Cosmic Acceleration and Extra Dimensions:

constraints on the modifications of the Friedmann equation

DESY Theory Workshop 2004

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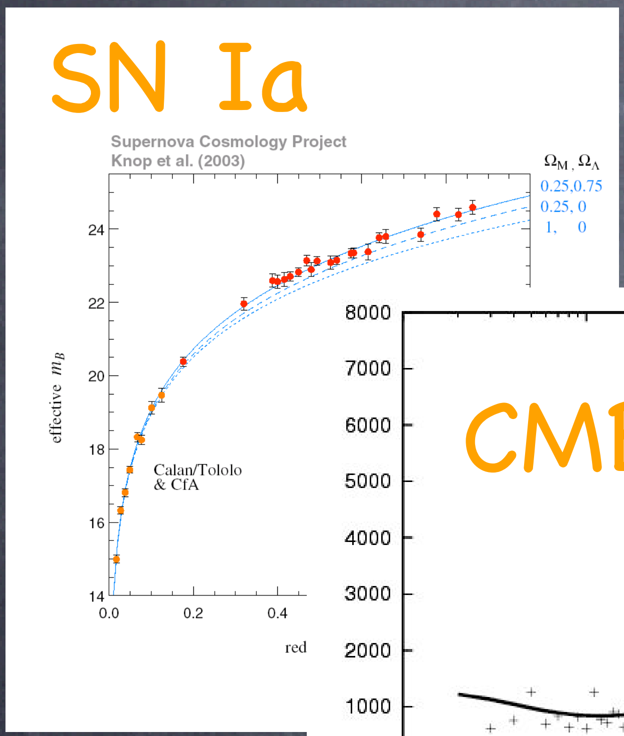
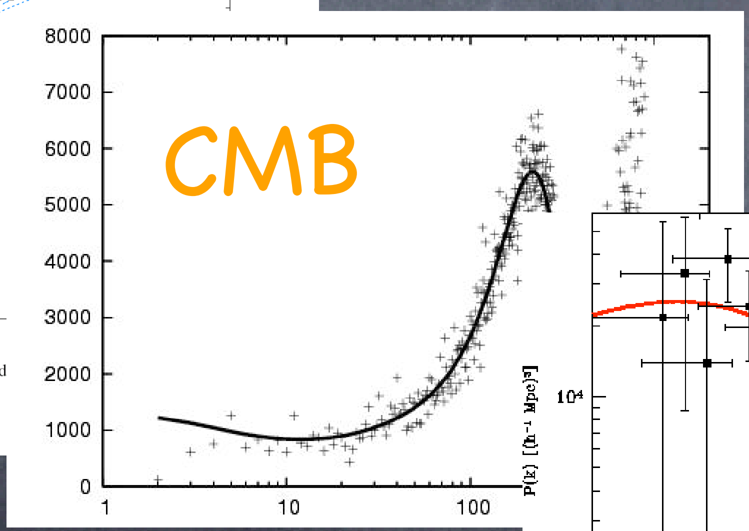
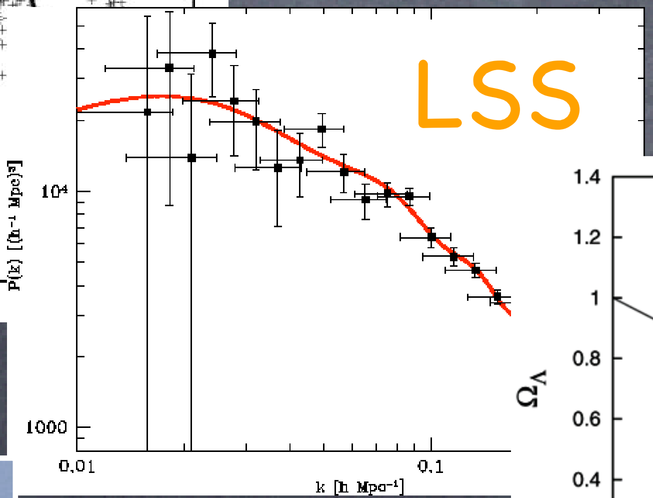
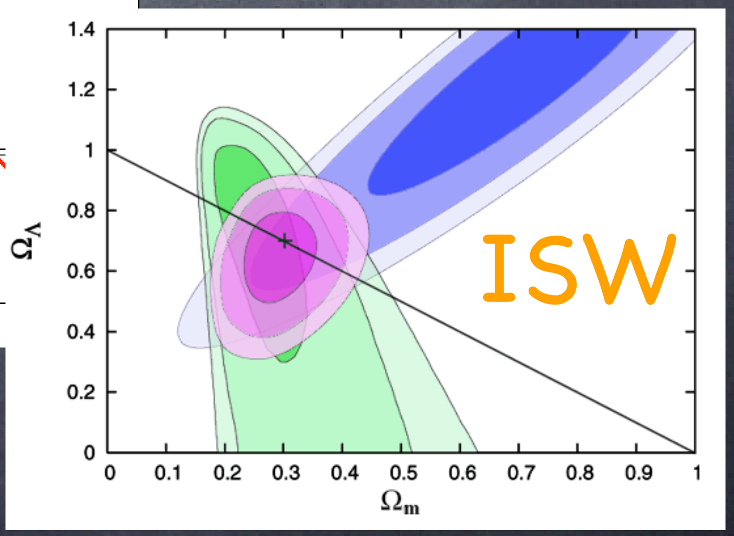
The Universe is accelerating!!!(?)









