Cosmological parameters from CMB measurements and the final 2dFGRS power spectrum

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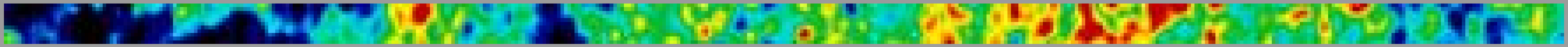
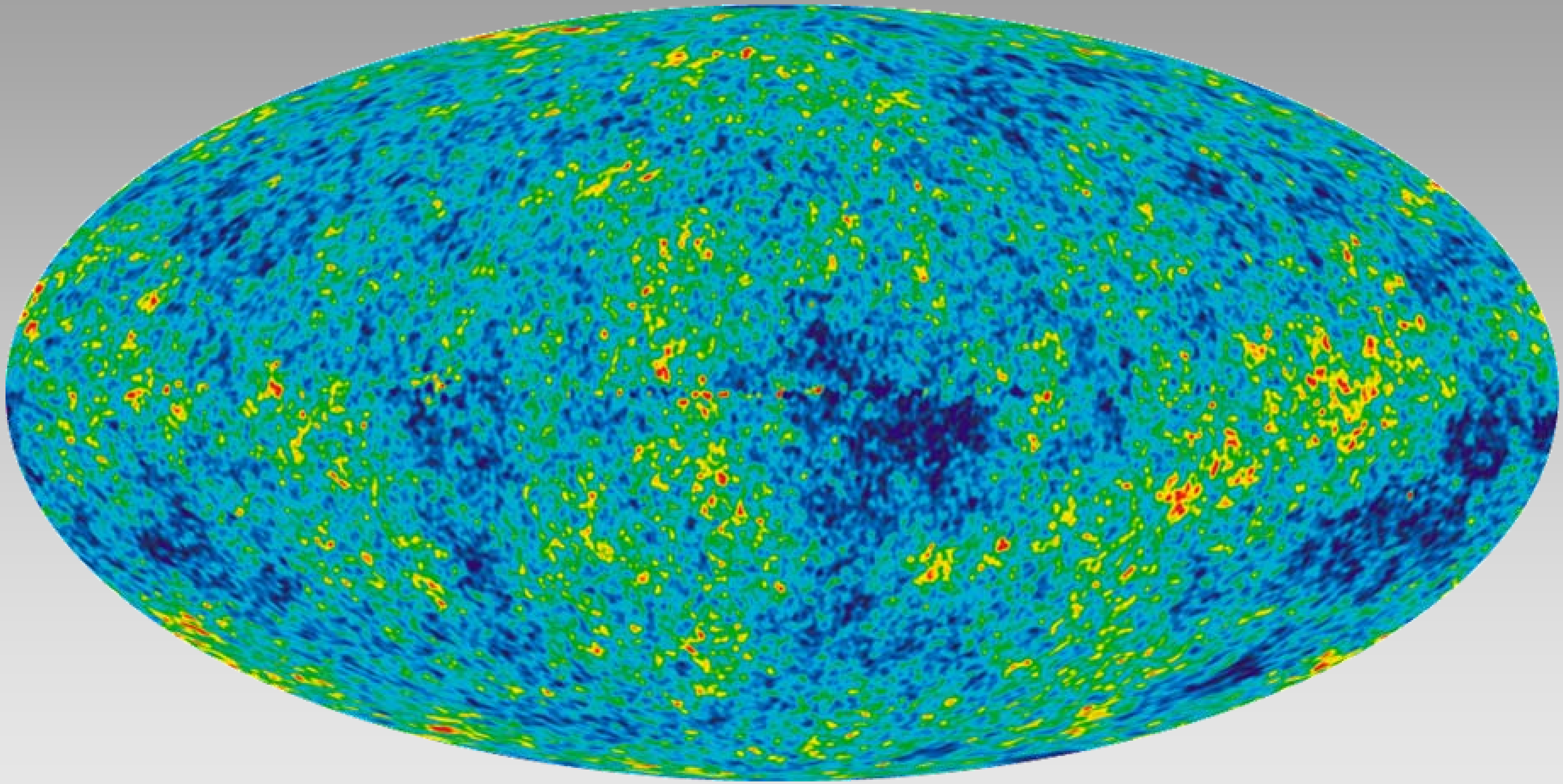
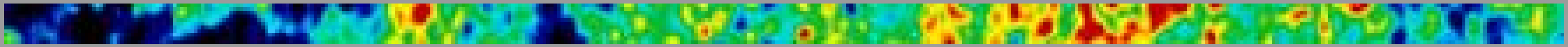
(2006, MNRAS, 366, 189 – astro-ph/0507583)

The datasets: CMB

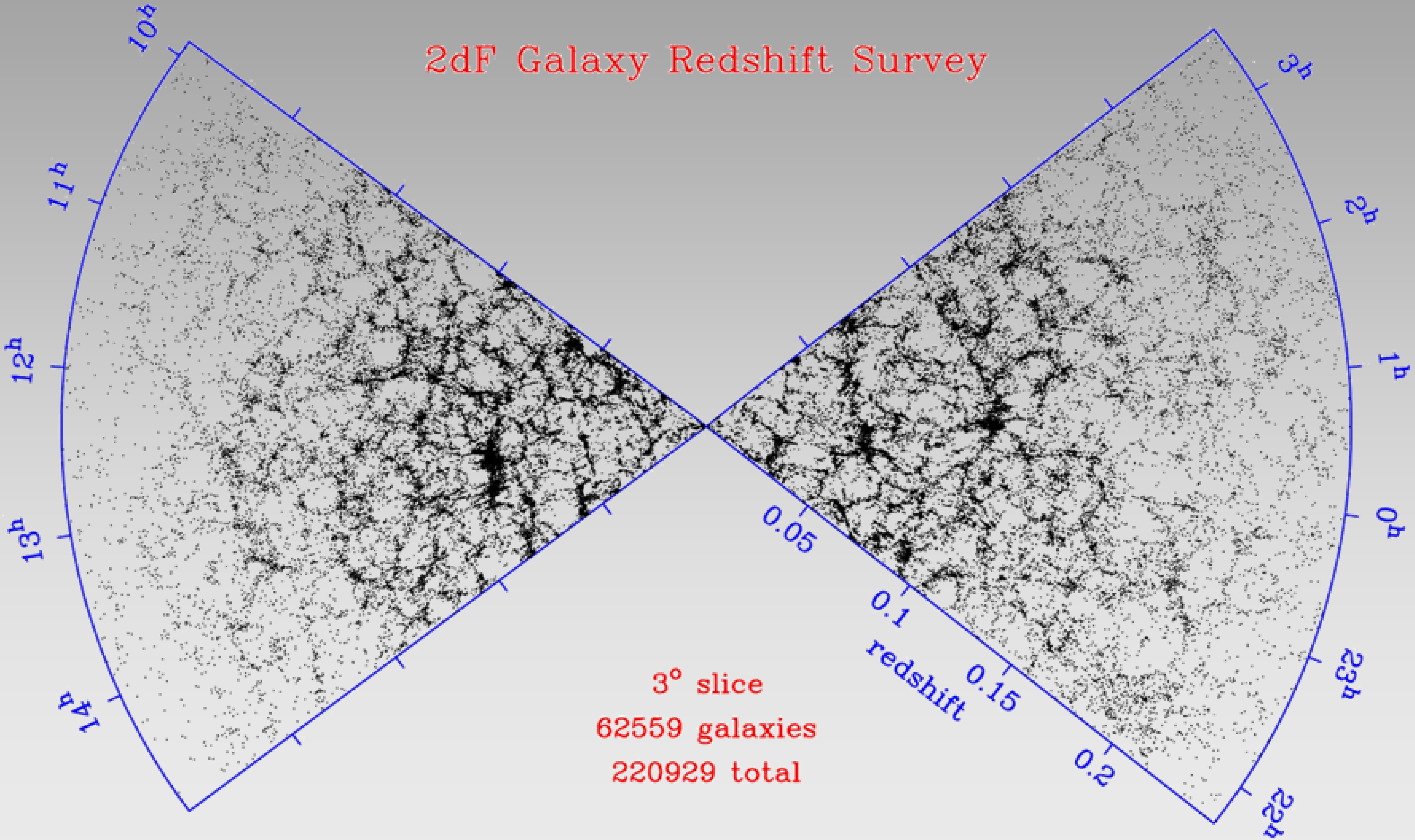




The datasets: LSS



- The final 2dFGRS is a powerful probe of LSS.



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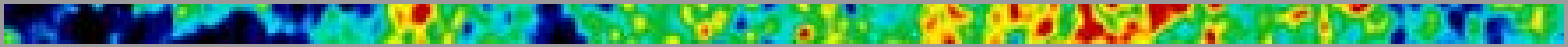
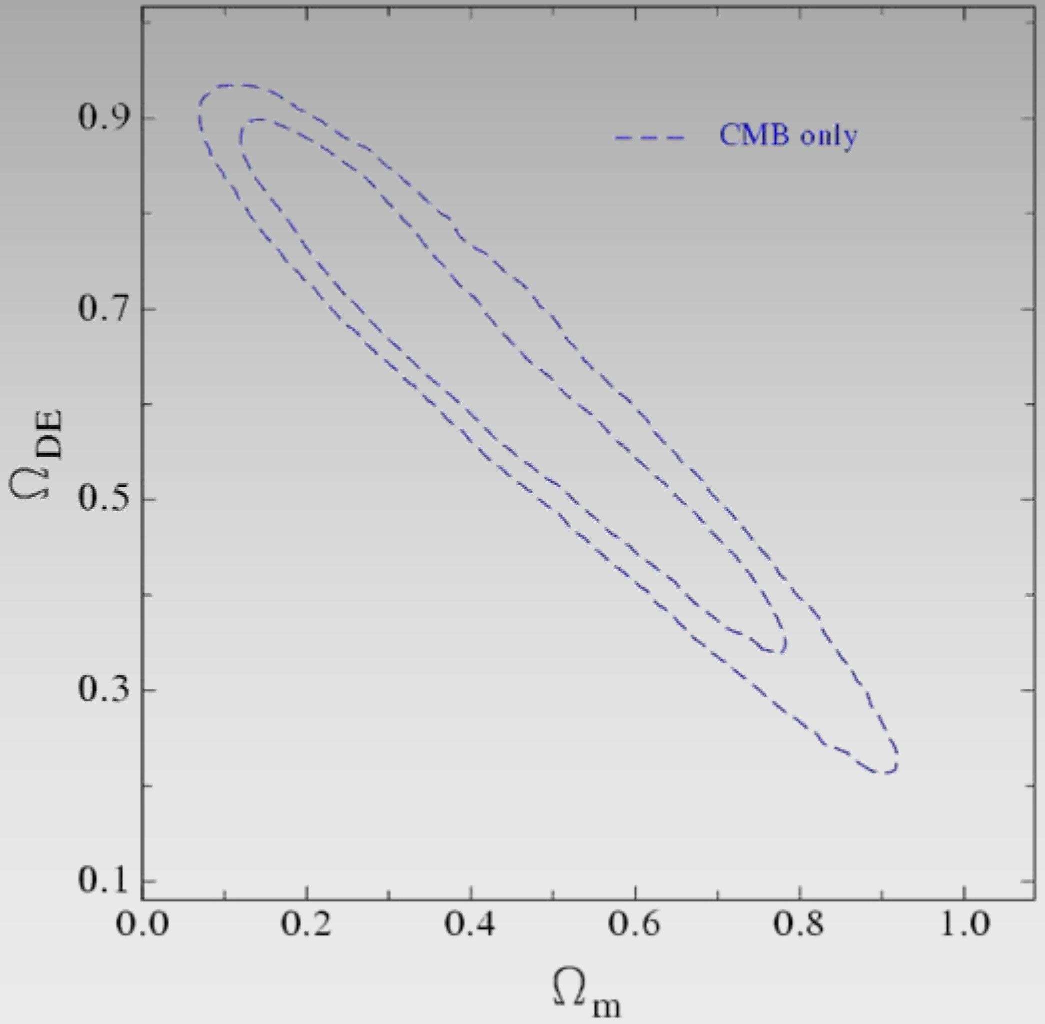


• Degeneracies impose limits on the precision attainable with CMB information



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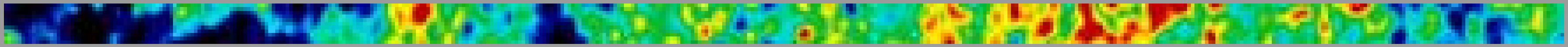

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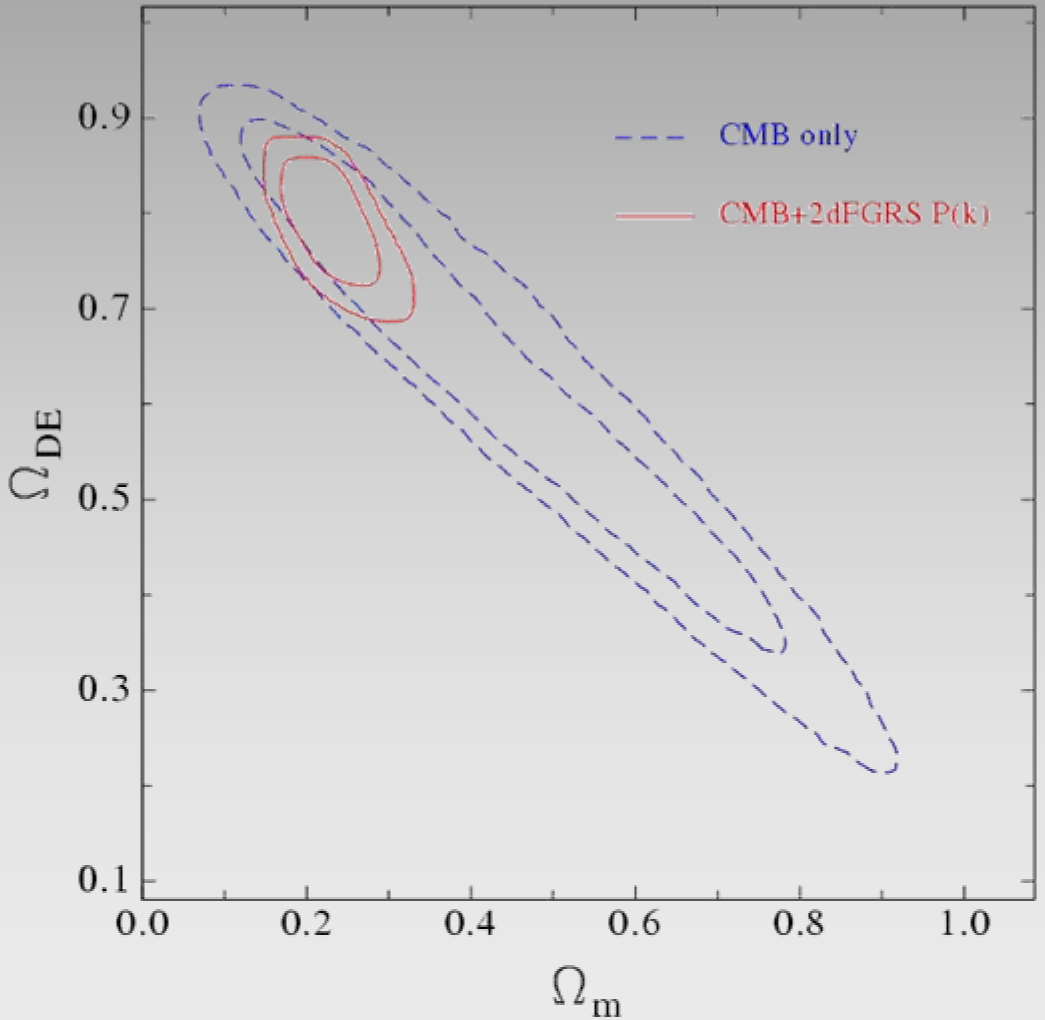
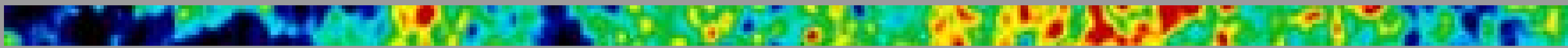
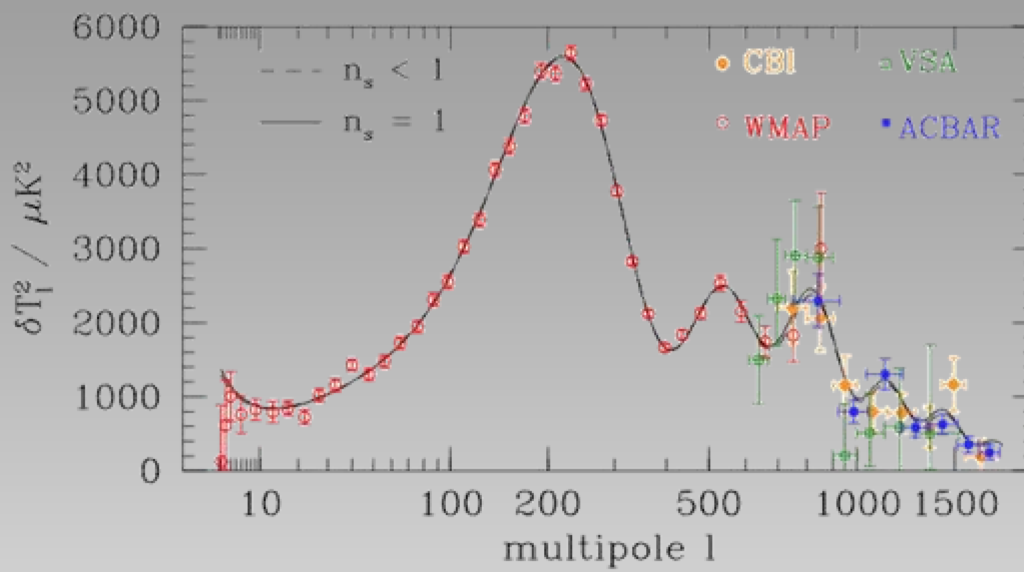


