Gamma Ray Bursts: Physics and Cosmology (II)

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Outline of the lectures

I. The Gamma-Ray Bursts phenomenon

- Basic Observations
- Standard scenarions for progenitors and physics
- Main open issues

II. Cosmology with Gamma-Ray Bursts

- Backgorund and motivations
- Measuring cosmological parameters with GRBs
- Shedding light on the early Universe with GRBs

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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*** *and a redshift distribution extending to at least* ***z = 9-10****. Thus, they are in principle very powerful tools for cosmology*

- **Part 1:** status and perspectives of the research activities aimed at using GRBs to investigate the expansion rate and geometry of the Universe, thus getting clues to "dark energy" properties and evolution

- **Part 2:** GRBs as tools for exploring the early Universe at the end of the "dark ages" (reionization, first stars, star formation rate and metallicity evolution in the first billion of years)

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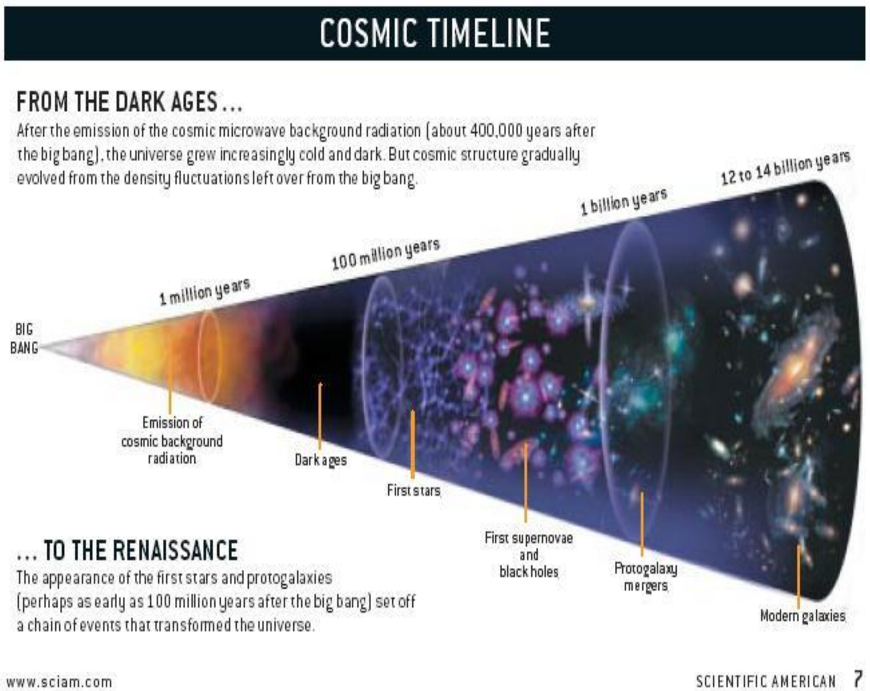
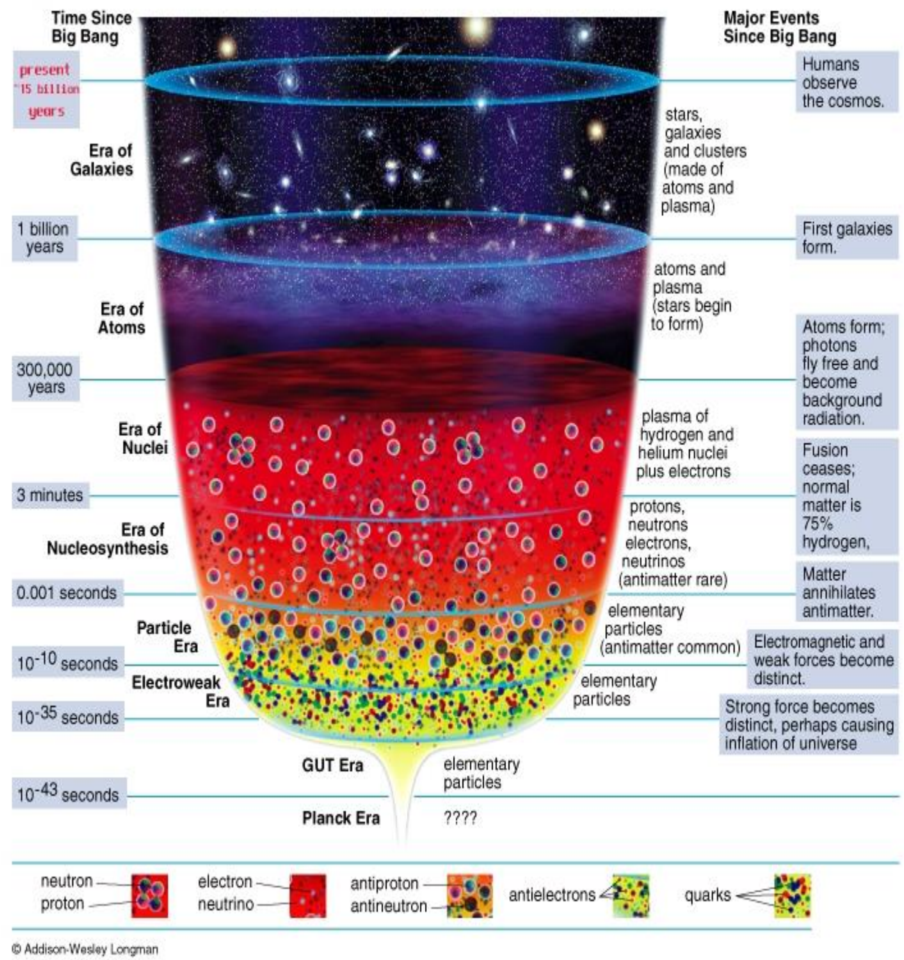
The accelerating and “dark” Universe

- the standard “hot big-bang” cosmological model as of middle ’90s **(general relativity + Hubble law + cosmological principle + dark matter + CMB)**





The accelerating and "dark" Universe

❑ the standard "hot big-bang" cosmological model as of middle '90s **(general relativity + Hubble law + cosmological principle + dark matter + CMB)**

$$\rho_c(t) = \frac{3H^2(t)}{8\pi G}$$

Critical density as a function of time. Value below is present value, based on present value of the Hubble parameter H

$$\rho_{c,0} = \frac{3H_0^2}{8\pi G} = 9.47x10^{-27}\,kg\,/\,m^3$$

$$H_0 = 71 km/s/mpc$$

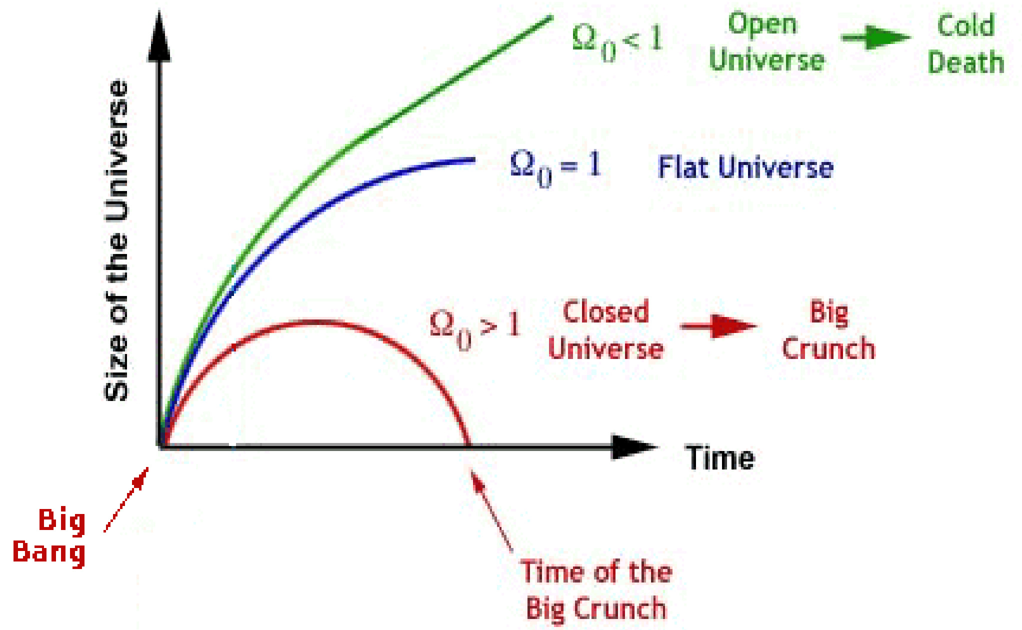
WMAP value for the Hubble parameter.

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

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

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

Effective mass density of relativistic particles (light plus neutrinos).



❑ the standard “hot big-bang” cosmological model NOW: inflation + CMB -> ~ flat Universe ($\Omega_{tot} = 1$), SN Ia (+ clusters, BAO) -> Ω_m **~0.3 -> accelerated espansion + dark energy (cosmological constant, quintessence, …)**

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

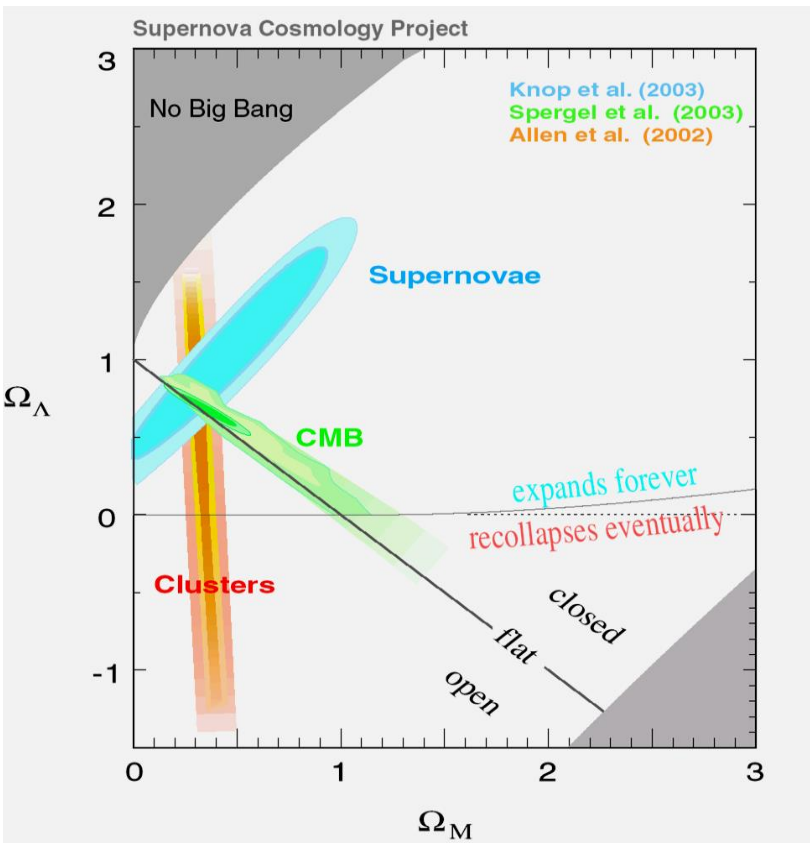
$$\Omega = \Omega_m + \Omega_{rel} + \Omega_\Lambda$$

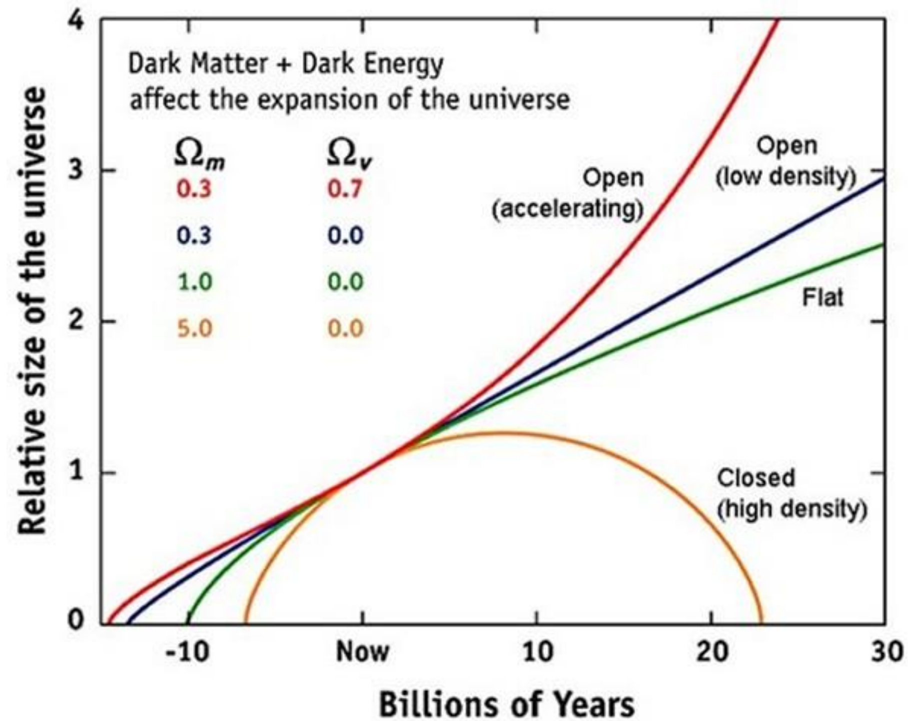
Total density parameter $\Omega = \frac{\rho}{\rho_c}$; $\Omega = 1$ for critical density universe

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

Effective mass density of relativistic particles (light plus neutrinos).

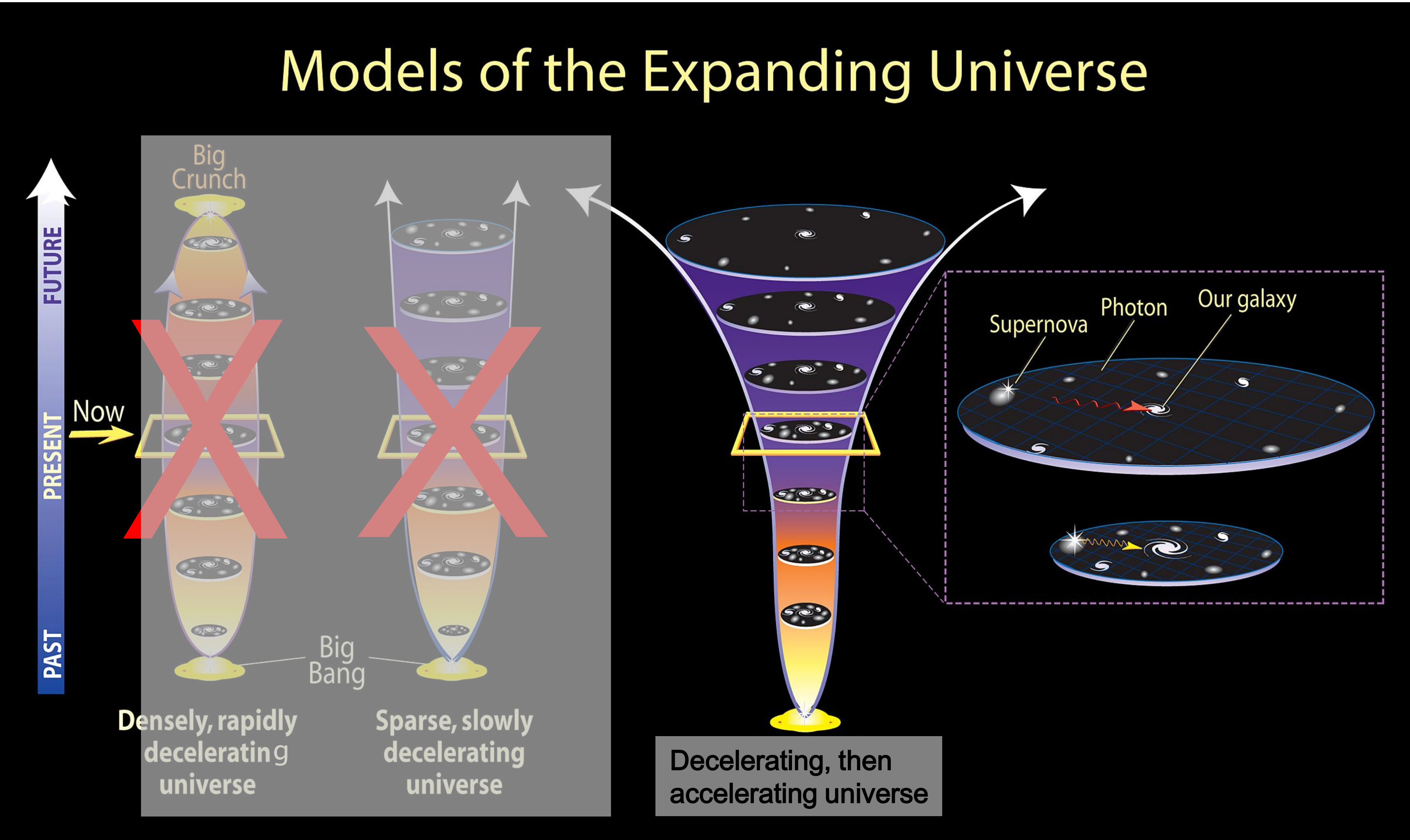
Effective mass density of the dark energy, taking the role described as the cosmological constant.



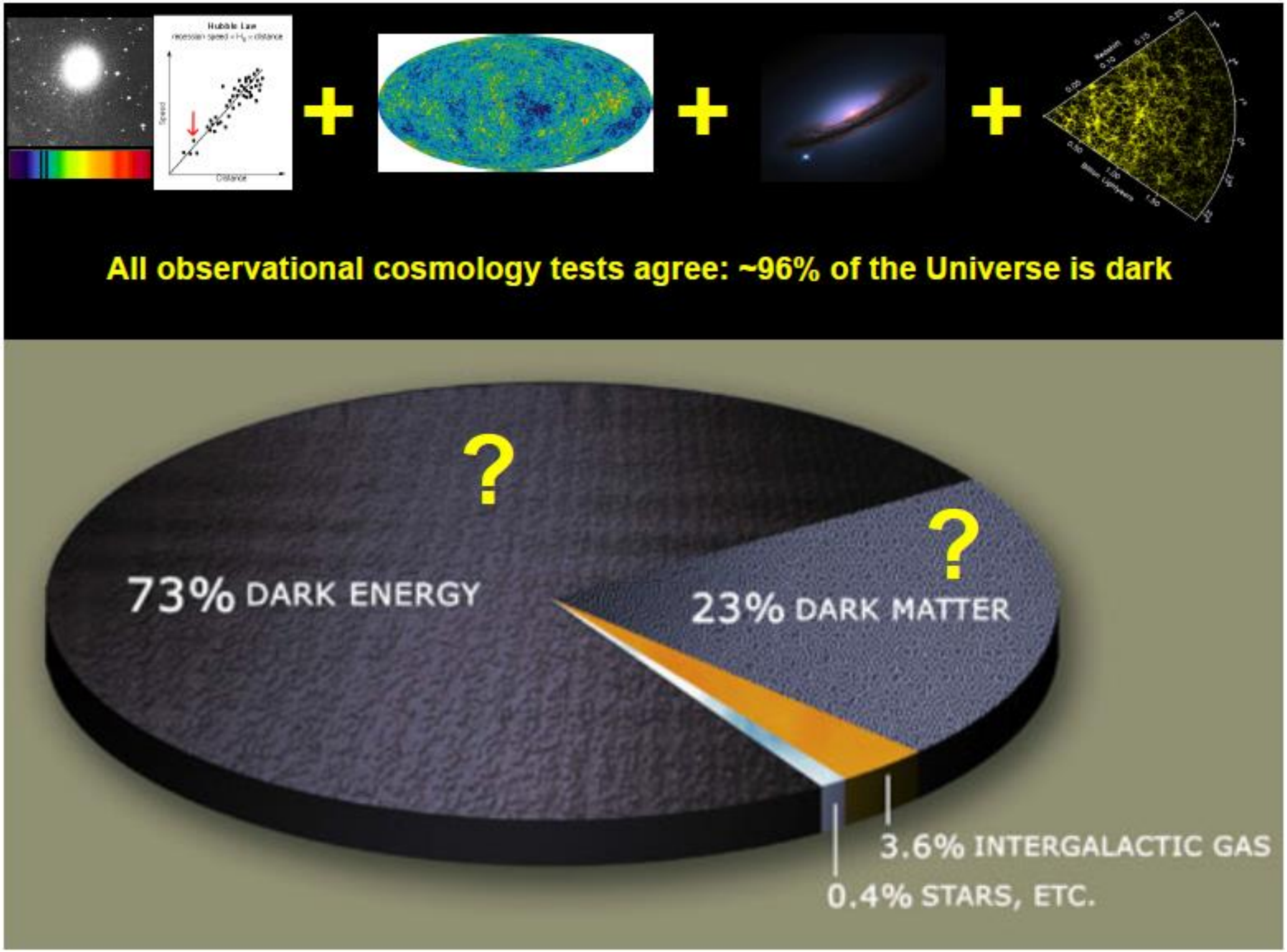


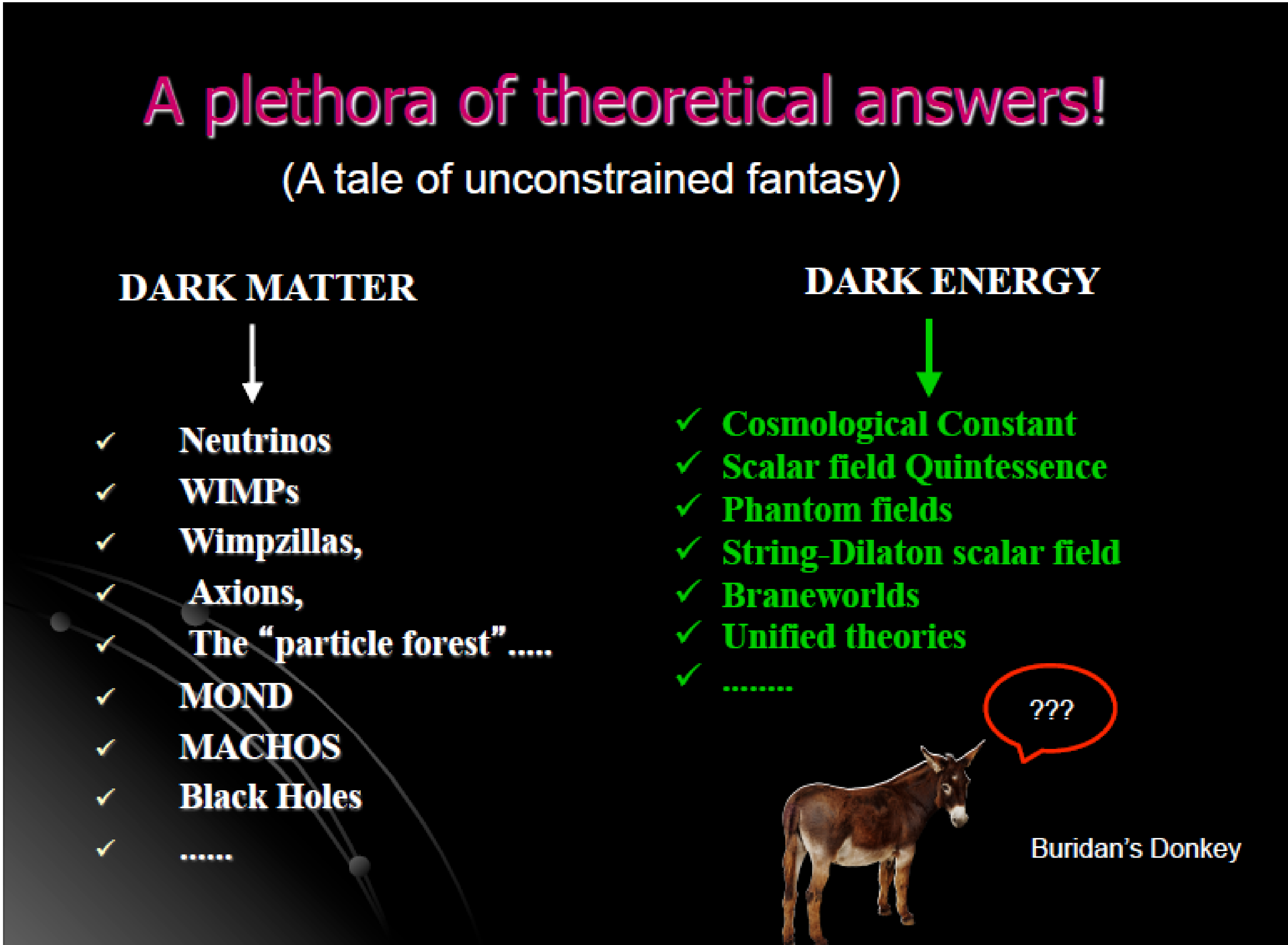
❑ the Universe expansion is **accelerating**

Universe now expanding ~20% faster than 5 billion years ago



- the Universe is **"dark"**





Courtesy: Prof. Capozziello (Università Federico II Napoli)

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Measuring cosmological parameters

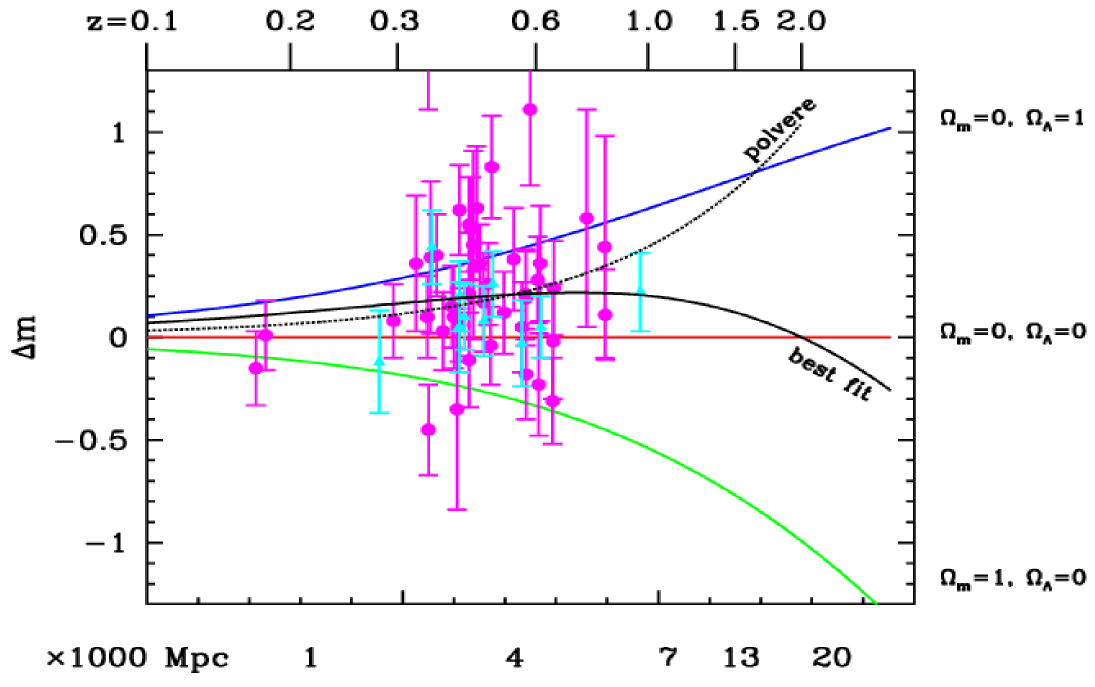
- Standard candles (e.g., Cepheids, very low redshift) + "standardized" sources (e.g., SN Ia) + large scale structure evolution (galaxies, clusters -> BAO) + CMB (matter-energy and space-time fluctuations at z ~1100, inflation)

- e.g., standard candles: a population of unevolving sources, having a fixed intrinsic luminosity

