Gamma Ray Bursts as Cosmological Probes

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Overview

- Cosmological models under study
- GRBs as standard candles
- Results
- Outlook

Cosmological Models

Generalized Chaplygin Gas model

- Generalized Chaplygin Gas (GCG)

$$p = -\frac{A}{\rho^{\alpha}}$$

[Bento, O.B., Sen, 2002-2004]

(α=1 corresponds to the Chaplygin gas)

- Has many interesting theoretical features. Unlike Q/K-Essence, the (G)CG has a (fair) good theoretical base.

- Dual behaviour:

  Dark matter (DM) at early times and dark energy (DE) (cosmological constant like) at late times.

- The perturbed GCG accounts for the CDM present in galaxies and that is necessary for structure formation.

- GCG unifies DM and DE into one single component.

Generalized Chaplygin gas model

- **Unified model for Dark Energy and Dark Matter**

Generalized d-brane

$$\mathcal{L} = -A^{\frac{1}{1+\alpha}} \left(1 - (g^{\mu\nu}\Theta_{,\mu}\Theta_{,\nu})^{\frac{\alpha+1}{2\alpha}}\right)^{\frac{\alpha}{\alpha+1}}$$

$\alpha = 1$: d-brane

Generalized Chaplygin gas

$$p = -\frac{A}{\rho^{\alpha}}$$

$\alpha = 1$: Chaplygin gas

$p \ll \rho$
Dust

$p = \alpha\rho$
$\alpha = 1$: stiff matter

$p = -\rho$
De Sitter

[Kamenschik, Moschella, Pasquier 2001]
[Bilic, Tupper, Viollier 2002; Bento, O.B., Sen 2002]

Model 1

- **A massive complex scalar field *Φ*:**

$$\mathcal{L} = g^{\mu\nu}\Phi^*_{,\mu}\Phi_{,\nu} - V(|\Phi|^2)$$

Writing in terms of its mass, *m*:

$$\Phi = \left(\frac{\phi}{\sqrt{2m}}\right)\exp(-im\theta)$$

Scale of inhomogeneities arises from the assumption: $\phi_{,\mu} << m\,\phi$

- **"Thomas-Fermi" approximation:**

$$\mathcal{L}_{TF} = \frac{\phi^2}{2}g^{\mu\nu}\theta_{,\mu}\theta_{,\nu} - V(\phi^2/2)$$

- **Equations of motion:**

$$g^{\mu\nu}\theta_{,\mu}\theta_{,\nu} = V'(\phi^2/2)$$

$$(\phi^2\sqrt{-g}g^{\mu\nu}\theta_{,\nu})_{,\mu} = 0$$

where $V'(x) \equiv dV/dx$**. Phase** θ **can be regarded as a velocity field whether** $V' > 0$**:**

$$U^\mu = \frac{g^{\mu\nu}\theta_{,\nu}}{\sqrt{V'}}$$

so that, on the mass shell, $U^\mu U_\mu = 1$**.**

Energy-momentum tensor takes the form of a perfect fluid:

$$\rho = \frac{\phi^2}{2} V' + V \qquad p = \frac{\phi^2}{2} V' - V$$

Covariant conservation of the energy-momentum tensor: $\dot{\rho} + 3H(p+\rho) = 0$

leads for the generalized Chaplygin gas:

$$\rho = \left(A + \frac{B}{a^{3(1+\alpha)}} \right)^{\frac{1}{1+\alpha}}$$

Furthermore, $d \ \ln \phi^2 = \dfrac{d(\rho - p)}{\rho + p}$

which, together with the Eq. of state implies that: $\phi^2(\rho) = \rho^{\alpha}(\rho^{1+\alpha} - A)^{\frac{1-\alpha}{1+\alpha}}$

- Generalized Born-Infeld theory: $\mathcal{L}_{GBI} = -A^{\frac{1}{1+\alpha}} \left[1 - (g^{\mu\nu}\theta_{,\mu}\theta_{,\nu})^{\frac{1+\alpha}{2\alpha}} \right]^{\frac{\alpha}{1+\alpha}}$

Model 2

- **Real scalar field ϕ:** $L = \partial_\mu \phi \ \partial^\mu \phi - V(\phi)$

$$V(\phi) = V_0 \exp[3(\alpha+1)\phi][\cosh(\frac{m\phi}{2})^{2/\alpha+1} + \cosh(\frac{m\phi}{2})^{-2\alpha/\alpha+1}]$$

where $m = \alpha + 1$.

