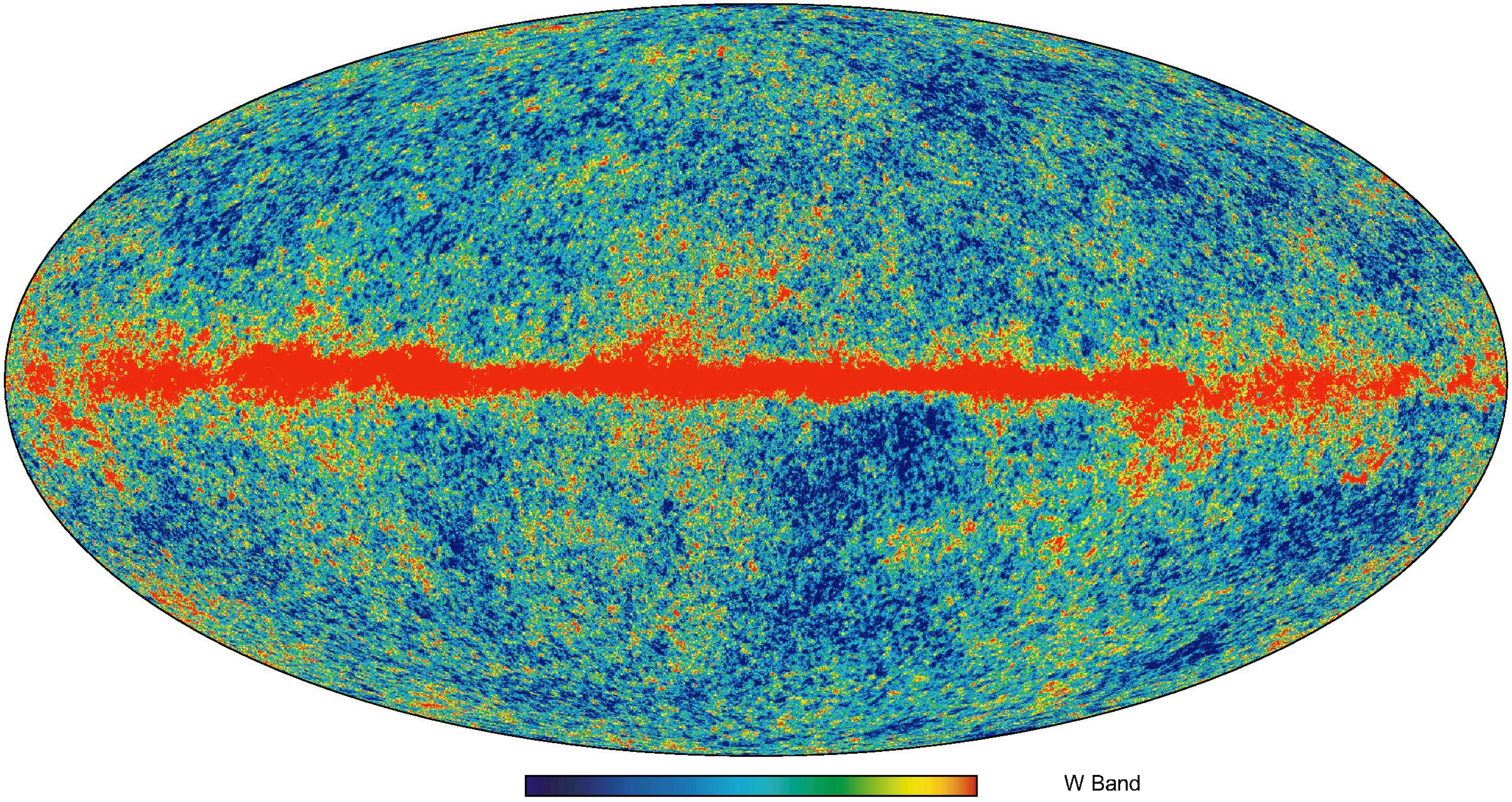
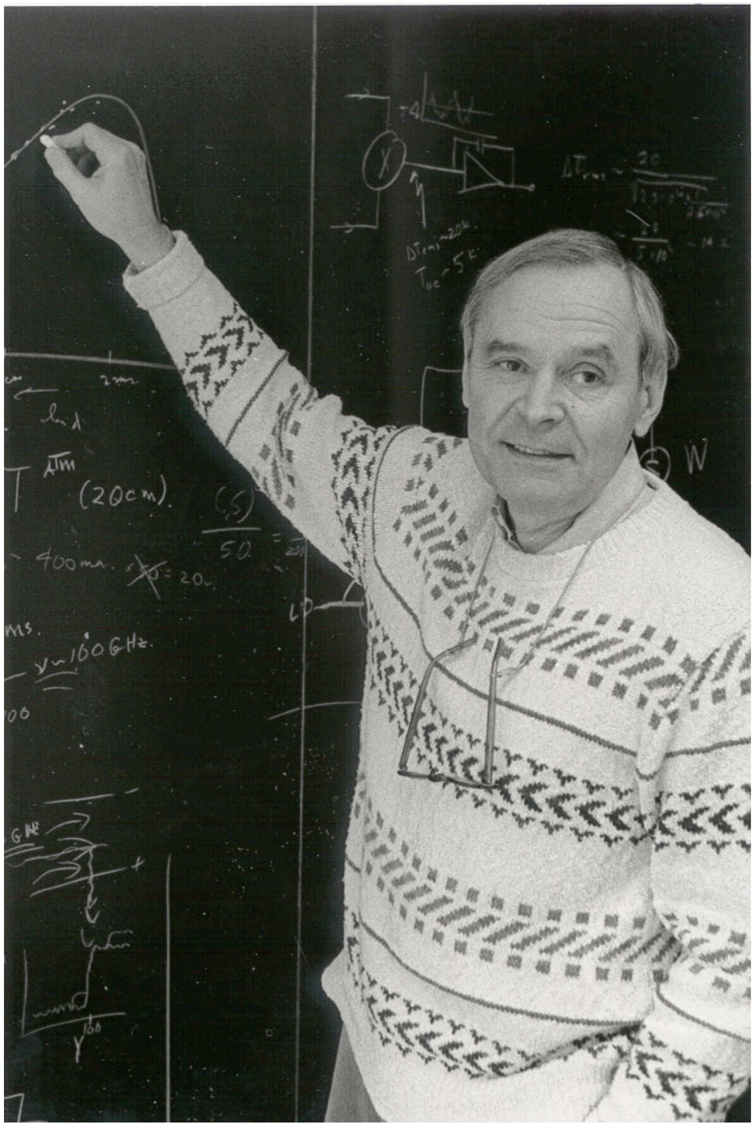
Cosmological implications of the first year WILKINSON MICROWAVE ANISOTROPY PROBE results

http://lambda.gsfc.nasa.gov



Licia Verde   University of Pennsylvania

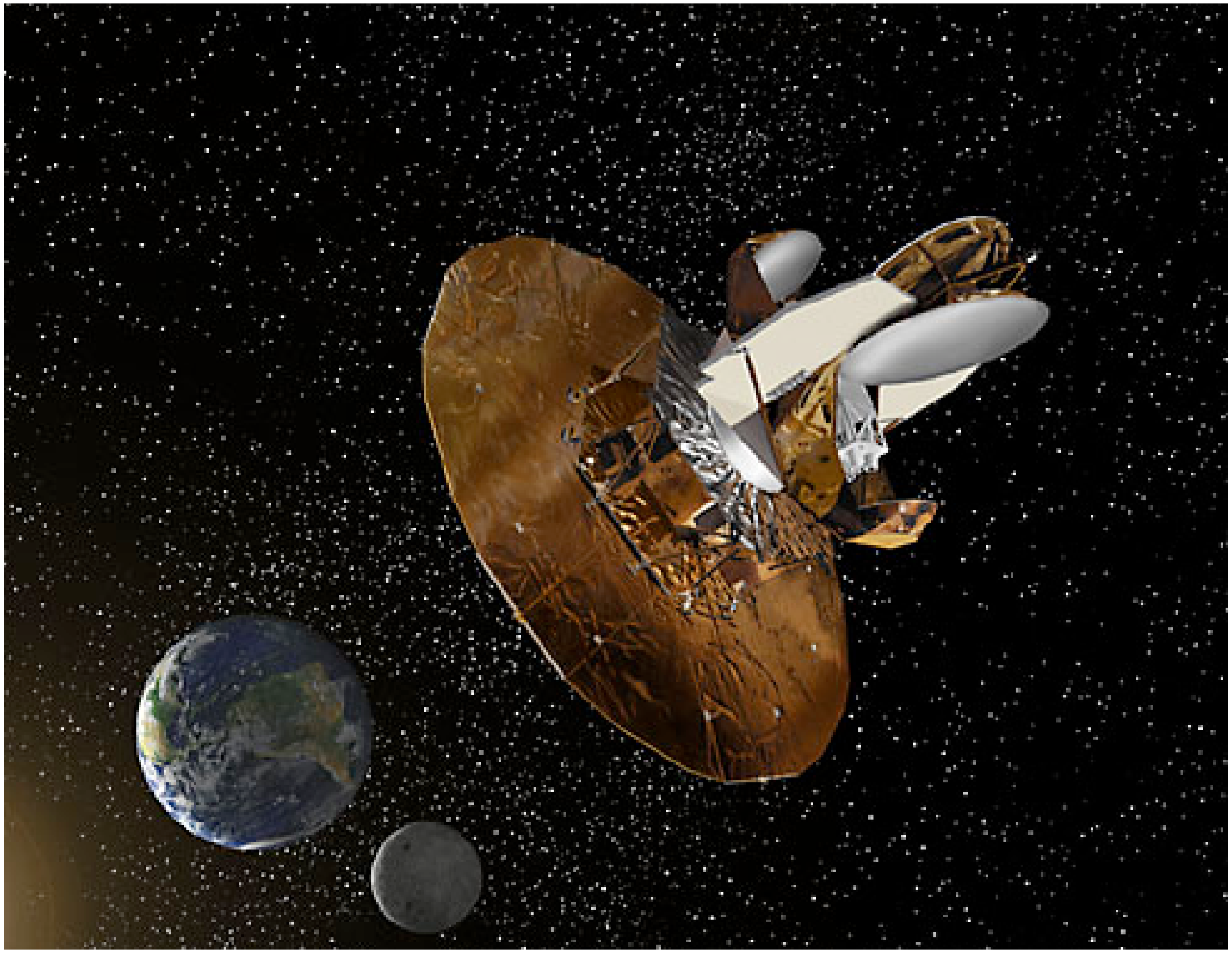


David Wilkinson 1935-2002

WMAP

A partnership between
NASA/GSFC and Princeton

Science Team:



NASA/GSFC

Chuck Bennett (**PI**)
Michael Greason
Bob Hill
Gary Hinshaw
Al Kogut
Michele Limon
Nils Odegard
Janet Weiland
Ed Wollack

Brown

Greg Tucker

UCLA

Ned Wright

UBC

Mark Halpern

Chicago

Stephan Meyer

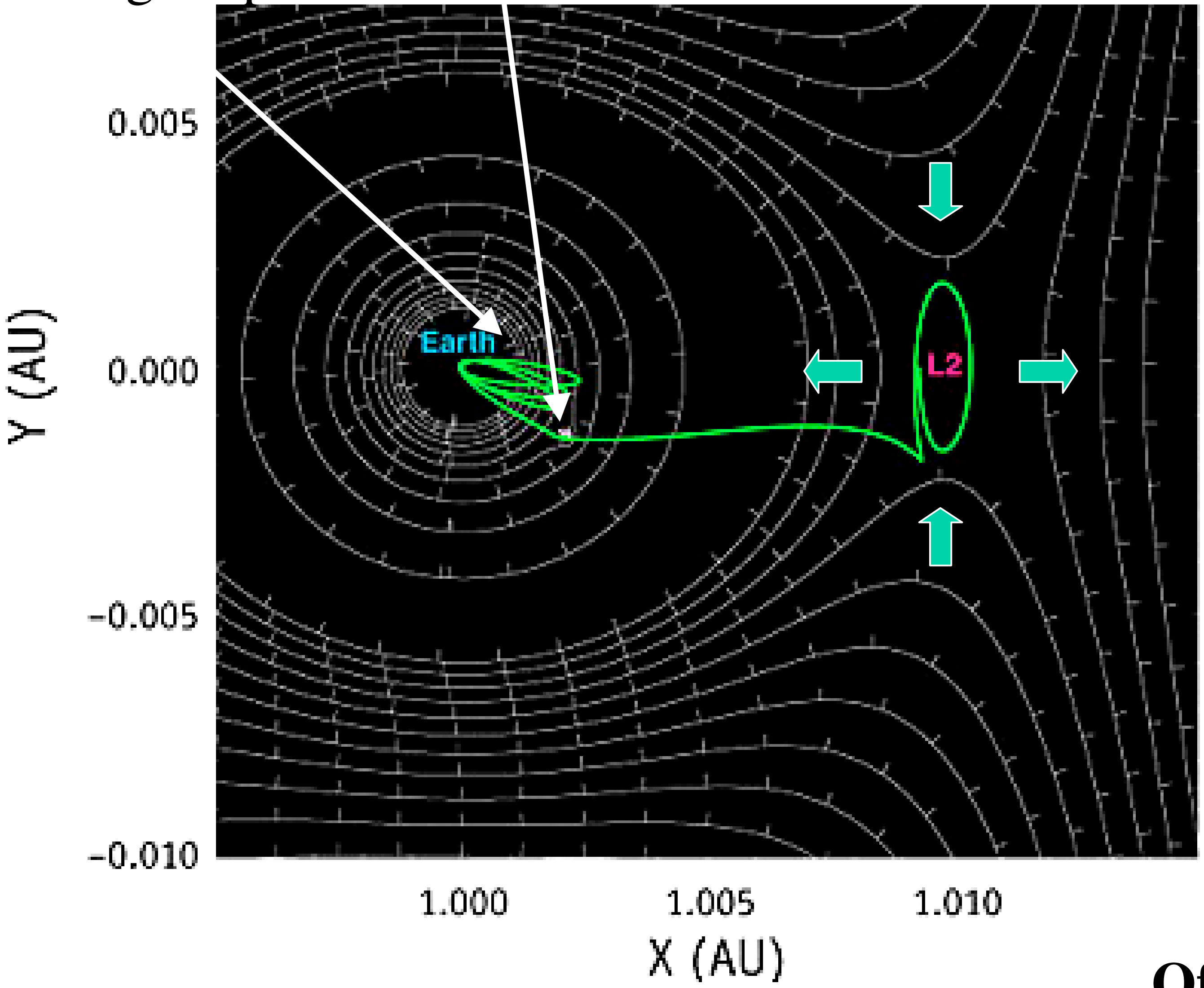
Princeton

Chris Barnes
Norm Jarosik
Eiichiro Komatsu
Michael Nolta
Lyman Page
Hiranya Peiris
David Spergel
Licia Verde

