XXIII Physics In Collision – Zeuthen 26^{th} June 2003

Status of observational cosmology and inflation

Laura Covi
DESY

OUTLINE

1. Introduction to Standard Cosmology

2. Observational data:

– Cosmic Microwave Background:

NEW results from DASI & WMAP !

– Large Scale Structure

– Lyman α and weak gravitational lensing

– Supernovae IA

3. The cosmological parameters:

– total energy density, matter and baryon content

– bounds on relativistic species (e.g. neutrinos)

– equation of state of the Dark Energy

4. Inflation and the primordial spectrum

– predictions from single–field inflation

– WMAP and inflation

5. Conclusions and outlook

Standard cosmology

Isotropic and homogeneous universe

$\Longrightarrow$ Friedmann-Robertson-Walker metric:

$$ds^2 = dt^2 - R^2(t) \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right)$$

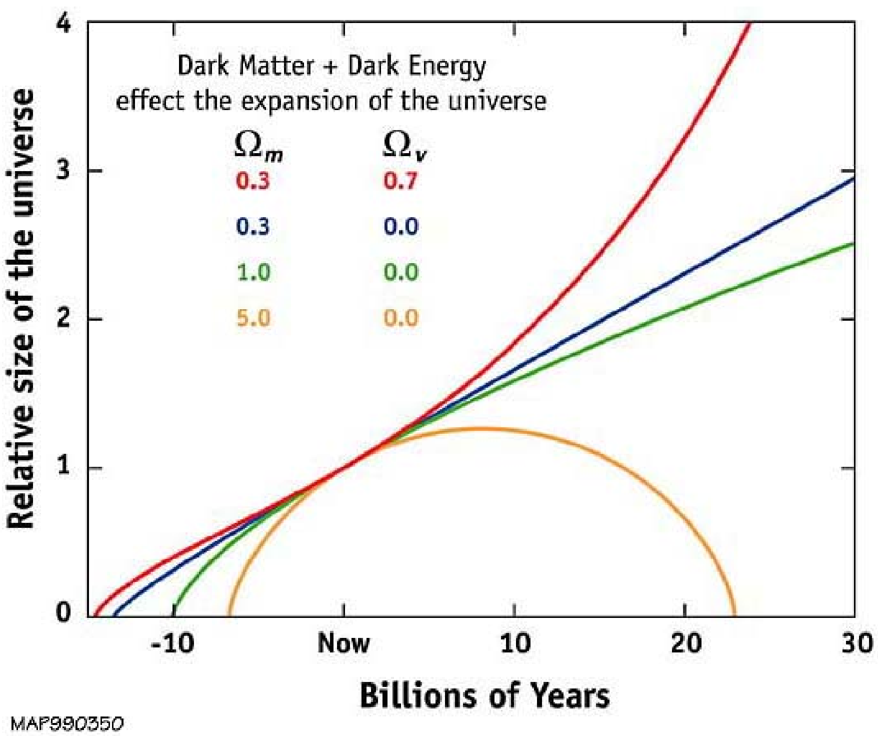
SCALE FACTOR CURVATURE $k = \pm 1, 0$

open/close or flat

The scale factor evolves according to

$$H^2 \equiv \left(\frac{\dot{R}}{R} \right)^2 = \frac{8\pi}{3M_{Pl}} \rho - \frac{k}{R^2} + \Lambda$$

Hubble parameter — energy density — curvature — cosmological constant



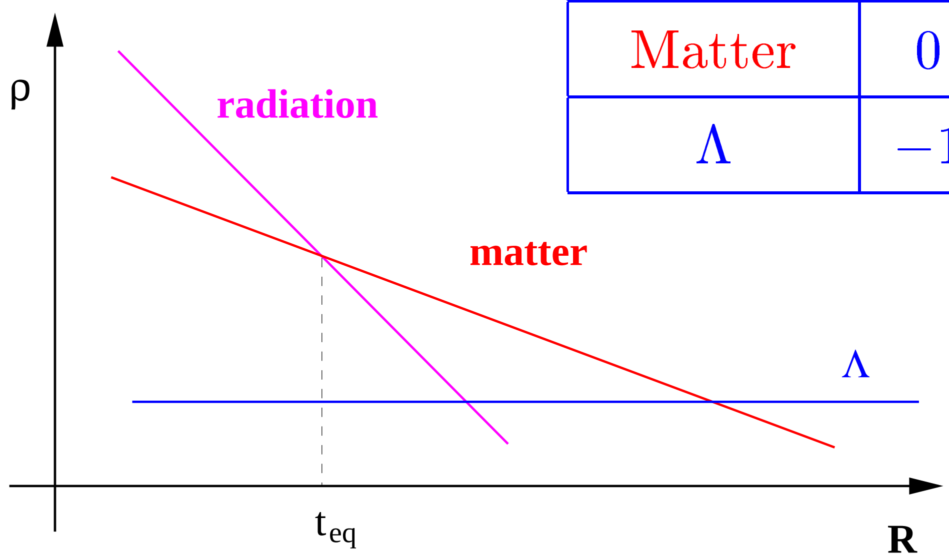
picture from http://map.gsfc.nasa.gov

Use the equation of state and the first law of thermodynamics:

$$P = w\rho \quad \text{and} \quad d(R^3\rho) = -P dR^3 = -w\rho\, dR^3$$

so we have

Type	w	$\rho(R)$	$R(t)$
Radiation	$1/3$	$\propto R^{-4}$	$\propto t^{1/2}$
Matter	0	$\propto R^{-3}$	$\propto t^{2/3}$
Λ	-1	const.	e^{Ht}



NOTATION: rescale the densities by the critical density

$$\rho_c = \frac{3M_{Pl}}{8\pi} H^2 \quad \Rightarrow \quad \Omega_i = \frac{\rho_i}{\rho_c}$$

The present Hubble parameter is measured as $H_0 = h\ 100$ km/s/Mpc, then $\Omega_i h^2$ is the energy density in units of $\rho_c/h^2 = 1.879 \times 10^{-29}$ g/cm^3 $= 1.054 \times 10^4$ eV/cm^3.

Also use redshift: $1 + z = \lambda_0/\lambda_{em} = R_0/R(t_{em}) \geq 1$ as a measure of distance/time.

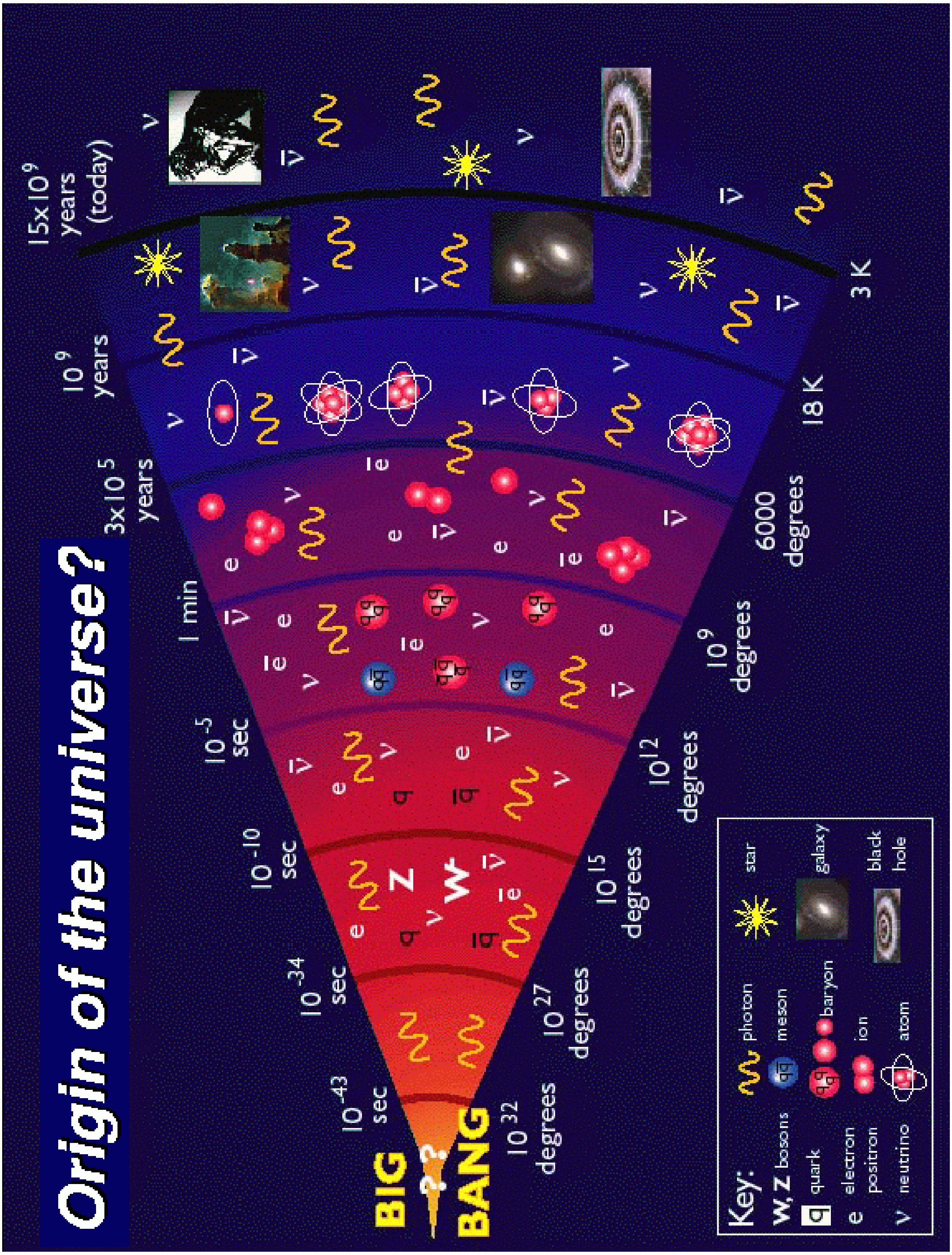


figure from E. W. Kolb

How did structure arise from an homogeneous state ?

$\Downarrow$

Small fluctuations in the density can act as seeds for the gravitational collapse

Assume initial gaussian curvature perturbations: the key quantity is then the power spectrum

$$\mathcal{P}(k) = k^3 \delta^2(k) \simeq k^3 |\delta\tilde{\rho}(k)|^2$$

where $\tilde{\rho}(k)$ is the Fourier transform of the density contrast $\delta\rho(x) = \rho(x) - \bar{\rho}$.

The evolution of the perturbations depends on the cosmological parameters $h, \Omega_{tot}, \Omega_M, \Omega_B$, the equation of state of the dominant component of the energy density and the nature of Dark Matter (Cold, Warm or Hot).

$\Downarrow$

Radiation dominance:	Matter dominance:
linear regime	non linear regime
oscillations	gravitational collapse
CMB anisotropies:	Large Scale Structure
acoustic peaks	peculiar velocities
	....

The present CMB anisotropies and the density contrast contain information on:

A) the "background":

the cosmological parameters, equation of state, etc...

