Gamma Ray Bursts
and
Cosmology

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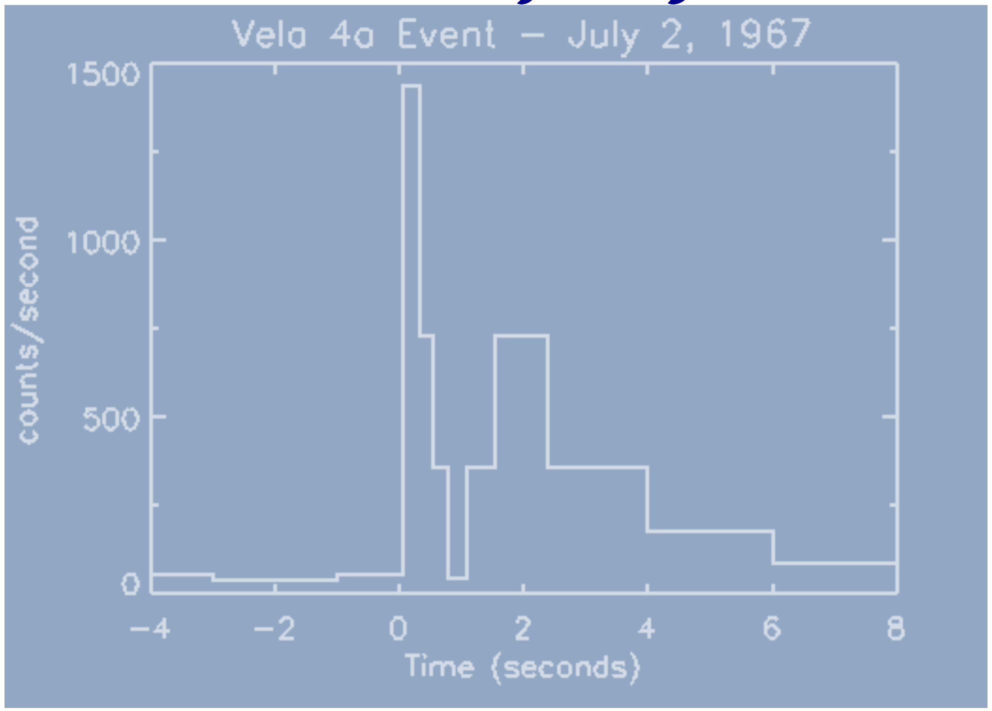
Summary

- ✓ Introduction on GRBs
- ✓ Properties and Features
- ✓ Correlations
- ✓ The Lx-Ta correlation
- ✓ GRBs as standard rulers
- ✓ Conclusions

Gamma-Ray Bursts: The story begins

Treates banning nuclear tests between USA and USSR in early 60s

VELA Satellites: X and soft γ-ray detectors



Brief, intense flashes of γ-rays

Klebesadel R.W., Strong I.B., Olson R., 1973, Astrophysical Journal, 182, L85

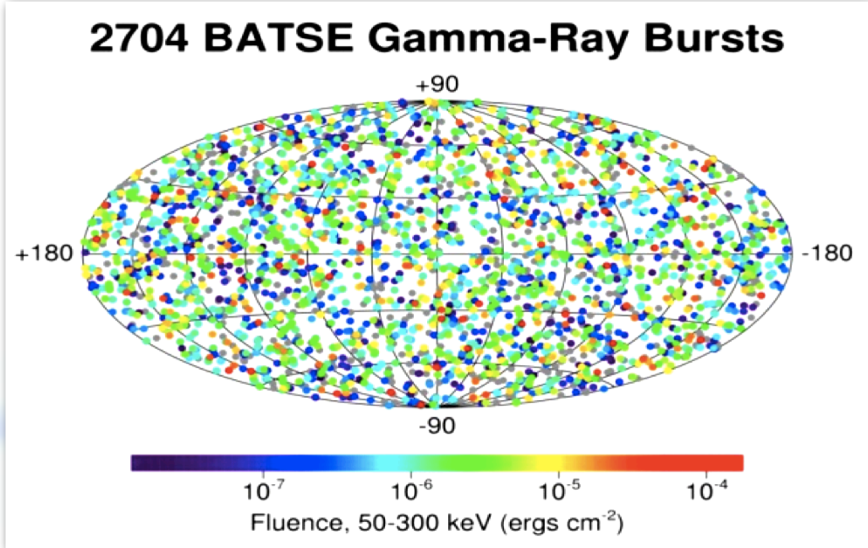
`Observations of Gamma-Ray Bursts of Cosmic Origin'

GRBs phenomenology

- Basic phenomenology
  - Flashes of high energy photons in the sky (typical duration is few seconds).
  - Isotropic distribution in the sky
  - Cosmological origin accepted (furthest GRBs observed z ~ 8 – billions of light-years).
  - Never seen two GRBs from the same location (distructive phenomenon?).
  - Extremely energetic and short: the greatest amount of energy released in a short time (not considering the Big Bang).
  - Sometimes x-rays and optical radiation observed after days/ months (afterglows).

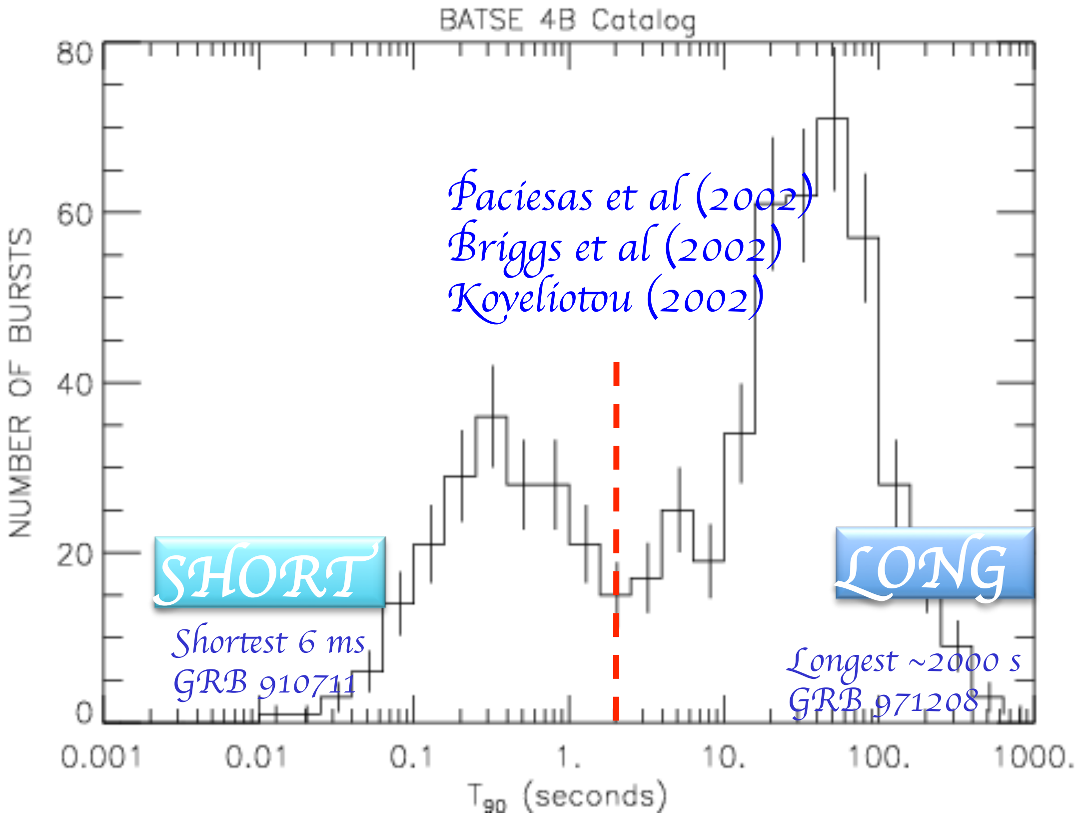
GRB observations

- First detected…
  - … in early '70 by military satellites (Vela).
  - Originally connected with Neutron Stars (NSs) in the Milky Way.
- Then CGRO came…
  - EGRET (10 MeV-10 GeV): Energetic Gamma-Ray Experiment Telescope ~ 1 burst/year.
  - BATSE (10 keV-10 MeV): ~ 1 burst per day.
  - Distribution in the sky found to be isotropic.
  - Cosmological origin?
- The afterglow era…
  - BeppoSax: X-ray afterglows ->
    - Direct observation of the "host galaxy"
    - A "smoking gun" for extragalactic origin!
  - Keck: optical afterglow.
- And the Swift Era…
  - On going mission
  - Dedicated to GRB (x-ray follow up)
  - New understanding of GRB afterglow…more open questions?
- The GLAST era
  - High energy emission
  - Connection to low energy



Two flavours, long and short

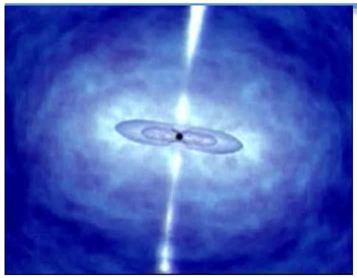
- 'Long' ($T_{90} > 2s$) and 'Short' ($T_{90} < 2s$) duration.



T90: time interval between the 5% of the total counts and the 95%. The 90% of the emission is associated to the duration of the event.

Short – Hard
Long - Soft

Progenitors



core collapse of massive stars ($M > 30\ M_{sun}$)

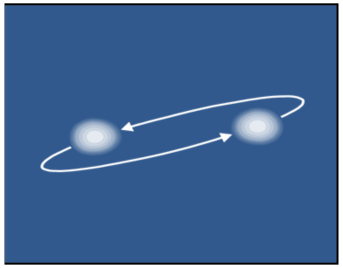
long GRBs

Collapsar or Hypernova (MacFadyen & Woosley 1999)

GRB simultaneous with SN

Supranova – two-step collapse (Vietri & Stella 1998)

GRB delayed by few months-years



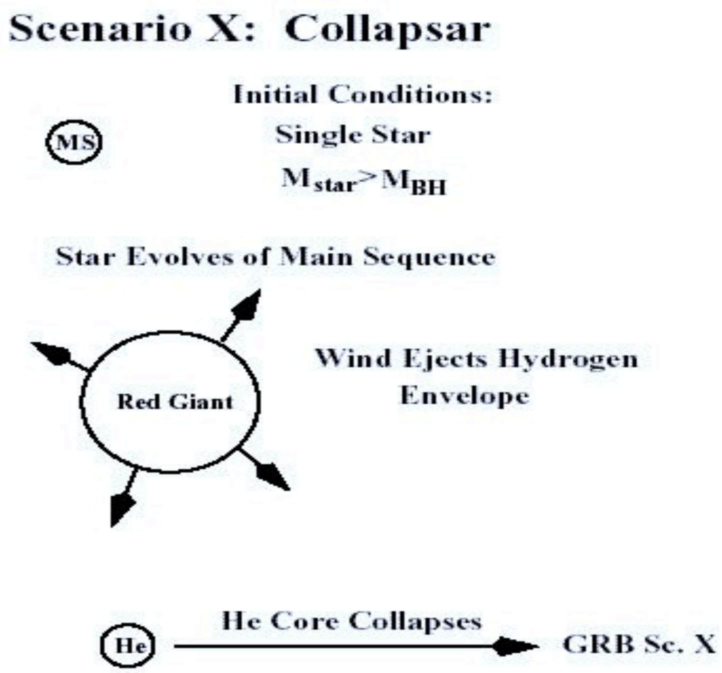
compact object mergers (NS-NS, NS-BH)

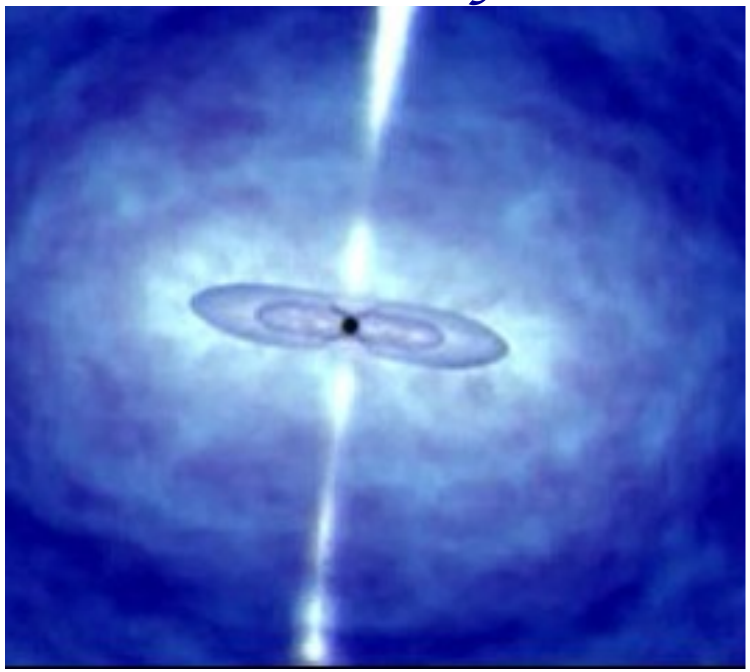
short GRBs

Discriminants: host galaxies, location within host, duration, environment, redshift distribution, ...

Collapsar model

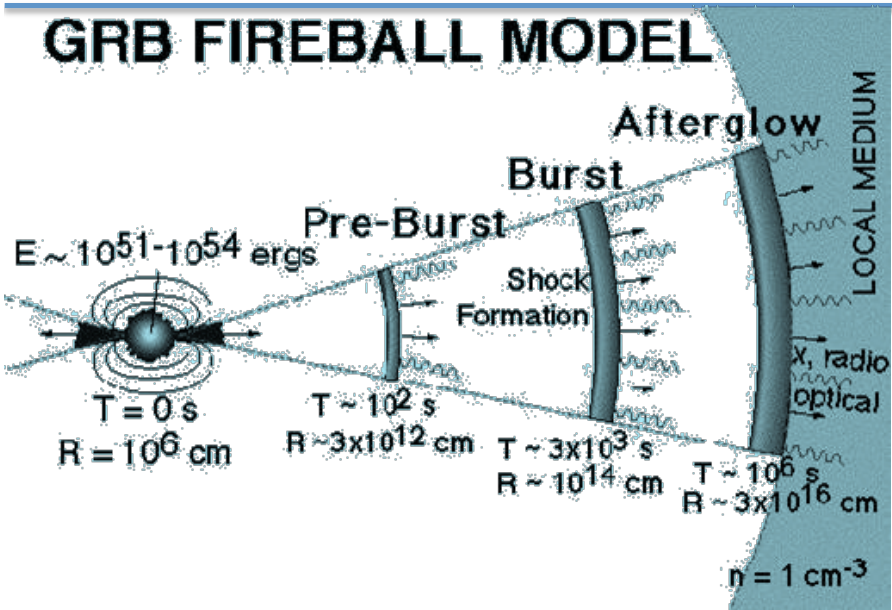
Woosley (1993)

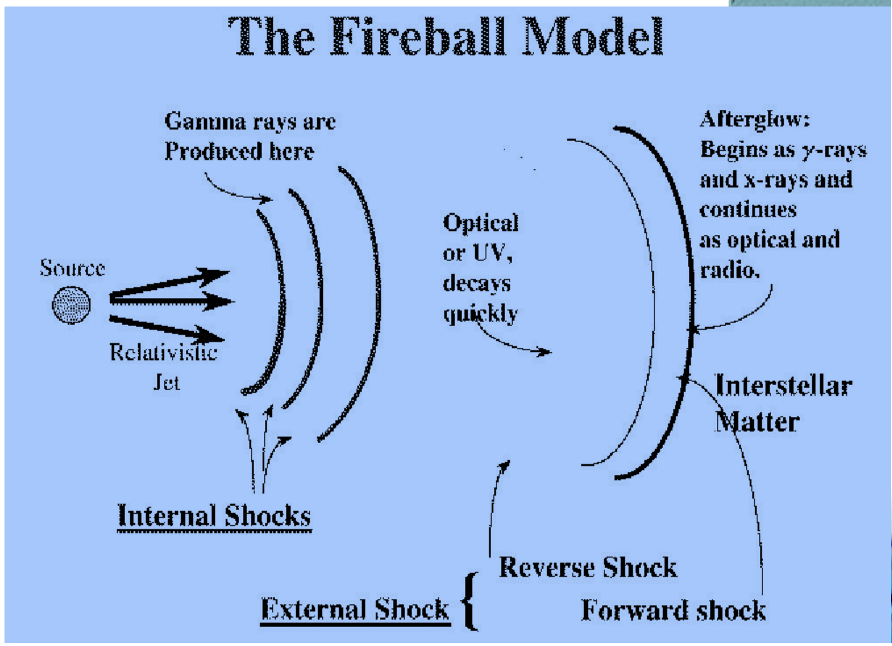




- *Very massive star that collapses in a rapidly spinning BH.*
- *Identification with SN explosion.*

Fireball model





Pair e^--e^+ accelerated with relativistic speed by the internal pressure.

More then one initial pulse intermittently produce some shells, i.e. fireballs with different Lorentz Γ.

The inner faster moving shell reaches the slower
internal shock produces γ rays
burst is observed

Furthermore
the shell interact with the interstellar medium
deceleration of the fireball
the external shock (afterglow)

The variability of the light-curve means huge energy small Volume and small time

Fireball

Invented even before knowing that GRBs are cosmological....

Issue: the fireball model does not explain the origin of the relativistic flow producing the fireball itself

Fireshell model explains it.

