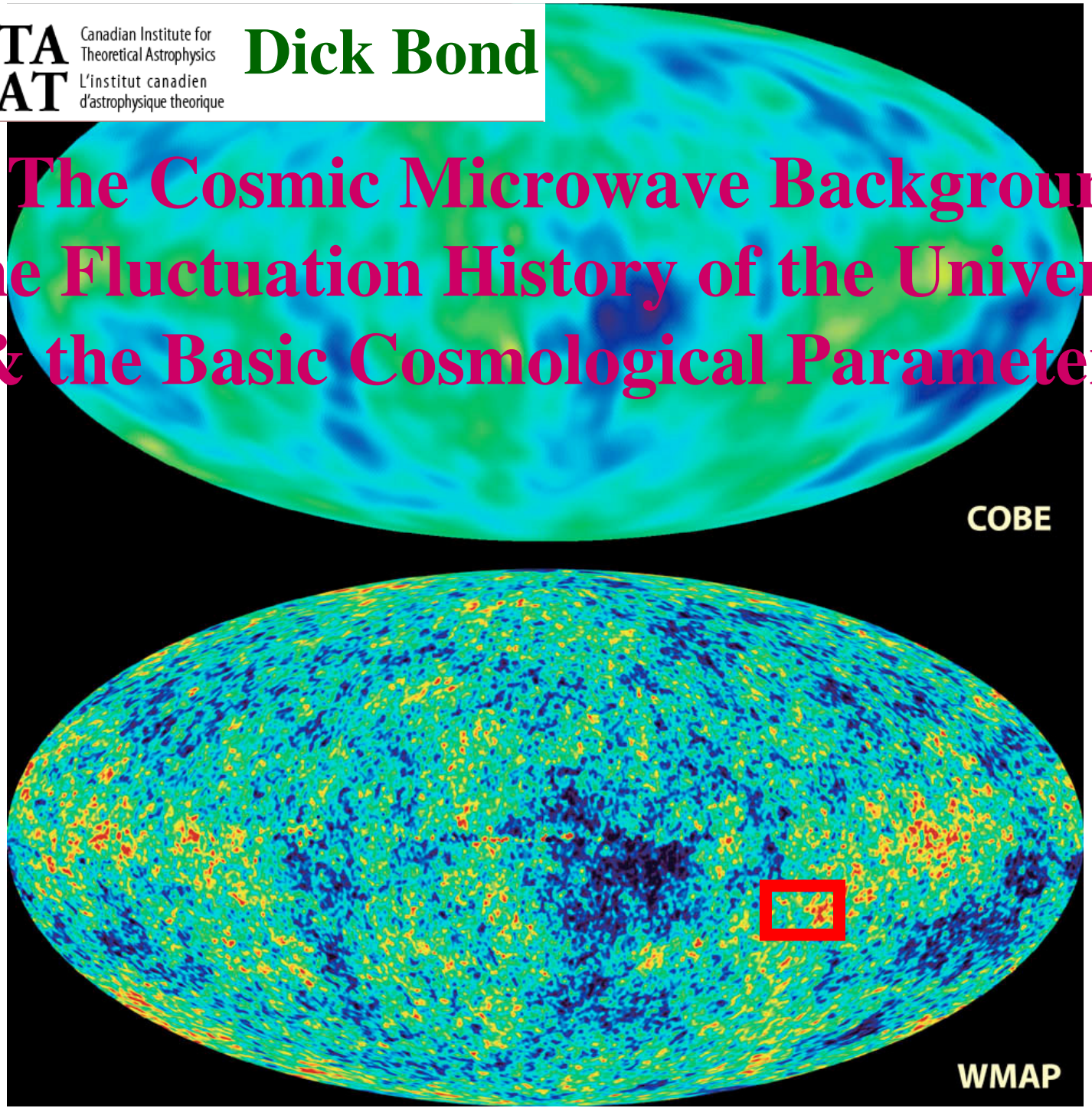
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique

Dick Bond

CIAR

L2: The Cosmic Microwave Background & the Fluctuation History of the Universe & the Basic Cosmological Parameters



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

SPECTRUM: near-perfect blackbody. no big energy/entropy injection at $z<10^{6.8}$ (cosmic photosphere). Limits hydro role in structure formation

CMB comes from afar (also Sunyaev-Zeldovich Effect from distant clusters … z>0.8)

CMB dipole: 300 km/s earth flow, 600 km/s Local Group flow

TO SHOW: gravitational instability, hierarchical Large Scale Structure, predominantly adiabatic mode

a "dark age" from hydrogen recombination (z~1100) to reionization (z~10-20)

