The Konus-\textit{Wind} catalog of gamma-ray bursts with known redshifts

I. Bursts detected in the triggered mode

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The talk is based on the paper Tsvetkova, Frederiks, Golenetskii et al., ApJ accepted
Motivation

- ~450 GRBs with reliable $z$ by 2016 June (>200 observed by Konus-Wind);
- Redshift -> distance, age, rest-frame energetics;
- The unbiased comparison between GRBs;
- Possibility to test GRB models;
- GRBs could probe the properties of high-redshift universe:
  - Cosmic expansion
  - Star formation history at high redshifts
  - Reionization history
  - Metal evolution
  - History of cosmic acceleration
  - Evolution of dark energy
Joint Russian-US Konus-\textit{Wind} experiment

- The Konus-Wind (KW) is aimed primarily at GRB and SGR studies;
- Launched on November 1, 1994: almost 23 years of continuous operation;
- Observation statistics (triggers): 2900 – GRBs (Fermi $\sim$1500, BATSE $\sim$2700, Swift $\sim$1150), 260 – SGRs, 1000 – SFs.

**Advantages**

- Wide energy band (20 keV–20 MeV);
- Exceptionally stable background;
- The orbit of s/c excepts interferences from radiation belts and the Earth occultation;
- Continuous observations of all sky;
- Duty circle 95%;
- Observes almost all bright events ($>10^{-6}$erg cm$^{-2}$ s$^{-1}$).

Two modes:

- Waiting mode: G1, G2, G3 @ 2.944 s resolution;
- Triggered mode:
  - LC res. is 2 ms –256 ms, from $T_0$-0.512 s to $T_0$+230 s;

- Two NaI detectors (S1 and S2) are located on opposite faces of spacecraft, observing correspondingly the southern and northern celestial hemispheres;
- $\sim$100-160 cm$^2$ effective area;
- Now in orbit near L$_1$, up to 2.1 million km ($\sim$7 light s) from Earth;
- Light curves (LCs) in three energy windows: G1 ($\sim$20–80 keV, at present), G2 ($\sim$80–300 keV), and G3 ($\sim$300–1200 keV).
The burst sample

- 150 triggered GRBs (1997 Feb to 2016 Jun);
- $0.1 \leq z \leq 5$;
- 12 Type I (the merger-origin, typically short/hard) GRBs;
- 138 Type II (the collapsar-origin, typically long/soft) GRBs;
- 32 GRBs have reasonably-constrained (from optical/IR afterglow or in two spectral band simultaneously) jet breaks times -> collimation.

Svinkin et al. (2016)
Analysis

Durations ($T_{100}, T_{90}, T_{50}$) + spectral lags

Time intervals for spectral analysis were selected based on $T_{100}$ and PCR

Spectral analysis (CPL & Band models)

Observer-frame energetics (in 10 keV – 10 MeV range) + Redshift

Rest-frame energetics + Jet break time

Collimation-corrected energetics
$T_{100}$ is determined at 5σ excess above background. The durations were calculated using the counts in the G2+G3 energy band ($\sim$80–1200 keV at present).
Durations and spectral lags

The observer-frame energy band G2+G3 corresponds to different energy bands in the source-frame thus introducing a variable energy-dependant factor which must be accounted for when analyzing the rest-frame durations and spectral lags.

For the 58 GRBs selected for the spectral lag analysis, the numbers of lags calculated are as follows: $\tau_{\text{lagG2G1}} = 55$, $\tau_{\text{lagG3G1}} = 32$, $\tau_{\text{lagG3G2}} = 38$.

