The Sound of Darkness

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Credits

- Ananda & Bruni, PRD, 74, 023523 (2006). astro-ph/0512224
- Ananda & Bruni, PRD, 74, 023524 (2006). gr-qc/0603131
- Balbi, Bruni & Quercellini, astro-ph/0702423
- Quercellini, Balbi & Bruni, astro-ph/0706.3667
- work in progress with Balbi, Quercellini and students in Tor Vergata/Portsmouth

Outline

- simple 2-parameter unified dark matter (UDM) model with constant speed of sound (affine EoS)
- observational constraints (CMB, BAO, SNe)
- fluid, Quintessence or K-essence?
- the standard LCDM cosmological model is recovered if the speed of sound is exactly zero: affine EoS as useful parametrization at low redshift?

ΛCDM as UDM

- ΛCDM is the standard "concordance" model of cosmology
- ΛCDM can be seen as a UDM with vanishing speed of sound, $c_s^2 = dP/d\rho = 0$

Motivations

- Go beyond ΛCDM
- Two main alternatives:
  - GR + dark components (DM+DE or UDM)
  - modified gravity (f(R), branes, etc...)
- Simplicity + Skepticism:
  - use GR and a parametric EoS for dark component(s), rooted in local physics
  - $P=P(\rho)$: same EoS in the background for fluid, Quintessence or K-essence fields; different perturbations for fluid and fields, because of different effective speed of sound c^2_{eff}

UDM model

- Assume just GR, flat RW dynamics and a single UDM component:
$$H^2 = \frac{8\pi G}{3}(\rho_r + \rho_b + \rho_X)$$
- Assume UDM is barotropic, $P=P(\rho)$, and violates SEC, in order to source acceleration. Then also assuming a non negative $c_s^2 = dP/d\rho$ leads to a sort of cosmic no-hair theorem: from energy conservation
$$\dot{\rho}_X = -3H(\rho_X + P_X)$$
- an effective Λ follows: $p_\Lambda = -\rho_\Lambda$, fixed point of dynamics: de Sitter.

UDM model

- Simplest model for barotropic UDM:
  - assume constant speed of sound: $c_s^2 = dP/d\rho = \alpha$
  - from this it follows an Affine EoS:

$$P_X \simeq p_0 + \alpha \rho_X$$

- can be seen as first order in Taylor expansion
- extrapolate to any time; with $\rho_\Lambda = -(1+\alpha)p_o$ we get

$$\rho_X(a) = \rho_\Lambda + (\rho_{Xo} - \rho_\Lambda)a^{-3(1+\alpha)}$$

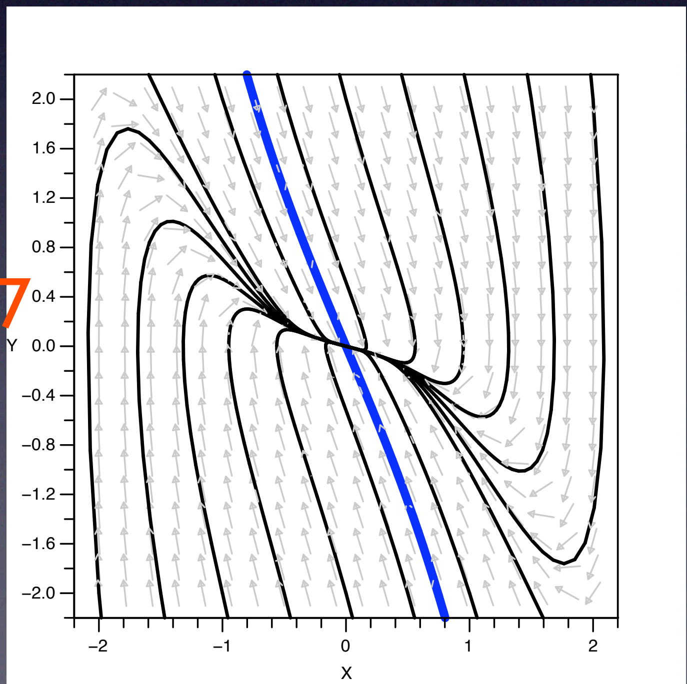
- also $w_X = P_X/\rho_X = -(1+\alpha)\Omega_\Lambda/\Omega_X + \alpha,$

