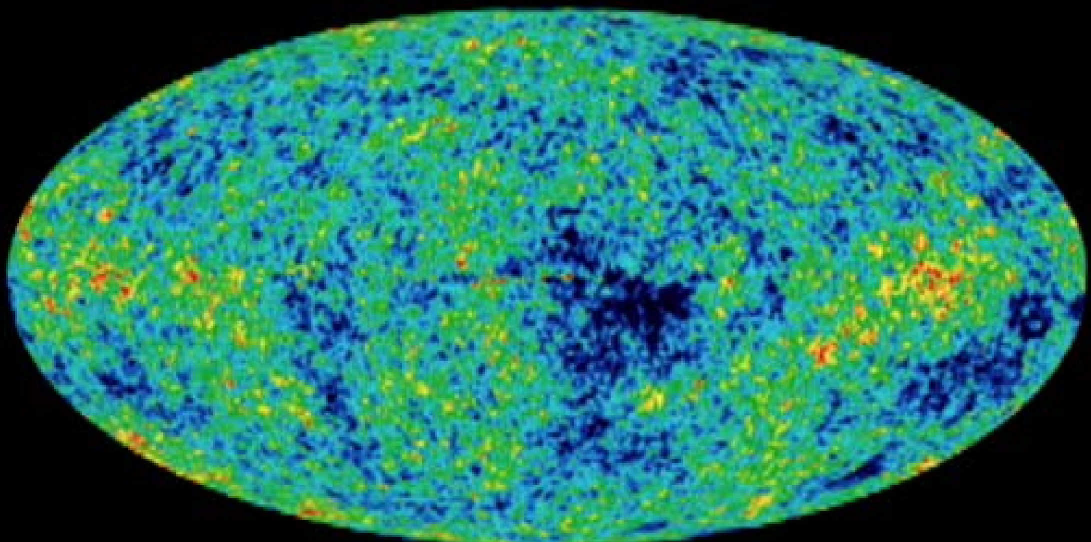
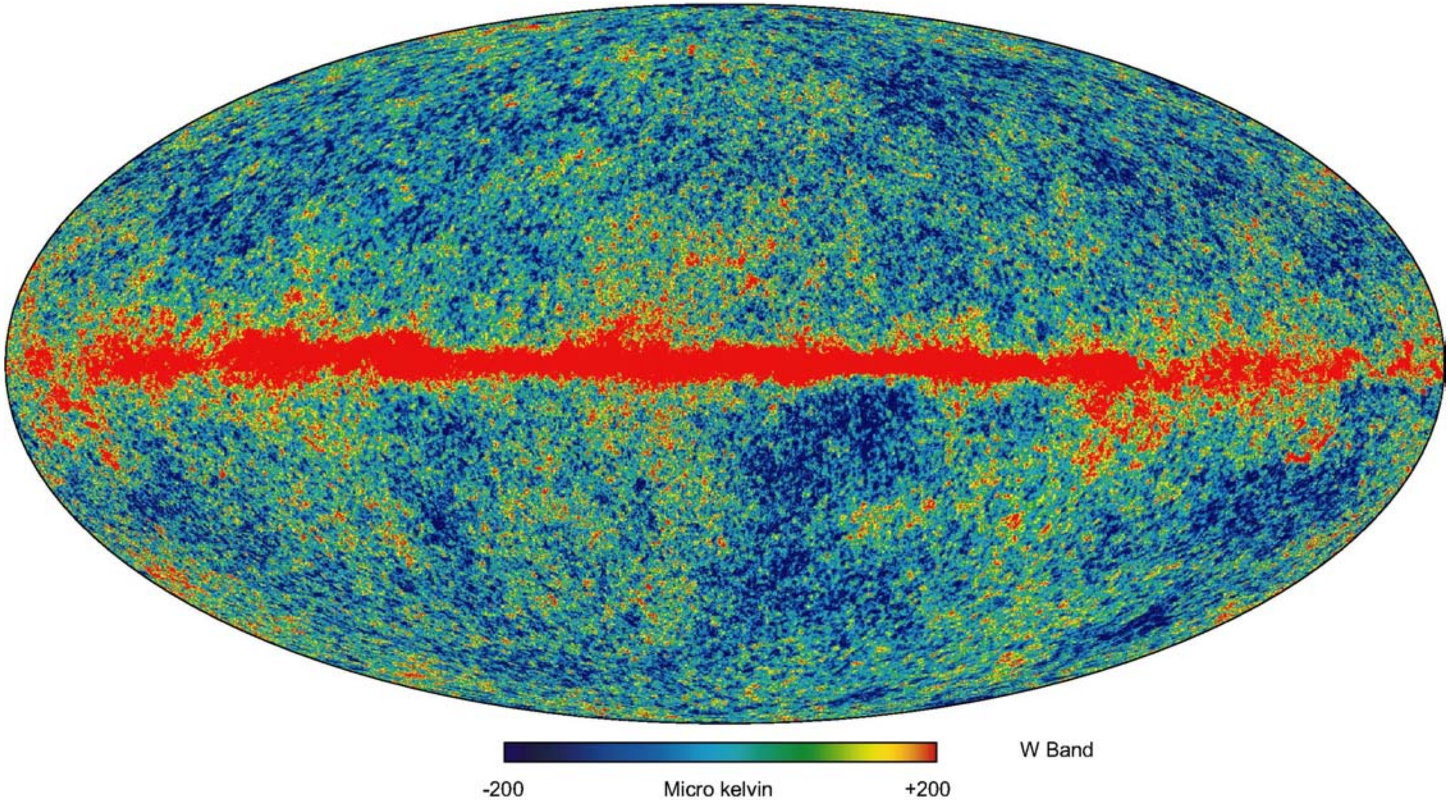
Cosmological implications of WMAP first year results



Licia Verde

University of Pennsylvania

Cosmological implications of WMAP first year results



Licia Verde

University of Pennsylvania

www.physics.upenn.edu/~lverde

Overview

Wilkinson Microwave Anisotropy Probe

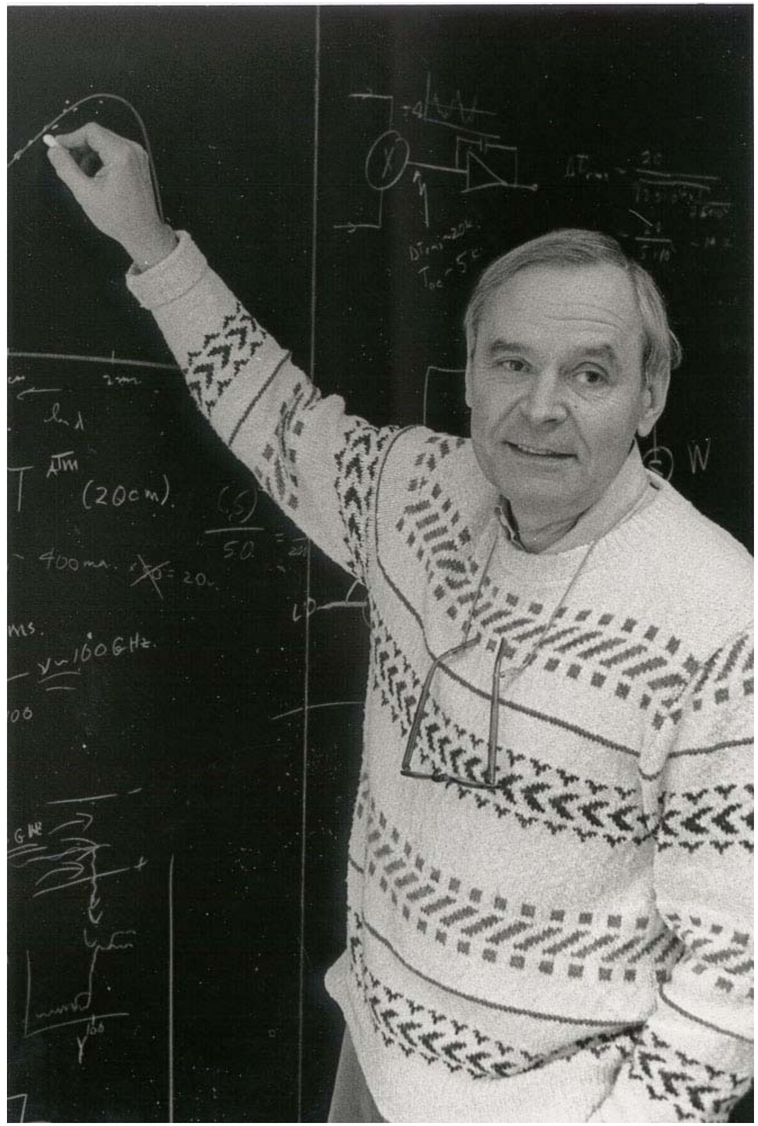
What we can learn from CMB and why

What we have learned from WMAP

Adding external data sets into the analysis

What all this tells us about the Universe

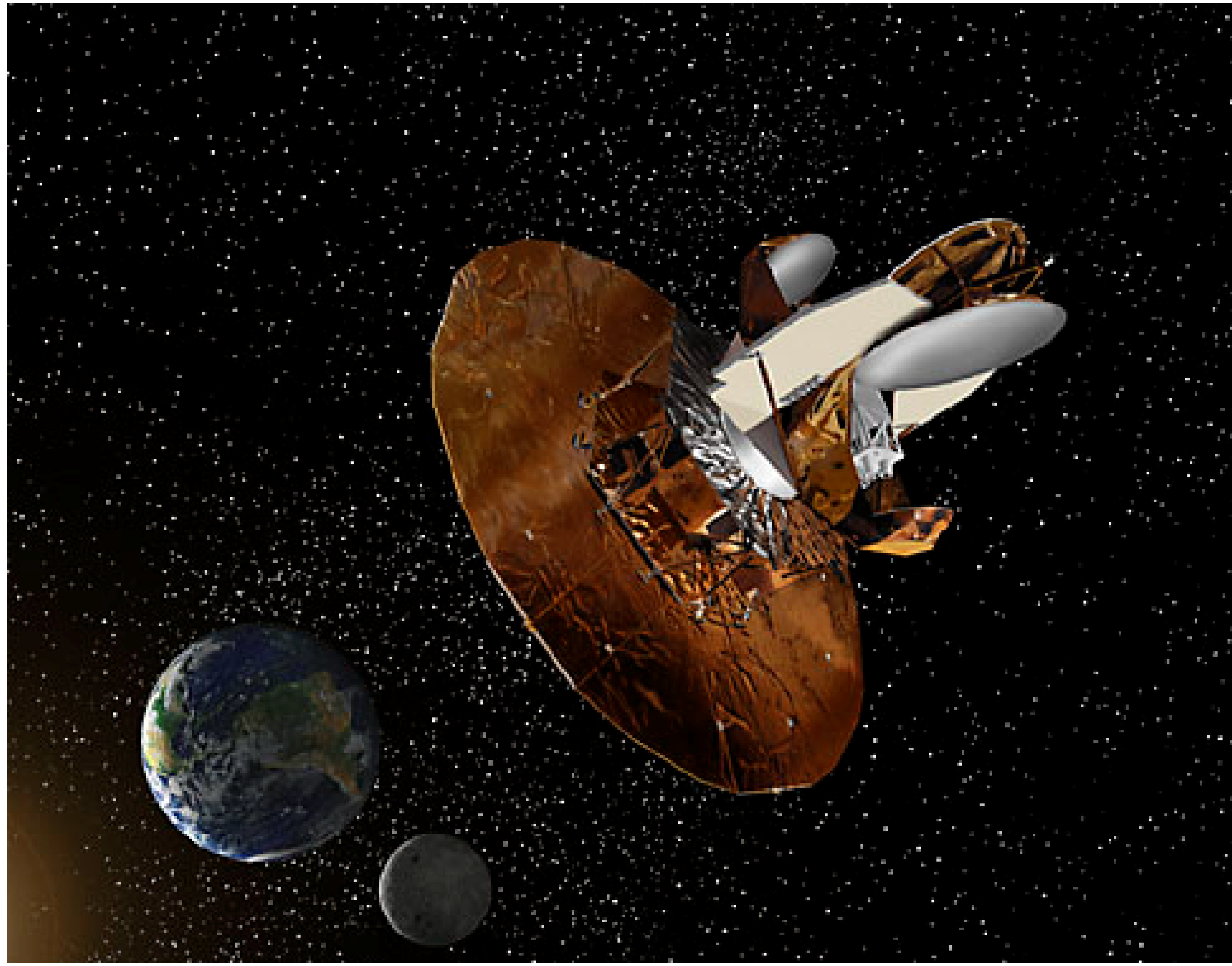
Conclusions



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

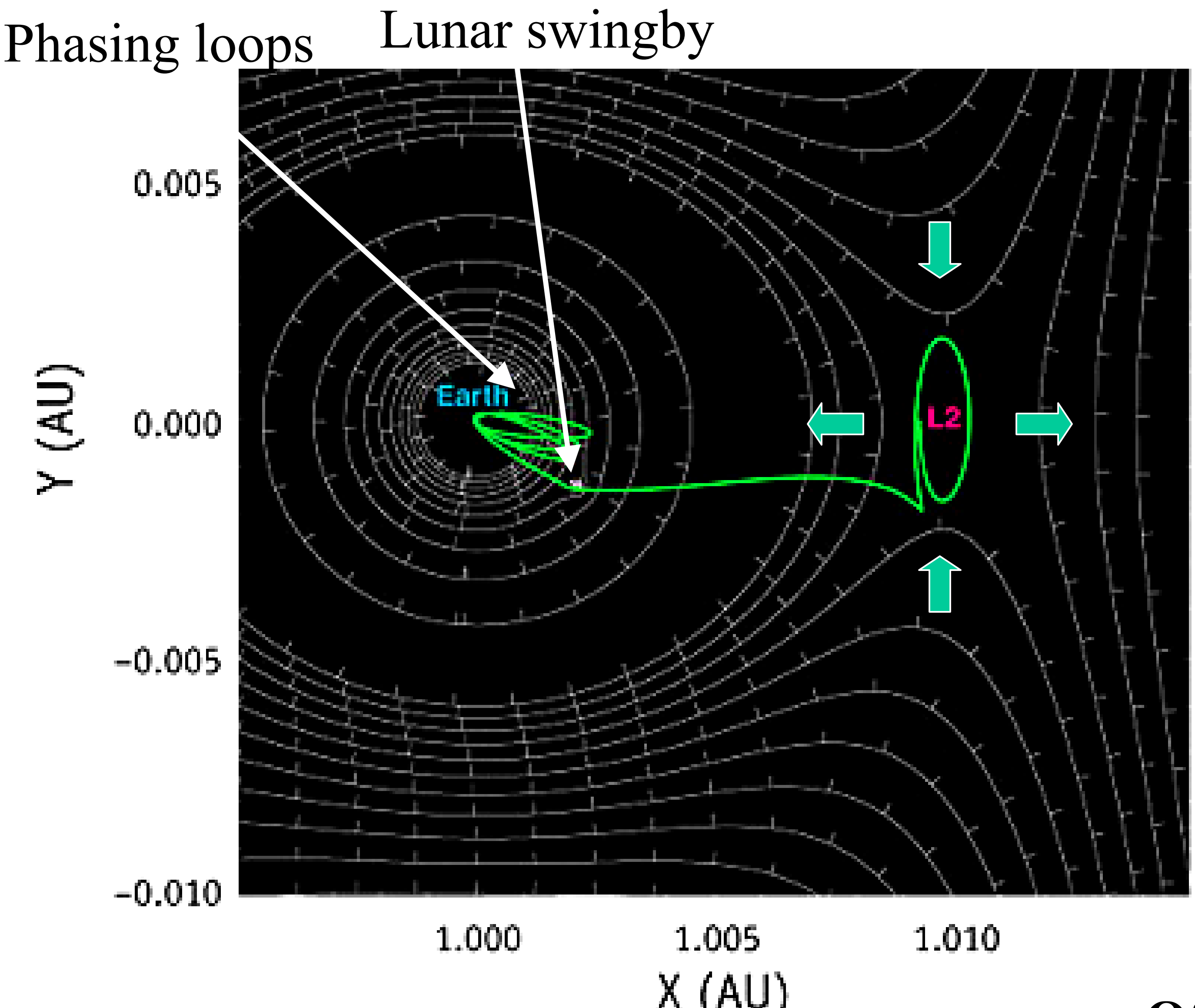
Stephan Meyer

Princeton

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

Launched from cape Canaveral on June 30 2001

Trajectory

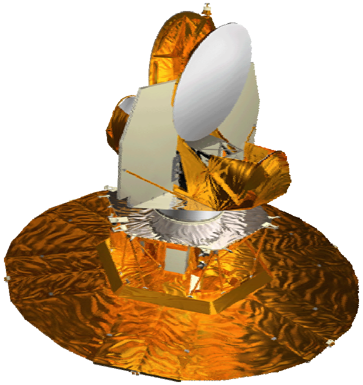


100 days to L2, 1.5e6 km from Earth.

Official arrival date: Oct 1, 2001

(Most of) WMAP Science Team, August 2002

WMAP’s Purpose

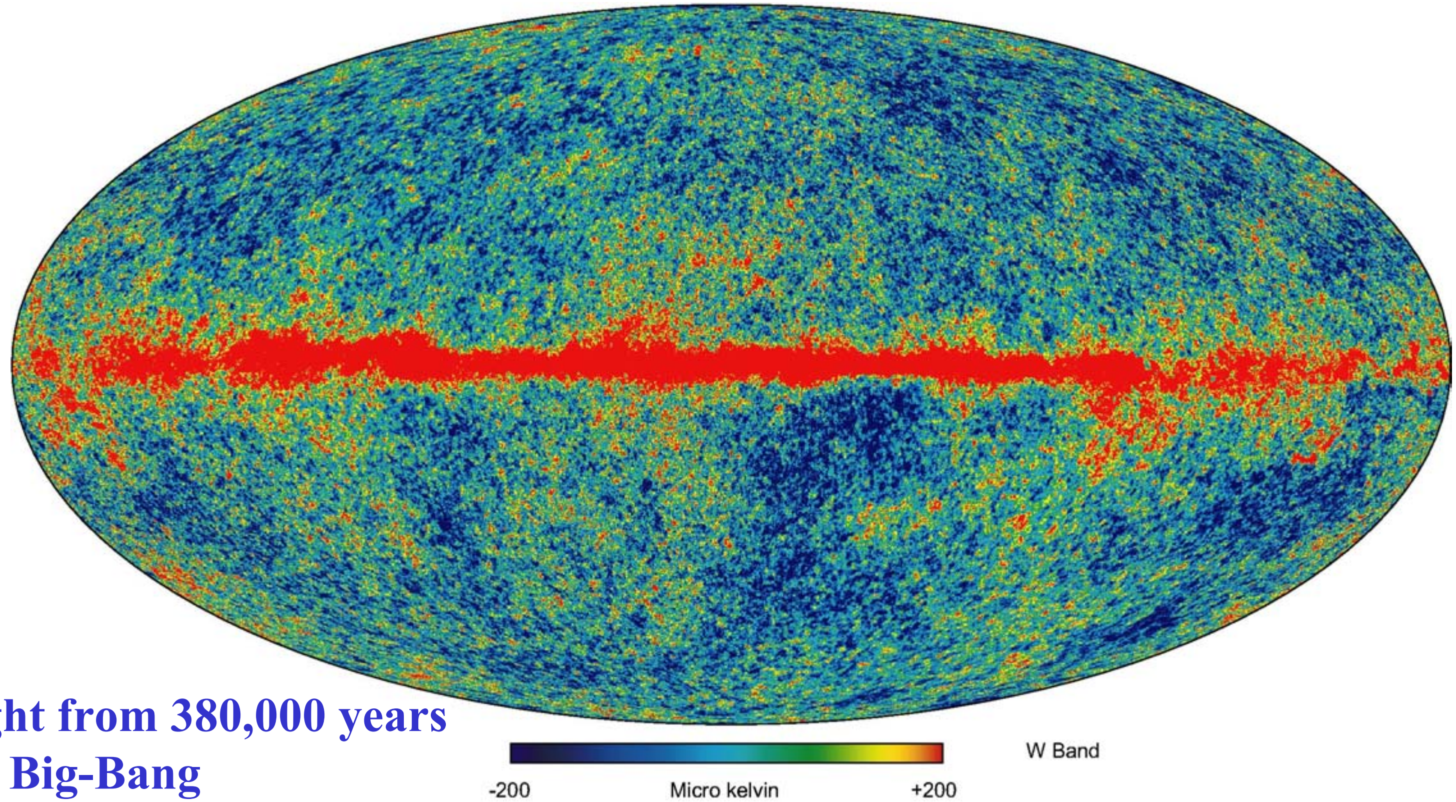


To make a high resolution map of the cosmic microwave background (CMB) radiation to determine the cosmology of our universe.

