High redshift constraints on dark energy cosmology from the $E_{p,i}$-E_{iso} correlation

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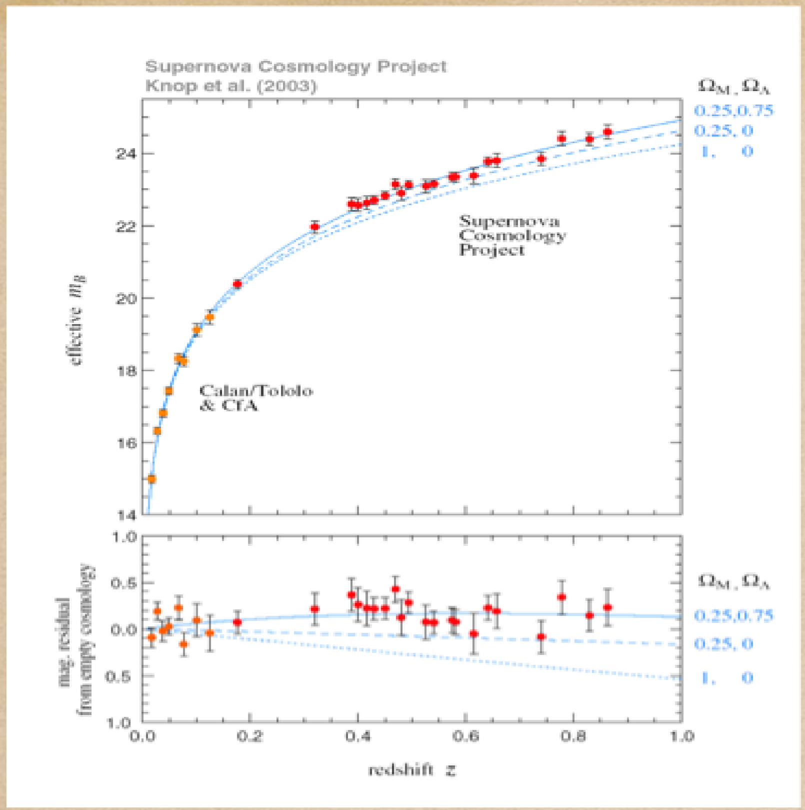
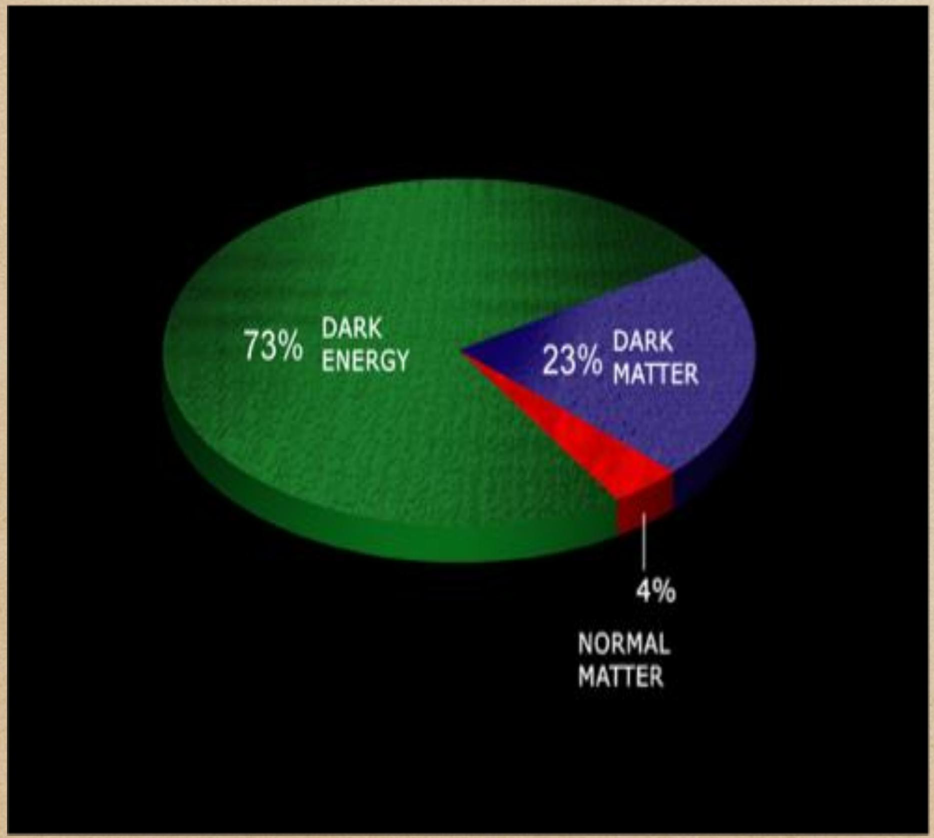
Outline

- Motivation for building up the Hubble diagram behind the SNeIa
  - Upadated calibrating technique for the Amati relation
- Building up the GRBs Hubble Diagram and testing cosmological models
- Discussion (a first "smell" of resutls from joined QSOs GRBs HD)

A surprising portrait of the Universe



In 1998 two groups of astronomers published first results about SNeIa that hinted that the Universe could be accelerating. After collecting more data both groups confidently announced that they discovered that now the expansion rate of the universe is accelerating, forcing to revise the standard cosmological model.



