Evidence for X-ray lines in Gamma-Ray Burst Afterglows

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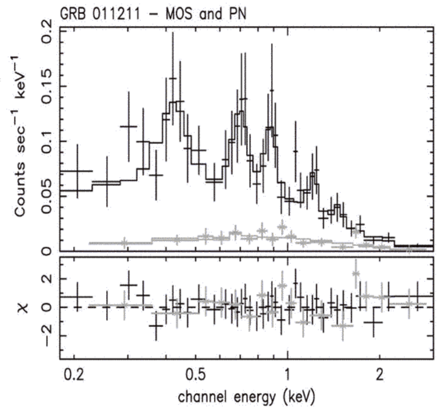

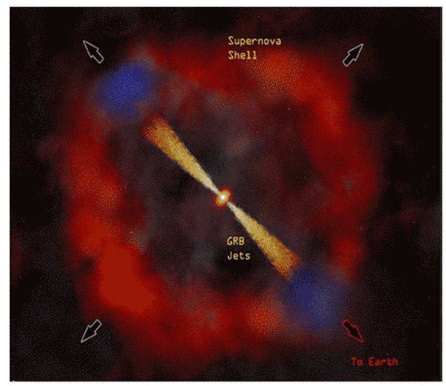

With Contributions from:-

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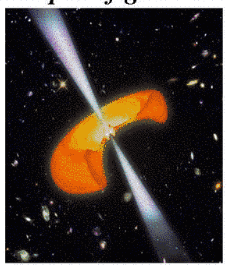
Overview of talk

- **XMM-Newton spectra of Gamma-ray burst afterglows**
- **the signature of Supernova ejecta in GRB 011211 and evidence for soft X-ray lines in afterglows.**
- **Statistical significance debate in GRB 011211**
- **X-ray absorption in afterglow spectra is common (Swift, XMM-Newton)**
- **no strong Fe K line observed in XMM-Newton or Swift spectra**
- **Soft/thermal spectra in some Swift early-time flares?**

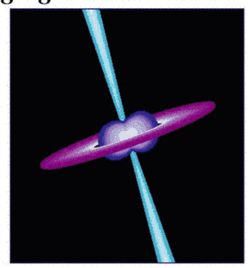
Two Possible Models for the Progenitor

- High energy (high mass), compact objects $\Rightarrow$ two leading models

collapse of giant star



merging neutron star binary



Long γ-ray bursts (10-100s)?

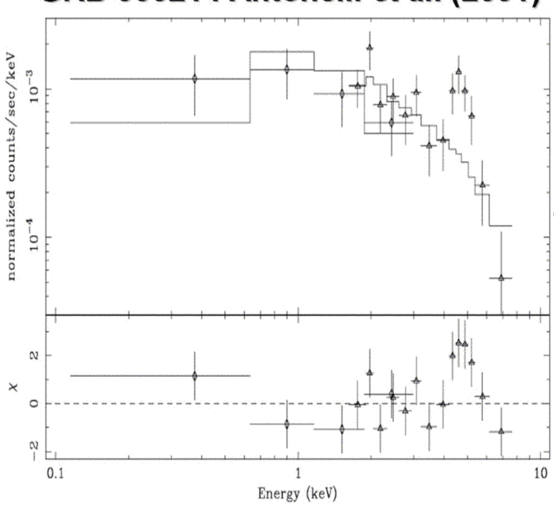
Short γ-ray bursts (<1 s)?

- Both models are energetically plausible (releasing 10^{51} - 10^{54} erg, isotropic)
- Collaspar (Supernova/Hypernova) progenitors are favored for long bursts
- Origins of short Gamma-ray bursts may be NS-NS or NS-BH mergers
- Evidence for Supernova comes from X-ray emission lines, optical re-brightening and (most recently) direct spectroscopy (030329, 031203).

Initial X-ray afterglow observations detected iron lines

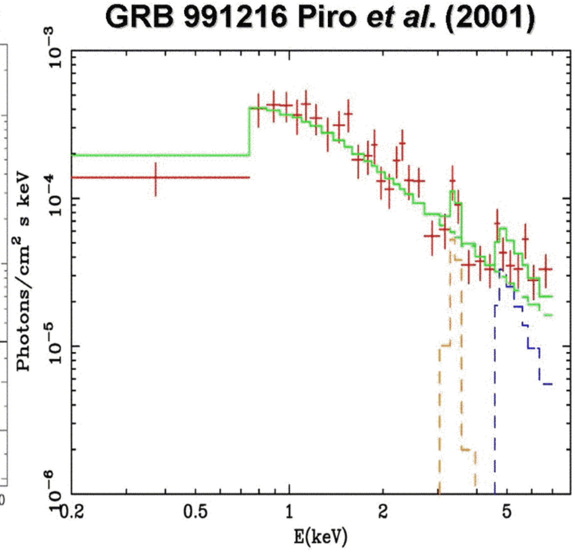
Beppo-SAX

GRB 000214 Antonelli *et al.* (2001)



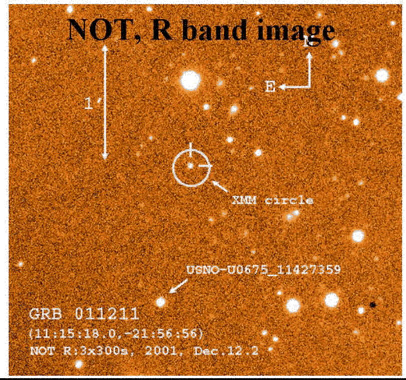
Chandra-ACIS

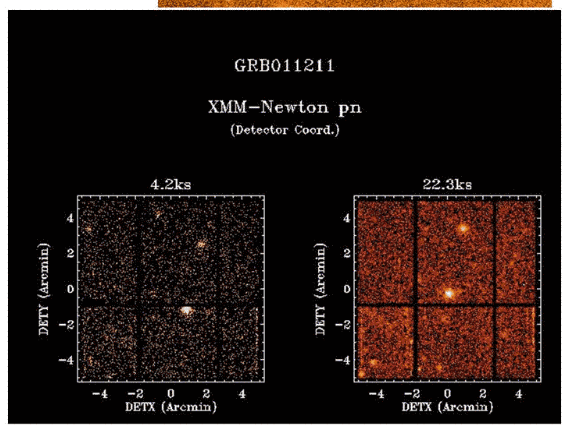
GRB 991216 Piro *et al.* (2001)