The datasets: CMB & LSS



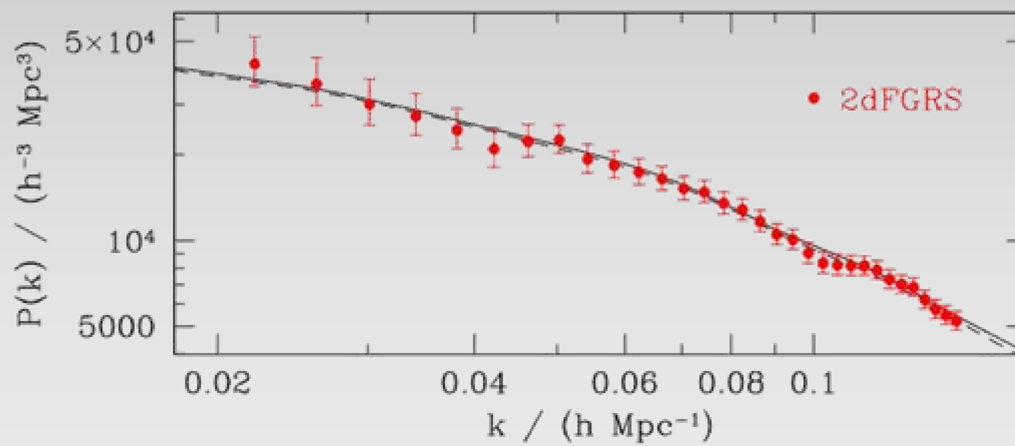
- CMB:

  - WMAP1 (TT & TE), ACBAR, VSA, CBI.

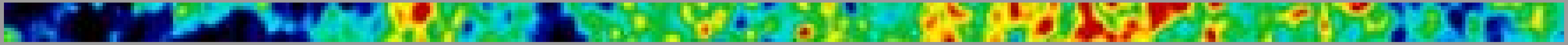


- LSS:

  - 2dFGRS $P(k)$ from Cole et al. (2005).



The datasets: LSS



- The final 2dFGRS is a powerful probe of LSS.
- Cole et al. (2005) measured $P(k)$ from the 2dFGRS.
- The measured $P(k)$ differs from the mass power spectrum.

    - It is a “pseudo-spectrum”: $\hat{P}(k) = P(k) \otimes W^2(k)$
    - Non-linear evolution.
    - Redshift space distortions.
    - Galaxy bias.

The datasets: LSS

- to model non-linearities,

  - We applied the scheme of Cole et al. (2005)

$$P_{\mathrm{gal}}(k) = b^2 \frac{1+Qk^2}{1+Ak} P_{\mathrm{lin}}(k)$$

where $A = 1.4$ and $Q = 4.6$

$$0.02\ h\ \mathrm{Mpc}^{-1} < k < 0.15\ h\ \mathrm{Mpc}^{-1}$$

The method: the parameter space

- Parameters of the homogeneous background

$$\omega_b = \Omega_b h^2, \quad \omega_{dm} = \Omega_{dm} h^2, \quad f_\nu = \Omega_\nu / \Omega_{dm}, \quad \Omega_{DE}, \quad w_{DE}, \quad \Omega_K$$

- Parameters of the initial fluctuations

$$P_s(k) = A_s \left(\frac{k}{k_0} \right)^{n_s} \quad P_t(k) = r A_s \left(\frac{k}{k_0} \right)^{n_t}$$

- The optical depth to the LSS: τ

- Other derived quantities:

$$\Omega_m, h, \sigma_8, z_{re}, t_0, \sum m_\nu, n_t$$

The method: MCMC

• To explore the parameter space we used **CosmoMC** and **CAMB**.

• The analysis was carried out on the "Cosmology Machine" at Durham University.

• The calculations have accounted for more than 30 CPU years.

The method: the parameter space

- Five parameters:

$$P_{b5} = (\omega_b,\ \omega_{dm}, \Omega_{DE}, \tau, A_s)$$

- Six parameters:

$$P_{b6} = (\omega_b,\ \omega_{dm}, \Omega_{DE}, \tau, A_s, n_s)$$

- Seven parameters:

$$P_{b6+f_\nu} = (\omega_b,\ \omega_{dm}, \Omega_{DE}, \tau, A_s, n_s, f_\nu)$$

$$P_{b6+\Omega_k} = (\omega_b,\ \omega_{dm}, \Omega_{DE}, \tau, A_s, n_s, \Omega_k)$$

$$P_{b6+w_{DE}} = (\omega_b,\ \omega_{dm}, \Omega_{DE}, \tau, A_s, n_s, w_{DE})$$

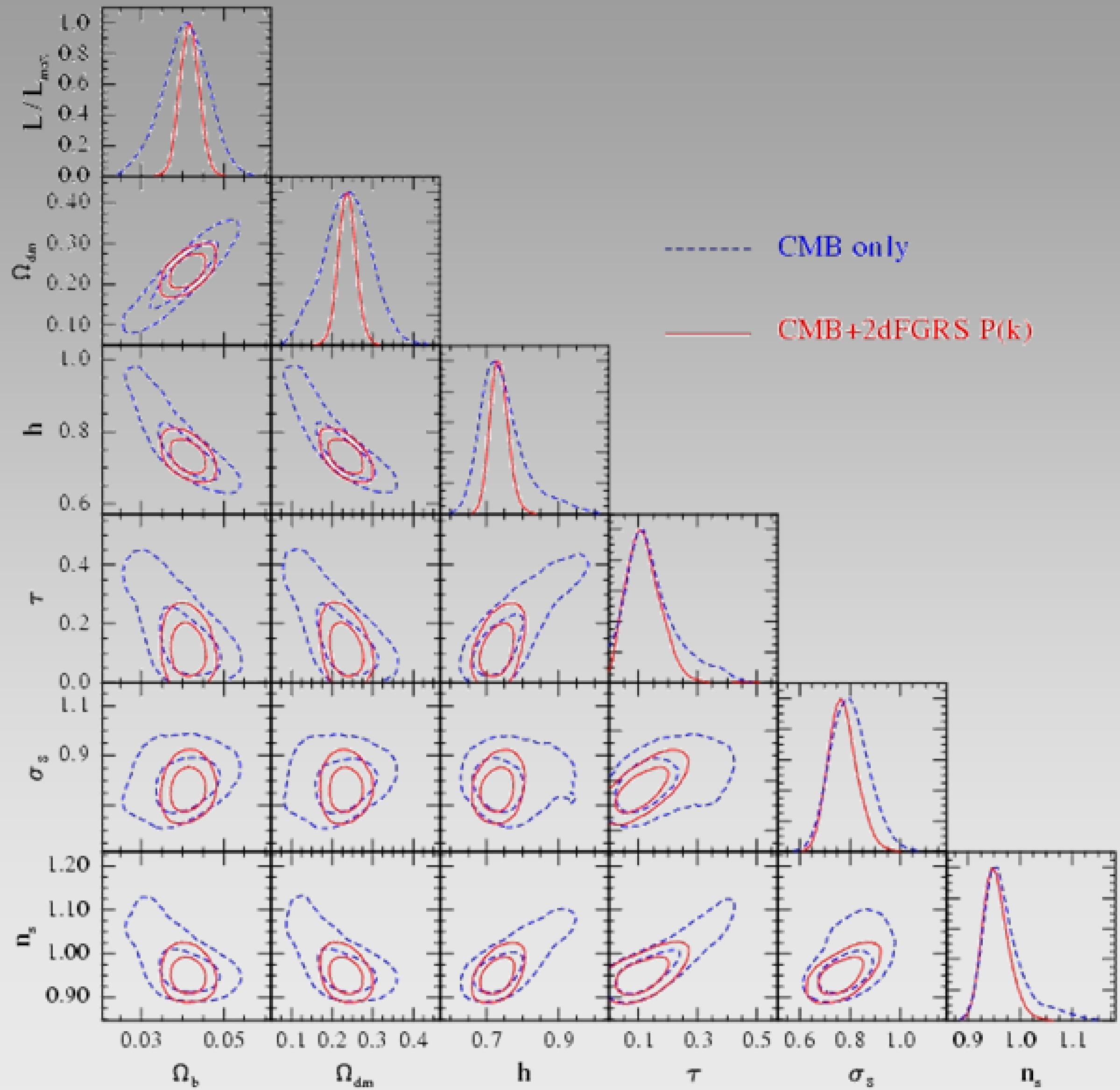
$$P_{b6+r} = (\omega_b,\ \omega_{dm}, \Omega_{DE}, \tau, A_s, n_s, r)$$

Results: the scalar spectral index

- Six parameters: the scalar spectral index.

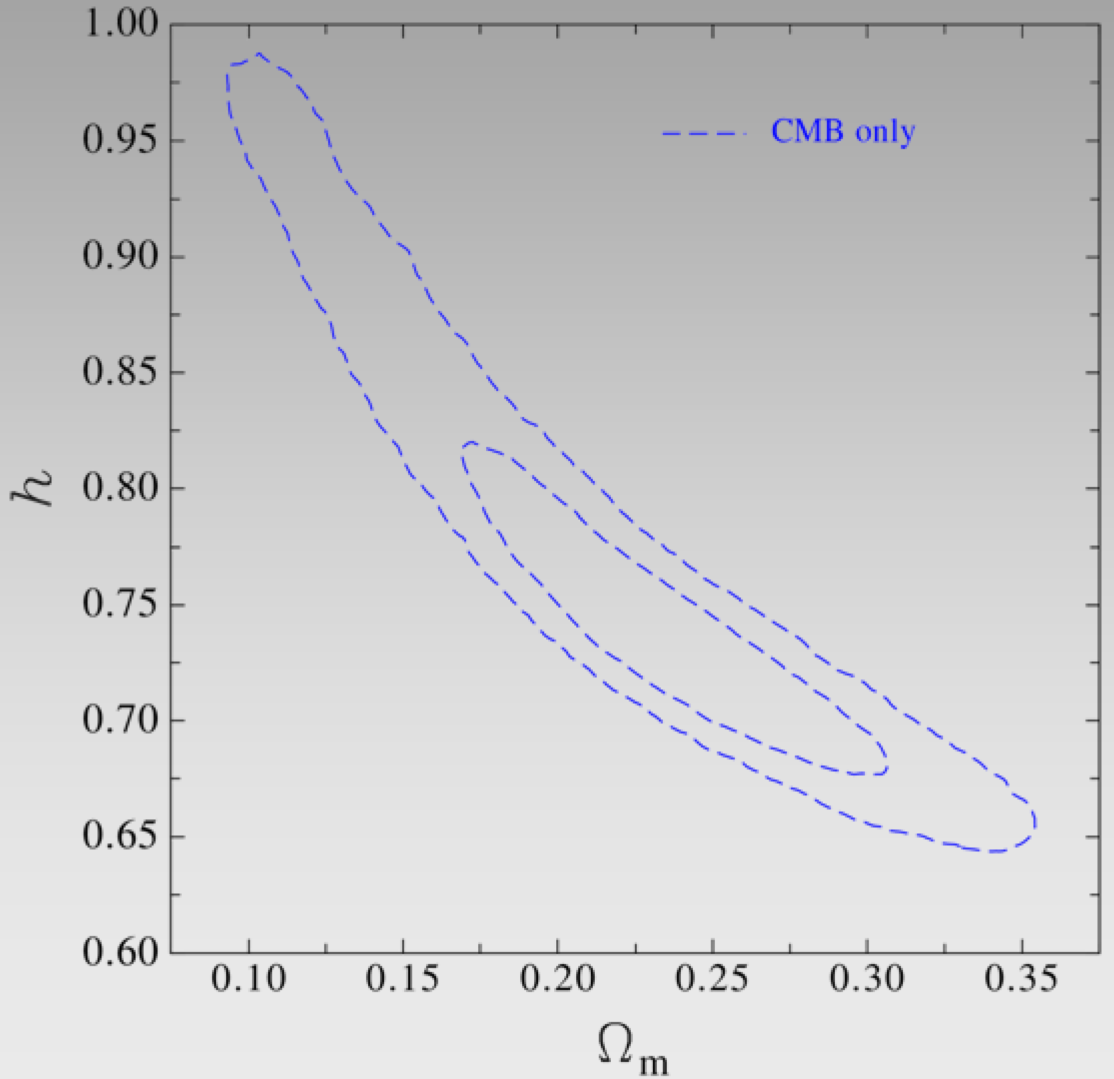
$$P_{b6} = (\omega_b,\ \omega_{dm}, \Omega_{DE}, \tau, A_s, n_s)$$

Results: the scalar spectral index



Results: the scalar spectral index

- CMB+2dFGRS gives tight constraints on Ω_m.



