Using Gamma-Ray Bursts for Cosmology

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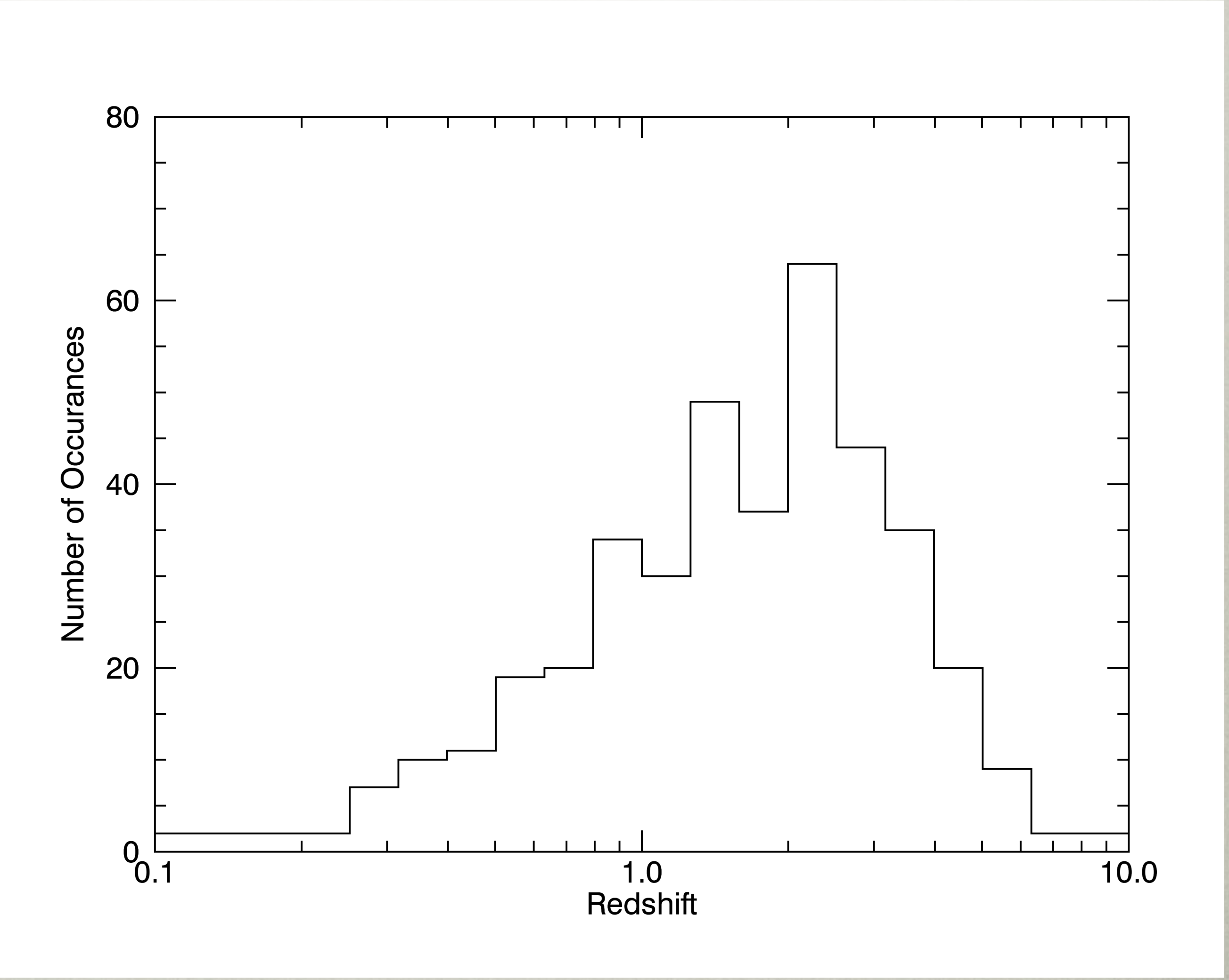
Gamma-Ray Bursts are Cosmological Objects

- Redshifts exist for well-located GRBs only:
  - Require X-ray, optical Afterglow observation
  - Spectroscopy of the host galaxy &/or intervening material
  - Almost certainly selected by brightness
- Current sample (Aug. 2015):
  - ~407; 175 for $z > 2$
  - Includes both short and long
  - Photometric redshift limits not included

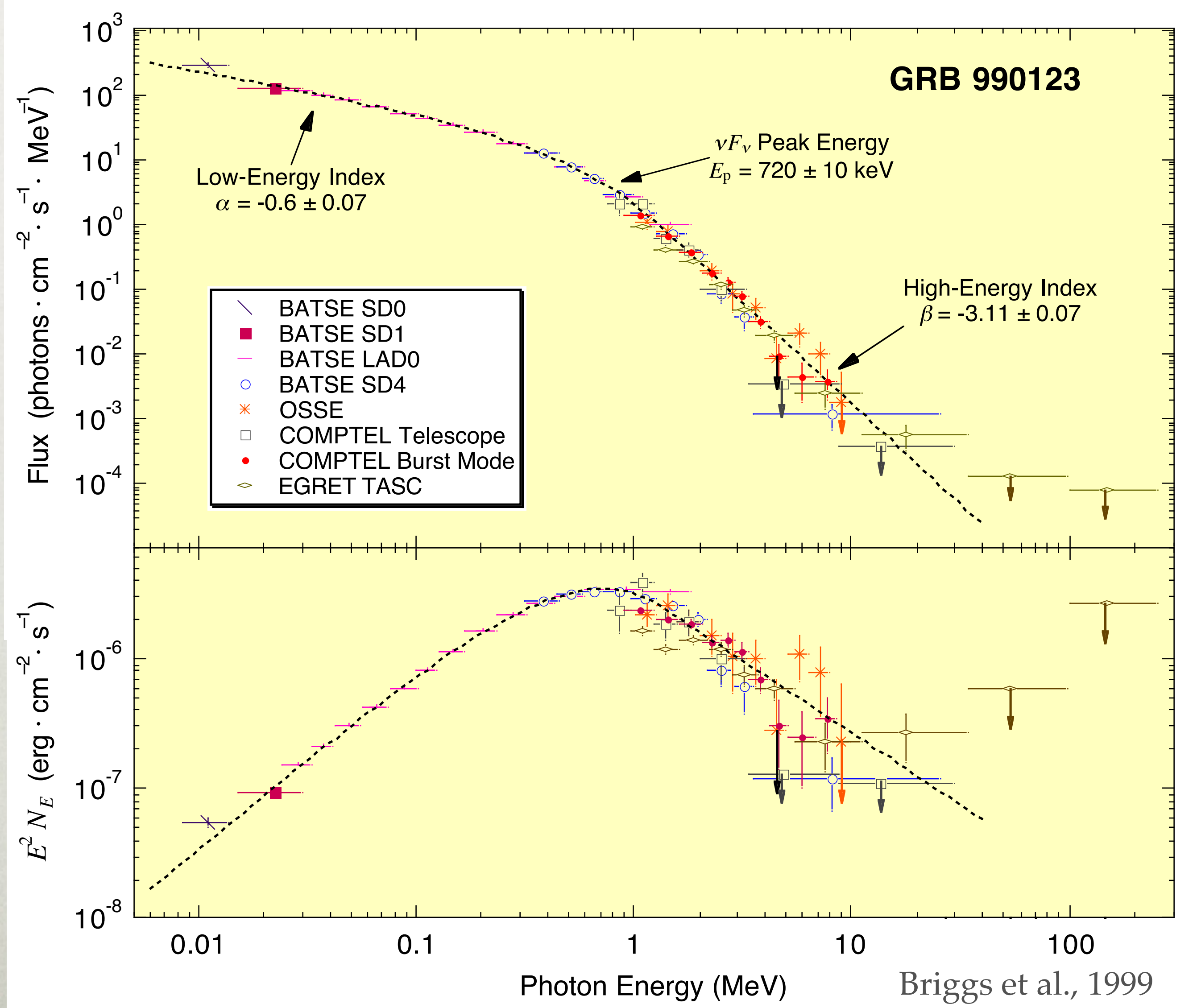


Source: J. Greiner, http://www.mpe.mpg.de/~jcg/grbgen.html

Characteristic Energy of GRB Spectra

E_{peak}: only spectral shape parameter that characterizes relative motion:

- Cosmological redshift ~ 1/(1+z)
- Jet Bulk Lorentz factor ~ Γ



Briggs et al., 1999

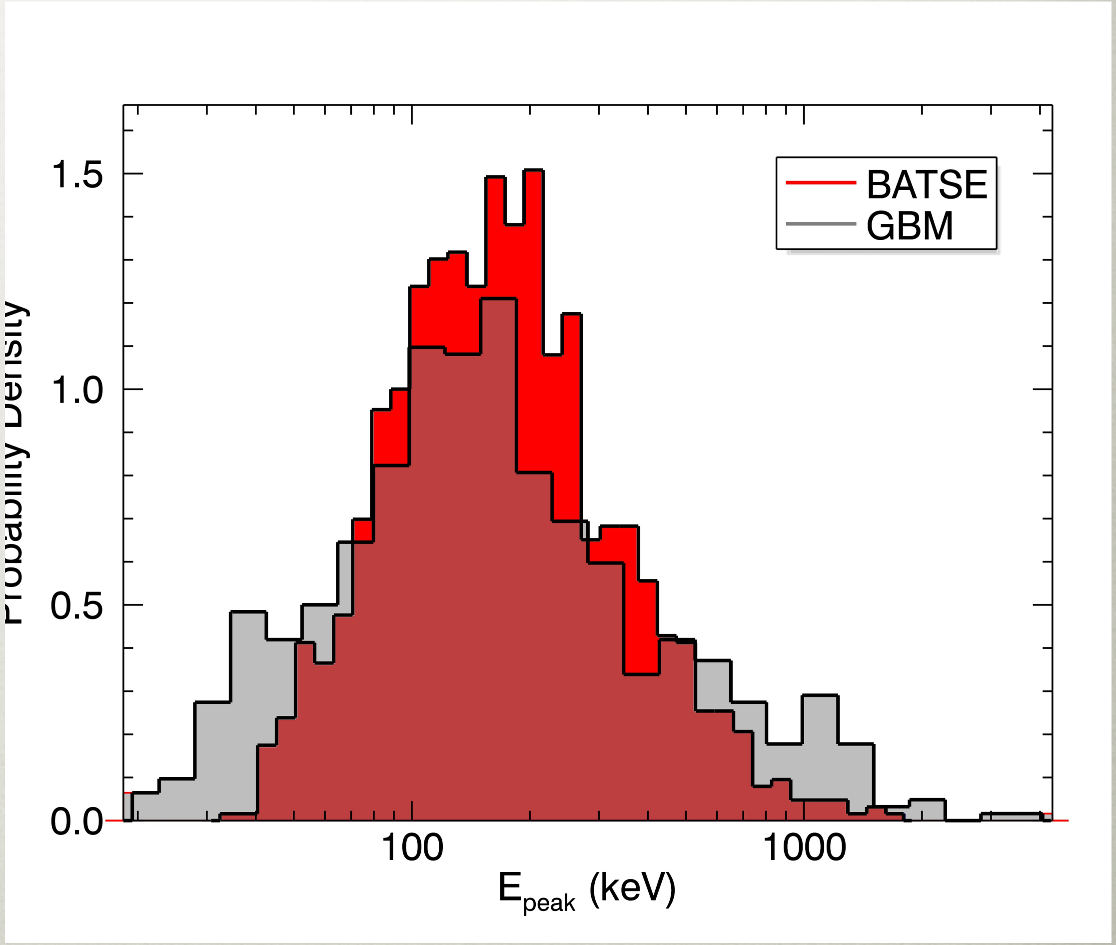
The E_{peak} Distribution is Peaked

Goldstein et al. 2013 (BATSE: 1297) & Gruber et al. 2014 (GBM: 680)

- Time-integrated spectra, but Peak Flux just as well
- High significance

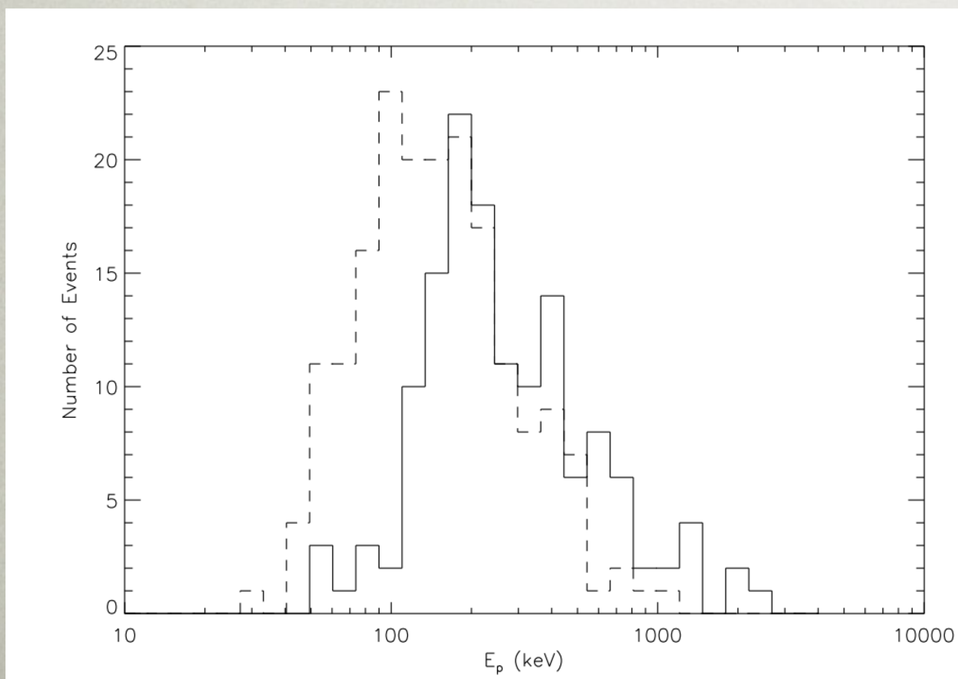
Effect of detector bandwidth:

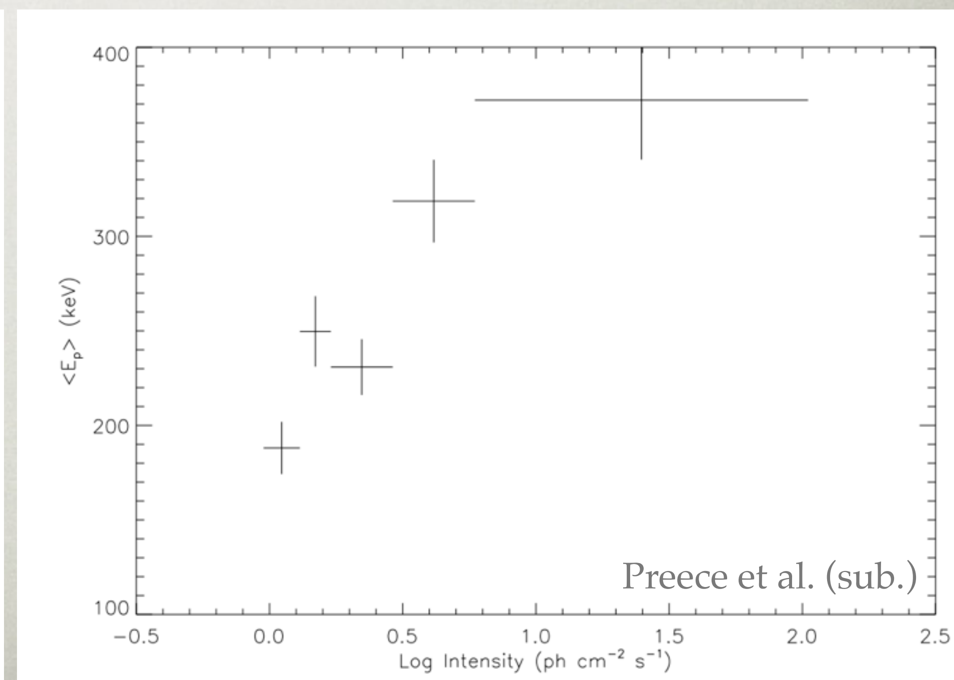
- Width is somewhat greater for GBM, with much larger bandpass
- Still peaked – no 'hidden' higher energy peak



E_{peak} Distribution Changes with Brightness

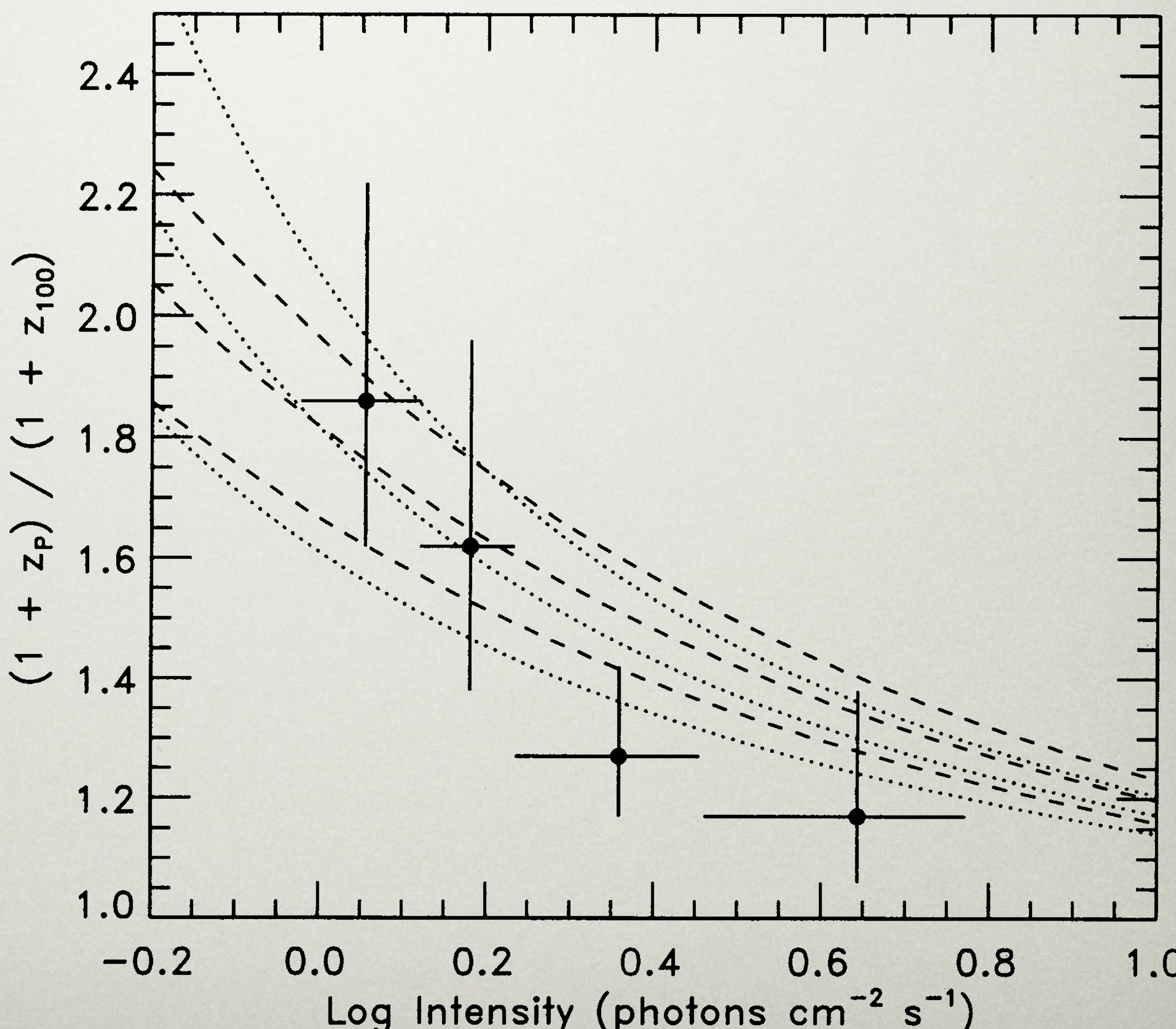
- 1421 Spectral fits with 'good' E_{peak}, binned by Peak Flux into 5 intensity groups
- Mean of each distribution shows trend (plot shows error on the mean)
- Shown to be an intrinsic effect; not a selection effect of dimming
- Verifies previous result (Mallozzi '95) with better statistics:





Shifts are Consistent with Cosmology

- Ranges of z derived from the shifting of the E_{peak} distributions as a function of peak flux:
  - The brightest 20% of bursts have assumed min. redshift z_{100}, chosen for bursts with a flux of 100 photons cm^{-2} s^{-1}.
  - The curves are conventional cosmological models:
    - $\Lambda = 0$ ($q_o = 1$) - *dashed*
    - $\Lambda > 0$ ($q_o = -1$) - *dotted*
    - Models were computed for three values of z_{100}: 0.08 (*lowest*), 0.10, 0.12