(Most of) WMAP Science Team, August 2002

Launched from cape Canaveral on June 30 2001

Trajectory



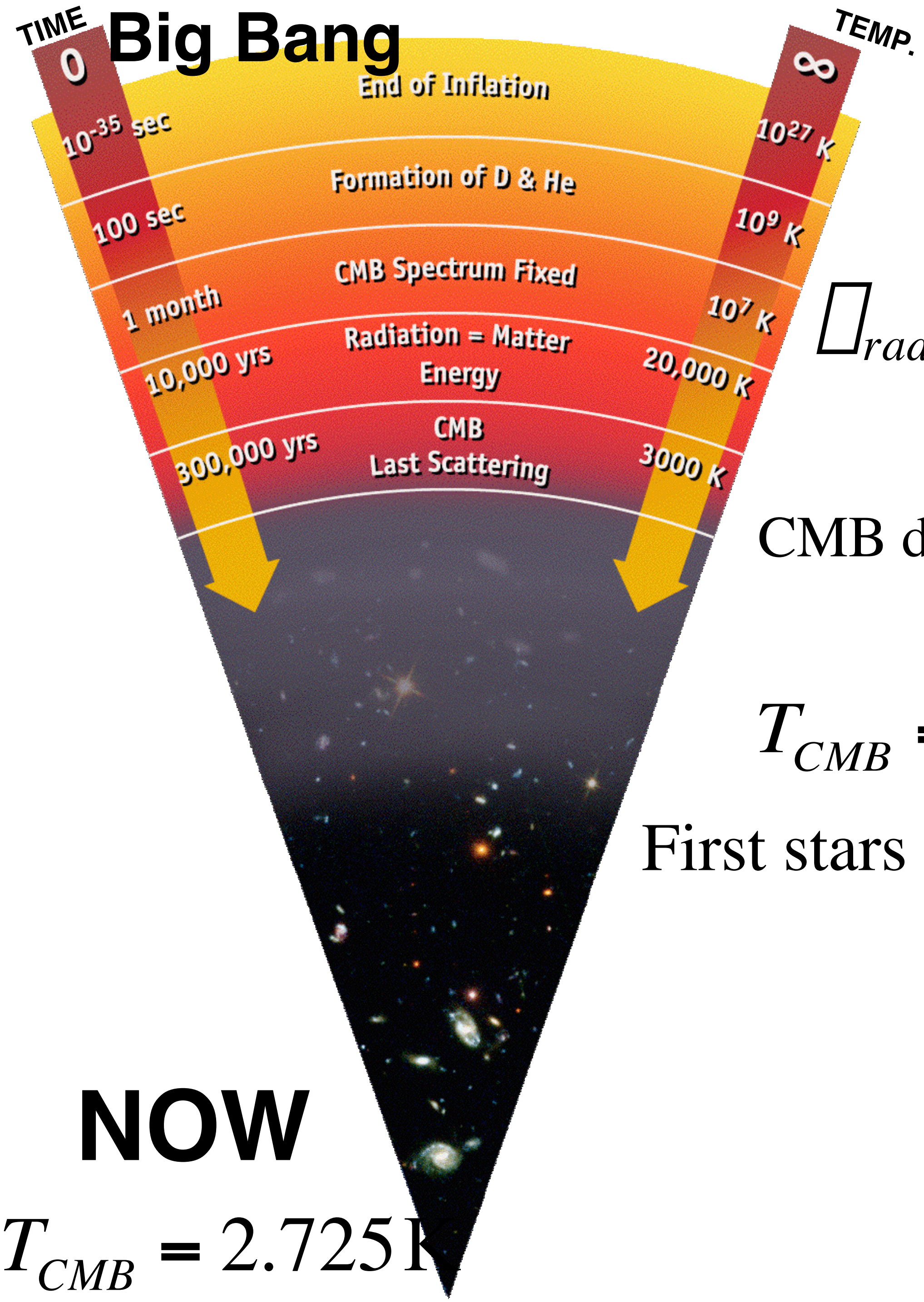
Phasing loops

Lunar swingby

100 days to L2, 1.5e6 km from Earth.

Official arrival date:
Oct 1, 2001

Cosmic History



Inflation-like epoch. new

$$\Box_{radiation} = \Box_{matter}$$

$z_{eq} = 3230$ $t_U = 56$ kyr

new

CMB decouples from plasma

$z_{dec} = 1089$ $t_U = 380$ kyr

$T_{CMB} = 2970\,\mathrm{K}$

First stars form new

$z_r = 20$ $t_U = 200$ Myr

new

$T_{CMB} = 2.725\,\mathrm{K}$

$z = 0$ $t_U = 13.7$ Gyr

CMB THEORY

HOW? ***WHY?***

"Seeing sound" (W. Hu)

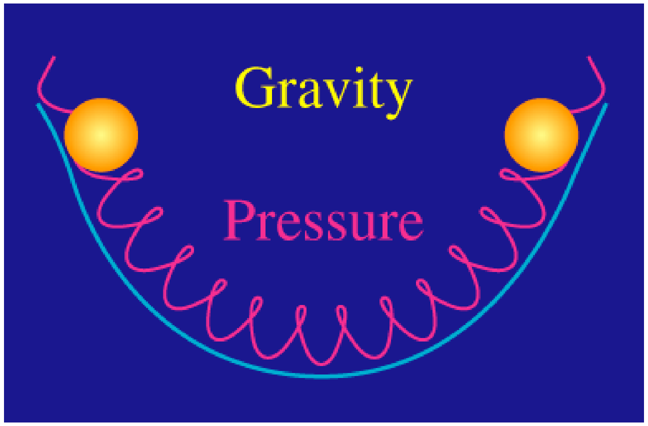
Last scattering surface : snapshot of the photon-baryon fluid

On large scales : primordial ripples

What put them there?

On smaller scales: { Photons radiation pressure
Gravity compression } Sound waves

Stop oscillating at recombination



Horizon size at LSS → Fundamental mode (over tones)

Some history

SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

R. A. SUNYAEV and YA. B. ZELDOVICH
Institute of Applied Mathematics, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

(Received 11 September, 1969)

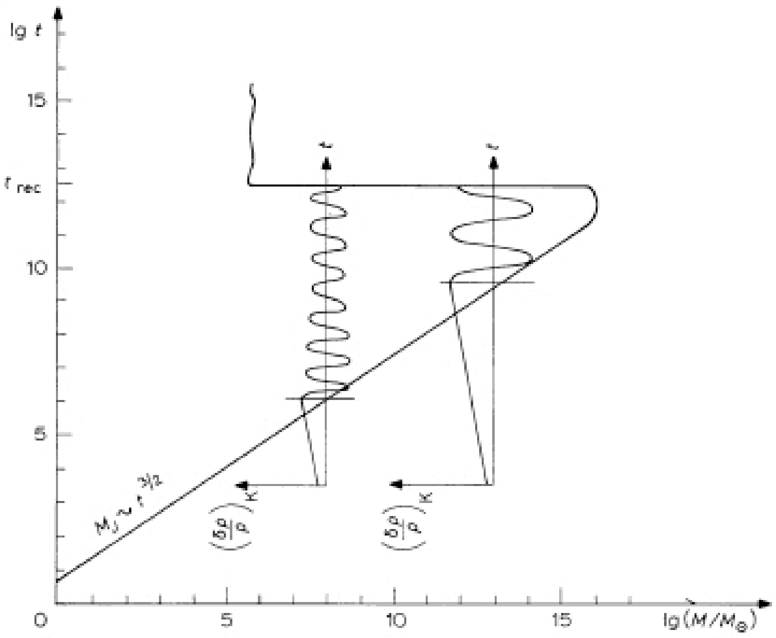


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until the moment when the considered mass is smaller than the Jeans mass and oscillations thereafter. It is apparent that at the moment of recombination perturbations corresponding to different masses correspond to different phases.

SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION*

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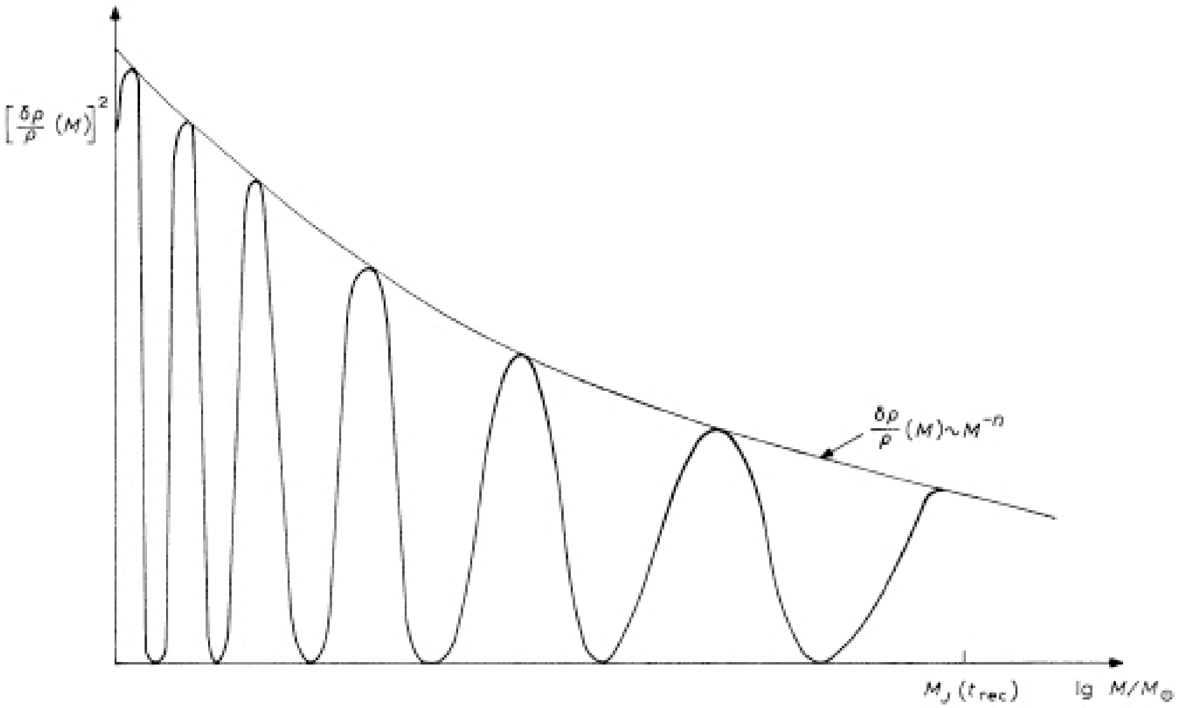
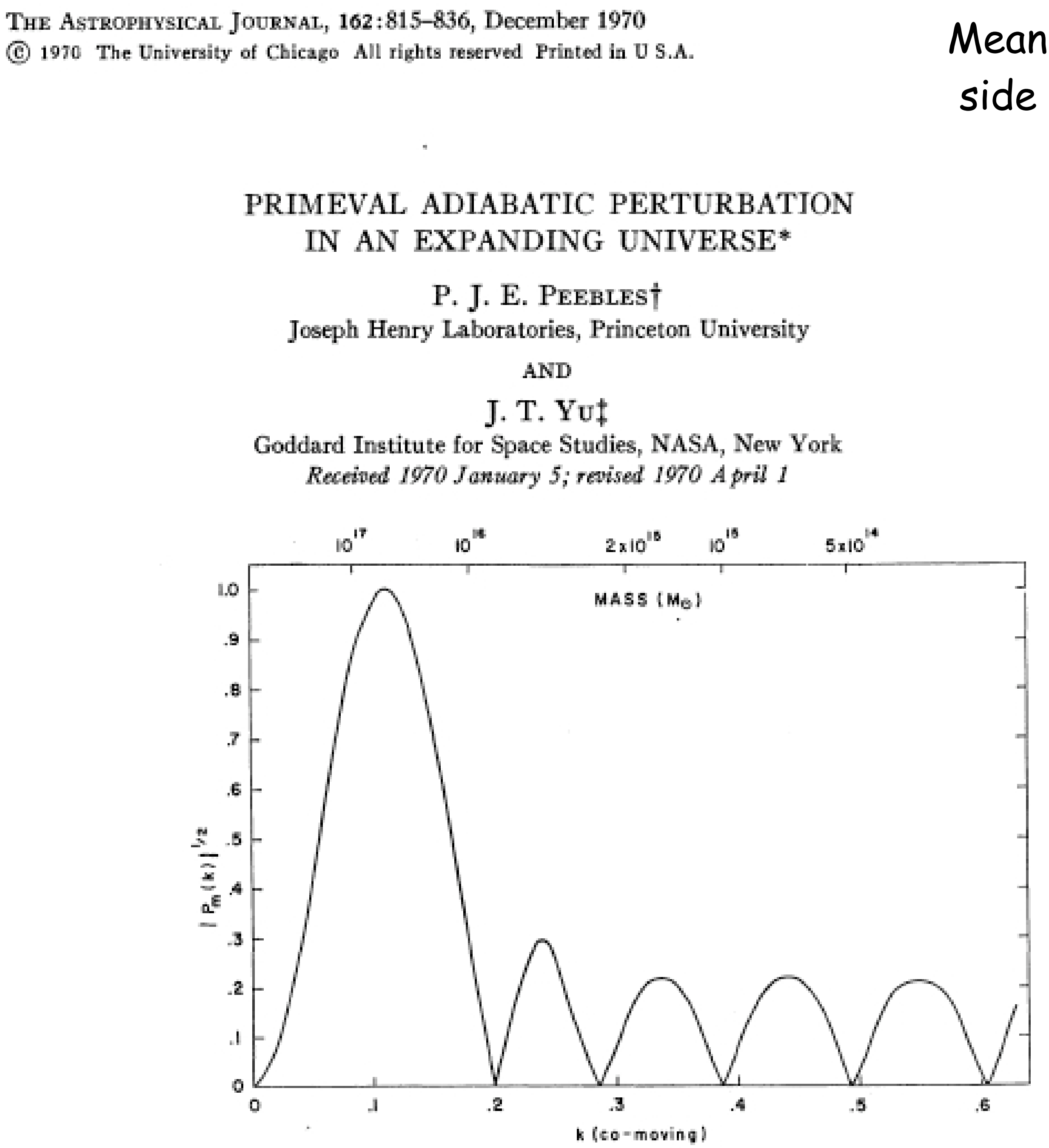


Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.

