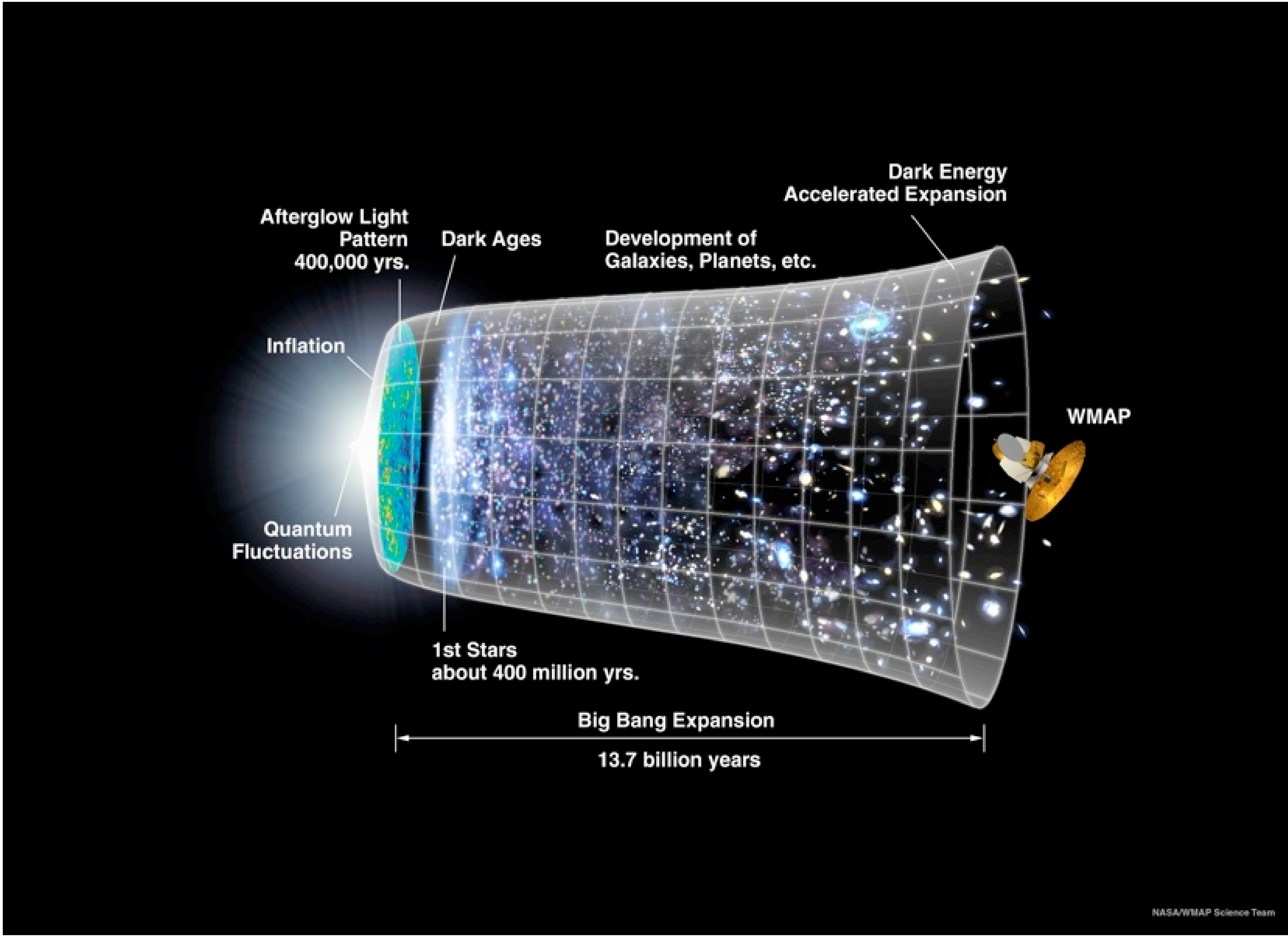
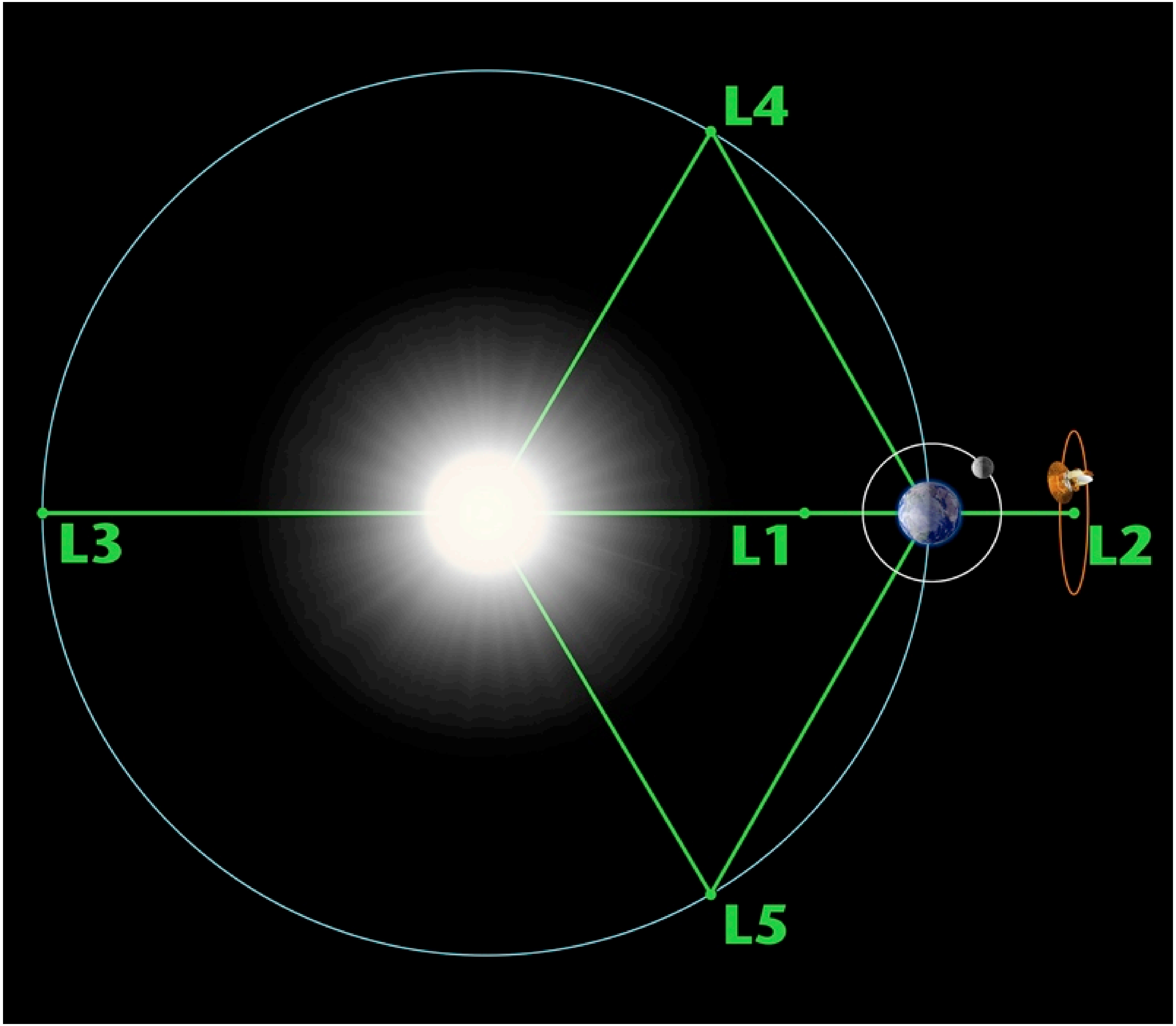
WMAP3年のデータとその意義

市川　和秀（宇宙線研究所）

第１９回「宇宙ニュートリノ」研究会


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

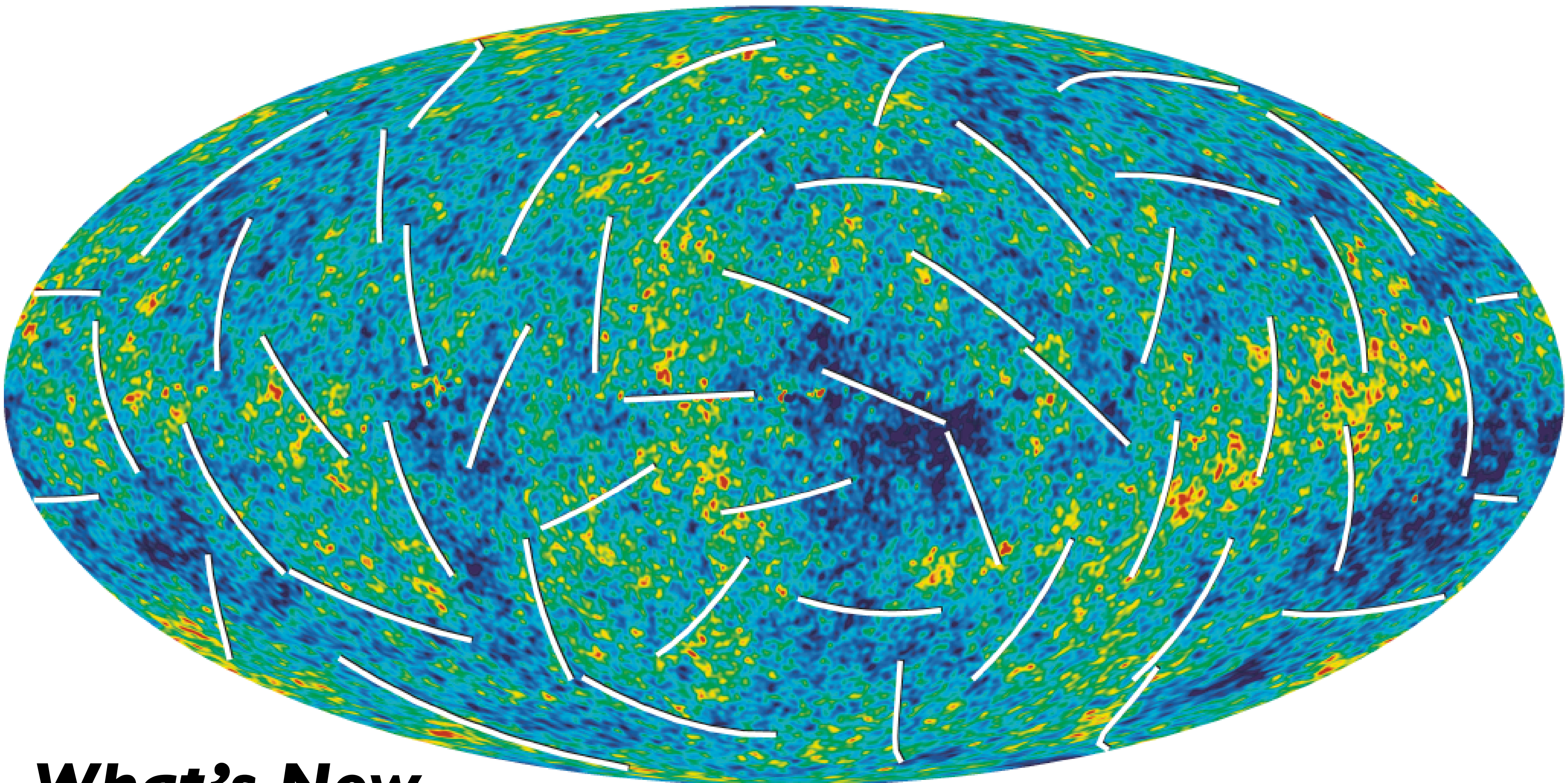

L4
L3
L1
L2
L5

WMAP: events

1993.9	First discussion on the project (Wilkinson & Bennett)
1994.3.8	Named as Microwave Anisotropy Probe (MAP)
1995.12	Proposed to NASA
1996.4	Proposal approved
2001.6.30	Launched from the Cape Canaveral by a Delta II rocket
2001.10	Arrived at L2
2002.8	Completed 1st year
2003.2.11	1st data release, renamed as WMAP
2004.8	Completed 3rd year
2006.3.16	2nd data release
(2009.9	8-years of mission will end)

Three-year WMAP full-sky map

http://wmap.gsfc.nasa.gov

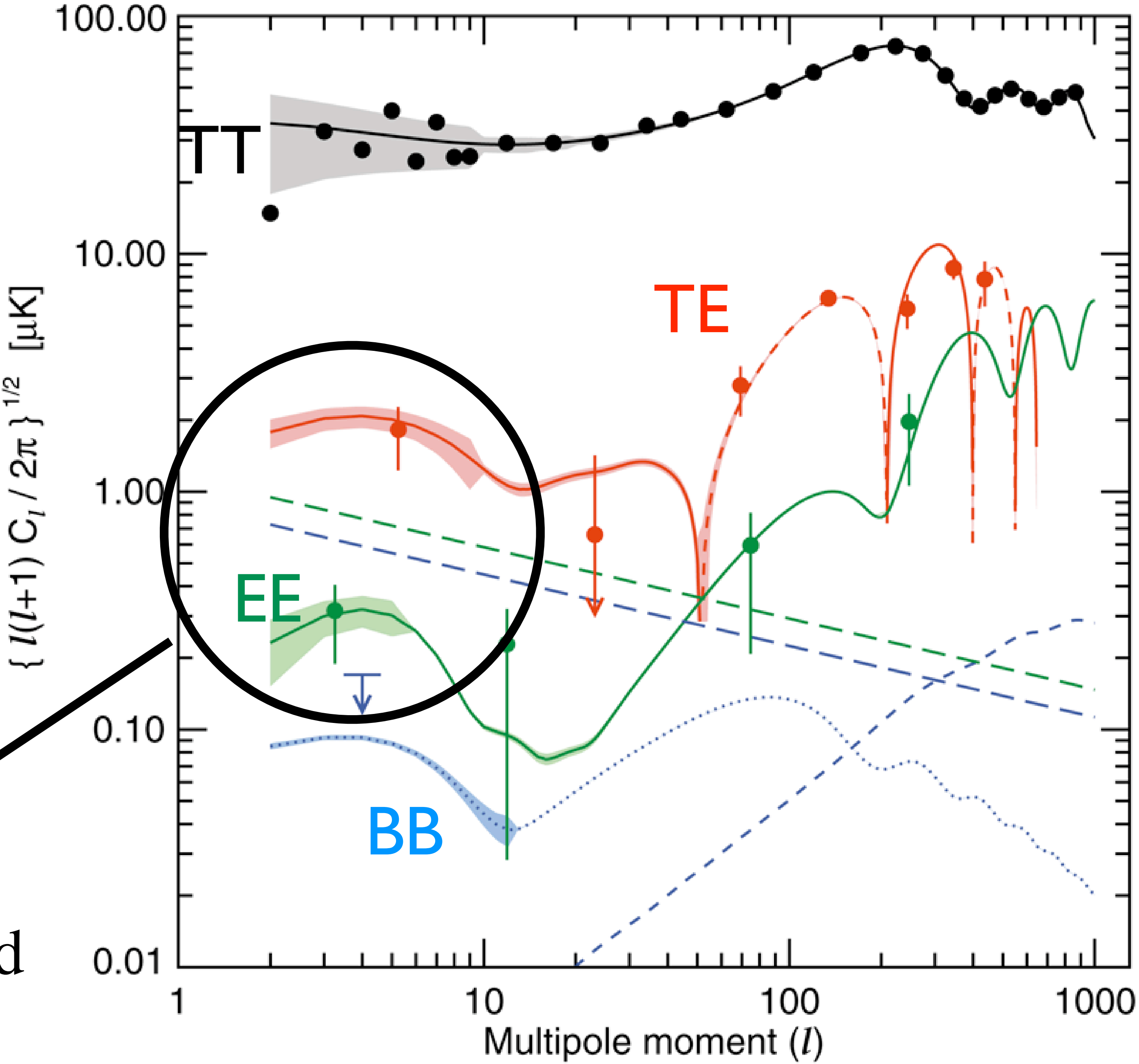


What's New

A more complete analysis of the polarization signal.

Three-year WMAP angular spectrum

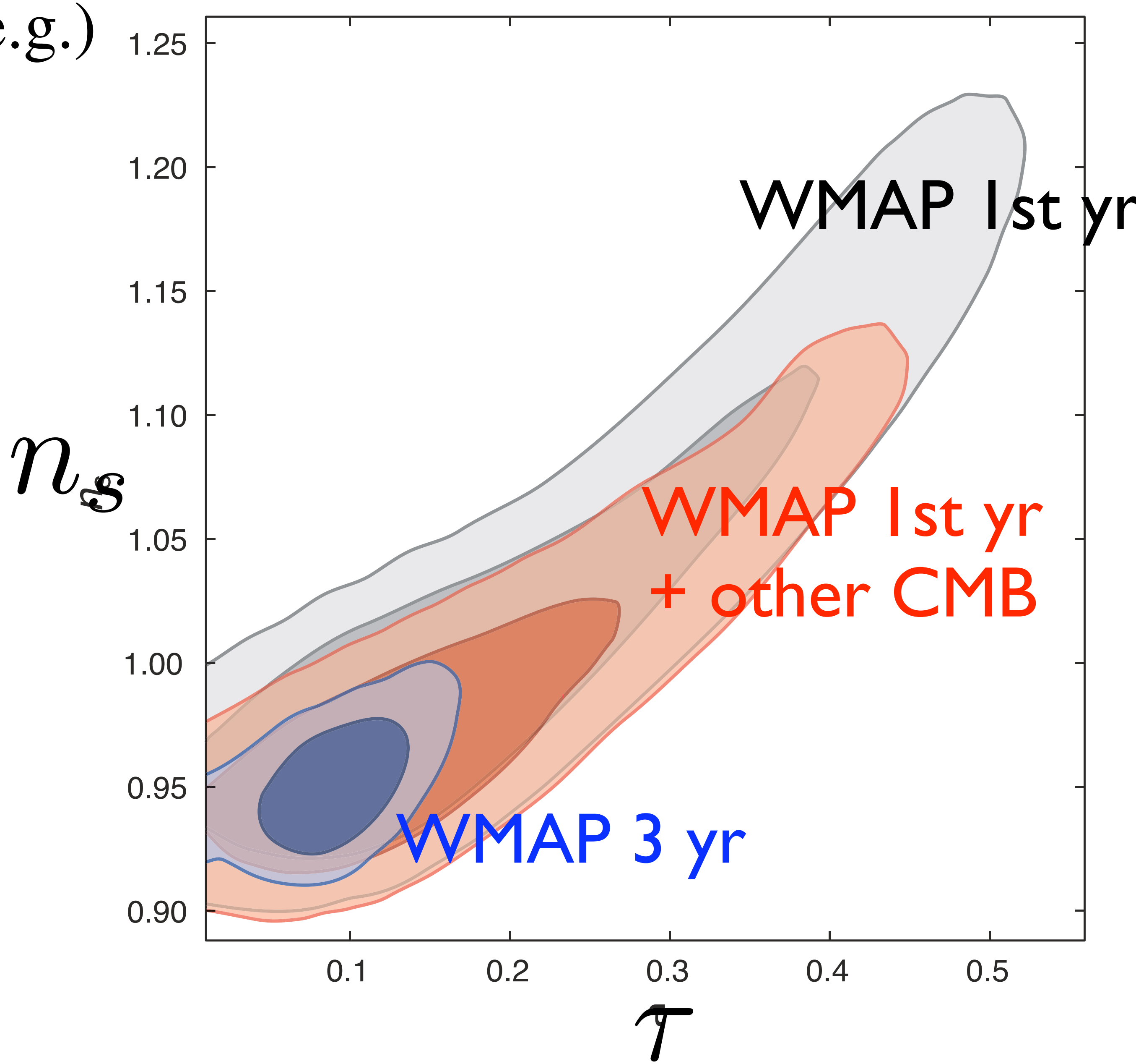
T:temperature
E,B:polarization



Evidence for reionization & τ determined accurately

Three-year WMAP cosmological parameter estimation

e.g.)



