Measuring the cosmological parameters with Gamma-ray Bursts

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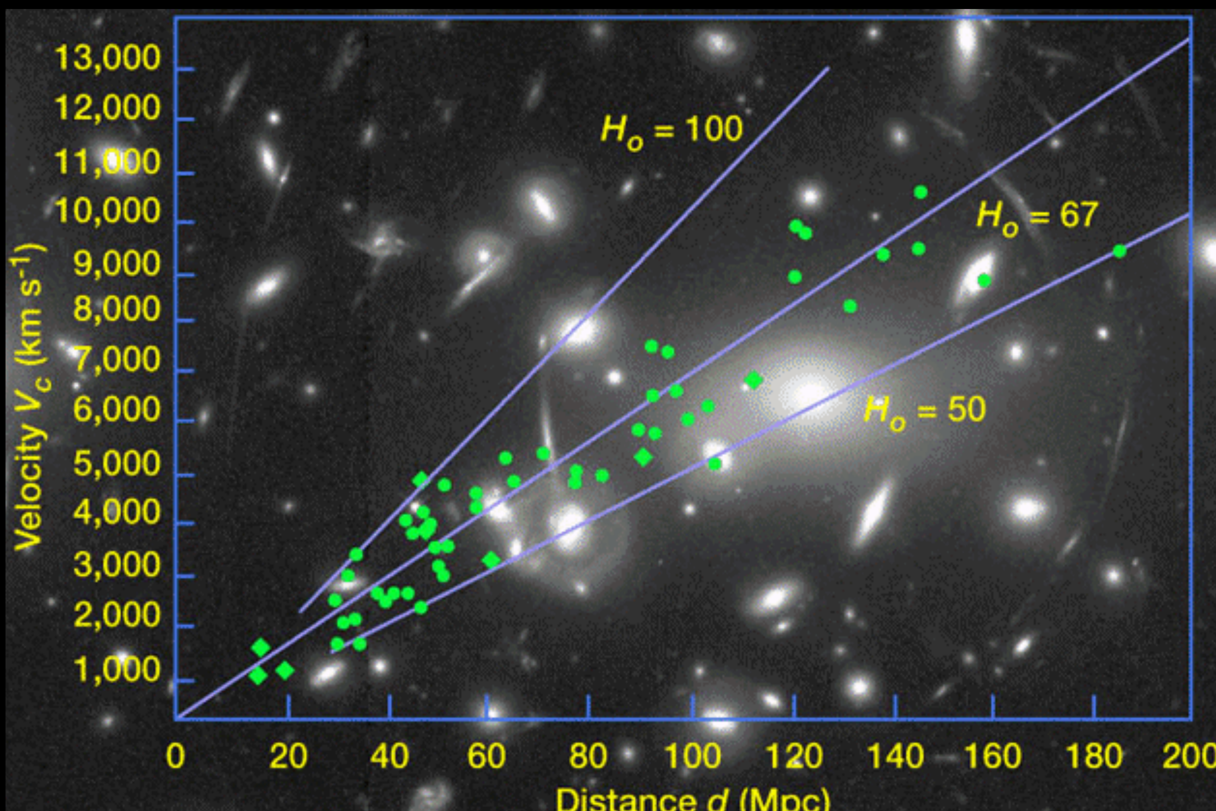
Summary

- The measurements of Ω_m and Ω_Λ with SNe-Ia
- SN systematics: the need of an independent measurement of Ω_m and Ω_Λ
- The measurements of Ω_m obtained with GRBs
- Future developments

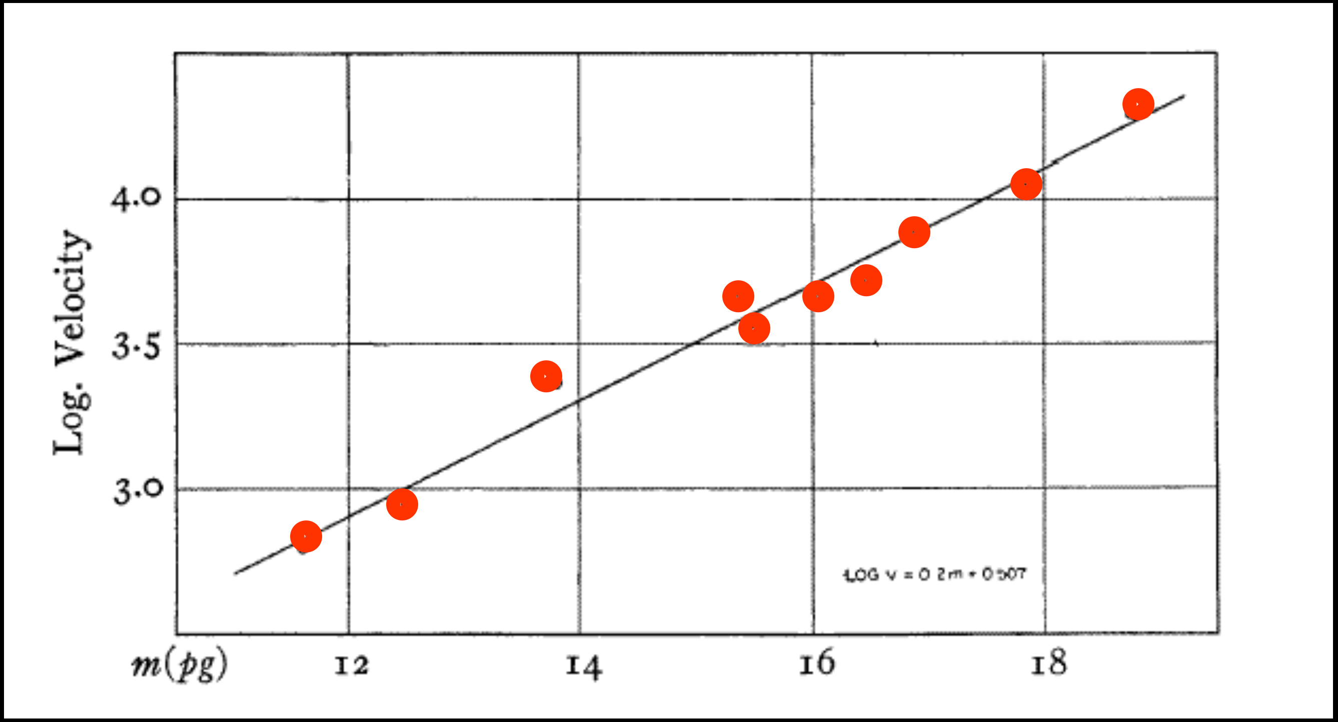
Measuring the cosmological parameters means to study the expansion rate of the Universe, and this is a (relatively) *easy* task



All it takes is to measure velocities and distances for a class of cosmological objects and to plot one vs. the other…

The Hubble Diagram

Hubble & Humason 1931



in the low red-shift limit → $cz = H_o \times D$

$$m = M + 5\log D - 5 \rightarrow m = 5\log cz + 25 - 5\log H_o + M$$

Standard Candles

A population of unevolving sources, having a fixed intrinsic luminosity

In the local Universe there are many classes of astrophysical objects that match this requirements

74±3%
Ia+NIR Cep
Freedman et al. 2012

74±8%
HII
Chavez et al. 2012

74±5%
Ia+Cep
Riess et al. 2009

72±6%
water maser
Reid et al. 2012

66±8%
Lensing
Paraficz et al. 2010

63-73 $km s^{-1}$ Mpc^{-1}
WMAP- LAMBDA
data product

TABLE 1
Sample of Recent Determinations of H_0

H_o ($km\ s^{-1}\ Mpc^{-1}$)	Technique	Reference
94 ± 11[a]	Lens 0957 + 561	Grogin & Narayan (1996)
81 ± 8	Cepheids in 4 Virgo spirals	van den Bergh (1995a)
80 ± 12	SB fluctuations	Jacoby et al. (1992)
78 ± 11	Globulars in M87	Whitmore et al. (1995)
76 ± 7	PN in Virgo Cluster	Jacoby (1996)
75 ± 8	PN in Fornax cluster	McMillan et al. (1993)
74 ± 14	Tip of RG branch	Sakai et al. (1996)
73 ± 6 ± 7	SNe II exp. photospheres	Kirshner (1996)
73 ± 6	D_n -σ (Vir, For, Leo)	Mould (1996)
70 - 74	Tully-Fisher	Giovanelli (1996)
70 ± 13	Novae in Virgo	Della Valle & Livio (1995)
66 ± 12	IR Tully-Fisher	Malhotra et al. (1996)
65 ± 6	SN Ia lightcurves	Riess et al. (1996)
64 ± 3	4 SNe Ia	Hamuy et al. (1996)
55 ± 17	Sunyaev - Zel'dovich effect	Birkinshaw & Hughes (1994)
55 - 60	SNe Ia (theory)	van den Bergh (1995b)
52 ± 9	SNe Ia (1937C)	Saha et al. (1994)
52 ± 8	SNe Ia (1972E)	Saha et al. (1995)
43 ± 11	Galaxy diameters	Sandage (1993a)

How to measure the cosmological parameters Ω_m and Ω_Λ ?

The Hubble Diagram at high z

$$m = M + 5\log D - 5$$

For an object of known absolute magnitude ***M****, the* measurement of the apparent magnitude ***m*** at a given ***z*** is sensitive to the universal parameters, through the luminosity distance:

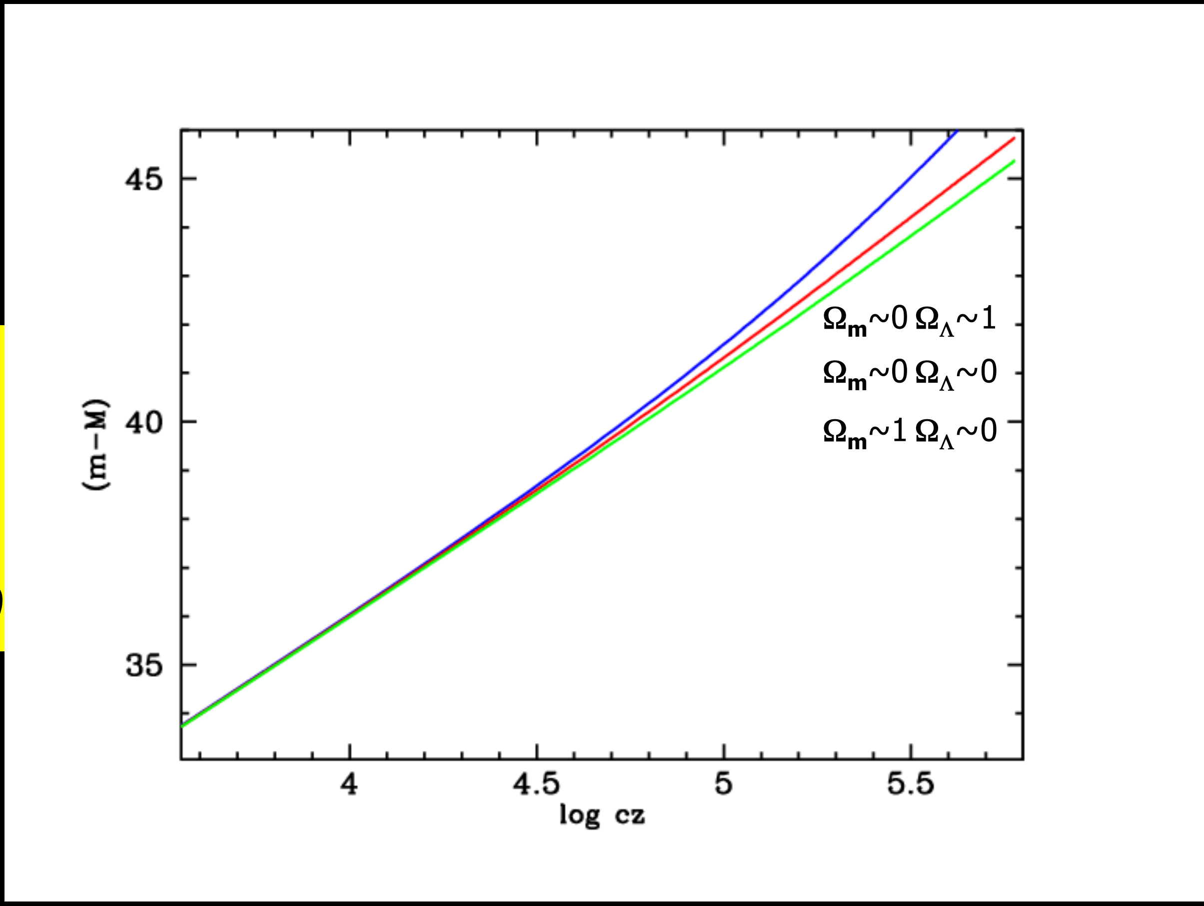
$$m = M + 5\log[D_L(z;\Omega_M;\Omega_\Lambda)] + K + 25 + A$$

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

$$k = 1 - \Omega_M - \Omega_\Lambda$$

$$q_o = \frac{\Omega_M}{2} - \Omega_\Lambda$$

$$S(x) = \begin{cases} \sin(x) \text{ if } & k<0 \\ x \text{ if } & k=0 \\ \sinh(x) \text{ if } & k>0 \end{cases}$$



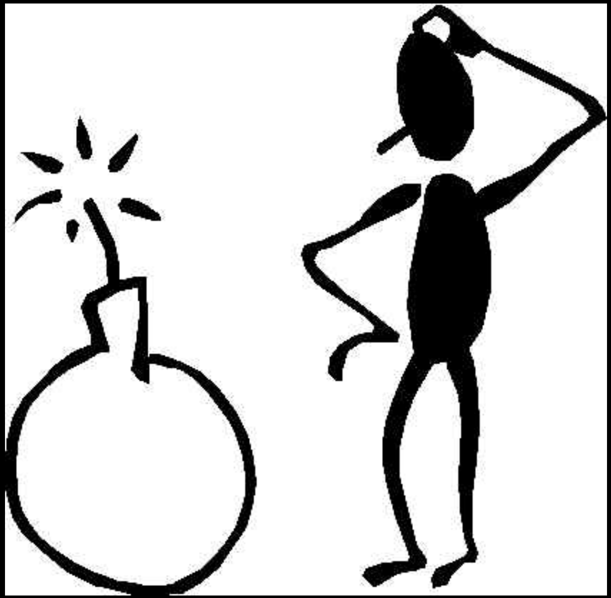
Standard Candles

$$m = M + 5\log[D_L(z;\Omega_M;\Omega_\Lambda)] + K + 25 + A$$

A population of unevolving sources, having a fixed intrinsic luminosity

at all redshifts

The problem is to find a class of objects as bright as galaxies (to be detected up to cosmological distances) but which does not evolve !



Pioneering Hubble diagrams (Sandage et al. 1976) provided formal values of q_o=1±0.5 (cfr. ~ -0.5). These measurements (based on galaxies luminosity) cannot be trusted because of the stellar population evolution and merging.

