Results from Observing Campaigns on Cygnus X–3 During 2010–2011

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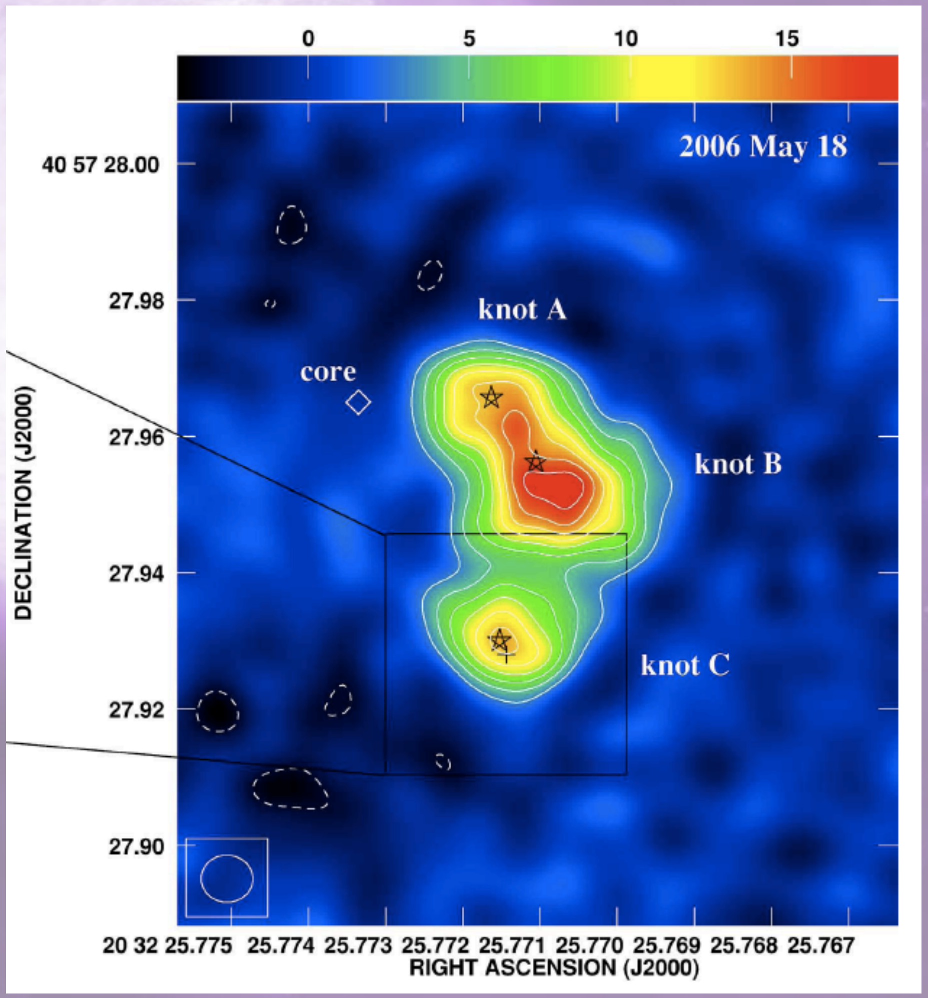
X-ray Binaries: Celebrating 50 Years Since the Discovery of Sco X-1 July 10 2012

Cygnus X–3

- Bright X-ray binary, D ~9 kpc, orbital period 4.8 h
- Mass and nature of the accretor is uncertain due to heavy extinction in the optical/UV, and uncertainty on the mass of the Wolf-Rayet giant mass donor
- Many peculiarities of the source can be attributed to the strong stellar wind in which the compact object is embedded, e.g.
  - Variable absorption component
  - Photoionized H- and He-like X-ray emission lines
  - P-Cygni profiles indicating wind speeds of ~1000 km/s
  - Radiative Recombination Continua (RRCs)
  - Featureless, suppressed power spectrum

