Cosmology with long GRBs: non-Gaussian features in the data

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Plan

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- Long and Short GRBs
- Astrophysical Applications
- Cosmology with Long GRBs
- Extreme Value theory and Δ statistics
- Analysis of Calibrated Long GRB errors using Δ statistic
- Results & Conclusions
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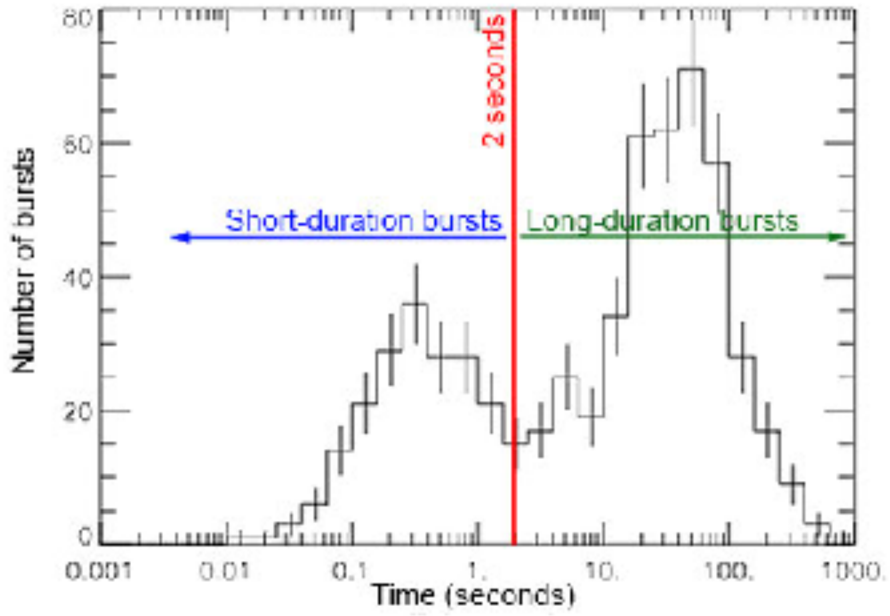
Gamma Ray Burst (GRB)

- Gamma Ray Bursts are short lived bursts of high energy gamma rays. Wavelengths ranging from 0**.3A to 0.03A**.
- There are two different categories of GRBs: **long duration** and **short duration**. It is believed these different types come from different sources.
- **GRBs** were discovered by the US Vela Nuclear Test Detection Satellites in the 1960s.
- Until 1990's scientists didn't know where these flashes were coming from or what was causing them.

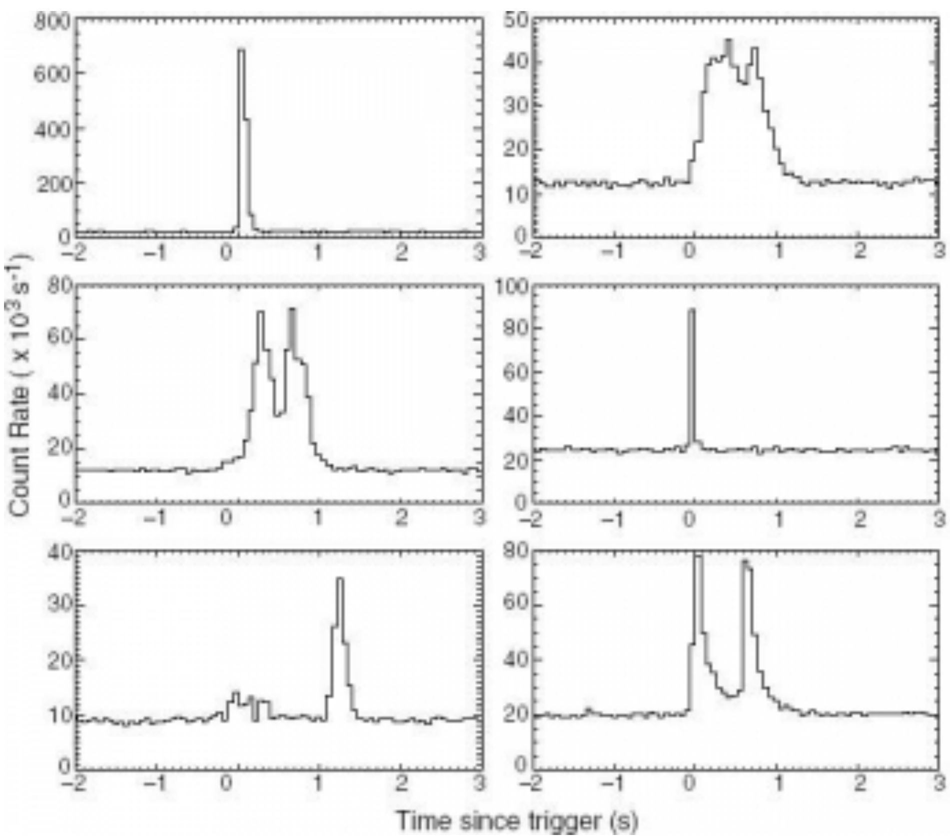
All GRBs are not same!

