Measuring Cosmological Parameters with Gamma-Ray Bursts

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Why looking for more cosmological probes ?

- different distribution in redshift -> different sensitivity to different cosmological parameters

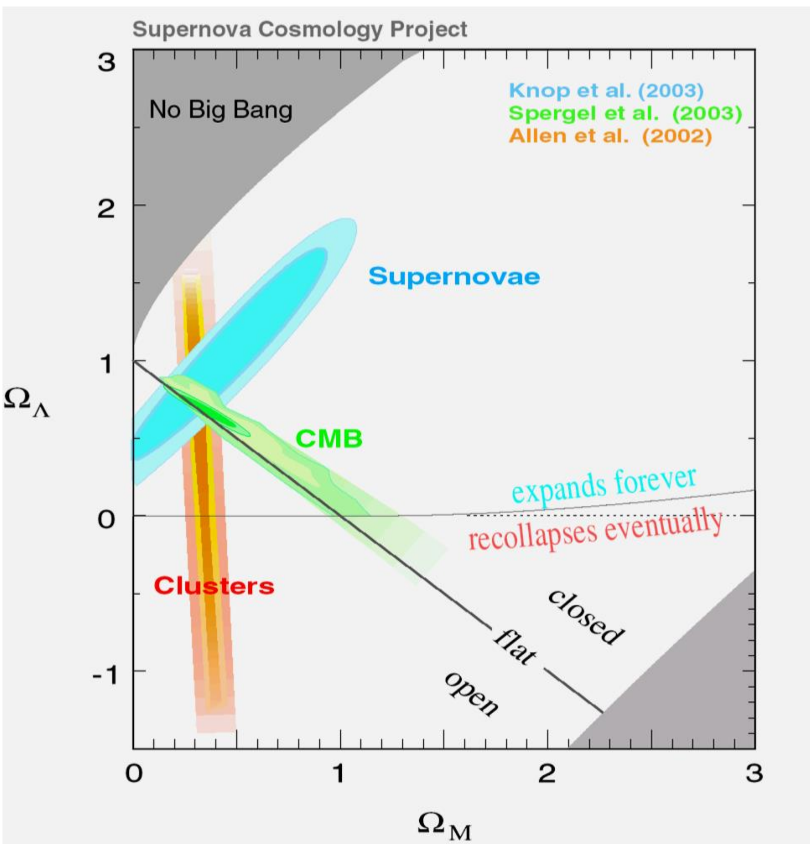
$$\Omega = \Omega_m + \Omega_{rel} + \Omega_\Lambda$$

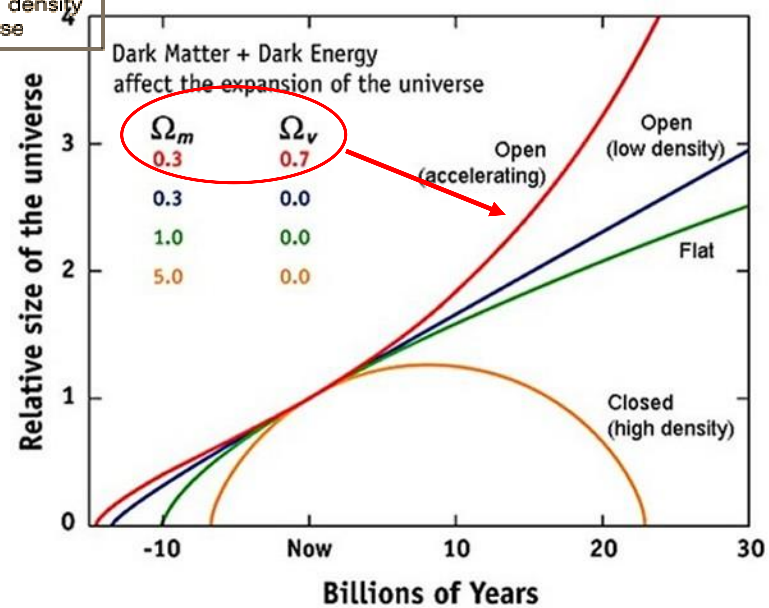
Total density parameter $\Omega = \frac{\rho}{\rho_c}$, $\Omega = 1$ for critical density universe

Ω_m: Mass density including ordinary mass (baryonic mass) plus dark matter.

Ω_{rel}: Effective mass density of relativistic particles (light plus neutrinos).

Ω_Λ: Effective mass density of the dark energy, taking the role described as the cosmological constant.





$$D_L = (1+z)c \div H_o \,|k|^{0.5} \times S\left\{|k|^{0.5} \int_0^z \left[k(1+z)^2 + \Omega_M (1+z')^3 + \Omega_\Lambda\right]^{-0.5} dz'\right\}$$

❑ Each cosmological probe is characterized by possible systematics

❑ e.g SN Ia:

➢ different explosion mechanism and progenitor systems ? May depend on z ?

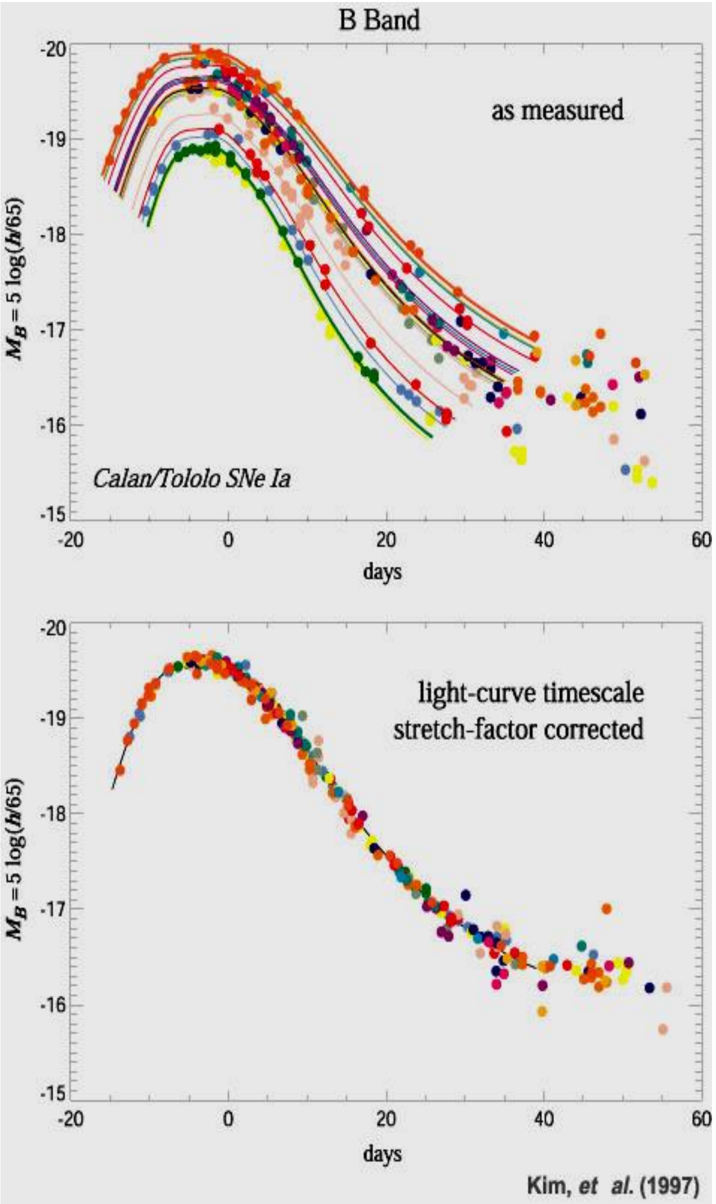
➢ light curve shape correction for the luminosity normalisation may depend on z

➢ signatures of evolution in the colours

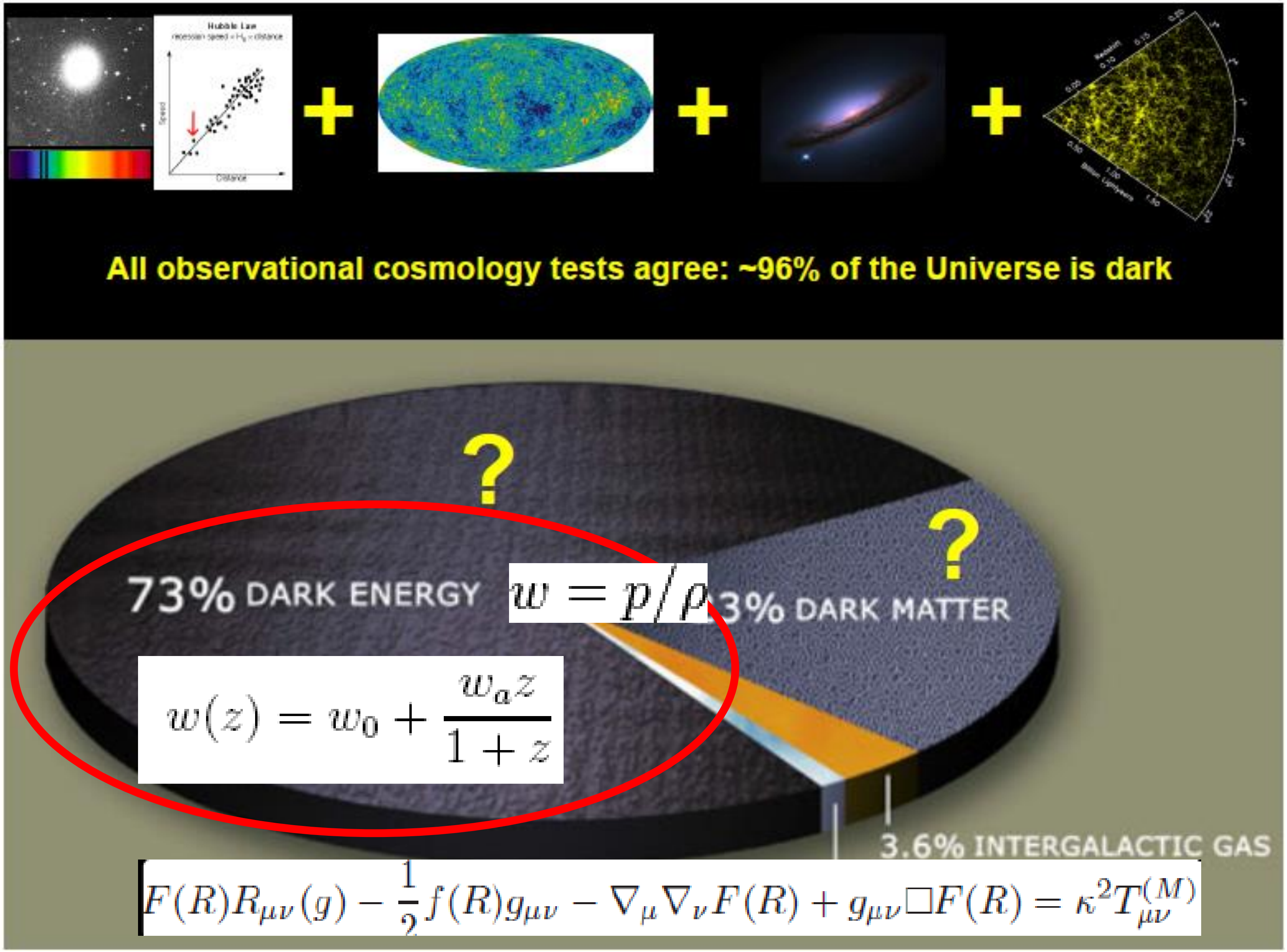
➢ correction for dust extinction

➢ anomalous luminosity-color relation

➢ contaminations of the Hubble Diagram by no-standard SNe-Ia and/or bright SNe-Ibc (e.g. HNe)

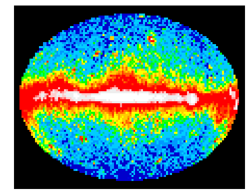


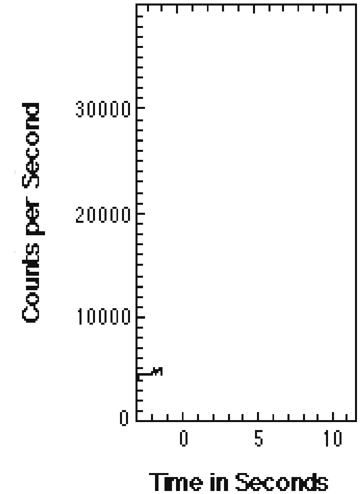
Control of systematics by combination of different probes is fundamental for investigation of DE properties / alternative cosmologies