Mallozzi et al. '95

GRB Luminosity Relations

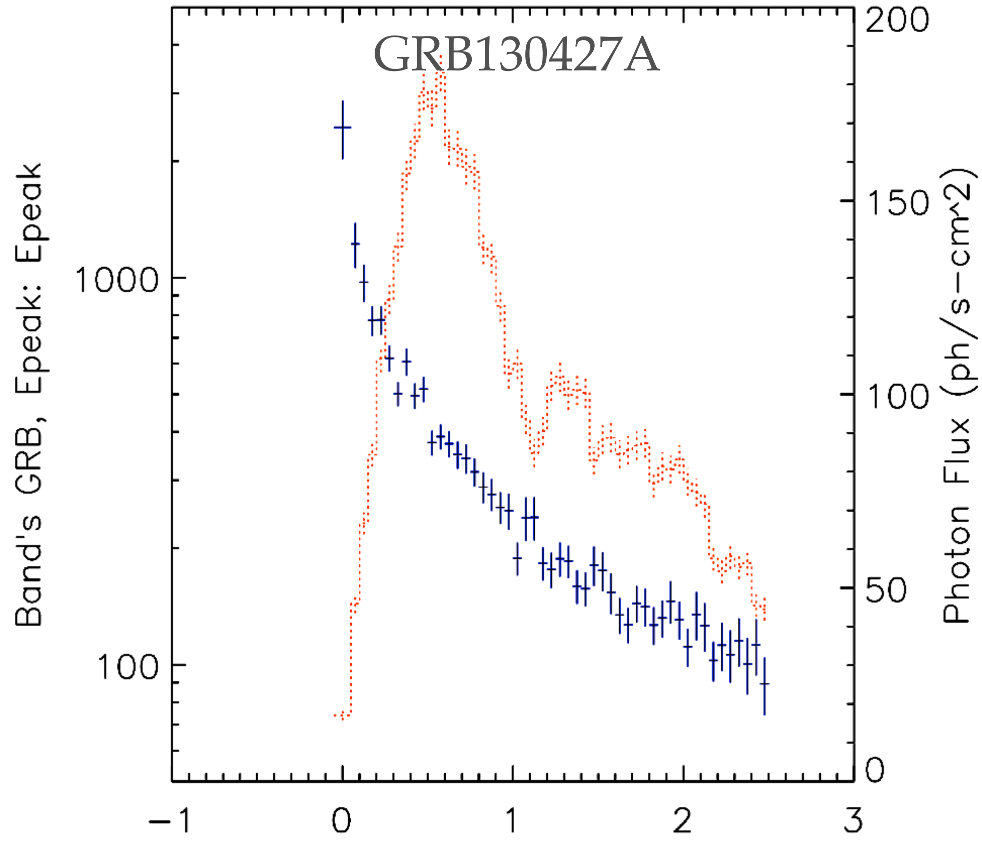
Certain observed properties correlate with the rest-frame energy/luminosity

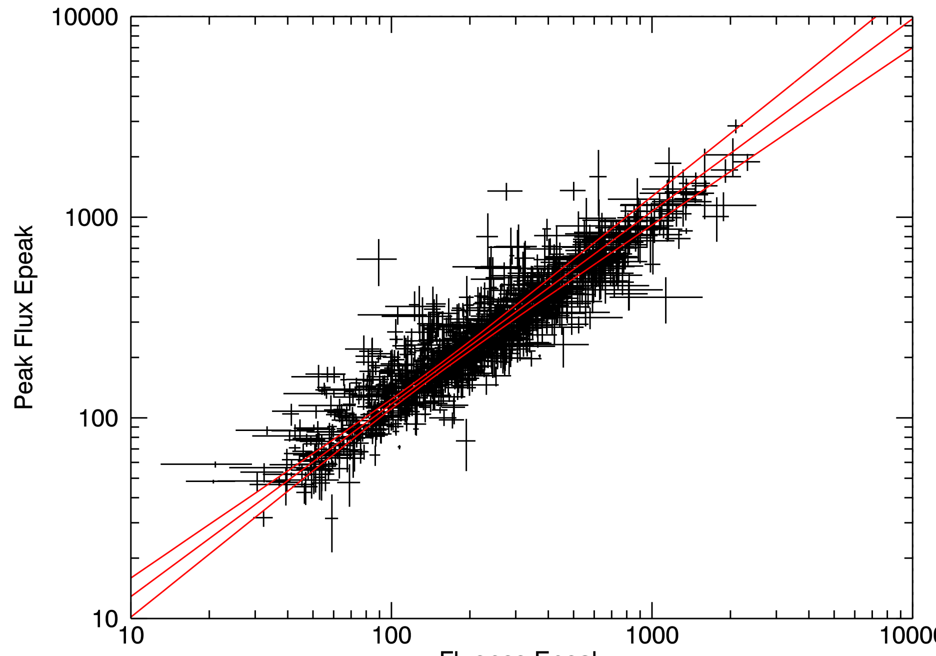
$$\frac{\mathcal{L}_{bol}}{\mathcal{L}_0} = \xi[\mathcal{O}(1+z)^{\lambda}]^{\eta}$$ power law

- Amati Relation (Amati et al. 2002): Peak E_{peak} vs. S_{bol}
- Ghirlanda Relation (Ghirlanda et al. 2004): Fluence E_{peak} vs. $S_{\mathrm{bol}}F_{\mathrm{beam}}$
- Yonetoku Relation (Yonetoku et al. 2004): Peak E_{peak} vs. $L_{\mathrm{peak,iso}}$
- Variability-Luminosity Relation (Fenimore & Ramirez-Ruiz 2000; Reichart et al. 2001); etc.

Which E_{peak}?

- E_{peak} can vary widely w/in a burst
- All of the Luminosity Relations can't be correct, can they?
    - Some depend on E_{peak} from time-averaged spectra, others the peak spectra
        - How independent are these?
        - They are clearly correlated!
- 1188 GRBs from the BATSE Spectroscopy Catalog (Goldstein, 2013)
    - BEST fits were either COMP or BAND
    - 2 s Peak Flux value ~ 1.4 times larger (on average)

