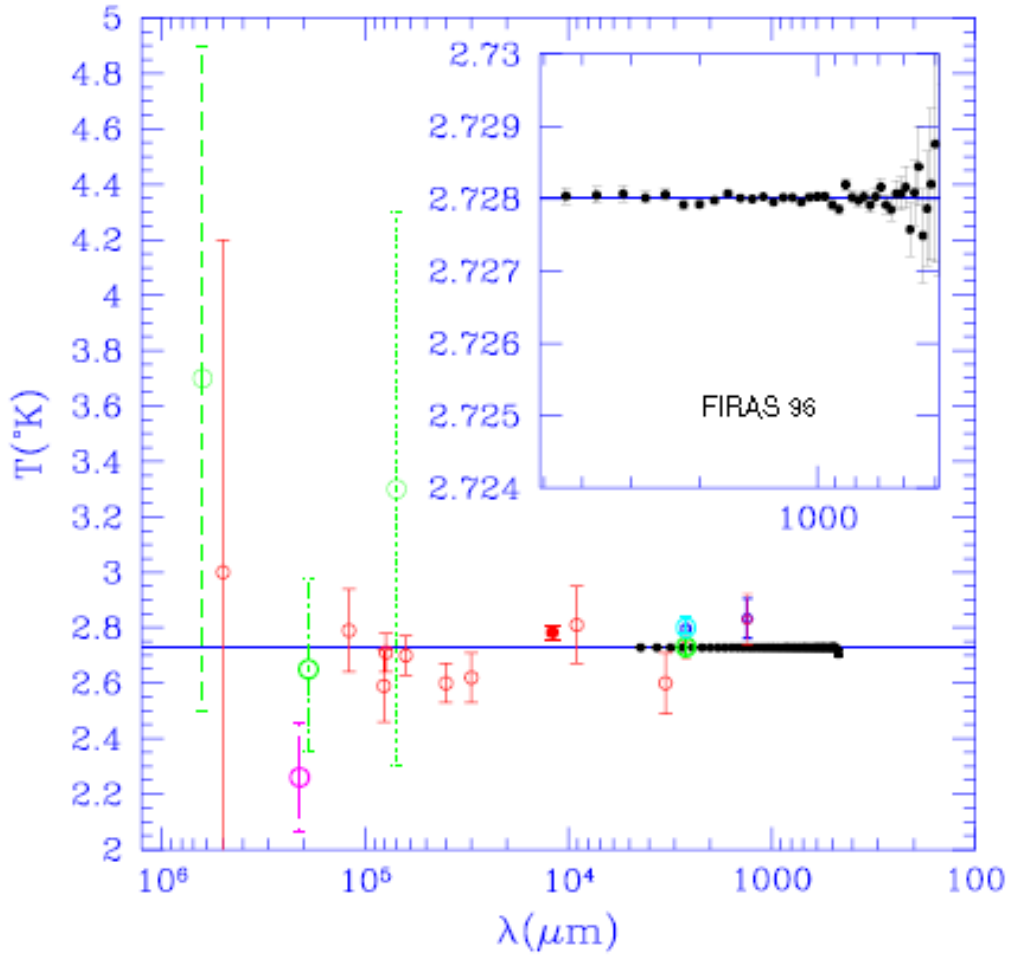


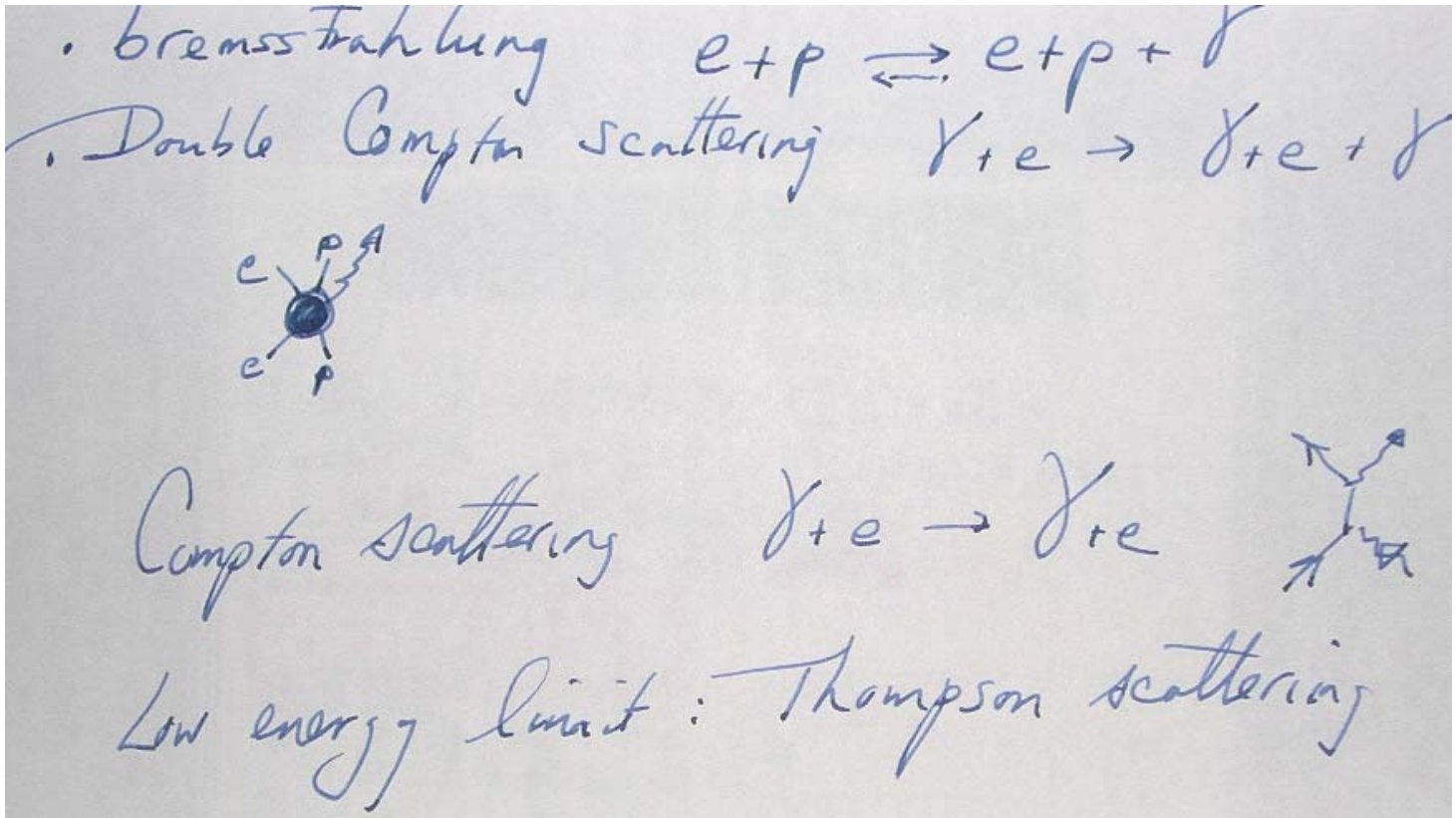
FIG. 1. Selected old and new data on CMB distortions in terms of thermodynamic temperature. The dotted point at 7 cm is the original Penzias and Wilson (1965) result, the long-dashed point at 63 cm is from Howell and Shakeshaft (1966). The situation in the Rayleigh–Jeans region was improved quite a bit with the White Mountain collaboration results (solid). Results from Bersanelli (1995) at 21 cm and Staggs and Wilkinson (1995) at 19 cm are shown. The point with the small error bar at $\lambda = 1.2$ cm is that of Johnson and Wilkinson (1987). Cyanogen results are given at 2640 μm (Roth et al. 1993, Crane 1989, 1995). The tiny error bars are from FIRAS (Fixsen et al. 1996). The inset gives a blowup of the region for FIRAS.