Meanwhile,on the other
side of the iron curtain…



THE ASTROPHYSICAL JOURNAL, 162:815–836, December 1970

PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

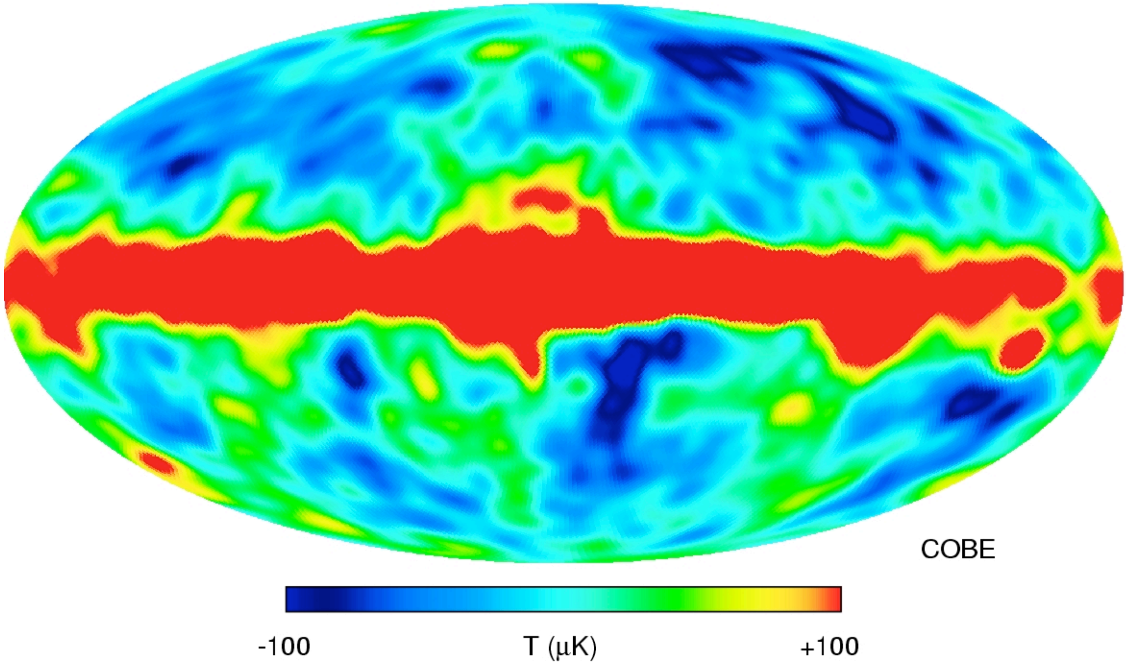
P. J. E. PEEBLES†
Joseph Henry Laboratories, Princeton University

AND

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

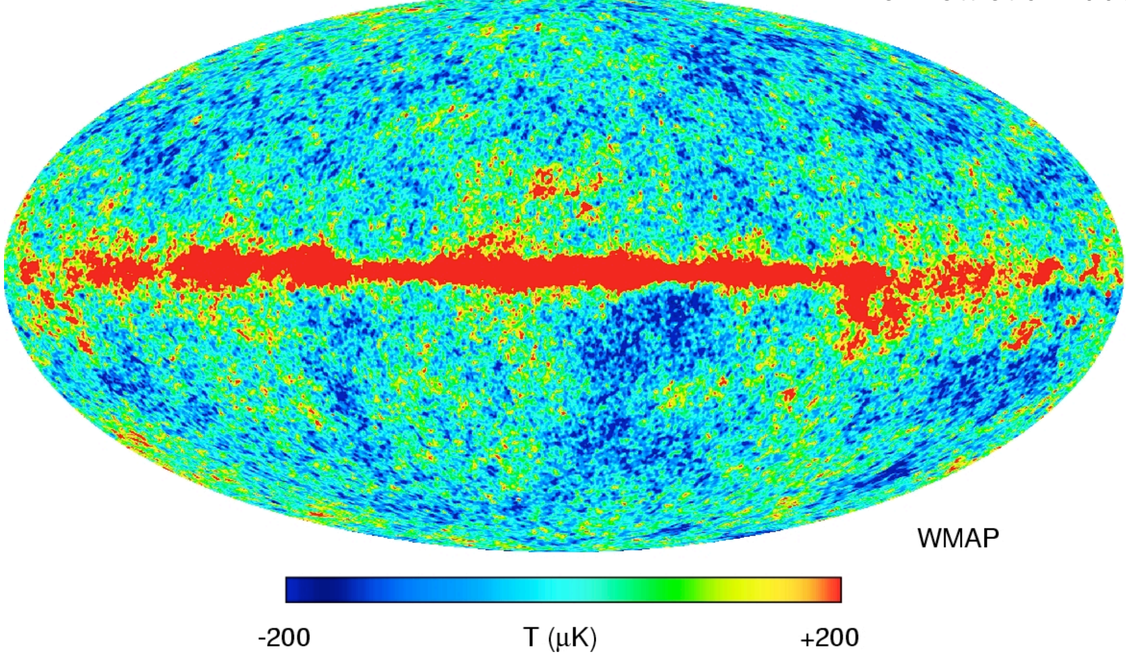
Received 1970 January 5; revised 1970 April 1

COBE 1992



Bennett et al 2003

WMAP 2003



Compress the CMB map to study cosmology

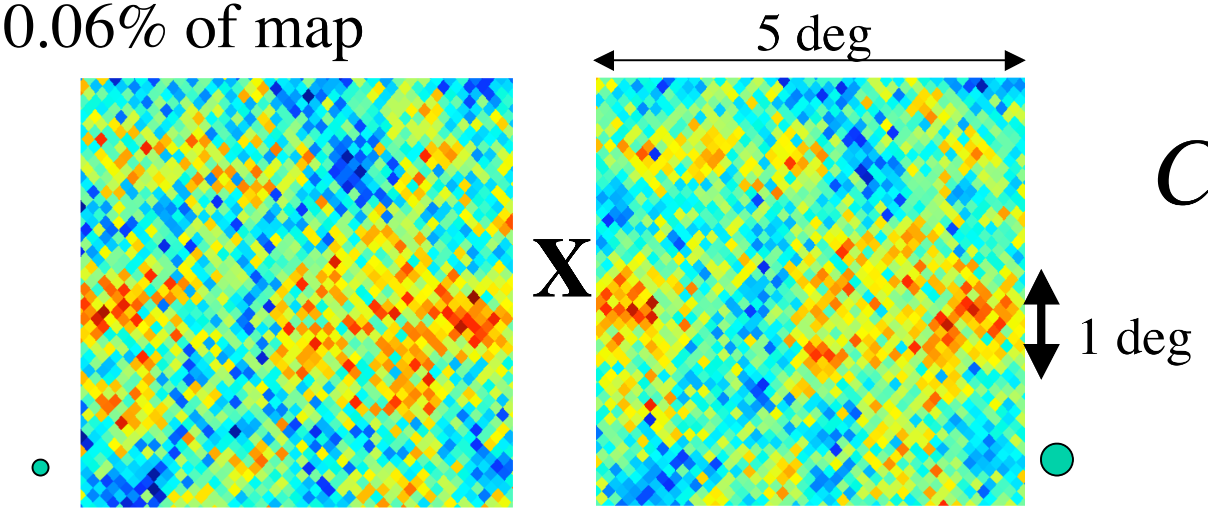
Express sky as: $$\Delta T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

If the anisotropy is a Gaussian random field

(real and imaginary parts of each a_{lm} independent normal deviates, not correlated.)

