Measuring cosmological parameters with Gamma-Ray Bursts

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THE X-RAY UNIVERSE 2017

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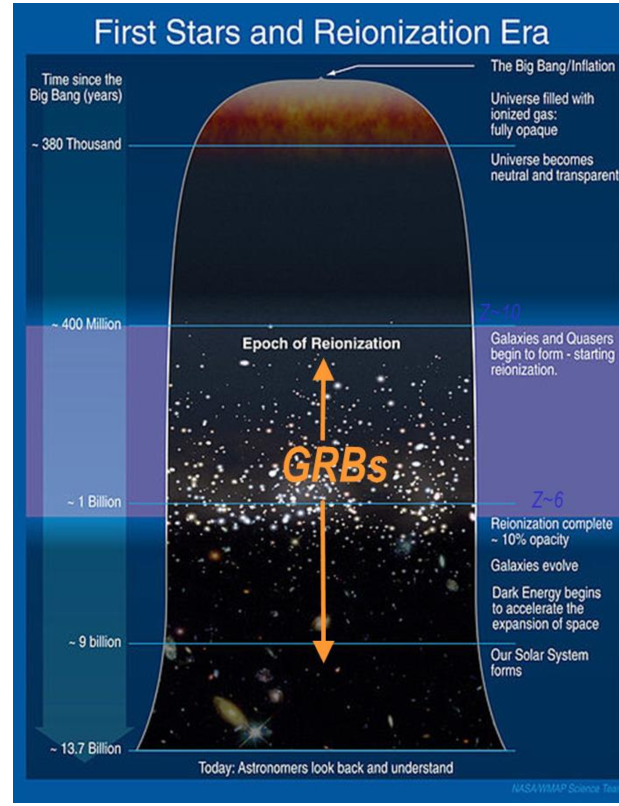
Centro Congressi Frentani, Rome, Italy

Gamma-Ray Bursts are the most luminous and remote phenomena in the Universe, with isotropic-equivalent radiated energies in X-gamma rays up to more than ***10^{54} erg released in a few tens of seconds,*** *association with star-forming regions and a redshift distribution extending to at least* ***z = 9-10****. Thus, they are in principle very powerful tools for cosmology*



a) Investigating the expansion rate and geometry of the Universe, thus getting clues to "dark energy" properties and evolution

b) Exploring the early Universe (re-ionization, first stars, star formation rate and metallicity evolution in the first billion of years) **THESEUS mission concept (see poster P01)**

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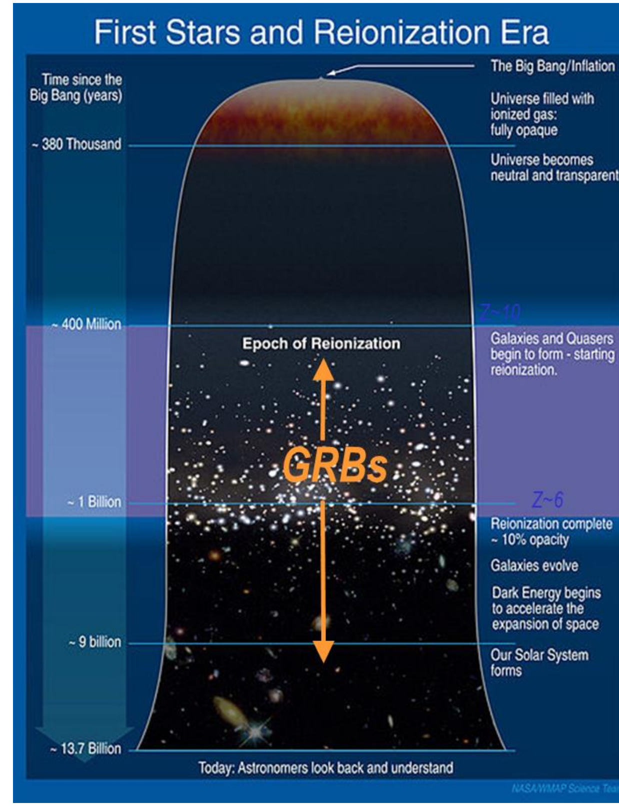

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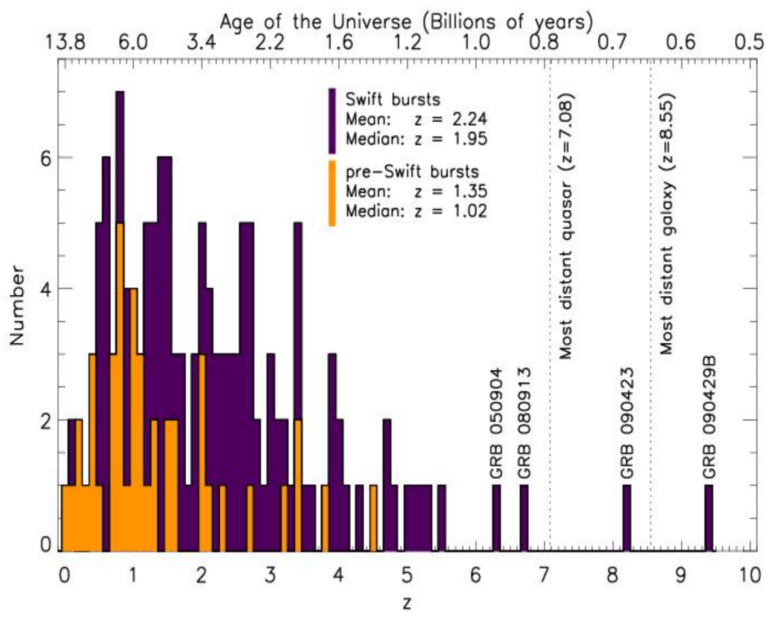
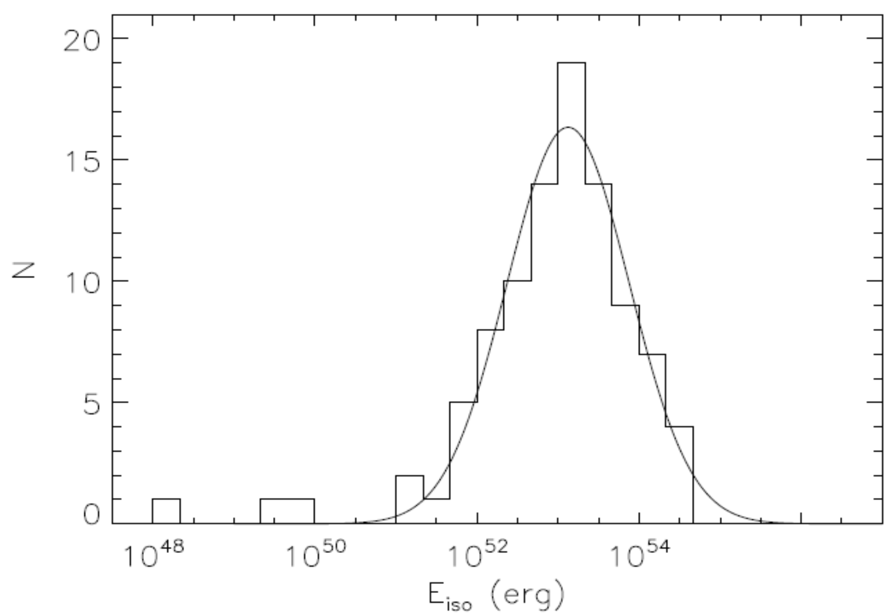
Are Gamma-Ray Bursts standard candles ?

- all GRBs with measured redshift (~400, 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)**



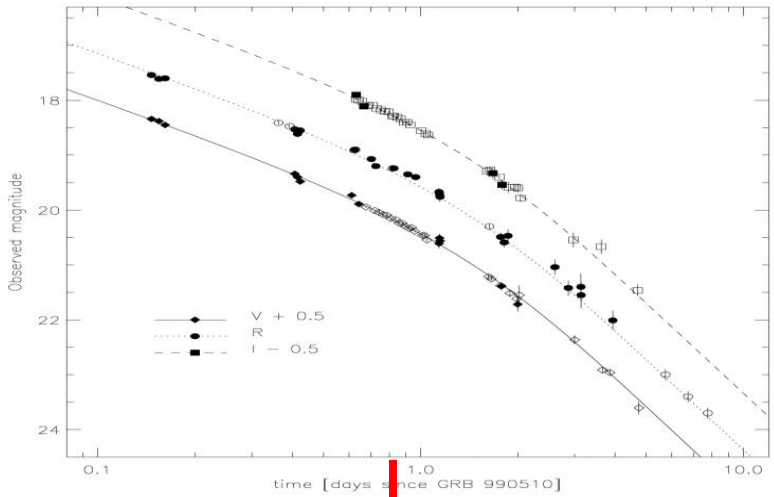
Jakobsson et al., 2010

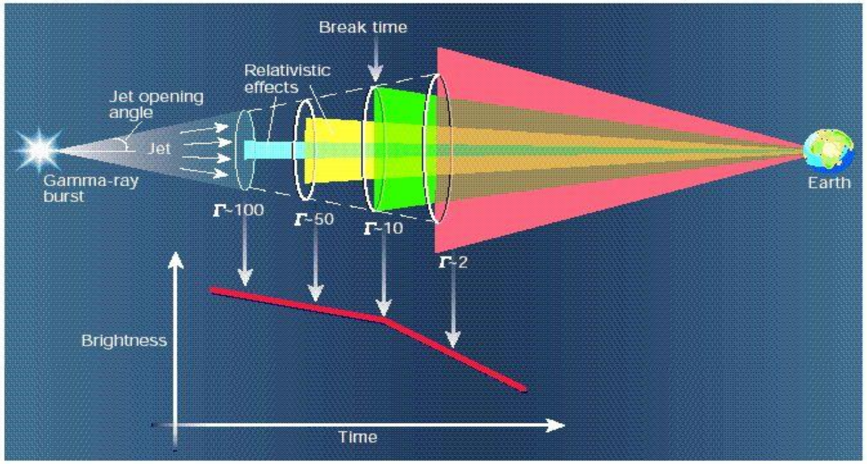


Amati et al. 2009

- 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

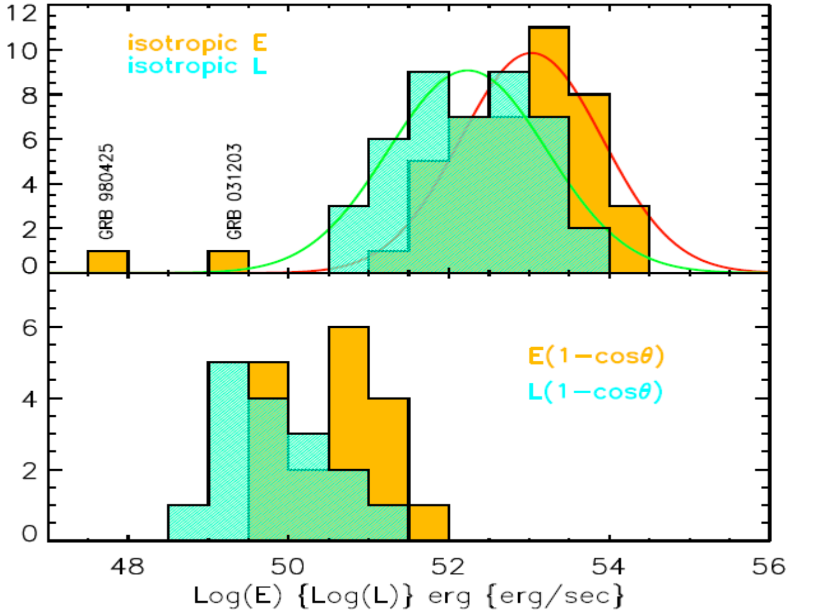
-> more clustered but still not standard (and model dependent, small sample,..)