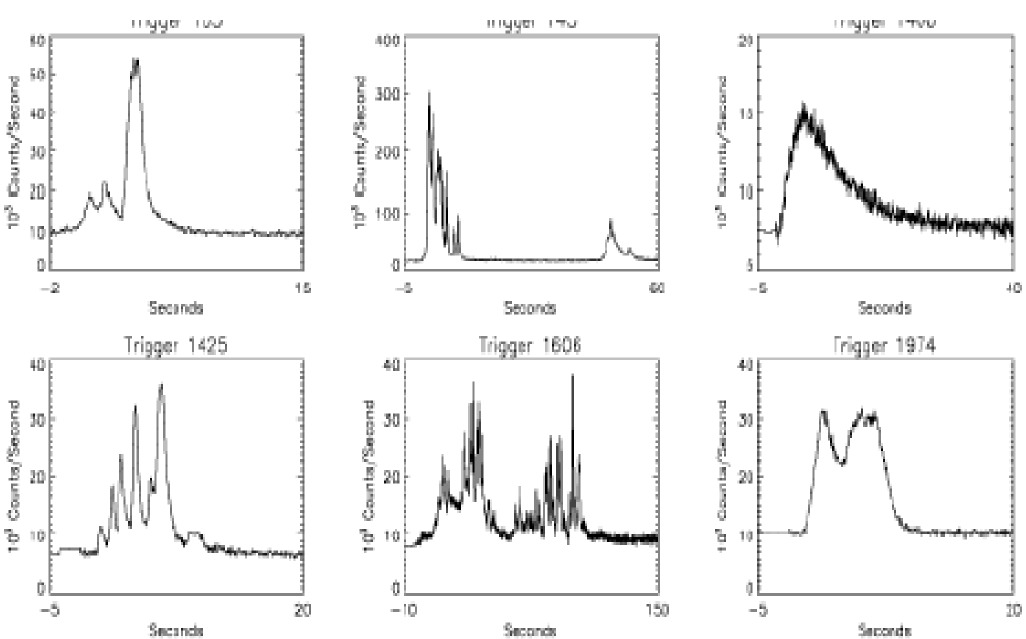


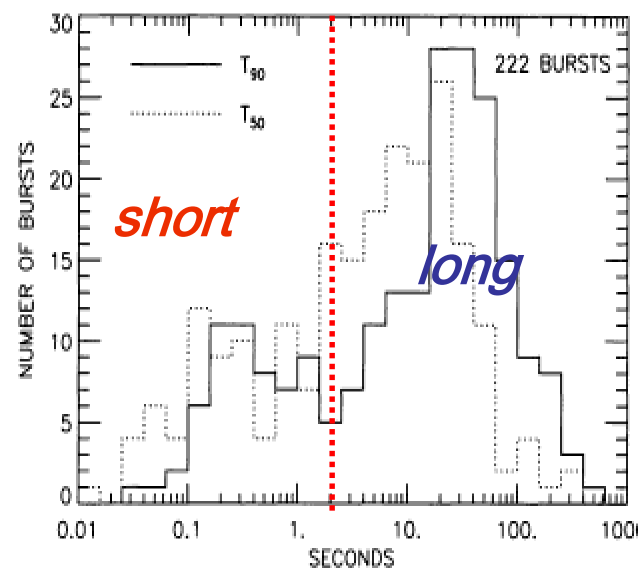
The Gamma-Ray Bursts phenomenon

- sudden and unpredictable bursts of hard-X / soft gamma rays with huge flux
- most of the flux detected from 10-20 keV up to 1-2 MeV, with fluences typically of ~10^{-7} – 10^{-4} erg/cm^2 and bimodal distribution of duration
- measured rate (by an all-sky experiment on a LEO satellite): ~0.8 / day; estimated true rate ~2 / day



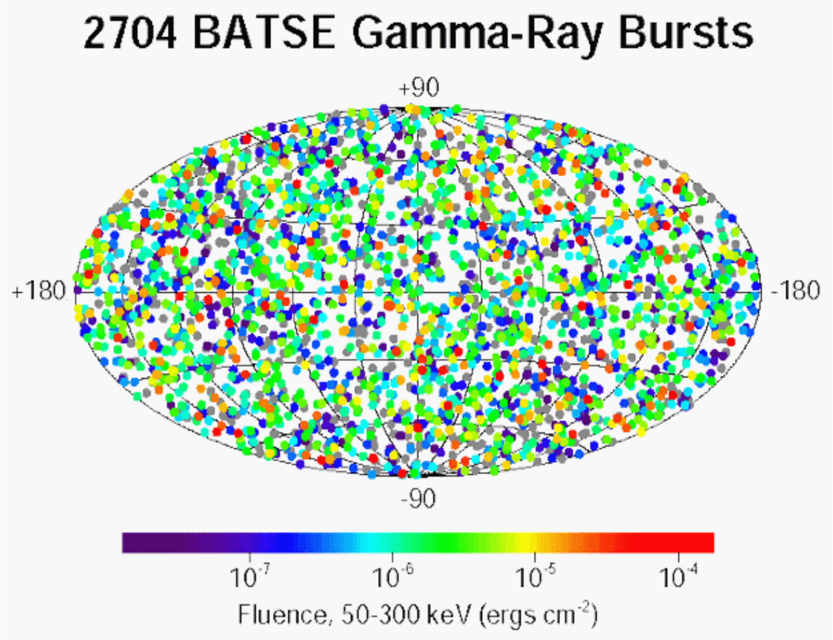


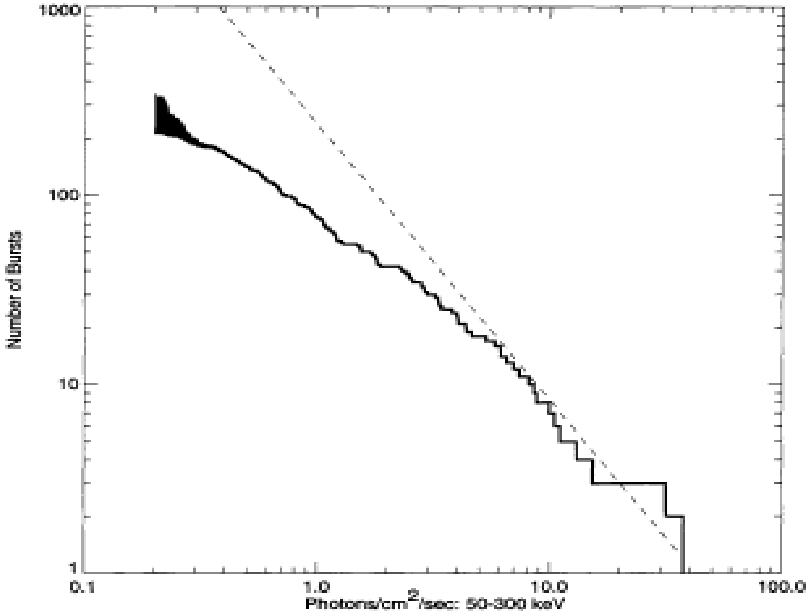




Early evidences for a cosmological origin of GRBs

- ❑ isotropic distribution of GRBs directions
- ❑ paucity of weak events with respect to homogeneous distribution in euclidean space
- ❑ **given the high fluences (up to more than 10^{-4} erg/cm2 in 20-1000 keV) a cosmological origin would imply huge luminosity**
- ❑ thus, a "local" origin was not excluded until 1997 !

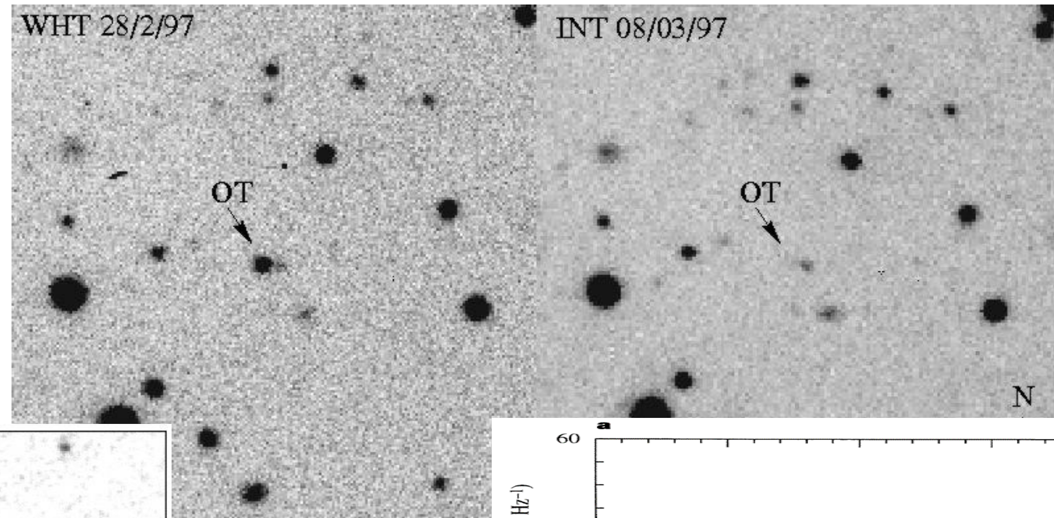


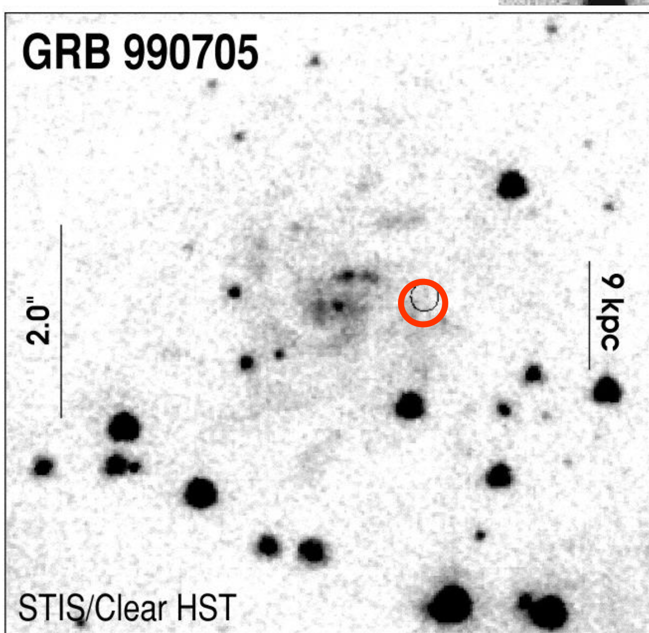


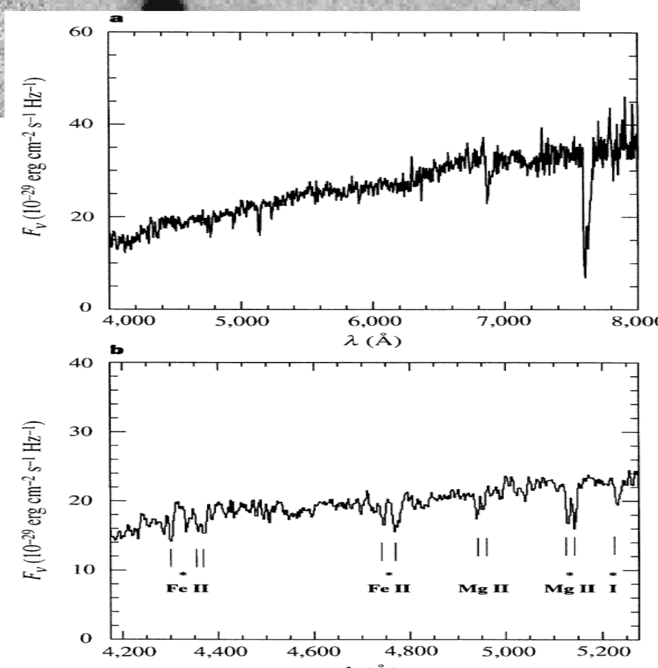
Establishing the cosmological distance scale of GRBs

- **1997:** accurate (a few arcmin) and quick localization of X-ray afterglow -> optical follow-up -> first optical counterparts and host galaxies

- Optical spectroscopy of afterglow and/or host galaxy –> first measurements of GRB redshift



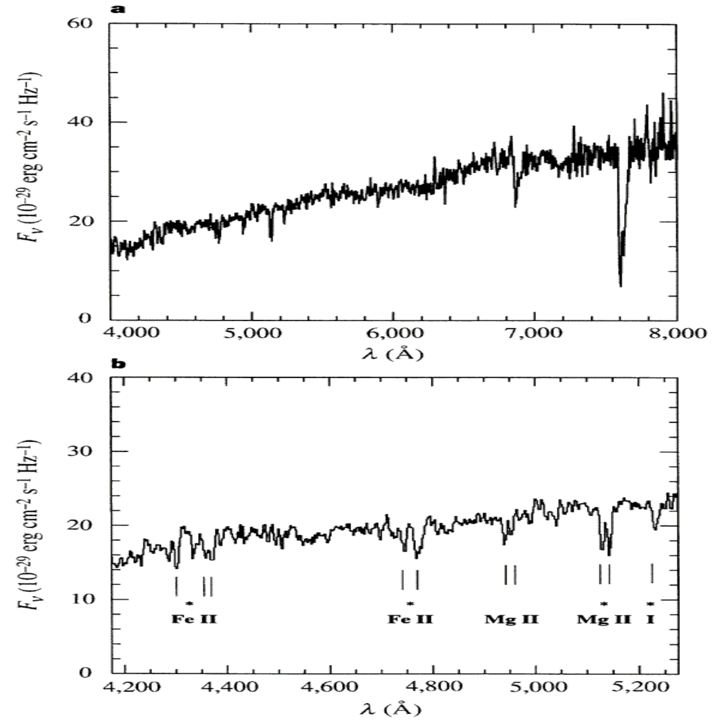


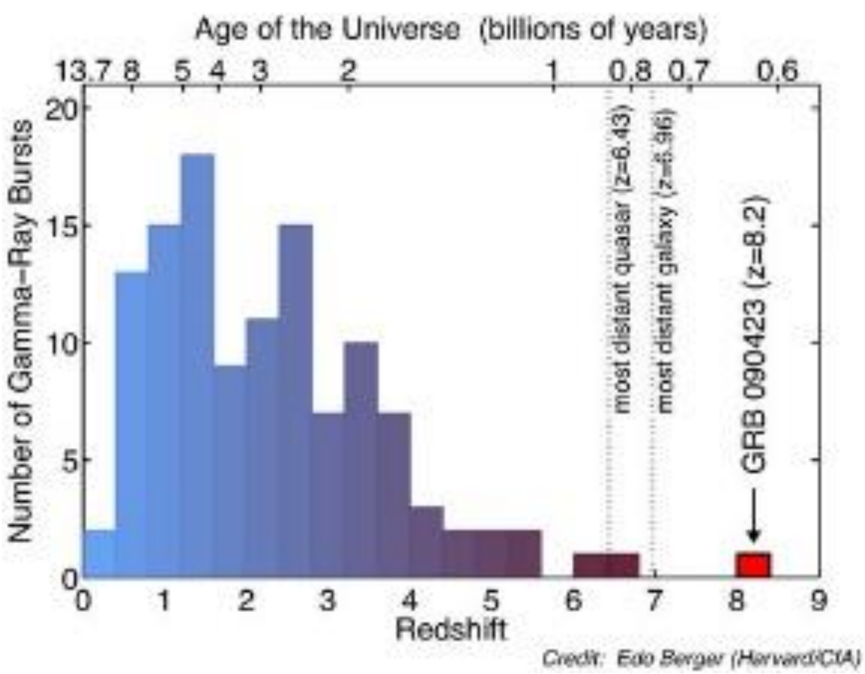


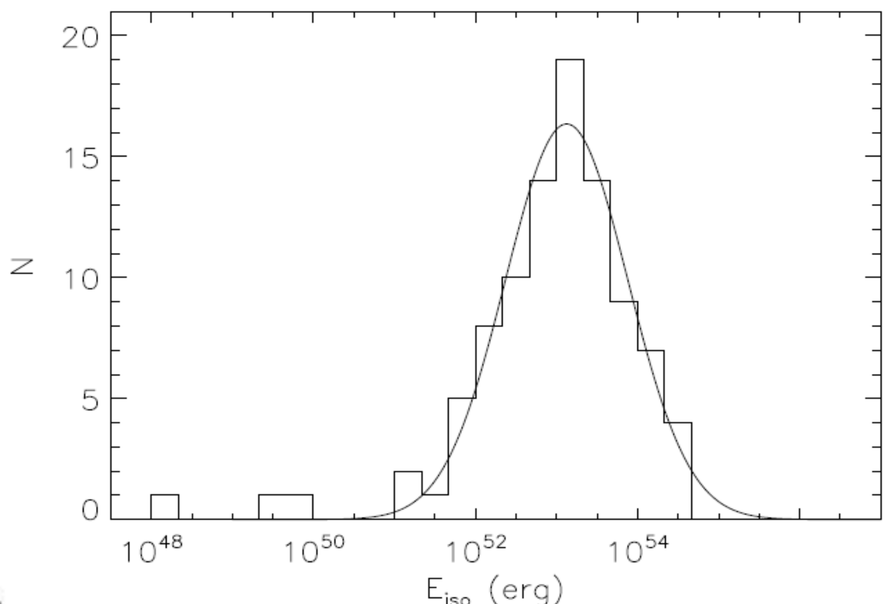
➢ optical spectroscopy of afterglow and/or host galaxy –> first measurements of GRB redshift