all the statistical information is contained in the angular power spectrum

0.06% of map

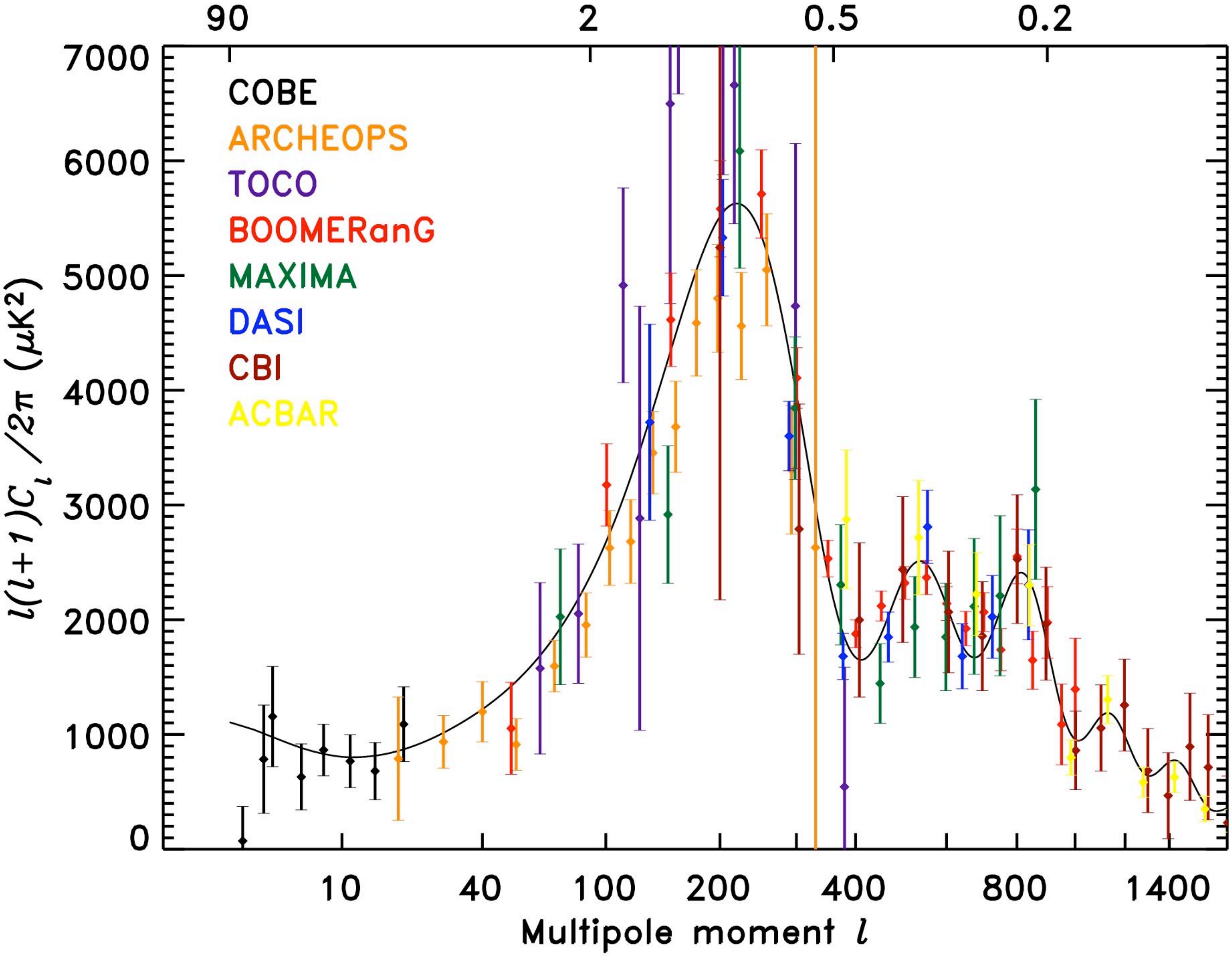


Raw 94 GHz
near NEP

+/- 32 uK

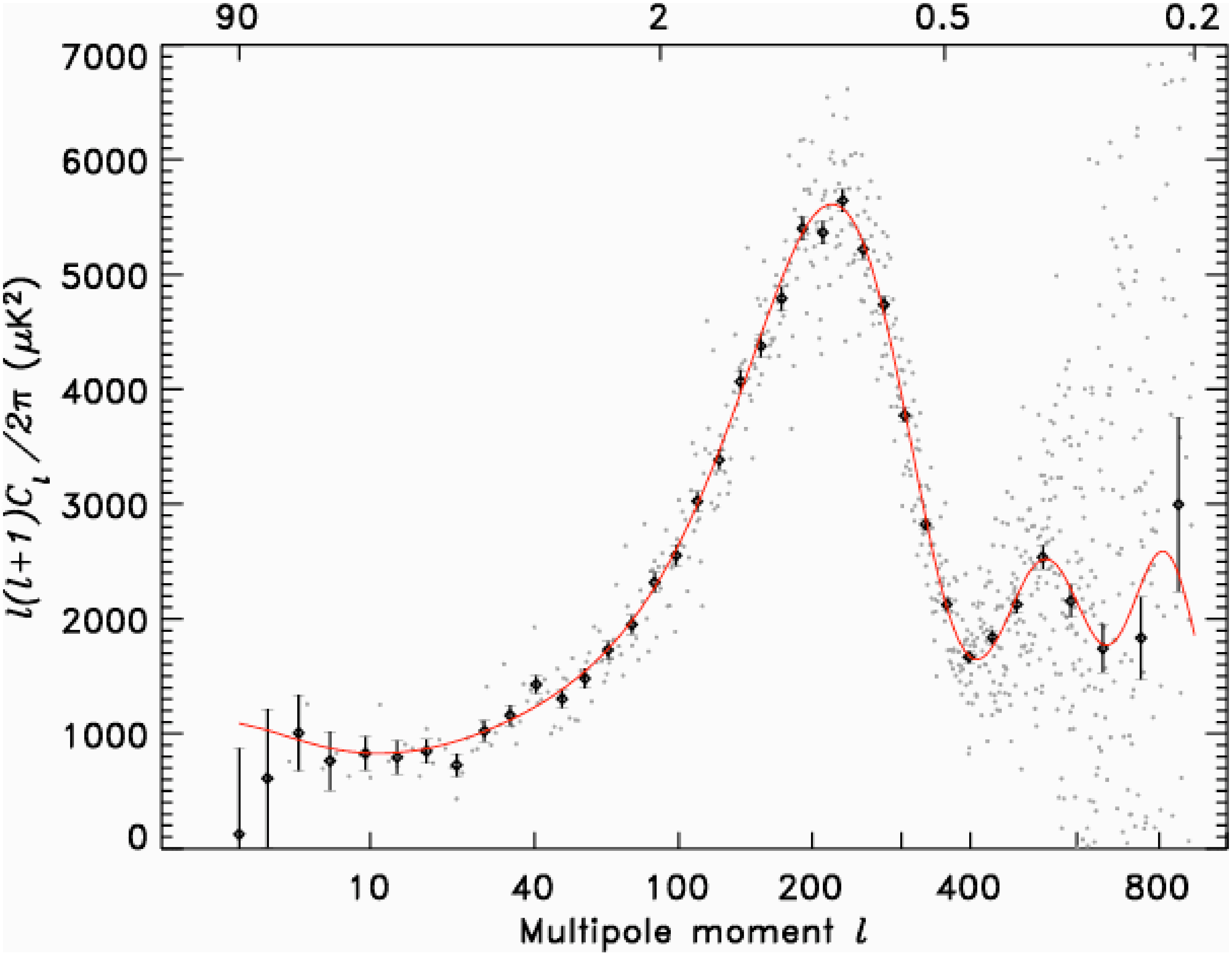
Raw 61 GHz
near NEP

$$C_l = \frac{1}{2l+1}\sum_m |a_{lm}|^2$$



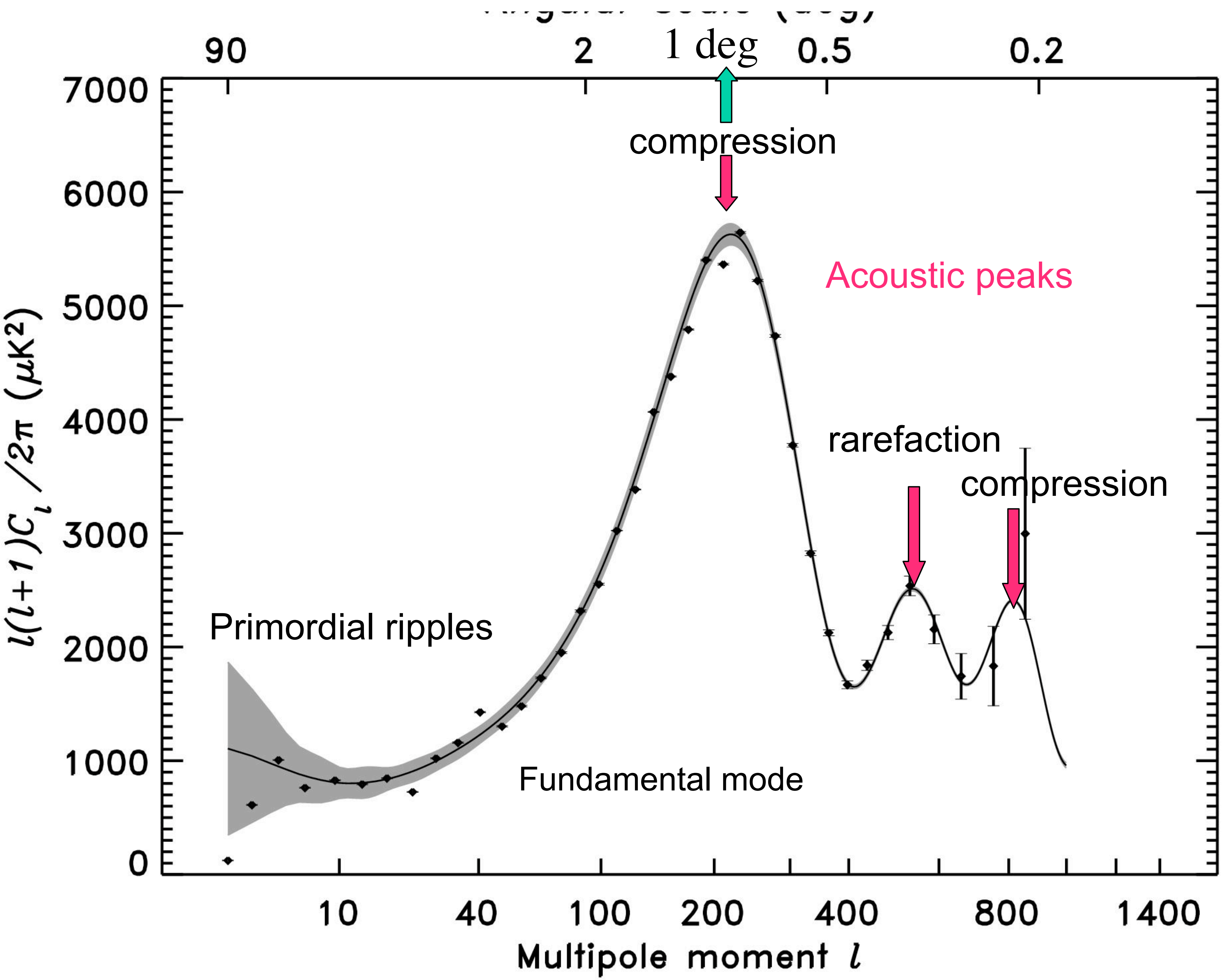
Before 11 Feb. 2003

(From Hinshaw et al 2003)



After

Why C_ℓ only? (Komatsu et al. 2003)



1 deg

compression

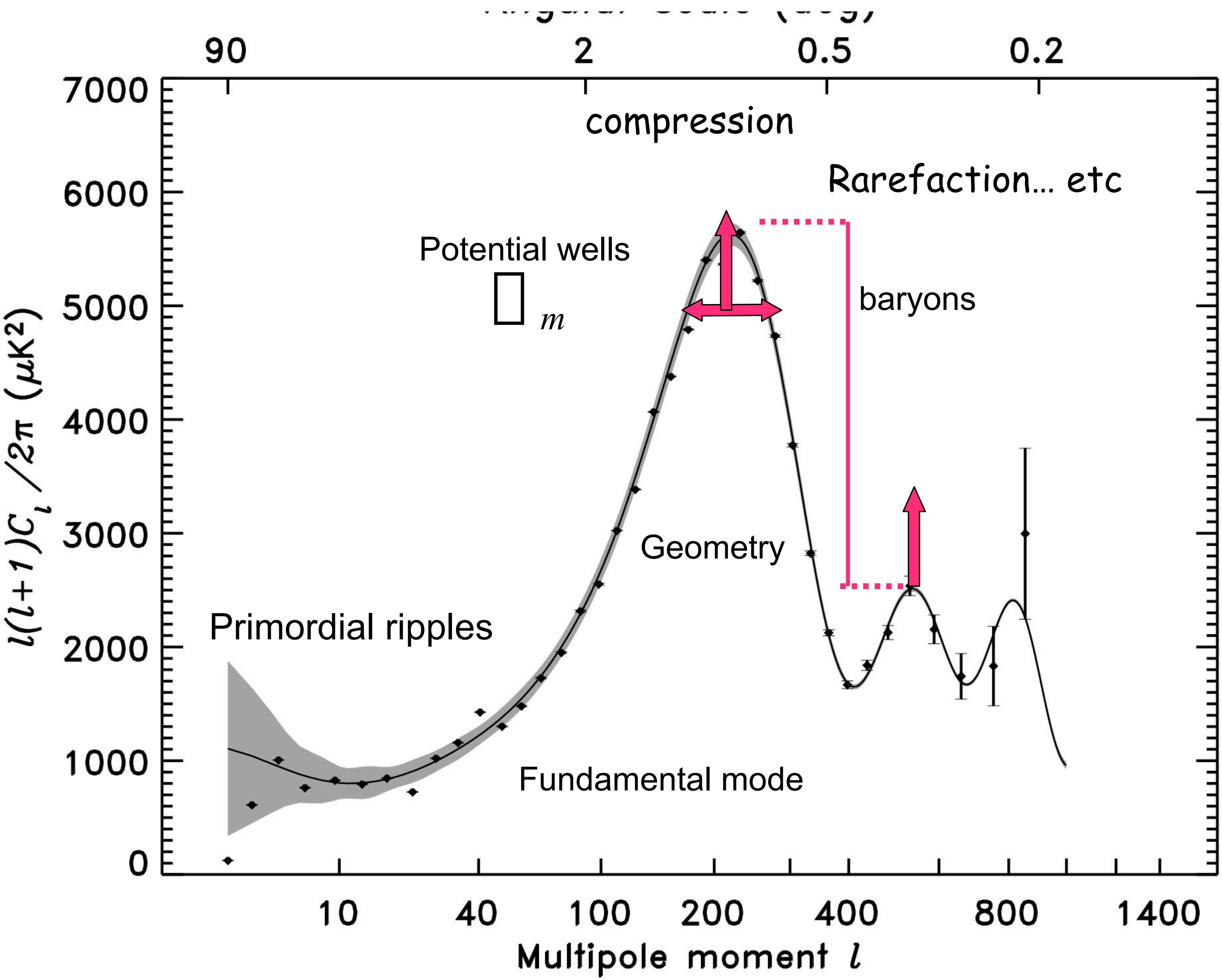
Acoustic peaks

rarefaction

compression

Primordial ripples

Fundamental mode



compression

Rarefaction… etc

Potential wells

$\square_m$

baryons

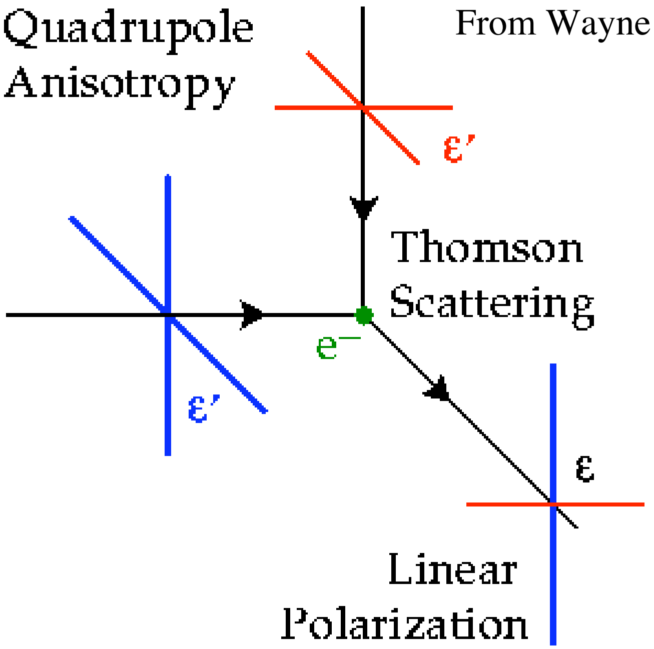
Geometry

Primordial ripples

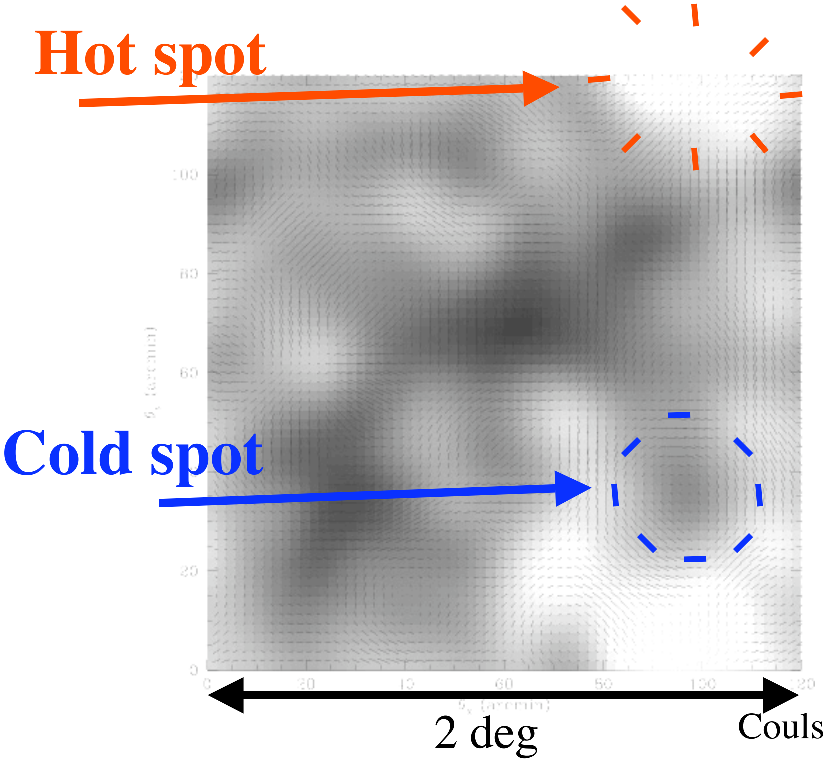
Fundamental mode

POLARIZATION EFFECT #1: CONFIRMATION OF PHYSICAL ASSUMPTIONS.