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

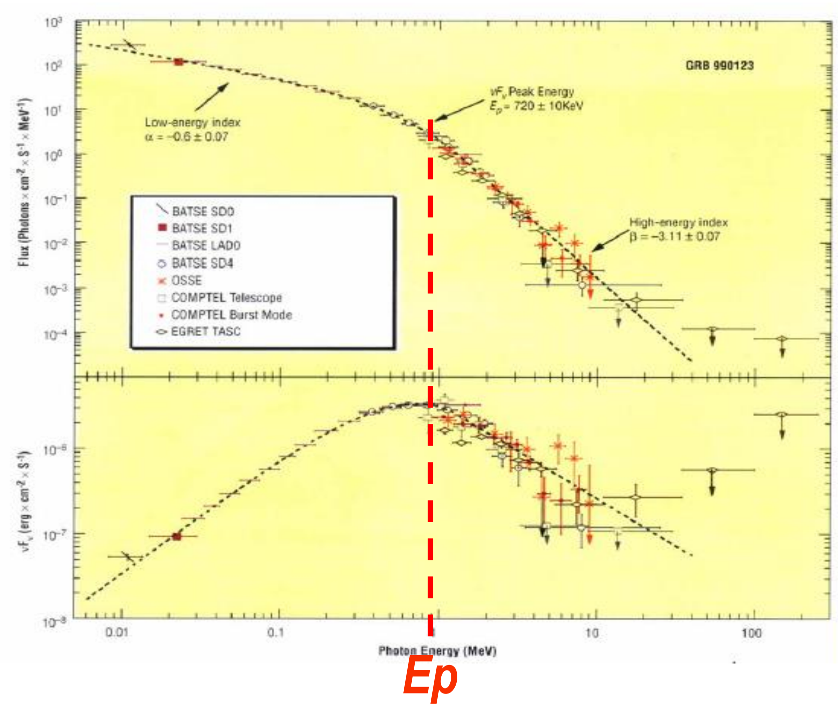
$$E_\gamma = (1-\cos\theta) E_{\gamma,iso}.$$

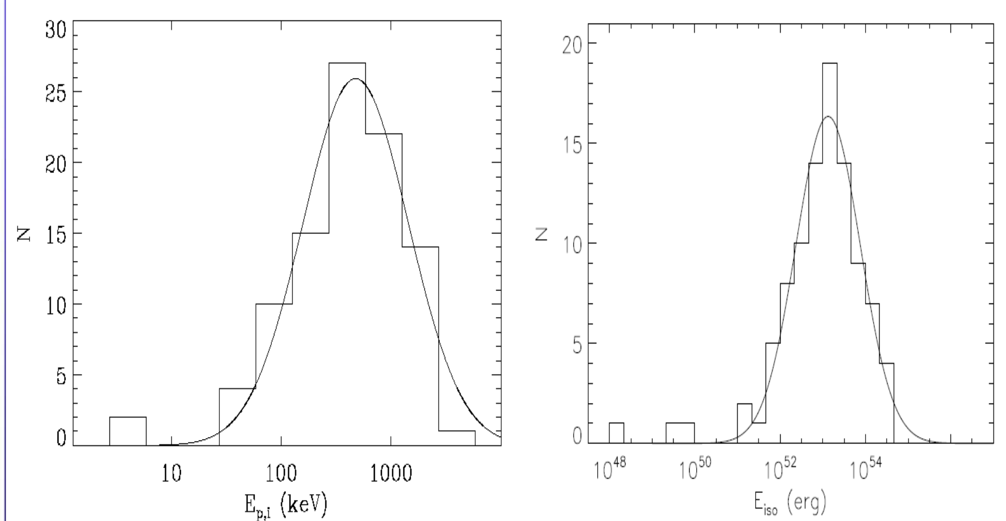


"Standardizing" GRBs: the Ep,i – "intensity" correlation

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

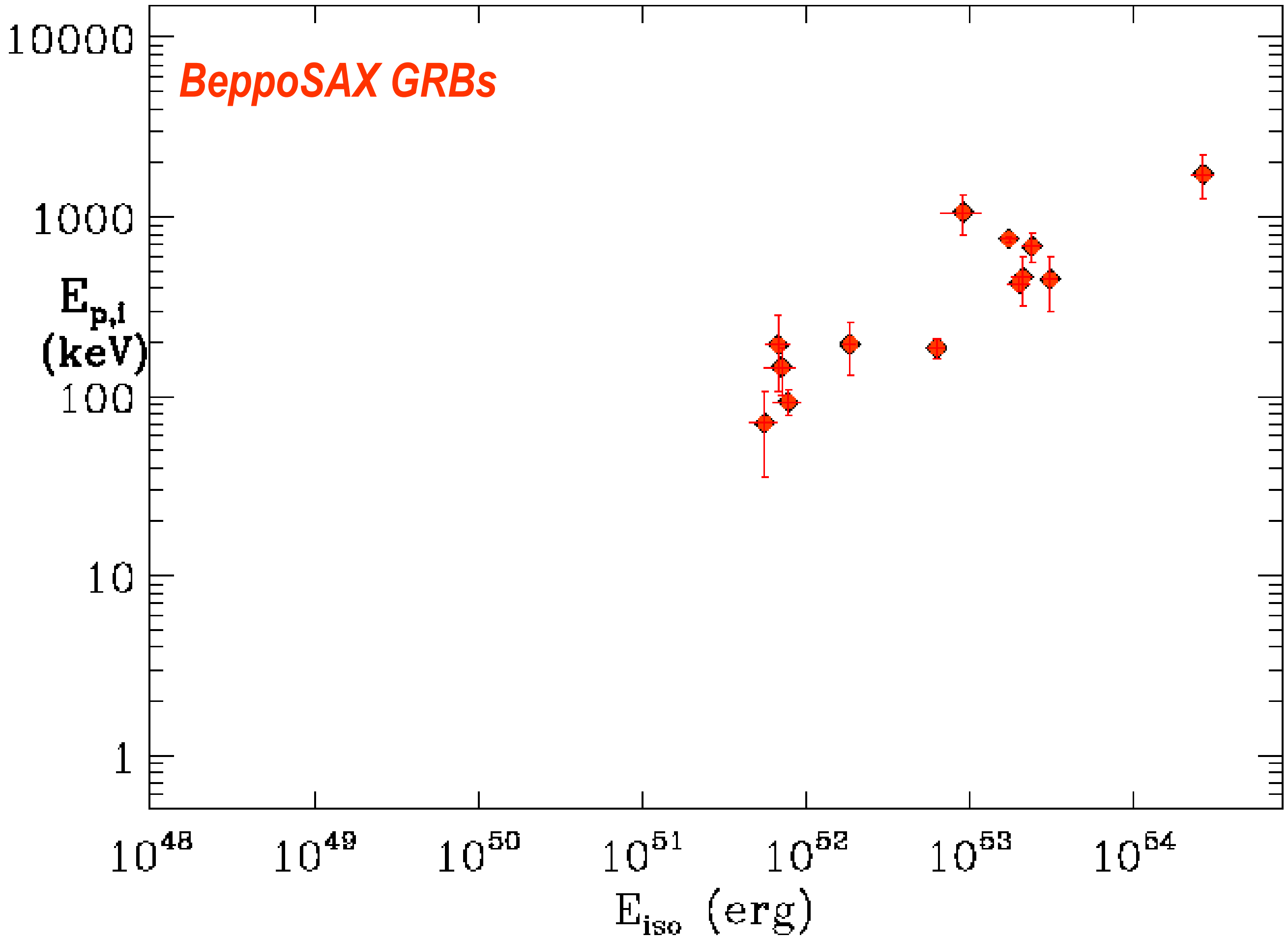
$$E_{p,i} = E_p \times (1 + z) \qquad E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\, N(E)\, dE \ \ \mathrm{erg}$$





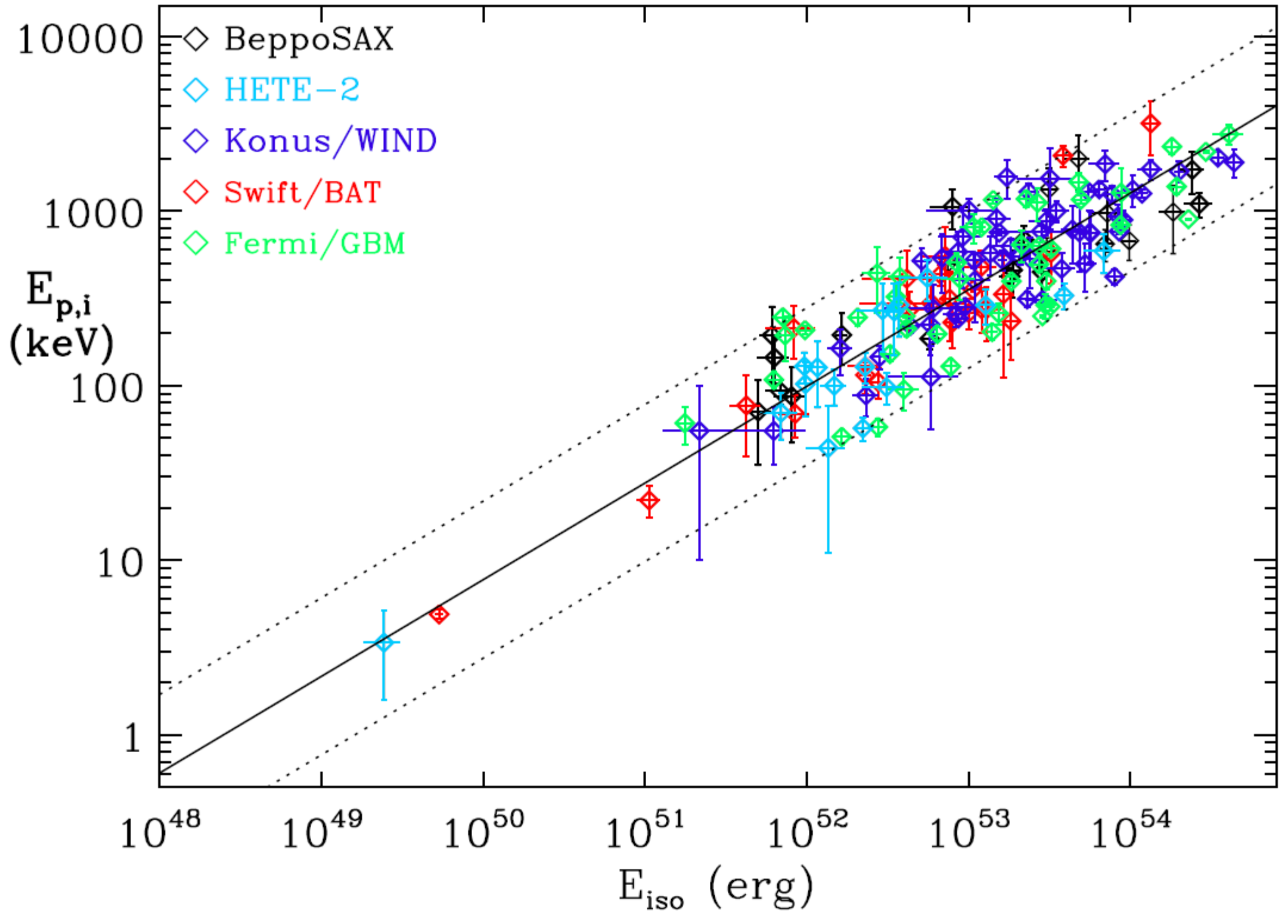
Amati (2009)