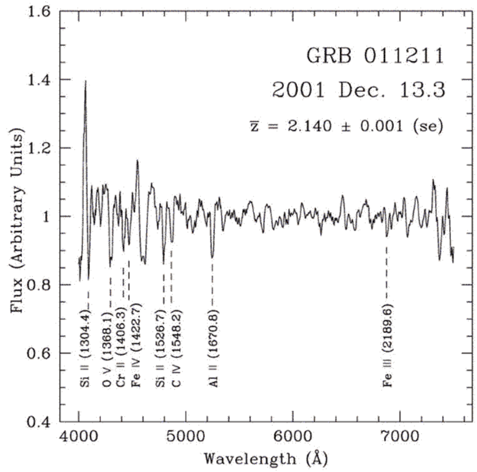


Fe Line observed by Beppo-Sax 12 hours after burst. Indicates Fe rich progenitor or Fe rich environment. However later analysis (Sako et al. 2005), show early claims of Fe lines may not be statistically significant in GRB afterglows

GRB 011211; discovery of X-ray and Optical afterglows





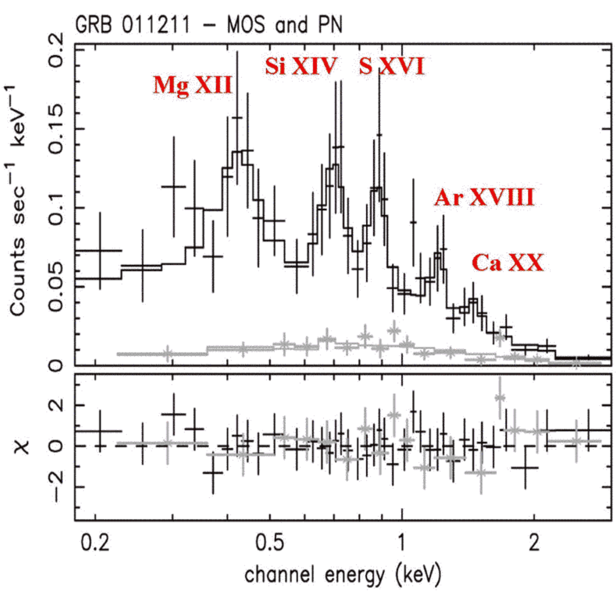


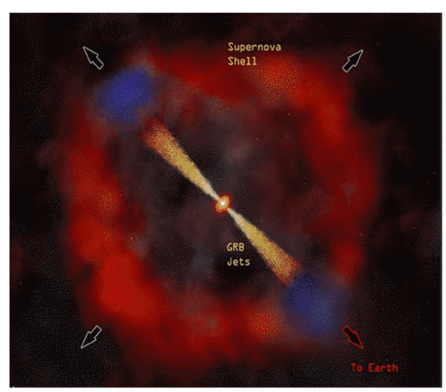
GRB 011211 host galaxy at z=2.14 (Holland et al. 2002)

The signature of Supernova ejecta in GRB 011211

Reeves et al (2002): Nature 416, 512

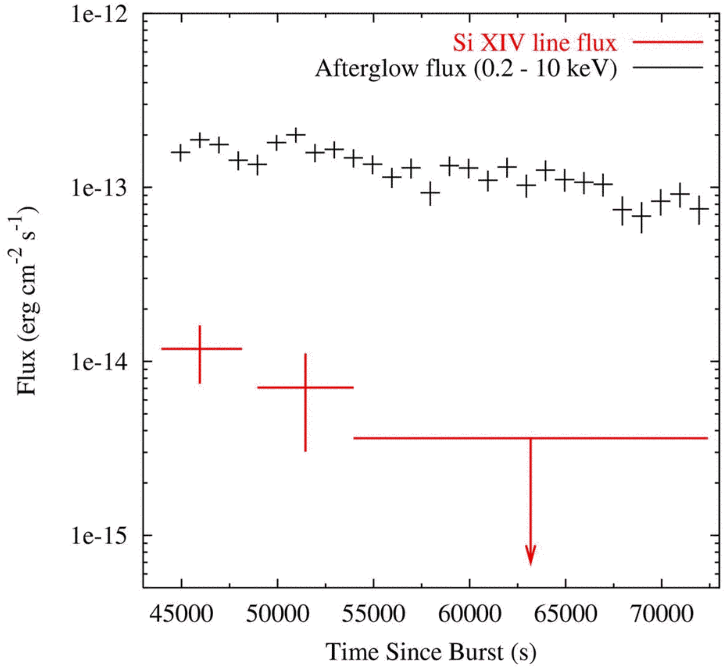
Decaying **X-ray lines from Mg, Si, S, Ar and Ca are detected after 11 hours.** *No iron line detected*. **Outflow velocity of line emitting matter 0.1c**





Lines may originate from an expanding shell of enriched gas originating from the GRB progenitor (also see Butler et al. 2003; GRB 020813)

XMM-Newton Variability of GRB 011211



Line emission is ***short lived*** (in first 10 ks of observation flux). Thermal emission favoured for lines.