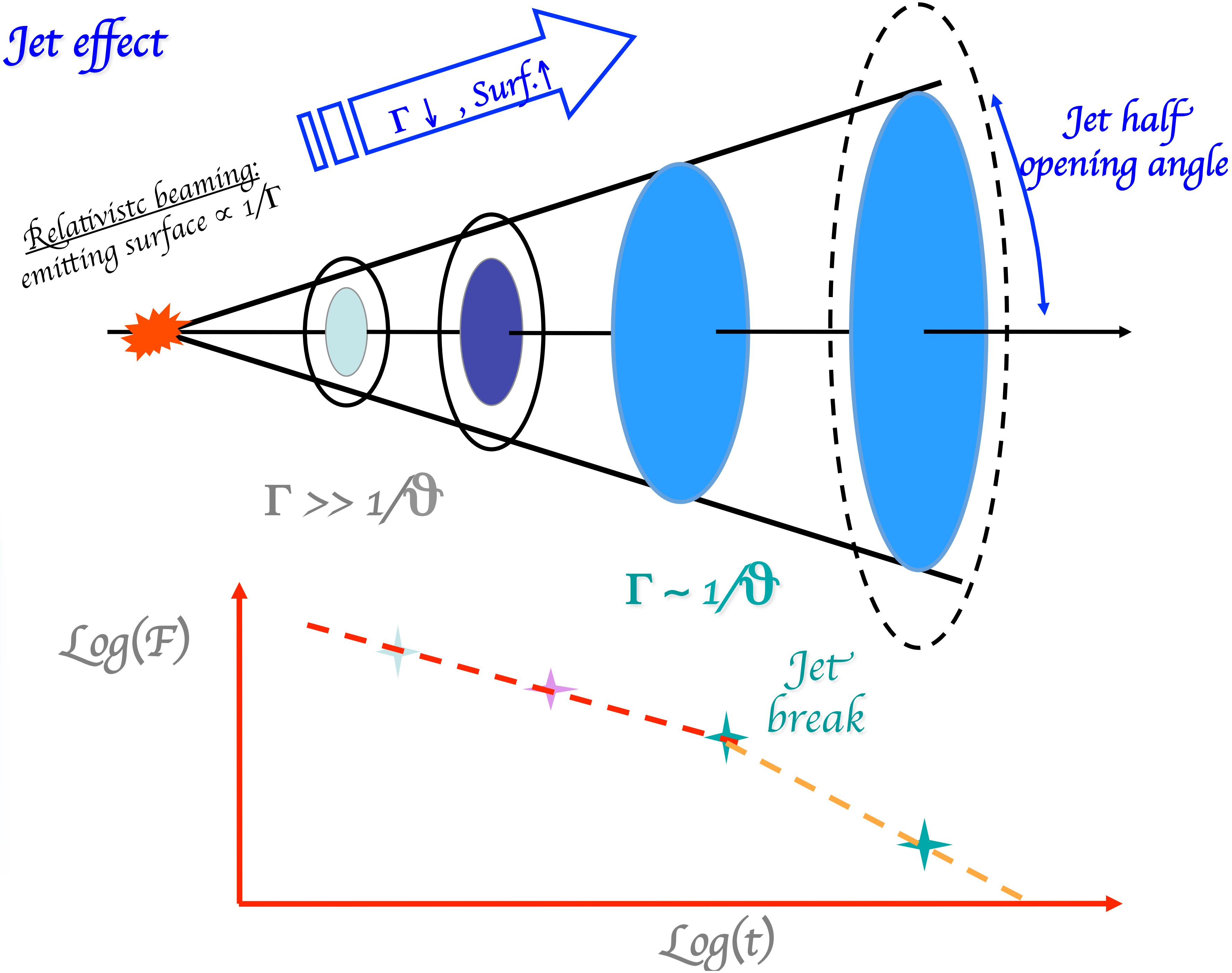
- The inner engine has to create a huge amount of energy to accelerate ~ $10^5\ M_\odot$ to the relativistic speed

- The flux is collimated in a jet of opening angle ~5°-20° (observation of GRB060218 shows wider angle 37° according to the isotropic model of the fireshell)

- Short and long depend on the duration determined by the inner engine → different progenitors

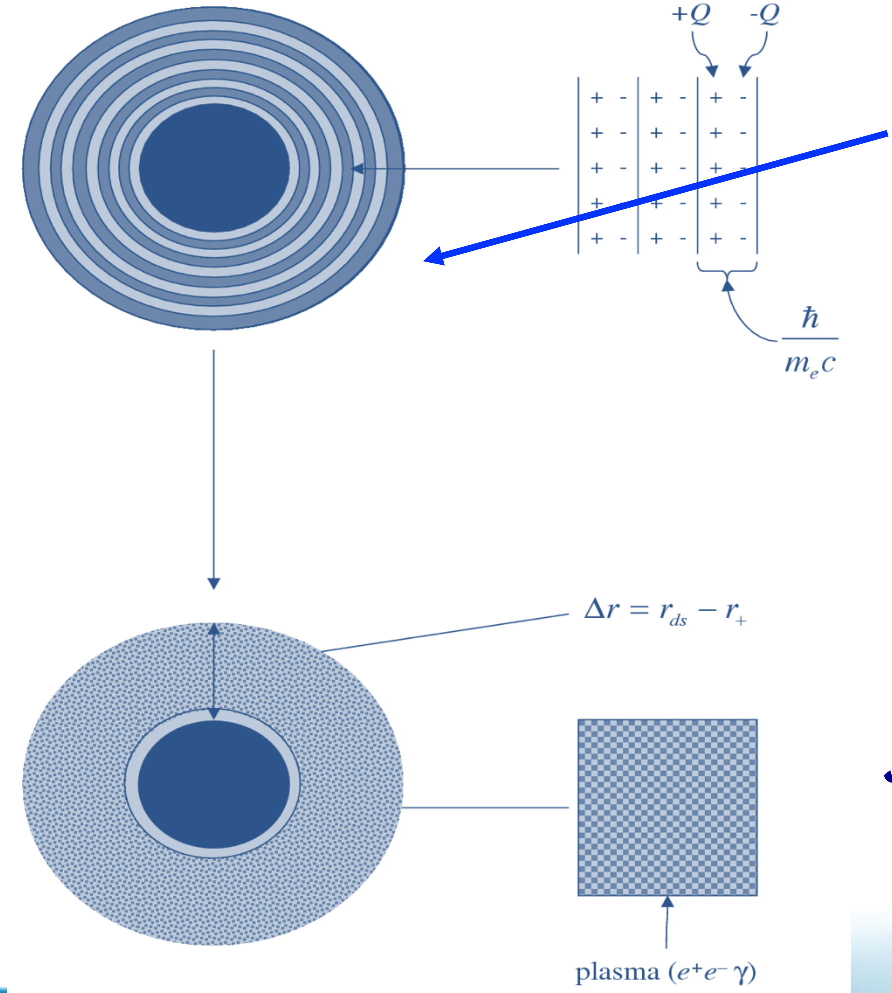
- Host Galaxies → young and with the strong stellar formation

Jet effect



Γ ↓ , Surf.↑
Relativistc beaming:
emitting surface ∝ 1/Γ
Jet half
opening angle
Γ >> 1/ϑ
Γ ~ 1/ϑ
Log(F)
Jet
break
Log(t)

The fireshell model

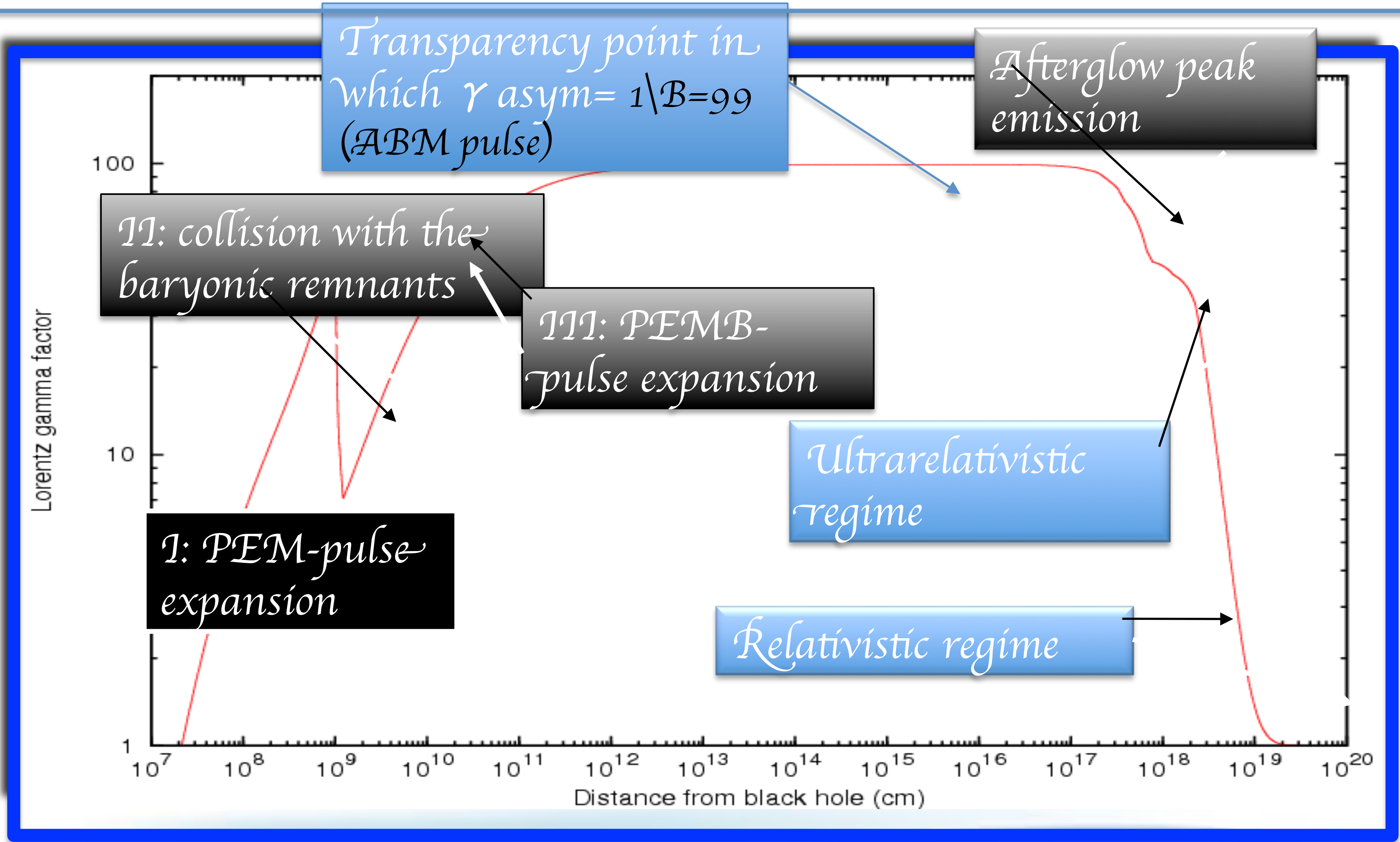


- GRB originated by the process of "vacuum polarization"
- (Heisenberg et al.1935)

$E_c=(m^2c^3)/he$

Formation of "E_{tot} e^+" (Damour & Ruffini 1975)

The fireshell model

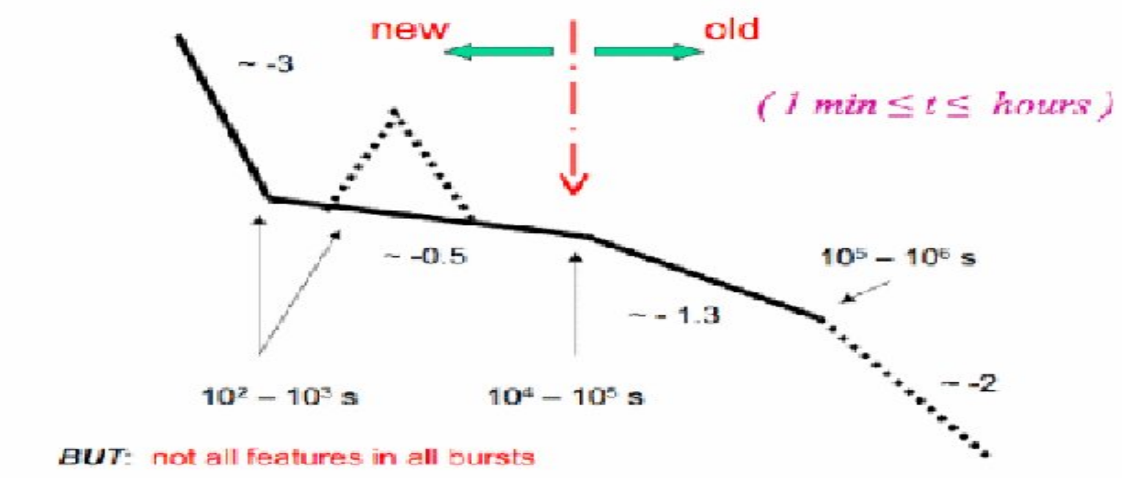


2004: satellite SWIFT (~200 GRBs)

BAT → 15-150 keV
XRT → 0.2-10 keV
UVOT → 170-650 nm

BAT reveals the location of the GRB and in 20-70s wheel the system so that the event is simultaneously followed by XRT and UVOT

Observe the afterglow in the initial phase and study the Transition between prompt and afterglow.

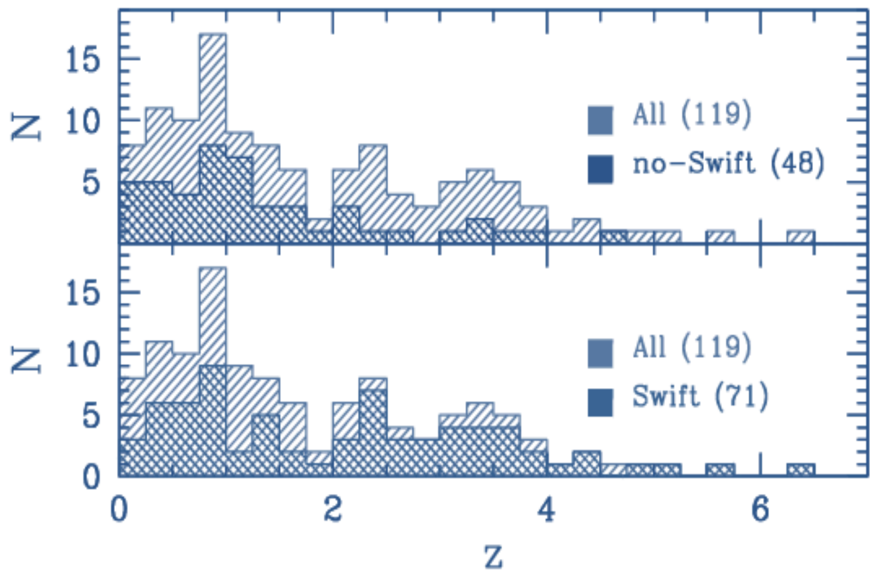


Energy and Power

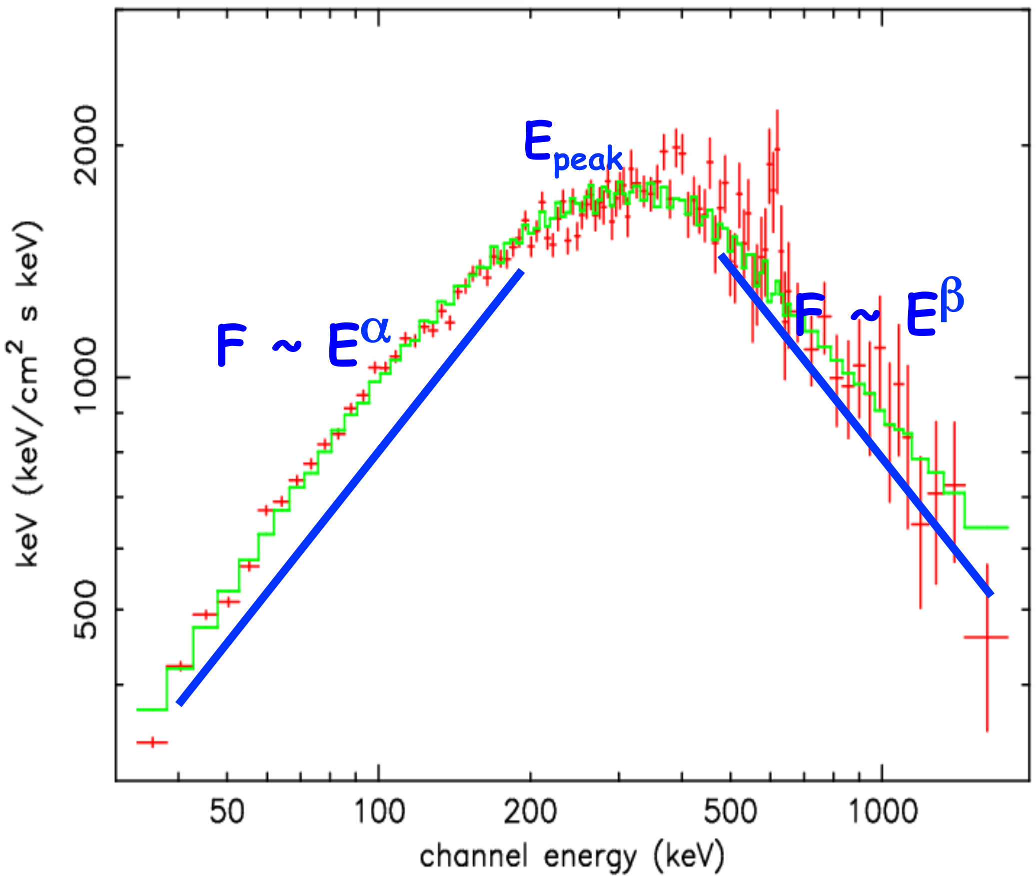
Huge isotropic equivalent energy!