➢ **redshifts higher than 0.01 and up to > 8**
GRB are cosmological

➢ **their isotropic equivalent radiated energy is huge (up to more than 10^{54} erg in a few tens of s !)**



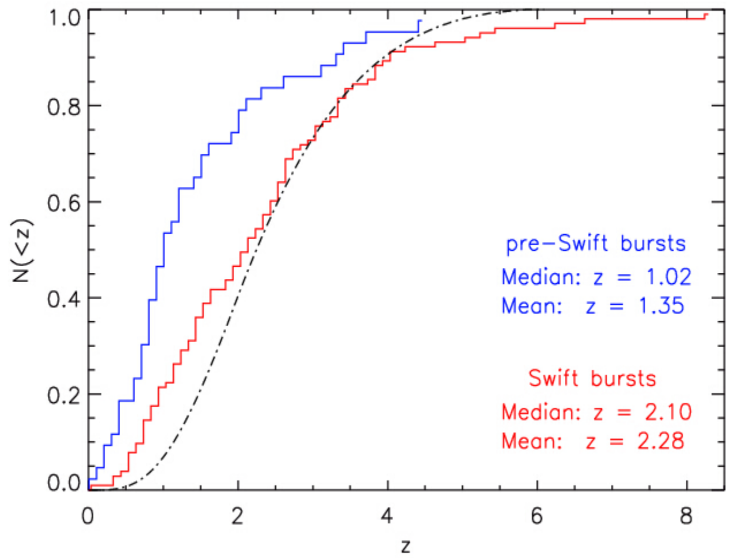


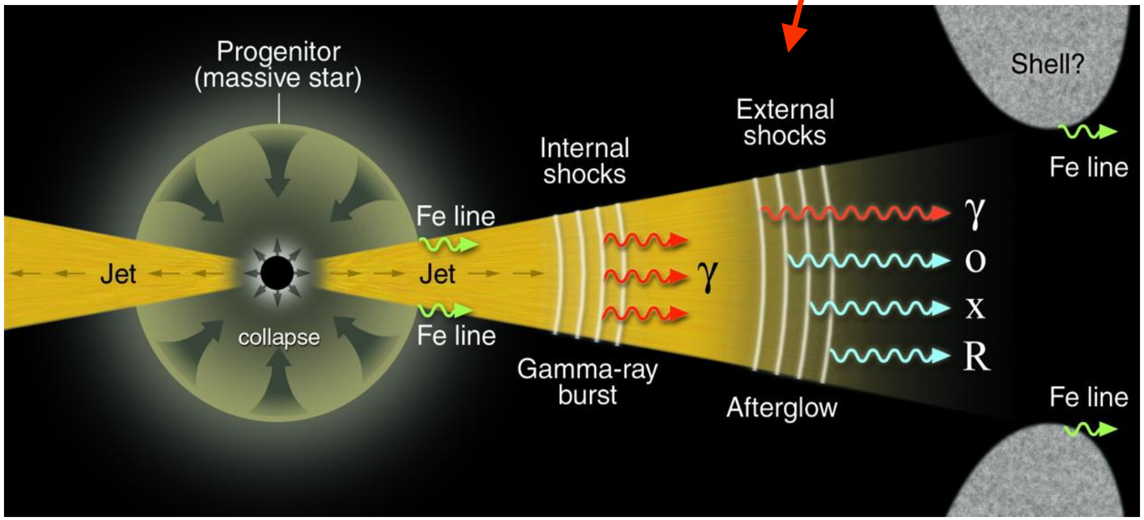


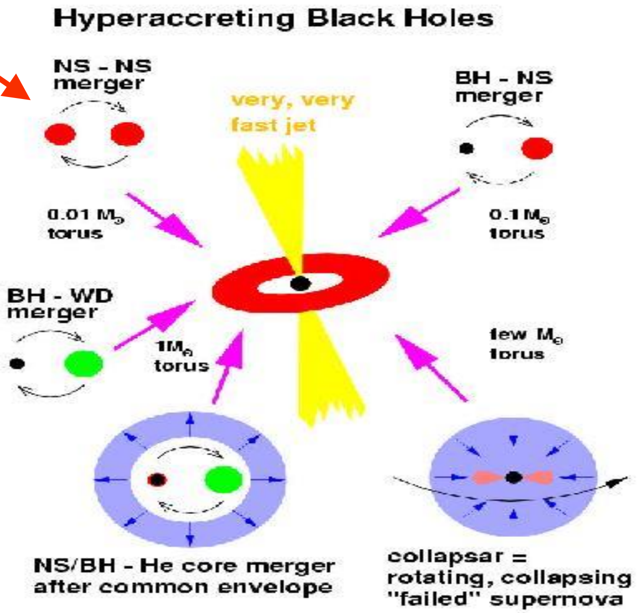
➢ redshifts higher than 0.01 and up to > 8: GRB are cosmological !

➢ their isotropic equivalent radiated energy is huge (up to more than 10^{54} erg in a few tens of s !)

➢ fundamental input for origin of long / short







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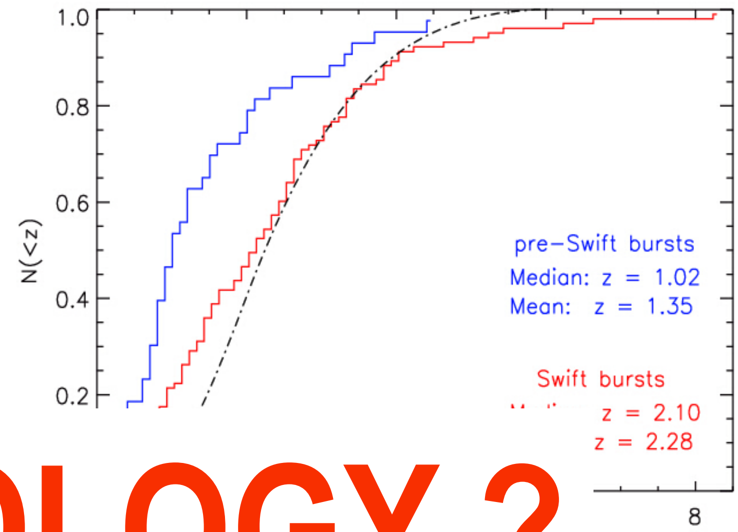
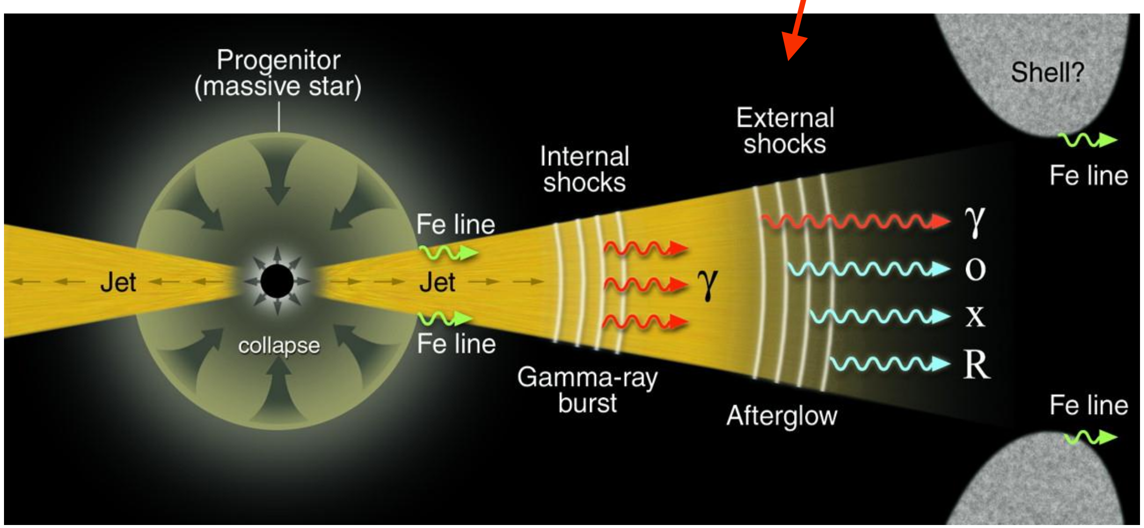
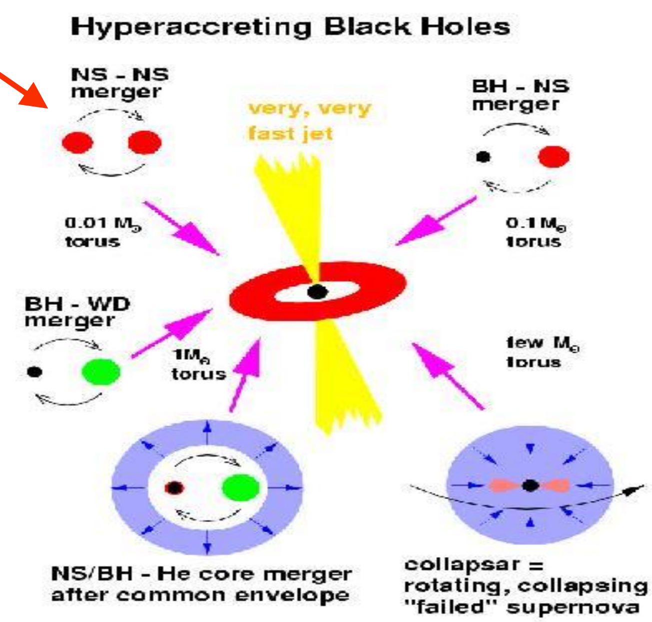


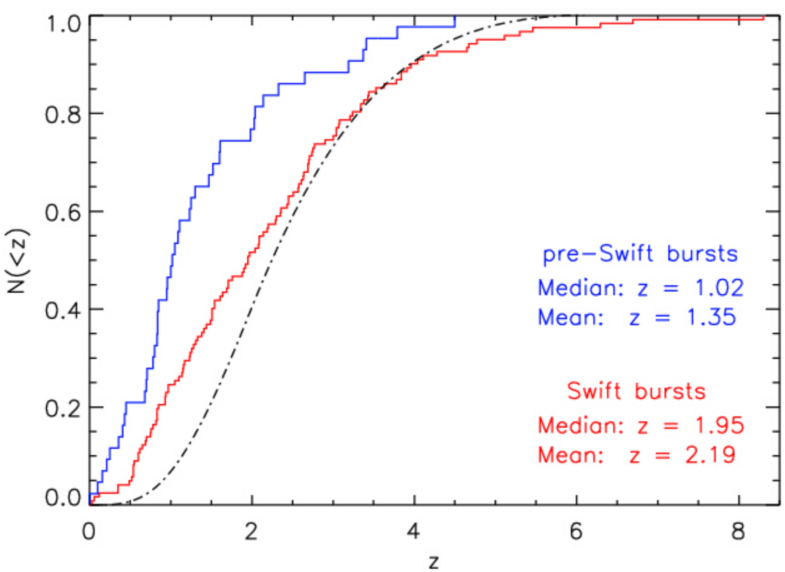
GRB COSMOLOGY ?



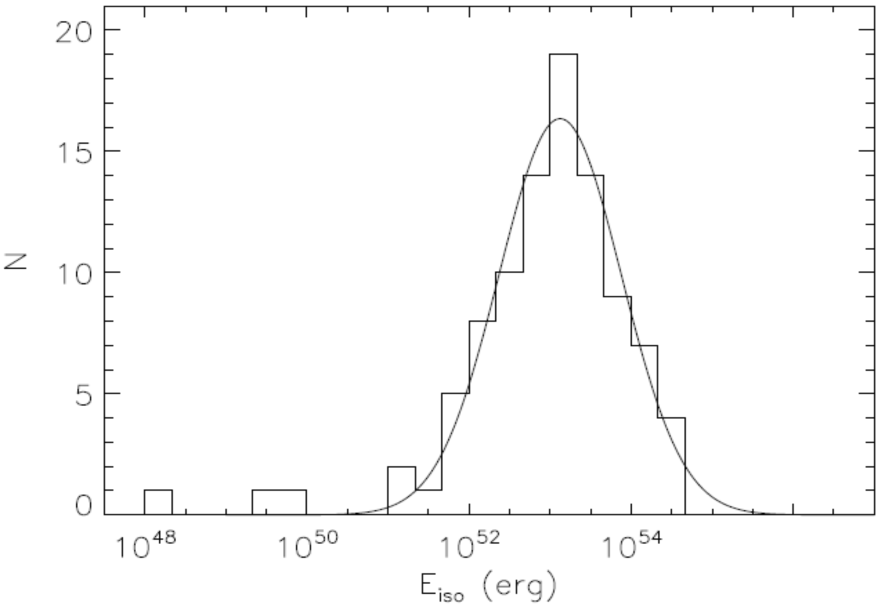


Are Gamma-Ray Bursts standard candles ?