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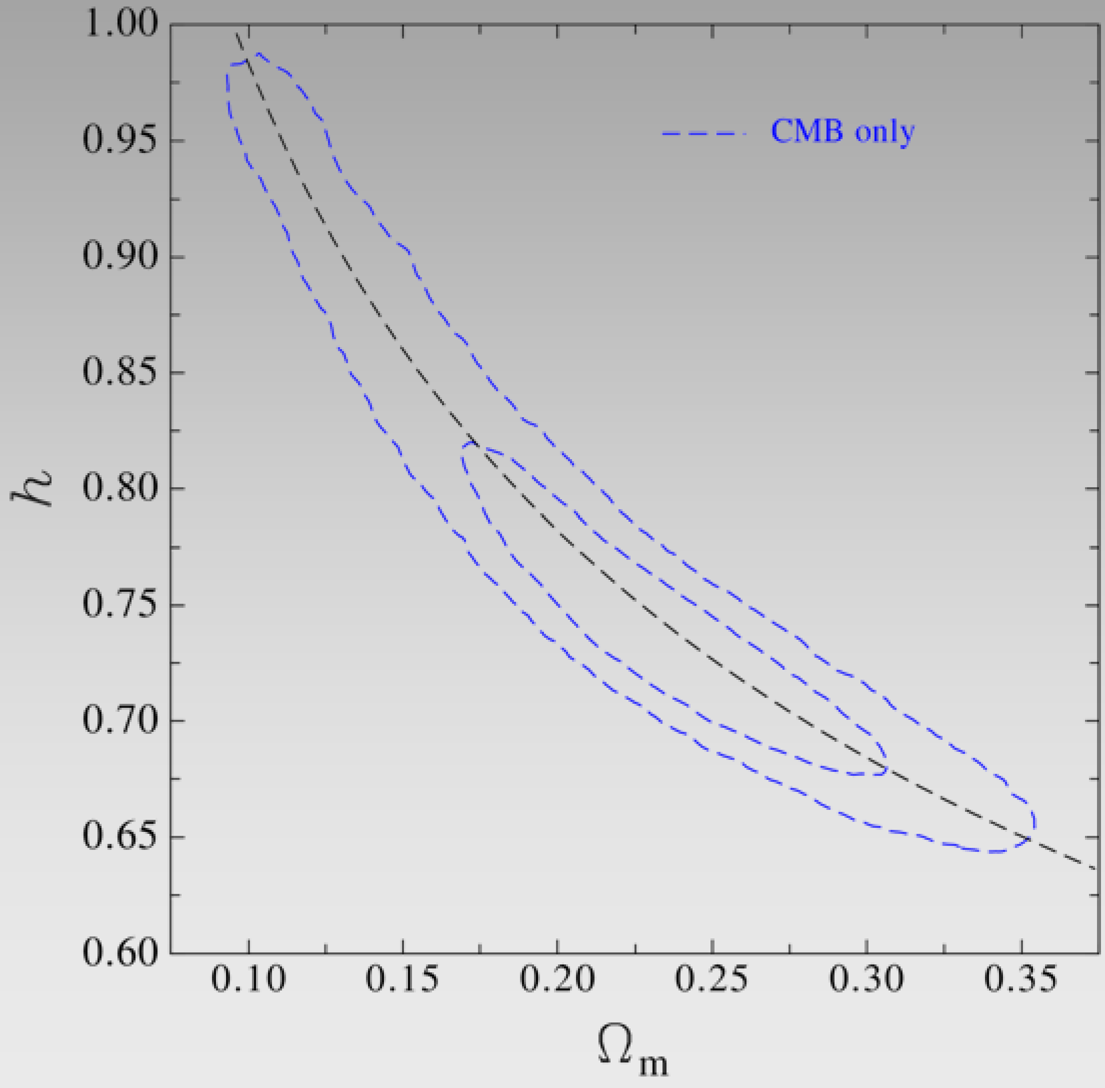

$$\Omega_m h^3 = const$$

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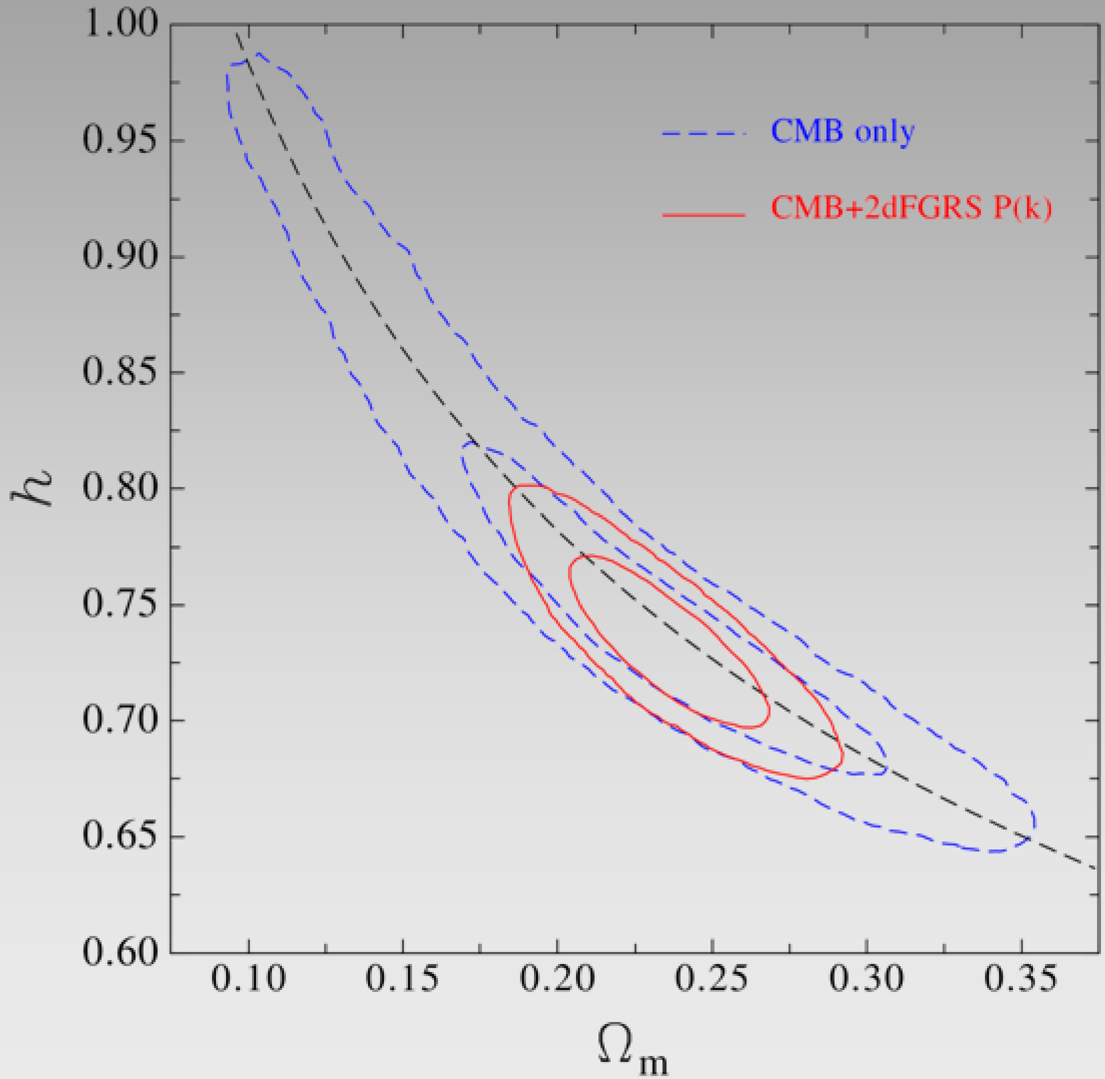

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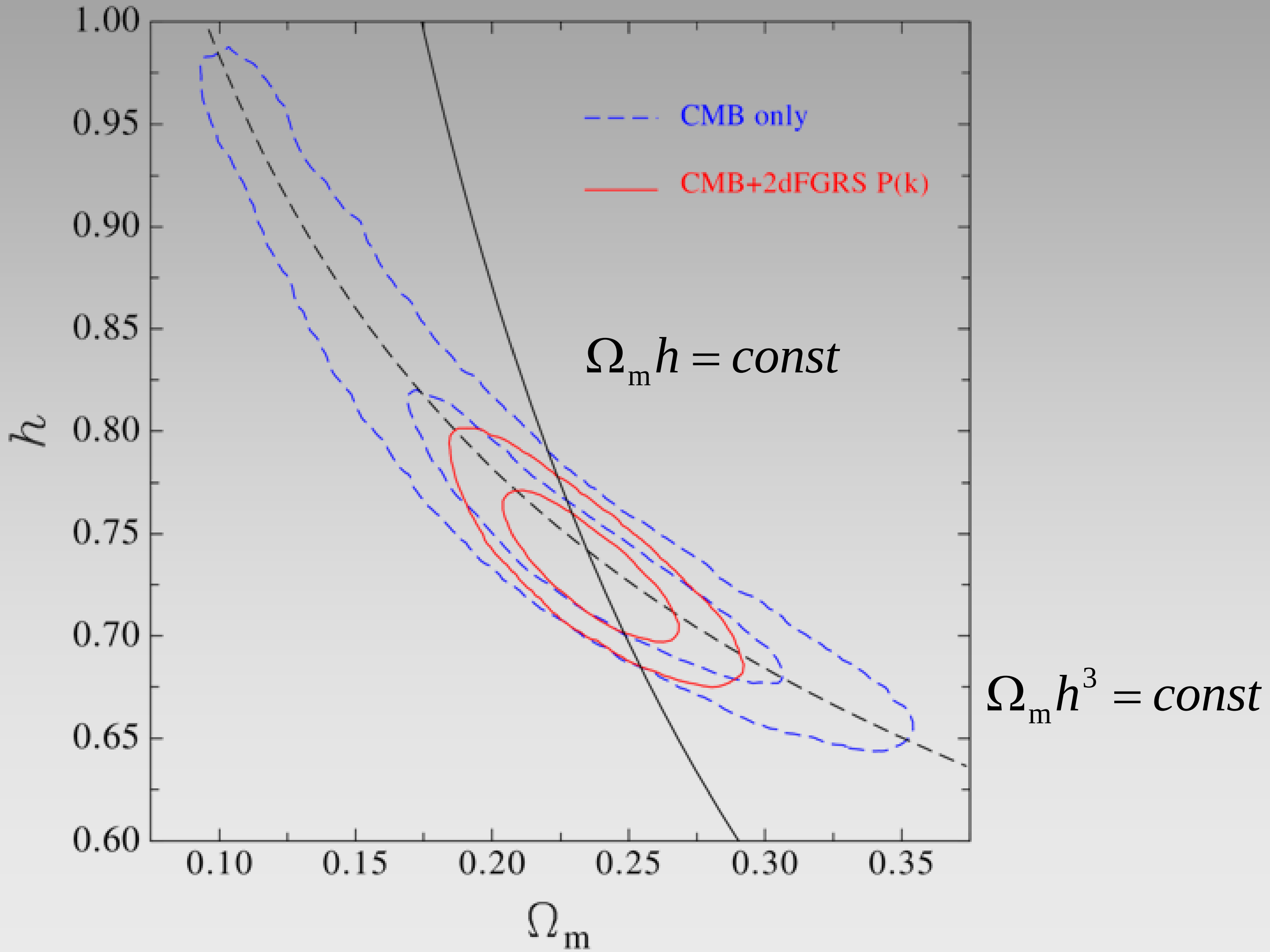
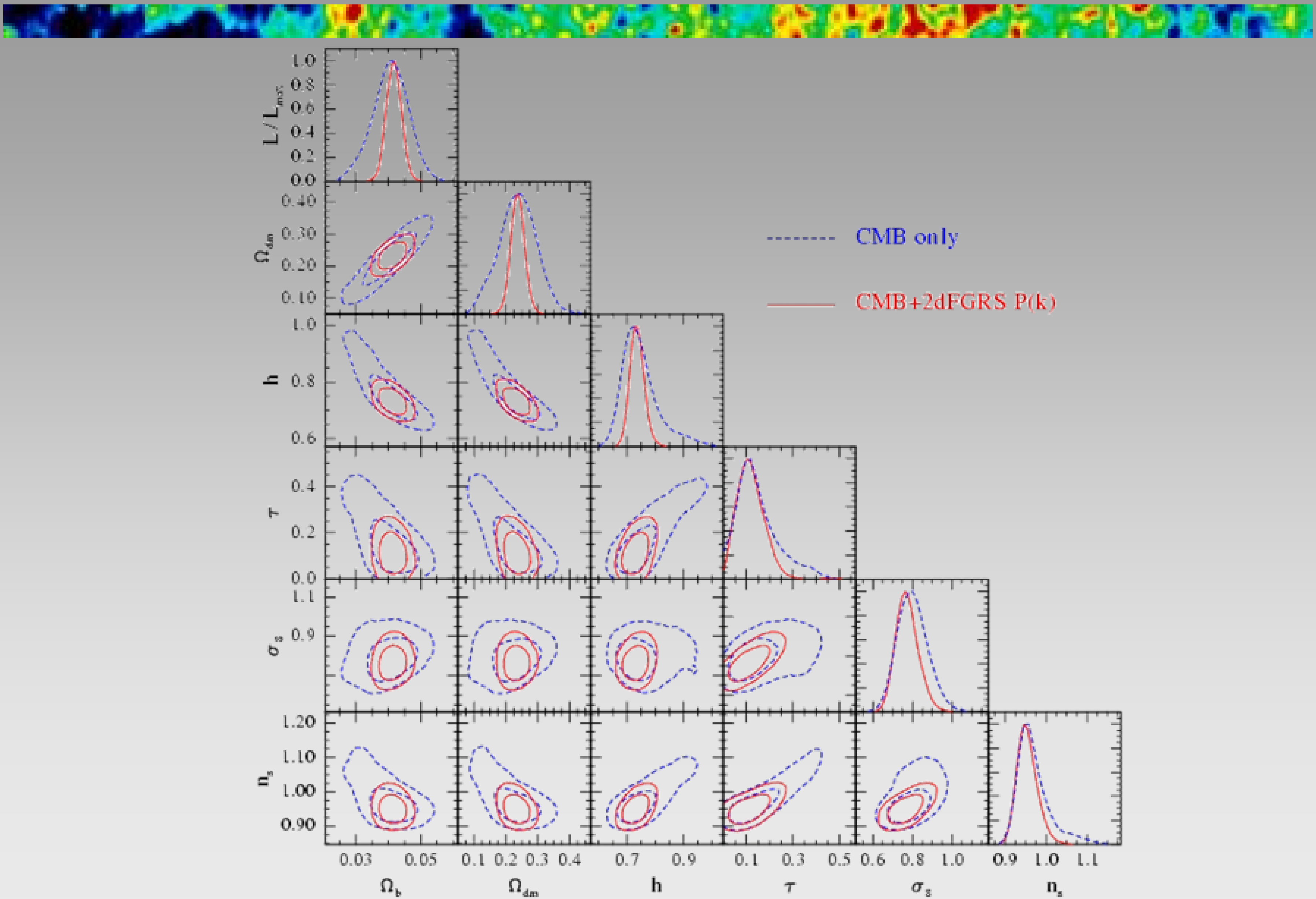
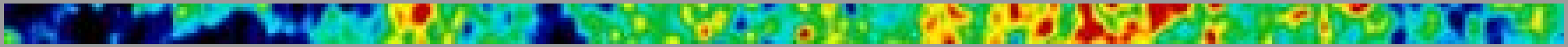