Tests of the Dark Energy - Dark Matter Unification

- **CMBR Constraints** [Bento, O. B., Sen 2003, 2004; Amendola et al. 2004]
- **SNe Ia** [O. B., Sen, Sen, Silva 2004; Bento, O.B., Santos, Sen 2005]
- **Gravitational Lensing** [Silva, O. B. 2003]
- **Structure Formation**

  [Sandvik, Tegmark, Zaldarriaga, Waga 2004; Bento, O. B., Sen 2004; Bilic, Tupper, Viollier 2005; …]
- **Cosmic topology** [Bento, O. B., Rebouças, Silva 2006]
- **Inflation** [O. B., Duvvuri 2006]

Background tests:

$$\alpha \leq 0.6$$

$$0.65 \leq A_s \leq 0.85$$

$$A_S = \frac{A}{\rho_{Ch,0}^{1+\alpha}}$$

- Aleviates the coincidence problem, since the accelerated expansion starts after perturbations become non-linear.

- Degenerate with phantom XCDM models for z<2.

Fiducial GCG

- Flat GCG parameters
- Disregard baryons, Ω_{ch}=1.0
- Fiducial model: α=1, A_s=0.7

$$A_s = \frac{A}{\rho_{ch,0}^{1+\alpha}}$$

$1-\sigma$ *SNe Ia*

$\alpha = 2.8$

Fiducial XCDM

- CDM: Ω_m=0.45
- Dark Energy: Ω_X=0.55
- DE Equation of state: ω=-1.45
- Degenerate with the GCG fiducial model for z<2

Cosmological Tests

The m-z test

- A SNe Ia observed at redshift *z*, with absolute magnitude *M*, will be seen on Earth with an apparent magnitude, *m*, given by

$$m(z, H_0, \Theta) = M - 5\log d_L(z, H_0, \Theta) + 25$$

- Measuring m as a function of redshift, we may fit models to the data using a simple χ^2 test, and constrain the GCG parameter space

$$\chi^2(\mathbf{\Theta}) = \sum_{z=0}^{z_{max}} \left[\frac{m_{obs} - m(z, \mathrm{M}, \mathbf{\Theta})}{\sigma_\mu(z)} \right]^2$$

Silva, O.B., Ap. J. 599 (2003) 829
O.B., Sen, Sen, Silva, M.N.R.A.S. 353 (2004) 329
Bento, O.B., Sen, Santos, Phys. Rev. D71 (2005) 063501
Bento, O.B., Rebouças, Silva, Phys. Rev. D73 (2006) 043504

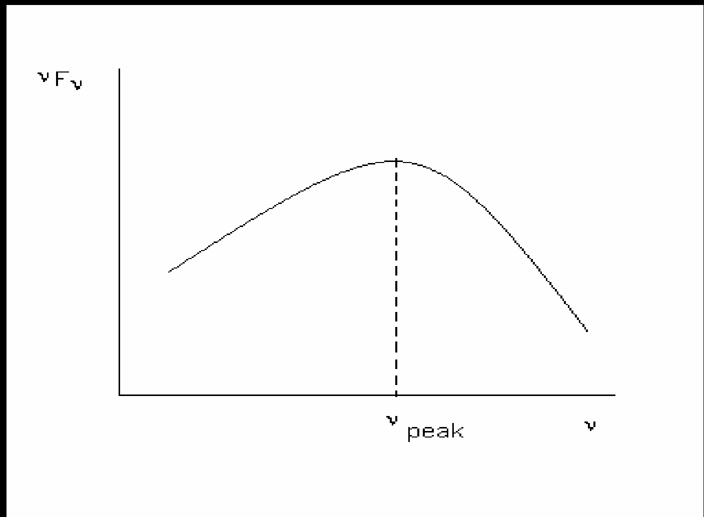
Gamma-ray what?

- GRBs are very energetic events that extend to high redshifts (SNe Ia can only be detected for $z<2$).
- GRBs are not subjected to dust extinction like SNe Ia.
- GRBs are not standard candles, but their absolute energy output or luminosity may be estimated.

Some GRB Observables

- Variability: Measures the complexity of the GRB spectrum.
- Time Lag: Measures the time offset between high and low energy GRB photons.
- Jet time break: Break in afterglow (AG) light curve

- Peak energy: Let F_ν denote the observed photon frequency spectrum. In the $(\nu - \nu F_\nu)$ plot there is a maximum. The energy corresponding to this maximum is defined as the peak energy, $E_p = h\nu_{peak}$.



Other relevant quantities:

- Isotropic equivalent luminosity, L_{iso}: Inferred luminosity assuming that the energy release is isotropic. (proportional to d_L^2).

- Isotropic equivalent energy, E_{iso}: Inferred energy release assuming isotropy (also proportional to d_L^2).

- Beaming corrected energy, E_γ:
  Estimated energy release assuming collimation into a beam with angular aperture θ, $E_\gamma = E_{iso}(1-\cos\theta)$.

