Discrete X-ray Spectral Features in Gamma-ray Bursts Afterglows

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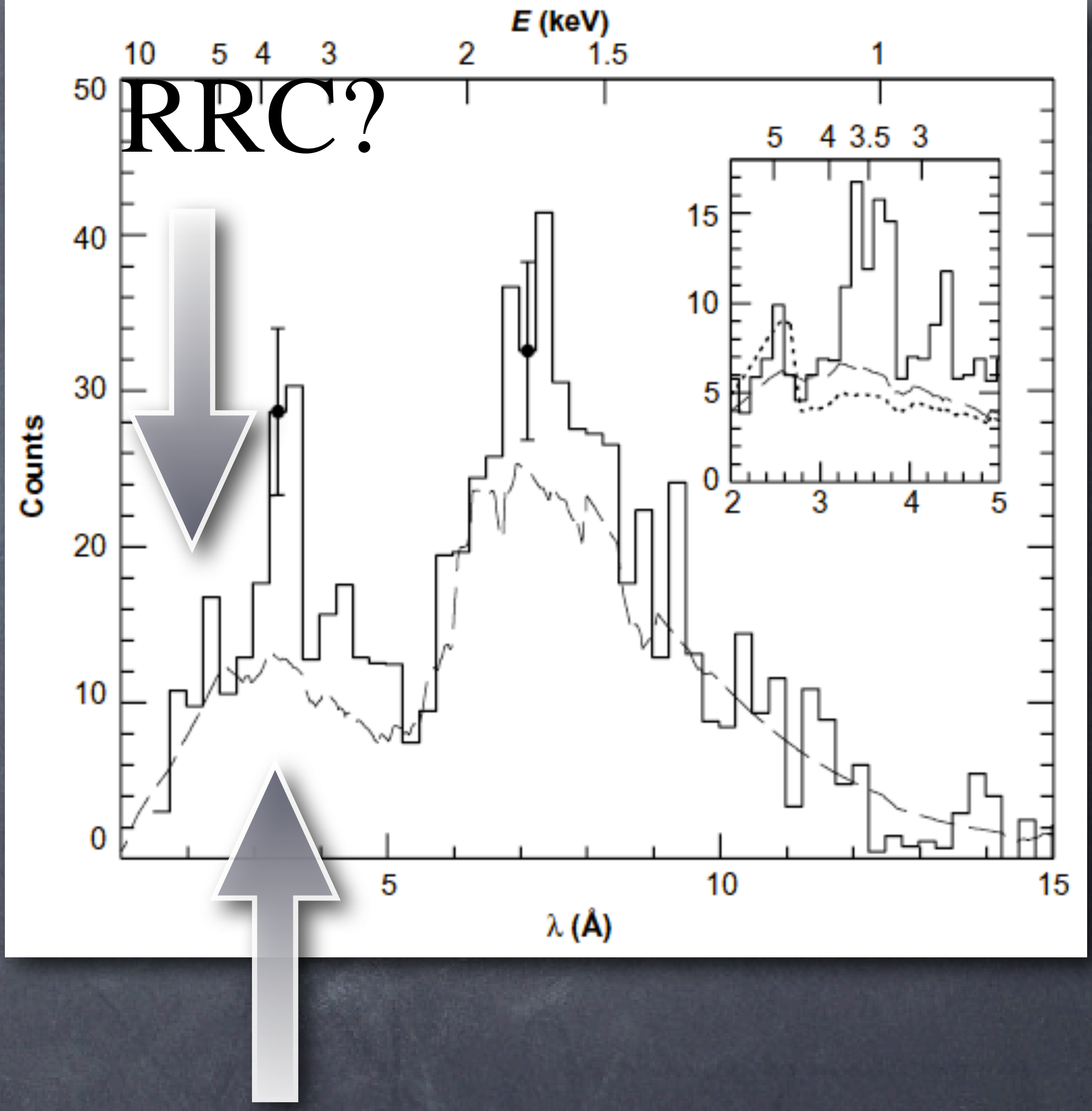
Production of discrete X-ray features during GRB afterglows

- X-ray band contains discrete transitions of most abundant metals (C, N, O, ... Fe, Co, Ni)
- X-ray spectroscopy
  - abundance estimates ⇒ progenitor star
  - dynamics ⇒ burst/circumstellar geometry
  - excitation mechanism, temperature, density ⇒ model constraints

- Many CCD observations with *XMM-Newton* + few high-resolution observations with *Chandra*; some with reported emission line detections

Observation of GRB991216

- Piro et al. (2000) reported the detection of an Fe line (and possibly an associated recombination continuum) in the X-ray afterglow of GRB991216 observed with the *Chandra*/HETG
  - first high-resolution grating observation of a GRB afterglow
  - The claimed single-trial signficance of the line is 4.7σ (occurs only once in ~380,000 random trials at this particular energy).