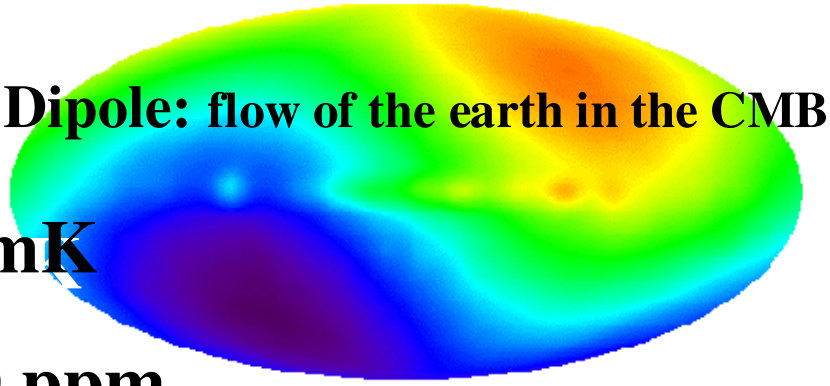
(nearly) Gaussian initial conditions

CMB

Nearly Perfect Blackbody

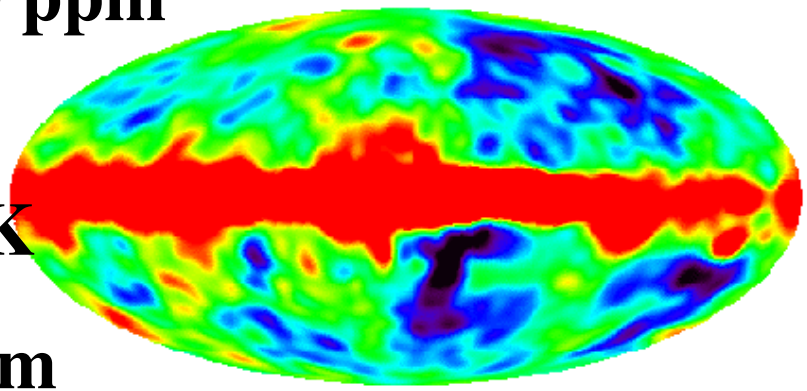
T=2.725 ±.001 K COBE/FIRAS

Dipole: flow of the earth in the CMB



~3 mK

~1000 ppm

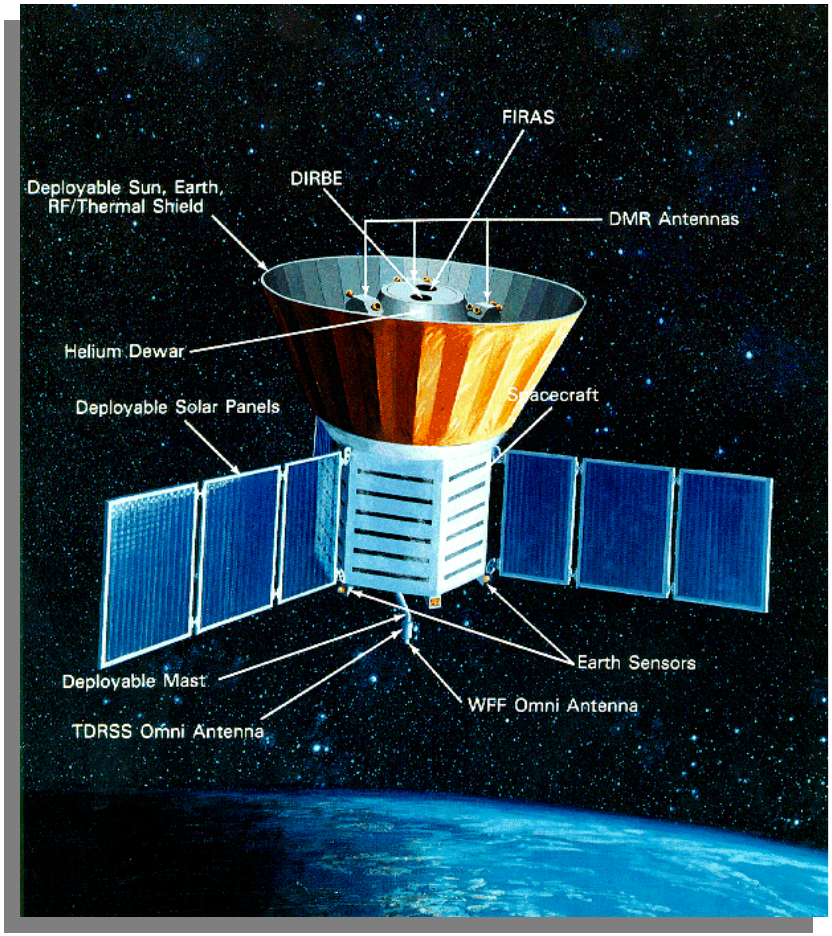


~30 μK

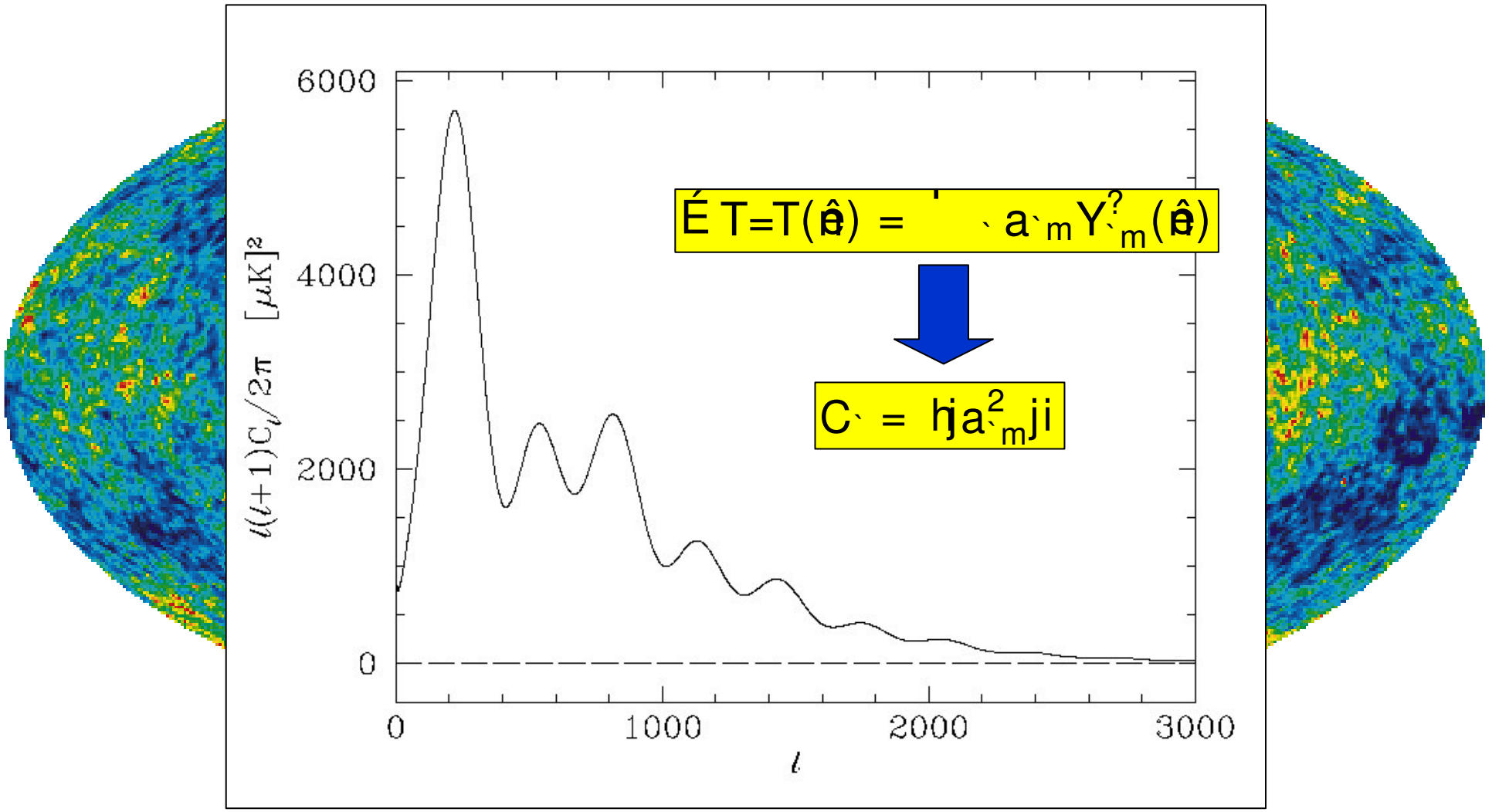
~10 ppm

COBE/DMR:

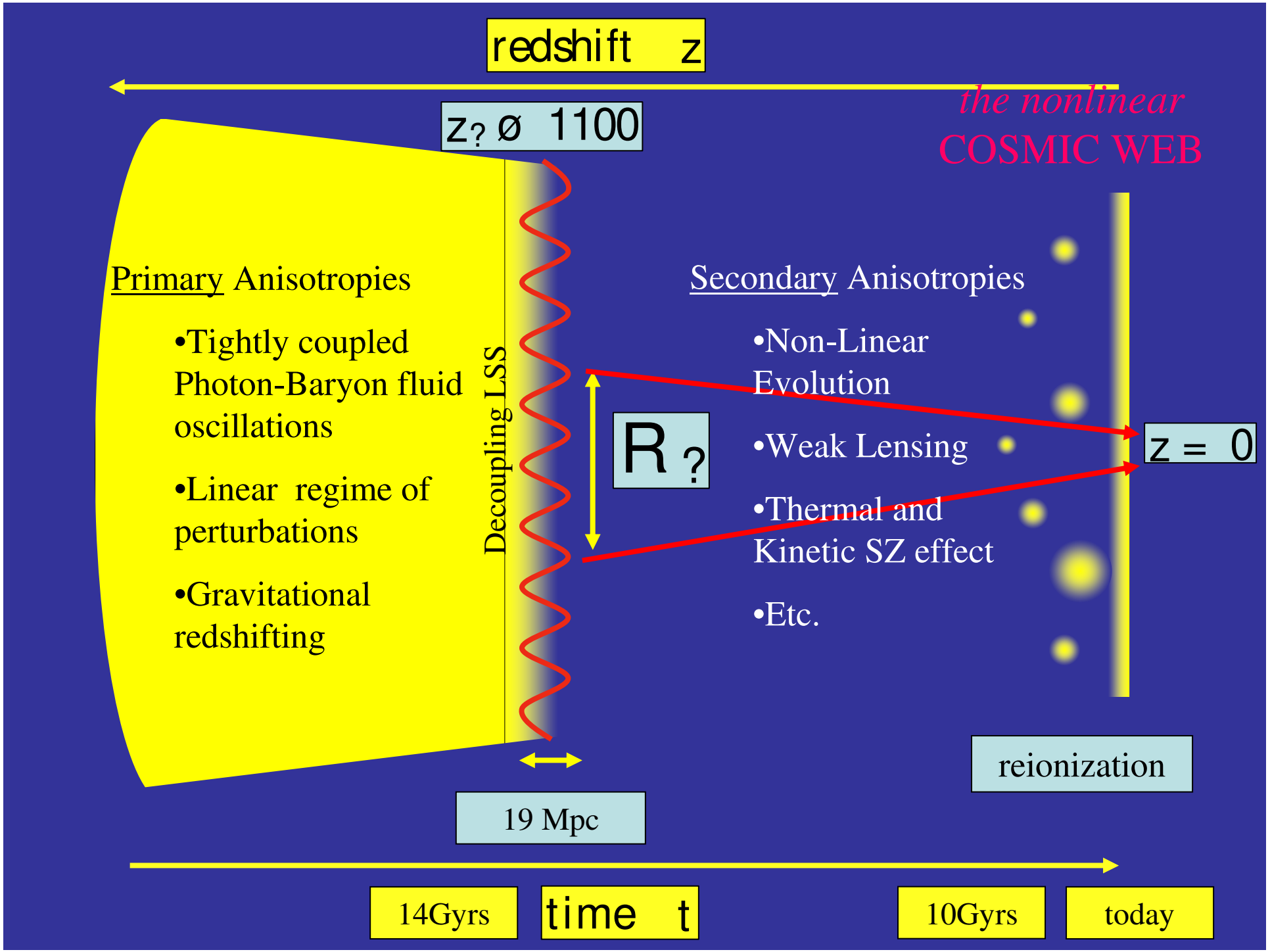
CMB + Galactic @7^{o}



WMAP3 thermodynamic CMB temperature fluctuations



Like a 2D Fourier transform, wavenumber Q ~ L + 1/2


redshift z
z? ø 1100
the nonlinear
COSMIC WEB
Primary Anisotropies
•Tightly coupled Photon-Baryon fluid oscillations
•Linear regime of perturbations
•Gravitational redshifting
Decoupling LSS
R ?
Secondary Anisotropies
•Non-Linear Evolution
•Weak Lensing
•Thermal and Kinetic SZ effect
•Etc.
z = 0
reionization
19 Mpc
14Gyrs
time t
10Gyrs
today

Compton depth

$\tau_C = \int_{now}^{z} n_e \sigma_T c \, dt$

$\sim 0.1 ((1+z_{re})/15))^{3/2}$ $(\Omega_b h^2 / .02) (\Omega_c h^2 / .15)^{-1/2}$

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

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

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

$\tau_C = .087 +- .03$

(.005 PL1)