➢ 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

193 long GRBs as of 2015

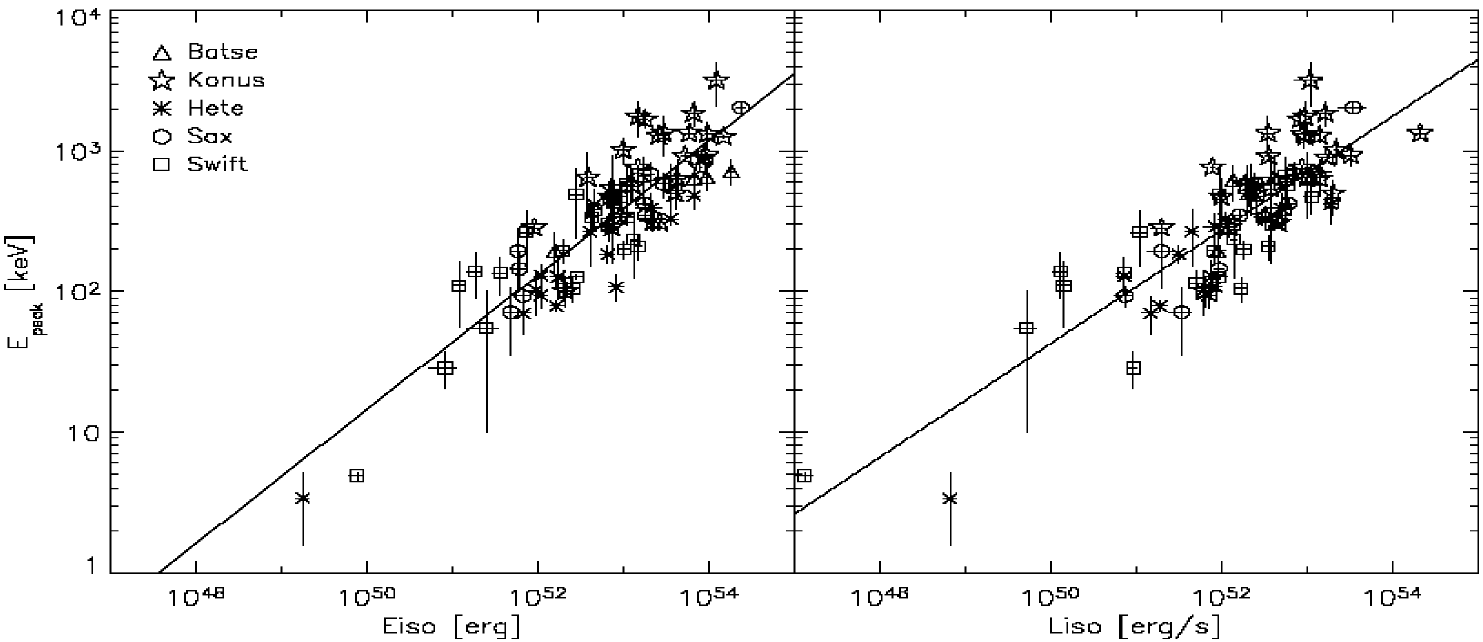


Amati & Della Valle 2013, 2017

- **the correlation holds also when substituting Eiso with Liso** (e.g., Lamb et al. 2004) **or Lpeak,iso** (Yonetoku et al. 2004, Ghirlanda et al., 2005)

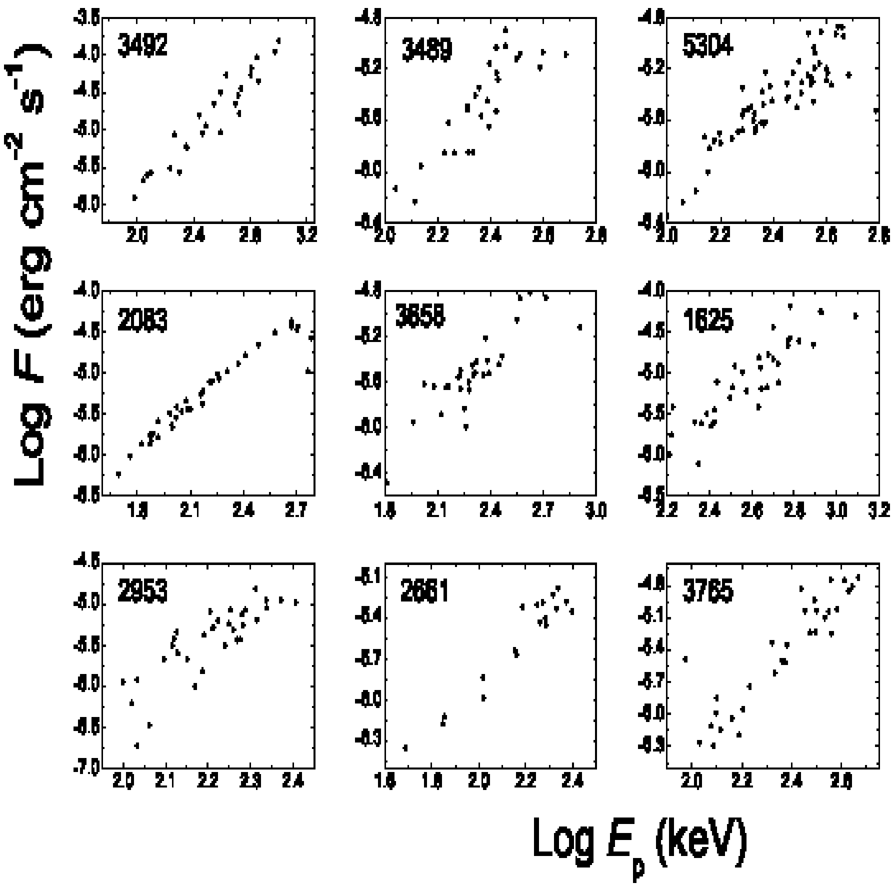
- this is expected because **Liso and Lpeak,iso are strongly correlated with Eiso**

- w/r to Eiso, **Lp,iso is subject to more uncertainties** (e.g., light curves peak at different times in different energy bands; spectral parameters at peak difficult to estimate; which peak time scale ?)

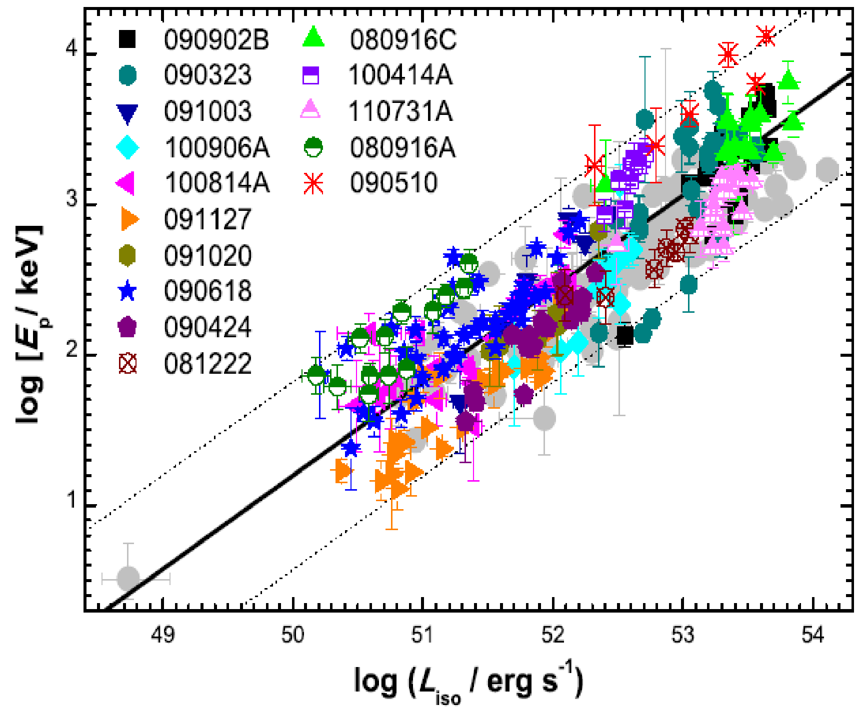


Nava et al. 2009

➢ **the Ep,i– Liso and Ep,i – Eiso correlation holds also within GRBs** (Liang et al.2004, Firmani et al. 2008, Ghirlanda et al. 2009, Li et al. 2012, Frontera et al. 2012, Basak et al. 2013): **robust evidence for a physical origin and clues to explanation**



BATSE (Liang et al., ApJ, 2004)



Fermi (e.g., Li et al. , ApJ, 2012)

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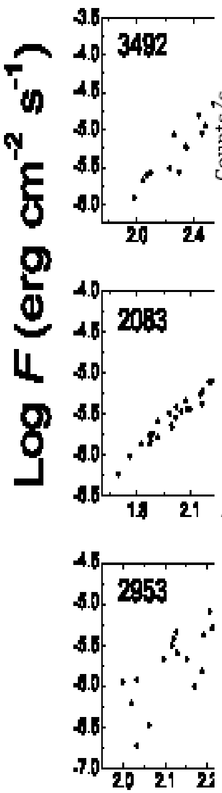