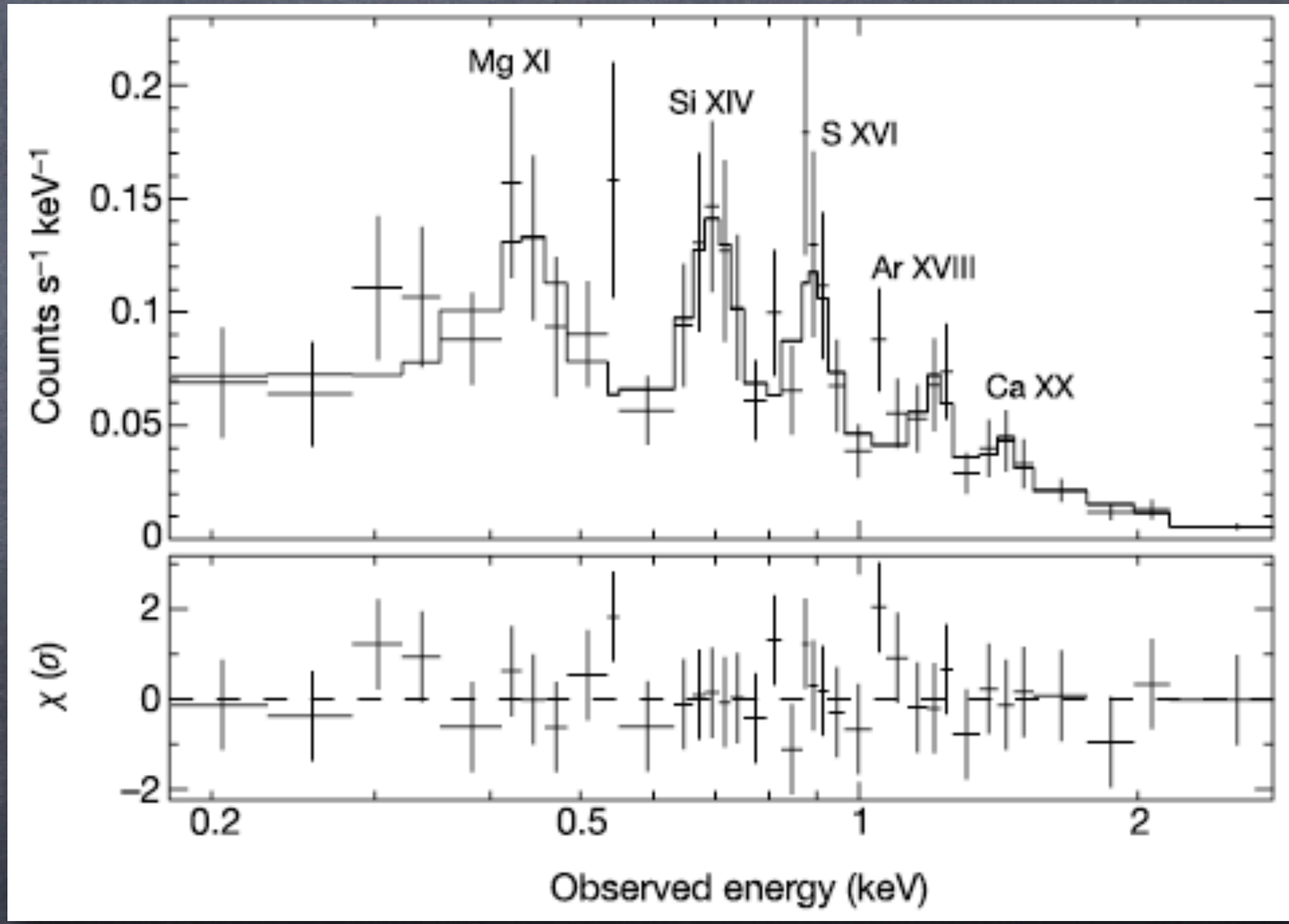


Fe line?

$z_{opt} = 1.02$

Soft X-ray Lines in GRB011211

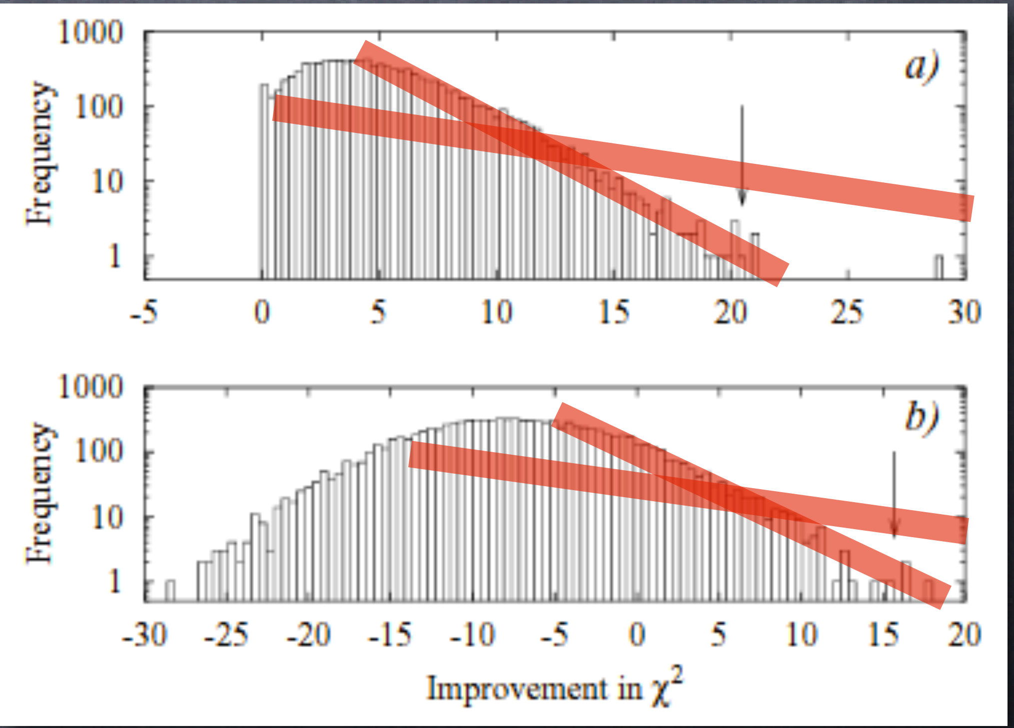
- Reeves et al. (2002; 2003) have reported the detection of multiple emission lines from mid-Z elements (Mg, Si, S, Ar, and Ca) during the first ~5 ksec (30 ksec total) of an *XMM-Newton* observation of GRB011211
- outflow v~0.1c
- F-test : 99.7%
  - ~1/300 (3.0σ)
- MC : 99.98%
  - ~1/5000 (3.7σ)