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

$$F = \frac{L}{4\pi D_L^2}$$

$$m = M + 5\log[D_L(z;\Omega_M;\Omega_\Lambda)]$$



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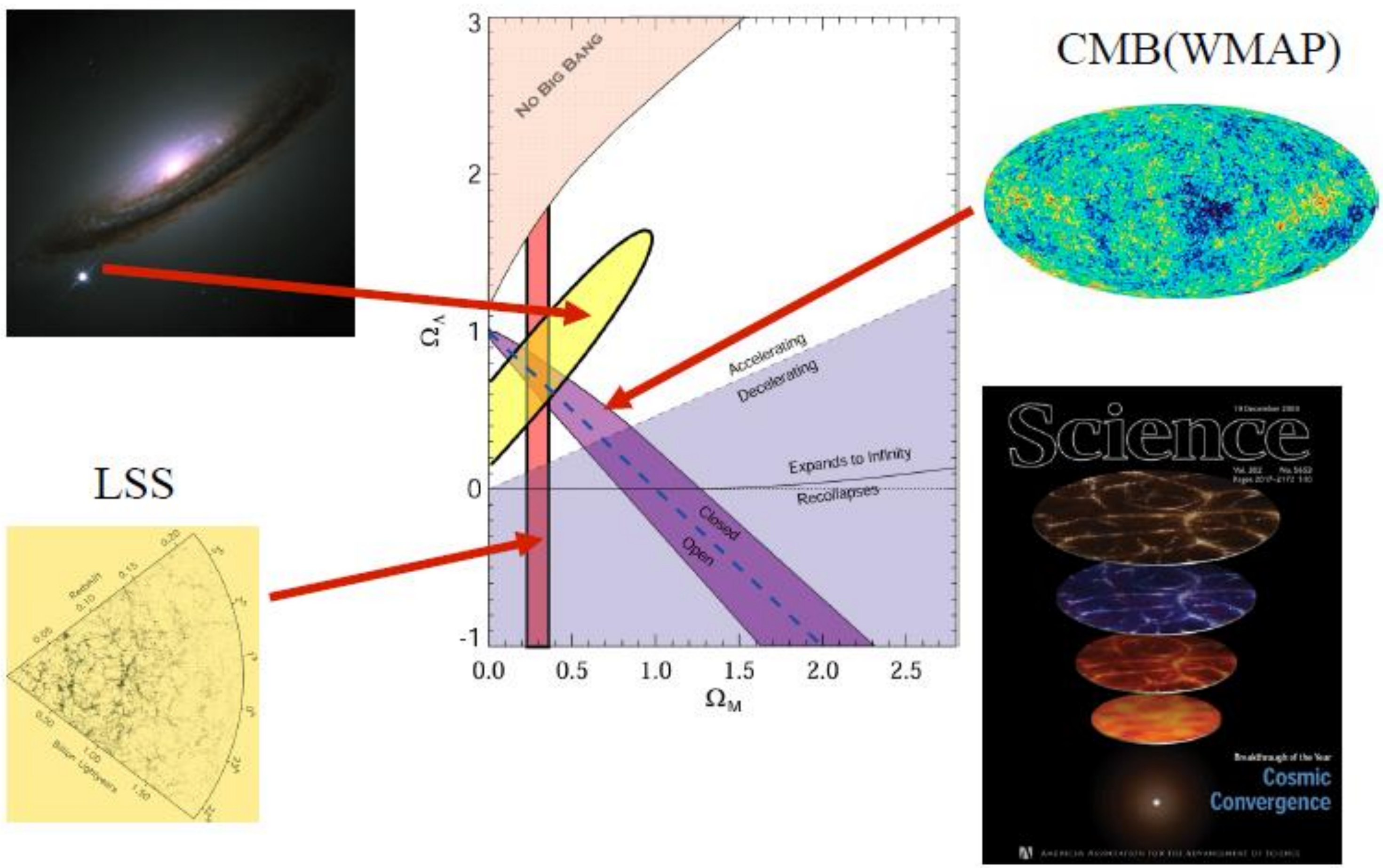
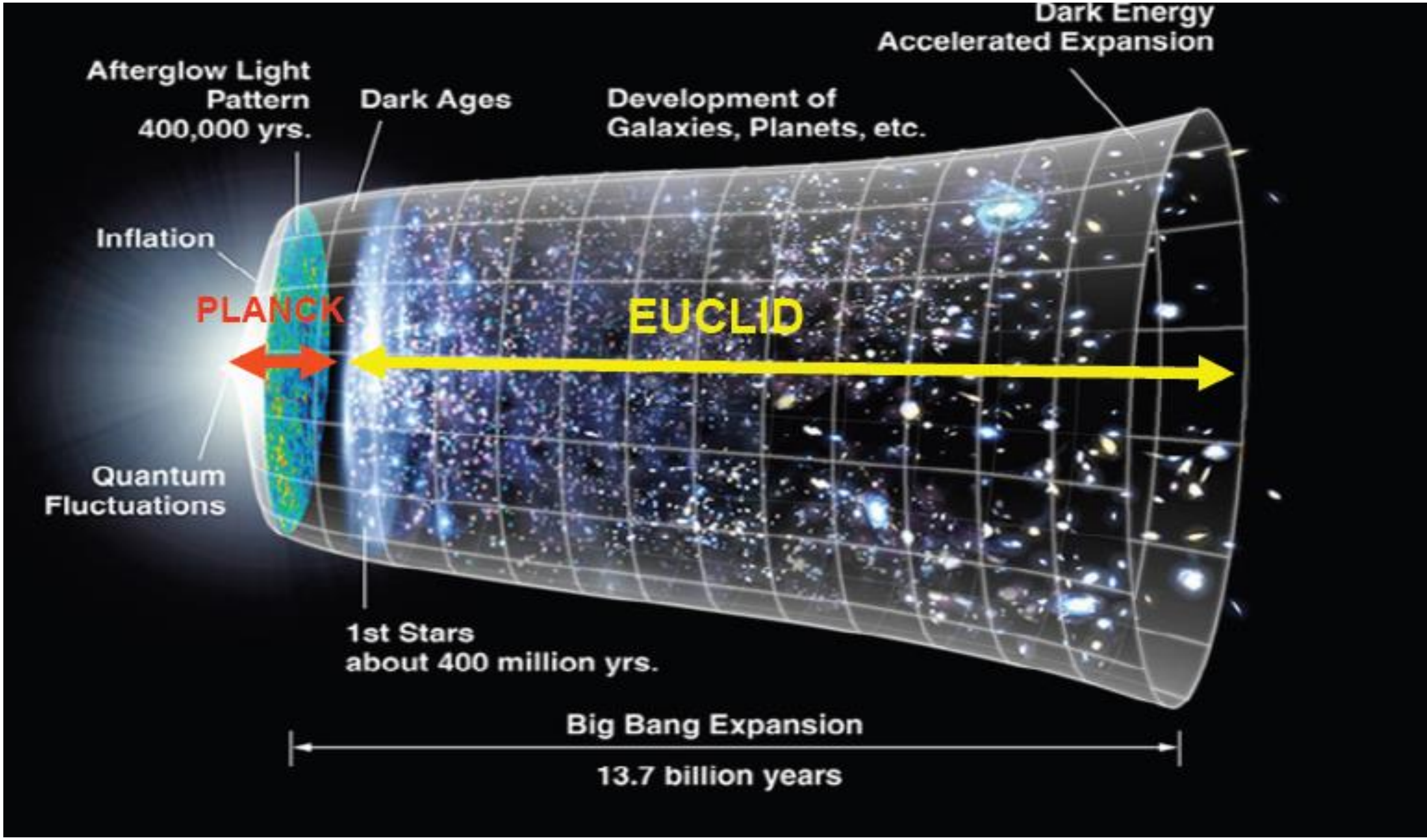
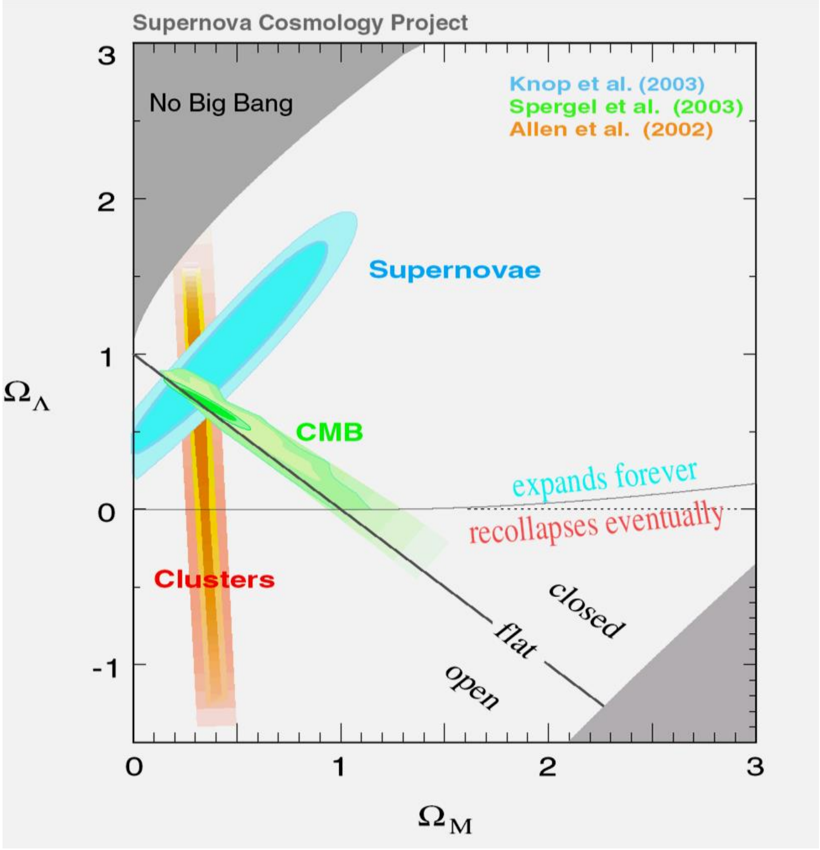




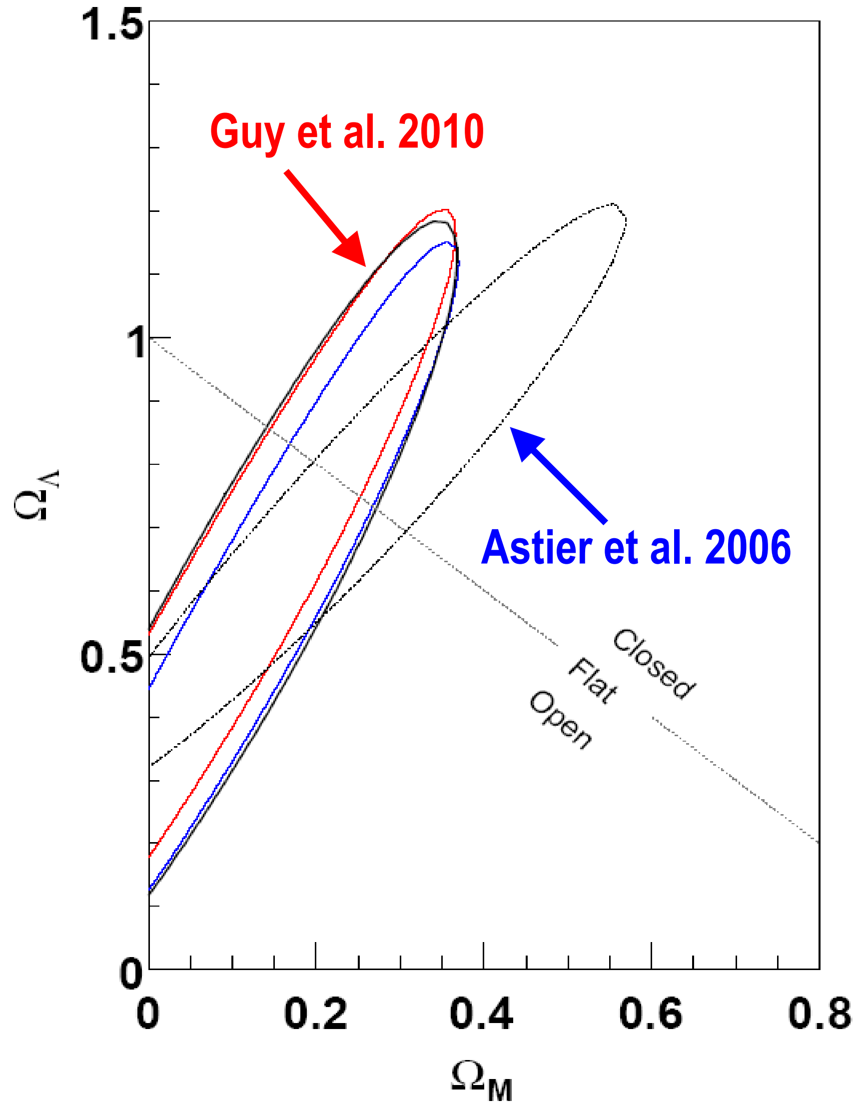
- e.g., EUCLID (> 2020) will investigate the distance-redshift relationship and the evolution of cosmic structures by measuring shapes and redshifts of galaxies and clusters of galaxies out to redshifts ~2, or equivalently to a look-back time of 10 billion years

Why looking for more cosmological probes ?

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



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



Recent results from SNLS (231 SNe Ia at 0.15 < z < 1.1, Guy et al. 2010) compared to those of Astier et al. 2006 (44 low redshift SNe along with the 71 SNe from the SNLS first year sample)

❑ **Each cosmological probe is characterized by possible systematics**

❑ **e.g SN Ia:**

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

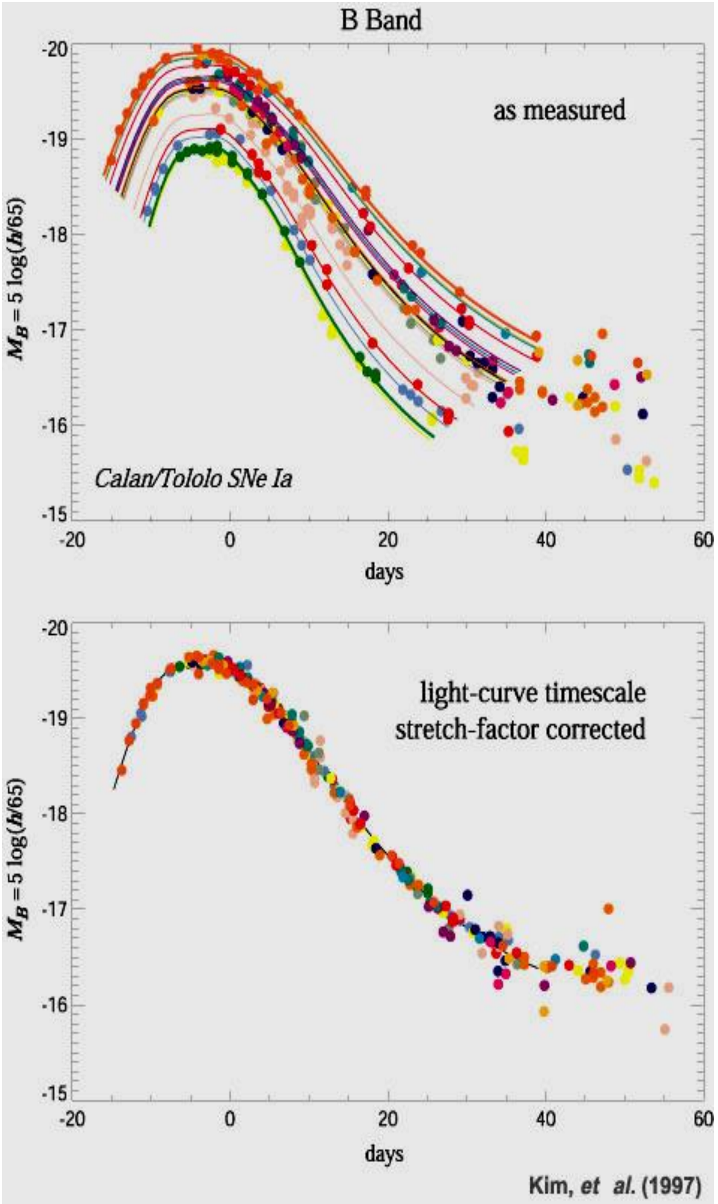
➢ light curve shape correction for the luminosity normalisation may depend on z

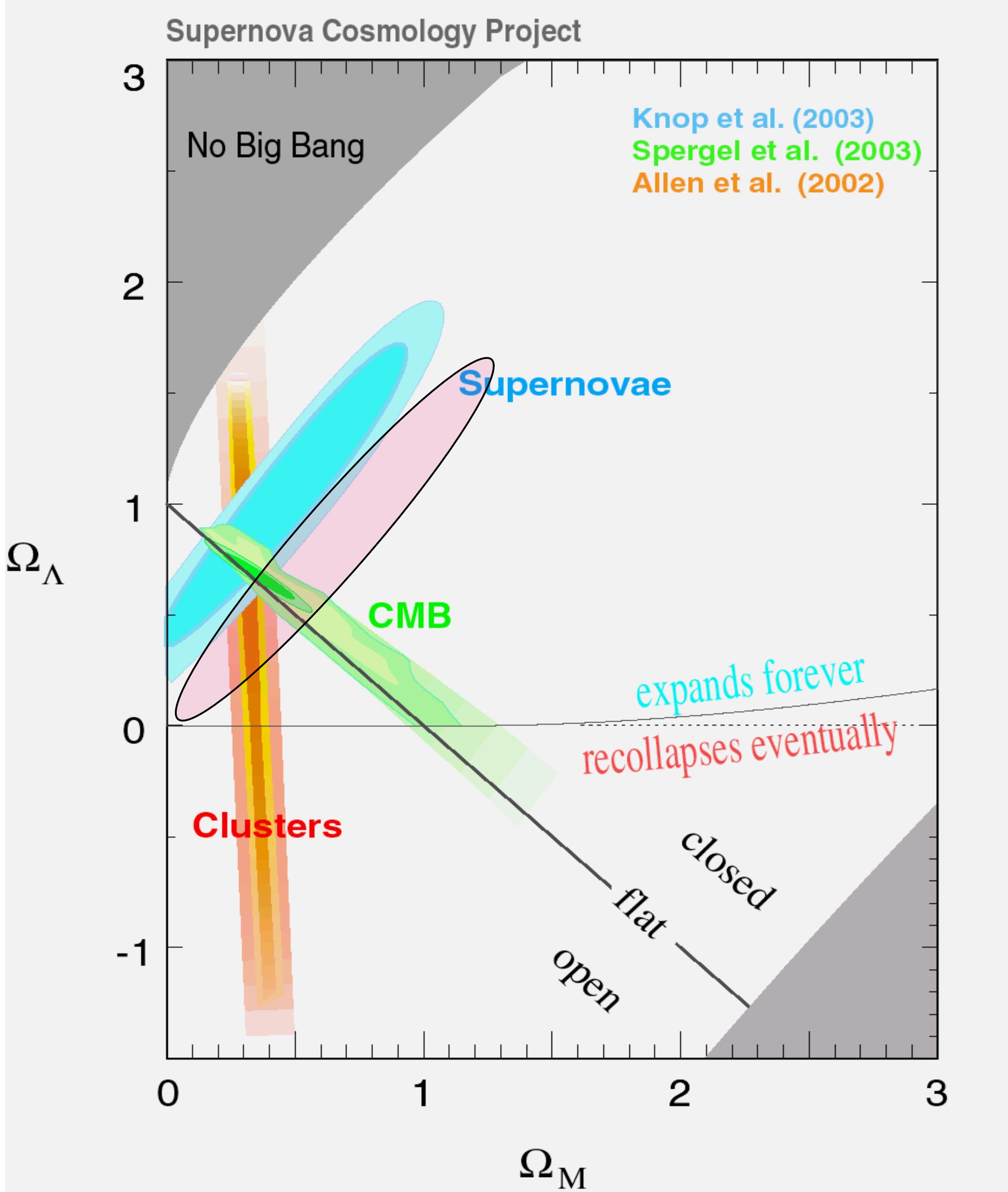
➢ signatures of evolution in the colours

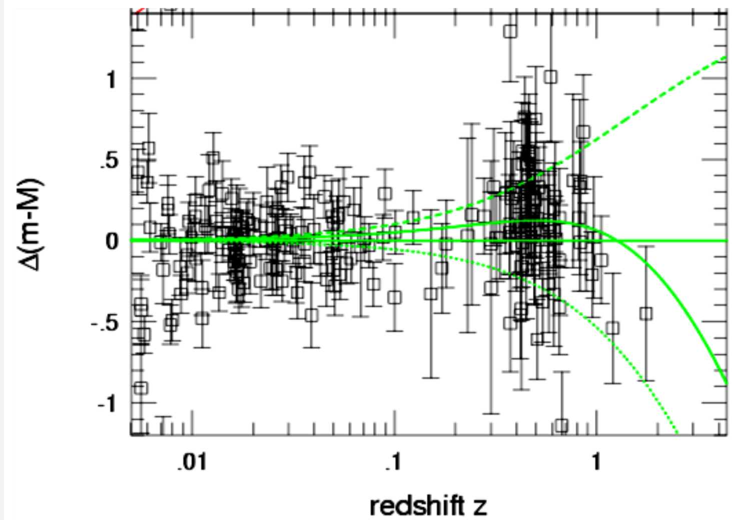
➢ correction for dust extinction

➢ anomalous luminosity-color relation

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







If the "offset from the truth" is just 0.1 mag….

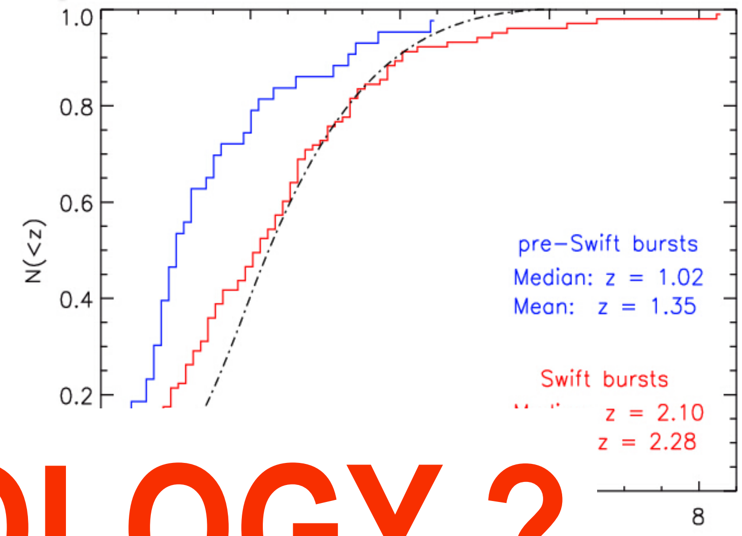
(slide by M. della Valle)

Gamma-Ray Bursts as cosmological probes

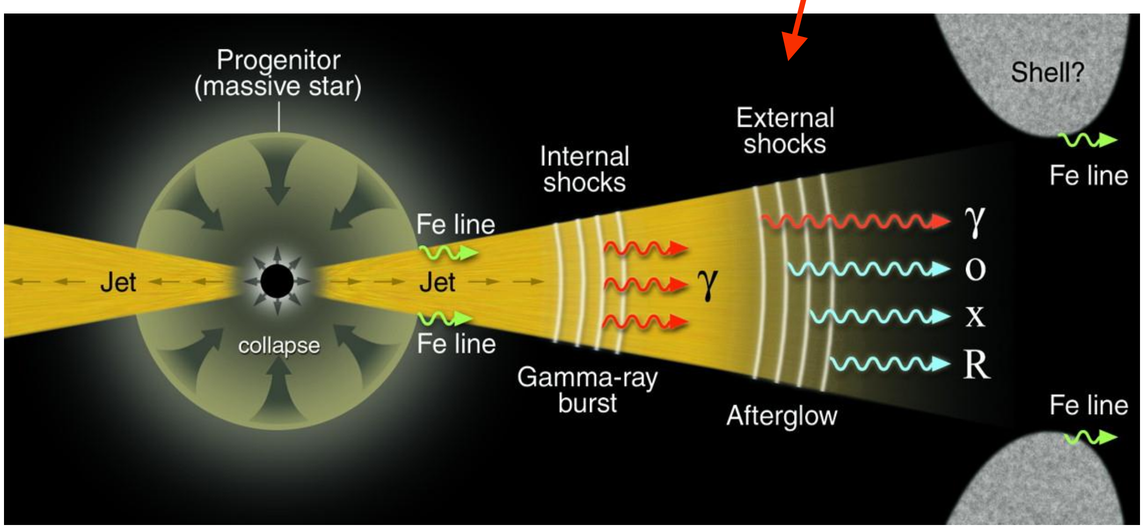
➢ **redshifts higher than 0.01 and up to > 8: GRB are cosmological !**

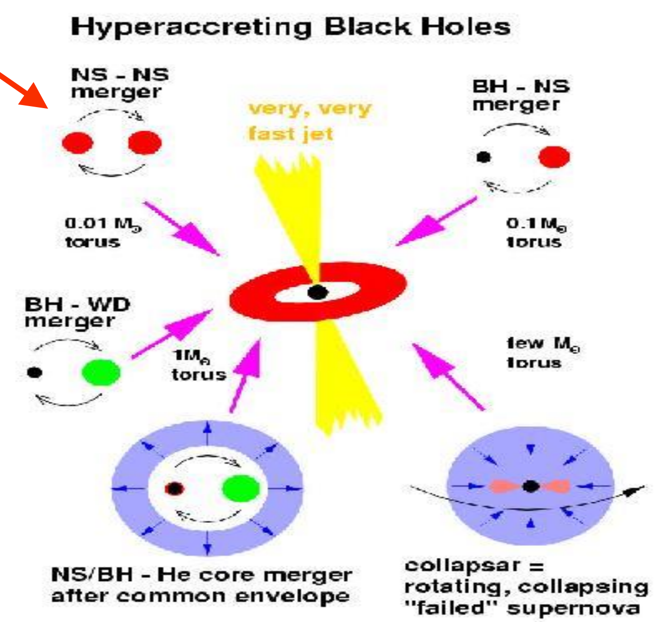
➢ **their isotropic equivalent radiated energy is huge (up to more than 10^{54} erg in a few tens of s**

➢ funda



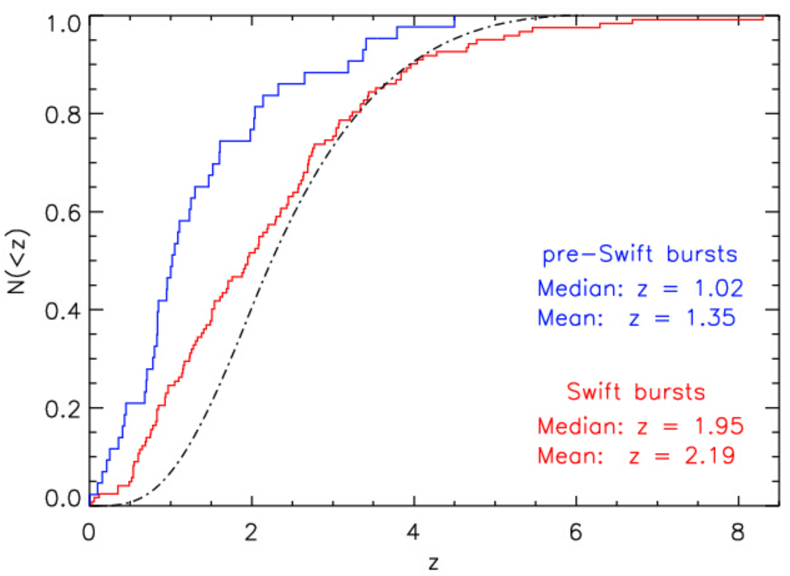
GRB COSMOLOGY ?



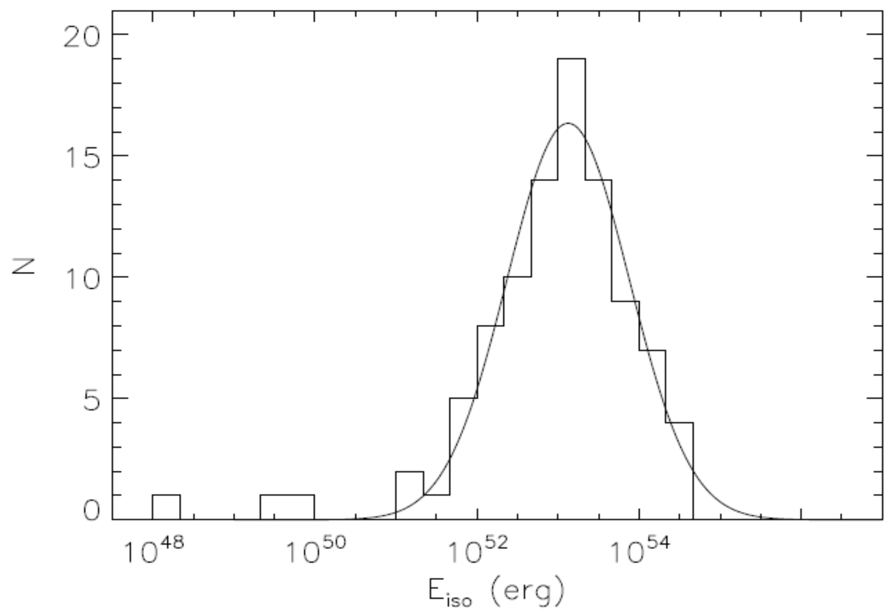


Are Gamma-Ray Bursts standard candles ?