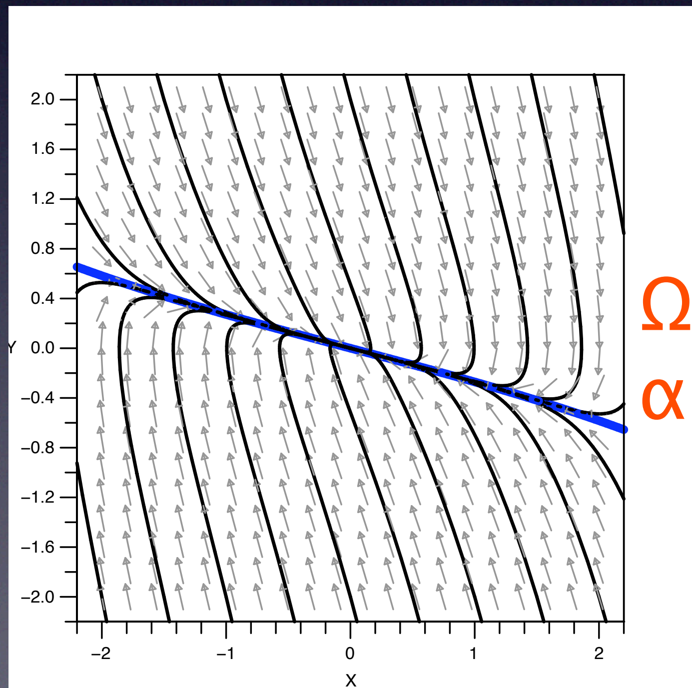
Quintessence Field

Affine EoS corresponds to scalar field potential:

$$V(\varphi) = \rho_\Lambda \left[\frac{3+\alpha}{4} + \frac{(1-\alpha)}{4} \cosh\left(\varphi\sqrt{3(1+\alpha)}\right)\right]$$

$\Omega_\Lambda = 0.7$
$\alpha = 0.8$





$\Omega_\Lambda = 0.7$
$\alpha = -0.8$

Quintessence

- Mimics well the affine EoS background dynamics only for negative α
- Speed of sound $c_s^2 = 1$, cannot work as UDM as it doesn't form structure
- Can in principle be used as a dark energy model, together with CDM

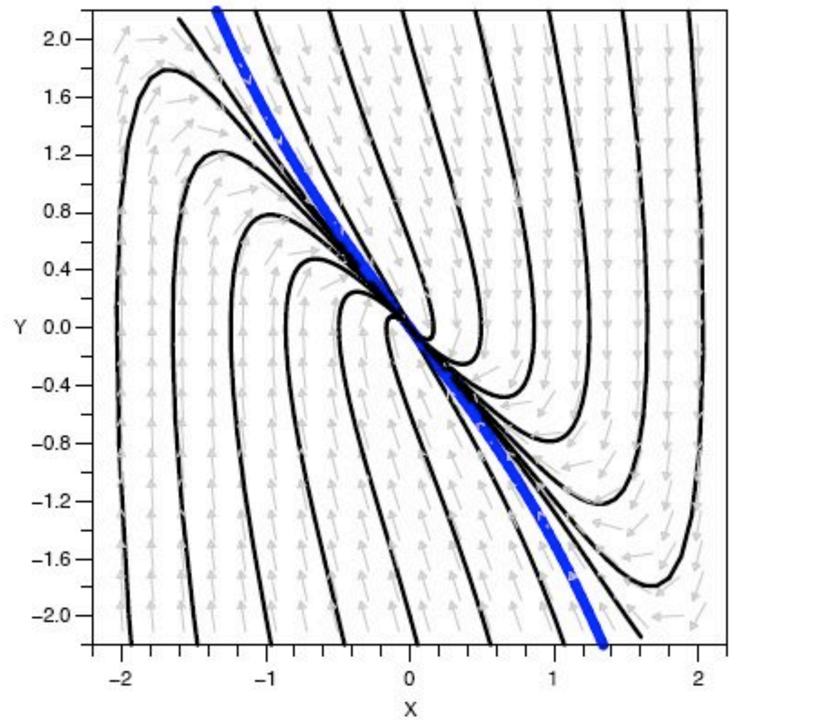


FIG. 5: Phase space for system (18)-(19) with $\alpha = 0$ and $\Omega_\Lambda = 0.7$. Here generic trajectories approach the fixed point along the single existing eigenvector $e_1 = e_2$, see text.