- **Structures of the CMB carry cosmological information (Age, Composition…)**

- **The cleanest picture of the infant universe → a clue to very early universe**

WILKINSON MICROWAVE ANISOTROPY PROBE

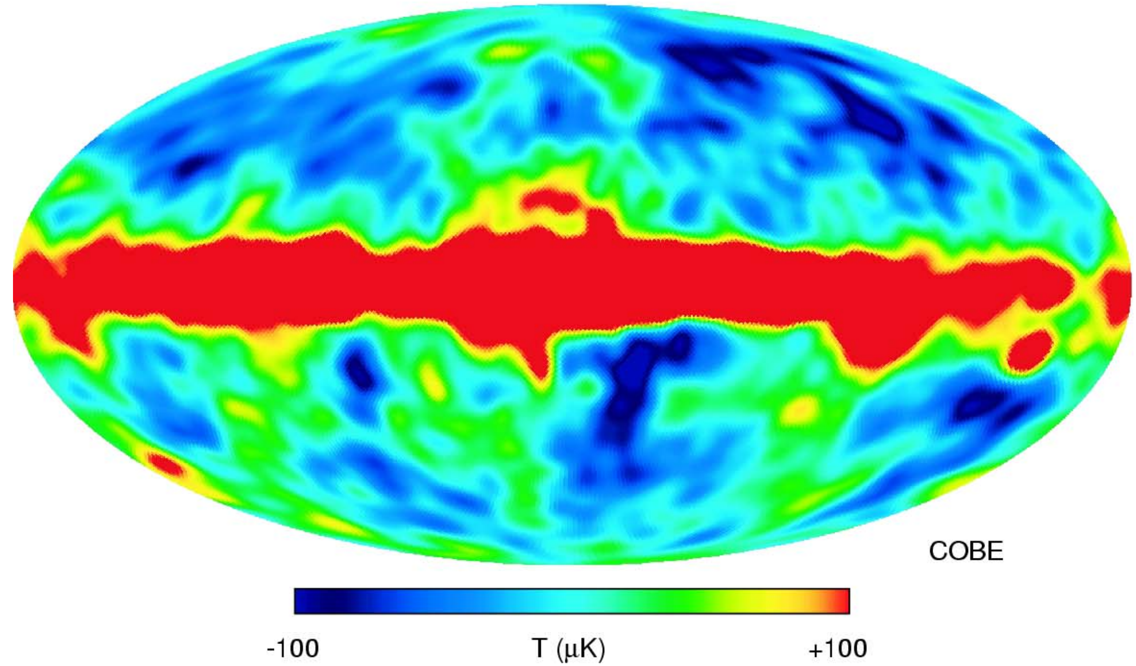


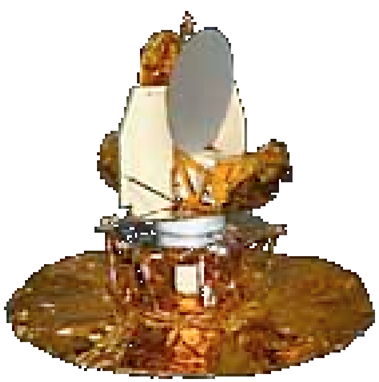
Fossil light from 380,000 years after the Big-Bang

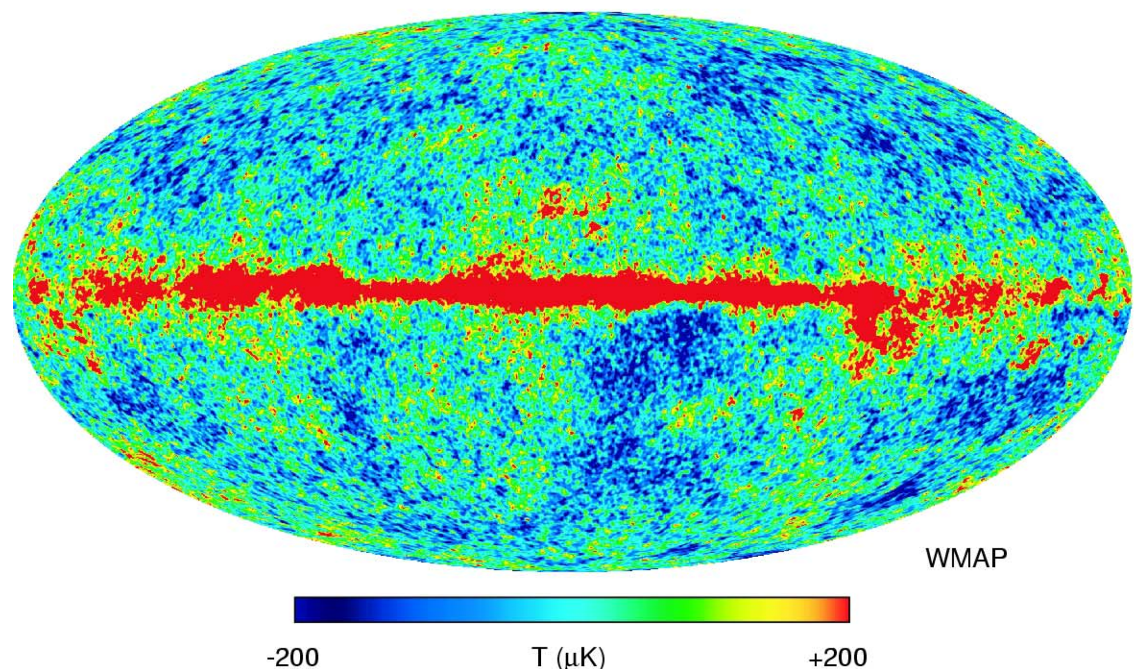
15 papers since February 2003… I will try to be brief

http://lambda.gsfc.nasa.gov

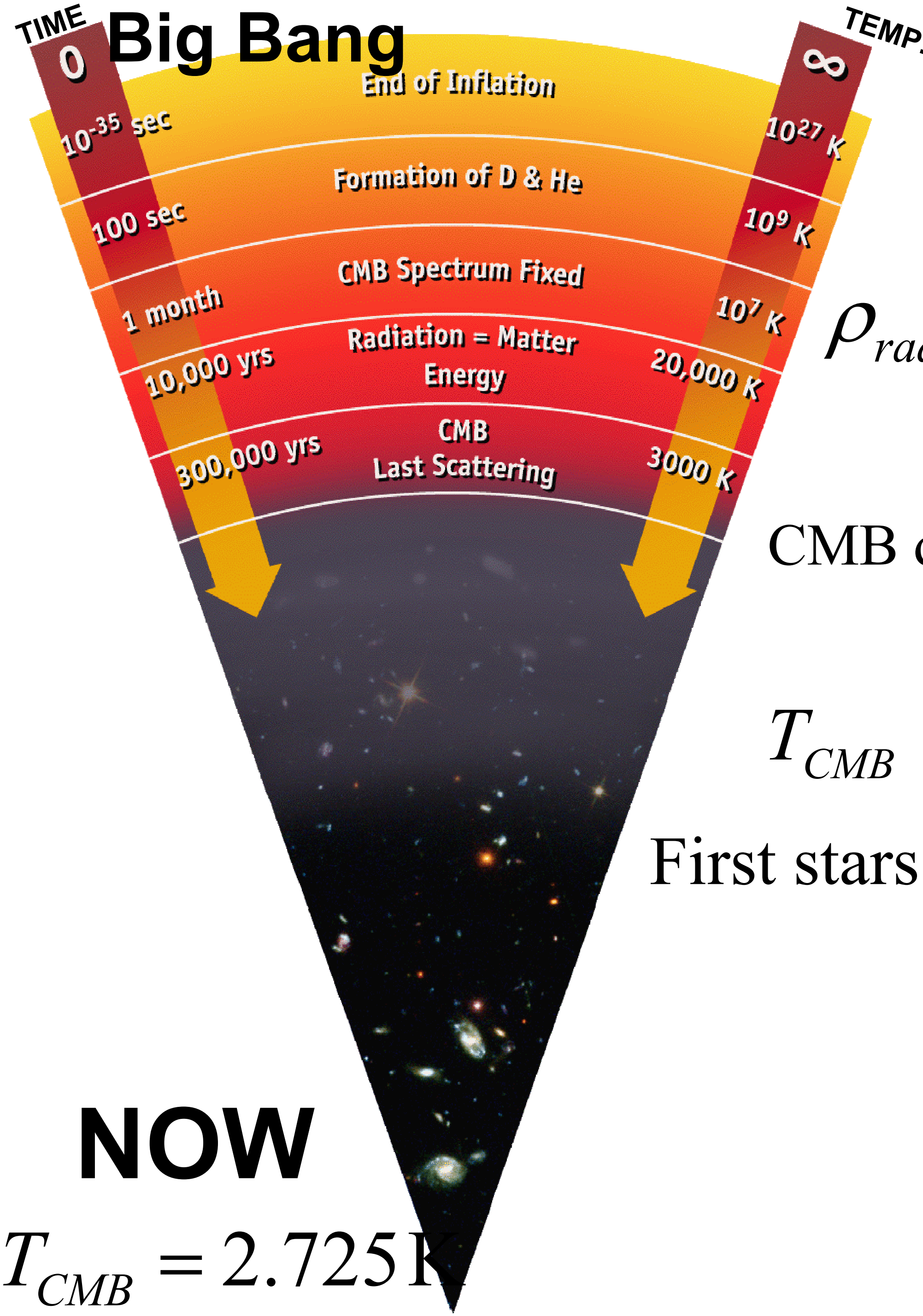
COBE ‘92







Bennett et al 2003



Cosmic History

Inflation-like epoch. new

$$\rho_{radiation} = \rho_{matter}$$

$$z_{eq} = 3230 \qquad t_U = 56 \text{ kyr}$$

new

CMB decouples from plasma

$$z_{dec} = 1089 \qquad t_U = 380 \text{ kyr}$$

$$T_{CMB} = 2970 \text{ K}$$

First stars form new

$$z_r = 20 \qquad t_U = 200 \text{ Myr}$$

new

NOW

$$T_{CMB} = 2.725 \text{ K}$$

$$z = 0 \qquad t_U = 13.7 \text{ Gyr}$$

Study cosmology with the CMB:

"Seeing sound" (W. Hu)

HOW? ***WHY?***

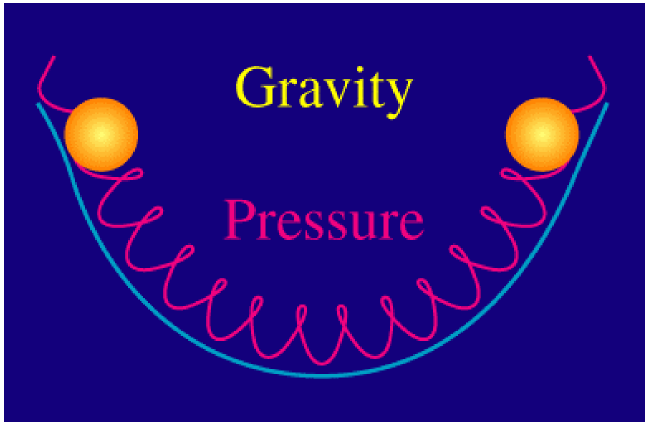
Last scattering surface : snapshot of the photon-baryon fluid

On large scales : primordial ripples

What put them there?

On smaller scales: $\left\{ \begin{array}{ll} \text{Photons} & \text{radiation pressure} \\ \text{Gravity} & \text{compression} \end{array} \right\}$ 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)

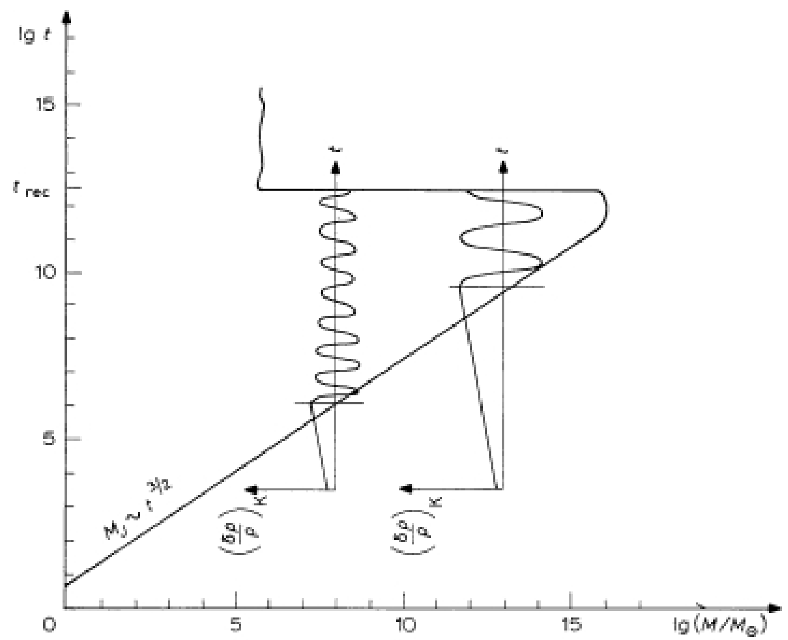


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until 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*

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)

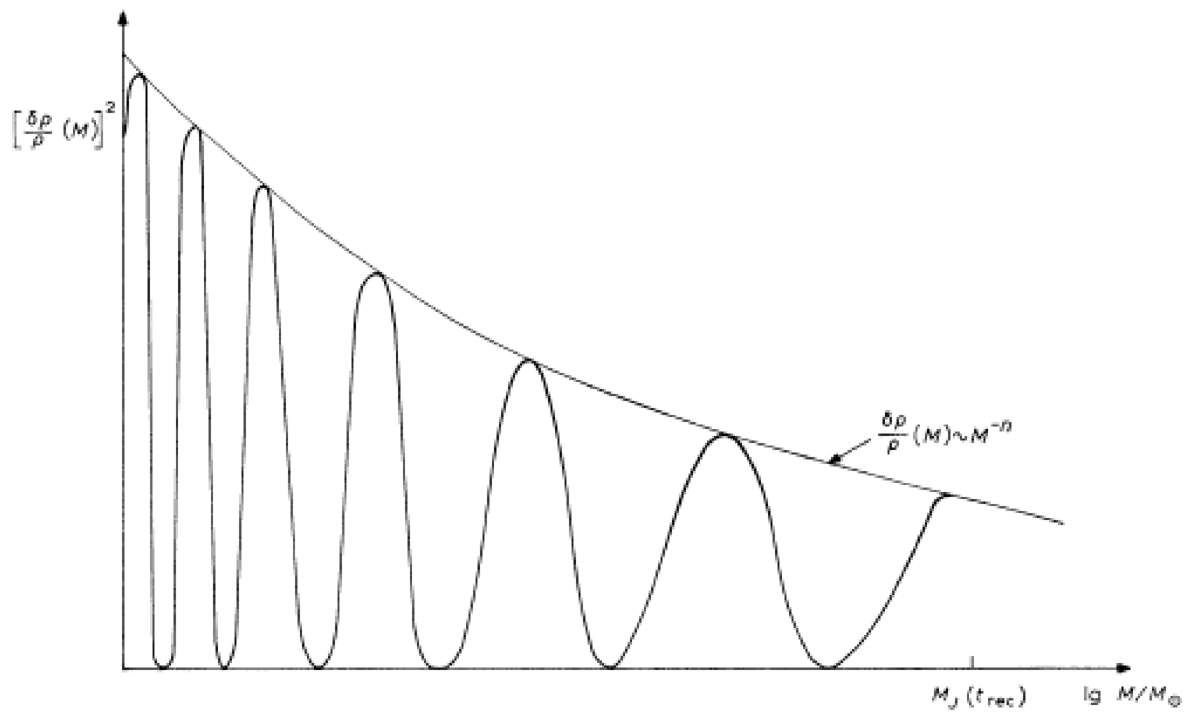


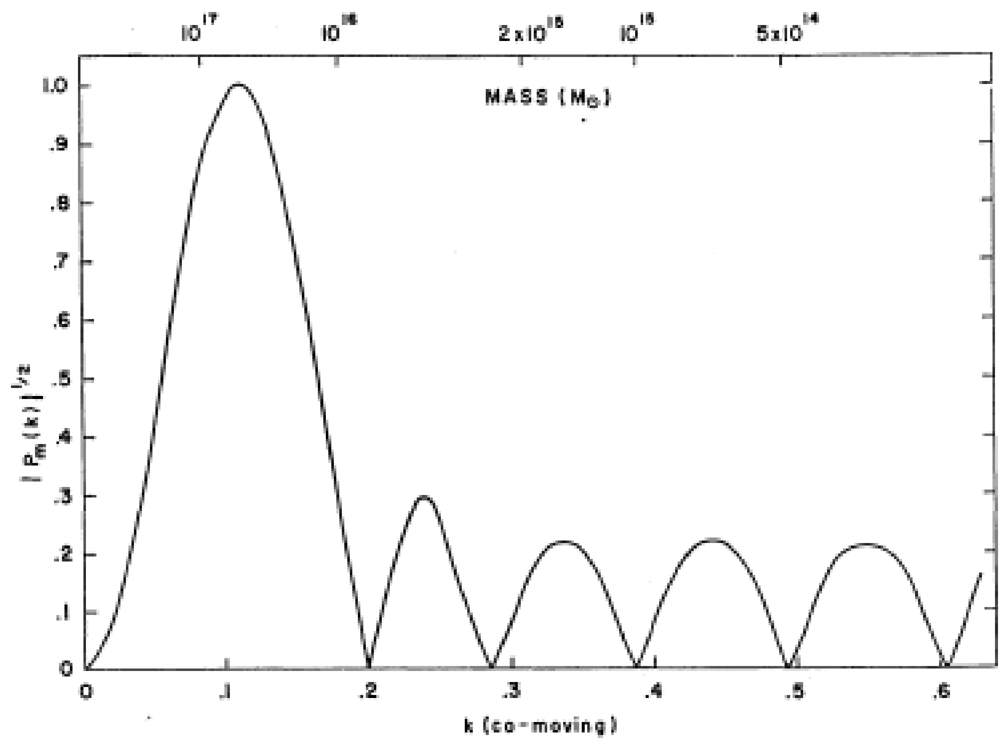
Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.