- all GRBs with measured redshift (~320, including a few short GRBs) lie at cosmological distances **(z = 0.033 – ~9.3**) (except for the peculiar GRB980425, z=0.0085)
- isotropic **luminosities and radiated energy are huge**, can be detected up to very high z
- no dust extinction problems; z distribution much beyond SN Ia **but… GRBs are not standard candles (unfortunately)**



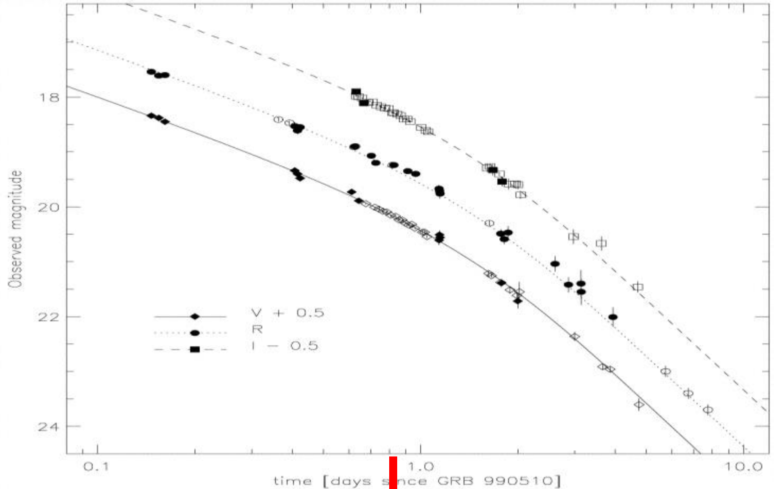
Jakobsson et al., 2010



Amati, 2009

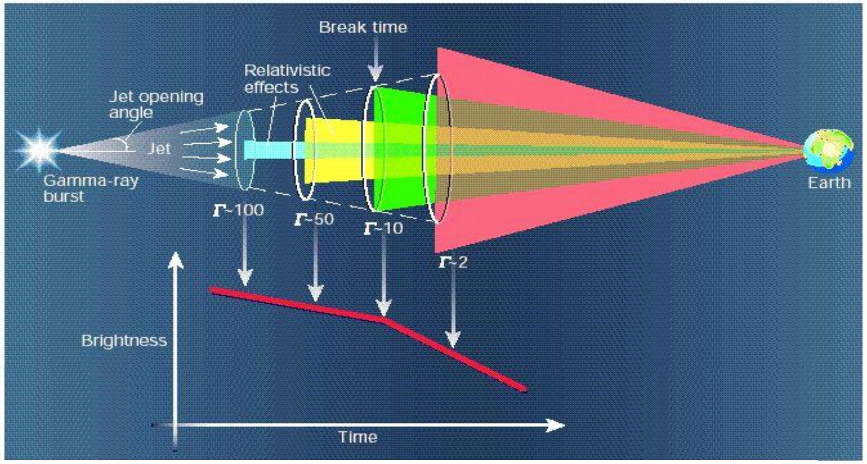
- jet angles, derived from break time of optical afterglow light curve by assuming standard afterglow model, are of the order of few degrees
- the collimation-corrected radiated energy spans the range ~5×10^{49} – 5×10^{52} erg

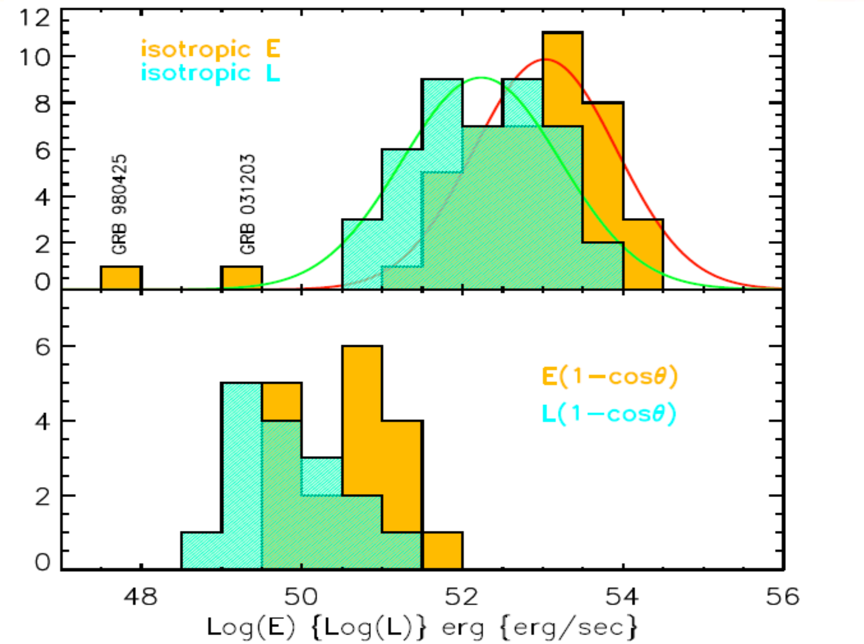
-> more clustered but still not standard (and jet angle estimates very unfirm)



$$\theta = 0.09 \left(\frac{t_{jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\gamma,iso,52}}\right)^{1/8}$$

$$E_\gamma = (1-\cos\theta)E_{\gamma,iso}.$$



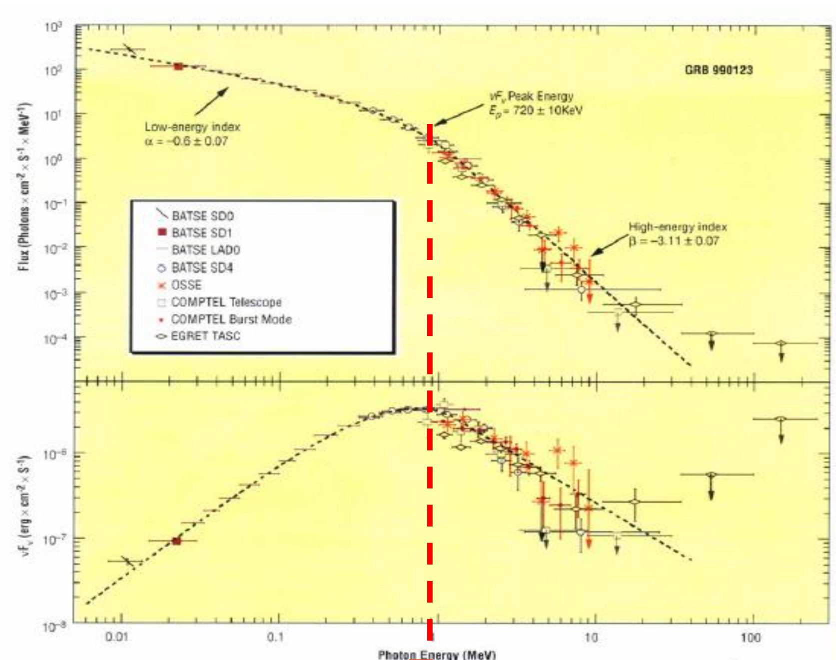


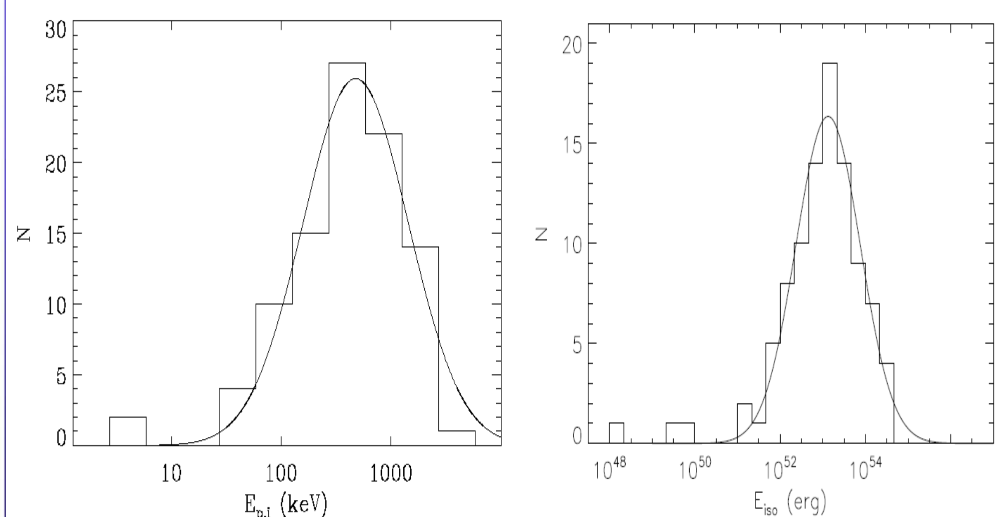
The Ep,i – "intensity" correlation

- GRB νFν spectra typically show a peak at a characteristic photon energy E_p
- **measured spectrum + measured redshift -> intrinsic peak enery and radiated energy**

$$E_{p,i} = E_p \times (1 + z)$$

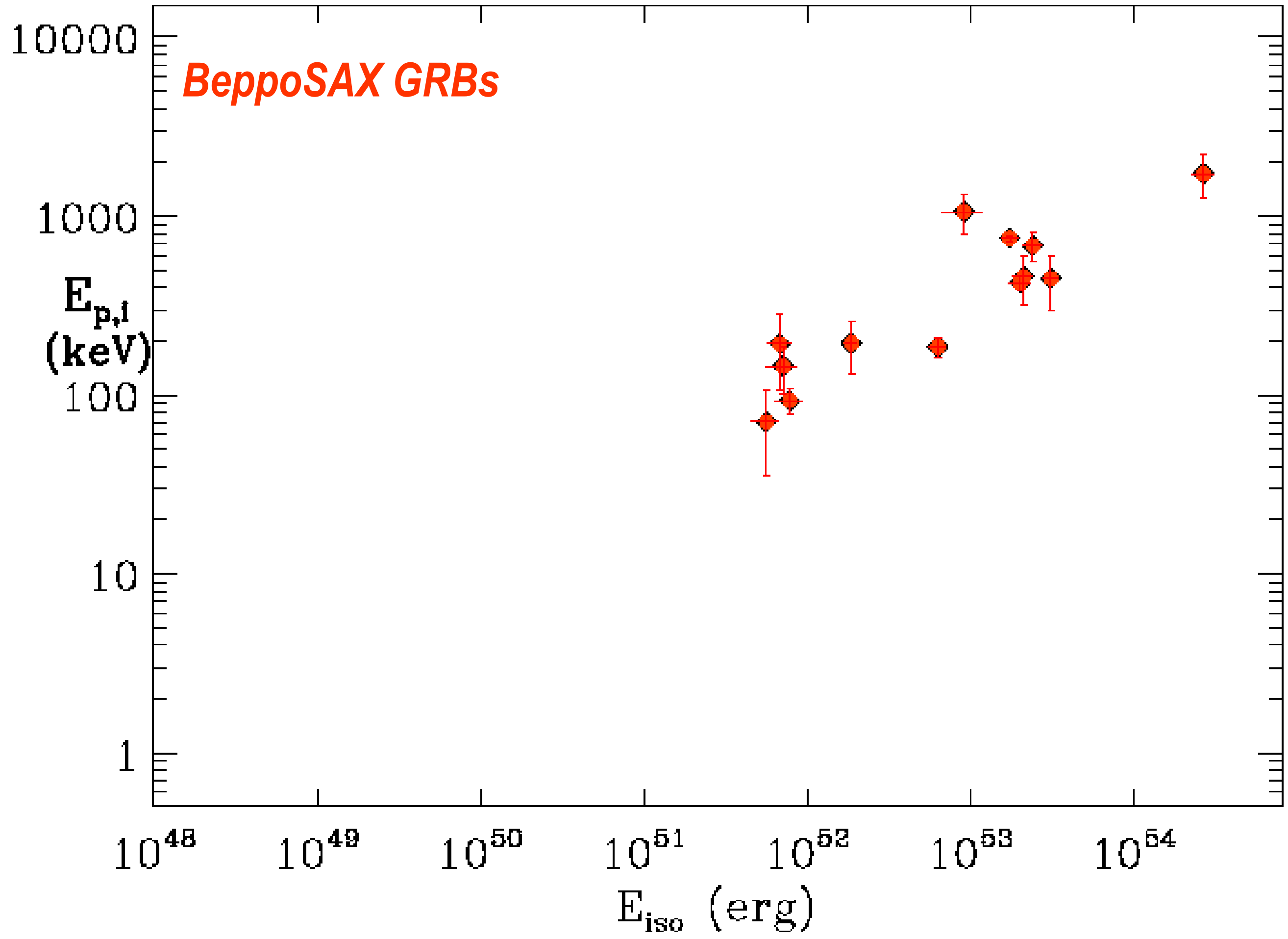
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\, N(E)\, dE \quad \text{erg}$$