What is causing it?

Modified Friedmann equations: Alternatives to EdS

EdS:

$$H^2 = \frac{8\pi G}{3}\rho_m$$

Observationally challenged

LCDM:

$$H^2 = \frac{8\pi G}{3}\rho_m + \frac{\Lambda}{3}$$

Fits observations better, c.c. problem

Exotic fluids:

$$H^2 = \frac{8\pi G}{3}(\rho_m + \rho_D)$$

Quintessence, Chaplygin gas, ...

Modified Friedmann equations: Alternatives to EdS ctnd.

Cardassian:

$$H^2 = \frac{8\pi G}{3} f(\rho_m)$$

???

$$f(H^2) = \frac{8\pi G}{3} \rho_m$$

Cardassian Models: an example

- MPC model (Freese, Gondolo & Wang, 2003)
- q>0, n<2/3

$$H^2 = \frac{8\pi G}{3}\rho_M\left(1+\left(\frac{\rho_M}{\rho_c}\right)^{q(n-1)}\right)^{1/q}$$

- no dark energy, only CDM
- at early times, CDM like behaviour, at late times cosmological constant type behaviour
- linear perturbation growth can be radically different
- "Star Trek inspired"

DGP-model

(Dvali, Gabadadze, Porrati 2000)

$$S = \frac{M_{\rm Pl}^2}{r_c} \int d^4x\, dy \sqrt{g^{(5)}}\,\mathcal{R} + \int d^4x \sqrt{g}\left(M_{\rm Pl}^2 R + \mathcal{L}_{\rm SM}\right)$$

$\mathcal{R}$

$g^{(5)}$

- 5-dimensional universe (gravity)
- flat extra dimension
- SM lives on the brane

DGP-model cntd.

$$S = \frac{M_{\rm Pl}^2}{r_c} \int d^4x\, dy \sqrt{g^{(5)}}\mathcal{R} + \int d^4x \sqrt{g}\left(M_{\rm Pl}^2 R + \mathcal{L}_{\rm SM}\right)$$

bulk

brane

cross-over scale r_c

large distances ($r \gg r_c$), gravity is 5D

small distance ($r \ll r_c$), gravity is 4D

DGP-model cntd.

add a cosmological metric:

$$ds_5^2 = g^{FRW} ds_4^2 - dy^2$$

Friedmann equation on the brane:

$$H^2 \pm \frac{H}{r_c} = \frac{8\pi G}{3}\rho_m$$

induced metric on the brane:

$$g_{\mu\nu}(x) = g^{(5)}_{\mu\nu}(x, y=0)$$

DGP-model cntd.