B) the initial conditions:

primordial power spectrum

$\rightarrow$ INFLATION

BUT some care is needed in disentangling within A and specially between A and B

$\rightarrow$ *beware of parameter degeneracies and correlations !*

CMB anisotropy and the power spectrum

CMB experiments measure the fluctuations in the temperature of the radiation coming from the last scattering surface. $\rightarrow$ sky maps

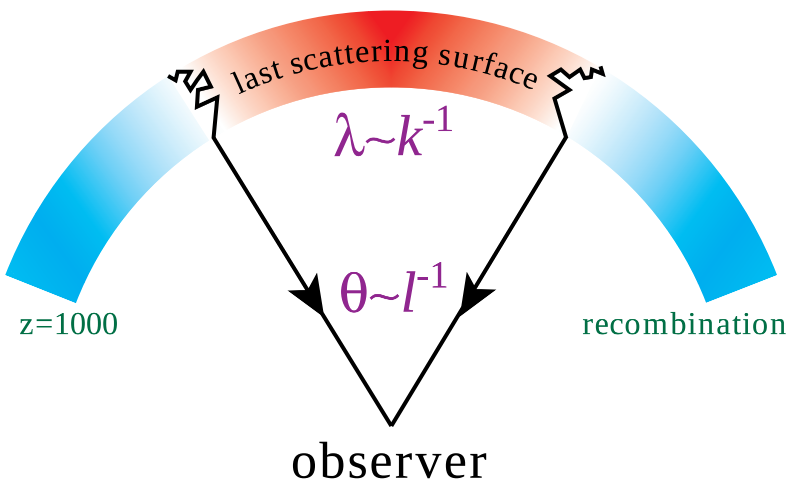
Describe the sky in terms of spherical harmonics:

$$\Delta T(\theta, \phi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

and obtain the temperature anisotropies as

$$C_\ell \equiv \frac{1}{2\ell + 1} \sum m |a_{\ell m}|^2 \Leftrightarrow \quad P(k)$$

Note: ℓ corresponds to k^{-1} on the last scattering surface !

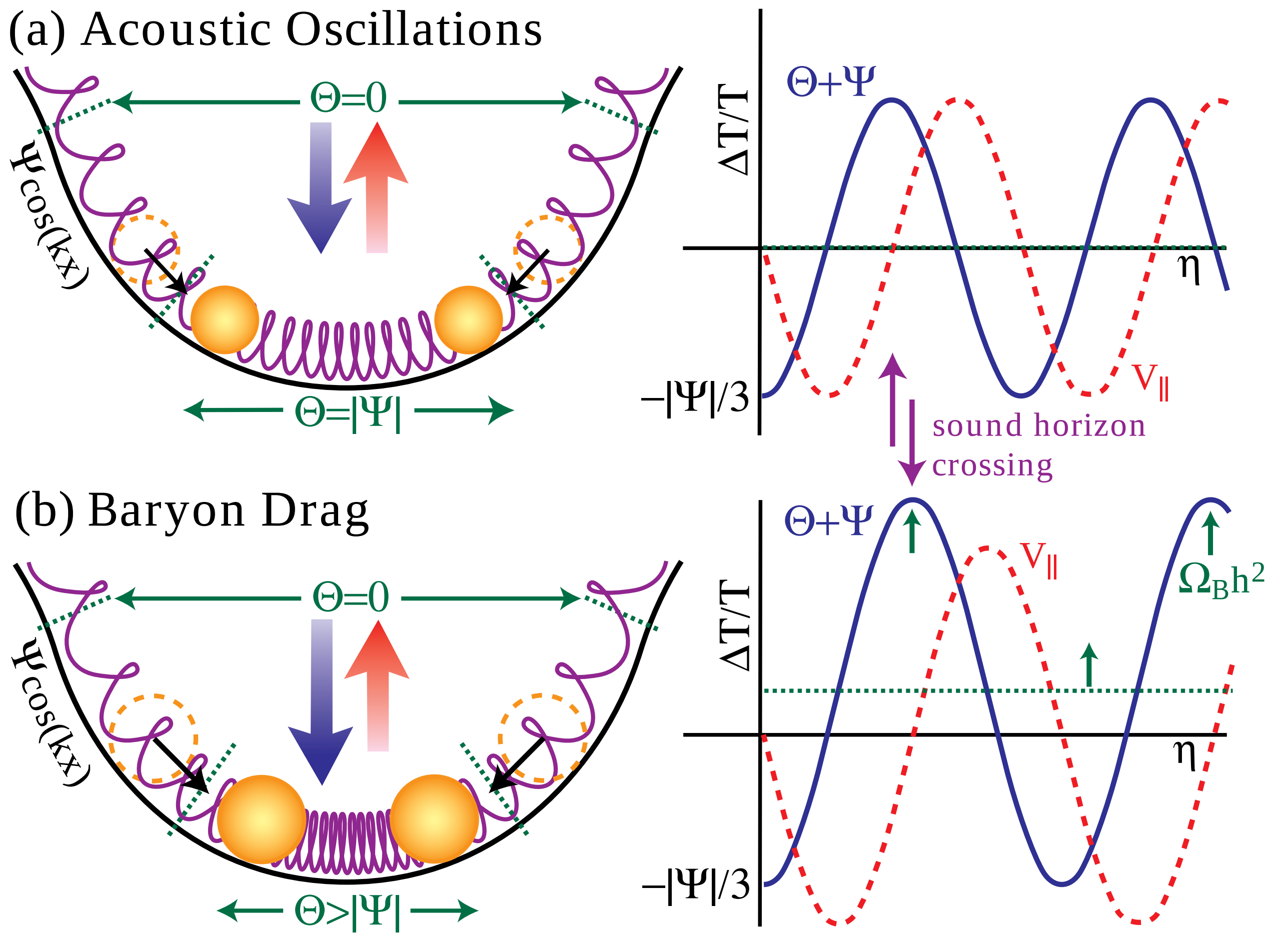


picture from W. Hu, http://background.uchicago.edu/~whu/

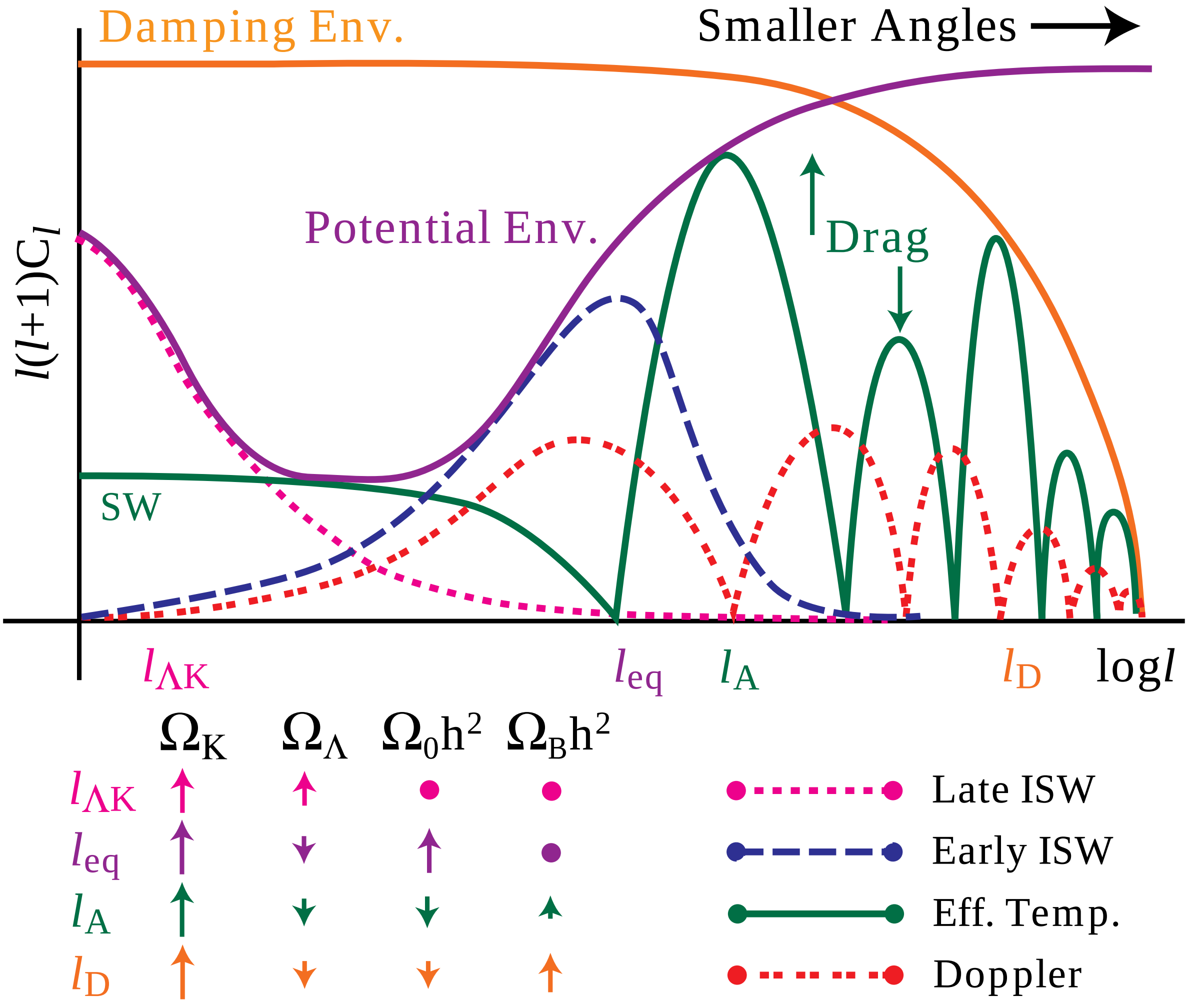
The Physics of the CMB

detailed review at http://background.uchicago.edu/∼whu/

As soon as λ is shorter than the sound horizon, the modes start to oscillate: first peak corresponds exactly to a maximal compression at wavelength equal to the horizon ! The even peaks instead are rarefaction peaks.



Dependence from cosmological parameters



picture from W. Hu, http://background.uchicago.edu/∼whu/

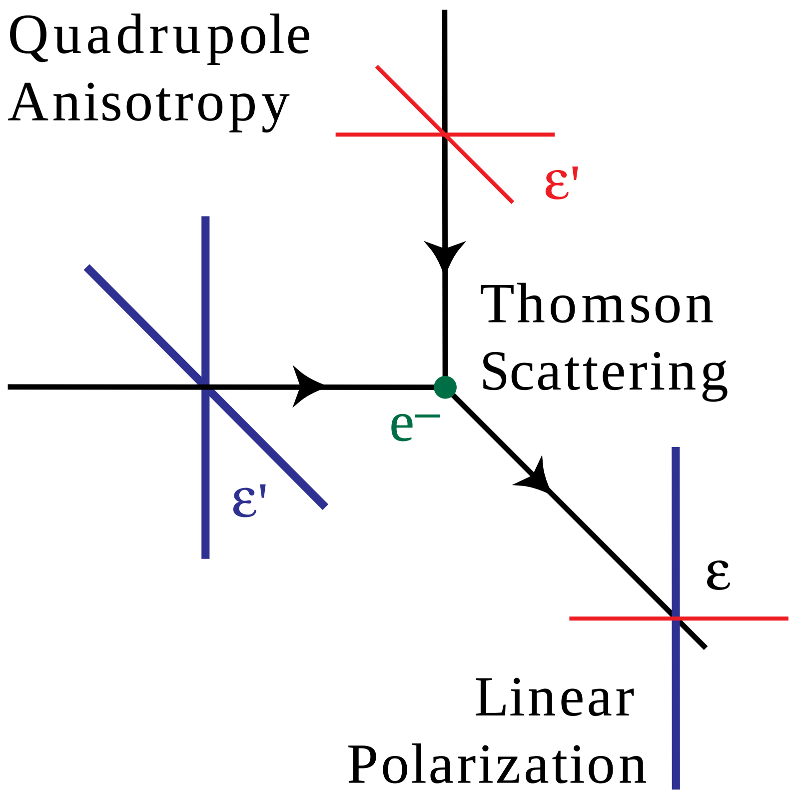
POLARIZATION OF THE CMB

Thomson scattering:

$$\frac{d\sigma}{d\Omega} = \sigma_T \; |\epsilon \cdot \epsilon'|^2 \qquad \text{for } \epsilon, \epsilon' \text{ polarization}$$

of incident and scattered light.