$z_{reh} = 11 +- 3$

differential visibility d exp(- τ_C) / dln a

nearly Gaussian pulse at z ~ 1100, width Δz~100, t~380000 yr

Small bump falling off from z ~ 10, with $\tau_C \sim 0.1$

BOOMERanG 98 Netterfield etal 2001

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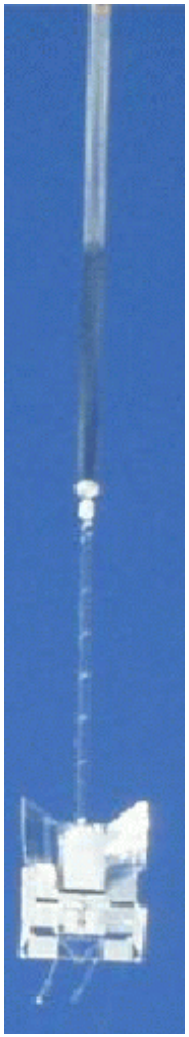
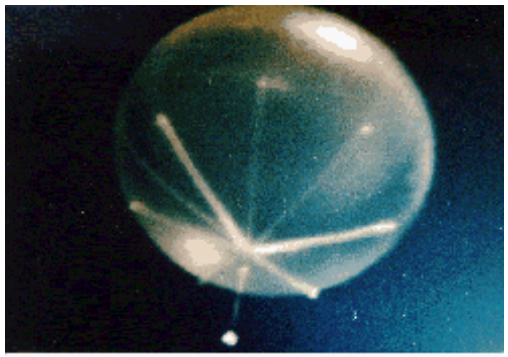
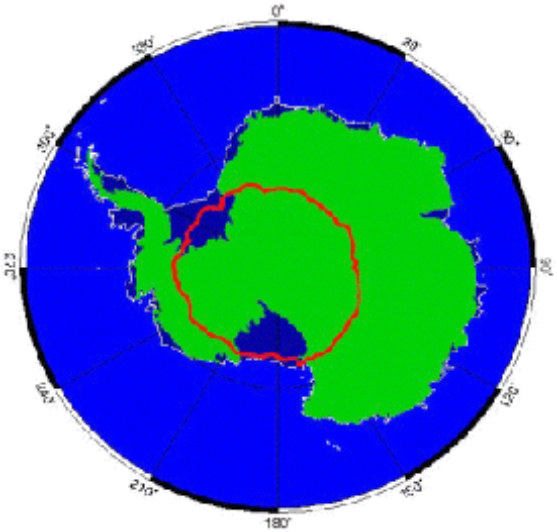
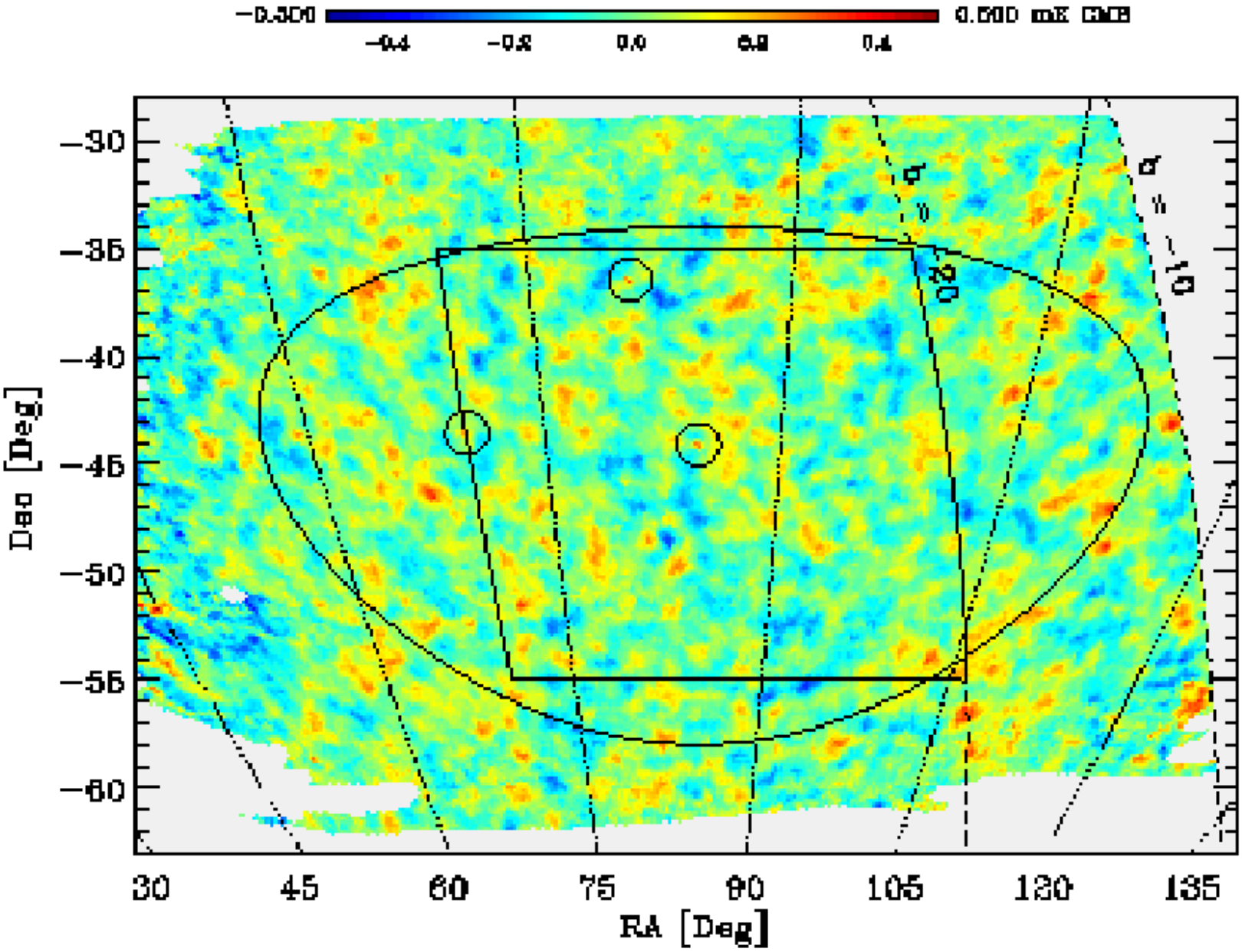






Boomerang B00 440 sq deg, B01 800 sq deg (B02 1200)



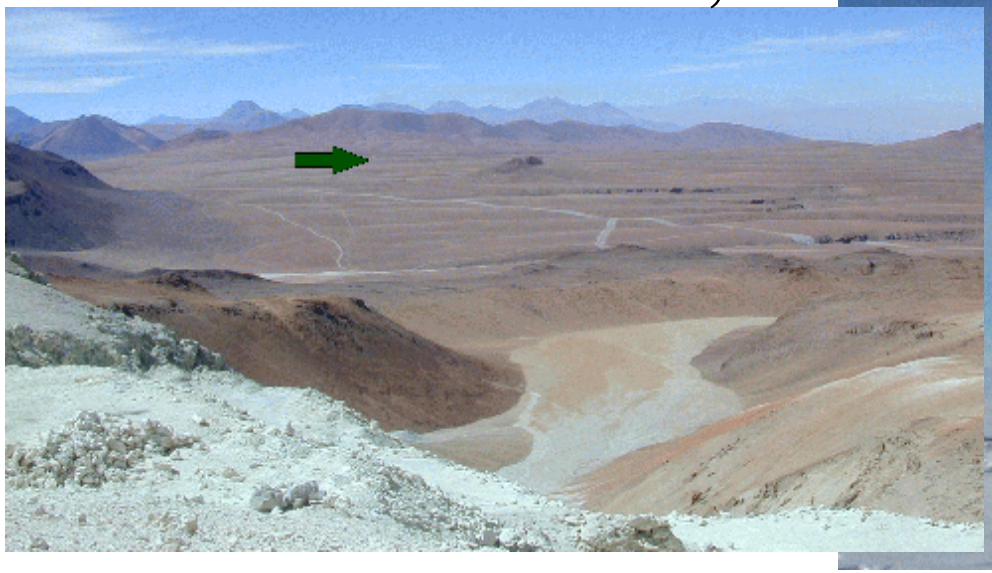
CBI:

Tony Readhead (PI), B. Mason, S. Myers, T. Pearson, J. Sievers, M. Shepherd, J. Cartwright, S. Padin, P. Udomprasert

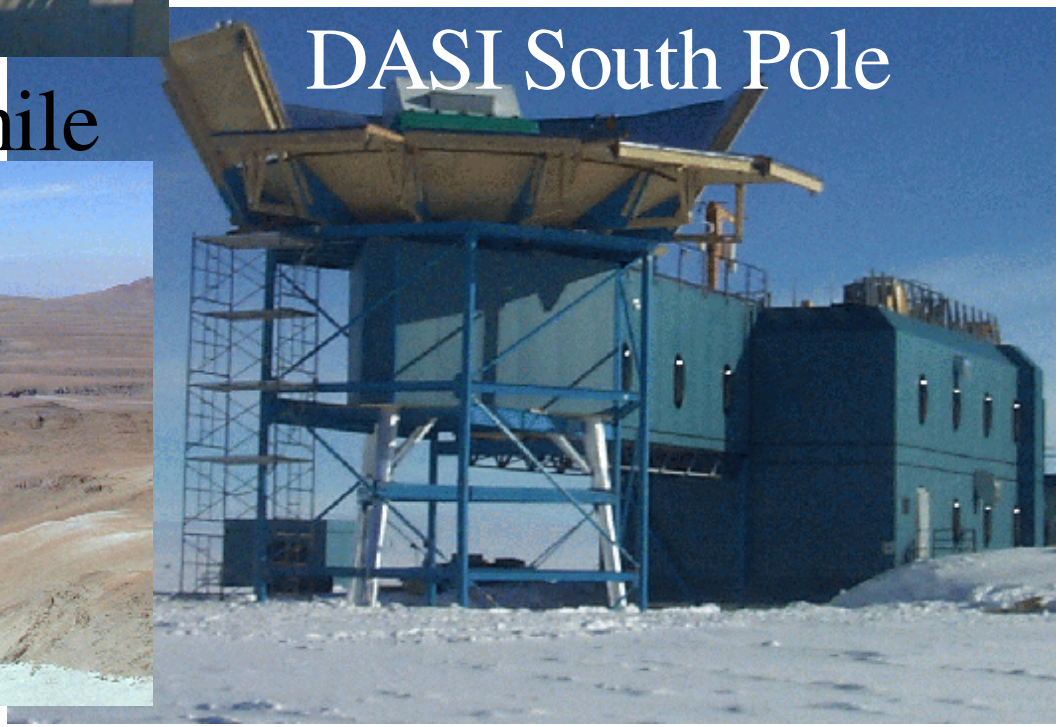
+ CITA/CIAR gp

(+ DASI gp)