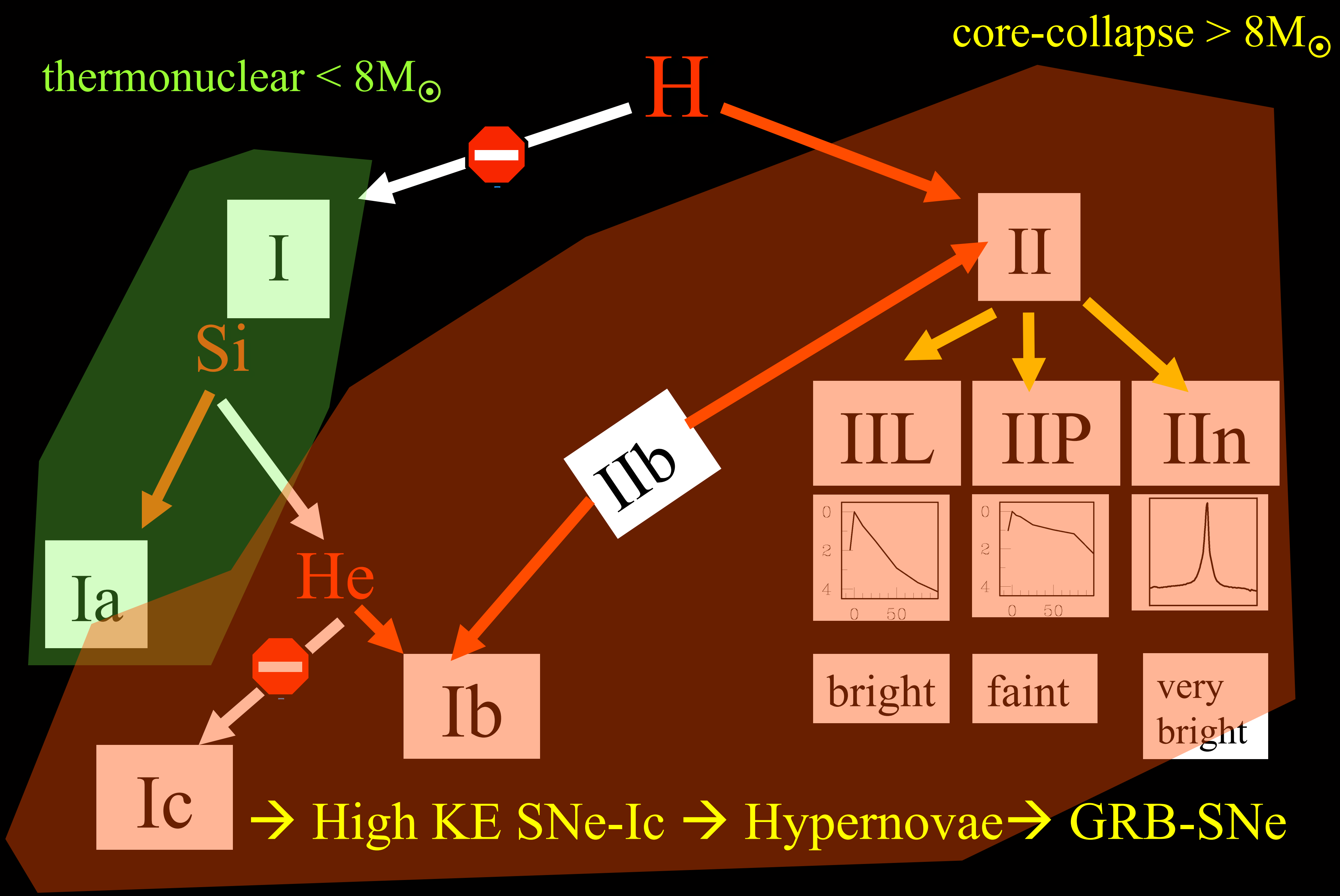
The evolution destroys the concept of standard candle (which is independent of age)

In 90's several pieces of observations converged to identify this class of very bright and no-evolving objects with

Supernovae

Ia type

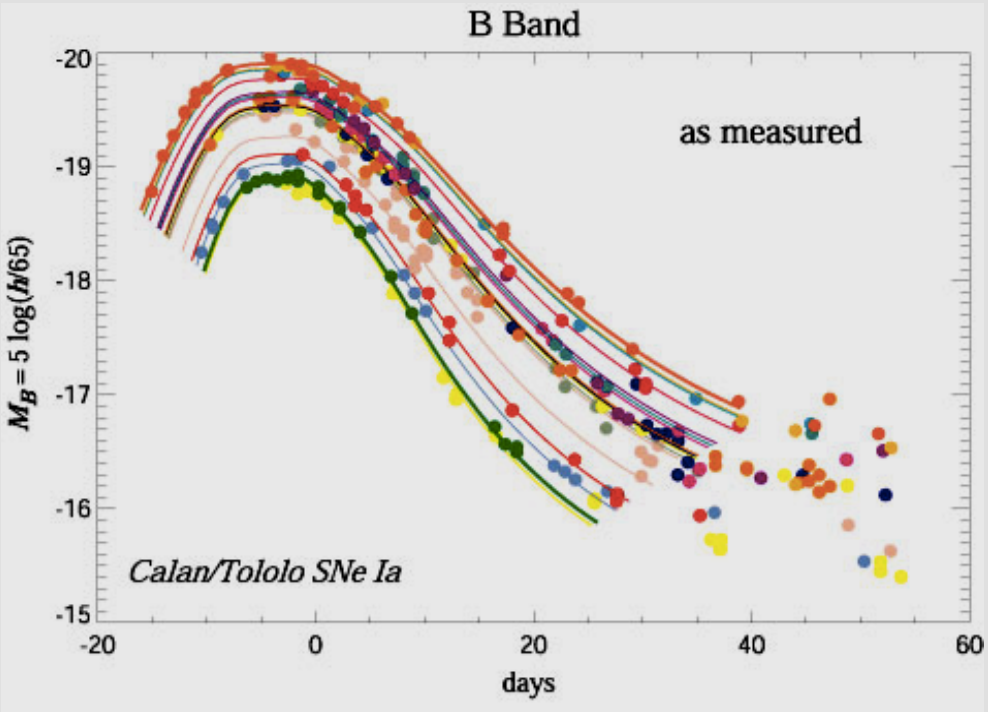
Supernova taxonomy



→ High KE SNe-Ic → Hypernovae → GRB-SNe

The commonly accepted idea is that SNe-Ia are the thermonuclear disruption of C-O WDs (3-8$M_{\odot}$) in binary systems.

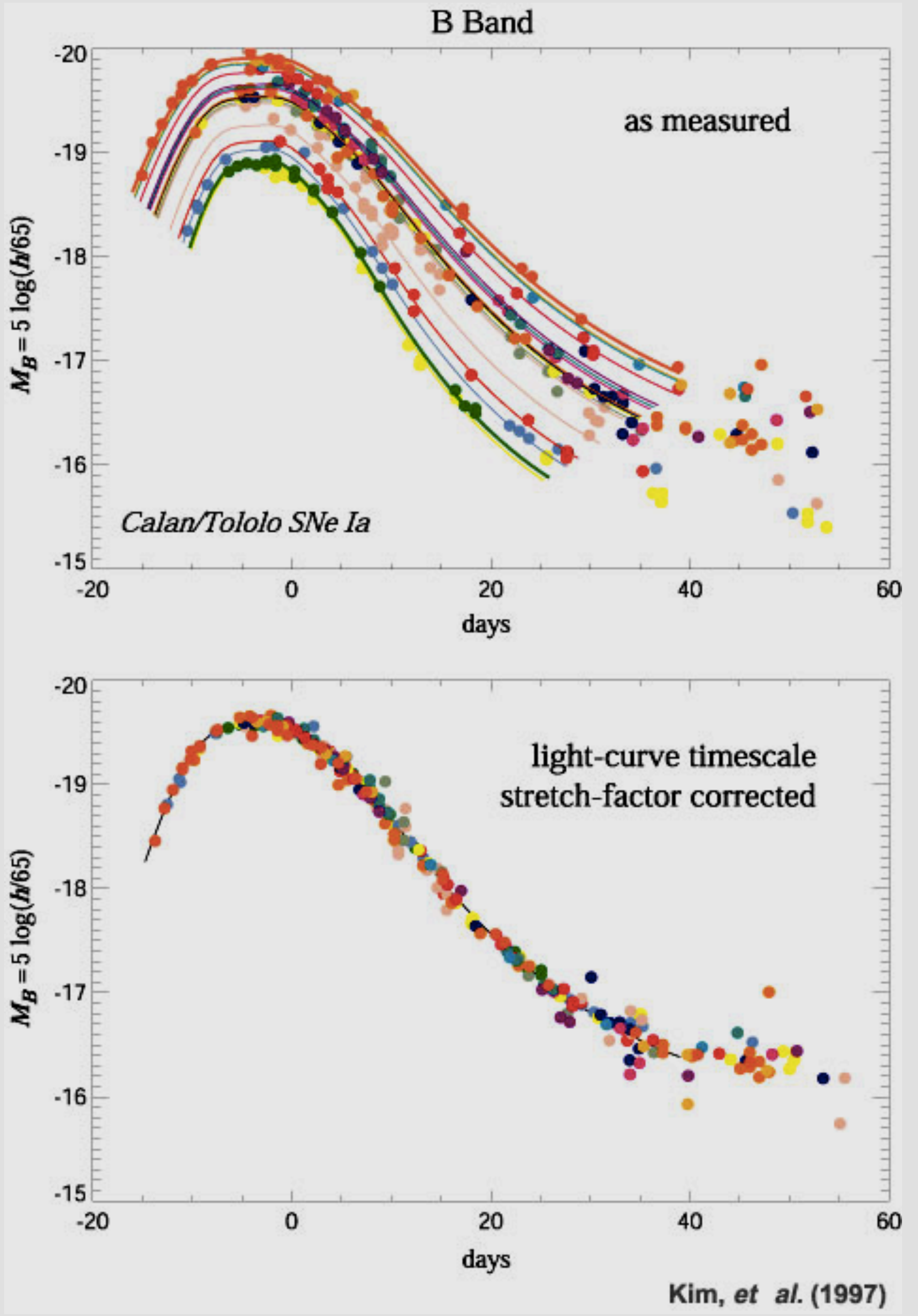
Are SNe-Ia standard candles ?



Are SNe-Ia standard candles ?

$$M_B = a \times \Delta m\left(15^d\right) + b$$

After correction for lightcurve shape ("Phillips relationship"), supernovae become "calibrated" candles with ~0.15 magnitude dispersion.



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BVRI LIGHT CURVES FOR 29 TYPE Ia SUPERNOVAE

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Discovery of a supernova explosion at half the age of the Universe

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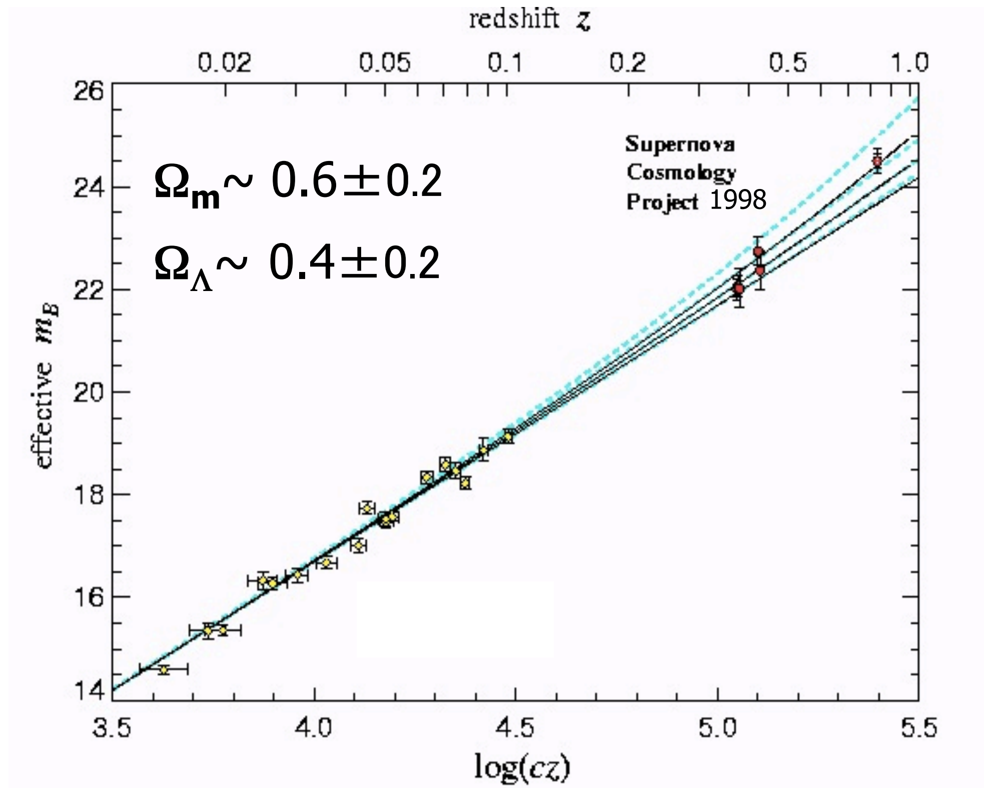
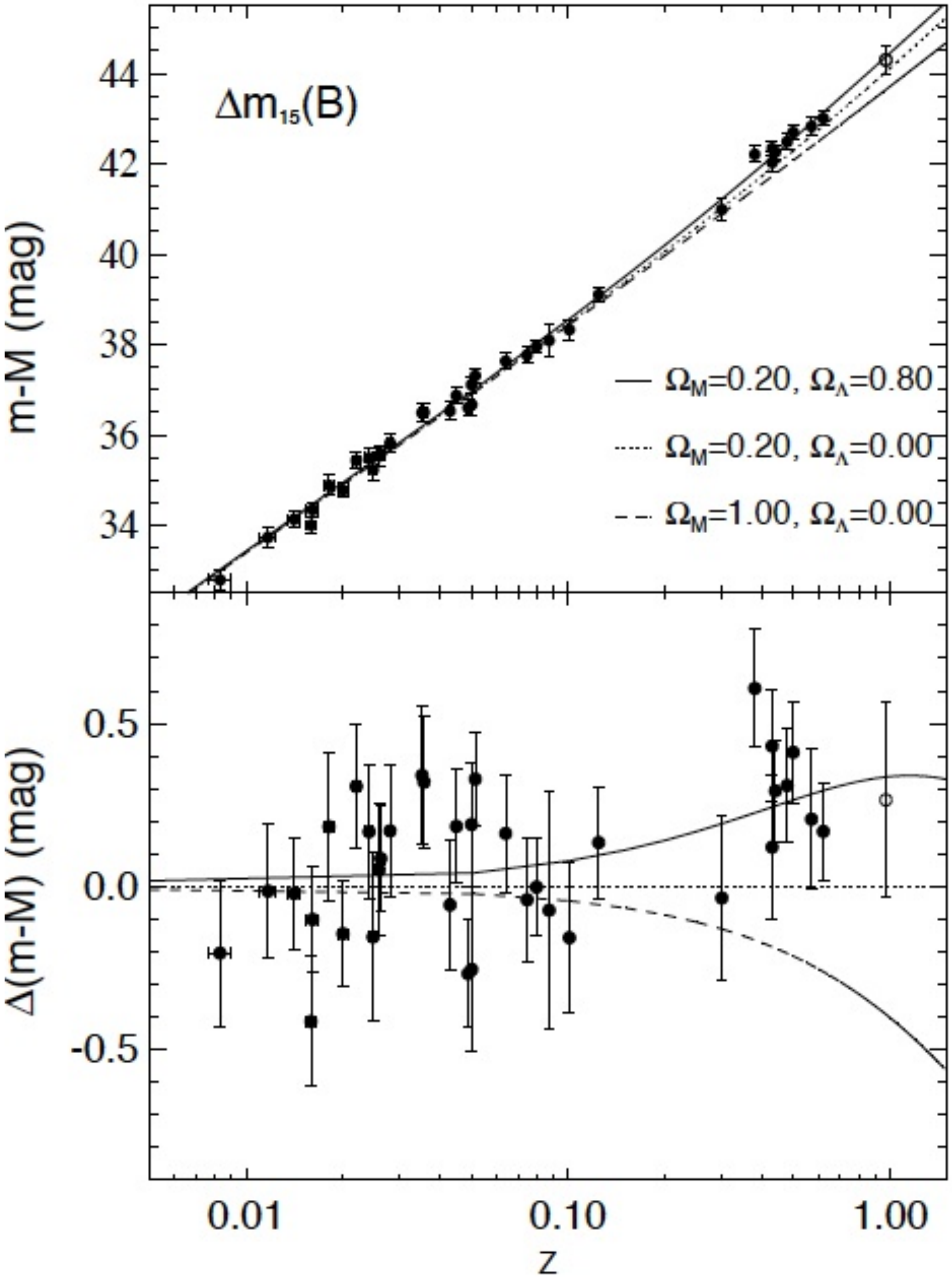
The ultimate fate of the Universe, infinite expansion or a big crunch, can be determined by using the redshifts and distances of very distant supernovae to monitor changes in the expansion rate. We can now find[1] large numbers of these distant supernovae, and measure their redshifts and apparent brightnesses; moreover, recent studies of nearby type Ia supernovae have shown how to determine their intrinsic luminosities[2–4]—and therefore with their apparent brightnesses obtain their distances. The >50 distant supernovae discovered so far provide a record of changes