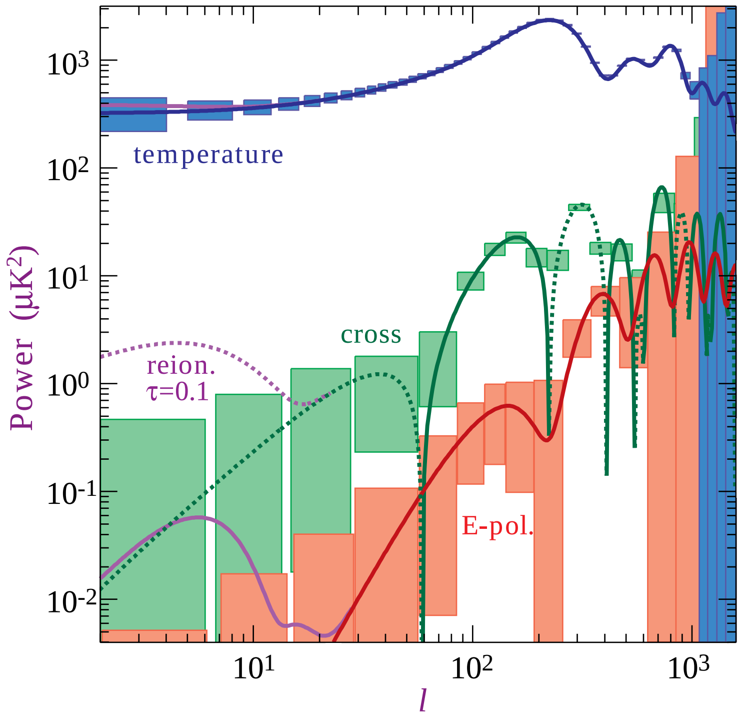
An homogeneous distribution or a dipole produce no net polarization; but a linear polarization arises from the local quadrupole in the velocity distribution !



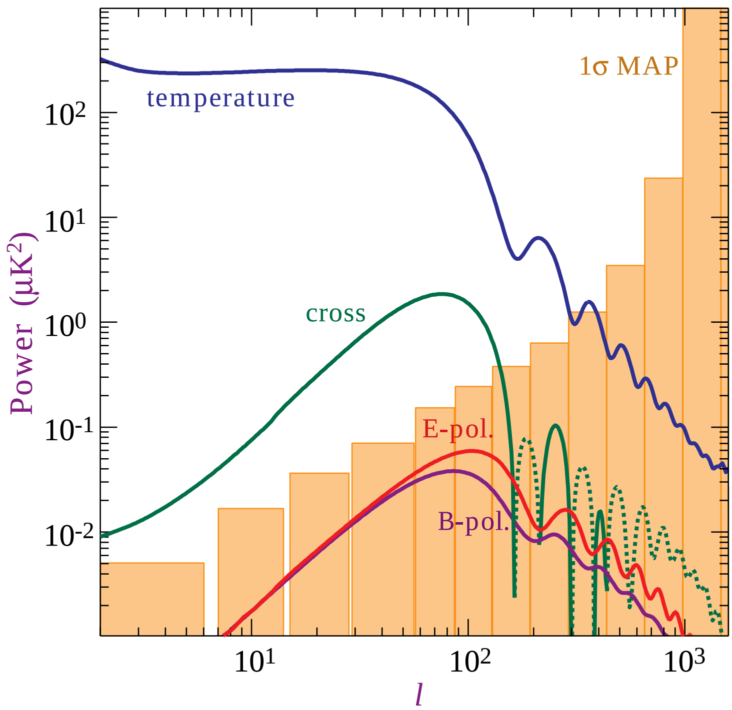
picture from W. Hu, http://background.uchicago.edu/∼whu/

Two polarization modes: E (grad) and B (curl).
Scalar density perturbations excite only the E mode, while tensor perturbations (gravity waves) excite both E and B at the same level.

Scalar CMB anisotropies



Tensor CMB anisotropies



pictures from W. Hu, http://background.uchicago.edu/∼whu/

THE DATA:
CMB NEWS

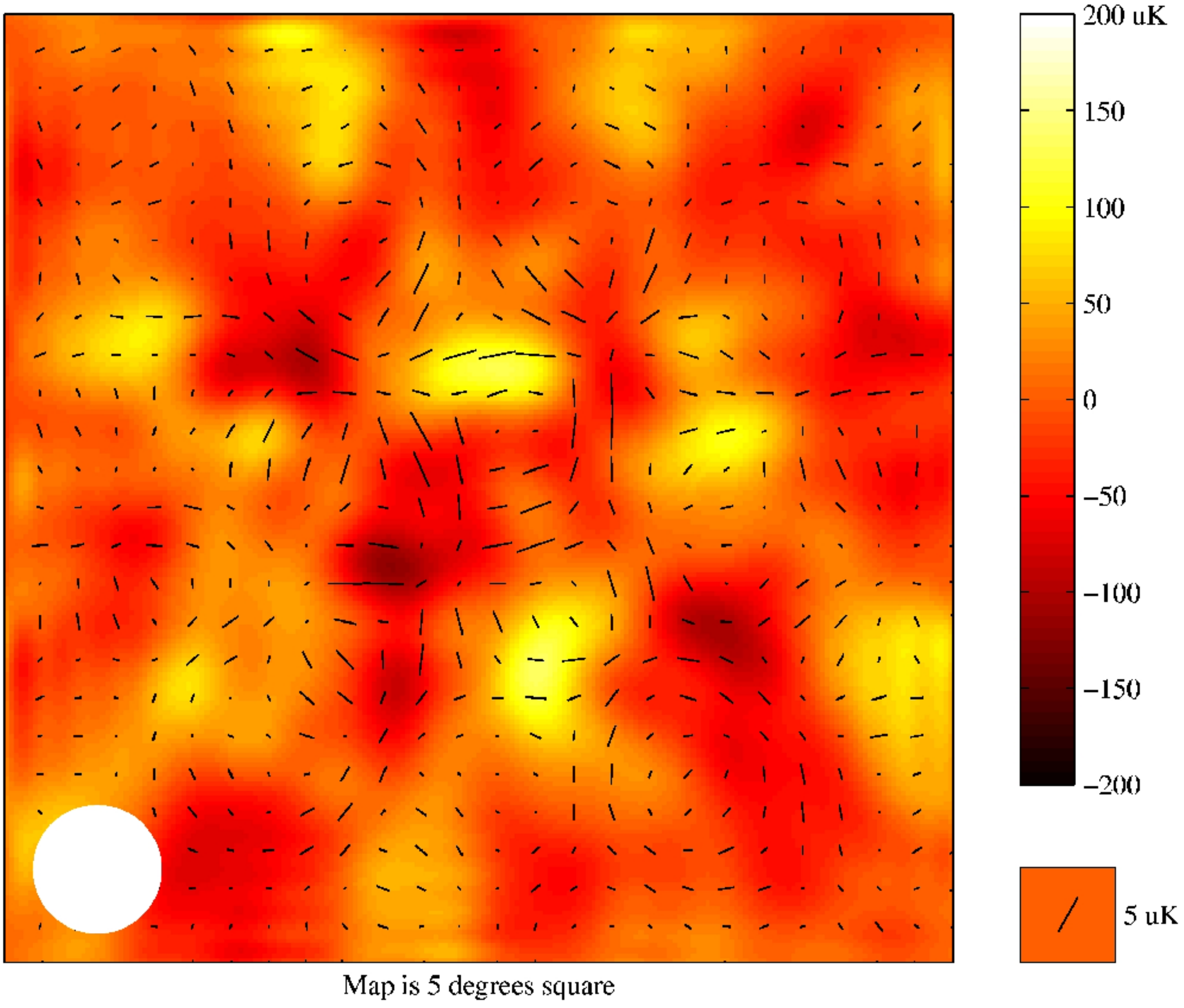
Degree Angular Scale Interferometer

http://astro.uchicago.edu/dasi

- Interferometer at the South Pole, funded by U Chicago and NSA
- Polarization team: U Chicago and UC Berkeley
- First evidence of the polarization of CMB release on the 19th September '02 at COSMO-02 !

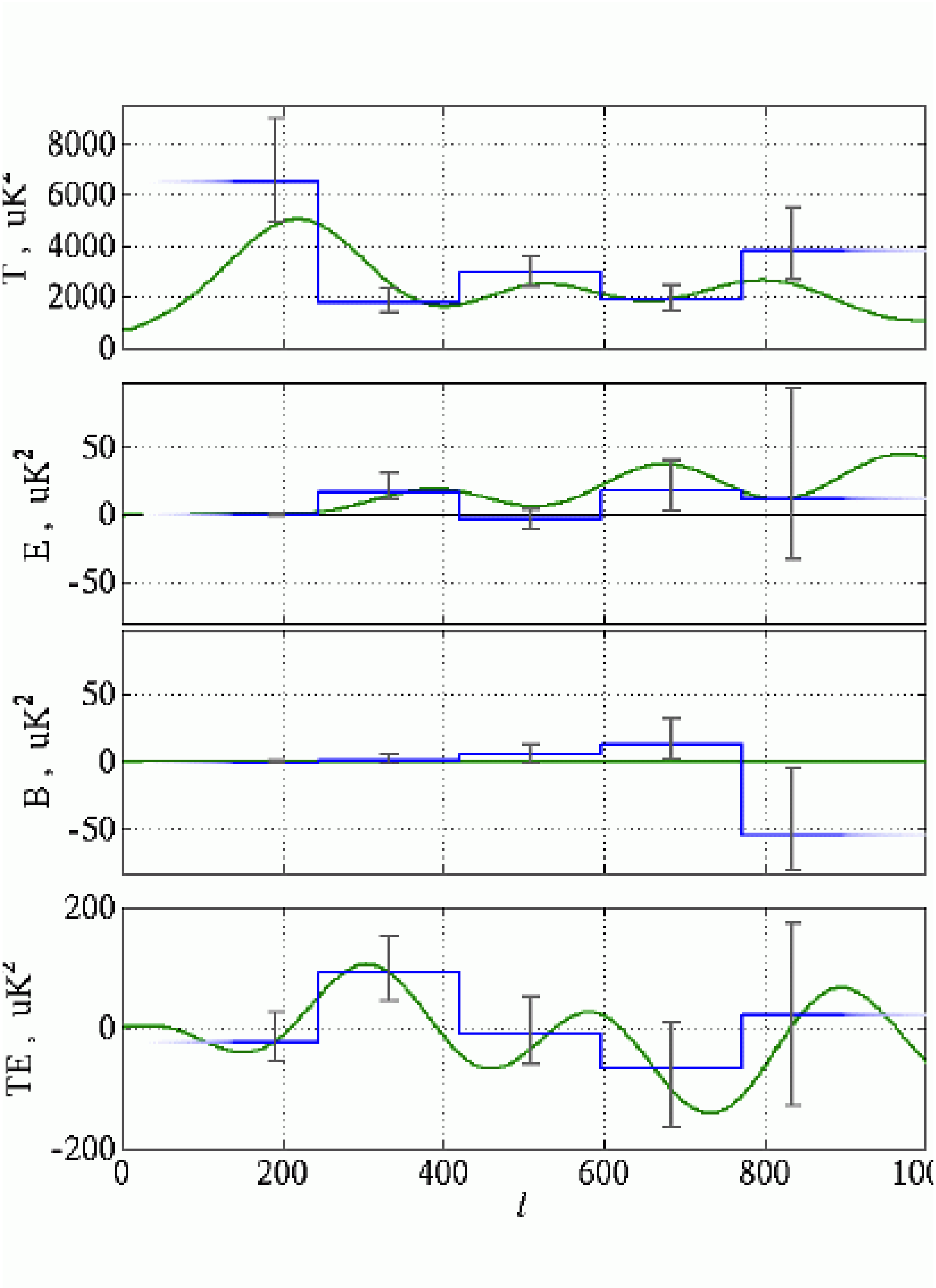
Temperature anisotropy and polarization map

http://astro.uchicago.edu/dasi



DASI data for $\langle TT \rangle, \langle EE \rangle, \langle BB \rangle, \langle TE \rangle$

Nature 420 (2002) 772, astro-ph/0209478

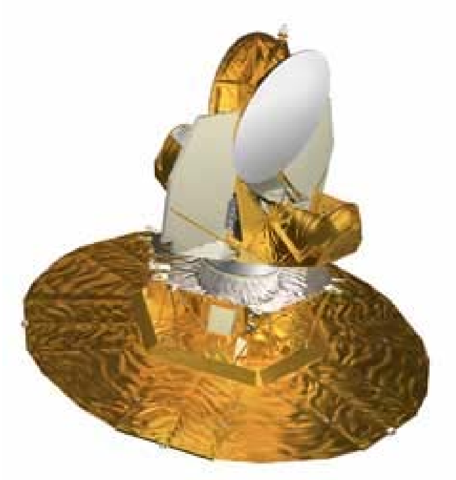


FIRST evidence for the E-mode polarization at 4.9σ !