Dozen years after its unexpected and somewhat serendipitous discovery, the accelerated expansion of the universe is taken for granted due to the flood of data from different astrophysical probes confirming it, and the question of the cause of this phenomenon is still unsolved. Although the spatially flat concordance ΛCDM model, made out of a cosmological constant accounting for ~ 70% of the energy budget and responsible of the cosmic speed up, is in full agreement with observations it is far from free of any conceptual and theoretical problems.

Dark Energy

In general the accelerated expansion of the Universe is now linked with existence of dark energy with an equation of state w, which should be smaller then $-1/3$ for dark energy to cause the accelerated expansion of the universe. When $w = -1$ dark energy can be identified with the cosmological constant. Otherwise it can depend on time.

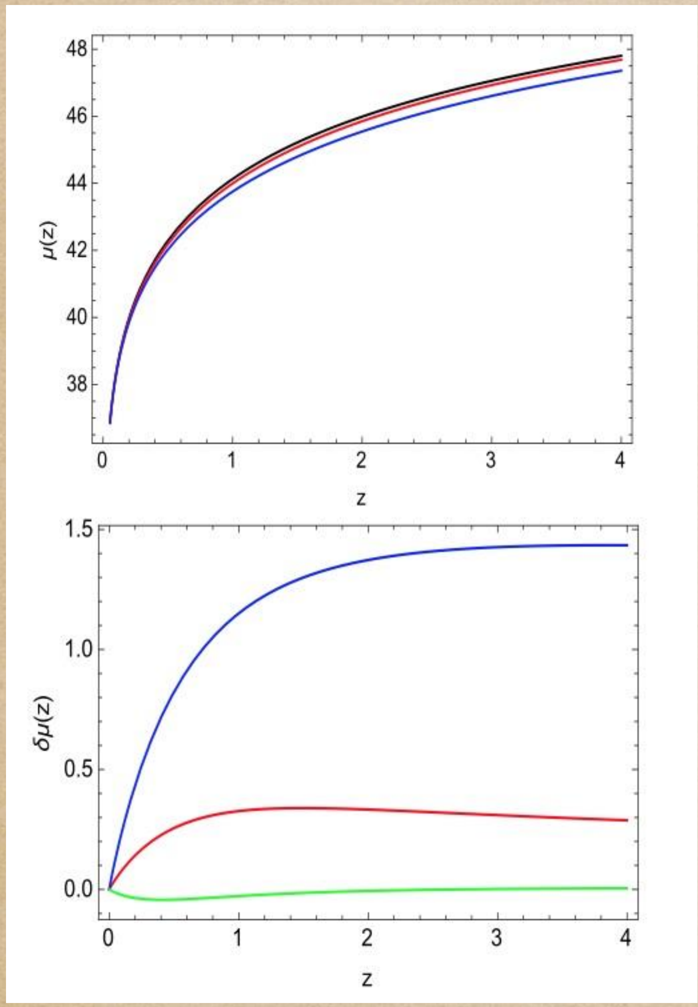
- Cosmological constant
- Quintessence (self interacting scalar field)*
- Scalar tensor theories
- F(R) theories
- Local geometry

*May be Dark Energy could contain both a constant and an evolving component

Dark Energy investigation

- The nature of dark energy can be studied observationally.
- The observations are mainly aimed at constraining the DE EoS. Under the simple yet efficient CPL (Chevallier & Polarski 2001; Linder 2003) parameterization, $w = w_0 + w_a(1-a)$ with $a = 1/(1+z)$ the scale factor and z the redshift, the main taks of observational cosmology has nowadays become to narrow down as much as possible the range for the (w_0, w_a) parameters.