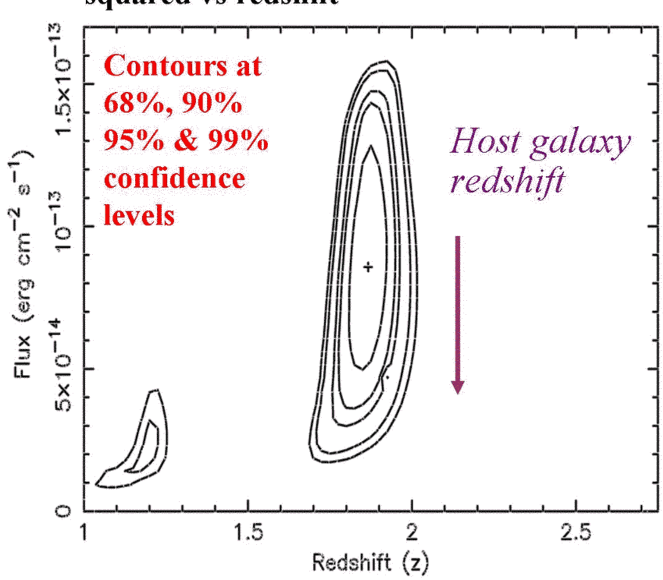
Line flux decreases *faster* than continuum

Short timescale - ***line emitting material resides close to burst origin (R<10^{15} cm)***

Duration between SN and burst is short **(or simultaneous) - <u>hence no iron line is detected</u>**

Determination of outflow velocity

Thermal line emission model fits - chi squared vs redshift

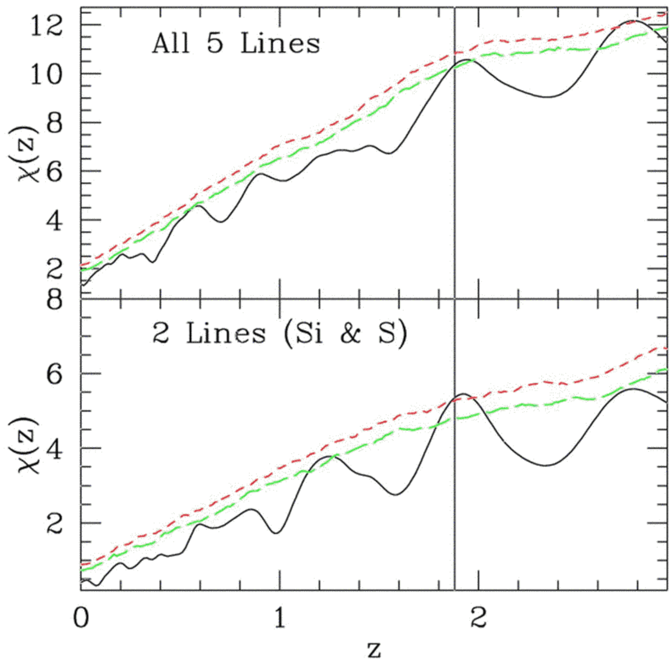


X-ray lines are observed at an apparent redshift of **z=1.88±0.06**, compared to the GRB host redshift of **z=2.140±0.001**

Thus the X-ray lines are "***blueshifted***" relative to the known redshift of GRB 011211.

The outflow velocity is then 0.086±0.004 c or 26000 km s^{-1}. Outflowing ejecta mass > solar mass

Rutledge & Sako (2003) - "Statistical significance overstated"



Significance vs redshift

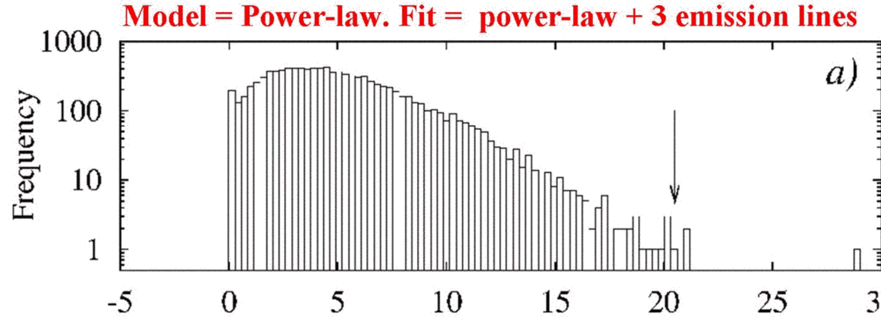
black: summed convolution of data with line set response.

broken lines: MC single trial limits for featureless spectra
green: 99%
red: 99.9%

Blind z search confidence: 97.4-98.8% (2 lines)

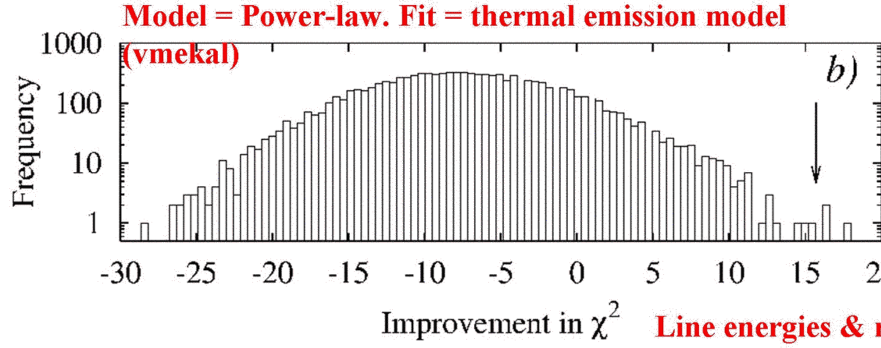
Estimation of statistical significance – Monte Carlo Simulations

Model = Power-law. Fit = power-law + 3 emission lines



10,000 MC simulations & spectral fits in each case

Model = Power-law. Fit = thermal emission model (vmekal)

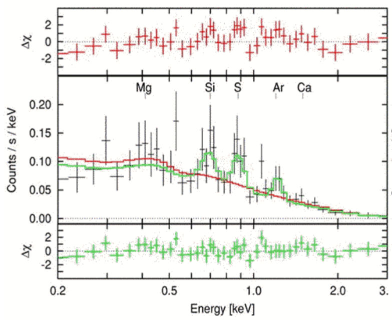


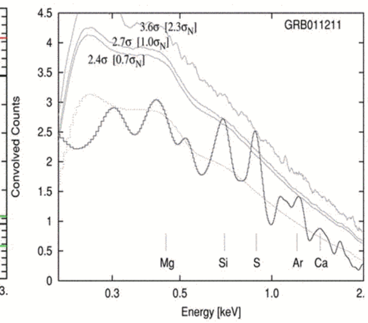
Frac. with observed fit improvement = 0.03% in each case (3.6 σ)