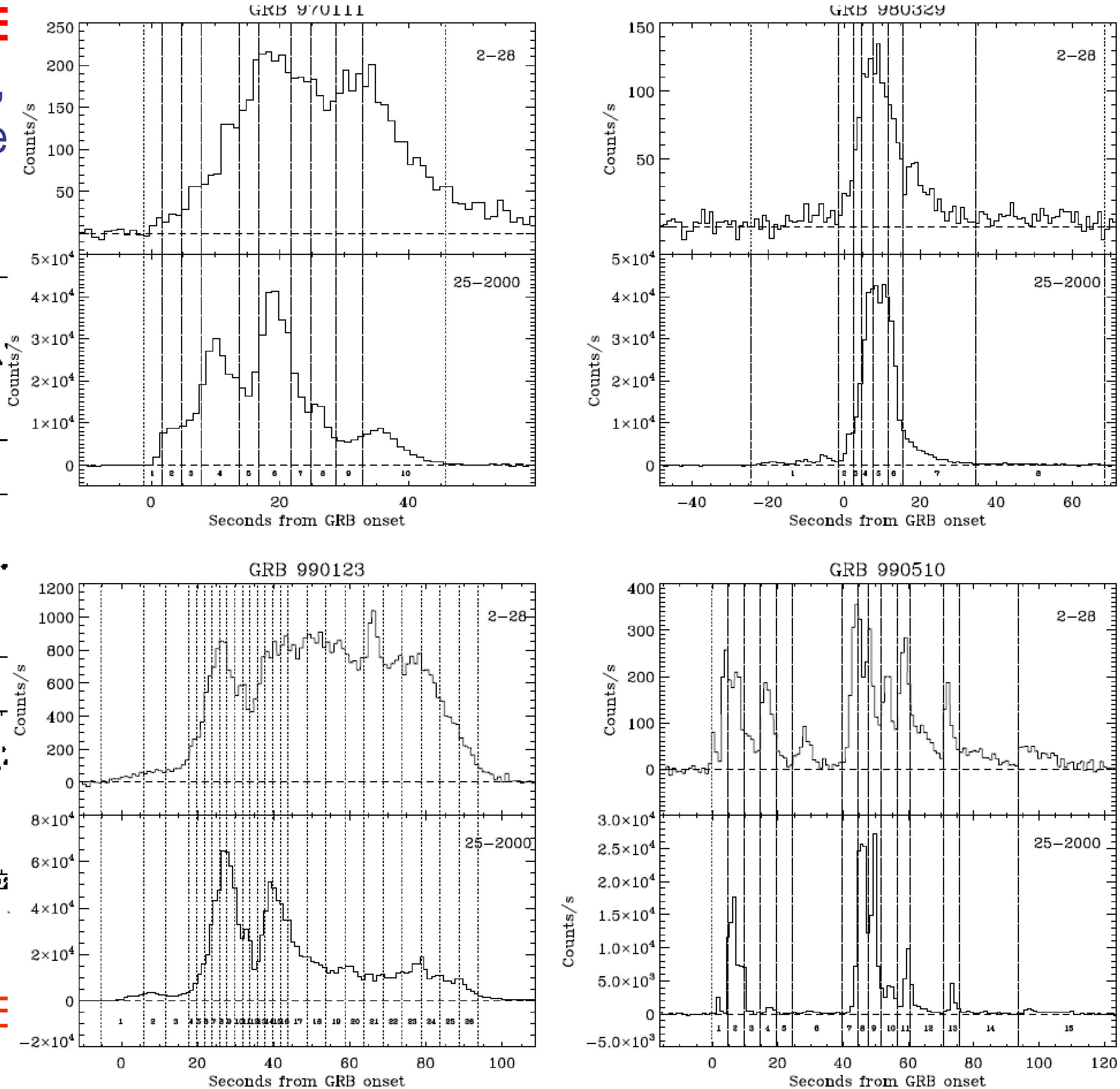

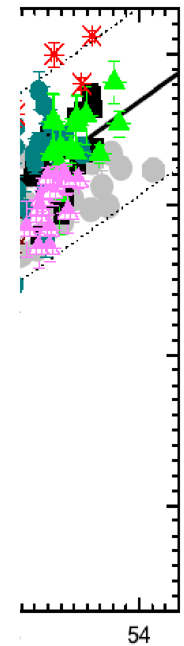

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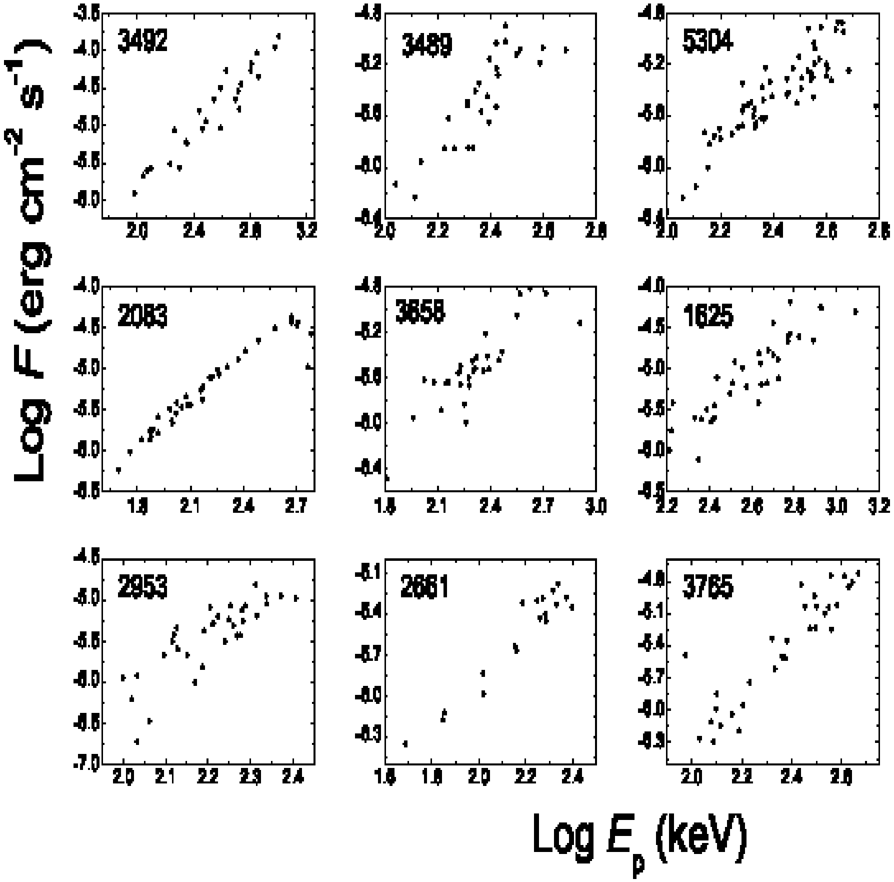

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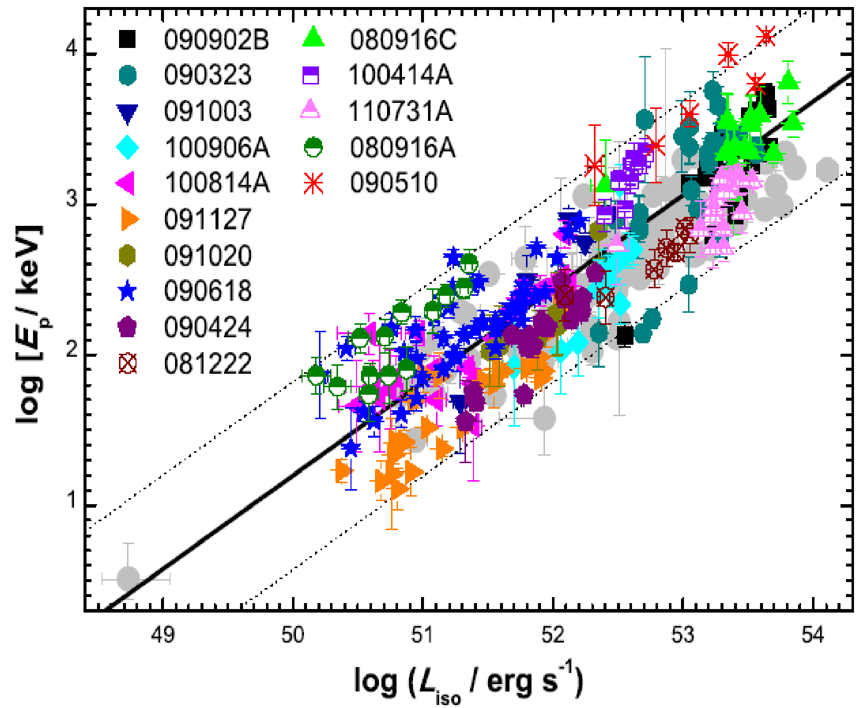


Fermi (e.g., Li et al. , ApJ, 2012)