K-essence

- Mimics well the affine EoS with a purely kinetic Lagrangian $\mathscr{L} = P(\chi),$
- speed of sound $c_s^2 = \alpha$

$$P = -\rho_\Lambda + c\chi^{\frac{1+\alpha}{2\alpha}}; \qquad \rho_\phi = \rho_\Lambda + \frac{c}{\alpha}\chi^{\frac{1+\alpha}{2\alpha}}$$

- EoS varies from α to -1

$$w_\phi = \frac{-\rho_\Lambda a^{3(1+\alpha)} + \rho_m \alpha}{\rho_\Lambda a^{3(1+\alpha)} + \rho_m}.$$

Observables

- We assume a flat cosmology, Ω_K=0, and we hold fixed:
  - baryon density value derived from WMAP3 data: $\Omega_b h^2$=0.02229±0.00075 (Spergel *et al.*, astro-ph/0603449)
  - H_o =72±0.8 km/s/Mpc measured by HST Key Project (Freedman *et al.*, Ap.J. 553, 47, 2001)
- 2 free parameters: Ω_Λ and α
- for comparison: ΛCDM has 2 parameters, 1 if Ω_K=0.

Observables

- Constrain the 2 parameters of the model, Ω_Λ and α, with likelihood test, using:
  - age $t_0 = 12.6^{+3.4}_{-2.4}$ Gyr (Krauss & Chaboyer, Science, 299, 65, 2003);
  - luminosity distance of type Ia SNe;
  - location of first acoustic peak in CMB;
  - baryon acoustic oscillations (BAO).

type Ia SNe

- distance moduli for SNe

$$\mu_0 = m - M = 5\log(d_L/\mathrm{Mpc}) + 25$$

$$d_L = (L/4\pi F)^{1/2} = (1+z)\int_0^z dz'/H(z')$$

  - 182 type Ia SNe: new Gold Data Set (Riess *et al.* astro-ph/0611572)

- we marginalise over calibration uncertainty, equivalent to marginalise over H_o

CMB peak location

- for a flat Universe, the location of the CMB peak only depends on Ω_m (DM) through the shift parameter

$$\mathcal{R} = \Omega_m^{1/2} H_0 D_A(z_{ls}), \quad D_A(z_{ls}) = \int_0^{z_{ls}} \frac{dz'}{H(z')},$$

$$z_{ls} = 1089$$

- we identify ρ_m with $\rho_X - \rho_\Lambda$, i.e. $\Omega_m = 8\pi G\tilde{\rho}_m/(3H_o^2)$
- using 5 MC Markov chains produced in the most recent analysis of WMAP data, we estimate

$$\mathcal{R} = 1.71 \pm 0.03$$

see http://lambda.gsfc.nasa.gov, cf. astro-ph/0604051

BAO

- detection of BAO in SDSS constrains the parameter

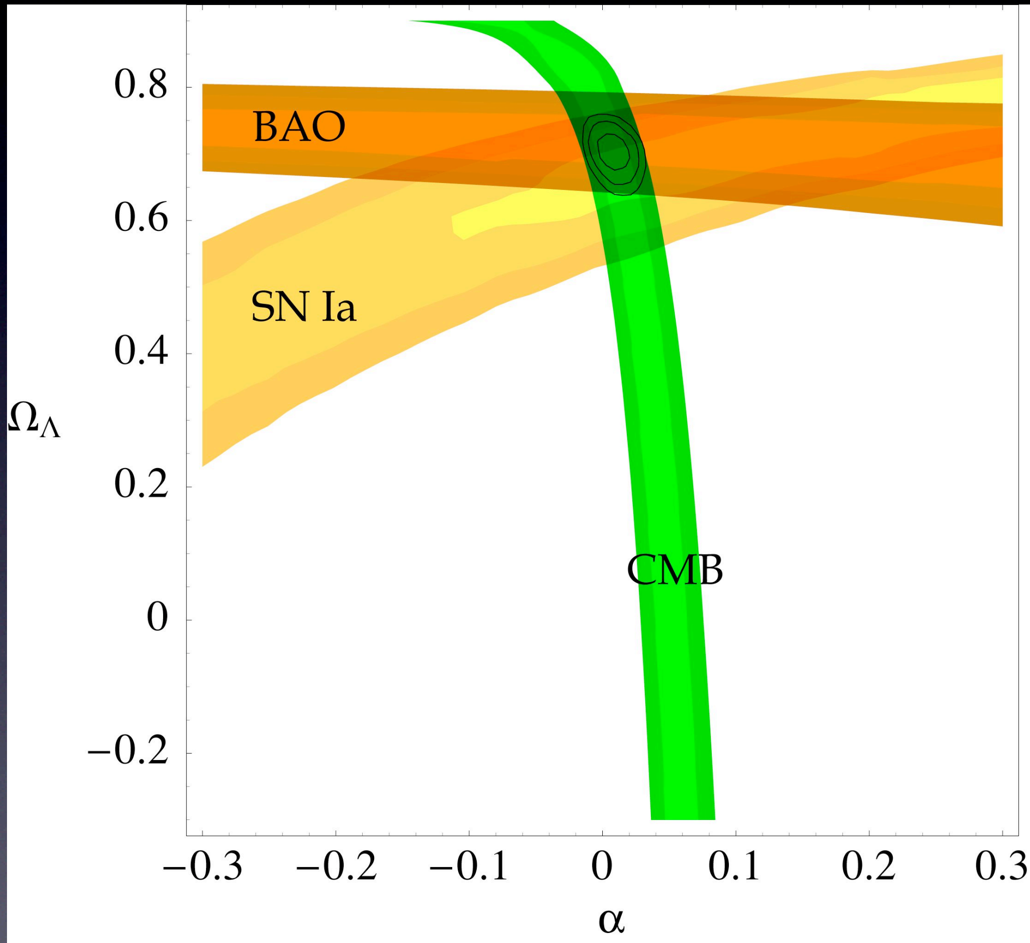
$$A = \Omega_m^{1/2} H_0 D_V , \quad D_V = \left[D_A^2(z) \frac{cz}{H(z)} \right]^{\frac{1}{3}}_{z=0.35}$$