Consistent with polarization generated by the scalar perturbations.

Wilkinson Microwave Anisotropy Probe

http://map.gsfc.nasa.gov



• satellite experiment, a collaboration between NASA/GSFC and Princeton, including also Brown and Chicago Univ., UCLA, UBC;

• launched on the 30th June 2001;

• first full sky observation completed in April '02;

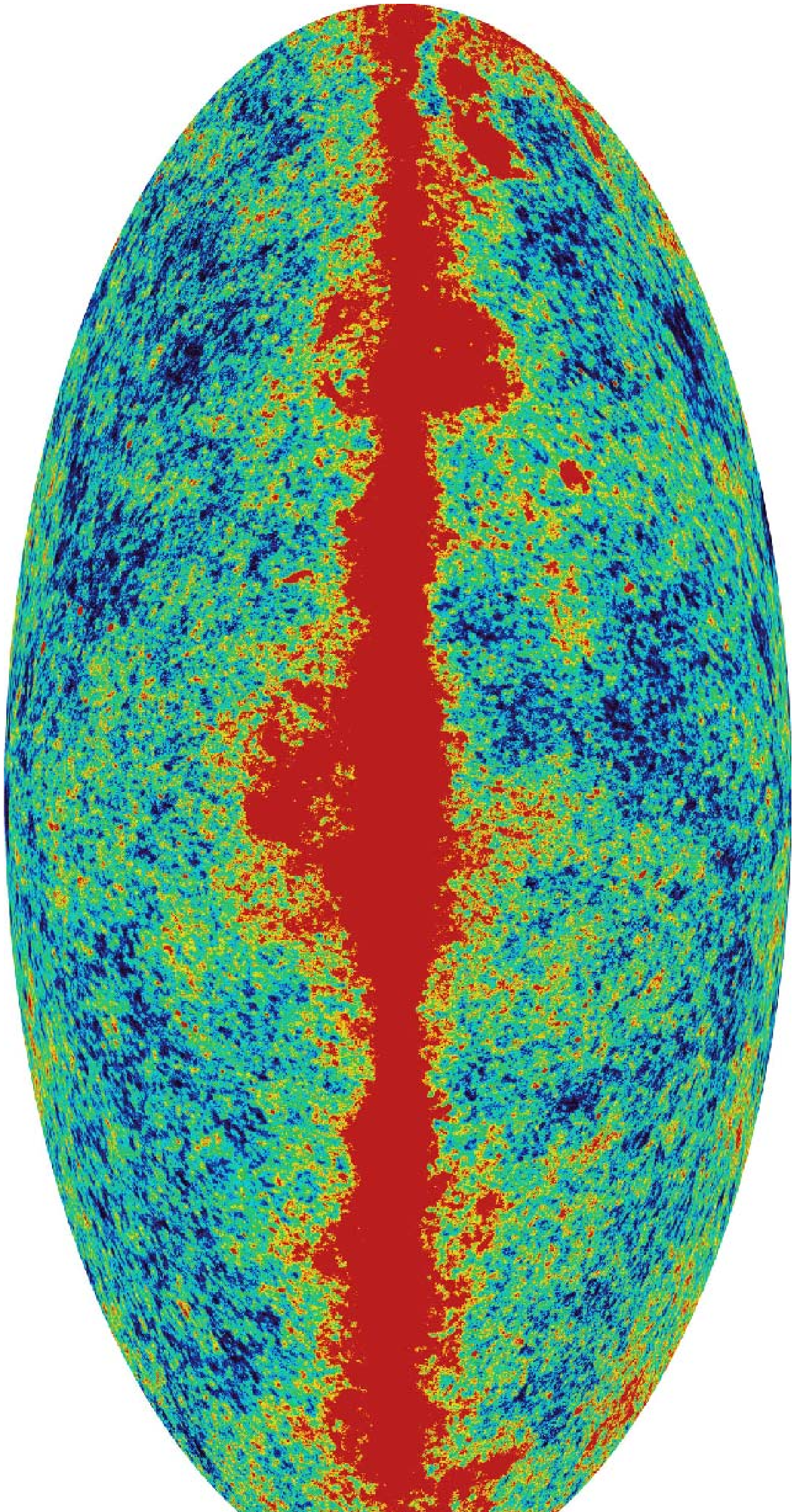
• first data release based on the first full-sky map in February '03; already third full sky-map competed on April '03;

• CMB anisotropy is measured in 5 different bands and combined → 1 full sky map

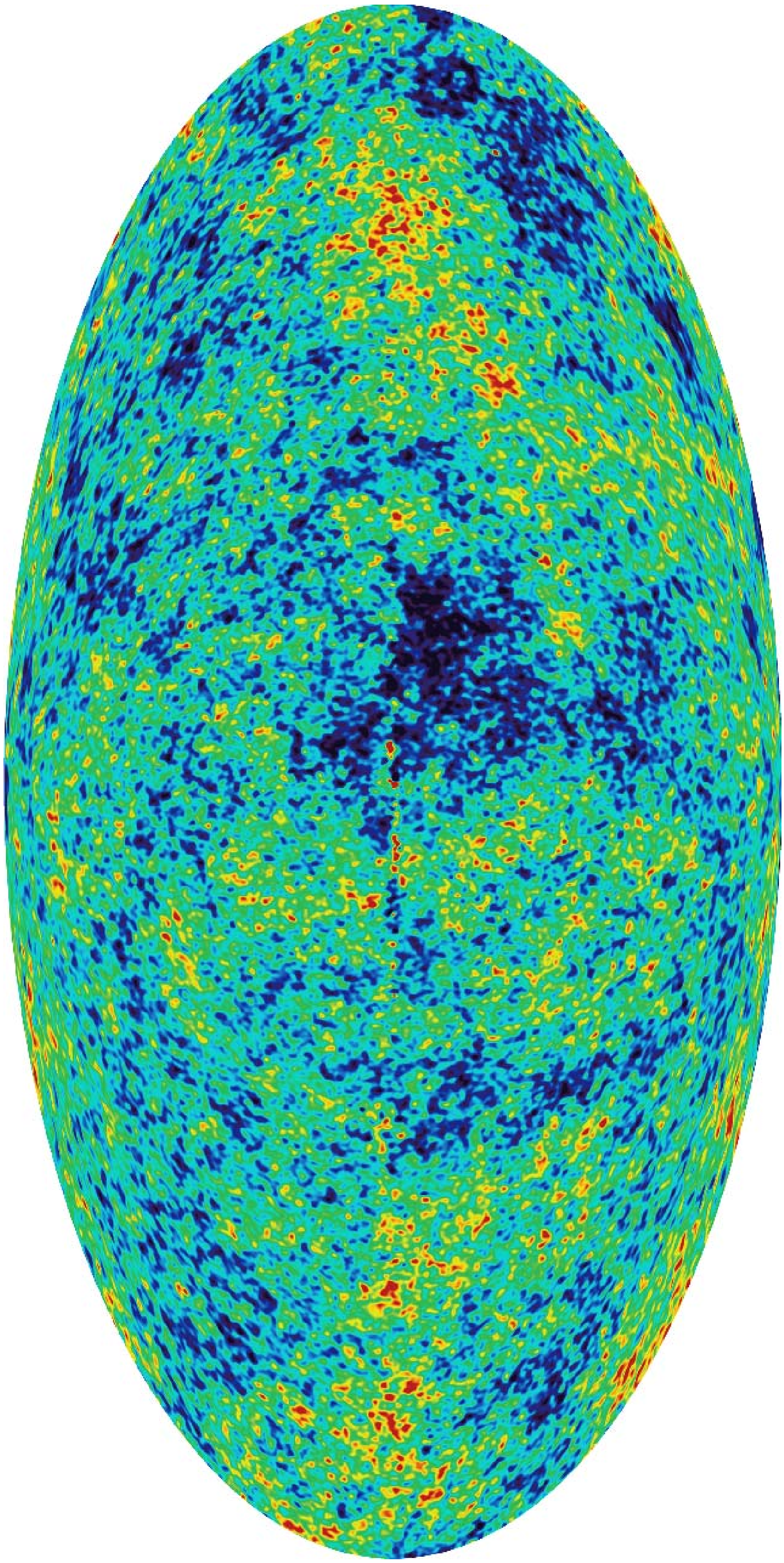
• Data and pictures publicly available on the portal LAMBDA: http://lambda.gsfc.nasa.gov/