GRB cosmology through the Ep,i - Intensity correlation

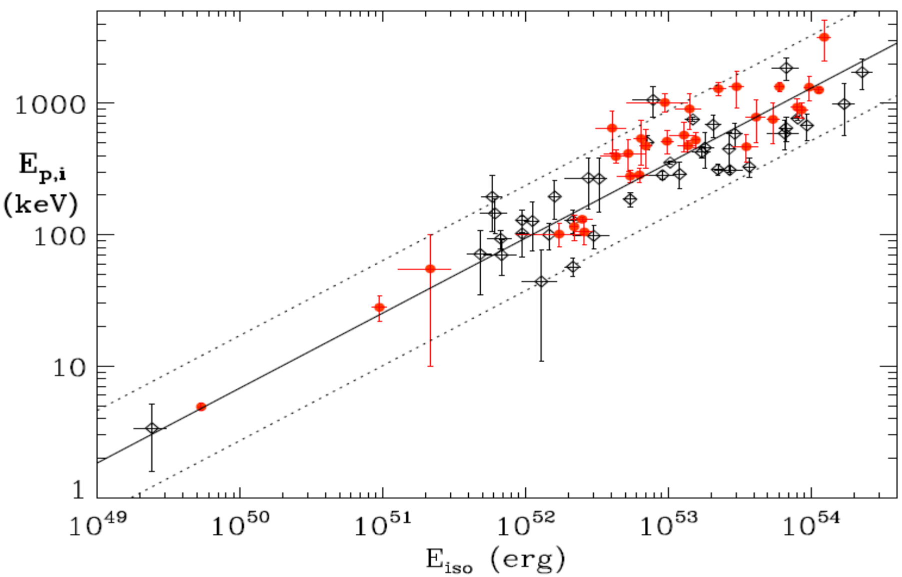
$$E_{p,i} = E_{p,obs} \times (1 + z)$$

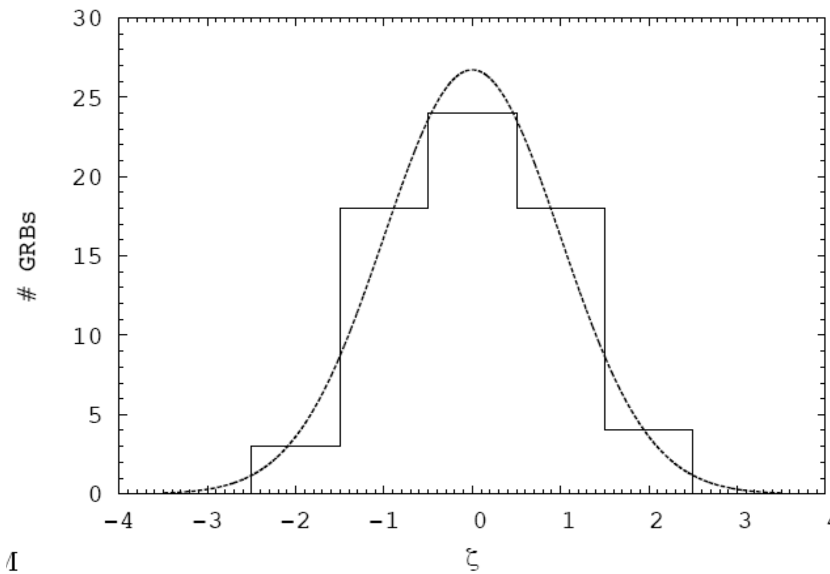
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$

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

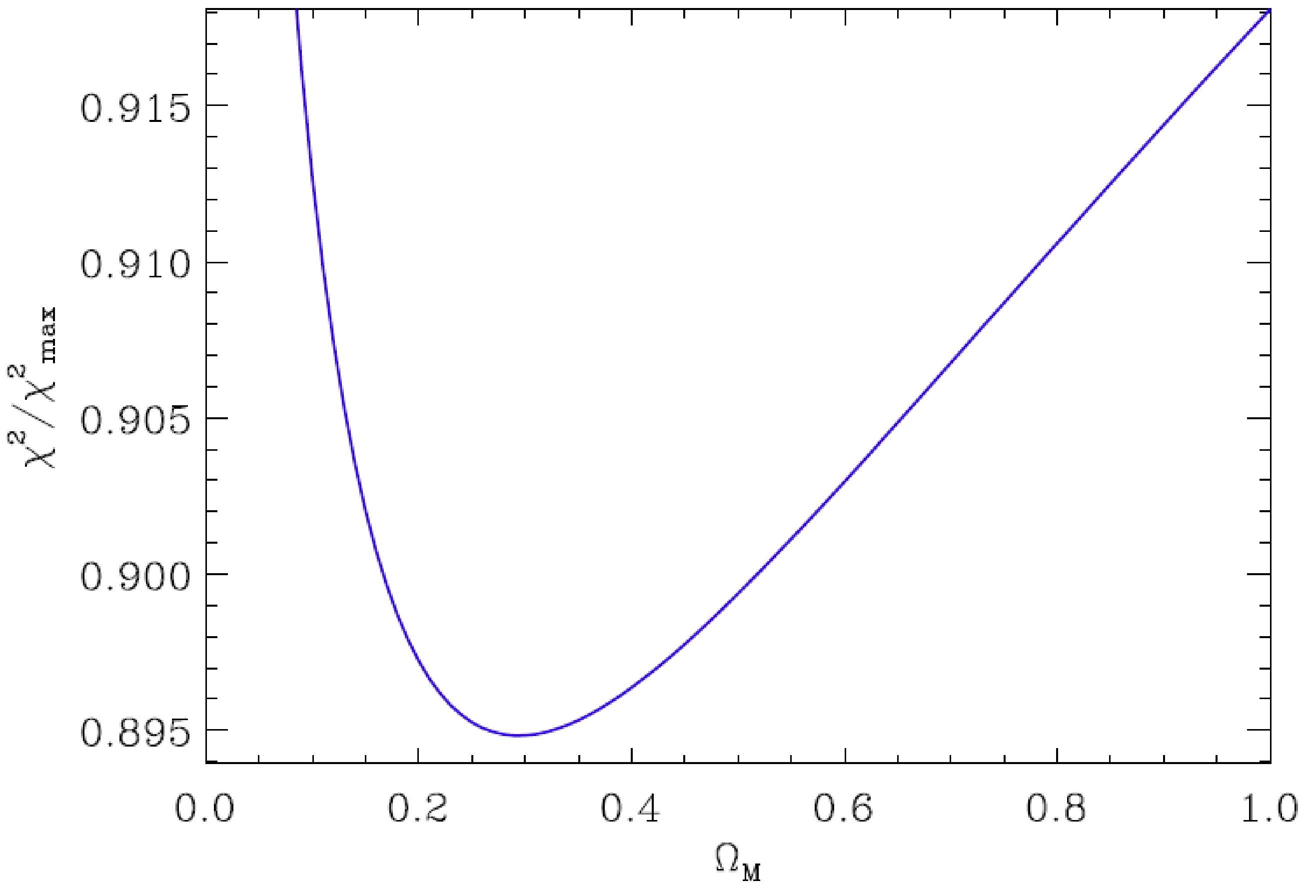
- not enough low-z GRBs for cosmology-independent calibration -> circularity is avoided by fitting simultaneously the parameters of the correlation and cosmological parameters

- 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

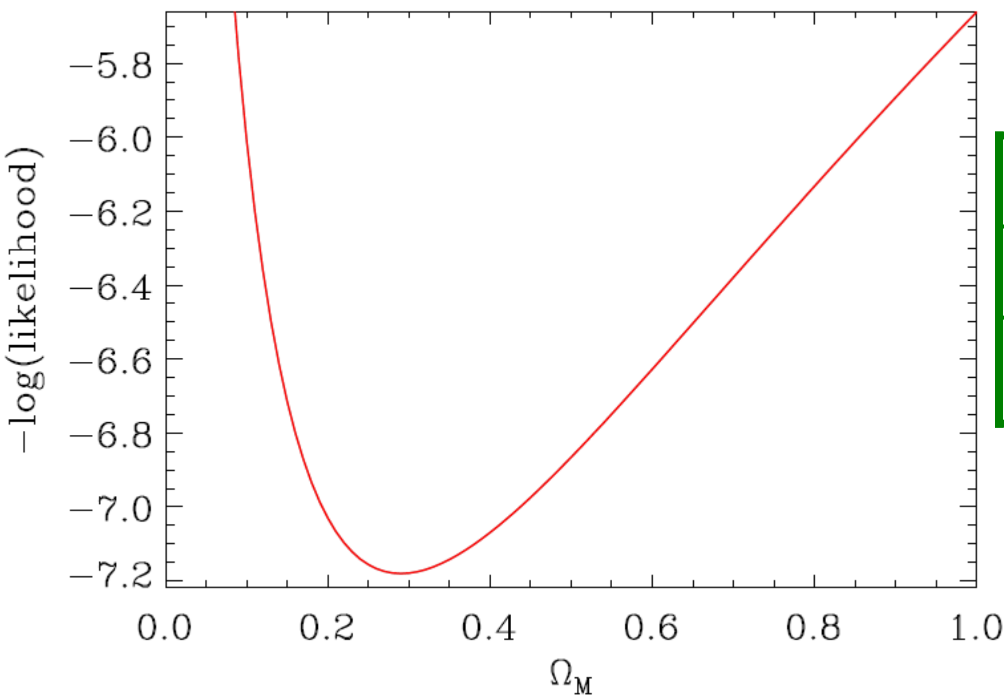


Amati et al. 2008, Amati & Della Valle 2013

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

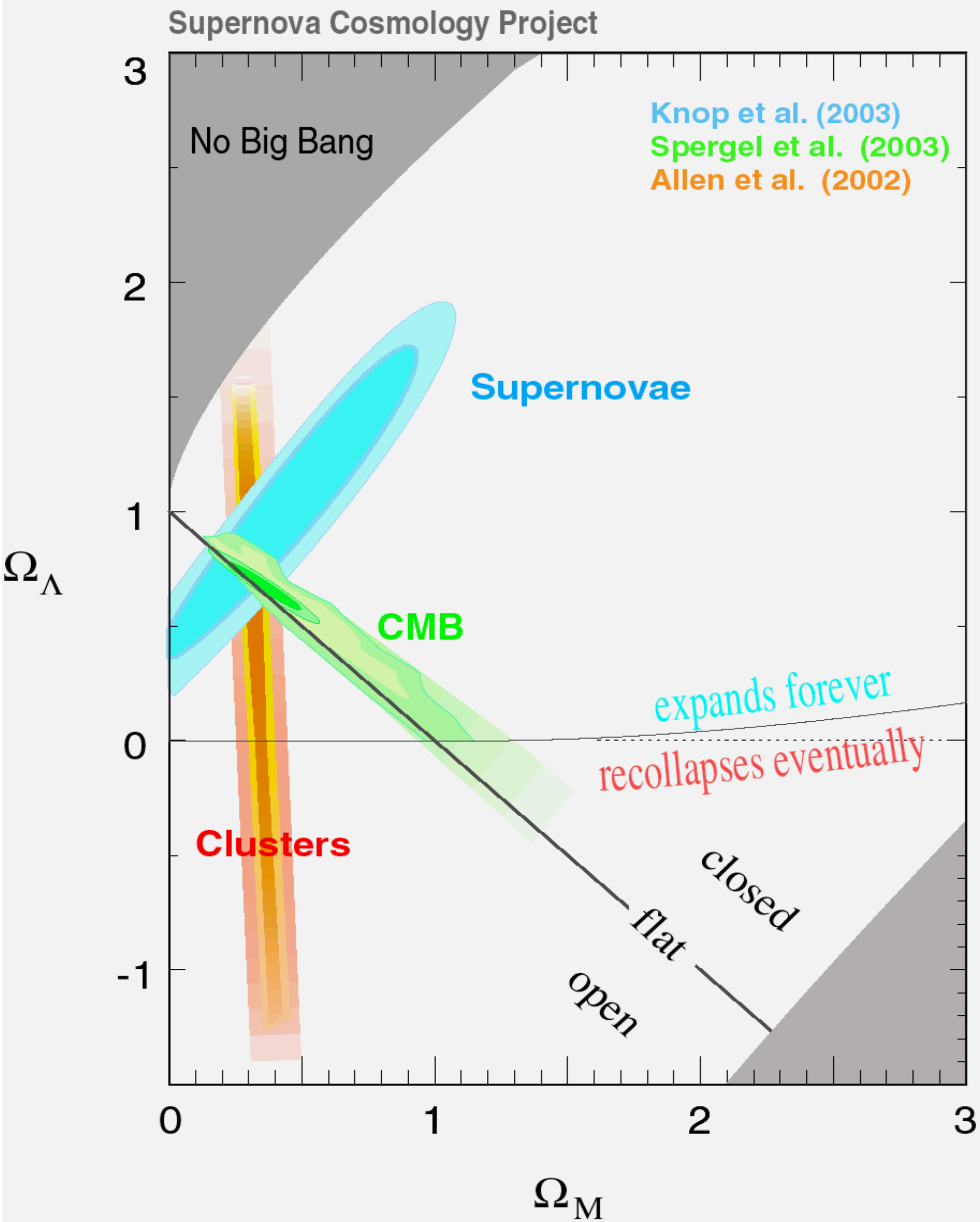
$$L(m, c, \sigma_v; \boldsymbol{x}, \boldsymbol{y}) = \frac{1}{2}\sum_i \log(\sigma_v^2 + \sigma_{y_i}^2 + m^2\sigma_{x_i}^2) + \frac{1}{2}\sum_i \frac{(y_i - m\,x_i - c)^2}{\sigma_v^2 + \sigma_{y_i}^2 + m^2\sigma_{x_i}^2}$$