- 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

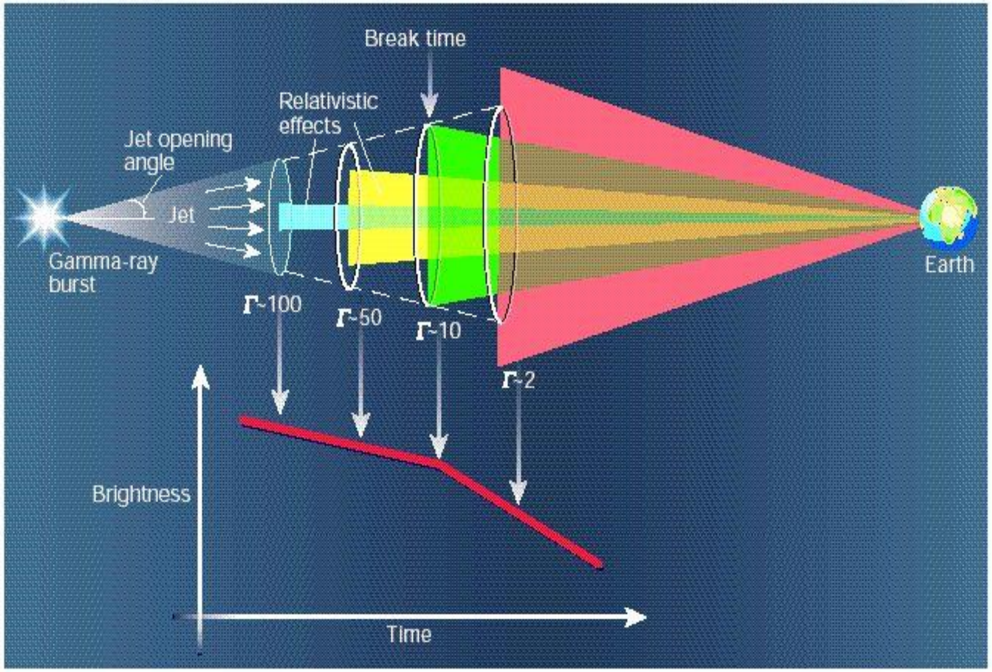


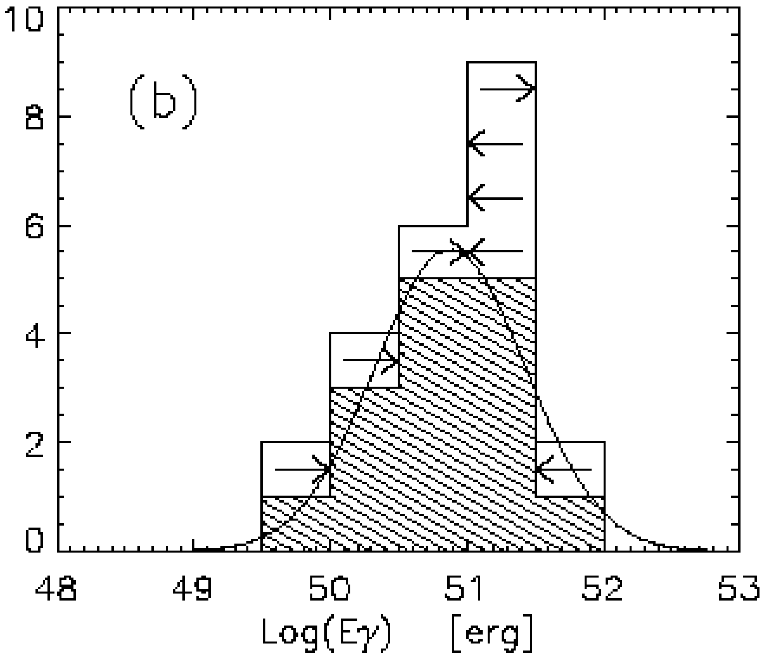
Amati, 2009

- jet angles, derived from break time of optical afterglow light curve by assuming standard scenario, are of the order of few degrees
- the collimation-corrected radiated energy spans the range ~5x10^{49} – 5x10^{52} erg-> **more clustered but still not standard**

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

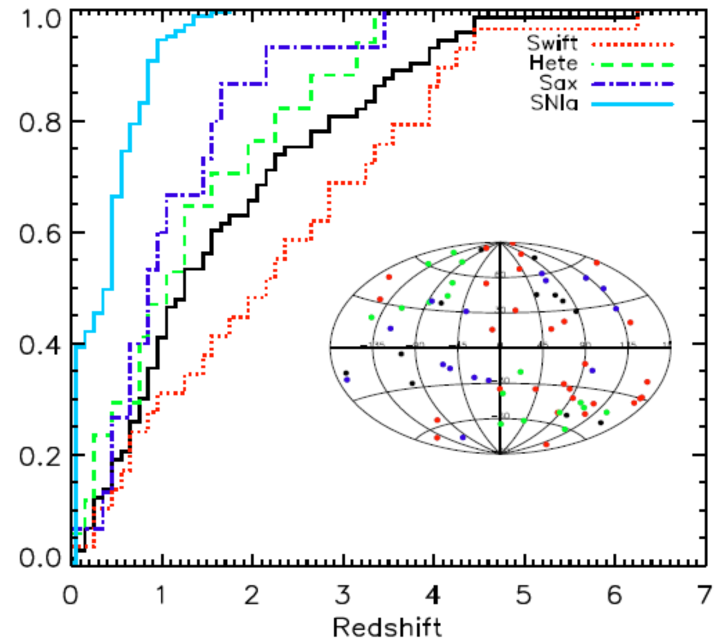
$$E_\gamma = (1-\cos\theta)E_{\gamma,iso}.$$

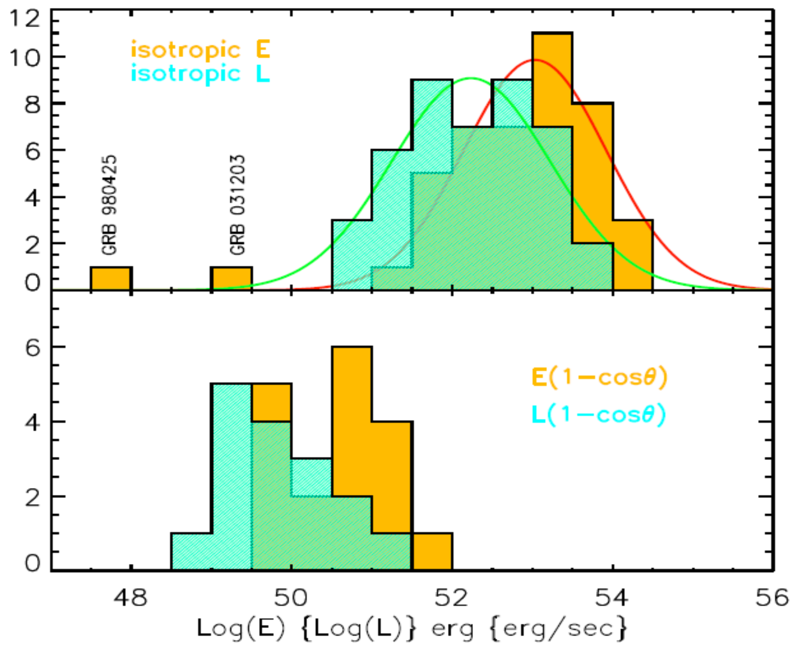


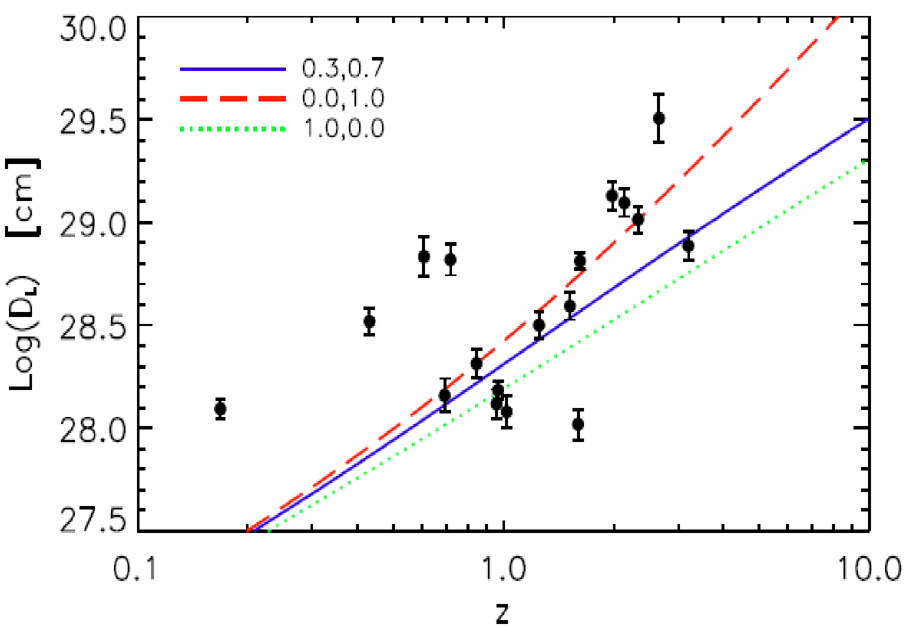


Ghirlanda et al., 2004

- GRB have huge luminosity, a redshift distribution extending far beyond SN Ia
- high energy emission -> no extinction problems

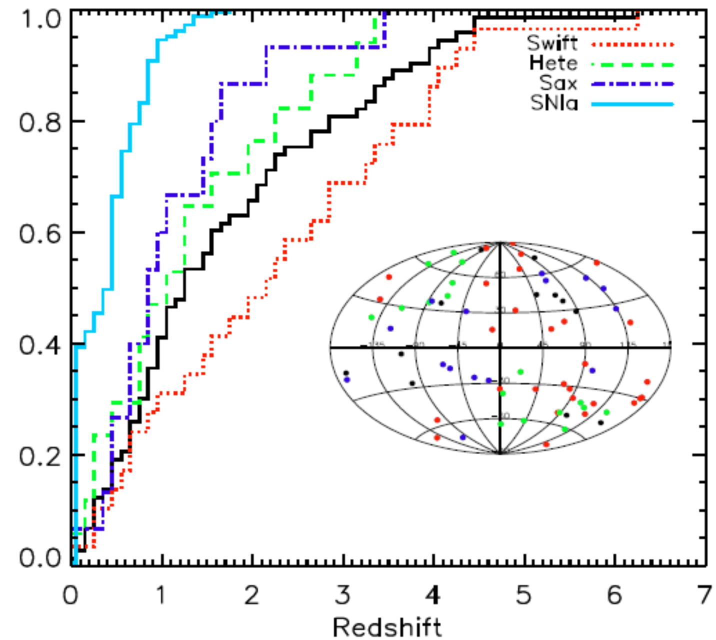


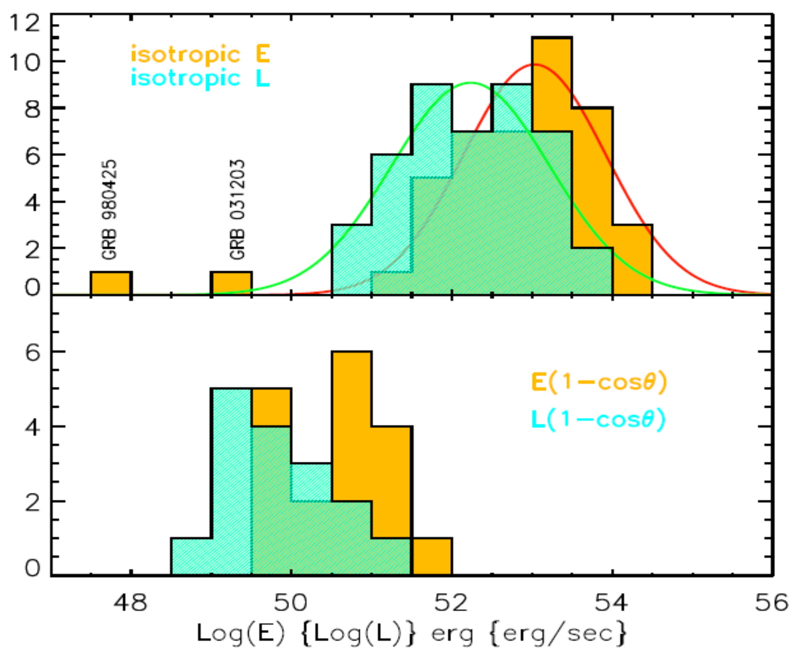


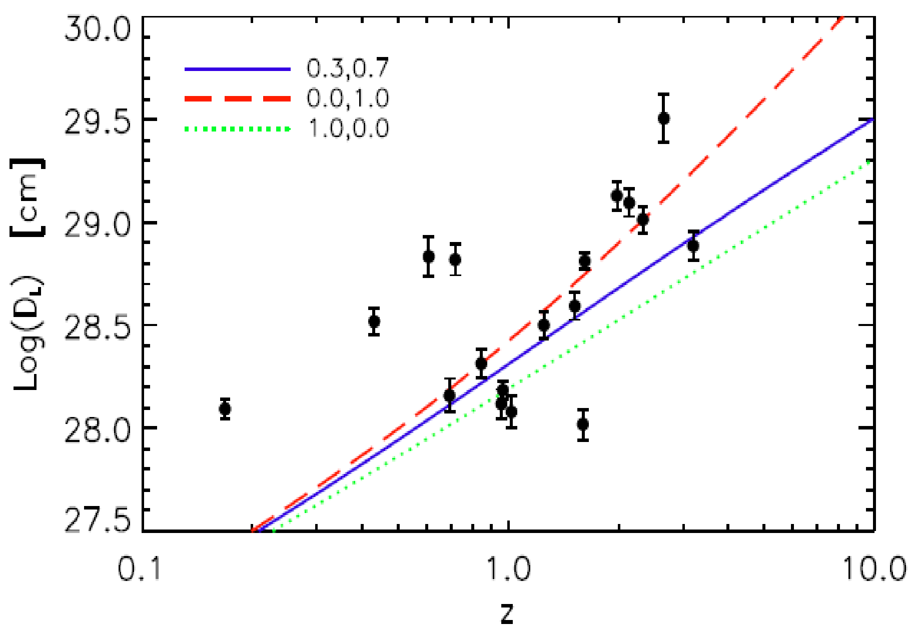


Ghirlanda et al, 2006

- GRB have huge luminosity, a redshift distribution extending far beyond SN Ia
- high energy emission -> no extinction problems
- **potentially powerful cosmological sources but need to investigate their properties to find ways to standardize them (if possible)**







Ghirlanda et al, 2006

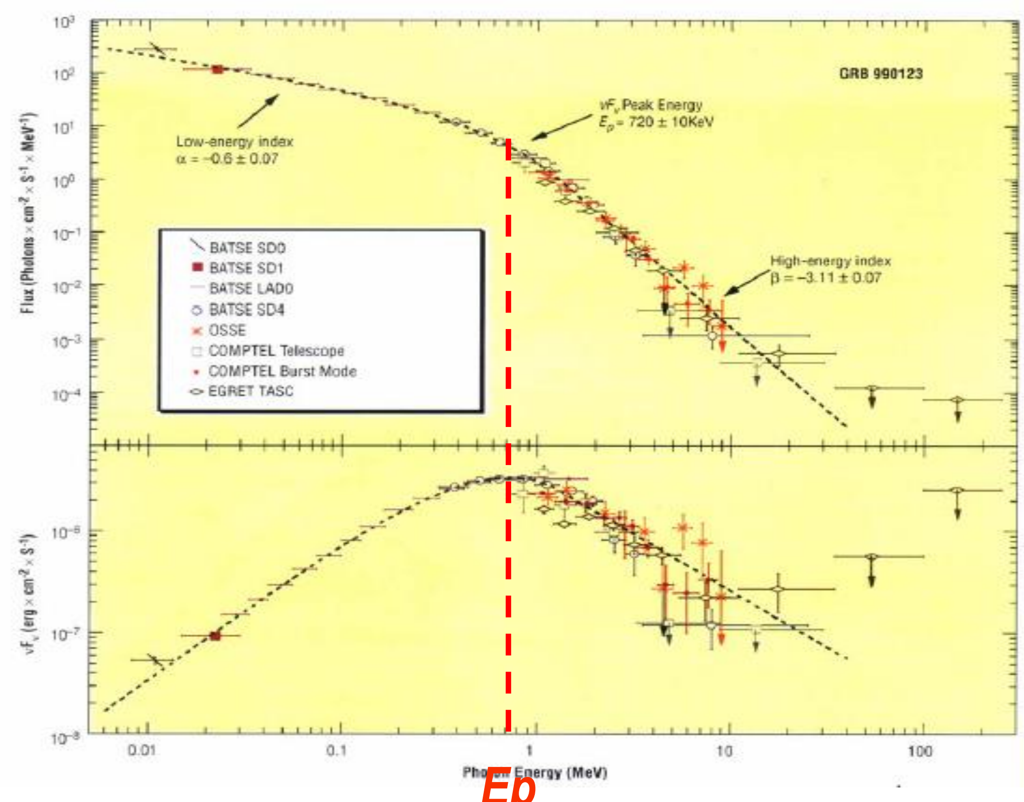
The Ep,i – Eiso correlation

- GRB spectra typically described by the empirical Band function with parameters α= low-energy index, β= high-energy index, E_0=break energy

$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right), \qquad (\alpha-\beta)E_0 \geq E$$

$$= A\left[\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha-\beta} \exp\,(\beta-\alpha)\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta}, \qquad (\alpha-\beta)E_0 \leq E$$

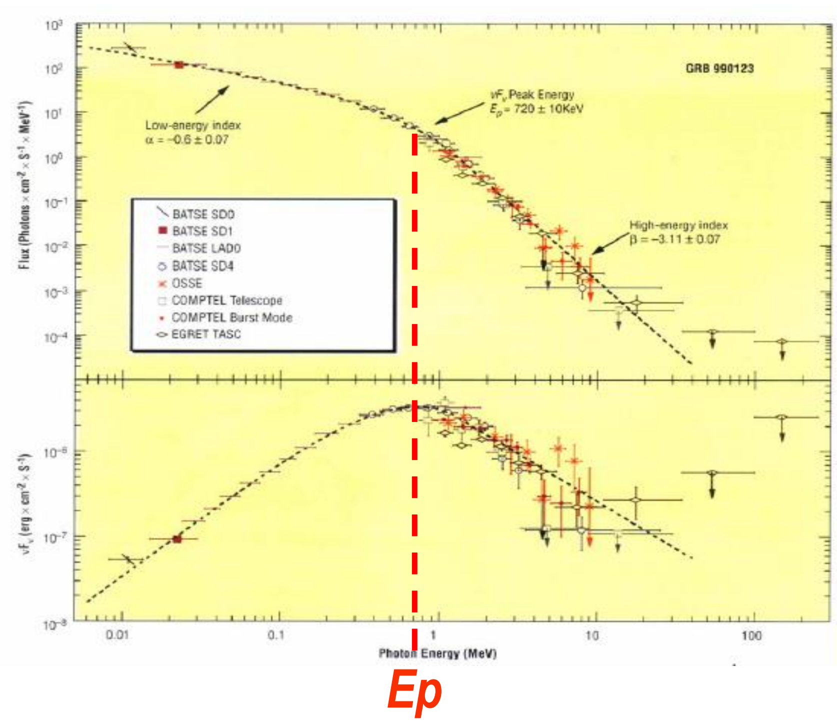
- **$E_p = E_0 \times (2 + \alpha)$ = peak energy of the $\nu F\nu$ spectrum**

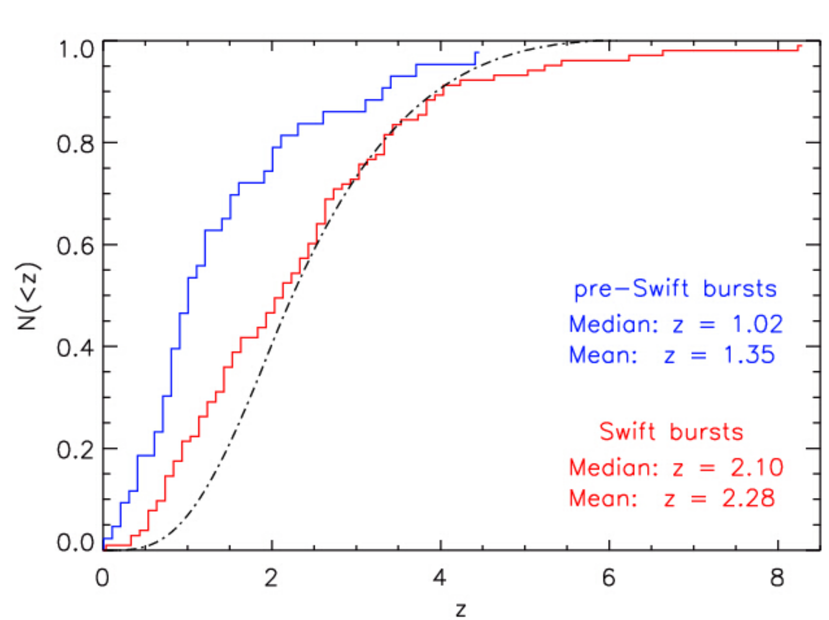


➢ since 1997: measured spectrum + measured redshift -> **intrinsic peak enery Ep,i and radiated energy, average luminosity, peak luminosity**

➢ lack of firm information on jet-opening angles -> use of isotropic-equivalent intensity indicators **(E_{iso}, L_{iso}, $L_{p,iso}$)**

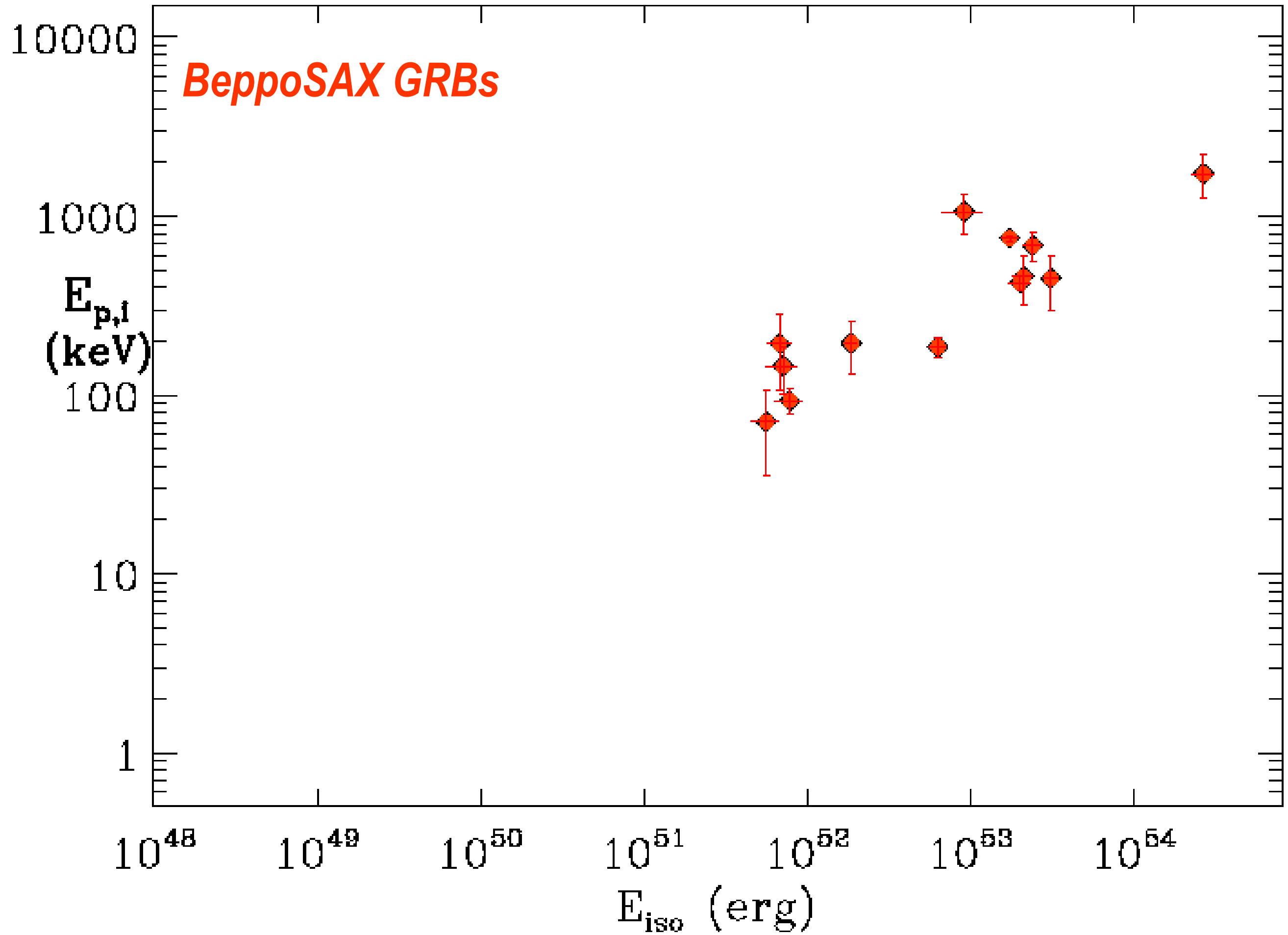
$$E_{p,i} = E_p \times (1 + z) \qquad\qquad E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \mathrm{erg}$$





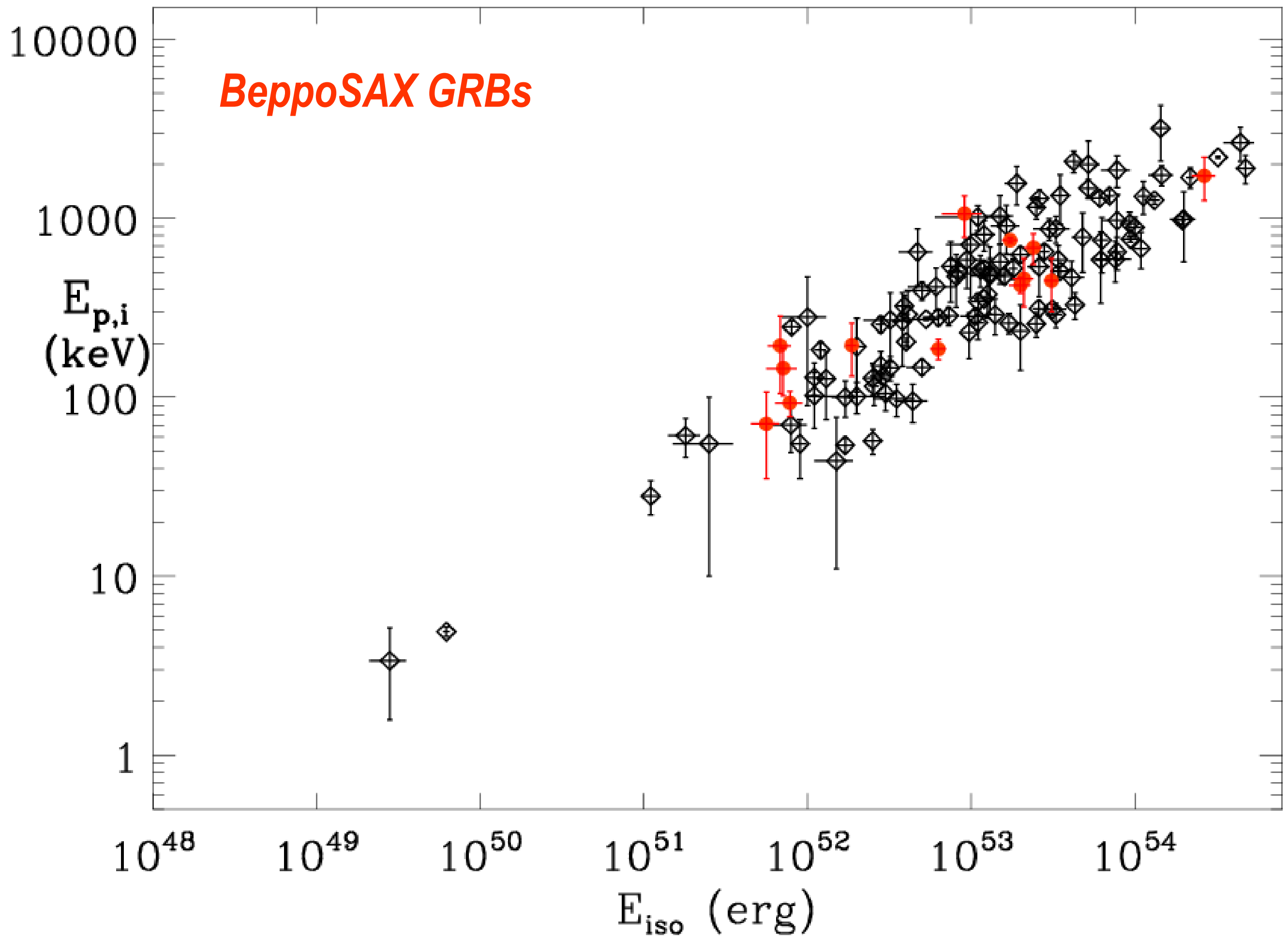
Jakobsson (2009)

➢ 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

130 long GRBs as of Sept. 2011



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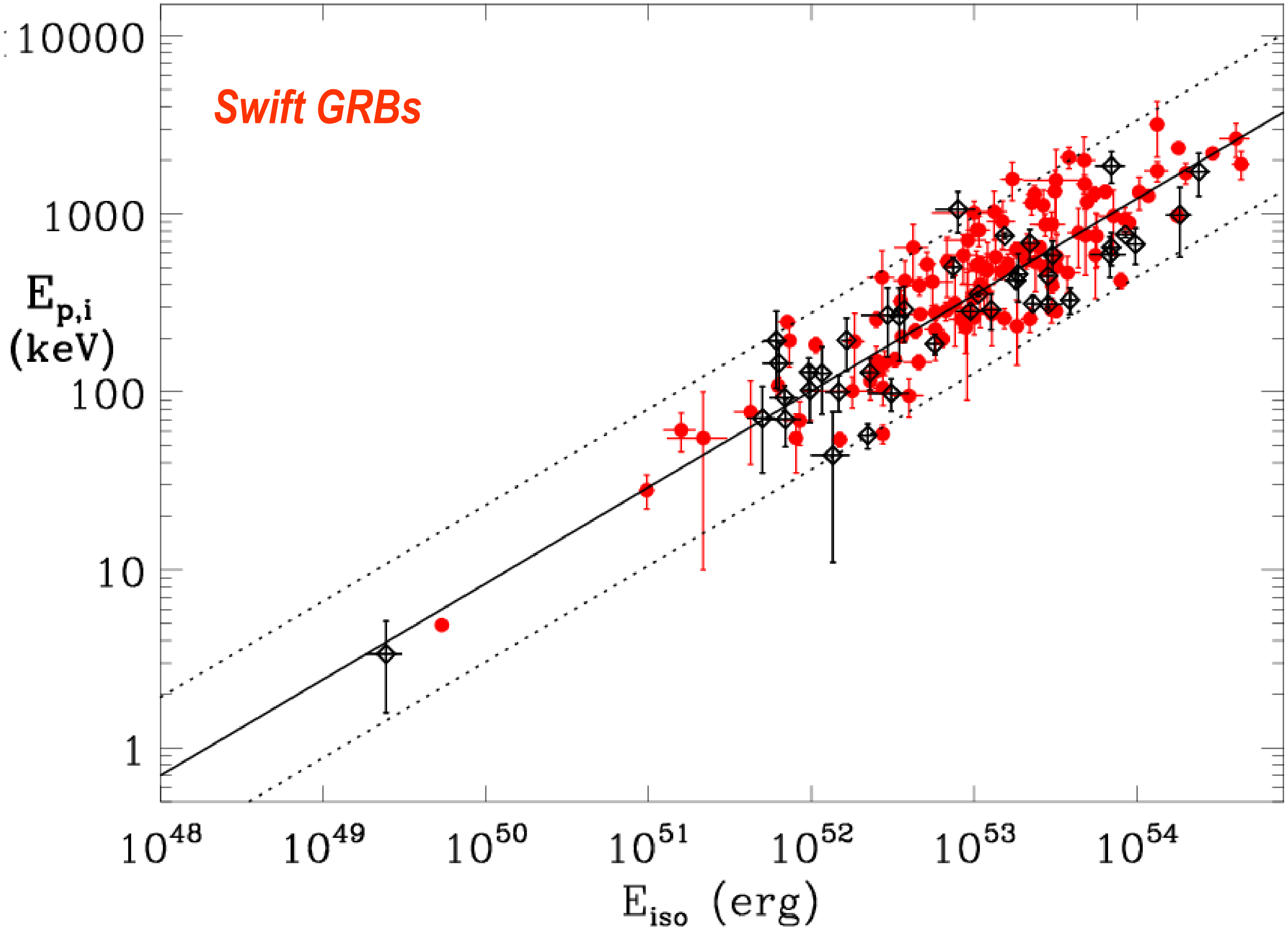
162 long GRBs as of June 2013