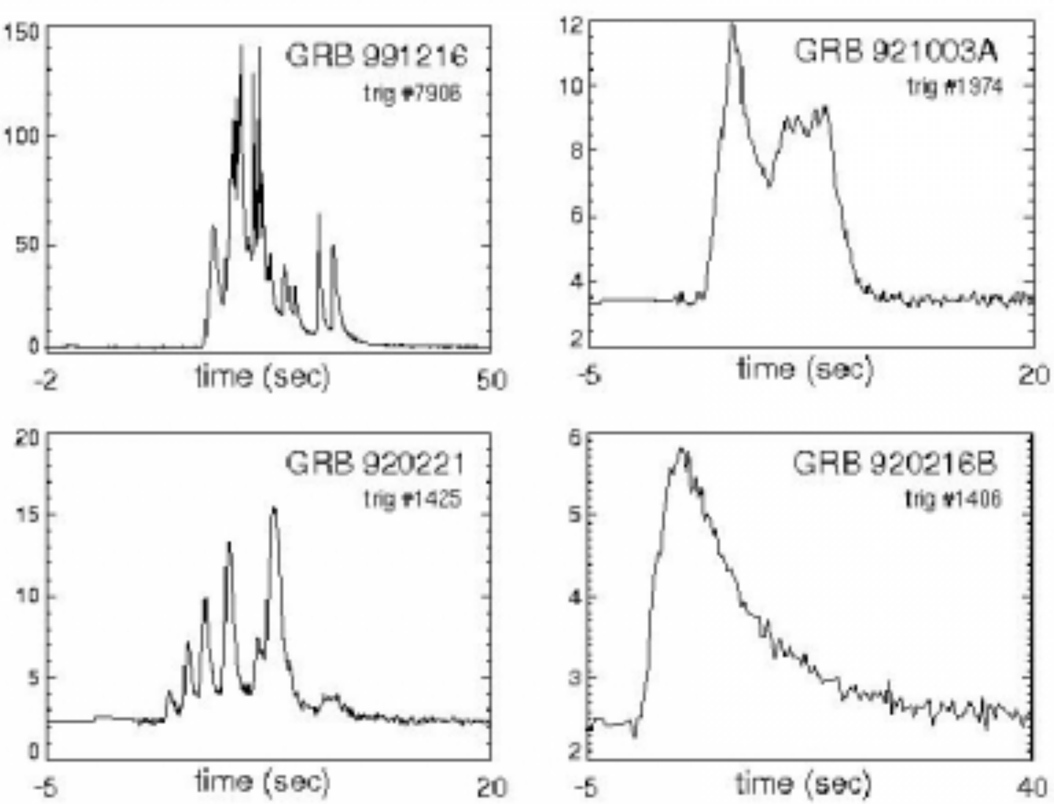
- Histogram of number of Bursts of different time duration clearly shows two different classes.
- Short GRBs: Duration less than 2 Sec.
- Long GRBs: Duration more than 2 sec.



Time v/s number of bursts for the GRBs observed by the BATSE (Compton Gamma-ray Telescope).

Light Curve of Short and Long GRBs





Long Duration Bursts (Long GRBs)

Long GRBs

- Duration (T_{90}) greater than 2 seconds. Average is about 30 seconds.
- Evenly distributed all over the sky.
- Believed to arise from core-collapse of massive stars.