- Ω_M could be constrained (Amati+08, 70 GRBs) to 0.27 (-0.18,+0.38) at 68% c.l. for a flat ΛCDM universe **(Ω_M = 1 excluded at 99.9% c.l.)**



Ωm (flat universe)	best	*68%*
70 GRBs (Amati+ 08)	0.27	0.09 – 0.65
193 GRBs (Amati+ 17)	0.29	0.14 – 0.57

Amati et al. 2008, Amati & Della Valle 2013


Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
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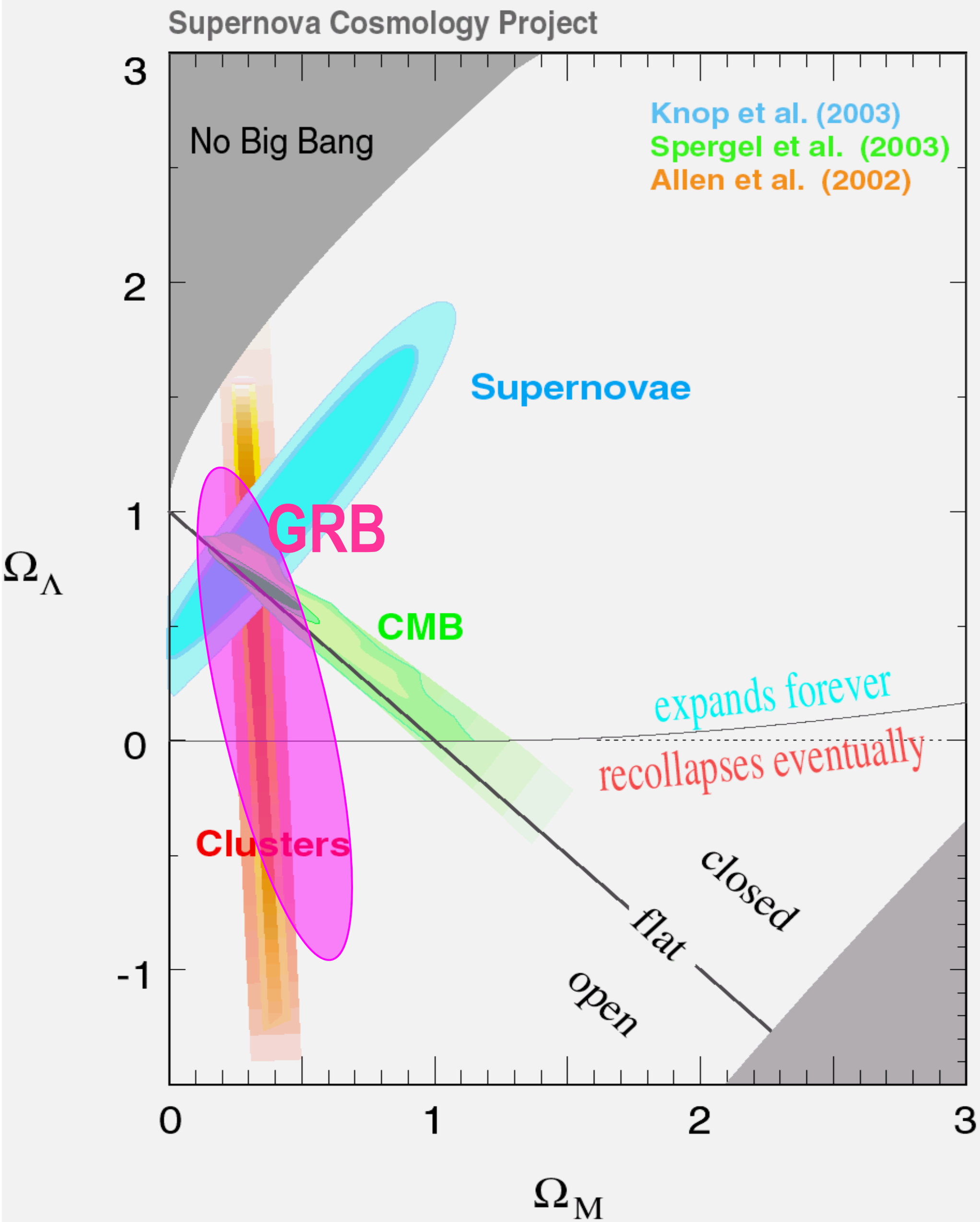

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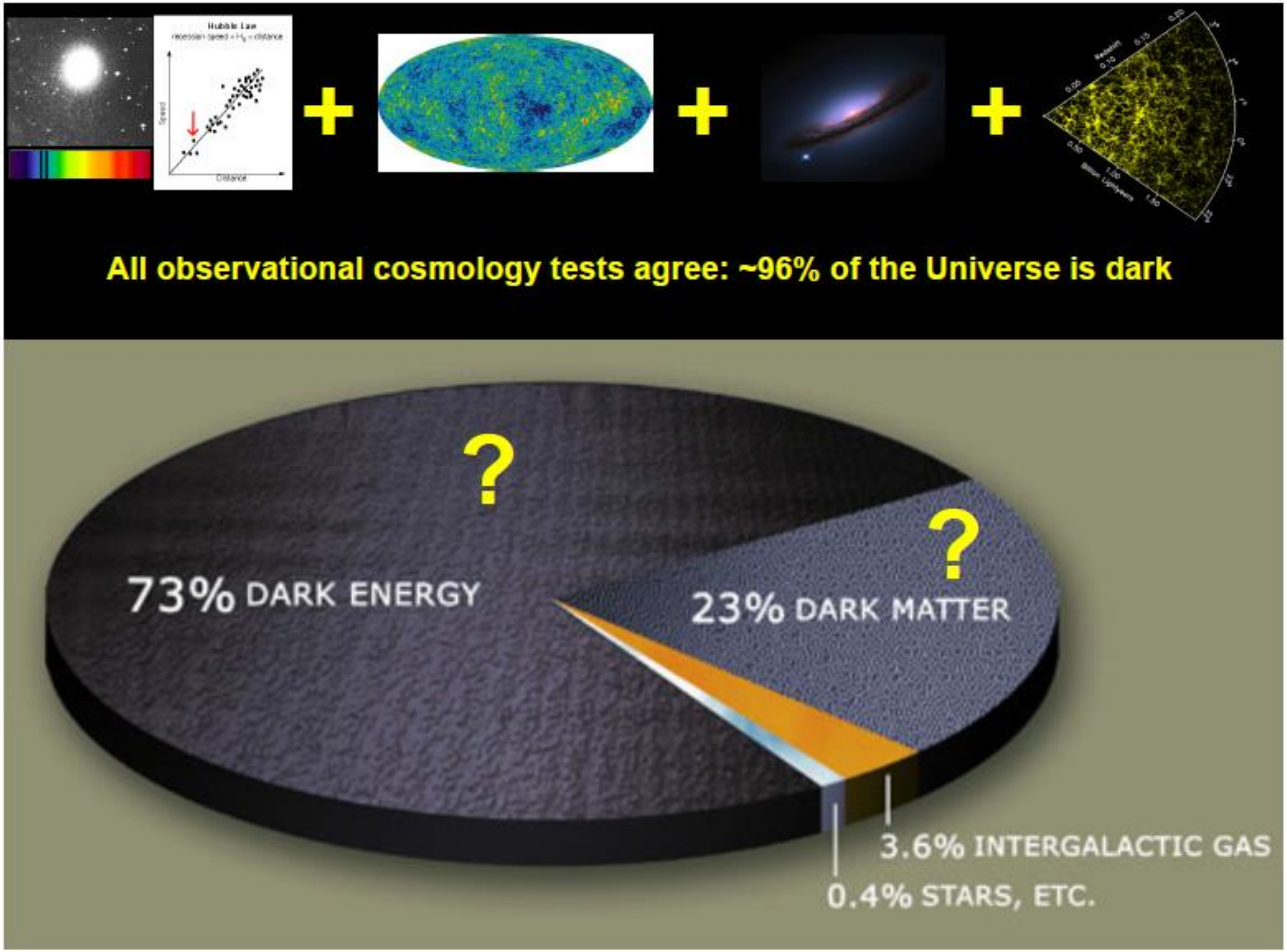
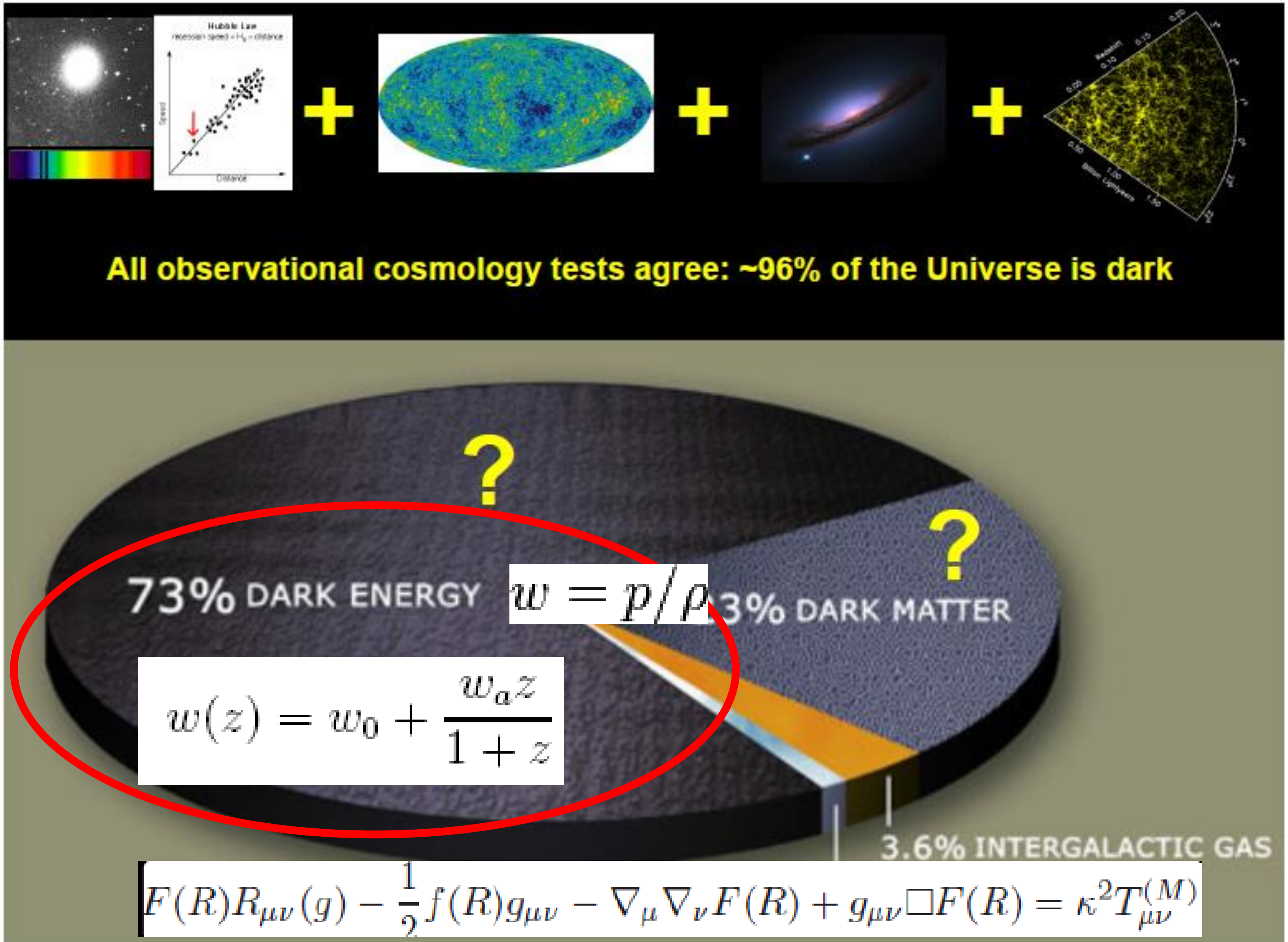
Perspectives