GRB typical Fluence (i.e. time int. flux) is $10^{-8} - 10^{-4}$ erg/cm^2 (1keV – 10 MeV)

119 GRBs with z



Spectra



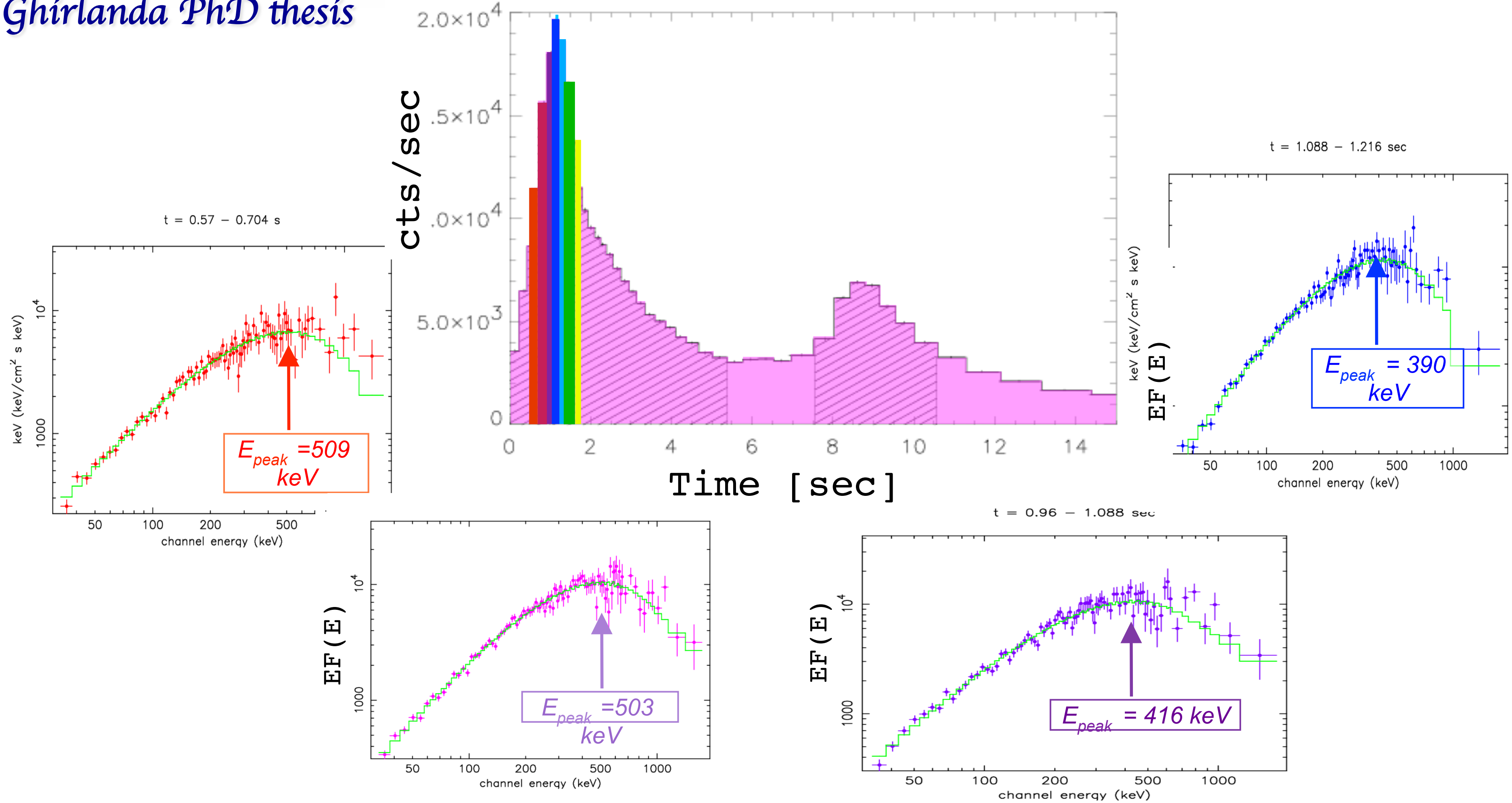
featureless continuum

power-laws - peak in νF_ν

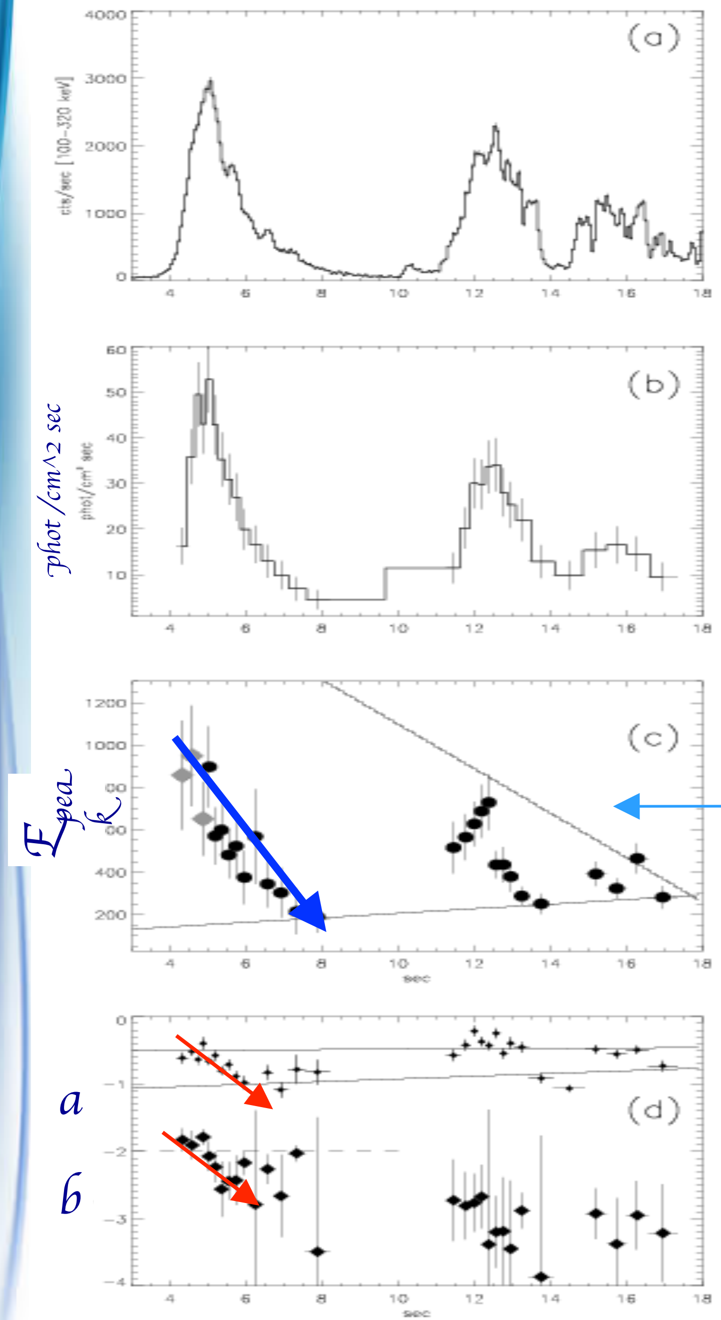
$$\mathcal{E}_{iso} = \frac{4\,\pi\, dl\wedge 2}{1+z} \int \mathcal{F}(\mathcal{E},z,\ldots)\,d\mathcal{E}$$

$$N_E(E) = \begin{cases} A\left(\frac{E}{100keV}\right)^{\alpha} exp\left(-\frac{E}{E_0}\right), & (\alpha-\beta)E_0 \geq E \\ A\left[\frac{(\alpha-\beta)E_0}{100keV}\right]^{\alpha-\beta} exp(\beta-\alpha)\left(\frac{E}{100keV}\right)^{\beta}, & (\alpha-\beta)E_0 \leq E \end{cases}$$

Ghirlanda PhD thesis



GRB spectrum evolves with time within single bursts



Hard to Soft evolution

E_{peak}, a(t), b(t)

Decrease independent of the rise and decay of the flux

Could GRBs be used as standard candles?

What are the main problems with cosmic distances?
What is the distance ladder?

Related issues to distance indicators

Internal errors: they are instrisic as any measurement method (e.g. galaxy magnitude, fitting). They can be reduced by adding further elements to the sample.

External errors: they are due to galactic extinction and absolute calibration. Usually the carry-out higher probability to introduce systematic error, and are more difficult to be evaluated.

Systematic errors

- *Malmquist's effetc*

  occurring when using a sample of limited-magnitude objects, looking only at ones brigther than a given apparent magnitude

- *Galactic rotation*

  systematic redshift and blueshift on the observed spectra

- *Scott's effect*

  more populated galaxy clusters instrinsically brighter and thus more visible (selection effect)

- *Galactic calibration error*

  assuming that Sun rotates on a plane coincident with Galacting Plane with pure circular motion

- *Internal galaxy evolution*

  intrinsic galaxy luminosity is functon of time and thus of the distance

- *Sky brightness*

  occurring when observing low-luminosity galaxies

High redshift GRBs

- GRBs are extremely energetic events and are expected to be visible out to z ~ 15-20 (Lamb & Reichart, 2000, ApJ, 536, 1), which is further than that obtainable by quasars (z_{max} ~ 6).
- Allow us to;
  - Locate high redshift host galaxies.
  - Map out star formation, since long duration GRBs are likely caused by the core collapse of massive stars.
  - Probe the environment immediately around the GRB.
  - Composition of the host galaxy.
  - Potential evolution of GRB properties and therefore progenitors.
  - Potential use of GRBs to derive an extended z Hubble-diagram.

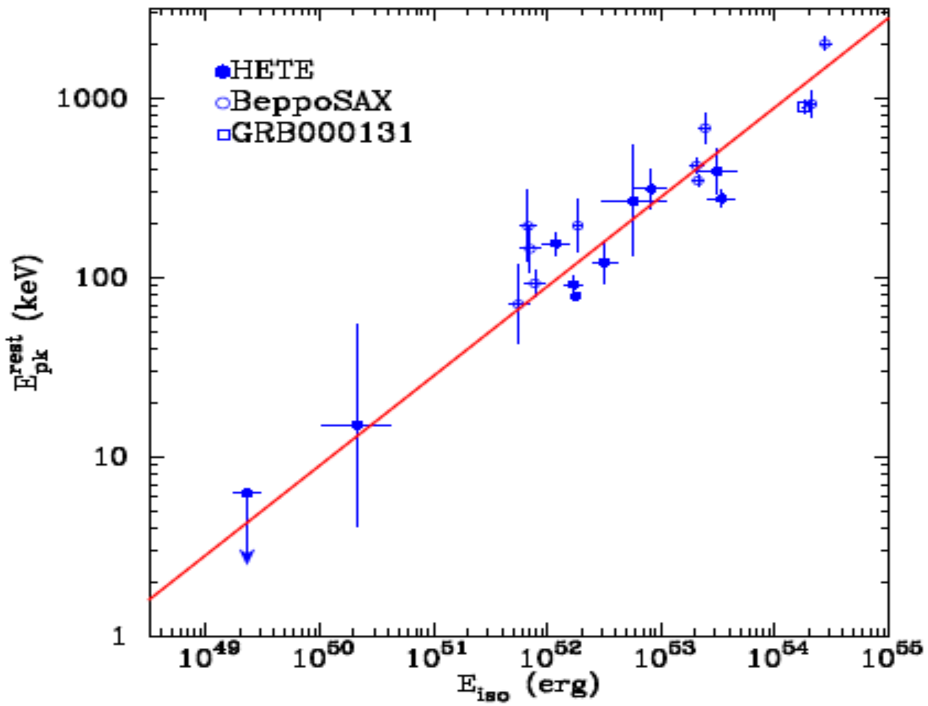
The overview on the existing correlations

- Amati
- Ghirlanda
- Firmani
- Liang and Zhang
- $E_{afterglow}$-E_{prompt}
- Spectral $_{lag}$
- Variability
- Minimum rise time
- L_x-T_a correlation

Energy scaling relation

- Radiated energy (E_{iso} or E_g) is well correlated with Spectral peak energy (E_{peak})
- Maybe used as "Cosmic Distance Scale" like type Ia Sne
- E_{peak} measurement essential
  - → Require large band width (at least $x10^2$)
    - BATSE found very few GRBs with E_{peak}<100 keV
    - Swift needs HETE or Konus for most events
- But, we do not know the physics yet

$\mathcal{E}_{iso}$- ν_{peak} correlation (Amati et al 2002, Atteia et al 2003)



$$\mathcal{E}_{iso} \propto \nu_{peak}^2$$

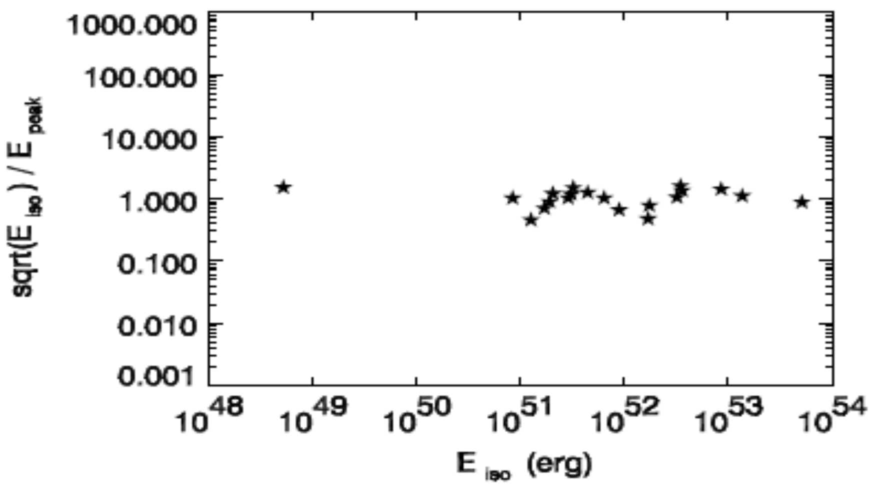
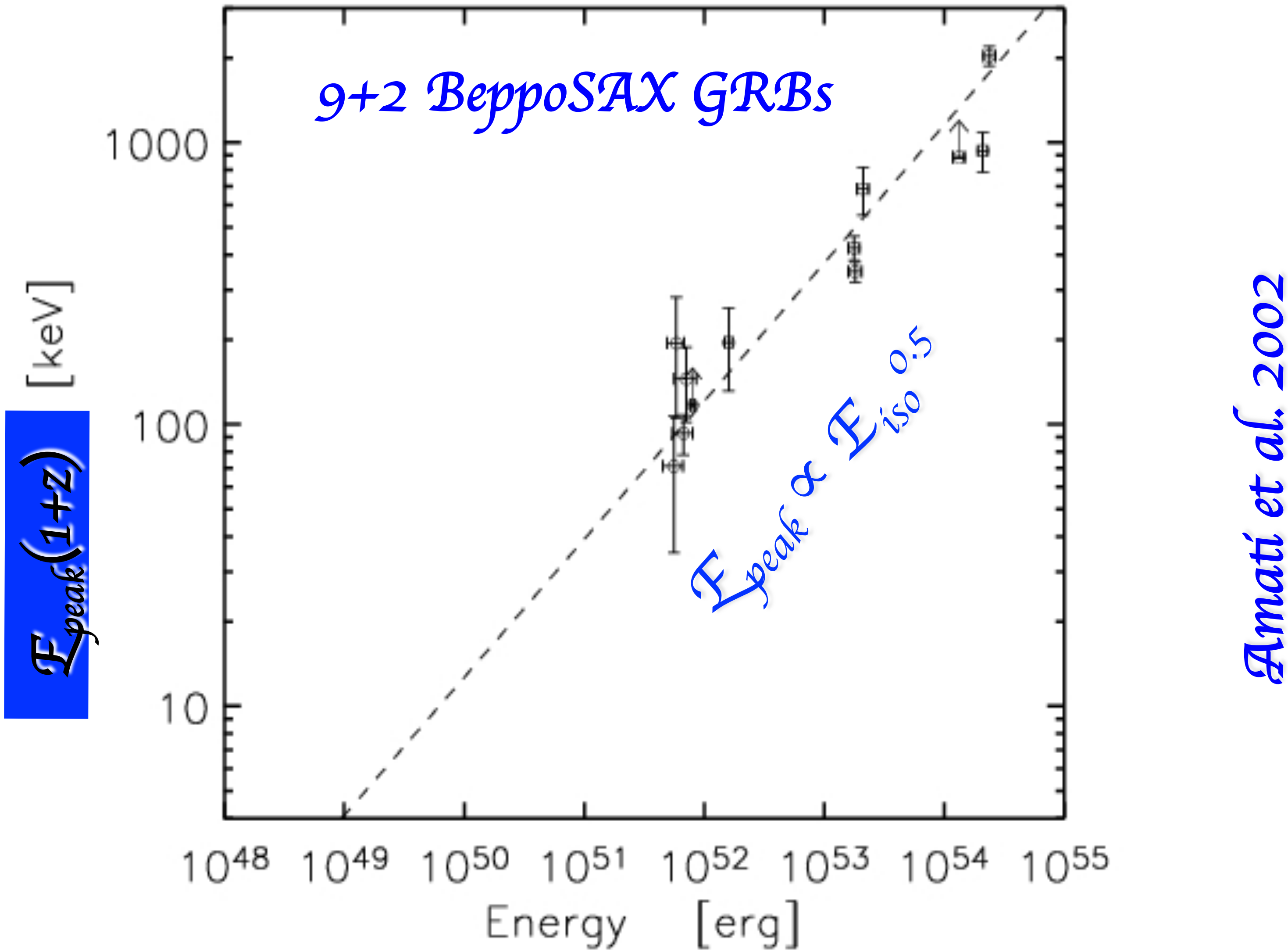
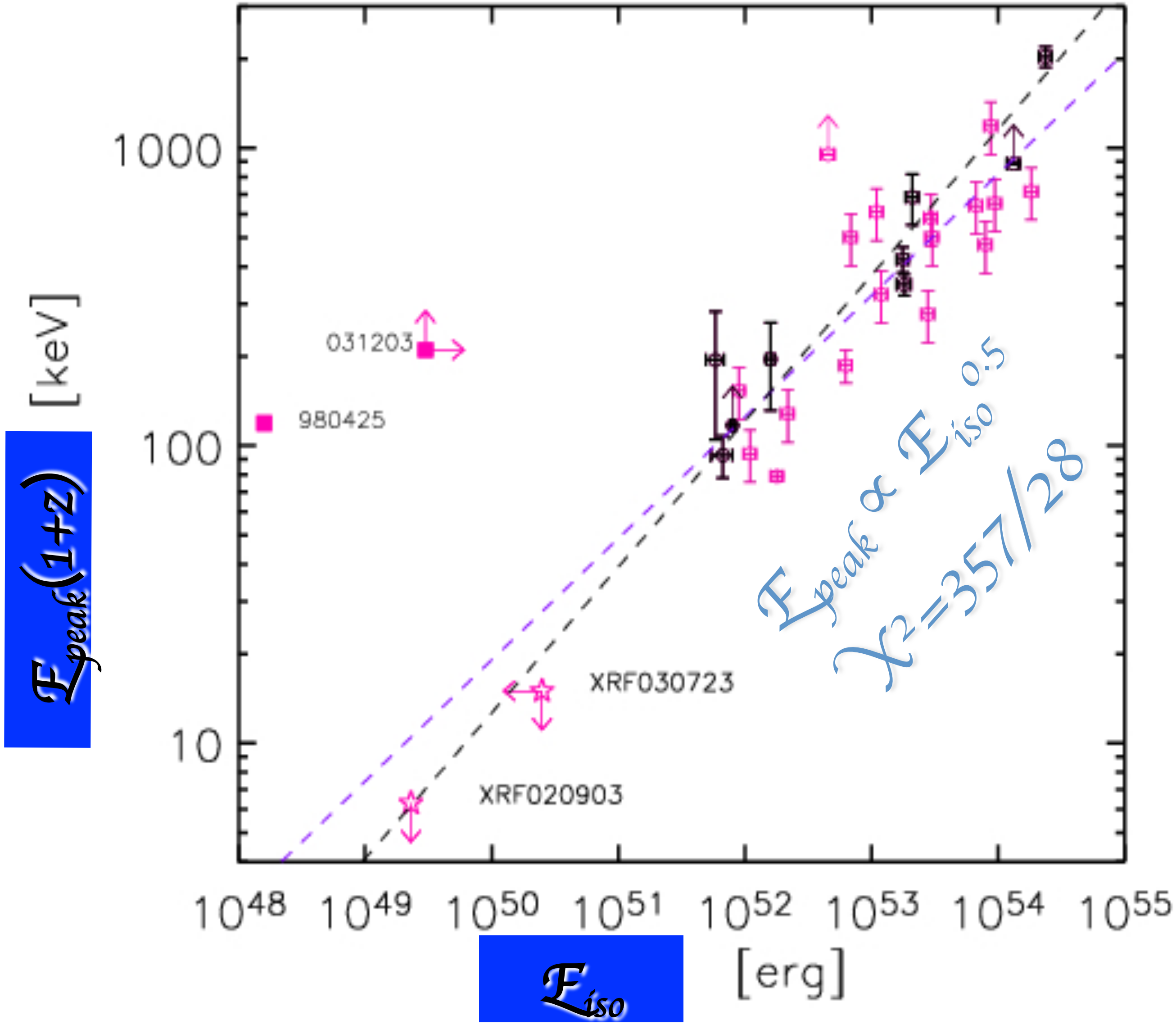