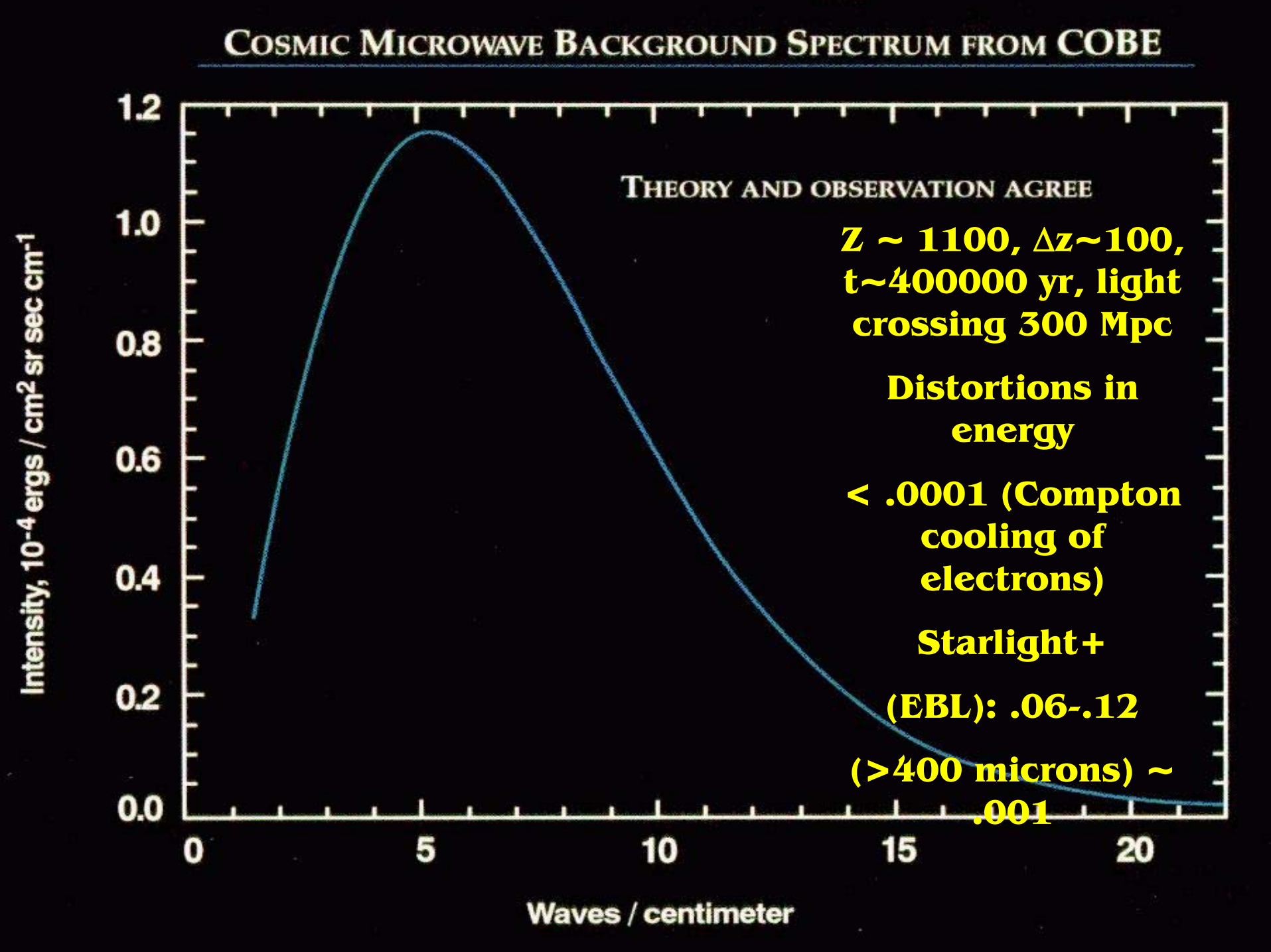
the Boltzmann transport equation for photons

$$\left.\frac{\partial f_k}{\partial \tau}\right|_q + \hat{q}\cdot\nabla f_k = \bar{\alpha}\,S[f_k]$$

Time derivative along the photon direction

Sources, sinks, scattering processes




COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
Z ~ 1100, Δz~100, t~400000 yr, light crossing 300 Mpc
Distortions in energy
< .0001 (Compton cooling of electrons)
Starlight+
(EBL): .06-.12
(>400 microns) ~ .001
Intensity, 10-4 ergs / cm2 sr sec cm-1
Waves / centimeter
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20