The spectral lag ($\tau_{\text{lag}}$) is a quantitative measure of spectral evolution, when the emission in a soft detector band peaks later or has a longer decay relative to a hard band; a positive $\tau_{\text{lag}}$ corresponds to the delay of the softer emission.
Spectral analysis

- Two types of spectra:
  - Time-integrated (TI) – the interval closest to $T_{100}$;
  - "Peak" – close to the time when the peak count rate (PCR) is reached;

- Two spectral models:
  - CPL:
  - Band function (Band et al., 1993):
    \[
    f(E) \propto E^\alpha \exp \left( -\frac{E(2 + \alpha)}{E_p} \right)
    \]
  - PL model (if both "curved" models result in ill-constrained fits): $f(E) \propto E^\alpha$
  - BEST model: $\chi^2_{\text{CPL}} \cdot \chi^2_{\text{Band}} > 6 \Rightarrow$ the Band function;

- 20 cnts/channel binning to ensure Gaussian-distributed count statistics.

- Band function is the best fit model for 54 TI (51 peak) spectra of Type II bursts;
- CPL is the best fit model for 83 TI (86 peak) spectra of Type II bursts;
- PL is the best fit model for GRB 080413B (both TI & peak spectra);
- All Type I burst spectra are fitted best by the CPL function.
Typical KW spectra

GRB 070125

Xspec spectral fits of the time-integrated (left) and the peak (right) spectra.

Fit model parameters

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Accumulation interval</th>
<th>Model</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$E_p$  (keV)</th>
<th>$F$  $(10^{-6}$ erg cm$^{-2}$ s$^{-1}$)</th>
<th>$\chi^2$/dof</th>
<th>Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best</td>
<td>Time-integrated</td>
<td>GRBM</td>
<td>$-1.10^{+0.08}_{-0.05}$</td>
<td>$-2.09^{+0.06}_{-0.08}$</td>
<td>$372^{+26}_{-31}$</td>
<td>$2.36^{+0.13}_{-0.13}$</td>
<td>88.6/89</td>
<td>0.49</td>
</tr>
<tr>
<td>Peak</td>
<td>34.560–50.432</td>
<td>GRBM</td>
<td>$-0.99^{+0.10}_{-0.09}$</td>
<td>$-2.27^{+0.15}_{-0.27}$</td>
<td>$370^{+57}_{-47}$</td>
<td>$2.50^{+0.24}_{-0.25}$</td>
<td>79.7/88</td>
<td>0.72</td>
</tr>
<tr>
<td>Good</td>
<td>Time-integrated</td>
<td>CPL</td>
<td>$-1.23^{+0.04}_{-0.04}$</td>
<td>--</td>
<td>$518^{+51}_{-35}$</td>
<td>$1.71^{+0.07}_{-0.06}$</td>
<td>118.0/90</td>
<td>0.026</td>
</tr>
<tr>
<td>Peak</td>
<td>34.560–50.432</td>
<td>CPL</td>
<td>$-1.09^{+0.06}_{-0.06}$</td>
<td>--</td>
<td>$455^{+45}_{-37}$</td>
<td>$1.92^{+0.10}_{-0.09}$</td>
<td>86.0/89</td>
<td>0.57</td>
</tr>
</tbody>
</table>
The fraction of the bursts which violate the \(-2/3\) synchrotron line-of-death: 9% (TI sp.) & 21% (peak sp.) of the 68% CL lower limits on \(\alpha\) are shallower. The \(-3/2\) synchrotron cooling limit: 7% (TI sp.) & 3% (peak sp.) of the 68% CL upper limits are steeper.
Peak energies

- $E_p$ for the BEST model varies from $\sim 40$ keV to $\sim 3.5$ MeV (GRB 090510);
- The TI spectrum $E_p$ distributions for both models peak around 250 keV;
- The peak spectrum $E_p$ distributions peak around 300 keV;
- The corresponding rest-frame $E_{p,z} = (1+z)E_p$ vary from $\sim 50$ keV to $\sim 6.7$ MeV (GRB 090510);
- The median $E_p \approx 650$ keV for Type I GRBs.
Observer-frame energetics

10^{-6} \, \text{erg cm}^{-2} < S < 2.9 \times 10^{-3} \, \text{erg cm}^{-2} \text{ (GRB 130427A)}

3 \times 10^{-7} \, \text{erg cm}^{-2}\text{s}^{-1} < F_{\text{peak,64}} < 9.0 \times 10^{-4} \, \text{erg cm}^{-2}\text{s}^{-1} \text{ (GRB 110918A)}
Rest-frame energetics