FIGURE 1. *Left Panel*. The E_{peak}- E_{iso} correlation measured at the end of 2003 with 21 GRBs detected by BeppoSAX (Amati et al. 2002), HETE-2 (Sakamoto et al. 2003, Lamb et al. 2003), and the IPN (Andersen et al. 2000). Note the extent of the correlation in E_{iso}. *Right Panel*. Illustration of the fact that the ratio $\sqrt{E_{iso}}$ / E_{peak} is close to a standard candle. This ratio appears almost constant over 4-5 orders of magnitude in E_{iso}. The ratio $\sqrt{E_{iso}}$ / E_{peak} is plotted here for 20 GRBs with known redshift detected with BeppoSAX, HETE-2, and the IPN.

Peak energy – Isotropic energy Correlation



+ 21 GRBs (Batse, Hete-II, Integral)

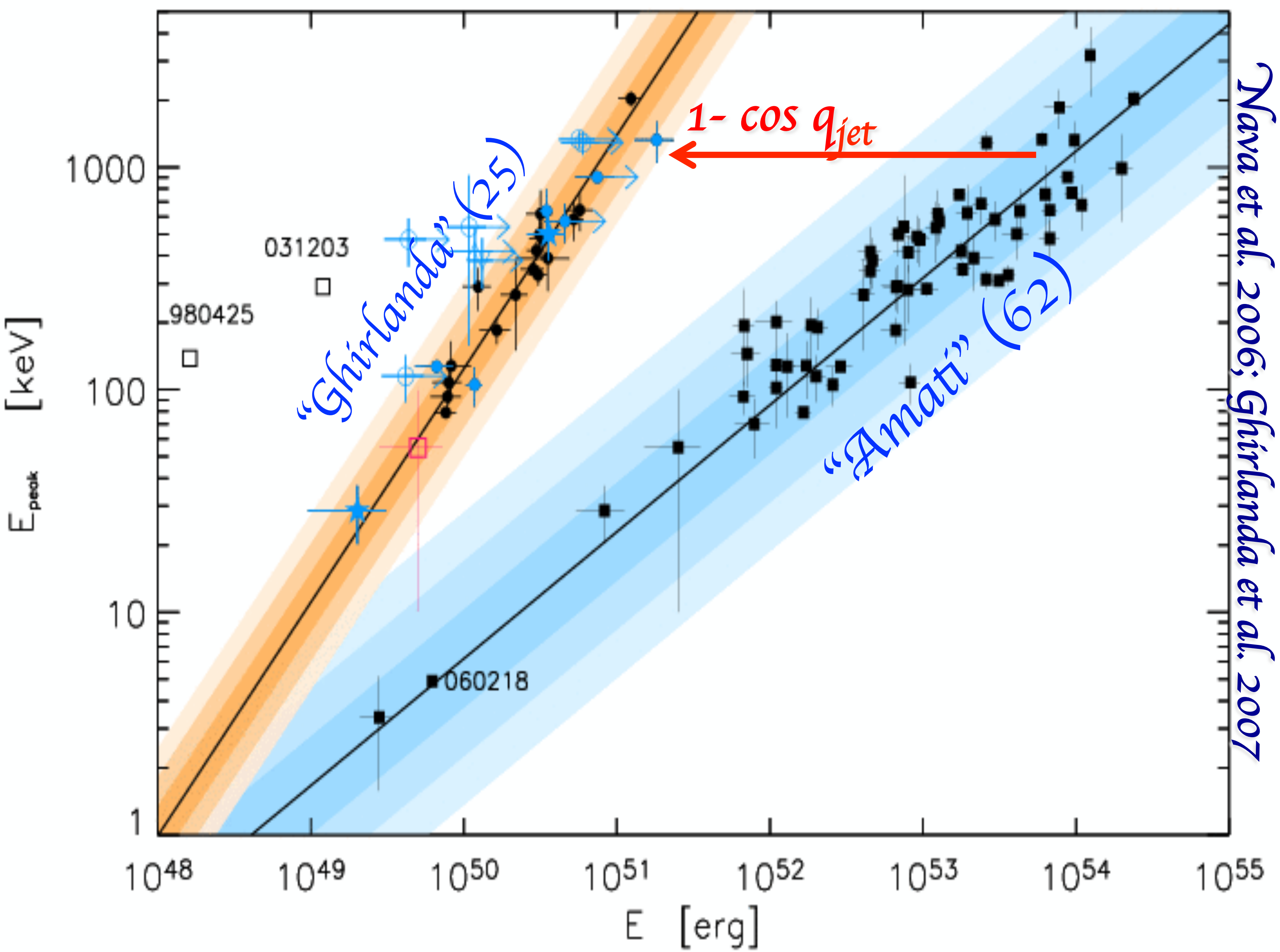


Ghirlanda, Ghisellini, Lazzati 2004

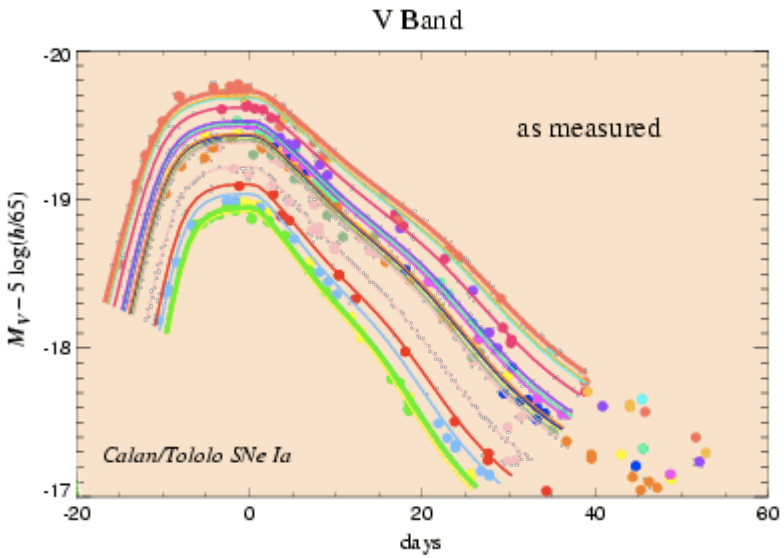
Amati 2006 (most recent update)

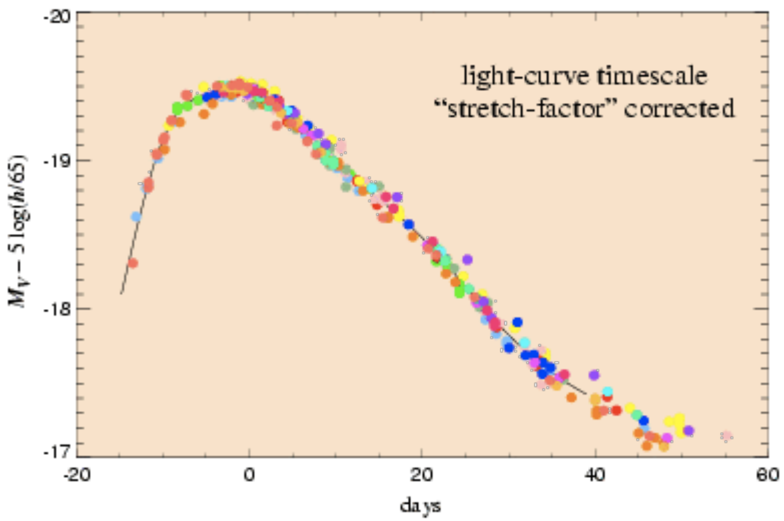
Why is the Ghirlanda relation, $E_g \propto (E_{peak})^{1.5}$, **different from the** Amati relation, $E_{iso} \propto (E_{peak})^{0.5}$?

Because of the correction of the beaming angle


1- cos q_jet
"Ghirlanda" (25)
"Amati" (62)
031203
980425
060218
1000
100
10
1
10^{48} 10^{49} 10^{50} 10^{51} 10^{52} 10^{53} 10^{54} 10^{55}
E [erg]
E_{peak} [keV]
Nava et al. 2006; Ghirlanda et al. 2007

The idea is Similar to Supernovae Ia





their luminosities vary with the shape of the lightcurve and with the colour

Perlmutter 1998

"Stretching": the slower and bluer

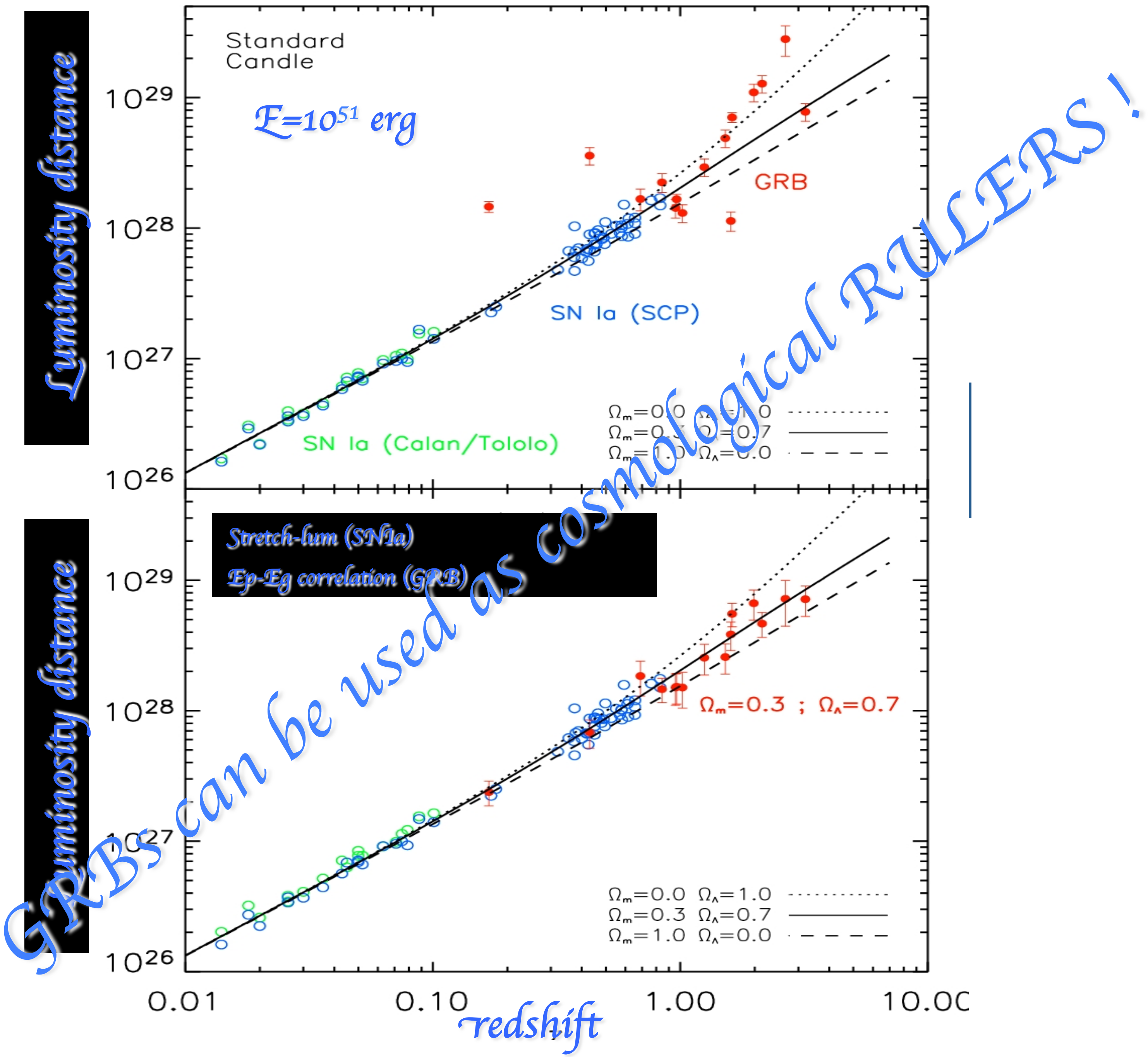
the brighter

What happens to SNe at high z?

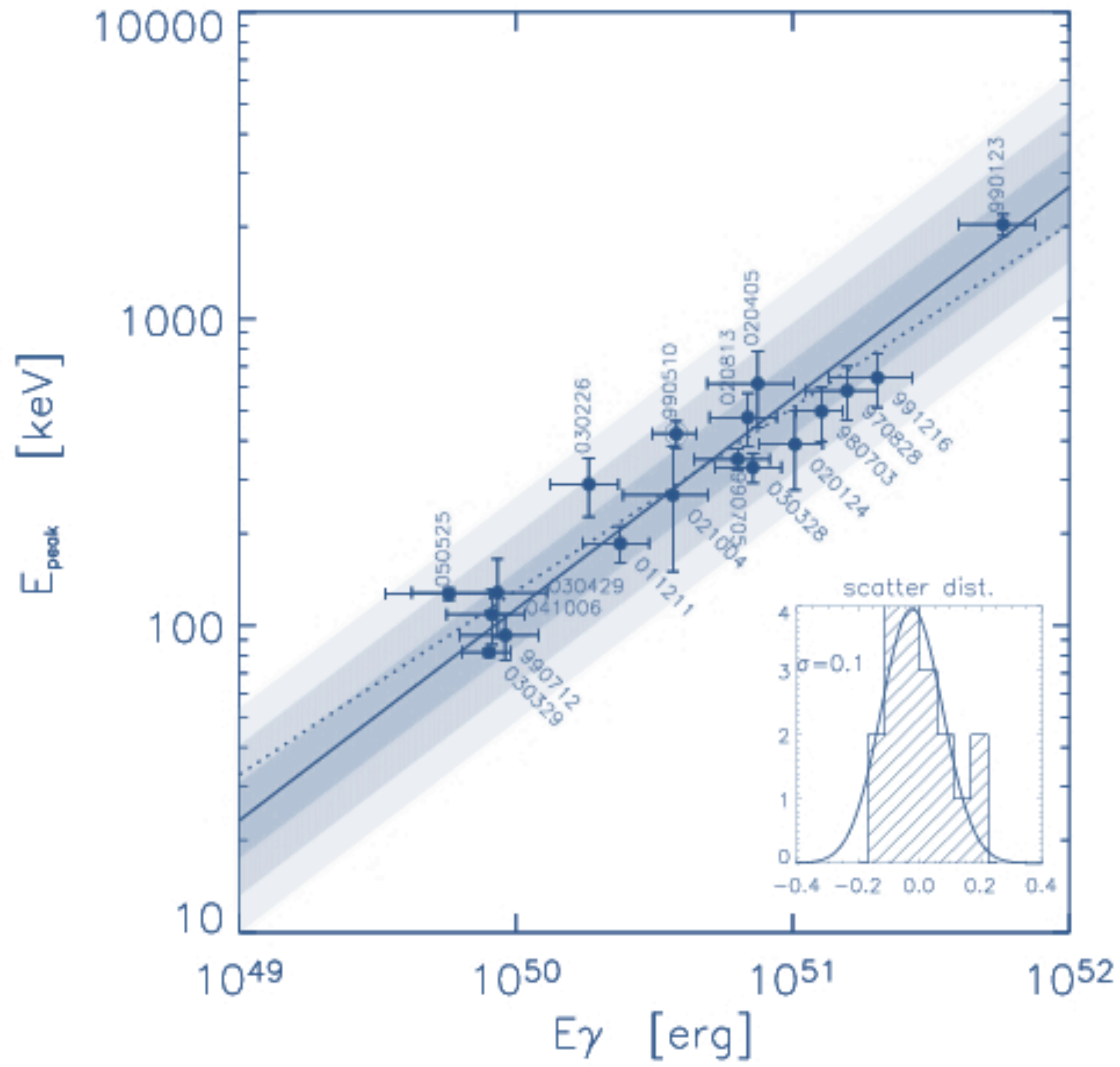
- The brighter- slower relation
- The brighter-bluer relation
- Depends on cosmology!