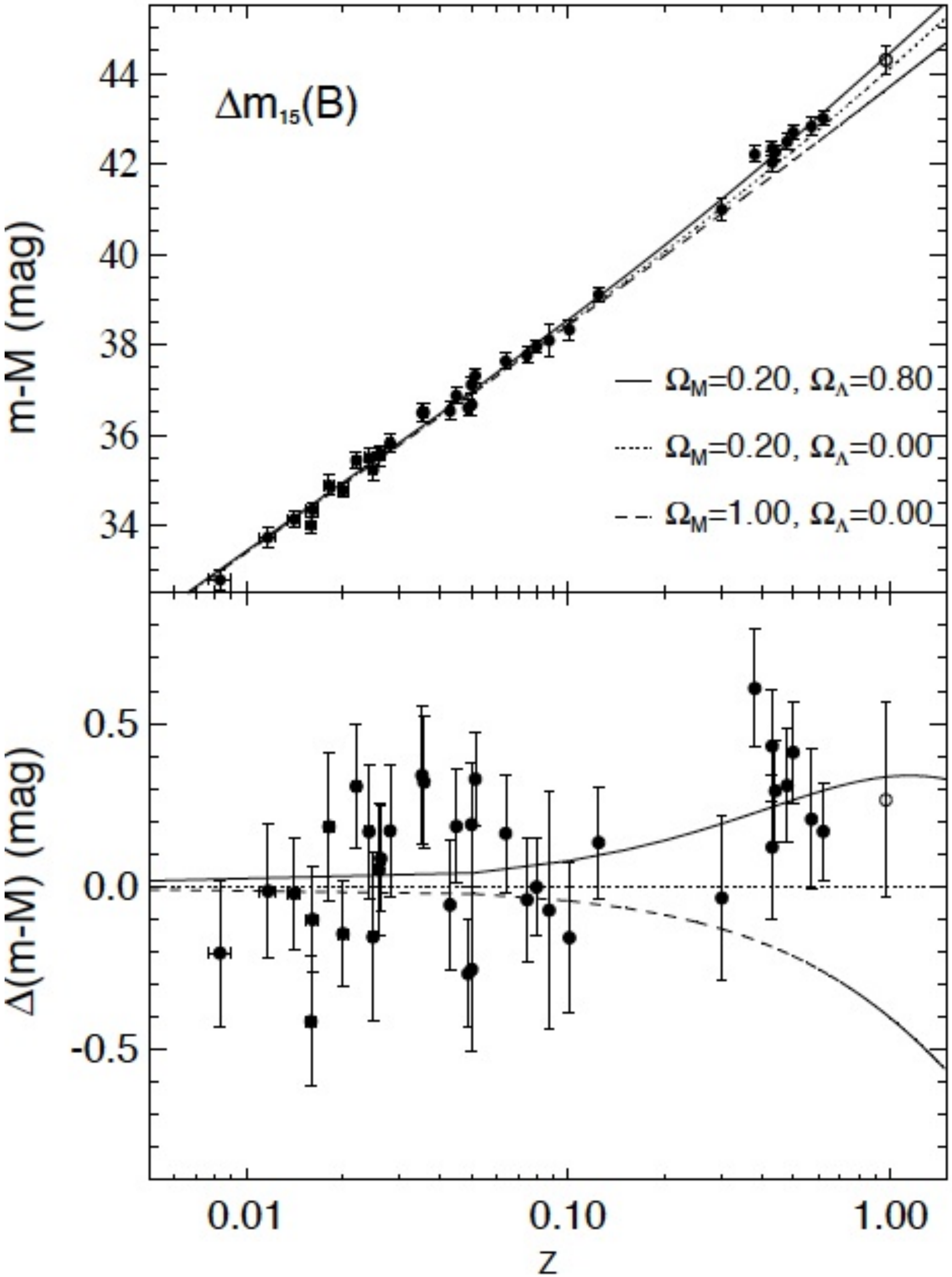




$\Omega_m \sim 0.20$

$\Omega_\Lambda \sim 0.80$

Riess at al. 1998



$\Omega_m \sim 0.20$

$\Omega_\Lambda \sim 0.80$

Riess at al. 1998

Schmidt et al. 1998

Perlmutter et al. 1999

Riess et al. 2001

Tonry et al. 2003

Knopp et al. 2003

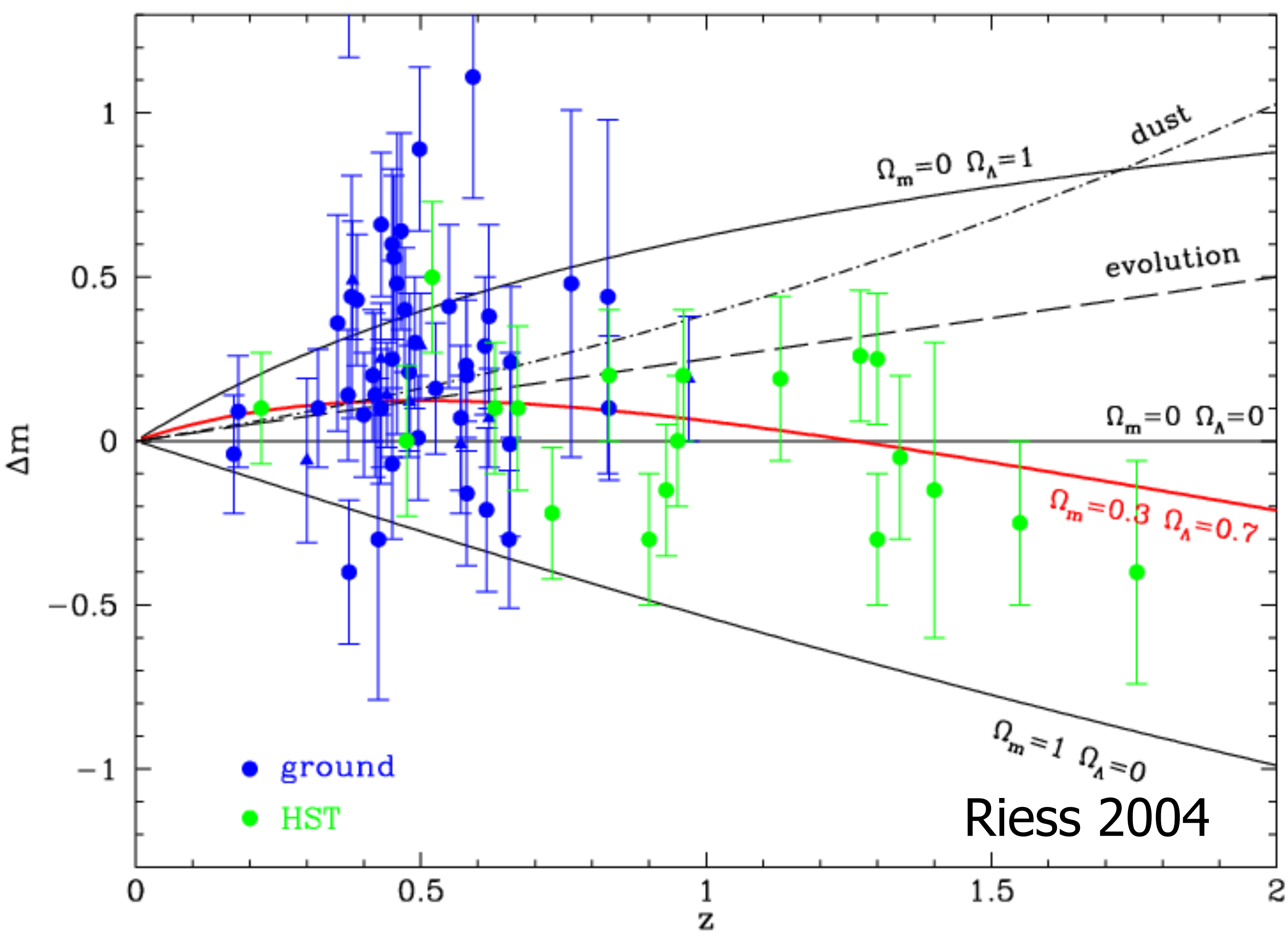
Riess et al. 2004

Astier et al. 2006

$\Omega_m \sim 0.29$

$\Omega_\Lambda \sim 0.71$

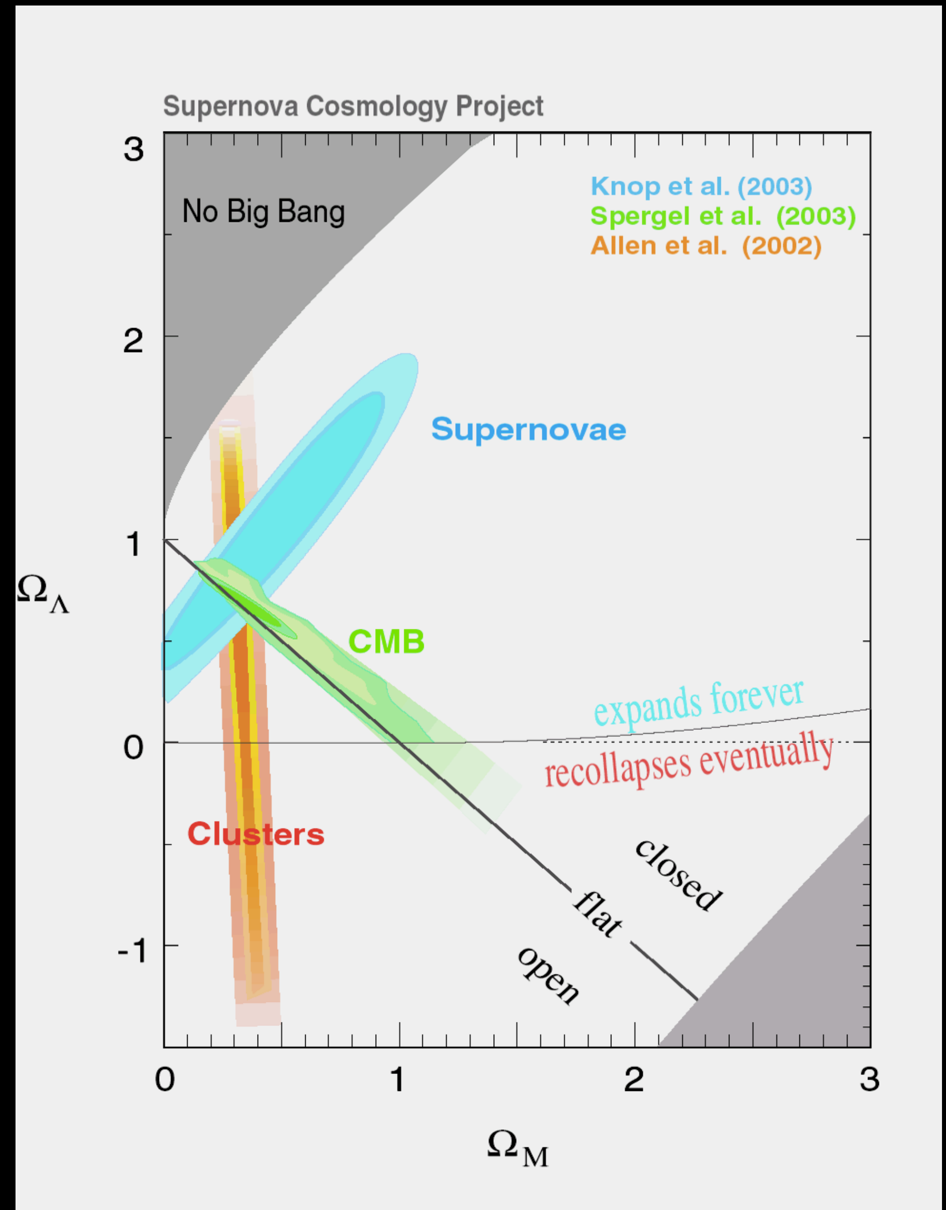
Hubble diagram (residuals)



Conclusions from SNe

The two teams consistently found that SNIa at redshifts $z \sim 0.5$ appear dimmer than expected by ~0.25 magnitudes. $z \sim 0.5$ is the transition epoch between acceleration and deceleration.

This result *suggests* (after assuming a flat universe) that the expansion of the Universe is *accelerating*, propelled by "dark energy", with $\Omega_\Lambda \sim 0.7$ and $\Omega_M \sim 0.3$.

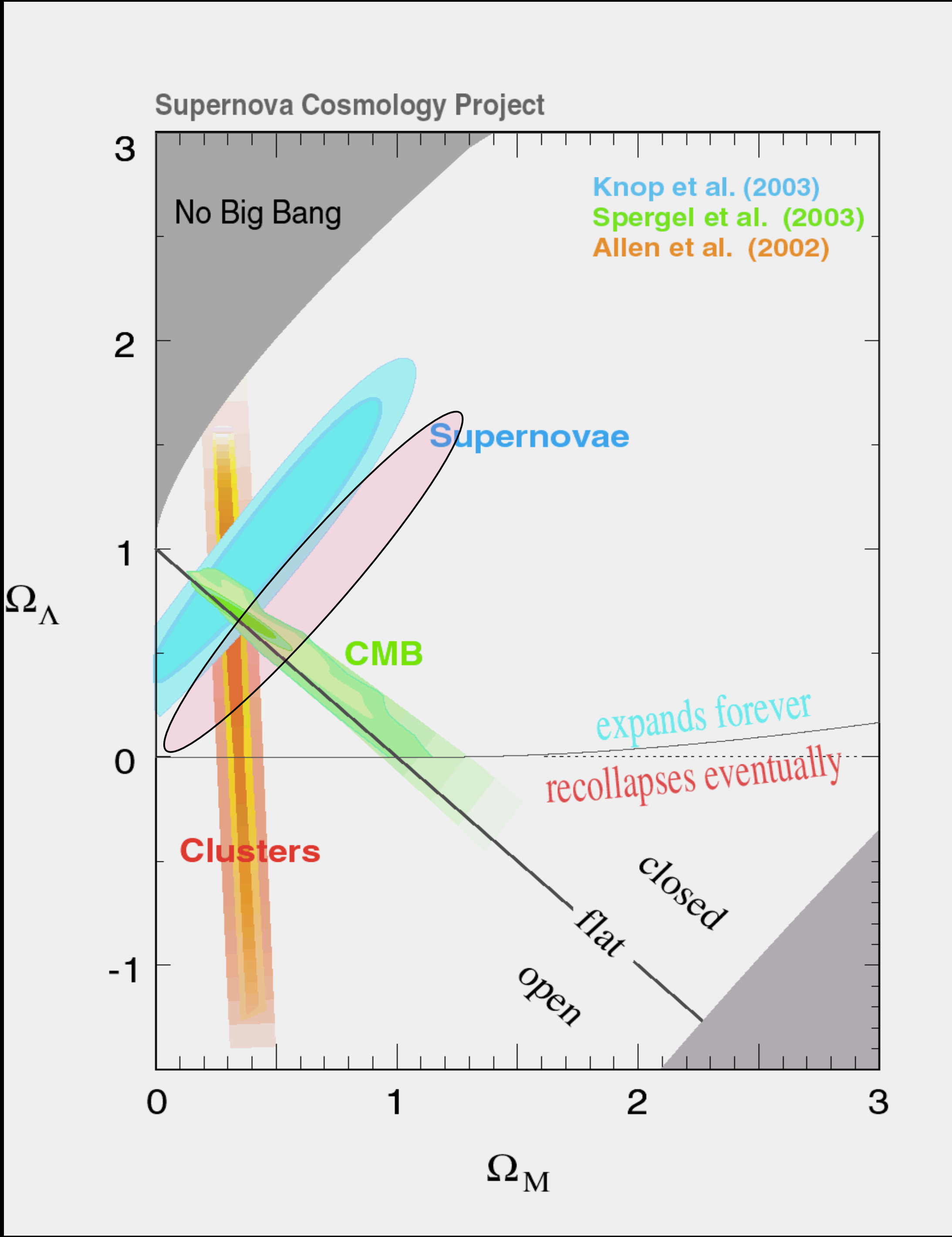


SN Systematics

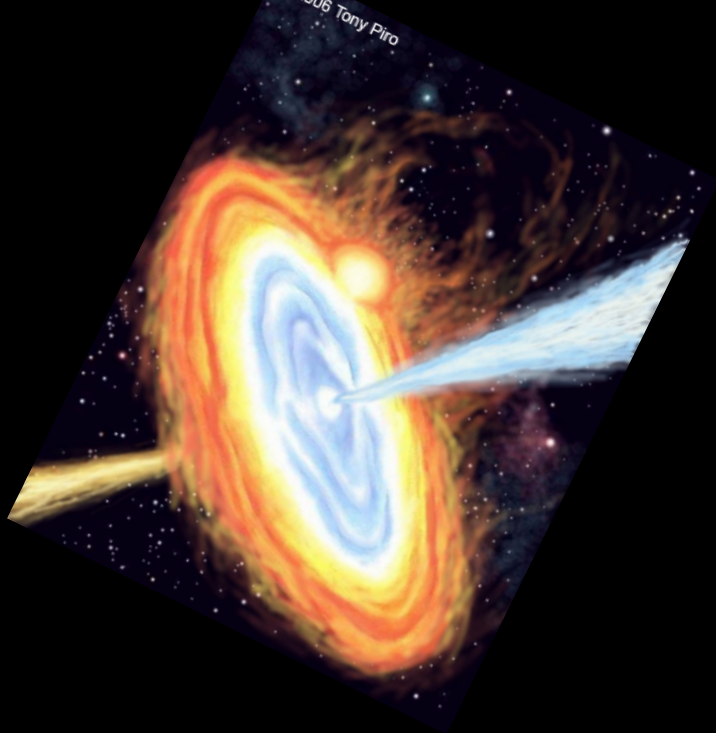
The cosmological interpretation rely on the lack of evolutionary effects on progenitors of type Ia SNe.