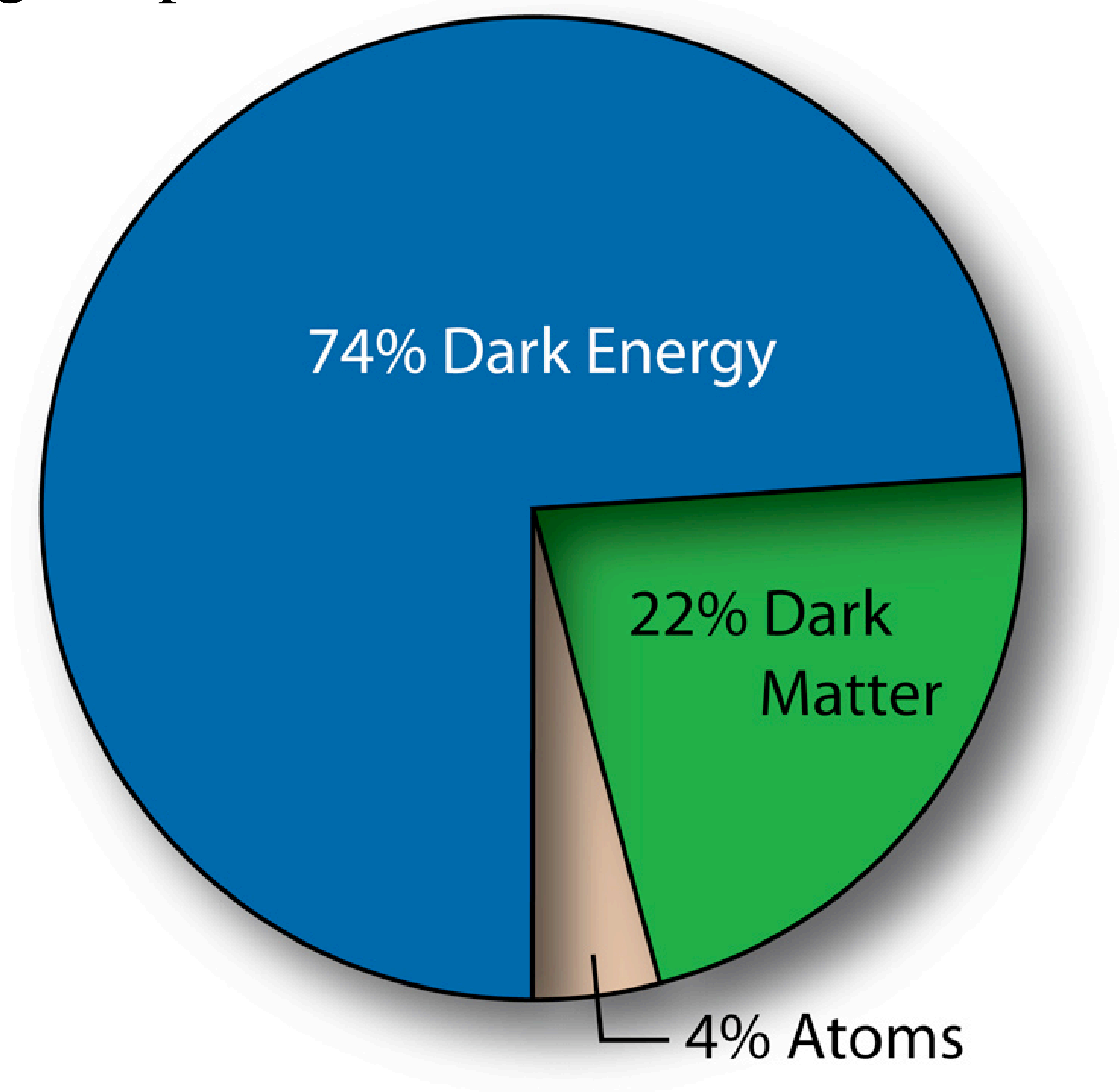
More than 50x reduction in model parameter space.

WMAP alone can now determine the parameters with precision ~ 5%.

Contents

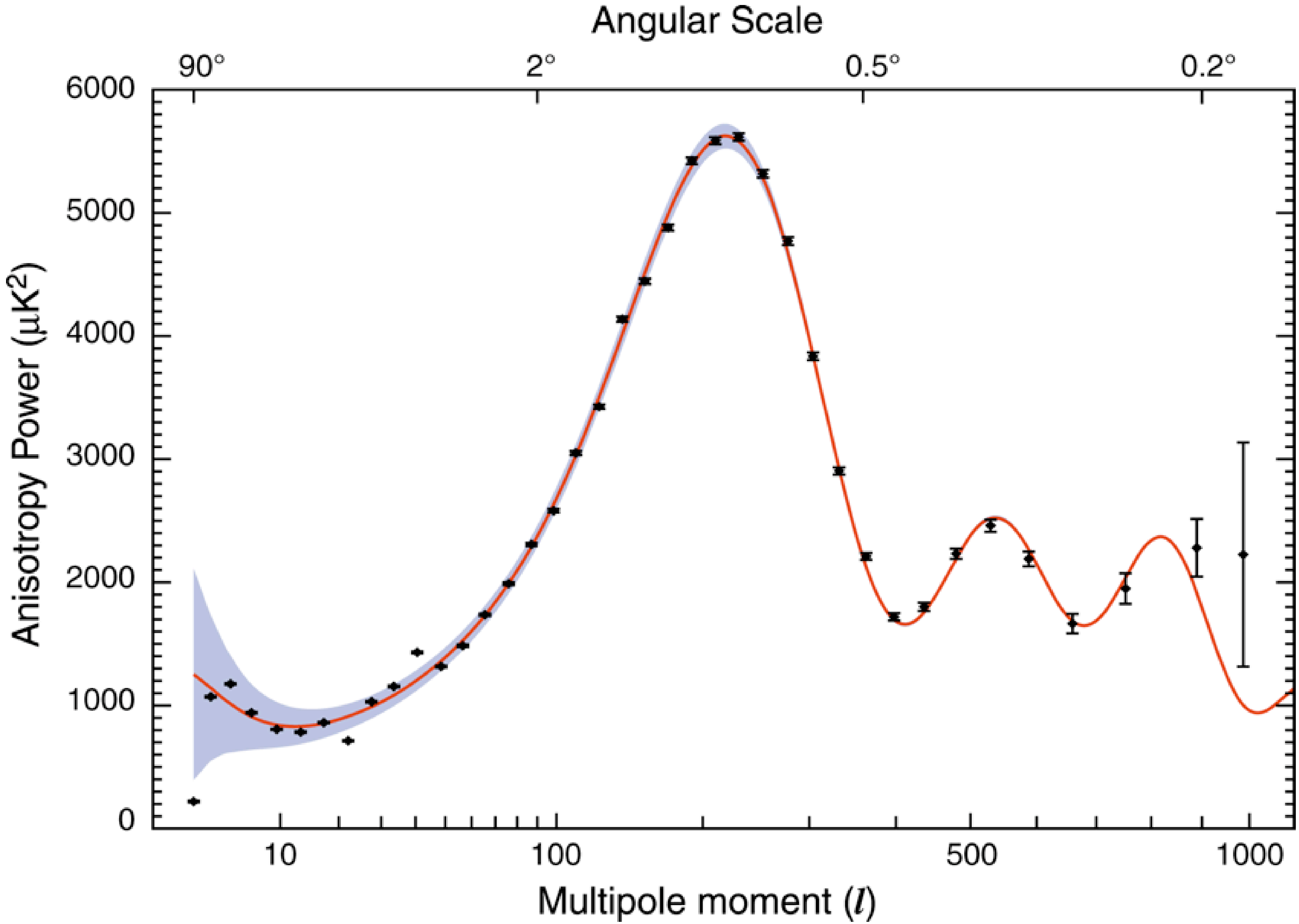
1. Implications for cosmology

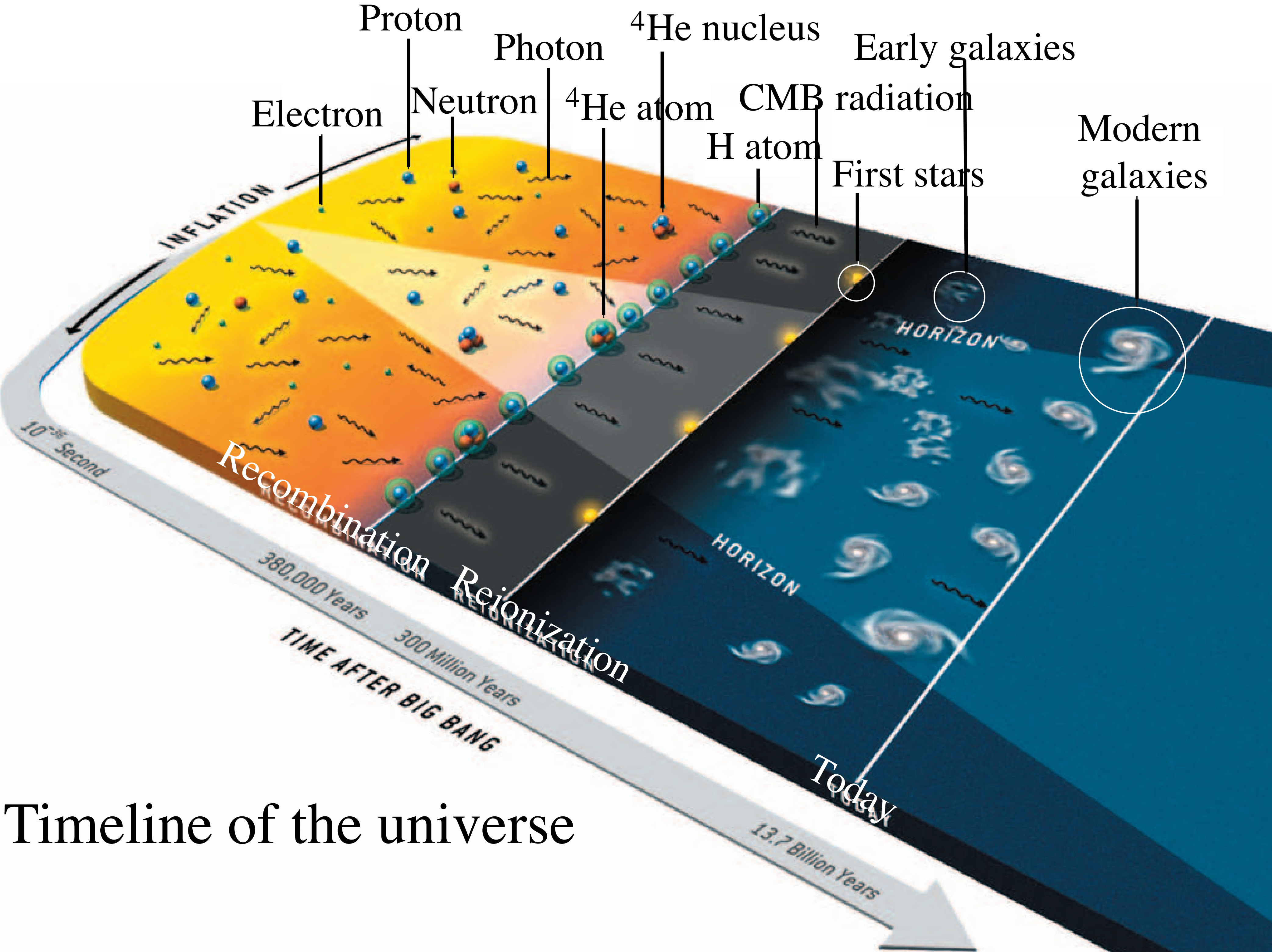
[Cosmological parameter estimation]



CMB angular spectrum

Almost all information comes from "TT" correlation.





Timeline of the universe

Standard model of cosmology

1. Cosmic expansion (Hubble's law)
2. BBN (He4, D, Li7)
3. CMB (COBE/FIRAS) & its anisotropy (COBE/DMR)
4. Cold dark matter (galaxy clustering)
5. Inflation (flatness & horizon problem,
   seed for structure formation)
6. Recent accelerated expansion (SN Ia)
7. Reionization (GP test for high-z quasars)

which is parametrized by $(\omega_b, \omega_m, h, \tau, n_s, A)$

→ Accurately predict CMB anisotropy pattern.
Values can be determined if anisotropy is probed down to subdegree scale.

Cosmological parameters (for "pow-law ΛCDM" universe)

h : Expansion rate

Hubble constant

$$H_0 = 100\ h\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

ω_b : Baryon density

$$\omega = \Omega h^2 = \rho h^2 / \rho_c$$

ω_m : Matter density (CDM+baryon)

Critical density $\rho_c = 3H_0^2 / 8\pi G$

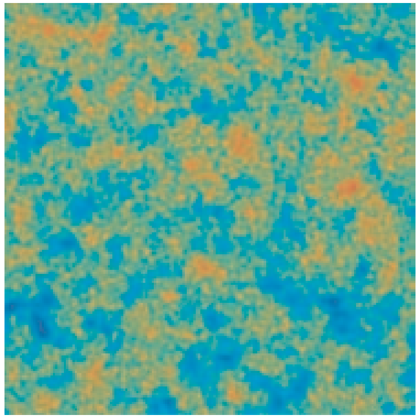
n_s : Scalar spectral index

A : Amplitude of density fluctuation

Primordial power spectrum $P(k) = Ak^{n_s - 1}$

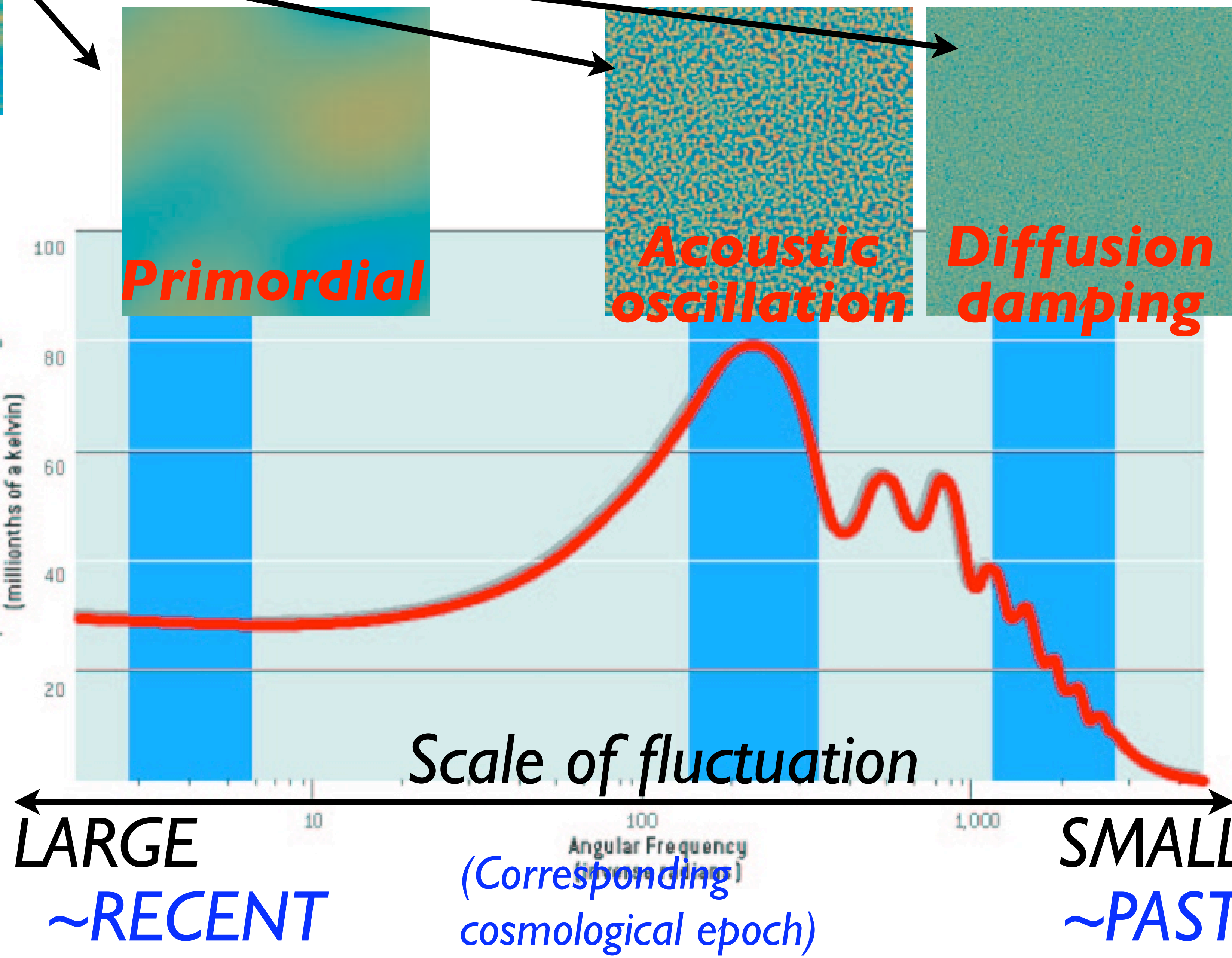
τ : Reionization optical depth

(NOTE: flat $\Omega_m + \Omega_\Lambda = 1$)