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

Meanwhile,on the other side of the iron curtain…

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



Compress the CMB map to study cosmology

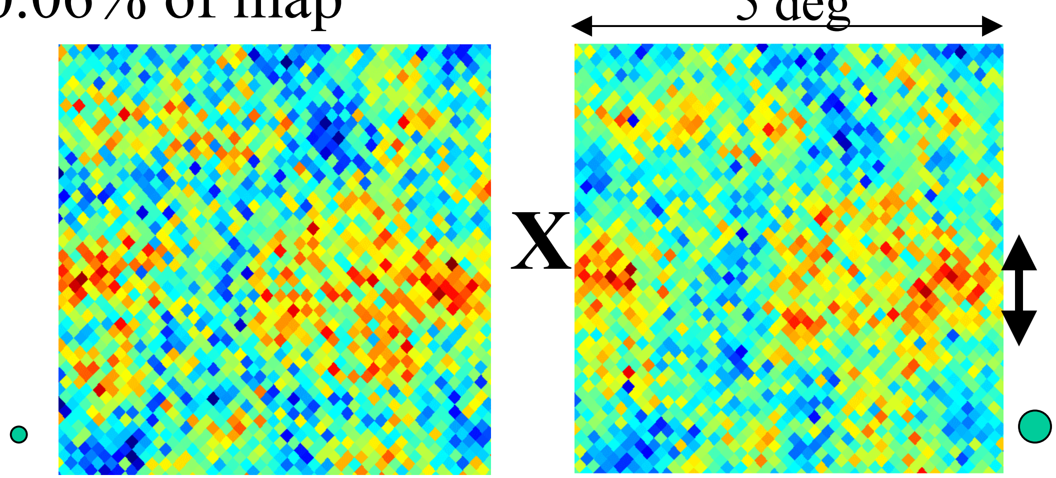
Express sky as: $$\delta T(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

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

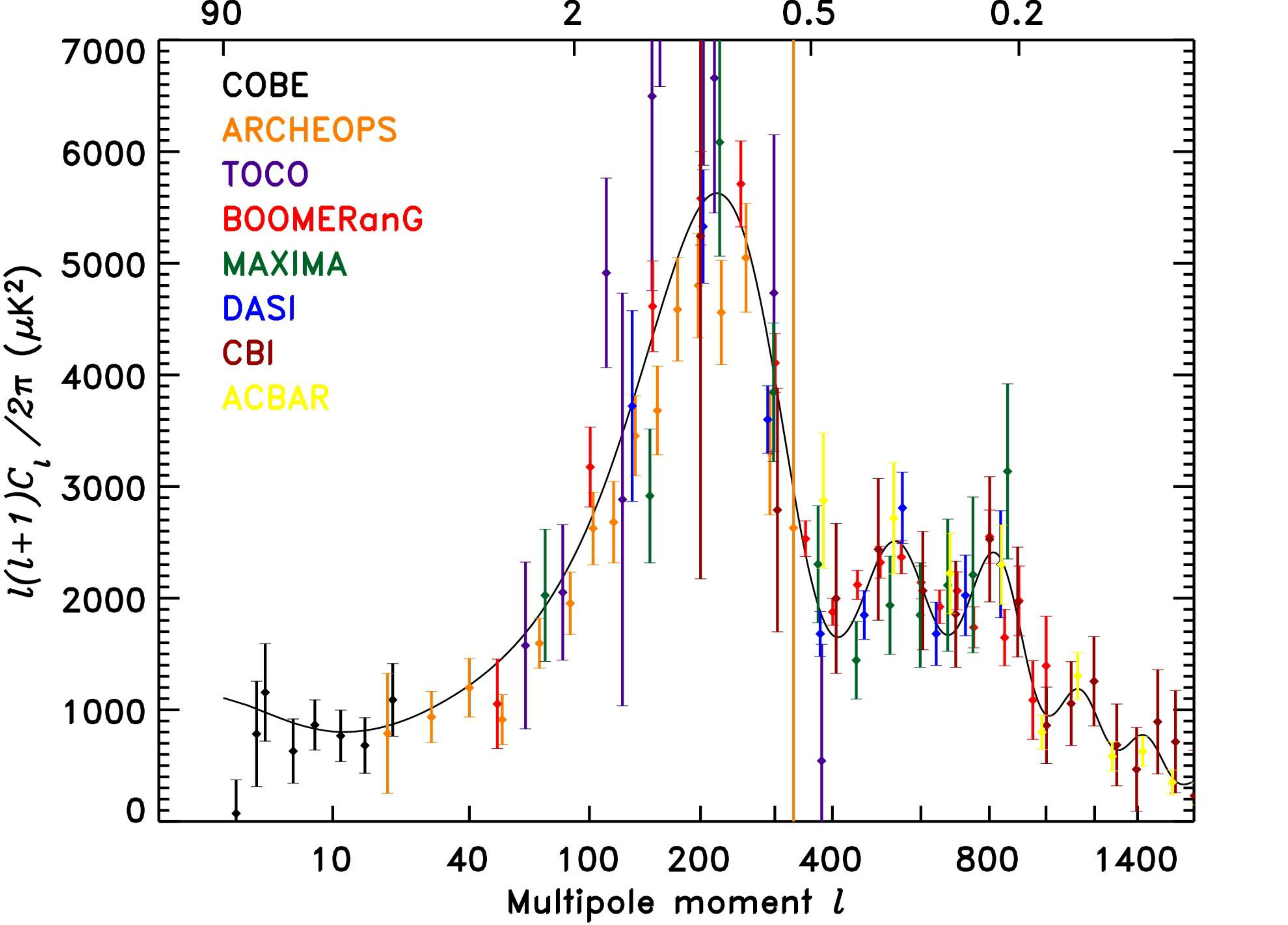


Raw 94 GHz near NEP

+/- 32 uK

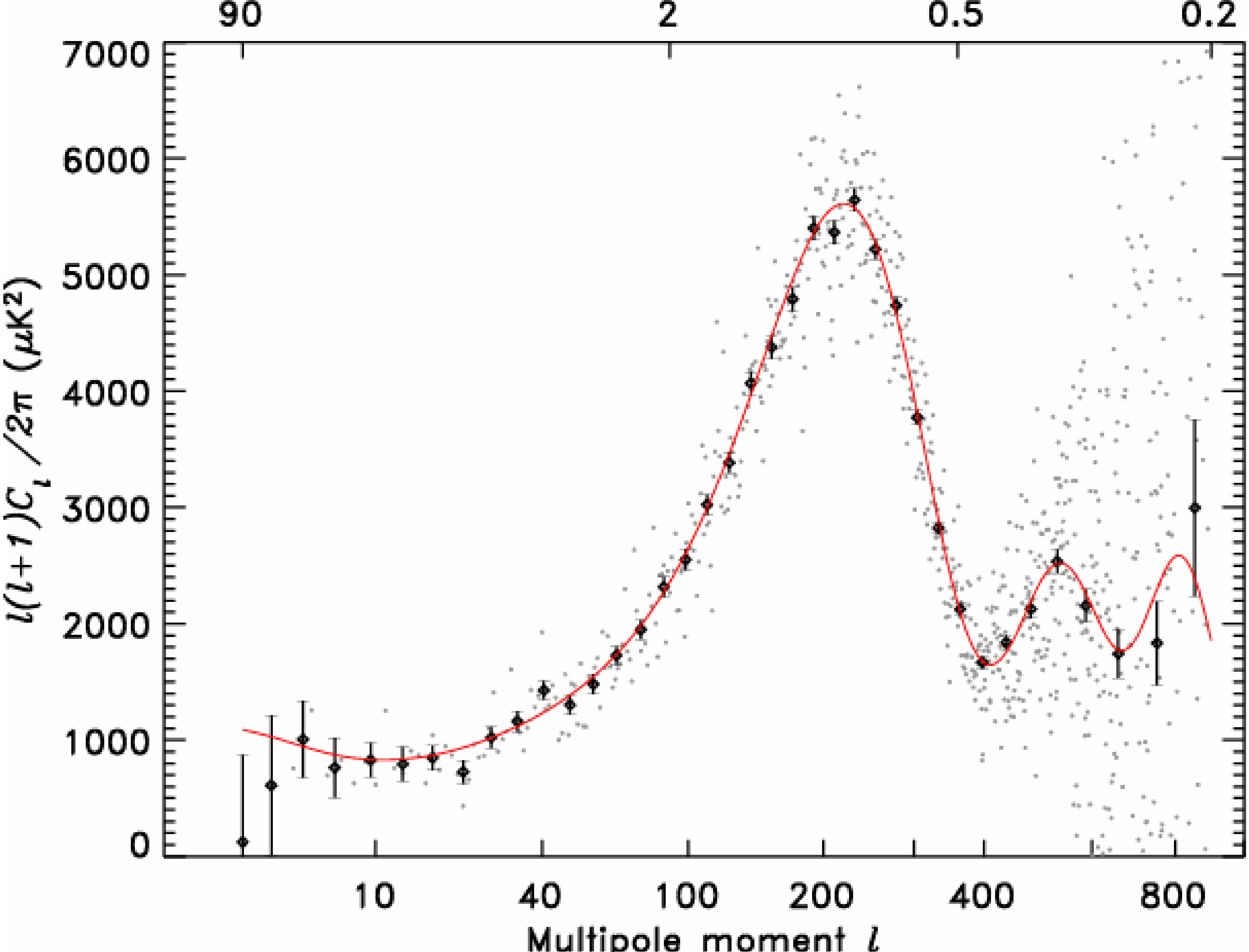
Raw 61 GHz near NEP

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



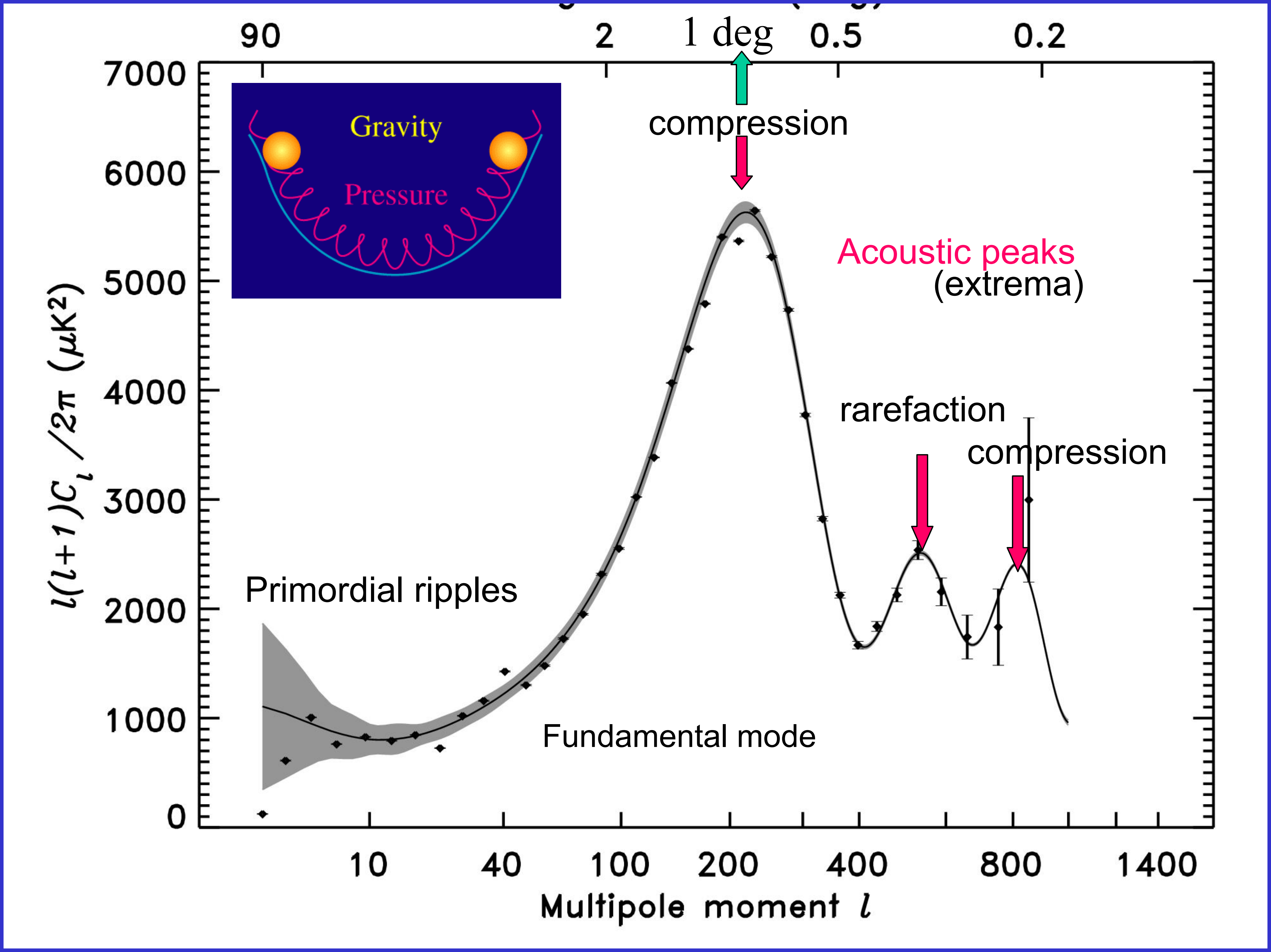
Before 11 Feb. 2003

(From Hinshaw et al 2003)

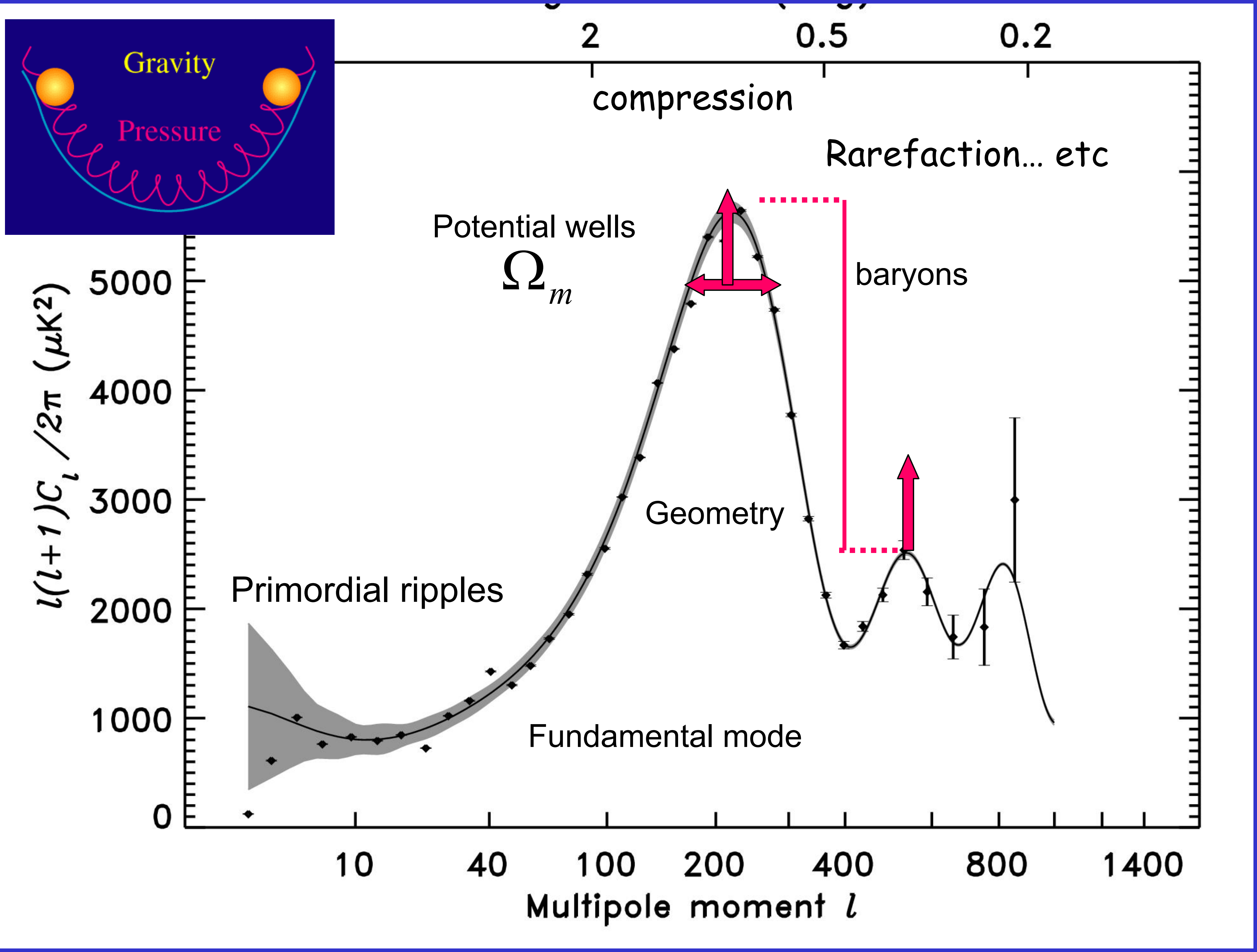


After

Why C_ℓ only? (Komatsu et al. 2003)



90
2
1 deg
0.5
0.2
compression
Gravity
Pressure
Acoustic peaks
(extrema)
rarefaction
compression
Primordial ripples
Fundamental mode
7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
10
40
100
200
400
800
1400
Multipole moment l



Gravity
Pressure
2
0.5
0.2
compression
Rarefaction... etc
Potential wells
Ω_m
baryons
Geometry
Primordial ripples
Fundamental mode
$l(l+1)C_l/2\pi$ (μK^2)
0
1000
2000
3000
4000
5000
10
40
100
200
400
800
1400
Multipole moment l

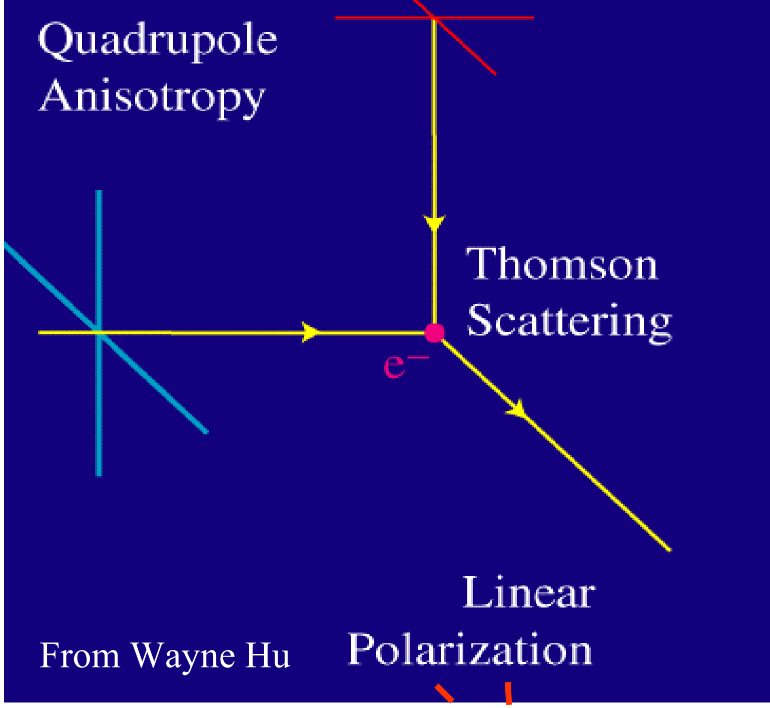
POLARIZATION

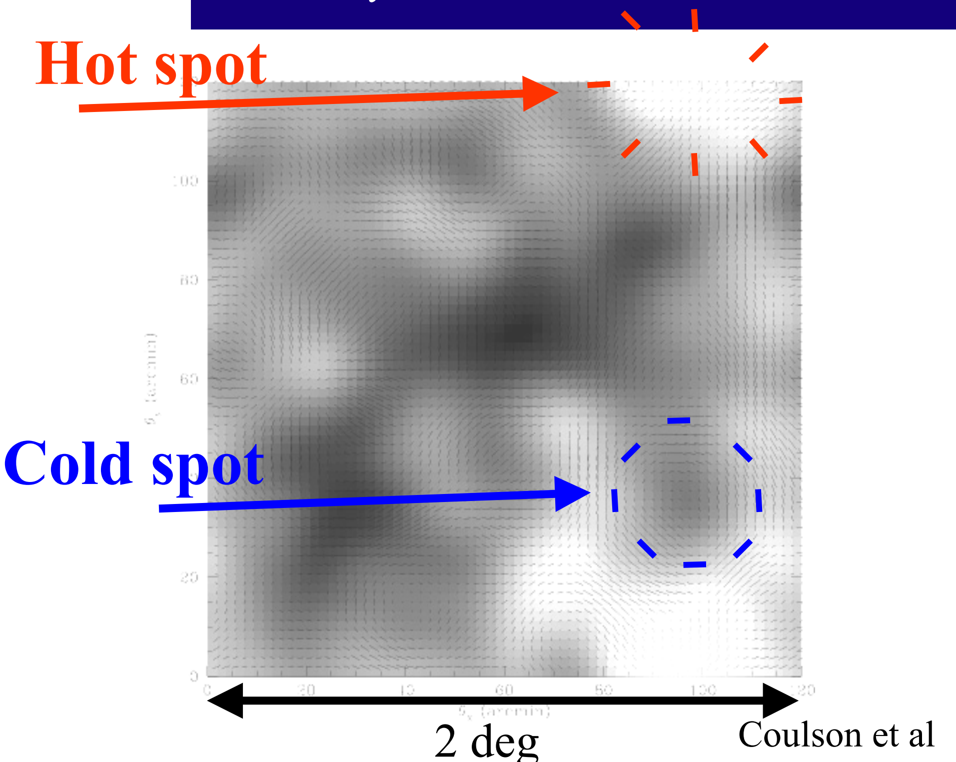
A: Confirm physical assumptions

- 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.