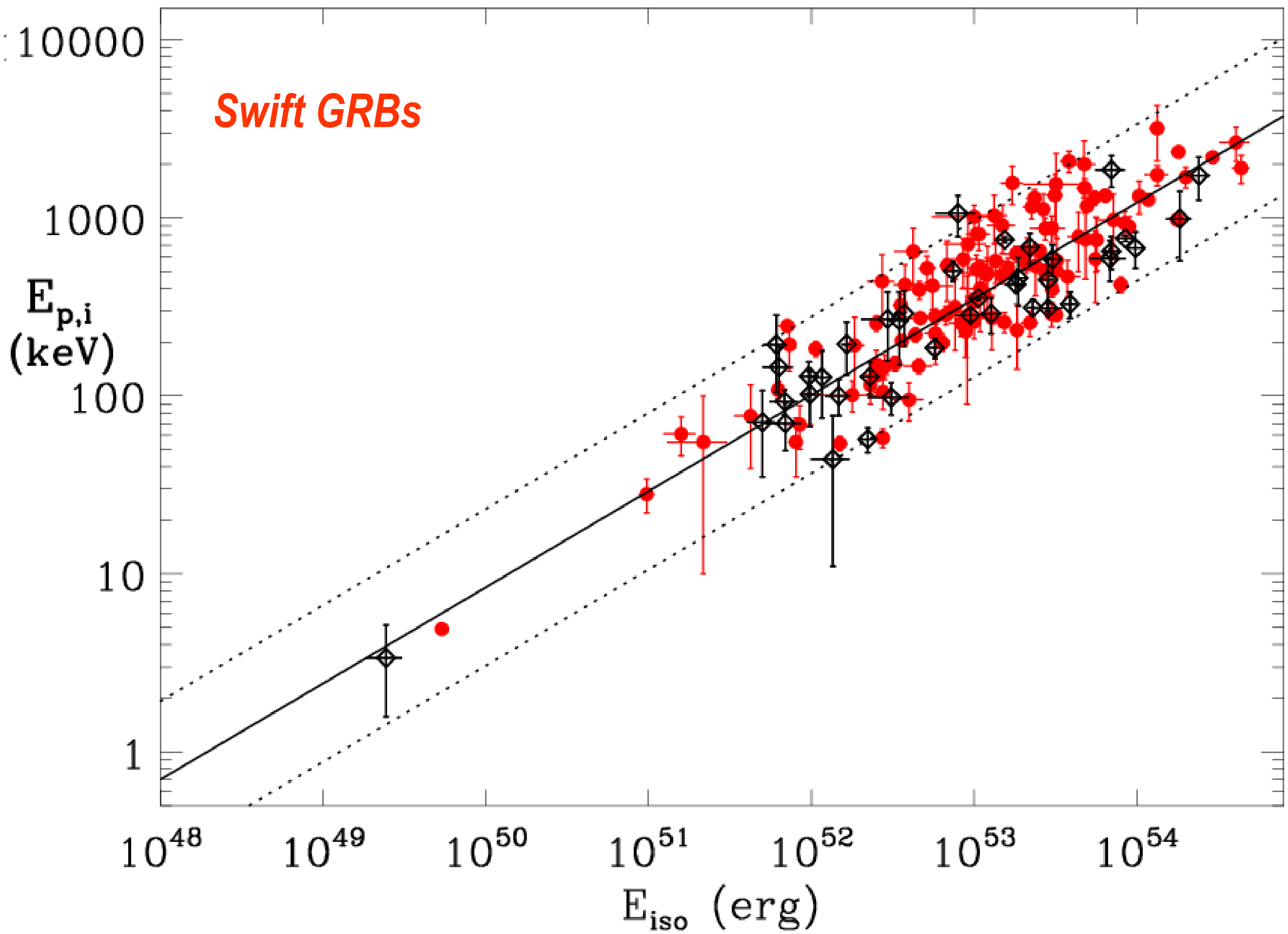
Amati (2009)

➢ Amati et al. (A&A 2002): significant correlation between Ep,i and Eiso found based on a small sample of BeppoSAX GRBs with known redshift

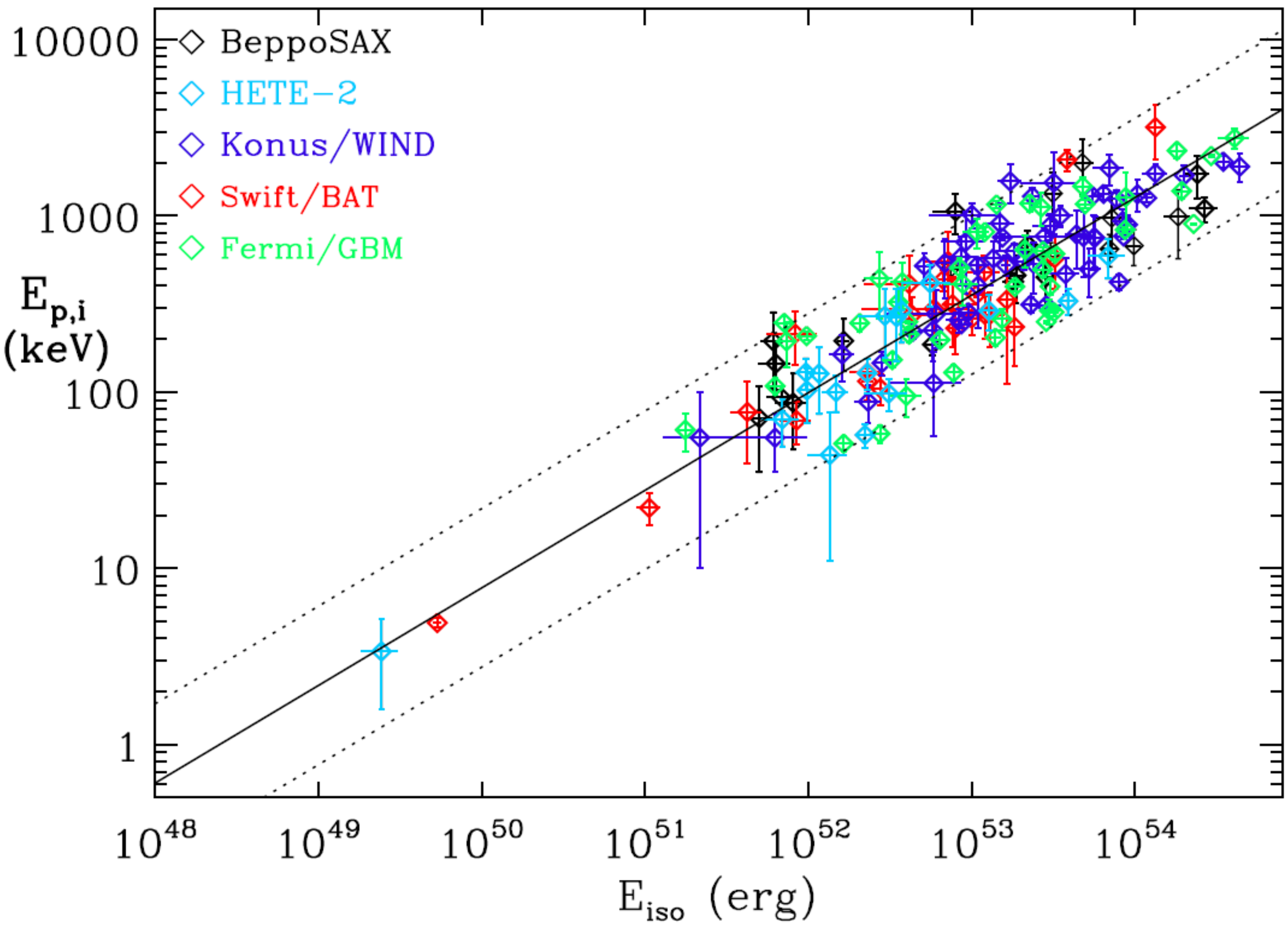


➢ Ep,i – Eiso correlation for GRBs with known redshift confirmed and extended by measurements of ALL other GRB detectors with spectral capabilities

162 long GRBs as of June 2013



- Amati, Frontera & Guidorzi (2009), Amati & Della Valle (2013): the normalization of the correlation varies only marginally **using GRBs with known redshift** measured by individual instruments with different sensitivities and energy bands



Amati & Della Valle 2013

"Standardizing" GRB with the Ep,i - Intensity correlation

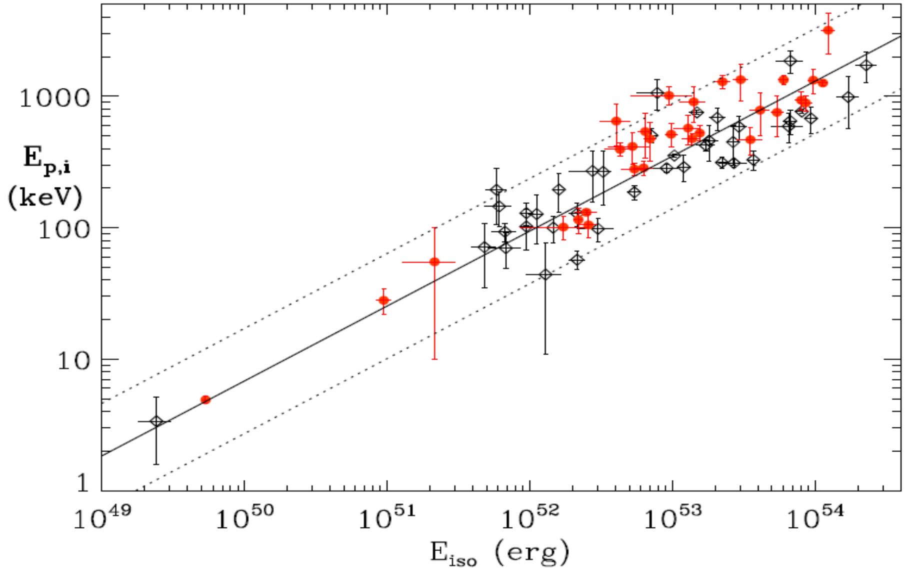
$E_{p,i} = E_{p,obs} \times (1 + z)$

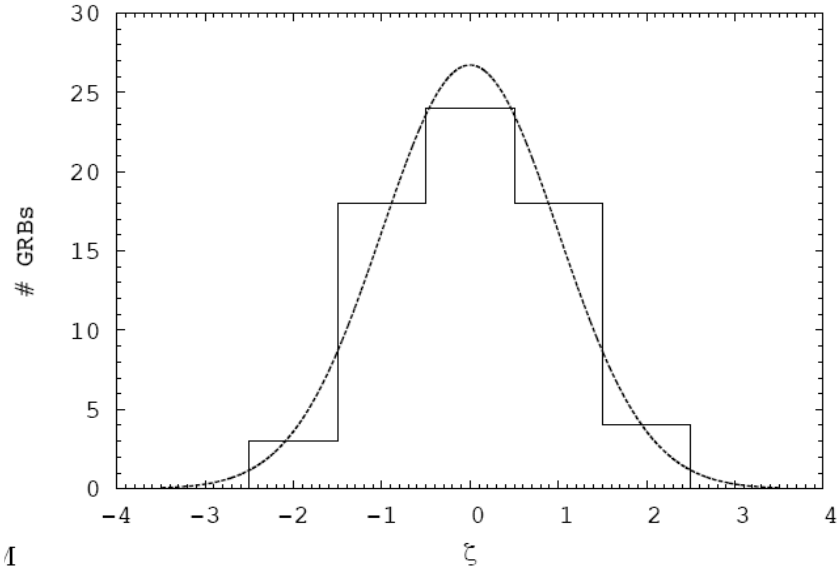
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\, N(E)\, dE \quad \text{erg}$$

→ $D_l = D_l(z, H_0, \Omega_M, \Omega_\Lambda, \ldots)$

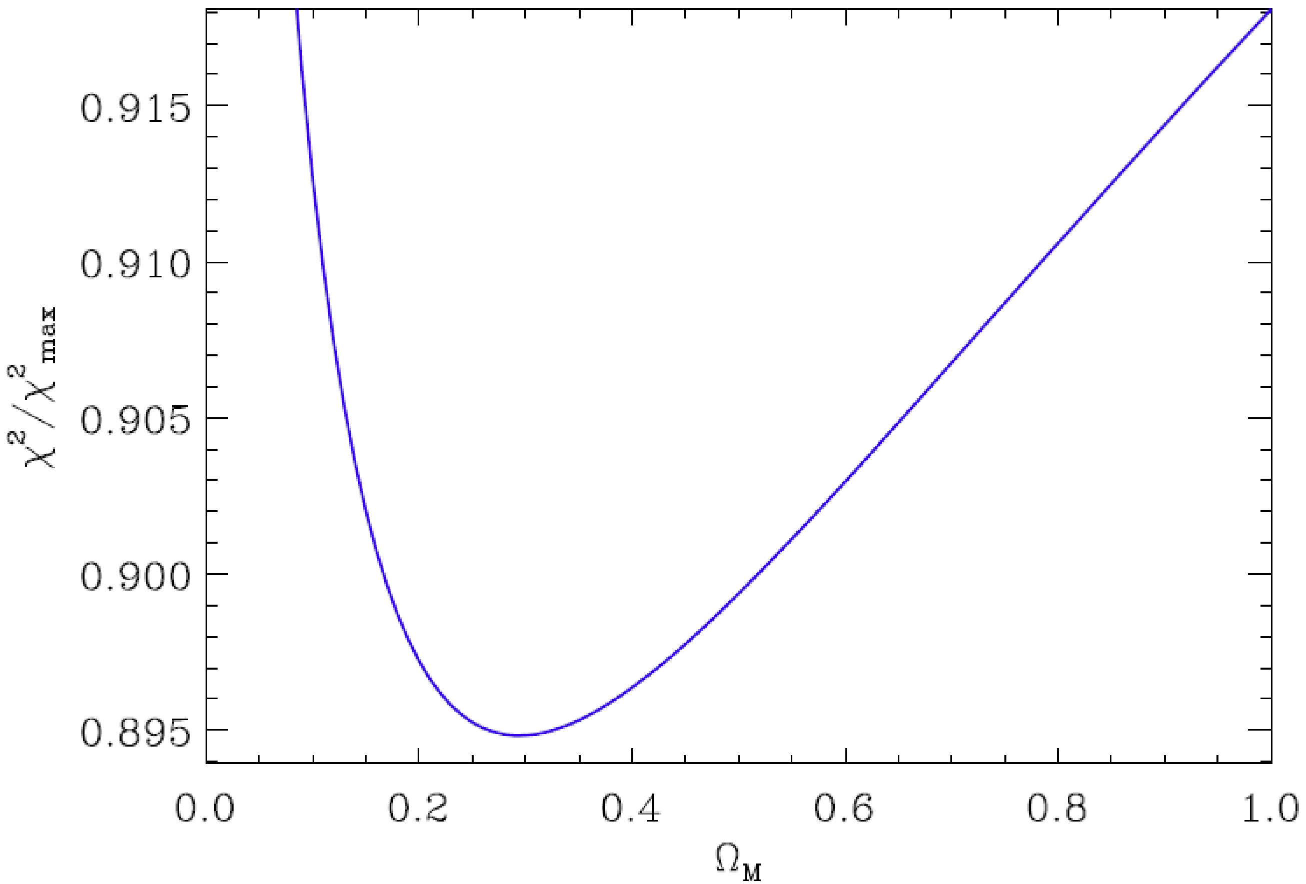
- not enough low-z GRBs for cosmology-independent calibration -> circularity is avoided by fitting simultaneously the parameters of the correlation and cosmological parameters

- does the extrinsic scatter and goodness of fit of the Ep,i-Eiso correlation vary with the cosmological parameters used to compute Eiso ?