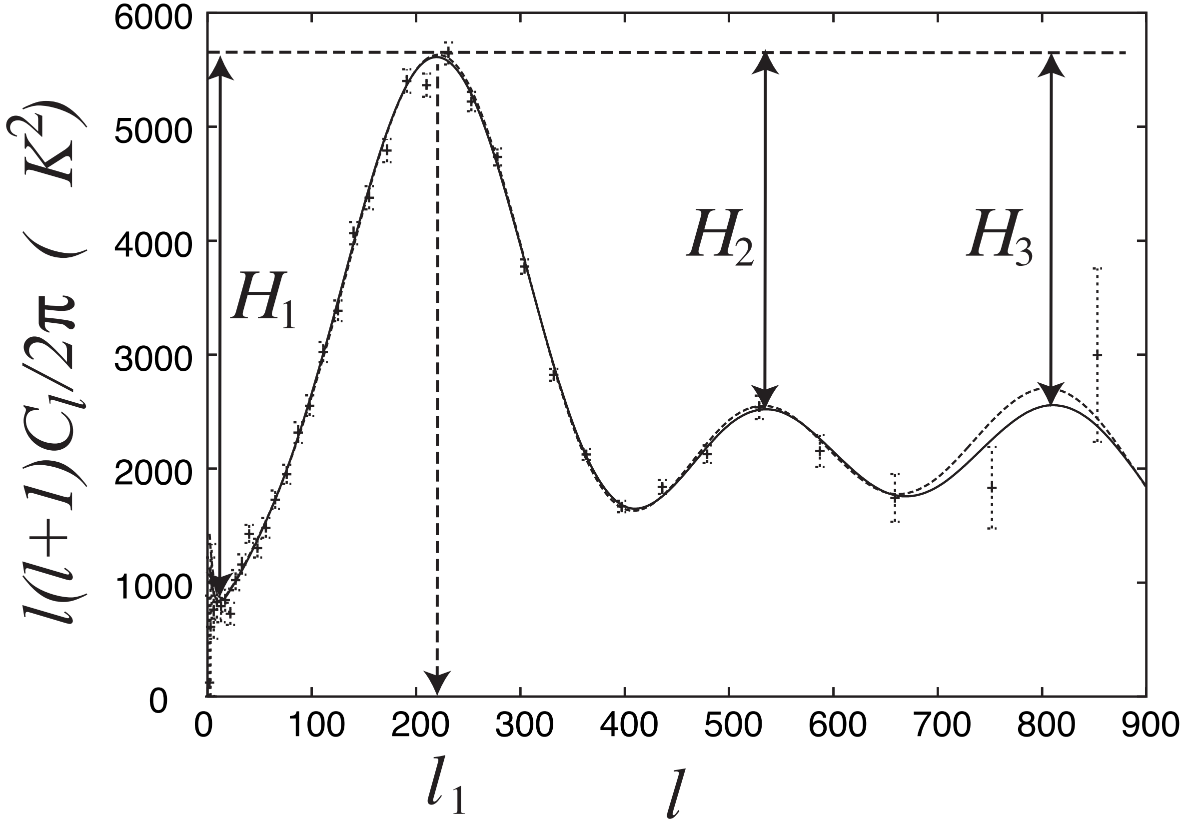


$$T(\vec{n}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\vec{n}) \qquad \langle |a_{lm}|^2 \rangle = C_l$$

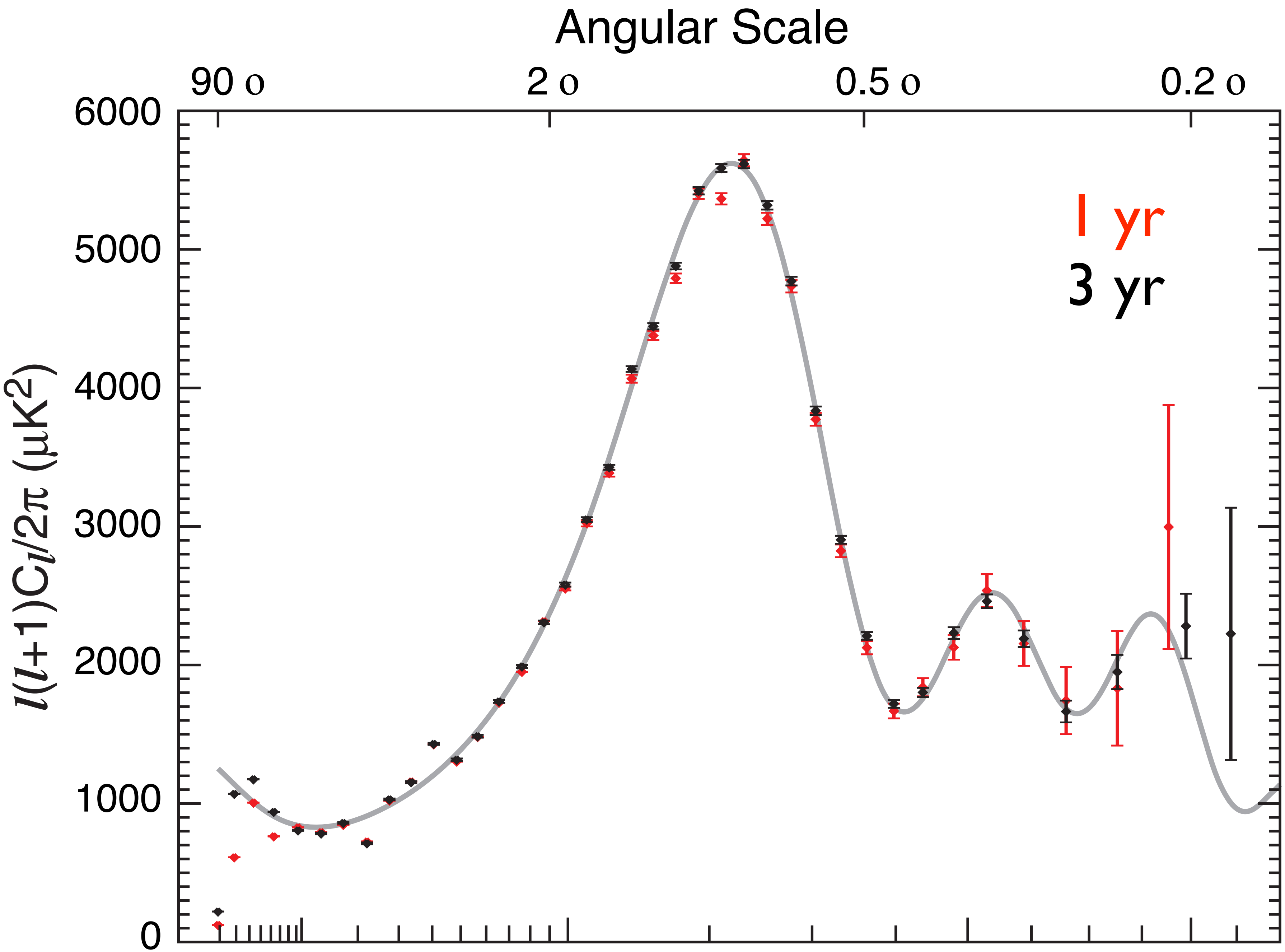
$$\frac{l(l+1)C_l}{2\pi}$$



$$\theta \sim \frac{180^\circ}{l}$$



$$
\begin{aligned}
\Delta\ell_1 &= 16\frac{\Delta\omega_b}{\omega_b} - 25\frac{\Delta\omega_m}{\omega_m} - 47\frac{\Delta h}{h} + 36\frac{\Delta n_s}{n_s}, \\
\Delta H_1 &= 3.0\frac{\Delta\omega_b}{\omega_b} - 3.0\frac{\Delta\omega_m}{\omega_m} - 2.2\frac{\Delta h}{h} - 1.7\frac{\Delta\tau}{\tau} + 18\frac{\Delta n_s}{n_s}, \\
\Delta H_2 &= -0.30\frac{\Delta\omega_b}{\omega_b} + 0.015\frac{\Delta\omega_m}{\omega_m} + 0.41\frac{\Delta n_s}{n_s}, \\
\Delta H_3 &= -0.18\frac{\Delta\omega_b}{\omega_b} + 0.21\frac{\Delta\omega_m}{\omega_m} + 0.56\frac{\Delta n_s}{n_s}.
\end{aligned}
$$



Angular Scale
90 o
2 o
0.5 o
0.2 o
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
1 yr
3 yr

WMAP Cosmological Parameters Model/Dataset Matrix

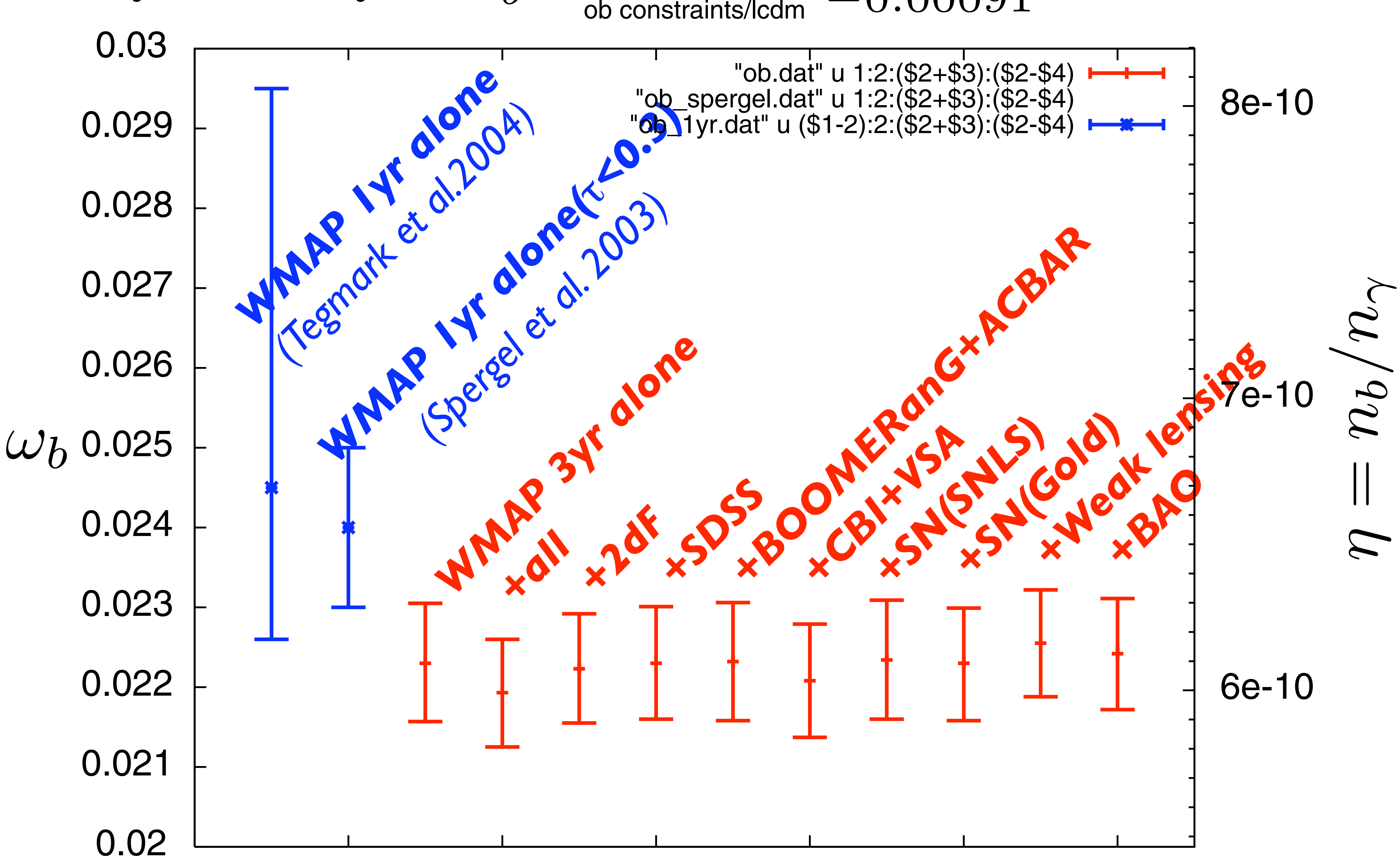
All: Galaxy clustering (2df, sdss); Other CMB (smaller scales) (boom+acbar, cbi+vsa); Supernova (sn astier, sn gold); Weak lensing (wl); Baryon acoustic oscillation (bao)

	Model	wmap	all	WMAP+ 2df	WMAP+ sdss	WMAP+ boom+ acbar	WMAP+ cbi+vsa	WMAP+ sn astier	WMAP+ sn gold	WMAP+ wl	WMAP+ bao
6 para.	**lcdm**	●	●	●	●	●	●	●	●	●	●
Inflationary GW	**lcdm+tens**	●		●	●	●	●				
Running	**lcdm+run**	●	●	●	●	●	●			●	
Neutrino mass	**cdm+mnu**	●	●	●	●						
# of relativistic species	**lcdm+nrel**		●	●	●						
Dark energy e.o.s	**wcdm+pert**	●	●		●			●	●		●

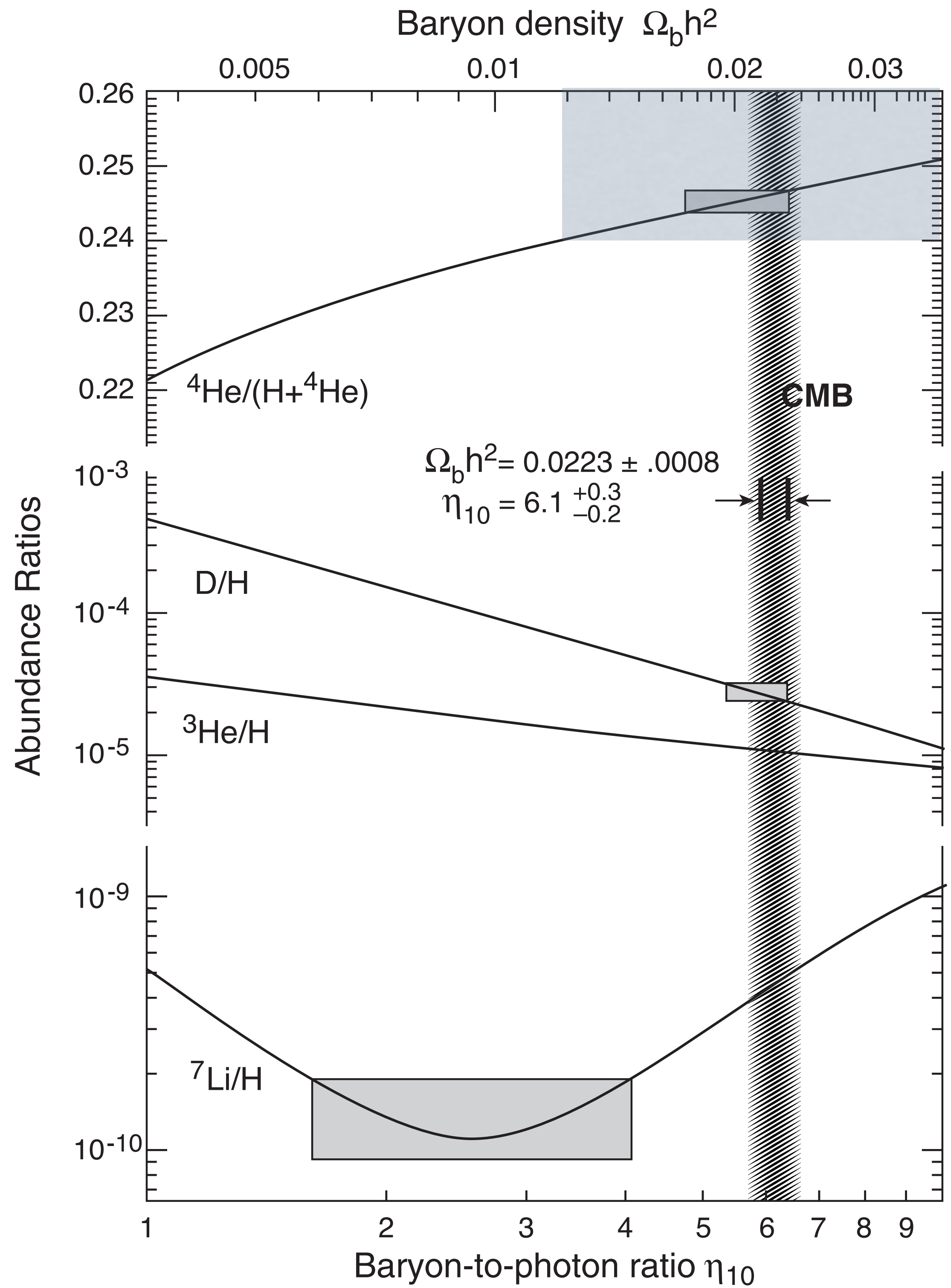
etc.