Why we use GRBs?

- high-z SNIa $z<1.7$
- suffer intergalactic dust extinction
- GRBs are detectable up to $z\approx 9$
- Free from dust extiction

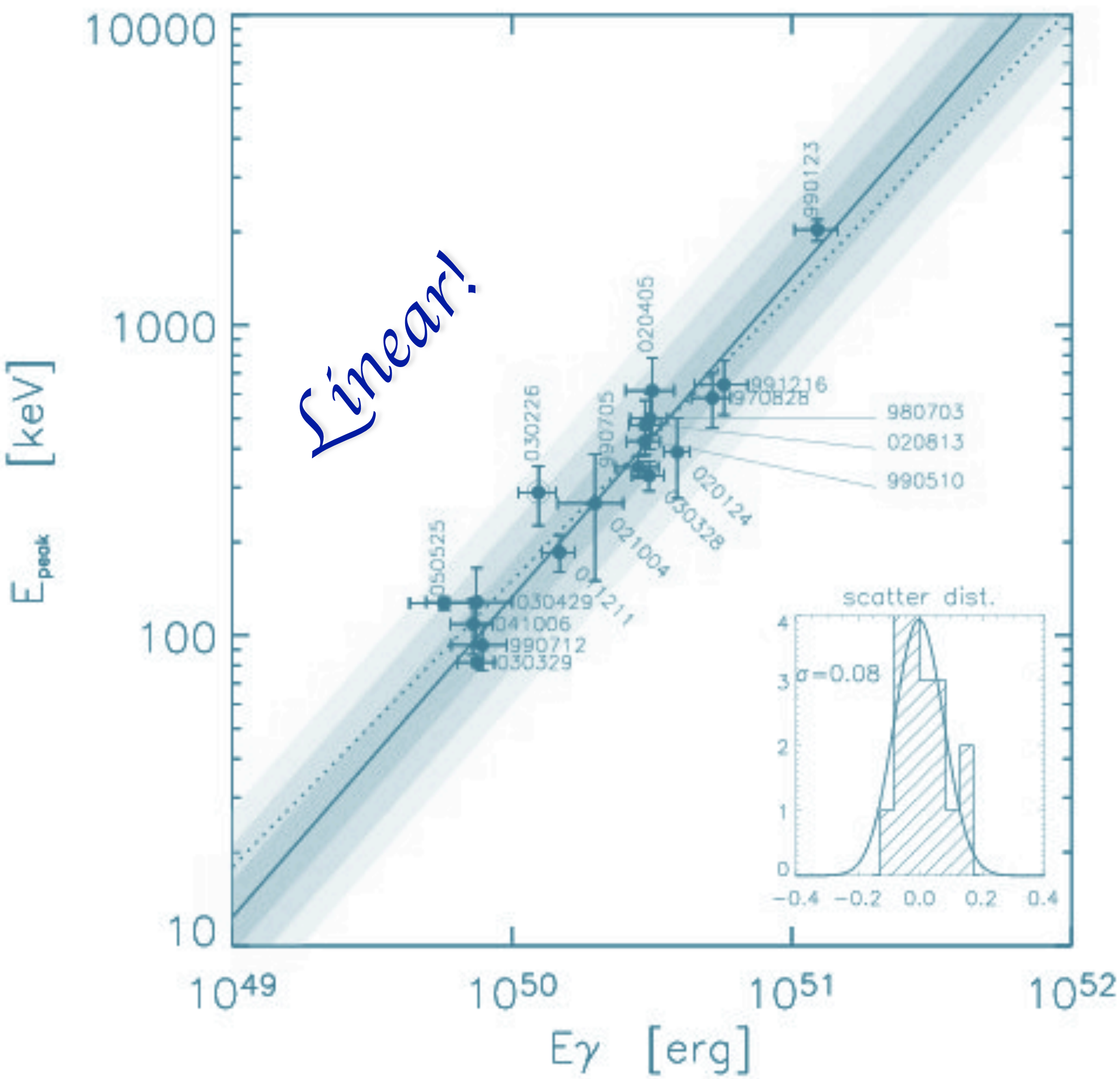

Luminosity distance
Standard Candle
E=10^51 erg
GRB
SN Ia (SCP)
SN Ia (Calan/Tololo)
Ωm=0.0 ΩΛ=1.0
Ωm=0.3 ΩΛ=0.7
Ωm=1.0 ΩΛ=0.0
Luminosity distance
Stretch-lum (SN1a)
Ep-Eg correlation (GRB)
Ωm=0.3 ; ΩΛ=0.7
0.01
0.10
1.00
10.00
redshift
GRBs can be used as cosmological RULERS !

Homogeneous density



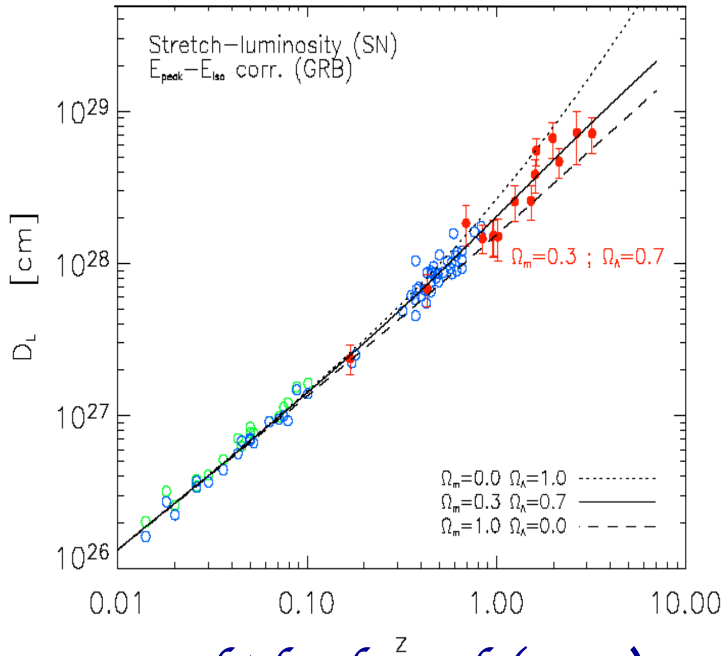
Nava L. et al. 2006

Wind density profile $n=r^{-2}$



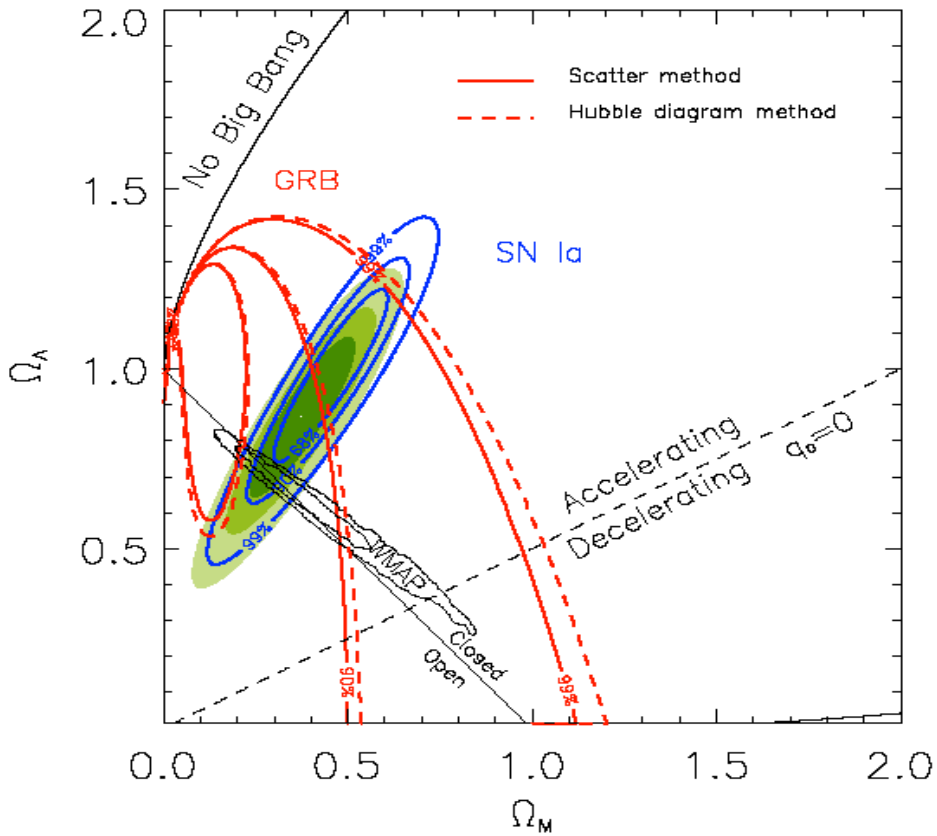
Nava et al. 2006

GRB for Cosmology

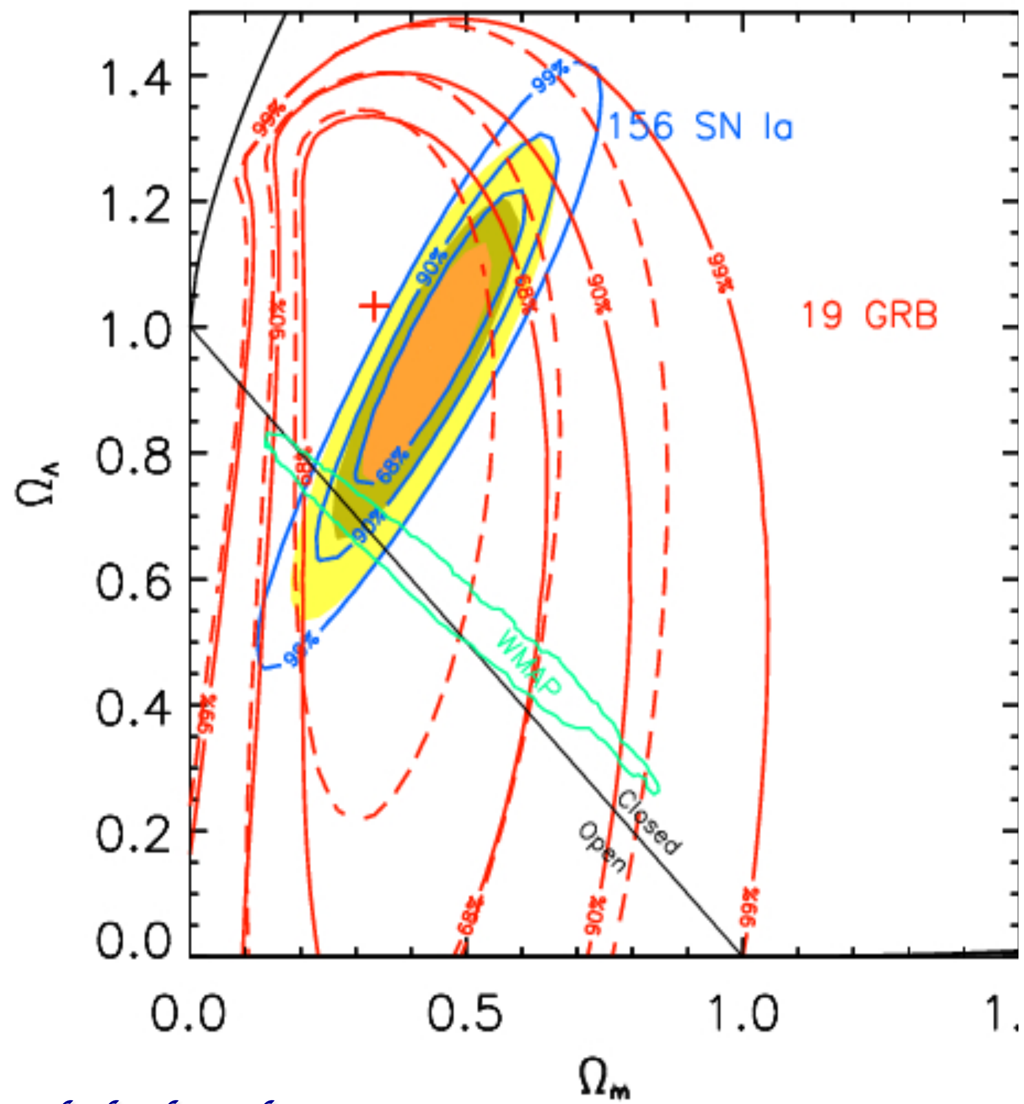


Ghirlanda et al. (2004)

15 GRB, 156 SN Ia



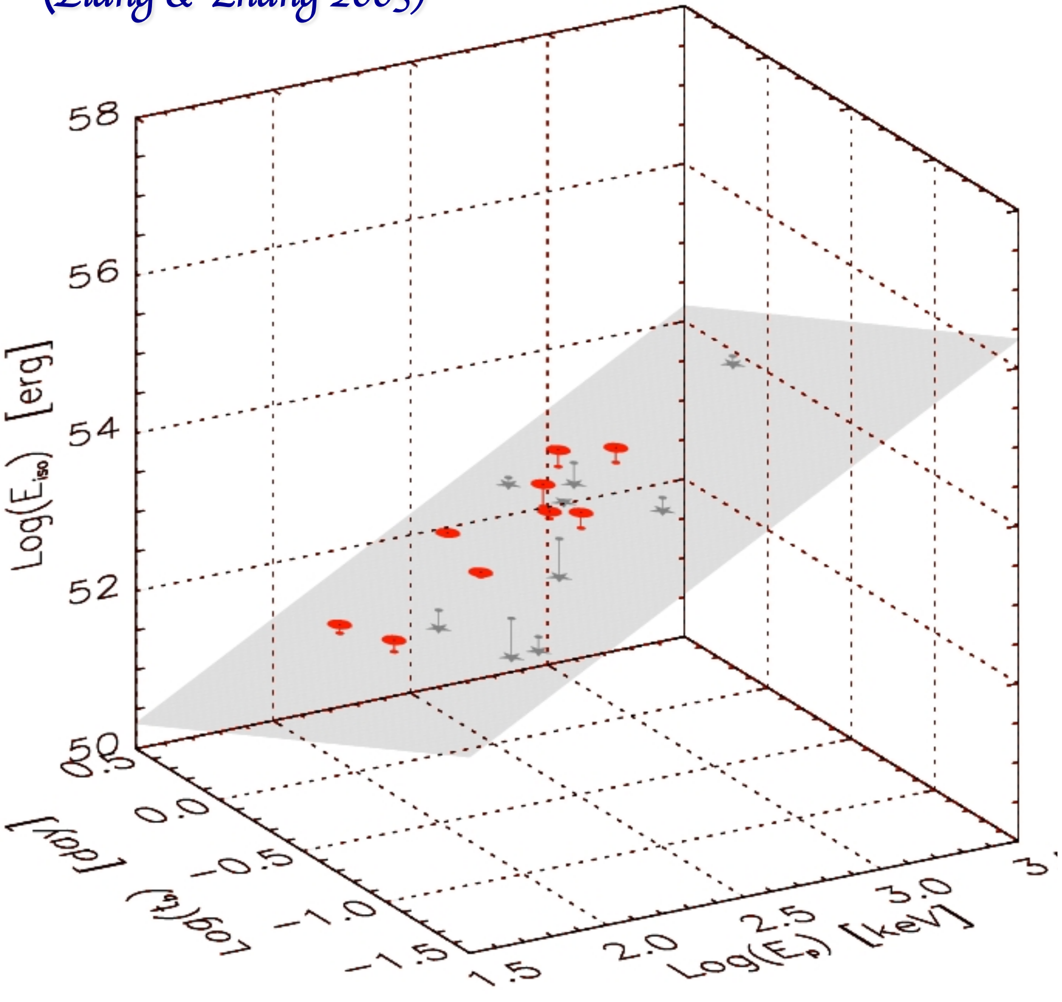
Linear is even better for cosmology



Ghirlanda et al. 2006 A&A

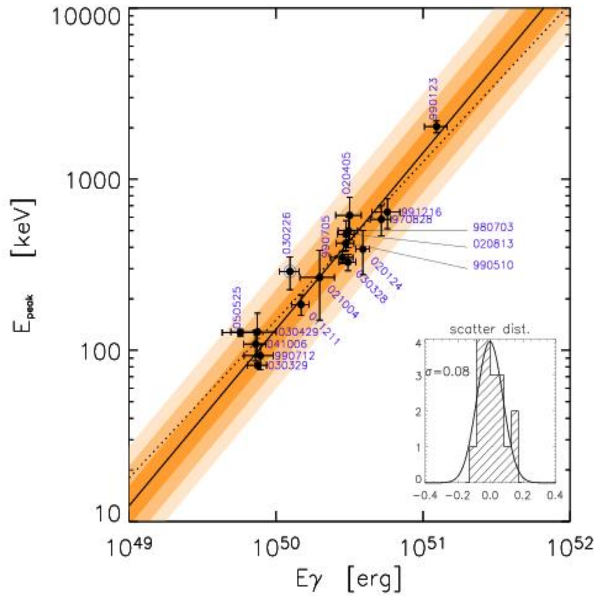
A completely empirical correlation between prompt (E_p, E_{iso}) and afterglow properties (t_{break})