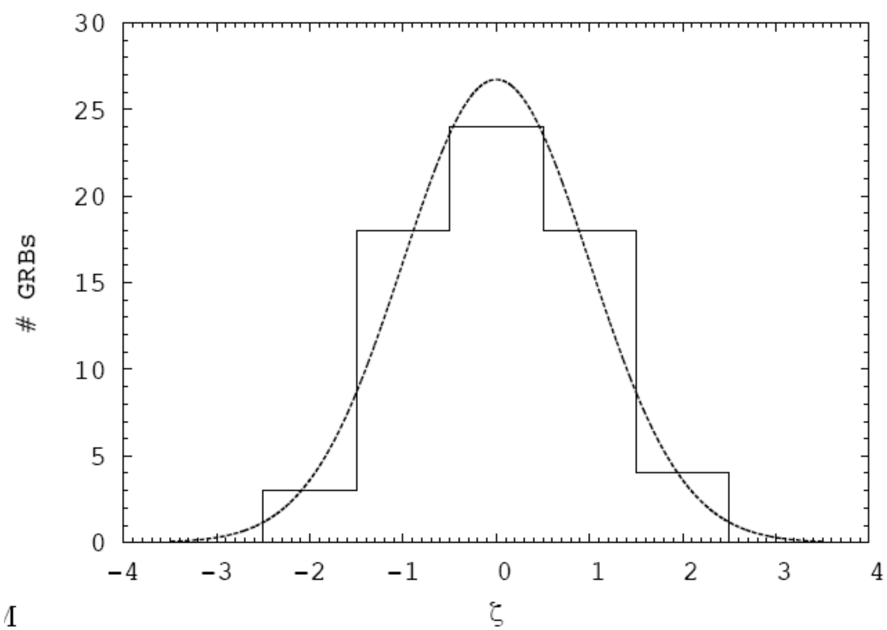


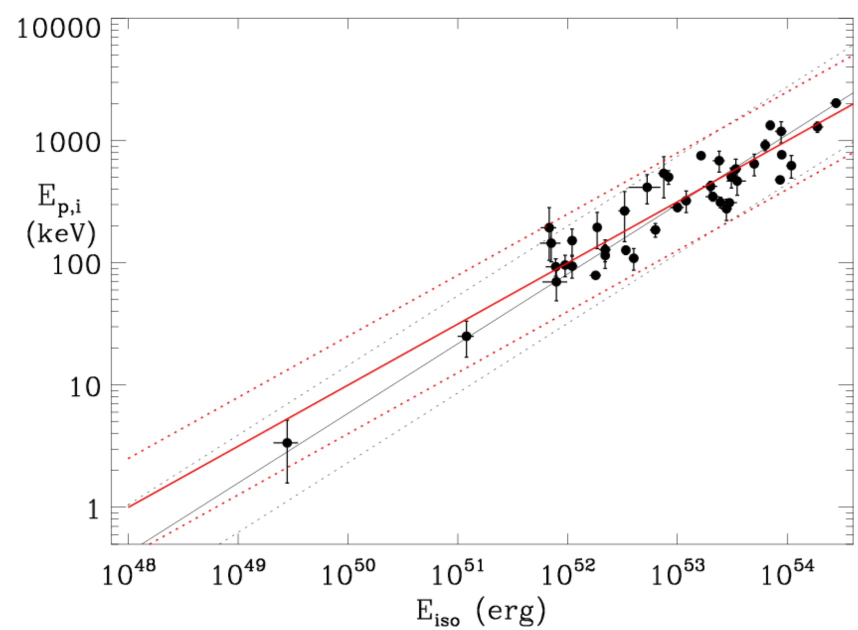
➢ **strong correlation but significant dispersion** of the data around the best-fit power-law; distribution of residuals can be fit with a Gaussian with σ(logEp,i) ~ 0.2

➢ 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) ~ 0.18 and index and normalization t ~0.5 and ~100, respectively



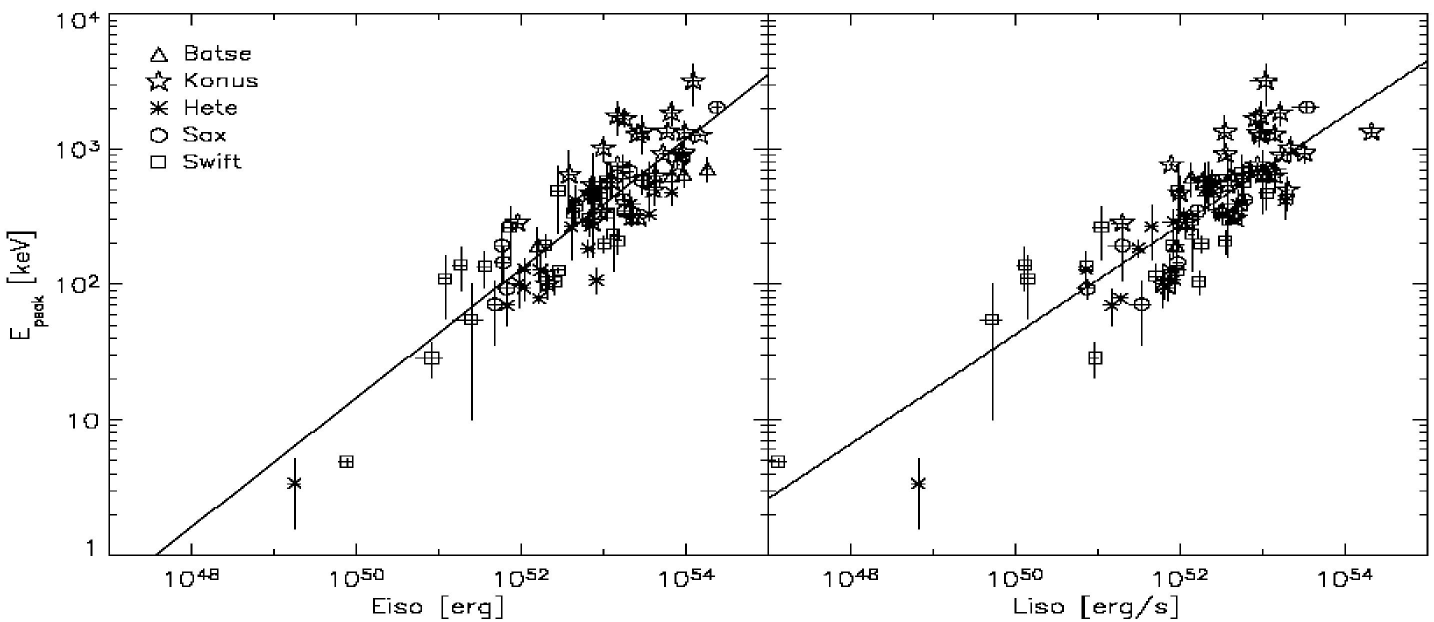


Correlation of Ep,i with other "intensity" indicators

➢ 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

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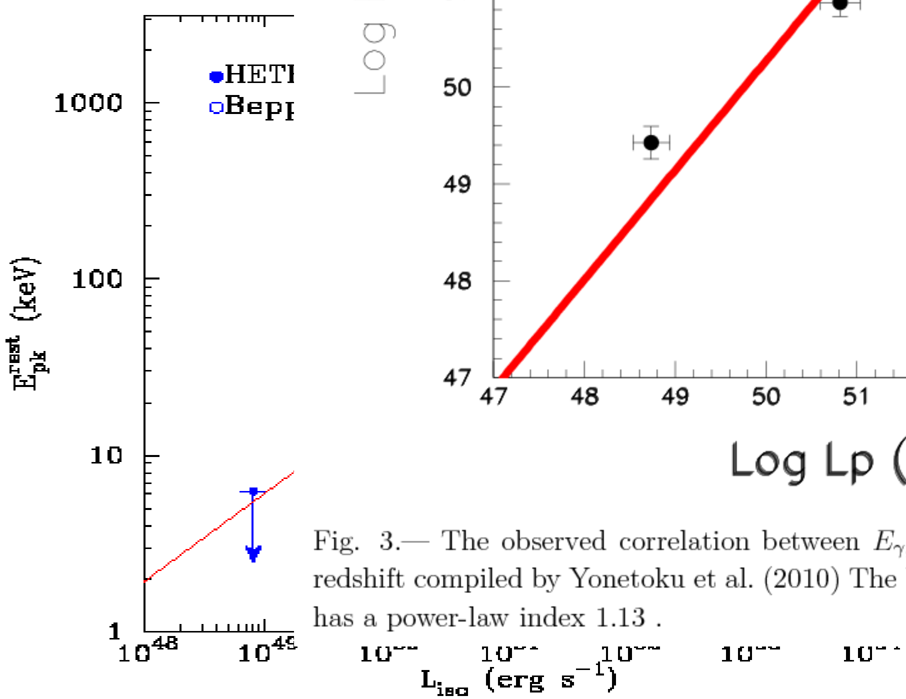


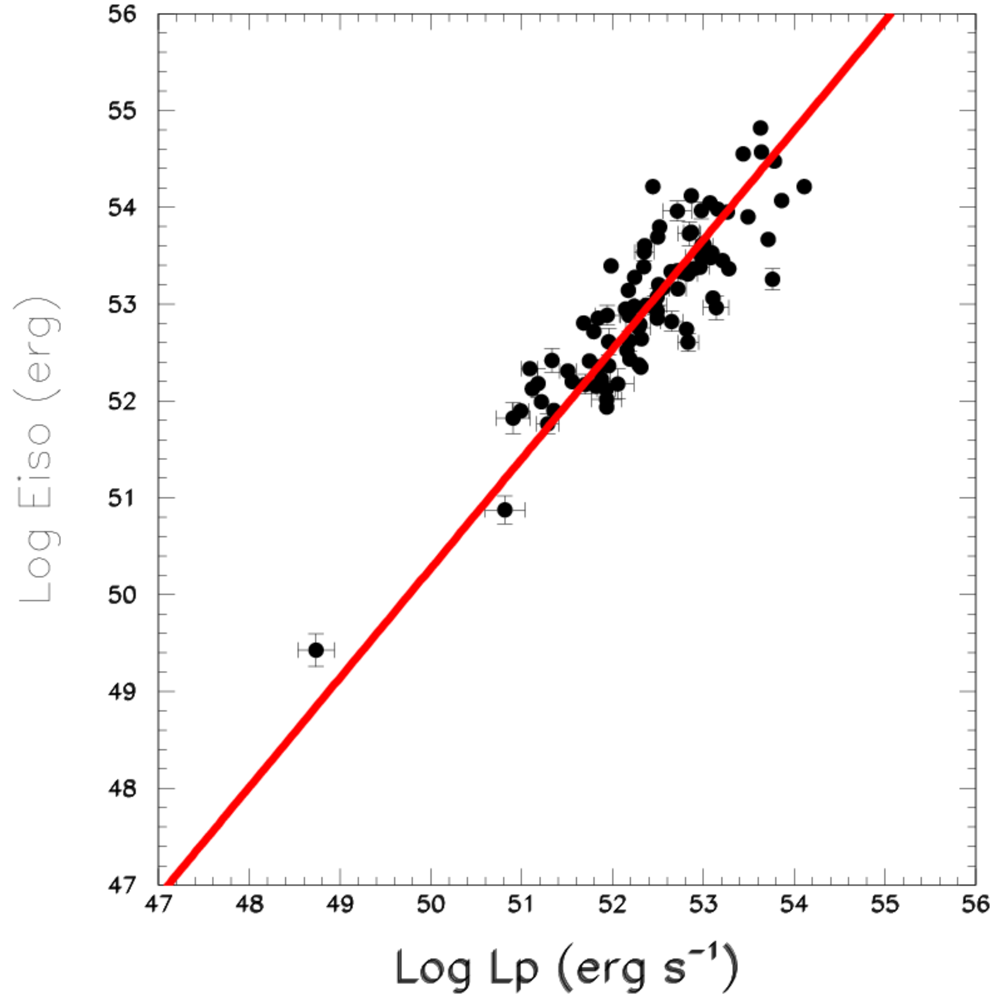
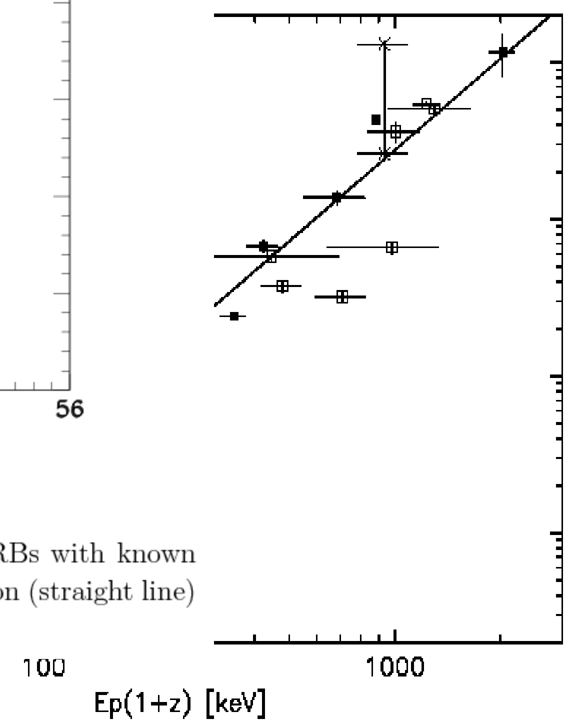


Fig. 3.— The observed correlation between $E_{\gamma,iso}$ and $L_{p,\gamma}$ and for 96 GRBs with known redshift compiled by Yonetoku et al. (2010) The best fit power-law correlation (straight line) has a power-law index 1.13 .



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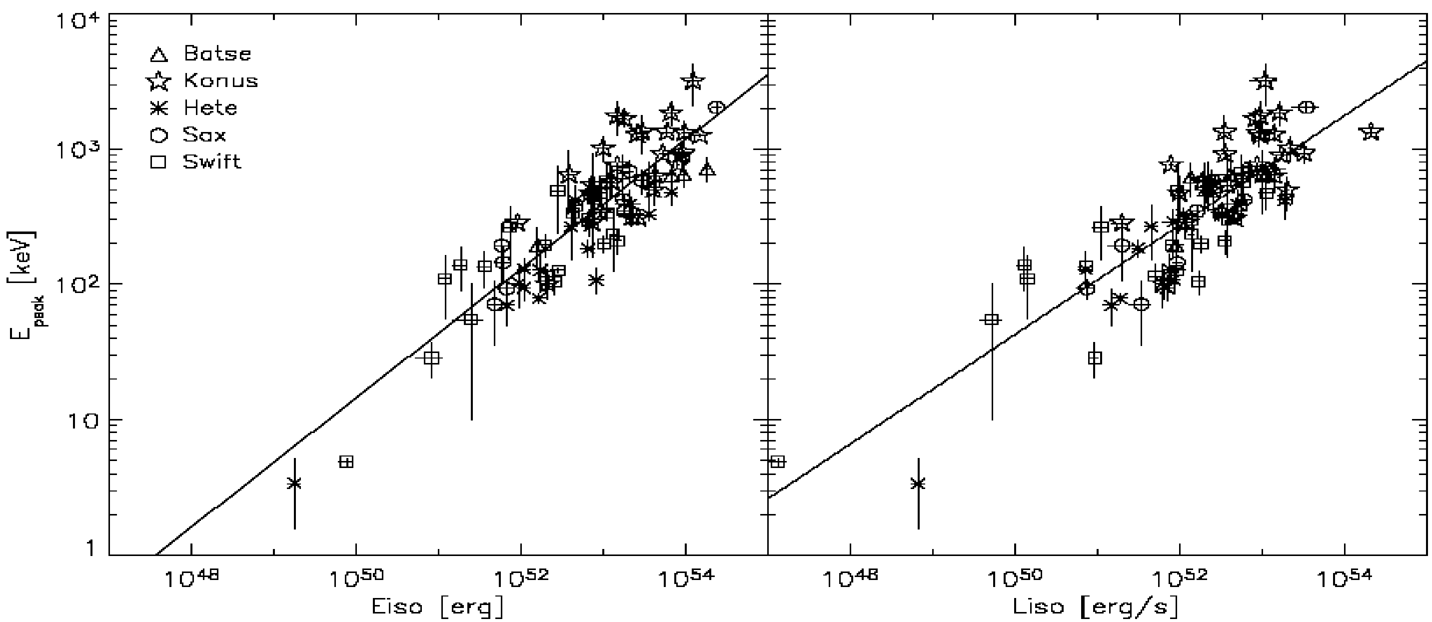
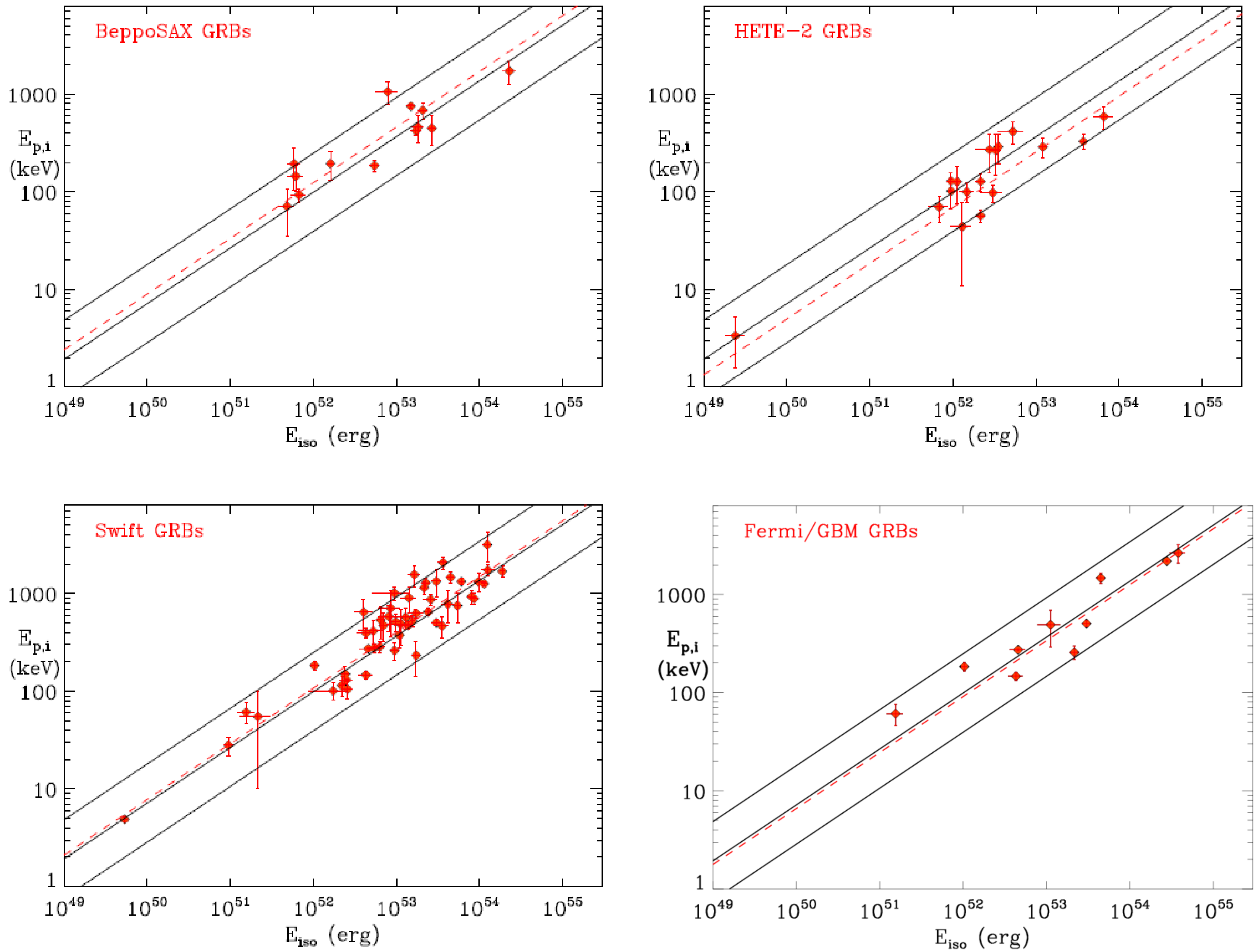


Nava et al. 2009

❑ Amati, Frontera & Guidorzi (2009): the normalization of the correlation varies only marginally using measures by individual instruments with different sensitivities and energy bands: **-> no relevant selection effects**



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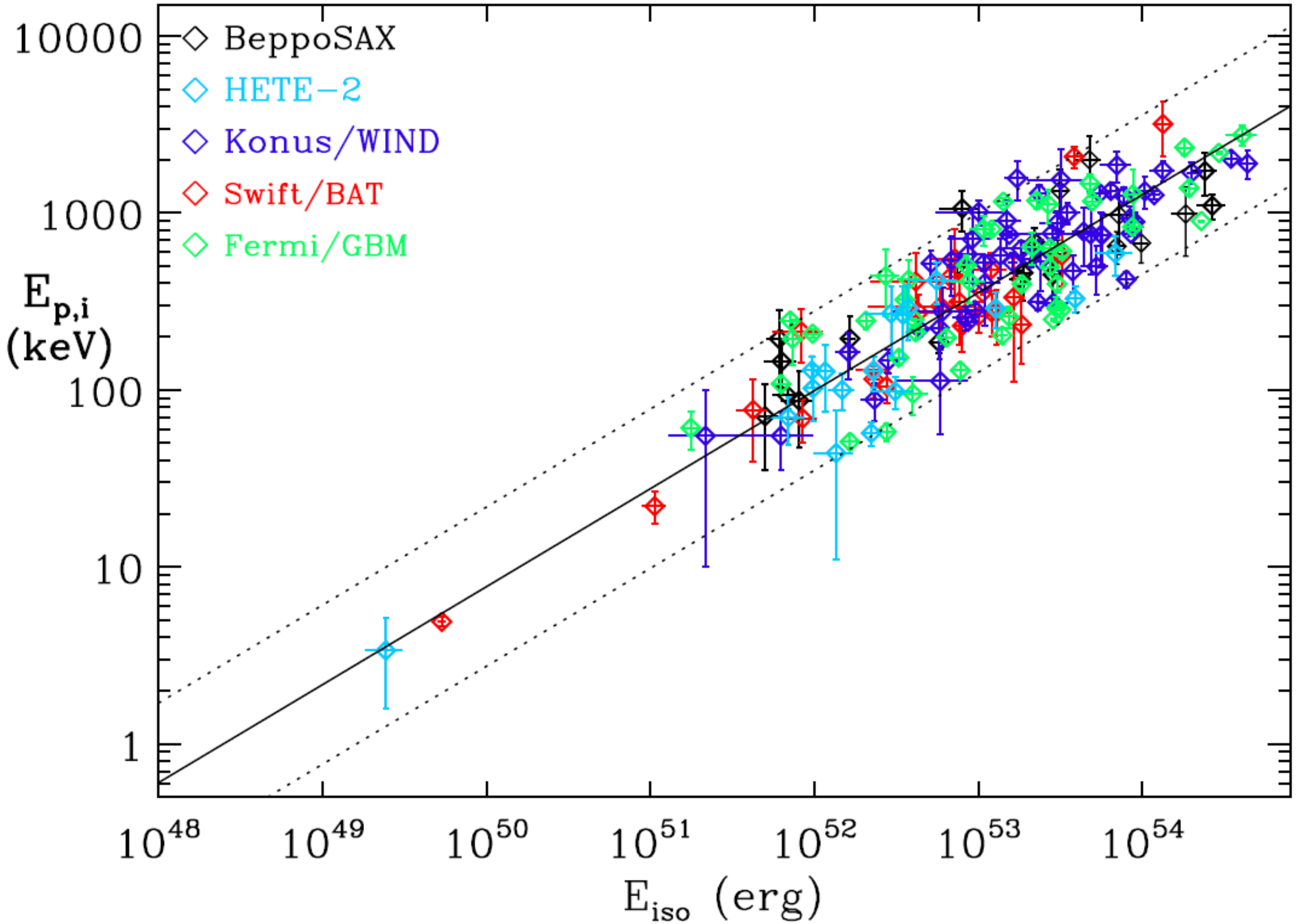
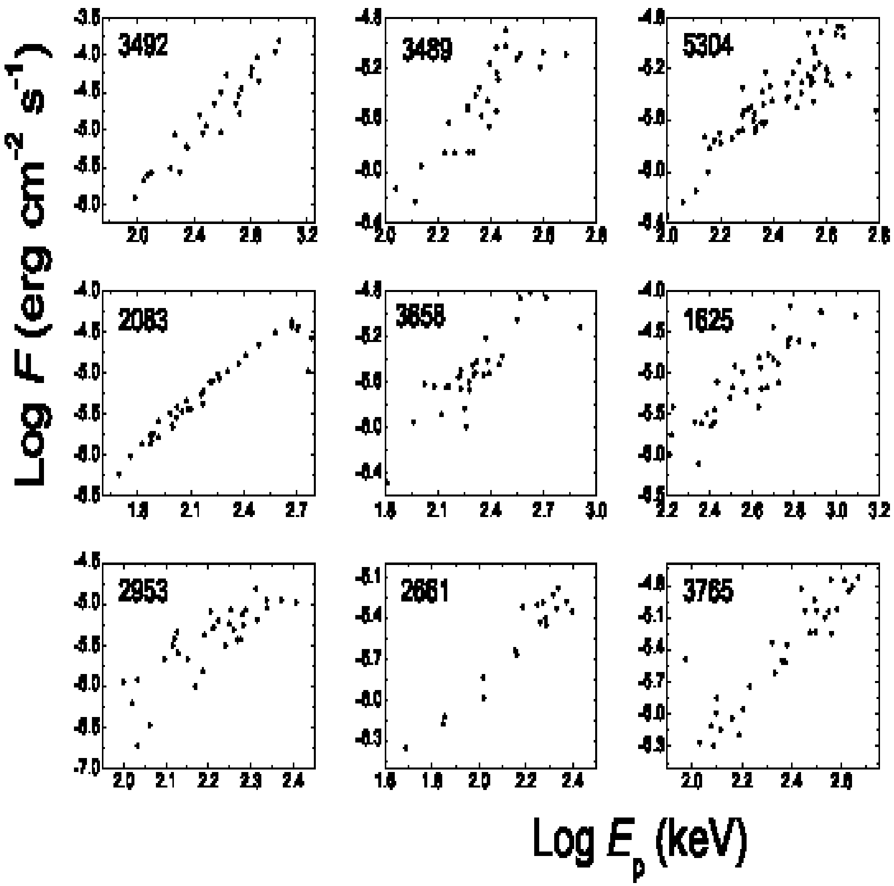
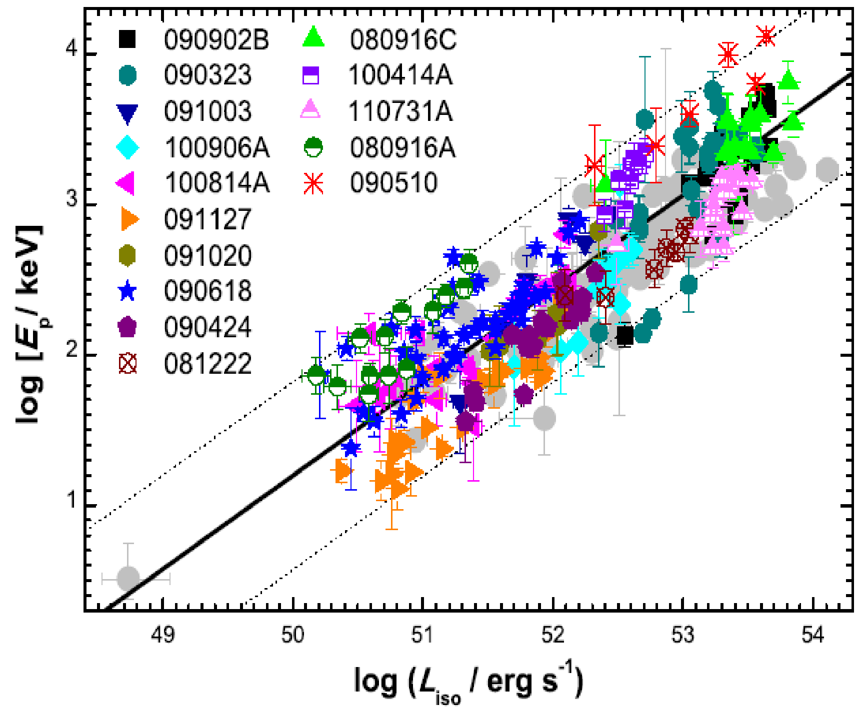


Amati & Della Valle 2013

➢ the Ep,i– Liso and Ep,I – Eiso correlation holds also within a good fraction of 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**