Planck dist fn

max entropy for fixed energy

Bose-Einstein dist fn

max entropy for fixed energy and number

$z >\sim 10^{5.4} (.02/\Omega_b h^2)^{1/2}$ but $< 10^{6.8}$

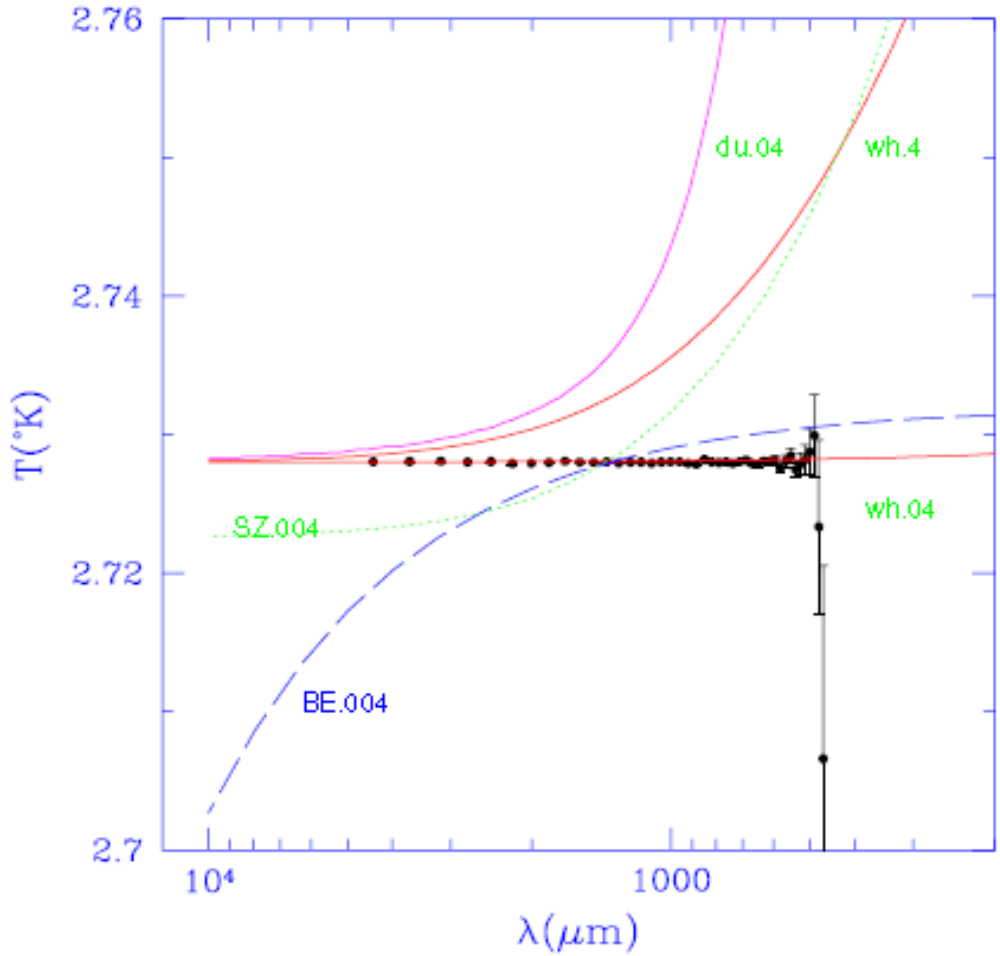
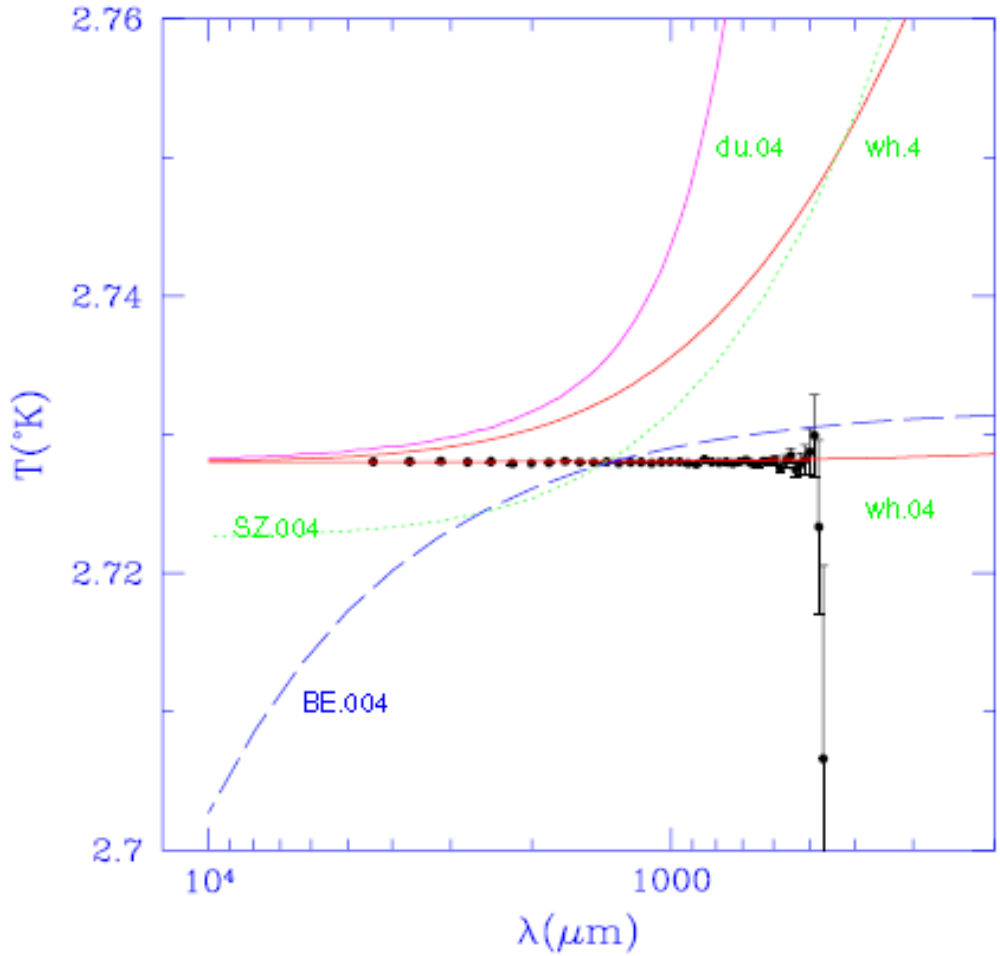


FIG. 2. Sample types of spectral distortions are compared with the FIRAS data (Fixsen et al. 1996). SZ.004 is a y-distortion with $y = 0.001$, BE.004 is a Bose–Einstein distortion with $\alpha = 0.0057$, du.04 is a model with ordinary dust grains with abundance 10^{-6} reprocessing injected energy which was taken to be 4% of that in the CMB between redshifts 50 and 25. Two models mimicking the effect of an optically thin abundance of needle-like grains (whiskers) acting over the same redshift, with 40% and 4% of the CMB energy injected, are also shown.