Results: the scalar spectral index



Results: a comparison with WMAP3



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parameter	WMAP1(ext.)+2dFGRS	WMAP3 only	WMAP3+2dFGRS
ω_b	0.0225 ± 0.0010	0.0223 ± 0.0008	0.0222 ± 0.0007
ω_m	0.127 ± 0.005	0.126 ± 0.009	0.1262 ± 0.0048
h	0.735 ± 0.022	0.74 ± 0.03	0.732 ± 0.021
τ	0.118 ± 0.060	0.093 ± 0.029	0.083 ± 0.029
n_s	0.954 ± 0.023	0.961 ± 0.017	0.948 ± 0.016
σ_8	0.773 ± 0.053	0.76 ± 0.05	0.737 ± 0.039
Ω_m	0.237 ± 0.020	0.234 ± 0.035	0.236 ± 0.020

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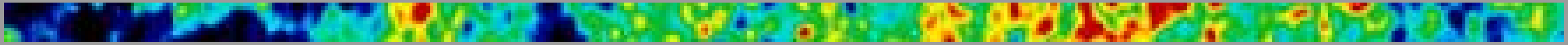

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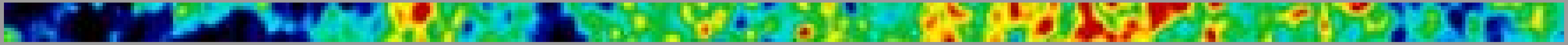

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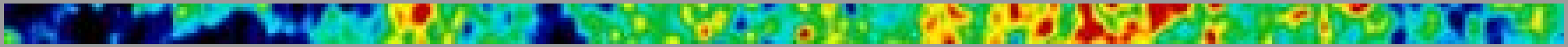

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Results: massive neutrinos

- The mass fraction of massive neutrinos

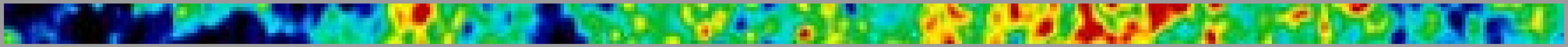
$$P_{b6+f_\nu} = (\omega_b,\, \omega_{dm}, \Omega_{DE}, \tau, A_s, n_s, f_\nu)$$

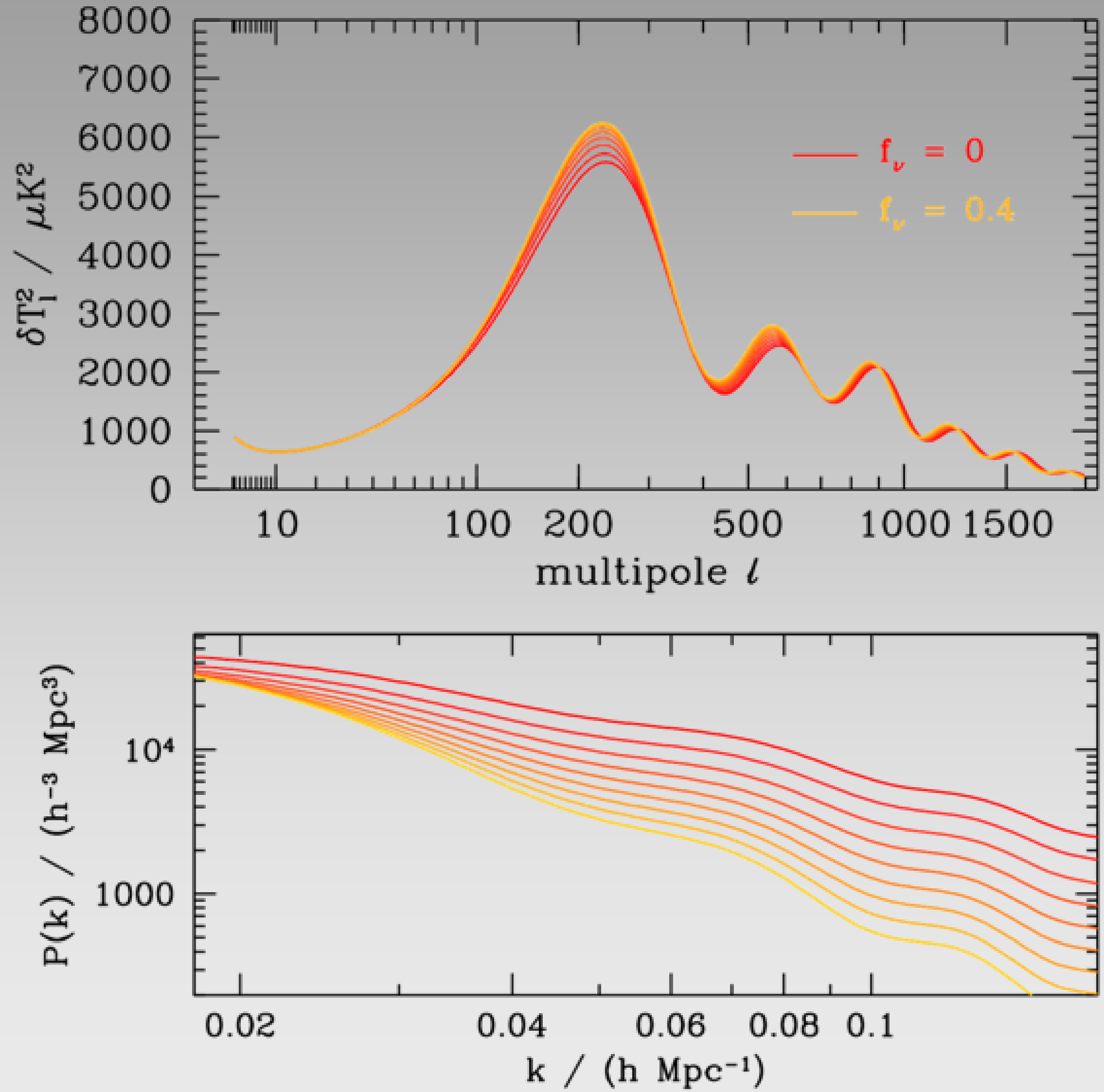
- Experiments suggest that neutrinos have a non-zero mass.

- Cosmological observations give the most precise constraint on $\sum m_\nu$.

- $P(k)$ is very sensitive on the neutrino mass fraction due to free-streaming.

Results: massive neutrinos





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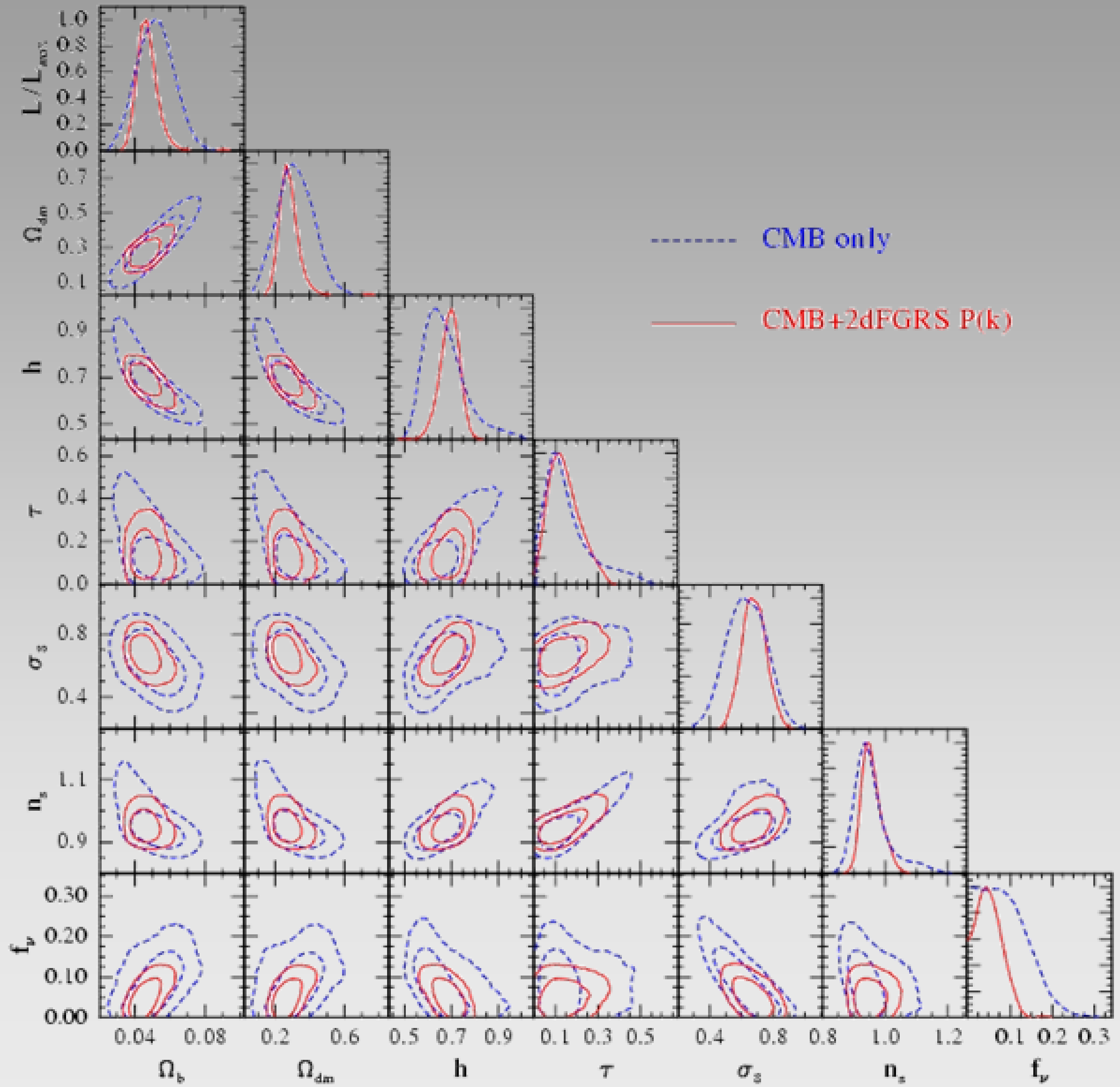


Results: massive neutrinos

- The constraints on f_ν are:

  - CMB: $f_\nu < 0.182 \quad (95\% \text{ c.l.})$

  - CMB + 2dFGRS: $f_\nu < 0.105 \quad (95\% \text{ c.l.})$

- These results can be converted into constraints on $\sum m_\nu$

$$\sum m_\nu = \omega_{dm} f_\nu 94.4 \text{ eV}$$

  - CMB: $\sum m_\nu < 2.09 \text{ eV } (95\% \text{ c.l.})$

  - CMB + 2dFGRS: $\sum m_\nu < 1.16 \text{ eV } (95\% \text{ c.l.})$

Results: non-flat models

- Testing the flatness hypothesis:

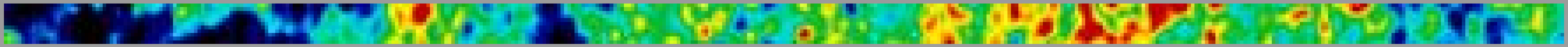
$$P_{b6+\Omega_k} = (\omega_b,\ \omega_{dm}, \Omega_{DE}, \tau, A_s, n_s, \Omega_k)$$

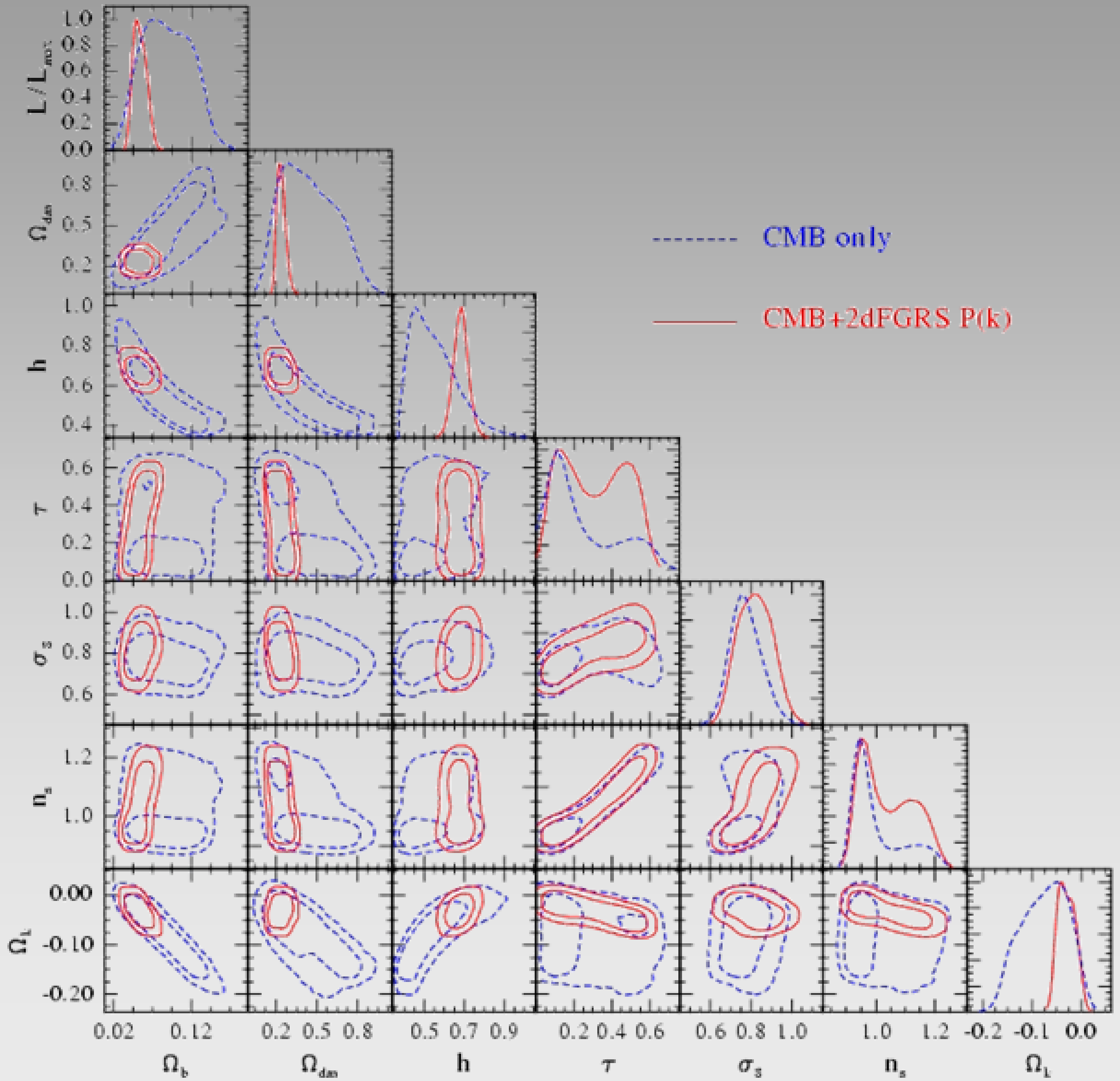
- There is a strong theoretical prejudice that $\Omega_k = 0$.

- The acoustic peaks show that it is *close* to flat.

- This is one of the most important predictions of inflationary models.