Necessity for new probes :
different distribution in redshift implies different sensitivity to different cosmological parameters

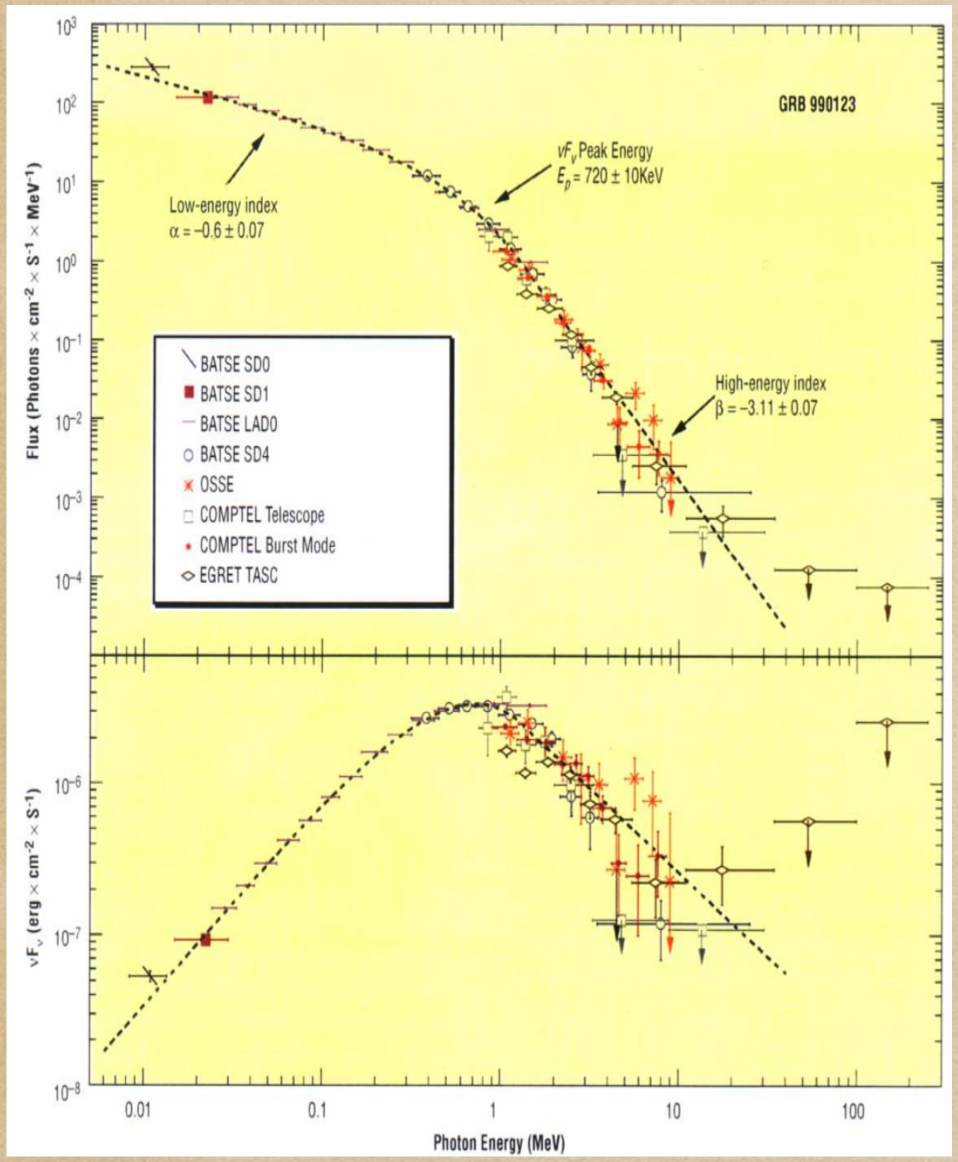


sensitivity to the dark energy equation of state increases at high redshift

GRBs as distances indicators

- GRBs have huge luminosity, a redshift distribution extending beyond SNeIa, and very high energy emission (no extinction problems).
- Unfortunately they are not standard candles, because their isotropic energy spans more than three orders of magnitude.
- The road to the standardization is the existence of robust phenomenological correlations between spectra and energetics in GRBs.

The $E_{p,i}$ – E_{iso} correlation



In contrast to the lightcurves of GRBs the shape of their spectra is simple

The spectrum of GRBs is nonthermal and can be empirically described by the so-called Band function, a broken power law characterized by the low-energy spectral index and the high energy index .

E_0=break energy

$E_p = E_0 \times (2 + a)$ = peak energy of the nFn spectrum

The robust correlation between the observed photon energy of peak spectral flux and the GRB radiated energy is at the base of the GRBs Hubble diagram.