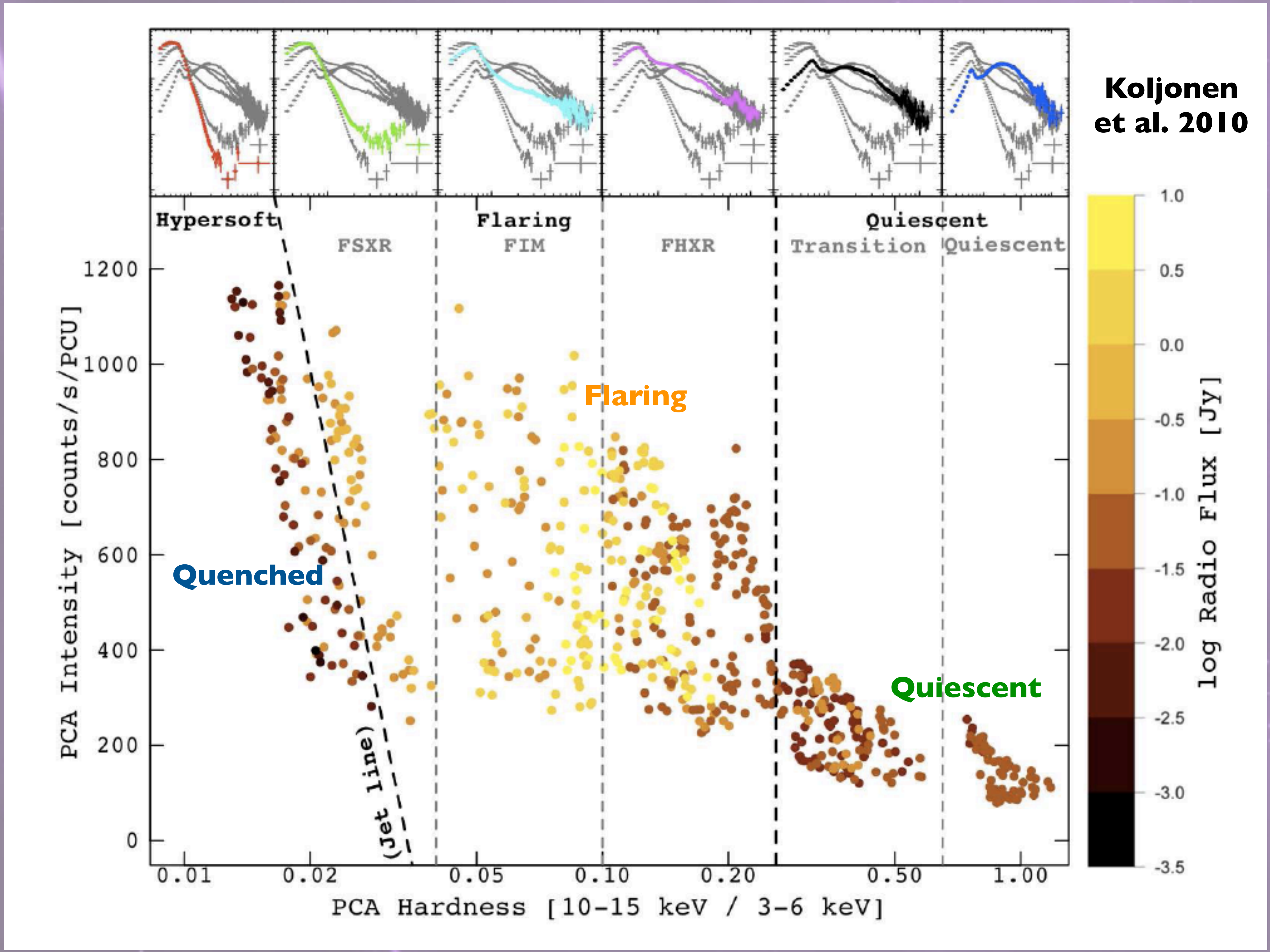
Cygnus X–3 as a radio source

- One of the brightest and most active X-ray binaries in the radio: base level ~100 mJy, major flares reach 1–20 Jy
- Occasional quenched states, where radio flux < 20 mJy, hard X-rays also suppressed
- After several days of radio quenching, a major flare has always followed
- VLBI observations of milli-arcsec-scale jet indicate a small jet inclination angle < 14°, opening angle < 12°