Results: non-flat models





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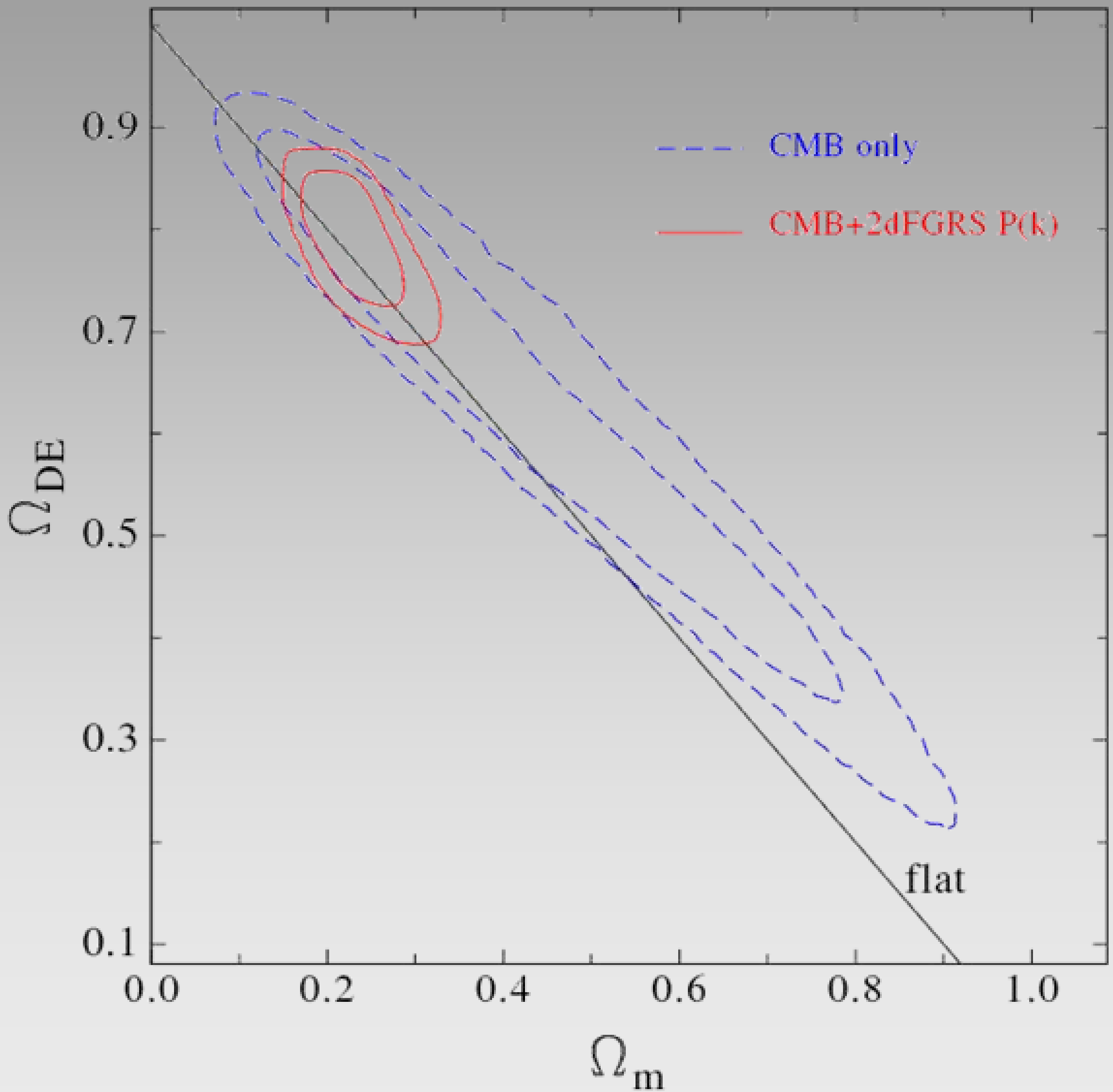

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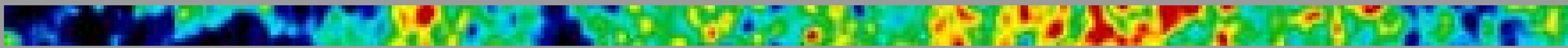
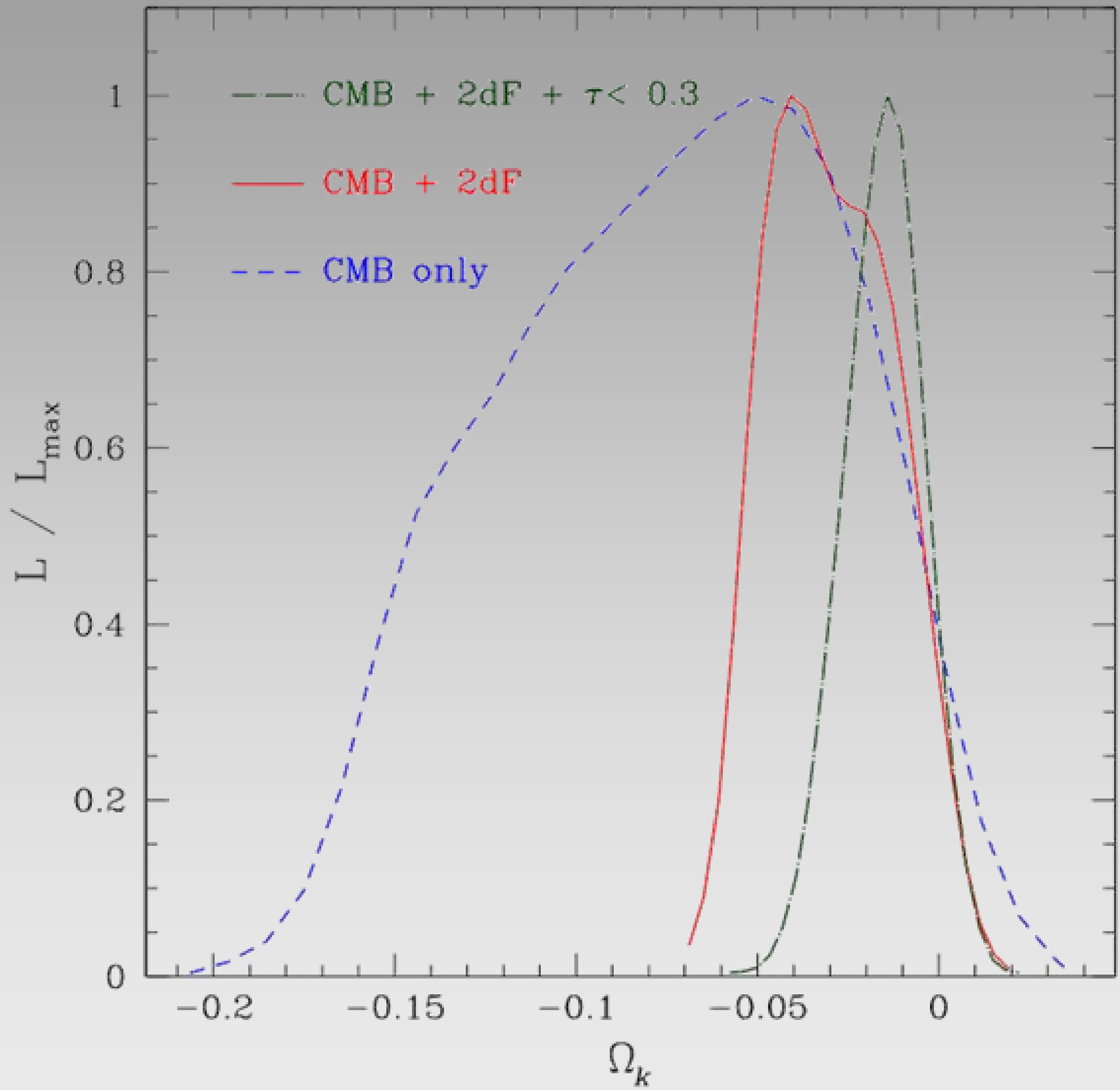


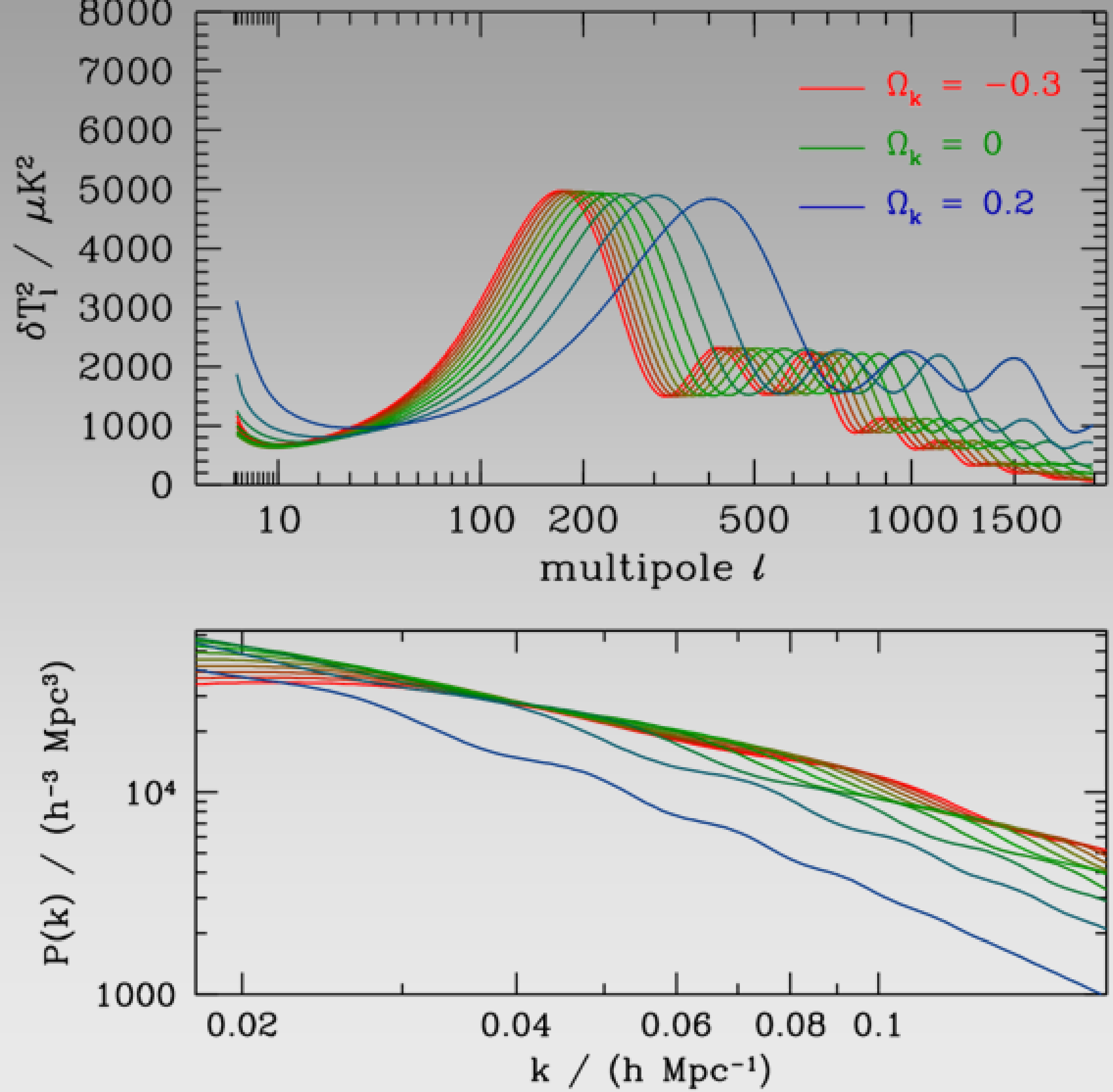


$$\Omega_k = -0.074^{+0.049}_{-0.052}$$

$$\Omega_k = -0.029^{+0.018}_{-0.018}$$

$$\Omega_k = -0.015^{+0.011}_{-0.011}$$

Results: non-flat models



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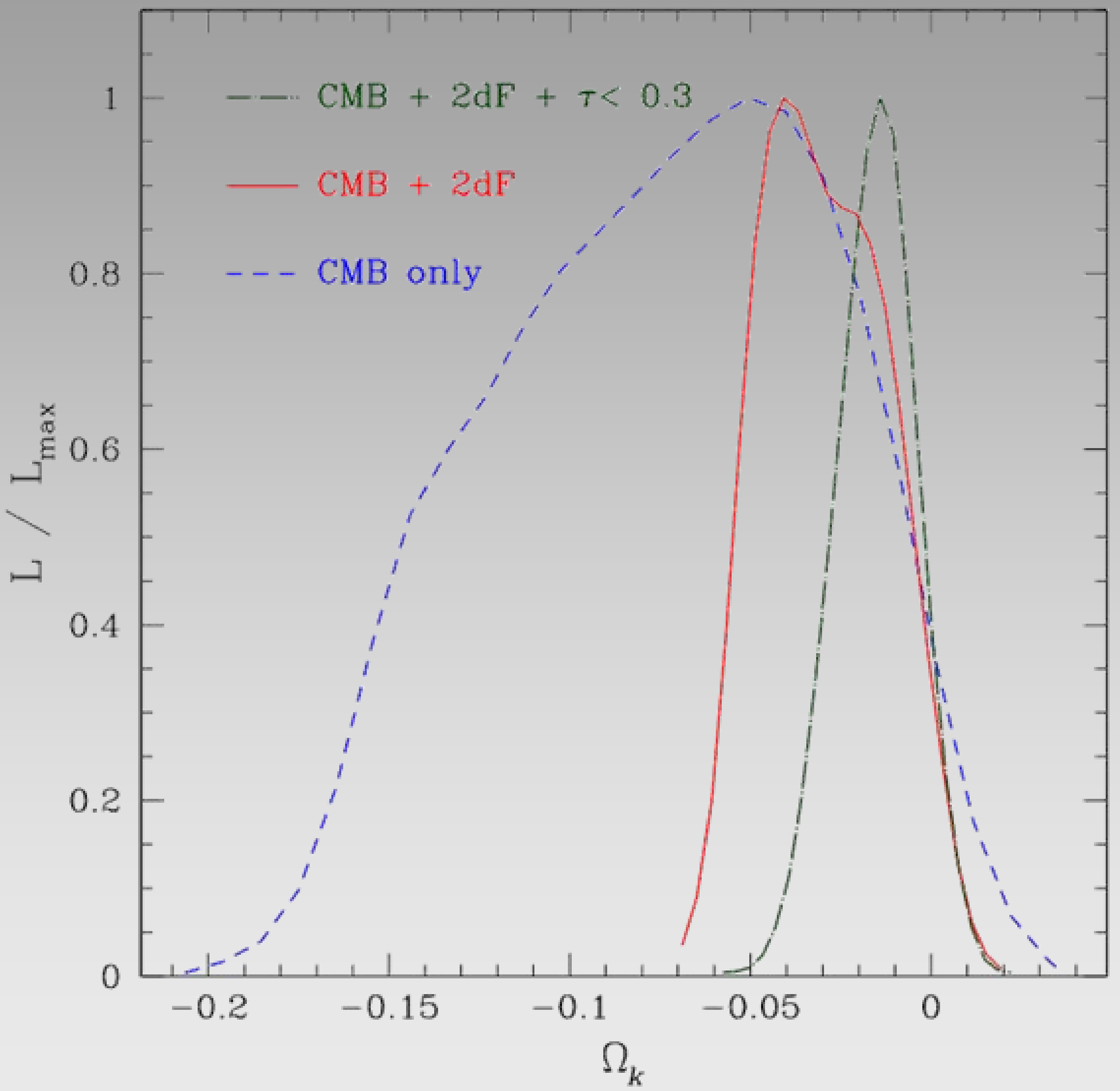