The Ep,i – Eiso correlation

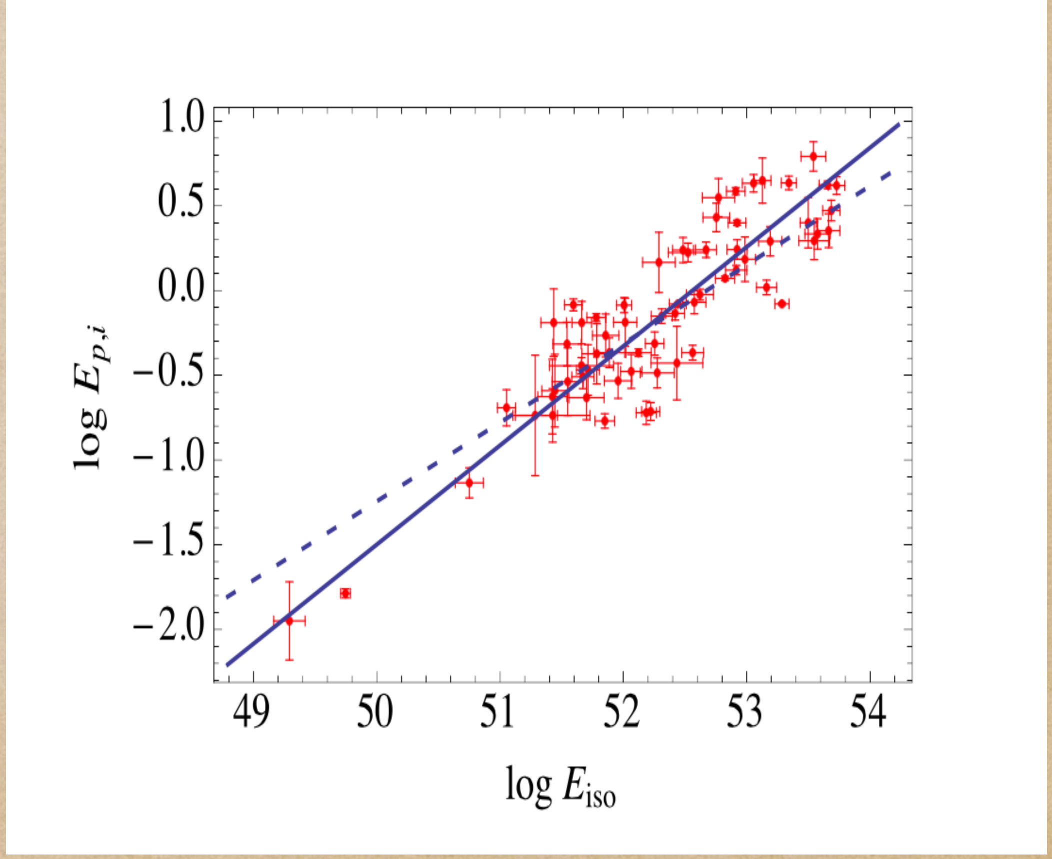
$$\log\left(\frac{E_{\rm iso}}{1\ {\rm erg}}\right) = b + a\log\left[\frac{E_{\rm p,i}(1+z)}{300\ {\rm keV}}\right]$$

$$E_{\rm iso} = 4\pi d^2{}_L(z,cp)(1+z)^{-1}\int_{1/1+z}^{10^4/1+z} EN(E)dE,$$

being $N(E)$ the Band function:

$$N(E) = \begin{cases} A\left(\frac{E}{100KeV}\right)^{\alpha}\exp\left(\frac{-E}{E_0}\right) & (\alpha-\beta)\,E_0 \geq 0 \\ A\left(\frac{(\alpha-\beta)E}{100KeV}\right)^{\alpha-\beta}\exp\,(\alpha-\beta)\left(\frac{E}{100KeV}\right)^{\beta} & (\alpha-\beta)\,E_0 \leq E\,. \end{cases}$$

Actually, one of the most important property of long GRBs is the evidence of a correlation between the the observed photon energy of peak spectral flux and the isotropic equivalent radiated energy:



Cosmological independent calibration

The lack of nearby GRBs induces the so called circularity problem : they can be used as cosmological tools, once the $E_{p,i}$ - E_{iso} correlation is calibrated, however the calibration procedure seems to be assumed for the calibration. In principle, such a problem could be solved in several way: it is possible, for instance, simultaneously constrain the calibration parameters and the set of cosmological parameters by considering a likelihood function defined in whole space (direct product).We use a procedure for calibrating the correlation in a way independent of the cosmological model, by applying a local regression technique to estimate the distance modulus $\mu(z)$ from the recently updated SNIa sample, called the Union2.1.