$z_{opt} = 2.14$

- The Monte Carlo method was elaborated in a later article (Reeves et al. 2003)
  - fit data and record the $\Delta\chi^2$ that results from adding three gaussian lines to the continuum model
  - repeat for 10000 simulated spectra
  - count the number of simulations which result in an equal or larger $\Delta\chi^2$

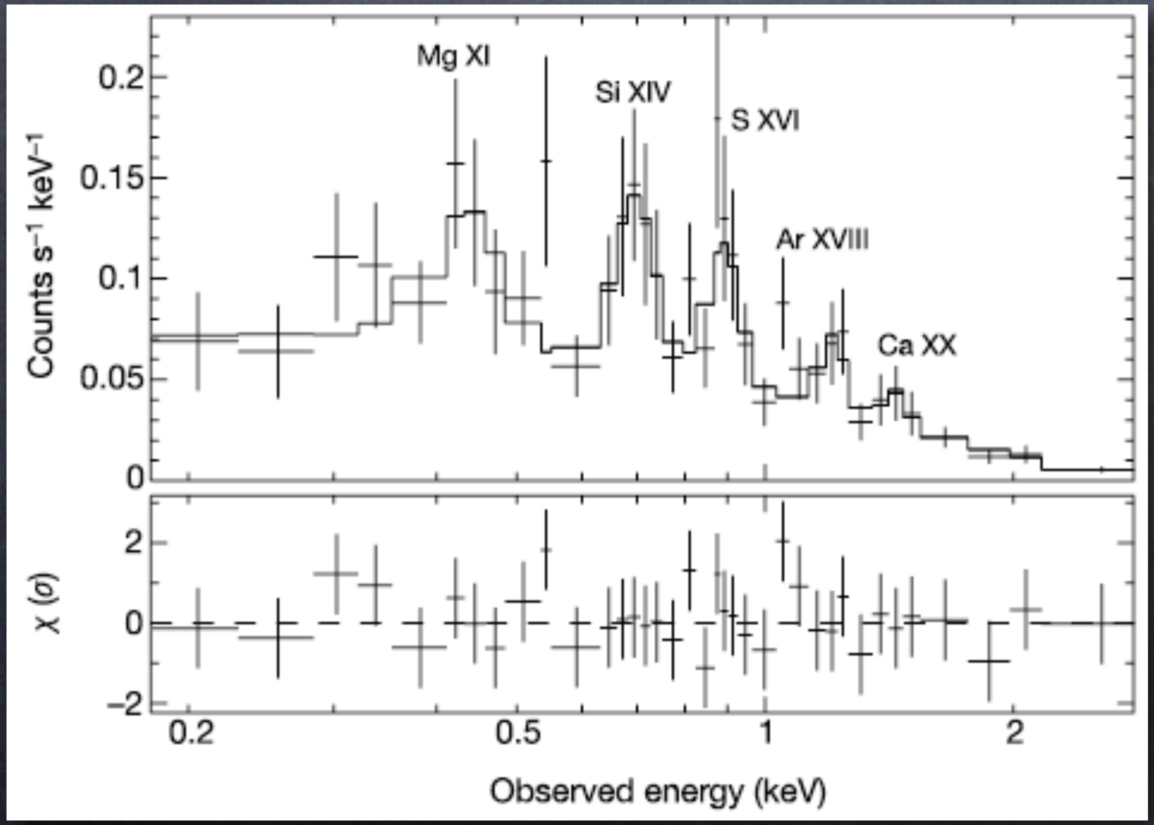
- Be careful!
  - automating the fit results in an underestimate of the $\Delta\chi^2$ (almost always find a local minimum; not a global minimum)