Source of (possible) Supernova systematics

1. unknown explosion mechanism (z?)
2. unknown progenitor systems (z?)
3. light curve shape correction methods for the luminosity normalisation may depend on z
4. signatures of evolution in the colours? (z?)
5. anomalous reddening law (R_V 1.5÷5)
6. contaminations of the Hubble Diagram by no-standard SNe-Ia and/or bright SNe-Ibc (e.g. HNe)

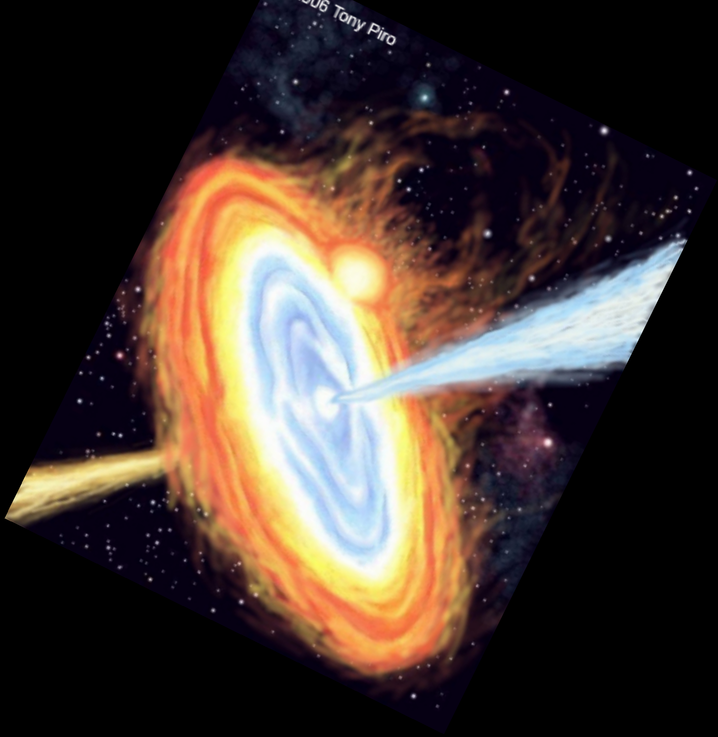


If the "offset from the truth" is just 0.1 mag....



GRBs allow us **today** to change the "experimental methodology" and provide an independent measurement of the cosmological parameters

Ghirlanda et al. 2004; Liang & Zhang 2005; Firmani et al. 2006; Amati et al. 2008; Kodama et al. 2008; Liang et al. 2008; Li et al. 2008; Cardone et al. 2009 and 2011; Liang et al. 2010, Capoziello et al. 2010; Wang et al. 2010, Demianski et al. 2010 and 2011



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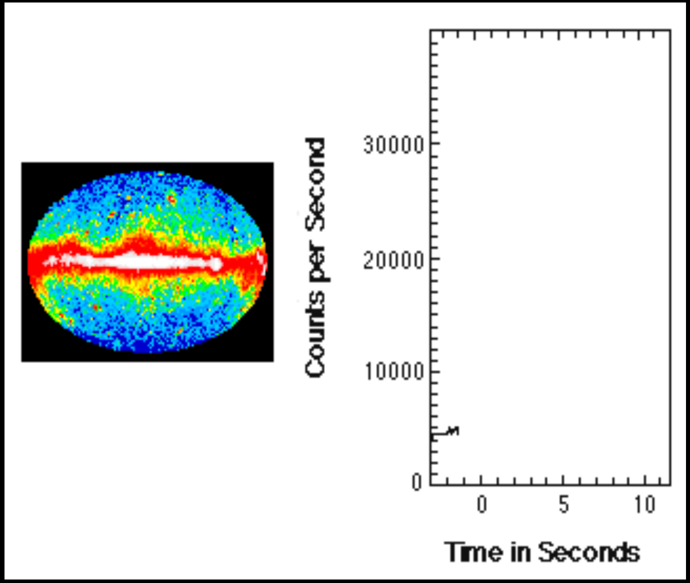
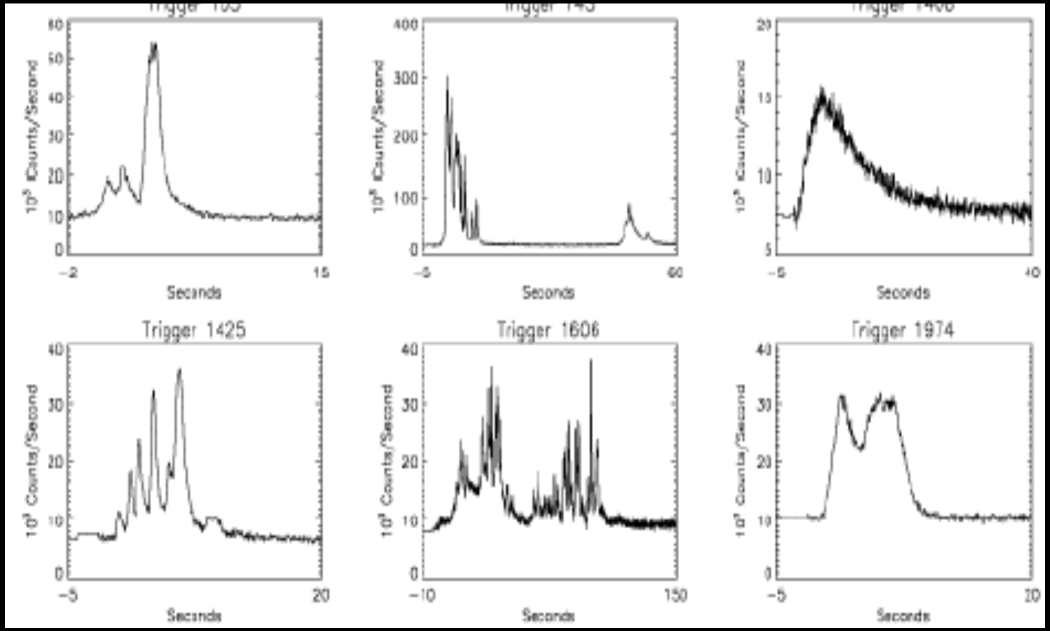
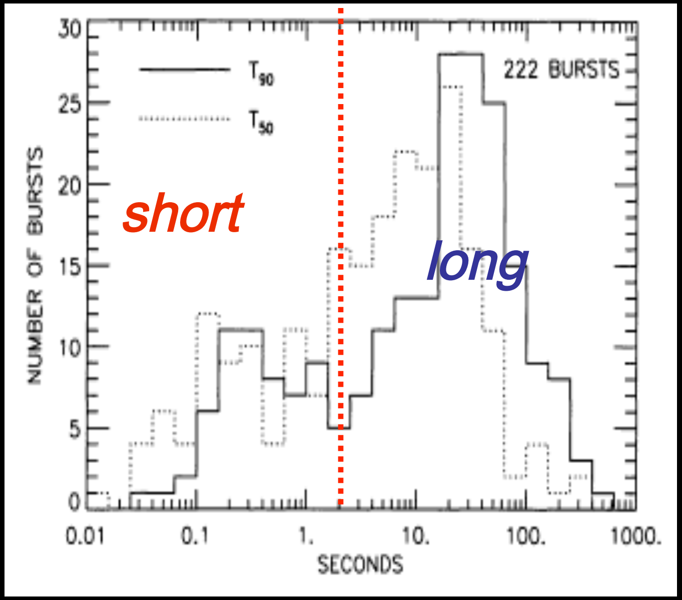
The Gamma-Ray Burst phenomenon

- 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: ~0.8 / day; estimated true rate ~2/d







GRBs Strengths

- GRBs are extremely bright → detectable out of cosmological distances (z=8.2 Salvaterra et al. 2009)

- SNe-Ia are currently observed at $z<1.7$. Then GRBs appear to be the only class of objects capable to study the evolution of the dark energy from $z\sim10$

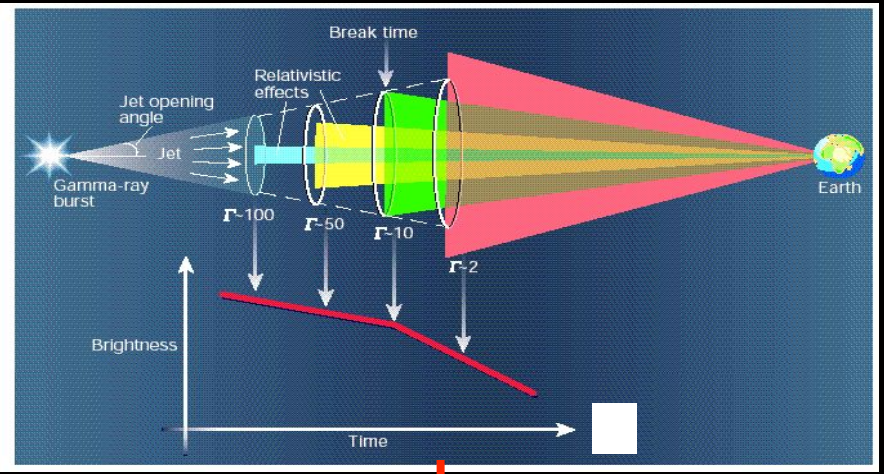
- No correction for reddening

GRBs weaknesses

- GRBs are not standard candles $E=10^{48-54}$erg
- GRBs cannot be standardize (like SNe-Ia)

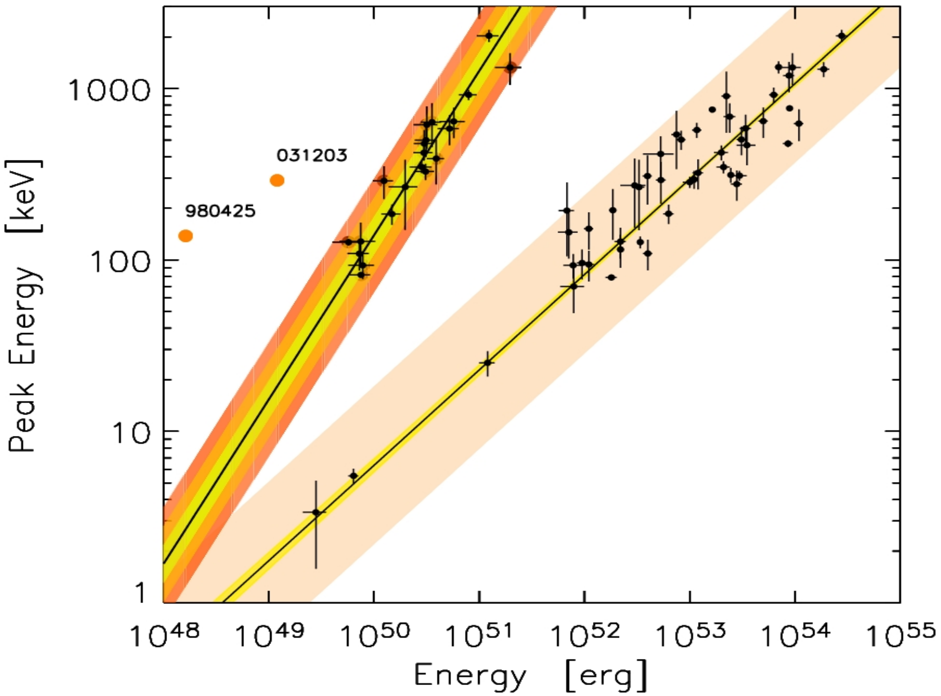
"Standardizing" GRB ?

2004: evidence that by substituting Eiso with the collimation corrected energy Eγ the dispersion of the luminosity function of GRBs decreases significantly (Ghirlanda et al. 2004; Firmani et al. 2006) but not enough !



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

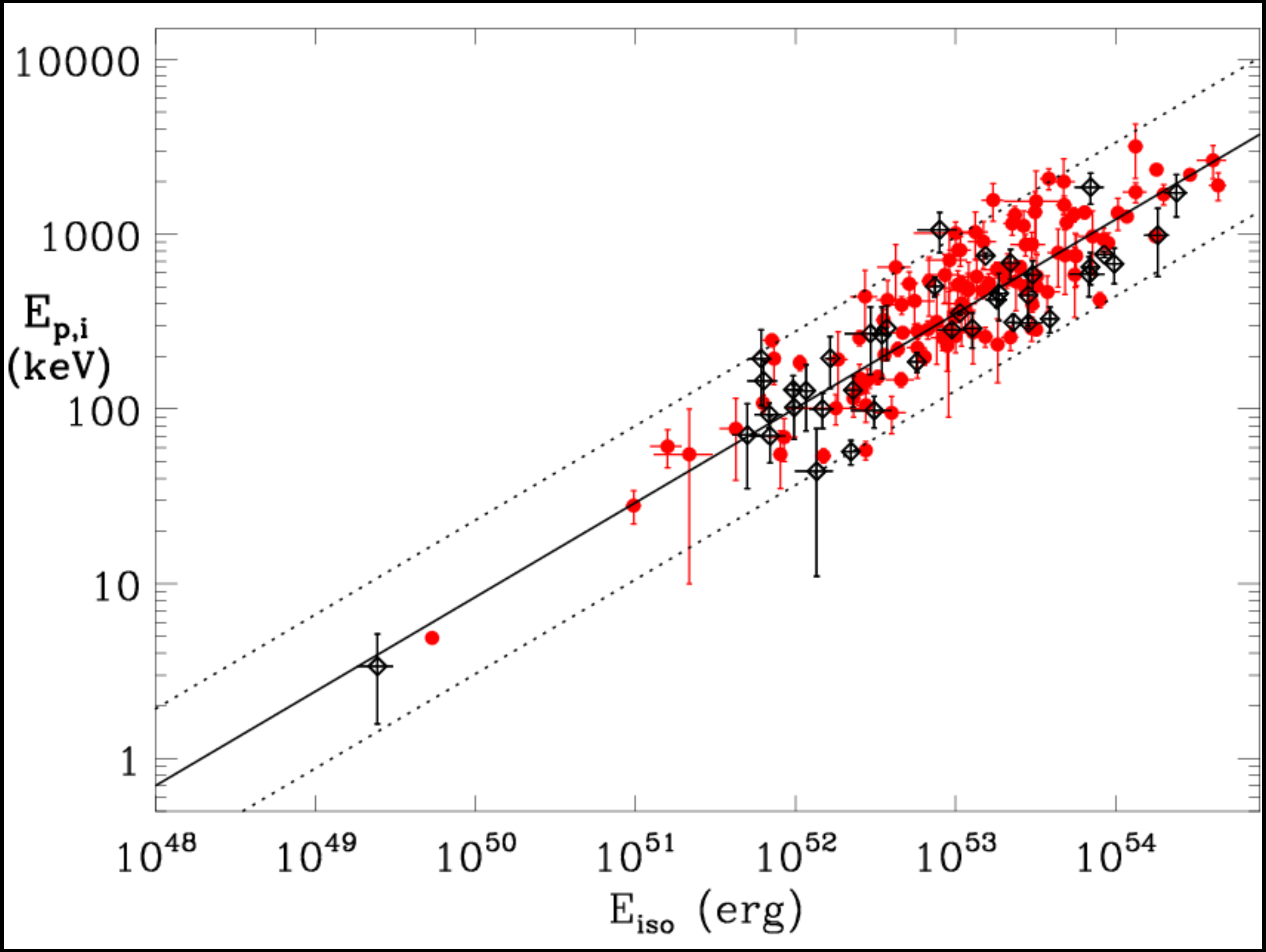
$$E_\gamma = (1 - \cos\theta) E_{\gamma,iso}.$$



GRBs weaknesses

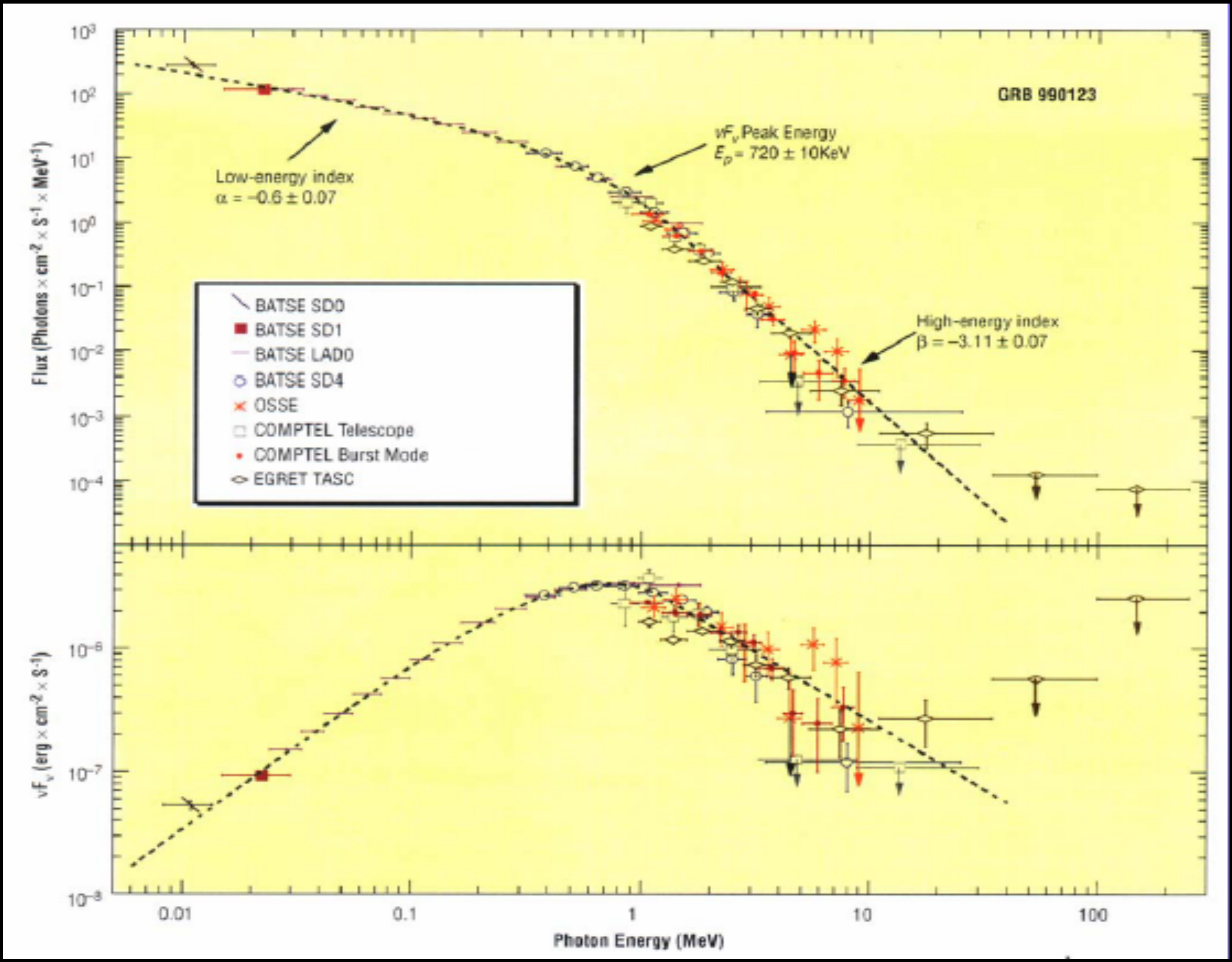
- GRBs are not standard candles $E=10^{48-54}$erg
- GRBs cannot be standardize (like SNe-Ia)
- GRBs cannot be calibrated in the local universe (too few and the only ones observed are peculiar/sub-energetic)