http://lambda.gsfc.nasa.gov/product/map/current/parameters.cfm

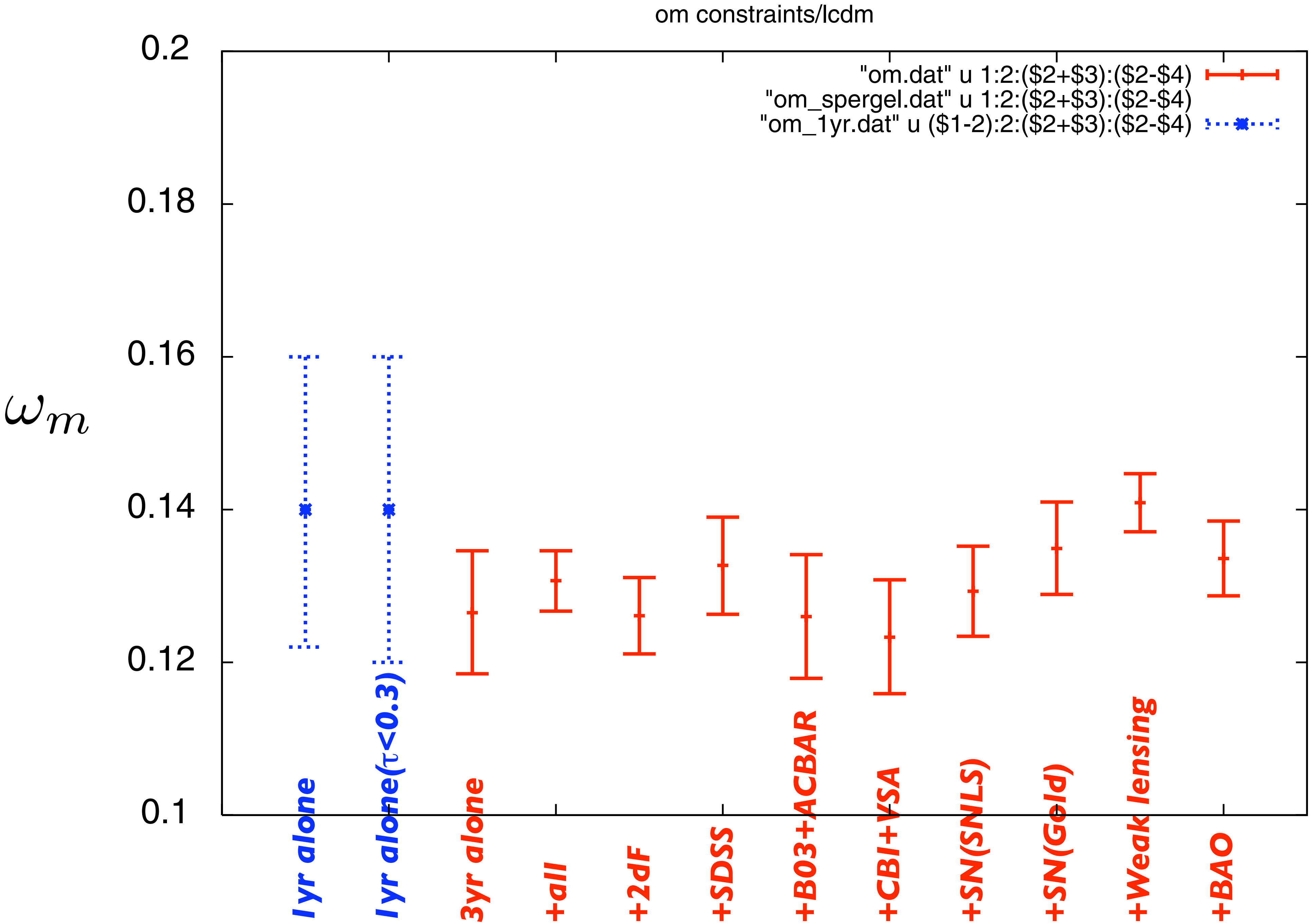
Baryon density: $\omega_b = 0.02233^{+0.00072}_{-0.00091}$



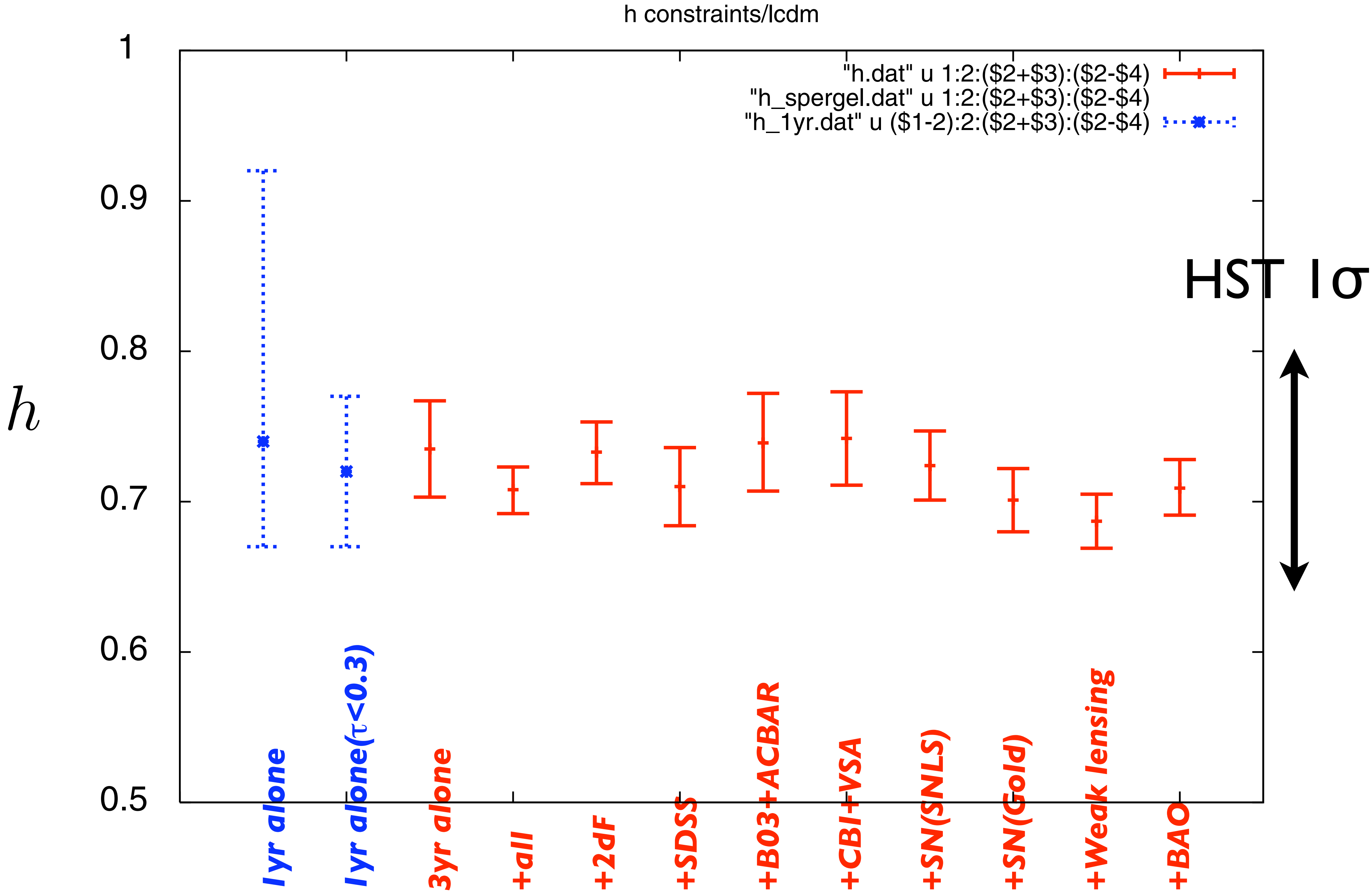
Consistent with D & He4 abundances.



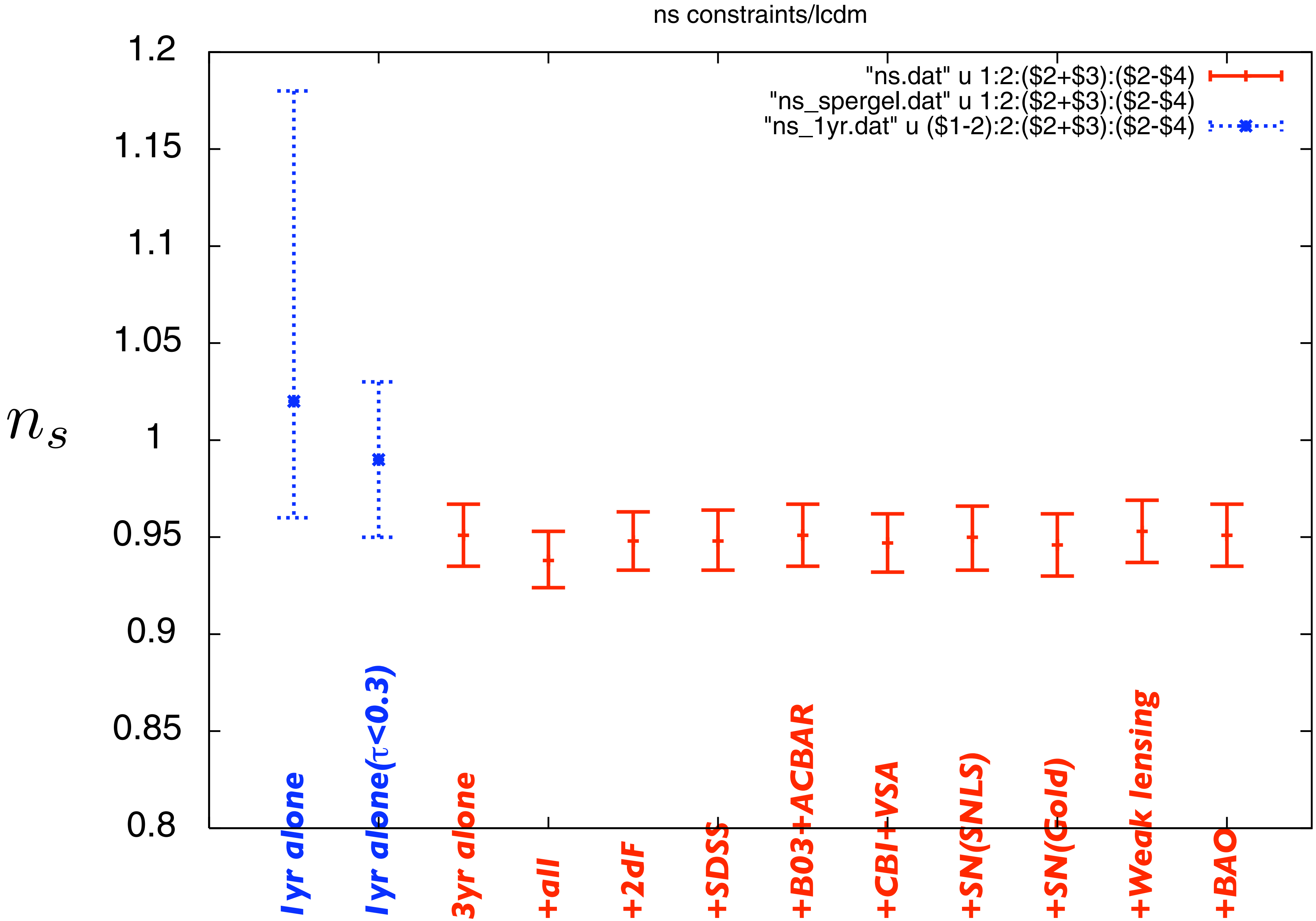
Matter density (CDM+baryon): $\omega_m = 0.1268^{+0.0073}_{-0.0128}$



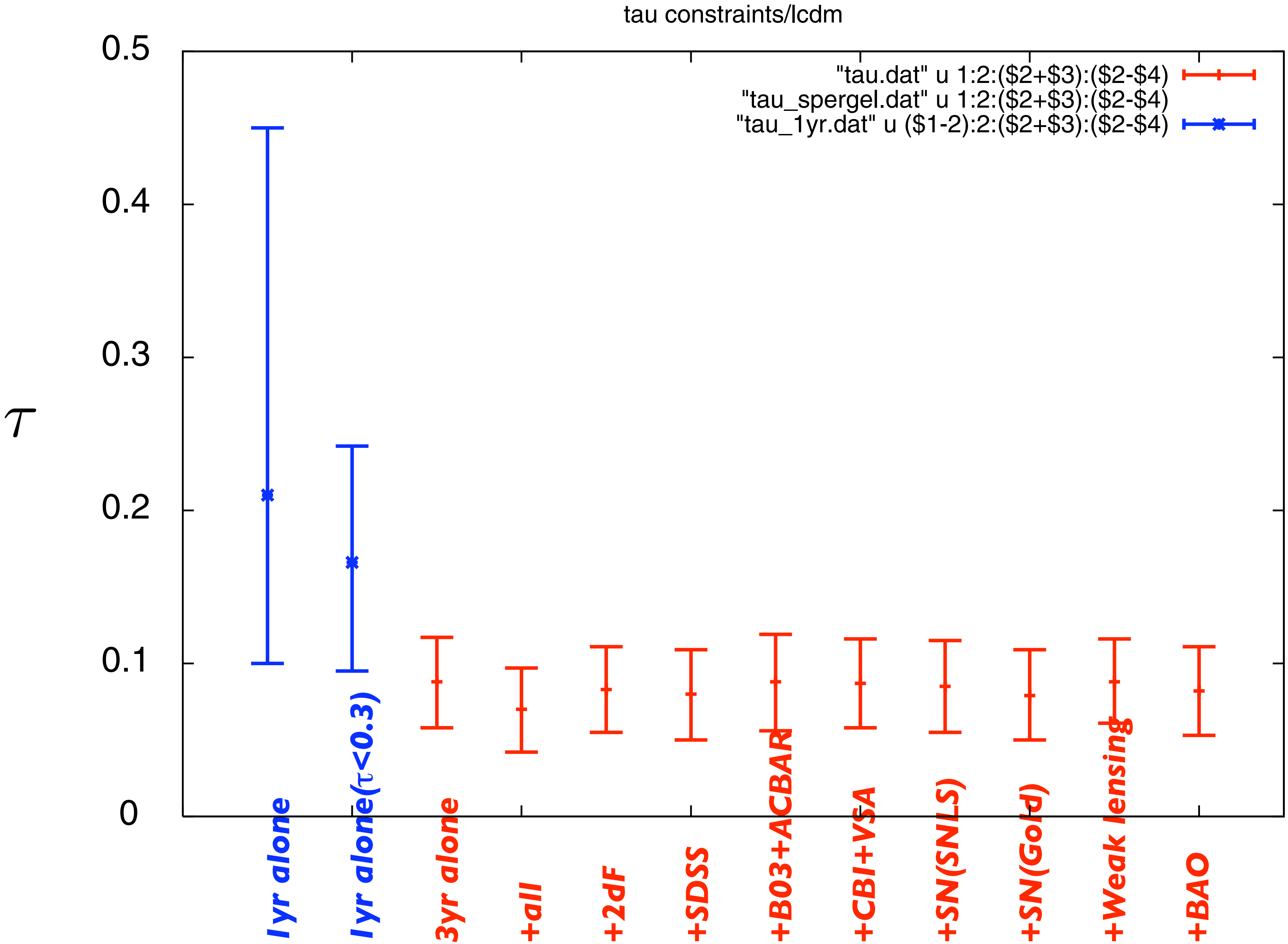
Expansion rate: $h = 0.734^{+0.028}_{-0.038}$



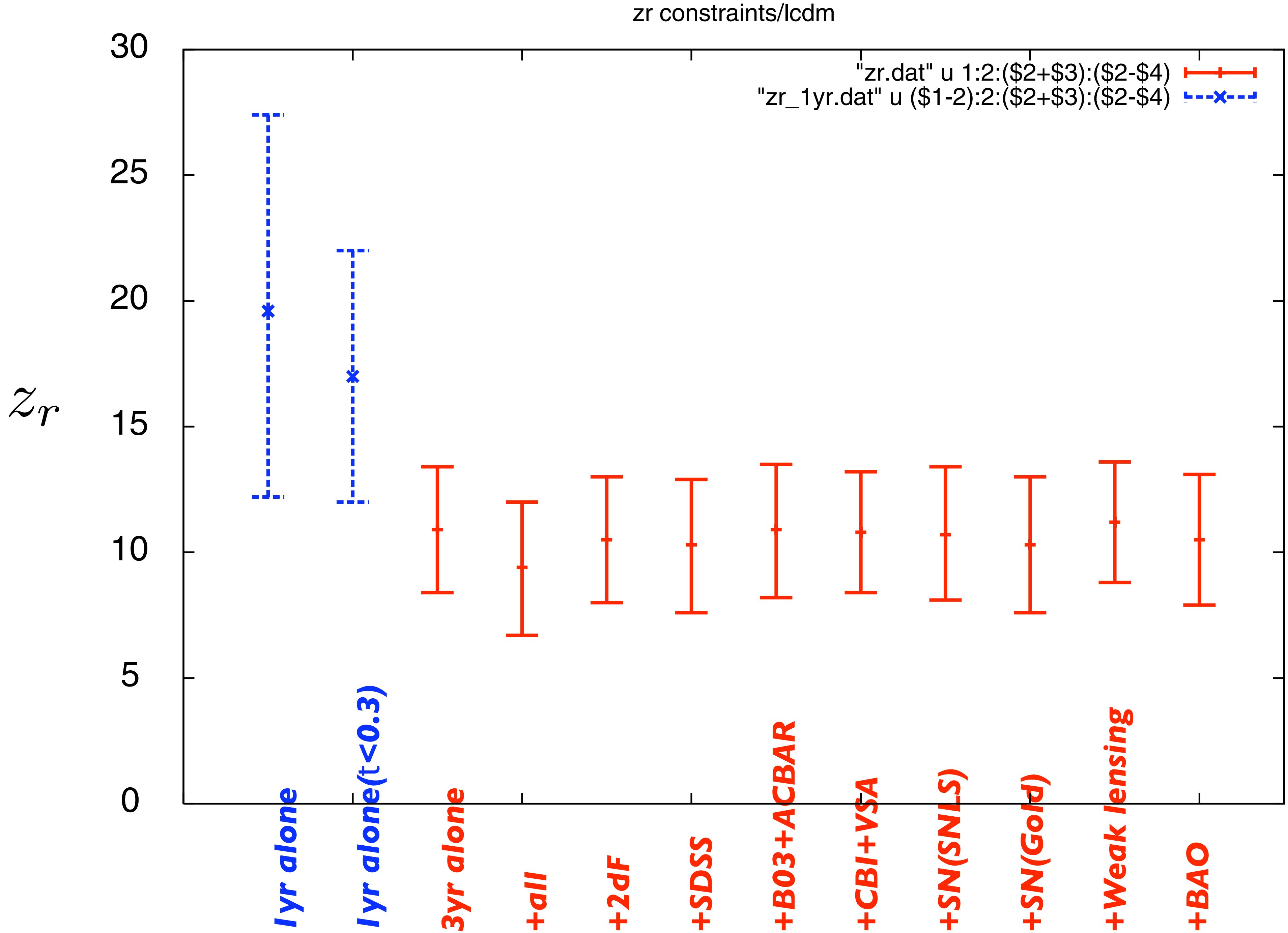
Scalar spectral index: $n_s = 0.951^{+0.015}_{-0.019}$