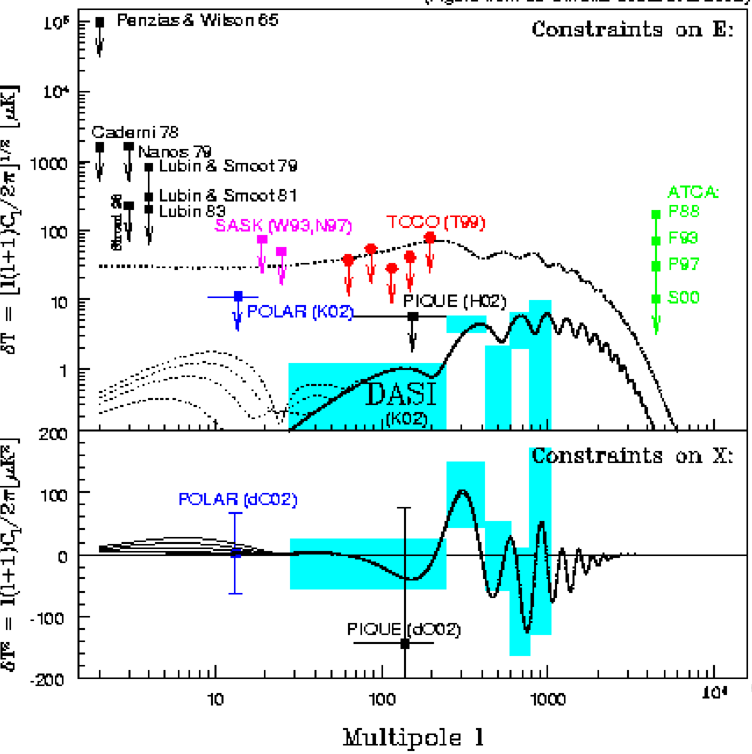


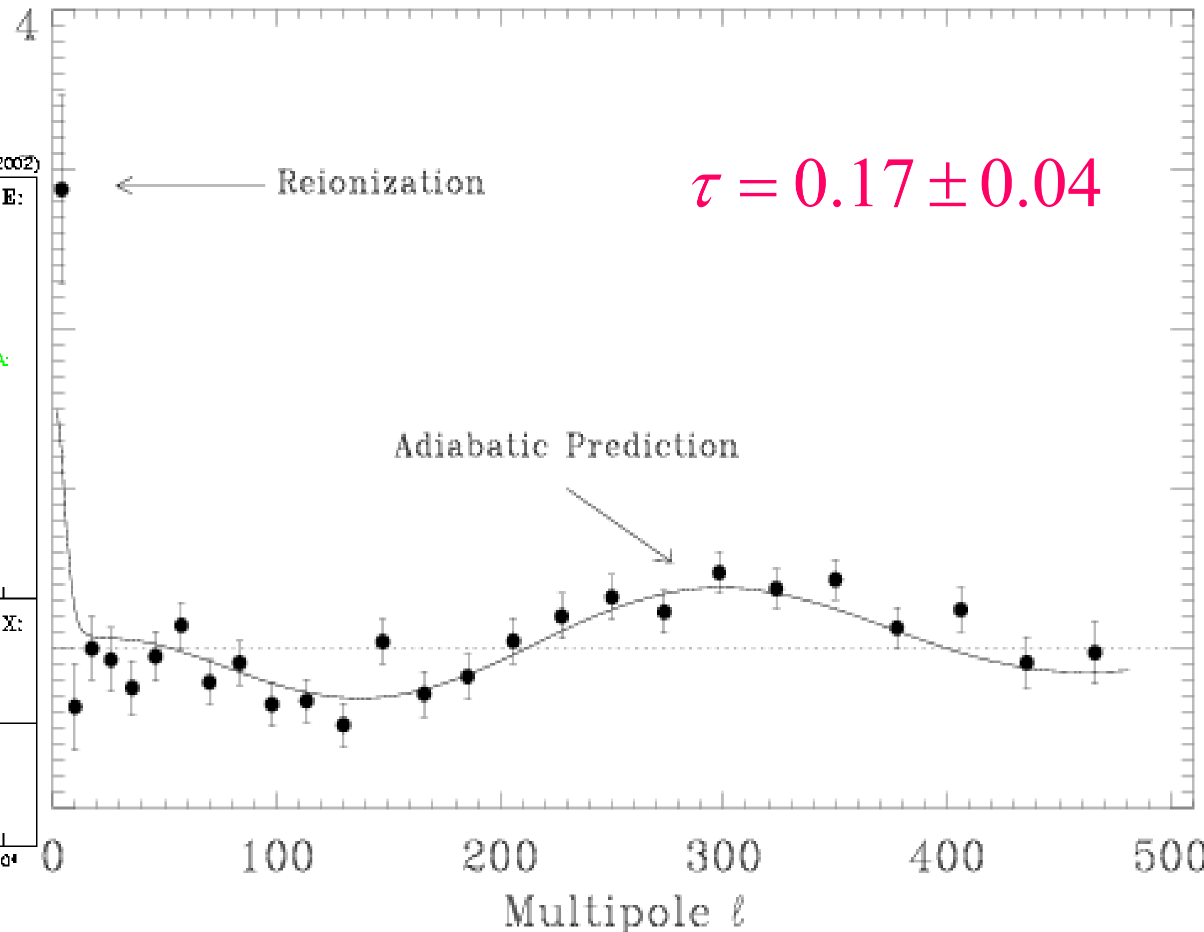


B: First stars

TE cross-correlation

(Figure from de Oliveira-Costa et al 2002)

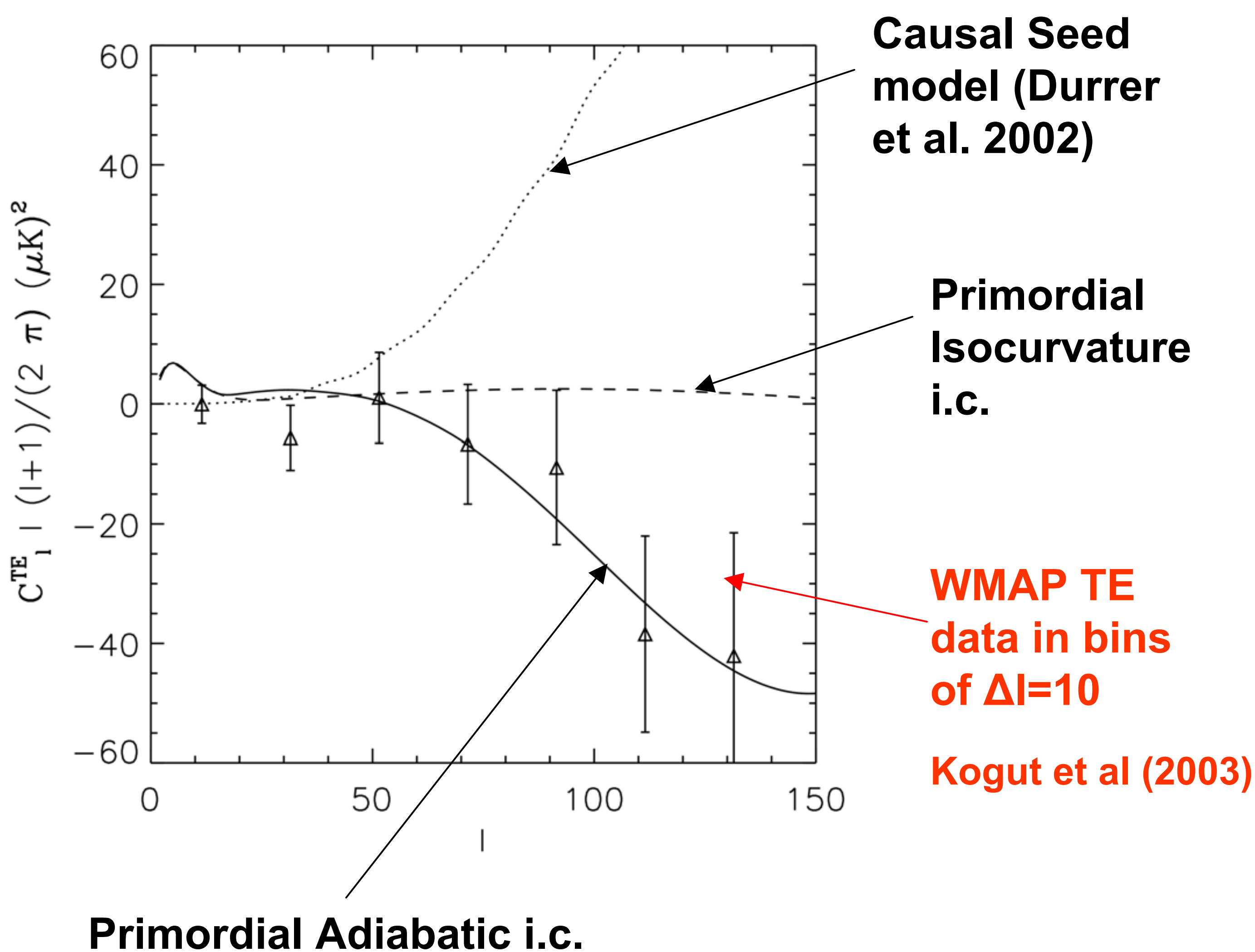




- The TT spectrum makes precise predictions for the TE spectrum
- We saw it.
- Triumph for the standard cosmological model.

(Kogut et al. 2003)

Large Scale TE anti-correlation



Peiris et al. 2003

Why does WMAP have such a good S/N? (A: obsession)

10 channels, from 20 to 95 GHz

Foregrounds not a problem!

- Instrument design (e.g.,Jarosik et al. 2003) Systematics are negligible

So… the rest of the analysis must have the same level of "obsession"

For example:

➡ To extract as much information as possible without introducing systematics the C_ℓ are obtained by optimally combining "only" 28 cross-correlations (method checked against other 2) (Hinshaw et al 2003)

➡ Point sources subtraction done in 3 different ways

(Hinshaw et al 2003, Bennett et al 2003, Komatsu et al 2003)

➡ In the covariance matrix we propagate beam errors, noise, sky cut etc…

(Hinshaw et al 2003,Verde et al. 2003)

We spent long time worrying about 2% error on the error!

Analysis: Method (Verde et al. 2003)

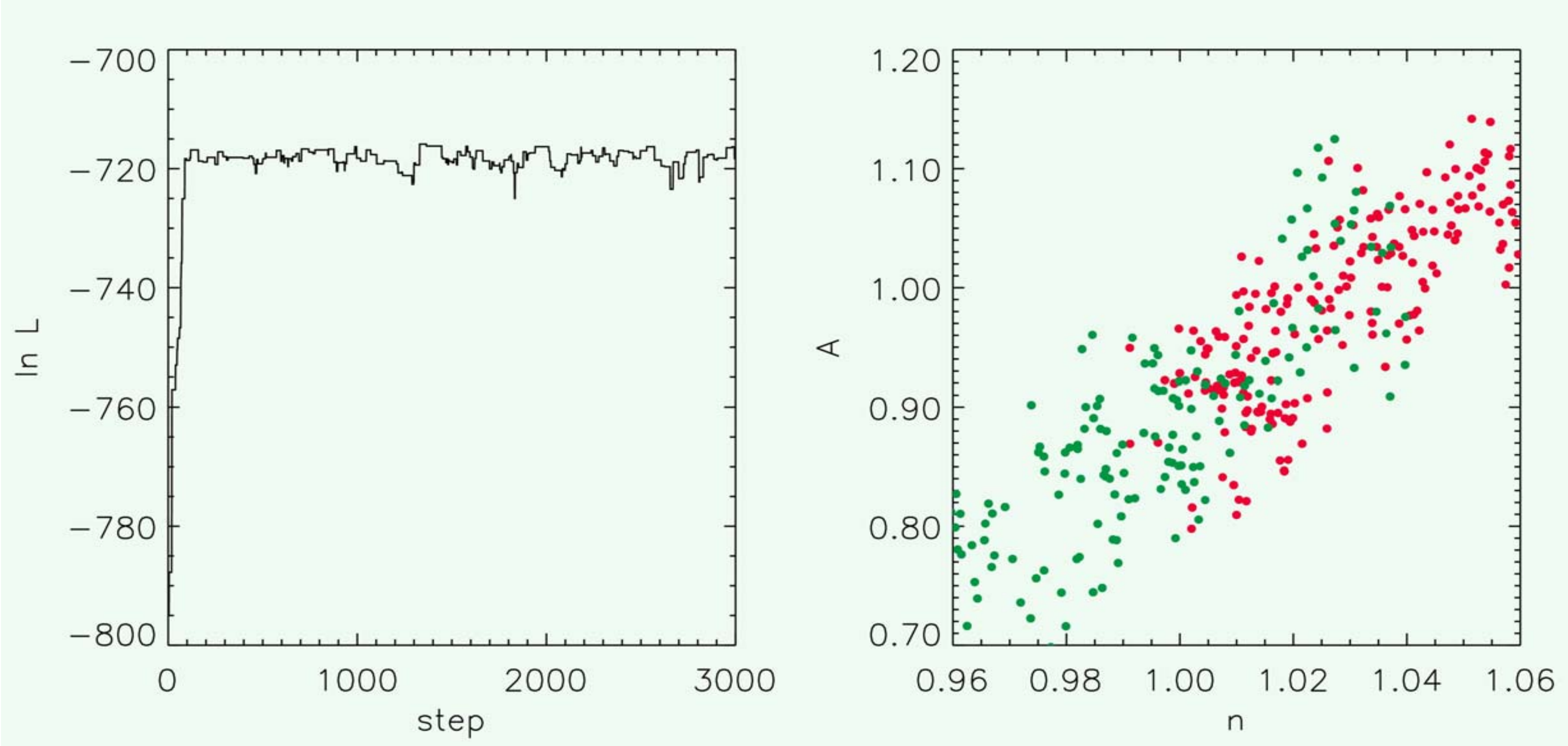
- Likelihood function is calibrated from 100,000 Monte Carlos
- New likelihood approximation

Meaning to χ^2

- Markov Chain Monte Carlo

Use a convergence/mixing criterion!

- Use "physical" parameters to reduce degneracies



RESULTS: WMAP only (TT+TE), flat LCDM

(Spergel et al. 2003)

- CMB appears to be Gaussian. $\Phi(\vec{x}) = \Phi_{gaus}(\vec{x}) + f_{NL}\Phi^2_{gaus}(\vec{x})$

  $-58 < f_{NL} < 134$

- 15% of CMB was re-scattered in a reionized universe.
- The estimated reionization redshift ~17, or 200 million years after the Big-Bang.

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

$\boxed{\Omega_m = 0.29 \pm 0.07}$

$\boxed{\Omega_b h^2 = 0.024 \pm 0.001}$

$\boxed{h = 0.72 \pm 0.05}$

$\boxed{n = 0.99 \pm 0.04}$

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

$\boxed{\sigma_8 = 0.9 \pm 0.1}$

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

$\boxed{z_{reion} \approx 17}$

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)

- CMB appears to be Gaussian. $\Phi(\vec{x}) = \Phi_{gaus}(\vec{x}) + f_{NL}\Phi^2_{gaus}(\vec{x})$

  $-58 < f_{NL} < 134$

- 15% of CMB was re-scattered in a reionized universe.
- The estimated reionization redshift ~17, 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)

$\Omega_m = 0.29 \pm 0.07$

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

$h = 0.72 \pm 0.05$

$n = 0.99 \pm 0.04$

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

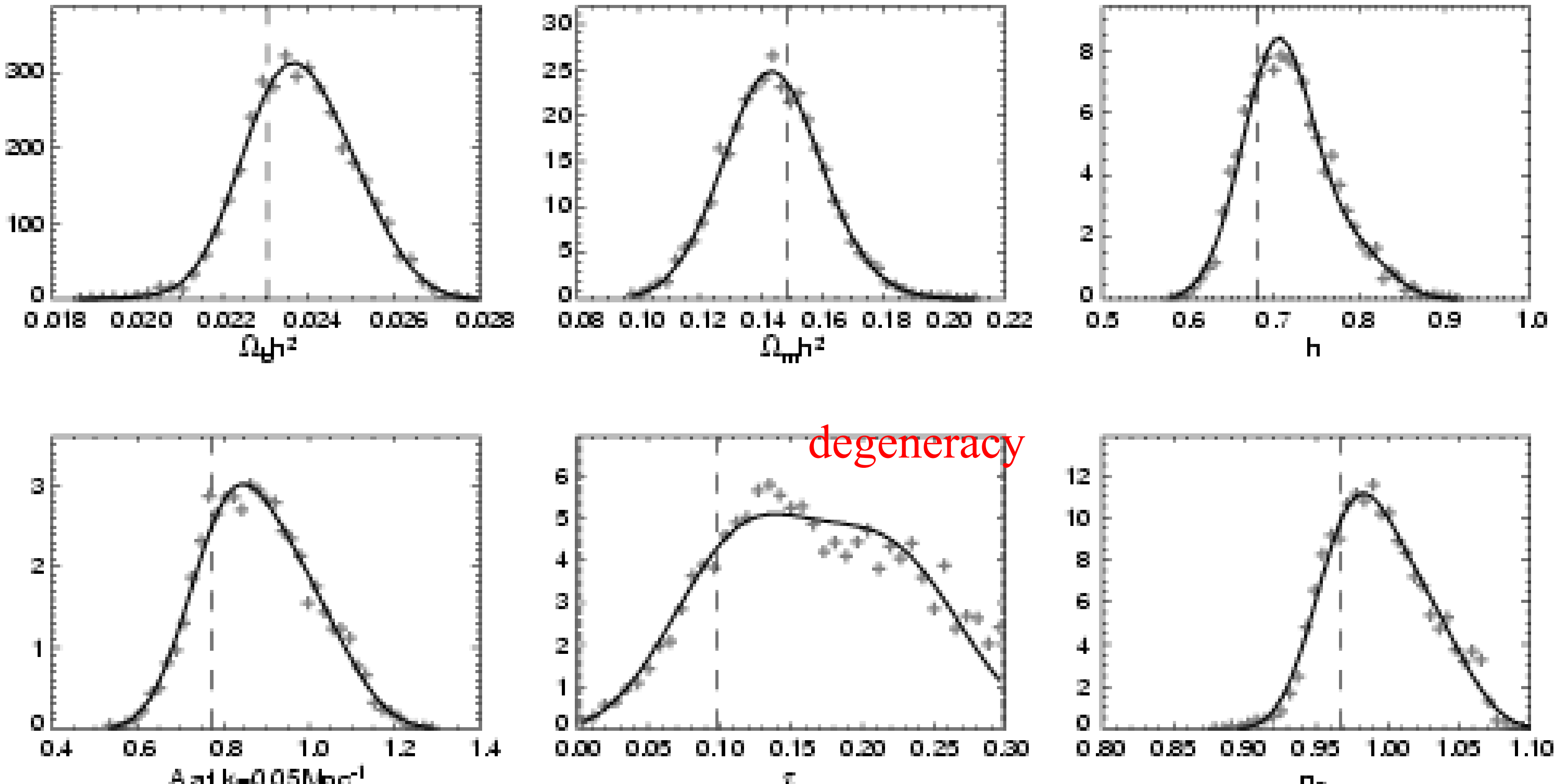
$\sigma_8 = 0.9 \pm 0.1$

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

$z_{reion} \approx 17$

(Kogut et al 2003)