The $E_{p,i}$-E_{iso} correlation for cosmology



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

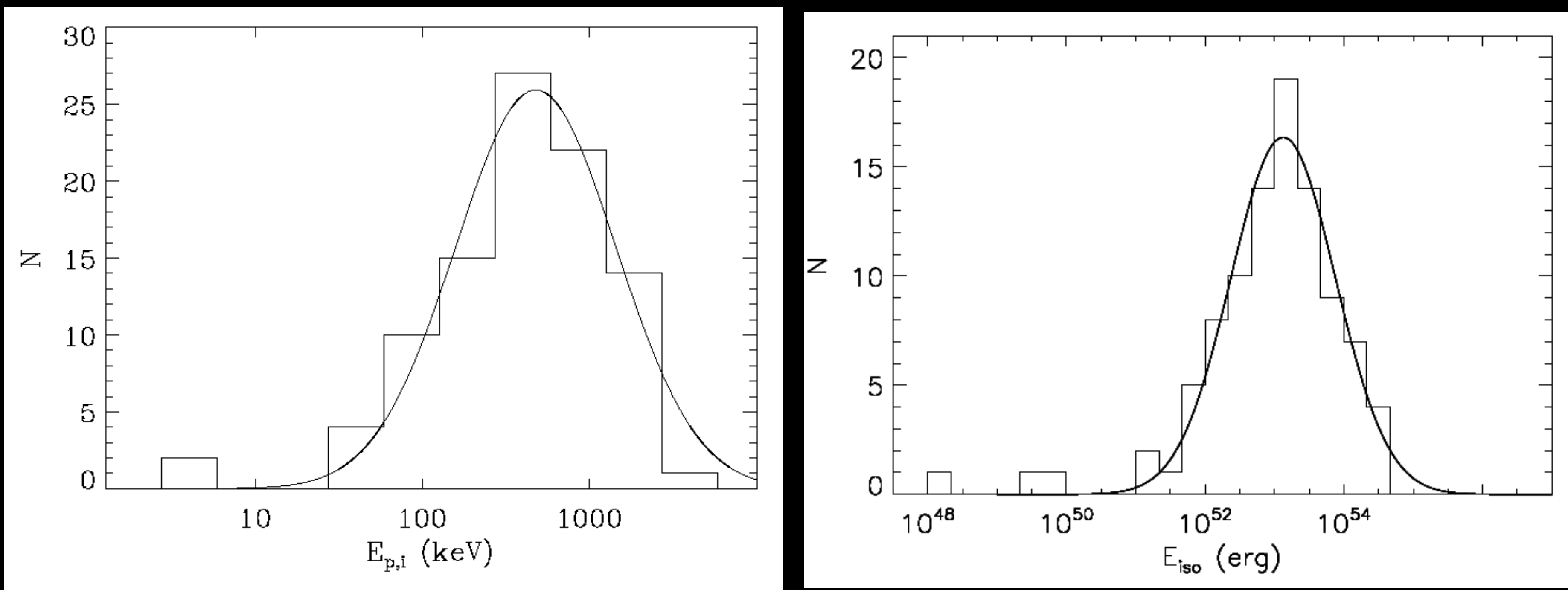
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$



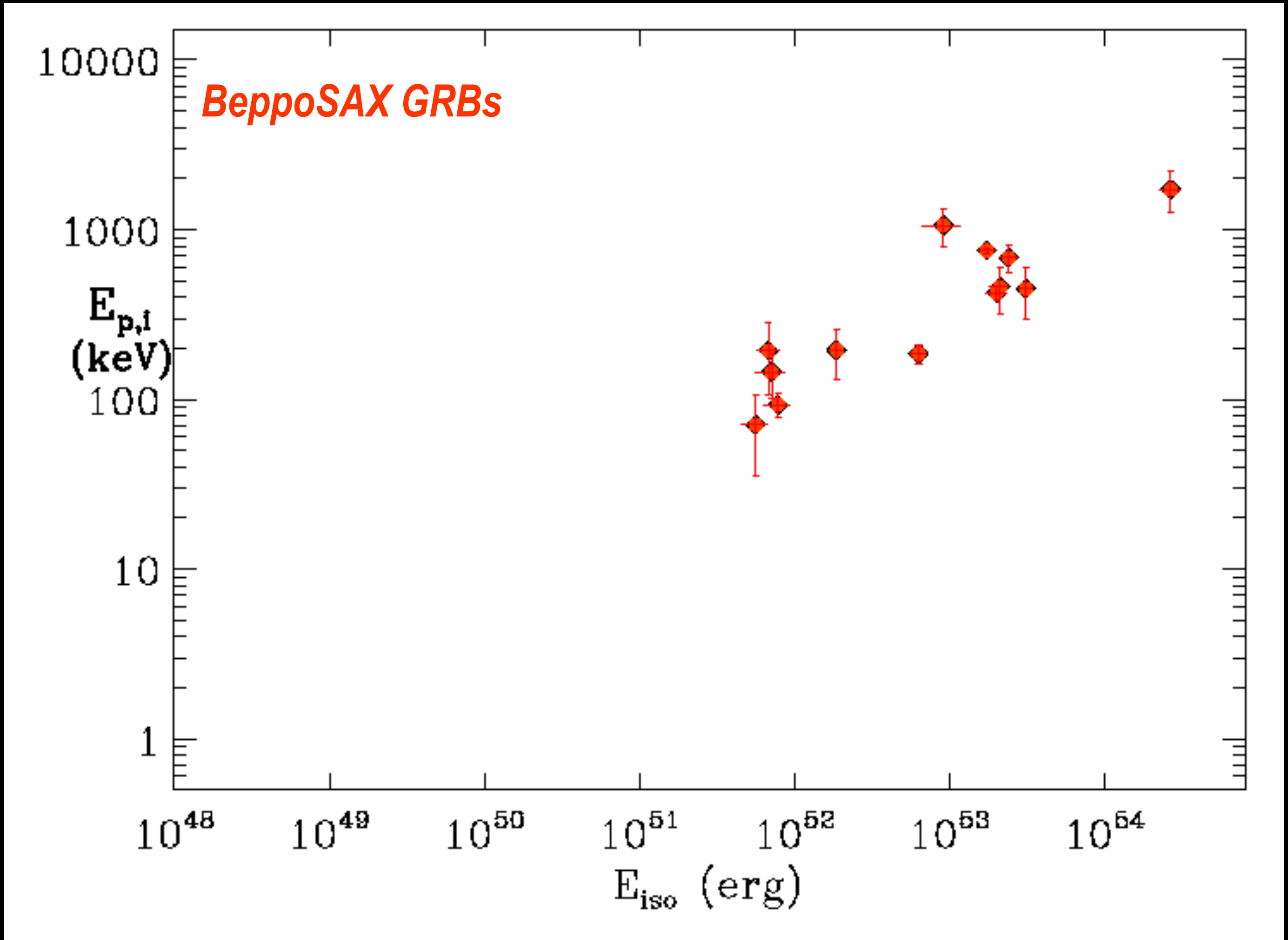
Peak Energy:

It is the "color" of the GRB, i.e. the frequency at which the GRB emits the main bulk of the energy produced in the outburst

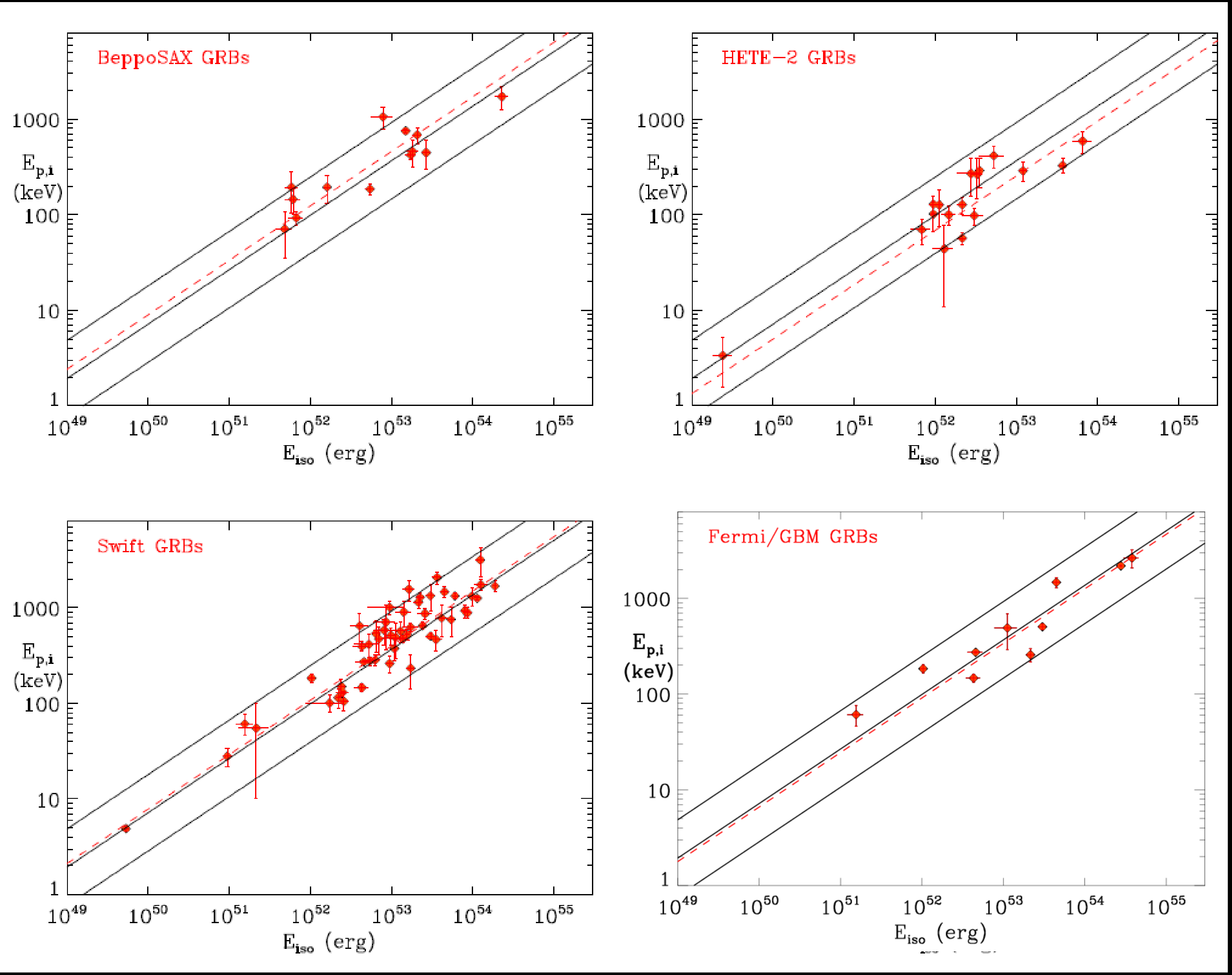
Both Ep, i and Eiso span several orders of magnitude and a distribution which can be described by a Gaussian plus a low – energy tail ("intrinsic" XRFs and sub-energetic events)



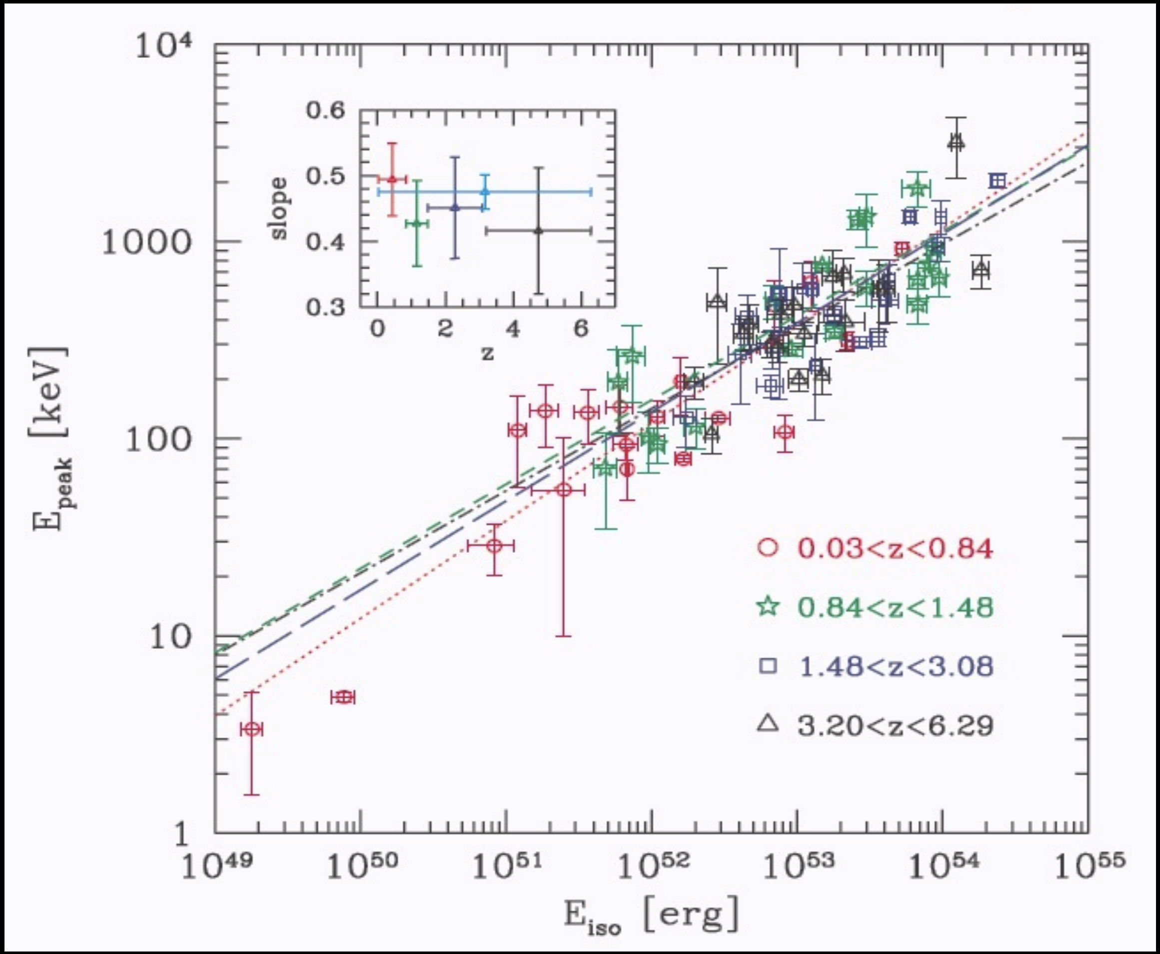
Amati et al. (A&A 2002): significant correlation between Ep,i and Eiso found based on a small sample of BeppoSAX GRBs with known redshift



The normalization of the correlation varies only marginally using GRBs measured by individual instruments with different sensitivities and energy bands (Amati et al. 2009)