Compton cooling distortion from hot gas (intraclusters)

Sunyaev-Zeldovich effect

$$z <\sim 10^{4.9} (.02/\Omega_b h^2)^{1/2}$$



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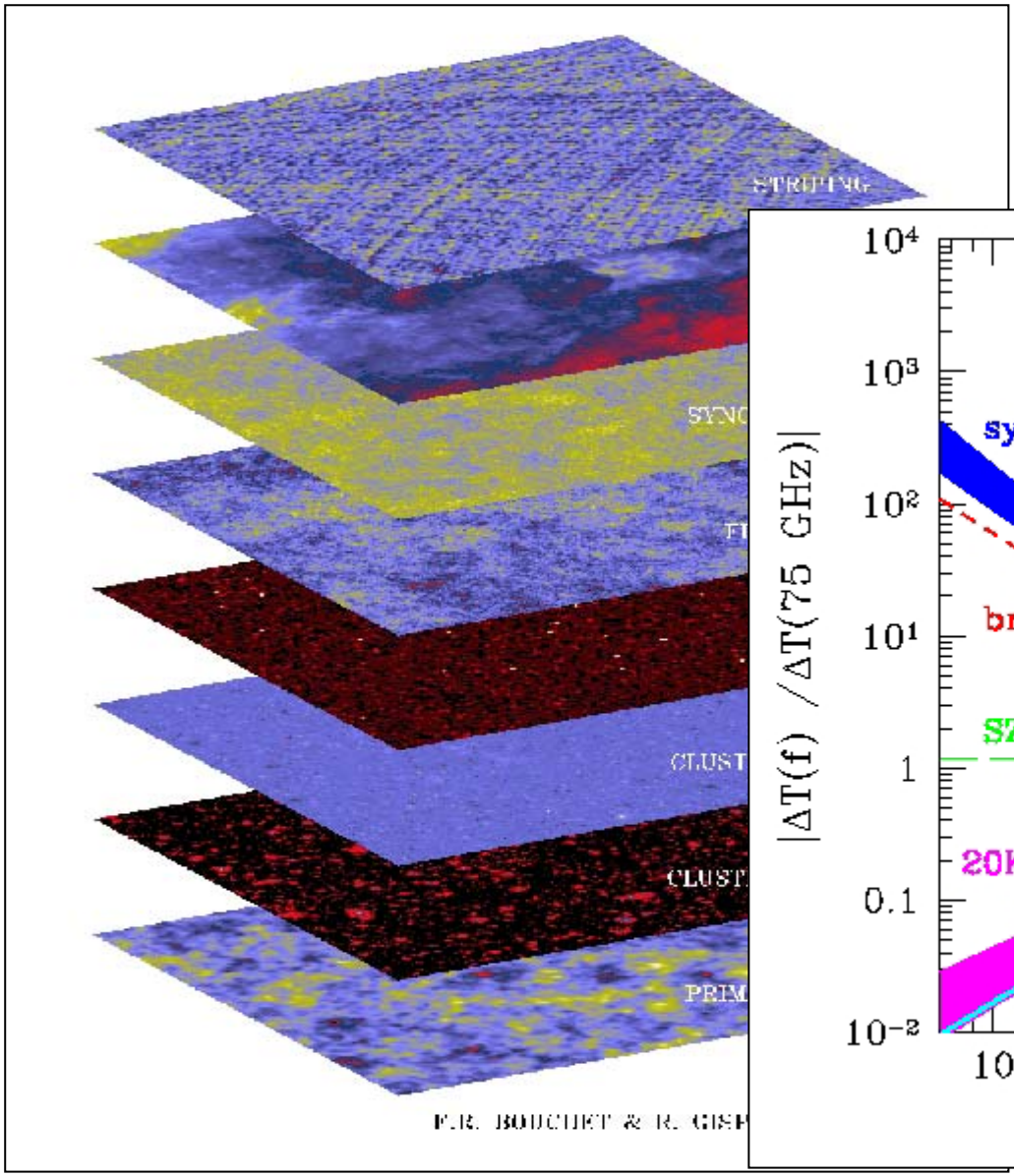
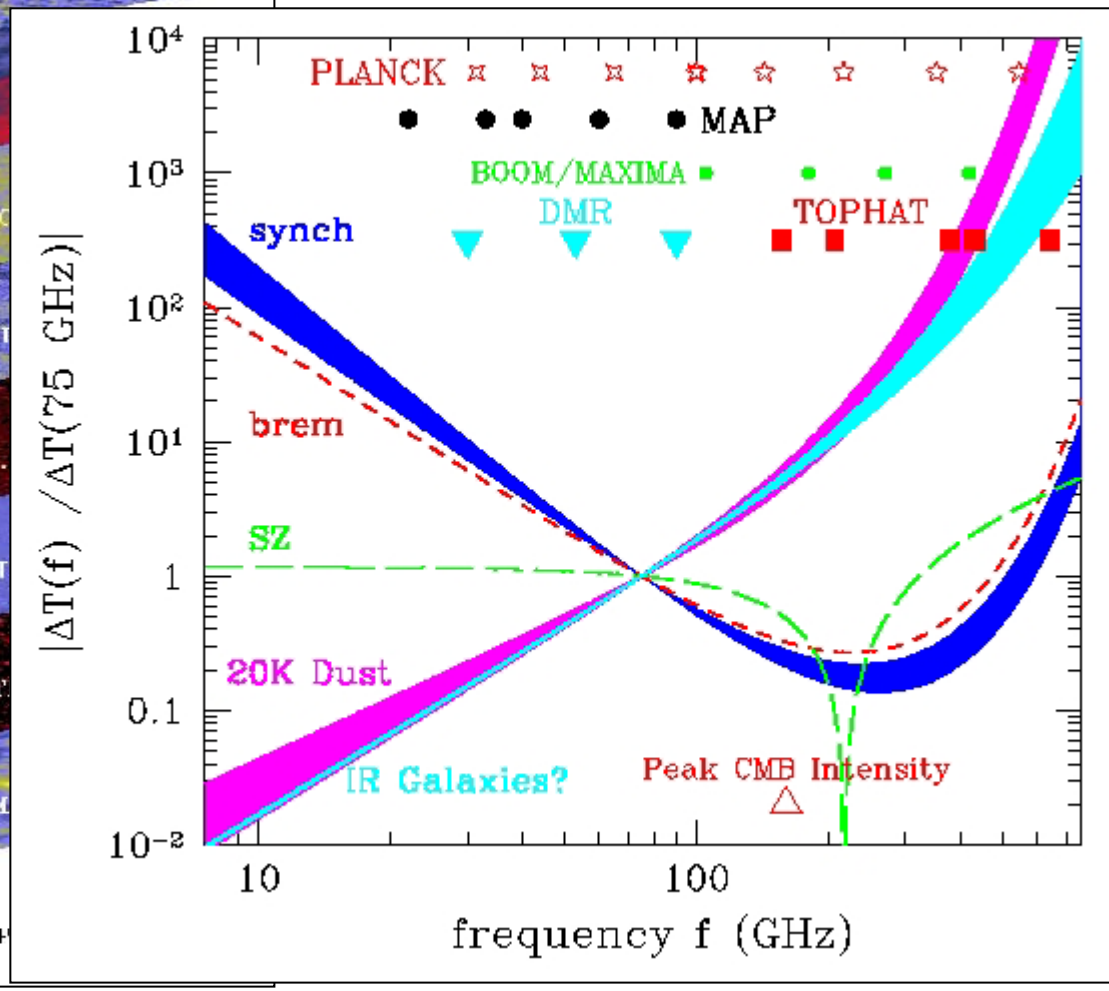
Secondary Anisotropies and foregrounds