- we use the value of A measured from the SDSS luminous red galaxy survey for n_s =0.98:

$$A = 0.469 \pm 0.017$$

cf. Eisenstein *et al.*, Astrophys. J., 633 (2005)

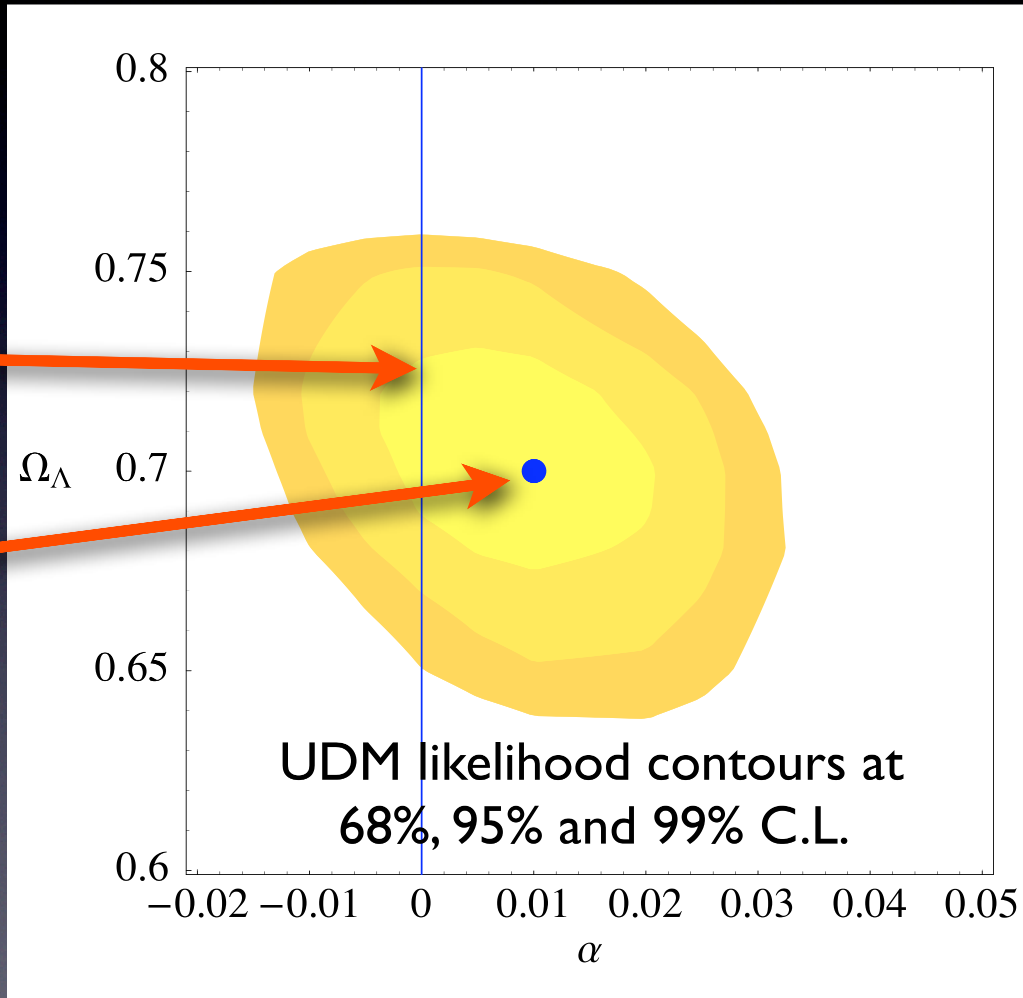
Combined Likelihood