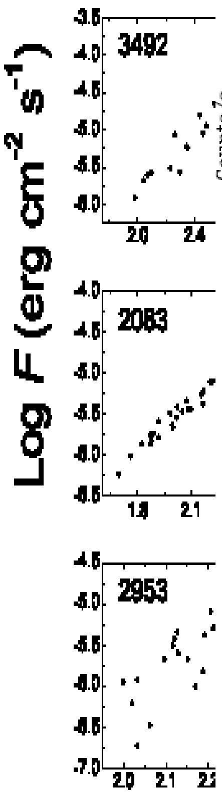


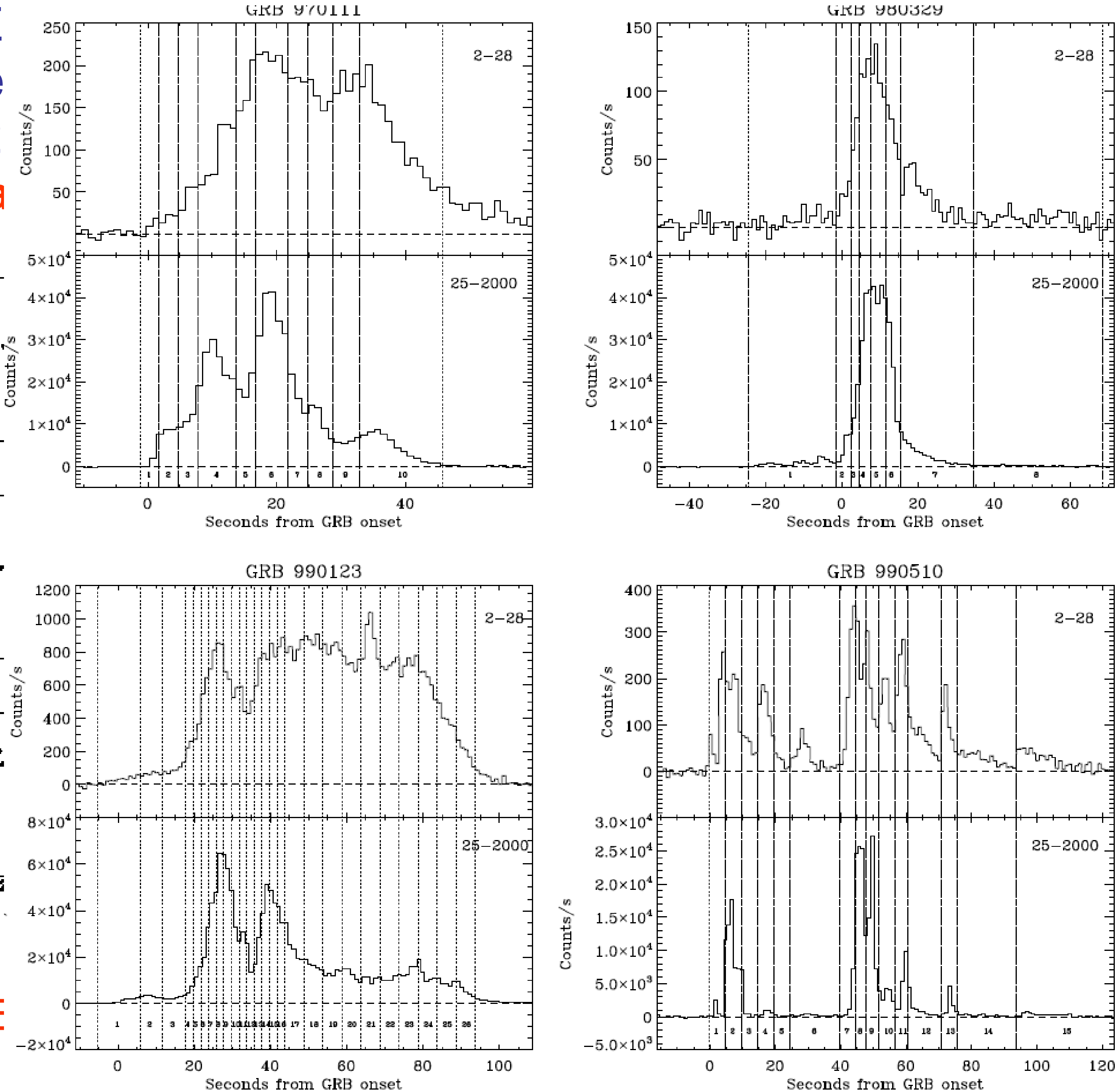
BATSE (Liang et al., ApJ, 2004)

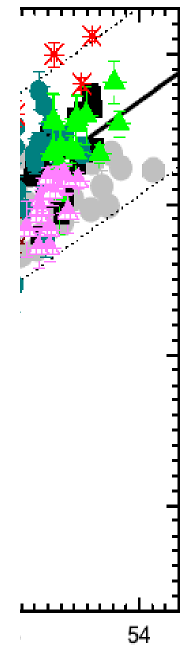


Fermi (e.g., Li et al. , ApJ, 2012)

➢ the E … on of GRBs (Liang e … Frontera et al. 2012 … ues to explana…







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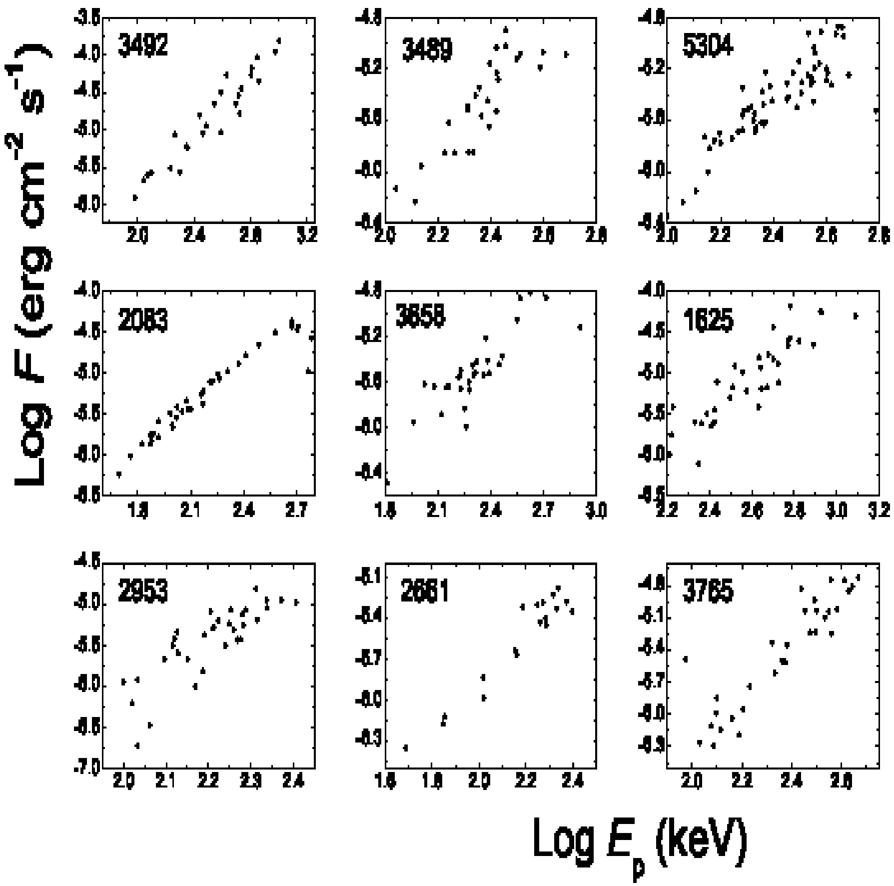
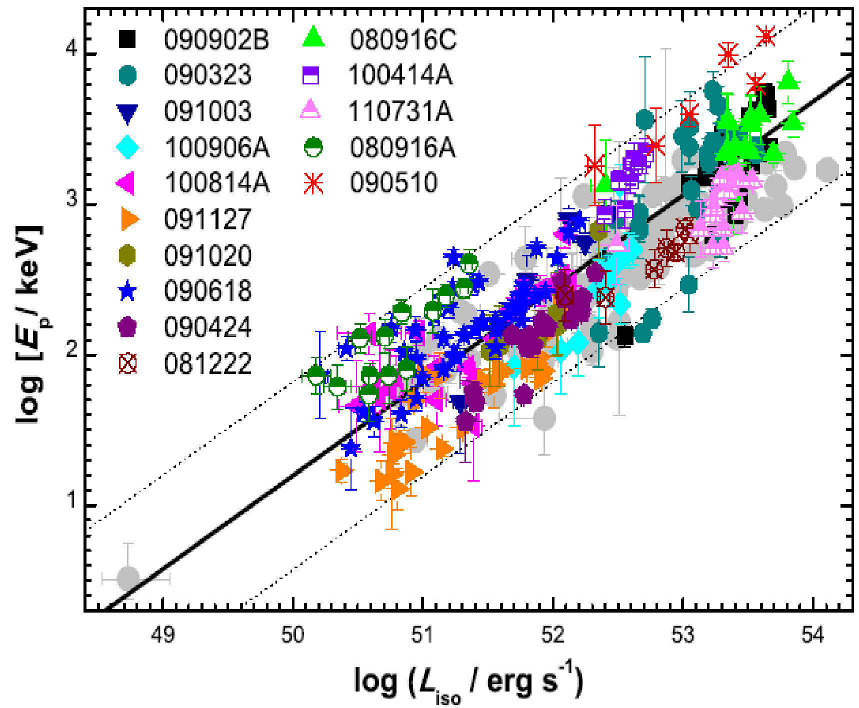




BATSE (Liang et al., ApJ, 2004)

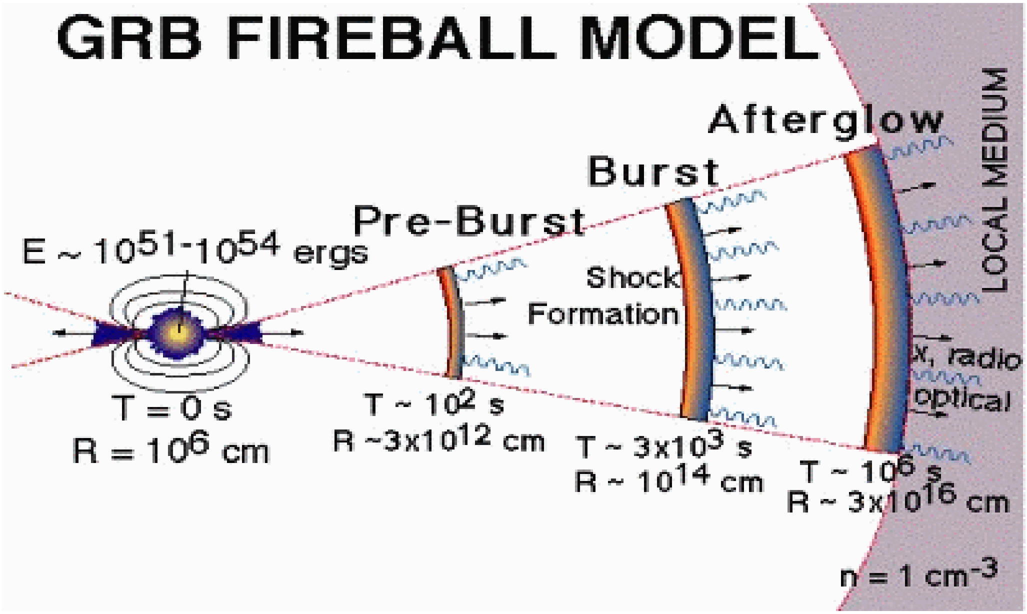
Fermi (e.g., Li et al. , ApJ, 2012)

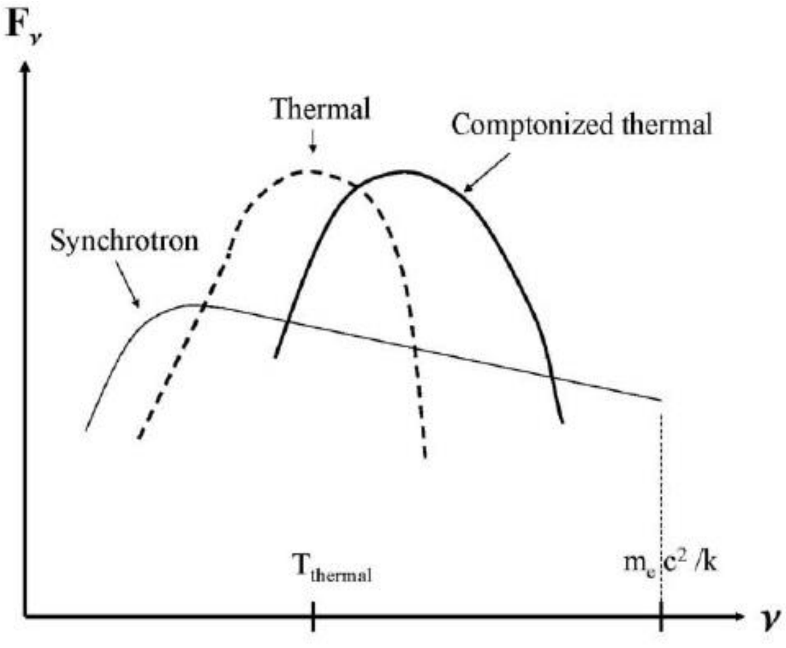
Implications: emission physics and geometry

- physics of prompt emission still not settled, various scenarios: SSM internal shocks, IC-dominated internal shocks, external shocks, photospheric emission dominated models, kinetic energy / Poynting flux dominated fireballs, …

- e.g. $E_{\rm pk} \propto \Gamma^{-2} t_{\rm var}^{-1} L^{1/2}$ for syncrotron emission from a power-law distribution of electrons generated in an internal shock (Zhang & Meszaros 2002, Ryde 2005)

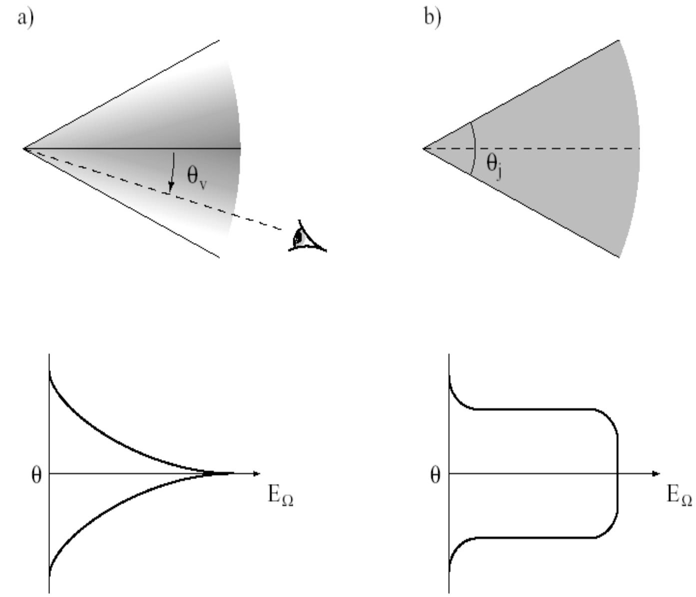
- e.g., $E_p \propto R_0^{-1/2} t_j^{-1/4} E_{\rm iso}^{1/2}$ in scenarios in whch for comptonized thermal emission from the photosphere dominates (e.g. Rees & Meszaros 2005, Thomson et al. 2006)

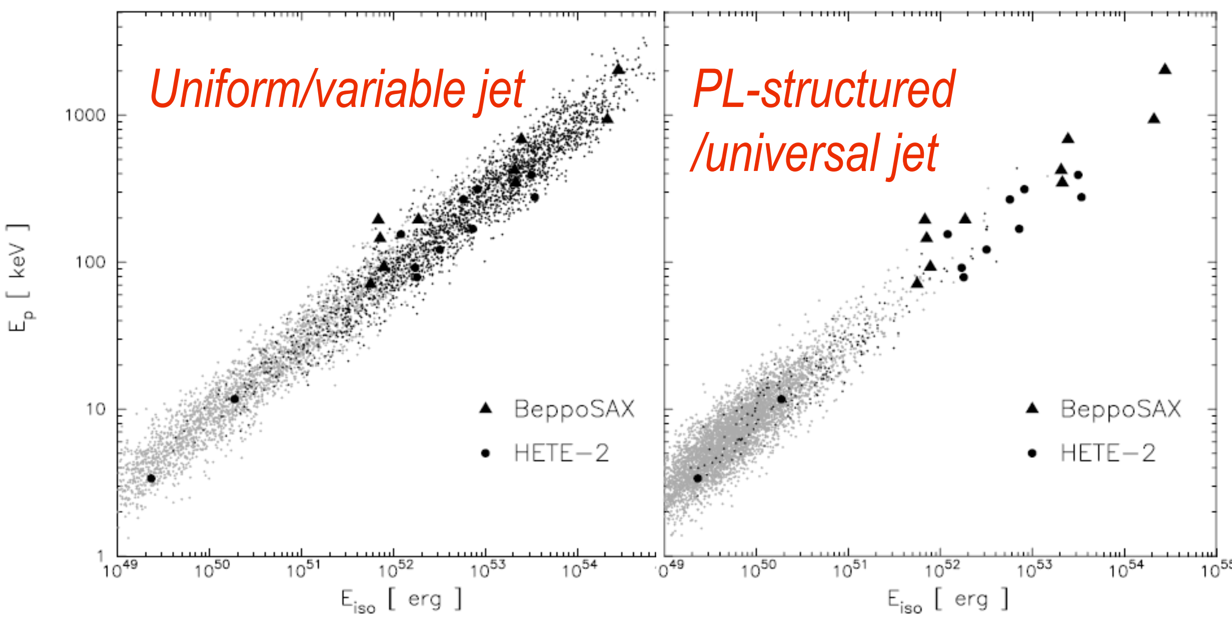




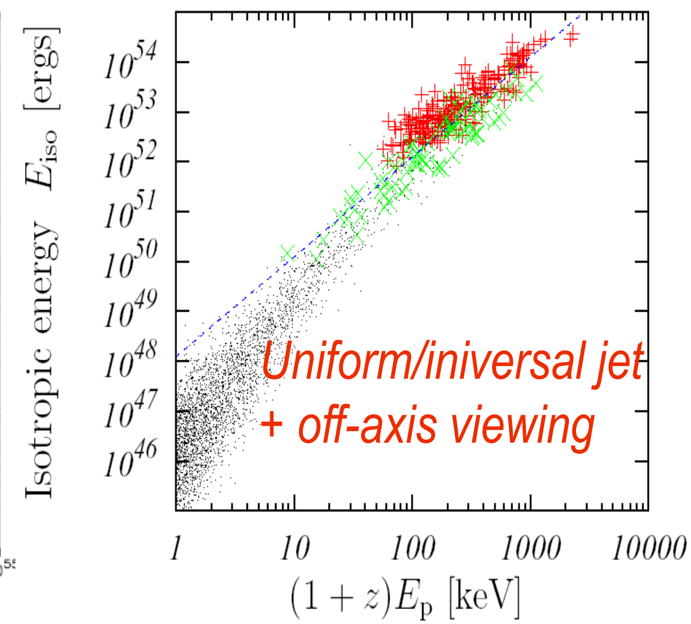
- ❑ jet geometry and structure and XRF-GRB unification models (e.g., Lamb et al. 2004)

- ❑ viewing angle effects: $\delta=[\gamma(1 - \beta\cos(\theta v - \Delta\theta))]^{-1}$, $\Delta Ep \propto \delta$, $\Delta Eiso \propto \delta^{(1+\alpha)}$ (e.g, Yamazaki et al.)





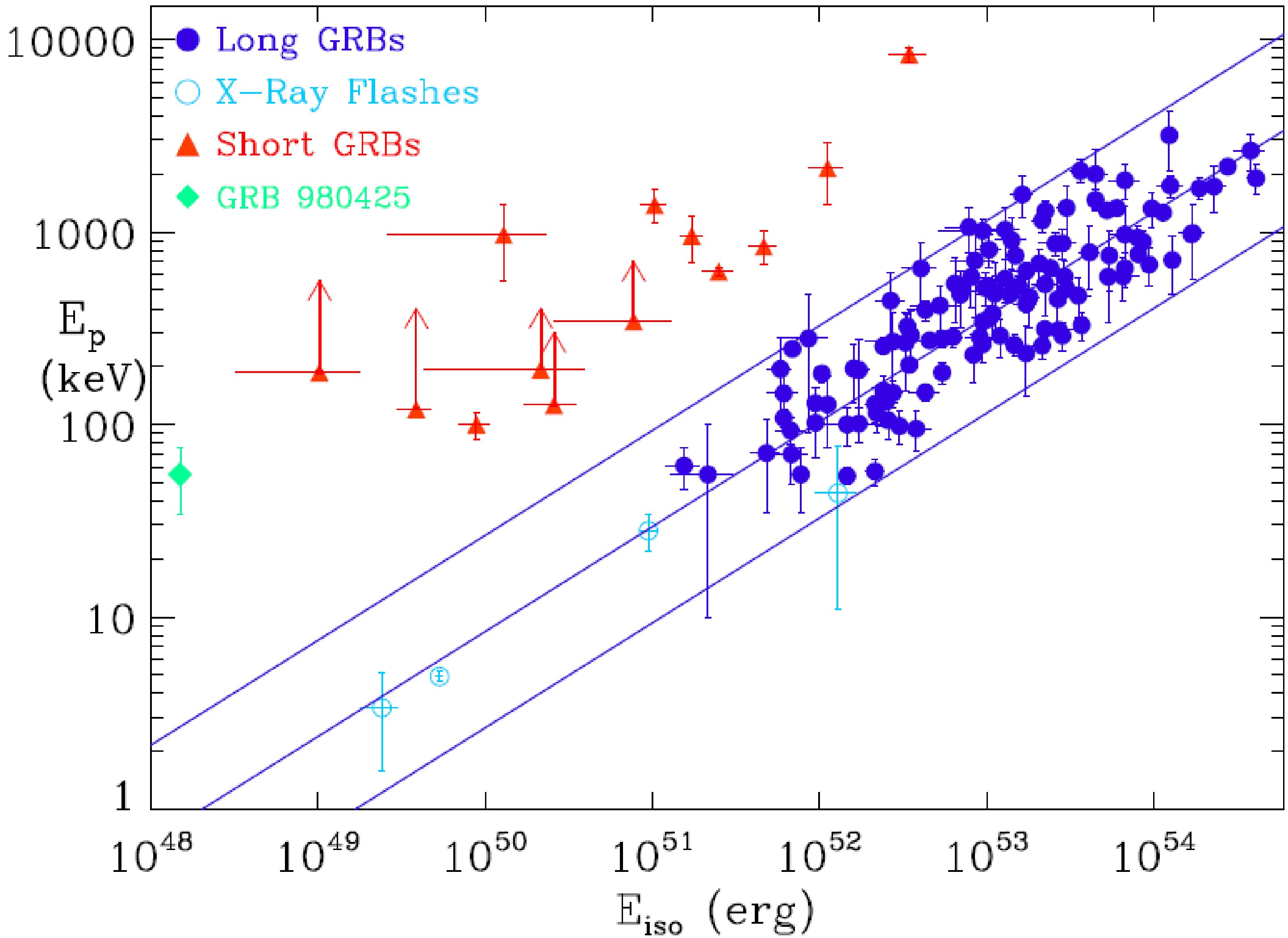
Lamb et al. 2005



Yamazaki et al. 2004

➢ *Implications: sub-classes of GRBs*

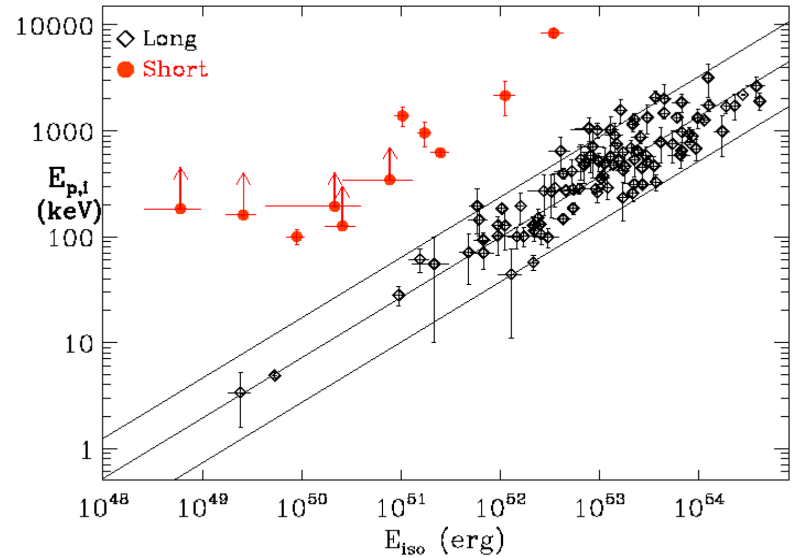
➢ Sept. 2012 Ep,i – Eiso plane: 148 long GRBs, 4 XRFs, 13 short GRBs

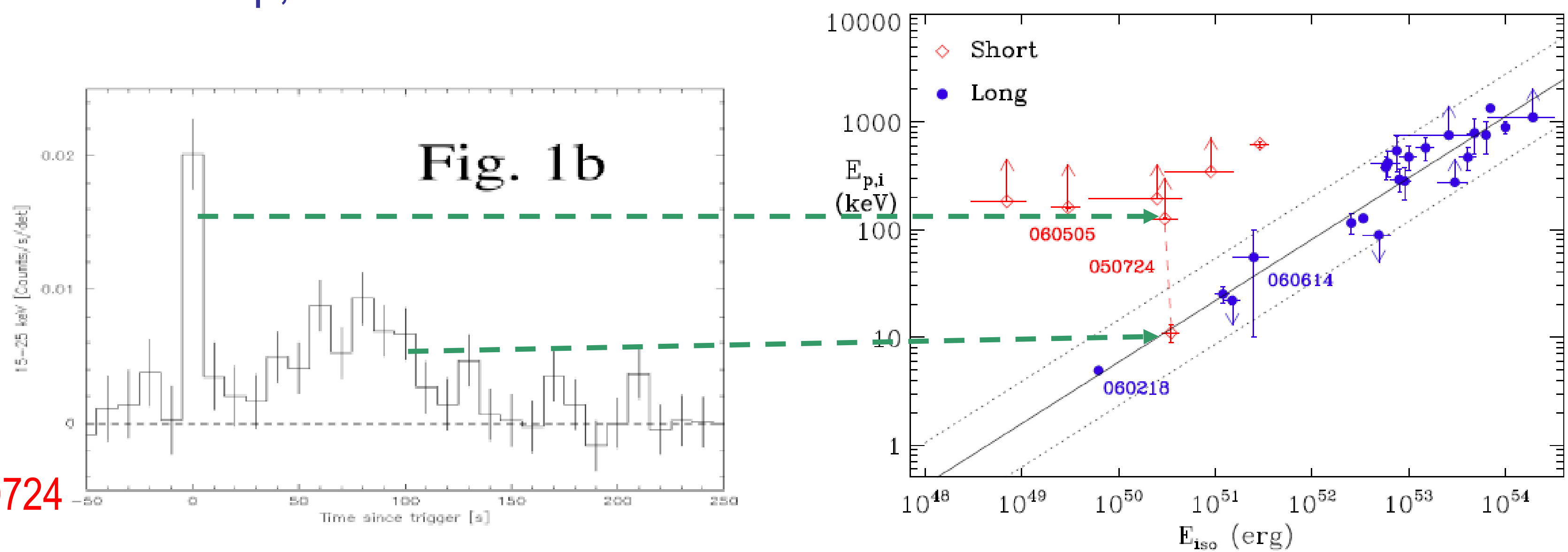


❑estimates and limits on Ep,i and Eiso are inconsistent with Ep,i-Eiso correlation holding for long GRBs

❑ low Eiso values and high lower limits to Ep,i indicate inconsistency also for the other short GRBs

❑ long weak soft emission in some cases, consistent with the Ep,i – Eiso correlations





GRB0050724

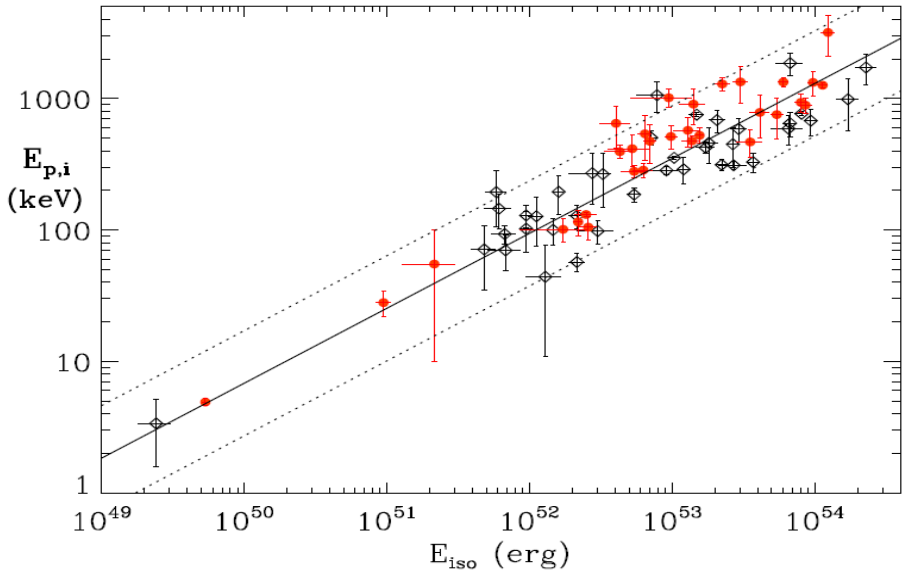
"Standardizing" GRB with the Ep,i - Intensity correlation

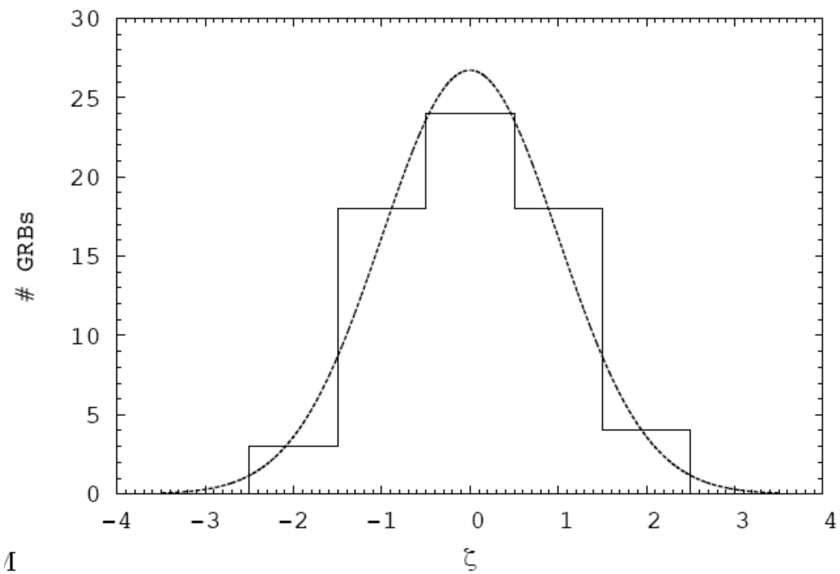
$E_{p,i} = E_{p,obs} \times (1 + z)$

$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg} \longrightarrow D_l = D_l(z\,,\,H_0,\,\Omega_M,\,\Omega_\Lambda,\ldots)$$

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

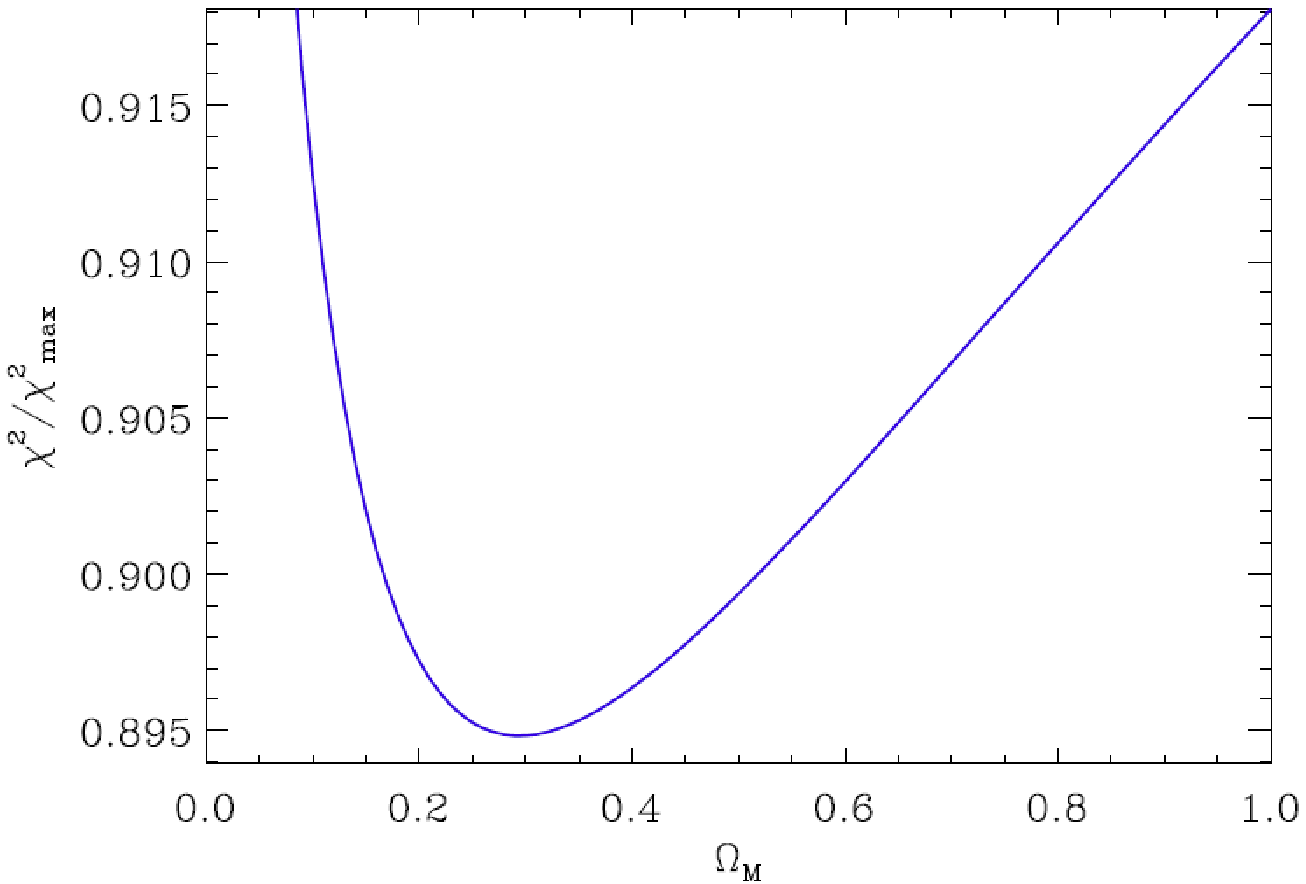
- does the extrinsic scatter and goodness of fit of the Ep,i-Eiso correlation vary with the cosmological parameters used to compute Eiso ?