Reionization optical depth: $\tau = 0.088^{+0.028}_{-0.034}$



Epoch of reionization: $z_r = 10.9 \pm 2.5$



1. Now, WMAP alone can determine the cosmological parameters [N.B. flatness assumed].

2. Some parameters are fully consistent with 1yr results (with $\tau < 0.3$). Some parameters are marginally consistent. Error bars ~ 1/sqrt(3)

3. Also, consistent with the other external data sets (although adopting different data sets evokes some scatter for h and ω_m)

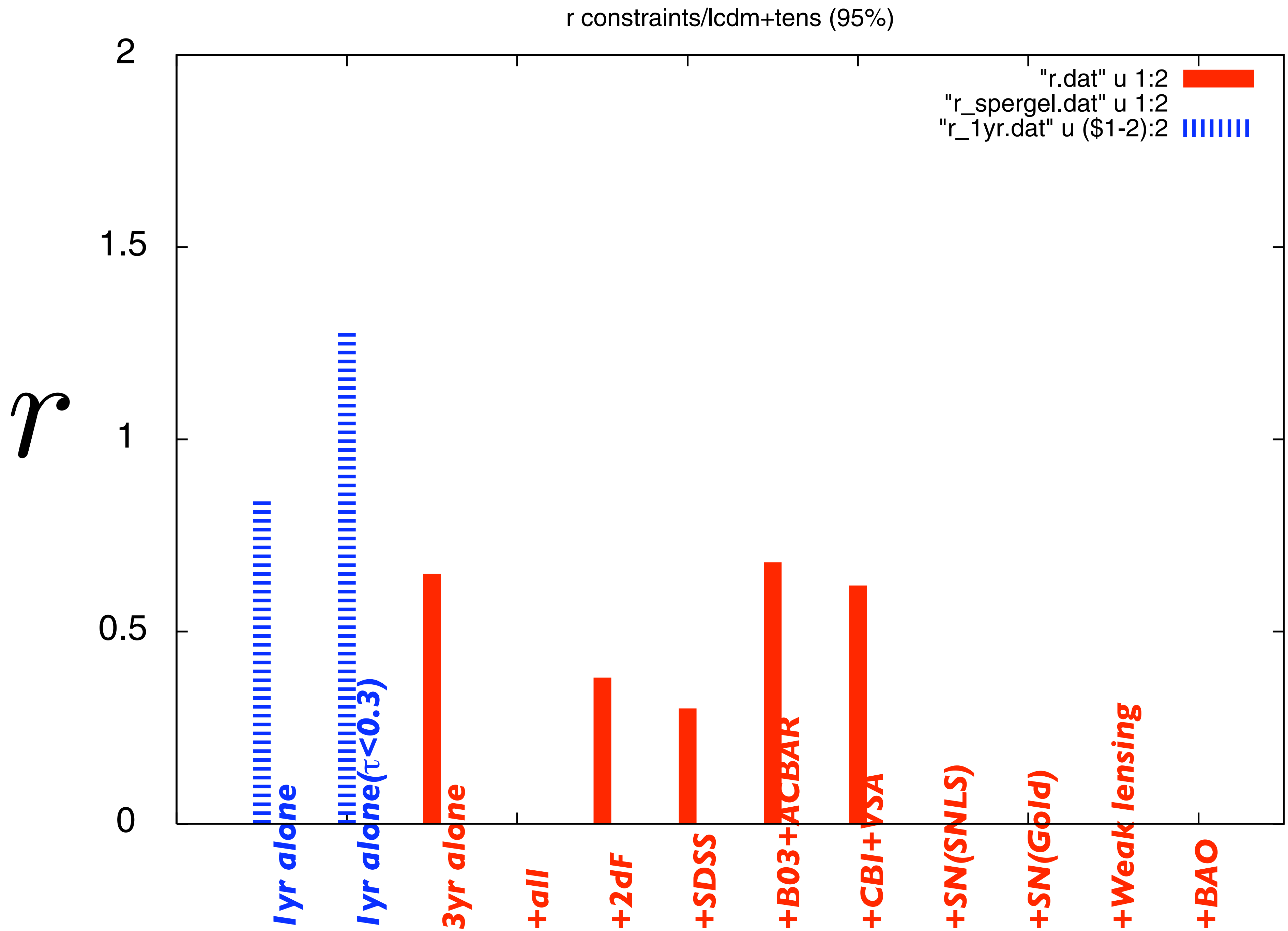
Inconsistency *among* non-WMAP data ?

Other cosmological models

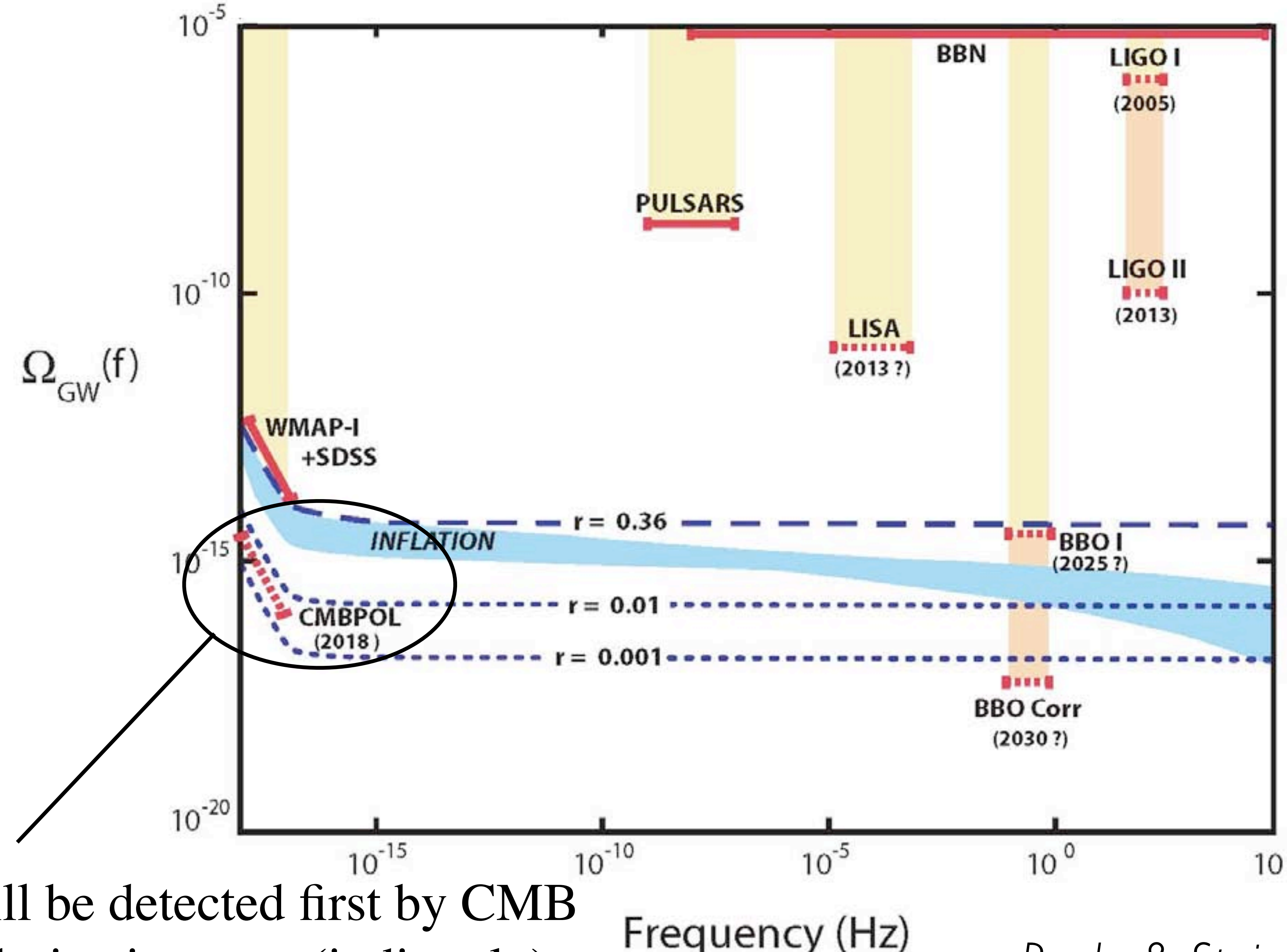
	Model	$-\Delta(2\ln\mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	8	5
M2	No Reionization ($\tau = 0$)	8	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	**Power Law ΛCDM**	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	0	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d\ln k \neq 0$)	-3	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	-6	7
M11	Running Spectral Index & Tensor Modes	-3	8
M12	Sharp cutoff	-1	7
M13	Binned $\Delta^2_{\mathcal{R}}(k)$	-22	20

Power law ΛCDM is OK for WMAP.

Ratio of scalar to tensor: $r < 0.55$ (95%)



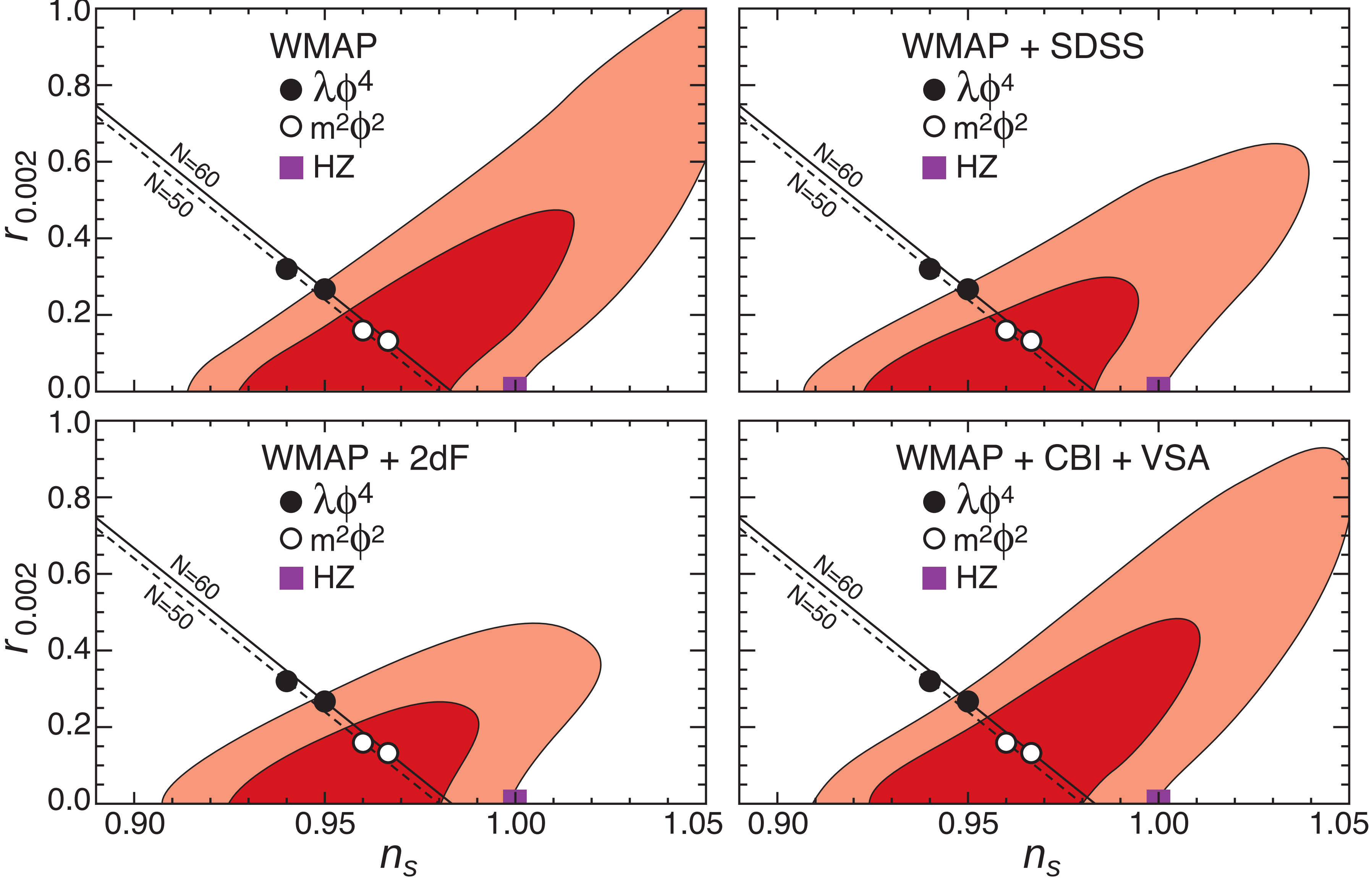
Direct measurement of primeval gravitational waves



Will be detected first by CMB polarization exp. (indirectly)

Boyle & Steinhardt

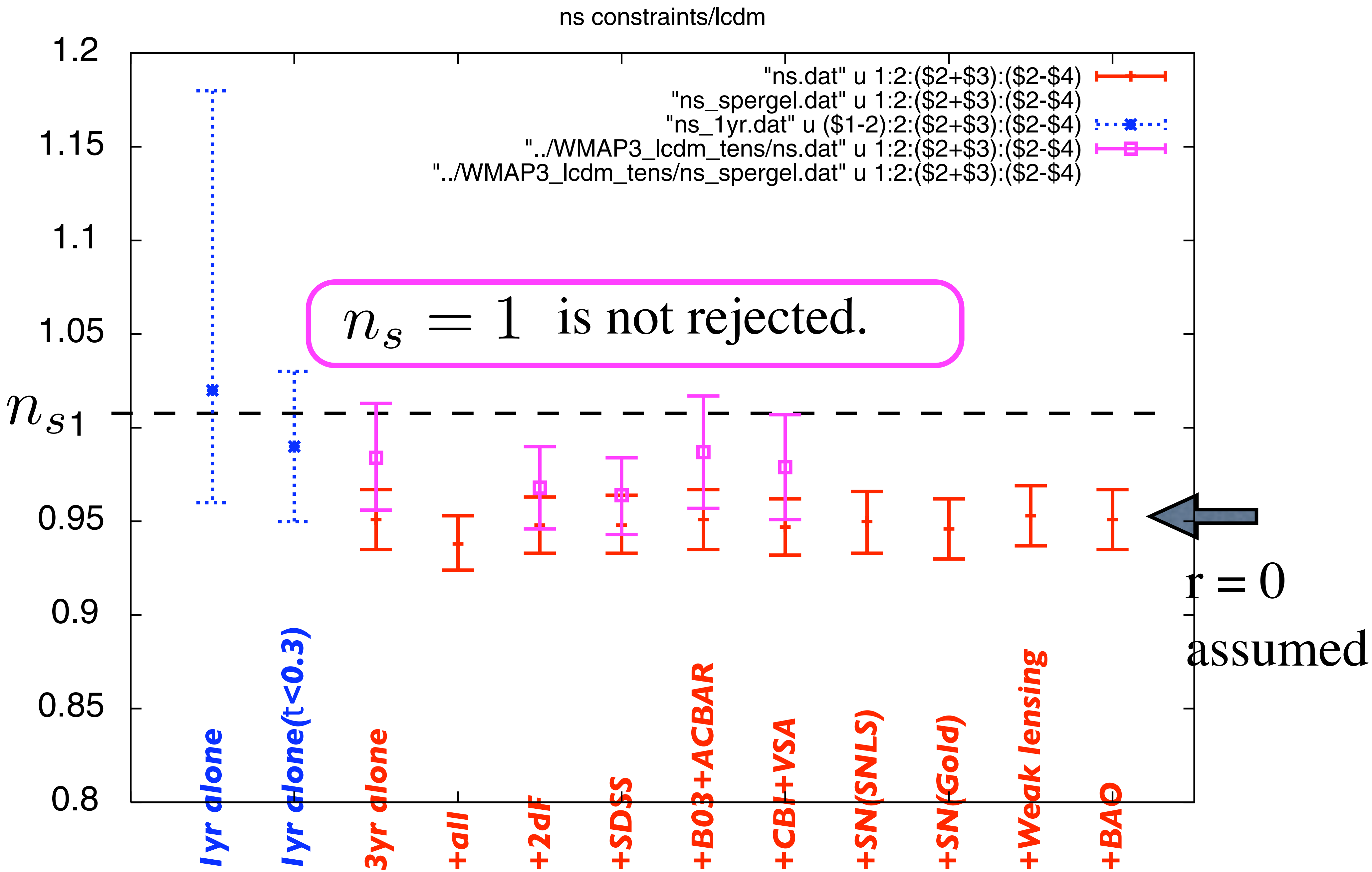
(Fig. 14 of Spergel (2006) seems to be incorrect in ver. 1.)