- Assuming a circum-burst medium with constant density, n, and that a fraction η_γ of the fireball kinetic energy is released in the prompt γ-ray phase, then

$$\theta = 0.161\left(\frac{t_{jet}}{1+z}\right)^{3/8}\left(\frac{n\eta_\gamma}{E_{iso,52}}\right)^{1/8}$$

GRBs as Standard Candles

- Time lag is correlated with L_{iso}:

$$L_{iso} \propto \tau^{\beta_\tau} \quad , \quad \beta_\tau = -1.27$$

- Variability is correlated with L_{iso}:

$$L_{iso} \propto V^{\beta_V} \quad , \quad \beta_V = 1.57$$

- E_γ is correlated with E_p (Ghirlanda relation):

$$E_\gamma \propto [(1+z)E_P]^a \quad , \quad a = 1.4$$

Circularity Problem

- SNe Ia: Use low-redshift SNe Ia to calibrate luminosity estimators, and use high-redshift ones to study cosmology.
- GRBs: No low-redshift GRBs to calibrate estimators!

Possible solutions

- Consider calibration as a free parameter, and use statistical treatment to study cosmology through the choice of a calibration that reduces the scatter in the Hubble diagram, etc.

Our suggestion:

- Use SNe Ia to measure d_L for $z<1.5$.
- Use GRBs correlations to generate a low-redshift population and calibrate luminosity estimators.
- Use high-redshift GRBs for cosmological studies.

Pros and Cons

- Less free parameters, but no data points for $z<1.5$.
- Direct test for events with $z>1.5$.

Using V and τ_{lag} in Cosmology

- Measure V and τ_{lag}
- Using (V-L_{iso}) and (τ_{lag}-L_{iso}) relations, find two estimates of L_{iso}.
- Combine both estimates as a weighted average
- Calculate luminosity distance
- Consider Gaussian error propagation

Testing Our Method

Testing the Calibration Procedure

- Consider fiducial V-L_{iso} and τ_{lag}-L_{iso} relations.
- Generate a mock low-redshift GRB population to account for the intrinsic statistical scatter around the fiducial relations.
- Fit the relations to the generated sample.

Calibration Procedure

Fid. Values			
β_V	σ_{logV}	β_τ	$\sigma_{log\tau}$
1.57	0.20	-1.27	0.35

GRB Population	
N_{total}	N(z<1.5)
120	40
500	100
1000	200

Results

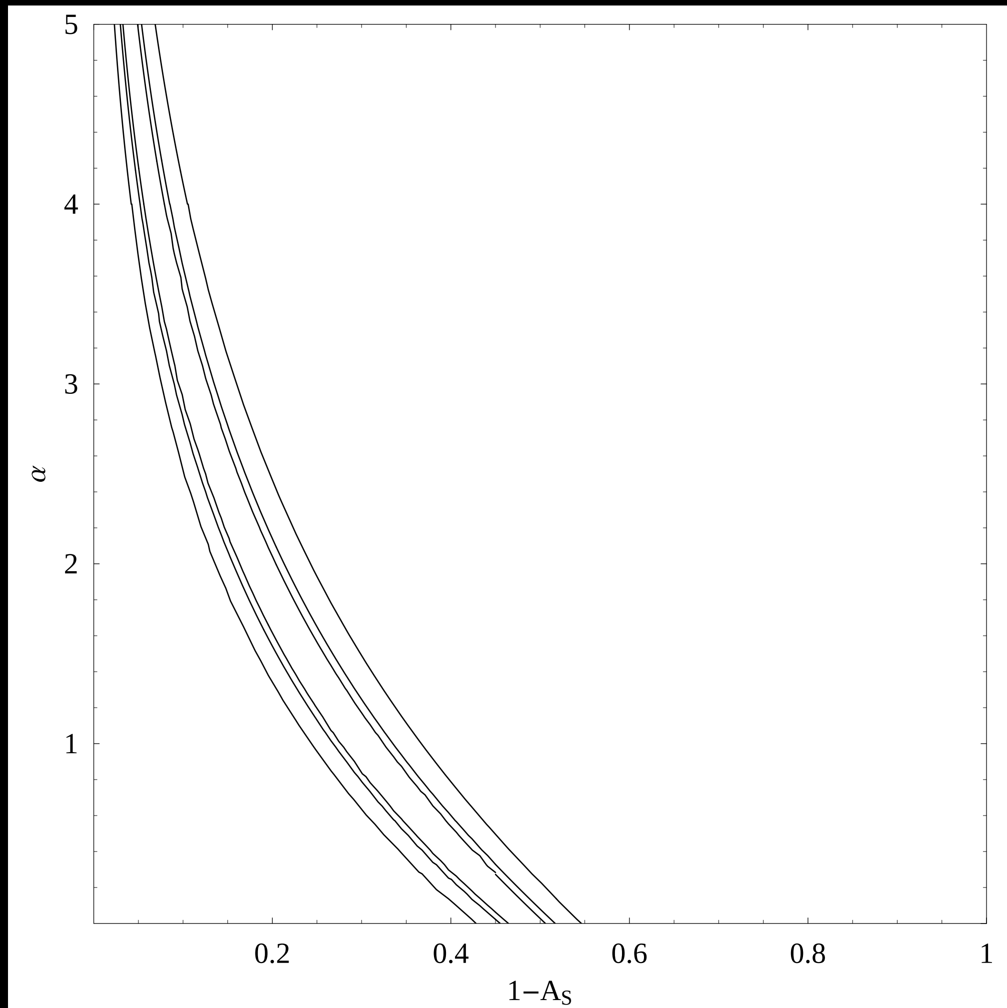
Uncertainty in distance modulus for various calibrations	
N(z<1.5)	σ_μ
40	0.68
100	0.66
200	0.66