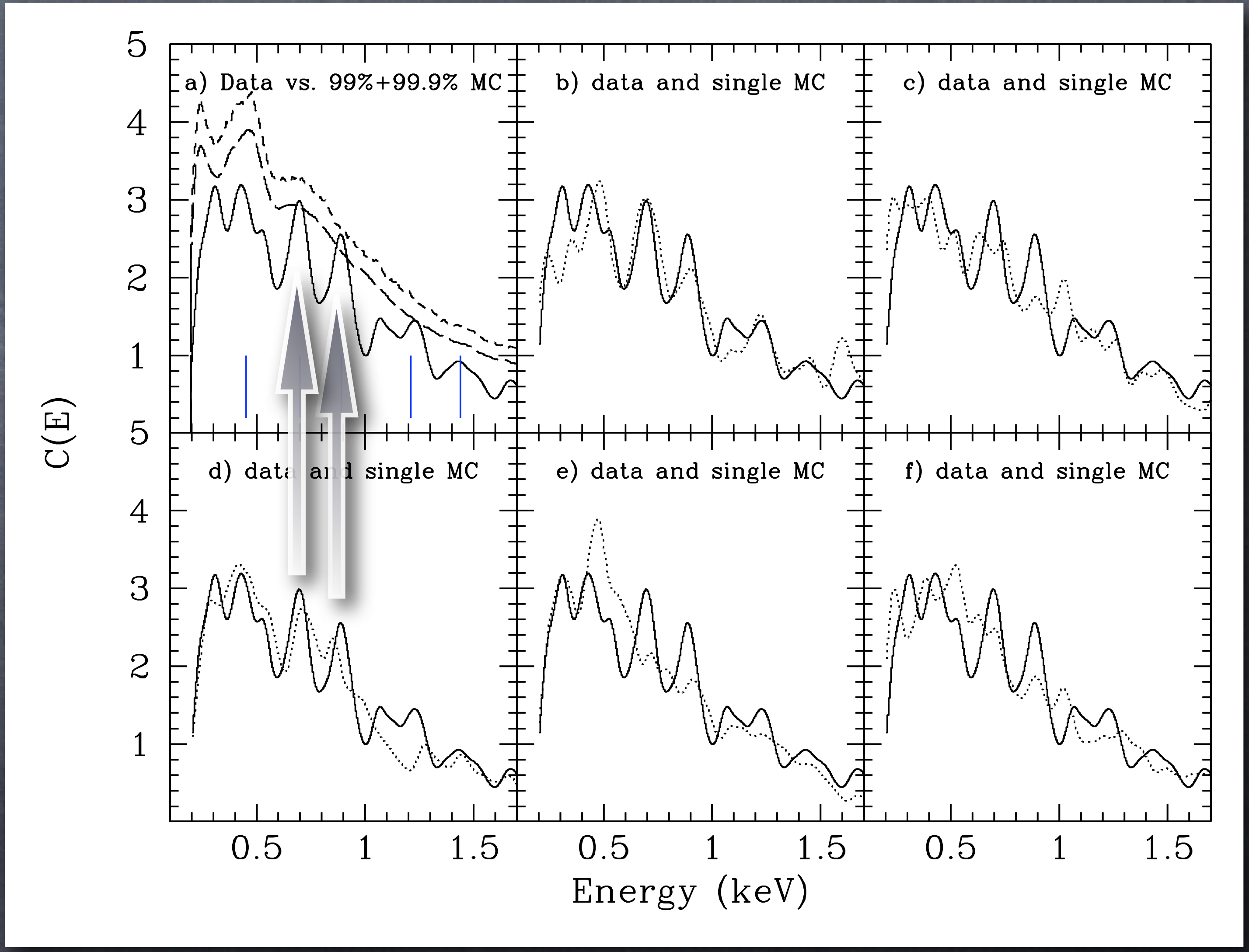
Reeves et al. (2003)

- Rutledge & Sako (2002): MC simulations to estimate multi-trial significances (i.e., chances of seeing fluctuations at an arbitrary energy - velocity shifts are not known!)
- matched-filter

seen in ~20% of the simulations
~1.3σ



Reeves et al. (2002)



Rutledge & Sako (2002)

- 21 follow-up X-ray observations with useful spectral data (>100 counts detected) analyzed by Sako, Rutledge, & Harrison (2005)
  - includes all *ASCA*, *Beppo-SAX*, *XMM-Newton*, and *Chandra* observations up to GRB040106
  - 16 targets at CCD resolution; 5 with *Chandra* gratings
  - previously claimed detections are not statistically significant
  - few other notable cases (e.g., GRB030227, GRB040106), but none are detected in more than one or more instruments/spectral orders