(Liang & Zhang 2005)

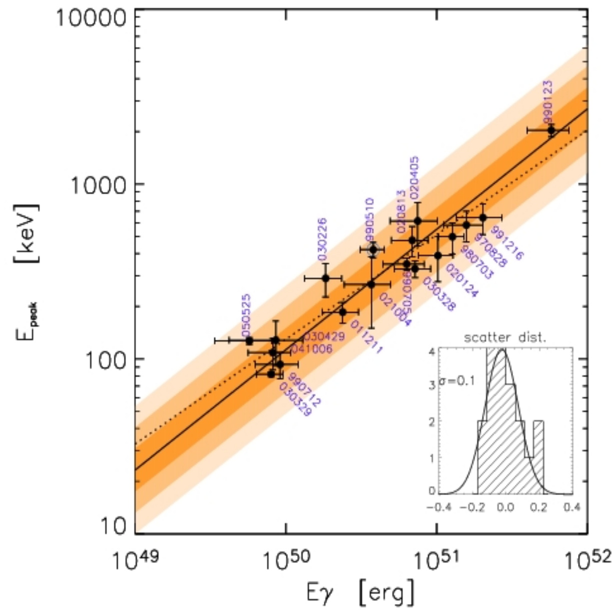


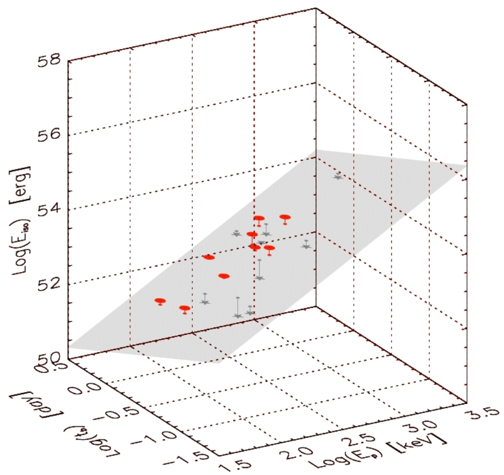
Nava L. et al. 2006

Model dependent: uniform jet + homogeneous density



Model dependent: uniform jet + wind density



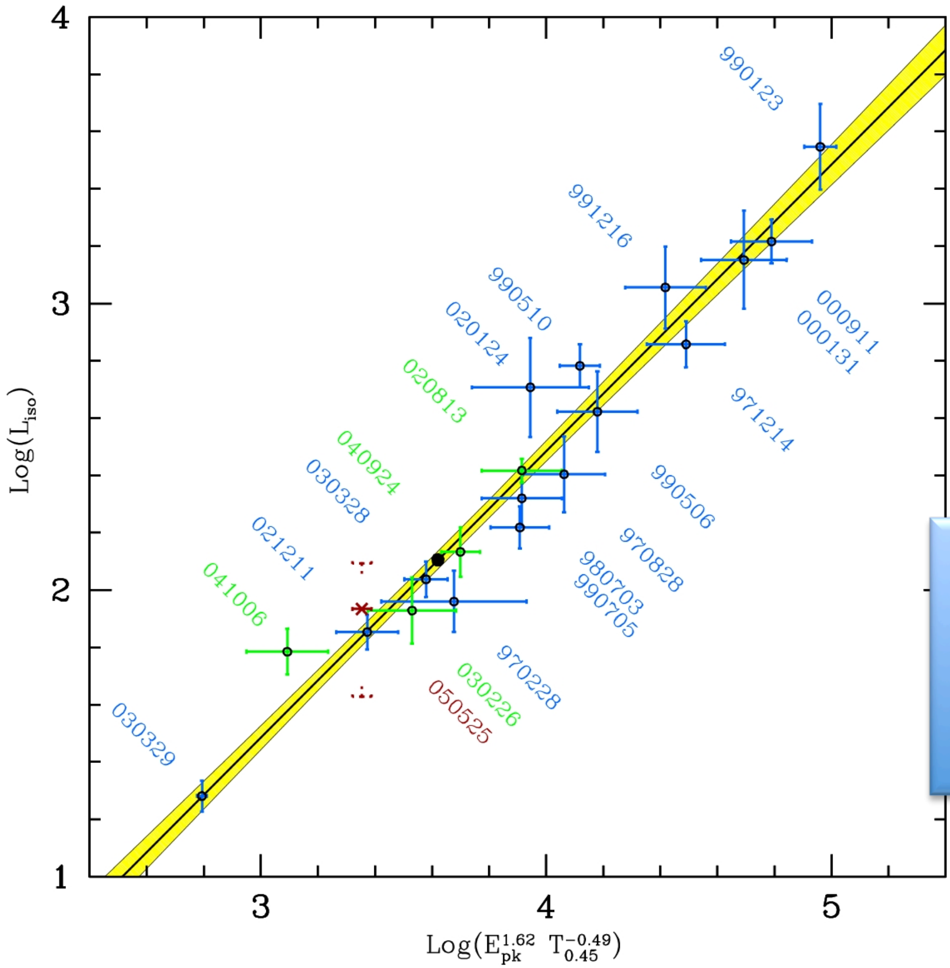


EMPIRICAL

Through simple algebra it can be verified that the model dependent correlations are consistent with the empirical correlation! (Nava et al. 2006)

... still not convinced ? ...

A new correlation between L_{iso}, E_p, $T_{0.45}$



Good fit

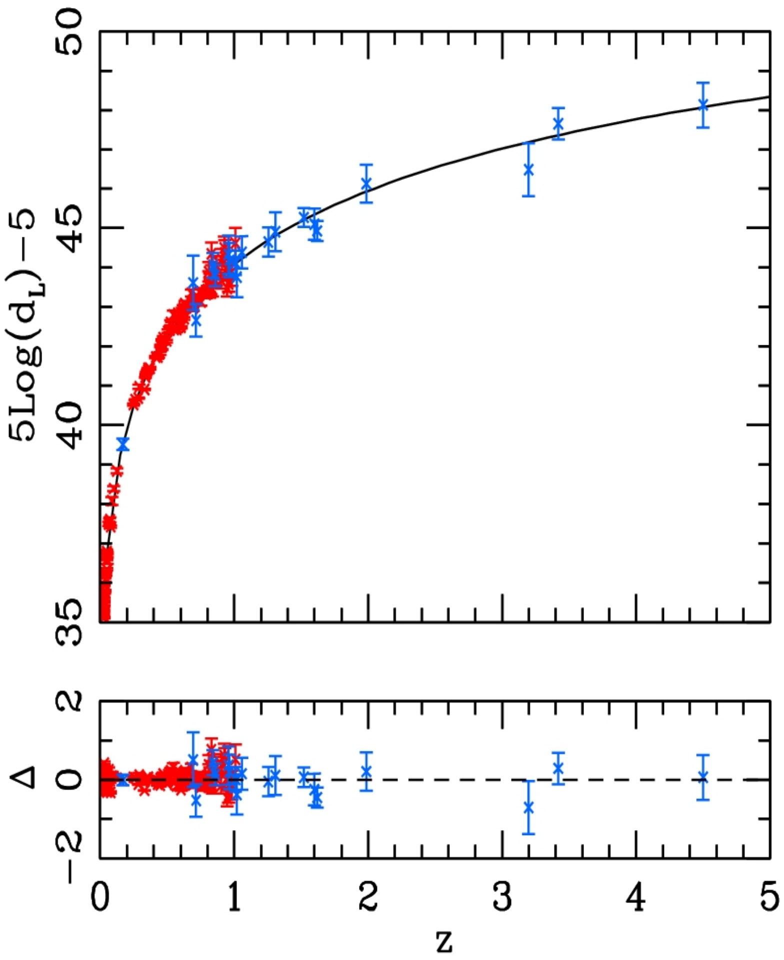
Consistent

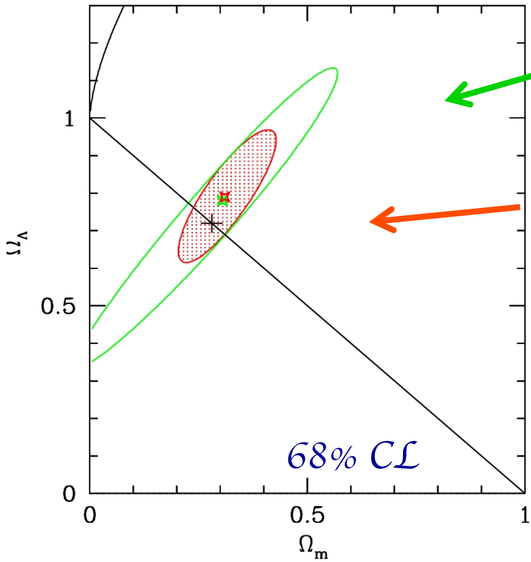
With other corr

ONLY PROMPT EMISSION PROPERTIES

Firmani et al. 2006

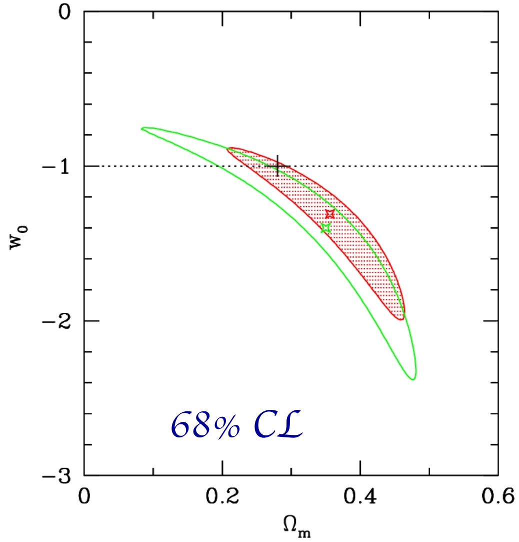
GRBs + Legacy SNIa

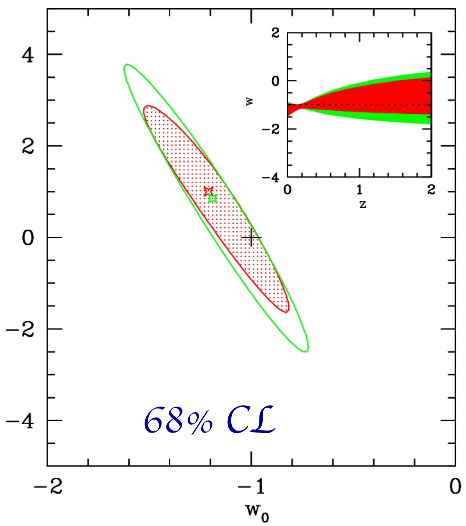




115 SN Ia

19 GRBs + 115 SN Ia

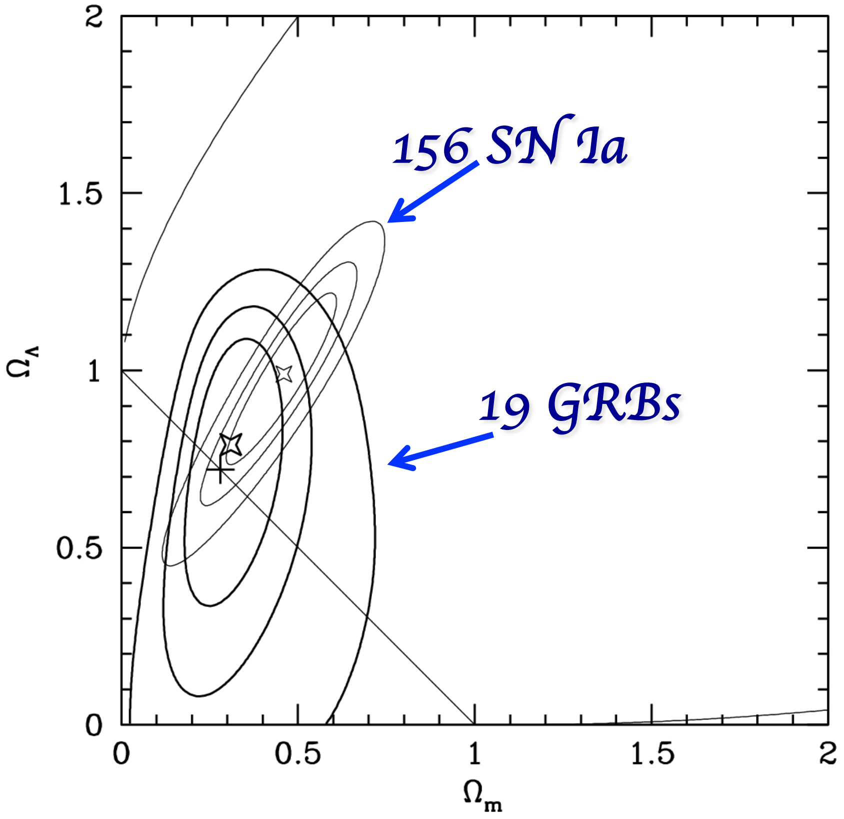


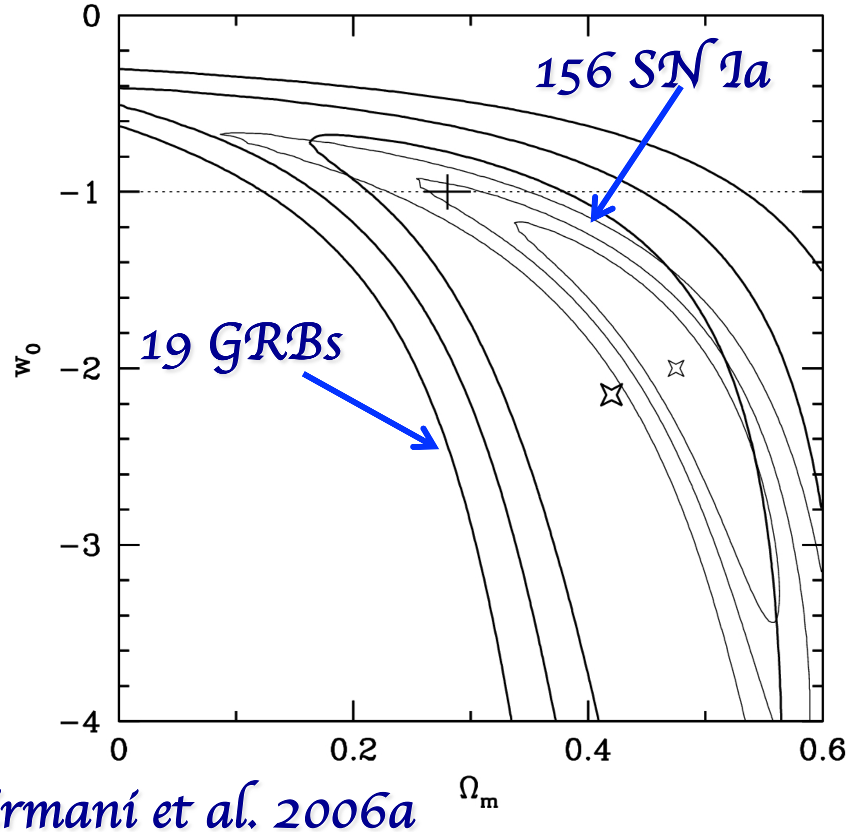


GRB+SN prefer ΛCDM

Firmani et al. 2006b

Cosmological Constraints with the Liso-Ep-T0.45 correlation

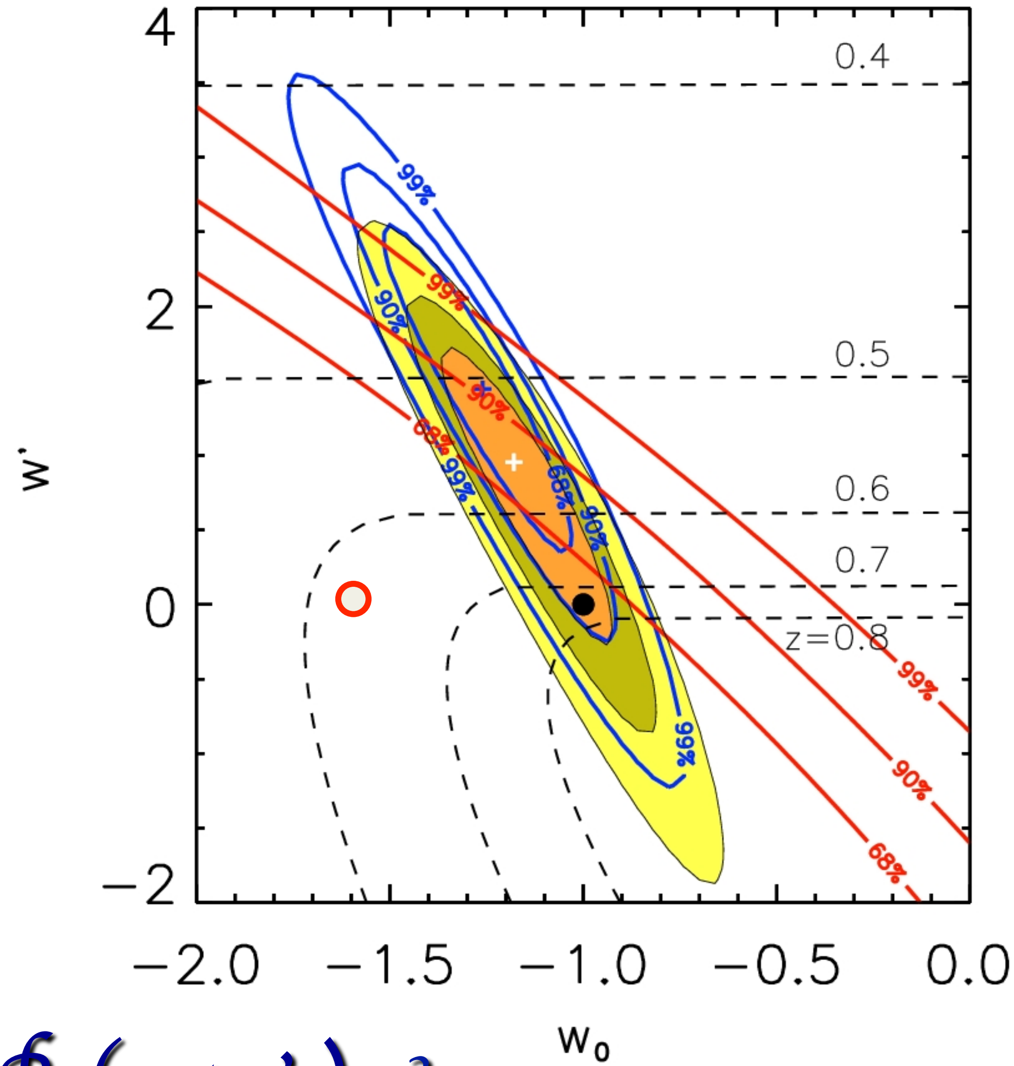




Firmani et al. 2006a

... and its evolution (even darker)