$$H^2 \pm \frac{H}{r_c} = \frac{8\pi G}{3}$$

$$H^2 = \frac{8\pi G}{3}\rho_m + r_c^{-1}\sqrt{r_c^{-2} + \frac{32\pi G}{3}\rho_m} + \frac{1}{2}r_c^{-2}$$

Generalized Friedmann equation

$$f(H^2) = \frac{8\pi G}{3}\rho_m \Leftrightarrow f(H^2) = H_0^2\Omega_m(1+z)^3$$

critical scale H_c of new physics

early times, $f(H)=H^2$

$$H^2\left[1+\sum_{n=1} c_n\left(\frac{H_c}{H}\right)^n\right]H = H_0^2\Omega_m(1+z)^3$$

$$H^2\left[1+c_1\frac{H_c}{H}+\left(\frac{H_c}{H}\right)^2+\ldots\right] = H_0^2\Omega_m(1+z)^3$$

Generalized Friedmann equation

$$H^2\left[1+c_1\frac{H_c}{H}+\left(\frac{H_c}{H}\right)^2+\ldots\right]=H_0^2\Omega_m(1+z)^3$$

DGP

C.C.

leading term

$$\left(\frac{H}{H_0}\right)^2=\Omega_m(1+z)^3+(1-\Omega_m)\left(\frac{H_0}{H}\right)^{n-2}$$

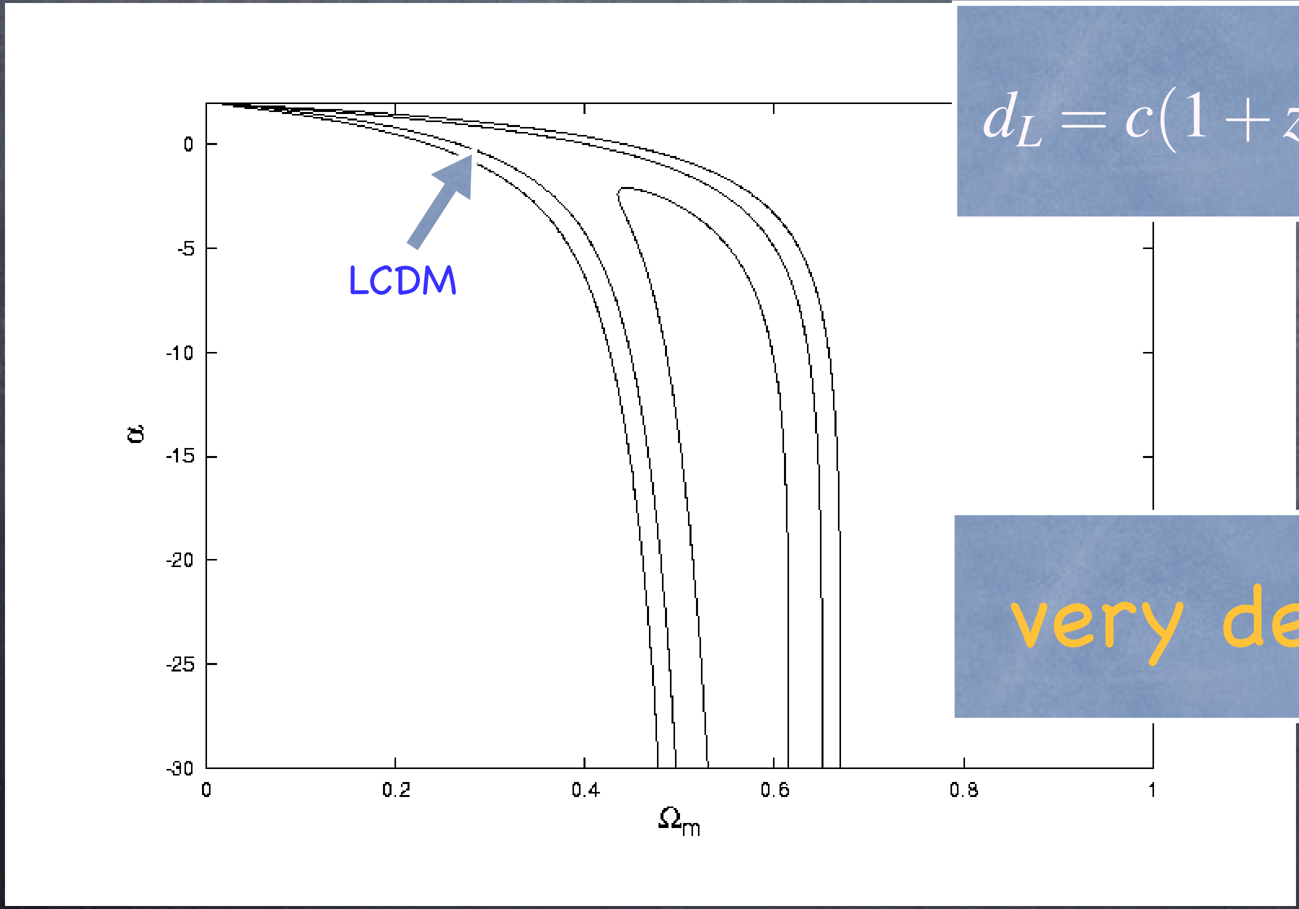
$$\left(\frac{H}{H_0}\right)^2=\Omega_m(1+z)^3+(1-\Omega_m)\left(\frac{H}{H_0}\right)^{\alpha}$$