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Results: tensor modes

- Including tensor modes:

$$P_{b6+r} = (\omega_b,\ \omega_{dm}, \Omega_{DE}, \tau, A_s, n_s, r)$$

- These are related to the Horizon Flow Parameters (Schwarz et al., 2001):

$$\varepsilon_0 \equiv \frac{d_{\mathrm{H}}(N)}{d_{\mathrm{H}i}}, \qquad d_{\mathrm{H}} \equiv H^{-1}$$

$$\varepsilon_{m+1} \equiv \frac{\mathrm{d}\ln(|\varepsilon_m|)}{\mathrm{d}N}, \qquad m \geq 0$$

Results: tensor modes

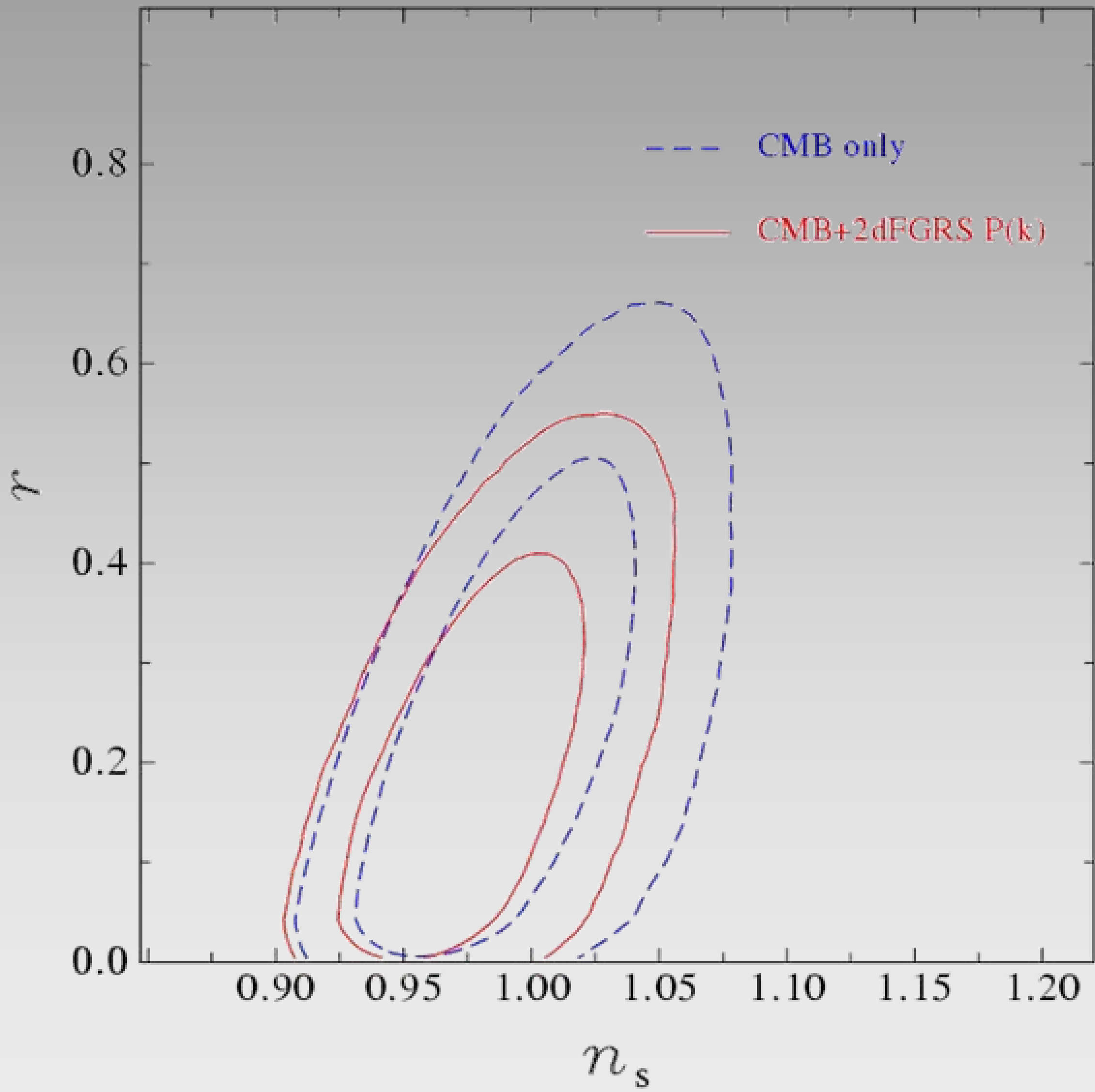
- According to this definition:

$$\varepsilon_1 \equiv \frac{\mathrm{d}\ln(d_{\mathrm{H}})}{\mathrm{d}N}$$

- We can constrain these parameters:

$$1 - n_s = 2\varepsilon_1 + \varepsilon_2$$
$$r = 16\varepsilon_1$$
$$n_t = -r/8 = -2\varepsilon_1$$

Results: tensor modes



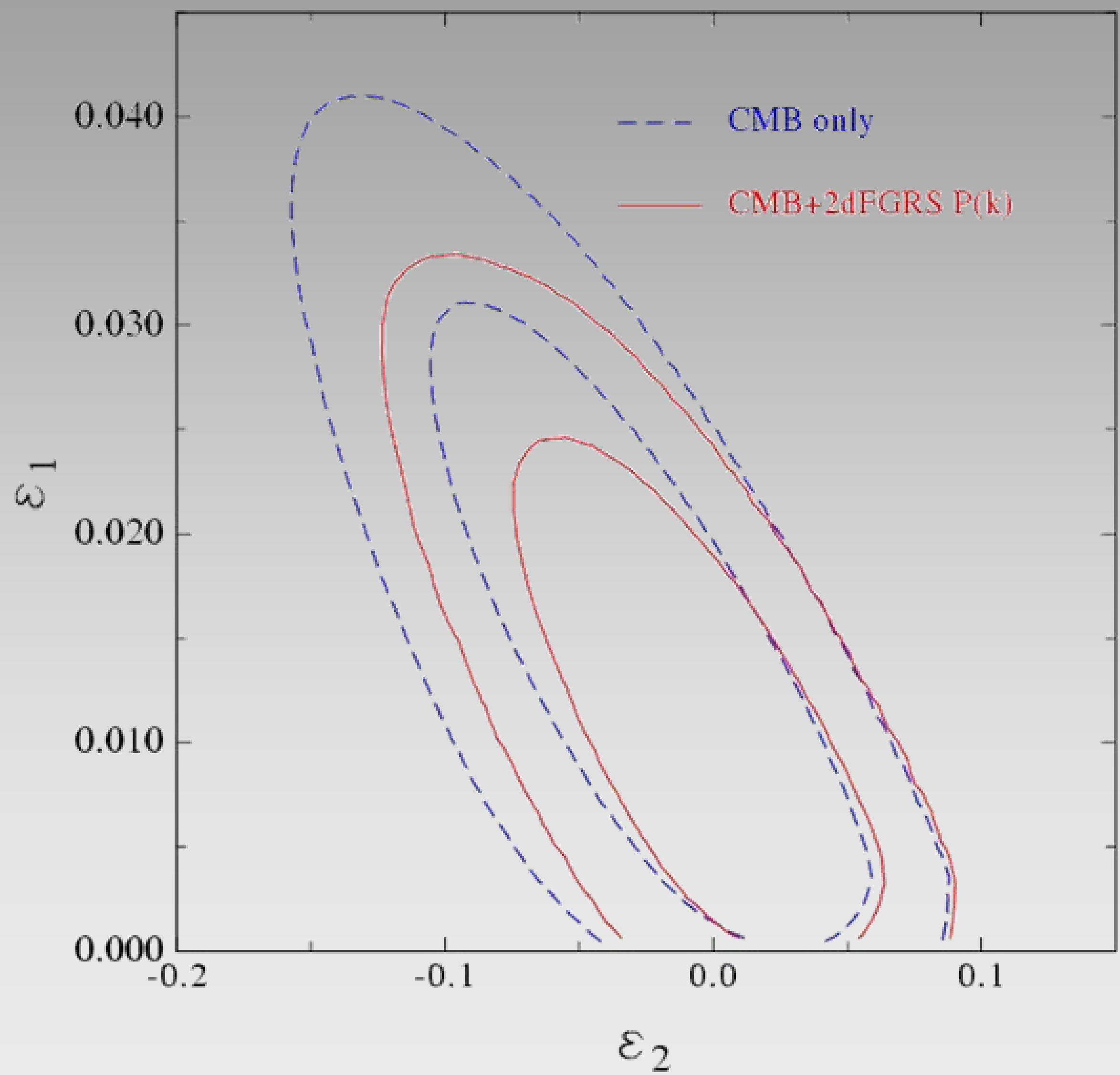
$r < 0.52 \quad (95\%)$

$r < 0.41 \quad (95\%)$

$$n_s = 0.994^{+0.033}_{-0.033}$$

$$n_s = 0.979^{+0.028}_{-0.028}$$

Results: tensor modes



$$\varepsilon_1 = 0.0123^{+0.0080}_{-0.0082}$$

$$\varepsilon_2 = 0.004^{+0.040}_{-0.040}$$

Results: tensor modes

- Power law inflation: the scale factor a grows as t^{p}.

$$\varepsilon_1 = \frac{1}{p}$$

$$\varepsilon_i = 0 \quad \forall i > 1$$

- There is a relation between r y n_s:

$$r = 8(1 - n_s)$$

-CMB: $n_s = 0.978^{+0.010}_{-0.010}$

-CMB + 2dFGRS: $n_s = 0.9762^{+0.0094}_{-0.0092}$

$$r < 0.31 \quad (95\%)$$

Results: tensor modes

- Power law inflation: the scale factor a grows as t^p.

$$\varepsilon_1 = \frac{1}{p}$$

$$\varepsilon_i = 0 \quad \forall i > 1$$

- There is a relation between r y n_s:

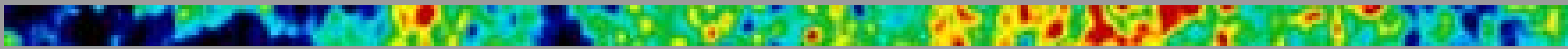
$$r = 8(1 - n_s)$$

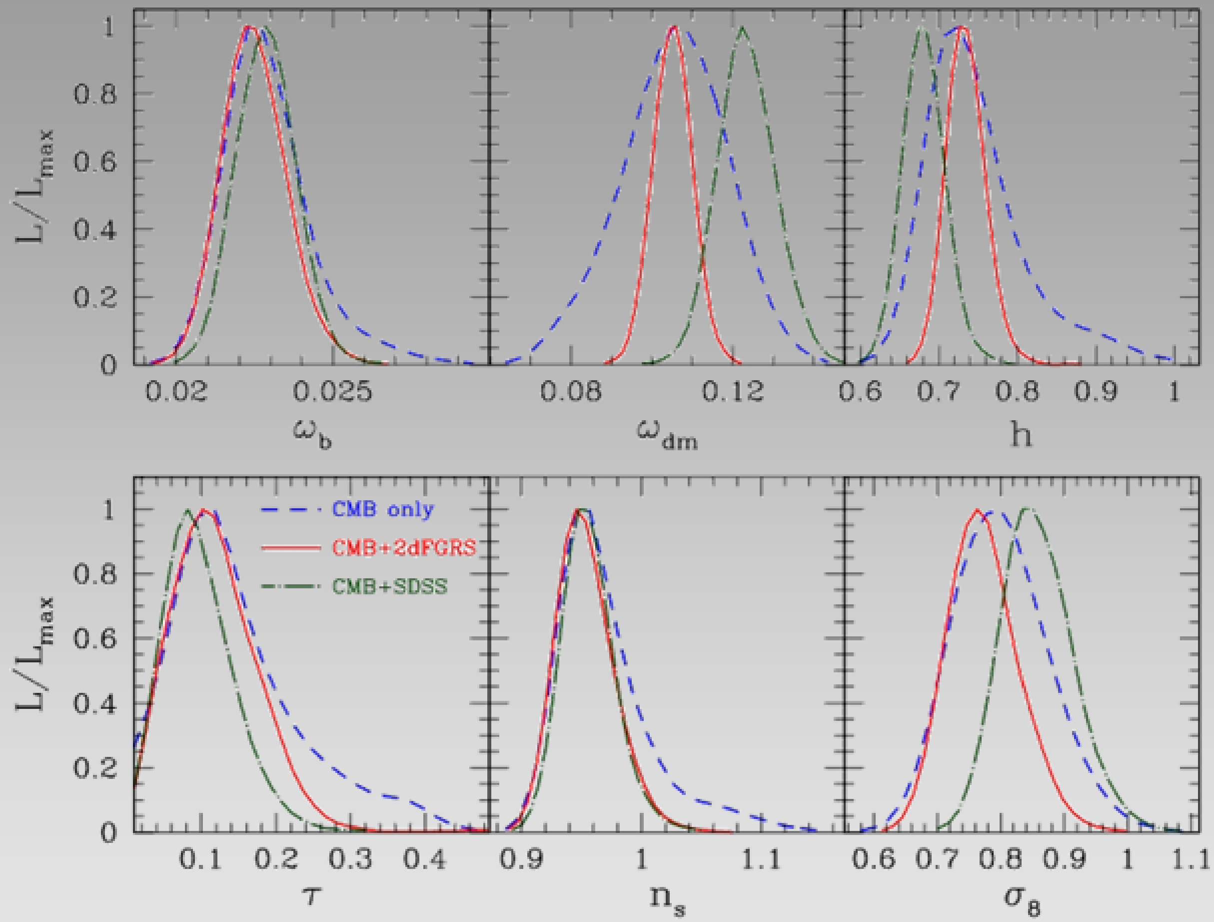
- The values of ε_1 and ε_2 are in agreement with these models:

$$\varepsilon_1 = 0.0123^{+0.0080}_{-0.0082} \qquad \left(p = 81^{+163}_{-32}\right)$$

$$\varepsilon_2 = 0.004^{+0.040}_{-0.040}$$

Results: 2dFGRS vs. SDSS





CMB: $\Omega_m = 0.237 \pm 0.055$

CMB+2dFGRS: $\Omega_m = 0.237 \pm 0.020$

CMB+SDSS: $\Omega_m = 0.317 \pm 0.035$

Results: differences between 2dFGRS and SDSS

• This has implications for other parameters.

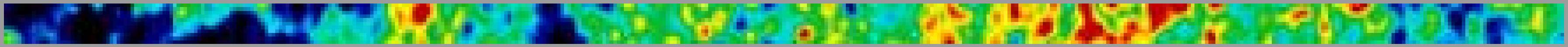
• The dark energy equation of state w_{DE}

$$P_{b6+w_{DE}} = (\omega_b,\ \omega_{dm}, \Omega_{DE}, \tau, A_s, n_s, w_{DE})$$

• There is evidence of the accelerating expansion of the Universe.