- Polarization of the CMB is produced by Thompson scattering of a quadrupolar radiation pattern.
- At decoupling, the quadrupole is produced by velocity gradients.
- A component of the polarization is correlated with the temperature anisotropy.



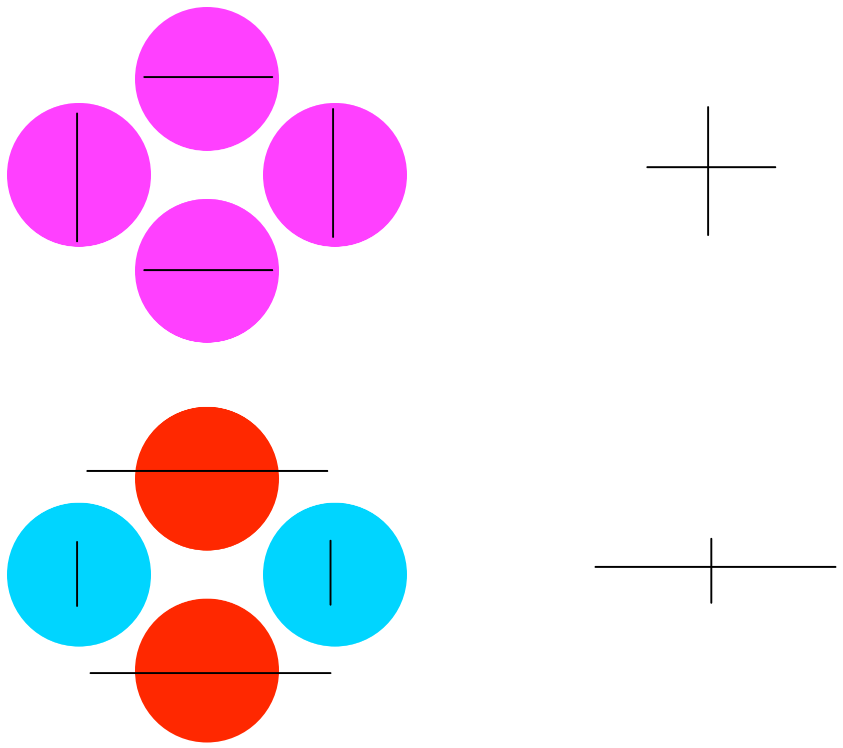
From Wayne Hu



Coulson et al

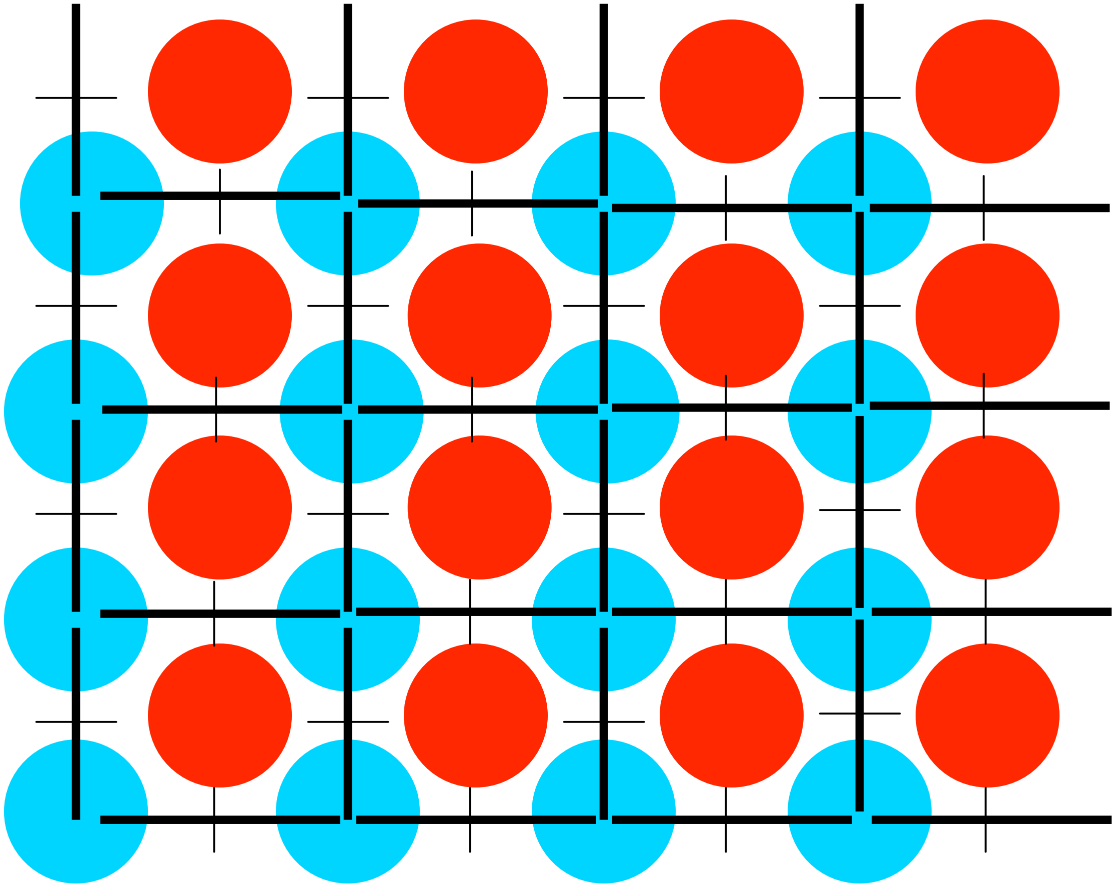
Generation of CMB polarization

- Temperature quadrupole at the surface of last scatter generates polarization.



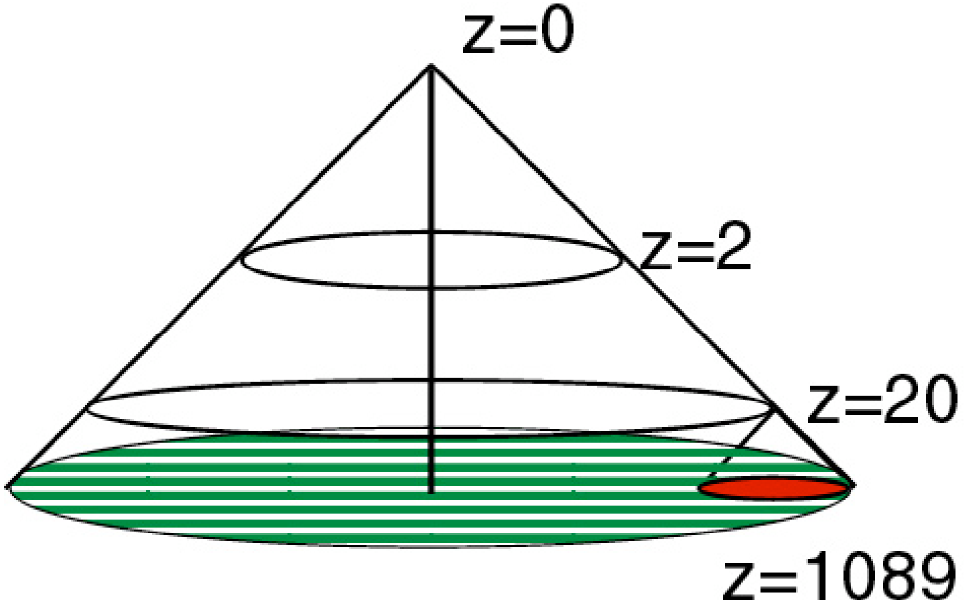
Temperature-polarization correlation

- Radial (tangential) pattern around cold (hot) spots.



POLARIZATION EFFECT #2: REIONIZATION BY FIRST OBJECTS.

Based on Tegmark



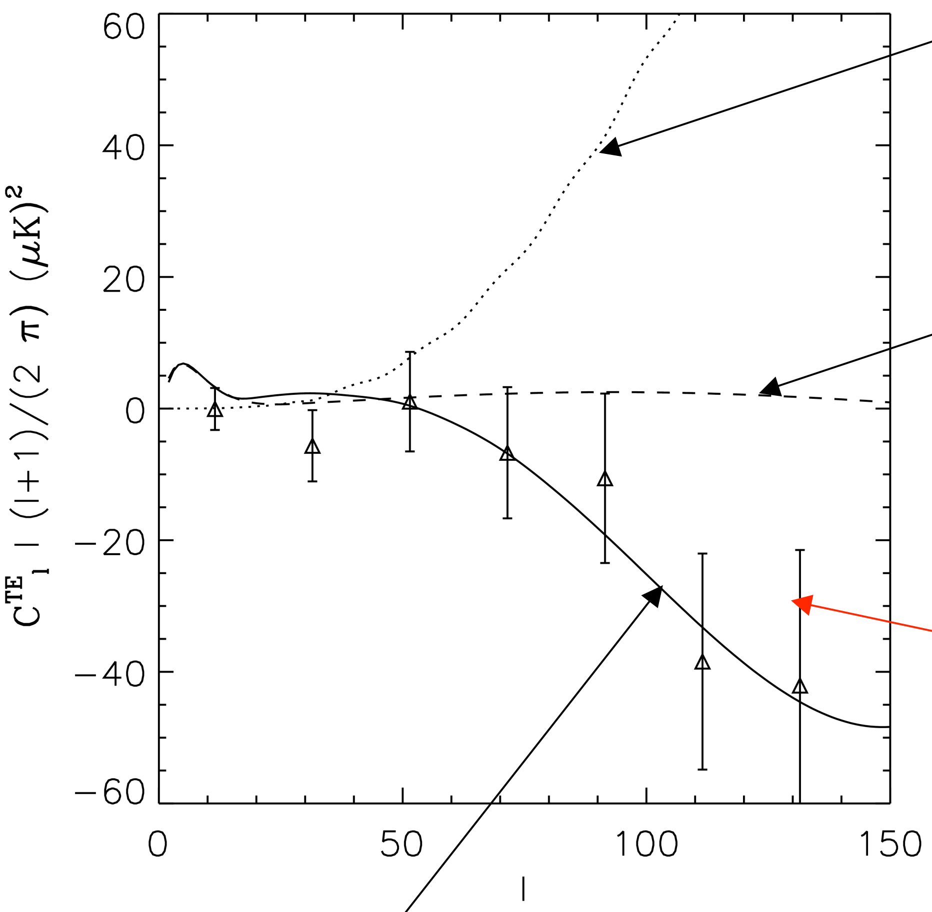
Conformal spacetime diagram with one spatial dimension not shown.

Stars form near z~20, light reionizes the plasma.

Free electrons scatter CMB photons, uniformly suppressing the fluctuations by 30% for l>40.

Free electrons see the local z~20 CMB quadrupole and polarize the CMB at large angular scales, where no other mechanism of polarization operates.

Large Scale TE anti-correlation



Causal Seed model (Durrer et al. 2002)

Primordial Isocurvature i.c.