$$\frac{s_{tot+}}{n_{B+}} = 2.56 \times 10^{10} \left(\frac{\Omega_B h^2}{0.01}\right)^{-1}, \qquad \frac{s_{\gamma+}}{n_{B+}} = 1.31 \times 10^{10} \left(\frac{\Omega_B h^2}{0.01}\right)^{-1}$$

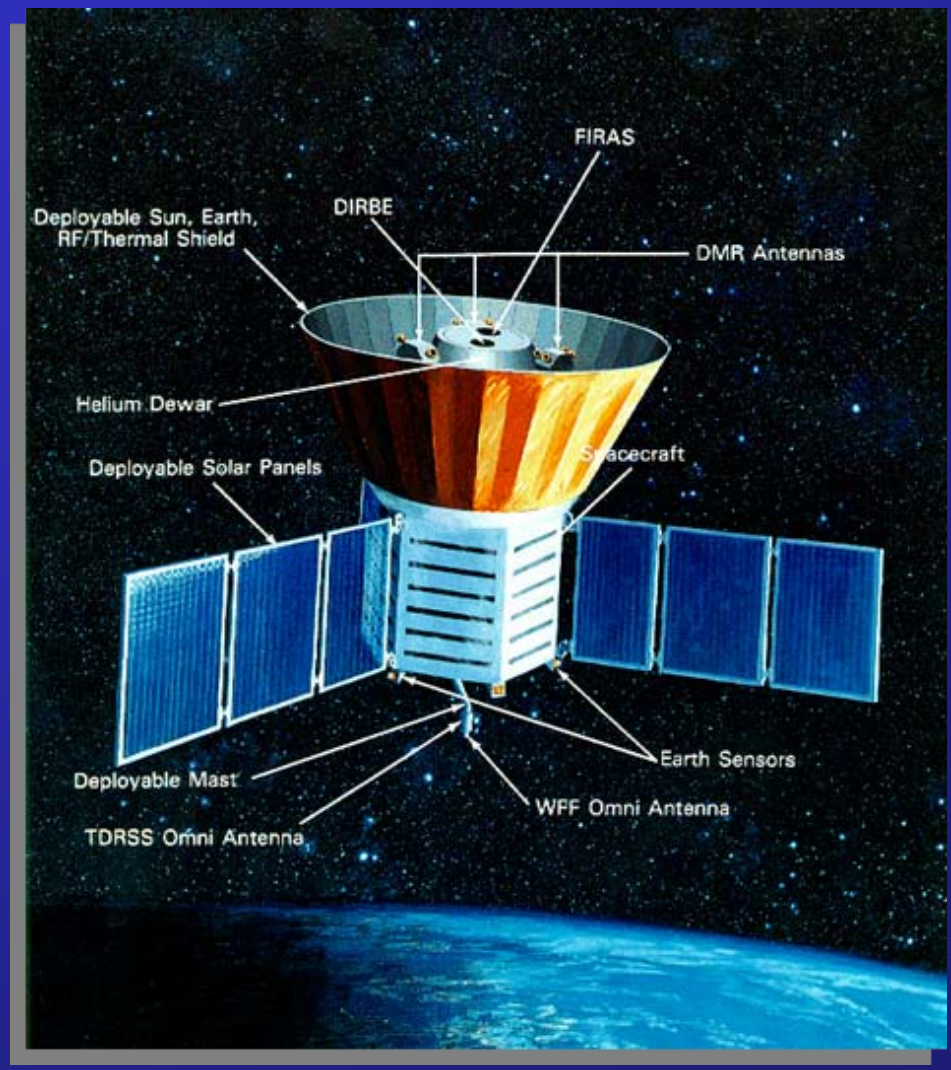
Compton y-parameter: $\bar{y} < 1.5 \times 10^{-5} \quad (95\%\ CL)$,