- 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

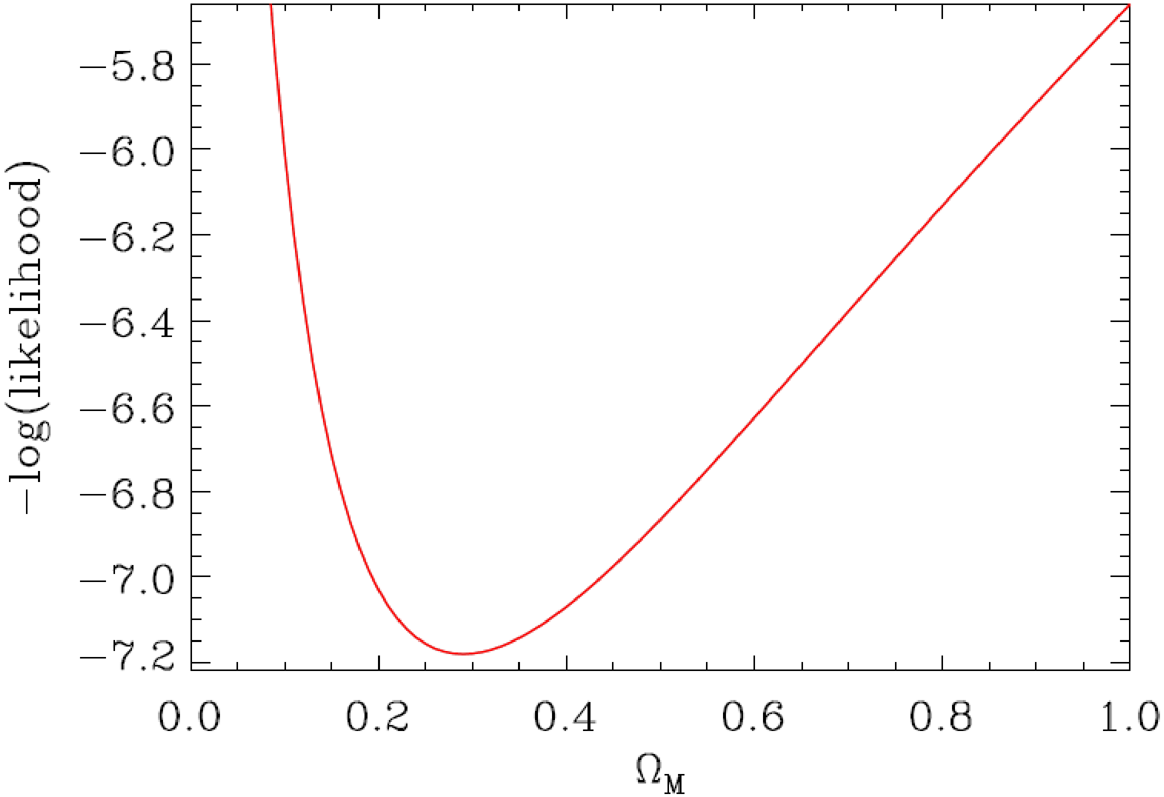


Amati et al. 2008, 2013

- 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 0.04-0.43 (68%) and 0.02-0.71 (90%) for a flat ΛCDM universe (Ω_M = 1 excluded at 99.9% c.l.)

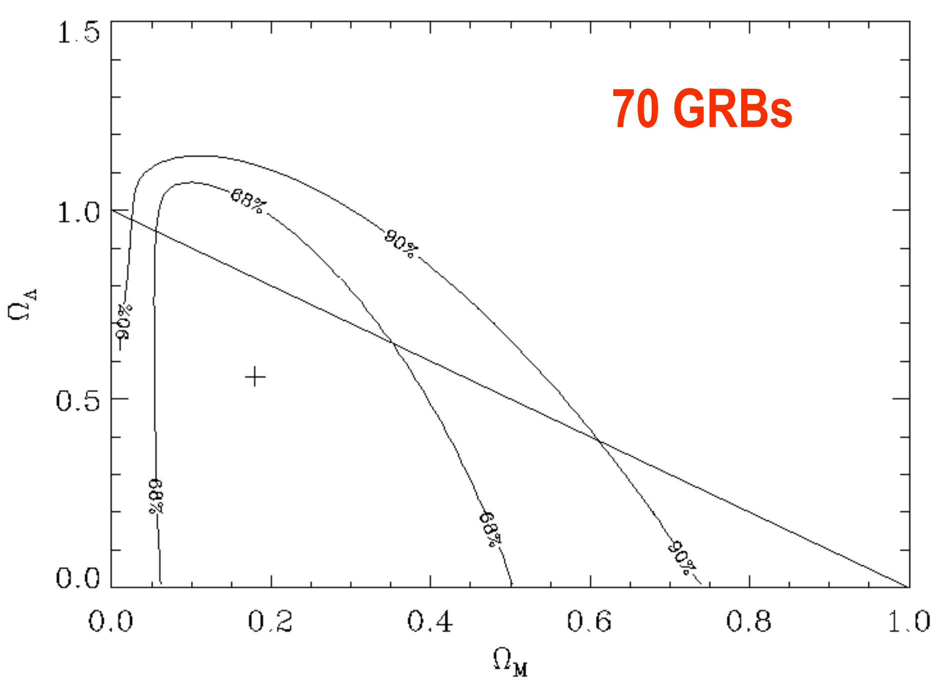


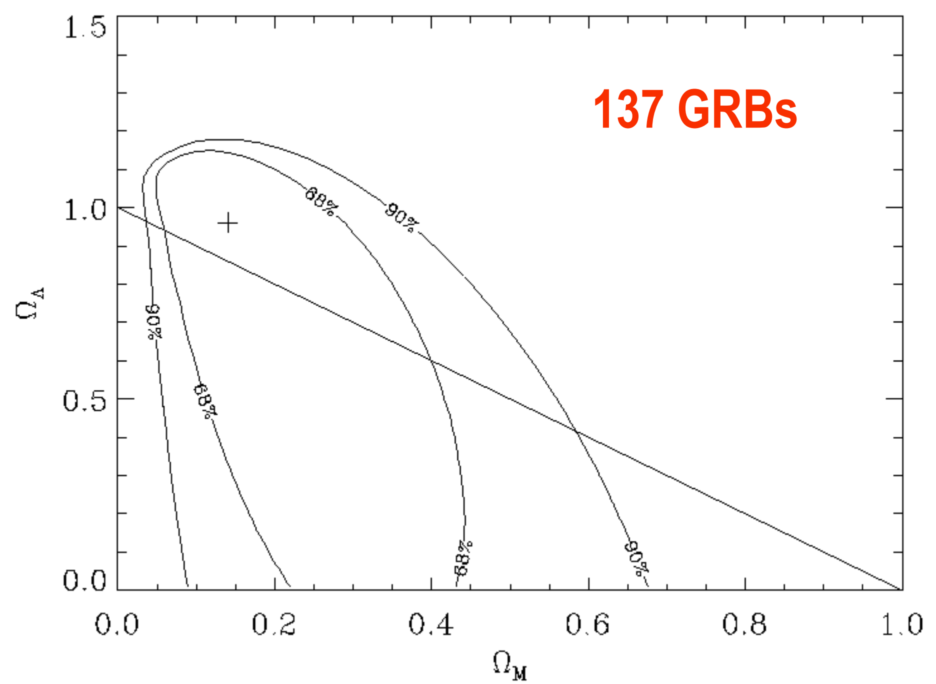
Amati et al. 2008, 2013

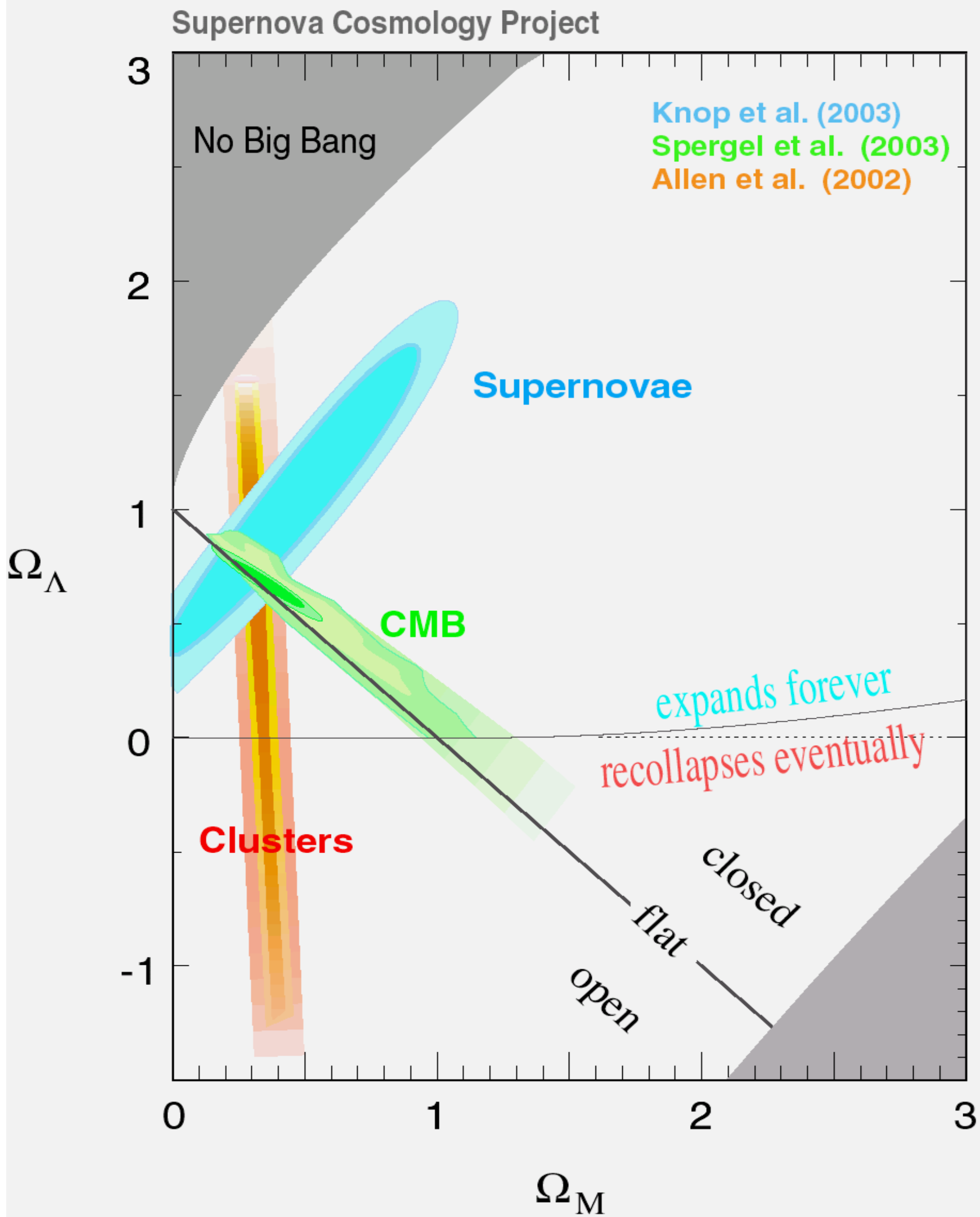
➢ analysis of updated sample of 137 GRBs (Amati+12) shows significant improvements w/r to the sample of 70 GRBs of Amati et al. (2008)

➢ 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
recollapses eventually
closed
flat
open
3
2
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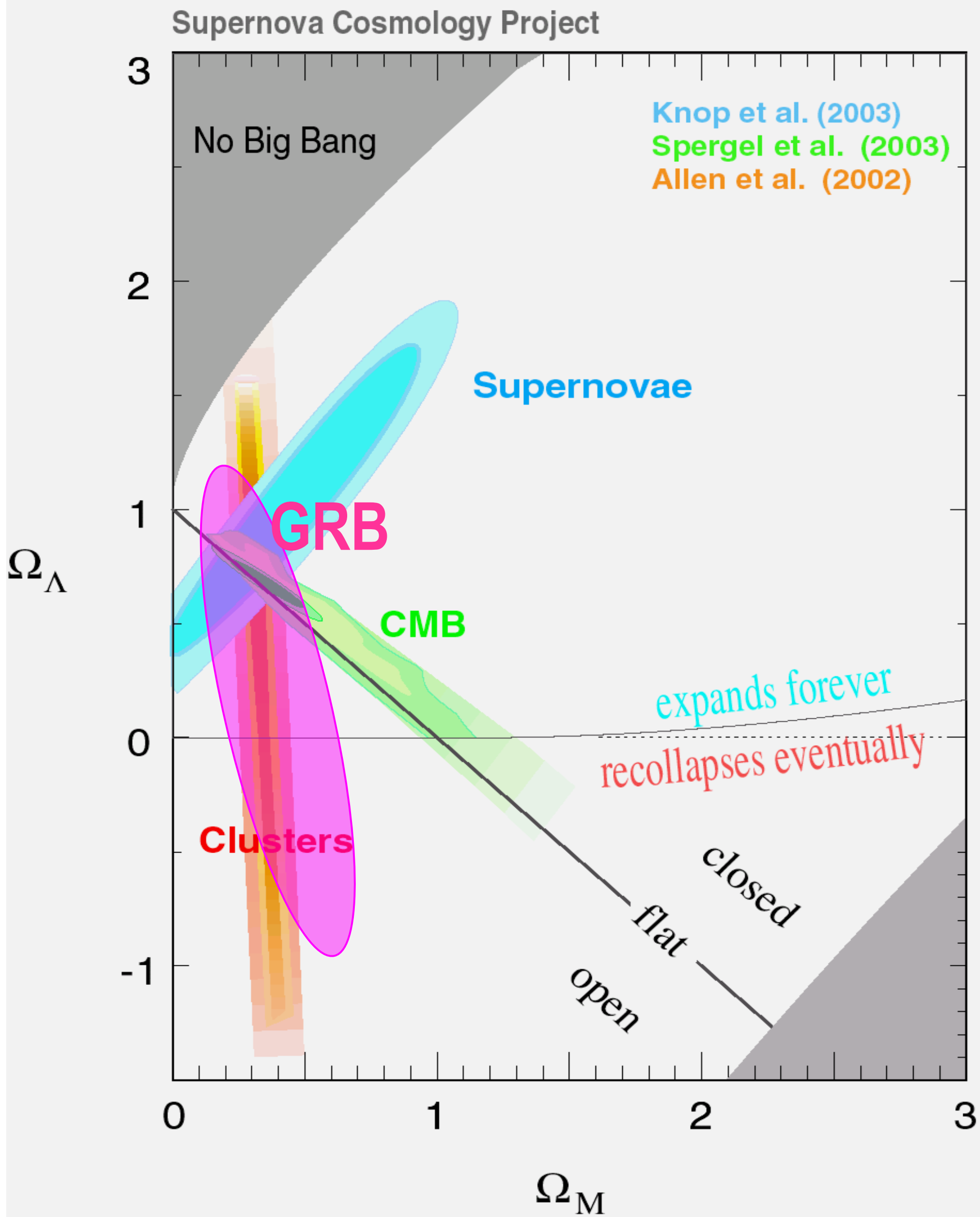
Ω_Λ
Ω_M



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Perspectives

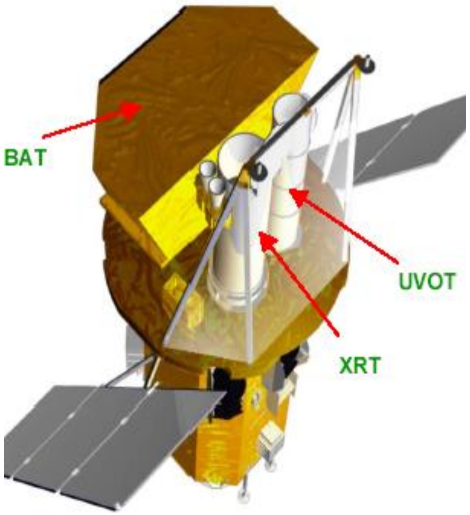
❑ **present and near future: main contribution expected from joint Fermi + Swift measurements**

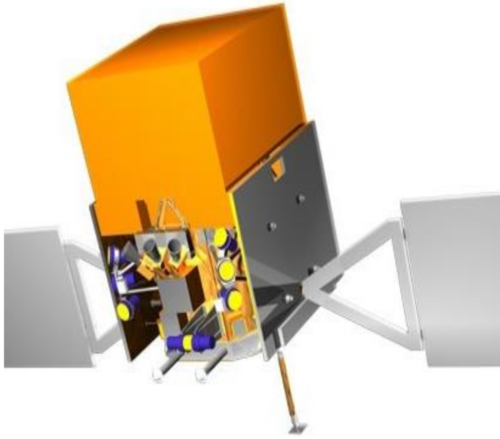
➢ Up to 2009: ~290 Fermi/GBM GRBs, Ep estimates for ~90%, ~35 simultaneously detected by Swift (~13%), 13 with **Ep and z** estimates **(~10% of Swift sample)**

➢ 2008 pre-Fermi : 61 Swift detections, 5 BAT Ep (8%), 15 BAT + KONUS + SUZAKU Ep estimates (25%), 20 redshift (33%), 11 with **Ep and z** estimates **(~15% of Swift sample)**

➢ Fermi provides a dramatic increase in Ep estimates (as expected), but a only small fraction of Fermi GRBs is detected / localized by Swift (~15%) -> **low number of Fermi GRBs with Ep and z (~5%)**.

➢ **Summary: 15-20 GRB/year in the Ep,i – Eiso plane**





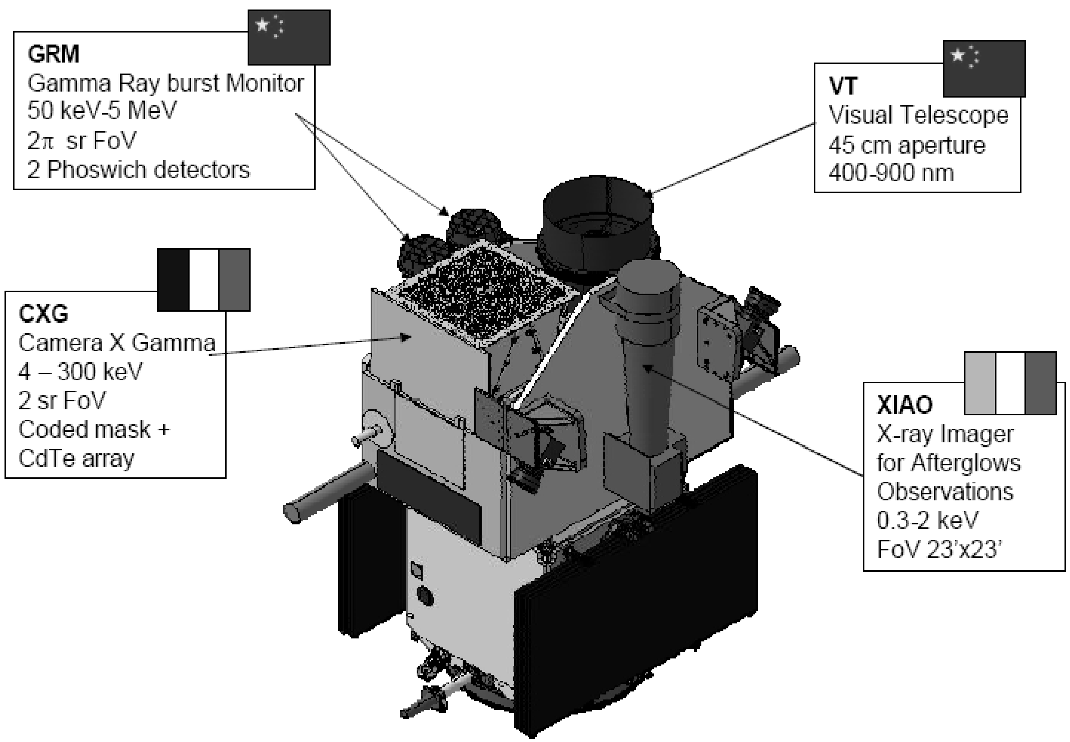
❑ In the > 2020 time frame a significant step forward expected from SVOM (+ UFFO, CALET/GBM ?)

➢ spectral study of prompt emission in 5-5000 keV -> accurate estimates of Ep and reduction of systematics (through optimal continuum shape determination and measurement of the spectral evolution down to X-rays)

➢ fast and accurate localization of optical counterpart and prompt dissemination to optical telescopes -> increase in number of z estimates and reduction of selection effects

➢ optimized for detection of XRFs, short GRB, sub-energetic GRB, high-z GRB

➢ substantial increase of the number of GRB with known z and Ep -> test of correlations and calibration for their cosmological use



❑ 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)

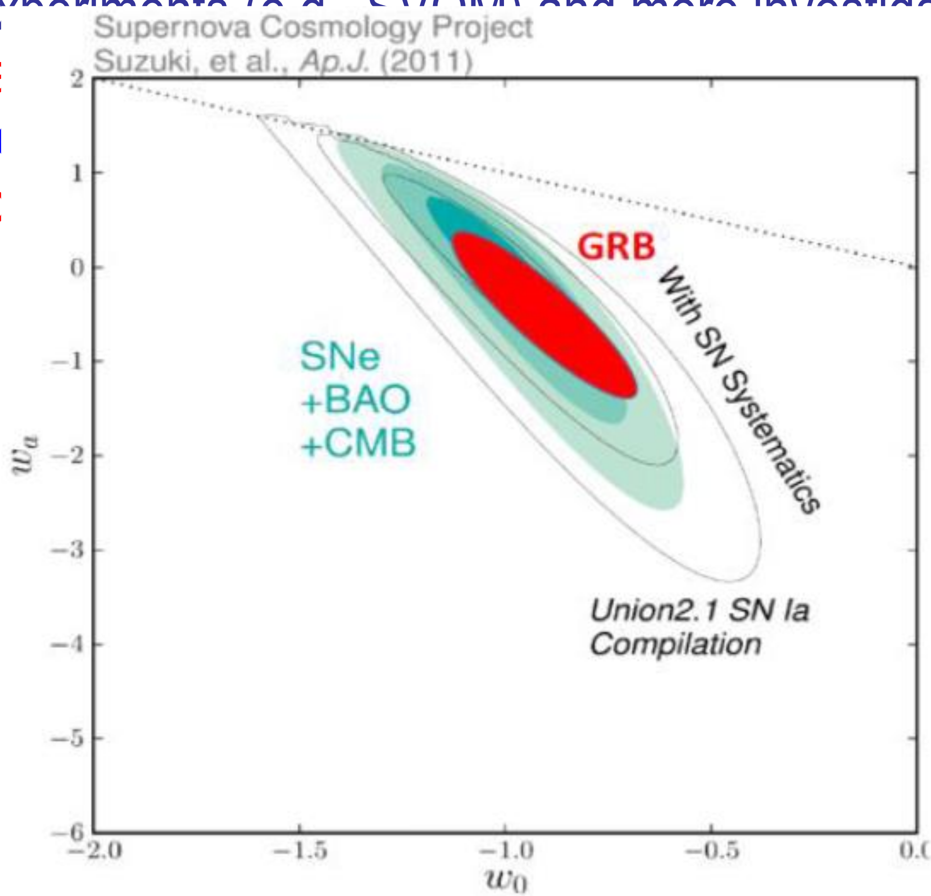
GRB #	Ω_M (flat)	w_0 (flat,Ω_M=0.3,w_a=0.5)
70 (real) GRBs (Amati+ 08)	$0.27^{+0.38}_{-0.18}$	<-0.3 (90%)
156 (real) GRBs (Amati+ 13)	$0.29^{+0.28}_{-0.15}$	$-0.9^{+0.4}_{-1.5}$
250 (156 real + 94 simulated) GRBs	$0.29^{+0.16}_{-0.12}$	$-0.9^{+0.3}_{-1.1}$
500 (156 real + 344 simulated) GRBs	$0.29^{+0.10}_{-0.09}$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

- 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 ex… …ions (in particular: reliable estima… …rove the significance and reliability … …osmology (e.g. investigation c…

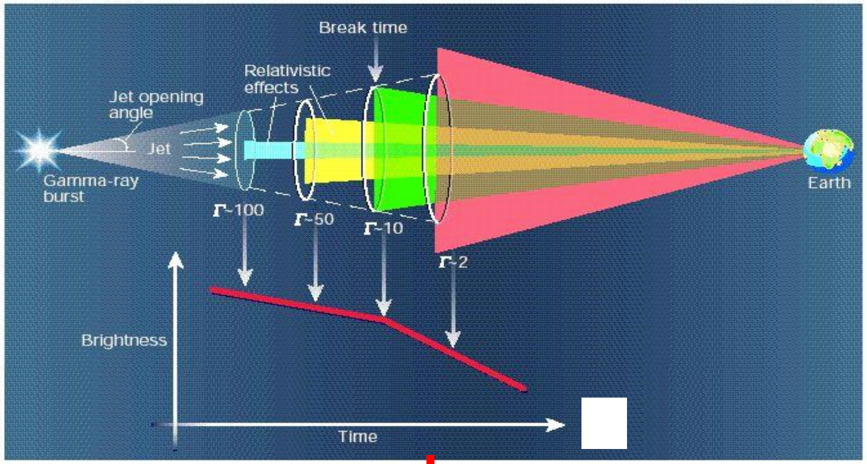


$$w(z) = w_0 + \frac{w_a z}{1+z}$$

Amati et al. 2015

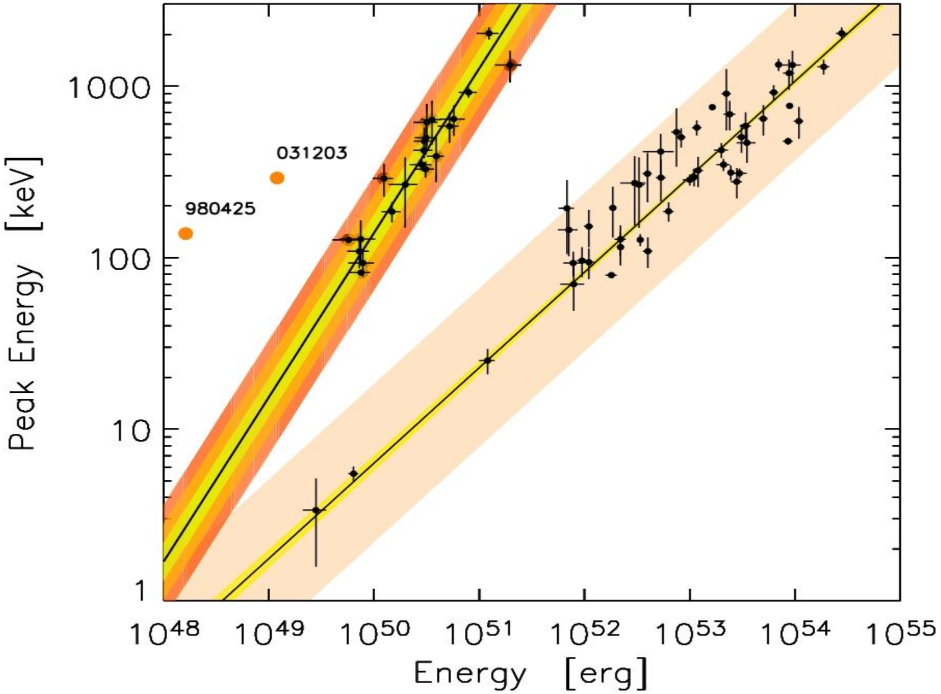
❑ Accounting for collimation

➢ 2004: evidence that by substituting Eiso with the collimation corrected energy Eγ the logarithmic dispersion of the correlation decreases significantly and is low enough to allow its use to standardize GRB (Ghirlanda et al., Dai et al, and many)