Cosmological independent calibration:the local regression procedure can be schematically sketched as below:

- Set a redshift z where μ(z) has to be reconstructed
- Sort Union 2.1SNe-Ia sample (SNe-Ia collected and fit with a single lightcurve filter and uniformly analyzed)
- Select the first n

$$n = \alpha N_{SNeIa}$$

- fit a first order polynomial to the data previously selected and weighted, and use the 0^{th} order term as best fit value of the modulus of distance μ (z)
- evaluate the error σ_{μ} as the root mean square of the weighted residuals with respect to the best fit value

GRBs Hubble diagram

We include in the calibration some power- law terms representing the z-evolution:

$g_{iso}(z) = (1 + z)^{k_{iso}}$ and $g_p(z) = (1 + z)^{k_p}$ so that

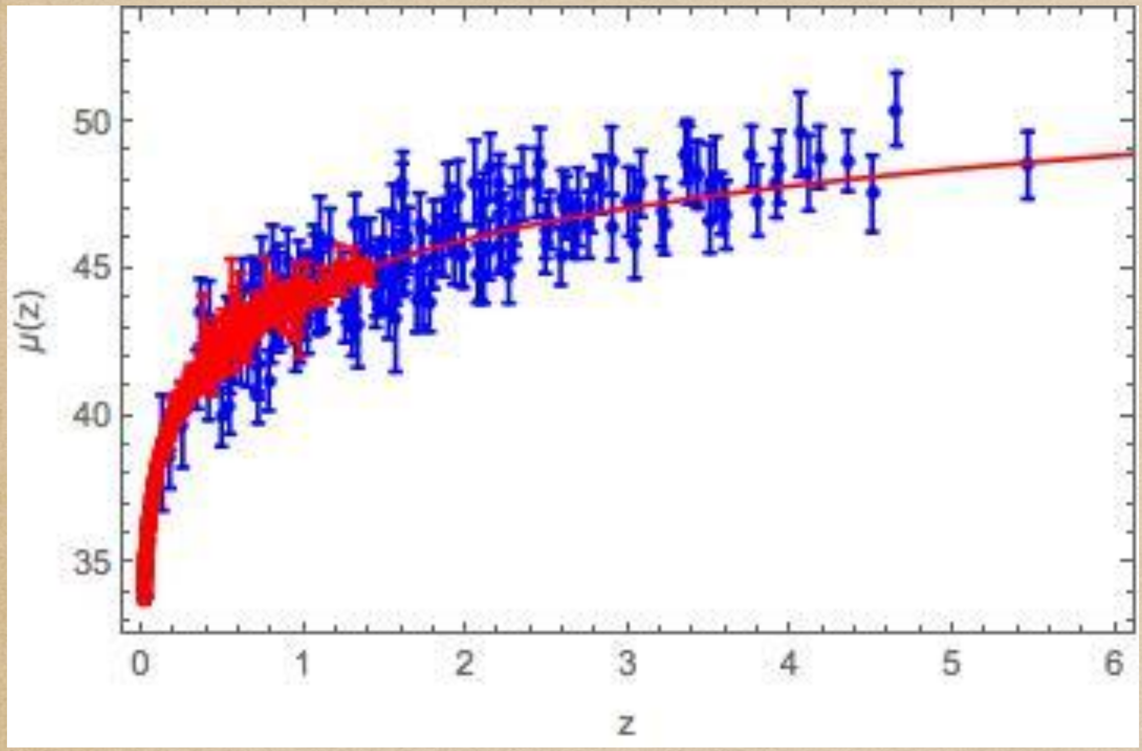
$E' = E_{iso}/ g_{iso}(z)$ and $E' = E_{p,i}/ g_p(z)$

are the deevolved quantities

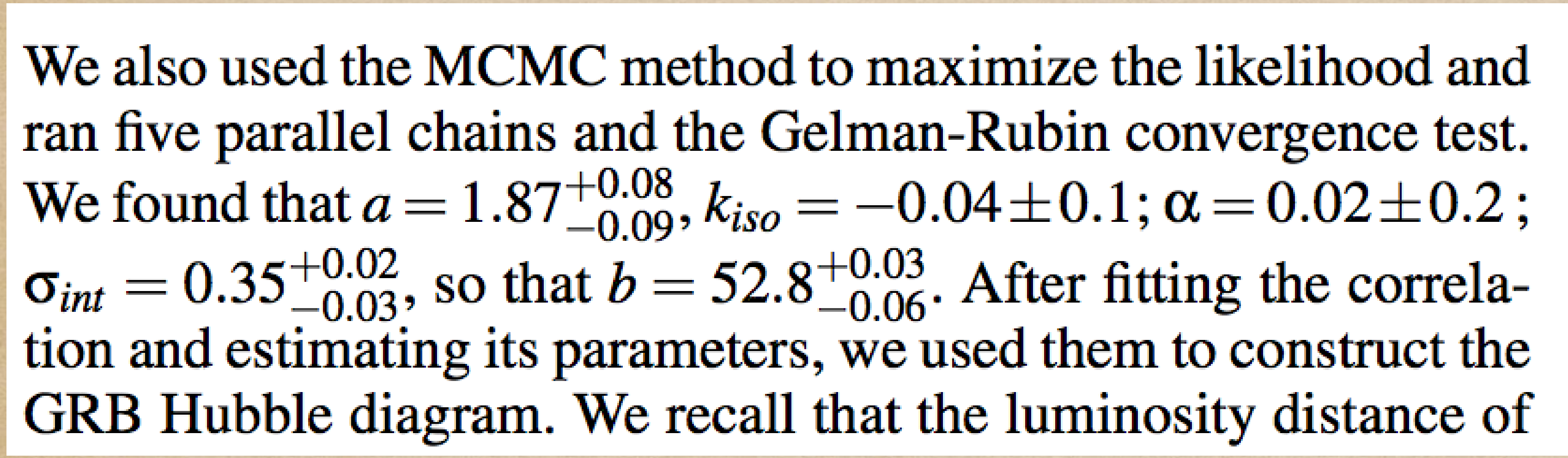
$$L^{3D}_{Reichart}(a, k_{iso}, k_p, b, \sigma_{int}) = \frac{1}{2}\frac{\sum \log(\sigma_{int}^2 + \sigma_{y_i}^2 + a^2\sigma_{x_i}^2)}{\log(1+a^2)}$$
$$+ \quad \frac{1}{2}\sum \frac{(y_i - ax_i - (k_{iso} - \alpha)z_i - b)^2}{\sigma_{int}^2 + \sigma_{x_i}^2 + a^2\sigma_{x_i}^2},$$