The Case for GRB991216

~2.8σ single-trial

seen in ~40% of simulations

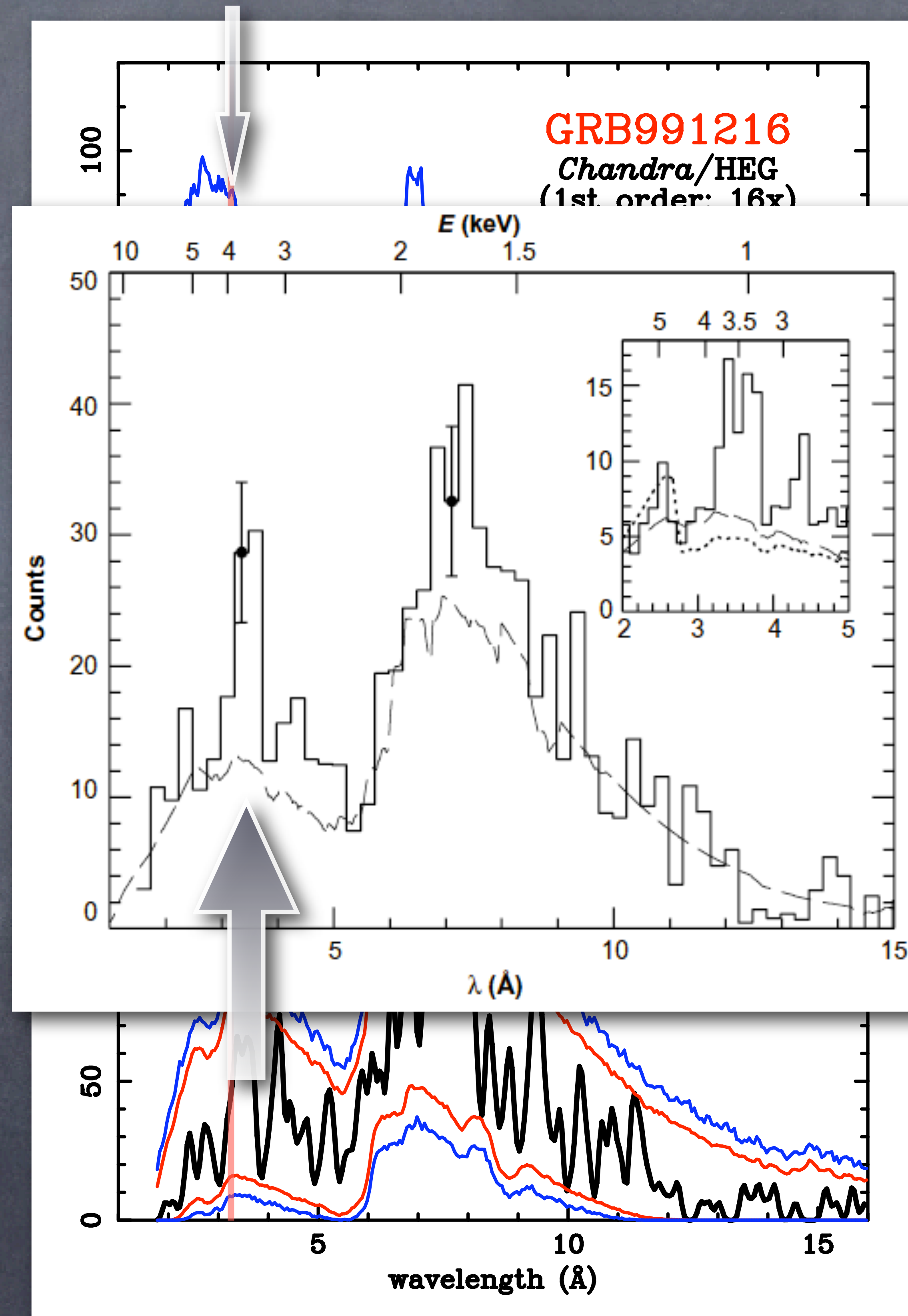
~0.8σ multi-trial

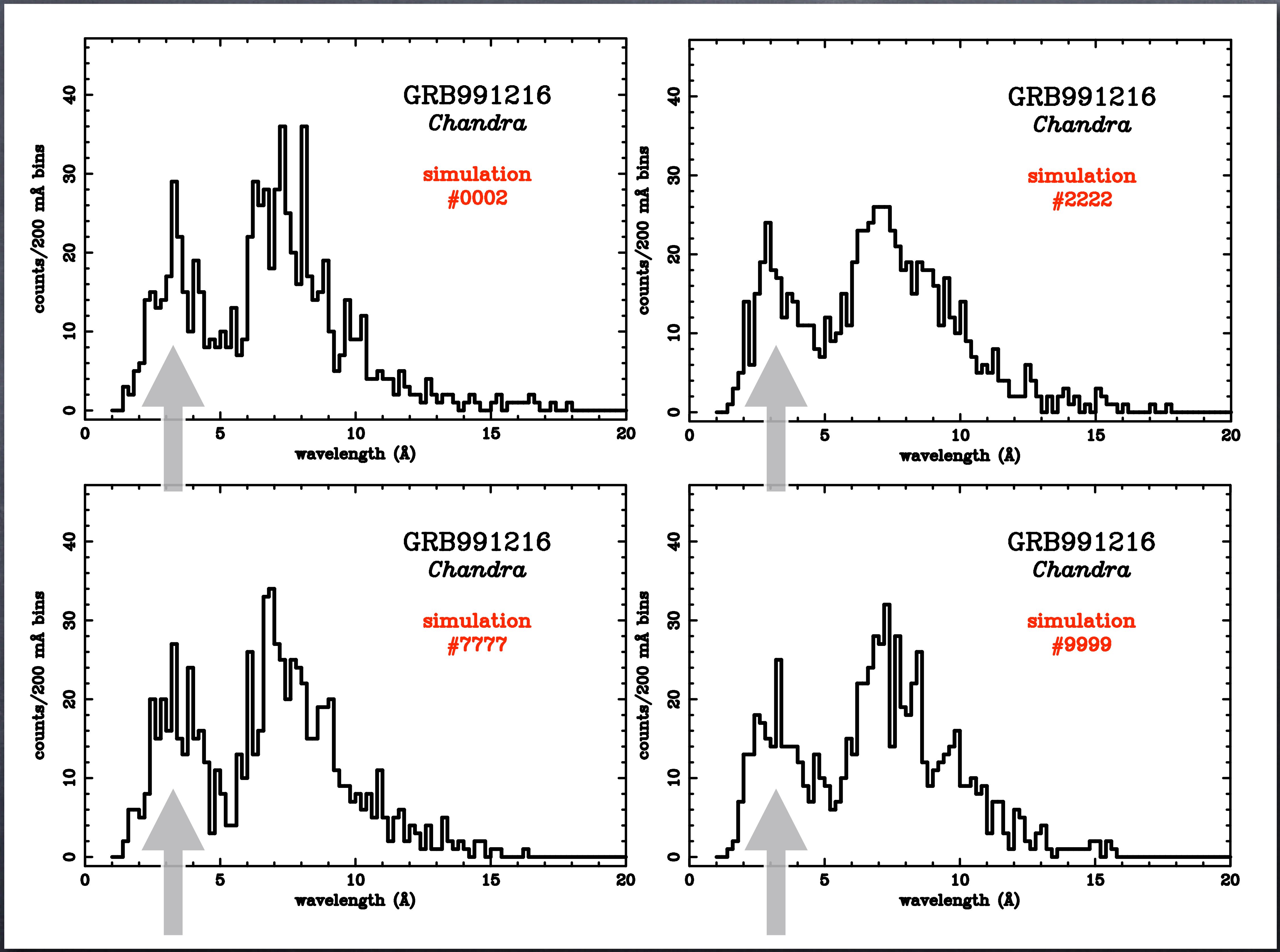
- Re-analysis
  - continuum adopted by Piro et al. (2002) is probably not reliable; the true single-trial probability is ~2.8σ
  - multi-trial? The feature can be identified as Fe XXVI Lyα at z=1.02 (Vreeswijk et al. 1999); the highest-redshift optical absorption-line system.