- a fraction of the extrinsic scatter of the $E_{p,i}$-E_{iso} correlation is indeed due to the cosmological parameters used to compute E_{iso}
- Evidence, independent on SN Ia or other cosmological probes, that, if we are in a flat ΛCDM universe , Ω_M is lower than 1 and around 0.3



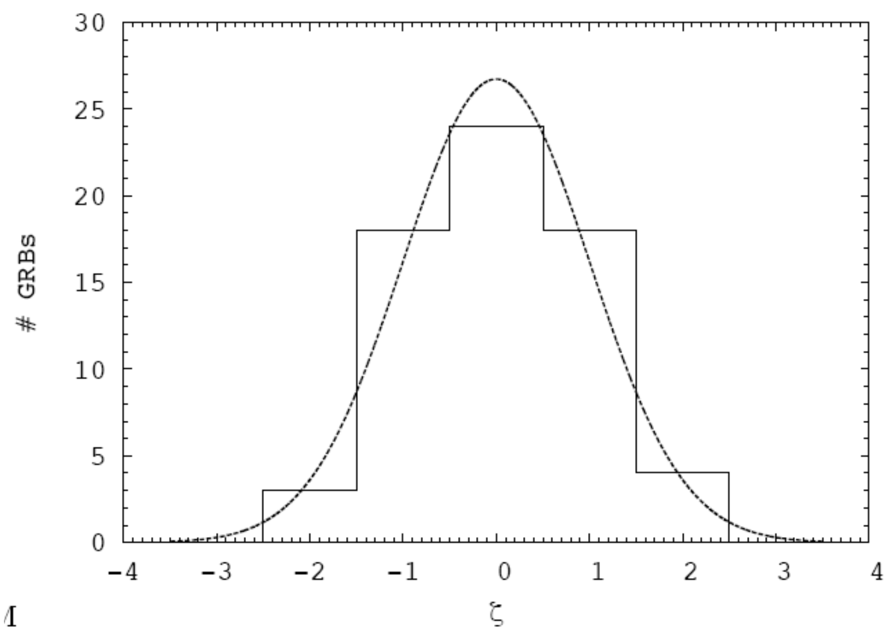
Amati et al. 2008, Amati & Della Valle 2013

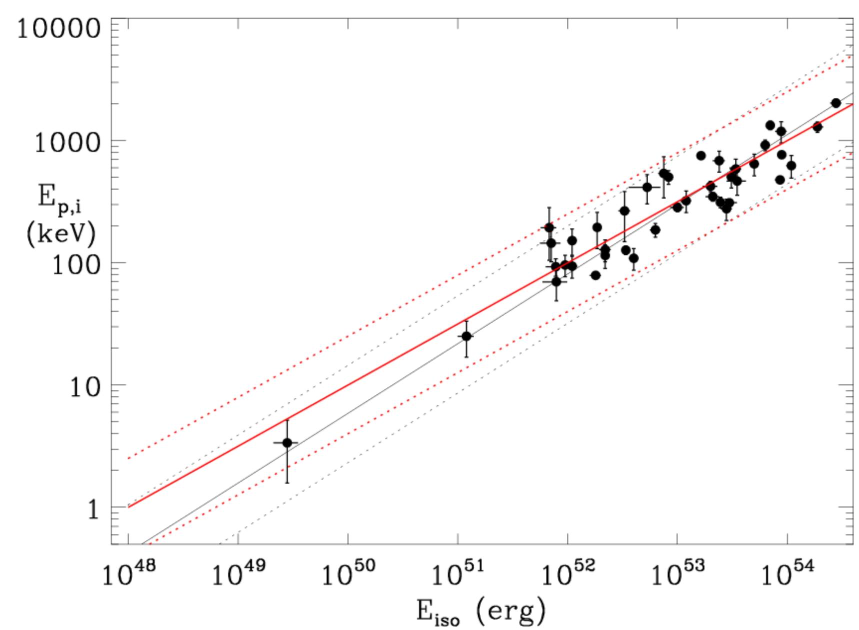
➢ **strong correlation but significant dispersion** of the data around the best-fit power-law; distribution of residuals can be fit with a Gaussian with σ(logEp,i) ~ 0.2

➢ the "extra-statistical scatter" of the data can be quantified by performing a fit whith a max likelihood method (D'Agostini 2005) which accounts for sample variance and the uncertainties on both X and Y quantities

$$L(m, c, \sigma_v\,; \boldsymbol{x}, \boldsymbol{y}) = \frac{1}{2}\sum_i \log\left(\sigma_v^2 + \sigma_{y_i}^2 + m^2\,\sigma_{x_i}^2\right) + \frac{1}{2}\sum_i \frac{(y_i - m\,x_i - c)^2}{\sigma_v^2 + \sigma_{y_i}^2 + m^2\,\sigma_{x_i}^2}$$

➢ with this method Amati et al. (2008, 2009) found an extrinsic scatter σ_{int}(logEp,i) ~ 0.2 and index and normalization t ~0.5 and ~100, respectively

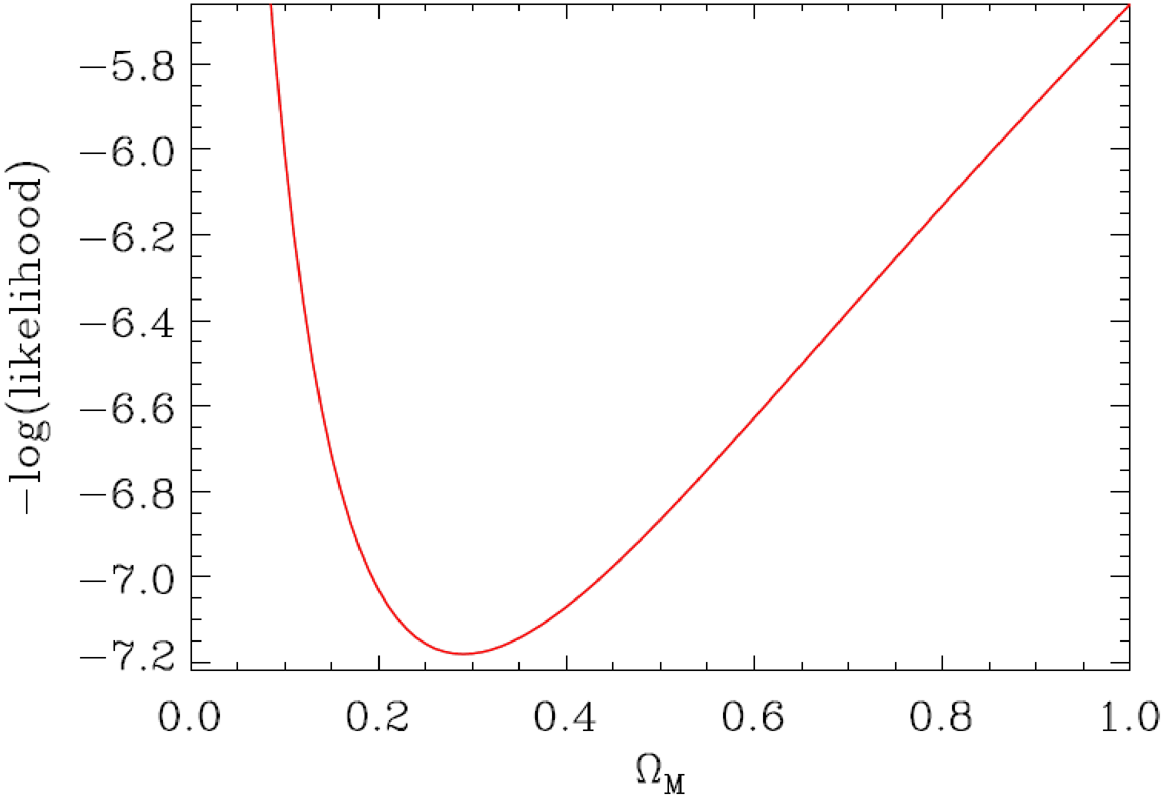




- By using a maximum likelihood method the extrinsic scatter can be parametrized and quantified (e.g., Reichart 2001)

$$L(m, c, \sigma_v ; \boldsymbol{x}, \boldsymbol{y}) = \frac{1}{2}\sum_i \log\left(\sigma_v^2 + \sigma_{y_i}^2 + m^2\,\sigma_{x_i}^2\right) + \frac{1}{2}\sum_i \frac{(y_i - m\,x_i - c)^2}{\sigma_v^2 + \sigma_{y_i}^2 + m^2\,\sigma_{x_i}^2}$$

- Ω_M could be constrained (Amati+08, 70 GRBs) to 0.04-0.43 (68%) and 0.02-0.71 (90%) for a flat ΛCDM universe (Ω_M = 1 excluded at 99.9% c.l.)