Short GRBs

- $T_{90} < 2$Sec. Average ~ 300 milliseconds.
- Significantly dimmer than long GRBs and have higher energies.
- Believed to arise from merger of compact objects e.g. neutron star or black hole.

Why Study GRBs

- Very high luminosity and Gamma rays are immune to dust extinction. Thus can be observed up to very high redshift. Compare it with optical photons which suffer from dust extinction due to ISM.
- Arise from massive stars: Intrinsic luminosity does not depend on host galaxy mass.
- Associated with death of massive stars: Important tool to probe star formation rate and IMF at high redshift.
- Provide exciting opportunity to detect Pop-III stars.
- Important tool to study re-ionization of IGM and ISM (Wang et al. 2015).

Cosmology with Long GRBs

- Correlations between spectral properties and energetics of GRBs have been found (Amati et al. 2002; Ghirlanda et al. 2004; Liang & Jhang 2005).
- Using the above correlations GRBs can be standardized as standard candles and their distances can be determined.
- Can be used to estimate Cosmological parameters and to study the nature of dark energy.
- Compared to SNe Ia which can be observed up to z~1.7 (due to dust extinction) GRBs can be detected to larger distances.

Amati Relation

- Correlation between the isotropic-equivalent energy of long-duration GRBs and the peak energy of their integrated spectra in the GRB frame.
- Ep,i is calculated from the observed peak energy, $E_{p,obs}$, by the following relation:

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

- The Amati Relation is given by

$$E_{p,i} = K.(E_{iso}/10^{52}\ ergs)^{m} \quad (m\sim0.5)$$

- Amati relation can be expressed logarithmically as

$$log\ E_{iso} = a+b\ \log E_{peak}$$

Ghirlanda Relation

- Ghirlanda (2004) obtained following relation between the peak energy in the υFυ rest frame spectrum(E_p) and the beaming-corrected energy(E_γ),

$$E_p = 267.0 (E_\gamma / 4.3 * 10^{50} ergs)^{0.706 +- 0.047}\ keV$$

- The above correlation is empirical, so far explanation of its origin is not available.
- Amati & Ghirlanda relations are used to calibrate long GRBs for cosmological applications.

Challenges

- Relation between E_p & E_{iso} is empirical. Underlying physics is not completely known.
- Calibration of high-z GRBs is done using SNe Ia. Cosmological inputs are required in calibration: Circularity problem.
- GRB data available in a large range of redshifts. There are claims of evolution of GRBs with redshift (Li-Xin Li 2007).

Non-Gaussian Errors in the GRB Data

Calibrated GRB data

- Data:
- 67 Long GRBs from Rong-Gen Cai. et al. 2013.
- Union2 data (SNe Ia) from Amanullah et al 2010.
- Combination of the above two data sets.

Observables:

- Redshift z of host galaxy.
- Distance modulus

$\mu = m - M$

- Position in the sky.

- μ in terms of Luminosity distance:

$\mu = 5\log d_L + 25,$

d_L in Mpc.

- Luminosity distance in LCDM cosmology

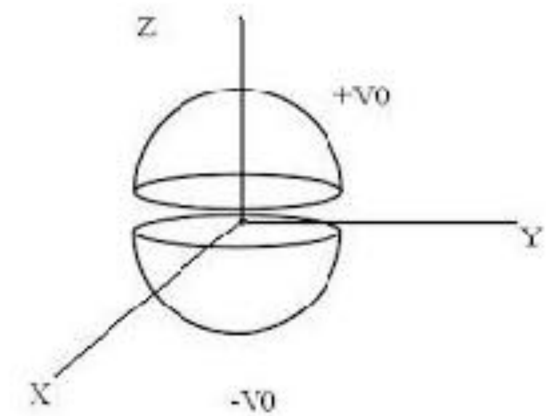
$$d_L = \frac{c(1+z)}{H_o}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda)}}$$

Method

- Distribute the GRB data over the sky.
- Define a plane to divide the sky into two hemispheres (say north and south).
- Two subsets of data. Calculate χ^2 for both subsets and take their difference Δ.
- Rotate the plane, obtain different subsets, again calculate Δ.
- Find the maximum of Δ.

$$\Delta_{\chi 2} = \max \{\Delta\}$$

- What is the distribution of $\Delta_{\chi 2}$?