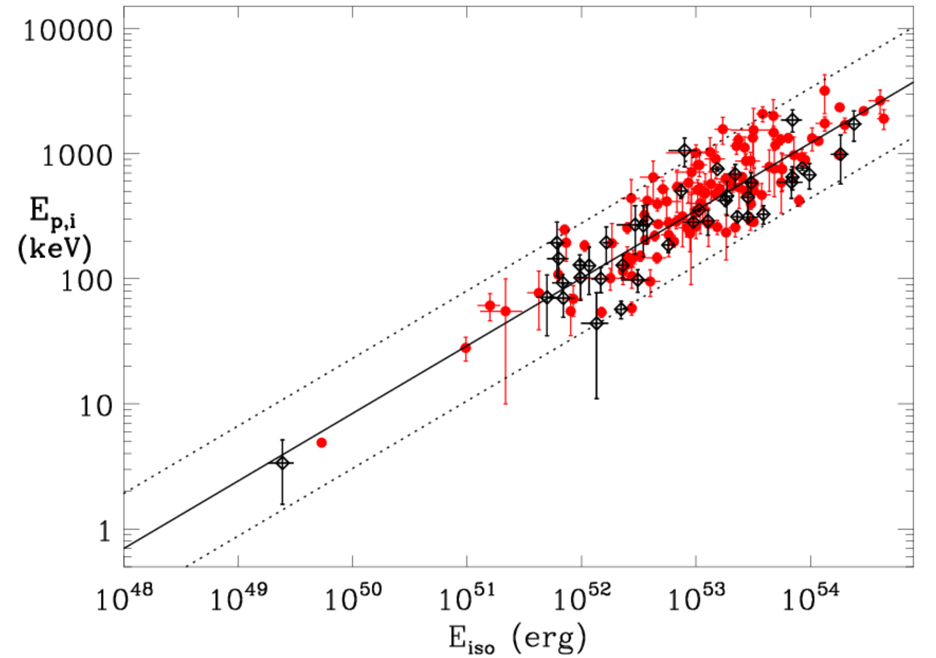
No evidence of evolution of index and normalization of the correlation with redshift



Ghirlanda et al. 2008

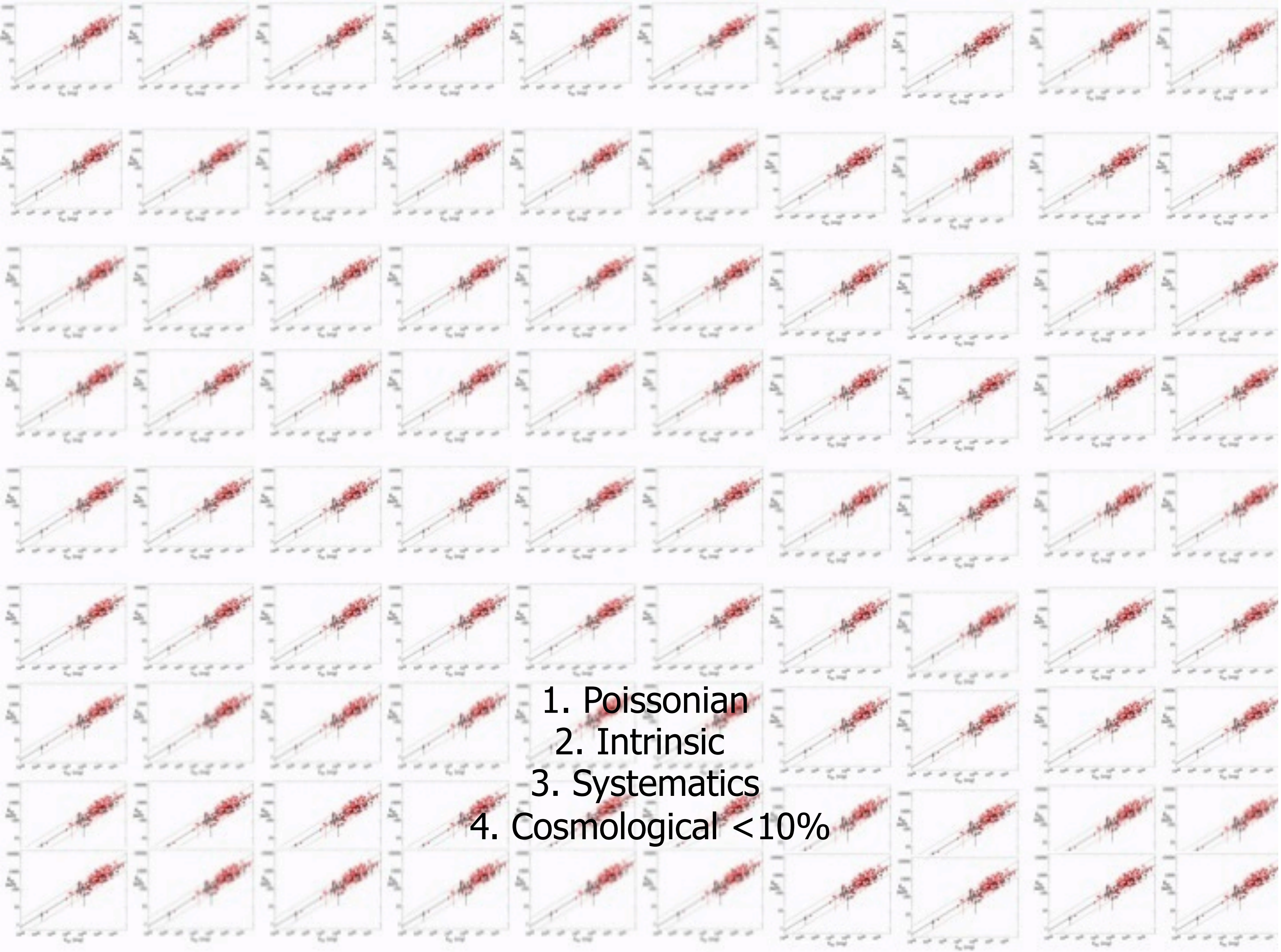
The Scatter of the Amati relation

1. Poissonian
2. Intrinsic
3. Systematics
4. Cosmological <10%



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

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



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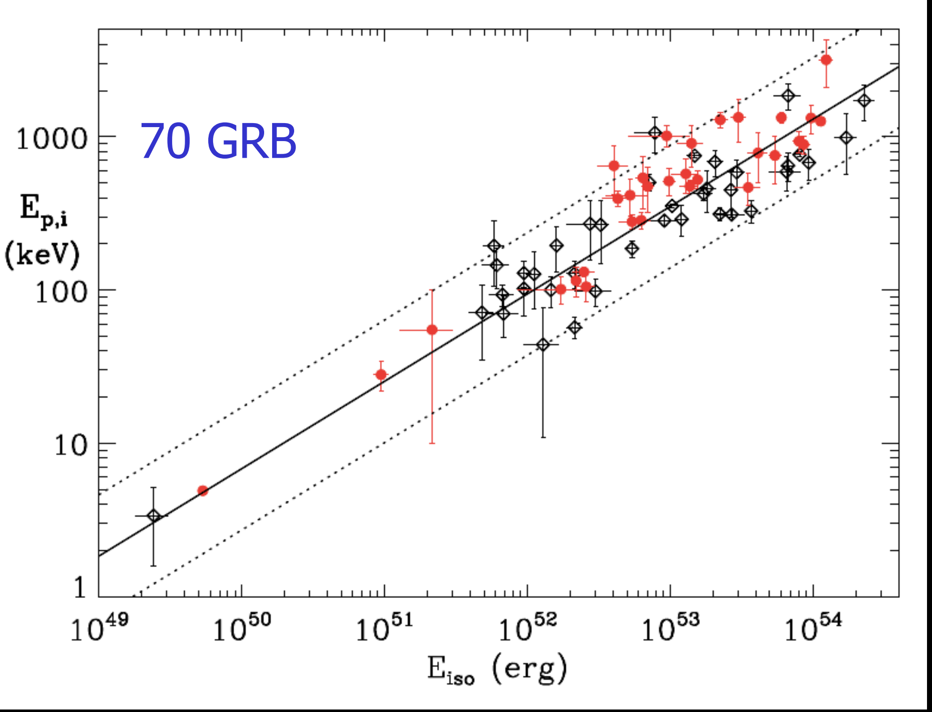
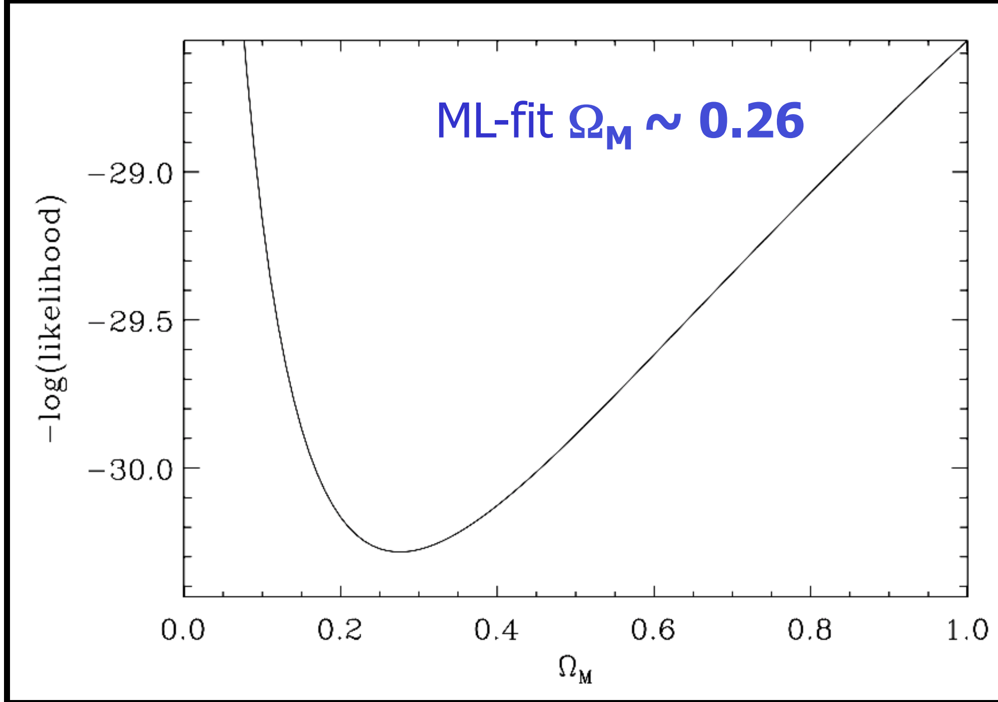
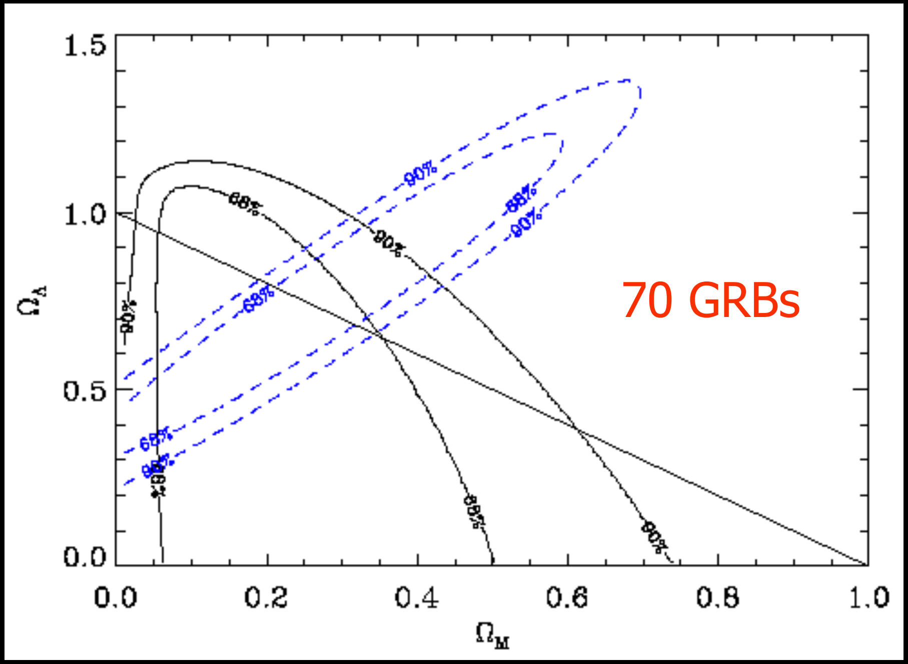




We find clear evidence that the observed scatter of the $E_{p,i}$-E_{iso} correlation depends on the choice of cosmological parameters used to compute E_{iso} . In other words the observed dispersion is sensitive at varying the values of the cosmological parameters

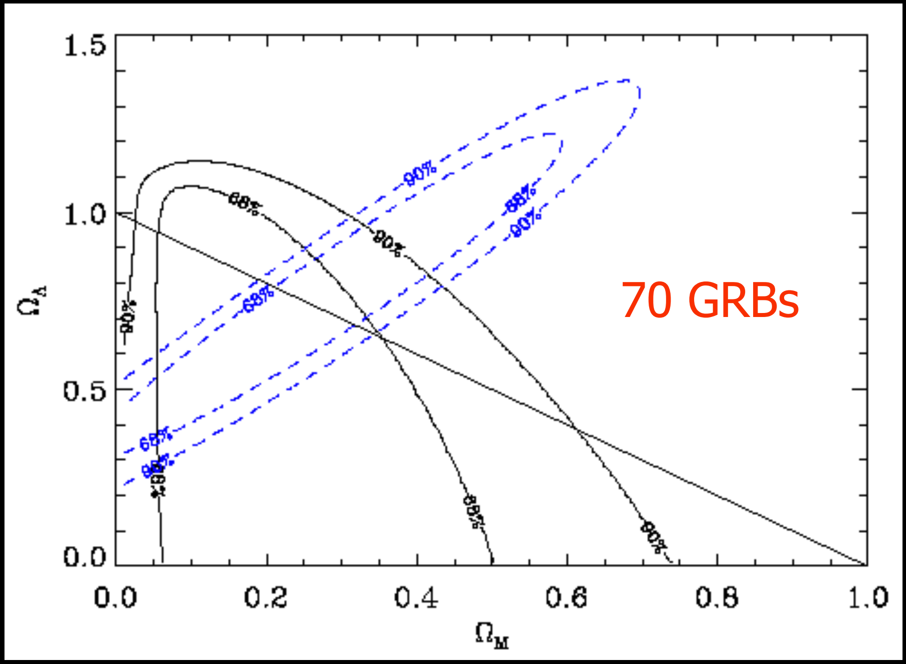
By using a maximum likelihood method the extrinsic scatter can be parametrized and quantified (e.g., Reichart 2001, D' Agostini 2005)

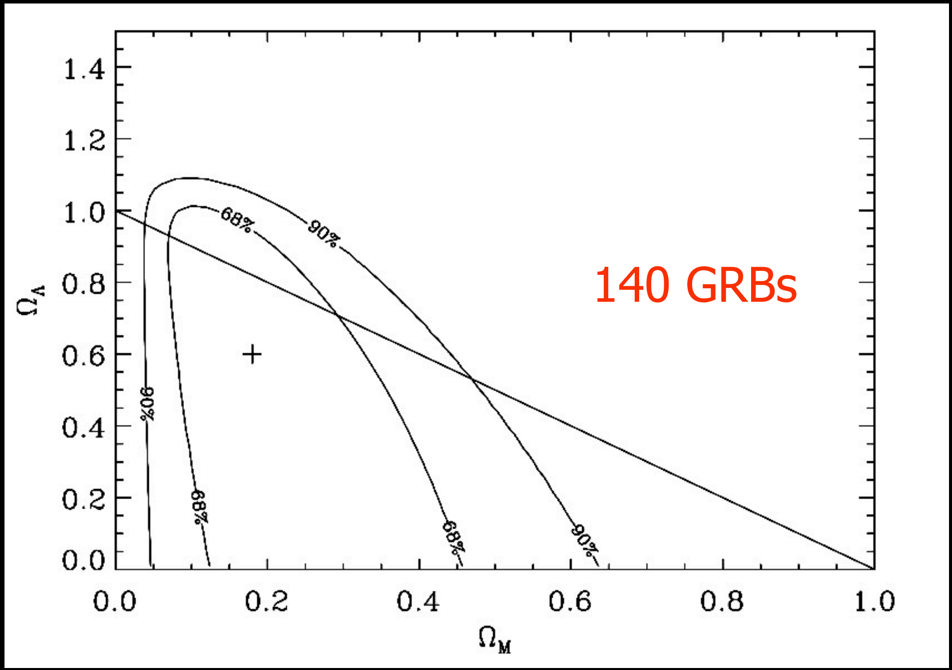
$$L(m, c, \sigma_v\,;\boldsymbol{x}, \boldsymbol{y}) = \frac{1}{2}\sum_i \log\left(\sigma_v^2 + \sigma_{y_i}^2 + m^2\,\sigma_{x_i}^2\right) + \frac{1}{2}\sum_i \frac{(y_i - m\,x_i - c)^2}{\sigma_v^2 + \sigma_{y_i}^2 + m^2\,\sigma_{x_i}^2}$$



Ω_M = 1 excluded at 99.9% c.l.