Dvali&Turner (2003)

Constraints: SN Ia

$$\left(\frac{H}{H_0}\right)^2 = \Omega_m(1+z)^3 + (1-\Omega_m)\left(\frac{H_0}{H}\right)^\alpha$$

- data: 194 SNIa, from Barris etal. (2004)
- marginalized over h (H_0)



$$d_L = c(1+z)\int_0^z \frac{dz}{H(z)}$$

very degenerate

Fits to CMB: effective fluid description

- fluctuations or not?
- if only background expansion is modified, one can model it by an effective, nonfluctuating, fluid:
-

$$\rho_D(a) = \rho_{0D} \exp\left(-3\int_1^a \frac{da'}{a'}[1+\omega(a')]\right)$$

- equivalent to modifying the Friedmann equation

Fits to CMB: effective fluid description

- Friedmann:

$$\left(\frac{H}{H_0}\right)^2 = \frac{\Omega_m}{a^3} + (1-\Omega_m)\exp\left(-3\int_1^a \frac{da'}{a'}[1+\omega(a')]\right)$$

- hence

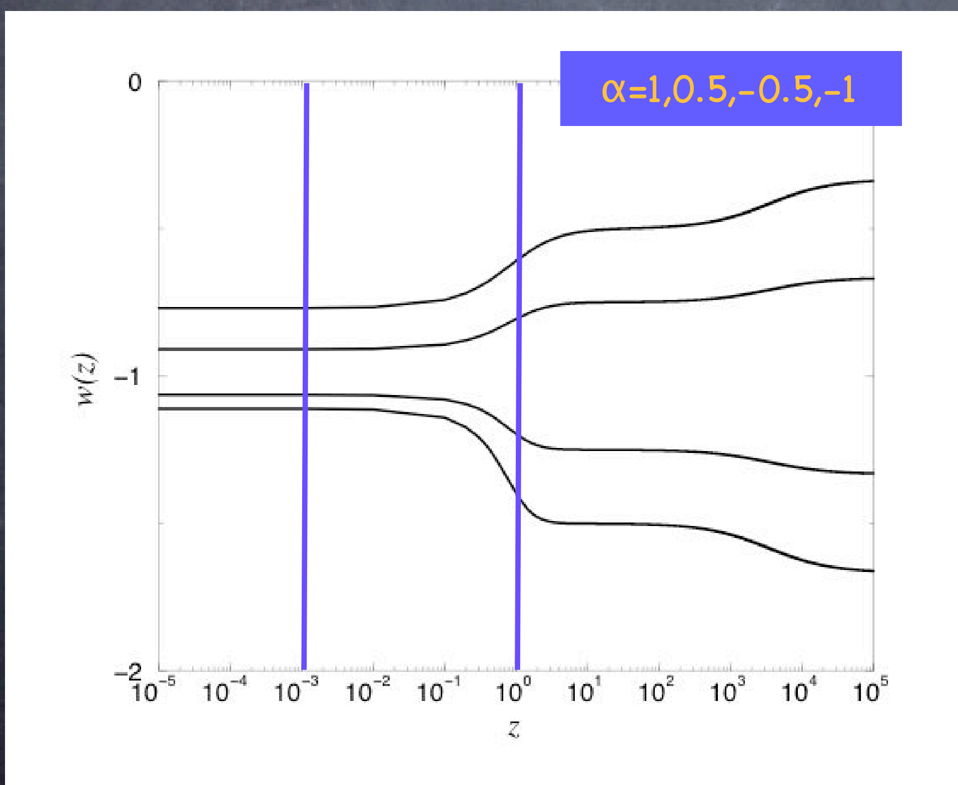
$$\left(\frac{H}{H_0}\right)^\alpha = \exp\left(-3\int_1^a \frac{da'}{a'}[1+\omega(a')]\right)$$