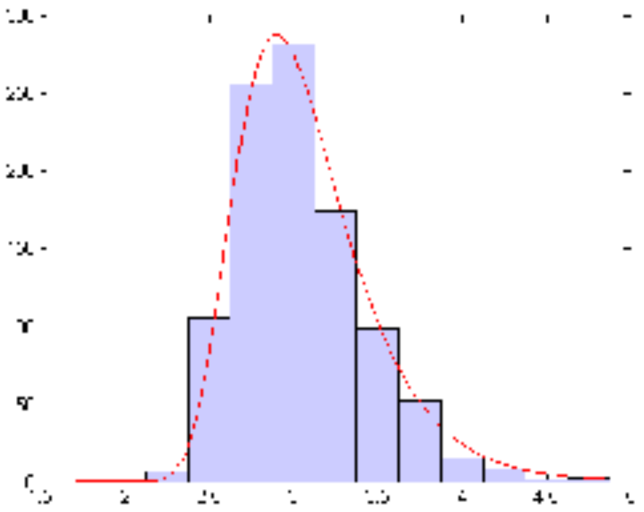
Extreme Value Theory

- Consider a sample of random numbers $\{x_i\}$.

  Find the maximum of the sample, i.e.,

  $x = max\ \{x_1, x_2, x_3, \ldots\}$

- Extreme value distributions i.e., distribution of x are Gumbel, Frechet or Weibull.
- Gumbel if x_i are not bounded. Analytic form for CDF:



Gumbel distribution

$$G(x) = \exp\left(-\exp\left[-\left(\frac{x-\alpha}{\beta}\right)\right]\right)$$

- The Pdf :

$$g(x;\alpha,\beta) = \frac{1}{\beta}\exp\left[-\left(\frac{x-\alpha}{\beta}\right)\right]\exp\left(-\exp\left[-\left(\frac{x-\alpha}{\beta}\right)\right]\right)$$

Method continued

If error in μ in i^{th} data point is Gaussian with ~ $N(0, \sigma_i)$ then

$$\mu_i^{ob} = \mu_i^{th} \pm \sigma_i.$$

Define

$$\chi_i \equiv \frac{\mu_i^{ob} - \mu_i^{th}}{\sigma_i}.$$

$$\chi_i \sim N(0, 1).$$

Define for a subset of the data

$$\chi^2_{\text{sub}} = \sum_{\text{sub}} \chi_i^2.$$

- Obtain $\Delta_{\chi 2}$ from difference of χ^2_{sub} in different hemispheres.
- Shuffle the positions to obtain distribution of $\Delta_{\chi 2}$ - bootstrap distribution. (Gupta et al. 2010)