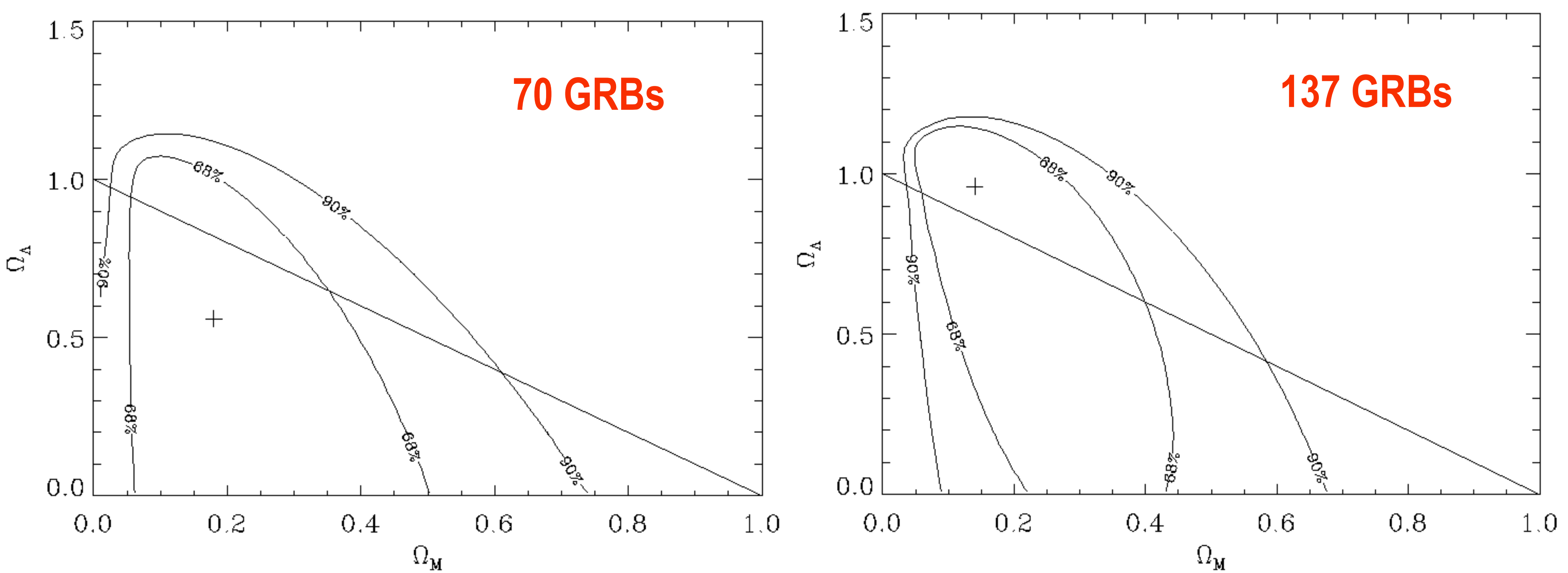


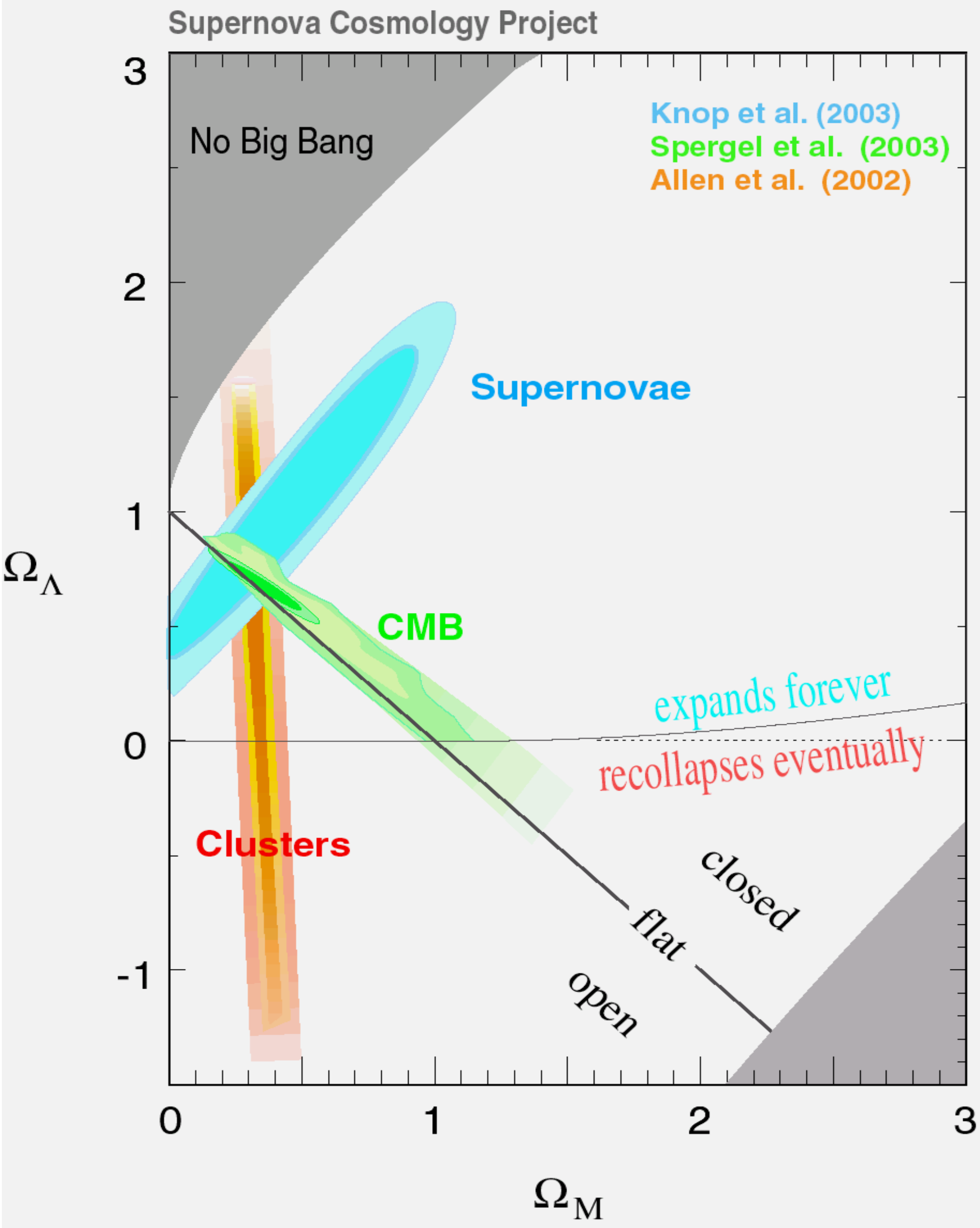
Amati et al. 2008, 2013

- analysis of updated sample of 137 GRBs (Amati+12) shows significant improvements w/r to the sample of 70 GRBs of Amati et al. (2008)

- this evidence supports the reliability and perspectives of the use of the Ep,i – Eiso correlation for the estimate of cosmological parameters

Ωm (flat universe)	best	*68%*	*90%*
70 GRBs (Amati+ 08)	0.27	0.09 – 0.65	0.05 – 0.89
137 GRBs (Amati+ 12)	0.29	0.12 – 0.54	0.08 – 0.79




Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
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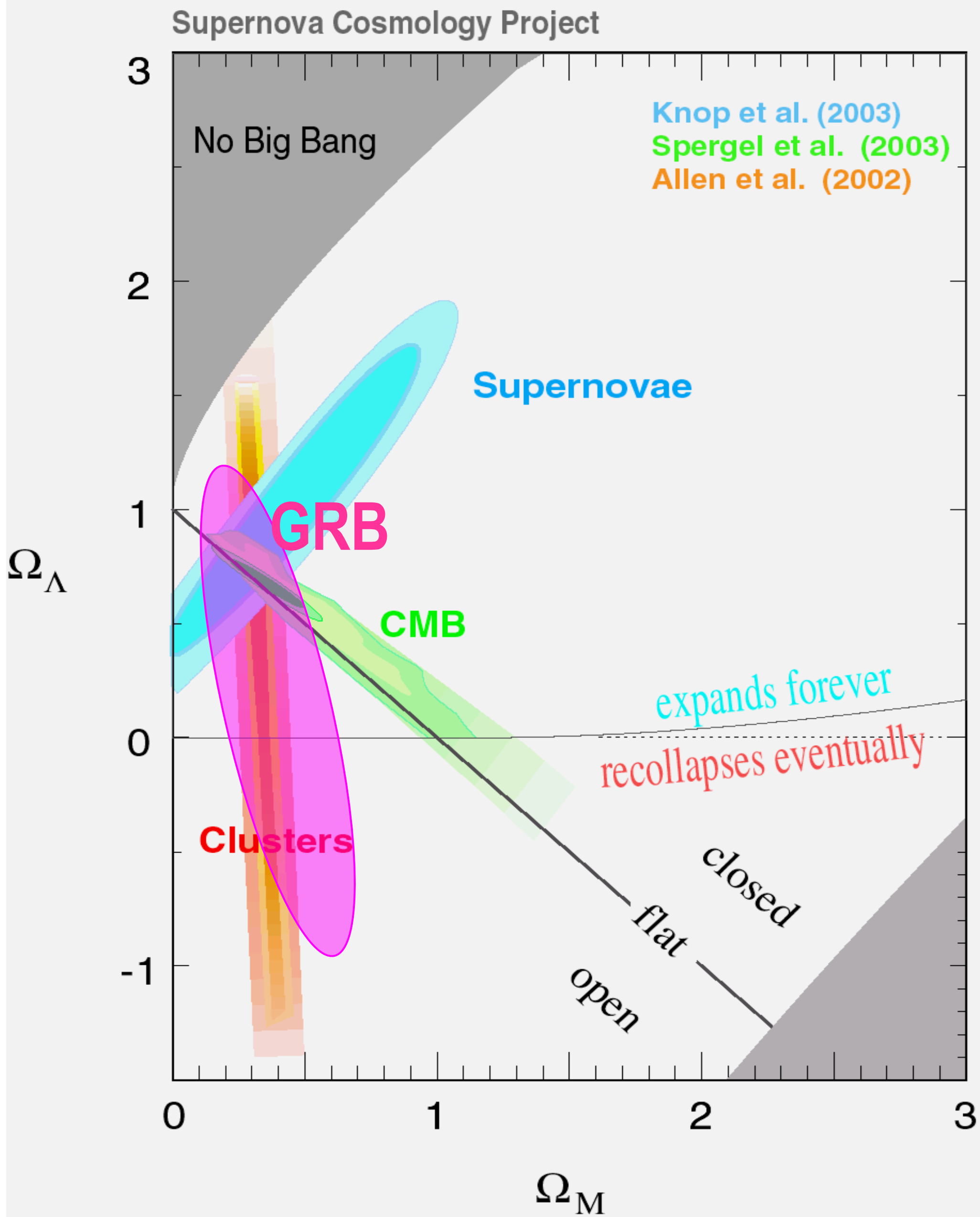
Ω_M



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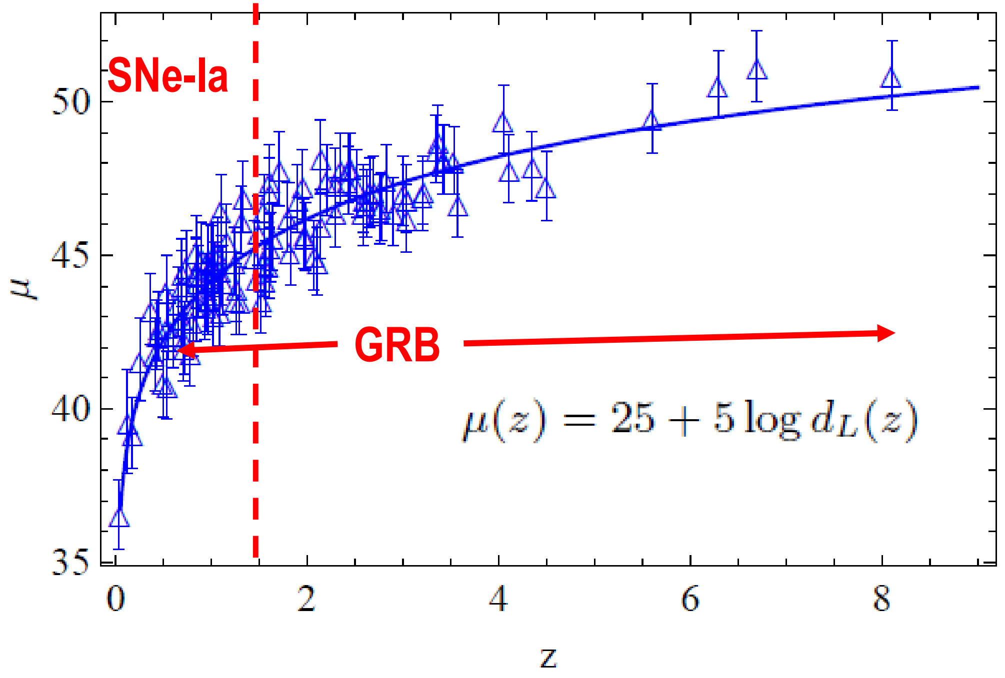
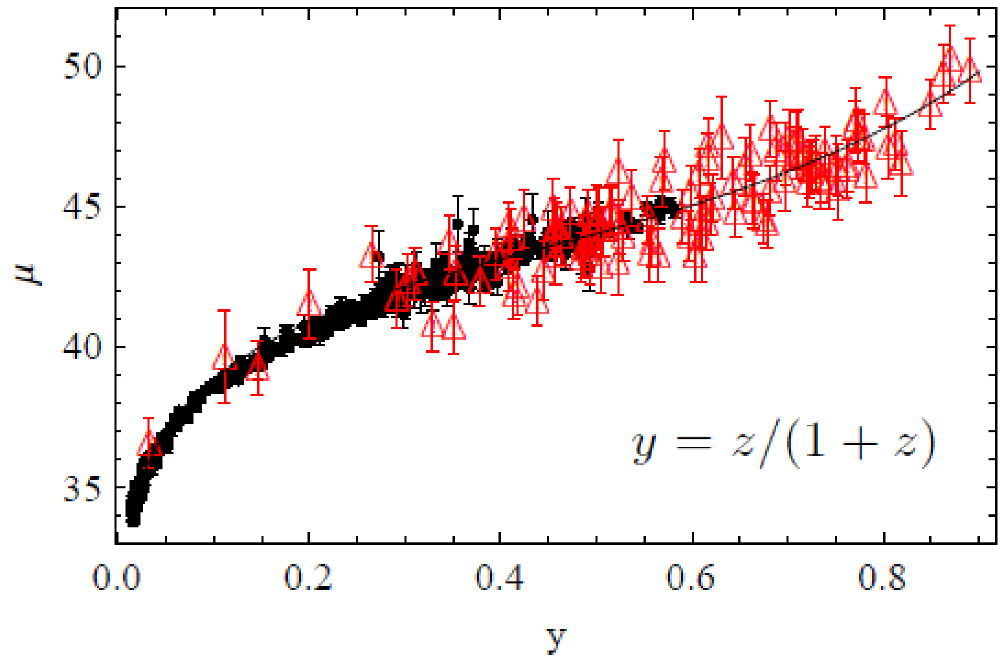
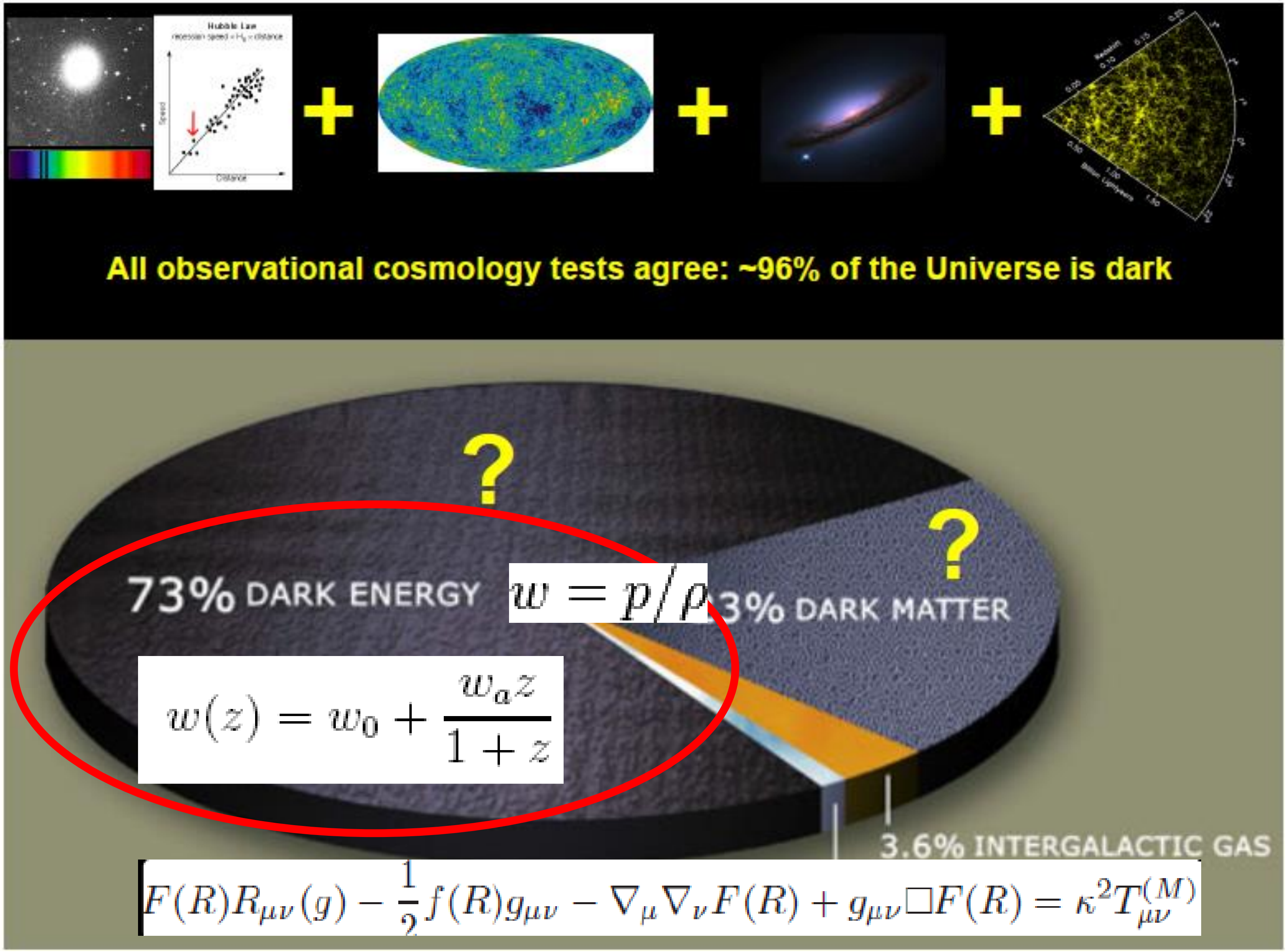
➢ The GRB Hubble diagram extends to much higher z w/r to SNe Ia