~3.1σ single-trial

seen in ~15% of simulations

~1.4σ multi-trial

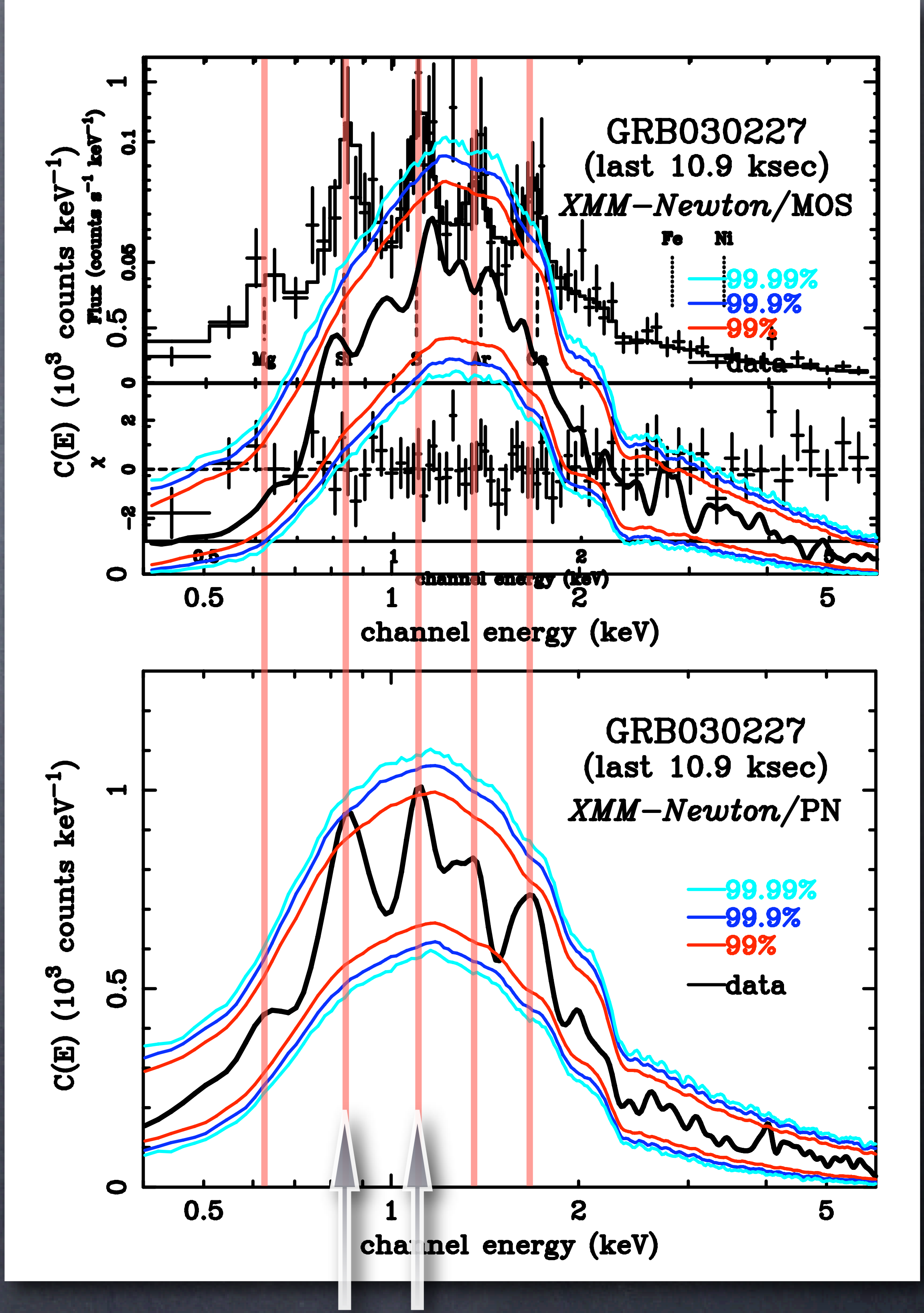



GRB991216
Chandra
simulation
#0002
GRB991216
Chandra
simulation
#2222
GRB991216
Chandra
simulation
#7777
GRB991216
Chandra
simulation
#9999
counts/200 mÅ bins
wavelength (Å)
0
5
10
15
20
10
20
30
40