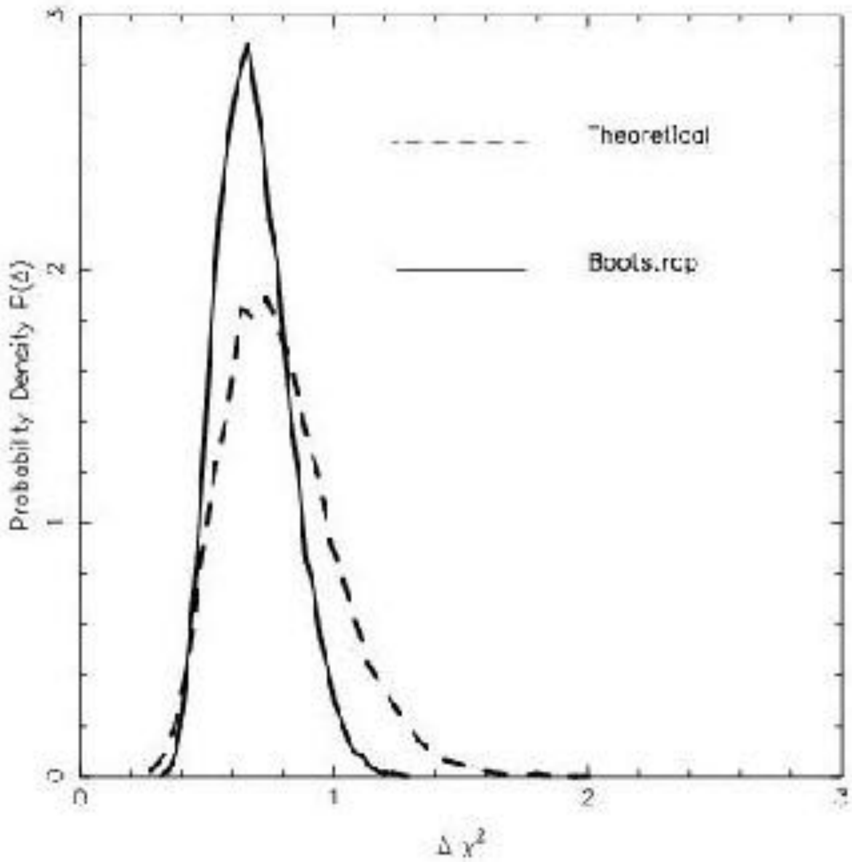
Best fit values

Assumed flat FRW universe i.e.

$$\Omega_m + \Omega_\Lambda = 1$$

Data Set	Data Point	Ω_m	H_0	χ^2 /dof
GRB	67	0.68	61	1.74
UNION2	557	0.27	70	0.97
UNGRB	624	0.29	70	1.07

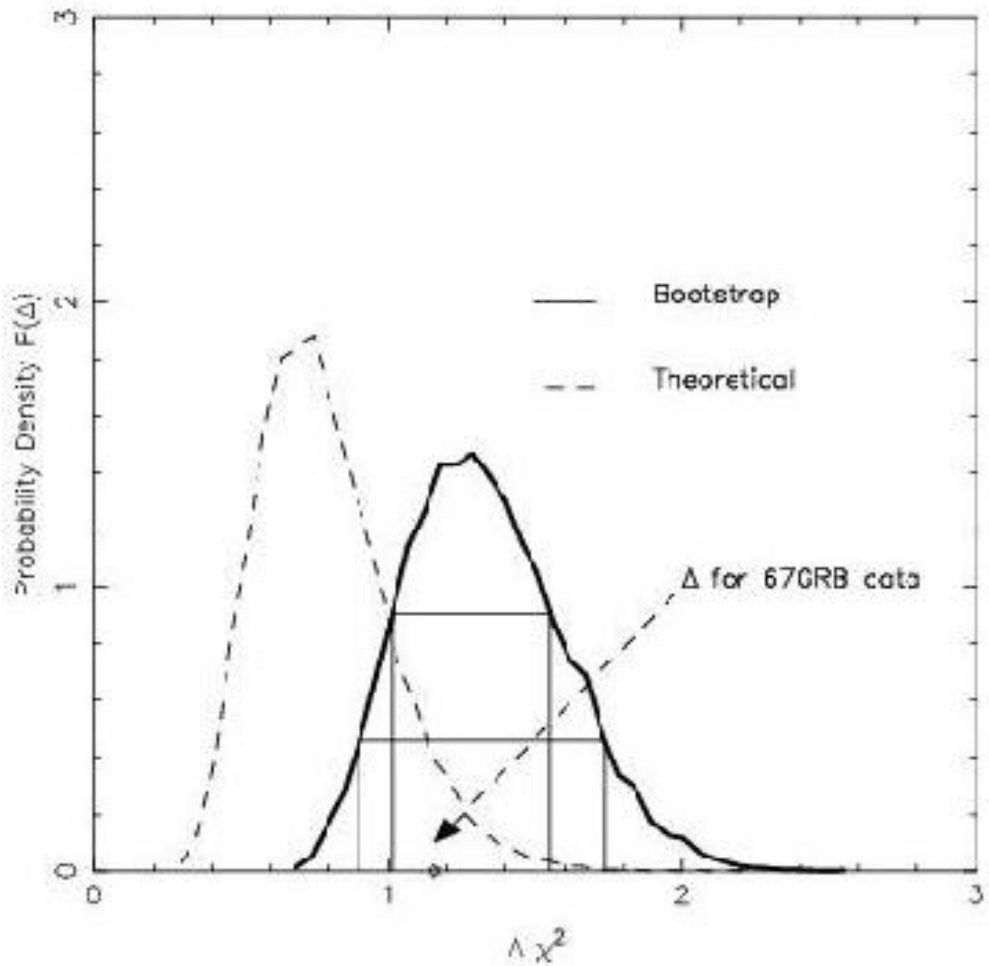
Distribution of Δ_{χ^2} for simulated data



- Gumbel with Gaussian errors lies on the right to the bootstrap.
- Bootstrap has an upper bound while theoretical Gumbel does not.