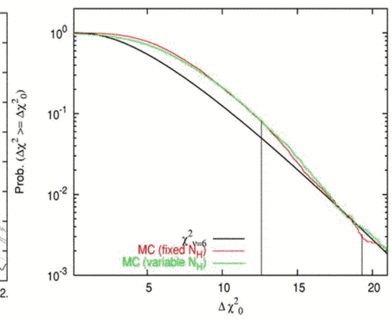
Line energies & redshift free in fits, N_H = Galactic

Reeves et al. (2003)

Independent Analysis of 011211 (Butler et al. 2005)







LRT(F-test) method

Reeves et al. (2003) find a 3σ detection for 3 lines (Si, S, Ar). Also found in Butler et al. (2005) analysis, but only 1.9σ if N_H> N_H(Galactic).

Matched Filter (RS03)

RS (2003) find only a 1.6σ detection, while Butler et al. find 1.3σ with this method. If N_H=N_H(Galactic) then 3σ found by Butler et al.

$\Delta\chi^2$ MonteCarlo

(Reeves et al. 2002, 2003)

Reeves et al. (2003) find a 3.6σ detection for 3 lines. Butler et al. also find a 3σ detection of lines for N_H=N_H(Galactic), but 1.8σ for N_H>N_H(Galactic).

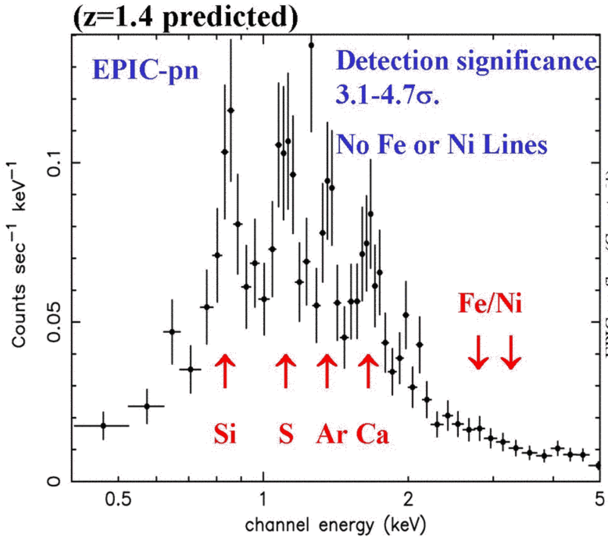
3 estimates from different authors appear to converge on 3σ significance for the 011211 lines. Crucial asssumption is whether N_H=N_H(Galactic), from mean XMM/SAX spectrum.

GRB 030227 - detection of transient Si, S, Ar, Ca

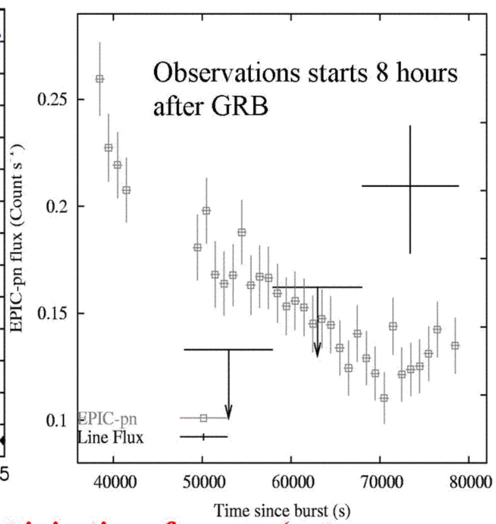
(Watson et al. 2003, ApJ 595, L29)

Lines appear in the last 10ks only

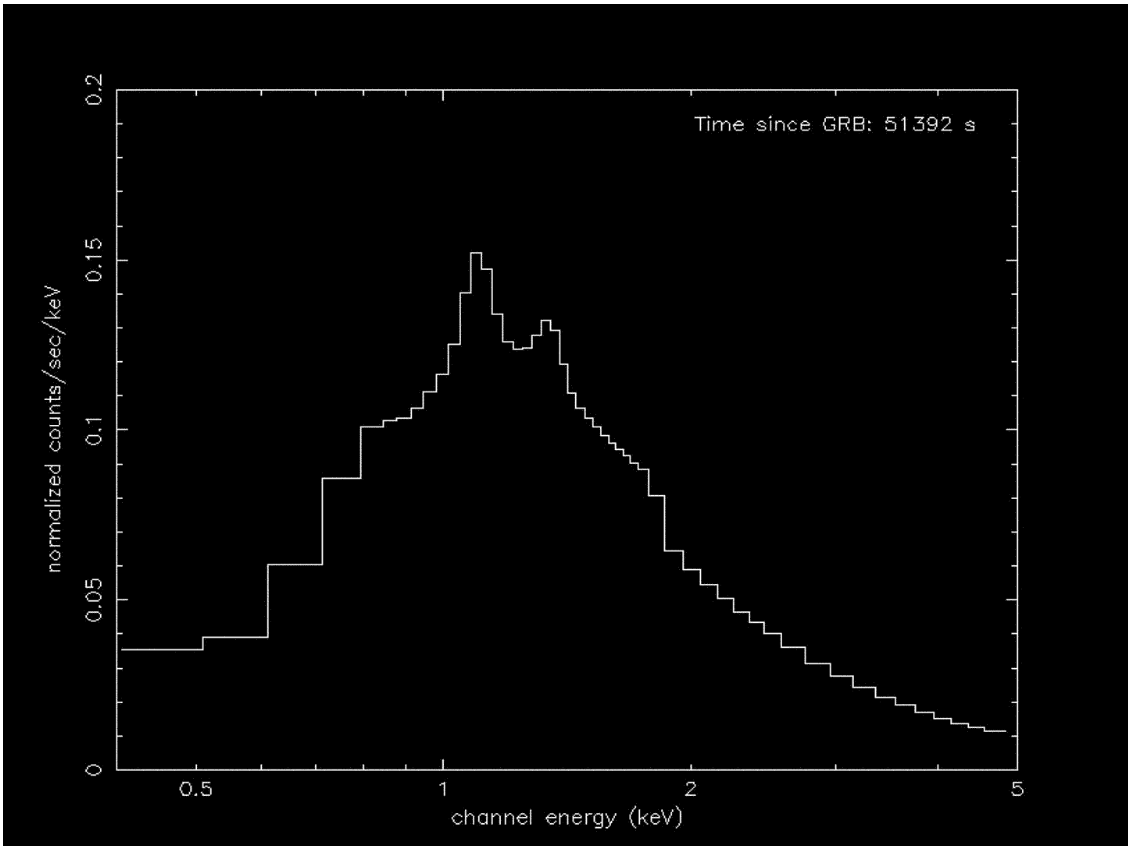
(z=1.4 predicted)