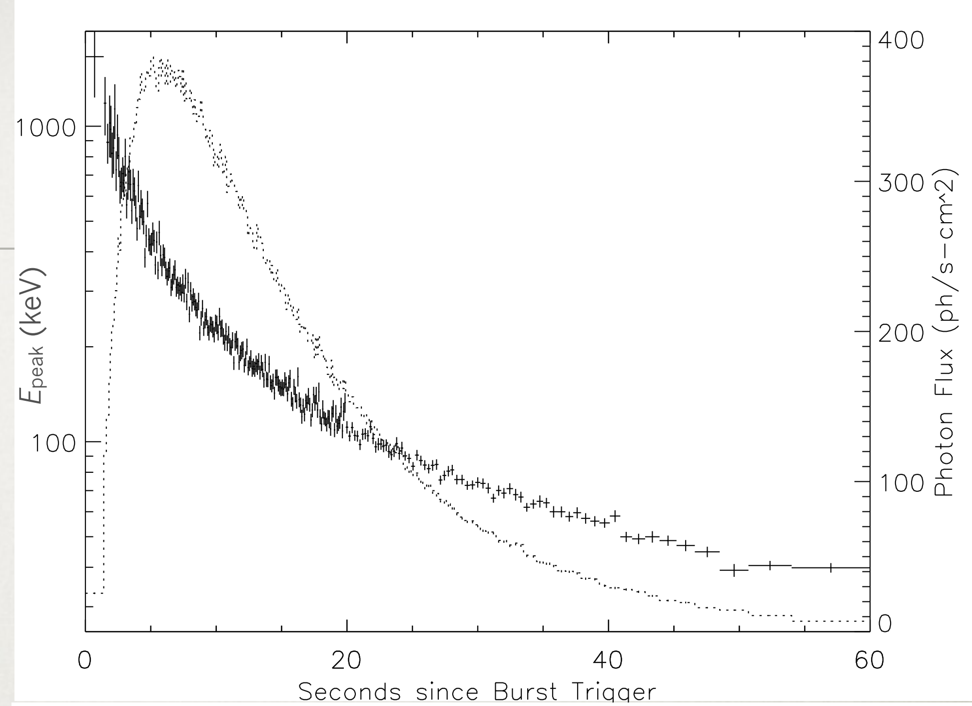


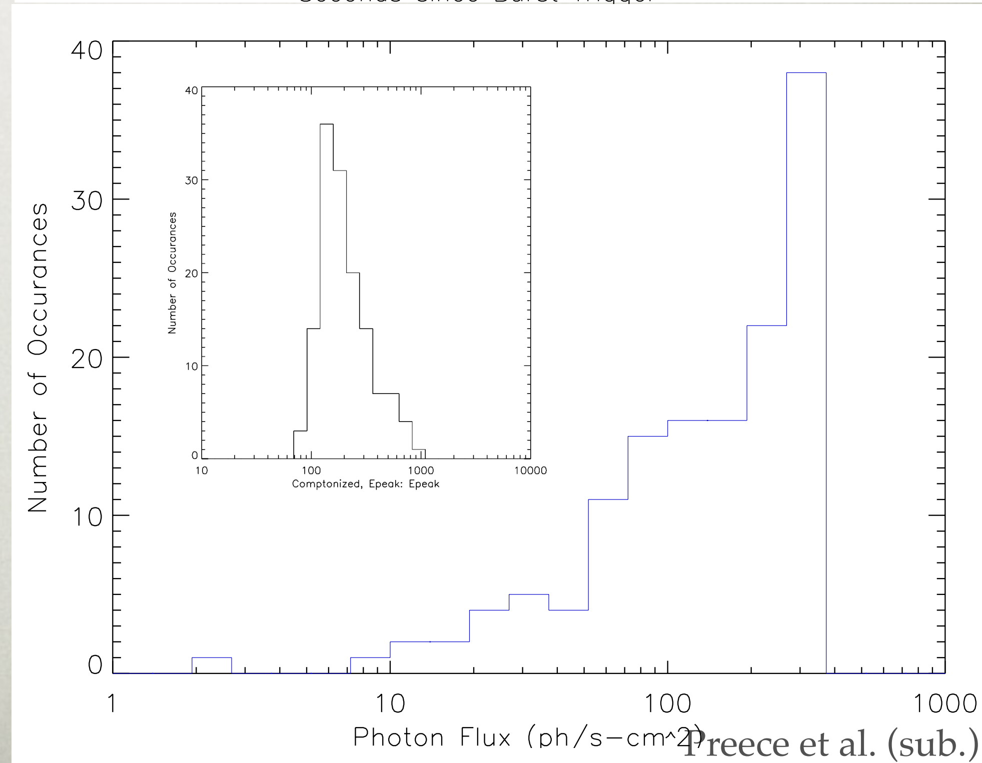


Preece et al. (sub.)

Why are E_{peak}s Correlated?

- We have investigated an impulsively-energized GRB pulse model
    - Simulated pulses with Norris model
    - Power-law Hard-to-Soft Spectral evolution
- Bright pulses are well sampled in time
    - No matter how high the initial E_{peak} may be: internal distribution peaks at mean value
    - Internal Photon Flux dist. weights the average strongest at the peak
    - Result: Peak and Ave. values are correlated!





Preece et al. (sub.)

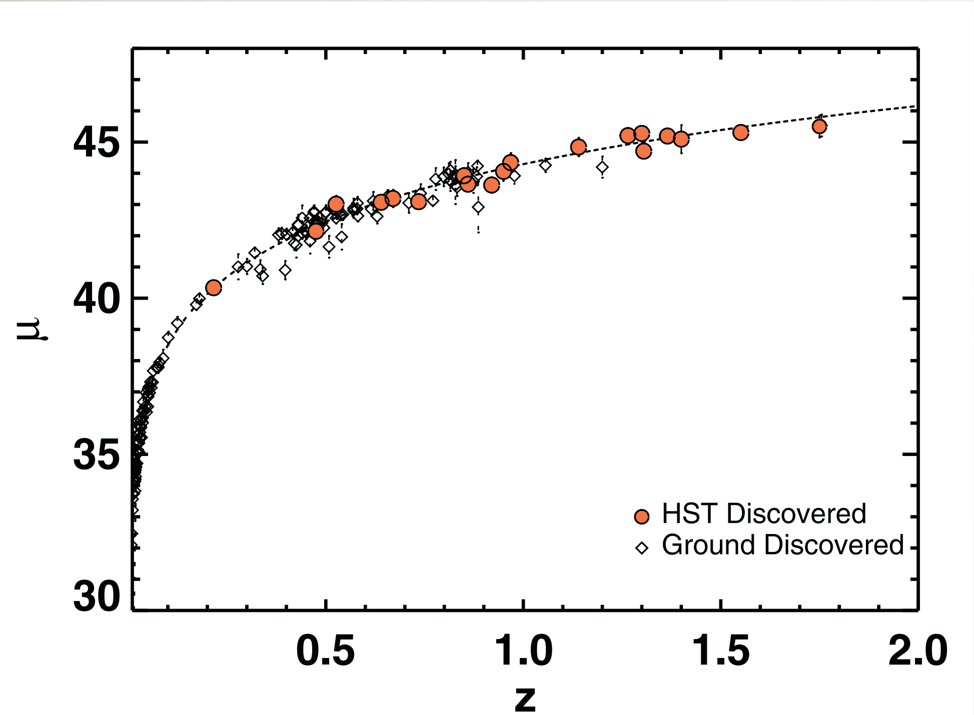
Estimating the Redshift and Distance of GRBs

- Have a calibration sample of GRBs w/ known $z < 1.5$
- Use the sample to calibrate the luminosity relations (Schaefer 2003; Firmani et al. 2006)
- Use multiple luminosity relations to estimate the redshift and distance of GRBs without known redshift (Schaefer and Collazzi 2007)
- The uncertainties arising from marginalizing over Cosmological models must be propagated and will be proportional to the contribution of uncertainty from all luminosity relations combined

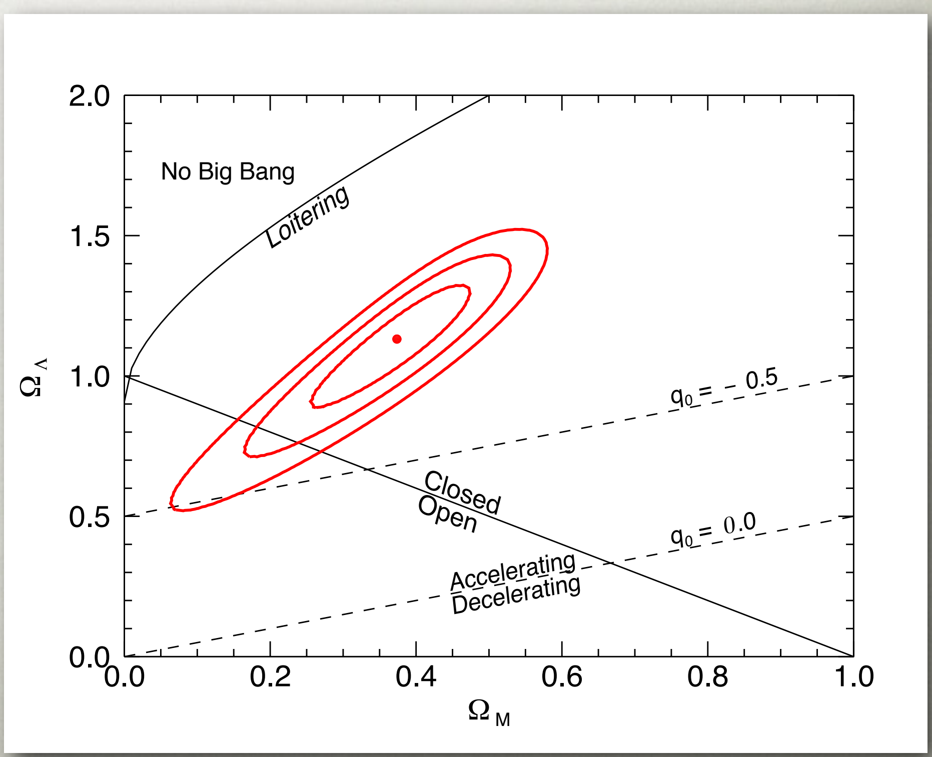
Goldstein (in prep.)