- Calibration with 40 low-redshift GRBs is adequate

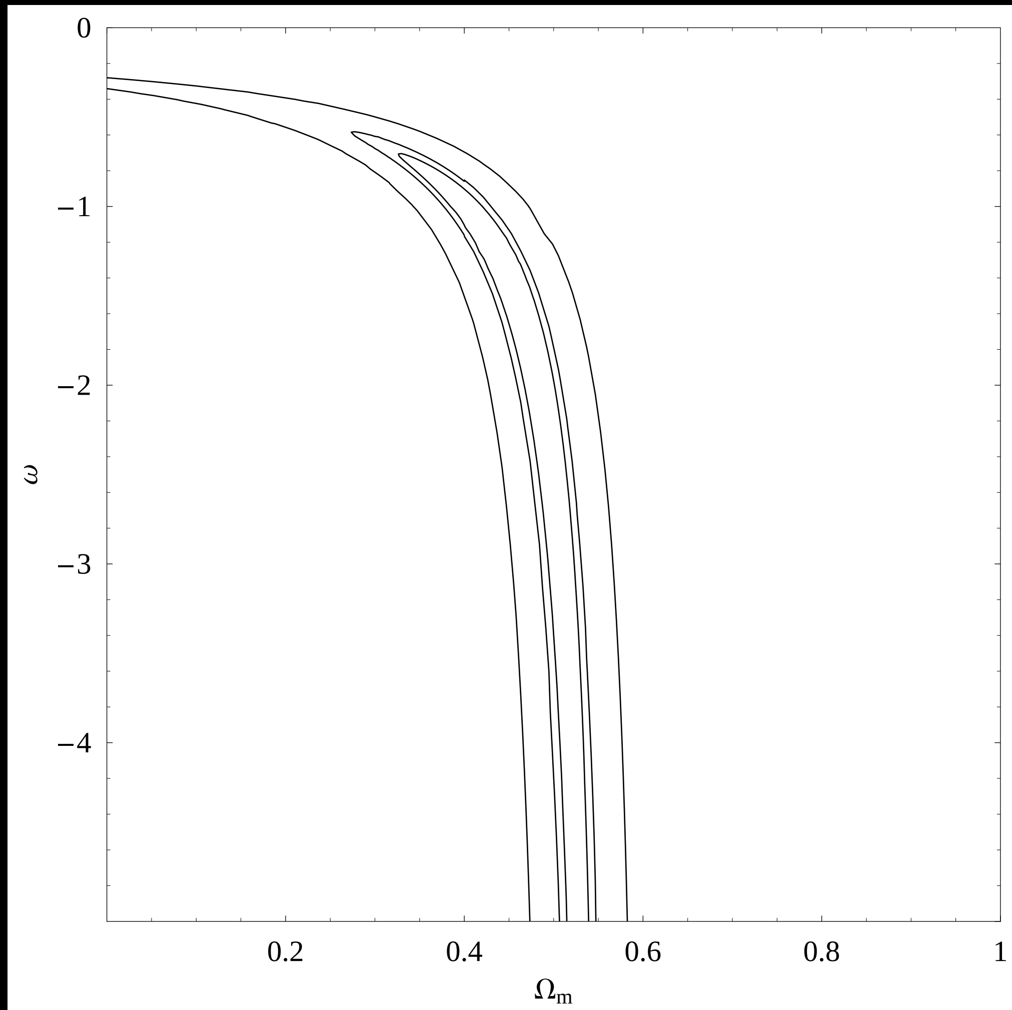
The Cosmological Test

- Consider larger high-redshift samples to overcome the large statistical uncertainty.
- We consider that the calibration was done using 100 z<1.5 GRBs.
- Consider N(z>1.5)=(150;500;1000).