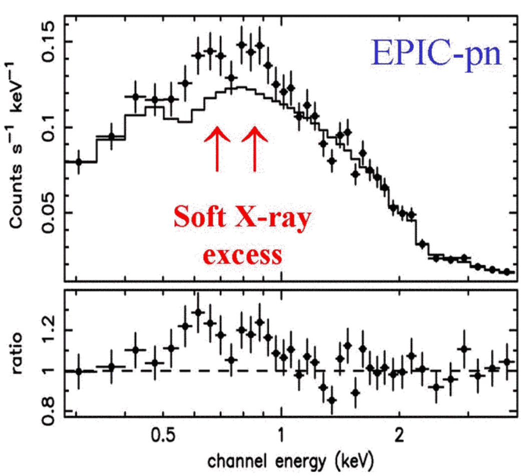
Line flux increases as continuum decreases



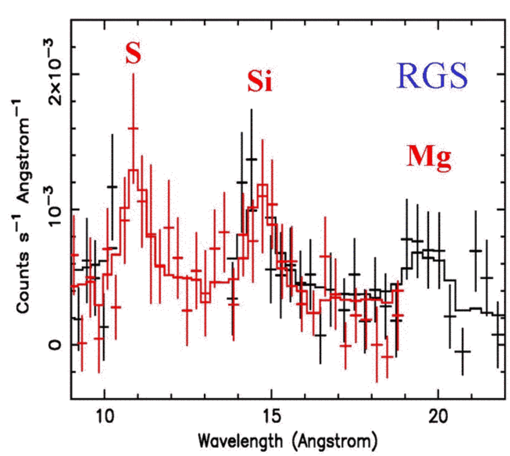
Increase in line flux implies post-burst injection of energy (note before the era of X-ray flares observed by Swift).



XMM-Newton observation of the GRB 040106 - yields the first RGS (grating) Spectrum



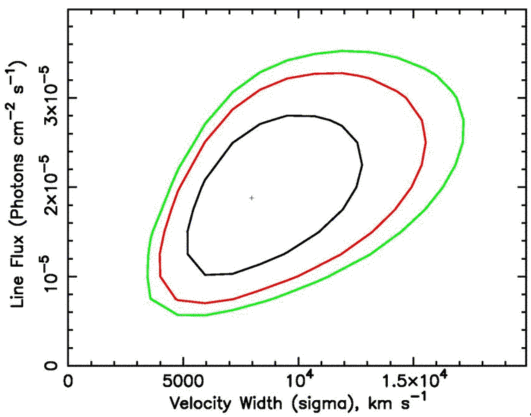
Lines detected in RGS at **0.65**, **0.85 and 1.1 keV** (19Å, 14.5Å, 11Å)., probably from **Mg, Si, S at z=1.3.** Line velocity width **16000 kms^{-1}** (FWHM)



Rapid follow-up after **6 hours**

Brightest afterglow observed to date with XMM-Newton

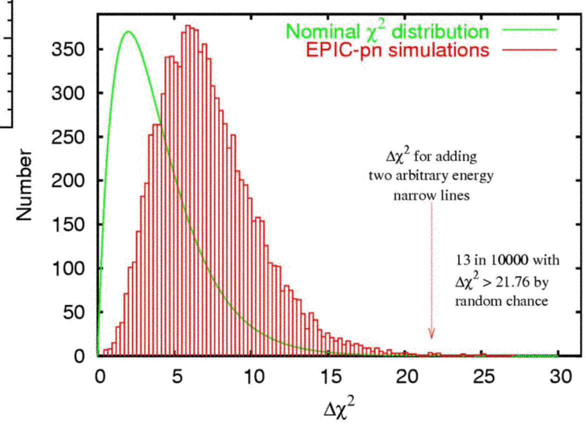
XMM-Newton observation of GRB 040106 (contd)



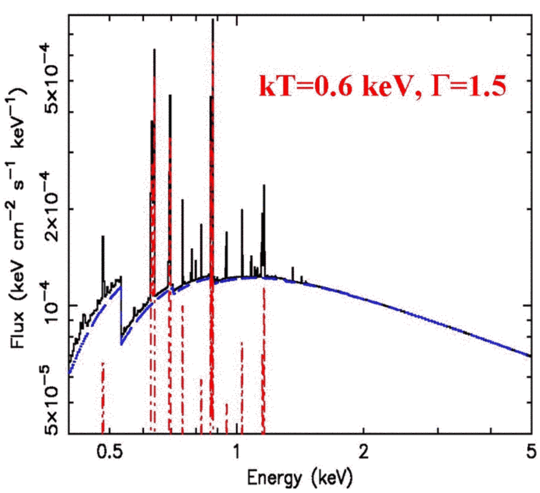
Lines appear *broadened* in RGS with velocities **σ=7000 km s^{-1}** (or 16000 km s^{-1} FWHM)