Type Ia Supernovae

Estimates on the evolution of dark energy out to $z \sim 1.5$



$$w(z) = -1.31 + 1.48z$$

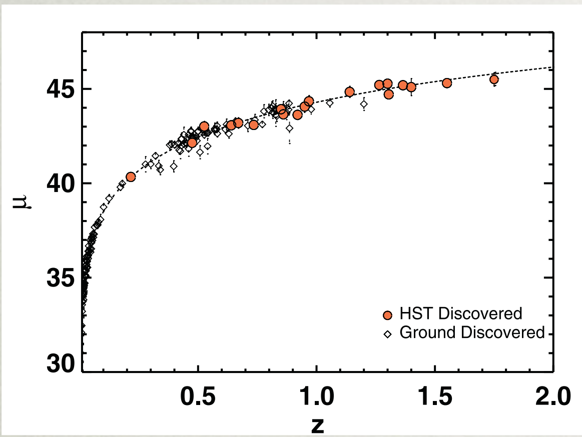


Press & Kirshner 2005

Riess et al. 2004

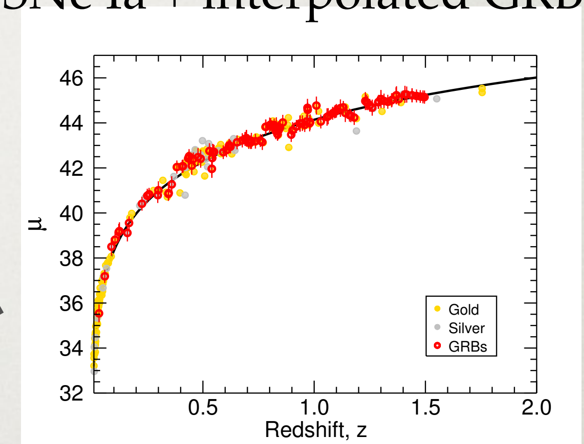
Estimating GRB Redshift and Distance

SNe Ia

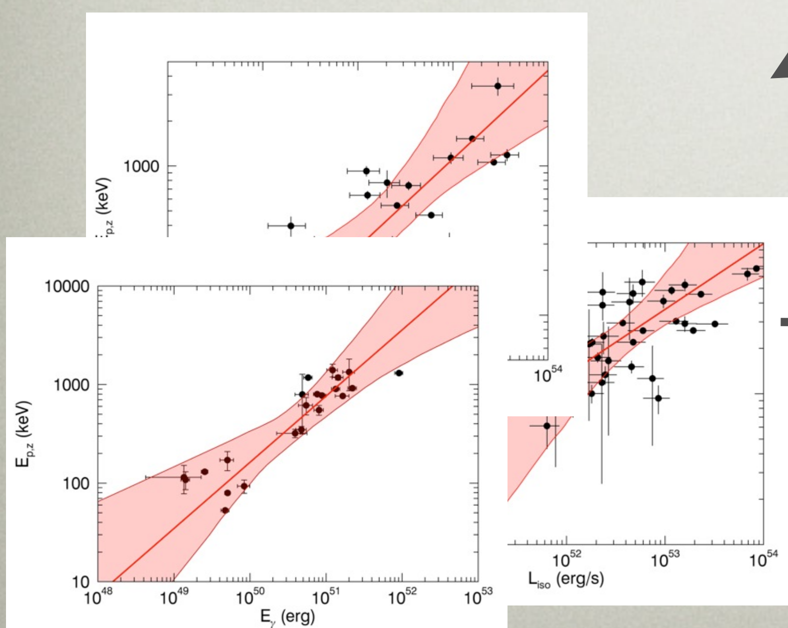


Interpolate z < 1.5 to find d_L

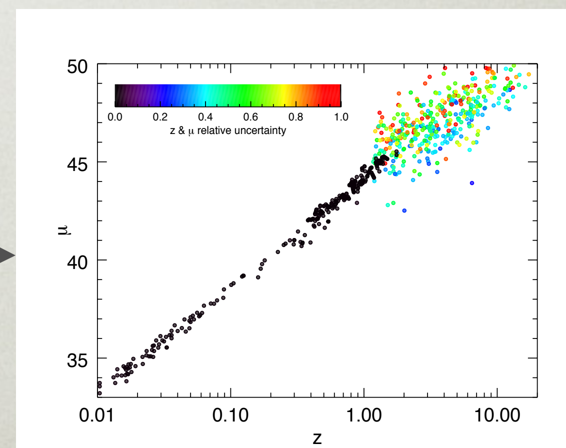
SNe Ia + interpolated GRBs



Use z < 1.5 to calibrate



Use correlations to find z > 1.5 and d_L

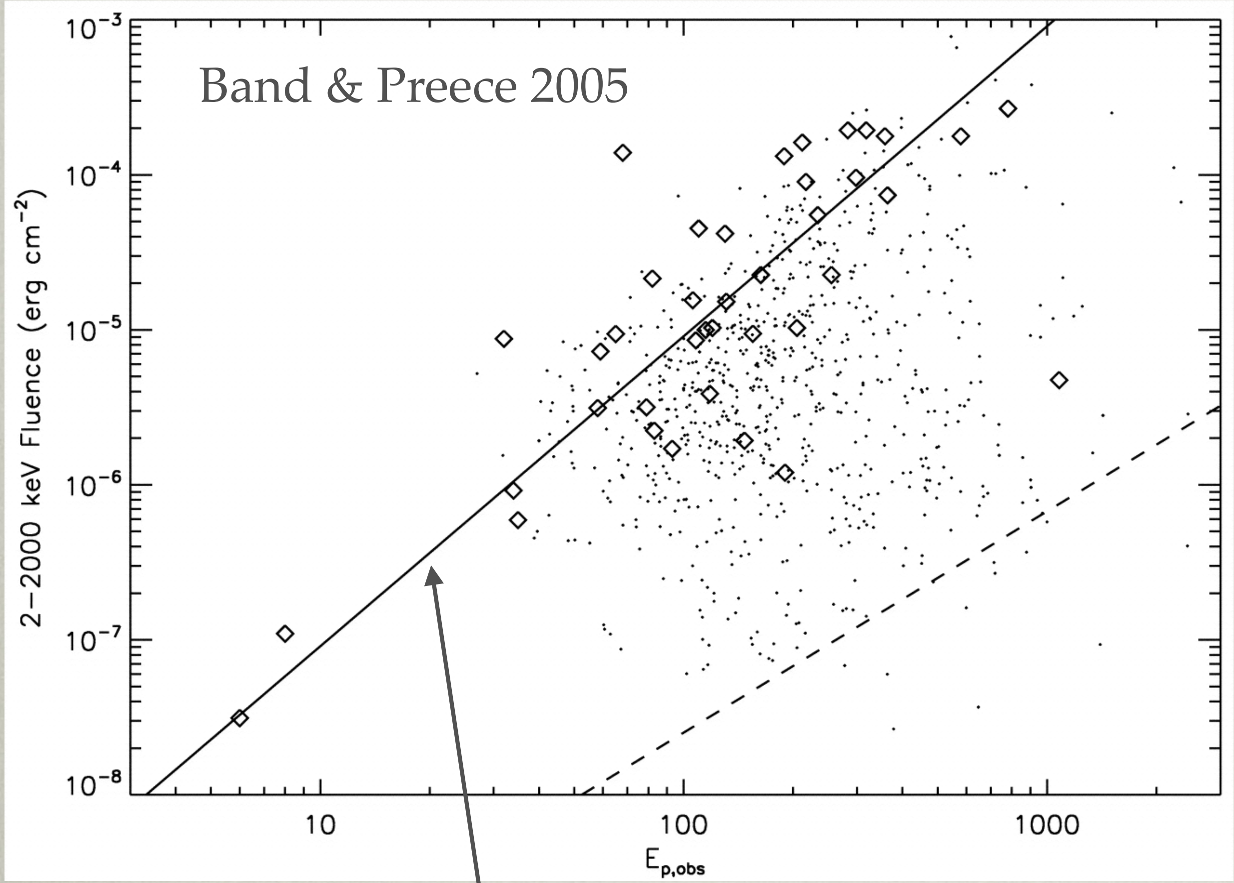


Goldstein (in prep.)

Conclusions

- GRBs are Cosmological objects w/ high redshifts
- There is an intrinsic correlation between the observed E_{peak} and intensity with hints of Cosmology
- There is an observed correlation between Peak and Fluence spectra derived E_{peak}