➢ The GRB Hubble diagram is consistent with SNe Ia Hubble diagram at low redshifts: reliability





Perspectives



$$w = p/\rho$$

$$w(z) = w_0 + \frac{w_a z}{1+z}$$

$$F(R)R_{\mu\nu}(g) - \frac{1}{2}f(R)g_{\mu\nu} - \nabla_\mu \nabla_\nu F(R) + g_{\mu\nu}\Box F(R) = \kappa^2 T^{(M)}_{\mu\nu}$$

❑ Enlargement of the sample (+ self-calibration)

- the simulatenous operation of Swift, Fermi/GBM, Konus-WIND is allowing an increase of the useful sample (z + Ep) at a rate of 20 GRB/year, providing an increasing accuracy in the estimate of cosmological parameters
- future GRB experiments (e.g., SVOM) and more investigations (in particular: reliable estimates of jet angles and self-calibration) will improve the significance and reliability of the results and allow to go beyond SN Ia cosmology (e.g. investigation of dark energy)

GRB #	Ω_M (flat)	w_0 (flat, Ω_M=0.3, w_a=0.5)
70 (real) GRBs (Amati+ 08)	$0.27^{+0.38}_{-0.18}$	<-0.3 (90%)
156 (real) GRBs (Amati+ 13)	$0.29^{+0.28}_{-0.15}$	$-0.9^{+0.4}_{-1.5}$
250 (156 real + 94 simulated) GRBs	$0.29^{+0.16}_{-0.12}$	$-0.9^{+0.3}_{-1.1}$
500 (156 real + 344 simulated) GRBs	$0.29^{+0.10}_{-0.09}$	$-0.9^{+0.2}_{-0.8}$
156 (real) GRBs, calibration	$0.30^{+0.06}_{-0.06}$	$-1.1^{+0.25}_{-0.30}$
250 (156 real + 94 simulated) GRBs, calibration	$0.30^{+0.04}_{-0.05}$	$-1.1^{+0.20}_{-0.20}$
500 (156 real + 344 simulated) GRBs, calibration	$0.30^{+0.03}_{-0.03}$	$-1.1^{+0.12}_{-0.15}$

$$w(z) = w_0 + \frac{w_a z}{1+z}$$

Amati & Della Valle 2013

❑ Enlargement of the sample (+ self-calibration + reliable jet angles)

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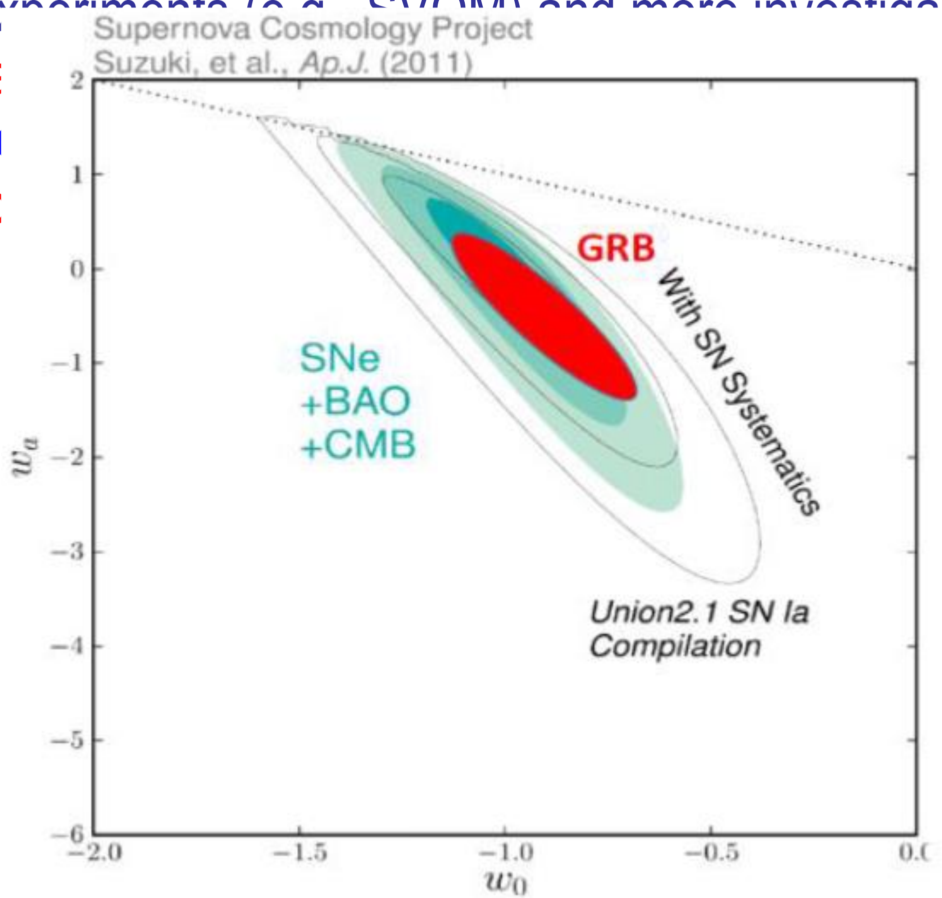


$$w(z) = w_0 + \frac{w_a z}{1+z}$$

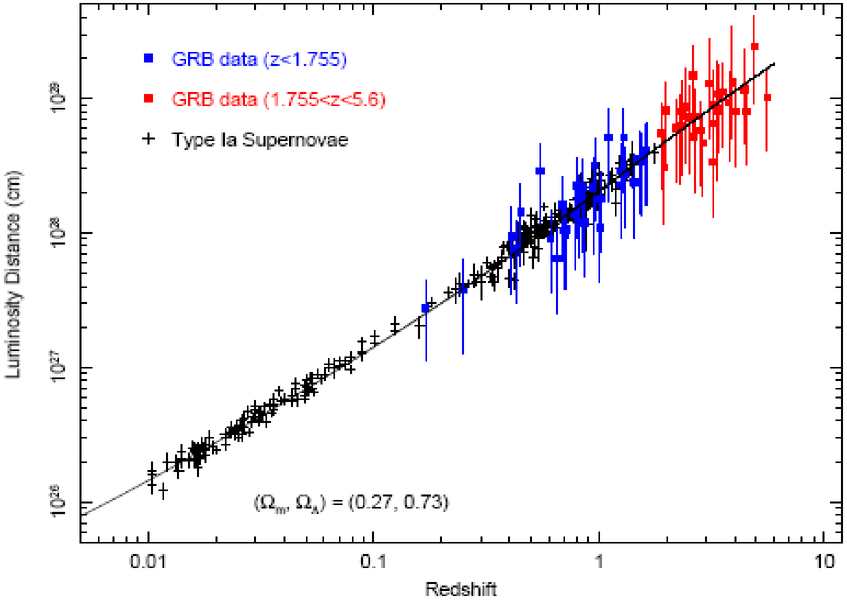
Amati et al. 2015

❑ Calibrating the Ep,i – Eiso correlation with SN Ia

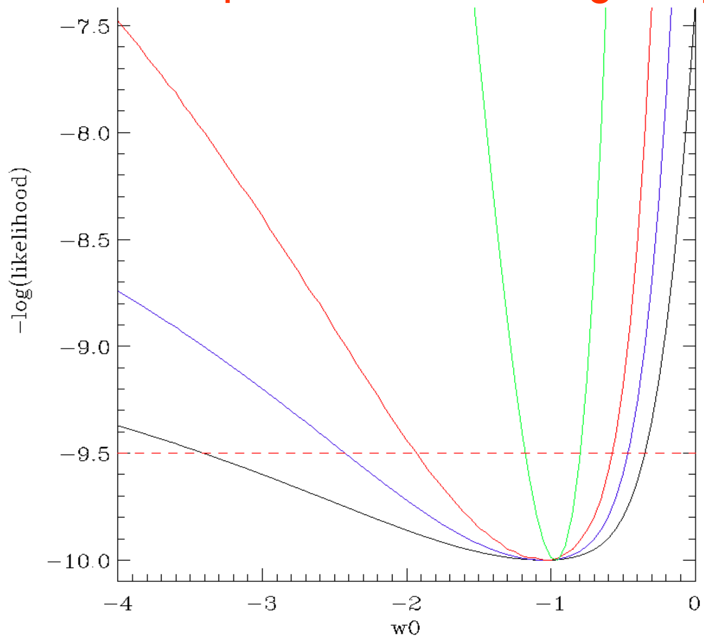
➢ Several authors (e.g., Kodama et al., 2008; Liang et al., 2008, Li et al. 2008, Demianski et al. 2010-2011, Capozziello et al. 2010, Wang et al. 2012) are investigating the calibration of the Ep,i - Eiso correlation at z < 1.7 by using the luminosity distance – redshift relation derived for SN Ia

➢ The aim is to extend the SN Ia Hubble diagram up to redshifts at which the luminosity distance is more sensitive to dark energy properties and evolution

➢ Drawback: with this method GRB are no more an indipendent cosmological probe



Kodama et al. 2008



Amati & Della Valle 13, Amati+ 13

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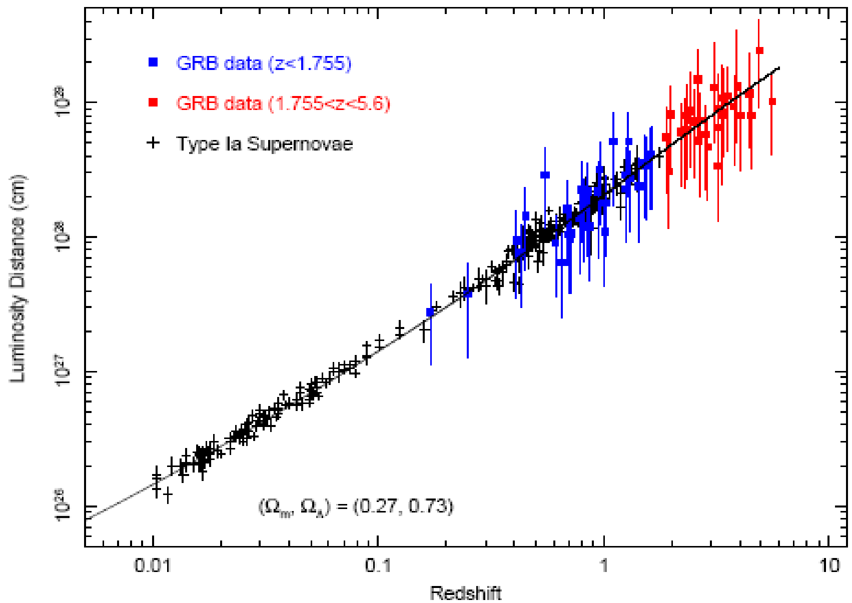

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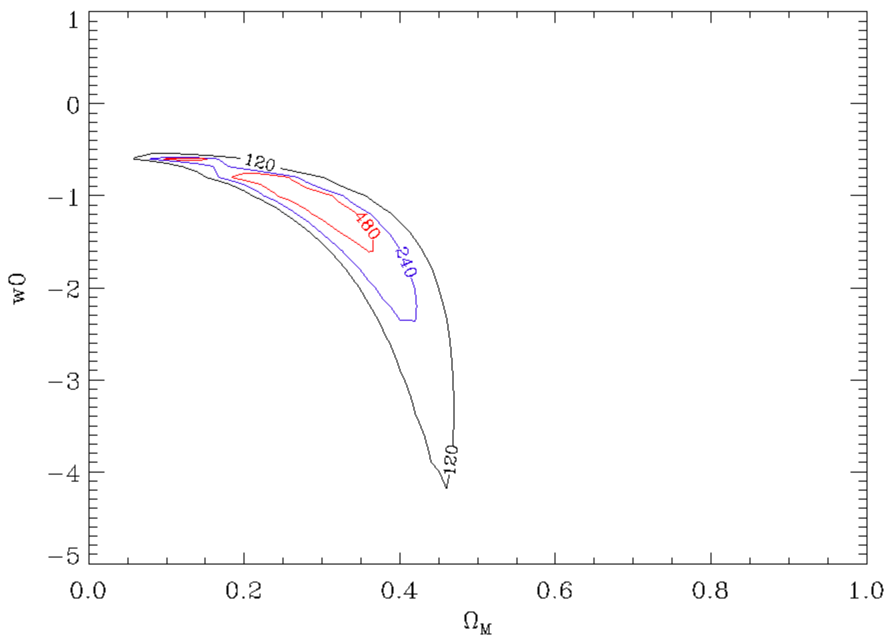

Amati & Della Valle 2013, Amati+ 2013

Conclusions

- Given their huge radiated energies and redshift distribution extending from ~ 0.1 up to > 9, GRBs, besides being the most relativistic sources in the Universe, are potentially a very powerful cosmological probe, complementary to other probes (e.g., SN Ia, clusters, BAO)

- The Ep,i – intensity correlation is a promising tool for "standardizing" GRBs for measuring cosmological parameters: recent analyses provide already evidence, independent on , e.g., SN Ia, that if we live in a flat ΛCDM universe, Ωm is ~ 0.3, consistent with "standard" cosmology)

- **Future GRB experiments and investigations will allow to get clues on "dark energy" EOS (cosmological constant vs "quintessence", etc.) and its evolution, and testing alternative, e.g., f(R), cosmologies.**