GRB030227

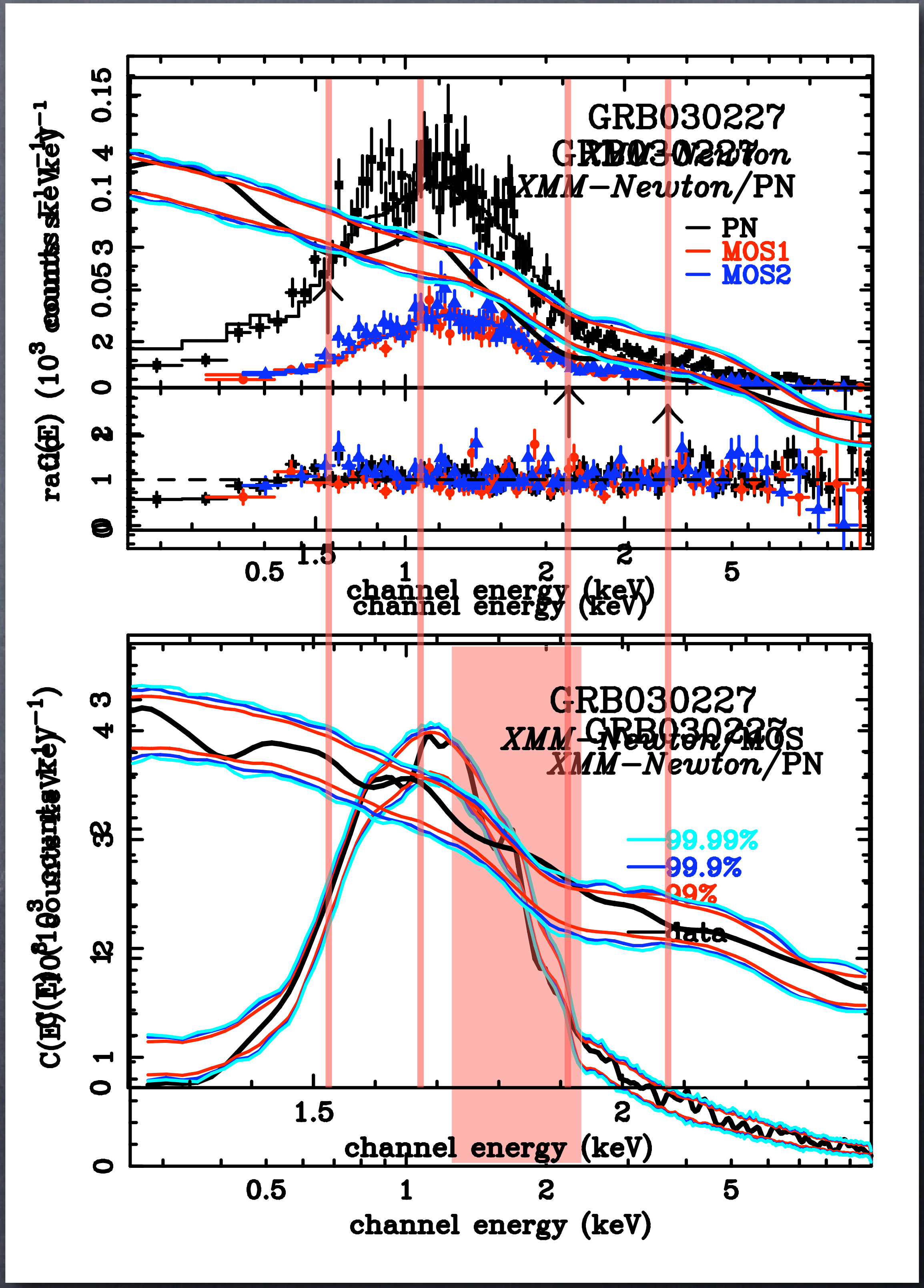
- Watson et al. (2003) have detected lines in the last 10.9 ksec of an *XMM-Newton* observation at a redshift of z=1.4 (no optical redshift measured)
  - the authors adopt a model in which “one expects to observe the Hydrogen-like emission lines Mg, Si, S and the Helium-like lines of Ar and Ca at an arbitrary redshift”
- Claimed significance 4 ~ 5σ