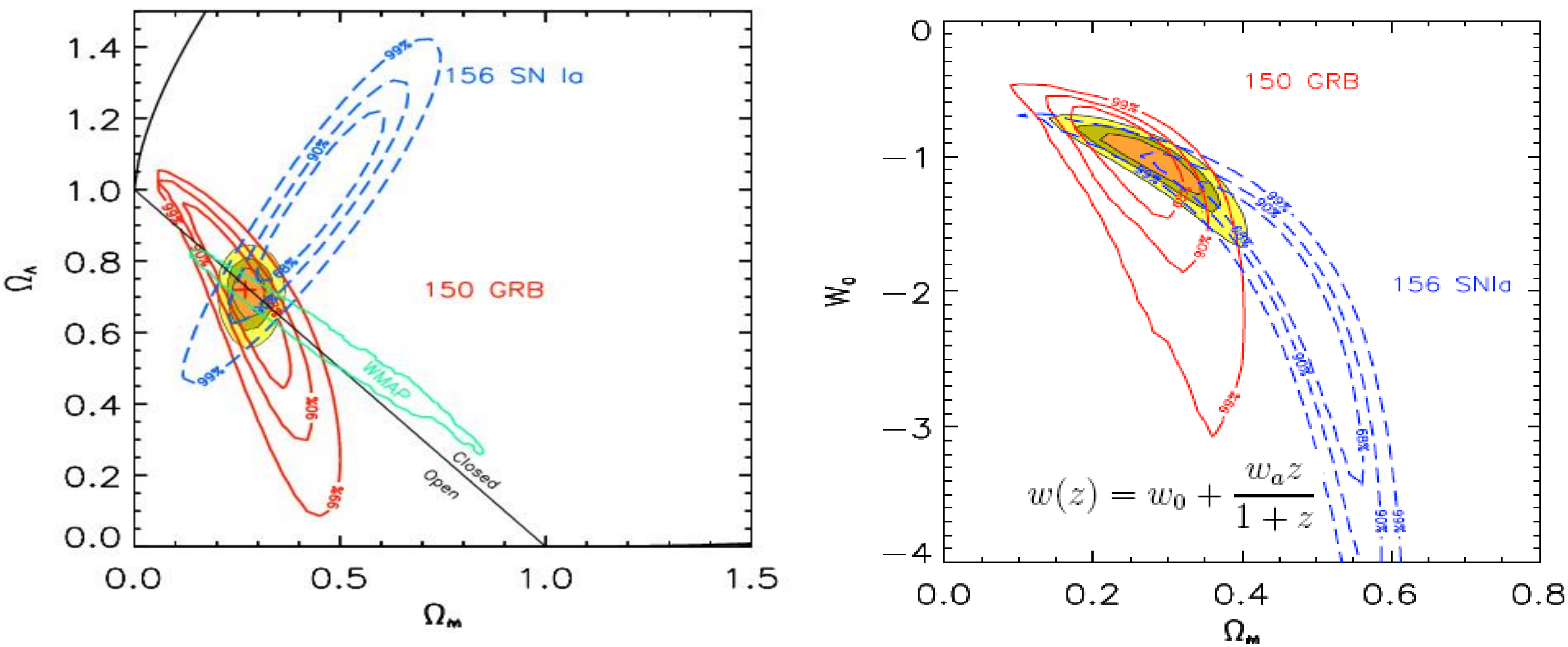
$$\theta = 0.09 \left(\frac{t_{jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\gamma,iso,52}}\right)^{1/8}$$

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



❑ Accounting for collimation: perspectives

- 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 (physics, methods, calibration) will improve the significance and reliability of the results and allow to go beyond SN Ia cosmology (e.g. investigation of dark energy)

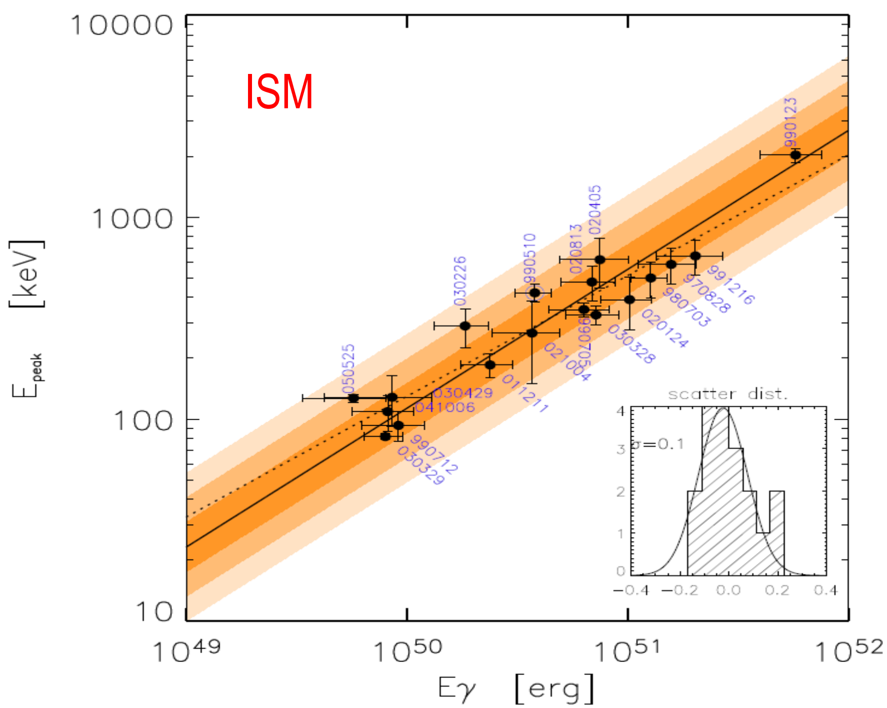


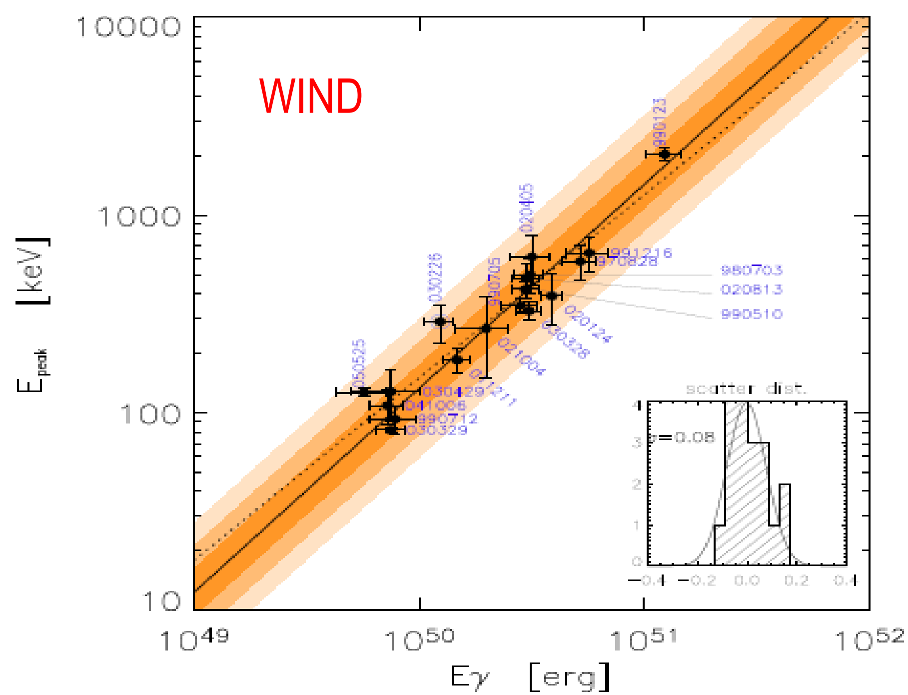
Adapted from Ghirlanda+ 2007

❑ Accounting for collimation: drawbacks

➢ the Ep-Eγ correlation is model dependent: slope depends on the assumptions on the circum-burst environment density profile (ISM or wind)

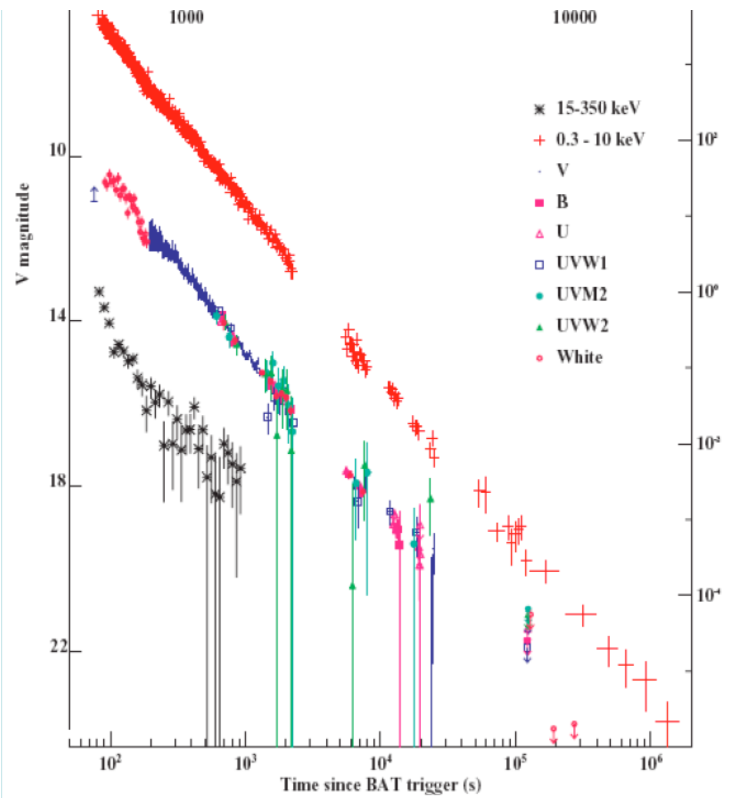
➢ **addition of a third observable introduces further uncertainties** (difficulties in measuring t_break, chromatic breaks, model assumptions) and substantially reduces the number of GRB that can be used (e.g., #Ep,i – Eγ ~ ¼ #Ep,i – Eiso)

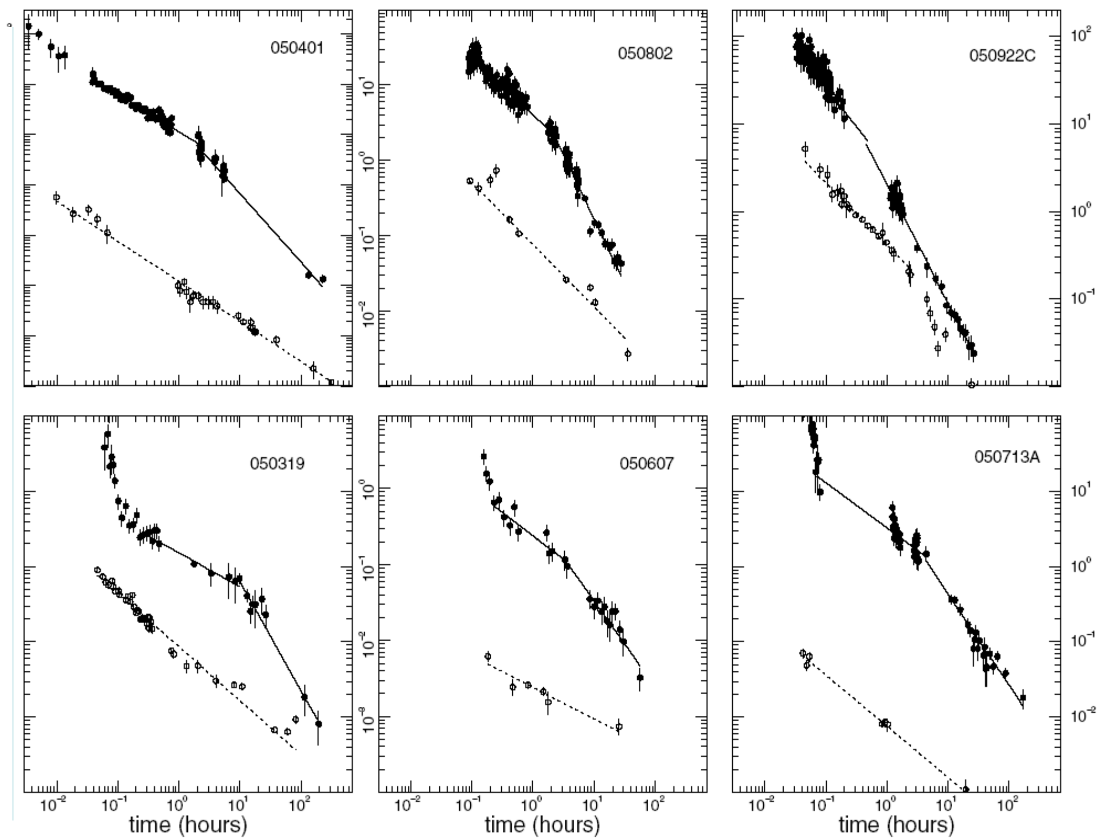




Nava et al.. , A&A, 2005: ISM (left) and WIND (right)

- ➢ lack of jet breaks in several Swift X-ray afterglow light curves, in some cases, evidence of achromatic break
- ➢ challenging evidences for Jet interpretation of break in afterglow light curves or due to present inadequate sampling of optical light curves w/r to X-ray ones and to lack of satisfactory modeling of jets ?



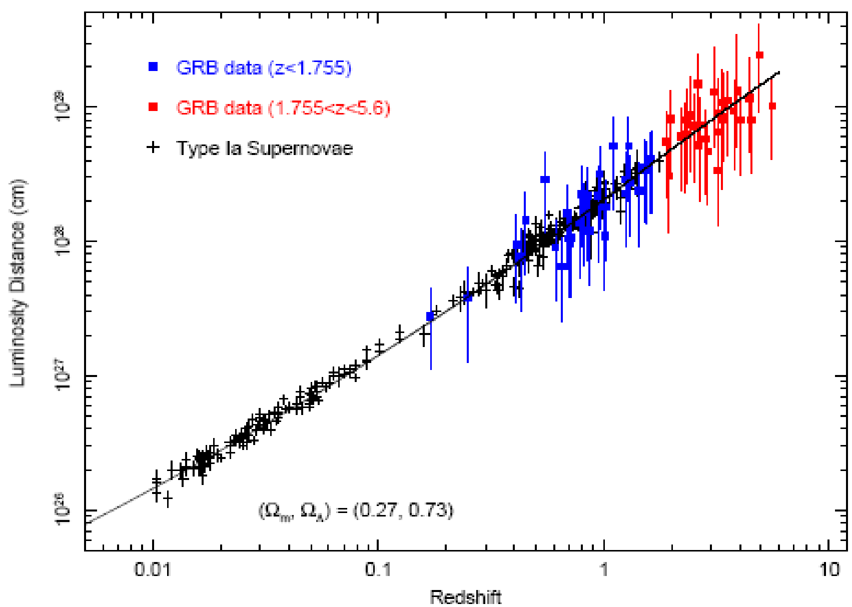


❑ Calibrating the Ep,i – Eiso correlation with SN Ia

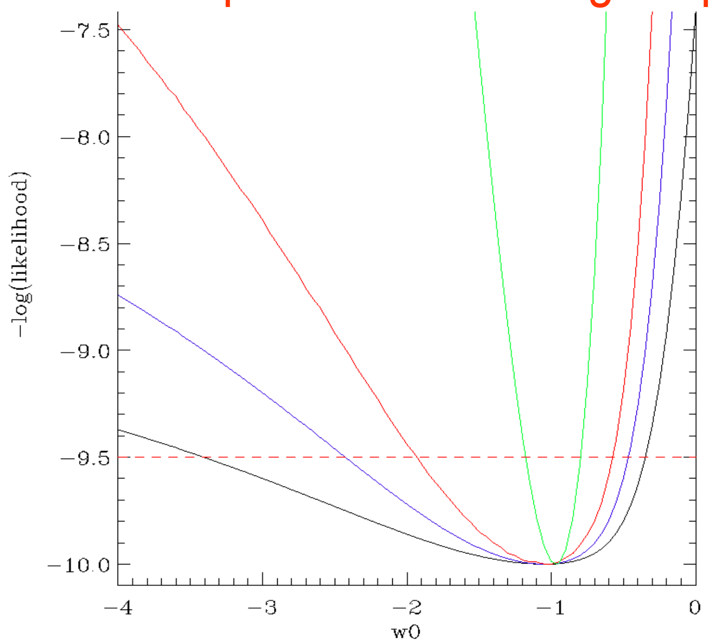
- Several authors (e.g., Kodama et al., 2008; Liang et al., 2008, Li et al. 2008, Demianski et al. 2010-2011, Capozziello et al. 2010, Wang et al. 2012) are investigating the calibration of the Ep,i - Eiso correlation at z < 1.7 by using the luminosity distance – redshift relation derived for SN Ia

- 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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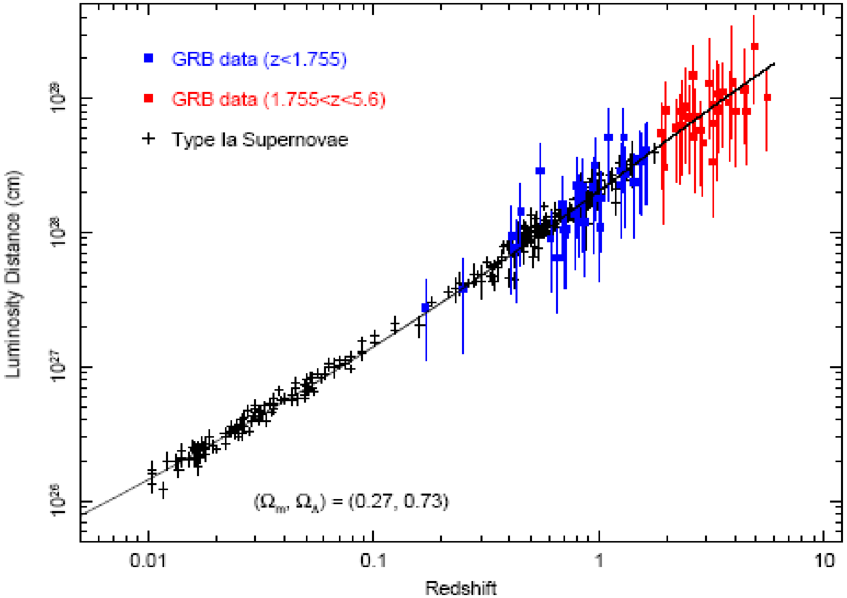
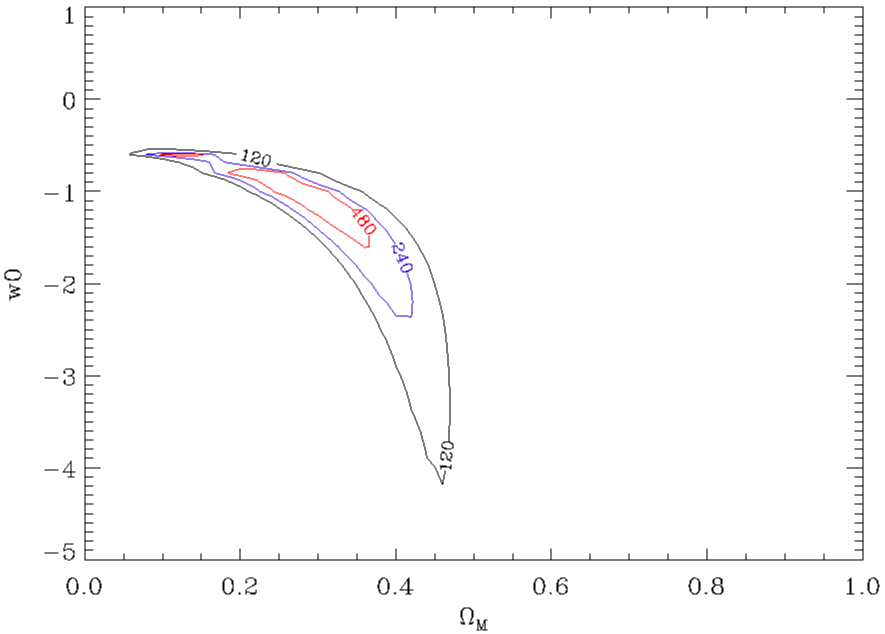


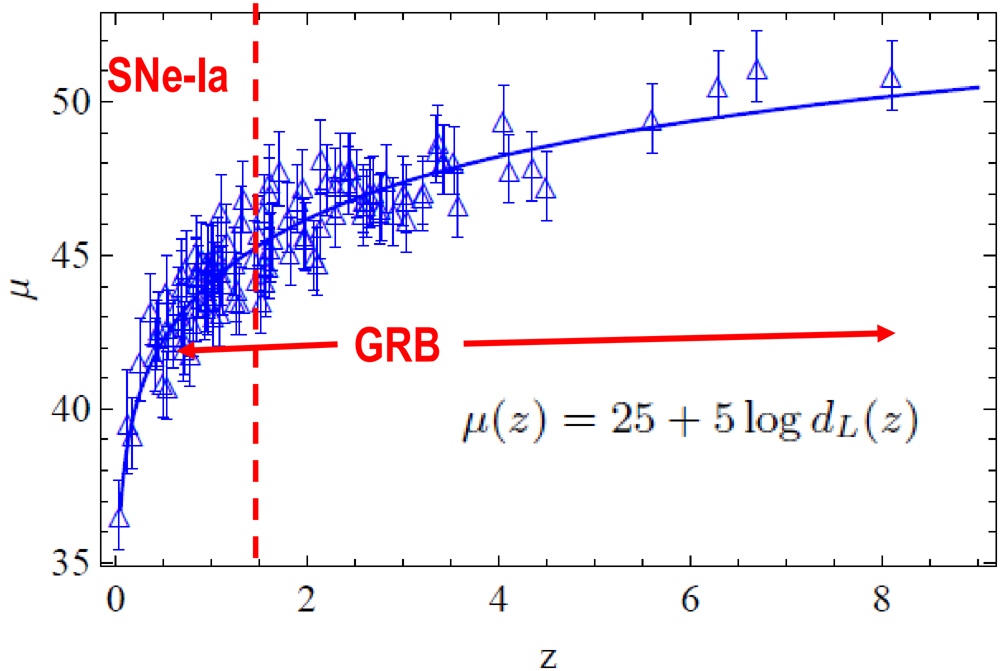
Kodama et al. 2008

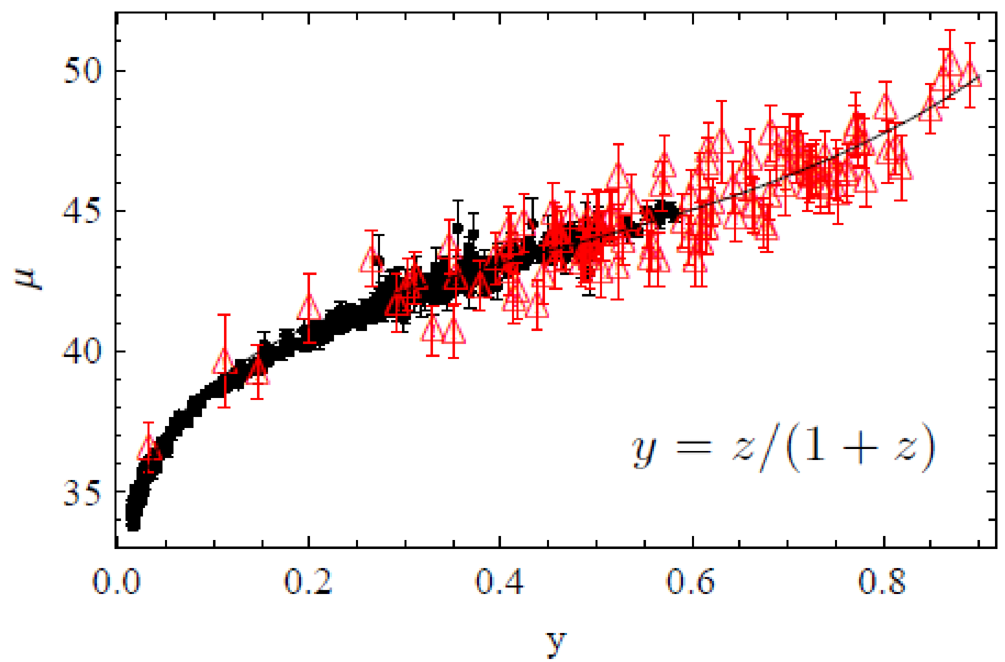


Amati & Della Valle 2013, Amati+ 2013

➢ 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**





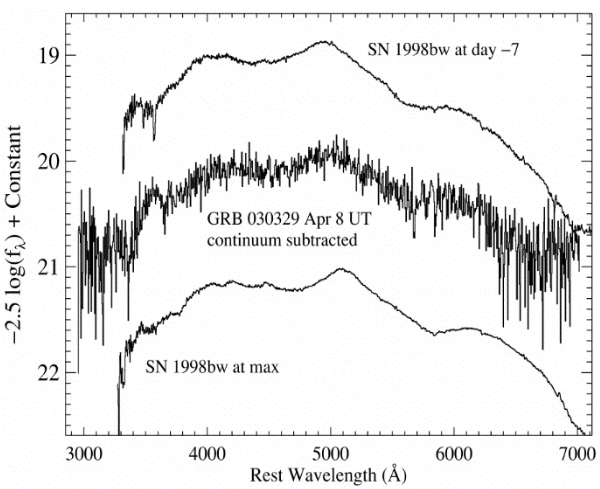
*Gamma-Ray Bursts are the most luminous and remote phenomena in the Universe, with isotropic-equivalent radiated energies in X-gamma rays up to more than **10^{54} erg released in a few tens of seconds** and a redshift distribution extending to at least **z = 9-10**. Thus, they are in principle very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

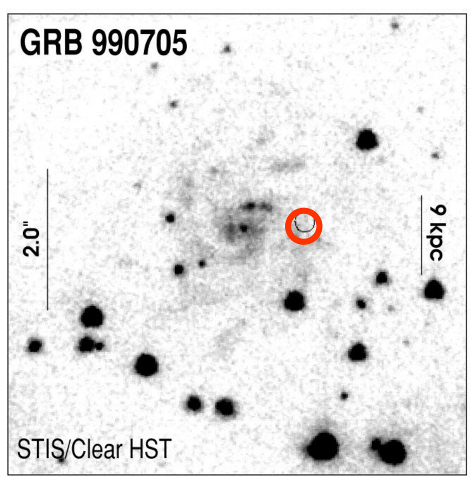
- **Part 1:** status and perspectives of the research activities aimed at using GRBs to investigate the expansion rate and geometry of the Universe, thus getting clues to "dark energy" properties and evolution

- **Part 2:** GRBs as tools for exploring the early Universe at the end of the "dark ages" (reionization, first stars, star formation rate and metallicity evolution in the first billion of years)

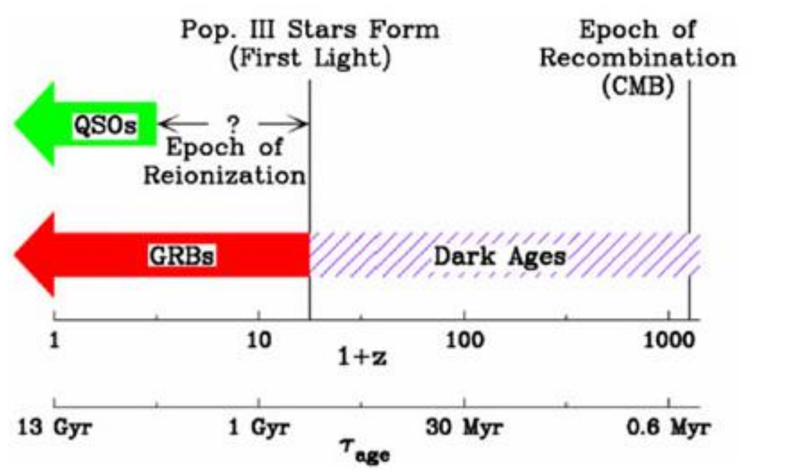
Gamma-Ray Burst as powerful probes of the early Universe

Because of their huge luminosities, mostly emitted in the X and gamma-rays, their redshift distribution extending at least to z ~10 and their association with explosive death of massive stars and star forming regions, GRBs are unique and powerful tools for investigating the early Universe: **SFR evolution, physics of re-ionization, galaxies metallicity evolution and luminosity function, first generation (pop III) stars**