GCG Model



XCDM Model



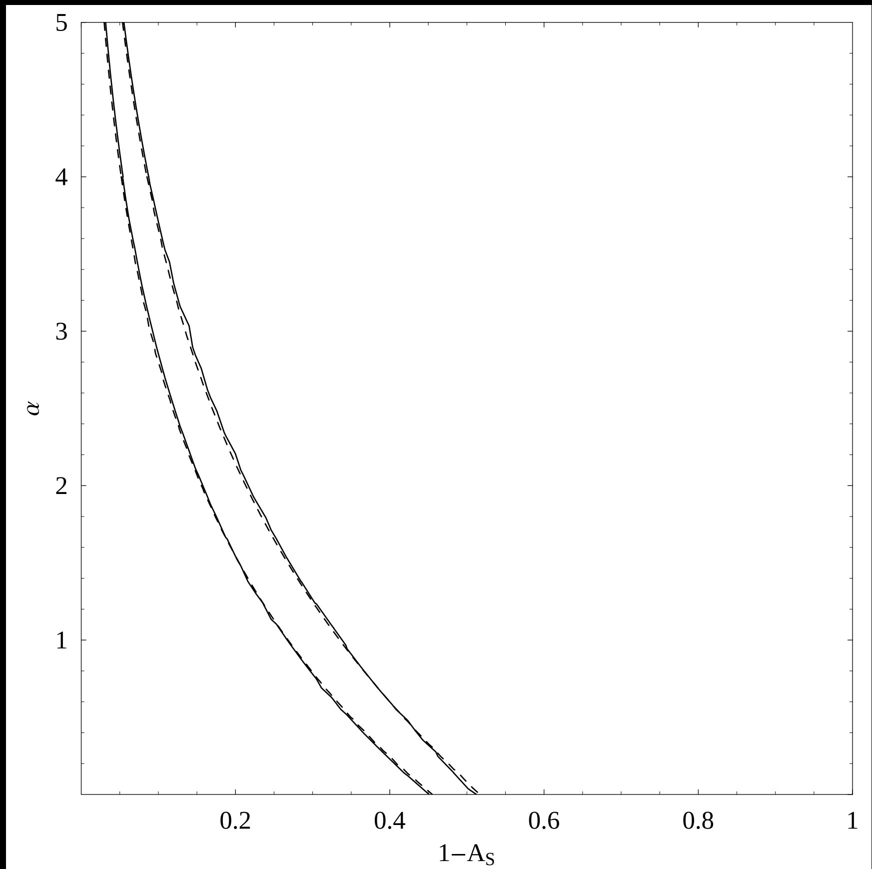
Comments

- Increasing the GRB sample improves the results, but the test remains inadequate to study the GCG model.
- A sample of $N(z>1.5) \geq 500$ will constrain the amount of matter in XCDM models, independently of the nature of DE.

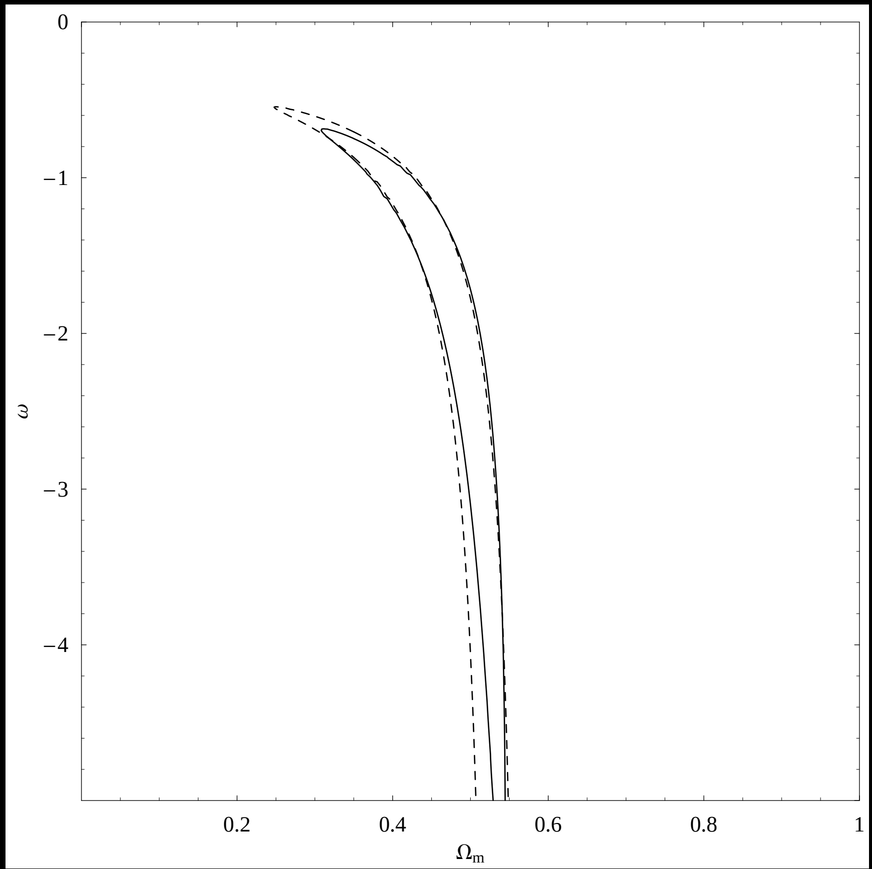
What about z<1.5 ?