CBI Atacama desert, Chile



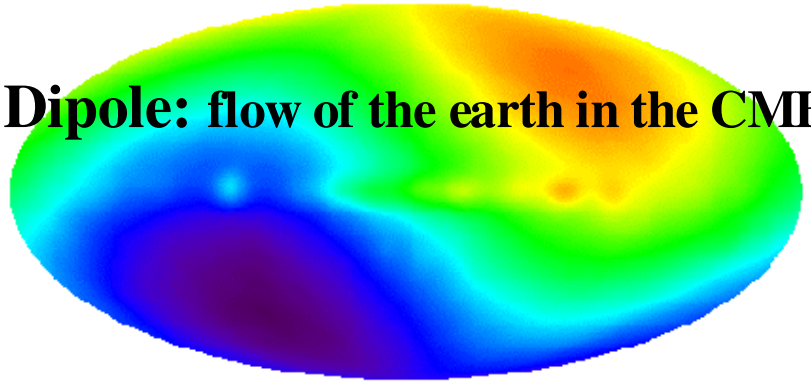
DASI South Pole



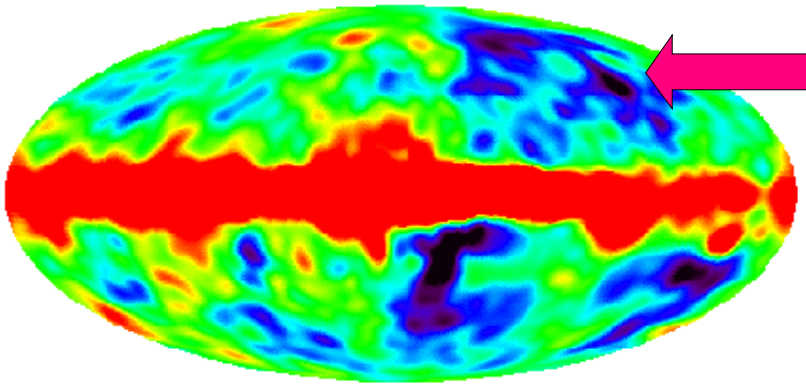
CMB

Nearly Perfect Blackbody

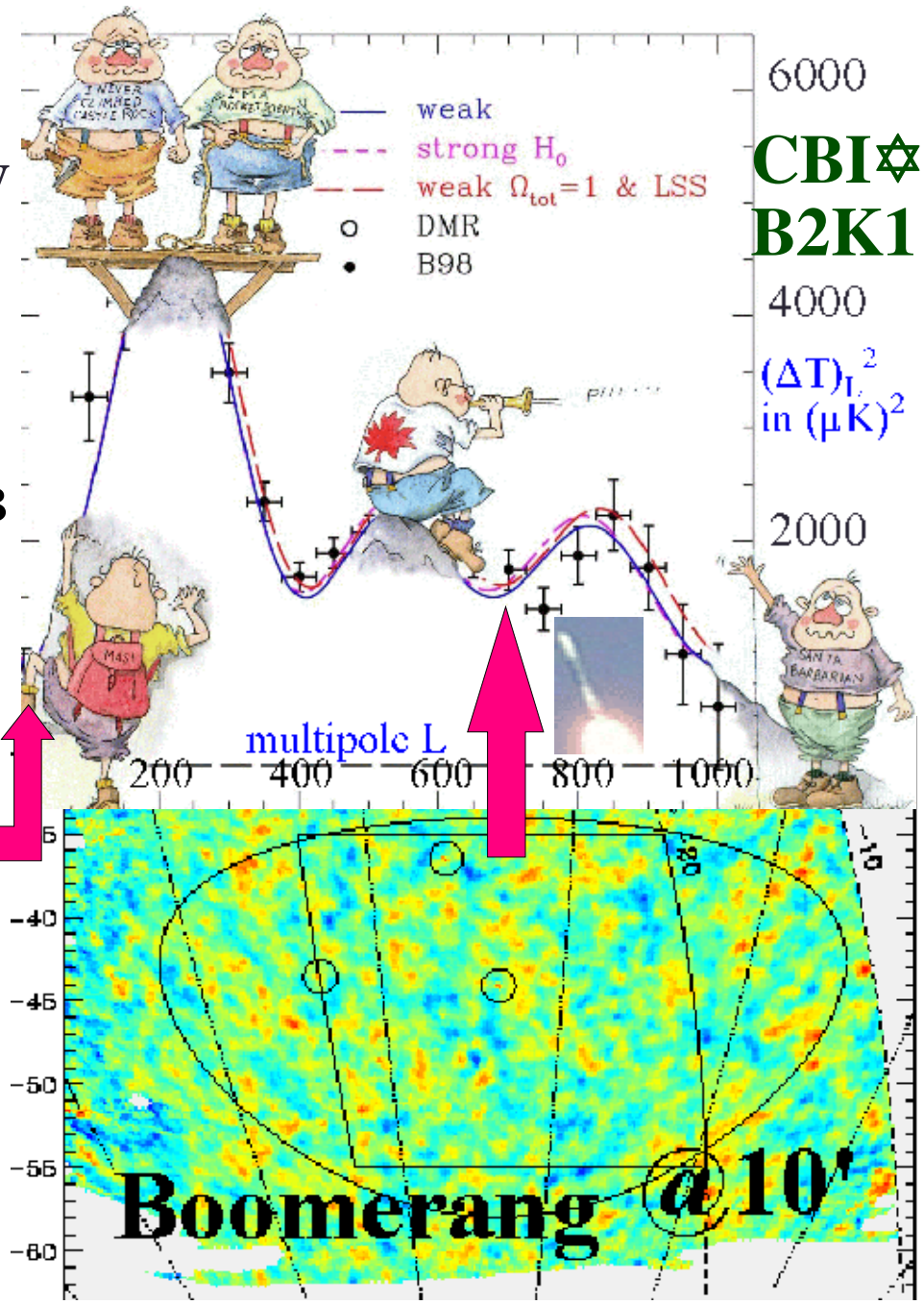
T=2.725 ±.001 K COBE/FIRAS

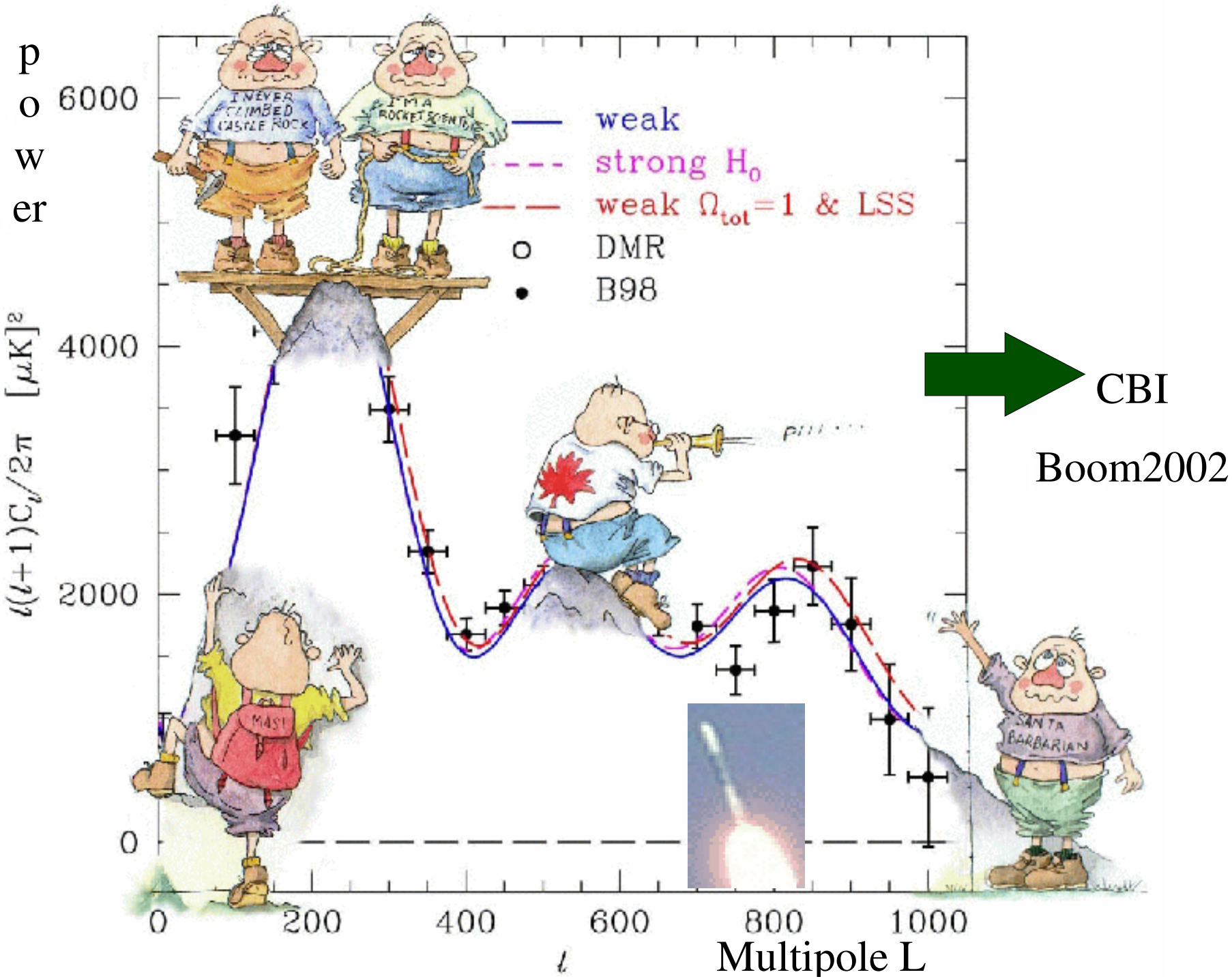


Dipole: flow of the earth in the CMB



COBE/DMR:
CMB + Galactic @7^{o}



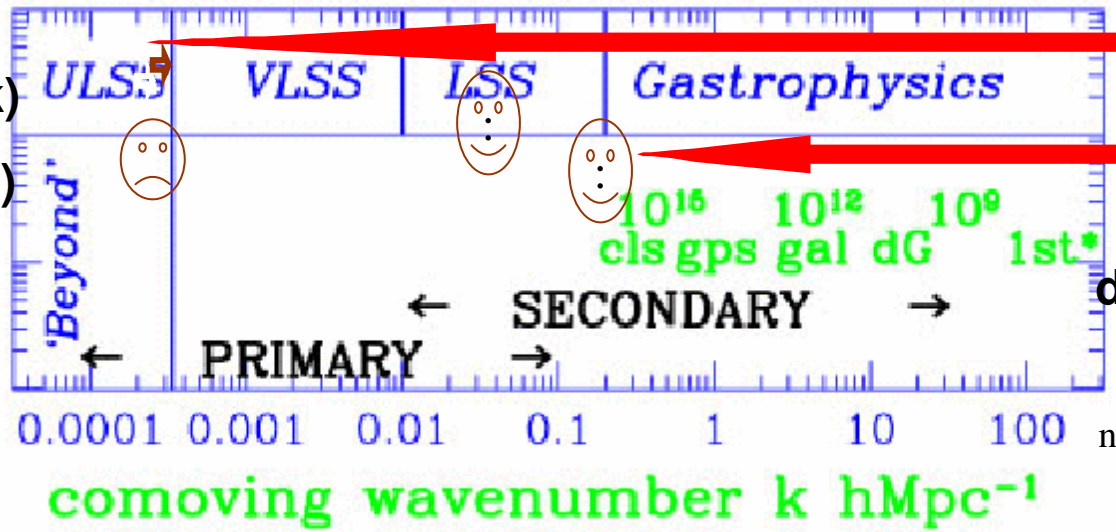

power
$\ell(\ell+1)C_\ell/2\pi$ [μK]^2
6000
4000
2000
0
0
200
400
600
800
1000
ℓ
Multipole L
weak
strong H_0
weak Ω_{tot}=1 & LSS
DMR
B98
I NEVER CLIMBED CASTLE ROCK
I'M A ROCKET SCIENTIST
MASI
SANTA BARBARIAN
CBI
Boom2002

resolution P(ln k)

dynamics H(ln a)

are related in inflation (HJ)

~10+ e-folds



$K_{hor}(t)=Ha$

$K_{NL}(t)$

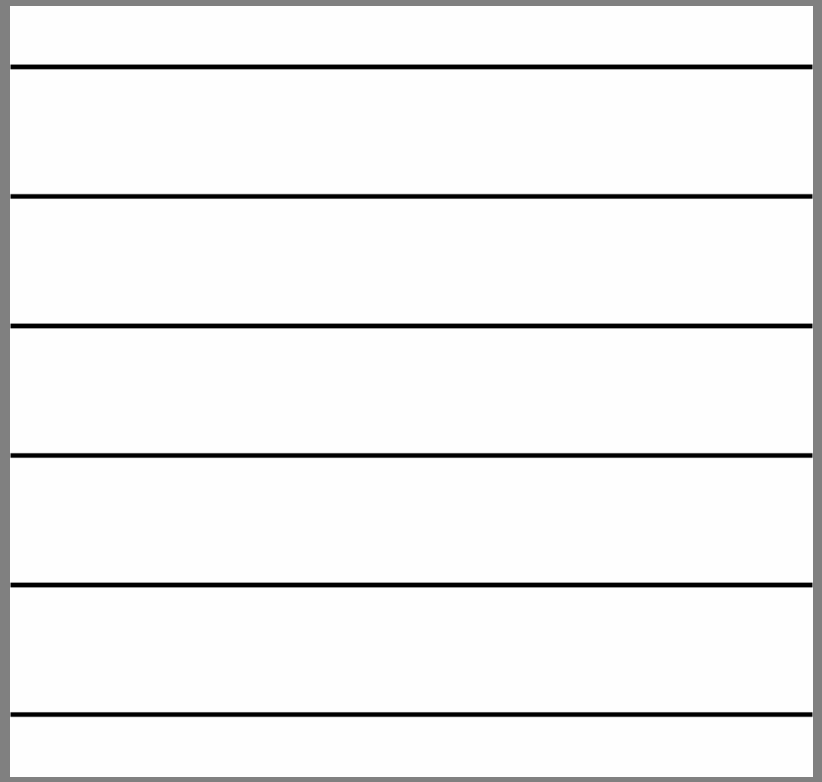
dynamics w(ln a)

~1+ e-folds

nonlinear Cosmic Web

Natural pertubation modes in an expanding flat universe are 3D Fourier waves

- Sound waves! alternating between hot & cold if we sit & watch.