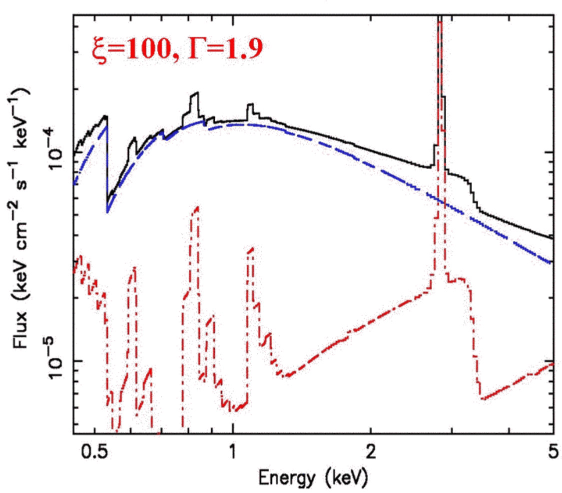
Monte Carlo based estimate of line probabilities. Line detections significance at **99.99% confidence** in EPIC-pn alone (blind trial).

Significant lines also found in Sako et al (2005) analysis.



Physical line emission mechanisms

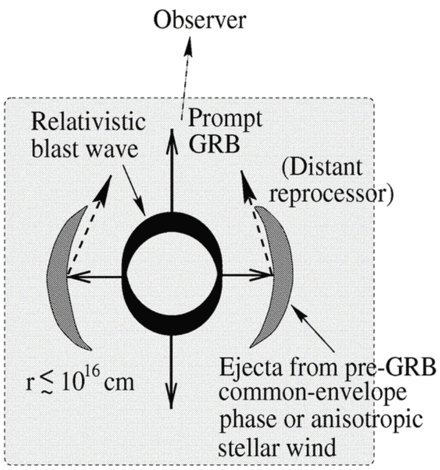




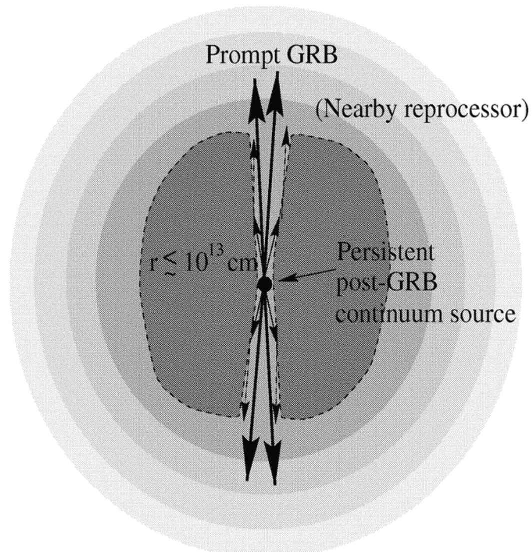
Collisionally ionised (thermal) plasma preferred over **reflection** model for producing soft X-ray line emission. Reflection model produces either strong Fe K line or edge - ***not observed in XMM spectra.***

Where do the lines originate from - possible scenarios

Torus geometries



Funnel geometries

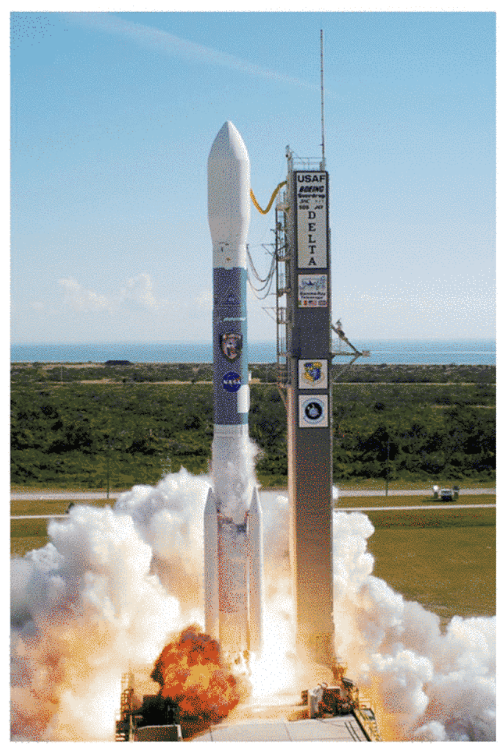


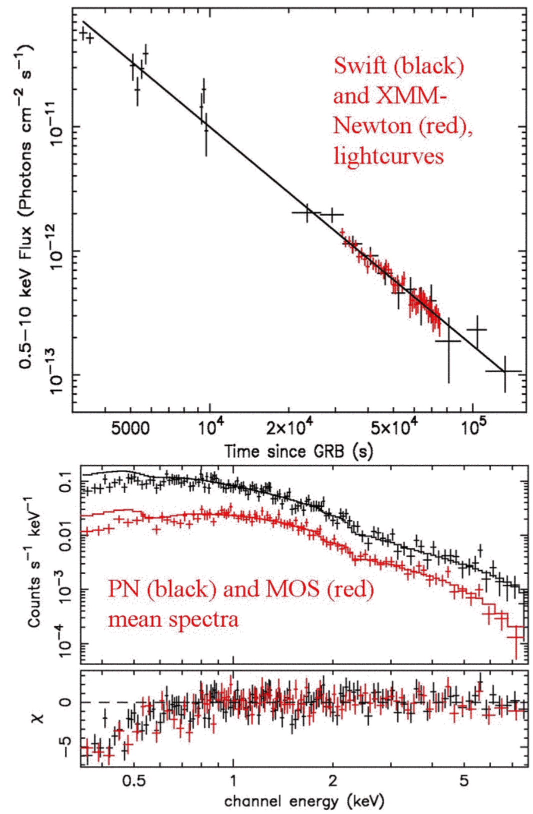
Swift launched sucessfully in November 2004!