• To distinguish between possible models: analyse w_{DE}

Results: differences between 2dFGRS and SDSS



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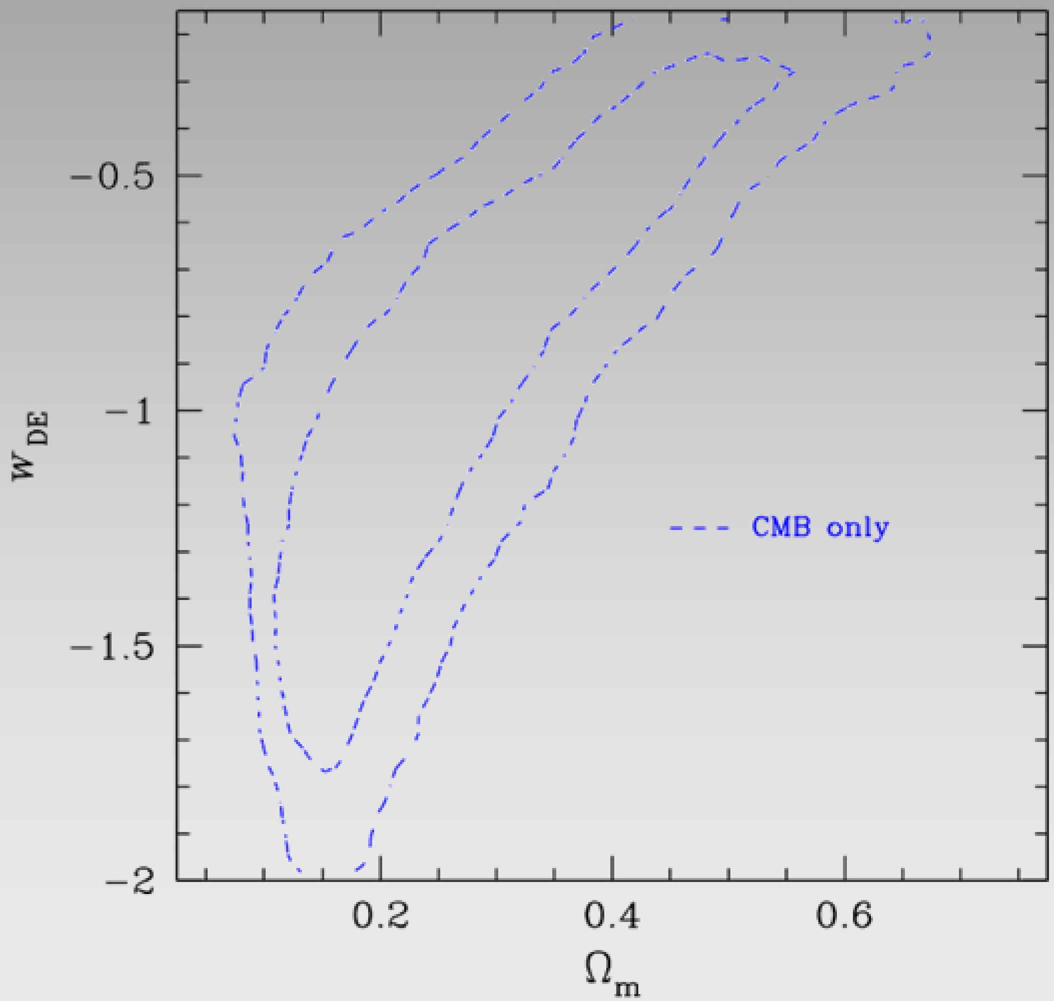

$$w_{\rm DE} = -0.93^{+0.49}_{-0.47}$$

Results: differences between 2dFGRS and SDSS

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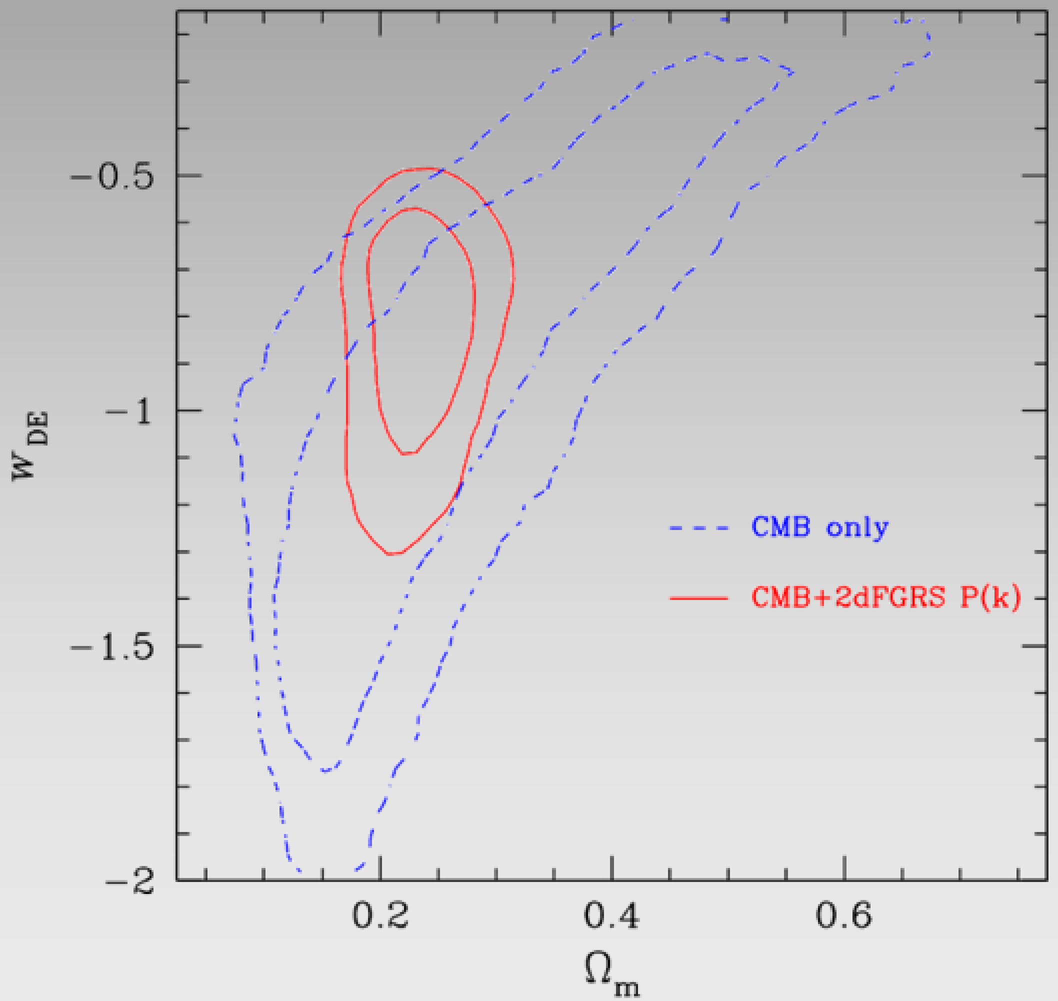

$$w_{DE} = -0.93^{+0.49}_{-0.47}$$

$$w_{DE} = -0.85^{+0.18}_{-0.17}$$

Results: differences between 2dFGRS and SDSS

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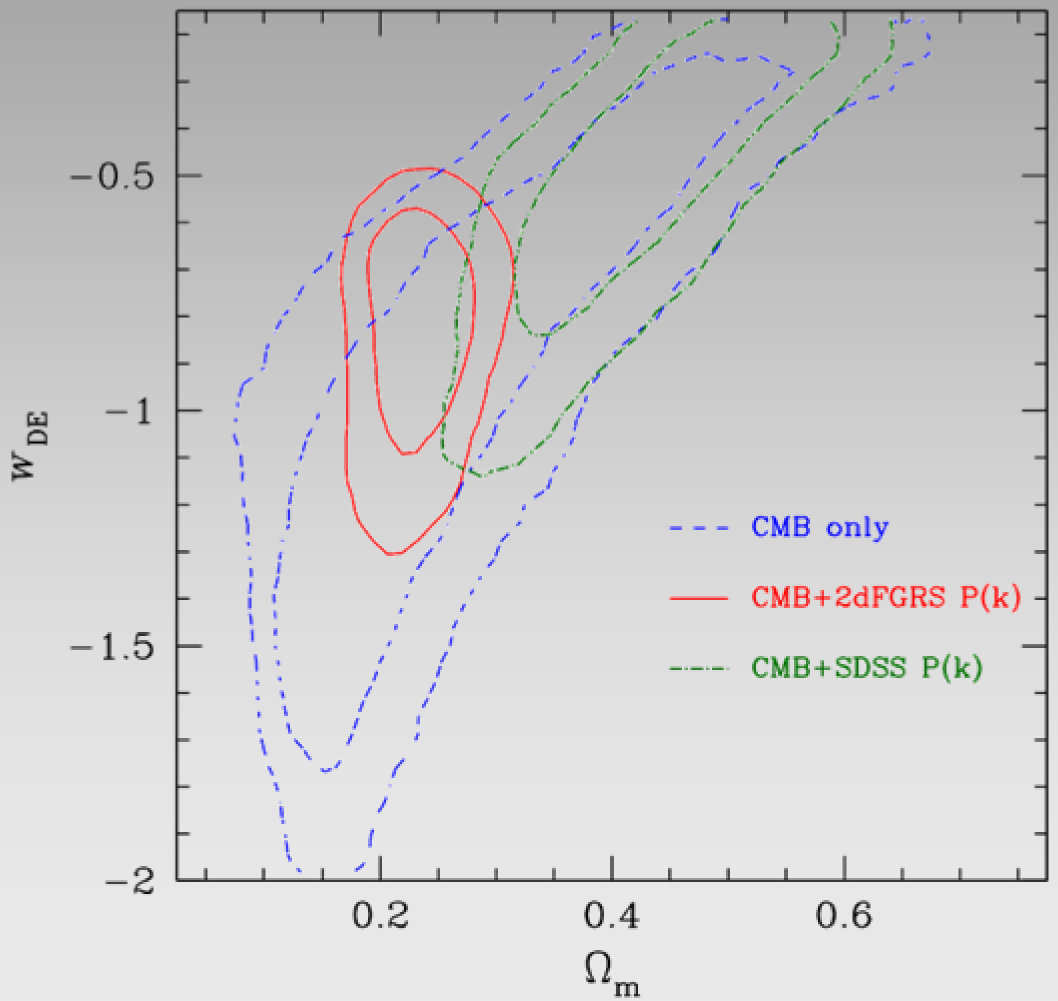

$$w_{DE} = -0.93^{+0.49}_{-0.47}$$

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$$w_{DE} = -0.45^{+0.23}_{-0.23}$$

Results: differences between 2dFGRS and SDSS

- Selection methods?

  - 2dFGRS: blue - SDSS: red.

- Modelling of $P(k)$?

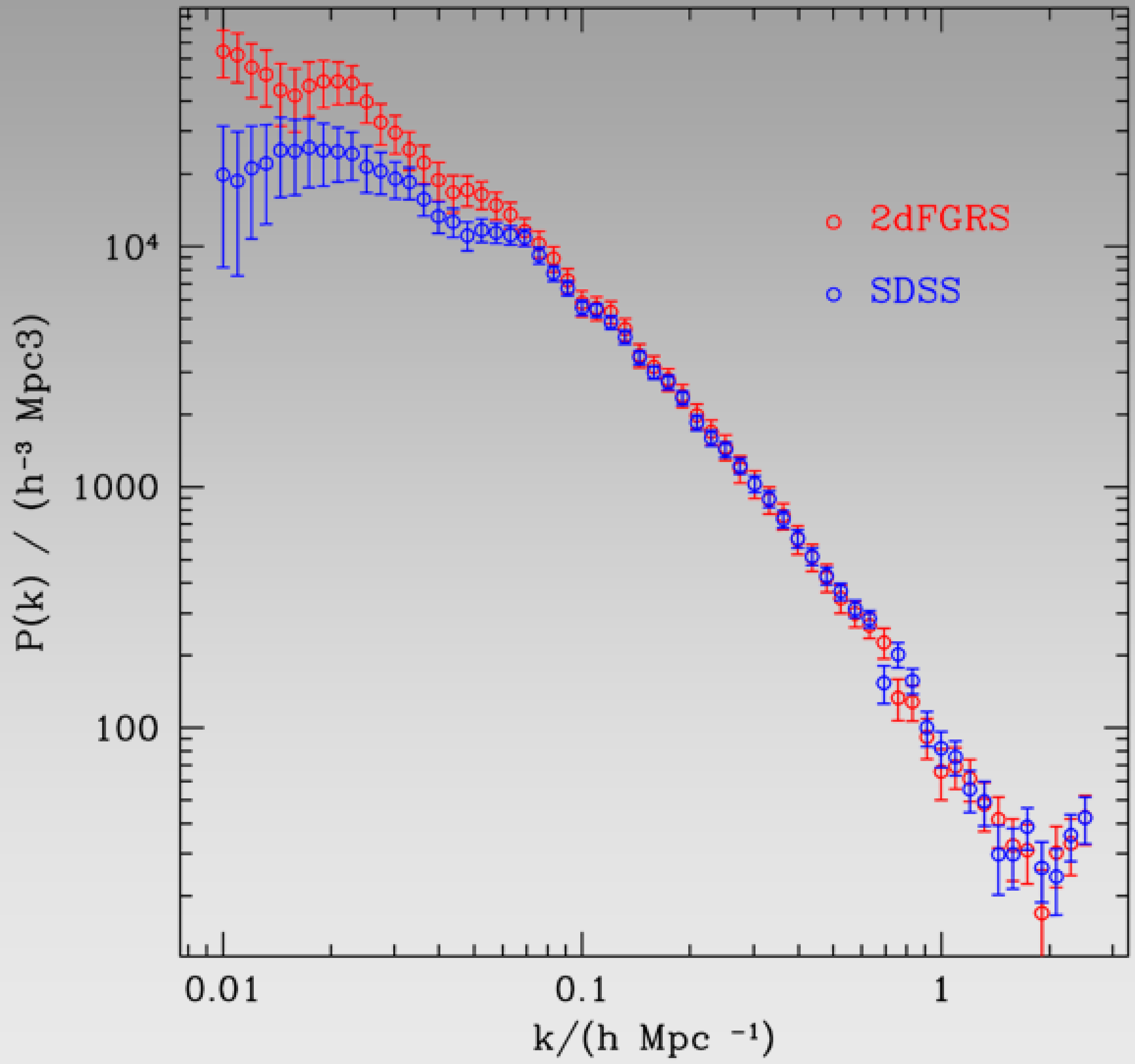
  - 2dFGRS: redshift space – SDSS: real space

- $P(k)$ estimator?