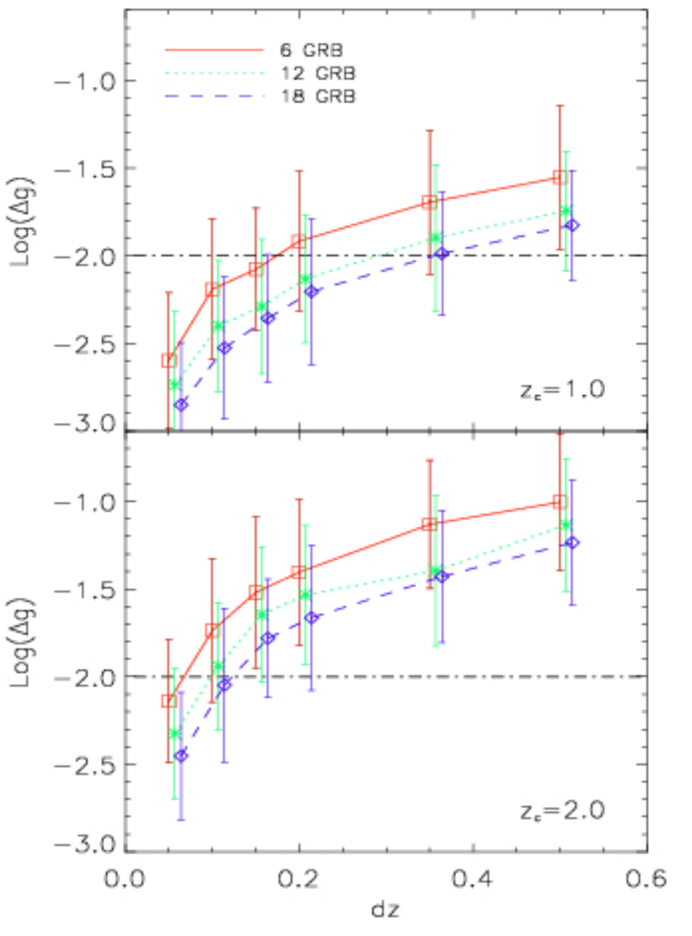
Flat Universe: W_{tot}=1, W_M=0.27



$P=(w_o+w'z)rc^2$

Firmani, Ghisellini, Ghirlanda & Avila-Reese, 2005

Calibration of the correlation …



Problem: there are few events at very low redshifts

do we really need very low redshifts???

e.g. 12 GRBs centered @ z=1 with a redshift dispersion of 0.15-0.2 are sufficient to calibrate the Ep-Eg correlation at <1% accuracy

The same precision is expected for the same number of bursts with 0.45< z< 0.75. This result suggests that is not necessary a large sample of low z GRBs for calibrating the slope of these correlations.

SN Hubble diagrams

★1997: Perlmutter et al. 1997, ApJ, 483, 565

— 7 SNe at z>0.35

— Consistent with Flat & W=1

★1998/9: Perlmutter et al. 1999, ApJ, 517, 565

Riess et al. 1998, AJ, 116, 1009

— 42 & 16 SN 0.16<z<0.83

— Universe will expand forever

— Expansion is *accelerating*

— "Dark Energy" is 'pushing'

★2004: Riess et al. 2004, ApJ, 607, 665

— 10 SNe at 1<z<1.76 with HST

— Deceleration⇒Acceleration at z~0.46

★2005: Astier et al. 2005, ApJ, 607, 665

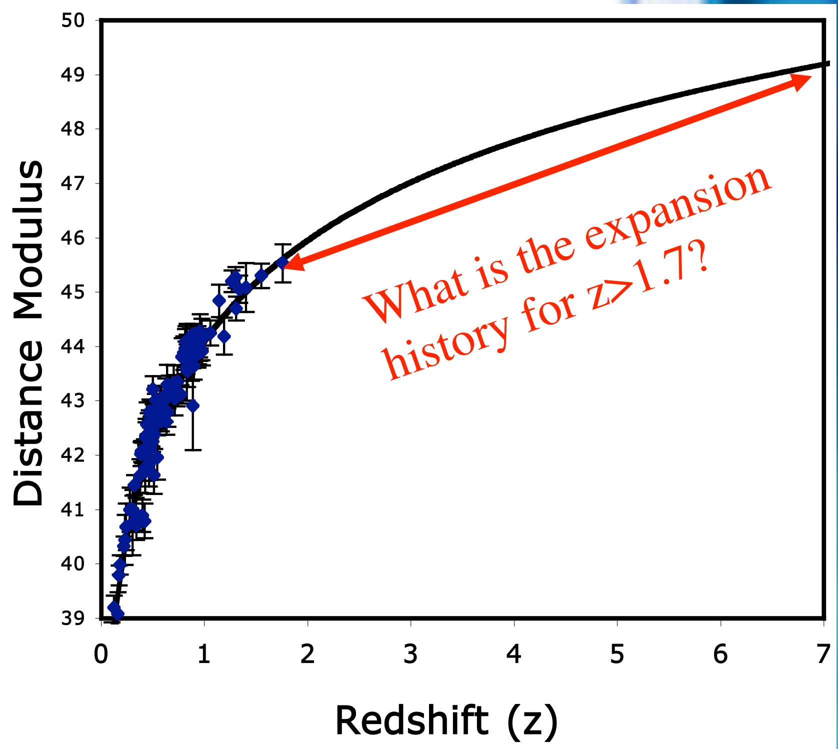
— 71 SNe at z<1

— w=-1.023±0.090

— No constraint on change of w

★2012-13: http://snap.lbl.gov/

— ~2000 SNe at z<1.7

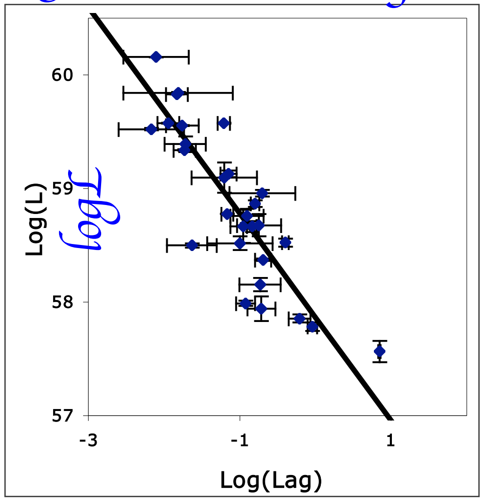


WHAT IT TOOK TO CONVINCE THE COMMUNITY:

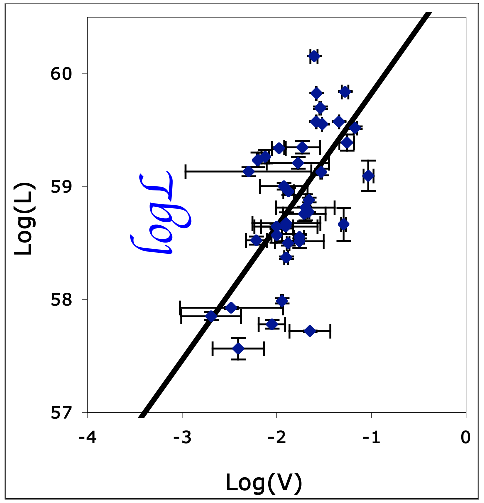
- Deep search for problems and complexities
- Confirmation by other methods

Calibration of six luminosity indicators

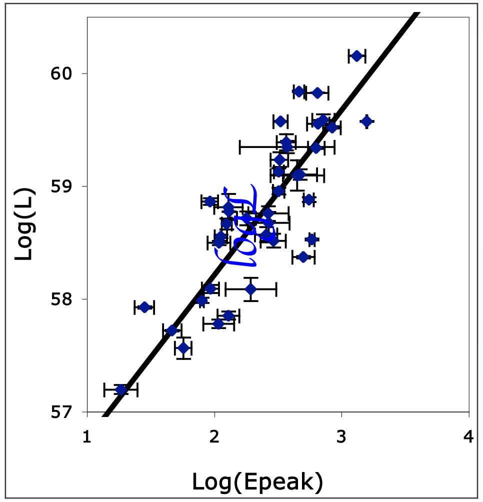
SPECTRAL LAG



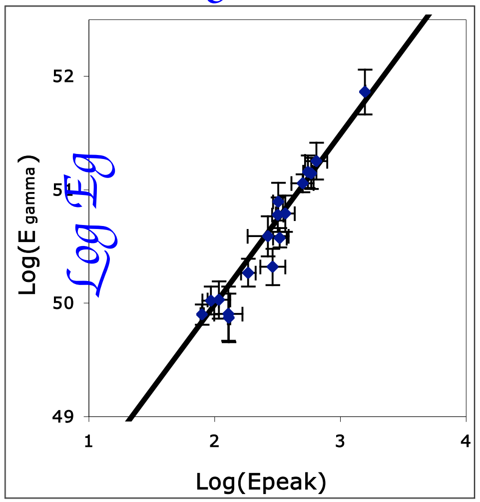
VARIABILITY



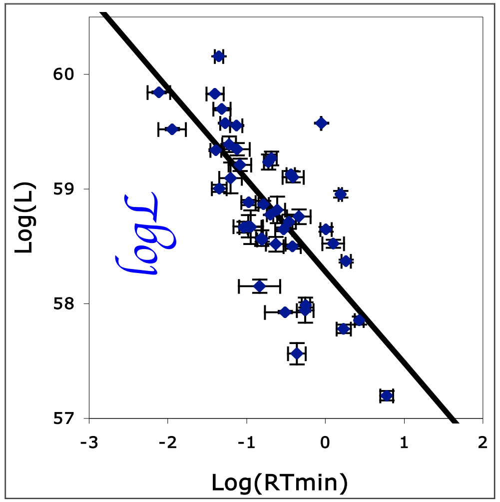
PEAK PHOTON ENERGY



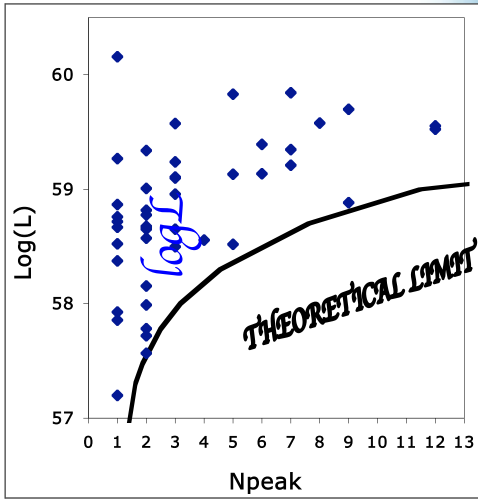
TIME OF JET BREAK



MINIMUM RISE TIME



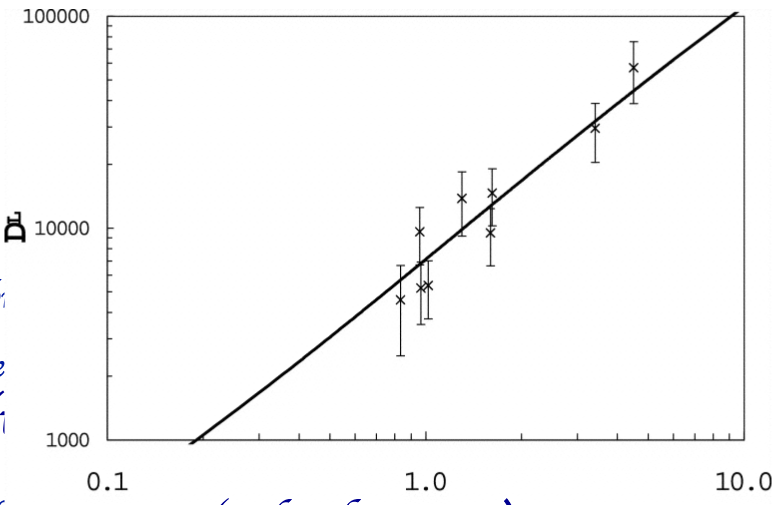
NUMBER OF PEAKS



GRB Hubble diagram

PRIOR WORKS:

Author (Reference)	# GRBs	# Lum Ind.
Schaefer (2001, three public talks)	8 GRBs	2 (t_{lag},V)
Schaefer (2003, ApJLett, 583, 67)	9 GRBs	2 (t_{lag},V)
Bloom et al. (2003, ApJ, 594, 674)	16 GRBs	1 (t_{b}
Xu, Dai, Liang (2005, ApJ, 633, 603)	17 GRBs	1 (t_{bre}
Firmani et al. (2006, MNRAS, 360, 1)	19 GRBs	1 (
Liang & Zhang (2005, ApJ, 633, 611)	15 GRBs	1 (t_{brea}
Schaefer (2007)	69 GRBs	5 (t_{lag},V,E_p, t_{break}, t_{rise})



(Schaefer 2003)

Capozziello, Cardone, Dainotti, Izzo, Ostrowsky, Willingale (2008, 2009,2010,2012):

- ★ 69 GRBs
- ★ from 0.17< z<6.29
- ★ 30 with SWIFT, 16 with HETE, 8 with BATSE, 11 with KONUS, 3 with SAX, 1 with INTEGRAL
- ★ Combine information from all 5 luminosity indicators to get best luminosity
- ★ Must simultaneously fit cosmology and luminosity relations

Calibration of the correlation …

Accuracy for individual SNe & GRBs:

OBJECT	σ_{μ} (overall) Median	Best
SNe*	0.23 mag	0.15 mag
GRB	0.60 mag	0.21 mag

*Gold & Silver sample from Riess et al. (2004 ApJ, 607, 665)

SN advantages:

★ 2.6X more accurate singly

★ Physics of SNe is well known

GRB dvantages:

★ Uniquely covers $0.7 < z < 6.6$

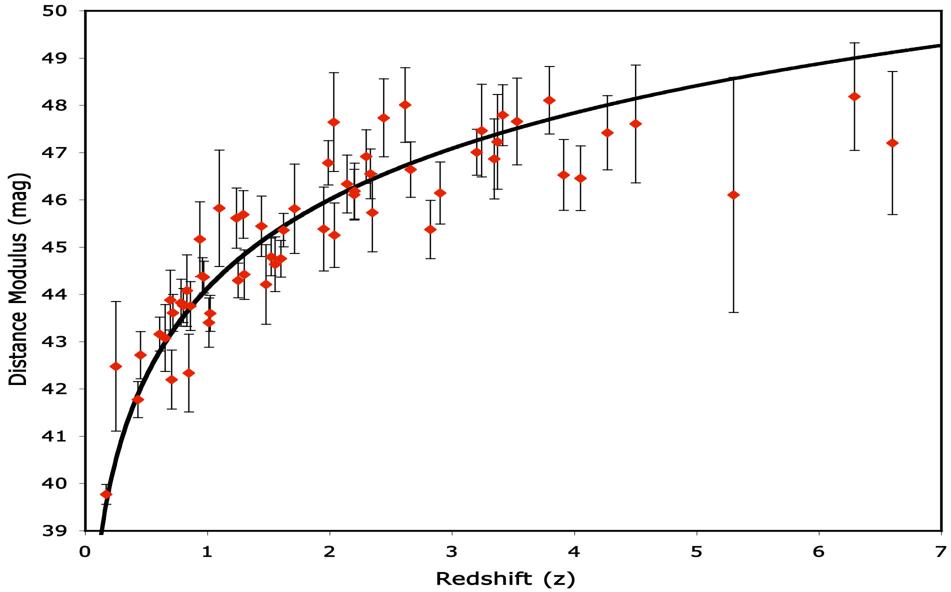
★ No problem from extinction

69 GRB Hubble diagram

'Standard' cosmology:

Flat Universe with W_M=0.27±0.04,

Cosmological Constant [w=-1 and unchanging for w=P/rc²]

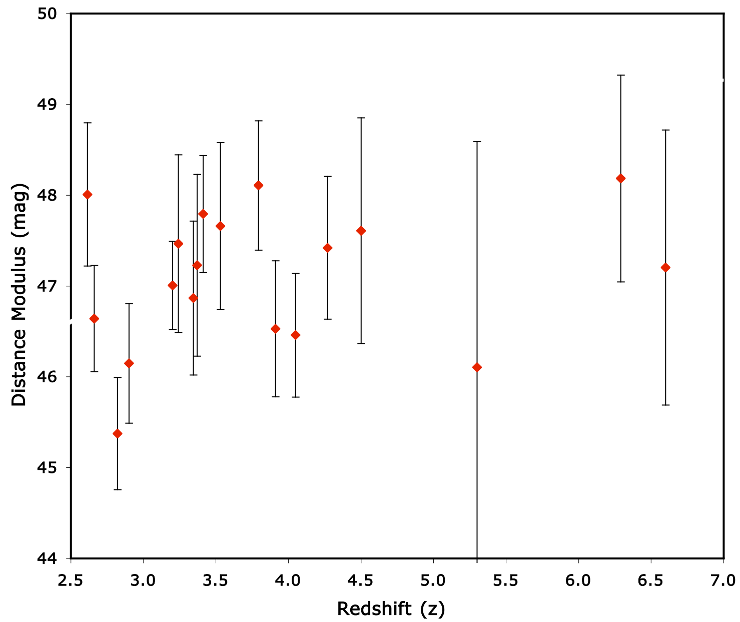


Appears to be flat at z> 2.5

'Standard' cosmology:

Flat Universe with $W_M=0.27\pm0.04$,

Cosmological Constant [$w=-1$ and unchanging for $w=P/rc^2$]



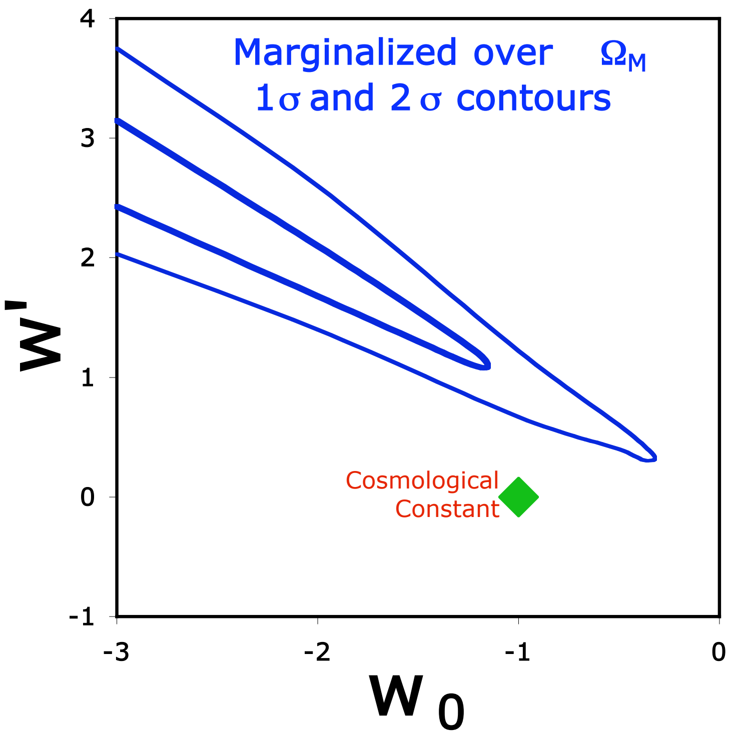
Search for best cosmology

Assume Flat Universe, marginalize over W_M

Assume Equation of state; $w=P/rc^2$, let w vary as $w_o+w'z$ or $w_o+w_a*z/(1+z)$

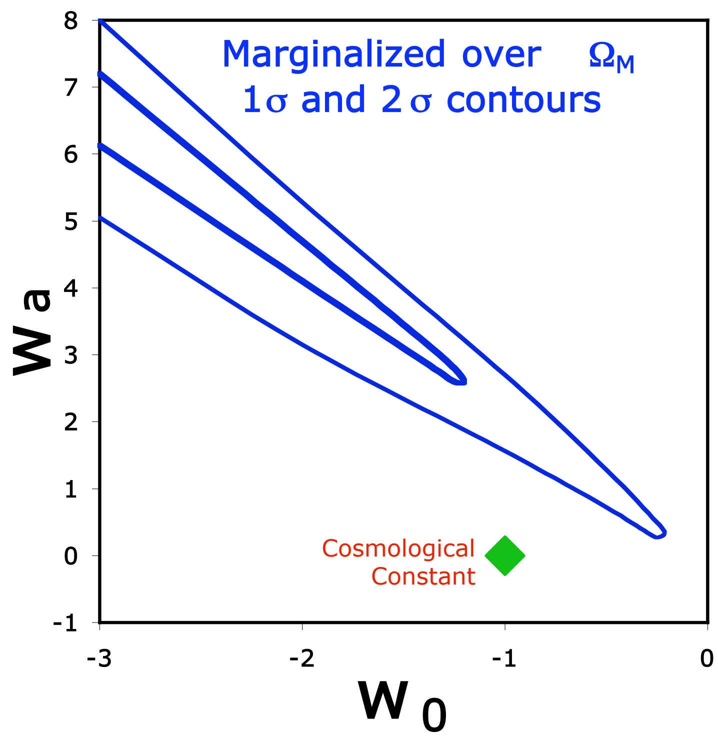
Cosmological Constant has $w=-1$ and $w'=w_a=0$

$w = w_o + w' z$



Cosmological Constant at 2.8s level

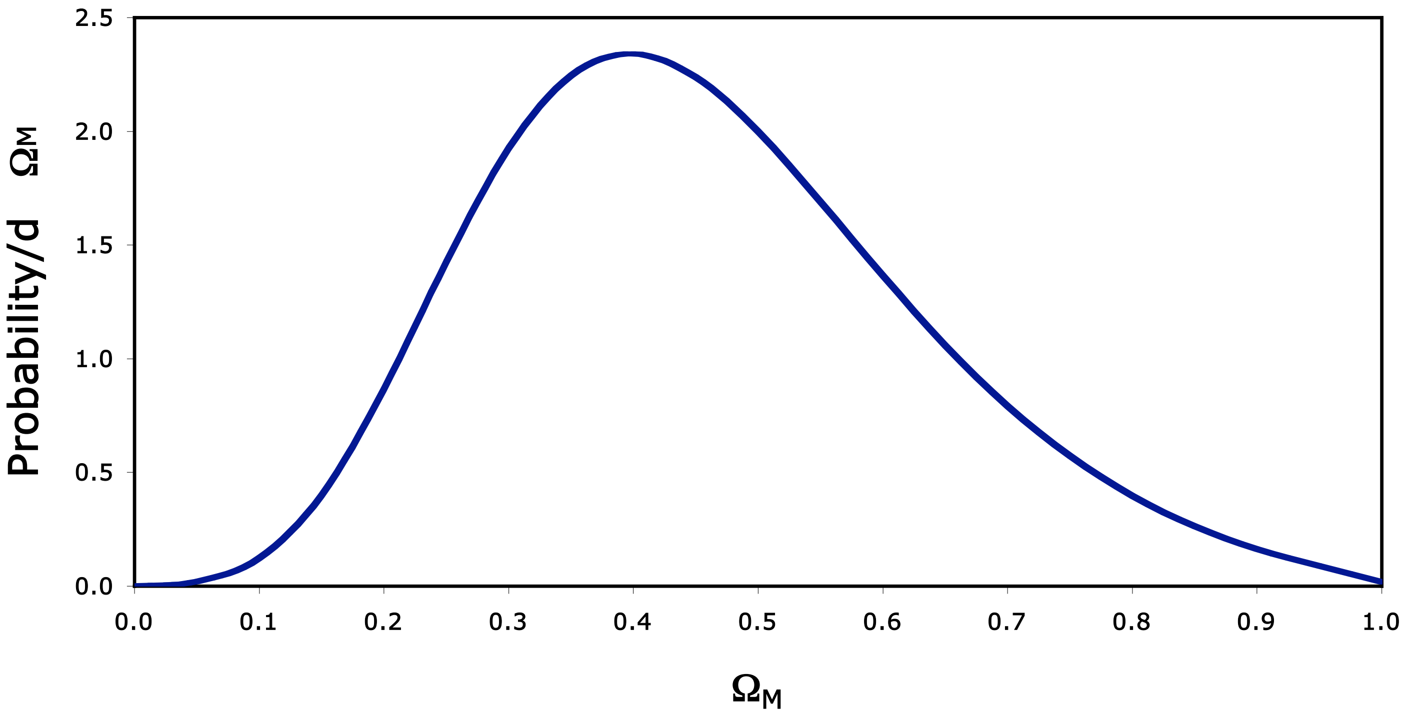
$w = w_o+w_a*z/(1+z)$



Cosmological Constant at 2.3s level

What is best IS BEST Ω_M?

Assume Flat Universe with $w_o = -1.4$ and $w' = 1.3$

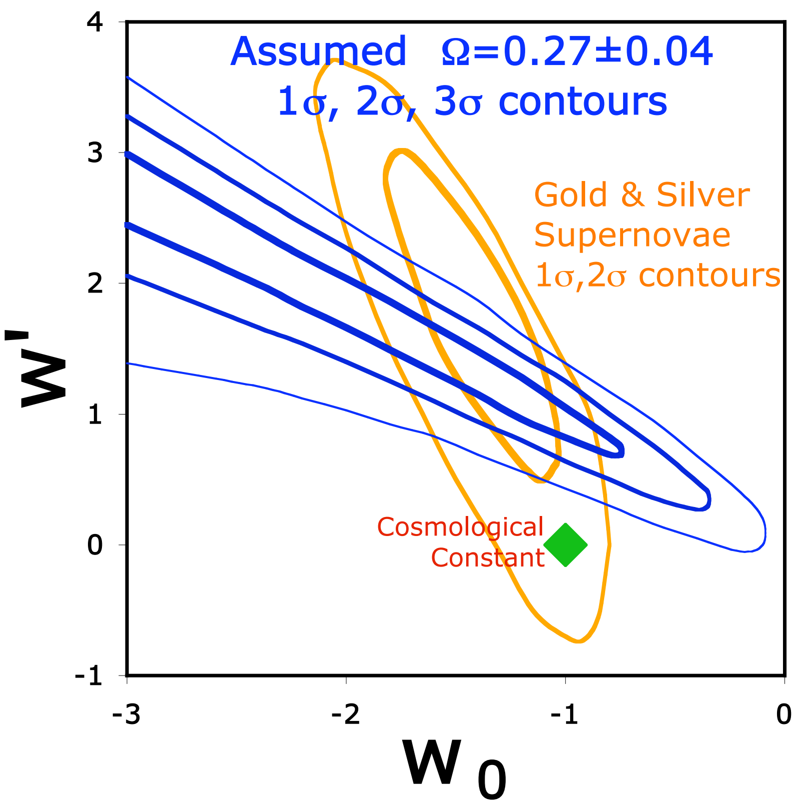


One Sigma: $0.25 < W_M < 0.59$

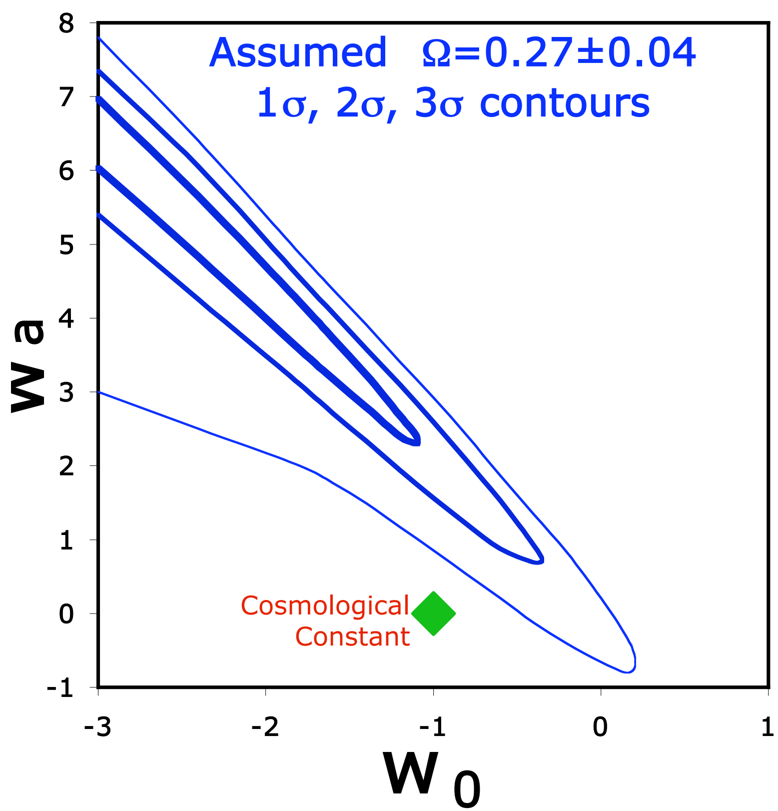
Search the best cosmology

Assume Flat Universe with Ω_M=0.27±0.04,

$w = w_0 + w' z$



$w = w_0 + w_a * z/(1+z)$



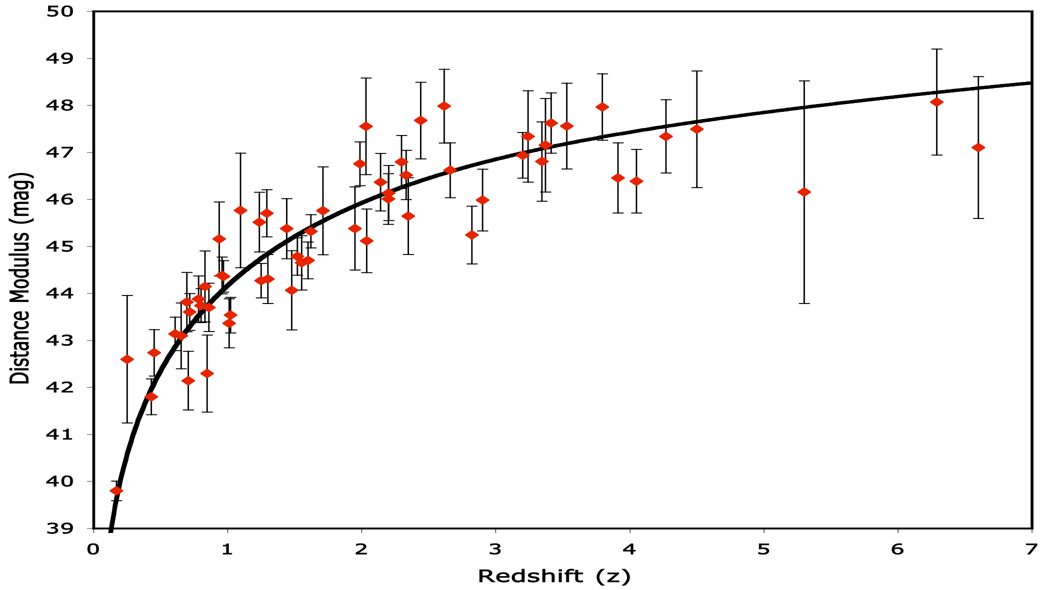
Cosmological Constant rejected at 3.5s level Cosmological Constant jected at 3.7s level

Best fit Cosmology

Best Fit cosmology:

Flat Universe with Ω_M=0.27±0.04,

w_o = -1.4, $w'=dw/dz$ = 1.3, $w=P/rc^2=w_o+w'z$



First results from new method

★ GRB HUBBLE DIAGRAM FLATTENS FOR z>2.5:

Best fit has $w_o = -1.4$ and $w' = 1.3$

Cosmological Constant rejected at 3.5s level

In good agreement with Gold & Silver SNe

If Dark Energy changes with time, then it is not vacuum energy

Questions and potential problems

★ MALMQUIST BIAS:

Very difficult problem to calculate, because conditions for detecting burst as a function of redshift are highly inhomogenous and not well known

★ GRAVITATIONAL LENSING AMPLIFICATION AND DEAMPLIFICATION BY FOREGROUND GALAXIES:

Any resulting bias is likely to be insignificant (Daniel Holz 2005)

★ WHAT ARE EFFECTS OF EVOLUTION?

the effects will be near-zero because the GRB luminosity indicators are based on quantities like conservation of energy in jet and light travel time which do not evolve With time or metallicity;

- while it does not matter if the typical luminosities change with time so long as the calibration of the relations is based on the physics of the situation. Furthermore no sign of evolution with redshift
- of the Epeak - Eiso correlation (either its slope and normalisation) is found (Ghirlanda et al. 2008 to appear on Mon Not. R. Astron. Soc.

Conclusions

★ *NEW METHOD TO MEASURE DARK ENERGY:*

Unique information for 1.7< z < 6.6

★ *FIRST RESULTS:*

69 GRBs from 0.17< z < 7

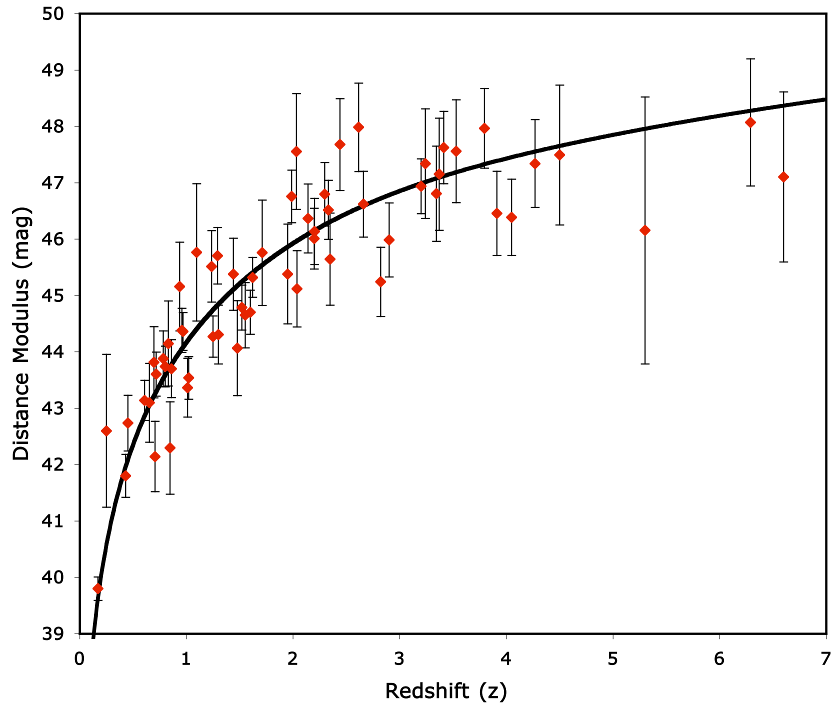
★ *HUBBLE DIAGRAM FLATTENS FOR z>2.5:*

Dark Energy changes over time,

(Cosmological Constant rejected at 3.5s)))

or Hi-z GRBs are brighter by ~3X

(Malmquist bias?)



★ *THIS RESULT MUST BE CONFIRMED OR DENIED BY INDEPENDENT STUDY:*

Independent GRB data

(69 more HETE & SWIFT bursts)

Independent methods

(perhaps lensing or quasars...)