NASA MIDEX Mission selected in 1999

Primary science is to study gamma-ray bursts throughout the Universe

International hardware participation from USA, UK and Italy





Swift/XMM-Newton Observations of GRB 050326

(Moretti et al. 2006, A&A in press)

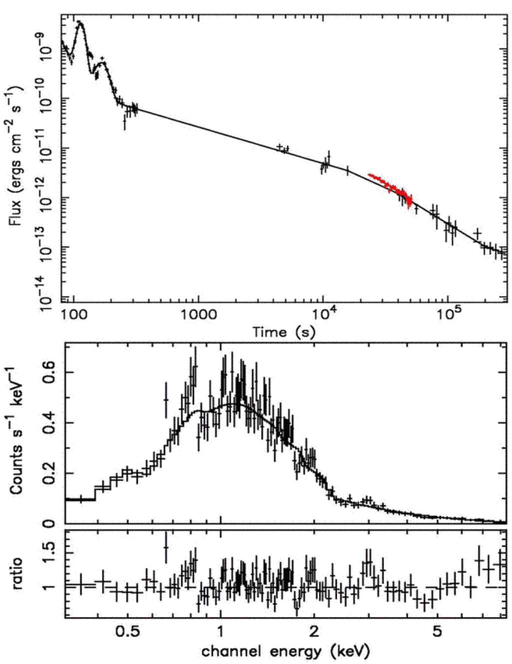
Swift XRT observations were delayed by 1hr after trigger. XMM-Newton pointing starts after 8 hrs.

Lightcurve unusually simple compared to other Swift bursts, can be fitted with a single power-law decay of index - **1.64±0.07.**

Spectrum is an absorbed power-law with no line features (**Γ=2.13±0.06**, **N_H>4x10^{21} cm^{-2} at z>1.5**).

XMM-Newton and Swift XRT datasets are consistent in Gamma (to within ±0.2, statistical errors on XRT) and in flux to 10%

Swift/XMM-Newton X-ray afterglow observations - GRB 050713a (Morris et al. 2006)



GRB 050713a observed with XMM-Newton for about 30ks useful exposure, 6 hrs after Swift trigger

XMM-Newton spectrum is absorbed with possible weak (3sigma) line features.

XRT/XMM lightcurve shows complex behavior:-

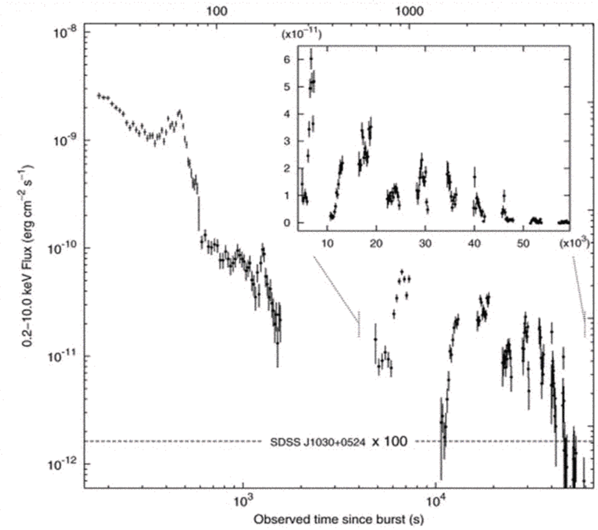
(i) Few hundred secs - fast decay (Gamma=4) and two flares. Strong soft to hard spectral evolution during big flare.

(ii) Flat "energy injection" stage out to 20000s (Gamma-0.7 decay)

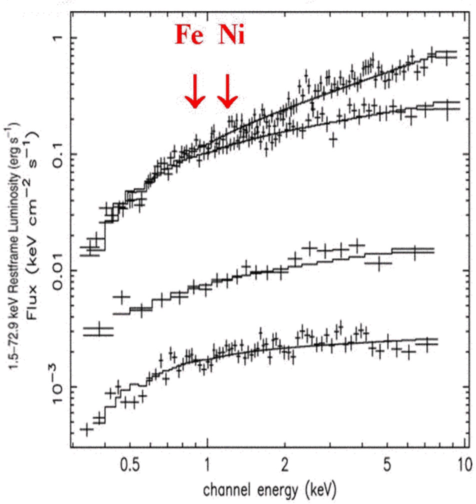
(iii) Steeper decay (Gamma=1.5) at t>20000

The z=6.3 burst, GRB 050904

XRT Lightcurve (Watson et al. 2005; Cusumano et al. 2005)



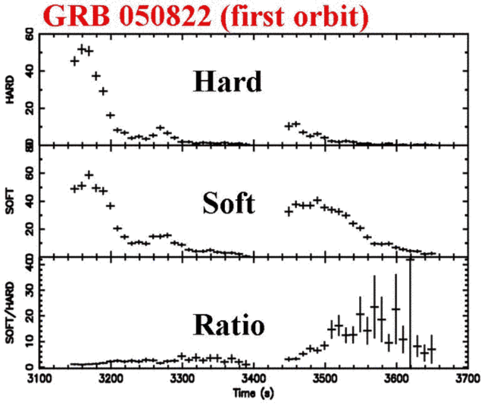
Spectral Evolution (hard to soft)

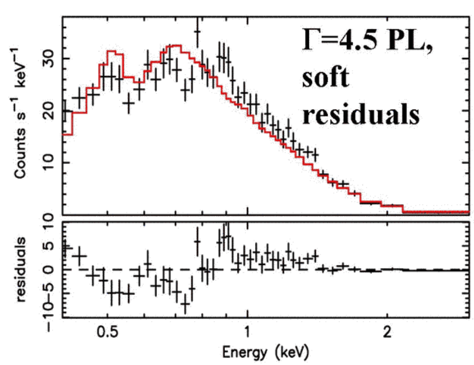


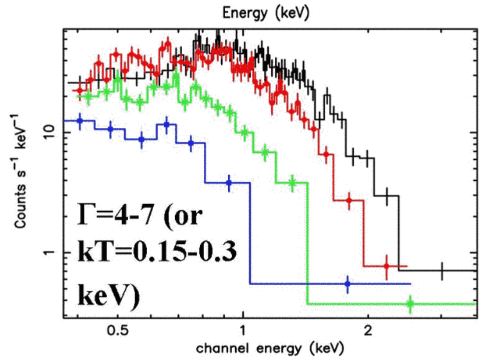
Spectrum evolves (hard-soft) from Γ=1.2-1.9. Excess absorption (3x10^{22}cm^{-2}, rest frame). No iron K line emission (<50 eV EW), observed at 0.9 keV.