- Once the correlation has been fitted, and its parameters have been estimated, we can now use them to construct the GRBs Hubble diagram. Actually it turns out that
- $$5\log d_L(z) = \left(\frac{5}{2}\right)\left\{b + a\log\left[\frac{E_{\rm p,i}}{300\ {\rm keV}}\right] + (k_{iso} - a\,k_p + 1) \times \log(1+z) - \log(4\pi S_{bolo}) + \beta\right\},$$

GRBs Hubble diagram



It turns out that
B=0.32


We also used the MCMC method to maximize the likelihood and ran five parallel chains and the Gelman-Rubin convergence test. We found that $a = 1.87^{+0.08}_{-0.09}$, $k_{iso} = -0.04 \pm 0.1$; $\alpha = 0.02 \pm 0.2$; $\sigma_{int} = 0.35^{+0.02}_{-0.03}$, so that $b = 52.8^{+0.03}_{-0.06}$. After fitting the correlation and estimating its parameters, we used them to construct the GRB Hubble diagram. We recall that the luminosity distance of

Cosmological constraints

$$\mu_{th}(z,\theta) = 25 + 5\log d_L(z,\theta)$$

Theoretically predicted

Set of cosmo parameters

- In order to constrain the parameters specifying different cosmological models, we maximize the likelihood function
  L(θ) ∝ exp [-x²(θ) /2] and the x²(θ) is defined as

$$\chi^2(\theta) = \sum_{i=1}^{N_{GRBs}} \left[\frac{\mu_{obs}(z_i) - \mu_{th}(z_i,\theta)}{\sigma_i}\right]^2$$

We sample the space of parameters, by running five parallel chains and use the Gelman - Rubin diagnostic approach to test the convergence. As a test probe, it uses the reduction factor *R*, which is the square root of the ratio of the variance between-chain and the variance within-chain. We finally extracted the constraints on the parameters by coadding the thinned chains. The histograms of the parametrs from the merged chains were then used to infer median values and confidence ranges

Cosmological constraints

$$w_{CPL} = w_0 + w_1\, z/(1+z)$$

CPL Parametrization

Id	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL
			Full dataset				No SNIa	
Ω_m	0.284	0.283	(0.276, 0.291)	(0.271, 0.30)	0.267	0.27	(0.25, 0.29)	(0.234, 0.31)
Ω_b	0.0459	0.459	(0.0446, 0.0473)	(0.0433, 0.0487)	0.055	0.054	(0.045, 0.068)	(0.037, 0.06)
w_0	-1.17	-1.18	(-1.25, -1.145)	(-1.31, -1.12)	-1.07	-1.06	(-1.18, -0.96)	(-1.3, -0.84)
w_a	0.618	0.603	(0.5, 0.71)	(0.44, 0.94)	0.64	0.73	(0.29,0.9)	(0.15, 0.92)
h	0.698	0.699	(0.689, 0.707)	(0.681, 0.714)	0.674	0.671	(0.65, 0.694)	(0.668, 0.703)

