Measuring the cosmological parameters with Gamma-ray Bursts

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Summary

• The measurements of $\Omega_m$ and $\Omega_\Lambda$ with SNe-Ia
• SN systematics: the need of an independent measurement of $\Omega_m$ and $\Omega_\Lambda$
• The measurements of $\Omega_m$ 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

\[ m = M + 5 \log D - 5 \rightarrow m = 5 \log cz + 25 - 5 \log H_0 + M \]

in the low red-shift limit \( \rightarrow \) \( cz = H_0 x D \)
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
### Table 1

<table>
<thead>
<tr>
<th>$H_0$ (km s$^{-1}$ Mpc$^{-1}$)</th>
<th>Technique</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>81 ± 8</td>
<td>Cepheids in 4 Virgo spirals</td>
<td>van den Bergh (1995a)</td>
</tr>
<tr>
<td>80 ± 12</td>
<td>SB fluctuations</td>
<td>Jacoby et al. (1992)</td>
</tr>
<tr>
<td>78 ± 11</td>
<td>Globulars in M87</td>
<td>Whitmore et al. (1995)</td>
</tr>
<tr>
<td>76 ± 7</td>
<td>PN in Virgo Cluster</td>
<td>Jacoby (1996)</td>
</tr>
<tr>
<td>75 ± 8</td>
<td>PN in Fornax cluster</td>
<td>McMillan et al. (1993)</td>
</tr>
<tr>
<td>74 ± 14</td>
<td>Tip of RG branch</td>
<td>Sakai et al. (1996)</td>
</tr>
<tr>
<td>73 ± 6 ± 7</td>
<td>SNe II exp. photospheres</td>
<td>Kirshner (1996)</td>
</tr>
<tr>
<td>73 ± 6</td>
<td>$D_n$ - $\sigma$ (Vir, For, Leo)</td>
<td>Mould (1996)</td>
</tr>
<tr>
<td>70 - 74</td>
<td>Tully-Fisher</td>
<td>Giovanelli (1996)</td>
</tr>
<tr>
<td>66 ± 12</td>
<td>IR Tully-Fisher</td>
<td>Malhotra et al. (1996)</td>
</tr>
<tr>
<td>65 ± 6</td>
<td>SN Ia lightcurves</td>
<td>Riess et al. (1996)</td>
</tr>
<tr>
<td>64 ± 3</td>
<td>4 SNe Ia</td>
<td>Hamuy et al. (1996)</td>
</tr>
<tr>
<td>55 ± 17</td>
<td>Sunyaev - Zel'dovich effect</td>
<td>Birkinshaw &amp; Hughes (1994)</td>
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<tr>
<td>55 - 60</td>
<td>SNe Ia (theory)</td>
<td>van den Bergh (1995b)</td>
</tr>
<tr>
<td>52 ± 9</td>
<td>SNe Ia (1937C)</td>
<td>Saha et al. (1994)</td>
</tr>
<tr>
<td>52 ± 8</td>
<td>SNe Ia (1972E)</td>
<td>Saha et al. (1995)</td>
</tr>
<tr>
<td>43 ± 11</td>
<td>Galaxy diameters</td>
<td>Sandage (1993a)</td>
</tr>
</tbody>
</table>

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
How to measure the cosmological parameters $\Omega_m$ and $\Omega_\Lambda$?
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:

$$m = M + 5\log[D_L(z; \Omega_M; \Omega_\Lambda)] + K + 25 + A$$
\[ D_L = \left(1 + z\right)c / H_0 | k |^{0.5} \times S \left[ | k |^{0.5} \int_0^z \left[ k(1 + z)^2 + \Omega_M(1 + z')^3 + \Omega_{\Lambda} \right]^{-0.5} \, dz' \right] \]

\[ k = 1 - \Omega_M - \Omega_{\Lambda} \]

\[ q_o = \frac{\Omega_M}{2} - \Omega_{\Lambda} \]

\[ S(x) = \begin{cases} 
  \sin(x) & \text{if } k < 0 \\
  x & \text{if } k = 0 \\
  \sinh(x) & \text{if } k > 0
\end{cases} \]
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 $q_o=1\pm0.5$ (cfr. $\sim -0.5$). 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

thermonuclear < 8\(M_\odot\)

\(\text{He} \rightarrow \text{Ia} \rightarrow \text{Ic} \rightarrow \text{High KE SNe-Ic} \rightarrow \text{Hypernovae} \rightarrow \text{GRB-SNe}\)

\(\text{Si} \rightarrow \text{Ib} \rightarrow \text{IIb} \rightarrow \text{II} \rightarrow \text{IIIL} \rightarrow \text{IIP} \rightarrow \text{IIIn}\)

core-collapse > 8\(M_\odot\)
The commonly accepted idea is that SNe-Ia are the thermonuclear disruption of C-O WDs (3-8M☉) in binary systems.
Are SNe-Ia standard candles?
Are SNe-Ia standard candles?

\[ M_B = a \times \Delta m(15^d) + b \]