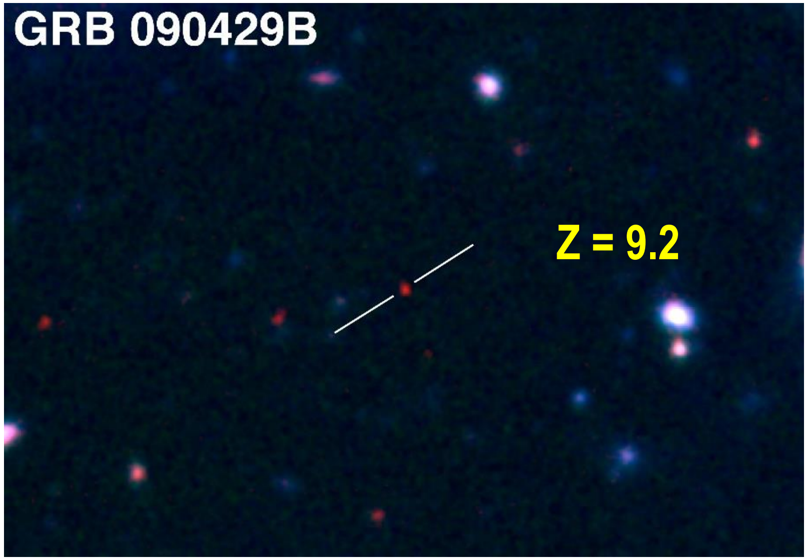
GRBs in Cosmological Context

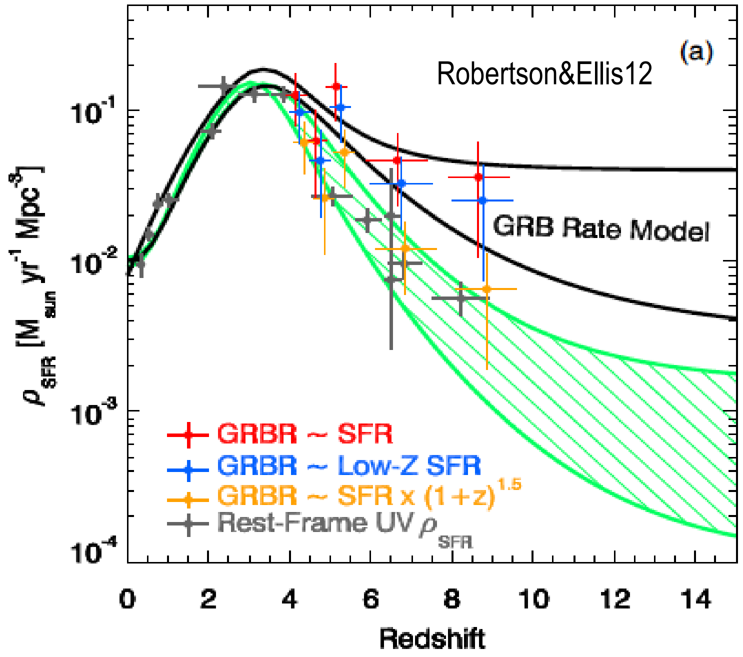


Lamb and Reichart (2000)

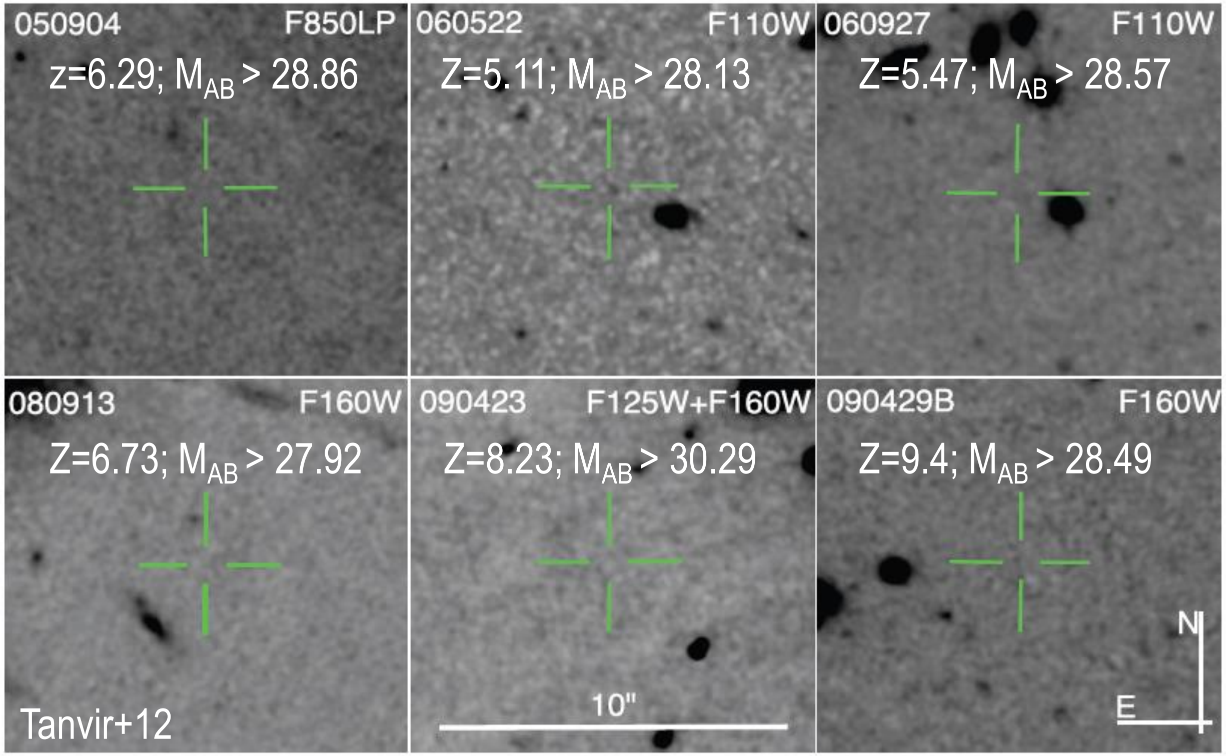
A statistical sample of high–z GRBs can provide fundamental information about:

- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys





- the number density and properties of low-mass galaxies

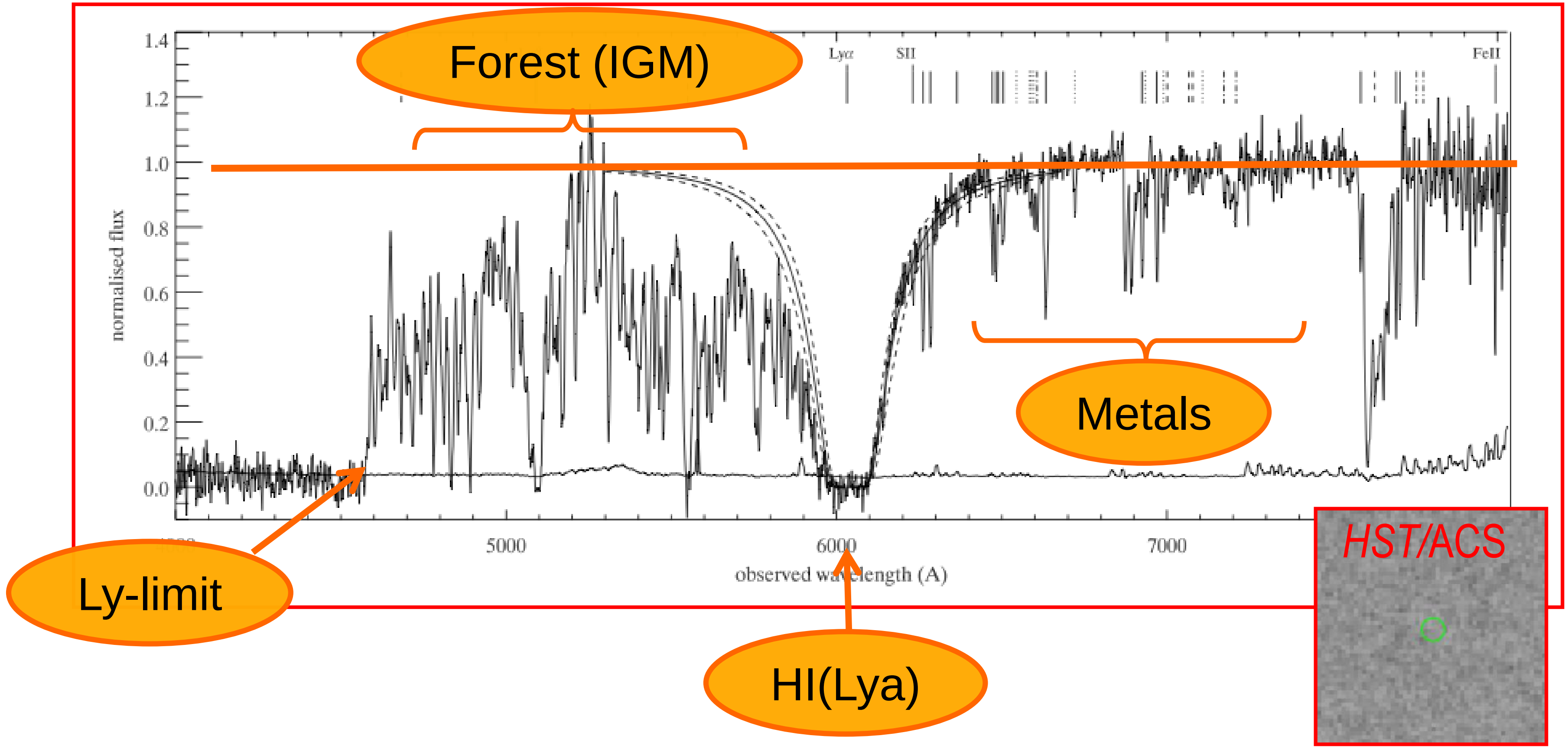


Robertson&Ellis12

Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8)

Afterglow spectra contain much information

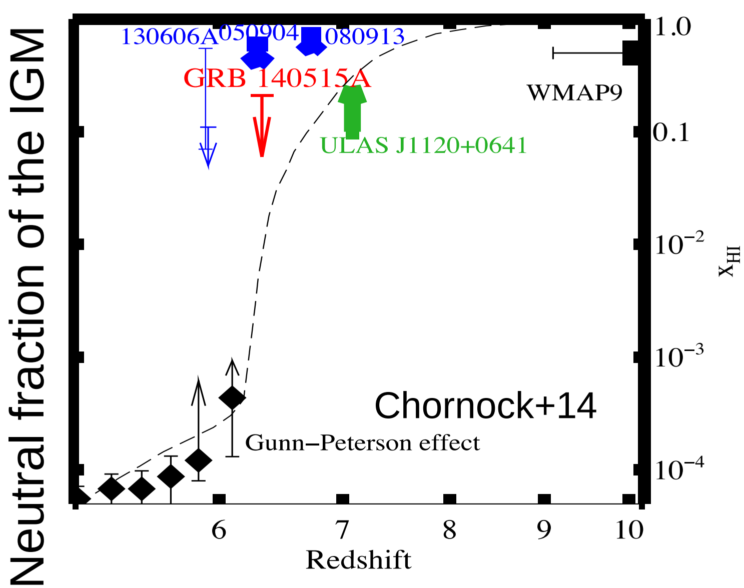
Abundances, HI, dust, dynamics etc. even for very faint hosts. E.g. GRB 050730: faint host (R>28.5), but z=3.97, [Fe/H]=-2 and low dust, from afterglow spectrum (Chen et al. 2005; Starling et al. 2005).

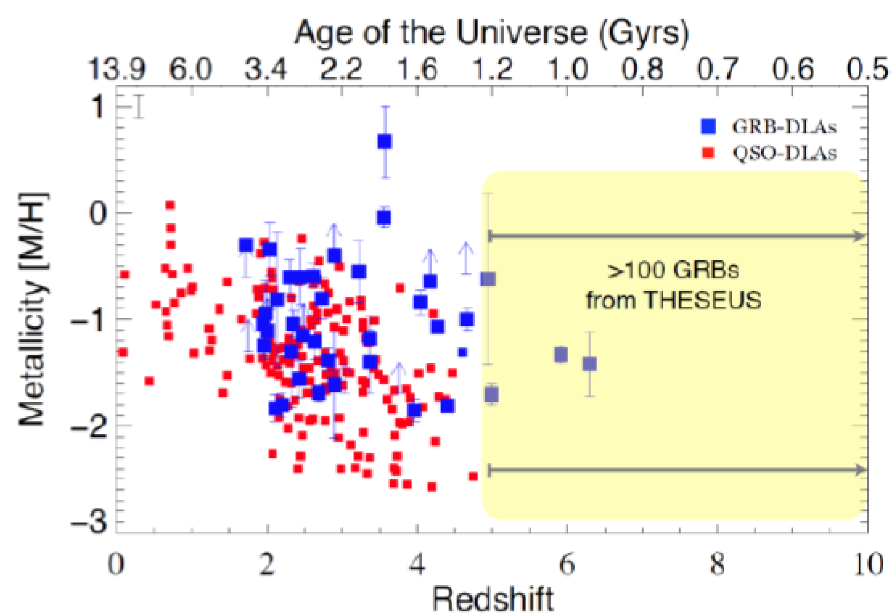


The first, metal–free stars (the so–called **PopIII stars**) can result in powerful GRBs (e.g. Meszaros+10). GRBs offer a powerful route to directly identify such elusive objects (even JWST will not be able to detect them directly) and study the galaxies in which they are hosted.

Even indirectly, the role of PopIII stars in **enriching the first galaxies** with metals can be studied by looking to the absorption features of PopII GRBs blowing out in a medium enriched by the first PopIII supernovae (Wang+12).

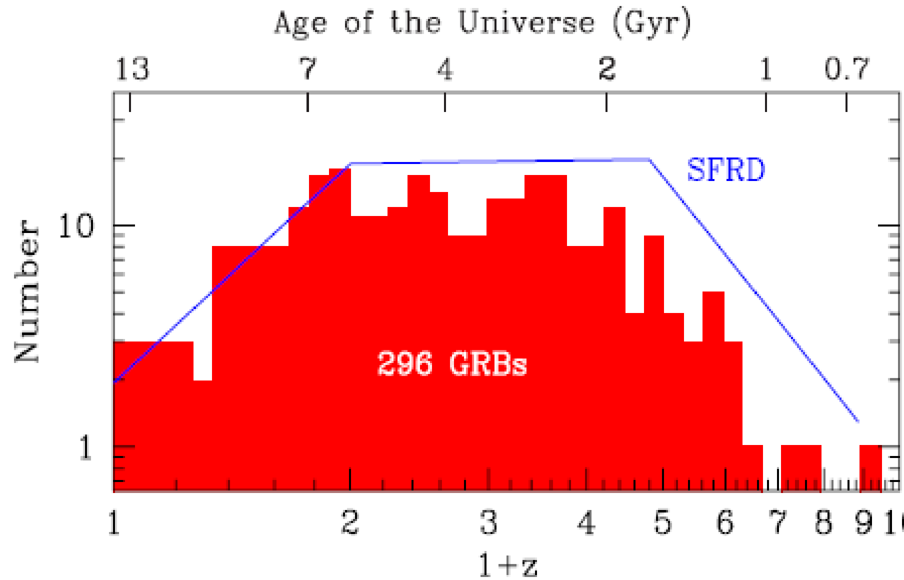
More generally, what is **the cosmic chemical evolution** at early times?





❑ GRB White paper for ESA/L2-L3

- **Time frame**: next decade
- **Collaboration**: D, UK, Fr, It, Ir, Dm, ..
- **Status**: theme for ESA/L2-3



- **Goals**: detect 1000 GRB/year for substantial increase of high-z GRBs (50 at z >9) -> GRBs as probes of Pop III stars, metal enrichment and reionization of the Universe, IGM,SFR evolution up to early Universe ; provide trigger and e.m. counterpart for next generation grav. wave and neutrino detectors; GRB polarisation

- **Payload**: different solutions proposed, e.g., multi-BAT or Compton Telescope or Lobster-eye telescope + X-ray telescope +NIR telescope; L2 orbit prefarable

Table 1: Scientific requirements for a future GRB mission with assumed 5 yr lifetime.

Requirement	Goal	Detector ability
1. Detect 1000 GRBs/yr	obtain 50 (5) GRBs at $z > 10(20)$	large FOV, soft response
2. Rapid transmission to ground	allow timely follow-up observations	communication network
3. Rapid localization to few $''$	opt/NIR identification of 1000 GRBs/yr	slewing X-ray or opt/NIR telescope
4. Provide z-indication	allow selection of high-z objects	multi-filter or spectroscopic capability

THESEUS
Transient High Energy Sources and Early Universe Surveyor

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

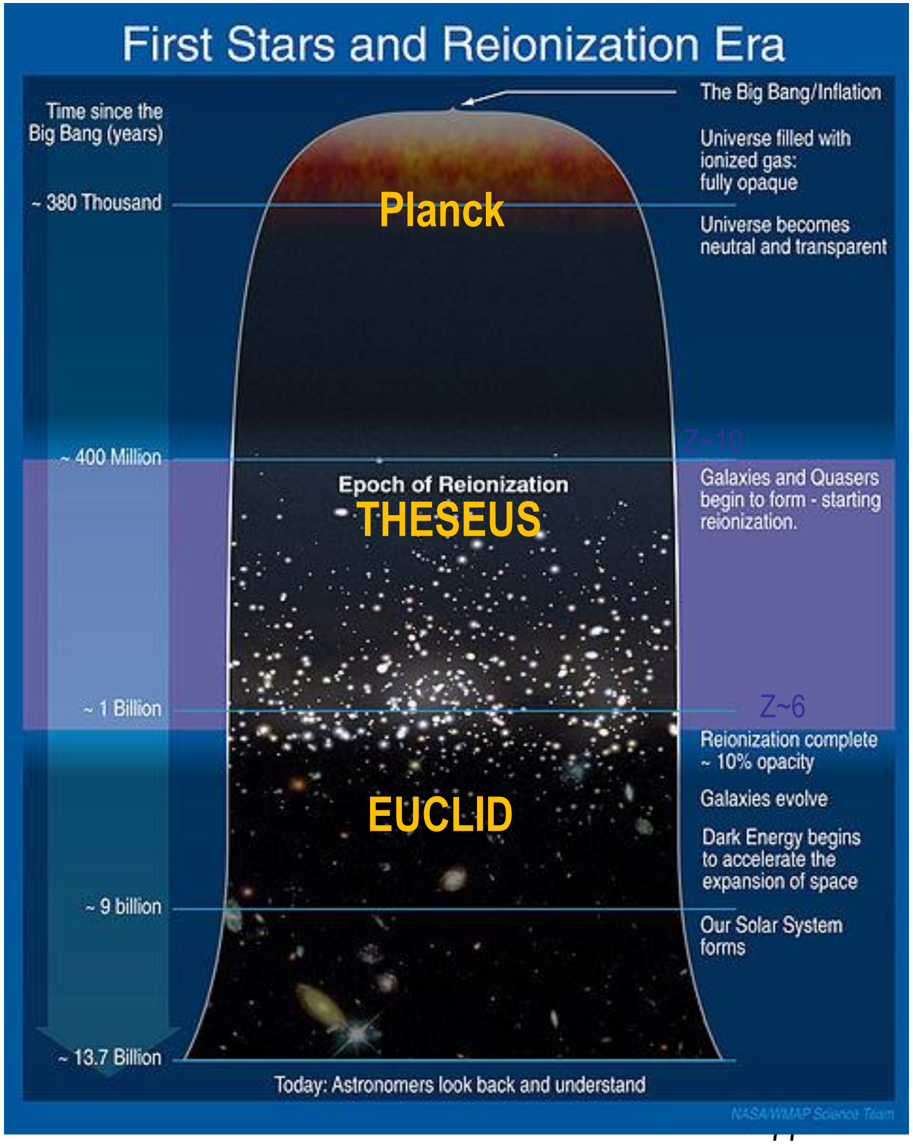
M4 proposal coordinators: Lorenzo Amati, Paul O'Brien (Univ. Leicester, UK), Diego Gotz (CEA-Paris, France), Alberto Castro-Tirado (IAA, Spain)

Payload consortium: Italy, UK, Spain, Denmark, Poland, Czech Republic, ESA (+ France, Hungary, Slovenia, Ireland)

International partners: USA (+ interest from Brasil, Japan, Israel, Turkey)

THESEUS: Main scientific goal

Exploring the Early Universe (cosmic dawn and reionization era) by unveiling the Gamma-Ray Burst (GRBs) population in the first billion years



The study of the Universe before and during the epoch of reionization represents one of the major themes for the next generation of space and ground–based observational facilities. Many questions about the first phases of structure formation in the early Universe will still be open in the late 2020s:

- *When and how did first stars/galaxies form?*
- *What are their properties? When and how fast was the Universe enriched with metals?*
- *How did reionization proceed?*

THESEUS payload

- **Soft X-ray Imager (SXI):** a set of « Lobster-Eye » X-ray (0.3 - 6 keV) telescopes covering a total FOV of 1 sr field with 0.5 – 1 arcmin source location accuracy, provided by a **UK** led consortium (+ **Czech Repubblic**)
- **InfraRed Telescope (IRT):** a 70 cm class near-infrared (up to 2 microns) telescope (IRT) with imaging and moderate spectral capabilities provided by a **Spanish** led consortium (+ **ESA, + Ireland ?**)
- **X-Gamma-rays Spectrometer (XGS)**: non-imaging spectrometer (XGS) based on SDD+CsI, covering the same FOV than the Lobster telescope extending its energy band up to 20 MeV. This instrument will be provided by an **Italian** led consortium (+**USA ?**)
- **Payload Data Handling System (PDHS): Poland** led consortium (+ **Denmark, Finland**)

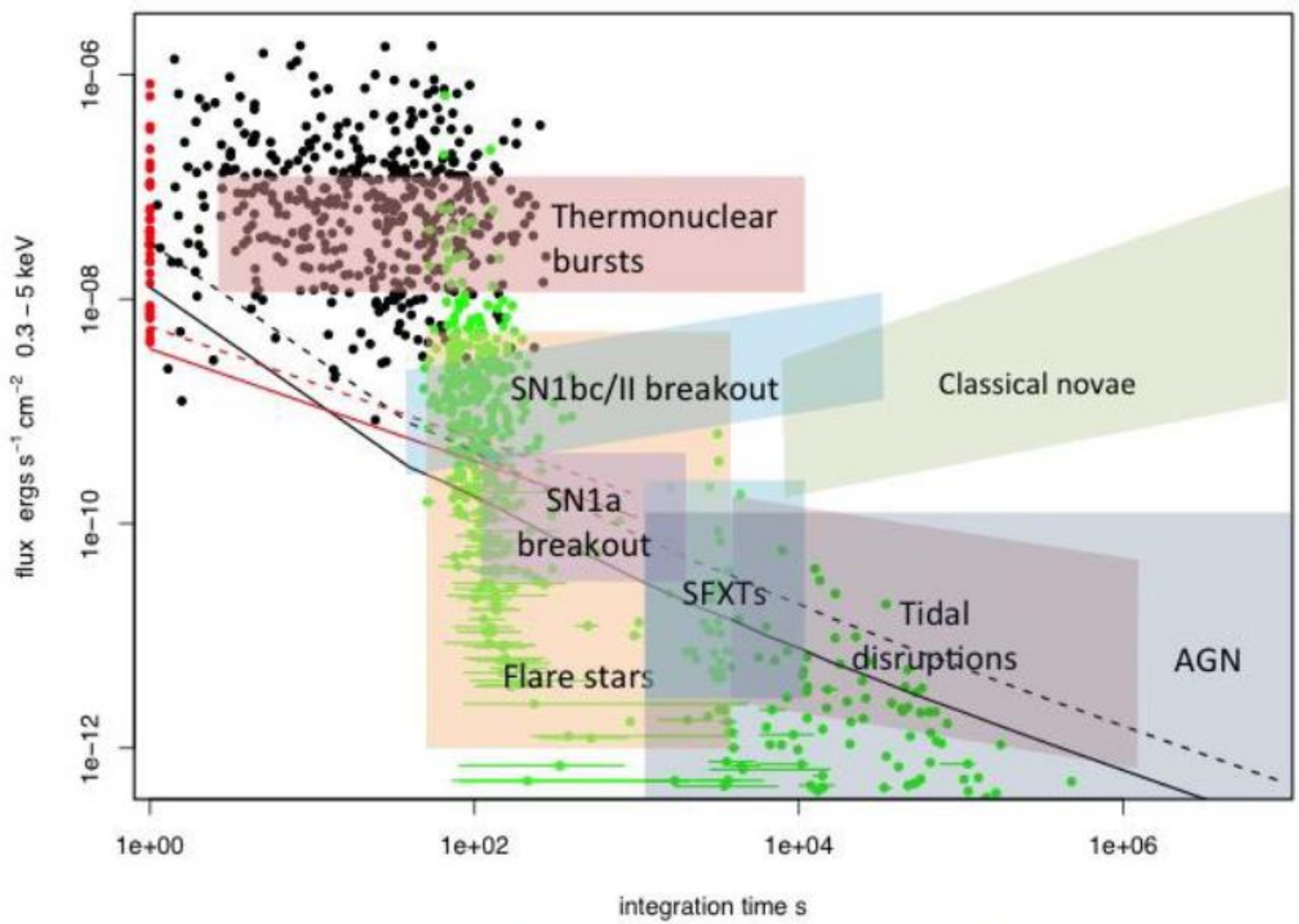


Figure 2.4: Sensitivity of the SXI (black curves) and XGS (red) vs. integration time. The solid curves assume a source column density of 5×10^{20} cm^{-2} (i.e. well out of the Galactic plane and very little intrinsic absorption). The dotted curves assume a source column density of 10^{22} cm^{-2} (significant intrinsic absorption). The black dots are the peak fluxes for Swift BAT GRBs plotted against T90/2. The flux in the soft band 0.3-10 keV was estimated using the T90 BAT spectral fit including the absorption from the XRT spectral fit. The red dots are those GRBs for which T90/2 is less than 1 second. The green dots are the initial fluxes and times since trigger at the start of the Swift XRT GRB light-curves. The horizontal lines indicate the duration of the first time bin in the XRT light-curve. The various shaded regions illustrate variability and flux regions for different types of transients and variable sources.

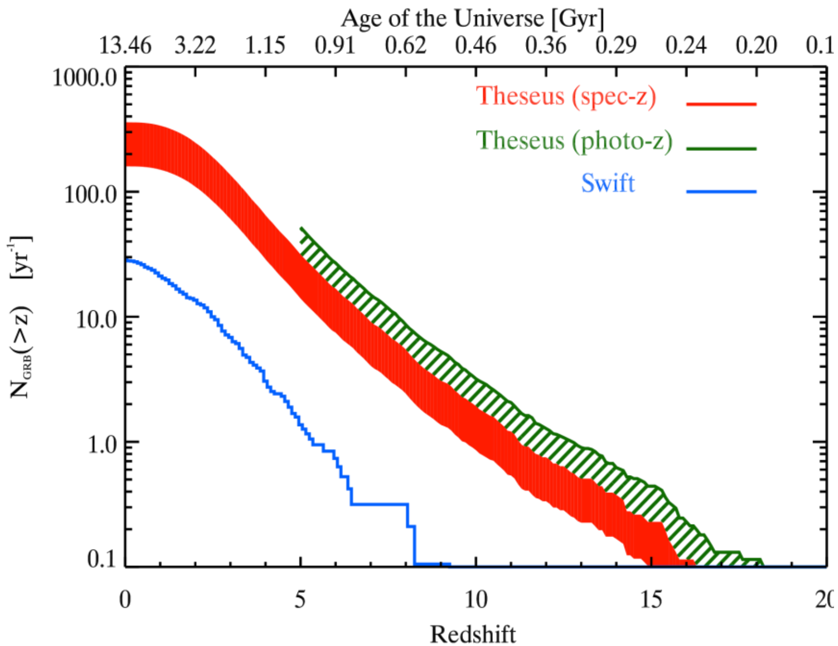
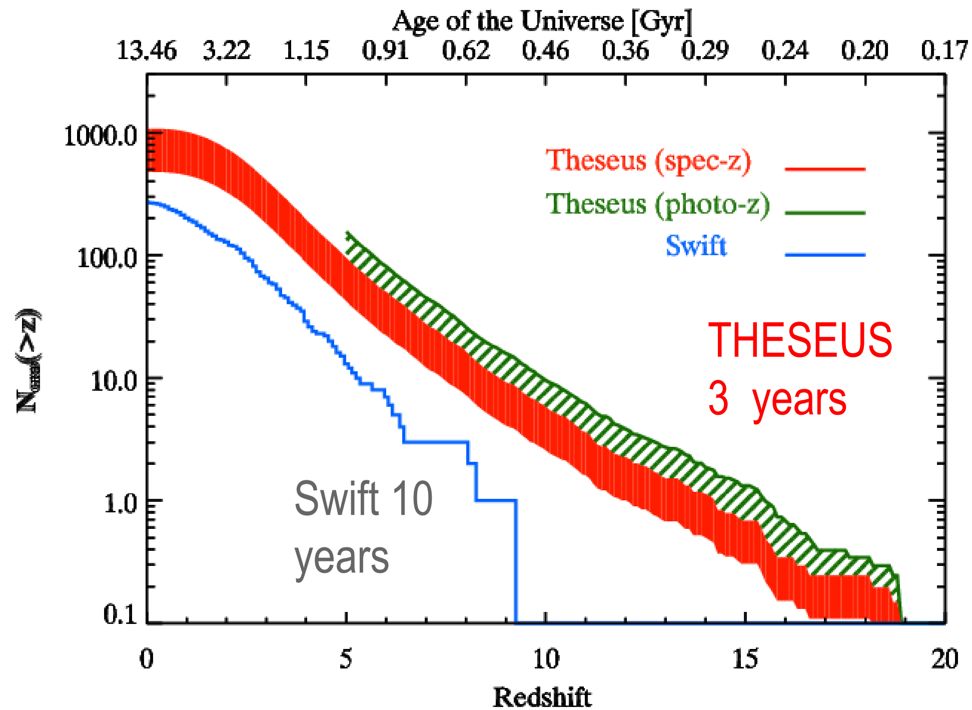


Figure 1. Rate of redshift measurement by Theseus. The solid filled (red) region repres
the rate of bursts as a function of redshift (cumulative distribution as in Fig.1) that wil



	Theseus rate = # yr^{-1}			
	All	z>5	z>8	z>10
Detections	310 – 700	23 – 52	4 – 9	1.5 – 3
Photometric z		23 – 52	4 – 9	1.5 – 3
Spectroscopic z	160 – 360	14 – 30	2 – 6	1 – 2

Ghirlanda + Salvaterra