WMAP TE data in bins of _l=10

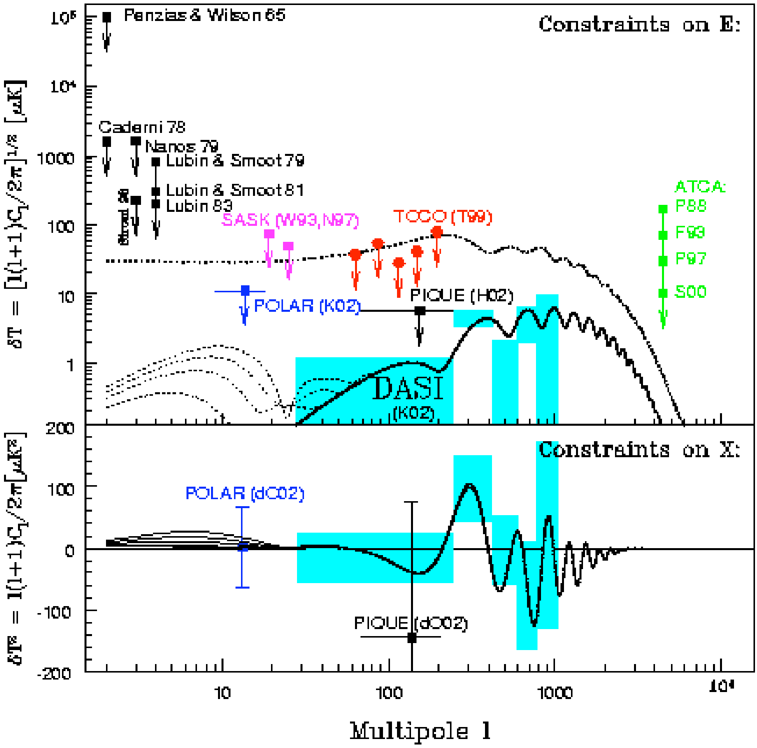
Kogut et al (2003)

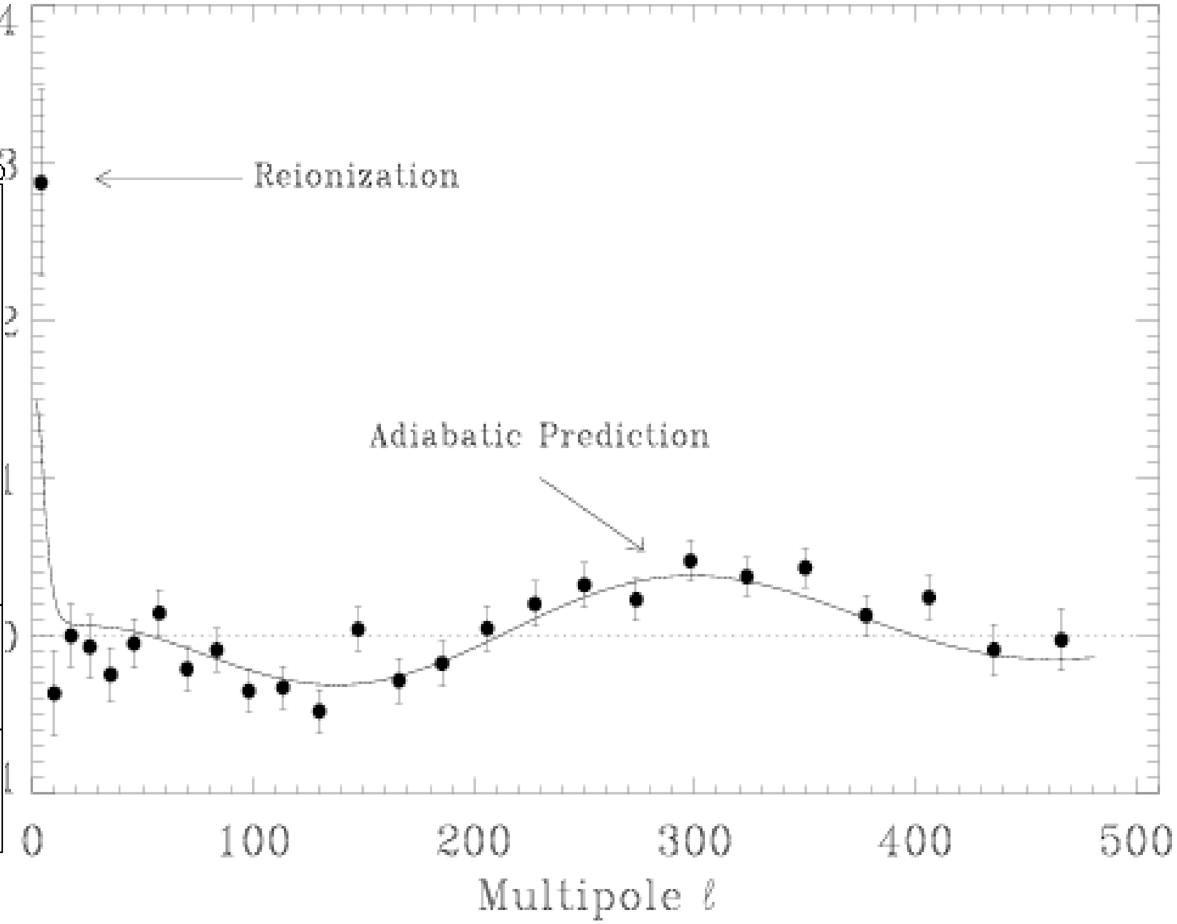
Primordial Adiabatic i.c.

Peiris et al. 2003

TE cross-correlation

(Figure from de Oliveira-Costa et al 2002)





- The TT spectrum makes precise predictions for the TE spectrum
- We saw it.
- Triumph for the standard cosmological model.

(Kogut et al. 2003)

Sachs&Wolfe 1967
Silk 1968
Peebles & Yu 1970
Sunyaev & Zel'dovich 1970

Interpretation:

The angular power spectrum is a function of ~15 cosmological parameters. Perturbations are linear.

The analysis path follows: Lineweaver

- Select parameters — e.g., Kosowsky et al.
- Compute model C_l with CMBFAST — Selkak & Zaldarriaga
- Compare to measured C_l , find $\mathbf{L}$ — Christensen et al.
- Repeat to find confidence regions.

The simplest best fit model has 6 parameters and

$$\frac{\chi^2}{\nu} = \frac{1431}{1342} = 1.07$$

The probability to exceed is 5%

Can combine data with external surveys as well.

RESULTS: WMAP only (TT+TE), flat LCDM (Spergel et al. 2003)

CMB appears to be Gaussian. (Komatsu et al.)

- 15% of CMB was re-scattered in a reionized universe.

- The estimated reionization redshift ~20,
  or 200 million years after the Big-Bang.

Flat LCDM still fits: 6 parameters fit *1348 points*

DM density $(2.25 \pm 0.38) \times 10^{-27}$ Kg/m^3

atomic density $(2.7 \pm 0.1) \times 10^{-7}\, cm^{-3}$

$\eta = (6.5^{+0.4}_{-0.3}) \times 10^{-10}$

Age at decoupling $372 \pm 14\, Kyr$

Age 13.4 ± 0.3 Gyr

$\sigma_8 = 0.9 \pm 0.1$

$z_{reion} \approx 17$

1σ marginalized

Fits not only the CMB but also a host of other cosmological observations.

RESULTS:

WMAP only (TT+TE), flat LCDM

(Spergel et al. 2003)

$\Omega_m = 0.29 \pm 0.07$

$\Omega_b h^2 = 0.024 \pm 0.001$

$h = 0.72 \pm 0.05$

$n = 0.99 \pm 0.04$

$\tau = 0.166^{+0.076}_{-0.071}$

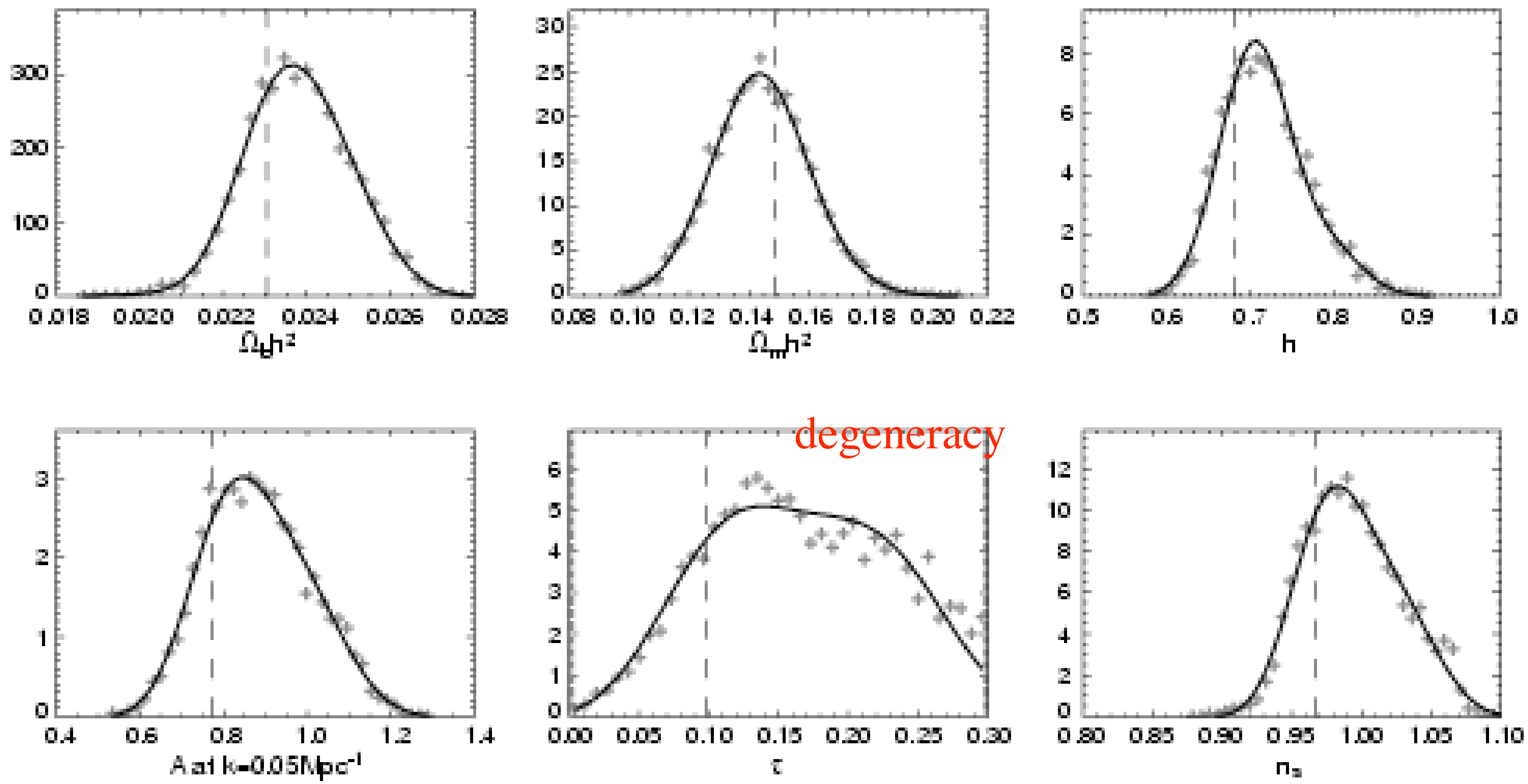
$\sigma_8 = 0.9 \pm 0.1$

TE alone: $\tau = 0.17 \pm 0.04$

(Kogut et al 2003)

$z_{reion} \approx 17$

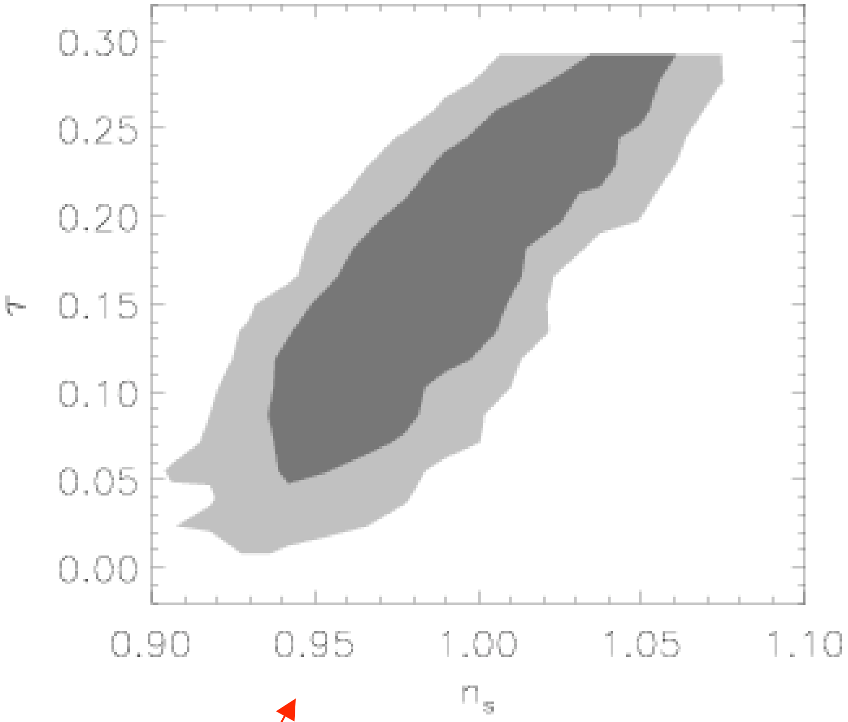
1σ marginalized



degeneracy

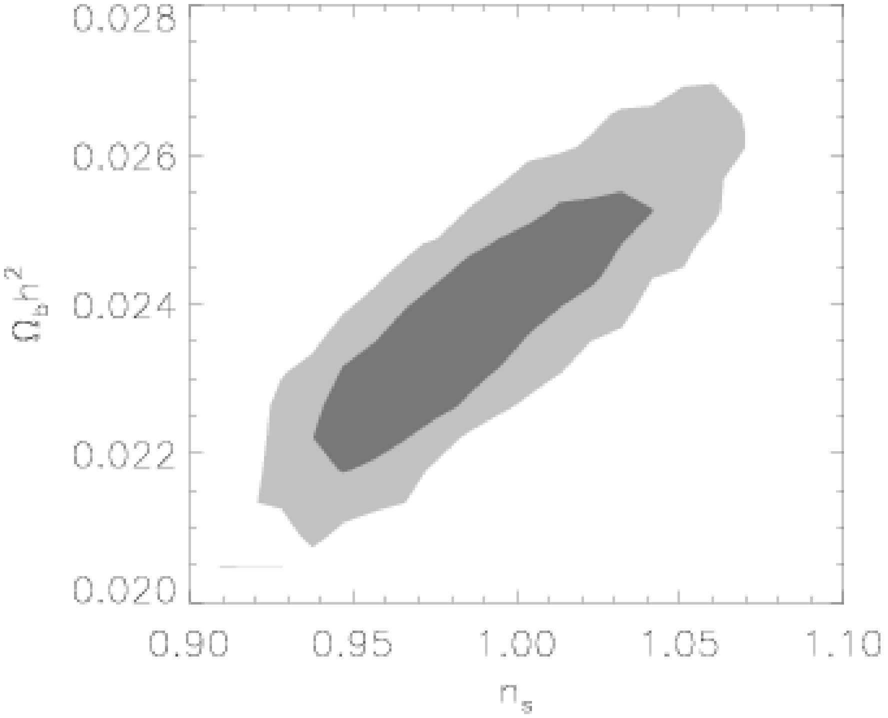
WMAP only: degeneracies

(TT+TE)