Perspectives



$$w = p/\rho$$

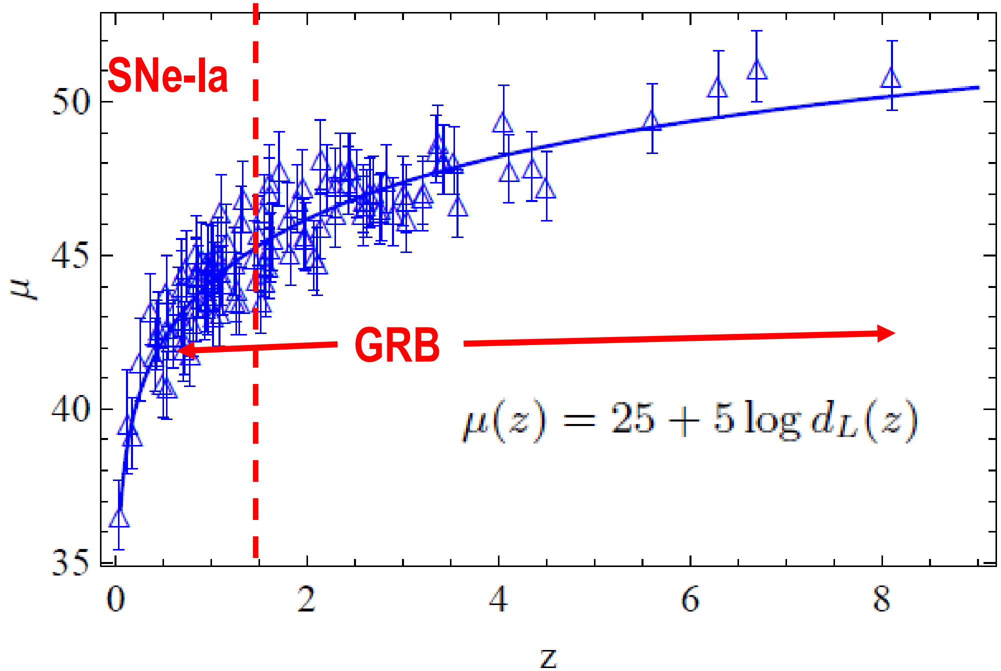
$$w(z) = w_0 + \frac{w_a z}{1+z}$$

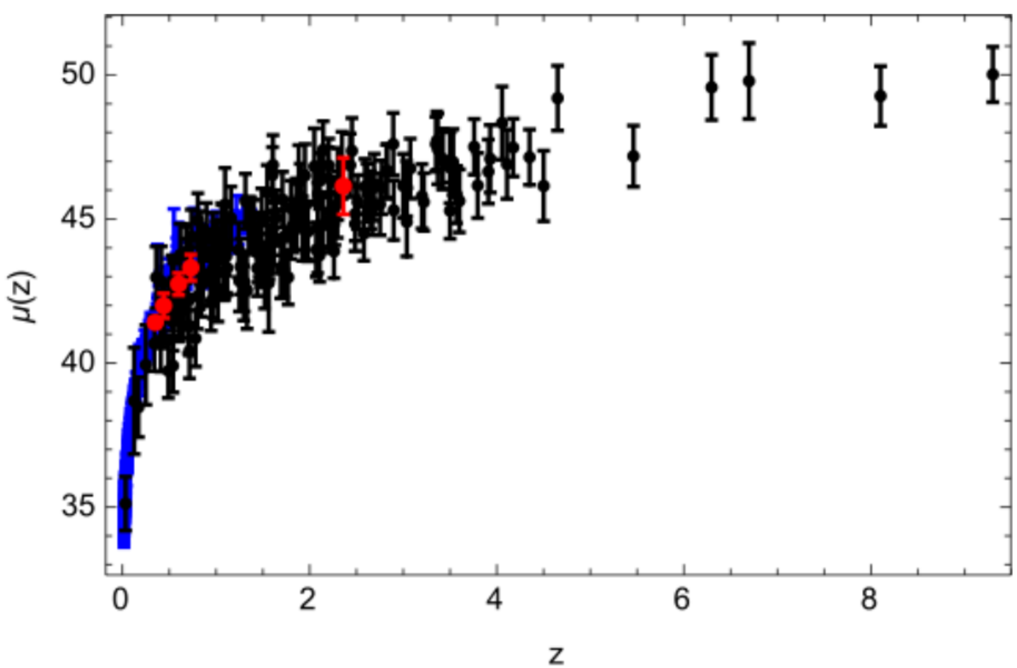
$$F(R)R_{\mu\nu}(g) - \frac{1}{2}f(R)g_{\mu\nu} - \nabla_\mu\nabla_\nu F(R) + g_{\mu\nu}\Box F(R) = \kappa^2 T^{(M)}_{\mu\nu}$$

➢ 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 and BAO points at low redshifts: reliability**

e.g., Demianski et al. 2017





❑ 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 the nvestigation 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	$0.30^{+0.06}_{-0.06}$	$-1.1^{+0.25}_{-0.30}$
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Amati & Della Valle 2013

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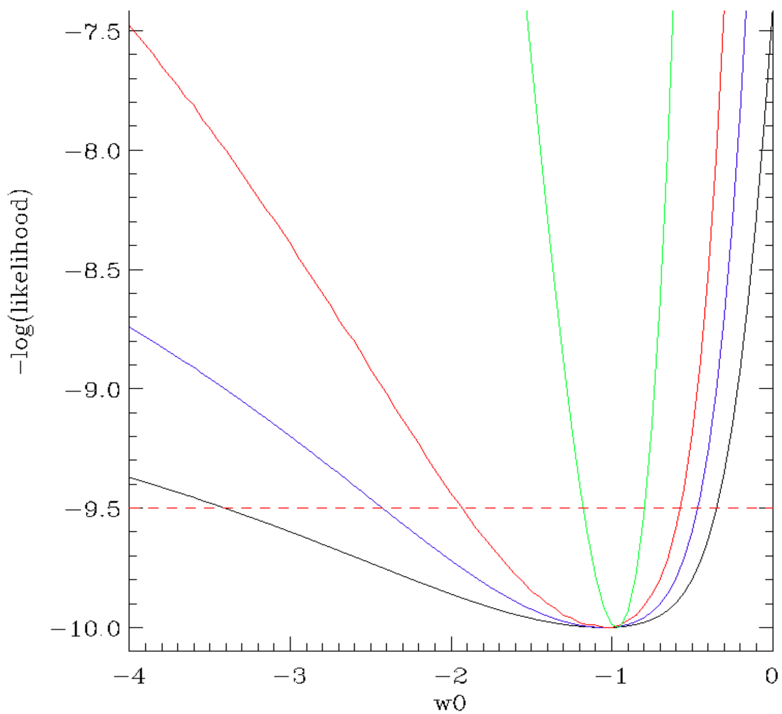
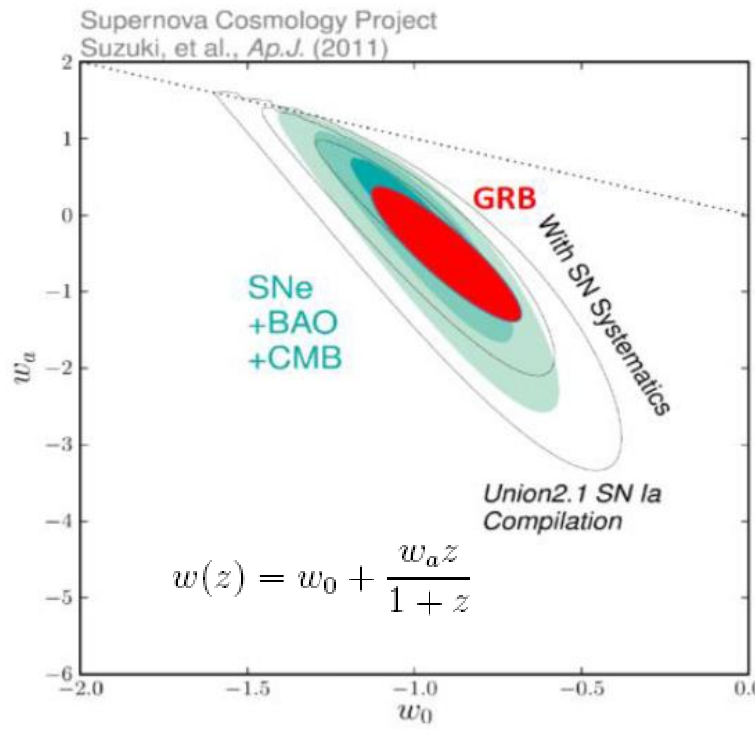