$$\omega(z) = -1 + \frac{\alpha\Omega_m(1+z)^3}{2\left(\frac{H}{H_0}\right)^2 - \alpha(1-\Omega_m)\left(\frac{H}{H_0}\right)^2}$$

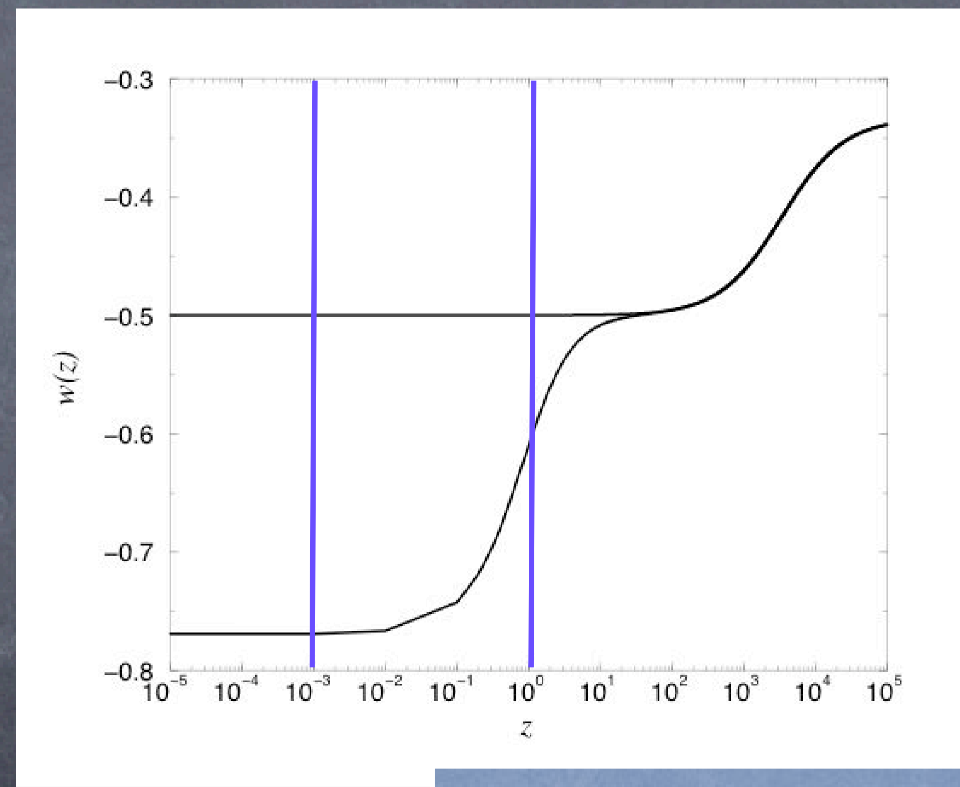
(radiation is ignored here for simplicity)

Fits to CMB: effective fluid description

$$\omega(z) = -1 + \frac{\alpha\Omega_m(1+z)^3}{2\left(\frac{H}{H_0}\right)^2 - \alpha(1-\Omega_m)\left(\frac{H}{H_0}\right)^2}$$