Tudose et al. 2007

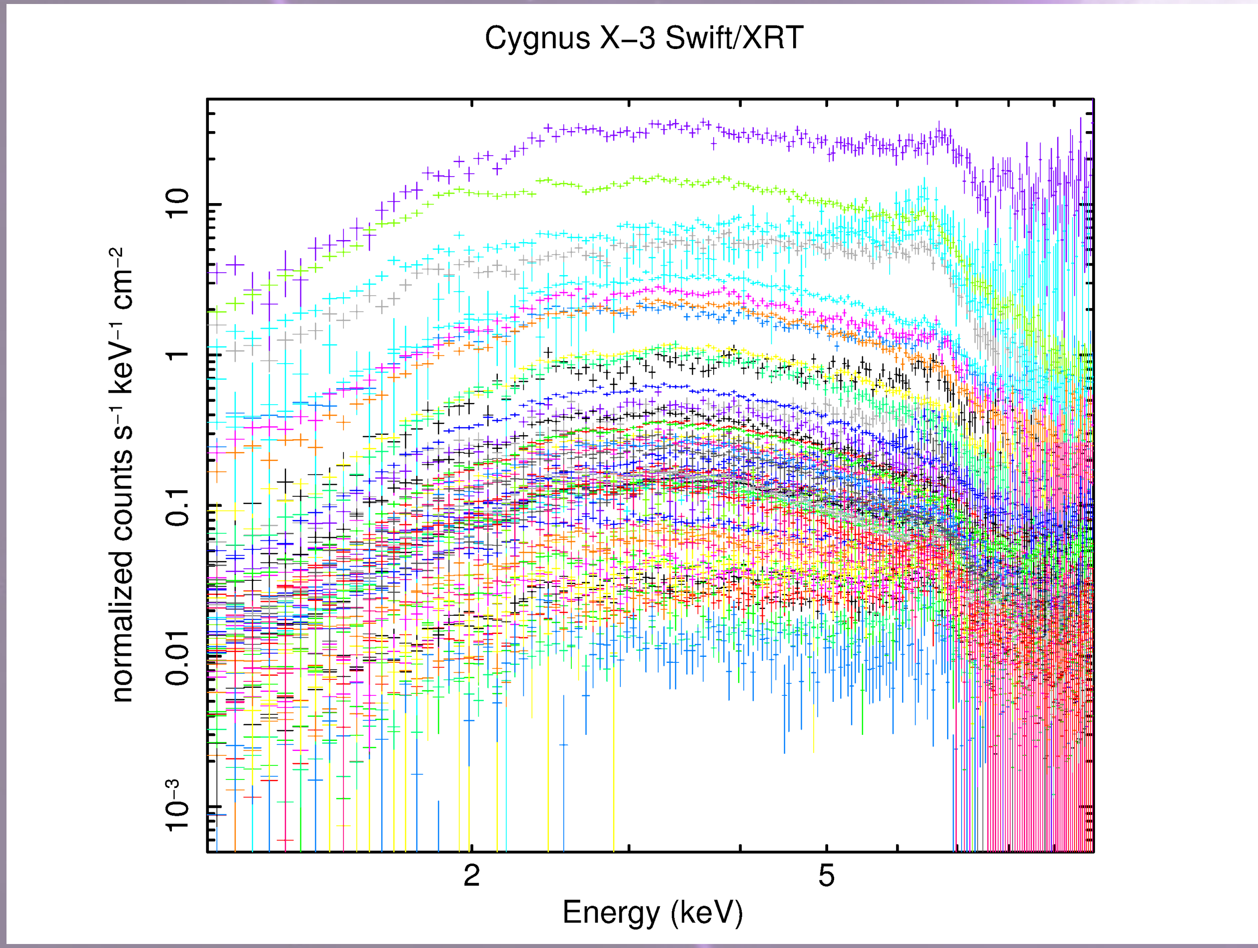
Cygnus X–3's spectral states



A complex range of behavior, determined by both X-ray and radio

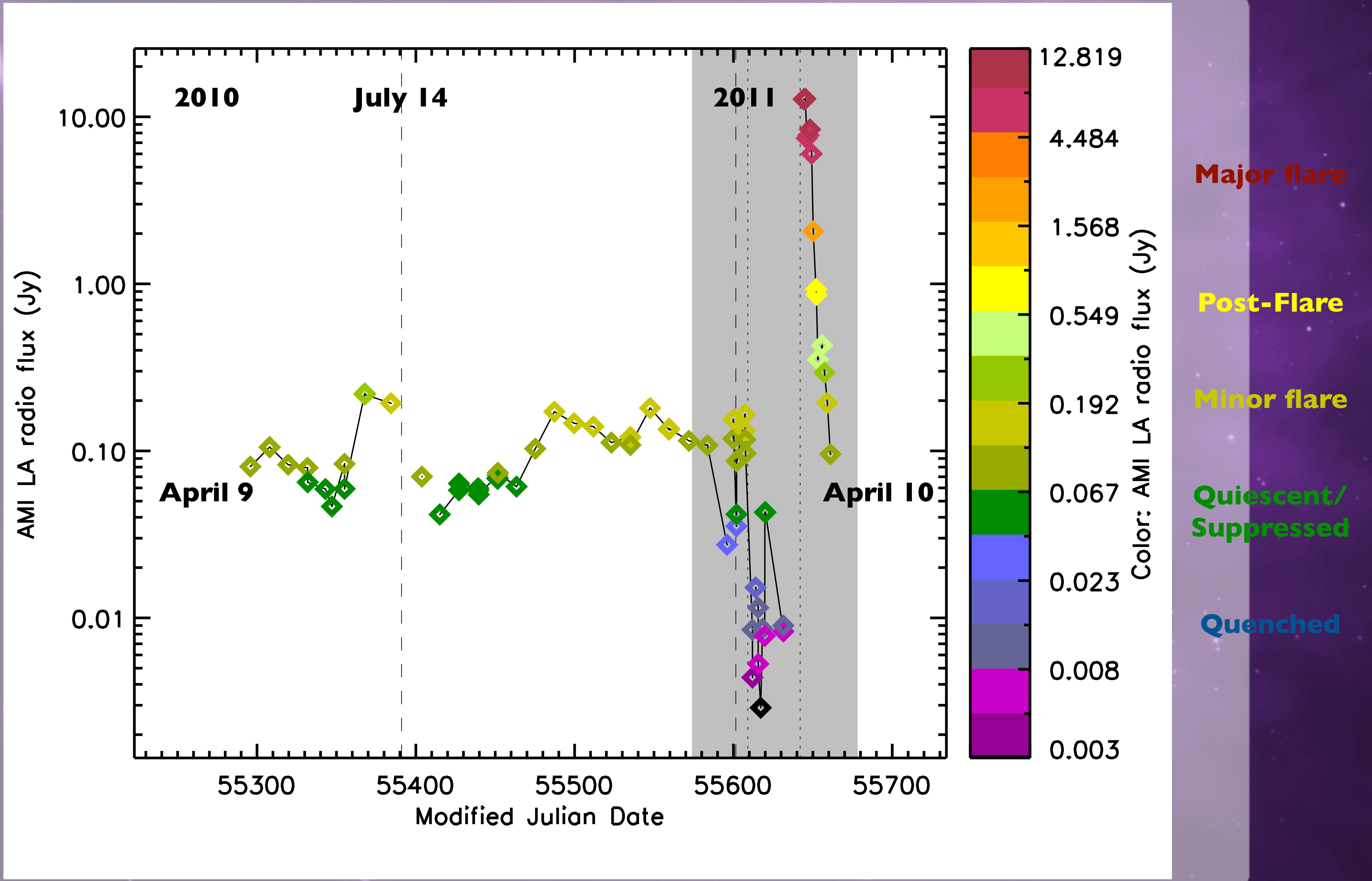
Data from monitoring & TOO campaigns

- 53 *Swift* monitoring campaign pointings + 33 TOO
- 28 *RXTE* TOO observations within 24 hours of *Swift*
- 15 GHz radio fluxes from AMI-LA within 48 hours of almost every observation