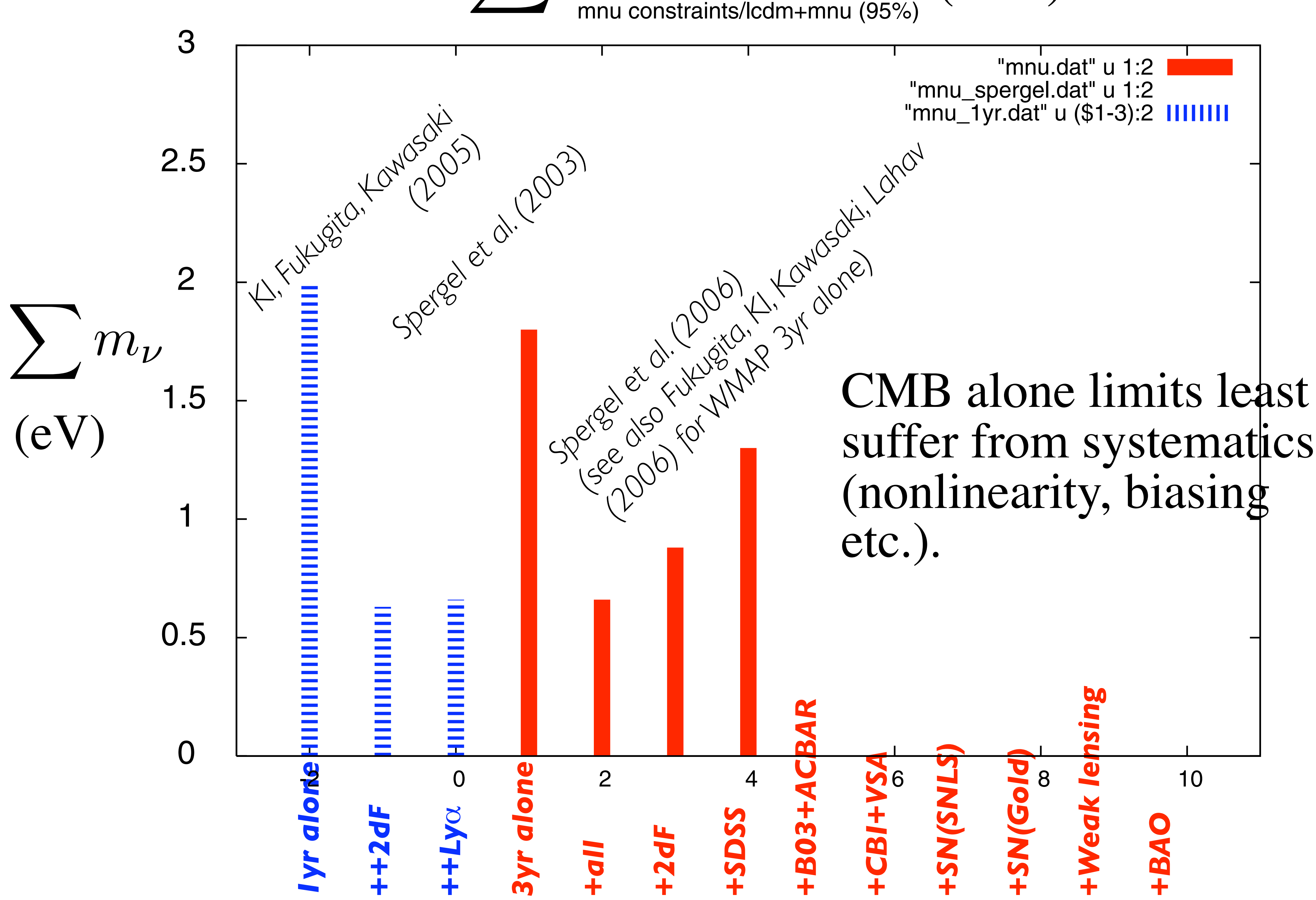
Spergel et al (2006)

- r < 0.8 (95% CL) WMAPII only
- r < 0.5 (95% CL) WMAPII+SDSS

Taken from the slide of Peiris for the Irvine meeting.

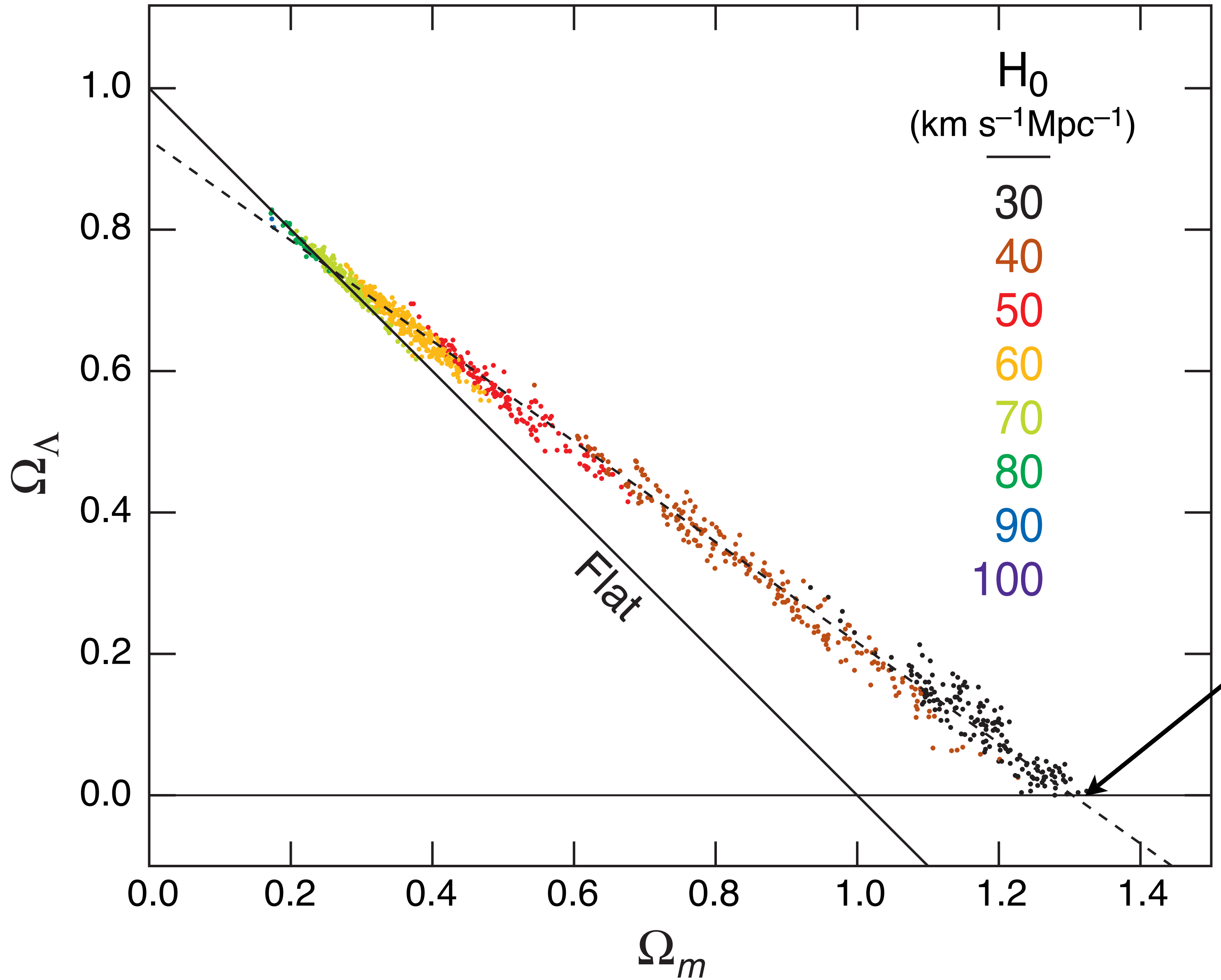

ns constraints/lcdm
"ns.dat" u 1:2:($2+$3):($2-$4)
"ns_spergel.dat" u 1:2:($2+$3):($2-$4)
"ns_1yr.dat" u ($1-2):2:($2+$3):($2-$4)
"../WMAP3_lcdm_tens/ns.dat" u 1:2:($2+$3):($2-$4)
"../WMAP3_lcdm_tens/ns_spergel.dat" u 1:2:($2+$3):($2-$4)
$n_s = 1$ is not rejected.
n_s
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
1yr alone
1yr alone(t<0.3)
3yr alone
+all
+2dF
+SDSS
+B03+ACBAR
+CBI+VSA
+SN(SNLS)
+SN(Gold)
+Weak lensing
+BAO
r = 0
assumed.

Neutrino mass: $\sum m_\nu < 2.0$ eV (95%)



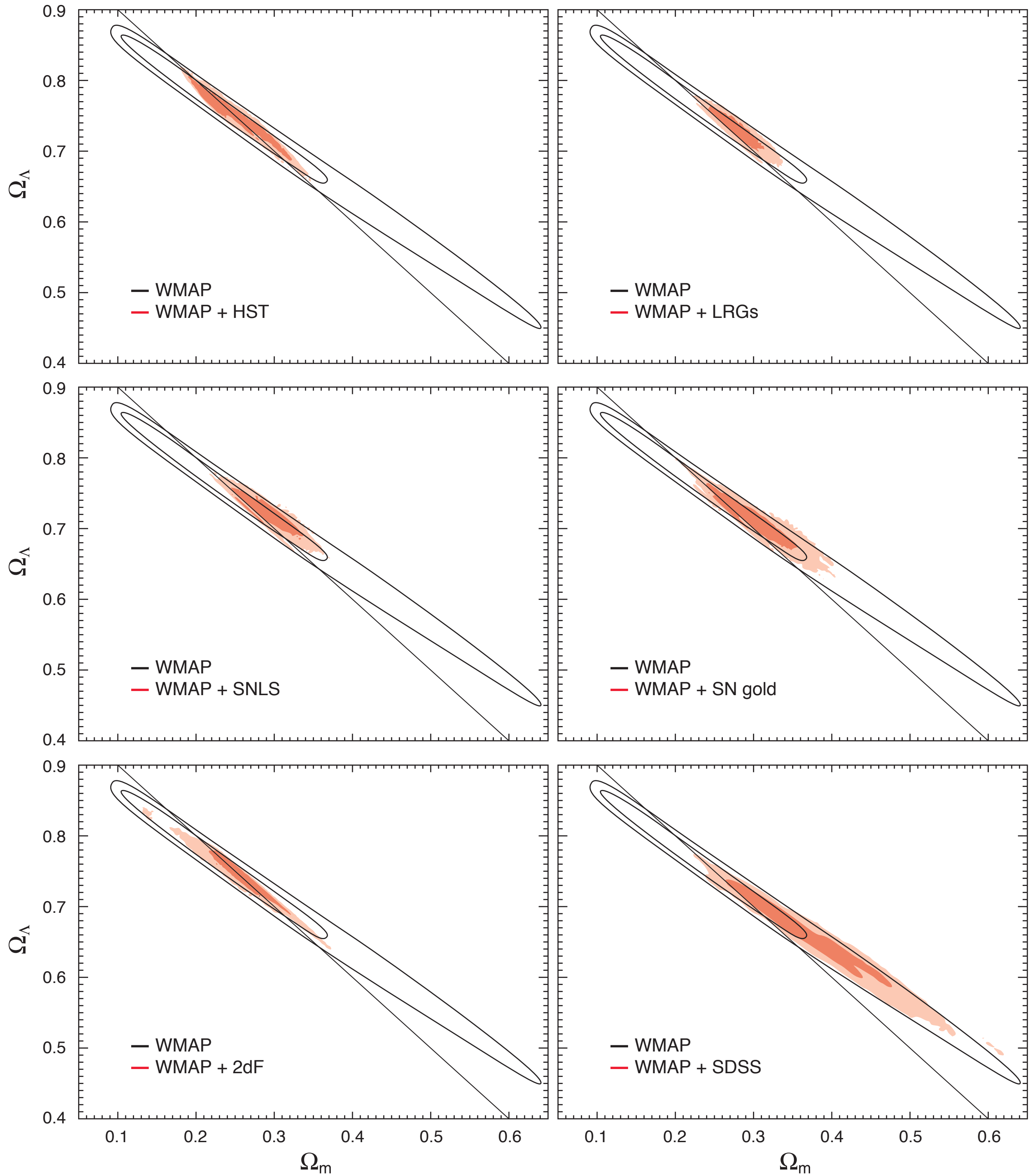
CMB alone limits least suffer from systematics (nonlinearity, biasing etc.).

Non-flat universe:



delta chi square = 0, but too small hubble.

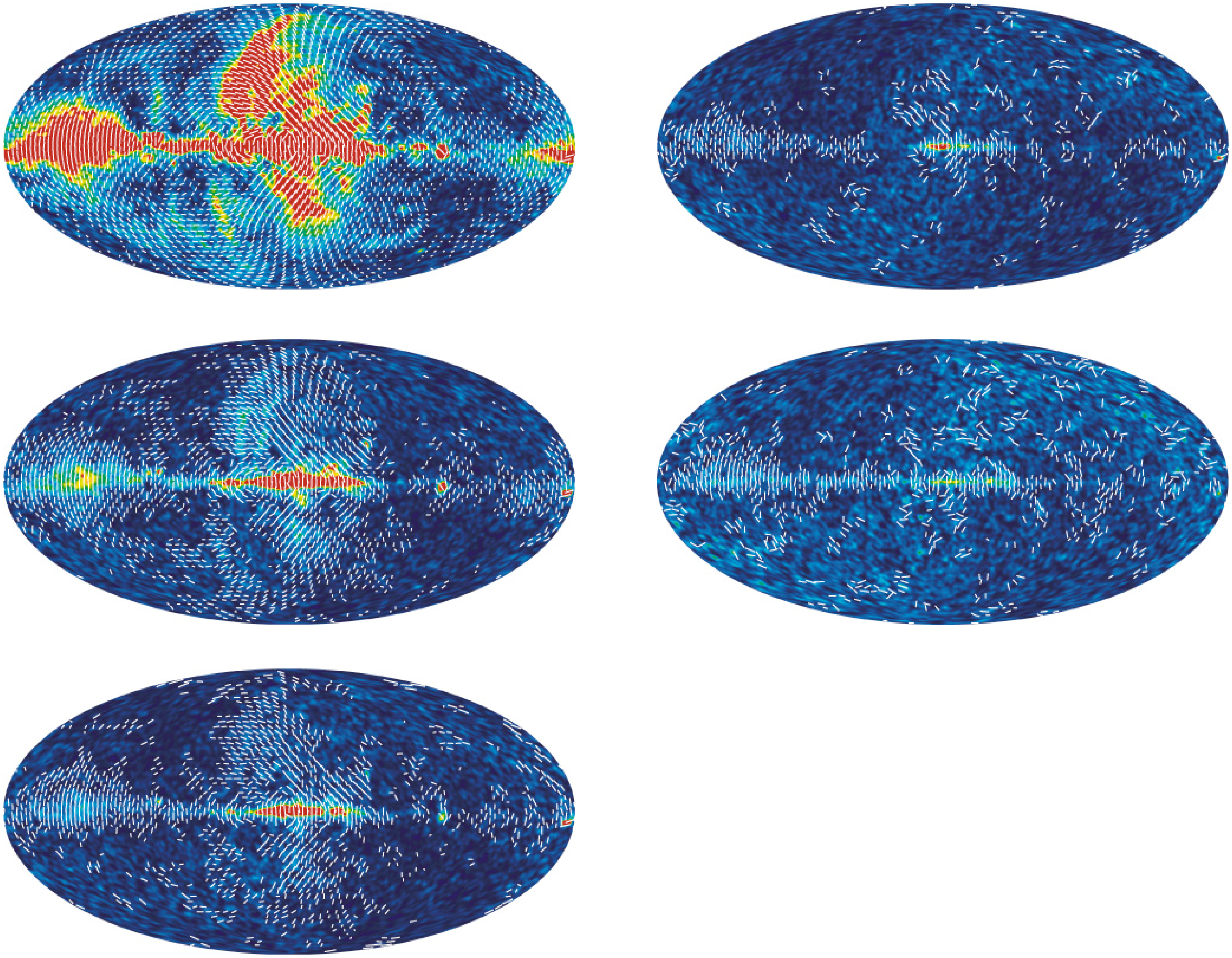
Combining with just one external data set favors flat universe.



1. Flat ΛCDM model well describes the WMAP data.

2. No non-standard physics was found.

2. Polarization and reionization

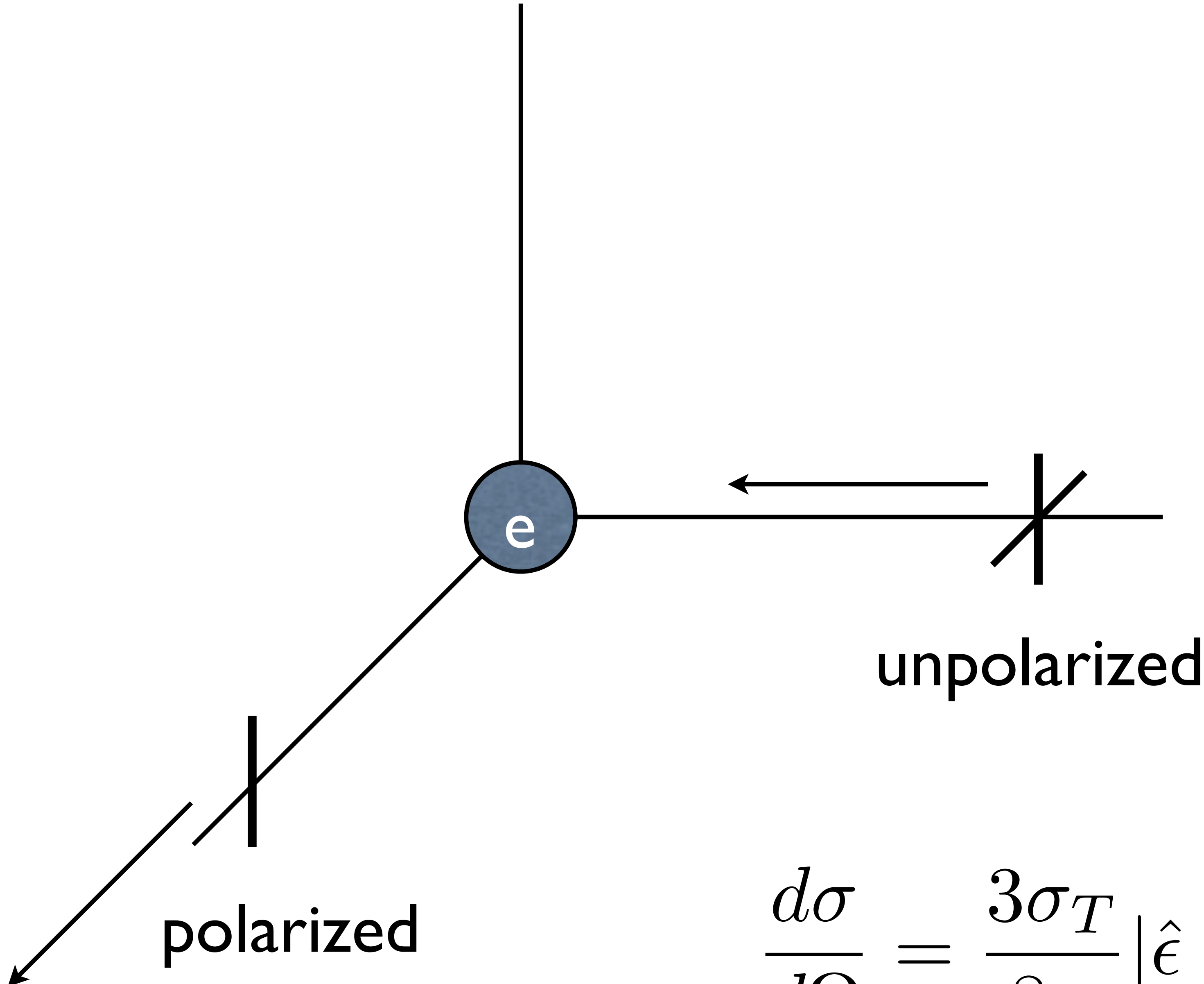


CMB photons are polarized.