1σ marginalized



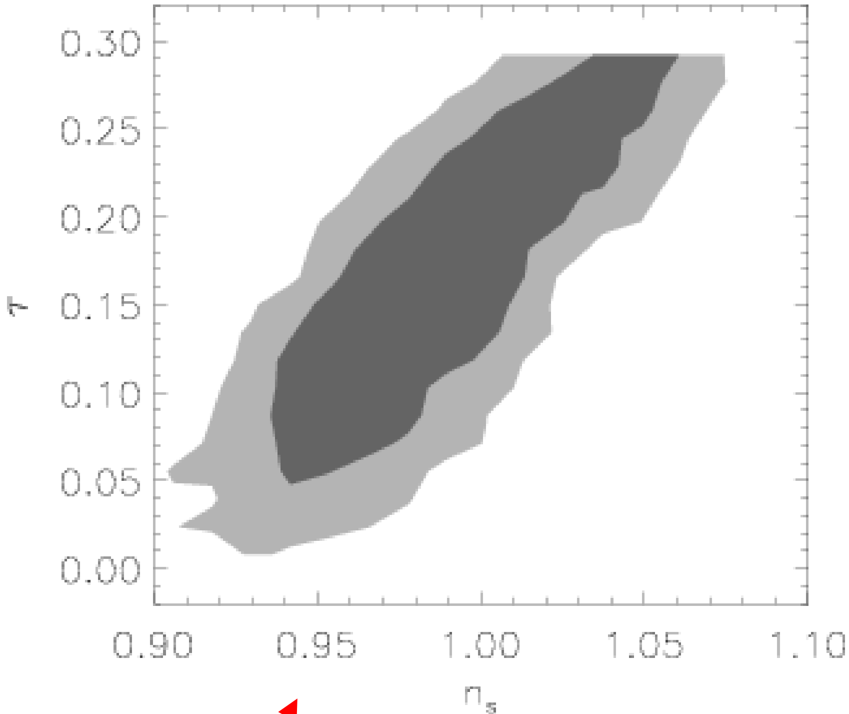
COBE View was Blurry

Sometimes higher resolution...

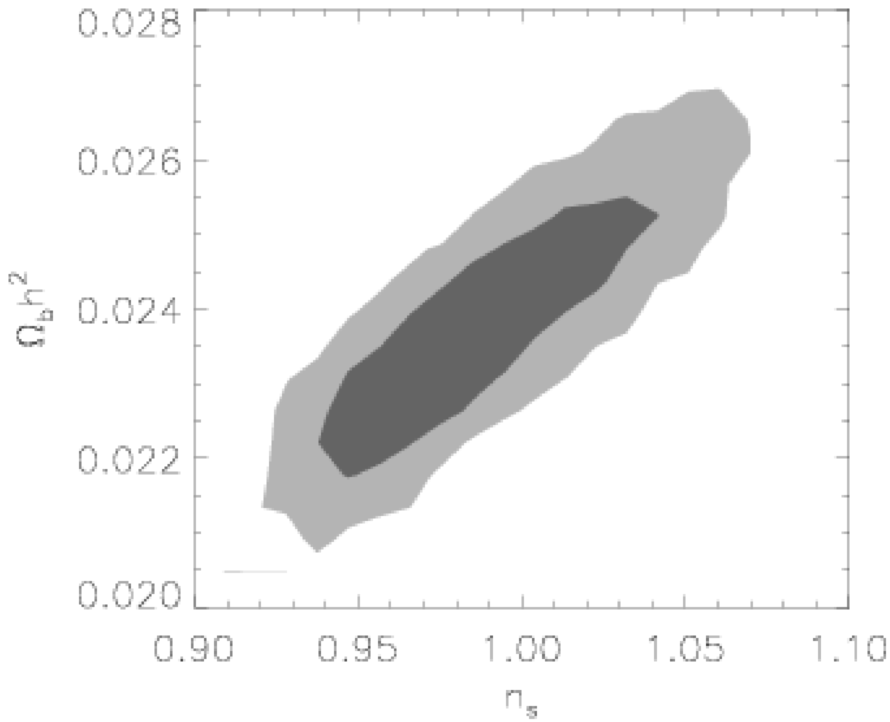
reveals the secret of the Universe

We're stuck with CDM

WMAP only: degeneracies
(TT+TE)



1 and 2 σ
joint confidence contours

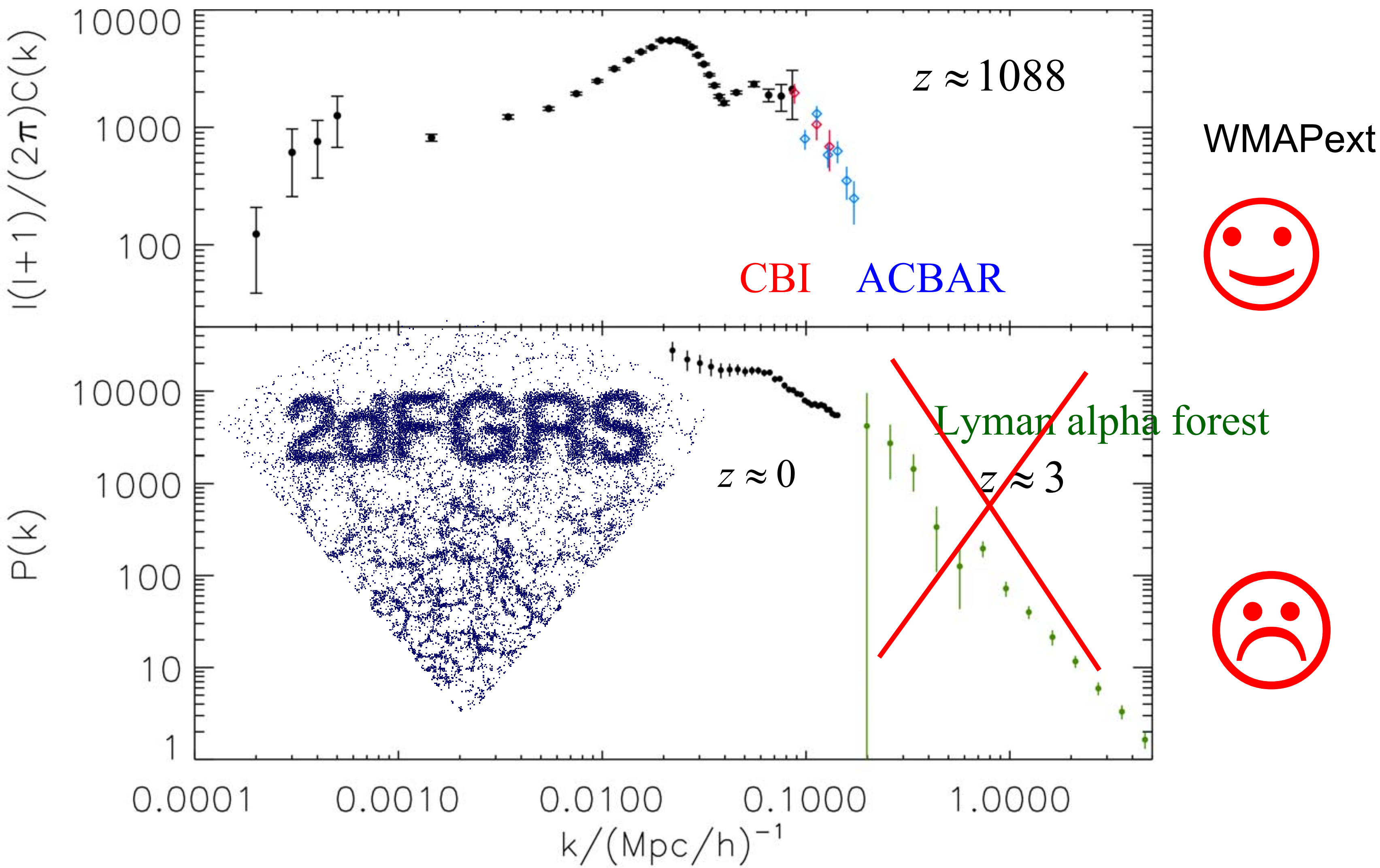


Main degeneracy

Will get better soon

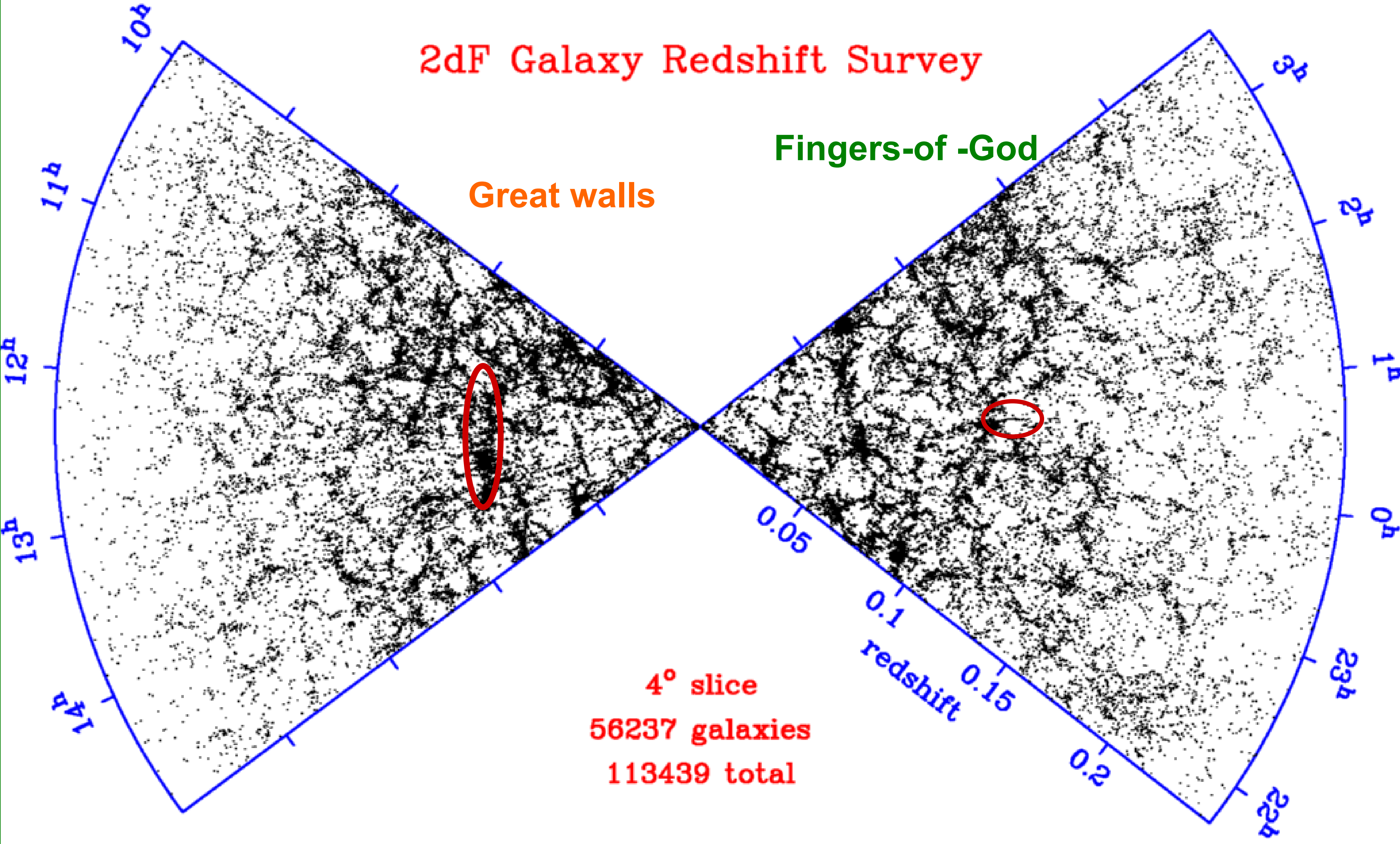
Polarization maps analysis under way

TEST MODEL CONSISTENCY and LIFT DEGENERACIES

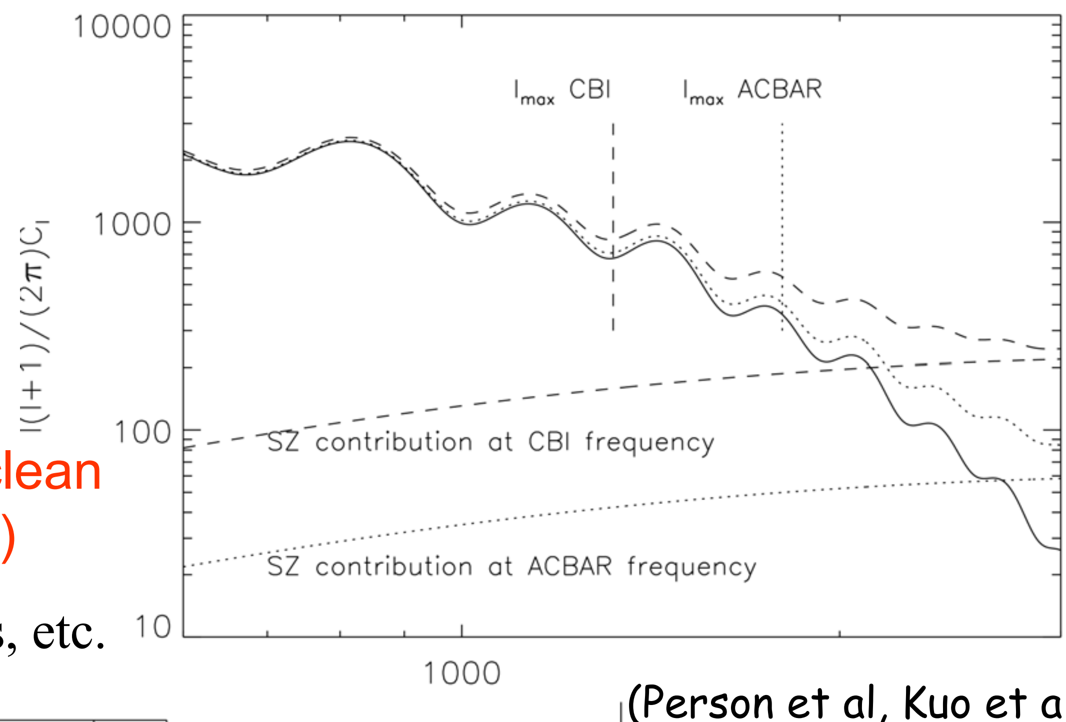


Complementary in scales/redshift

Beware of sistematics!!


2dF Galaxy Redshift Survey
Fingers-of -God
Great walls
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
0.05
0.1
0.15
0.2
redshift
4° slice
56237 galaxies
113439 total

External data sets:
modeling

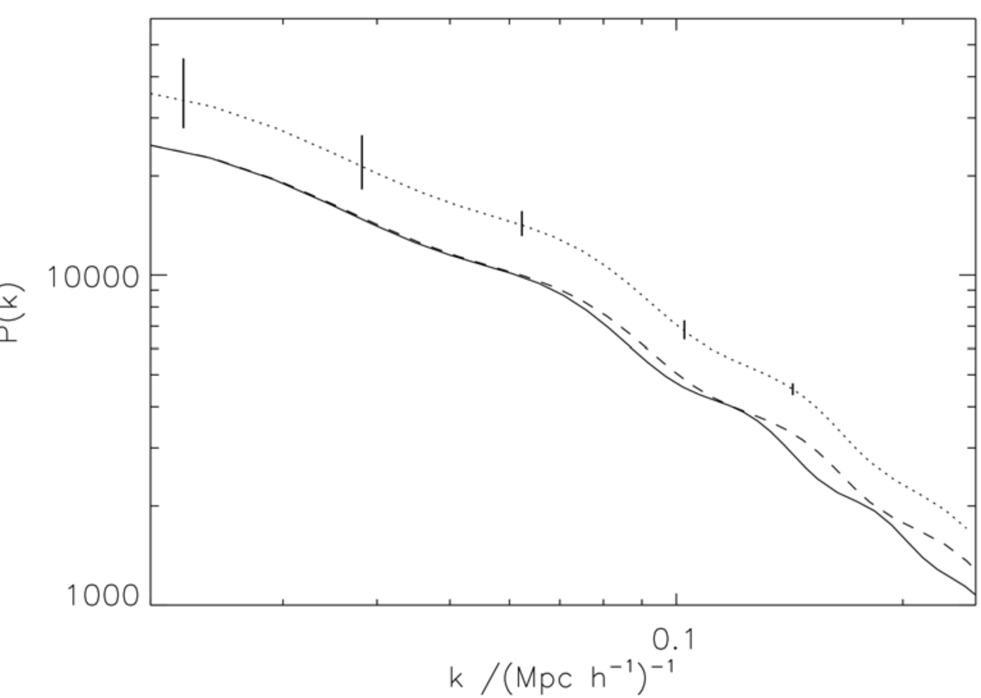


(boring details in Verde et al 2003)

(Person et al, Kuo et al)

Nothing will ever be as nice and clean as CMB (esp. as seen by WMAP!)

Bias, redshift space distortions, etc.



External data sets are consistent with the WMAP fit to LCDM model.

extrapolation

Consistency with a host of other observations :
stellar ages, Ho, clusters, large-scale structure,
D/H abundances etc…

(Spergel et al. 2003)

amazing

Beyond the standard LCDM model (minimal , 6 parameters)

Flatness?

Tensors?

Strange P(k)?

Neutrinos?