UDM likelihood contours at 68%, 95% and 99% C.L.

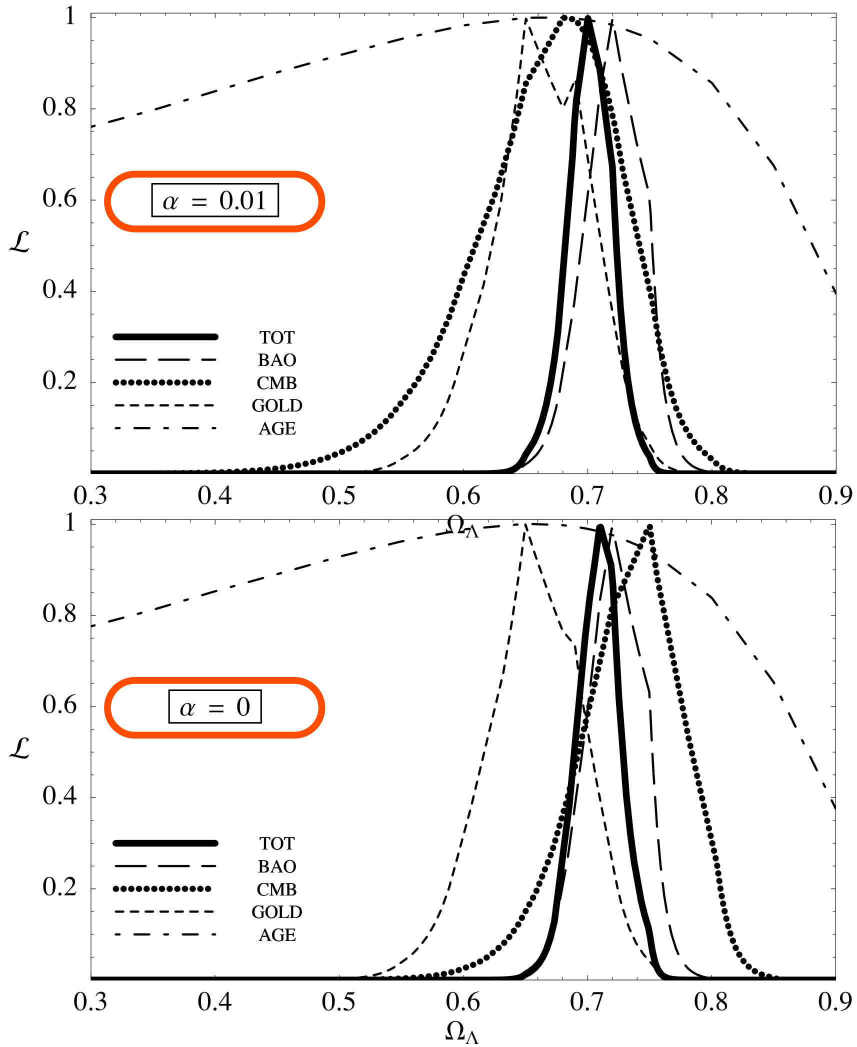
Combined Likelihood

- 2 parameter flat $\Omega_K = 0$ models
- flat ΛCDM recovered for $\alpha = 0$
- best fit:
  - $\Omega_\Lambda = 0.70 \pm 0.04$
  - $\alpha = 0.01 \pm 0.02$