After correction for lightcurve shape ("Phillips relationship"), supernovae become "calibrated" candles with \( \sim 0.15 \) magnitude dispersion.
BVRI LIGHT CURVES FOR 29 TYPE Ia SUPERNOVAE

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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 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 — and therefore with their apparent brightnesses obtain their distances. The >50 distant supernovae discovered so far provide a record of changes

\[ \Omega_m \sim 0.6 \pm 0.2 \]

\[ \Omega_\Lambda \sim 0.4 \pm 0.2 \]
$\Omega_m \sim 0.20$

$\Omega_\Lambda \sim 0.80$

Riess et al. 1998
$\Omega_m \sim 0.20$

$\Omega_\Lambda \sim 0.80$

Riess et 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)

Riess 2004
The two teams consistently found that SNIa at redshifts $z \sim 0.5$ appear dimmer than expected by $\sim 0.25$ 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 $\Omega_M \sim 0.3$. 

Conclusions from SNe
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

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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 $\sim 10^{-7} - 10^{-4} \text{ erg/cm}^2$ and bimodal distribution of duration
- measured rate: $\sim 0.8 / \text{ day}$; estimated true rate $\sim 2 / \text{ d}$
GRBs Strengths

• GRBs are extremely bright \( \rightarrow \) detectable out of cosmological distances \((z=8.2 \text{ Salvaterra et al. 2009})\)

• 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 $E=10^{48-54}\text{erg}$
• GRBs cannot be standardize (like SNe-Ia)
2004: evidence that by substituting $E_{\text{iso}}$ with the collimation corrected energy $E_\gamma$ the dispersion of the luminosity function of GRBs decreases significantly (Ghirlanda et al. 2004; Firmani et al. 2006) but not enough!

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

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

• GRBs are not standard candles $E = 10^{48-54}$ erg
• GRBs cannot be standardized (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
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 $E_p$, $i$ and $E_{iso}$ 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 $E_{p,i}$ and $E_{iso}$ 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
The Scatter of the Amati relation

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

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

\[ D_L = (1+z)c / H_0 \left| k \right|^{0.5} \times S \left| k \right|^{0.5} \int_0^{z'} \left[ k(1+z)^2 + \Omega_M (1+z')^3 + \Omega_\Lambda \right]^{-0.5} dz' \]
1. Poissonian
2. Intrinsic
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4. Cosmological <10%
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)

$$L(m, c, \sigma_v ; x, y) = \frac{1}{2} \sum_{i} \log \left( \frac{\sigma_v^2 + \sigma_{y_i}^2 + m^2 \sigma_{x_i}^2}{\sigma_v^2 + \sigma_{y_i}^2 + m^2 \sigma_{x_i}^2} \right) + \frac{1}{2} \sum_{i} \frac{(y_i - m x_i - c)^2}{\sigma_v^2 + \sigma_{y_i}^2 + m^2 \sigma_{x_i}^2}$$
\( \Omega_M = 1 \) excluded at 99.9% c.l.

<table>
<thead>
<tr>
<th>( \Omega_m ) (flat universe)</th>
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<th>68%</th>
<th>90%</th>
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<tbody>
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### Ω_m (flat universe)

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<td><strong>SNe-la Perlmutter et al. 1998+1999</strong></td>
<td>0.28</td>
<td>0.19 – 0.38</td>
<td></td>
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</table>
Swift + Konus-WIND + Fermi/GBM \rightarrow

**30 GRBs/yr** in the $E_p,i - E_{iso}$ plane

SVOM (from 2017) \rightarrow

**50 GRBs/yr** in the $E_p,i - E_{iso}$ plane

$140 + 150 = 290 \ (<2018)$

$290 + 250 = 540 \ (<2023)$
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### Table: Constraints on \( \Omega_m \) from GRBs

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<td>300 GRBs (&lt;2018)</td>
<td>?</td>
<td>0.16 – 0.47</td>
<td>0.11 – 0.65</td>
</tr>
<tr>
<td>600 GRBs (&lt;2023)</td>
<td>?</td>
<td><strong>0.19 – 0.38</strong></td>
<td><strong>0.15 – 0.50</strong></td>
</tr>
</tbody>
</table>
GRBs do it better

GRBs can constraints the equation of state of DE (pressure to energy density ratio, $p = w \rho_{\text{DE}}$) 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 $\Lambda$. Bronstein was executed on Stalin’s order in 1938 presumably for reasons not directly related to the decaying $\Lambda$. 
- No cosmic acceleration
- $-1/3 < w < -1$ "Quintessence"
- $w = -1$ Cosmological constant
- $w < -1$ Phantom Energy
\[ w(z) = w_0 - w' \times \frac{z}{1+z} \]

\[ w(z=0) = w_0, \quad w' = \frac{dw}{dz} \]

\[ \Omega_m = 0.27 \pm 0.04 \]

Riess et al. 2004
The two teams consistently found that SNIa at redshifts $z \sim 0.5$ appear dimmer than expected by $\sim 0.25$ 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 \( z \sim 10 \), 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 \( \Omega_m < 1 \) 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 \( \Omega_m \) with an accuracy comparable to SNe-Ia.

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