Comparison with Cardassian



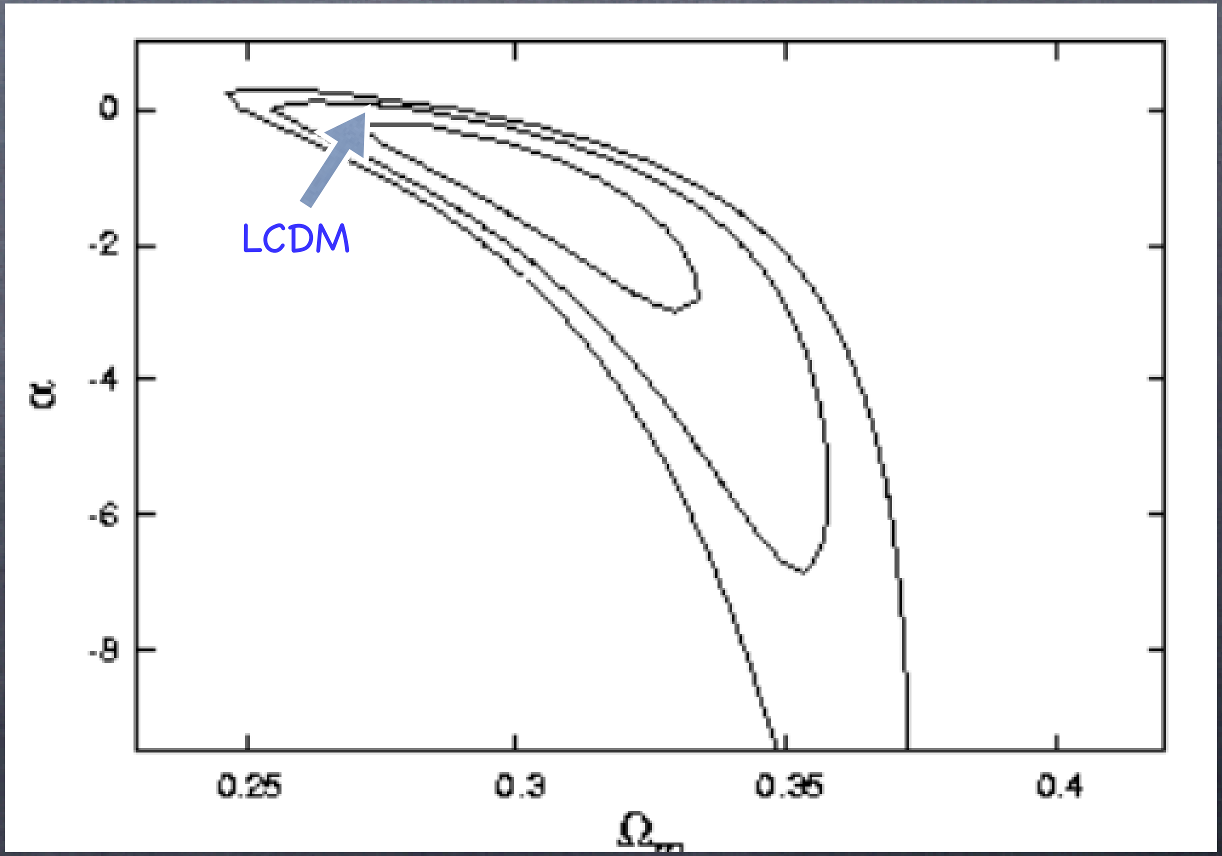
$$H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}\rho_m$$

$$H^2 = \frac{8\pi G}{3}\rho_m + A\rho_m^{1/2}$$

(radiation included)