The most energetic KW burst:
GRB 090323 ($E_{\text{iso}} = 5.81 \times 10^{54}$ erg).
The most luminous burst:
GRB 110918A ($L_{\text{iso}} = 4.65 \times 10^{54}$ erg s$^{-1}$).

e.g. Bloom et al. (2001) or Kovacs et al. (2011)

$$k' = \frac{F[E_1/(1+z), E_2/(1+z)]}{F[e_1, e_2]}$$

$e_1 = 10 \text{ keV}, e_2 = 10 \text{ MeV};$
$E_1 = 1 \text{ keV}, E_2 = (1+z) \cdot 10 \text{ MeV}$
Collimation-corrected rest-frame energetics

32 (2 Type I & 30 Type II) GRBs have reasonably-constrained (from optical/IR afterglow or in two spectral band simultaneously) $t_{\text{jet}}$:
1.9° < $\theta_{\text{jet}}$ < 25.5°
5.5×10^{-4} < 1-\cos \theta_{\text{jet}} < 0.098

The brightest KW GRB in terms of both $E_\gamma$ and $L_\gamma$ is GRB 090926A ($E_\gamma \approx 1.23 \times 10^{52}$ erg, $L_\gamma \approx 5.50 \times 10^{51}$ erg s^{-1}, $\theta_{\text{jet}} \approx 6.20°$)

CBM with constant number density
Sari et al. (1999)

$$\theta_{\text{jet,HM}} = \frac{1}{6} \left( \frac{t_{\text{jet}}}{1 + z} \right)^{3/8} \left( \frac{n \eta}{E_{\text{iso,52}}} \right)^{1/8}$$

Stellar-wind-like CBM
Li & Chevalier (2003)

$$\theta_{\text{jet,WM}} = 0.2016 \left( \frac{t_{\text{jet}}}{1 + z} \right)^{1/4} \left( \frac{\eta \gamma A_\ast}{E_{\text{iso,52}}} \right)^{1/4}$$

$$A_\ast = (\dot{M}_w/(4\pi v_w))/(5 \times 10^{11} \text{ g cm}^{-1})$$

$$n = 1 \text{ cm}^{-3}, \eta_\gamma = 0.2, A_\ast = 1$$
Hardness-duration distribution
Hardness-duration distribution

$z < 1.7$
Hardness-intensity correlations

Amati relation
\[ N=137, \rho_s=0.70 \]
\[ P=1.4\times10^{-21} \]
\[ a = 0.469 \]

Yonetoku relation
\[ N=136, \rho_s=0.73 \]
\[ P=1.6\times10^{-23} \]
\[ a = 0.494 \]
Hardness-intensity correlations

**Amati relation**

\[ N=137, \rho_S=0.70 \]
\[ P=1.4\times10^{-21} \]
\[ a = 0.469 \]

**Yonetoku relation**

\[ N=136, \rho_S=0.73 \]
\[ P=1.6\times10^{-23} \]
\[ a = 0.494 \]
Hardness-intensity correlations

Amati relation
\[ \rho_s = 0.80 \]
\[ P = 7.2 \times 10^{-8} \]
\[ a = 0.561 \]

Ghirlanda relation
\[ N = 30 \]
\[ \rho_s = 0.77 \]
\[ P = 4.5 \times 10^{-7} \]
\[ a = 0.604 \]

Coll.-corrected Yonetoku relation
\[ N = 30 \]
\[ \rho_s = 0.64 \]
\[ P = 9.7 \times 10^{-5} \]
\[ a = 0.729 \]

Yonetoku relation
\[ \rho_s = 0.78 \]
\[ P = 2.9 \times 10^{-7} \]
\[ a = 0.496 \]

☆ GRB 110918A Frederiks et al. (2013)
# Hardness-intensity correlations

Nukers estimate (Tremaine et al. 2002):

\[
\chi^2 = \sum_{i=1}^{N} \frac{(y_i - ax_i - b)^2}{a^2\sigma^2_{xi} + \sigma^2_{yi} + \sigma^2_{\text{int}}}
\]