- DE is known to influence the dynamics only at z<1. Does a low-redshift sample improve results?
- Is a high-redshift sample really relevant?
- Consider a sample made up of 400 high-z and100 low-z GRBs.

GCG model



XCDM model



Comments

- For GCG models, no effect.
- For XCDM models, an upper limit on the DE equation of state is imposed, without much effect on the allowed matter content.
- Better precision might improve the results.

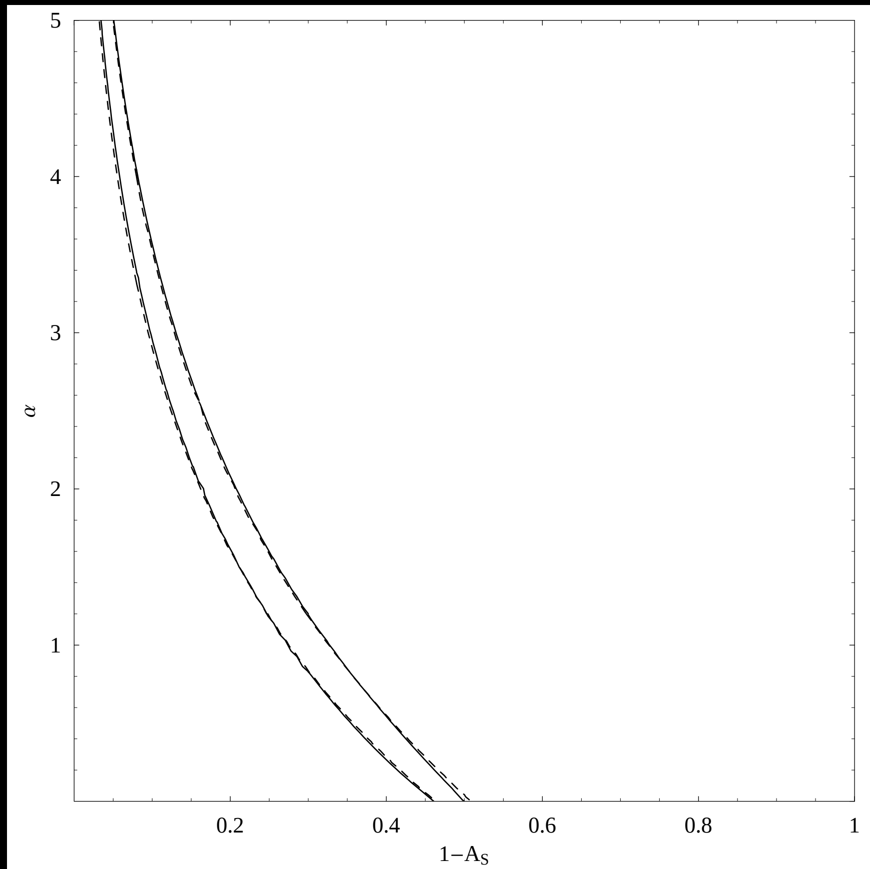
Ghirlanda Relation

- The correlations previously considered are affected by the large statistical uncertainty, and are not very precise.
- A much tighter correlation was found by Ghirlanda et al. (2004) which relates E_γ to E_p.
- Uncertainty in μ around 0.5 mag.