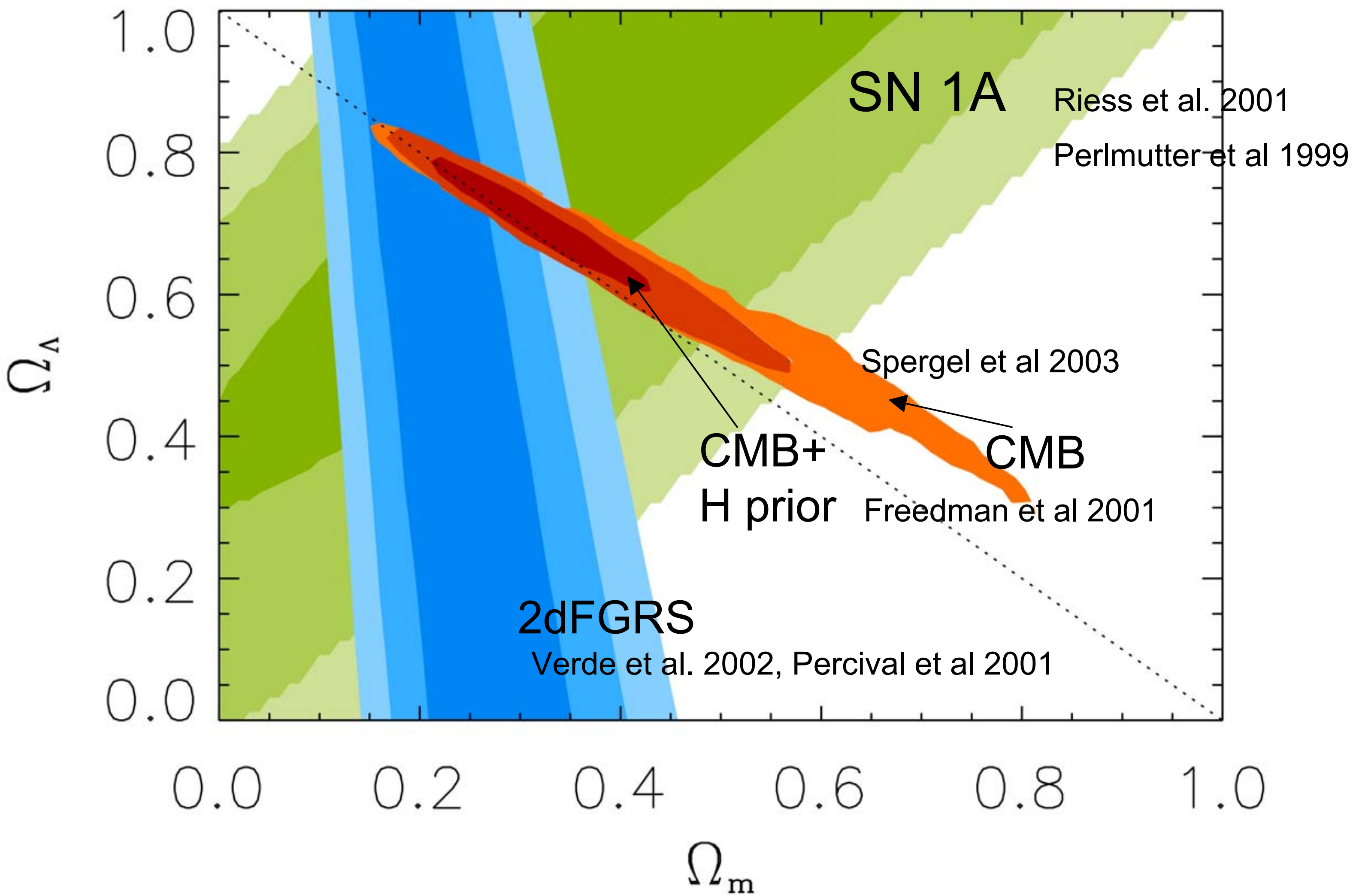
Quintessence?

Running spectral index?

Isocurvature?

Beyond LCDM:

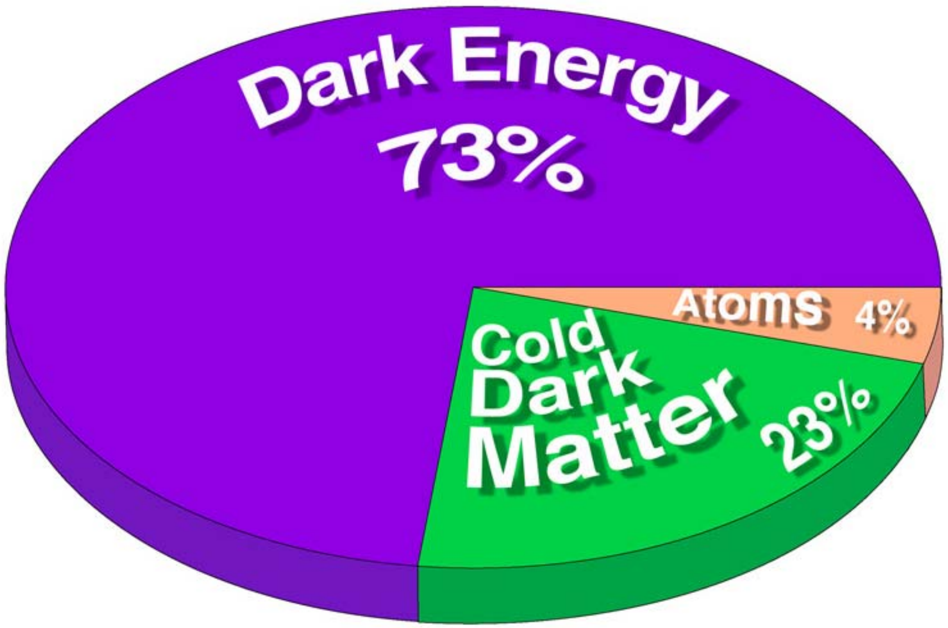
Flatness

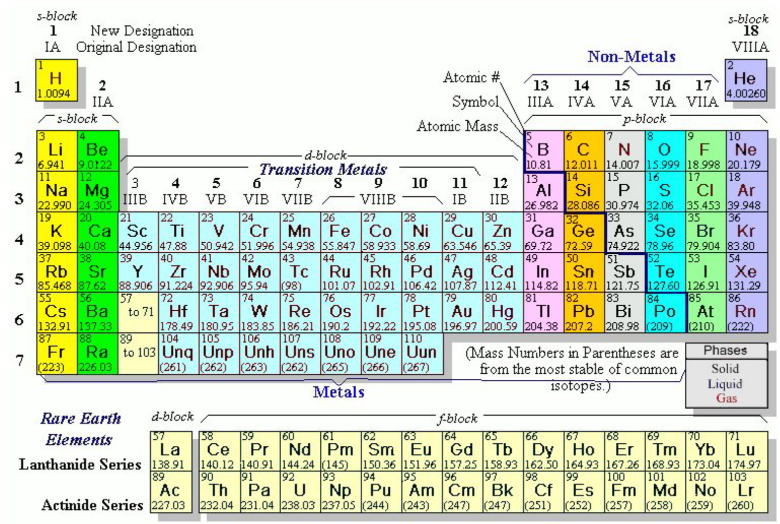


$$\Omega = 1.02 \pm 0.02$$

NEW?

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





the dark side of the Universe

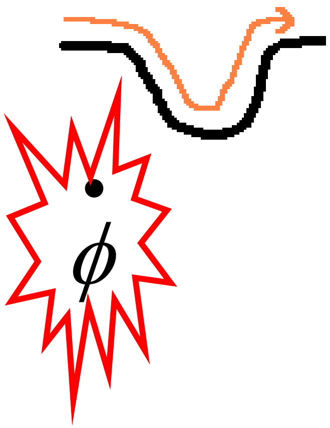
About 85% of mass in the Universe is made of matter unknown to Earth

We have some candidates and experiments for direct dark matter searches: progress might come soon

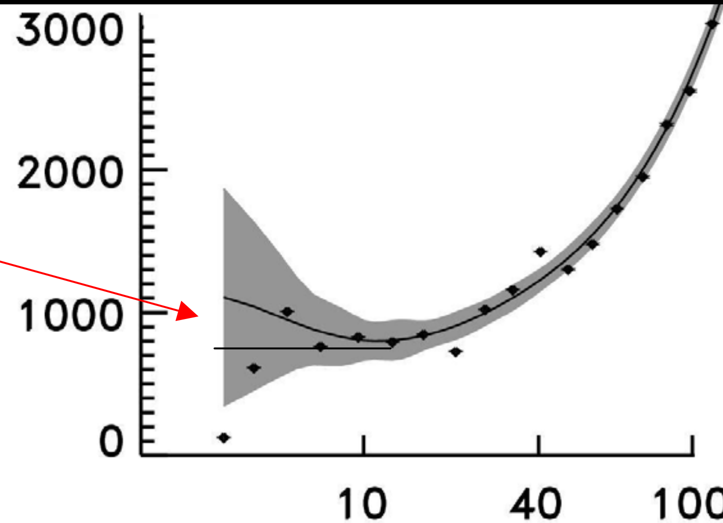
73% of what's in the Universe is not even matter

what it is?

Low quadrupole….



ISW



Cross-correlate CMB with LSS in the foreground !

Boughn & Crittenden (2003) } (X-ray, Radio galaxies)

Nolta et al. (2003)

Scranton et al. (2003) (SDSS)

Afshordi et al. (2003) (2MASS)

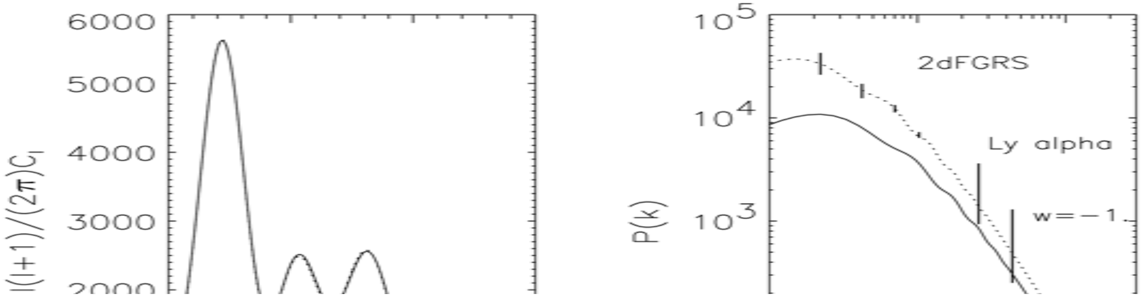
Gaztanaga et al. (2003) (APM)

Looks like we've got to live with Λ !

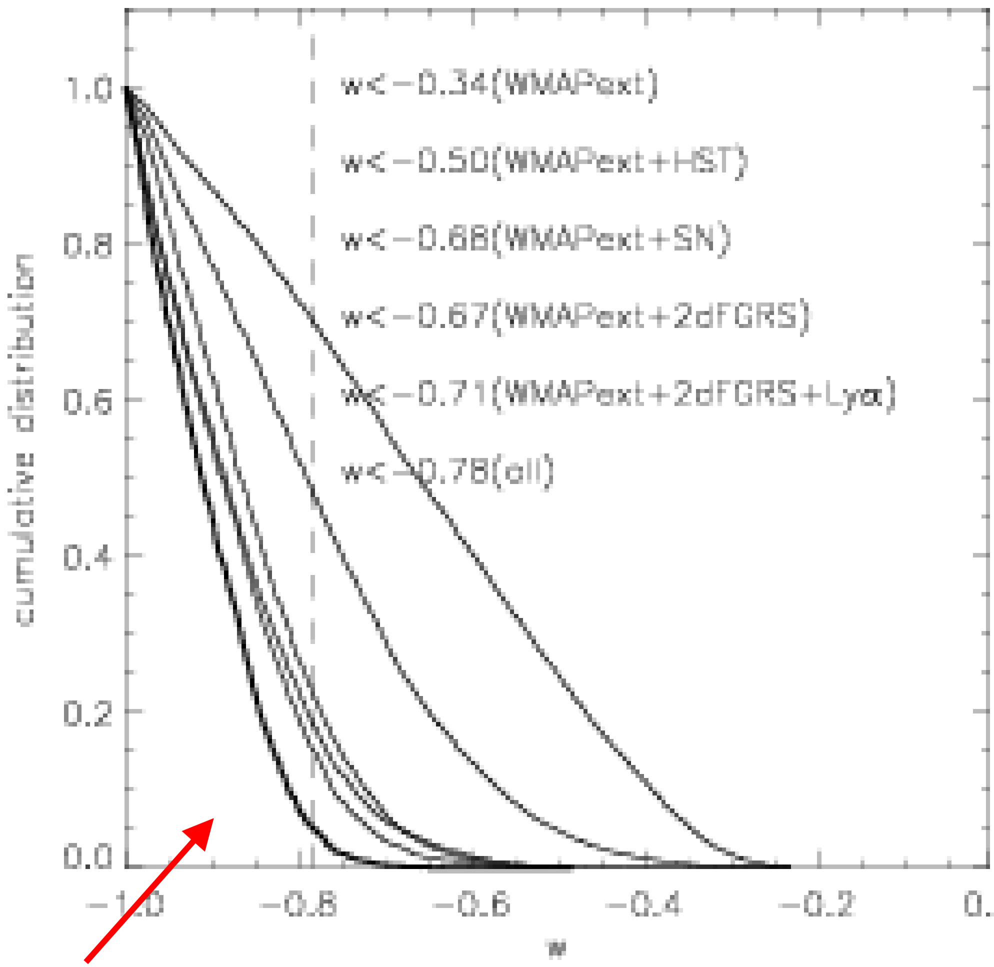
DO NOT CONFUSE THIS EFFECT WITH SZ!

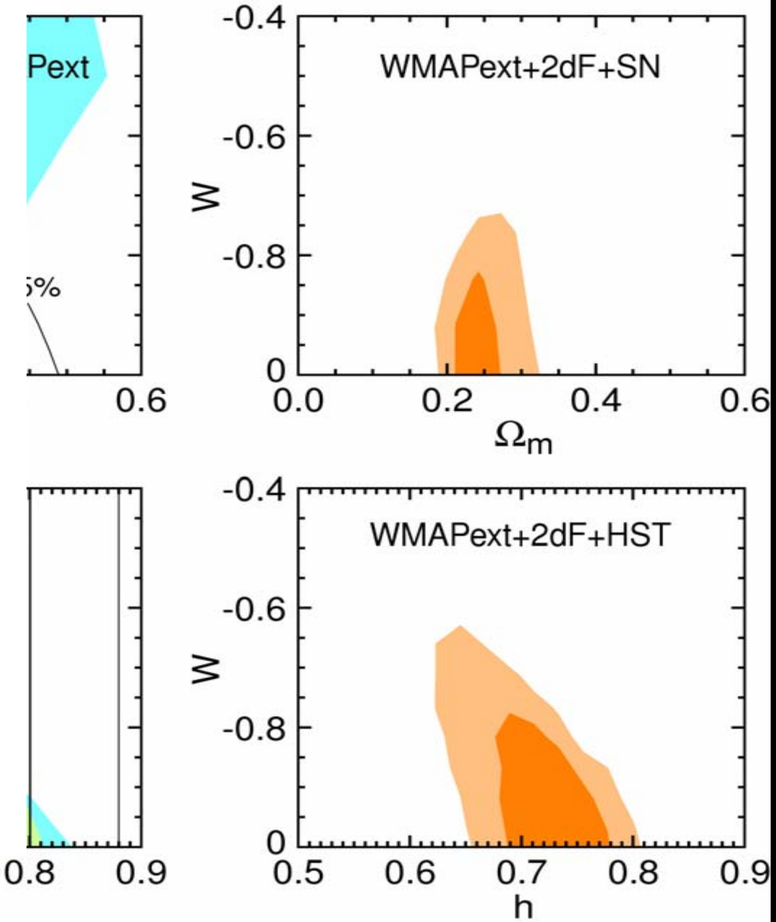
Constraints on QUINTESSENCE

$$w = \frac{p}{\rho}$$



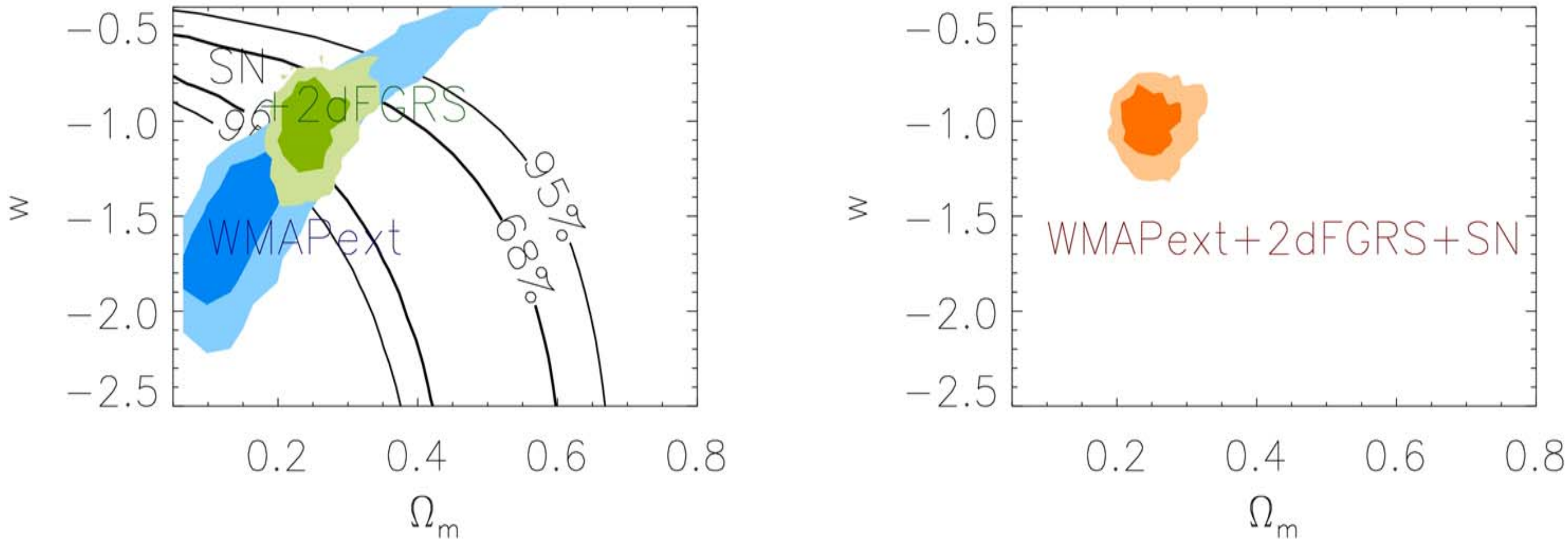
P(k) amplitude!



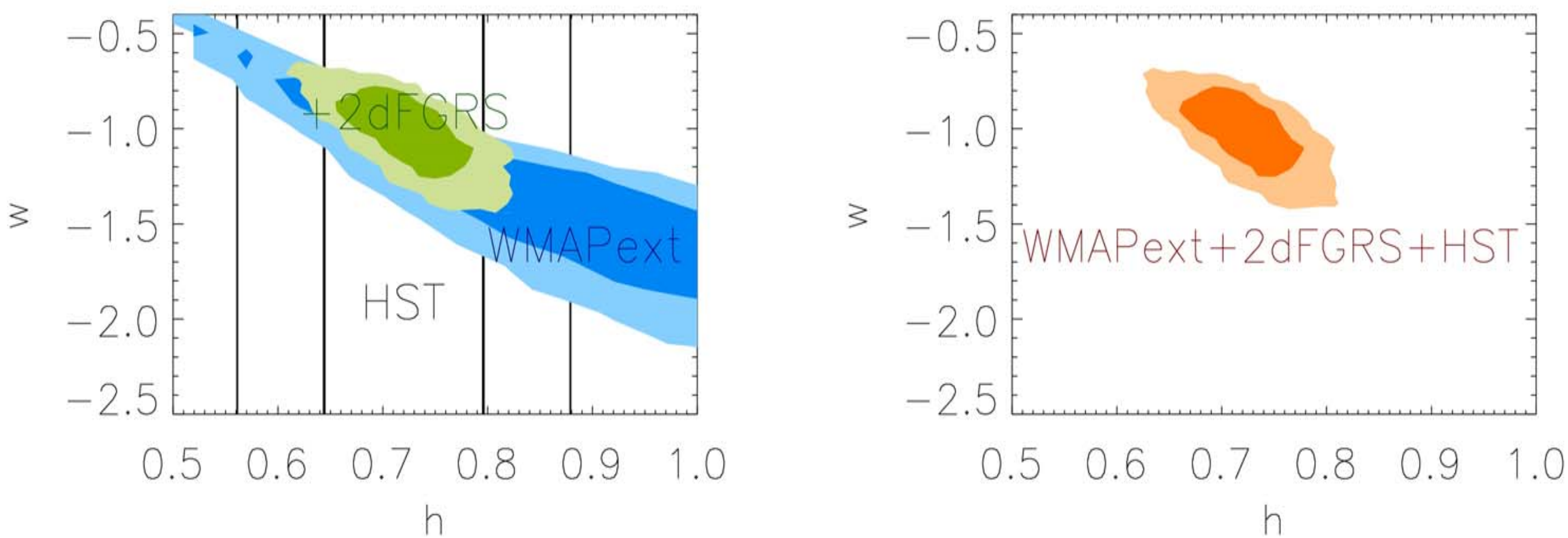


$w < -0.8$

Quintessence

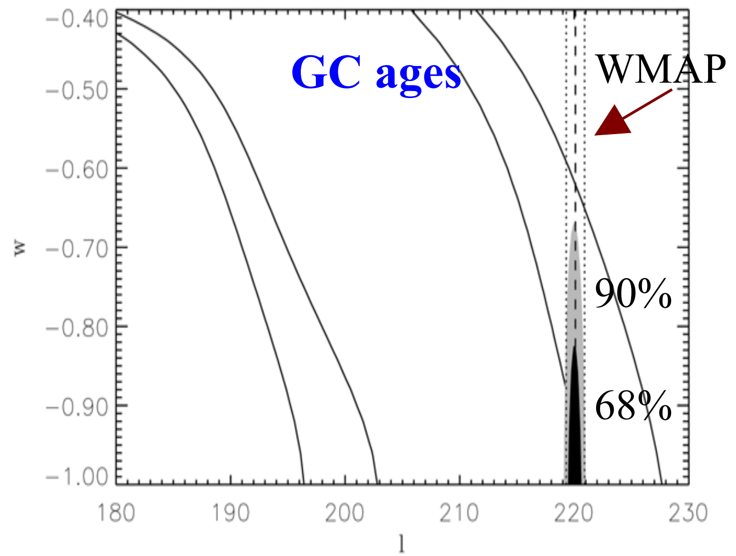


$$w = -0.98 \pm 0.12$$



Other measures for w:

e.g. stellar ages & peak location



(From Jimenz, LV, Treu,Stern 2003)

The next big thing!