• Expected 4 years of observation → 8 sky maps

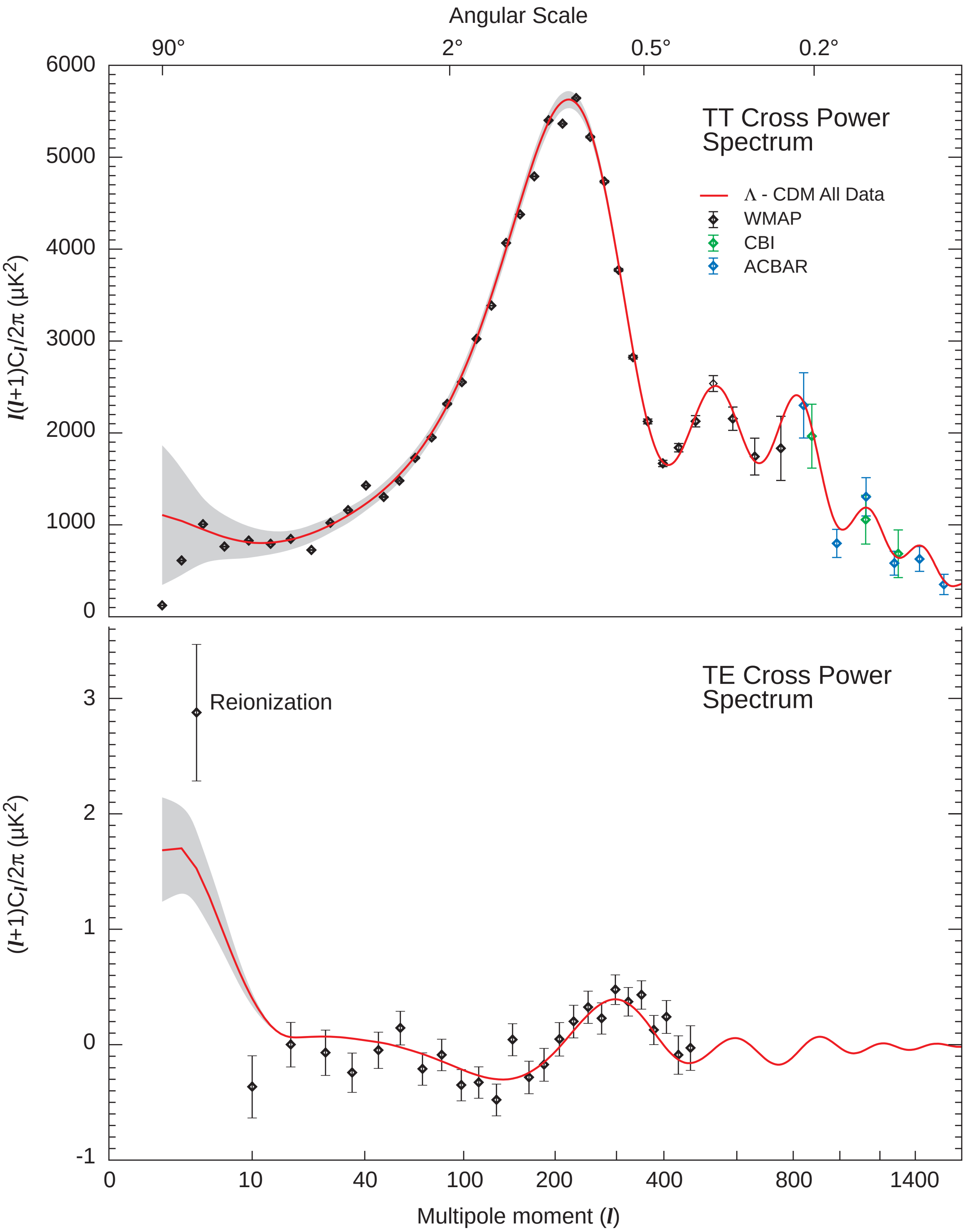
Ka-Band Map (33 GHz) (Dipole subtracted)



Combined map (Also Milky way subtracted)



WMAP: the anisotropies in $\langle TT \rangle$ and $\langle TE \rangle$



Consistent with DASI and with prediction of (pure) scalar perturbations.

Excess in polarization at low ℓ $\quad\rightarrow$ reionization !

Large Scale Structure data

Information on the density contrast can be obtained from the distribution of galaxies in our universe.

Assumption: the visible matter follows the distribution of the invisible Dark Matter

$\rightarrow$ bias parameter

Also it is necessary to correct for the non-linearity on small scales to obtain the present linear spectrum

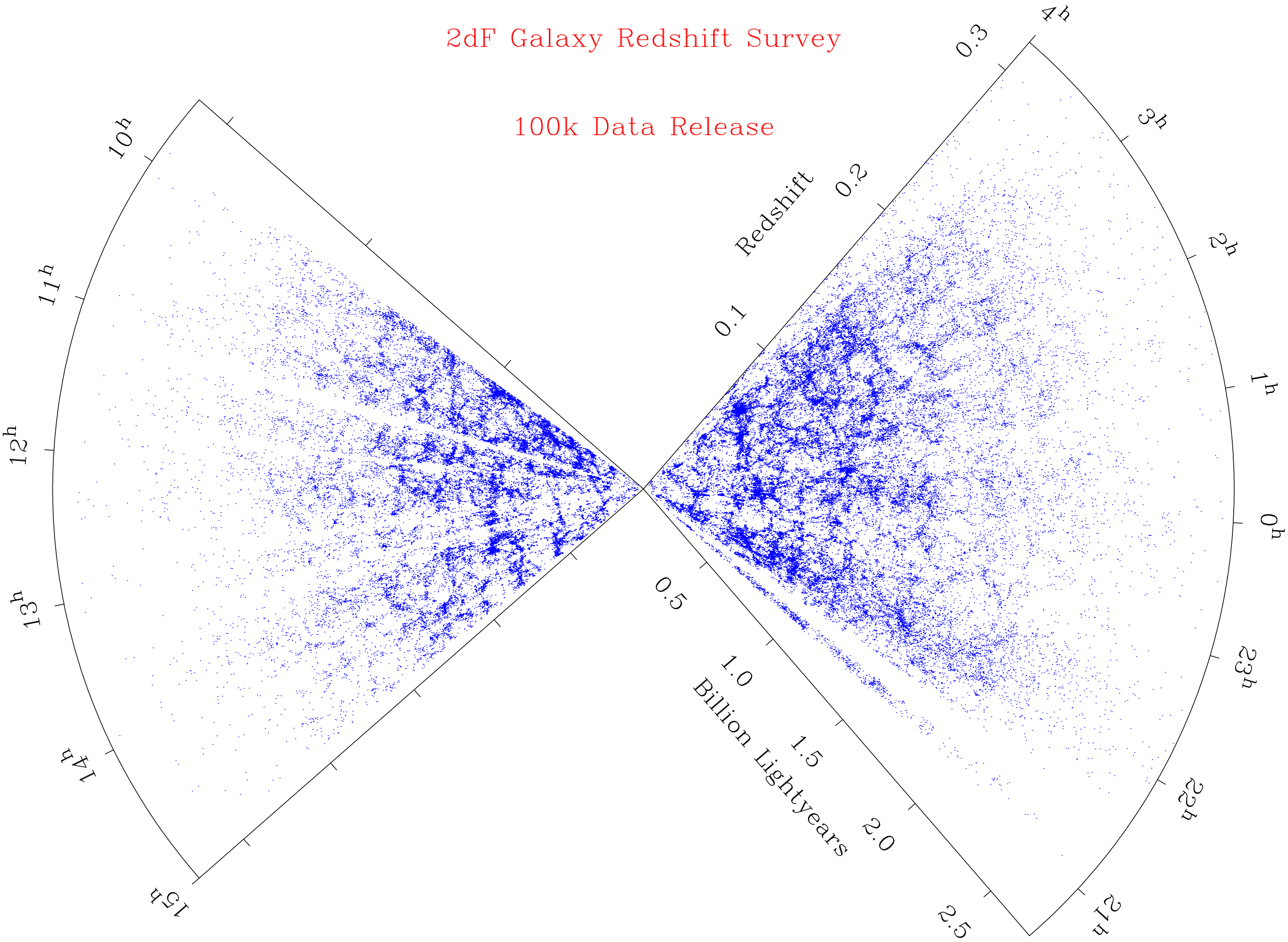
Some present surveys:

• 2 degree Field Galaxy Redshift Survey (2dF GRS) soon to be completed; recent data release with about 400.000 galaxies

http://www.mso.anu.edu.au/2dFGRS/

• Sloan Digital Sky Survey (SDSS) is ongoing and aims at 1 million of galaxies in one quarter of the sky; data release 1 in April this year

http://www.sdss.org/



2dF Galaxy Redshift Survey
100k Data Release
Redshift
0.1
0.2
0.3
0.5
1.0
1.5
2.0
2.5
Billion Lightyears
10^h
11^h
12^h
13^h
14^h
15^h
4^h
3^h
2^h
1^h
0^h
23^h
22^h
21^h

Other ways to measure the density contrast: use photons of distant objects as a probe of the intervening densities

– Lyman α forest data:

measure the absorption lines in the spectra of distant quasars caused by intergalactic hydrogen

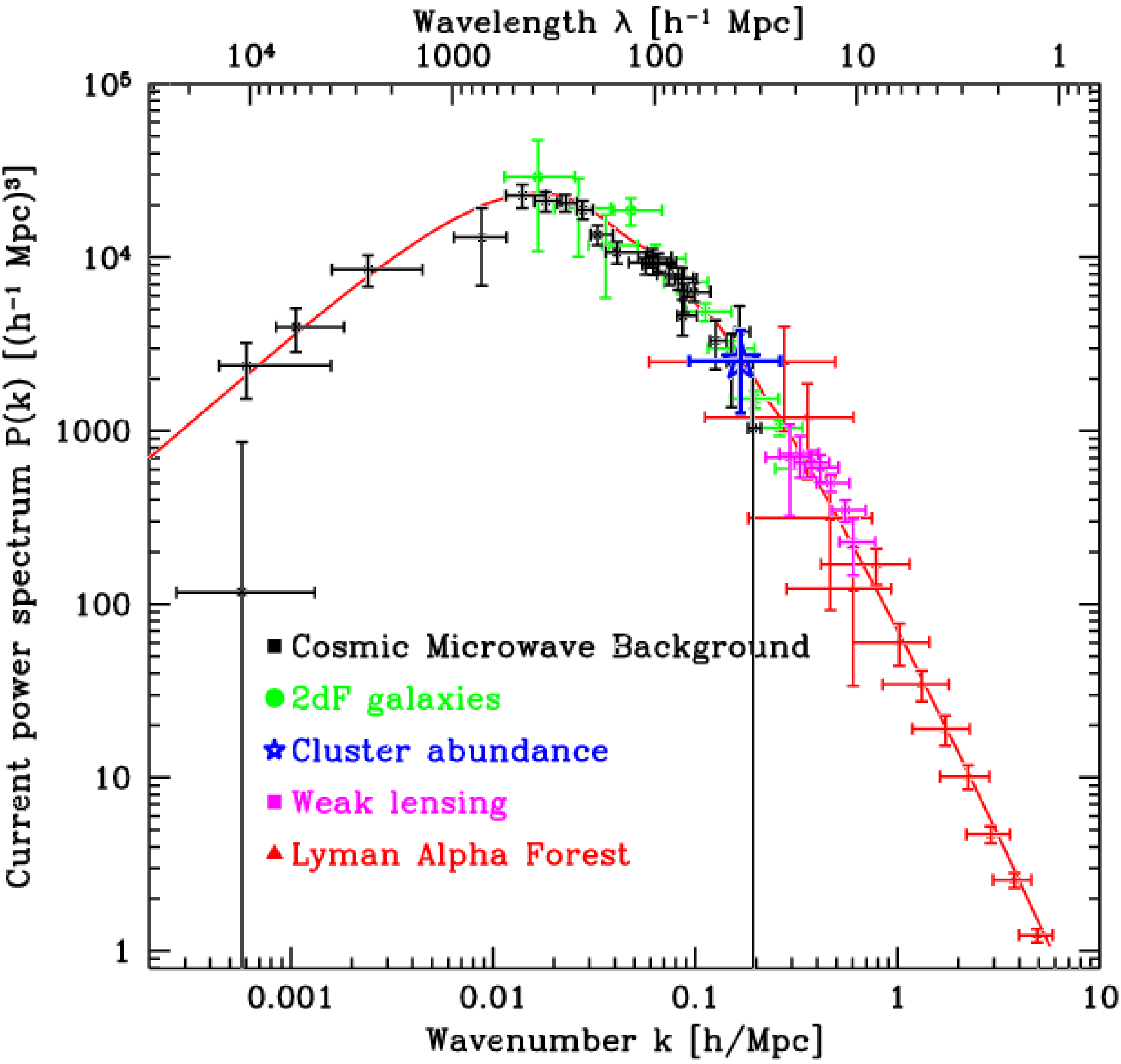
$\rightarrow$ cosmic gas distribution out to large distances

$\rightarrow$ possible to access the very small scales

– Weak gravitational lensing data:

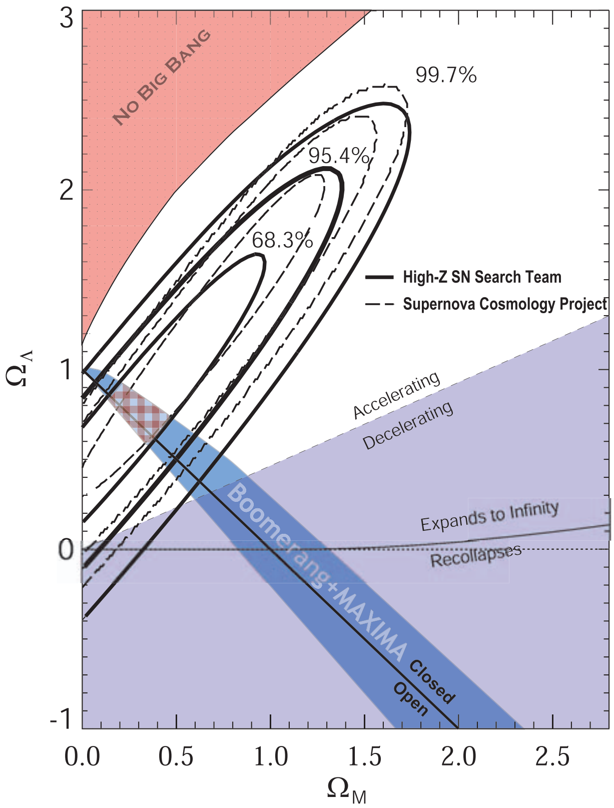
measure the shear (distortion) in the images of distant objects due to the gravitational potential of the intervening matter $\rightarrow$ matter distribution along the line of sight

A compilation of present data (before WMAP)



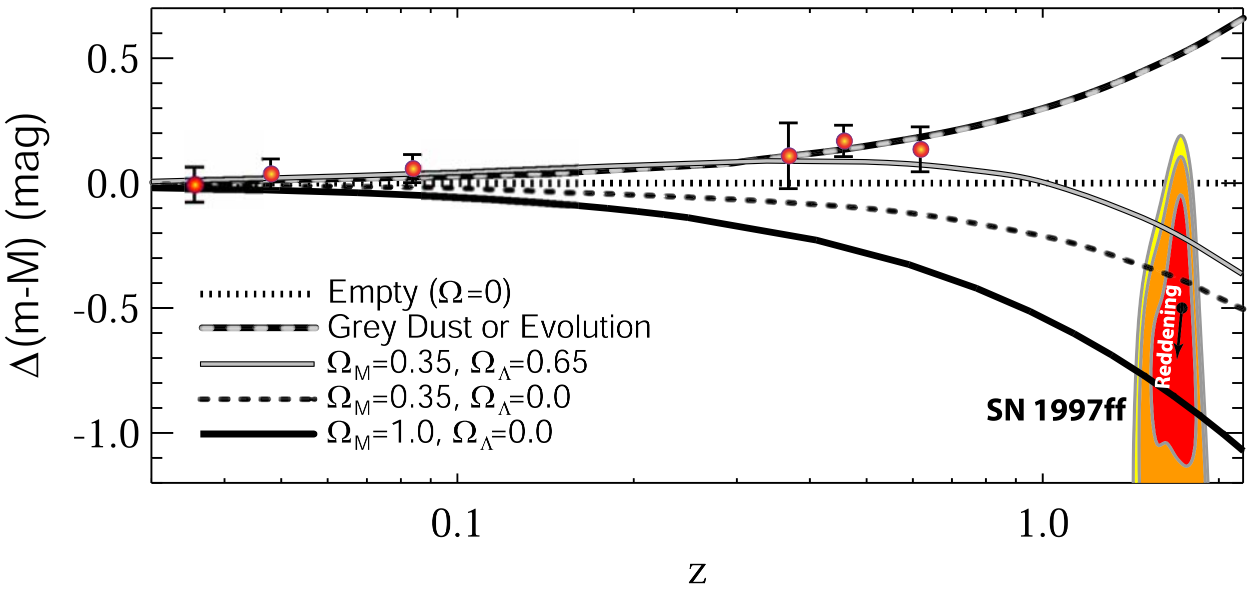
Tegmark & Zaldarriaga, PRD66 (2002) 103508, astro-ph/0207047

SN–IA:
statistics improved, but results basically unchanged from last year



The collaborations are looking for other SN, especially at large redshifts.

A. Riess et al., Ap. J. 560 (2001) 49



THE COSMOLOGICAL PARAMETERS

“Best” Cosmological Parameters:
Table 3 from ***Wilkinson Microwave Anisotropy Probe (WMAP)* Observations: Preliminary Maps and Basic Results**,
C. L. Bennett et al. (2003), accepted by the *Astrophysical Journal*;
available at `http://lambda.gsfc.nasa.gov/`

Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	T_{cmb}	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.5}$	0.44	0.04	0.05
Power spectrum normalization (at $k_0 = 0.05$ Mpc^{-1})[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05$ Mpc^{-1})[c]	n_s	0.93	0.03	0.03
Running index slope (at $k_0 = 0.05$ Mpc^{-1})[c]	$dn_s/d\ln k$	-0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc^{-1})	r	< 0.90	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	195	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2
Age at decoupling (kyr)	t_{dec}	379	8	7
Age at reionization (Myr, 95% CL))	t_r	180	220	80
Decoupling time interval (kyr)	Δt_{dec}	118	3	2
Redshift of matter-energy equality	z_{eq}	3233	194	210
Reionization optical depth	τ	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_r	20	10	9
Sound horizon at decoupling (°)	θ_A	0.598	0.002	0.002
Angular diameter distance to decoupling (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale[d]	ℓ_A	301	1	1
Sound horizon at decoupling (Mpc)[d]	r_s	147	2	2

[a] from *COBE* (Mather, J. C. et al., 1999, ApJ, 512, 511)

[b] derived from *COBE* (Mather, J. C. et al., 1999, ApJ, 512, 511)

[c] $l_{\mathrm{eff}} \approx 700$

[d] $\ell_A \equiv \pi \theta_A^{-1} \quad \theta_A \equiv r_s\, d_a^{-1}$

Total matter density

The position of the first peak on the CMB power spectrum measures directly the geometry of the universe and therefore the total matter density.

Global fit: $\Omega_{tot} = 1.02 \pm 0.2$

WMAP: Spergel et al. '03

consistent with Boomerang and Maxima !

CDM density

CMB is less sensitive to the matter density, due to a degeneracy with h; a constraint comes from combining with SN-IA or the measure of H_0.

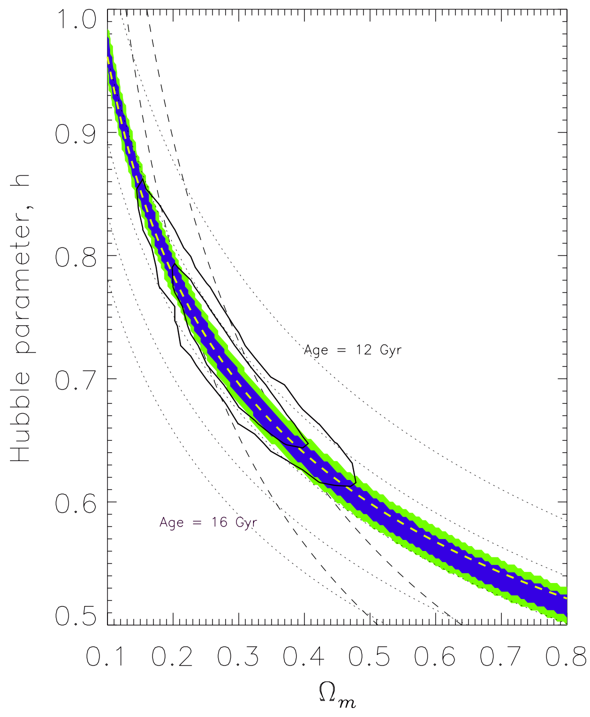


figure from WMAP: Bennett et al. '03

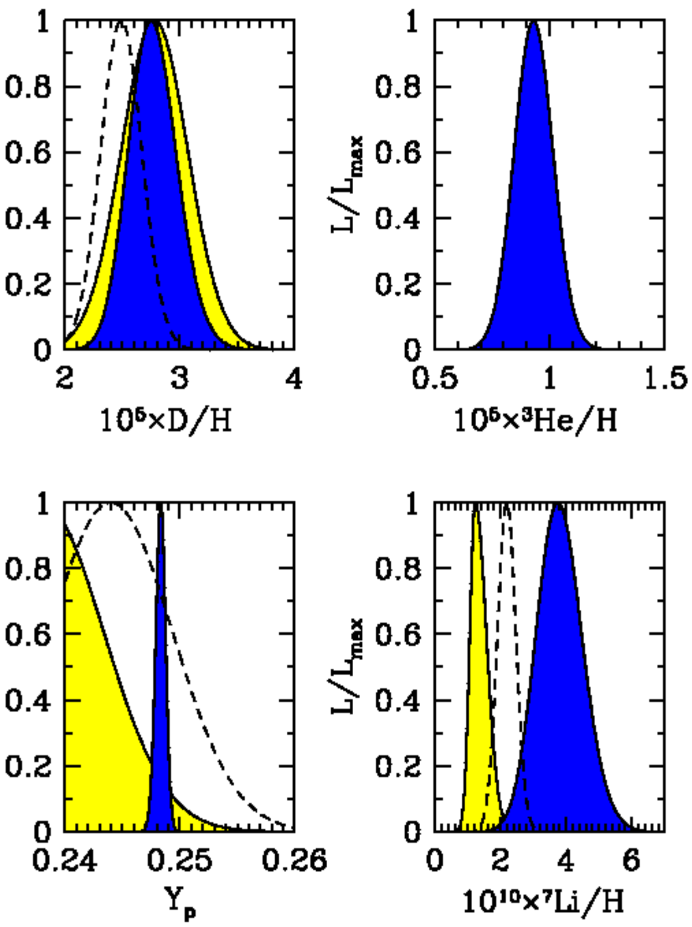
Baryon content

Very precise measurement of the baryon density from the relative odd and even peak height !

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

WMAP: Spergel et al. '03

Fully consistent with the Deuterium abundance from Nucleosynthesis and much more precise. Some tension with He^4 and Li^7 abundances.



WMAP prediction

DATA:
yellow and
– – – – –

Cyburt, Fields & Olive, astro-ph/0302431

Upper bound on the density of Hot DM

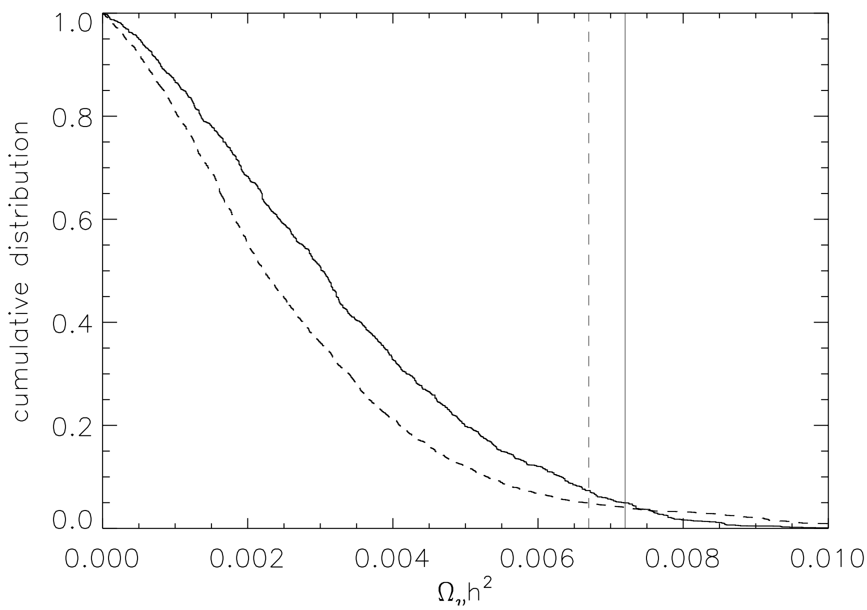
Hot DM consist of relativistic particles with a relatively large free-streaming length

$$\lambda_{FS} \simeq 1200/m_{\mathrm{eV}} \;\; \mathrm{Mpc}$$

where m_{eV} is the mass of the particle

HDM influences strongly structure formation since it suppresses power at scales smaller than λ_{FS}.