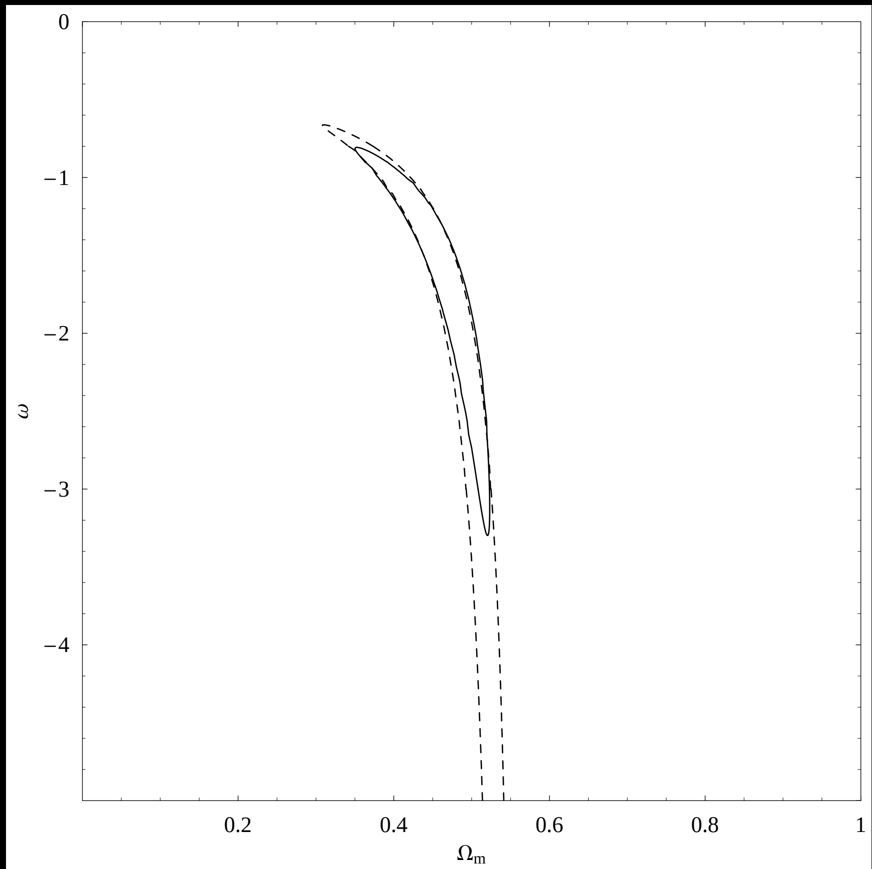
Error Budget

	Rel. Error	% of $(\sigma_{dL})^2$
σ_{S_γ}	10%	5%
σ_k	5%	1%
σ_C	8%	5%
σ_a	5%	5%
σ_{E_p}	17%	52%
σ_n	50%	14%
$\sigma_{t_{jet}}$	20%	16%

GCG Model



XCDM Model



GCG models features:

- The confidence regions follow the curve

$$\left(1 - A_s\right)^{1/(1+\alpha)} = const$$

- This happens because GRBs measure the quantity that dominates at a probed redshift and:

$$H_{ch}(z >> 0) = \Omega_{ch}\left(1 - A_s\right)^{1/(1+\alpha)}(1+z)^3$$

- Improvement in precision might allow obtaining better results, but high redshifts will be always problematic.
- Moreover, the transition from matter dominated to vacuum dominated expansion is faster than for XCDM models.

Comments on XCDM Models

- High redshift GRBs are good tools to constrain the total amount of matter, but rather poor ones to probe DE.

- Information from the $z<1.5$ range is crucial to get insights on the nature of DE, but it does not constrain the amount of DM.

- However, both redshift ranges are important as no limits on the amount of matter can be obtained from z<1.5 probes alone.

- Thus, it is fair to conclude that GRBs offer a new window to probe DM and are complementary to constraints arising from LSS studies.

GRBs X SNe Ia

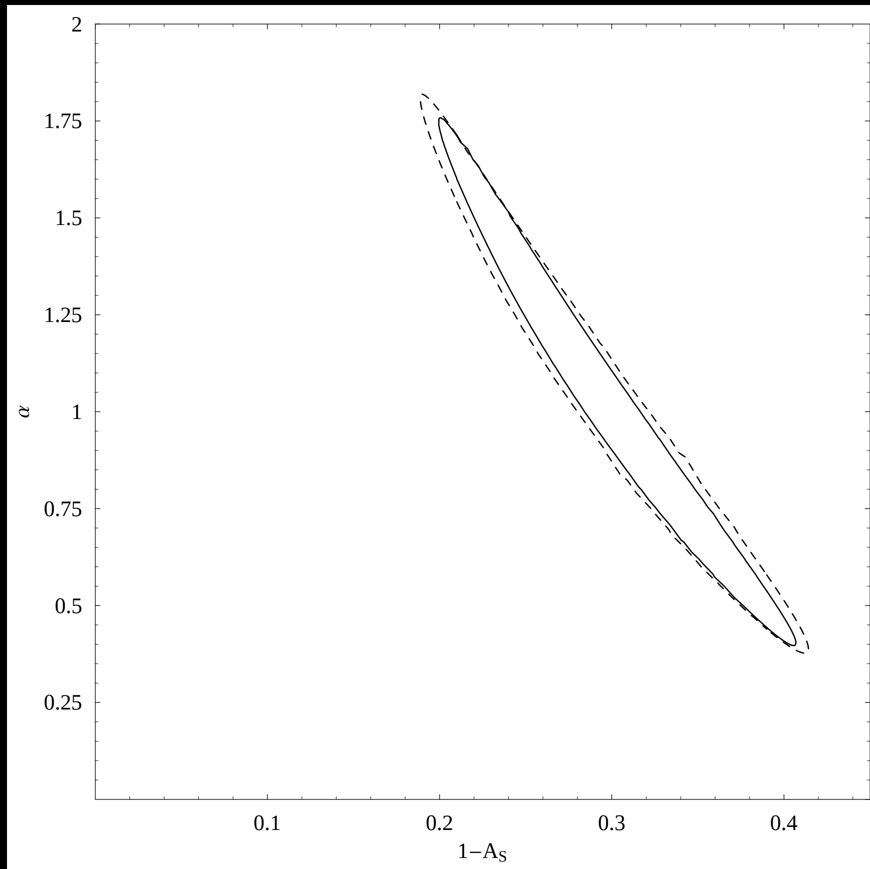
- GRBs are “easily” detected at z>2
- Systematic effects still to be understood (not considered so far).
- $\sigma_\mu \approx 0.5$