- Various GRB Luminosity Relations purport to determine redshifts from observables
  - Some may be dominated by selection effects
  - Determination of Cosmological parameters directly using these is circular
  - Must be calibrated using GRBs w/ known redshifts
- Construction of non-circular GRB Hubble Diagram is on-going

AMATI ET AL. (2002) RELATION



$$E_p = C_1 \left(\frac{E_{\rm iso}}{10^{52} \text{ ergs}} \right)^{\eta_1}$$

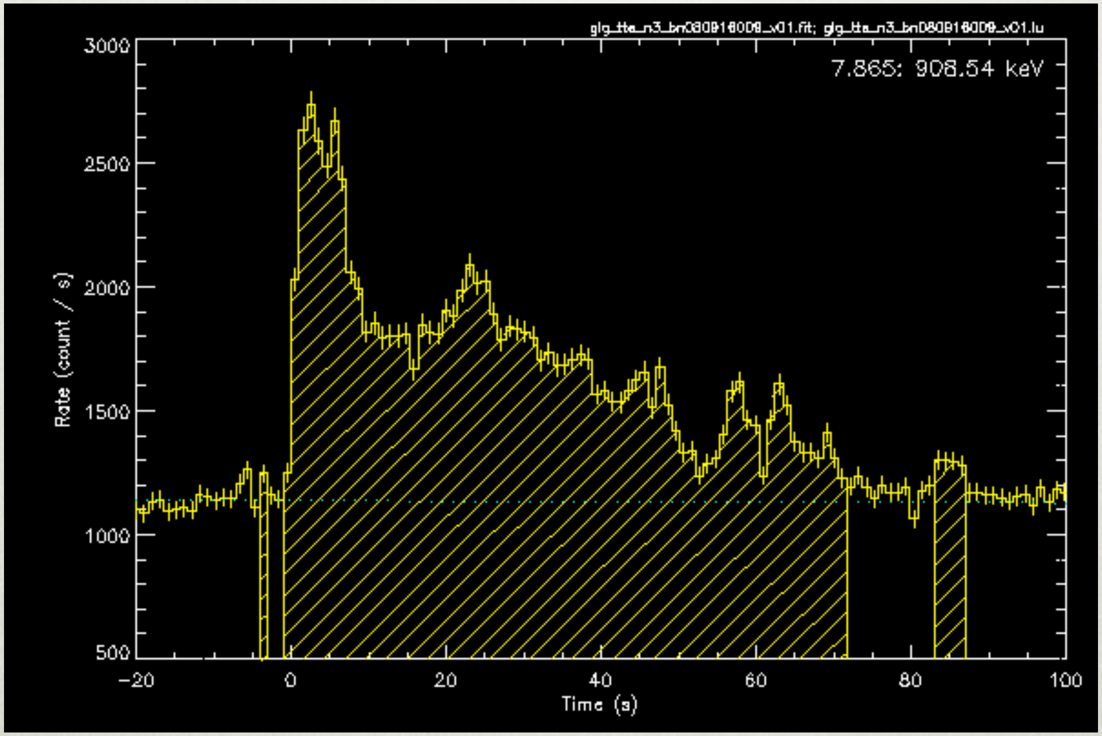
$$\xi_1 = \frac{E^2_{p,\rm obs}}{S_\gamma} = \frac{4\pi d_L^2 C_1^2}{(10^{52} \text{ ergs})(1+z)^3} = A_1(z)$$

- BATSE (all bursts - dots) and Friedman & Bloom (2005; diamonds - known redshifts)
- Invert relation to find redshift (assumes the Cosmology is known!)
- Suffers from possible selection effects

All bursts should lie *above* the solid line!