chemical potential: $|\mu_\gamma|/T_\gamma < 0.9 \times 10^{-4} \quad (95\%\ CL)$,

general distortions: $\frac{\delta E}{E_{cmb}}(500\text{–}5000\ \mu\mathrm{m}) < 0.00025\ (1\sigma)$

COBE Mission

- COsmic Background Explorer
- First satellite mission to measure CMB
- Launched in 1989
- Collected data for four years
- Passively cooled
- First anisotropy detection announced in 1992

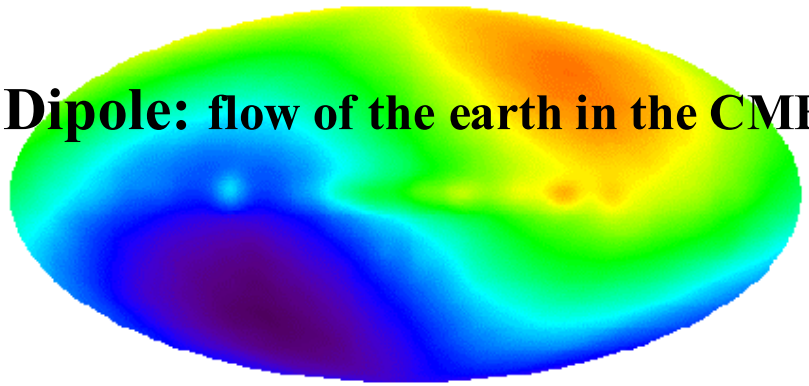


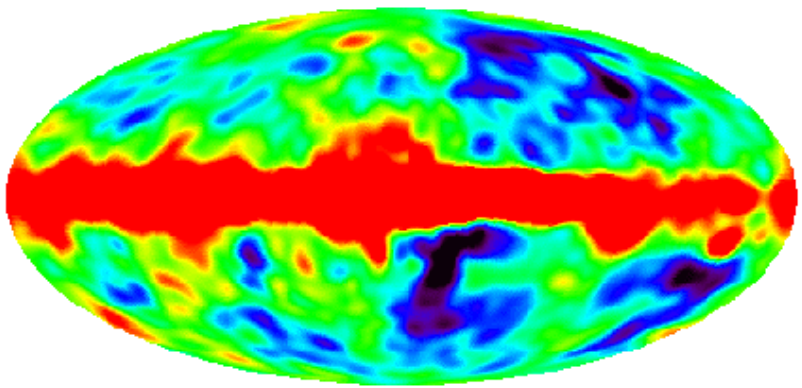
CMB

Nearly Perfect Blackbody

T=2.725 ±.001 K COBE/FIRAS

Dipole: flow of the earth in the CMB





COBE/DMR:

CMB + Galactic @7^{o}

The CMB shows the hot big bang paradigm holds, with:

no big energy injection at $z<10^{6.8}$ (cosmic photosphere). Limits hydro role in structure formation

CMB comes from afar (Sunyaev-Zeldovich Effect from distant clusters ... $z>0.8$)

300 km/s earth flow, 600 km/s Local Group flow

gravitational instability, hierarchical Large Scale Structure, predominantly adiabatic mode

a "dark age" from hydrogen recombination ($z\sim1100$) to reionization ($z\sim10$-20)