- No detection is expected beyond z>2
- Systematics under control
- $\sigma_\mu \approx 0.14$ or less

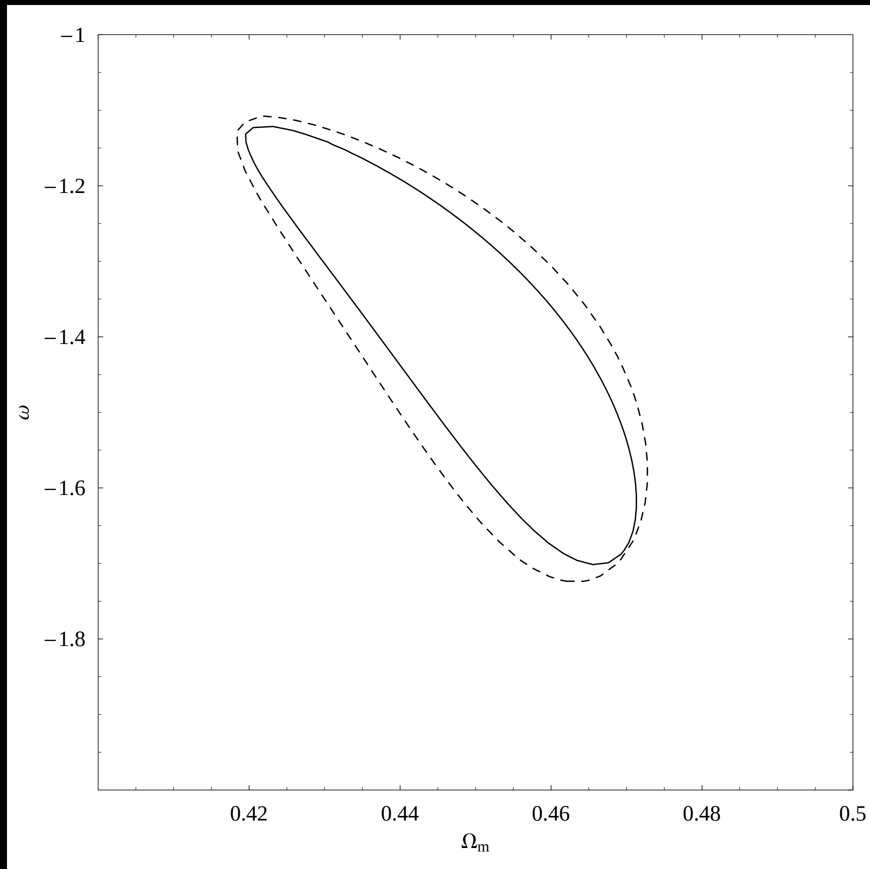
GRBs and SNe Ia

- When considering future GRB experiments, one can use the SNAP specifications for SNe Ia.
- Build a χ^2 estimator for both SNe Ia and GRBs, and compute the corresponding confidence regions.
- Dashed line corresponds to SNe Ia, while the solid one to SNe Ia + GRBs.

GCG Models



XCDM Models



So, can GRBs help?

- The impact of GRBs as cosmological probes depends on the cosmological model under investigation.
- Until SNAP or another large SNe Ia survey start yielding results, GRBs may help in tightning constraints on DE and DM models.

Can GRBs Help??

- However, even after SNAP, GRBs might be used as a consistency check.
- Adding GRBs data to SNe Ia data may not affect results significantly, unless new and more precise GRB luminosity estimators become available.

This is complicated matter...

- Selection effects
- Gravitational lensing
- Lack of a physical model for GRBs
- Unverified assumptions