- long waves are slow, short waves are fast.
- Everybody started at same time, and we see them all at one time. Makes a characteristic pattern of waves on the sky.



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

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

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

Time derivative along the photon direction

Sources, sinks, scattering processes

Photon Transport in Perturbed Geometry

$$\partial f / \partial t|_q + q \cdot \nabla f - \text{GR term} = aS[f]$$

Green function is a delta function of a null geodesic

Picture is photons propagate freely in the curved (fluctuating) geometry, periodically undergoing small scale Thompson scattering

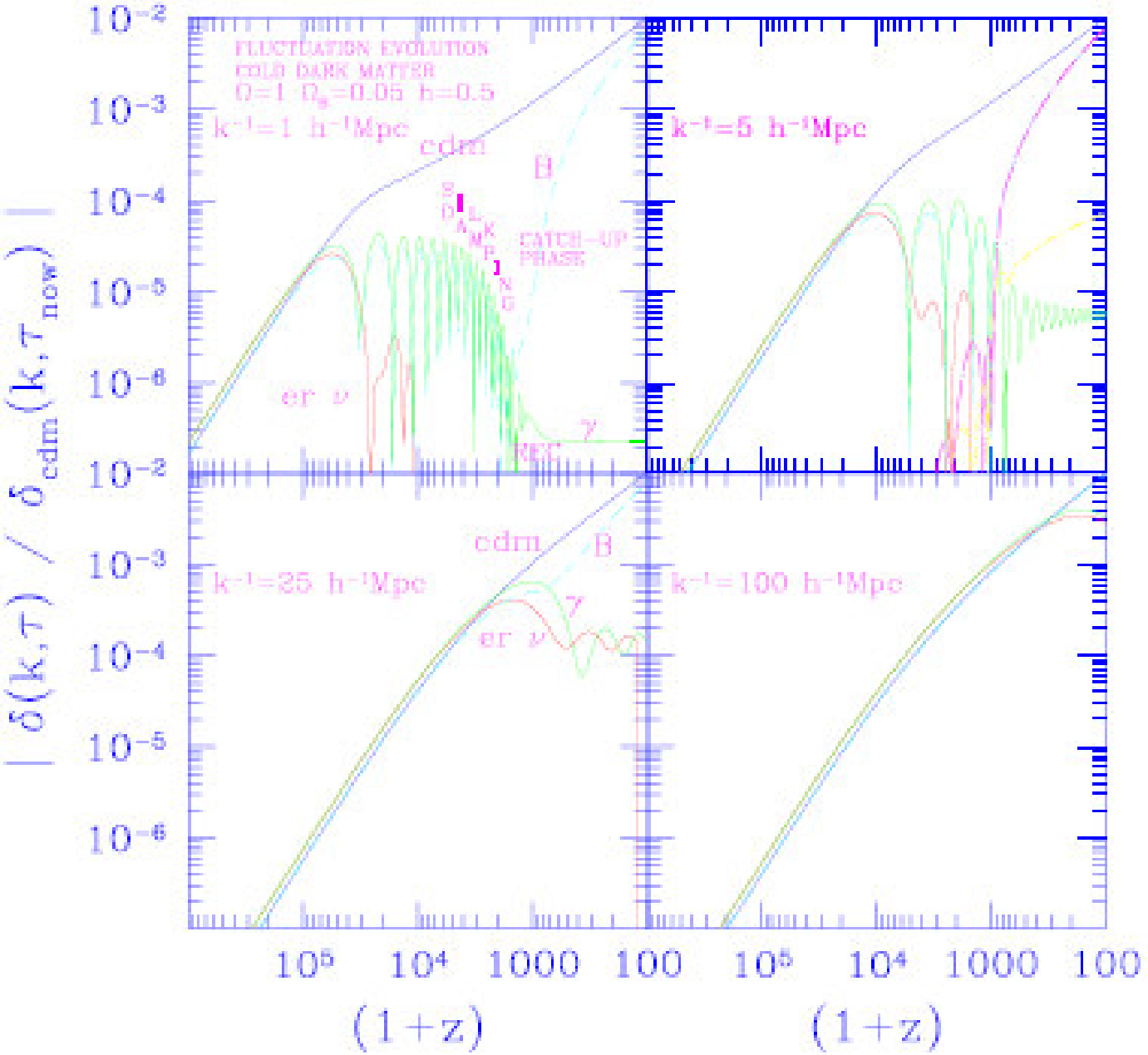
Regimes: tight coupling (of baryons and photons)

free-streaming

Sources probed via the differential visibility

Coupled linearized equations for photons (with polarization) baryons, dark matter, neutrinos, and metric variables