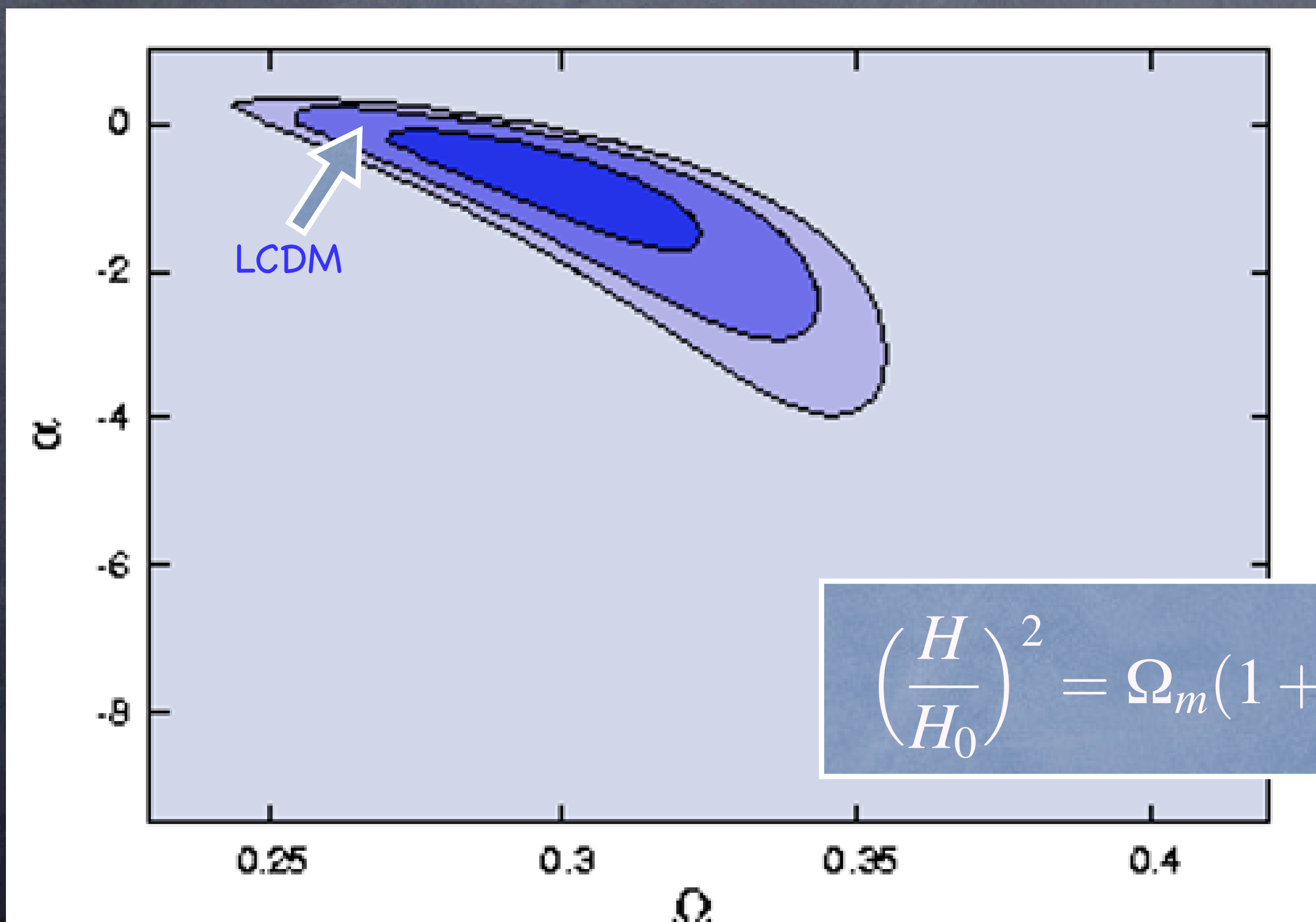
Fits to WMAP

- CMBFast
- fit to the TT power spectrum



Fits to WMAP: combined contours

- CMB+SN Ia



$$\left(\frac{H}{H_0}\right)^2 = \Omega_m(1+z)^3 + (1-\Omega_m)\left(\frac{H}{H_0}\right)^\alpha$$

Conclusions

- Brane worlds can lead to a modified Friedmann equation on the brane
- corrections of form $\sim H^n$ arise, also in Cardassian type scenarios
- observational data indicates that a correction of the form $\sim 1/H$ is preffered slightly over a cosmological constant and significantly over a $\sim H$ correction
- fluctuations?
- brane world construction?
- Large Scale Structure constraints?