Requirements for polarization:

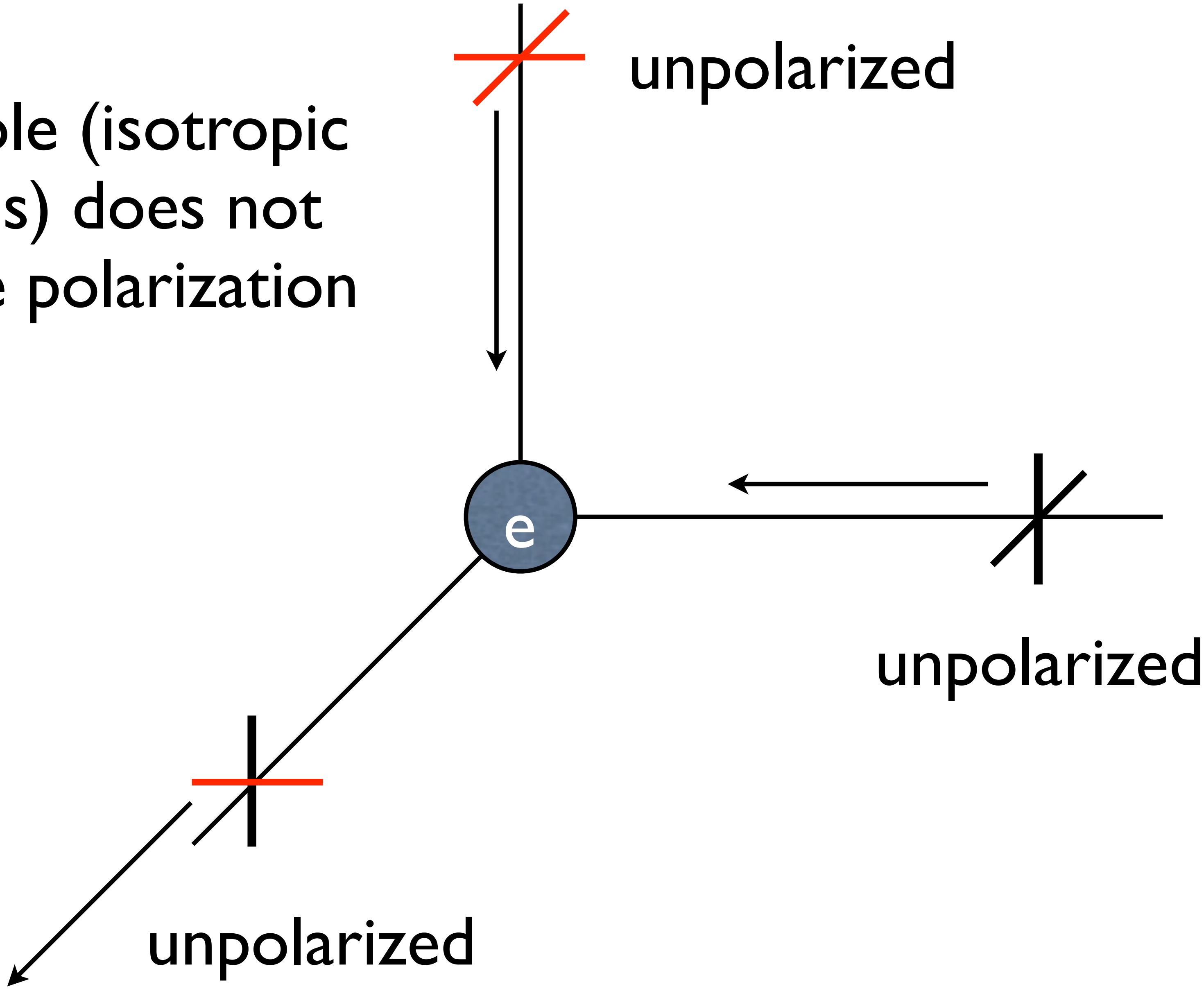
1) Free electrons (Thomson scattering)

2) Quadrupole pattern in CMB anisotropy

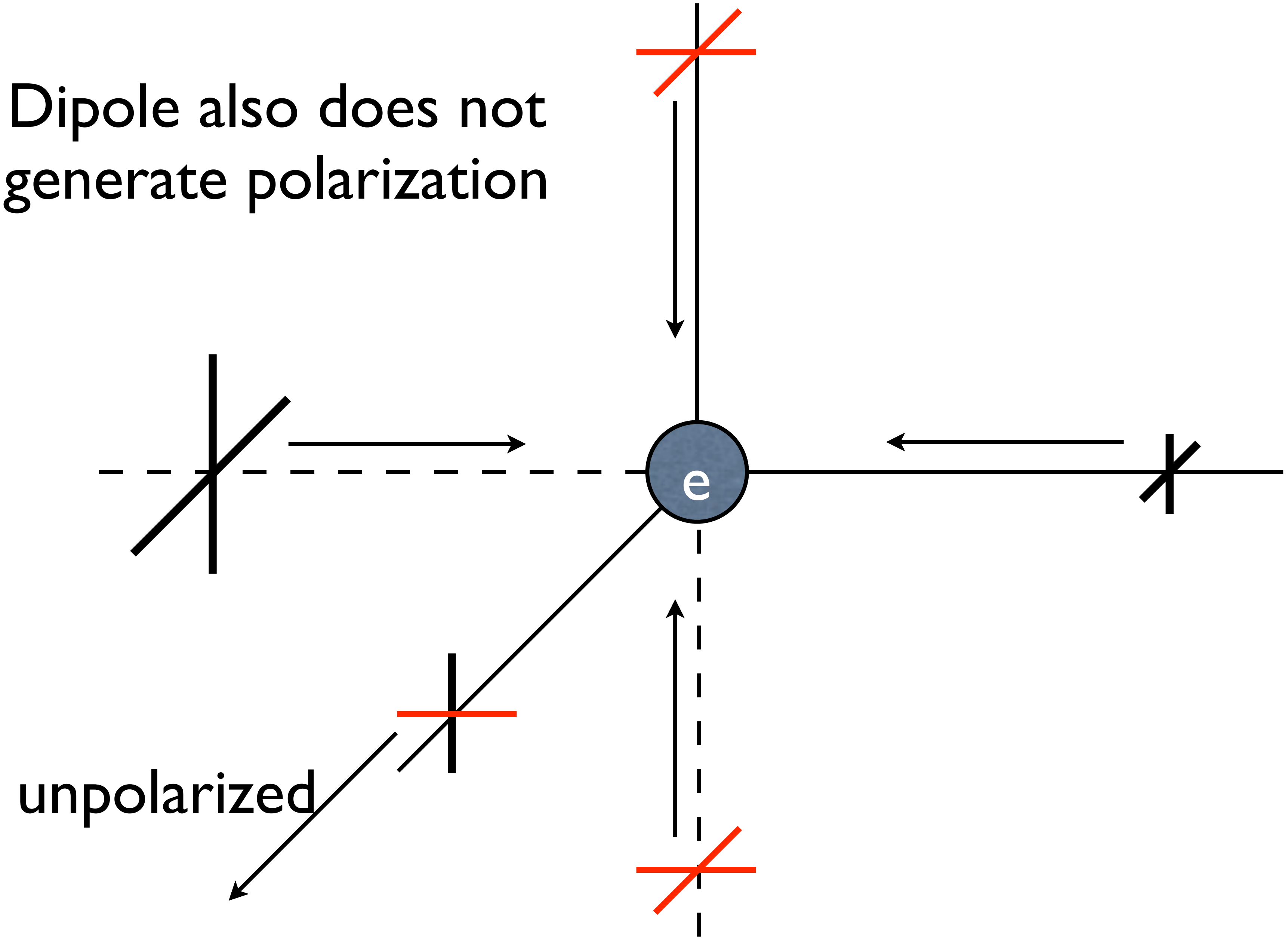


$$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi}|\hat{\epsilon} \cdot \hat{\epsilon}'|^2$$

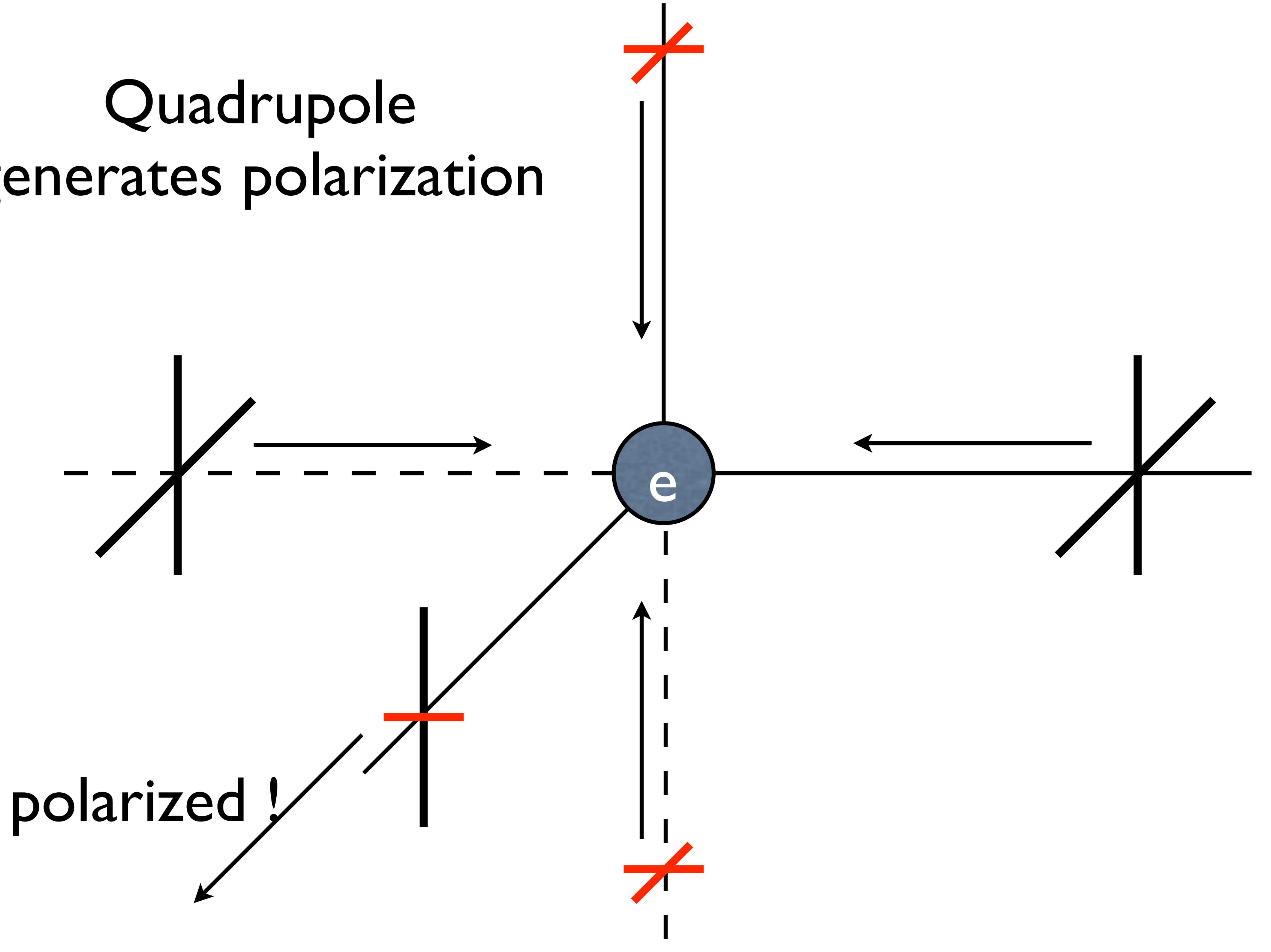
Monopole (isotropic photons) does not generate polarization



Dipole also does not generate polarization



Quadrupole generates polarization



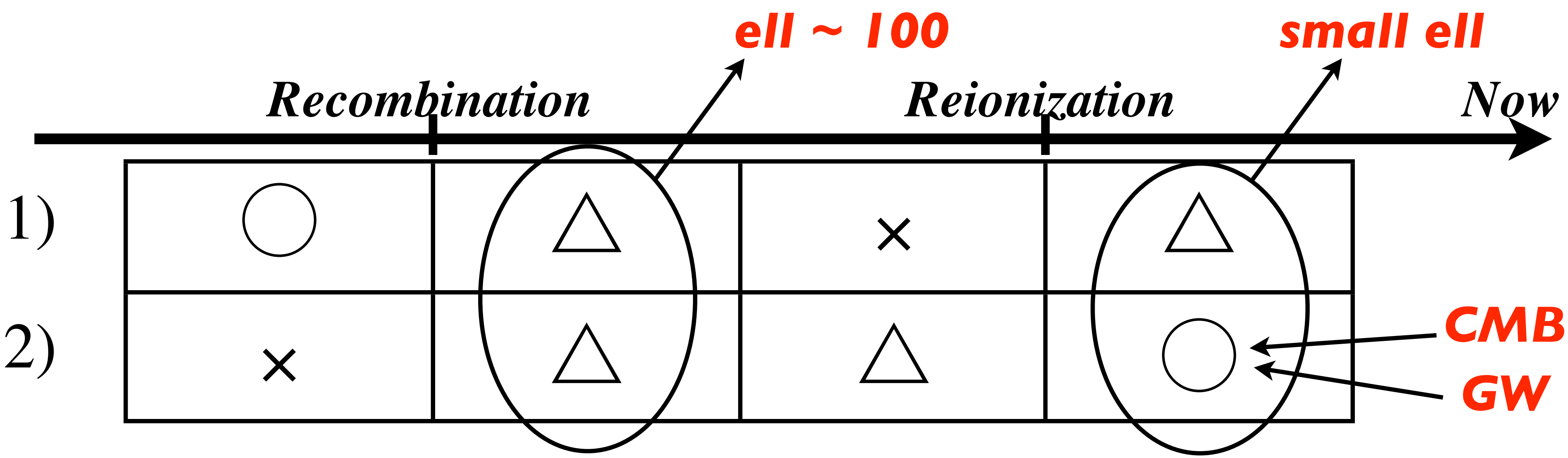
CMB photons are polarized.

Requirements for polarization:

1) Free electrons (Thomson scattering)

2) Quadrupole pattern in CMB anisotropy

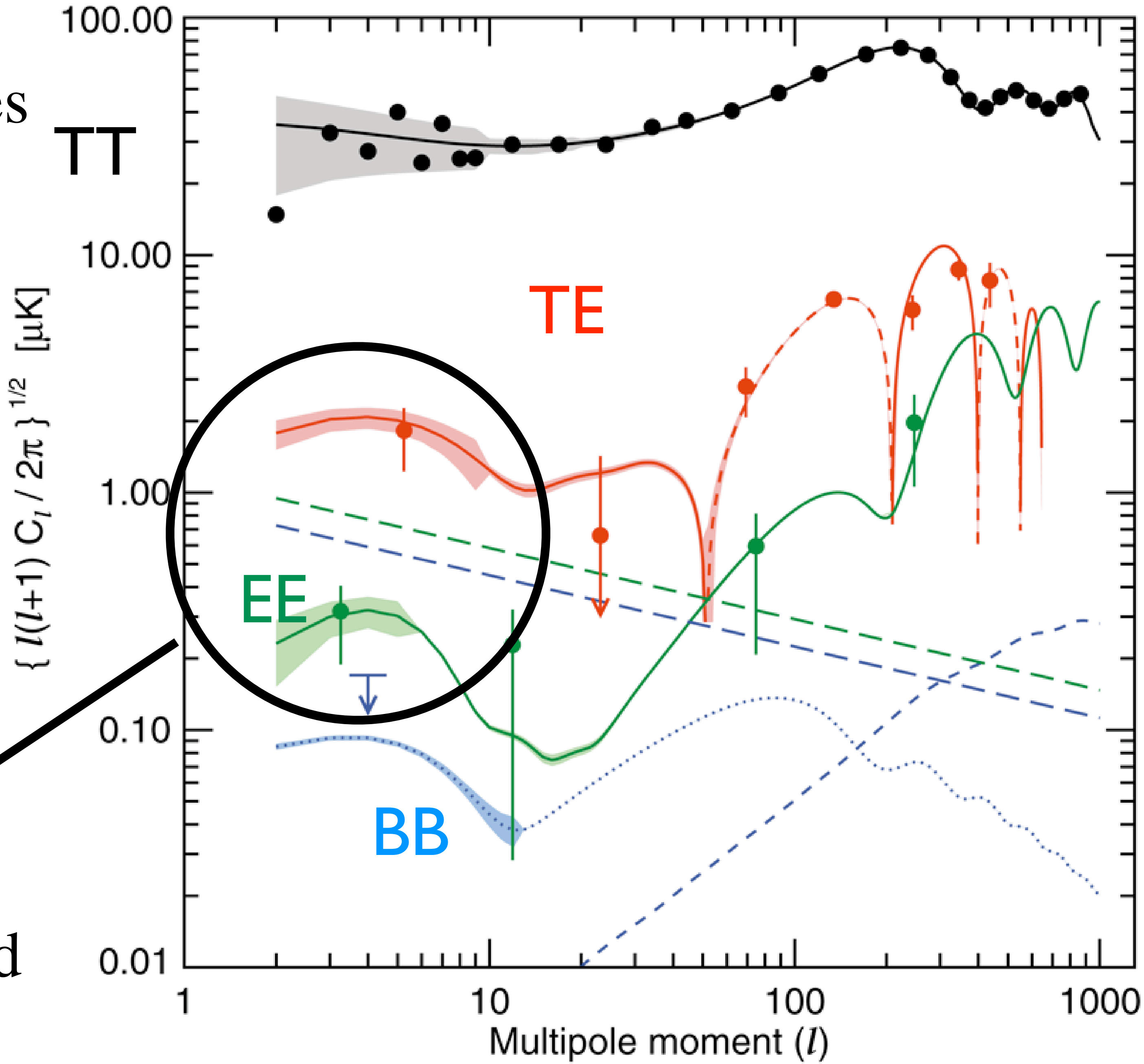
When in the cosmic history both 1) & 2) exist ?