(nearly) Gaussian initial conditions

Recombination

Of Hydrogen

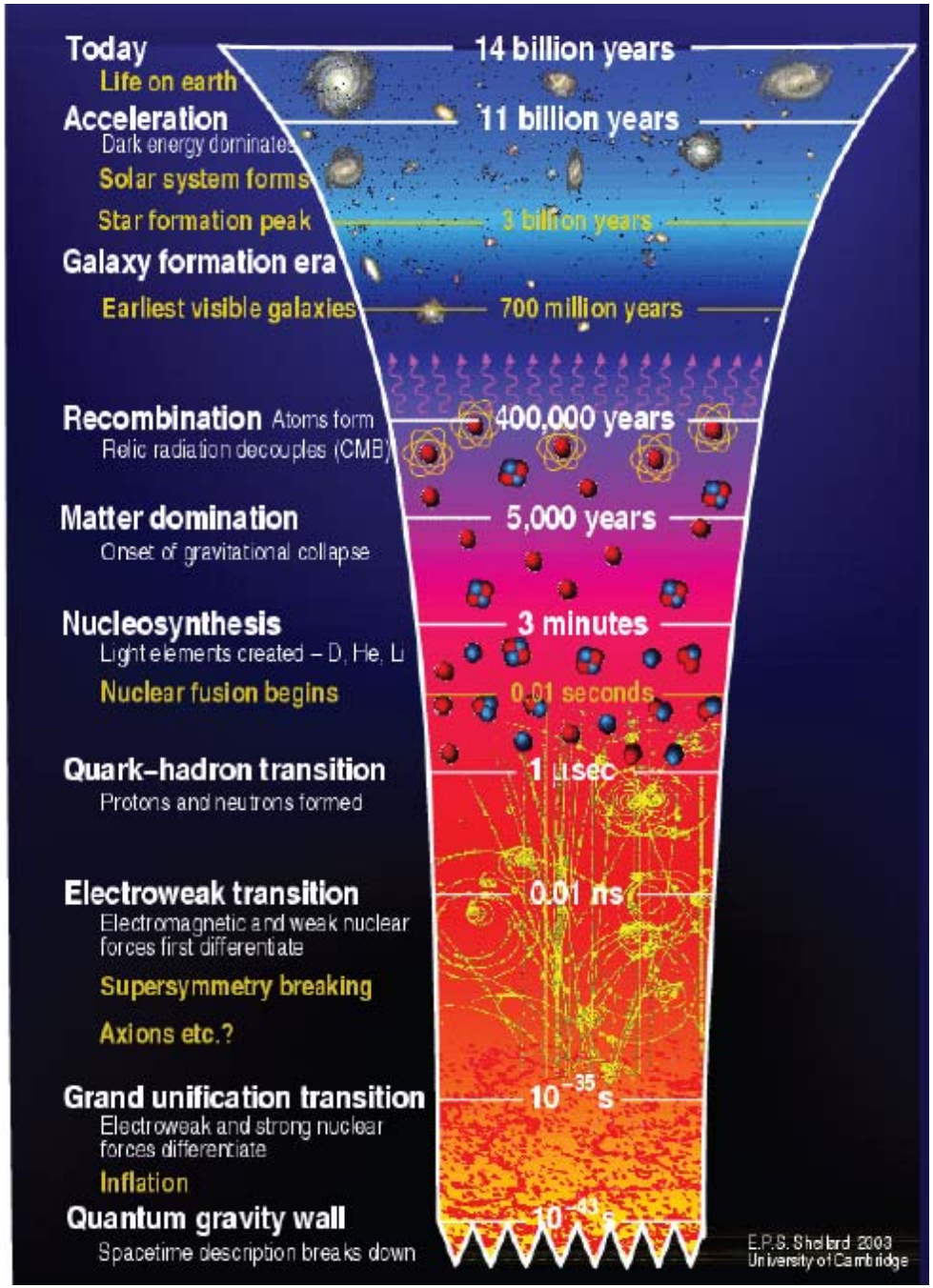
$\sim 10^{10}$ photons per baryon

Lower temperature ~ 3000K cf. 10000K

Novel: redshift from the wings of Lyman alpha 2p to 1s line & 2s to 1s + $\gamma\gamma$, 0.12 sec

Known since late sixties, modify for dark matter 80s, more H lines 90s

Of Helium (90s)


Today
14 billion years
Life on earth
Acceleration
11 billion years
Dark energy dominates
Solar system forms
Star formation peak
3 billion years
Galaxy formation era
Earliest visible galaxies
700 million years
Recombination Atoms form
400,000 years
Relic radiation decouples (CMB)
Matter domination
5,000 years
Onset of gravitational collapse
Nucleosynthesis
3 minutes
Light elements created – D, He, Li
Nuclear fusion begins
0.01 seconds
Quark–hadron transition
1 μsec
Protons and neutrons formed
Electroweak transition
0.01 ns
Electromagnetic and weak nuclear forces first differentiate
Supersymmetry breaking
Axions etc.?
Grand unification transition
10^{-35} s
Electroweak and strong nuclear forces differentiate
Inflation
Quantum gravity wall
10^{-43} s
Spacetime description breaks down
E.P.S. Shellard 2003
University of Cambridge