Cosmological constraints

Quintessence scalar field

$$V(\varphi) \propto \exp\left\{-\sqrt{\frac{3}{2}}\varphi\right\}$$

$$a^3(t) = \frac{t^2}{2}[(3H_0-2)t^2+4-3H_0],$$

$$H(t) = \frac{2\left(2(3H_0-2)t^2+4-3H_0\right)}{3t\left((3H_0-2)t^2+4-3H_0\right)},$$

$$\Omega_M = \frac{(4-3H_0)\left((3H_0-2)t^2+4-3H_0\right)}{\ldots},$$

Scalar field Quintessence

Id	$\langle x\rangle$	$\tilde{x}$	68% CL	95% CL	$\langle x\rangle$	$\tilde{x}$	68% CL	95% CL
			Full dataset				No SNIa	
Ω_b	0.051	0.051	(0.503, 0.0514)	(0.049, 0.052)	0.051	0.051	(0.0504, 0.0514)	(0.0498,0.0517)
H_0	0.928	0.928	(0.924, 0.931)	(0.92, 0.936)	0.928	0.927	(0.924,0.931)	(0.92, 0.936)
h	0.664	0.664	(0.661, 0.67)	(0.657, 0.676)	0.664	0.664	(0.661,0.6681)	(0.657, 0.676)

Cosmological constraints

Early Dark Energy

Early Dark Energy

Id	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL
		Full dataset				No SNIa		
Ω_m	0.286	0.287	(0.276, 0.281)	(0.28, 0.294)	0.285	0.285	(0.271, 0.298)	(0.258, 0.312)
Ω_b	0.0417	0.0423	(0.040 0.0432)	(0.037, 0.044)	0.0379	0.0379	(0.0344, 0.04)	(0.0319, 0.044)
w_0	-0.679	-0.6	(-0.85, -0.56)	(-1.33, -0.5)	-0.65	-0.63	(-0.75, -0.53)	(-0.85,-0.50)
Ω_e	0.022	0.0223	(0.0215, 0.0231)	(0.0206, 0.0237)	0.0293	0.0292	(0.0286, 0.297)	(0.0283, 0.03)
h	0.716	0.714	(0.706, 0.727)	(0.70, 0.747)	0.671	0.671	(0.657,0.686)	(0.645, 0.71)

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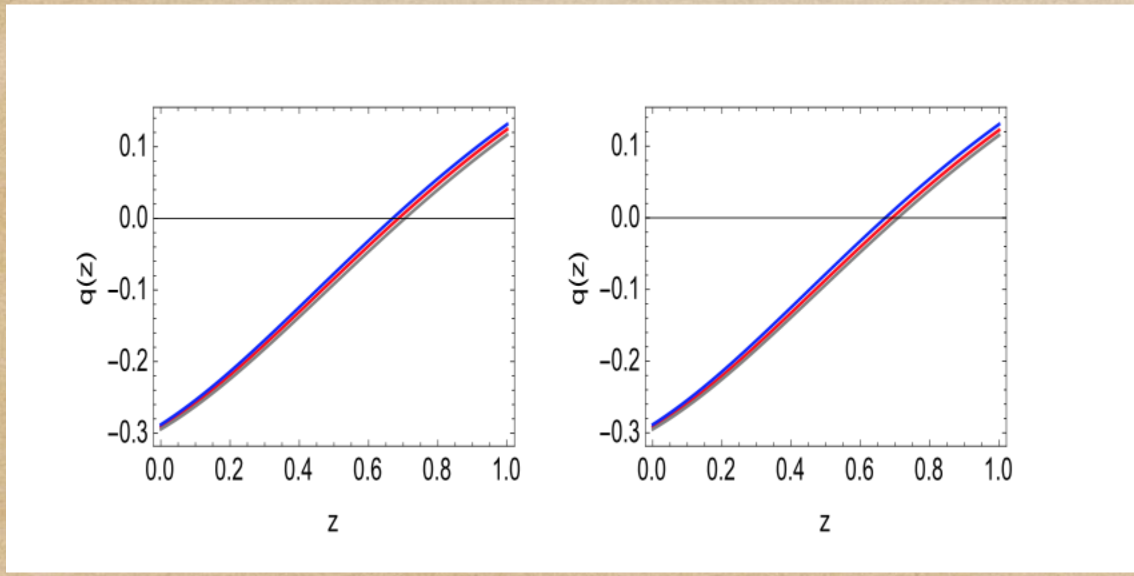
$\Omega_m, \Omega_e, w_0) +$

$\frac{4}{3} N_{eff} + 1 \Big) .$

In agreement with results from CMB (Planck collaboration)