In both cases, much weaker than temperature anisotropy.

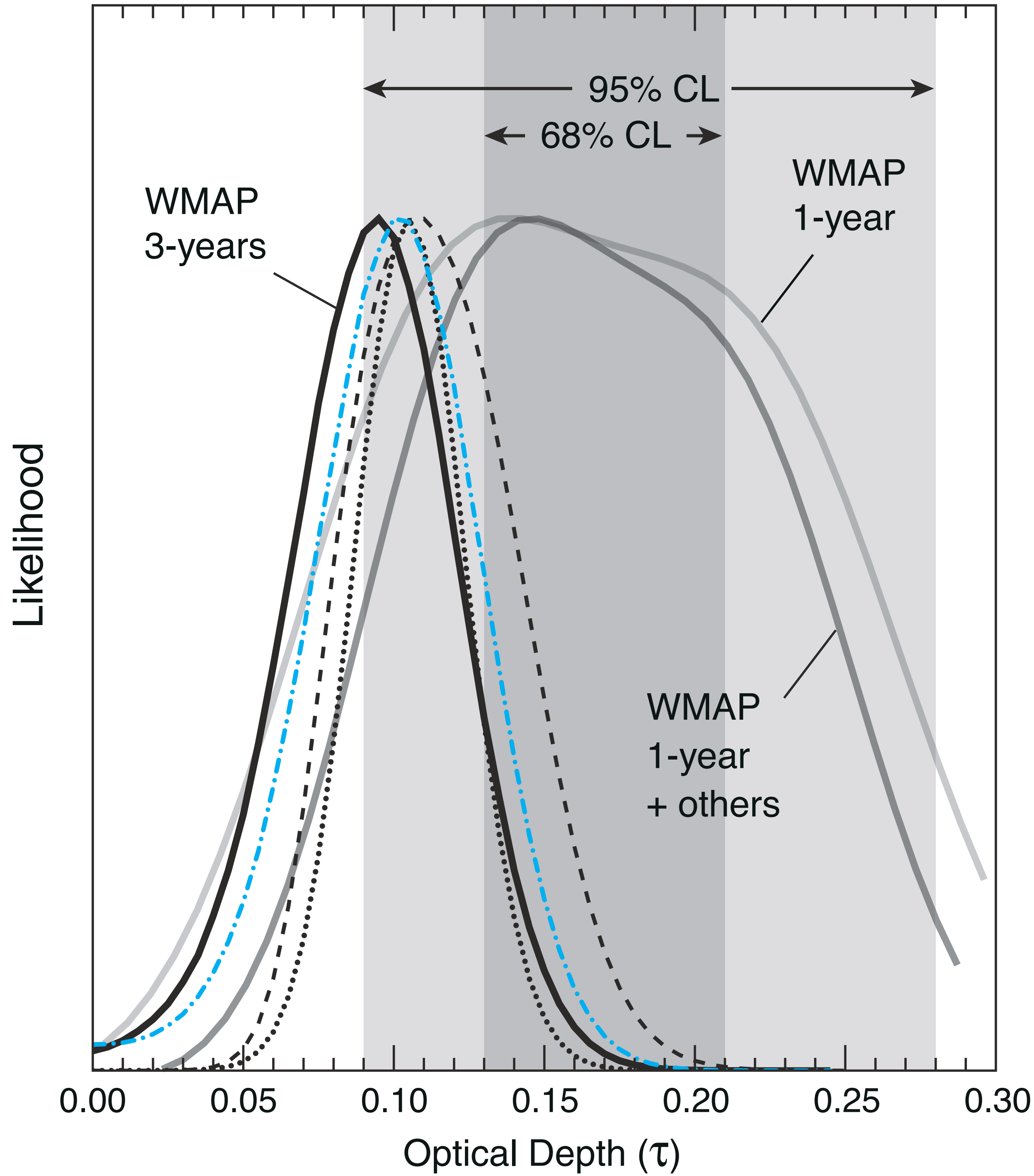
Especially, signal of reionization should appear at large scales (low l).

T:temperature
E,B:polarization



Evidence for reionization
& τ determined accurately

Measureing τ



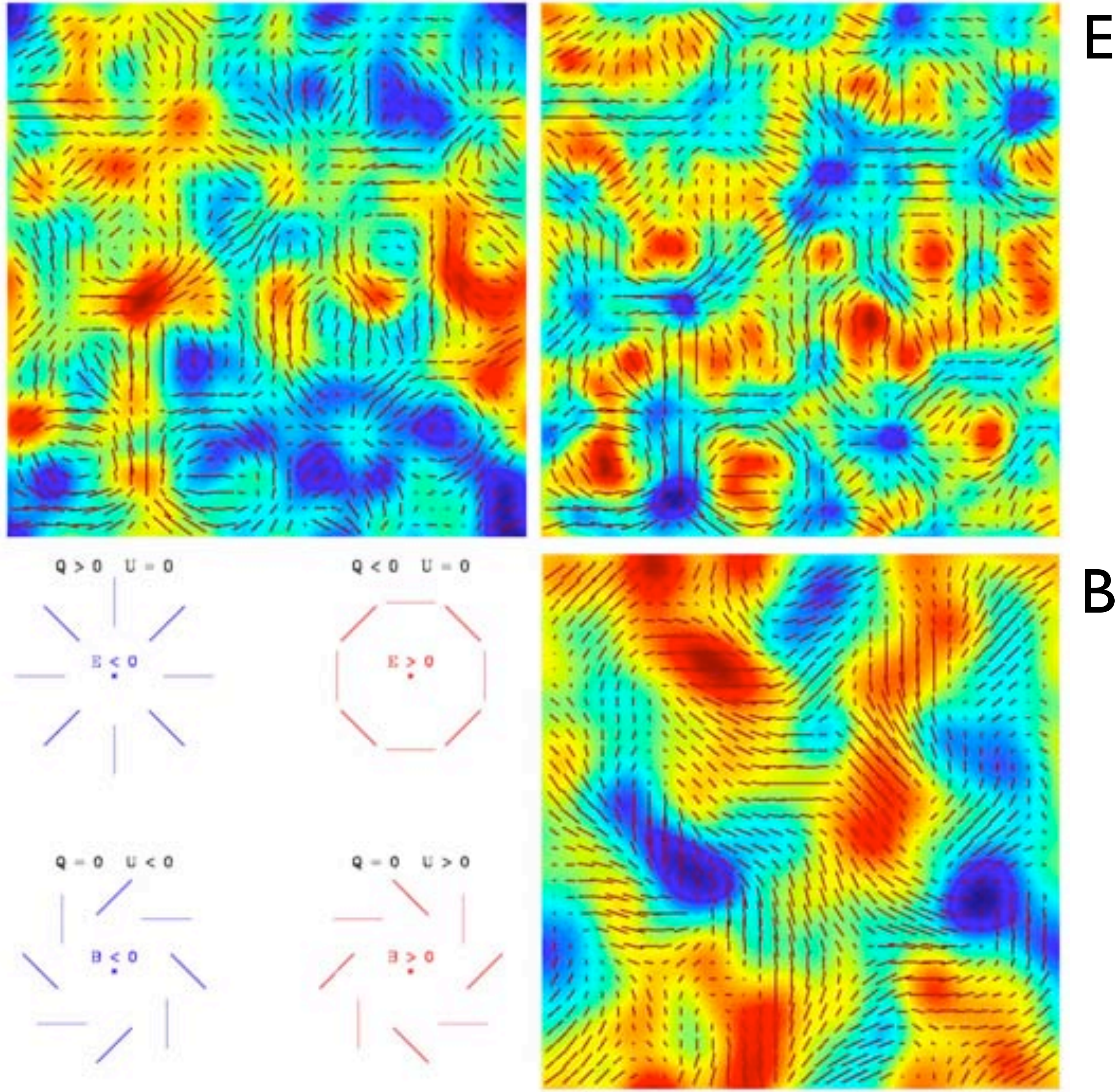
Some broadening of the likelihood in 1yr data turned into a sharp peak in 3yr data.

Polarization patterns: decomposition into E & B

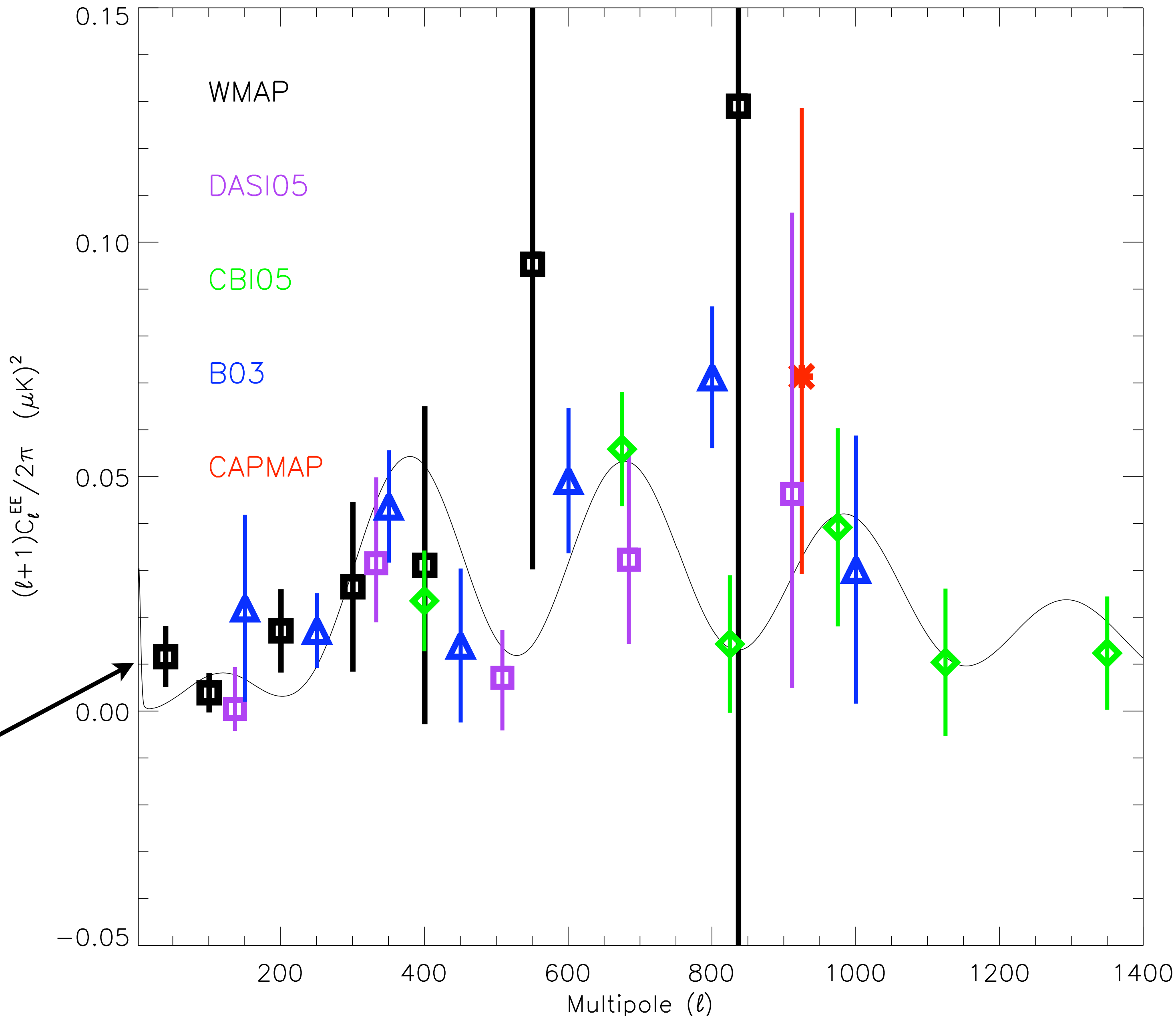
CMB→E

Gravitational wave→E & B

For large scales, E probes reionization and B probes GW from inflation.

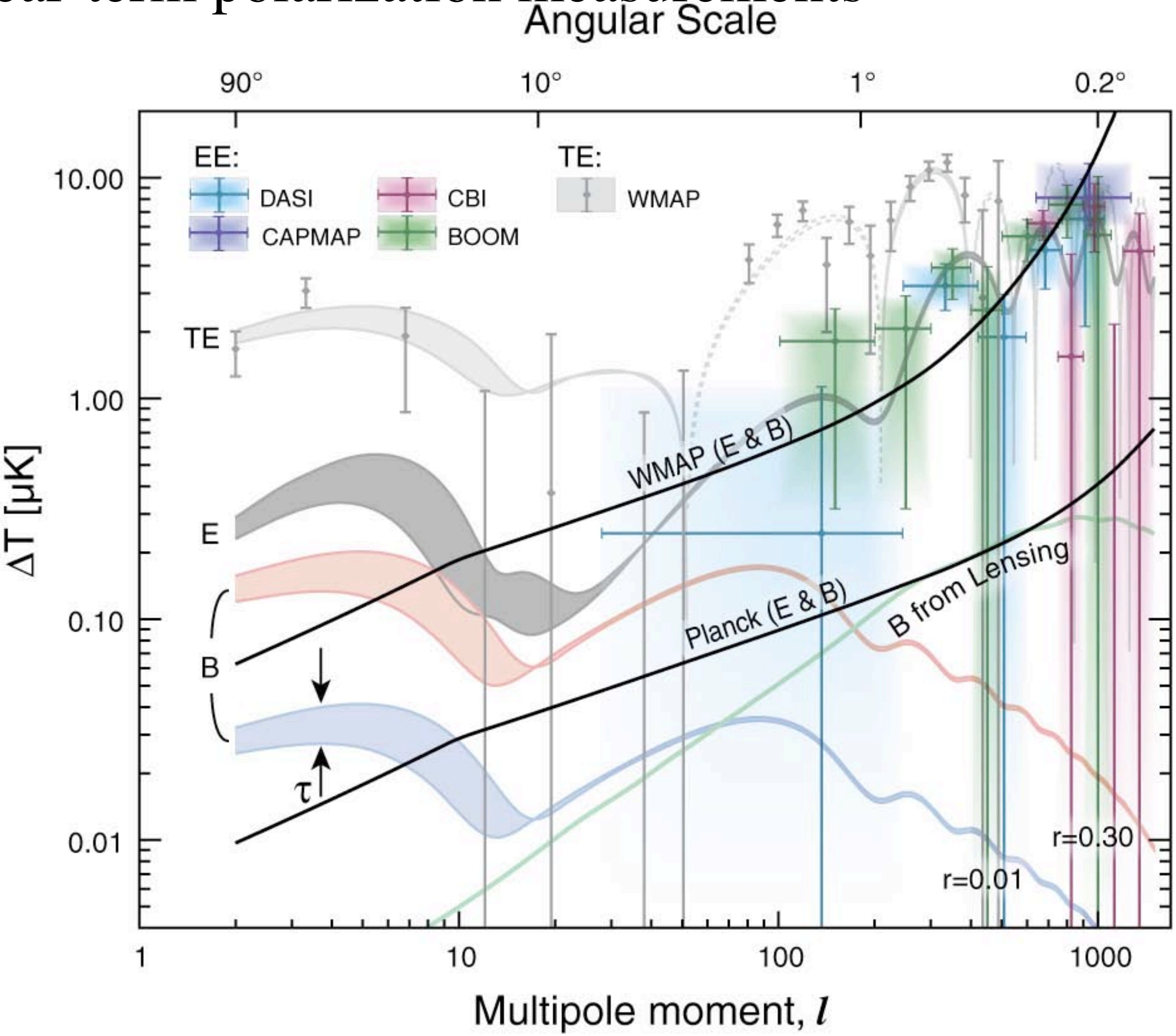


EE spectrum measurements: present status



Only WMAP can do at very large scales.

Current & near-term polarization measurements



Nearing to detect BB at large scales.

"Holy grail"

1. Polarized foreground is better understood and the measured polarization map can be corrected to CMB polarization map more reliably.

2. Accordingly, EE correlation is detected at large scales, which accurately measures the optical depth of reionization.

3. BB correlation is not detected, but polarization experiments are nearing a range of great interest to probe the primordial inflationary gravitational waves.

WMAP 3yr result is a new milestone in CMB research.