Supernovae?

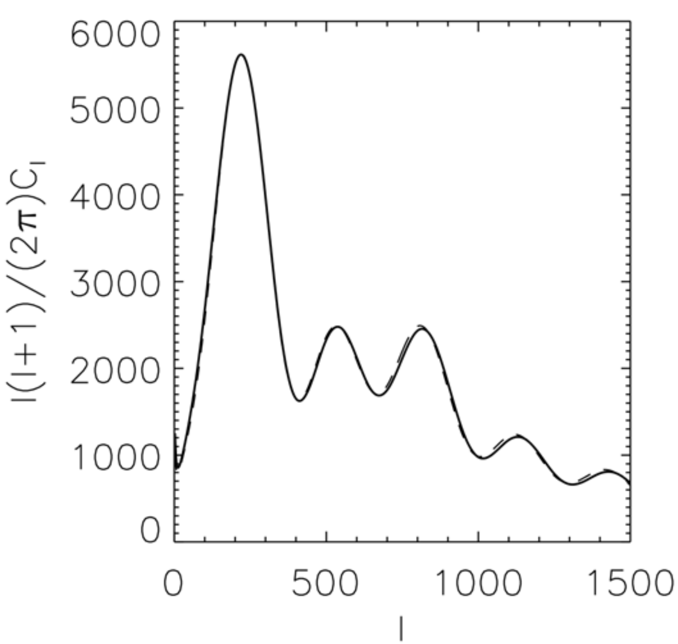
Cross-correlations?

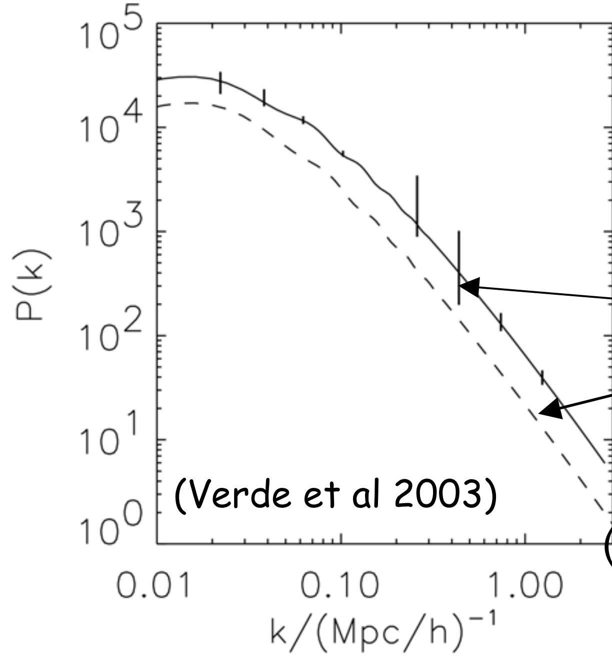
Evolution of clustering?

Stellar clocks?

Etc….

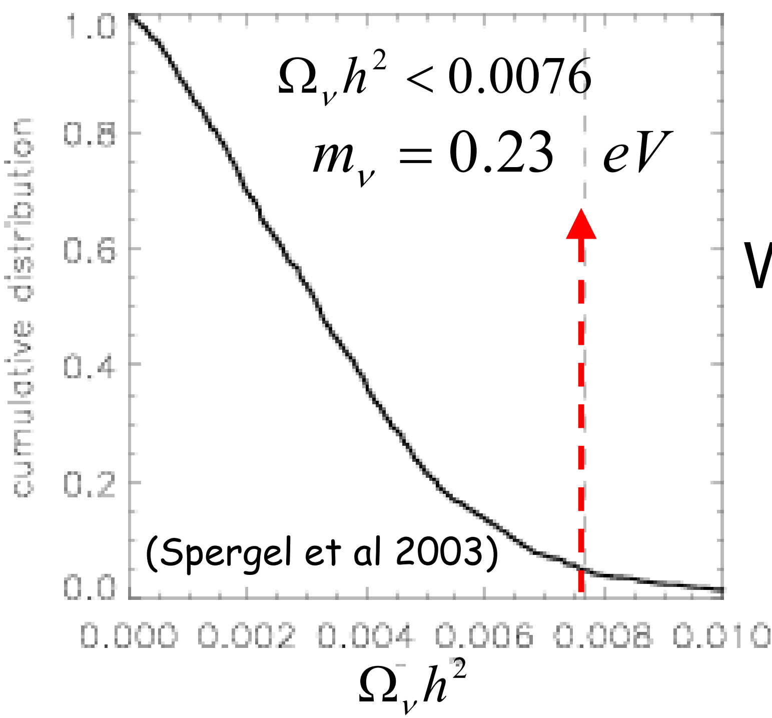
Why constant?





P(K) amplitude

(Verde et al 2003)



CONSTRAINTS ON **NEUTRINO MASS**

WMAP+CBI+ACBAR+2dFGRS(+Lyα)

P(K) amplitude!

See NEW SDSS results:
Tegmark et al. 2003

(see also Elgaroy et al.2002, Hansen 2003, Hannestad 03)

Probing the earliest epochs.

Peiris et al.

Models of the early universe "predict" the spectrum of fluctuations that seed the formation of cosmic structure.

Khoury et al.

Generic Inflation & ekpyrosis favor. $n_s = 0.95 \pm 0.02$

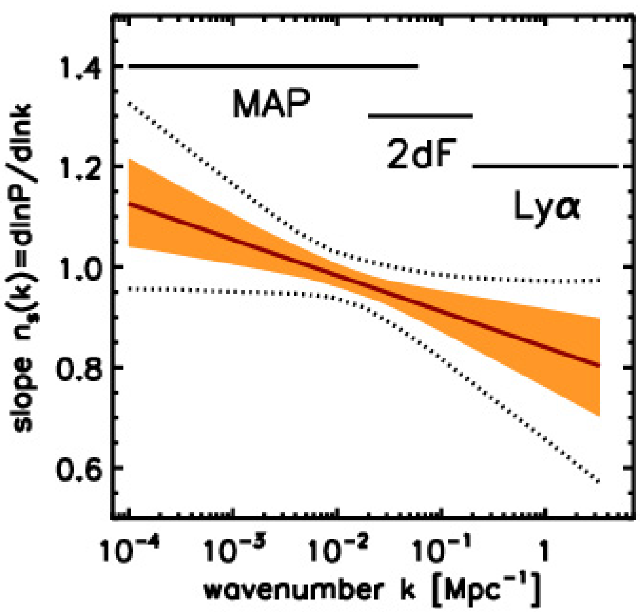
Power law index from WMAP data alone: $n_s = 0.99 \pm 0.04$

For WMAP in combination with CBI + ACBAR +Lyman alpha and 2dFGRS.

$n_s = 0.93 \pm 0.03$ k=0.05 1/Mpc

$$\frac{dn_s}{d \ln k} = -0.031 \pm 0.017$$

See McDonald et al. for related considerations



The data prefer, but do not require, a running spectral index.

$n_s = 0.96 \pm 0.02$

Running spectral index:

(all data)

Parameters do not shift when adding other data sets.

$\Omega_m = 0.27 \pm 0.04$

$\sigma_8 = 0.84 \pm 0.04$

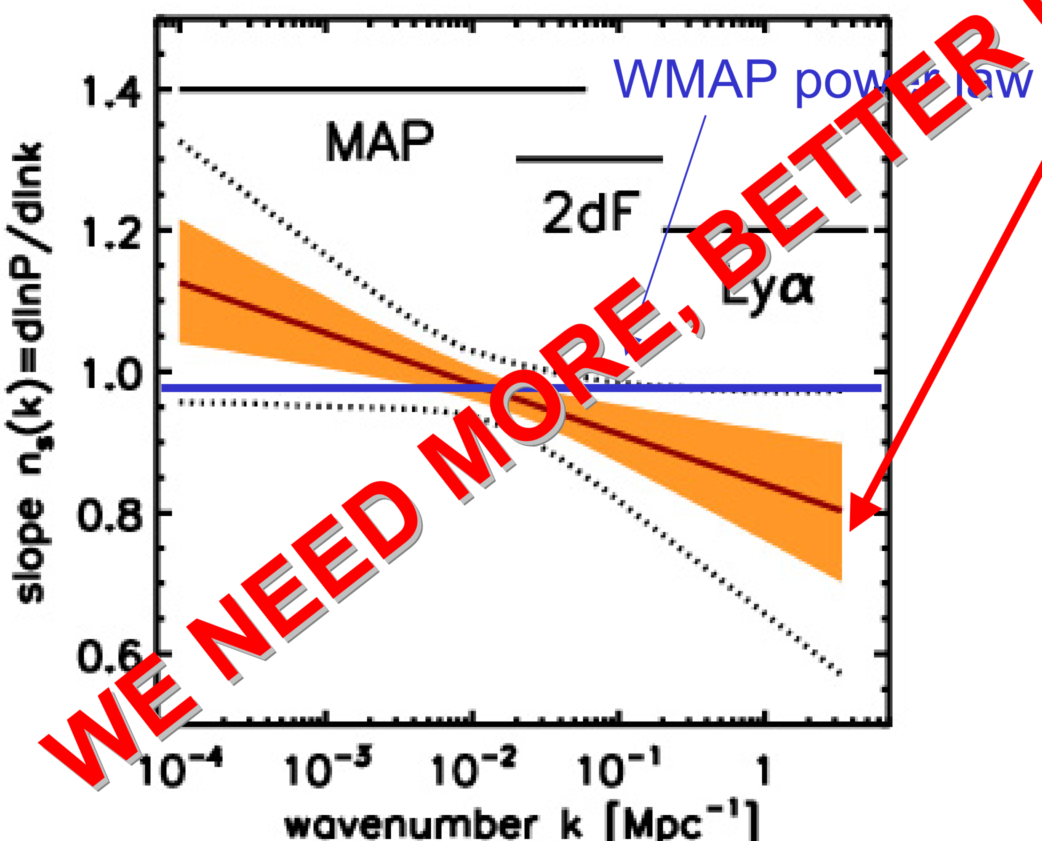
$\tau = 0.17 \pm 0.06$

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

$n_s = 0.93 \pm 0.03$

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

2σ suggestion (with Lyα)



WE NEED MORE, BETTER DATA (e.g. Planck!)

When adding tensors, the fit does not improve get limits on r (Peiris et al. 2003)

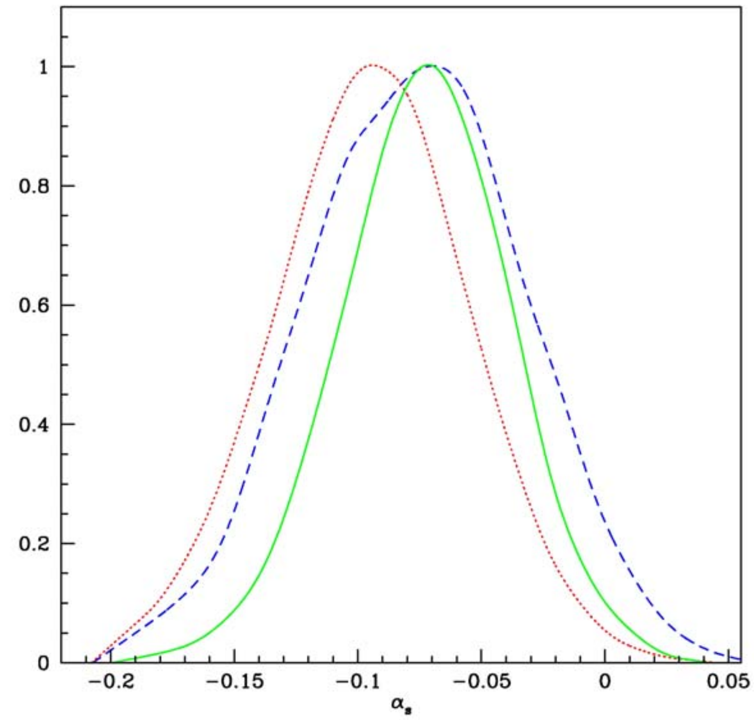
Since then….

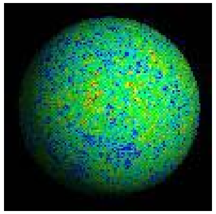
New results from VSA and CBI

Dickinson et al. astro-ph/0402498

Rebolo et al. astro-ph/0402466

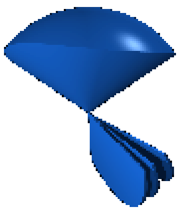
Redhead et al. astro-ph/0402359



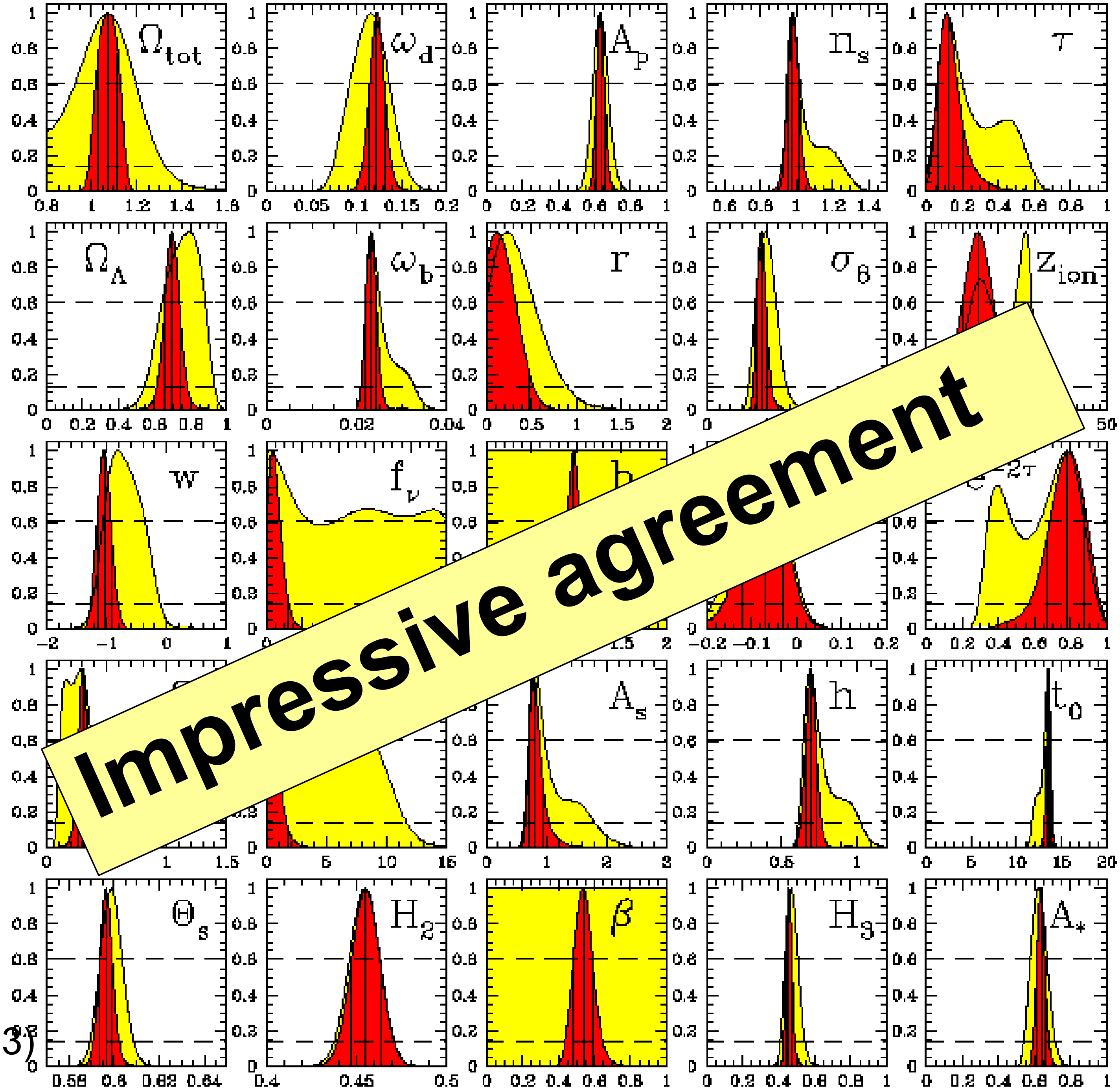


CMB

+



SDSS



Impressive agreement

(From Tegmark et al 2003)

Cosmology Now Has A Standard Model

Only 6 parameters "fit all"

- Basic parameters are accurately determined
  - Many can be measured using multiple techniques
  - CMB best fit now consistent with other measurements

Up to now 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 $z \approx 1088$

(Peiris et al. 2003)

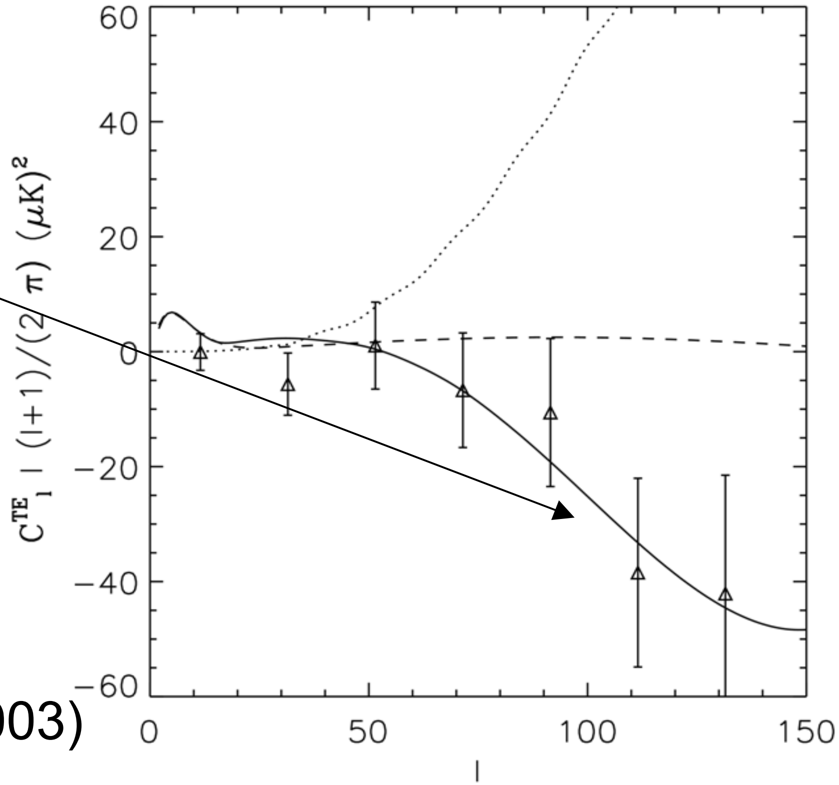
Constraints on inflation!