1 and 2 ▯

joint confidence contours



Main degeneracy

Will get better soon

TEST MODEL CONSISTENCY and LIFT DEGENERACiES

$z \simeq 1088$

WMAPext

CBI ACBAR

$z \simeq 0$

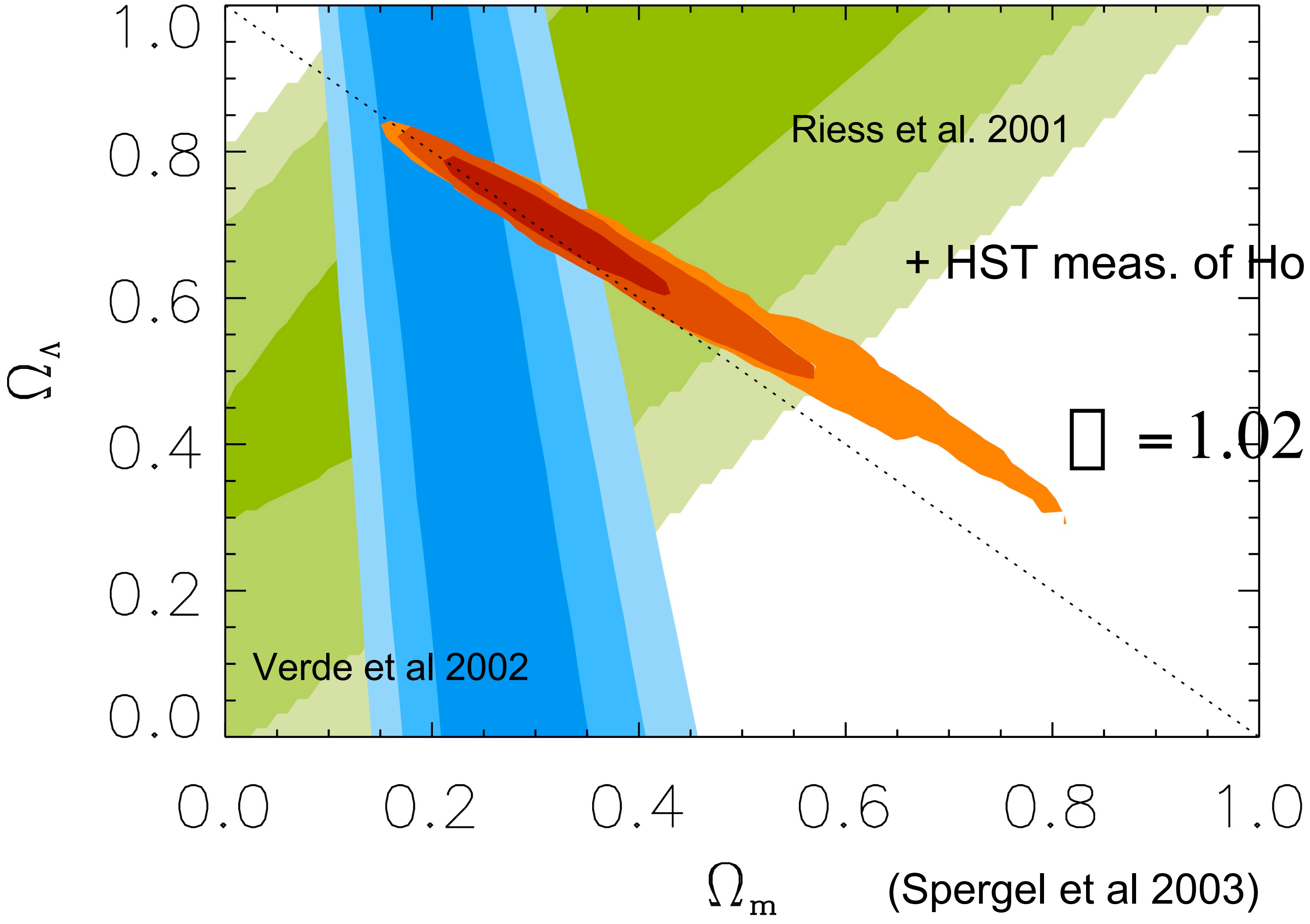
Lyman alpha forest

$z \simeq 3$

Complementary in scales and redshift

BEYOND LCDM model

FLATNESS



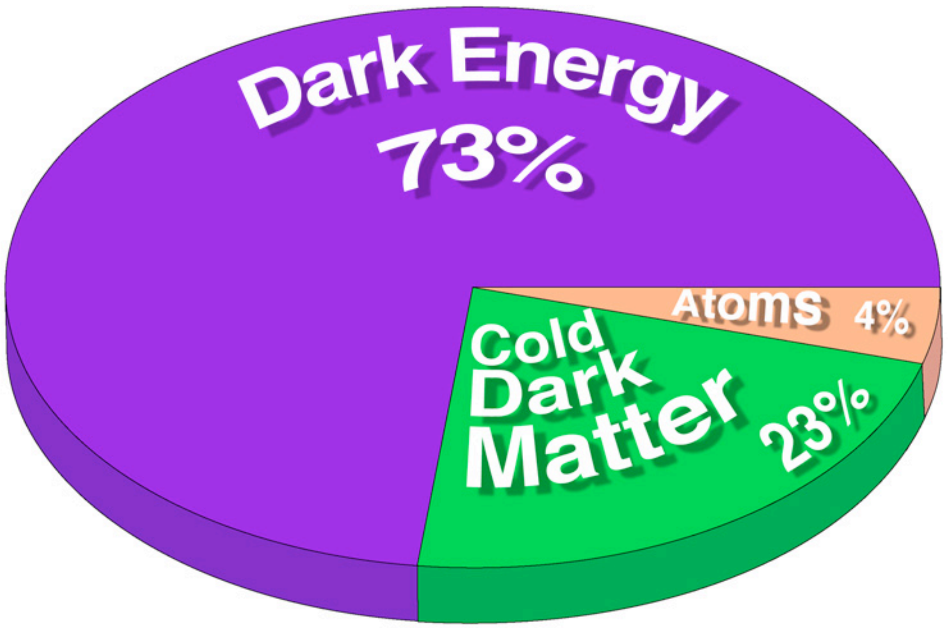
+ HST meas. of Ho

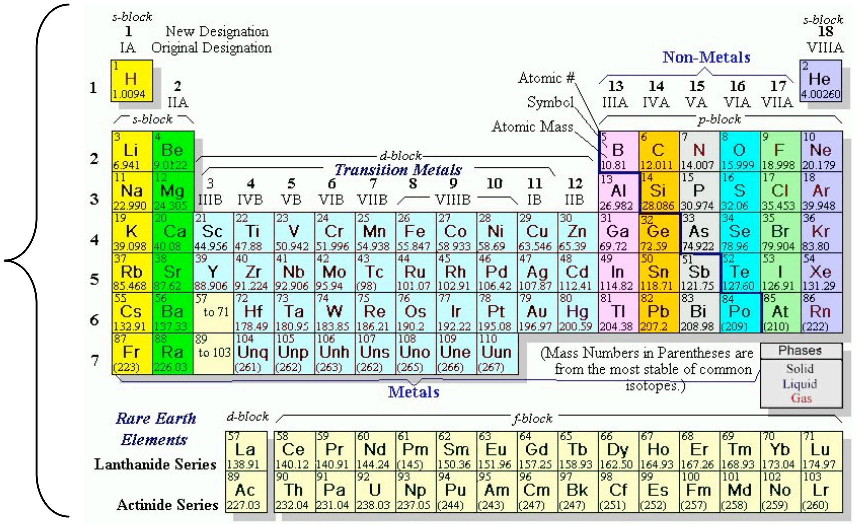
$\Omega = 1.02 \pm 0.02$

(Spergel et al 2003)

After

We (and all of chemistry) are a small minority in the Universe.




s-block

New Designation

Original Designation

Non-Metals

Atomic #

Symbol

Atomic Mass

p-block

d-block

Transition Metals

	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H 1.0094																	2 He 4.00260
2	3 Li 6.941	4 Be 9.0122											5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.179
3	11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.06	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.08	21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.75	52 Te 127.60	53 I 126.91	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	57 to 71	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.21	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra 226.03	89 to 103	104 Unq (261)	105 Unp (262)	106 Unh (263)	107 Uns (262)	108 Uno (265)	109 Une (266)	110 Uun (267)								

(Mass Numbers in Parentheses are from the most stable of common isotopes.)

Phases

Solid

Liquid

Gas

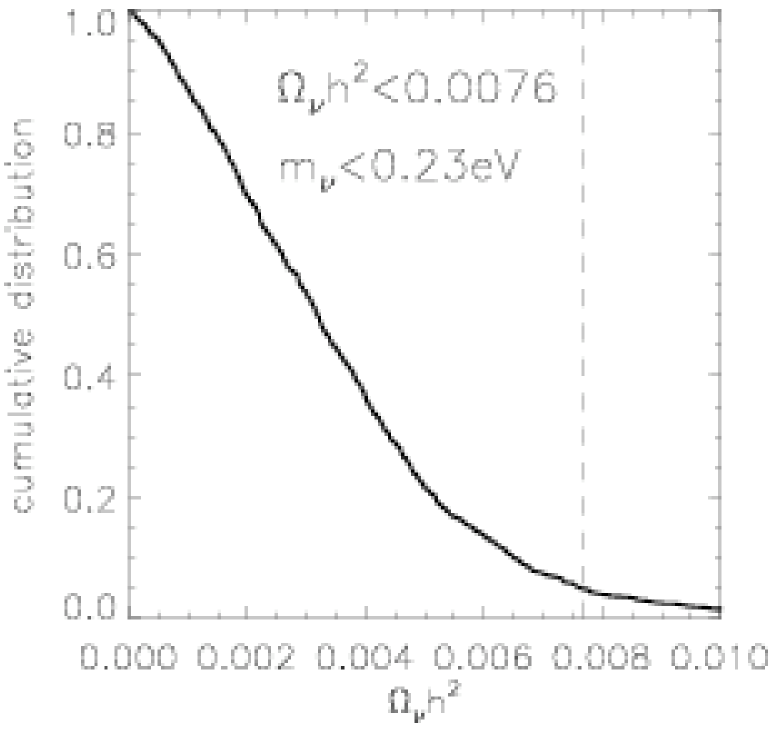
Metals

Rare Earth Elements

d-block

f-block

Lanthanide Series	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinide Series	89 Ac 227.03	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np 237.05	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)