Ghirlanda Relation

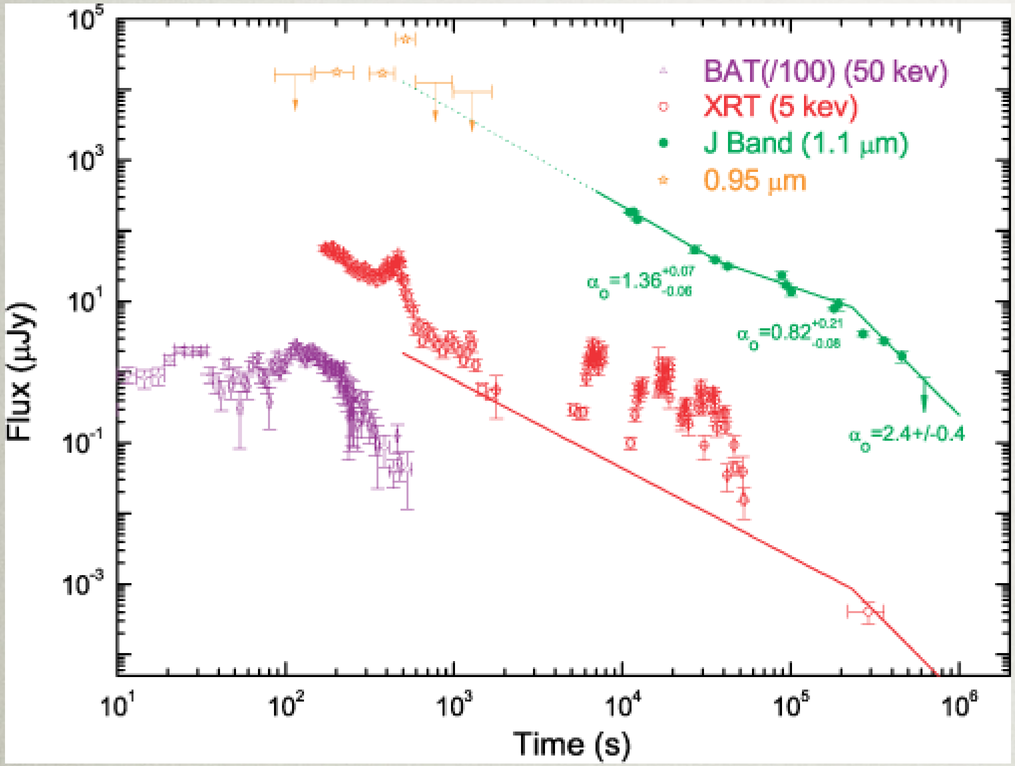
Time-integrated Epeak

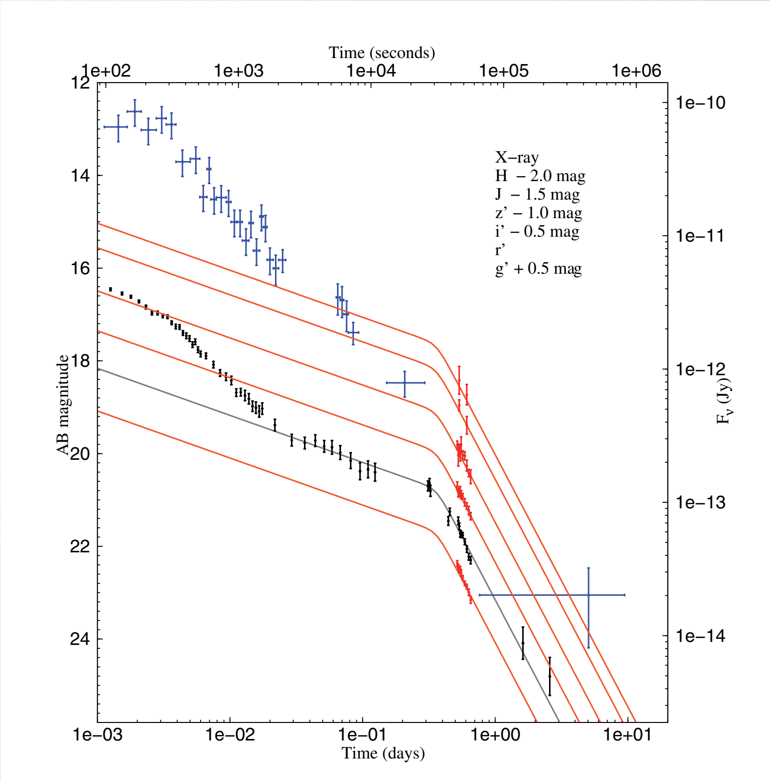


Collimation-corrected Energy

$$E_\gamma = \frac{4\pi F_\gamma d_L^2 f_B k}{1+z} \qquad f_B = 1 - \cos\theta_j$$

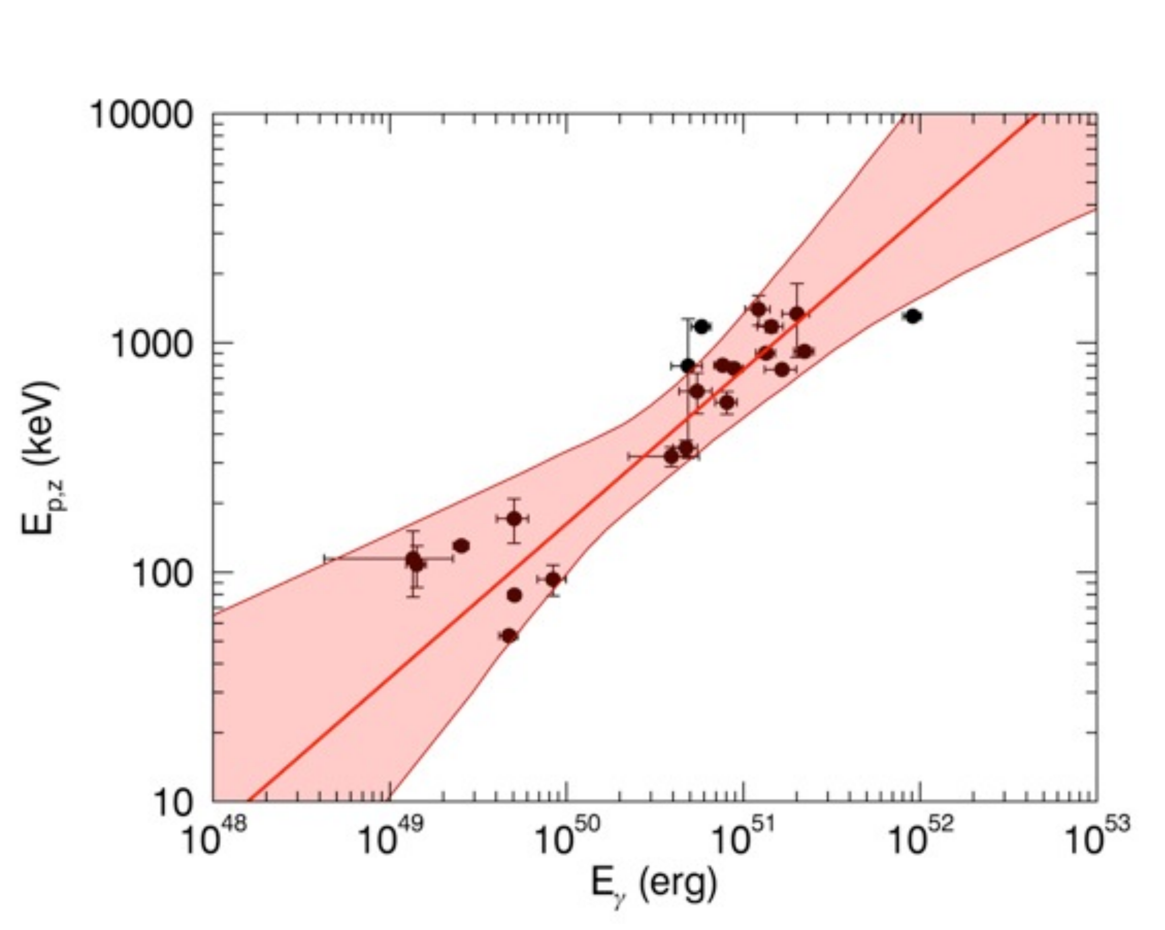
Jet Break - Jet Angle





$$\theta_j \approx 0.057 \left(\frac{t_j}{1\ \mathrm{day}}\right)^{3/8} \left(\frac{1+z}{2}\right)^{-3/8} \left(\frac{E_{iso}}{10^{53}\ \mathrm{erg}}\right)^{-1/8} \left(\frac{\epsilon}{0.2}\right)^{1/8} \left(\frac{n_p}{0.1\ \mathrm{cm}^{-3}}\right)^{1/8}$$

Ghirlanda Relation



Consequence of viewing geometry and relativistic effects within standard jet model

$$\Delta = \theta_j - \theta_v$$

$$E_\gamma \propto \Gamma_{jet}^{-3} \Delta^{-4}$$

$$E'_{peak} \propto E_{peak} \Gamma_{jet}^{-1} \Delta^{-2}$$