Ωm (flat universe)	Ω_M	68%	*90%*
70 GRBs (Amati+ 08)	0.26	0.10 – 0.62	0.07 – 0.87





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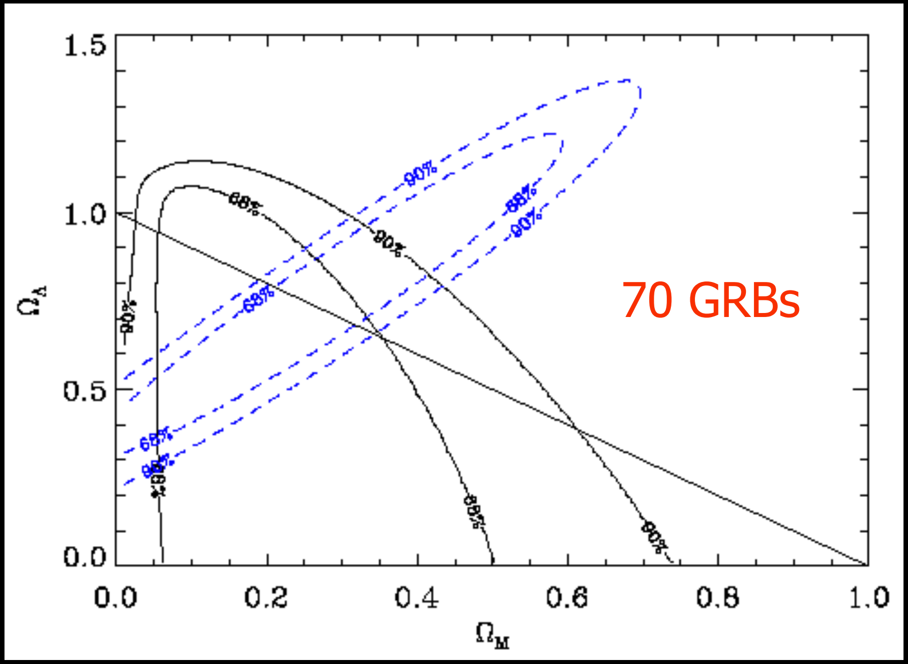
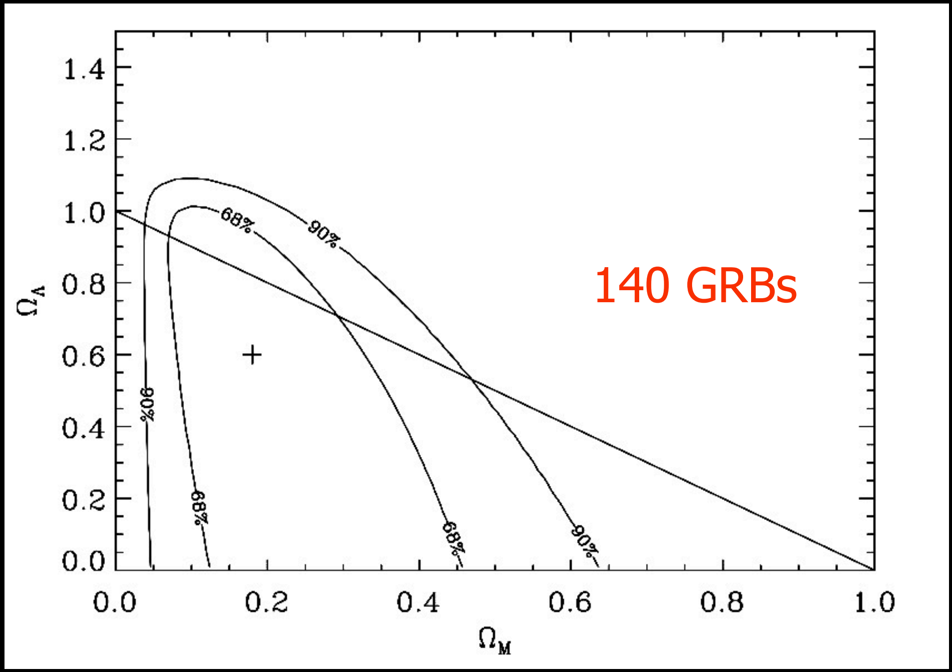
140 GRBs (Amati+ 13)	0.28	0.13 – 0.57	0.09 – 0.81





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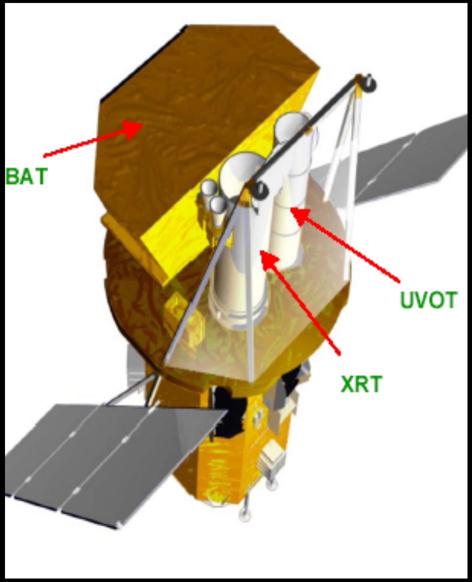
140 GRBs (Amati+ 13)	0.28	0.13 – 0.57	0.09 – 0.81
SNe-Ia Perlmutter et al. 1998+1999	0.28	0.19 –0.38	

Future

Swift + Konus-WIND + Fermi/GBM →

30 GRBs/yr in the Ep,i – Eiso plane

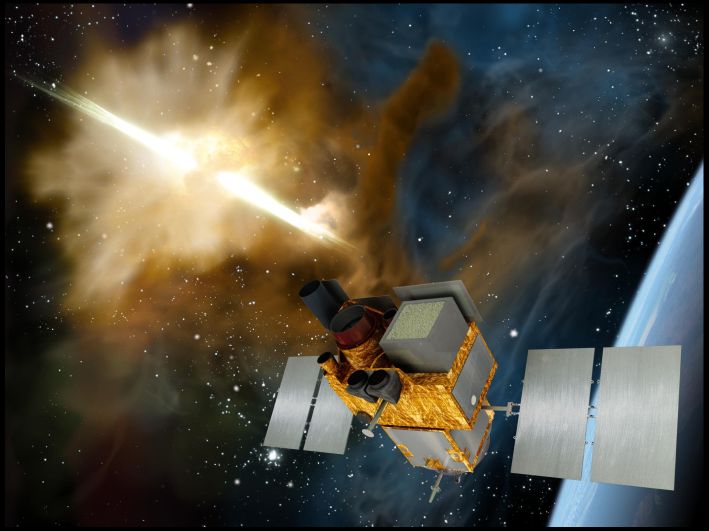


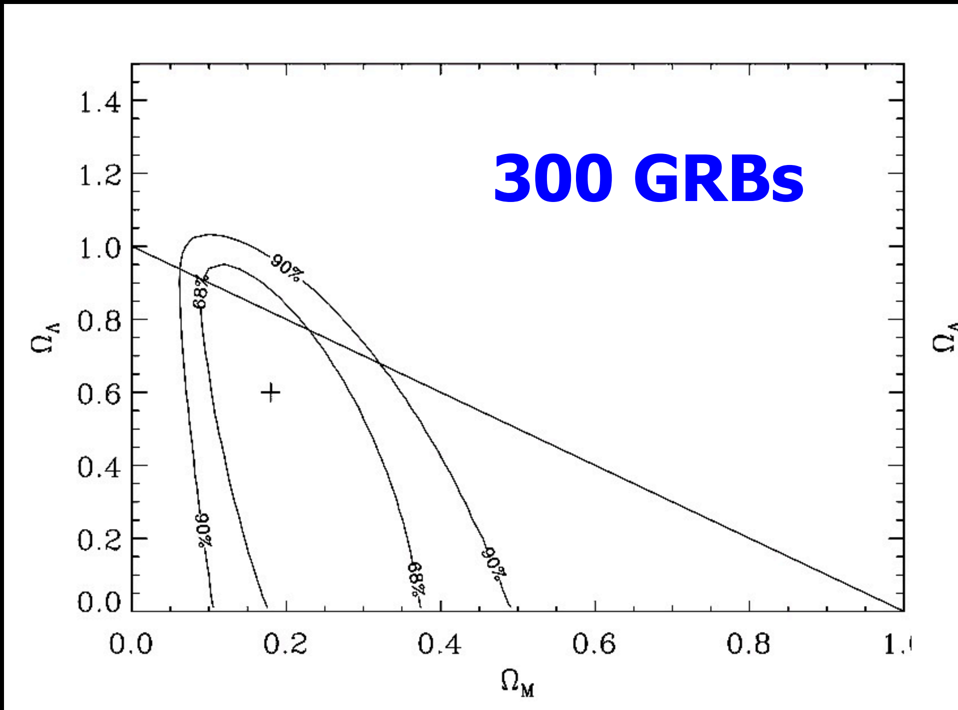
SVOM (from 2017) →

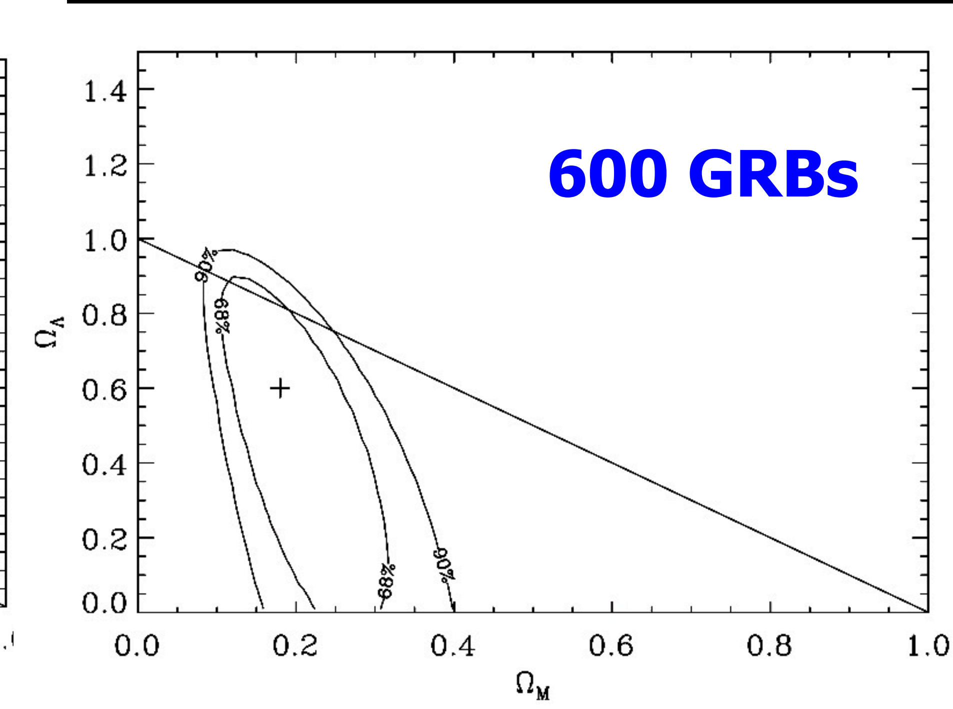
50 GRBs/yr in the Ep,i – Eiso plane

140+150 = 290 (<2018)

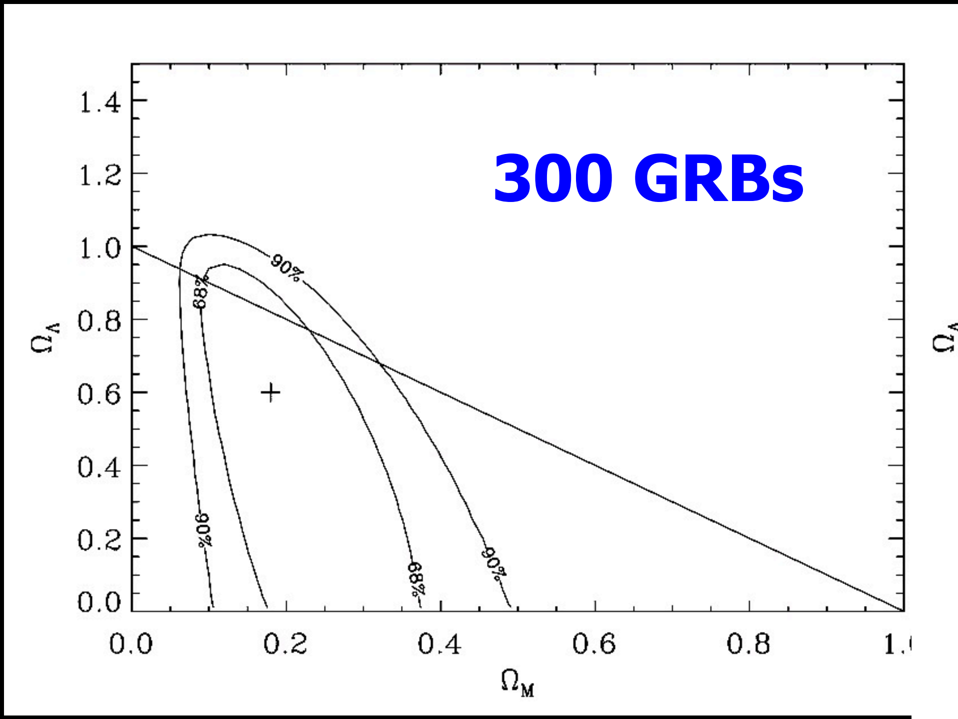
290+250 = 540 (<2023)

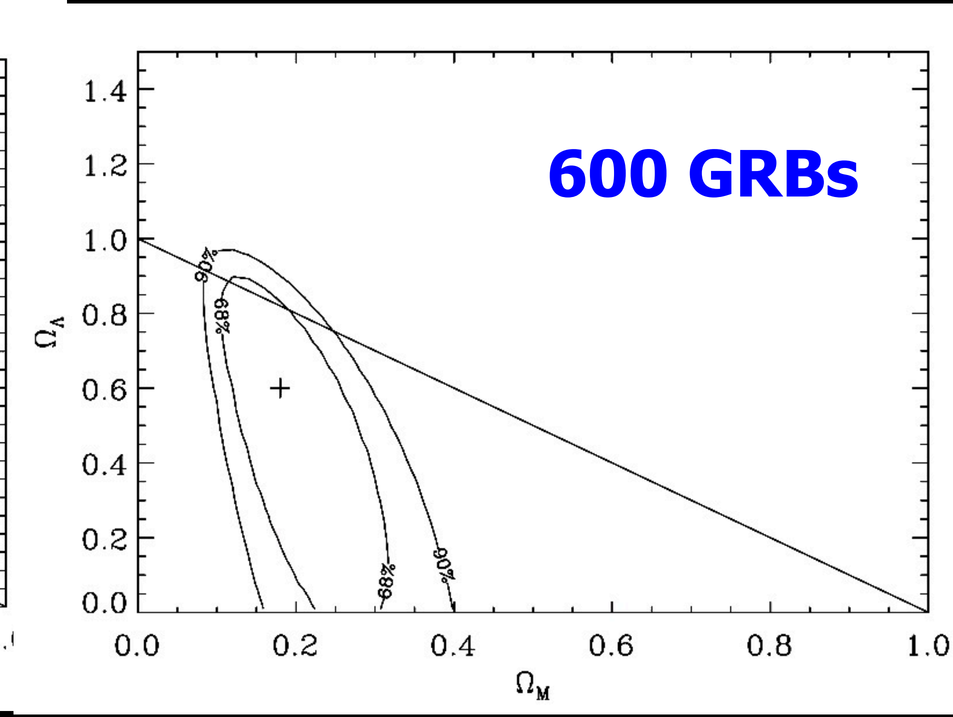






Ωm (flat universe)	Ω_M	68%	90%
70 GRBs (Amati+ 08)	0.26	0.10 – 0.62	0.07 – 0.87
140 GRBs (Amati+ 12)	0.28	0.13 – 0.57	0.09 – 0.81
300 GRBs (<2018)	?	0.19 – 0.38 0.16 – 0.47	0.11 – 0.65





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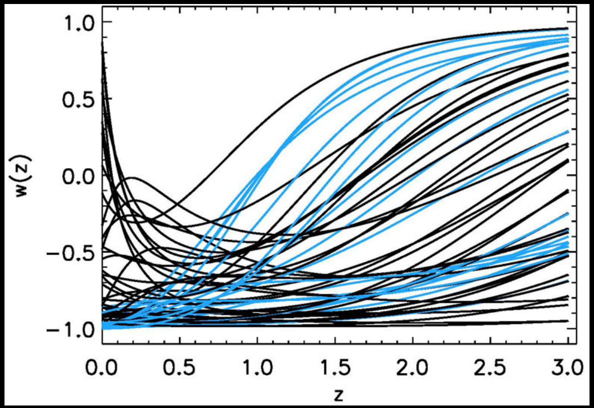
300 GRBs (<2018)	?	0.16 – 0.47	0.11 – 0.65
600 GRBs (<2023)	?	0.19 – 0.38 0.19 – 0.39	0.15 – 0.50