Modes: scalar (curvature or isocurvature), vector, tensor

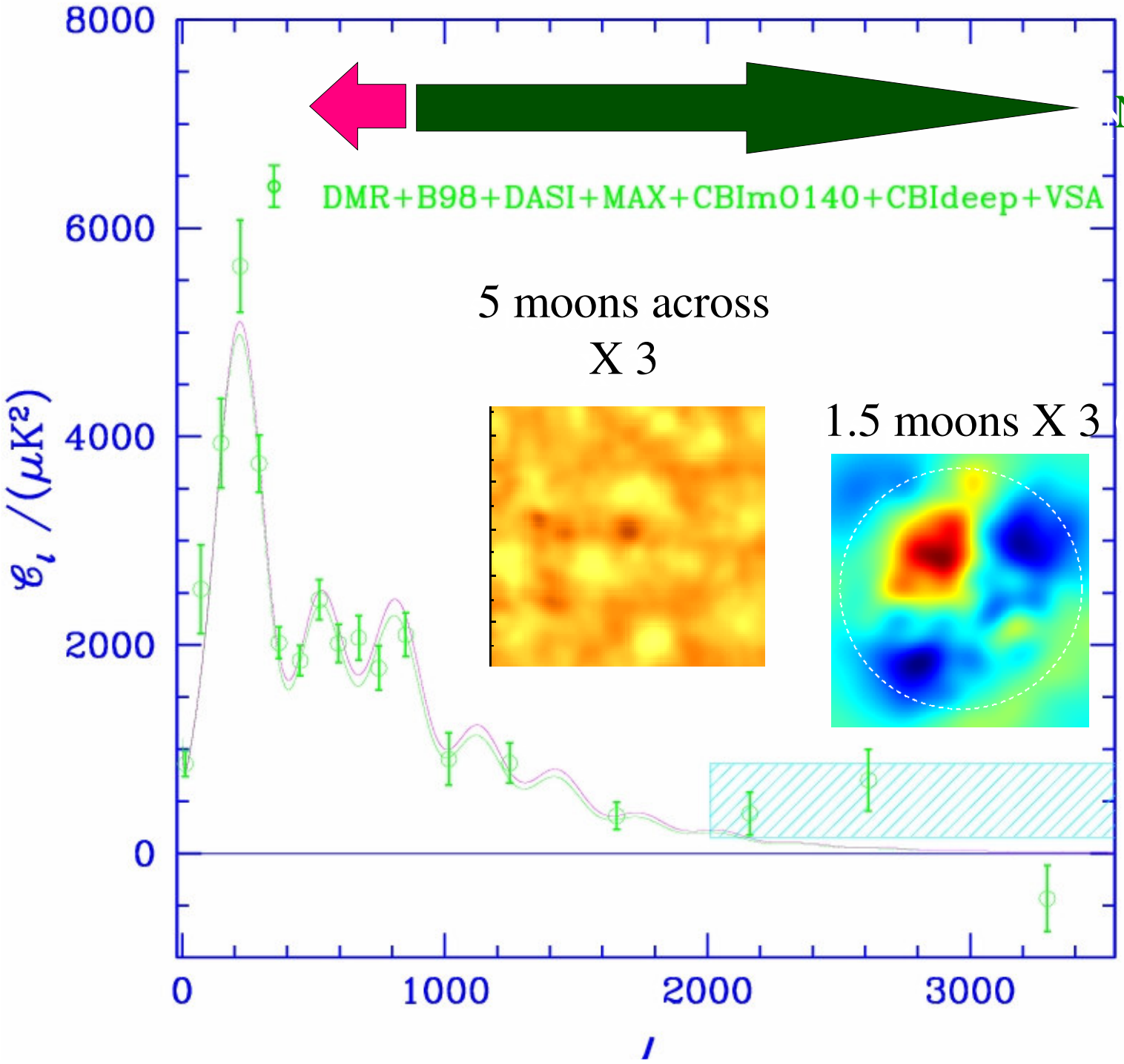


Output: transfer functions for dark matter and baryons to map initial power spectrum to pre-nonlinear one

(ICs for numerical simulations)