<table>
<thead>
<tr>
<th>Correlation</th>
<th>$N$</th>
<th>$\rho_S$</th>
<th>$P_{\rho_S}$</th>
<th>$a$</th>
<th>$b$</th>
<th>$a_{\text{int}}$</th>
<th>$b_{\text{int}}$</th>
<th>$\sigma_{\text{int}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type I GRBs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$E_p,i$ vs $S$</td>
<td>12</td>
<td>0.74</td>
<td>$5.8 \times 10^{-3}$</td>
<td>$0.408 \pm 0.043$</td>
<td>$4.98 \pm 0.22$</td>
<td>$0.496 \pm 0.117$</td>
<td>$5.52 \pm 0.62$</td>
<td>0.135</td>
</tr>
<tr>
<td>$E_p,i,2$ vs $E_{\text{iso}}$</td>
<td>12</td>
<td>0.83</td>
<td>$9.5 \times 10^{-4}$</td>
<td>$0.364 \pm 0.030$</td>
<td>$-15.70 \pm 1.53$</td>
<td>$0.266 \pm 0.068$</td>
<td>$-10.61 \pm 3.47$</td>
<td>0.181</td>
</tr>
<tr>
<td>$E_p,p$ vs $F_{\text{peak}}$</td>
<td>12</td>
<td>0.54</td>
<td>$7.1 \times 10^{-2}$</td>
<td>$0.340 \pm 0.045$</td>
<td>$4.39 \pm 0.19$</td>
<td>$0.349 \pm 0.161$</td>
<td>$4.52 \pm 0.74$</td>
<td>0.188</td>
</tr>
<tr>
<td>$E_p,p,2$ vs $L_{\text{iso}}$</td>
<td>12</td>
<td>0.67</td>
<td>$1.7 \times 10^{-2}$</td>
<td>$0.396 \pm 0.034$</td>
<td>$-17.68 \pm 1.78$</td>
<td>$0.243 \pm 0.078$</td>
<td>$-9.61 \pm 4.07$</td>
<td>0.200</td>
</tr>
<tr>
<td><strong>Type II GRBs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_p,i$ vs $S$</td>
<td>137</td>
<td>0.59</td>
<td>$3.7 \times 10^{-14}$</td>
<td>$0.418 \pm 0.002$</td>
<td>$4.06 \pm 0.01$</td>
<td>$0.295 \pm 0.031$</td>
<td>$3.66 \pm 0.14$</td>
<td>0.227</td>
</tr>
<tr>
<td>$E_p,i,2$ vs $E_{\text{iso}}$</td>
<td>137</td>
<td>0.70</td>
<td>$1.4 \times 10^{-21}$</td>
<td>$0.469 \pm 0.003$</td>
<td>$-22.35 \pm 0.14$</td>
<td>$0.338 \pm 0.026$</td>
<td>$-15.27 \pm 1.37$</td>
<td>0.229</td>
</tr>
<tr>
<td>$E_p,p$ vs $F_{\text{peak}}$</td>
<td>136</td>
<td>0.58</td>
<td>$2.2 \times 10^{-13}$</td>
<td>$0.453 \pm 0.004$</td>
<td>$4.68 \pm 0.02$</td>
<td>$0.363 \pm 0.041$</td>
<td>$4.31 \pm 0.21$</td>
<td>0.253</td>
</tr>
<tr>
<td>$E_p,p,2$ vs $L_{\text{iso}}$</td>
<td>136</td>
<td>0.73</td>
<td>$1.6 \times 10^{-23}$</td>
<td>$0.494 \pm 0.005$</td>
<td>$-23.32 \pm 0.26$</td>
<td>$0.347 \pm 0.029$</td>
<td>$-15.52 \pm 1.51$</td>
<td>0.251</td>
</tr>
<tr>
<td><strong>Type II GRBs with $t_{\text{jet}}$ estimates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$E_p,i,2$ vs $E_{\text{iso}}$</td>
<td>30</td>
<td>0.82</td>
<td>$4.1 \times 10^{-08}$</td>
<td>$0.536 \pm 0.004$</td>
<td>$-27.34 \pm 0.21$</td>
<td>$0.418 \pm 0.053$</td>
<td>$-19.62 \pm 2.82$</td>
<td>0.233</td>
</tr>
<tr>
<td>$E_p,i,2$ vs $E_{\gamma}$</td>
<td>30</td>
<td>0.76</td>
<td>$1.1 \times 10^{-06}$</td>
<td>$0.604 \pm 0.008$</td>
<td>$-27.93 \pm 0.42$</td>
<td>$0.499 \pm 0.077$</td>
<td>$-22.69 \pm 3.90$</td>
<td>0.266</td>
</tr>
<tr>
<td>$E_p,p,2$ vs $L_{\text{iso}}$</td>
<td>30</td>
<td>0.75</td>
<td>$1.5 \times 10^{-06}$</td>
<td>$0.529 \pm 0.008$</td>
<td>$-25.12 \pm 0.43$</td>
<td>$0.373 \pm 0.063$</td>
<td>$-16.91 \pm 3.30$</td>
<td>0.282</td>
</tr>
<tr>
<td>$E_p,p,2$ vs $L_{\gamma}$</td>
<td>30</td>
<td>0.61</td>
<td>$3.1 \times 10^{-04}$</td>
<td>$0.731 \pm 0.016$</td>
<td>$-33.87 \pm 0.78$</td>
<td>$0.376 \pm 0.097$</td>
<td>$-16.14 \pm 4.86$</td>
<td>0.343</td>
</tr>
</tbody>
</table>