Are the spectra of some soft flares in Swift thermal? (Butler et al. 2006, in prep).

GRB 050822 (first orbit)







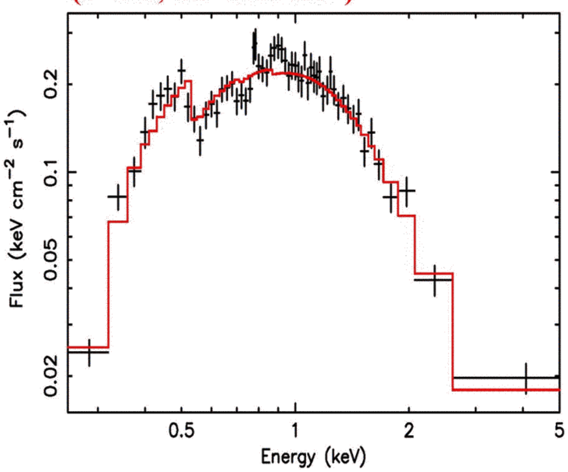
Spectra selected for >4σ deviations (blind trial) from power-law.

Very soft flare in Swift/XRT data

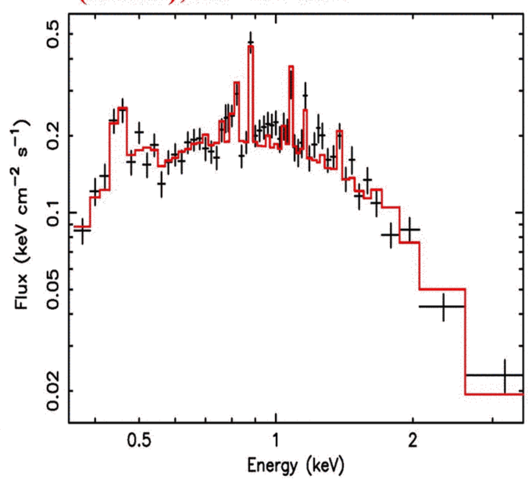
Spectra appear to better fit by thermal rather than PL models. Possible cooling during flare?

GRB 050822 - soft flare spectra

Black-body plus power-law model (Γ=3.5, kT=0.22 keV)

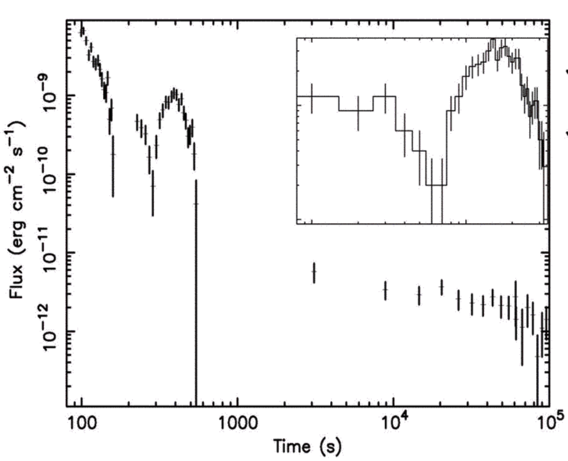


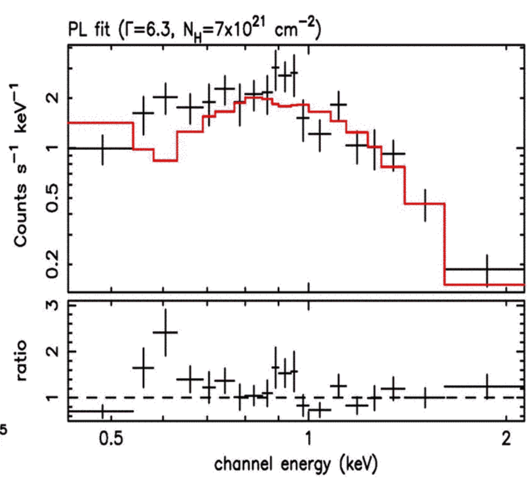
Optically thin thermal model (mekal), kT=1.4 keV



Thermal models appear to give a better fit to soft/flaring spectrum in GRB 050822. Can't distinguish between opt-thin and opt-thick models.

Soft Flare Swift/XRT Spectrum in GRB 050714B





Strong and soft flare seen at T=300-500s in XRT lightcurve.

Flare spectrum is very steep (Γ=6.3). Instead can be fitted with a thermal mekal (kT=1keV) or black-body model (kT=0.18 keV)

Emission lines and Spectra of GRB X-ray Afterglows

- XMM-Newton afterglow spectra show ***soft X-ray line emission*** in 3 bursts (**GRB 011211, GRB 030227, GRB 040106**). One soft X-ray line in Chandra (GRB 020813). No iron lines (claimed in SAX/Chandra/ASCA data) are observed in XMM-Newton(or Swift) spectra.

- High velocities of lines (**GRB 011211, GRB 040106**) strengthens association between long GRBs and **supernovae/hypernova**.

- Detections are **3-4σ (Monte-Carlo, blind trial).** No clear lines yet seen in Swift XRT (but has <10% of the XMM effective area).

- Nonetheless, ***no strong (e.g. >5σ) detections have been made***. Requires high resolution and high throughput spectra (difficult!)

- High intrinsic X-ray absorption a property of several (about 50%) of XMM-Newton (and also Swift) GRBs.

- Swift spectra of ***some early time flares may show soft/thermal spectra*** (as predicted by XMM-Newton results?)