& of course

C_L



NSF/Caltech/C
ITA/CIAR

May 23,2002

AAS Jun02

Grand unified spectrum

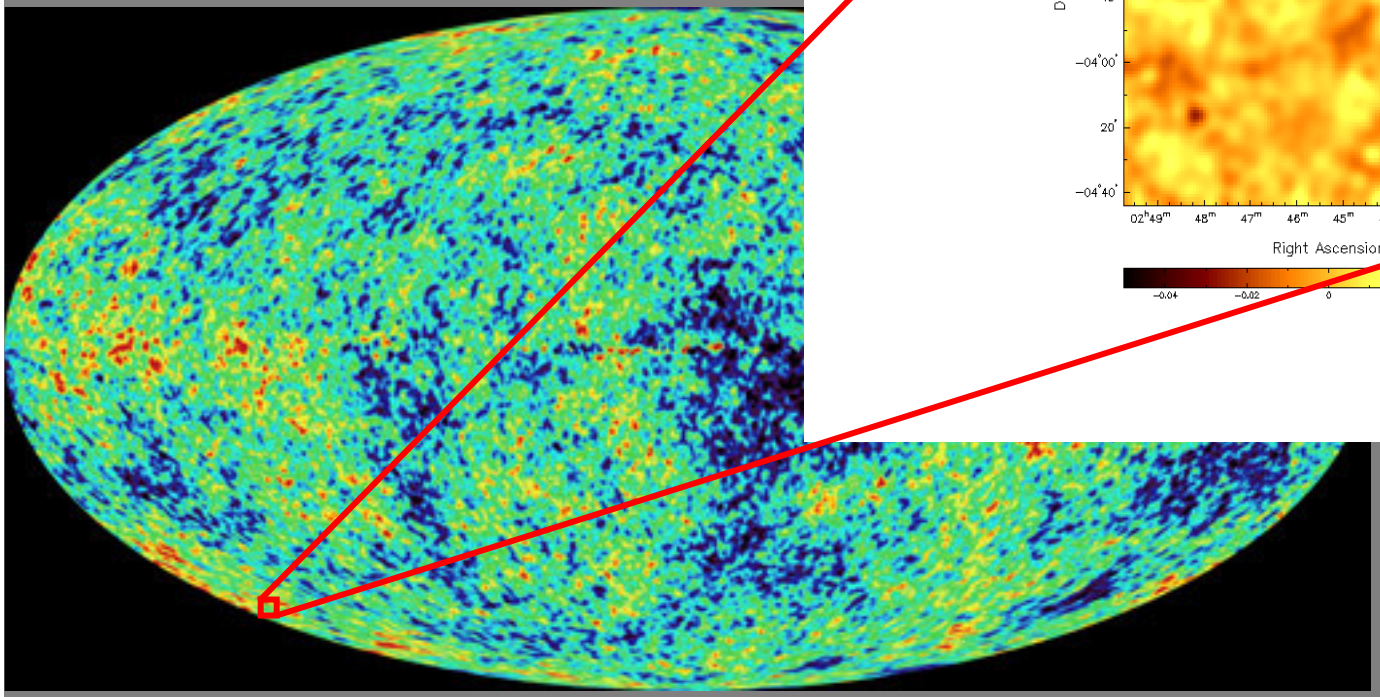
Adds

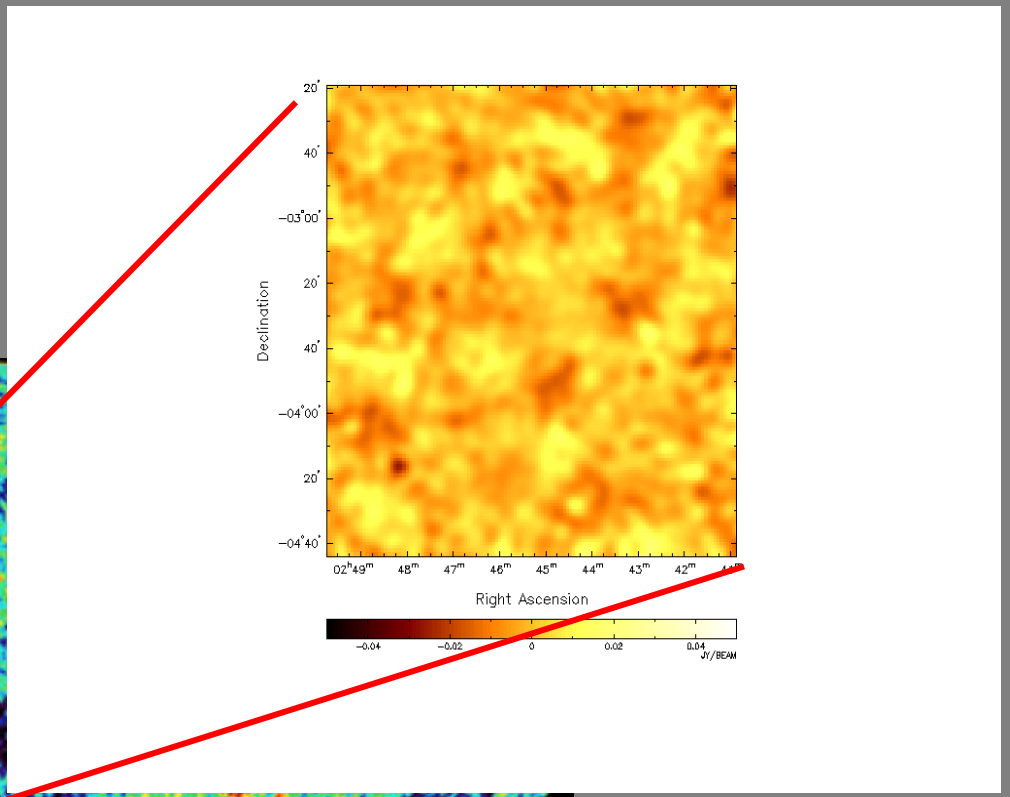
CBI mosaic

+CBI deep

+VSA

CBI Image of CMB Anisotropies

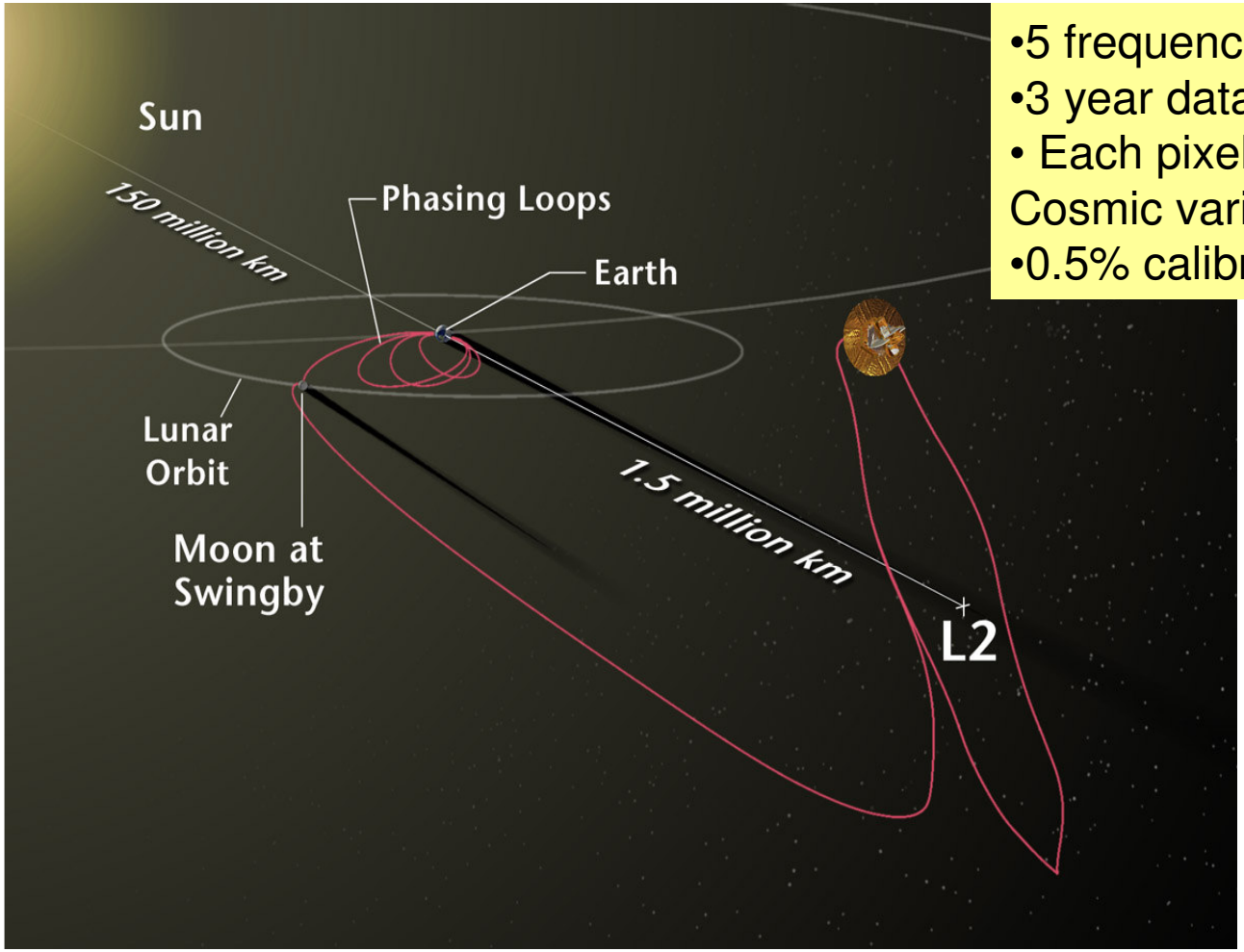




CBI – much smaller scale. But not all-sky.

WMAP

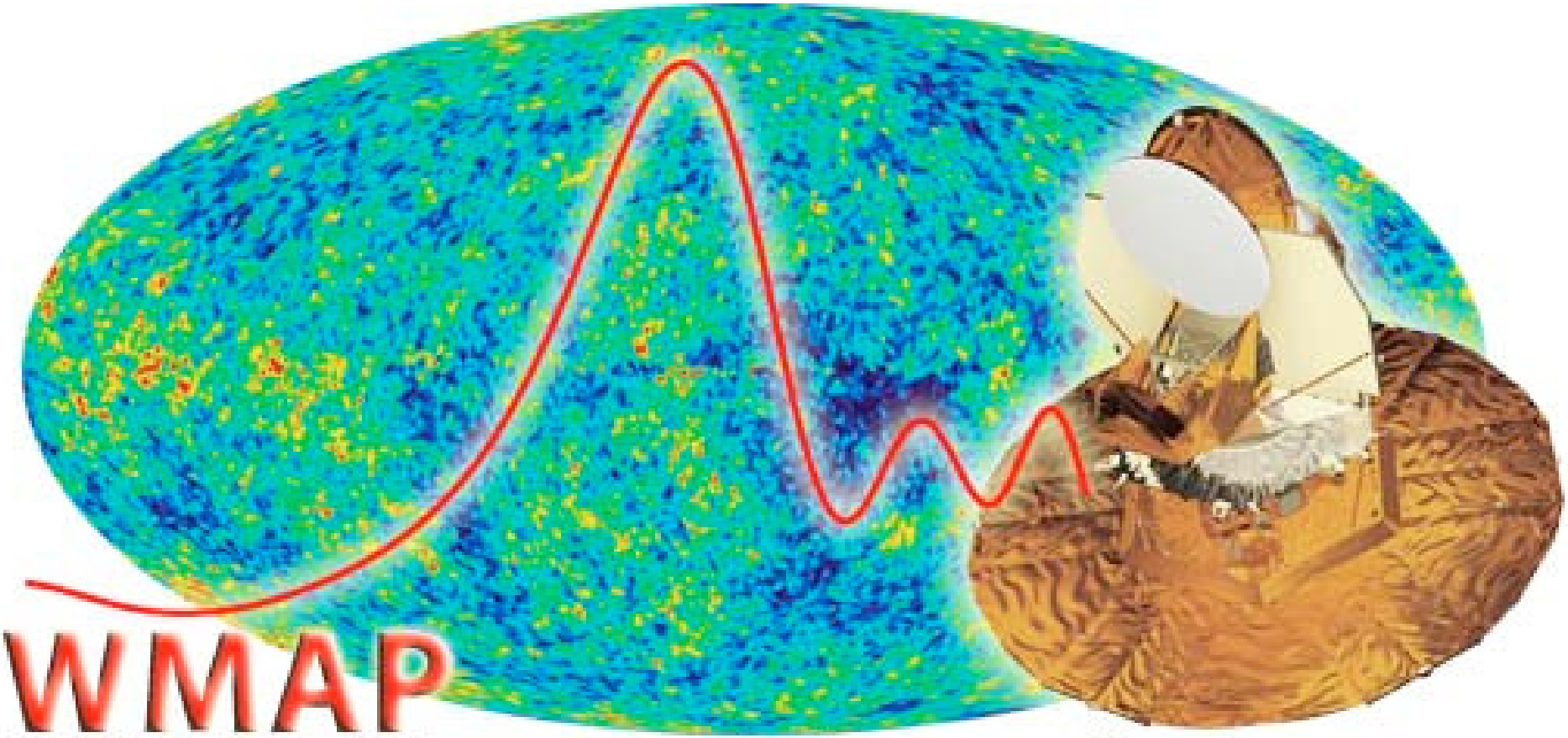
Wilkinson Microwave Probe (WMAP) – launch June 2001, 1 year data release – Feb 11, 2003, 3 year data release – Mar 16, 2006



- 5 frequency channels at 23-94 GHz
- 3 year data – sky is covered six times
- Each pixel observed ~27000 times.