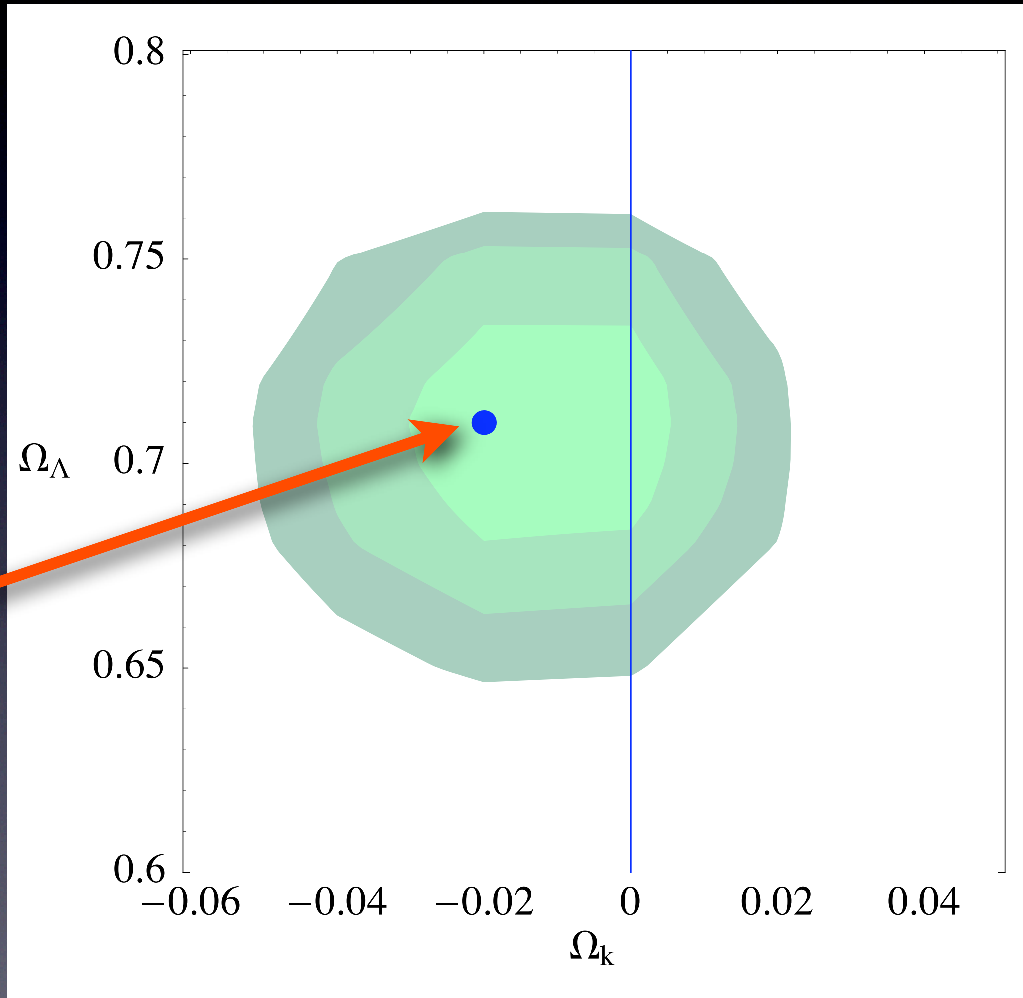
marginalised likelihood

- we marginalise the likelihood for Ω_Λ for the best fit α=0.01 and for α=0, representing the flat ΛCDM model.
- best fit for ΛCDM is Ω_Λ=0.71±0.04 at 95% C.L.
- for α=0, SNe prefer smaller Ω_Λ, in agreement with previous results (systematics? Nesseris & Perivolaropoulos, astro-ph/0612653)



ΛCDM

- ΛCDM recovered for $\alpha=0$
- ΛCDM 2 parameter model: Ω_Λ and Ω_K
- best fit is positively curved:
  - $\Omega_K = -0.02_{-0.02}^{+0.01}$
  - $\Omega_\Lambda = 0.71 \pm 0.04$
  - consistent with other work



Model comparison

- Bayesian model comparison using:
  - Akaike Information Criteria (AIC) $\mathrm{AIC} = -2\ln\mathcal{L} + 2k$
  - Bayesian I. C. (BIC) $\mathrm{BIC} = -2\ln\mathcal{L} + k\ln N$
  - Bayesian Evidence: average L over prior, likelihood of model given the data $E \equiv \int \mathcal{L}(p)P(p)dp$