Amati & Della Valle 2013

theseus

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

P01

http://www.isdc.unige.ch/theseus/

Lead Proposer (ESA/M5): Lorenzo Amati (INAF – IASF Bologna, Italy)

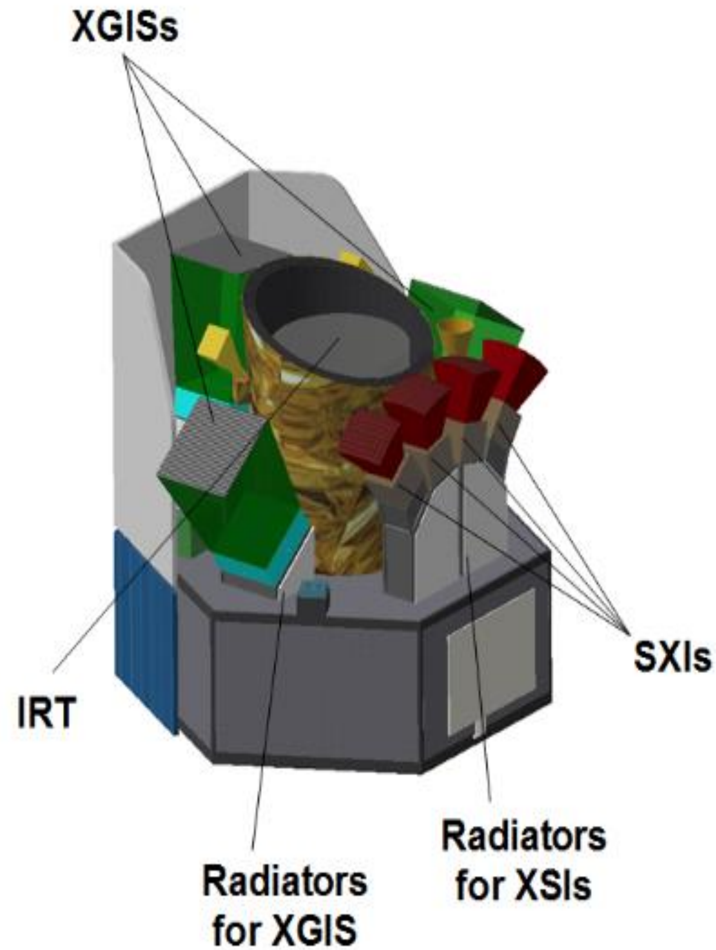
Coordinators (ESA/M5): Lorenzo Amati, Paul O'Brien (Univ. Leicester, UK), Diego Gotz (CEA-Paris, France), C. Tenzer (Univ. Tuebingen, D), E. Bozzo (Univ. Genève, CH)

Payload consortium: Italy, UK, France, Germany, Switzerland, Spain, Poland, Czech Republic, Ireland, Hungary, Slovenia , ESA

Interested international partners: USA, China, Brazil

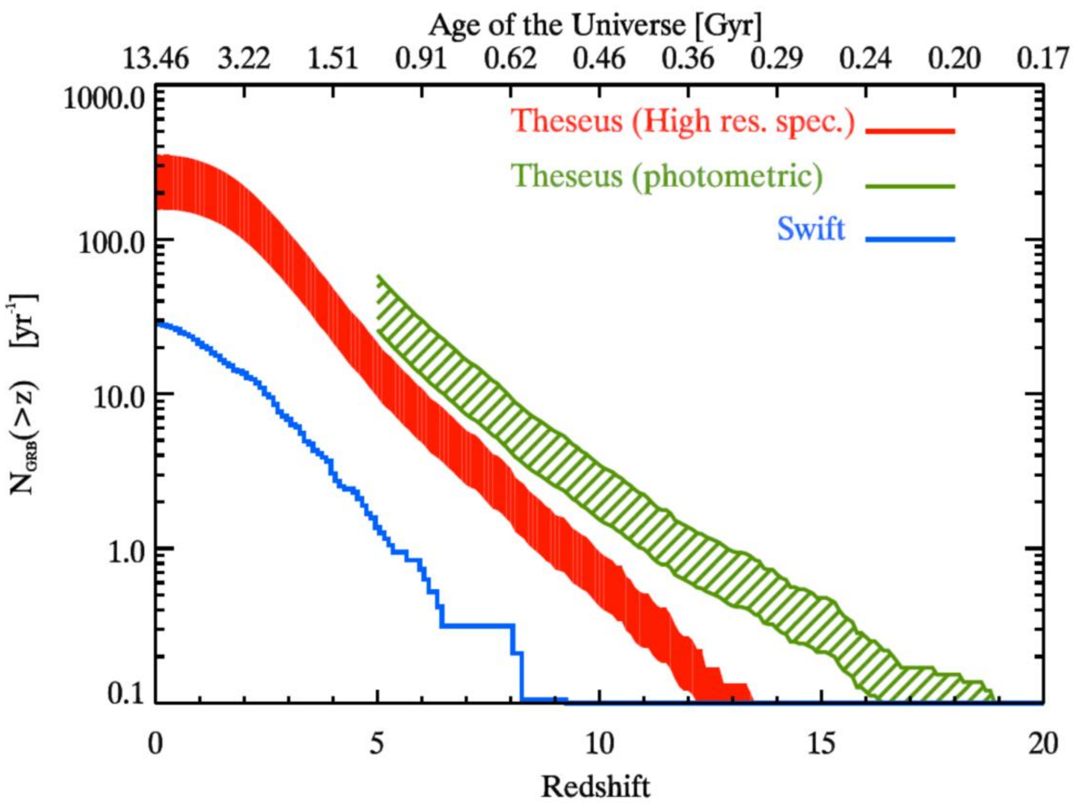
THESEUS payload

- **Soft X-ray Imager (SXI):** a set of four sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV of ~1sr with source location accuracy < 1-2';
- **X-Gamma rays Imaging Spectrometer (XGIS,)**: 3 coded-mask X-gamma ray cameras using bars of Silicon diodes coupled with CsI crystal scintillators observing in 2 keV – 10 MeV band, a FOV of ~2sr, overlapping the SXI, with ~5' source location accuracy;
- **InfraRed Telescope (IRT)**: a 0.7m class IR telescope observing in the 0.7 – 1.8 μm band, providing a 10'x10' FOV, with both imaging and moderate resolution spectroscopy capabilities



LEO (< 5°, ~600 km)
Rapid slewing bus
Prompt downlink

❑ Unveiling the high-z GRB population with THESEUS



THESEUS GRB#/yr	All	z > 5	z > 8	z > 10
Detections	387 - 870	25 – 60	4 – 10	2 - 4
Photometric z		25 – 60	4 – 10	2 - 4
Spectroscopic z	156 - 350	10 - 20	1 - 3	0.5 - 1

❑ Shedding light on the dark energy with THESEUS

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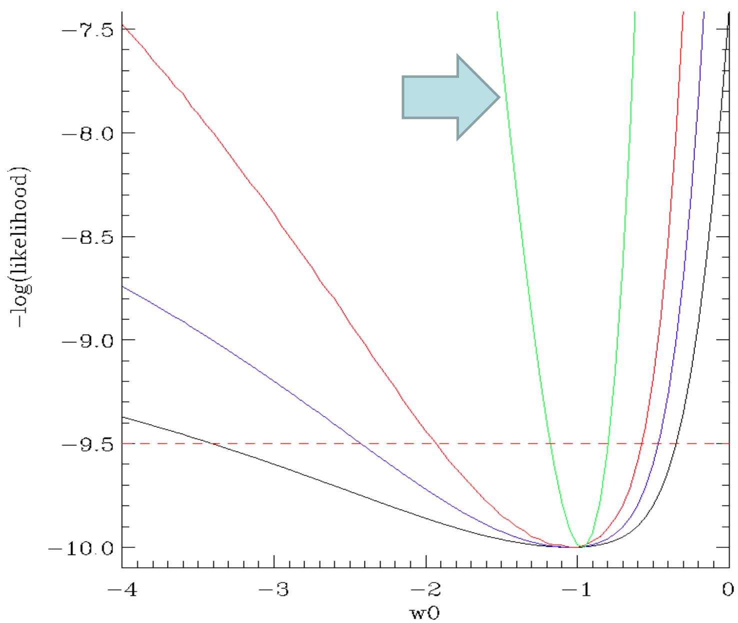

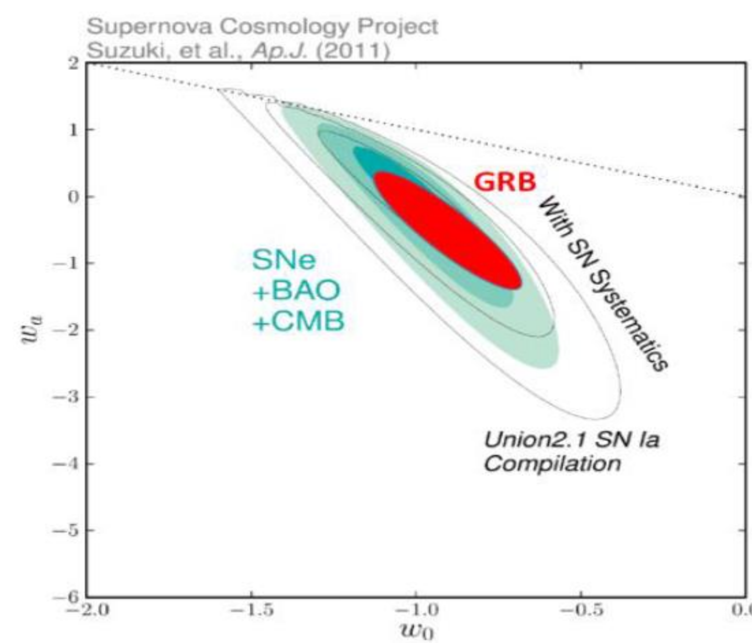

Conclusions

- 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.**

- **The THESEUS mission (submitted to ESA/M5 by an Italy-led European collaboration, with interest of USA, China, Brazil) will also fully exploit GRBs as powerful and unique tools to investigate D.E. and early universe**

- Researcher from worldwide institutions already provided their support to THESEUS/M4). **Please, provide your interest / support to amati@iasfbo.inaf.it or through the THESEUS web-site: http://www.isdc.unige.ch/theseus/**

❑ Shedding light on the early Universe with THESEUS (P01)