Cosmic variance limited up to l~800

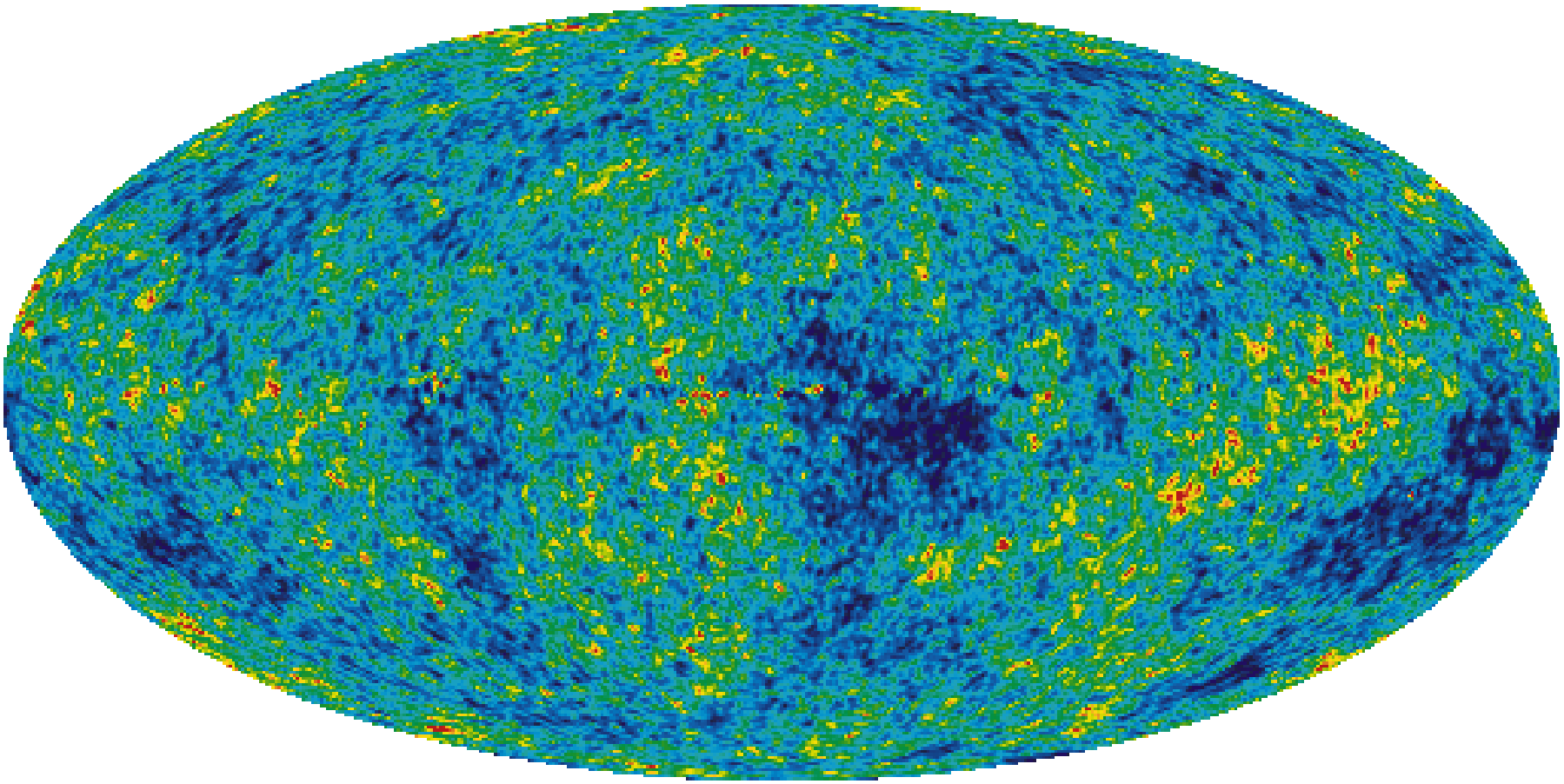
- 0.5% calibration uncertainty



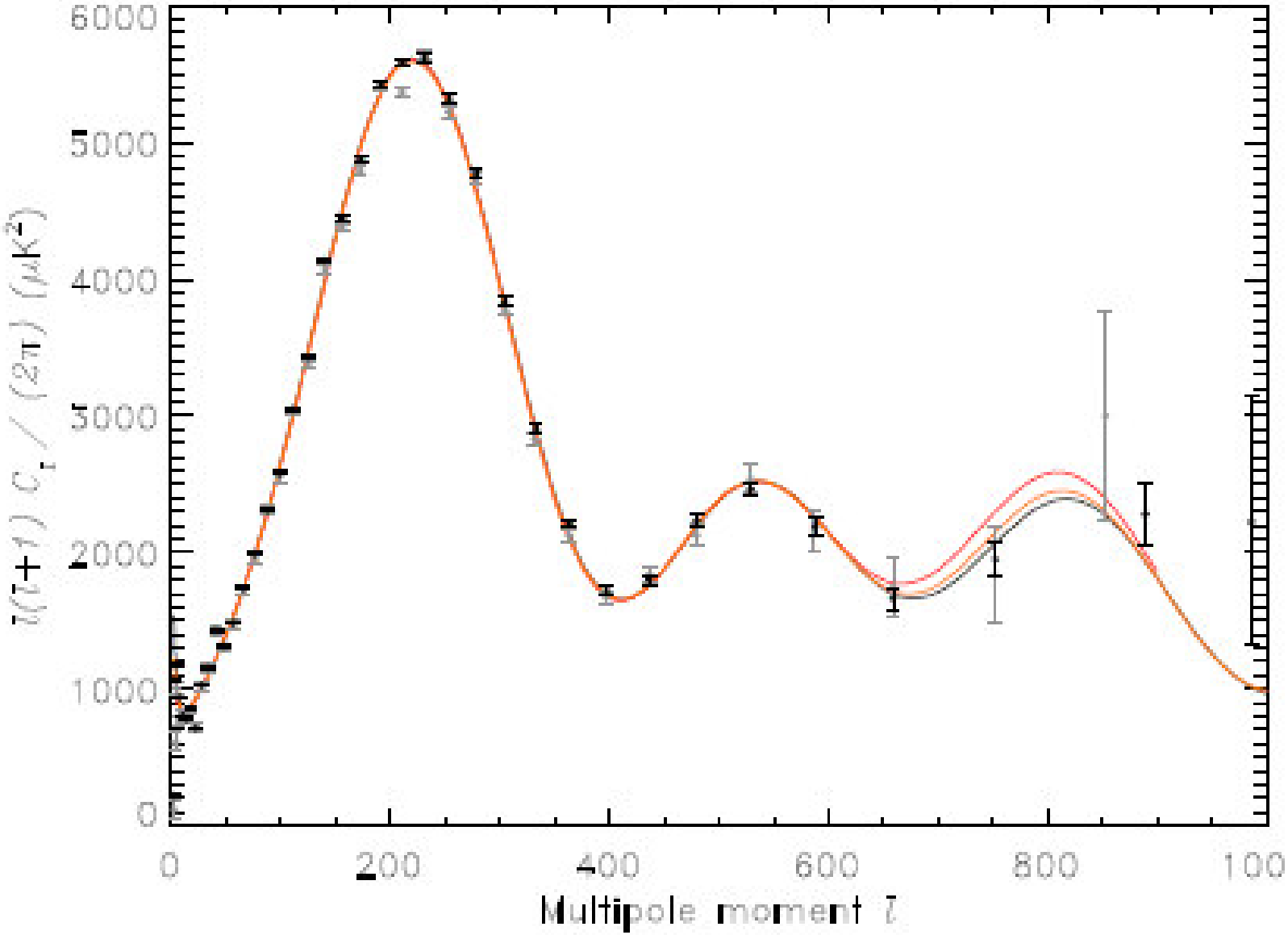
WMAP

Wilkinson Microwave Anisotropy Probe

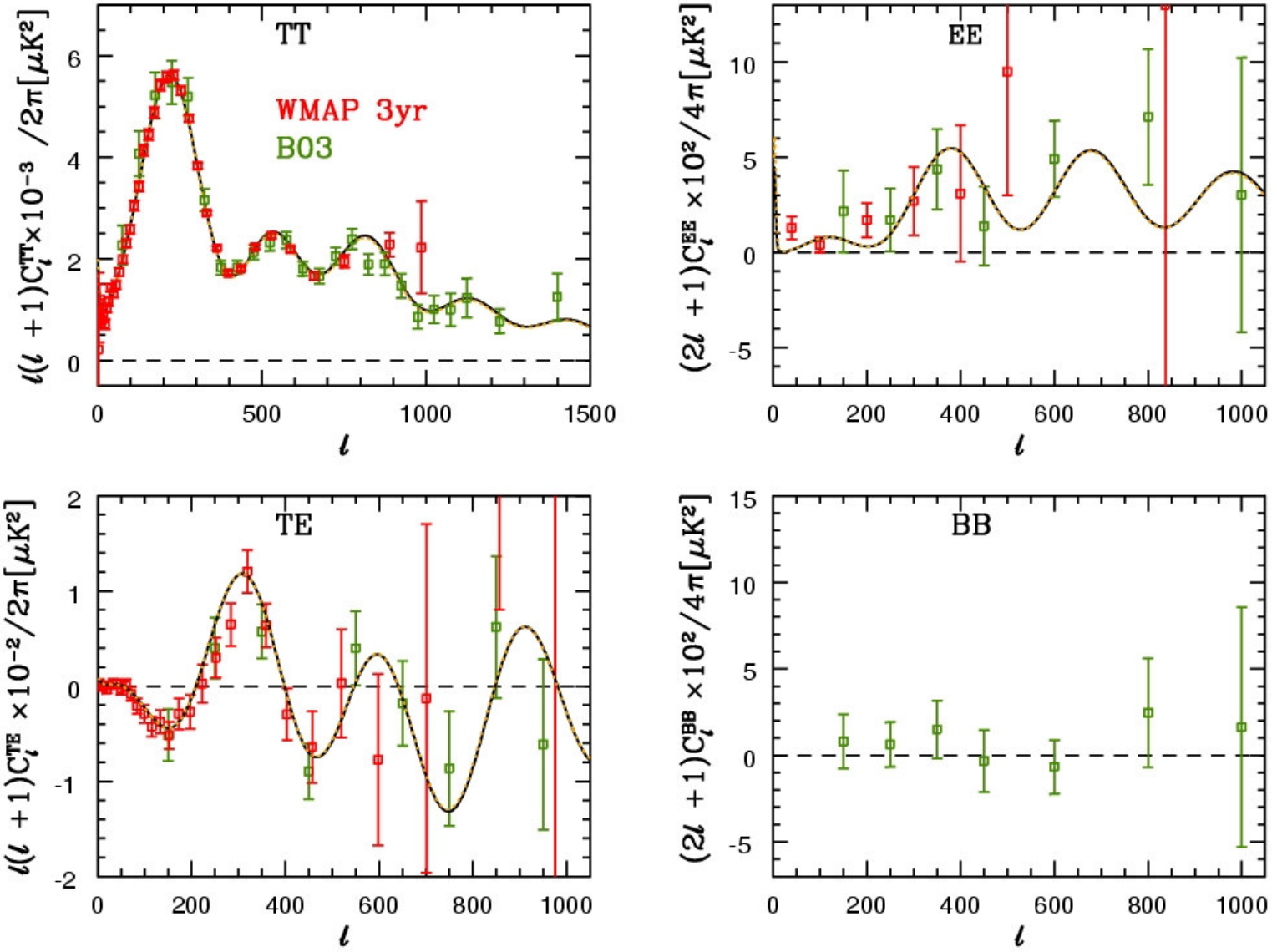
WMAP3 thermodynamic CMB temperature fluctuations



WMAP3 cf. WMAP1



WMAP3 sees 3rd pk, B03 sees 4th



CBI combined TT sees 5th pk