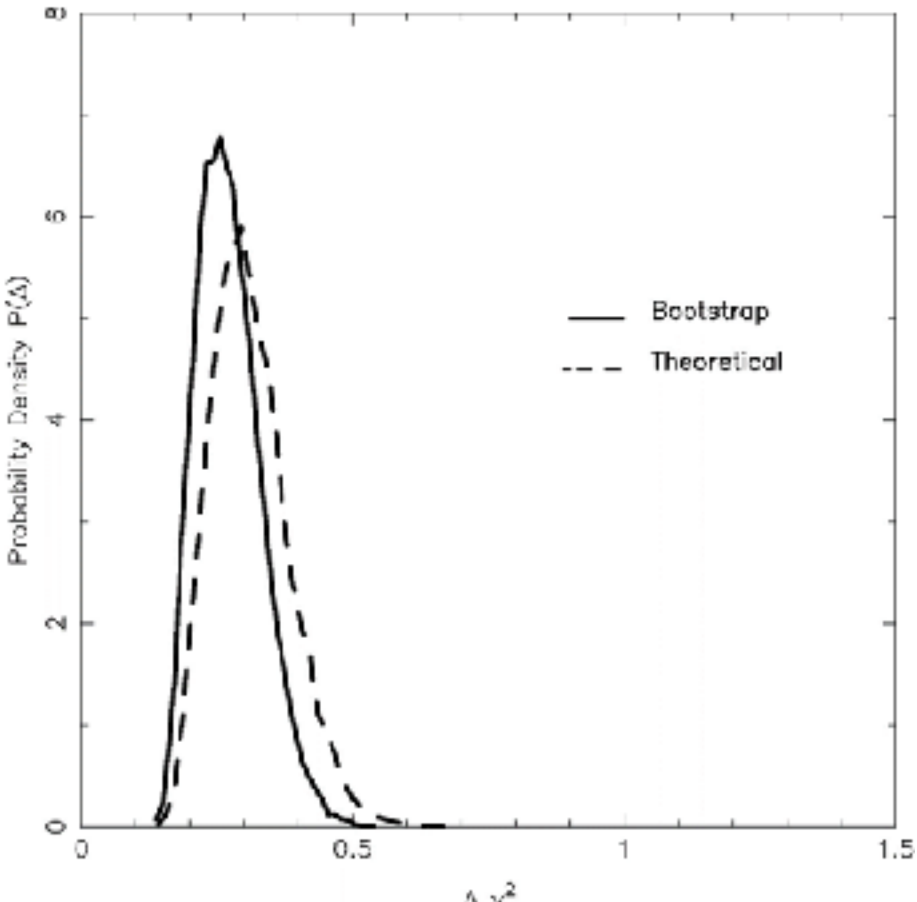
Result for GRB data

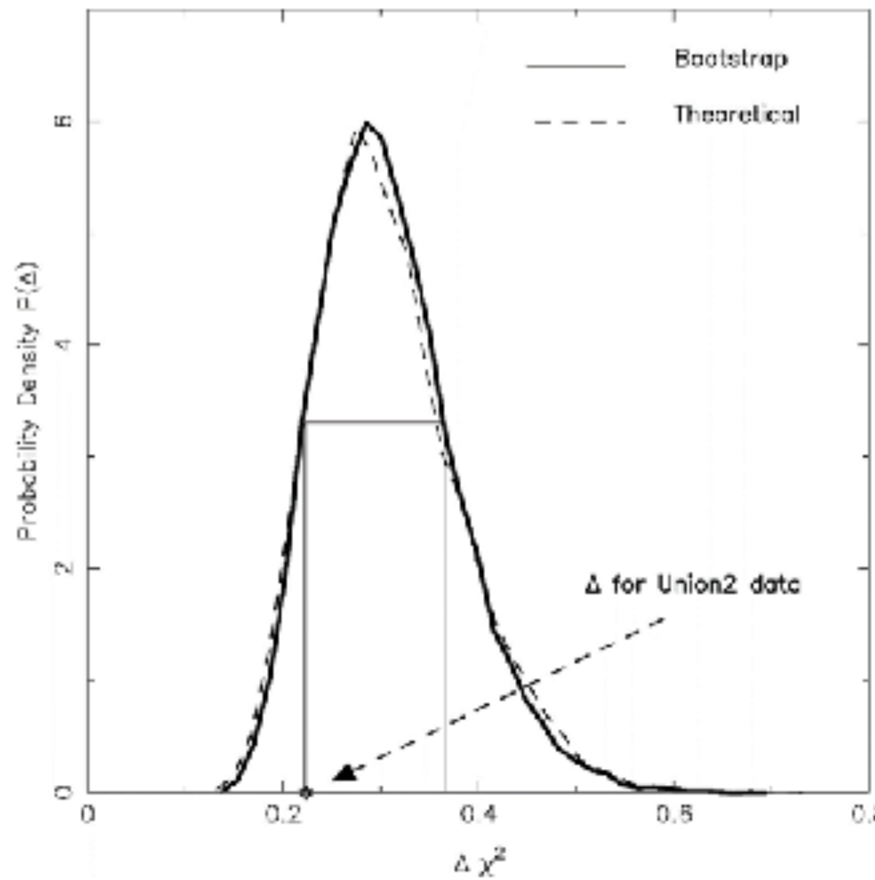
Distribution of Δ for GRBs



- **Bootstrap distribution lies on the right instead of left side indicating non-Gaussianity.**
- **Δ from data lies near to the peak of the bootstrap distribution.**