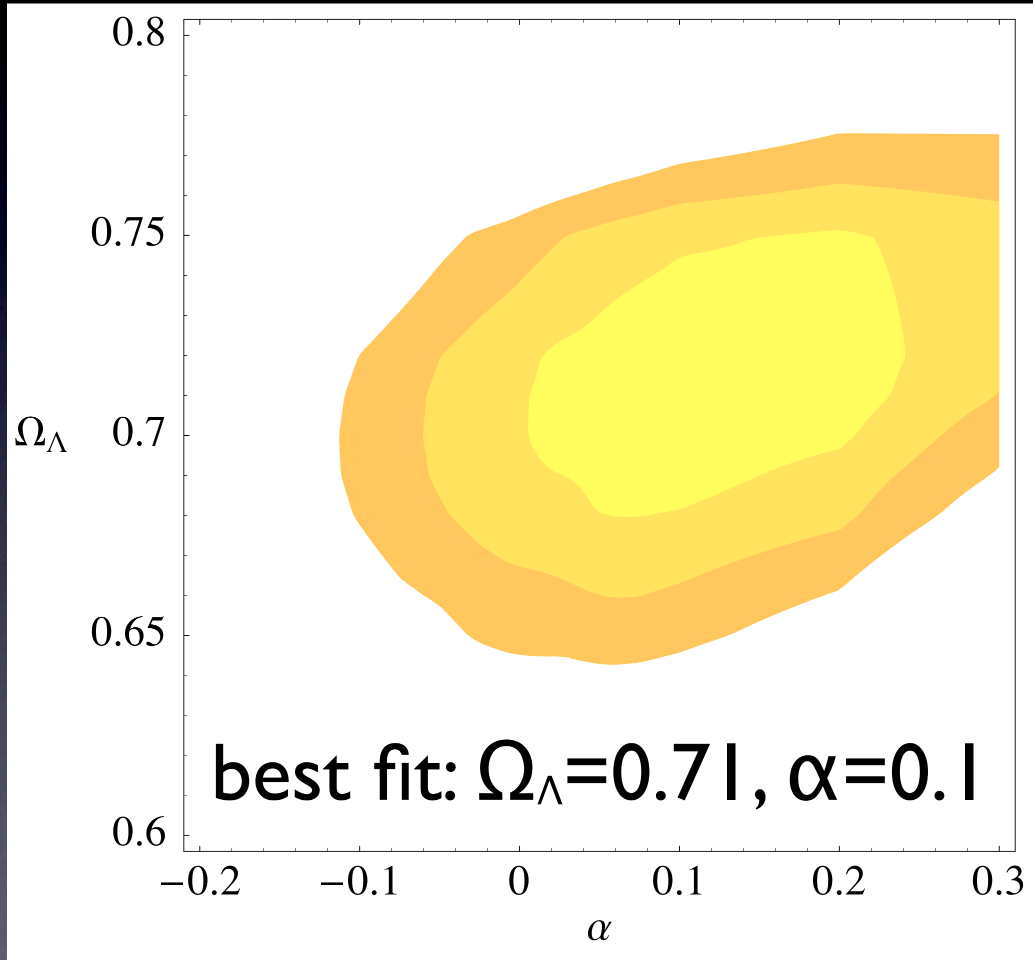
Model	χ^2	ΔAIC	ΔBIC	$\Delta\ln E$
flat ΛCDM	158.83	0	0	0
flat $\Lambda\alpha$DM	157.64	0.8	4	3.9
curved ΛCDM	161.53	4.7	7.9	3.4

TABLE I: Model comparison with information criteria and Bayesian evidence: the Δ's compare the flat $\Lambda\alpha$DM and the non-flat ΛCDM against the standard flat ΛCDM model.