Note. — $N$ is the number of bursts in the fit sample, $\rho_S$ is the Spearman correlation coefficient, $P_{\rho_S}$ is the corresponding chance probability, $a$ ($a_{\text{int}}$) and $b$ ($b_{\text{int}}$) are the slope and the intercept for the fits without (with) intrinsic scatter $\sigma_{\text{int}}$. 

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Selection effects

\[ S_{\text{lim}} \sim 3 \times 10^{-6} \, \text{erg cm}^{-2} \]

\[ F_{\text{lim}} \sim 1 \times 10^{-6} \, \text{erg cm}^{-2} \, \text{s}^{-1} \]

\[ E_{p,p,z} \sim 25(1+z)^2 \, \text{keV} \]
GRB detection horizon

\[ F_{\text{lim}} = 1 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1} \]

The highest \( z_{\text{max}} \):

**Type I**
\[ z_{\text{max}} \sim 5.3 \text{ for GRB 160410A} \quad (z_0 = 1.72) \]

**Type II**
\[ z_{\text{max}} \sim 16.6 \text{ for GRB 110918A} \quad (z_0 = 0.981) \]

G2: \( \sim 80 \text{ – } 300 \text{ keV} \)

**Trigger threshold:** 9σ

**Trigger time scales** \( \Delta T_{\text{trig}} \): 140 ms or 1 s,

\[ a = \frac{(1+z_0)}{(1+z)} \]

\( PCR_{z_0}(a \Delta T_{\text{trig}}) \) is reached in the observed G2 light curve on the modified time scale

\( N_{G2}(\alpha, \beta, a E_{p,p}) \) is the best spectral model count flux in G2 calculated using the DRM,

\( N_{G2}(\alpha, \beta, a E_{p,p}) \) is the corresponding flux in the redshifted spectrum.
Luminosity and energy release functions

Without loss of generality, the total luminosity function (LF; number of bursts per unit luminosity) $\Phi(L_{\text{ISO}}, z)$ can be rewritten as

$$\Phi(L_{\text{ISO}}, z) = \rho(z)\phi(L_{\text{ISO}}/g(z), \alpha_s)/g(z)$$

Lloyd-Ronning (2002)

- $\rho(z)$ – GRB formation rate (GRBFR)
- $\phi(L_{\text{ISO}}/g(z))$ – local LF
- $g(z) = (1 + z)^\delta$ – luminosity evolution (Lloyd-Ronning 2002)
- $\alpha_s$ – shape of the LF (Yonetoku 2004)