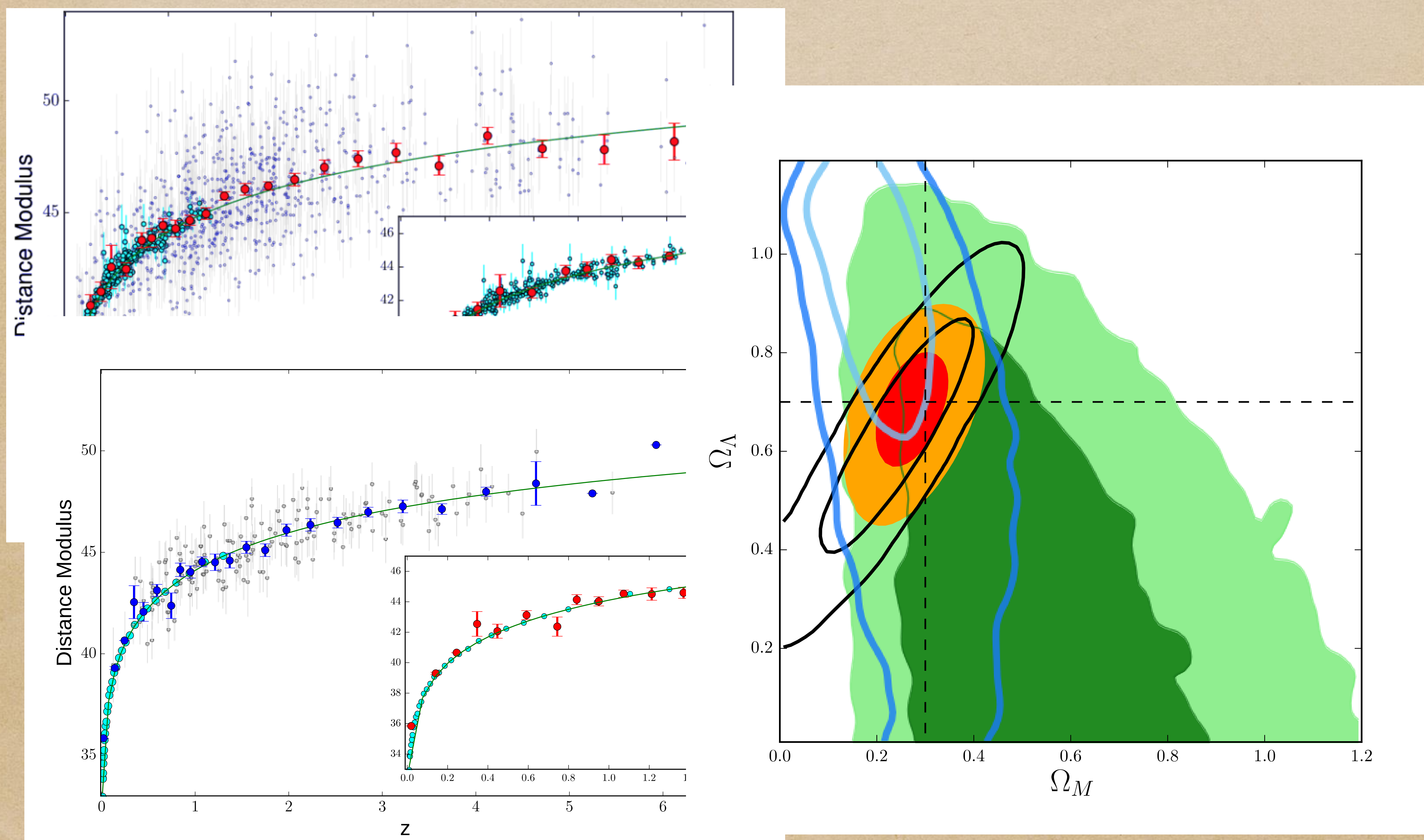
Cosmological constraints

To compare these models we assumed that the CPL is true and checked the occurrence of $\chi^2_{EDE/Quintessence} < \chi^2_{C2PL}$, varying the parameters specific of the EDE and scalar field model respectively. It turns out that the EDE and the scalar field quintessence are slightly favored by the present data,with a frequency greater than 74% for the scalar field, and with a frequency greater than 80% respectively. Moreover, it is worth noting that, also without the SNIa, the GRBs Hubble diagram is able to set the transition region from the decelerated to the accelerated expansion in all the tested cosmological models.



GRBs+QSOs Hubble diagram?

In collaboartion with Prof. Risaliti G. and collaborators (Florence University)



Conclusions

- The $E_{p,i}$-E_{iso} correlation has significant implications for the use of GRBs in cosmology. Here we take into account a possible redshift evolution effects of its correlation coefficients.Our results confirm That
- the correlation shows, at this stage, only very weak indications of evolution.
- The GRBs HD indicates an evolving dark energy, as favoured Dark Energy models
- Amazing results can be expected by a joined analysis of QSOs and GRBs Hubble diagram (cosmography could be updated)

Thanks a lot for your kind attention