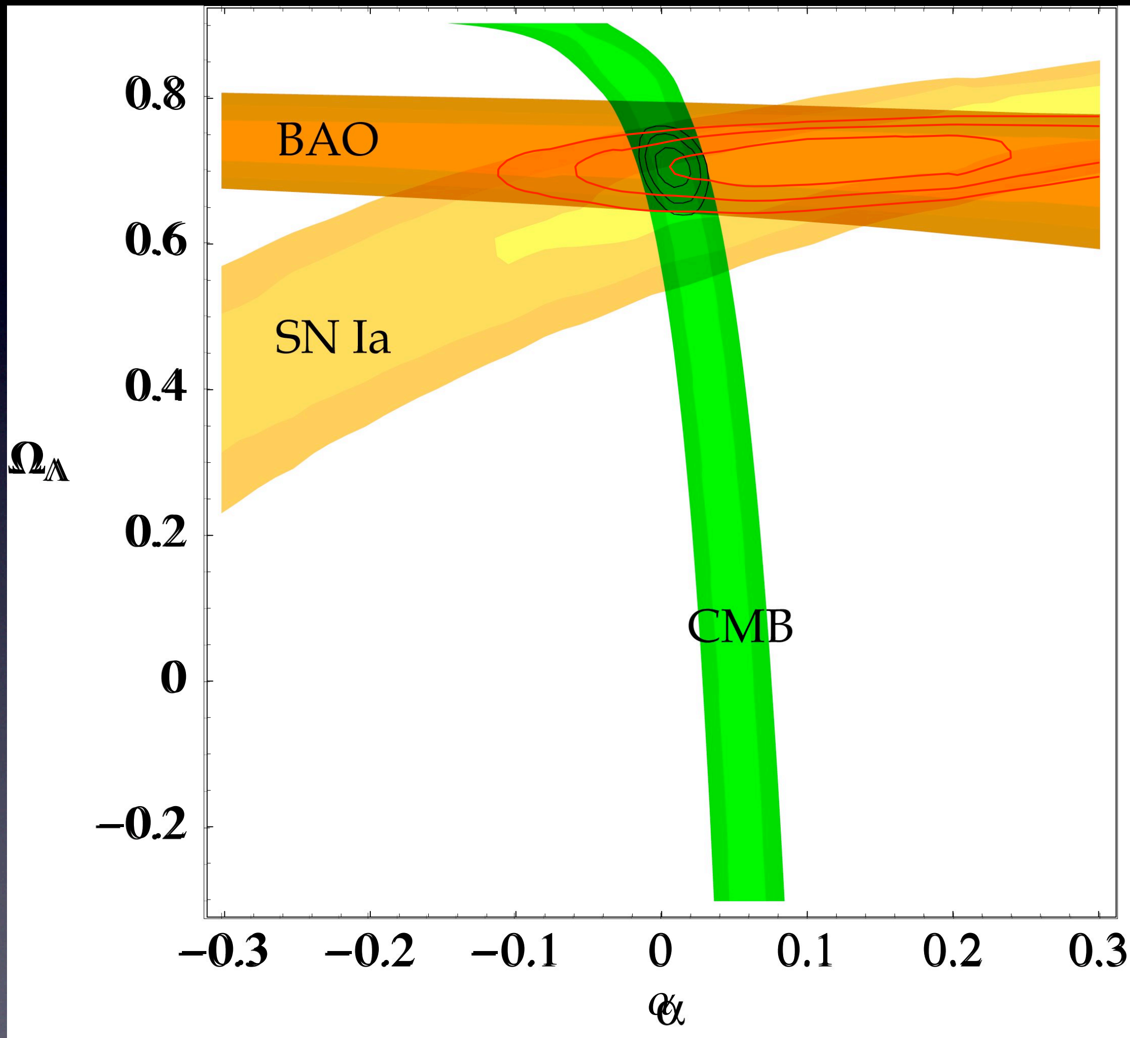
What do we learn?

- Speed of Sound: constant by assumption in Affine UDM ($c_s^2 = \alpha = 0$ for ΛCDM)
- Fits the data so far, $\Omega_\Lambda = 0.7$ and $\alpha = 0.01$, but let's have a closer look...

BAO & SNe only


0.8
0.75
0.7
0.65
0.6
Ω_Λ
−0.2
−0.1
0
0.1
0.2
0.3
α
best fit: Ω_Λ=0.71, α=0.1

BAO & SNe only



0.8
0.6
0.4
0.2
0
−0.2
Ω_Λ
BAO
SN Ia
CMB
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
α

Conclusions

- In progress: full CMB likelihood analysis of affine EoS models:
  - simplest UDM fluid with $c^2_{eff} = \alpha$ strongly constrained, i.e. $\alpha \sim 10^{-5}$ (cf. Muller PRD 71, 047302 (2005));
  - UDM with $c^2_{eff} = 0$ and $c^2_{eff} = 1$;
  - affine DE with $c^2_{eff} = 0$, $c^2_{eff} = \alpha$ and $c^2_{eff} = 1$ plus CDM.
- My feeling: model per-se is unlikely to survive tight CMB constrains, it may provide a useful parametrization at low/intermediate redshifts: future data may be able to exclude LCDM on the basis of a non-zero speed of sound for the dark component.