Non-parametric statistical technique: Lynden-Bell (1971)

Efron & Petrosian (1992)

Examples of evolving astrophysical objects:
- Galaxies: the local luminosity function varies for early- and late-type galaxies (Marzke et al. 1994)
- Quasars: $L \sim (1+z)^3$, $z<1.5$ (Boyle 1993; Hewett, Foltz, & Chaffee 1993); $L \sim (1+z)^{1.5}$, $z<3$ (Hewett et al. 1993)
Selection effects and luminosity (energy release) evolution

\[ F_{\text{lim}} = 2 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1} \]

\[ S_{\text{lim}} = 4.3 \times 10^{-6} \text{ erg cm}^{-2} \]

Red circles: Luminosity; Green squares: Energy release.

\[ \delta_L = 1.7 \]

\[ \delta_E = 1.1 \]
The present-time GRB luminosity and energy release functions

\[ L_{\text{iso}} \cdot \tau_0 = 1.7 \quad \delta_L = 1.7^{+0.9}_{-0.9} \quad (1\sigma \ \text{CL}) \]

\[ E_{\text{iso}} \cdot \tau_0 = 1.6 \quad \delta_E = 1.1^{+1.5}_{-0.7} \]

GRBs were brighter in the past

\[ \ln \psi(L'_i) = \sum_{j=2}^{i} \ln \left( 1 + \frac{1}{N'_j} \right) \]

The existence of a sharp cutoff of the isotropic energy distribution of KW and Fermi/GBM GRBs around \( \sim 1-3 \times 10^{54} \) erg was suggested recently by Atteia et al. (2017).
The present-time GRB luminosity and energy release functions

\[ \psi(x) \propto \begin{cases} 
    x^{\alpha_1}, & x \leq x_b \\
    x_b^{(\alpha_1 - \alpha_2)} x^{\alpha_2}, & x > x_b 
\end{cases} \]

\[ \psi(x) \propto x^\alpha \exp\left(-\frac{x}{x_{\text{cut}}}\right) \]

\(\alpha\) – PL index,
\(x_{\text{cut}}\) – cutoff luminosity (or energy).

\(\alpha_1, \alpha_2\) – PL indices at the dim and bright distribution segments,
\(x_b\) – breakpoint of the distribution.

<table>
<thead>
<tr>
<th>Data</th>
<th>Evolution (PL index)</th>
<th>Model</th>
<th>(\chi^2) (d.o.f.)</th>
<th>(\alpha_1)</th>
<th>(\alpha_2)</th>
<th>log (x_b) (log (x_{\text{cut}}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\psi(L'))</td>
<td>(\delta_L=1.7)</td>
<td>BPL</td>
<td>2.05 (133)</td>
<td>(-0.47 \pm 0.06)</td>
<td>(-1.05 \pm 0.11)</td>
<td>0.27 \pm 0.12</td>
</tr>
<tr>
<td>(\psi(L'))</td>
<td>(\delta_L=1.7)</td>
<td>CPL</td>
<td>18.5 (134)</td>
<td>(-0.60 \pm 0.04)</td>
<td></td>
<td>2.10 \pm 0.15</td>
</tr>
<tr>
<td>(\psi(E'))</td>
<td>(\delta_E=1.1)</td>
<td>BPL</td>
<td>19.2 (126)</td>
<td>(-0.36 \pm 0.01)</td>
<td>(-1.28 \pm 0.11)</td>
<td>1.30 \pm 0.04</td>
</tr>
<tr>
<td>(\psi(E'))</td>
<td>(\delta_E=1.1)</td>
<td>CPL</td>
<td>12.7 (127)</td>
<td>(-0.31 \pm 0.02)</td>
<td></td>
<td>2.09 \pm 0.04</td>
</tr>
<tr>
<td>(\psi(L_{\text{iso}}))</td>
<td>no evolution</td>
<td>BPL</td>
<td>2.32 (133)</td>
<td>(-0.47 \pm 0.06)</td>
<td>(-1.00 \pm 0.10)</td>
<td>0.96 \pm 0.15</td>
</tr>
<tr>
<td>(\psi(L_{\text{iso}}))</td>
<td>no evolution</td>
<td>CPL</td>
<td>8.90 (134)</td>
<td>(-0.54 \pm 0.04)</td>
<td></td>
<td>2.58 \pm 0.11</td>
</tr>
<tr>
<td>(\psi(E_{\text{iso}}))</td>
<td>no evolution</td>
<td>BPL</td>
<td>17.2 (126)</td>
<td>(-0.35 \pm 0.01)</td>
<td>(-1.29 \pm 0.12)</td>
<td>1.80 \pm 0.05</td>
</tr>
<tr>
<td>(\psi(E_{\text{iso}}))</td>
<td>no evolution</td>
<td>CPL</td>
<td>15.4 (127)</td>
<td>(-0.32 \pm 0.01)</td>
<td></td>
<td>2.63 \pm 0.04</td>
</tr>
</tbody>
</table>
**GRB formation rate**