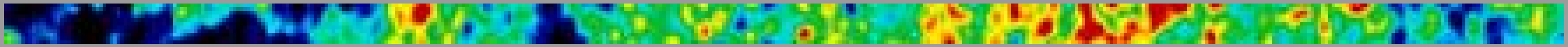
  - 2dFGRS: direct Fourier transform (FKP)

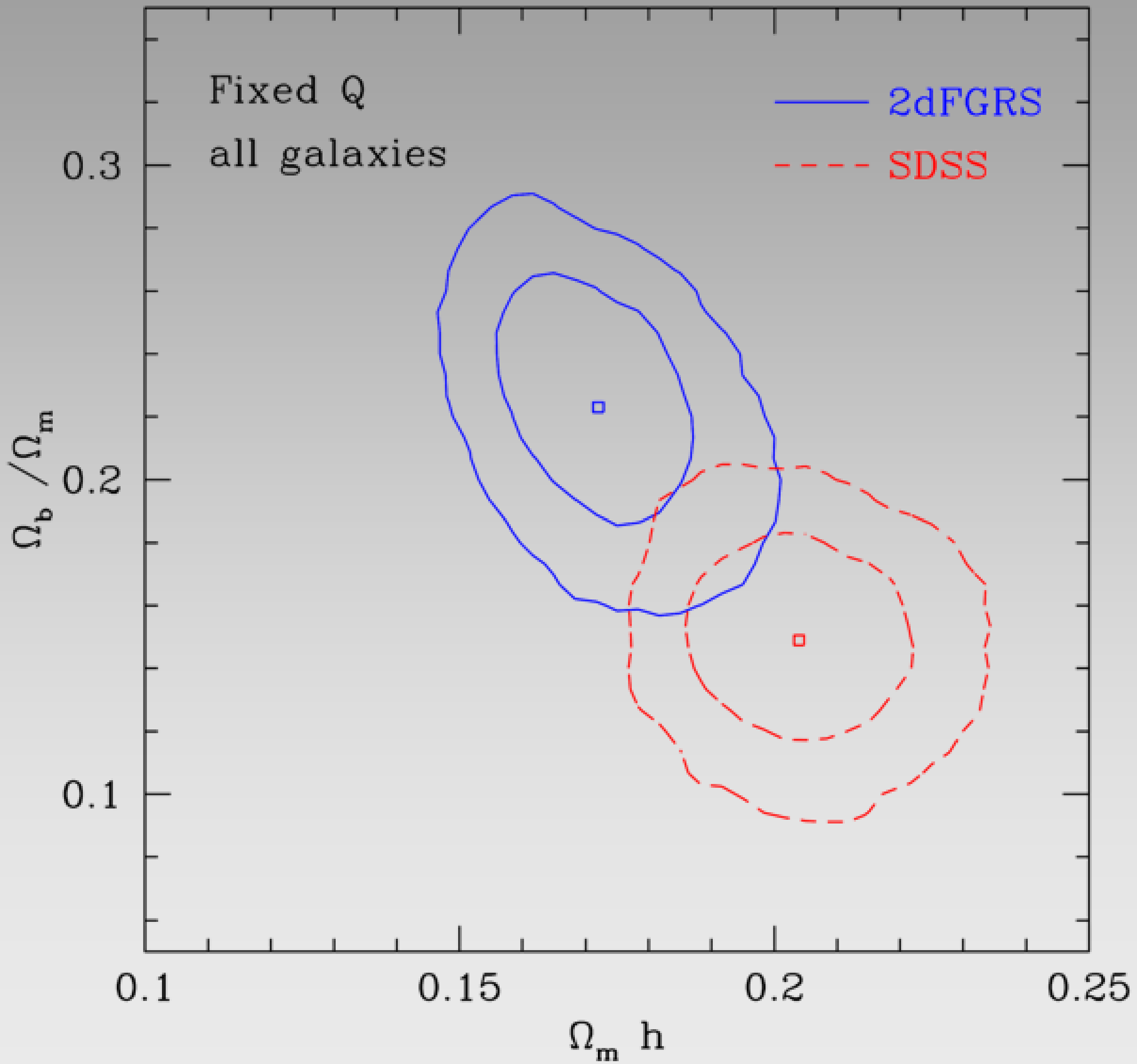
  - SDSS: fog compression, pseudo-Karhunen-Loève dec…

Results: differences between 2dFGRS and SDSS

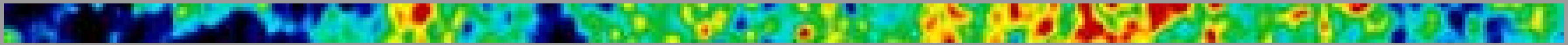


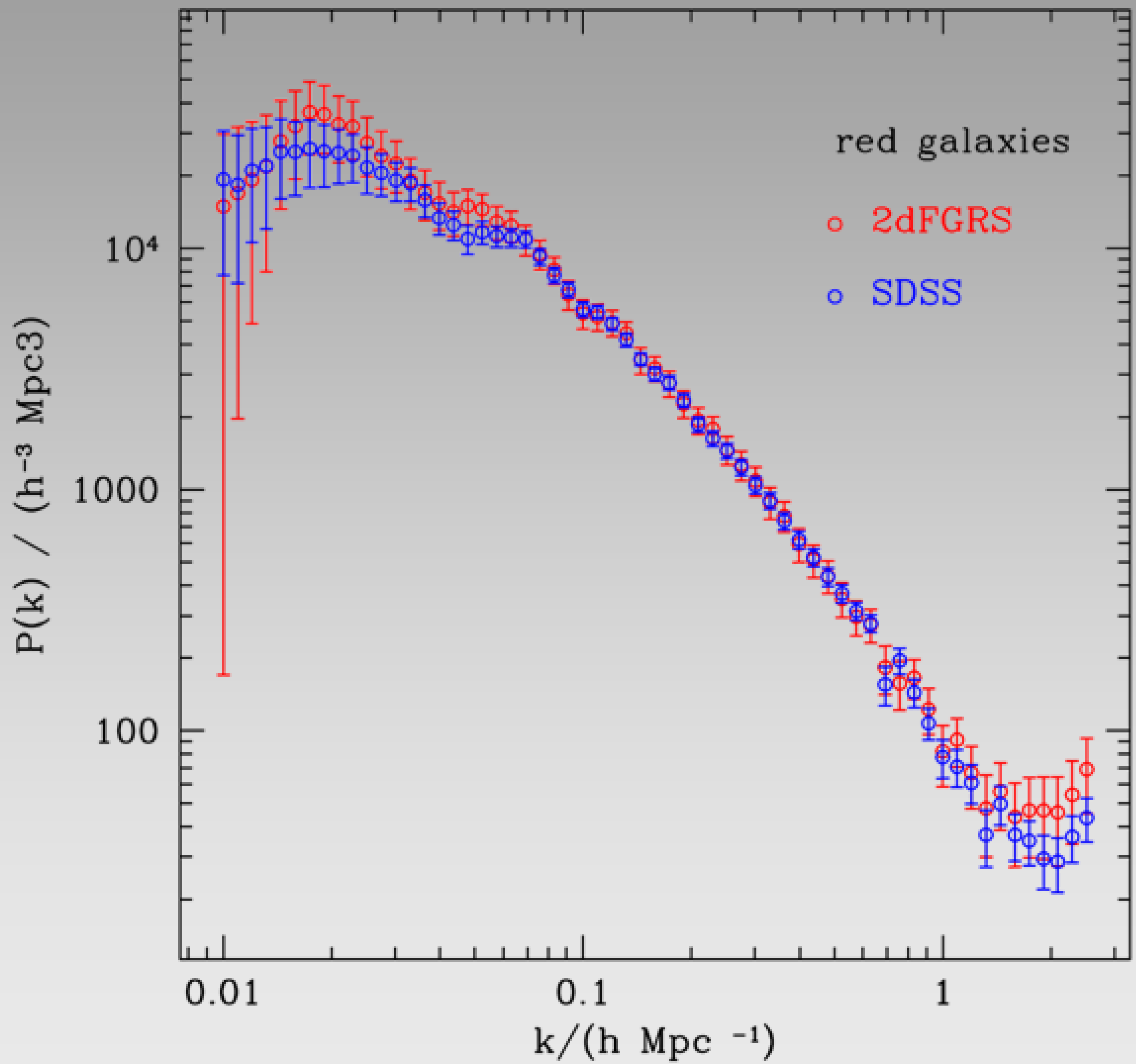
Results: differences between 2dFGRS and SDSS



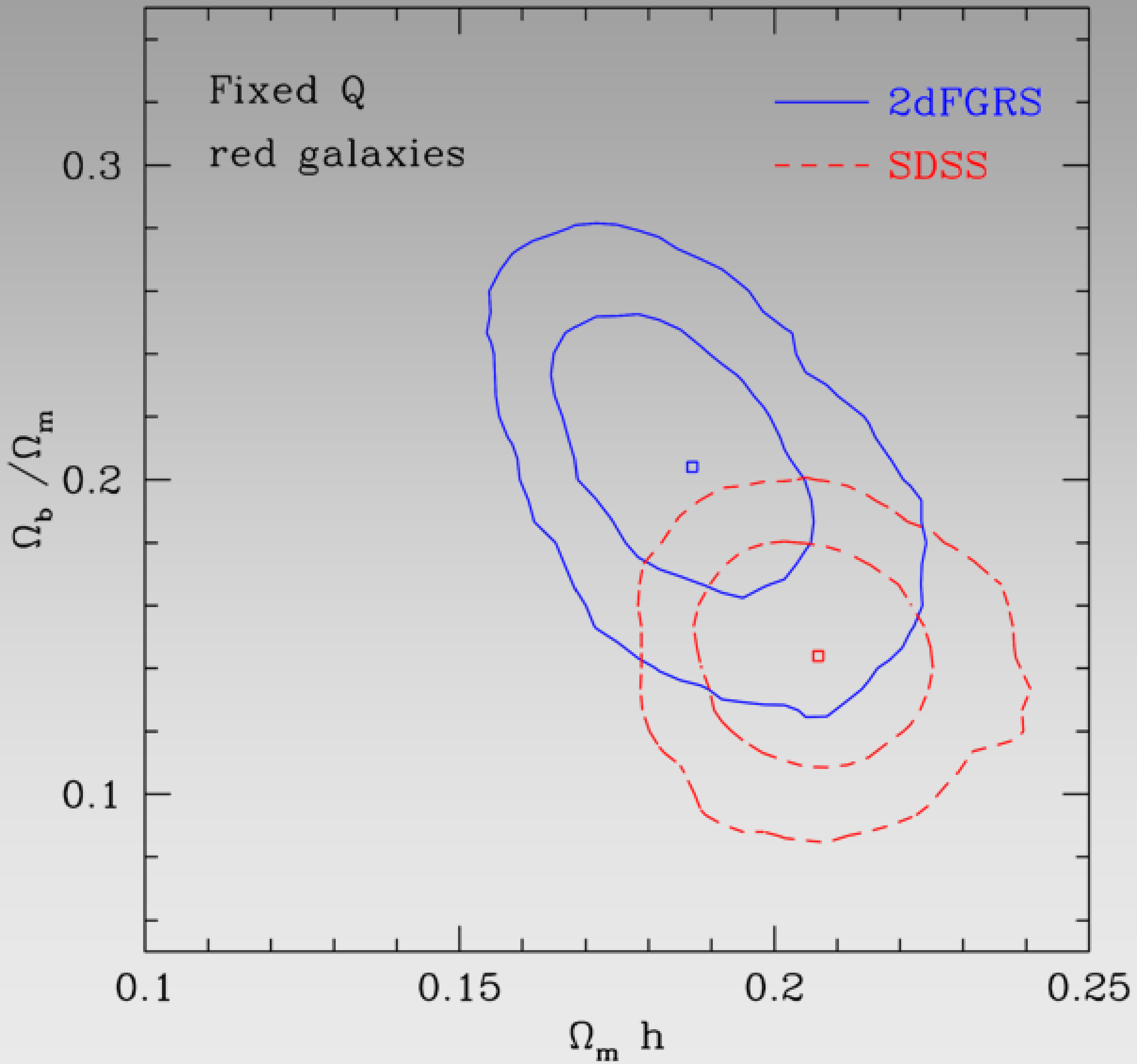


Results: differences between 2dFGRS and SDSS

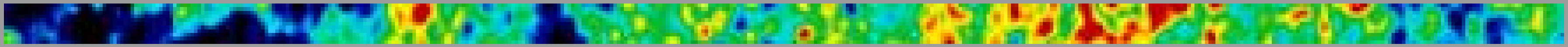


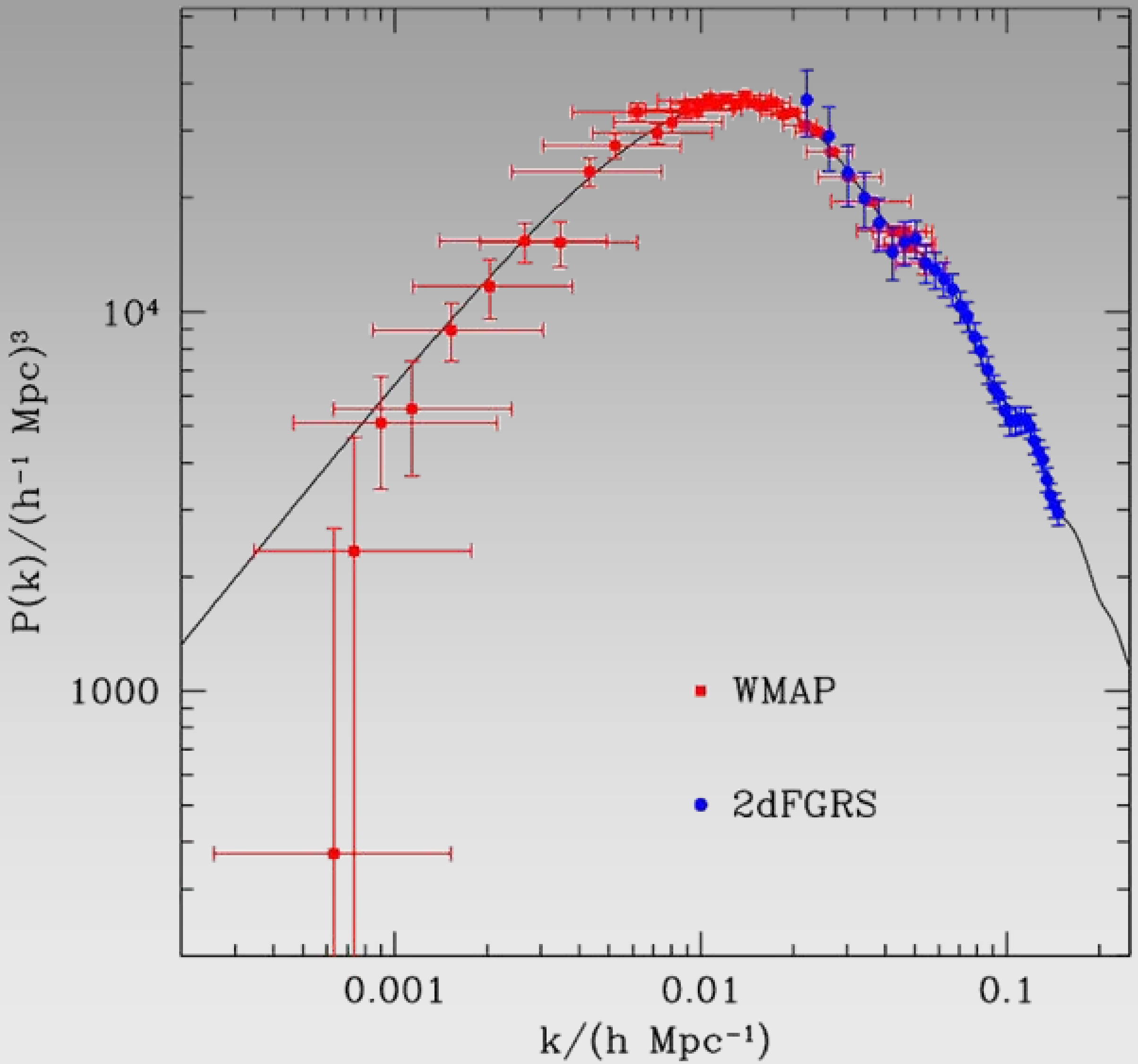


Results: differences between 2dFGRS and SDSS



Final remarks





Final remarks

- We found strong evidence from a deviation from scale invariance (n_s < 1 at 95% c.l.).

- We infer a density significantly below $\Omega_m = 0.3$.

- There is an impressive agreement between CMB and 2dFGRS.

- These results have been confirmed by WMAP3.

- There are differences with the results obtained with SDSS.

- Important to model nonlinearity and scale dependent bias.