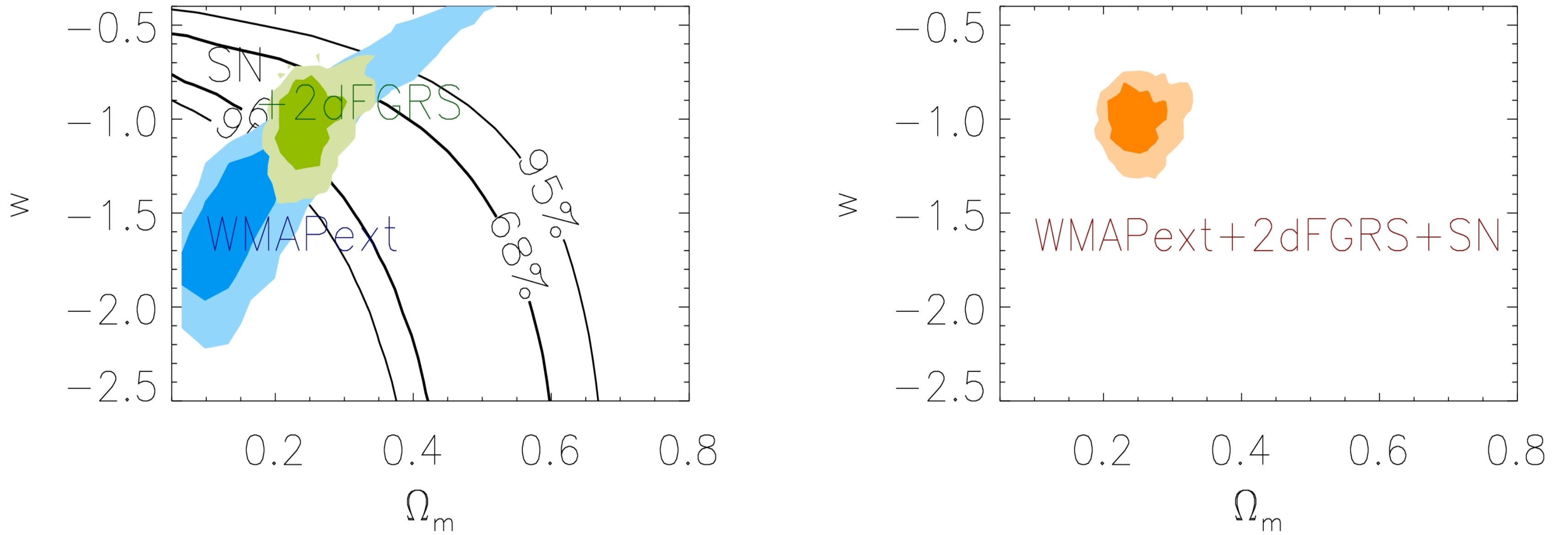
CONSTRAINTS ON NEUTRINO MASS

P(K) amplitude

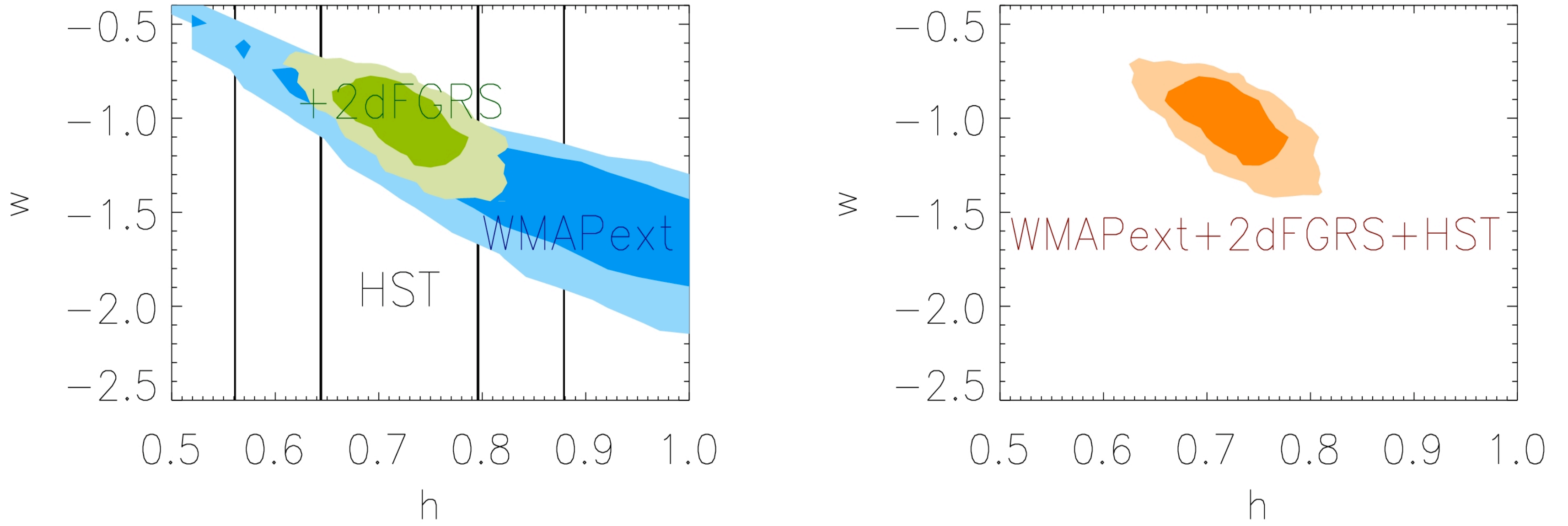
Factor of few better than previous cosmological constraints

(Elgaroey et al.2002)

Quintessence



$$w = -0.98 \pm 0.12$$



Running spectral index:

(all data) Parameters do not shift when adding other data sets.

$\Omega_m = 0.27 \pm 0.04$

$\sigma_8 = 0.84 \pm 0.04$

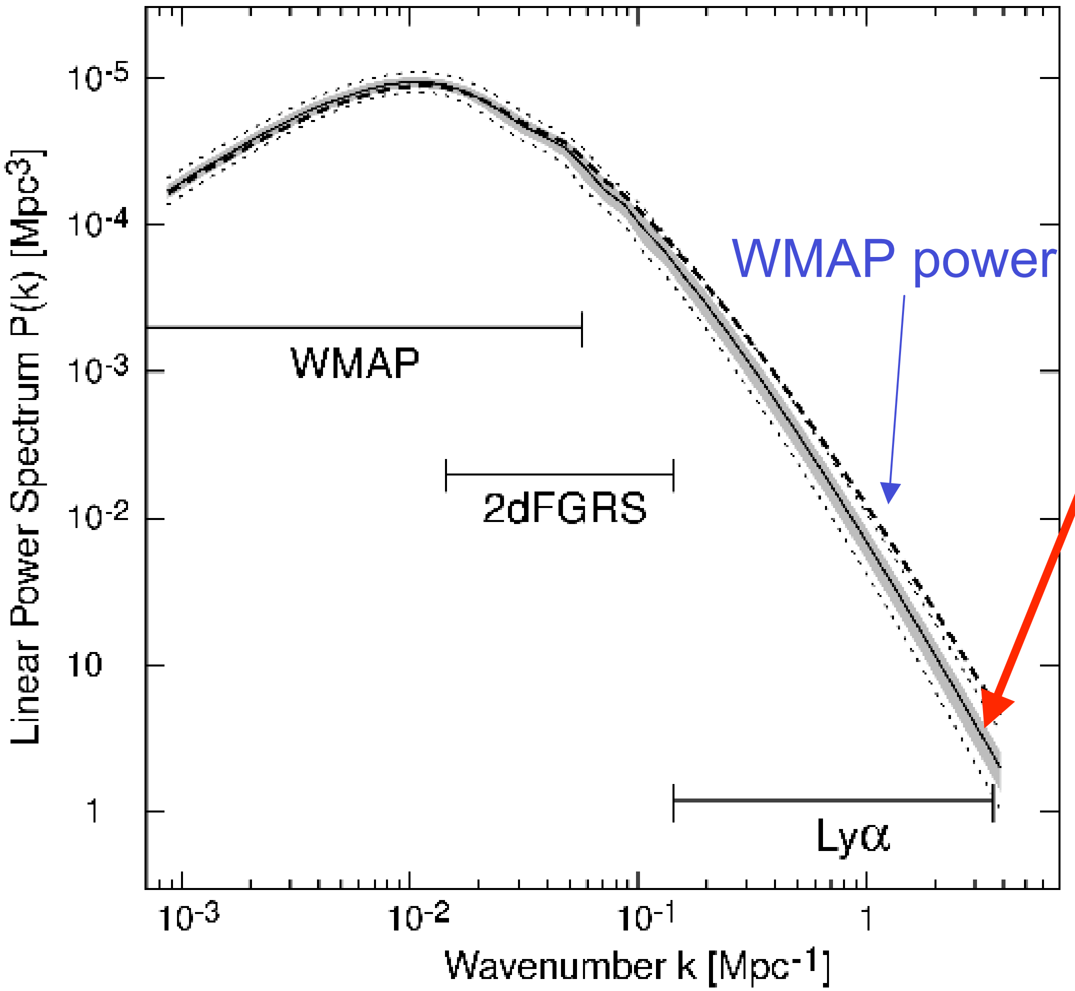
$\tau = 0.17 \pm 0.06$

$h = 0.71^{+0.04}_{-0.03}$

$n_s = 0.93 \pm 0.03$

$dn_s / d\ln k = -0.031^{+0.016 \ldots +0.023}_{-0.018 \ldots -0.025}$

$1.5 - 2\sigma$ suggestion

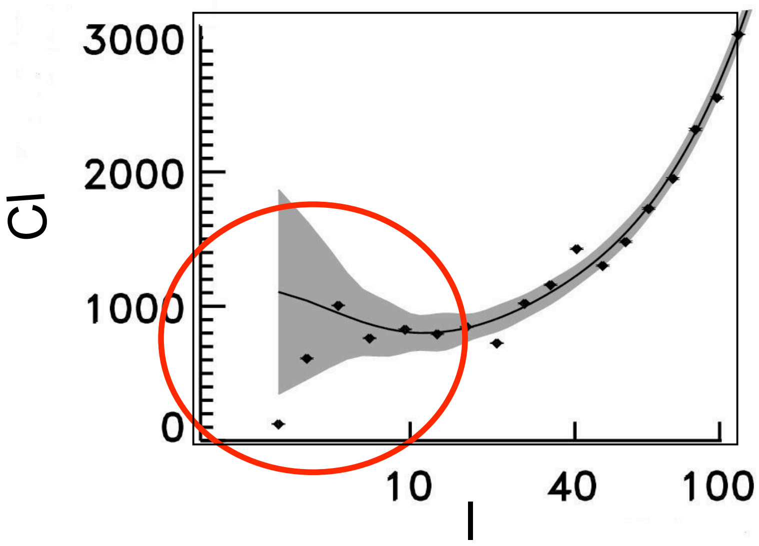


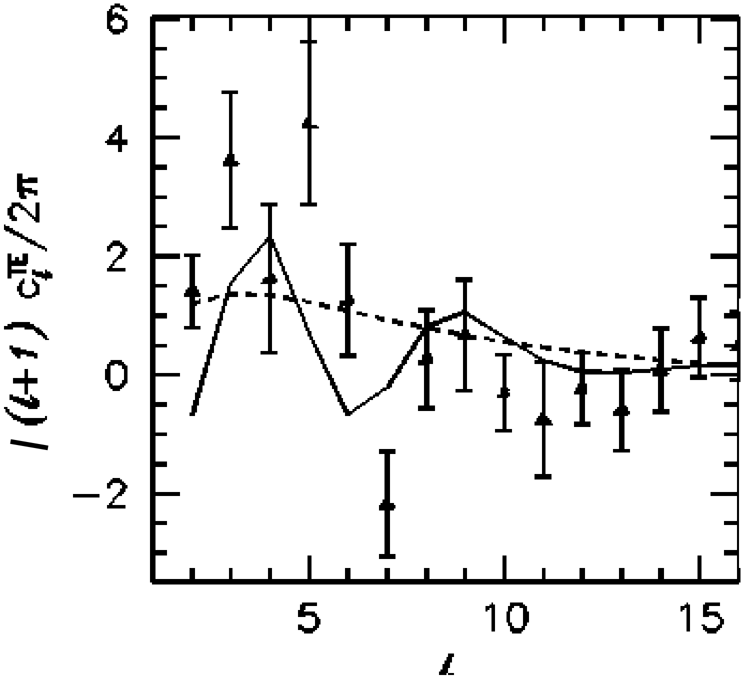
WMAP power law

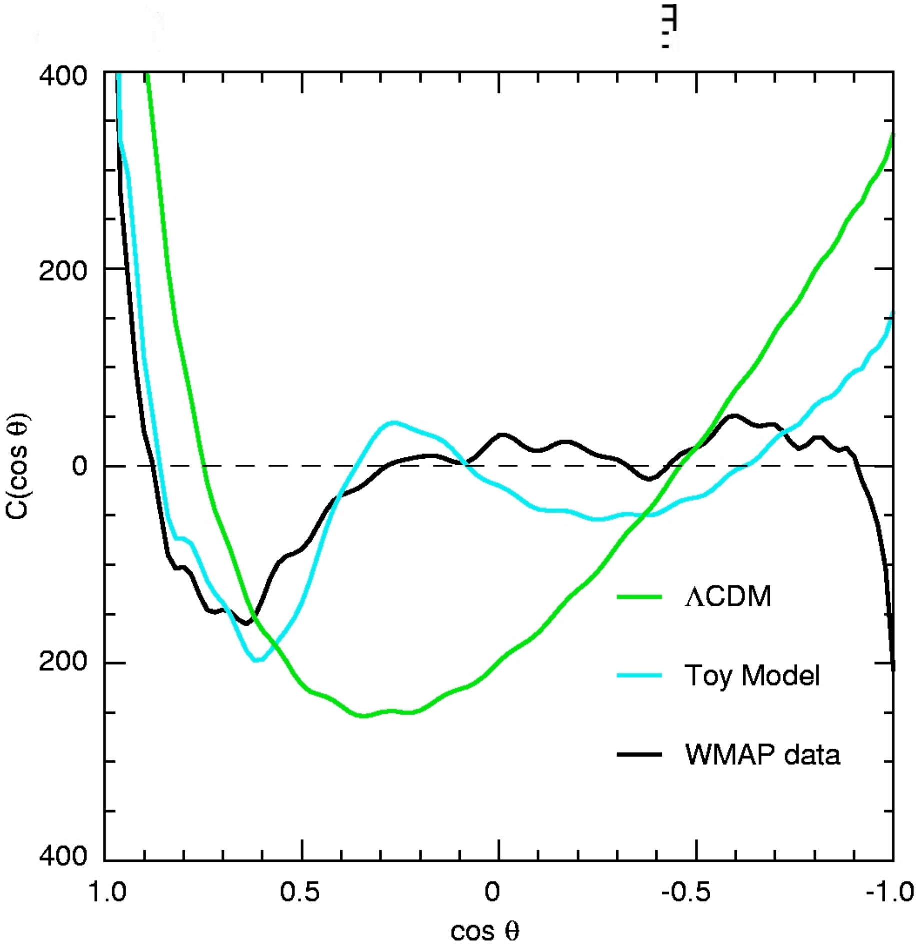
This is our “best fit” model

Can add tensors and get limits on r (Peiris et al. 2003)

INTRIGUING...


3000
2000
1000
0
Cl
10
40
100
l


6
4
2
0
−2
$l\,(l+1)\ c_l^{TE}/2\pi$
5
10
15
l


400
200
0
200
400
C(cos θ)
1.0
0.5
0
-0.5
-1.0
cos θ
ΛCDM
Toy Model
WMAP data

Conclusions:

For physicists

We have a standard cosmological model:
6 (or 7) parameters fit all.

For astronomers

Boring LCDM universe with a twist:

➡ the universe was reionized at $z \approx 17$

We have extrapolated forwards the $z \approx 1088$ observations. The model seems to work so well that we can attempt to extrapolate it backwards, before $z \approx 1088$

➡ Constraints on inflation!

(Peiris et al. 2003)

Data, software, papers and results are at: http://lambda.gsfc.nasa.gov

END