The low-z GRBFR excess over SFR is in agreement with the results reported in Yu et al. (2015) and Petrosian et al. (2015).

Cumulative rate evolution:

\[
\ln \psi(z_i) = \sum_{j=2}^{i} \ln \left(1 + \frac{1}{M_j}\right)
\]

Comoving density rate:

\[
\rho(z) = \frac{d\psi}{dz} (1 + z) \left(\frac{dV(z)}{dz}\right)^{-1}
\]

Differential comoving volume:

\[
\frac{dV(z)}{dz} = \frac{4\pi D_H^2 D_M^2}{E(z)}
\]

\(D_M\) is the transverse comoving distance.

Hubble distance: \(D_H = c/H_0\)

Normalized Hubble parameter:

\[
E(z) = \sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda}
\]


\(L_{iso}\): red open circles: no luminosity evolution; red filled circles: \(\delta_L = 1.7\);
\(E_{iso}\): green open squares: no energy evolution; green filled squares: \(\delta_E = 1.1\).
Summary

- A systematic study of 150 GRBs (from 1997 February to 2016 June) with known redshifts (0.1 ≤ z ≤ 5) was performed: 12 Type I (the merger-origin, typically short/hard) GRBs & 138 Type II (the collapsar-origin, typically long/soft) GRBs;

- Temporal analysis: burst durations & spectral lags;

- Spectral analysis with the CPL and Band functions;

- Energetics:
  - Observer-frame $S$ and $F_{\text{peak}}$ (10 keV–10 MeV);
  - Rest-frame $E_{\text{iso}}$ and $L_{\text{iso}}$;
  - Collimation-corrected $E_{\gamma}$ and $L_{\gamma}$ (for 32 GRBs with reasonably-constrained jet breaks).
Summary

- The “Amati” and “Yonetoku” correlations are confirmed for the KW sample;
- The correction for the jet collimation does not improve the “Amati” and “Yonetoku” correlations for the KW sample;
- The influence of instrumental selection: the regions above the limits, corresponding to the bolometric fluence $S_{\text{lim}} \sim 3 \times 10^{-6}$ erg cm$^{-2}$ (in the $E_{\text{iso}} - z$ plane) and bolometric peak energy flux $F_{\text{lim}} \sim 1 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$ (in the $L_{\text{iso}} - z$ plane) may be considered free from the selection biases;
- KW GRB detection horizon: Type I: $z_{\text{max}} = 5.3$, Type II: $z_{\text{max}} \sim 16.6$, stressing the importance of GRBs as probes of the early Universe;
- The GRB luminosity evolution (is present @ $\sim 1.6\sigma$ ), LF and EF, and the evolution of the GRBFR were estimated accounting for the instrumental bias;
- The derived GRBFR features an excess over the SFR at $z < 1$ and nearly traces the SFR at higher redshifts.
Thank you!

The talk is based on the paper Tsvetkova, Frederiks, Golenetskii et al., ApJ accepted

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