GRBs do it better



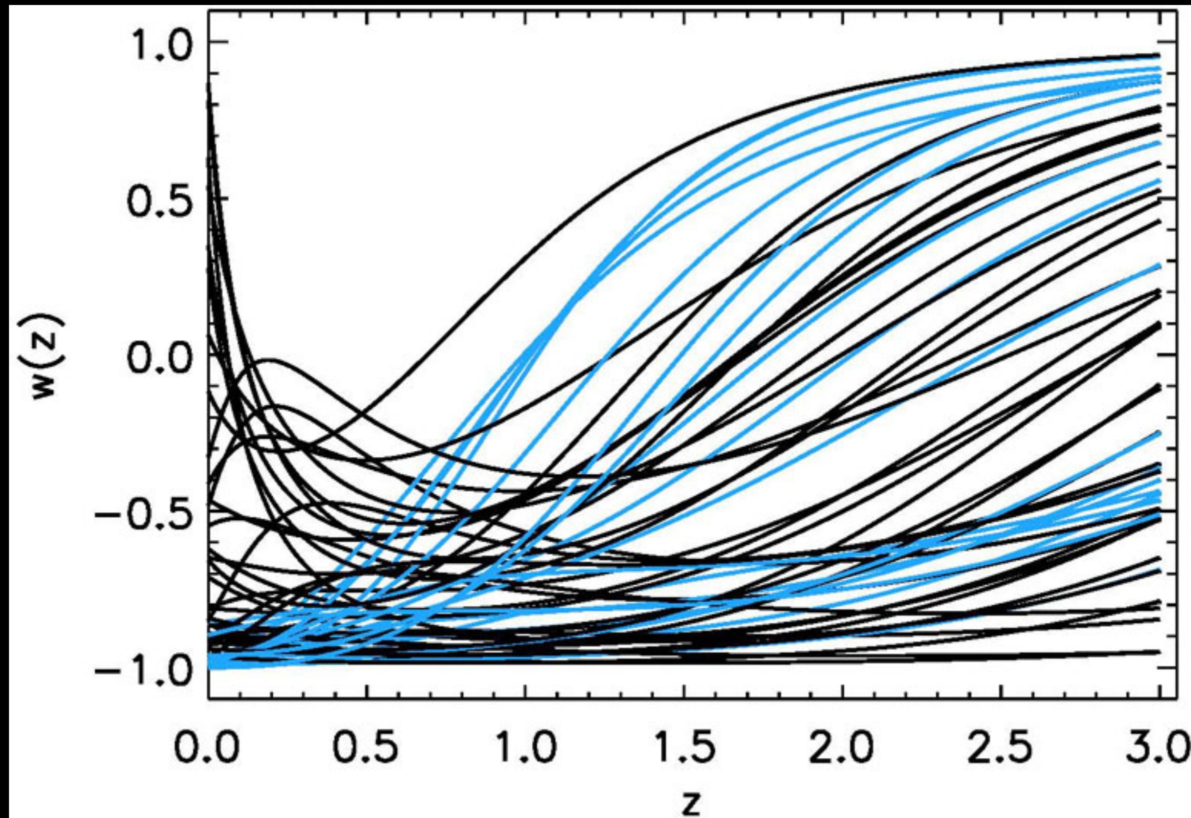
GRBs can constraints the equation of state of DE (pressure to energy density ratio, $p=w\rho_{DE}$) better than SNe-Ia

Time-dependent effects

A true cosmological constant, interpreted as a vacuum energy, is about 120 orders of magnitude smaller than its “natural” value. This is why there has been a lot of interest in models where the present energy density (or a dominant fraction of it) is rather some slowly varying cosmological constant term.

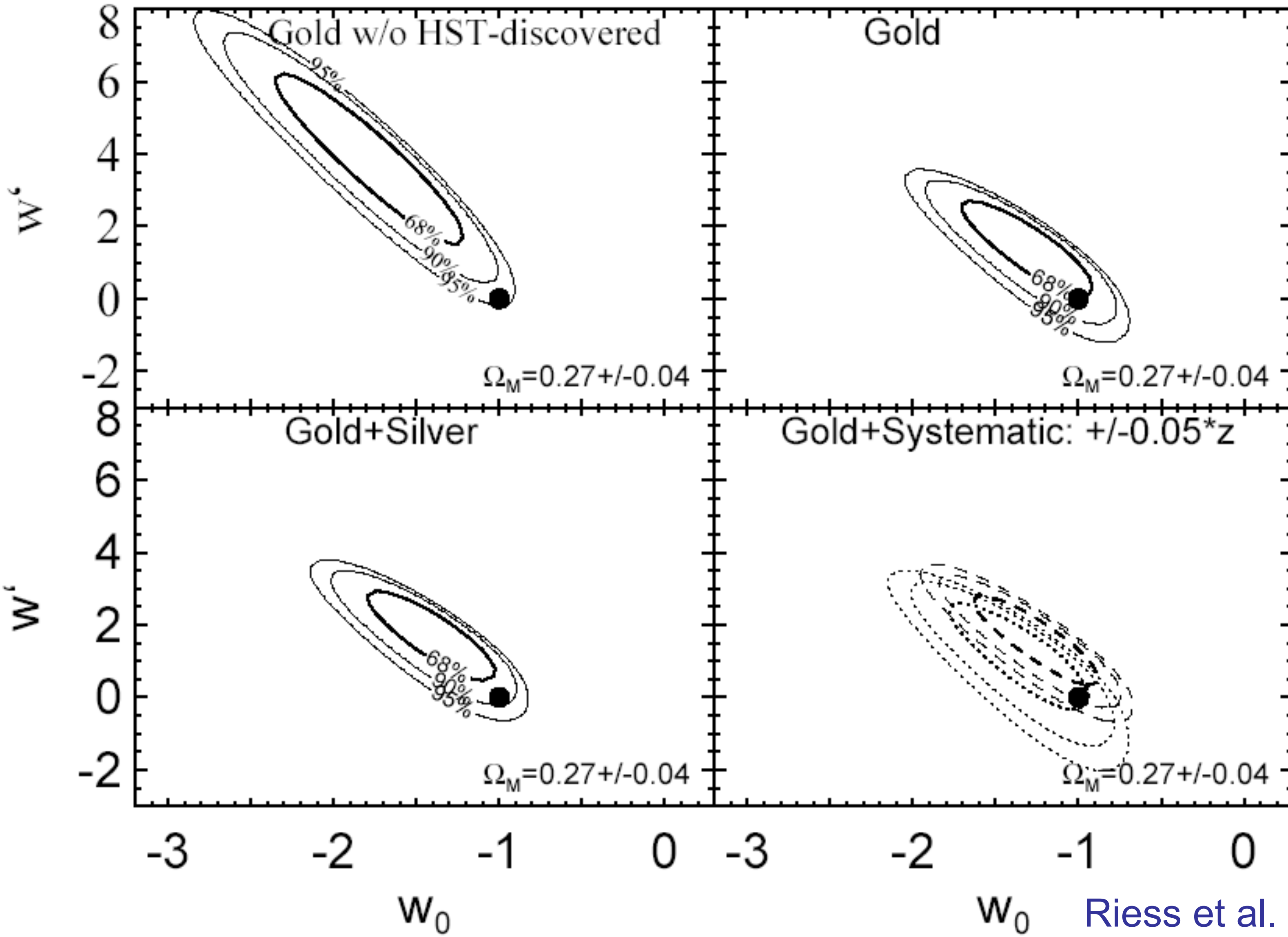
This idea was originally proposed by the Soviet cosmologist M.P.Bronstein as a decaying Λ

Bronstein was executed on Stalin’s order in 1938 presumably for reasons not directly related to the decaying Λ



• *w* 1/3	No cosmic acceleration
• *-1/3< w <-1*	“Quintessence”
• *w = -1*	Cosmological constant
• *w < -1*	Phantom Energy

$w(z)=w_o - w' \times z/(1+z)$ $w(z=0)=w_o$ $w' = dw/dz$



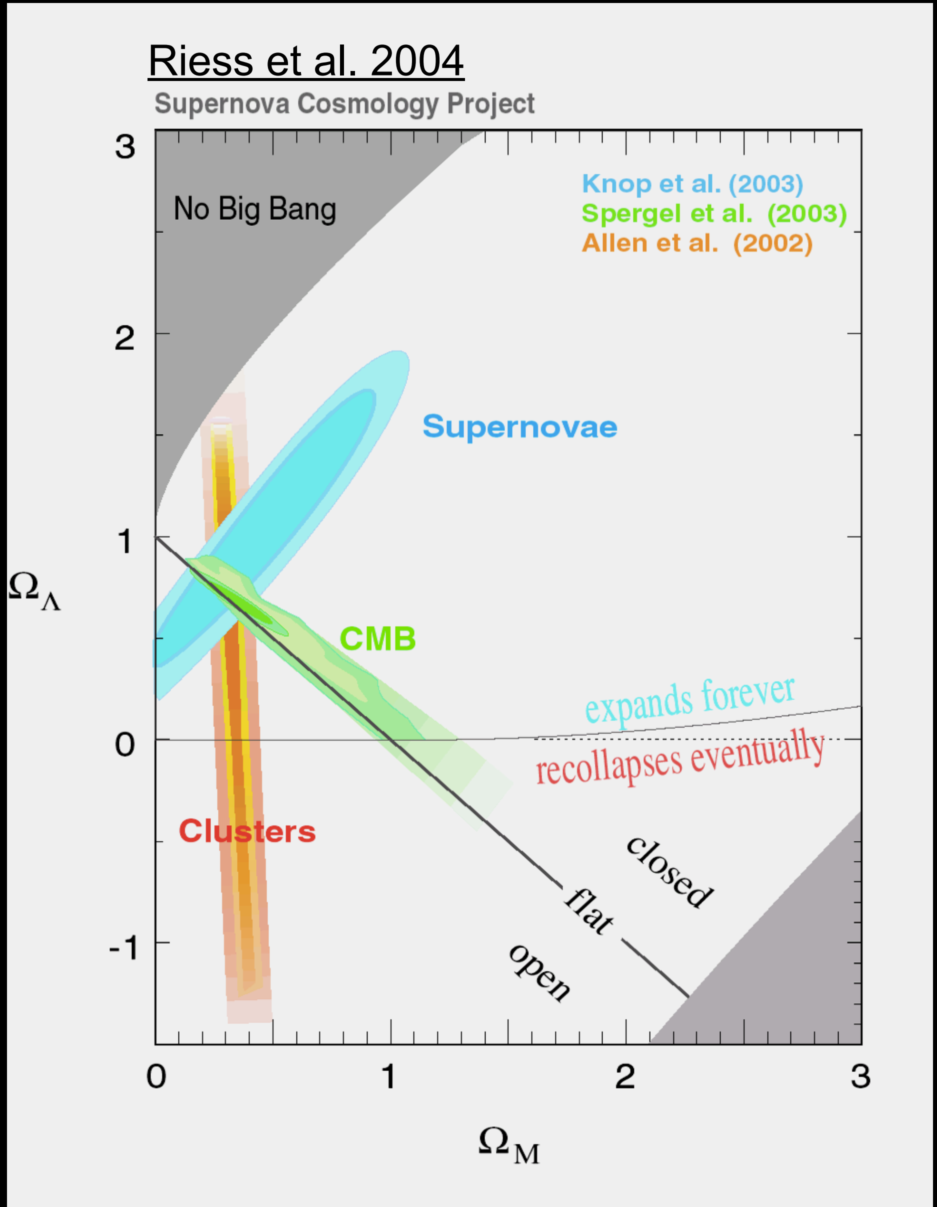
Riess et al. 2004

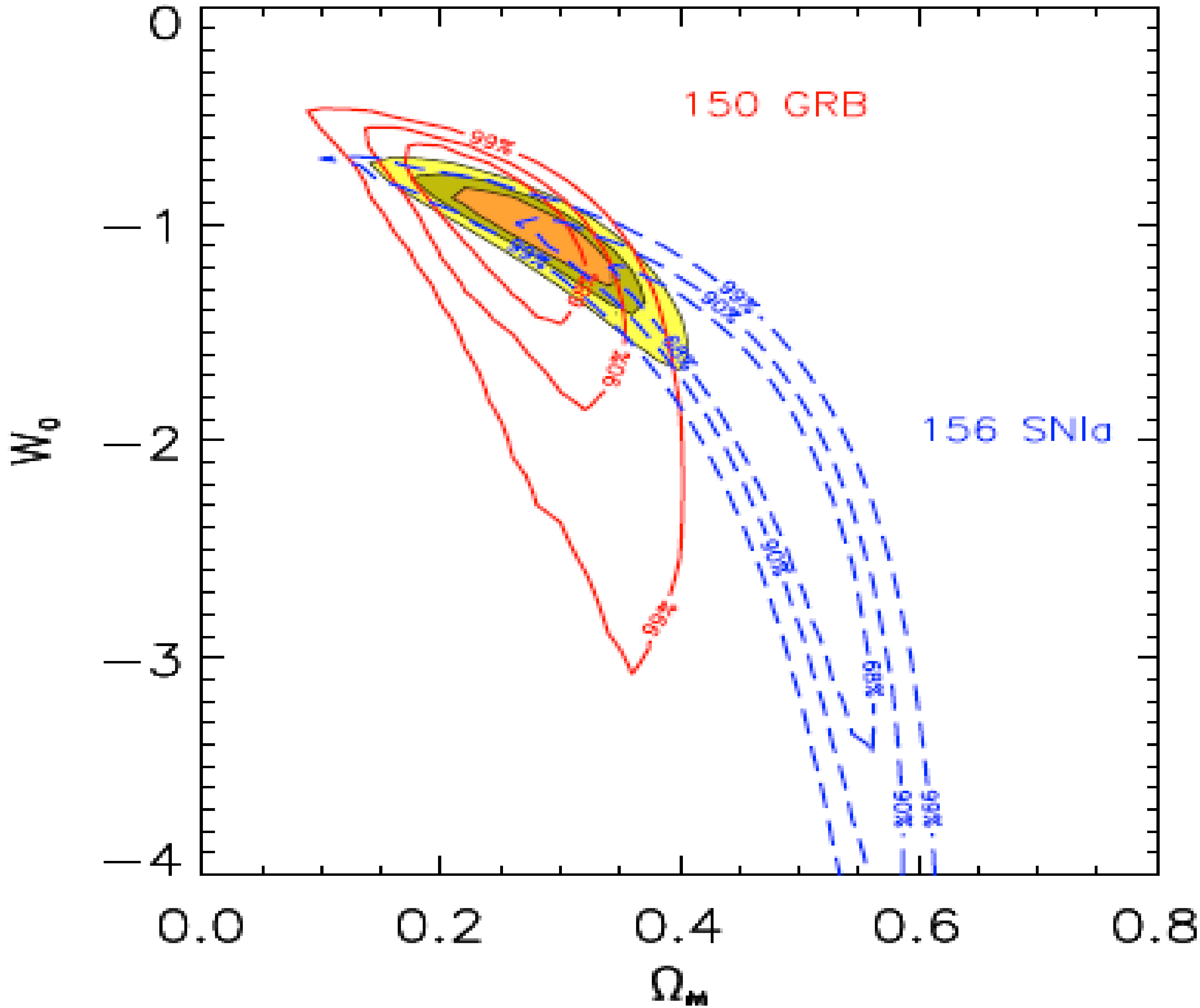
Conclusions from SNe

The two teams consistently found that SNIa at redshifts $z \sim 0.5$ appear dimmer than expected by ~0.25 magnitudes. $z \sim 0.5$ is the transition epoch between acceleration and deceleration.

This *suggests* (after assuming a flat universe) that the expansion of the Universe is *accelerating*, propelled by "dark energy", with $\Omega_\Lambda \sim 0.7$ and $\Omega_M \sim 0.3$.

Once we combine SN data with external flat-Universe constraints (WMAP), we find w= -1.02 (w <- 0.76 at the 95% confidence level) and w'=0, both implies that DE=cosmological constant.





Adapted from Amati+ 12 and Ghirlanda+ 2007

Conclusions

1. The huge radiated energy and redshift distribution, extending up to z ~ 10, make GRBs powerful cosmological tools, complementary to other probes (e.g., SN Ia, clusters, BAO).

2. Our analysis provides evidence, independent of SNe-Ia, that Ω_m is < 1 at >99.9% c.l.

3. The analysis of the dispersion gives $\Omega_m \sim 0.28$ consistent with SNe-Ia cosmology (admittedly with lower accuracy than SNe-Ia, but not dramatically lower).

4. A realistic extrapolation of the discovered number of GRBs via present and future space missions will allow us to measure Ω_m with an accuracy comparable to SNe-Ia.

5. GRBs trace the possible dependence of *w* on z better than SNe-Ia