Support for Inflationary Models

- Gaussianity
- Flat universe: $\Omega_{tot} = 1$ $\Omega_{tot} = 1.02 \pm 0.02$
- Power Spectrum spectral index nearly scale-invariant: $n_s \sim 1$

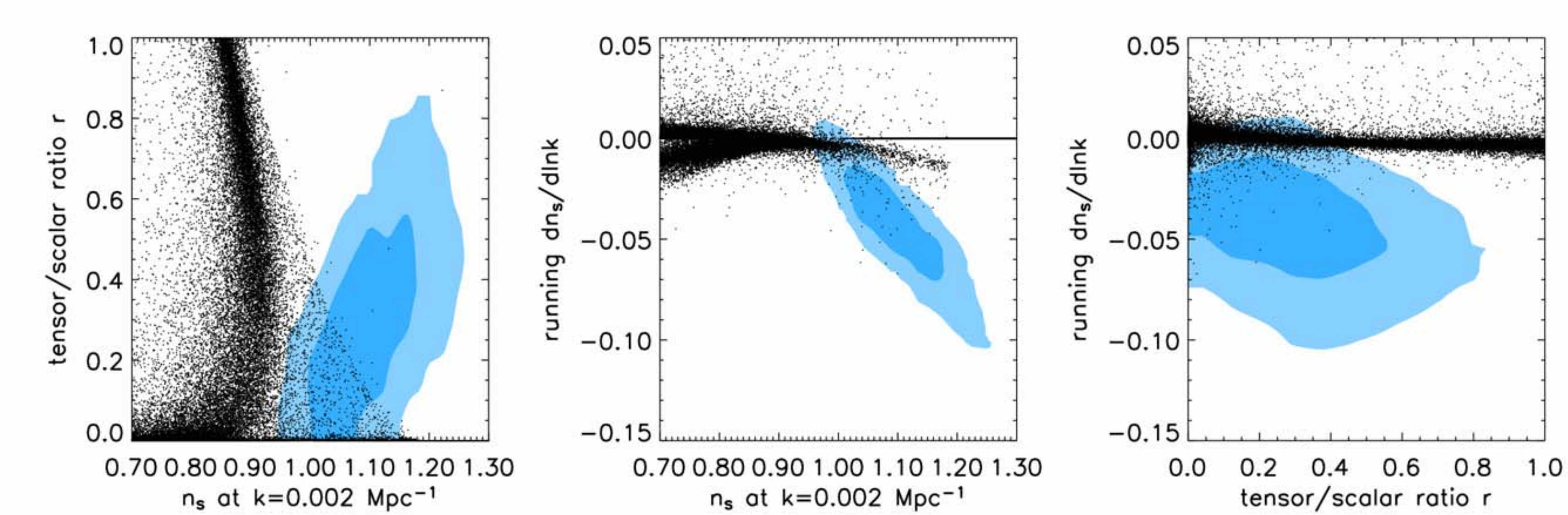
  $n_s = 0.99 \pm 0.04$

  $(n_s = 0.96 \pm 0.02)$
- Adiabatic superhorizon fluctuations
- Limits on Isocurvature fraction (e.g. r<0.53 for power law P(k))



(Peiris et al 2003)

“Generic” predictions of single field slow roll models (hybrid)

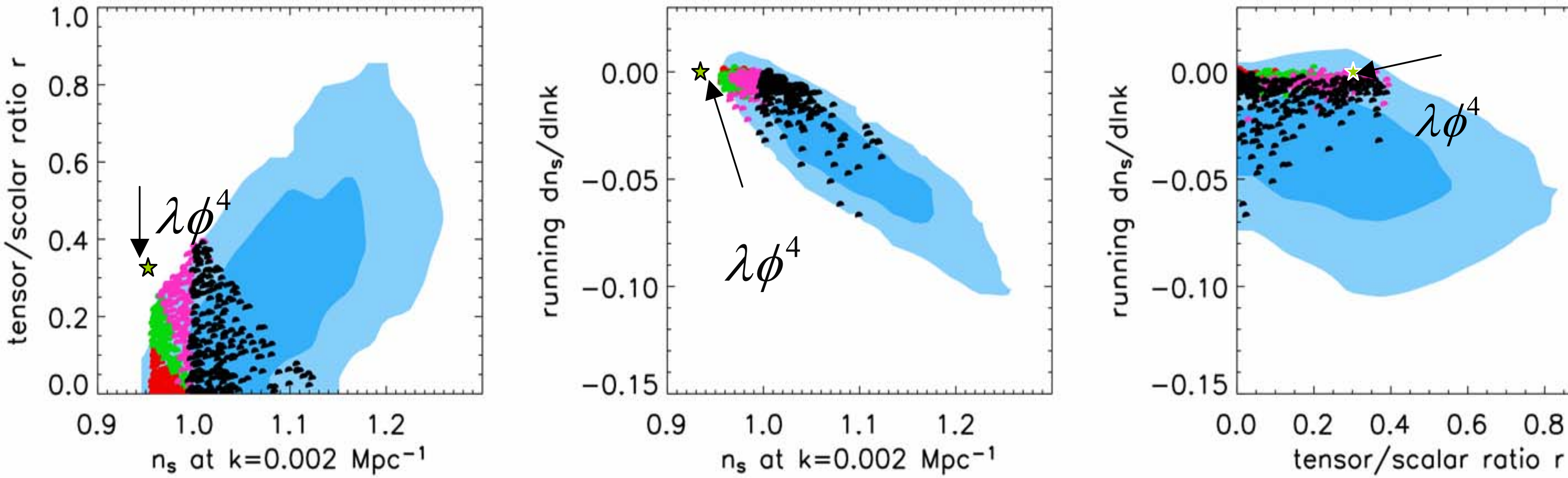


Each point is a “viable” slow roll model, able to sustain inflation for sufficient *e*-foldings to make the universe flat.

Monte Carlo simulations following Kinney (2002) and Easther and Kinney (2002)

(Peiris et al. 2003)

WMAP Constraints on Inflationary Models



Negative curvature (e.g.: new inflation)

Small positive curvature (e.g.: chaotic inflation, extended inflation)

Intermediate positive curvature

Large positive curvature (e.g.: hybrid inflation)

Recommended: For given model, sit on that point and run likelihood analysis (may need to integrate mode equation directly).

$\lambda\varphi^4$ model:

excluded at more than 3 sigma level.

Summary:

For physicists

Cosmology has now a standard model

6 parameters fit all.

Many aspects in common with particle physics

For astronomers

"Boring" LCDM universe with a twist:

the universe was reionized at $z \approx 17$

Up to now 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 $z \approx 1088$

new

Constraints on inflation!

(Peiris et al. 2003)
e.g.,Kinney et al. 03

See http://lambda.gsfc.nasa.gov for data, software etc.

You can do it!

- WMAP power spectra and f90 routine to compute likelihood is available at http://lambda.gsfc.nasa.gov (and instructions)
- Code to compute Cl given cosmological parameters is publicly available: CMFAST (Seljak, Zaldarriaga 1996) www.cmbfast.org
- MCMC code: A. Lewis code available at www.cosmologist.info,

  code used in WMAP analysis will be released soon.
- 2dFGRS power spectrum and covariance matrix are available:

  http://www.mso.anu.au/2dFGRS/
- SDSS power spectrum is now available (see Tegmark et al. 2003)
- Even more SN data are available (Tonry et al 2003, Riess et al. 2004)
- CBI data **(Pearson et al. 2002)** http://www.astro.caltech.edu/~tjp/CBI/data/index.html

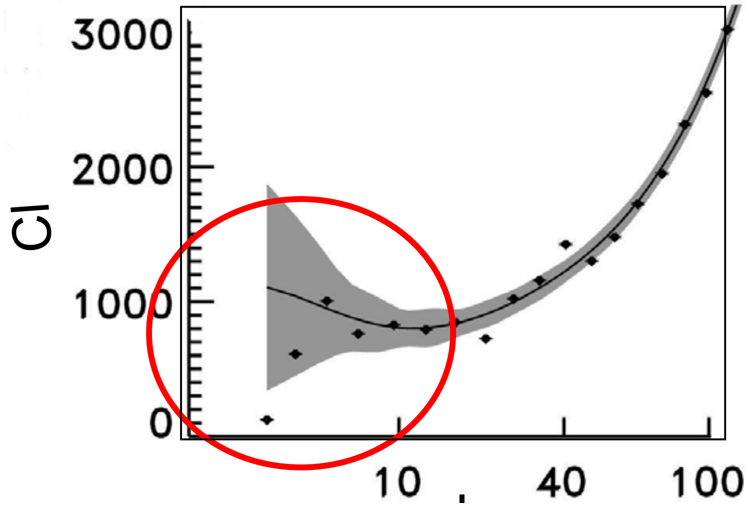
  ACBAR data **(Kuo et al. 2003)** http://cosmology.berkeley.edu/group/~swlh/acbar/data

  VSA (NEW…)
- Lyα data (more coming from SDSS soon)

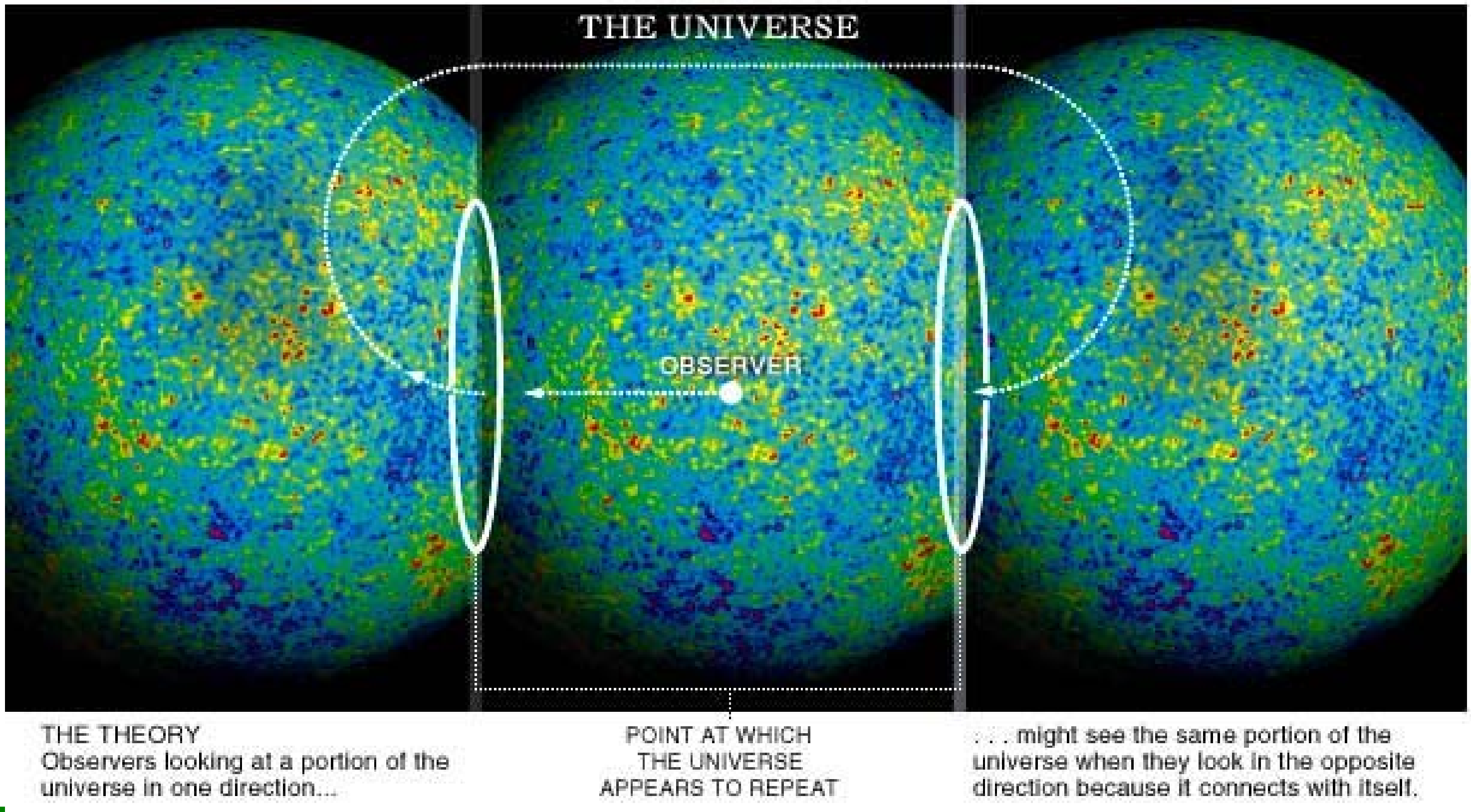
+ Clusters
  Weak lensing etc…

END

INTRIGUING...

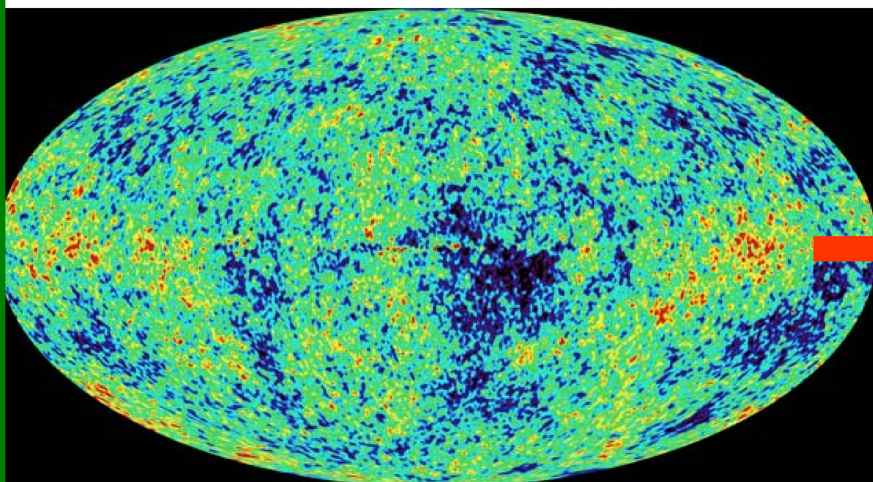


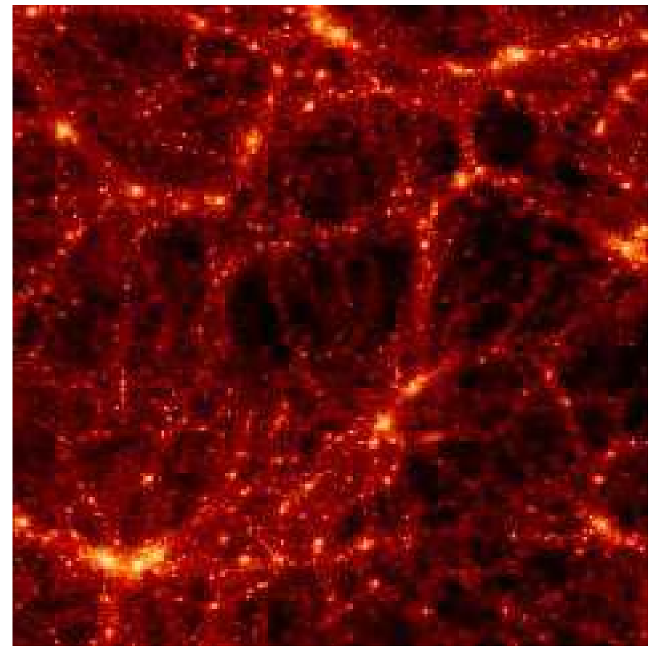
3000
2000
1000
0
Cl
10
40
100



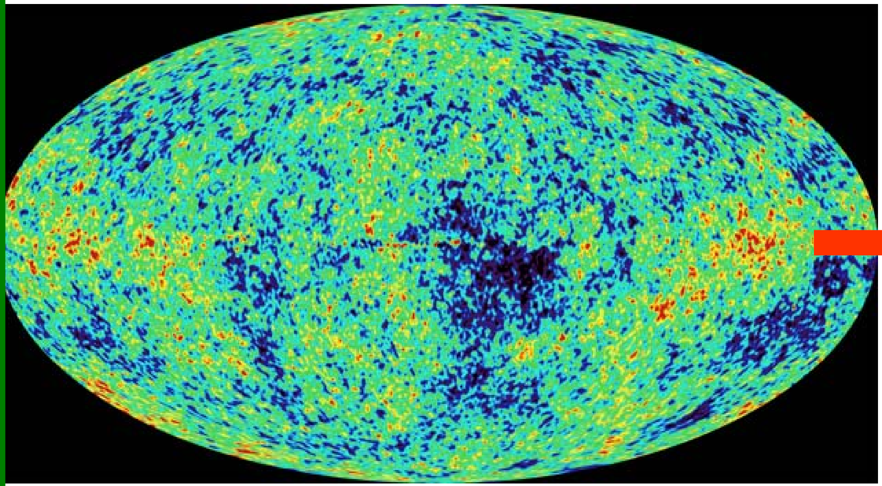
THE UNIVERSE
OBSERVER
THE THEORY
Observers looking at a portion of the universe in one direction...
POINT AT WHICH THE UNIVERSE APPEARS TO REPEAT
. . . might see the same portion of the universe when they look in the opposite direction because it connects with itself.

What's bias?

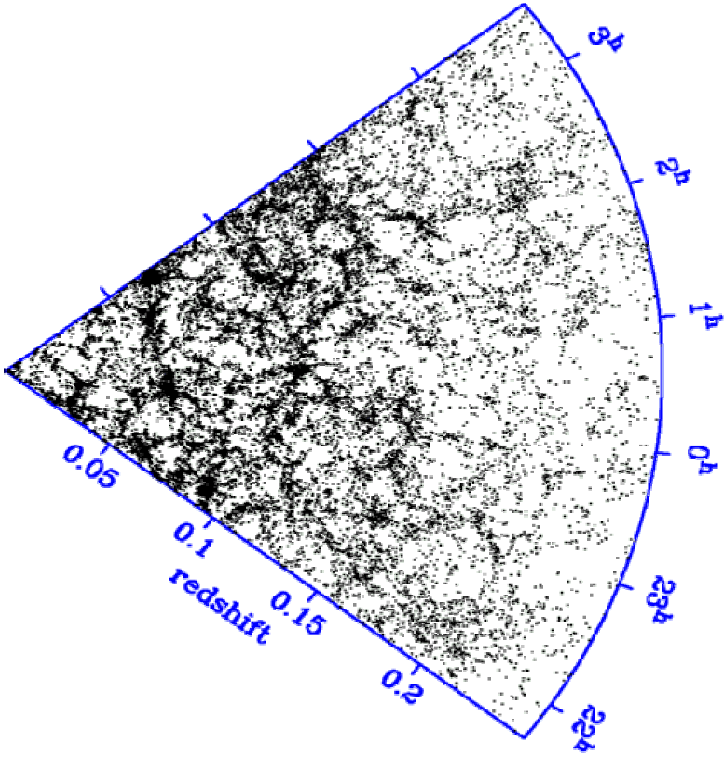




What's bias?



?



Measured for 2dFGRS (Verde et al 2002)