$\rightarrow$ stronger bound comes from LSS !



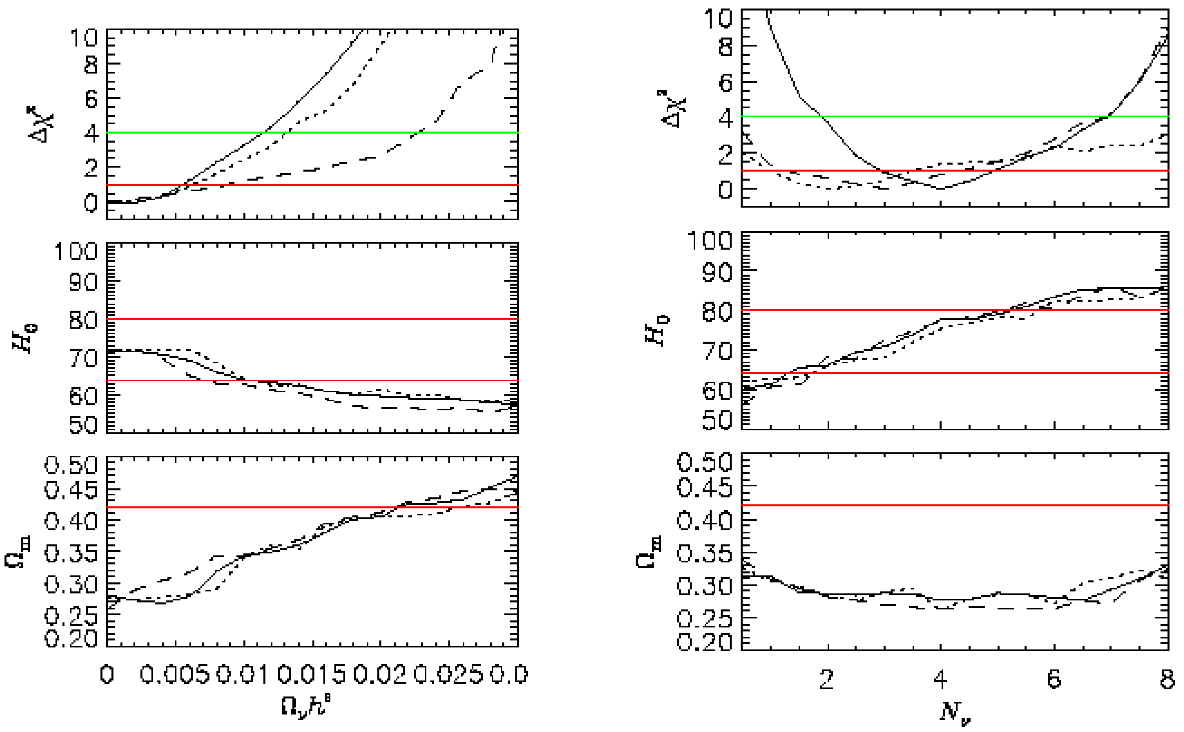
WMAP: Bennett et al. '03

For 3 degenerate neutrinos then at 98% CL one has

$$\Omega_\nu h^2 \leq 0.0076 \quad \Rightarrow \quad m_\nu \leq 0.23\,\mathrm{eV}$$

CAVEATS:

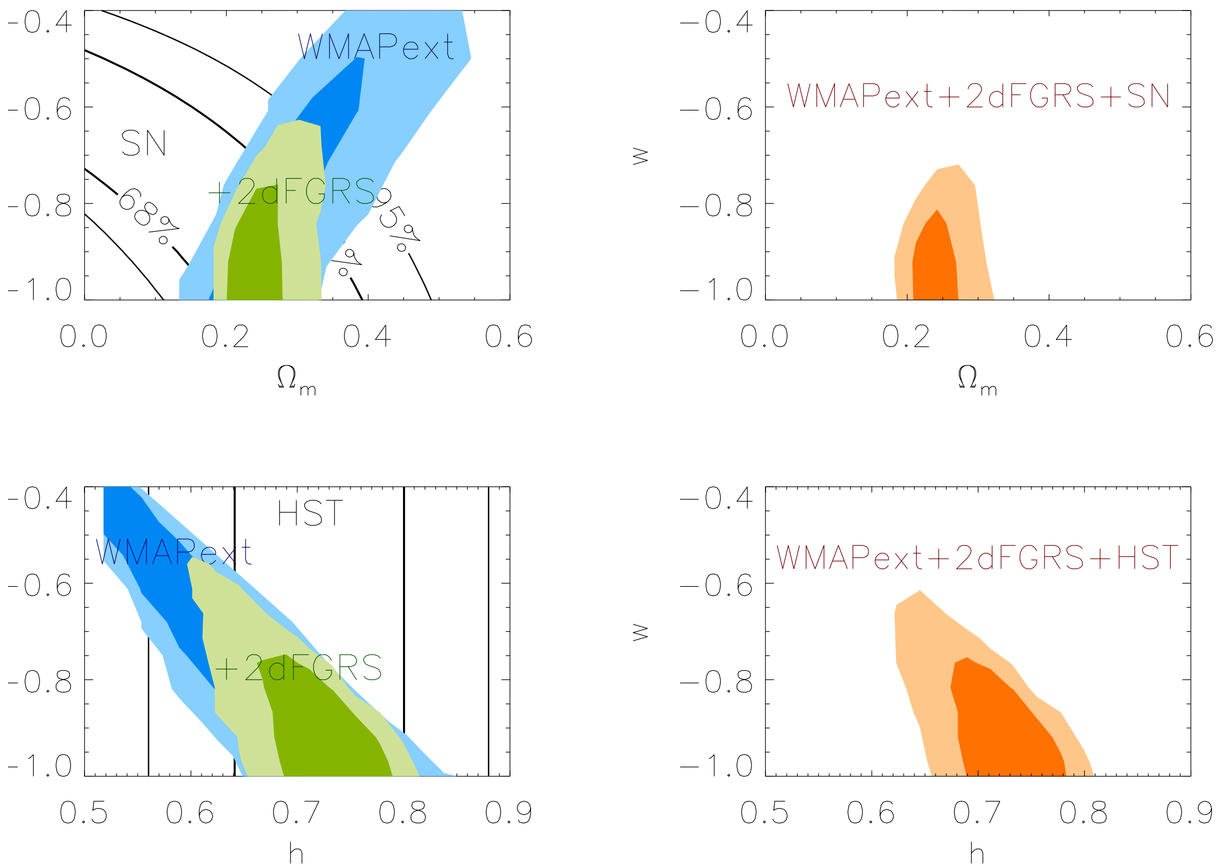
The limit strongly depends on the cosmological parameters and also the number of neutrinos:



S. Hannestad, JCAP 05 (2003) 004, astro-ph/0303076

And it is degenerate with the "running" of the spectral index.

Dark energy and its equation of state



WMAP: Spergel et al. '03

THE PRIMORDIAL SPECTRUM AND INFLATION

INFLATION: period of very fast expansion of the scale factor R, that solves some of the problems of the Standard Cosmology, like

Flatness — Isotropy/Homogeneity

Unwanted Relics — LSS....

How to obtain inflation ???

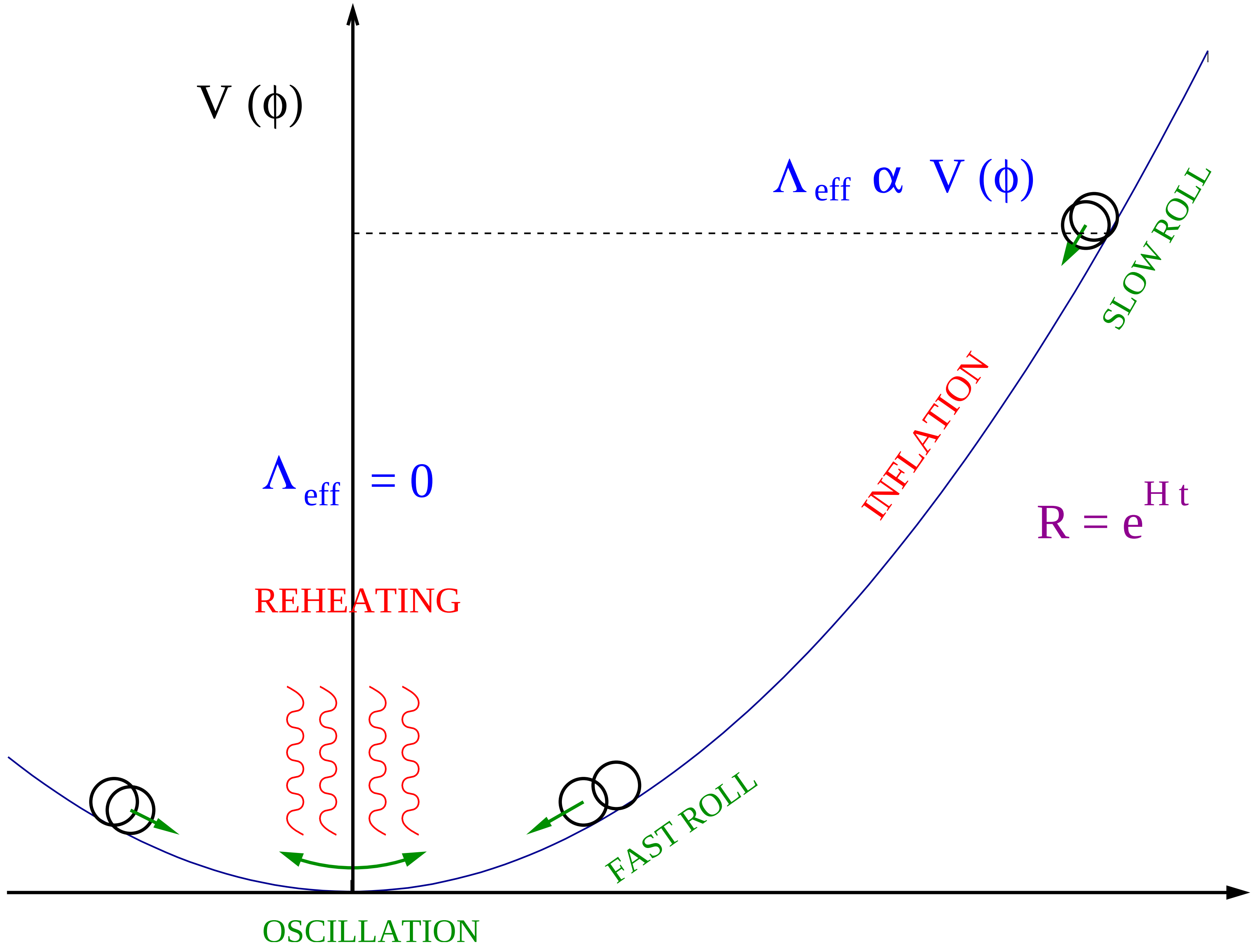
$\Rightarrow$ USE THE POTENTIAL ENERGY DENSITY OF A SCALAR FIELD ϕ AS AN <u>EFFECTIVE</u> COSMOLOGICAL CONSTANT:

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G\rho \simeq \frac{8\pi}{3} G V(\phi)$$

To have the effect of a constant $V(\phi)$ MUST be slowly varying

$\Rightarrow$ The scalar field has to slow roll towards the minimum ! $\Rightarrow$ ALMOST FLAT POTENTIAL

$$\ddot{\phi} \ll 3H\dot{\phi} \;\rightarrow\; 3H\dot{\phi} = -V'$$


V (ϕ)
Λ eff α V (ϕ)
SLOW ROLL
INFLATION
R = e H t
Λ eff = 0
REHEATING
FAST ROLL
OSCILLATION

(Single field) inflationary model

$$\Updownarrow$$

Flat Potential $V(\phi)$

- SLOW ROLL:

$$\begin{cases} \epsilon & = & \frac{1}{2M_P^2}\left(\frac{V'}{V}\right)^2 \ll 1 \\ |\eta| & = & \frac{1}{M_P^2}\frac{|V''|}{V} \ll 1 \end{cases}$$

- Enough expansion:

$$\mathcal{N} = \int_{t_i}^{t_f} dt H = \int_{\phi_f}^{\phi_i} d\phi \frac{V(\phi)}{M_P^2 V'(\phi)} > 50$$

- Sufficient reheating before Big Bang Nucleosynthesis:

$$T_{rh} > 1\text{MeV}$$

Huge number of models:

old inflation, new inflation, chaotic inflation, hybrid inflation, smooth inflation, topological inflation, ...

Quantum fluctuation of the inflaton

The inflaton rolls classically towards the minimum of the potential...

... but ϕ is a quantum field and in a de Sitter background its quantum fluctuations are given by

$$\delta\phi \simeq \frac{H}{2\pi} \qquad \text{GAUSSIAN}$$

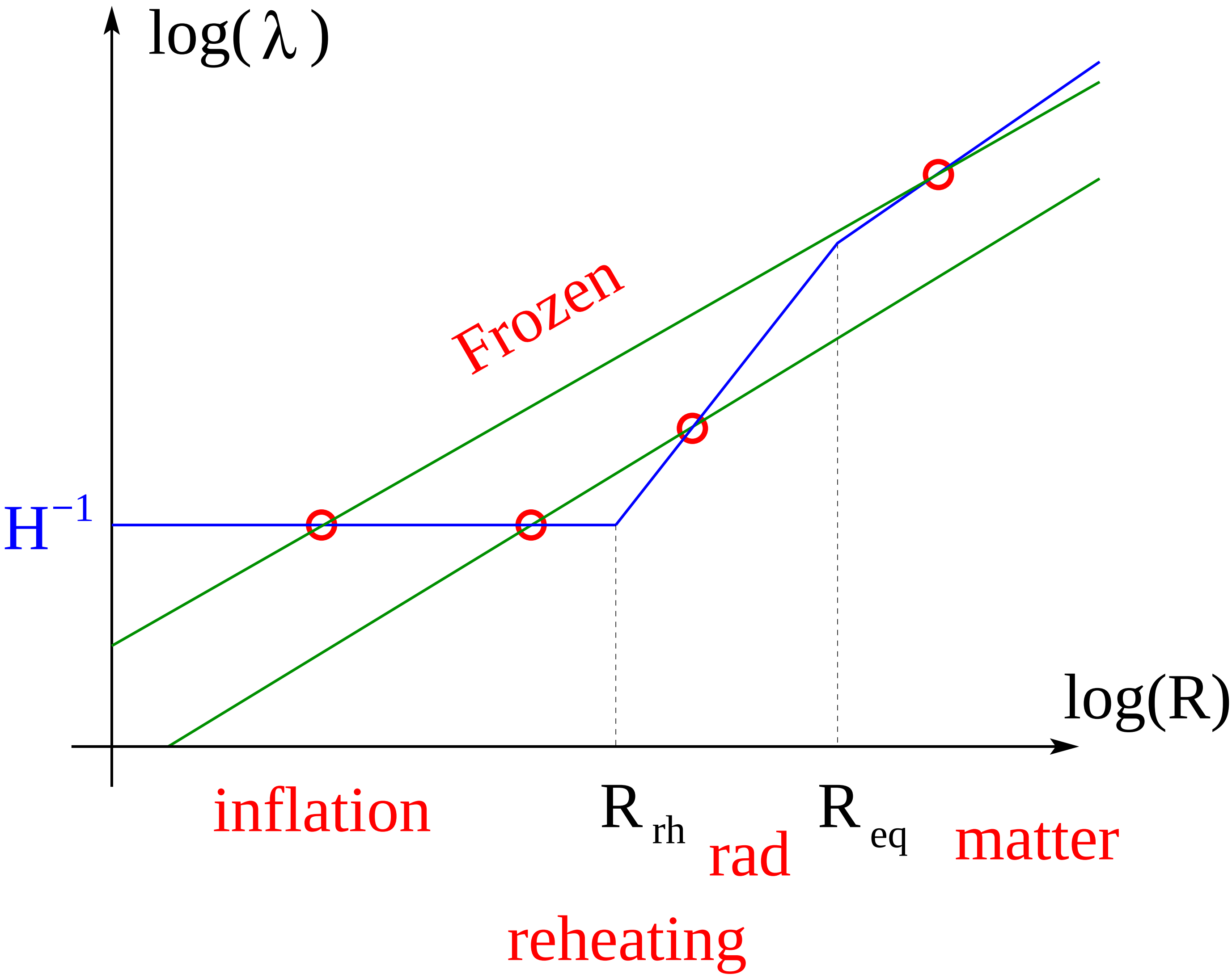
So the dynamics of the inflaton is slightly different in different parts of the universe and this generates density fluctuations:

$$\frac{\delta\rho}{\rho} \simeq H\delta t \simeq H\frac{\delta\phi}{\dot{\phi}} \simeq \frac{H^2}{2\pi\dot{\phi}}$$

$$\Downarrow$$

Primordial power spectrum of the curvature perturbations $\mathcal{P}$

INITIAL CONDITION FOR STRUCTURE FORMATION $\mathcal{P}(k) \Longrightarrow P(k)$



The amplitude of the density fluctuations at a scale λ is given by $\frac{H^2}{2\pi\dot{\phi}}$ computed at the time $\lambda = H^{-1}$.

If H and $\dot{\phi}$ were exactly constant during inflation, all the wavelenghts would have exactly the same amplitude

$\Rightarrow$ SCALE INVARIANT SPECTRUM (nearly !!!)

Inflationary predictions

- $\Omega_{tot} = 1$ FLAT UNIVERSE

  (with few exceptions...)

- Gaussian and adiabatic primordial perturbations

- Nearly scale-invariant spectrum of the primordial perturbations related to the inflaton potential (first order Slow Roll approximation):

  - scalar perturbations have power spectrum:

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{1}{12\pi^2 M_P^6} \frac{V^3}{V'^2}\bigg|_{k=aH} \qquad \propto k^{n-1}$$

  and spectral index:

$$n(k) - 1 = \frac{d\log(\mathcal{P}_{\mathcal{R}})}{d\log(k)}\bigg|_{k=aH} = 2\eta - 6\epsilon + \ldots$$

  - tensor perturbations have power spectrum

$$\mathcal{P}_{grav}(k) = \frac{1}{6\pi^2} \frac{V}{M_P^4}\bigg|_{k=aH}$$

  and spectral index

$$n_{grav}(k) = \frac{d\log(\mathcal{P}_{grav})}{d\log(k)}\bigg|_{k=aH} = -2\epsilon + \ldots$$

CMB observations agree with the (single field) inflationary predictions !

- $\Omega_{tot} = 1.02 \pm 0.2$

WMAP: Spergel et al.'03

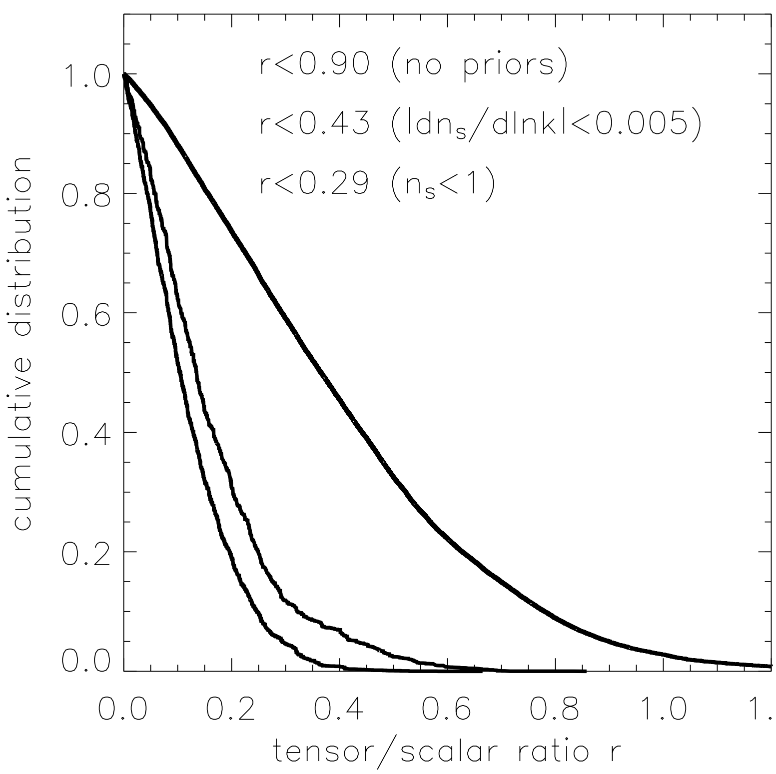
- the power spectrum is consistent with gaussianity and adiabaticity ($f_{iso} \leq 0.33$)

WMAP: Komatsu et al. '03, Peiris et al. '03

- the spectral index is very near to 1, $n = 0.99 \pm 0.4$ for WMAP only

WMAP: Spergel et al.'03

- no evidence for tensor perturbation so far, so for $r = \mathcal{P}_{grav}/\mathcal{P}_{\mathcal{R}}$ one finds



WMAP: Spergel et al. '03

SURPRISE:

the data seem to prefer a "running spectral index":

$$n(k) = n(k_0) + n'(k) \ln\left(\frac{k}{k_0}\right)$$

with

$$n'(k_0) = -0.031^{+0.016}_{-0.018}$$

What is the expected $n'(k_0)$ in single field inflation ?

It arises only at second order...

$$n'(k) = \frac{2}{3}\left((n-1)^2 - 4\eta^2\right) + 2\xi$$

with

$$\xi = \frac{M_P^4}{64\pi^2}\frac{V'V'''}{V^2}$$

expect $n' \propto (n-1)^2$ or the last term ξ must be large...

$\rightarrow$ "strange" potential $V(\phi)$!

Conclusions and Outlook

The era of precision cosmology continues:

- "concordance" ΛCDM model confirmed by the new data !
- overlap between CMB and LSS data for the power spectrum allows better constraints on the models of structure formation, e.g. $\Omega_\nu h^2$
- the simple single field inflationary paradigm with negligible tensor perturbation is sufficient to describe the data
- still some puzzles are present:

  - running spectral index ?

  - spectrum at low multi-poles ?

  - reionization ?

We are looking forward to the next year with more data from WMAP, Boomerang, LSS, etc...