seen in ~15% of the simulations
~1.5σ



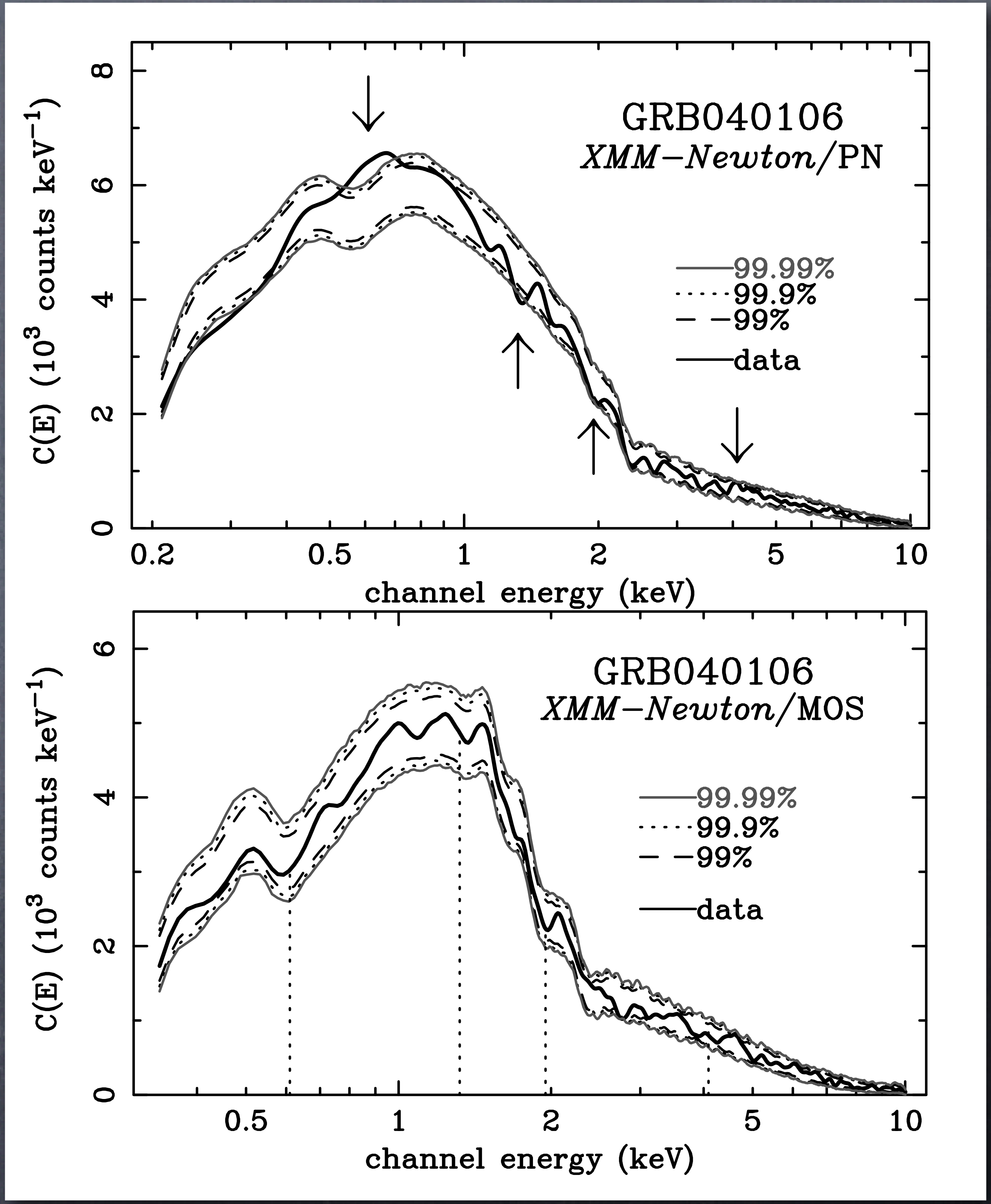
GRB030227 (cont'd)

- The total spectrum (all ~35 ksec) shows statistically significant features in the PN
  - this dataset contains the second highest number of counts of all GRBs observed to date
- But not in the MOS...



GRB040106

- Highest-quality X-ray spectrum of an afterglow.
- Significant excess at E~0.6 keV in the pn data (3.9σ multi-trial)
- Again, not detected in the MOS...



At what σ should one get excited?

- A 3σ feature, by definition, is something that appears randomly on average once in every ~370 trials
- If the spectrum has ~370 resolution elements, and one does not know a priori where to look, each spectrum would on average have one "3σ feature"

"You know, the most amazing thing happened to me tonight. I was coming here, on the way to the lectures, and I came in through the parking lot. And you won't believe what happened. I saw a car with the license plate ARW 357. Can you imagine? Of all the millions of license plates in the state, what was the chance that I would see that particular one tonight? Amazing!"

Feynman Lectures

"If you believe Gaussian statistics, you should be willing to bet your gold fish (4σ), your house (5σ), or your dog (6σ)."

Bob Kirshner "The Extravagant Universe"

Some personal comments on the reported detections...

- Most previous reports have claimed line detections always at the ~3 - 4σ level, irrespective of source brightness, exposure time, etc.
- Some of the features appear to be “transient”; seen in only a selected time interval
- A 3 - 4σ feature has a larger equivalent width and appears more “line-like” in low quality spectra

Recent Follow-up

- *Swift*/XRT observations of 10 X-ray afterglows (GRB041223, 050126, 050128, 050223, 050315, 050318, 050319, 050326, 050401, 050525) published; no reported detections of any obvious X-ray lines
- *XMM-Newton, Chandra,* and *Suzaku* have already followed-up a few *Swift* GRBs
  - CCDs have >10 times the effective area
  - no reported detections

Prospects

- High equivalent width metal lines are not present at $t \leq 2$ days from the GRB.
- Presence of weak narrow/broad lines is still possible.
  - Approved *Chandra* LETG ToO time (120 ksec) in Cycle 7 to follow-up the brightest afterglow.
  - detection of weak broad lines require very high statistics