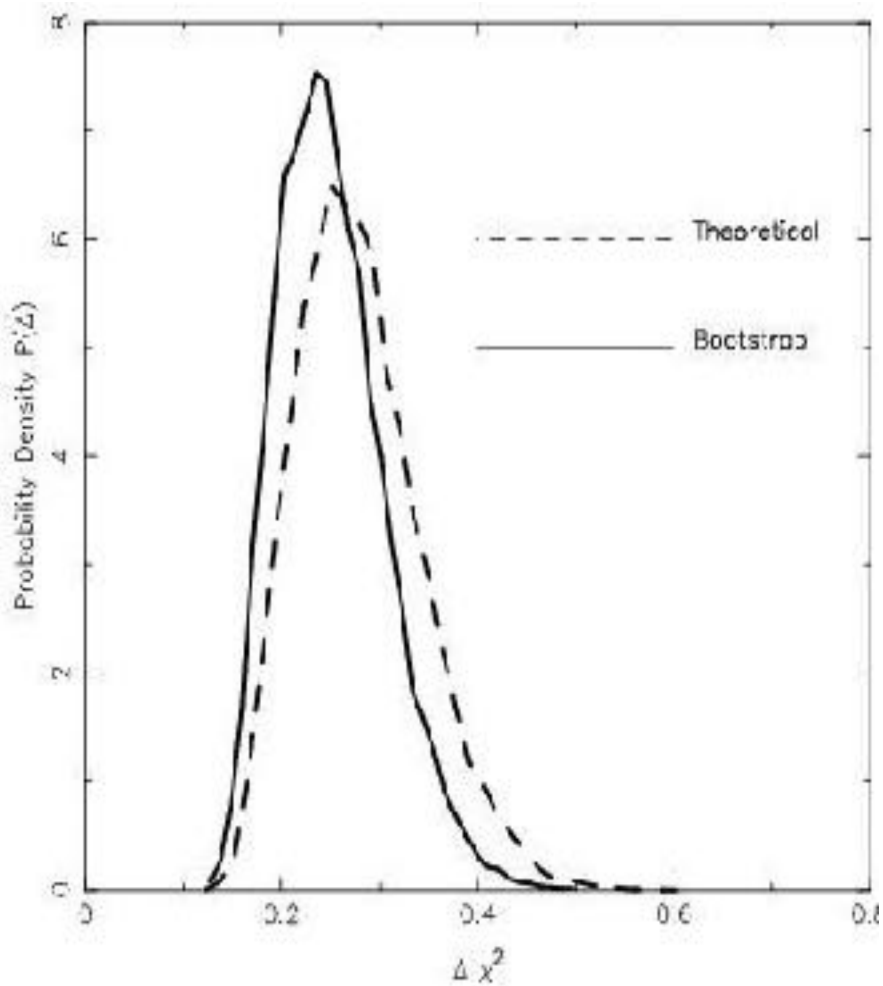
Result for Union2 (SNe) data

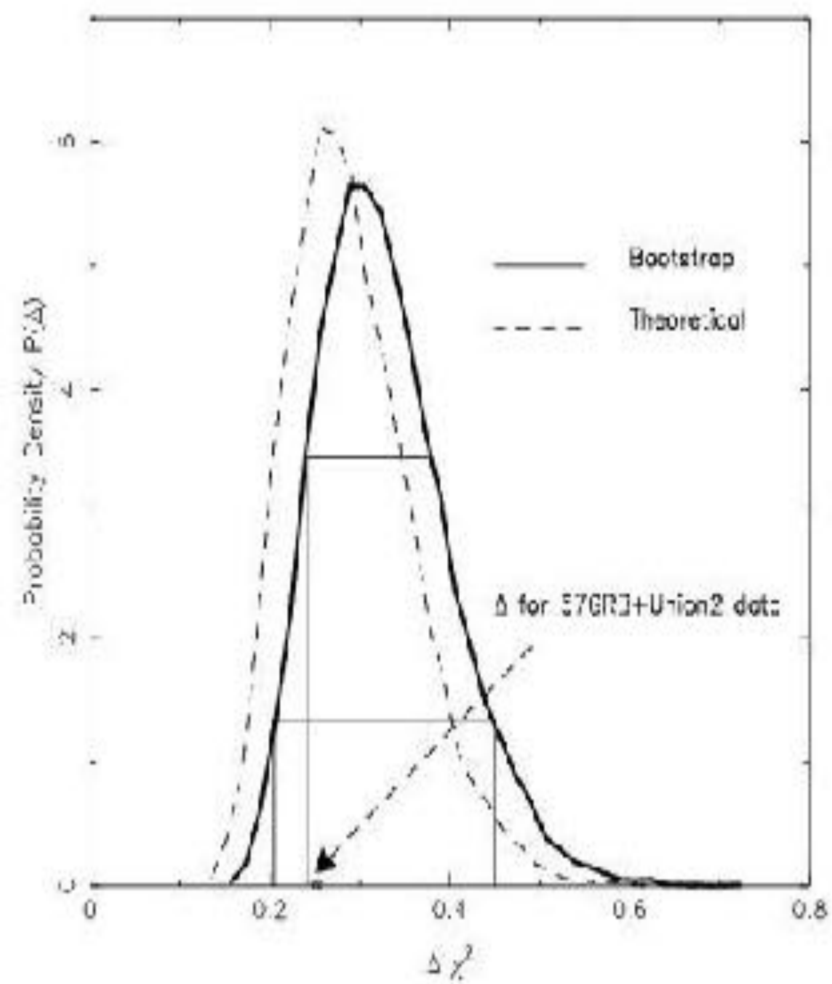




- Very weak signature of non-Gaussianity. (Gupta et al. 2014)
- Union2 data lies ~ 1 σ away from the peak of bootstrap distribution

Results for UNGRB





- Weak signature of non-Gaussianity.
- GRB data lies ~ 1 σ away from the peak of bootstrap distribution

Conclusions

- GRBs shows strong evidence for non-Gaussian features in the errors in the data.
- UNION2 and UNGRB data again shows some evidence for non-Gaussianity although weaker compared to GRBs.
- GRB Data is close to the peak of the bootstrap distribution indicating an isotropic distribution, no effect of shuffling the positions.
- Union2 & UNGRB is different from the peak by about a sigma, indicating a small effect of shuffling the SNe positions.

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THANK
YOU!