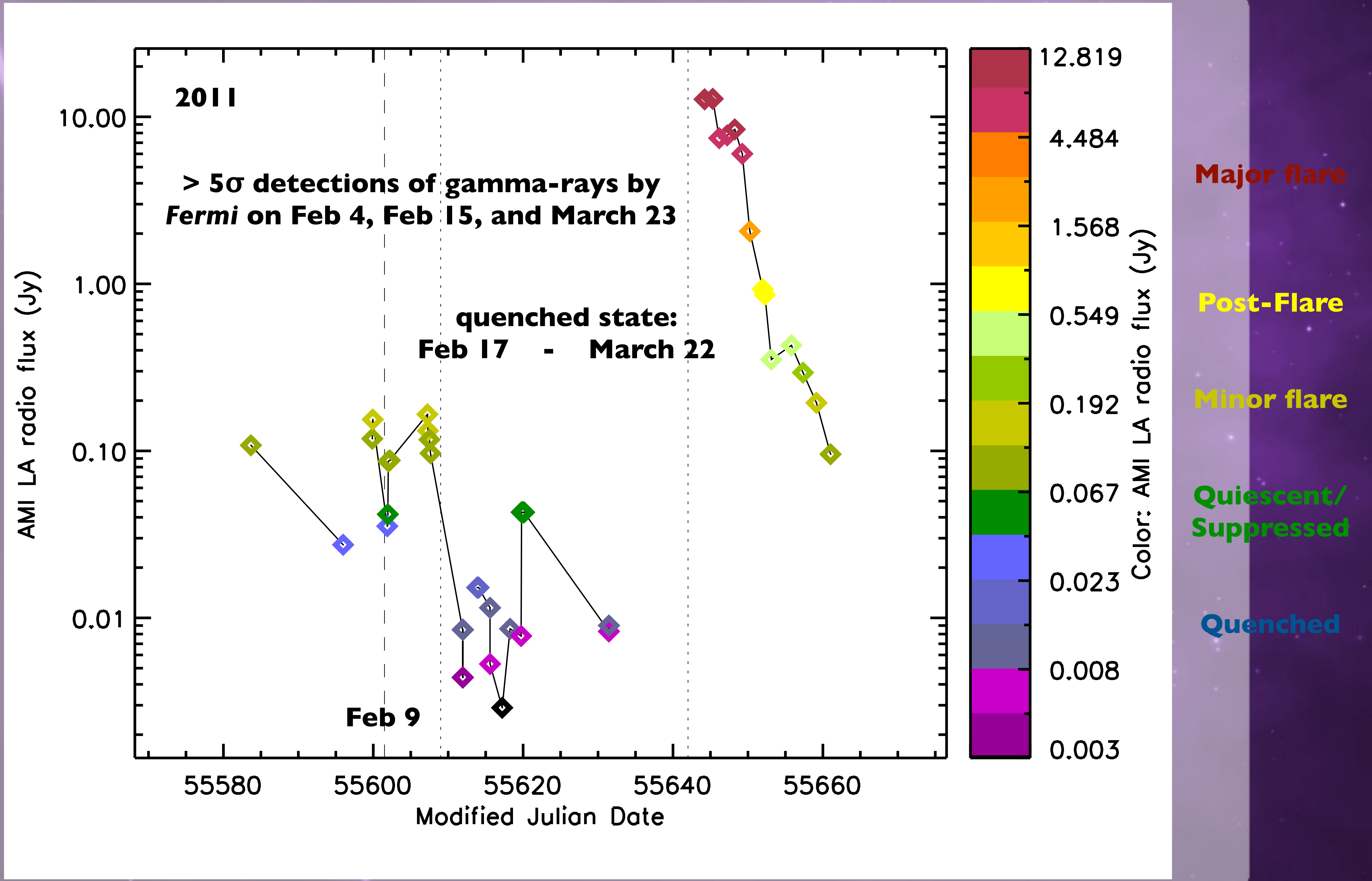
Objective: to model the X–ray spectrum of Cygnus X–3 from 0.5 keV up to hard X-rays in all the observed emission states

AMI-LA radio flux over the campaigns



Result plots are colored by radio flux, as a proxy for spectral state

AMI-LA radio flux over the campaigns



The entire range of Cygnus X–3's spectral states was sampled

Continuum model

- The following continuum was fit between 1–60 keV: `constant*TBabs*pcfabs*edge*edge*CompPS`

- Cross-calibration / timing difference factor

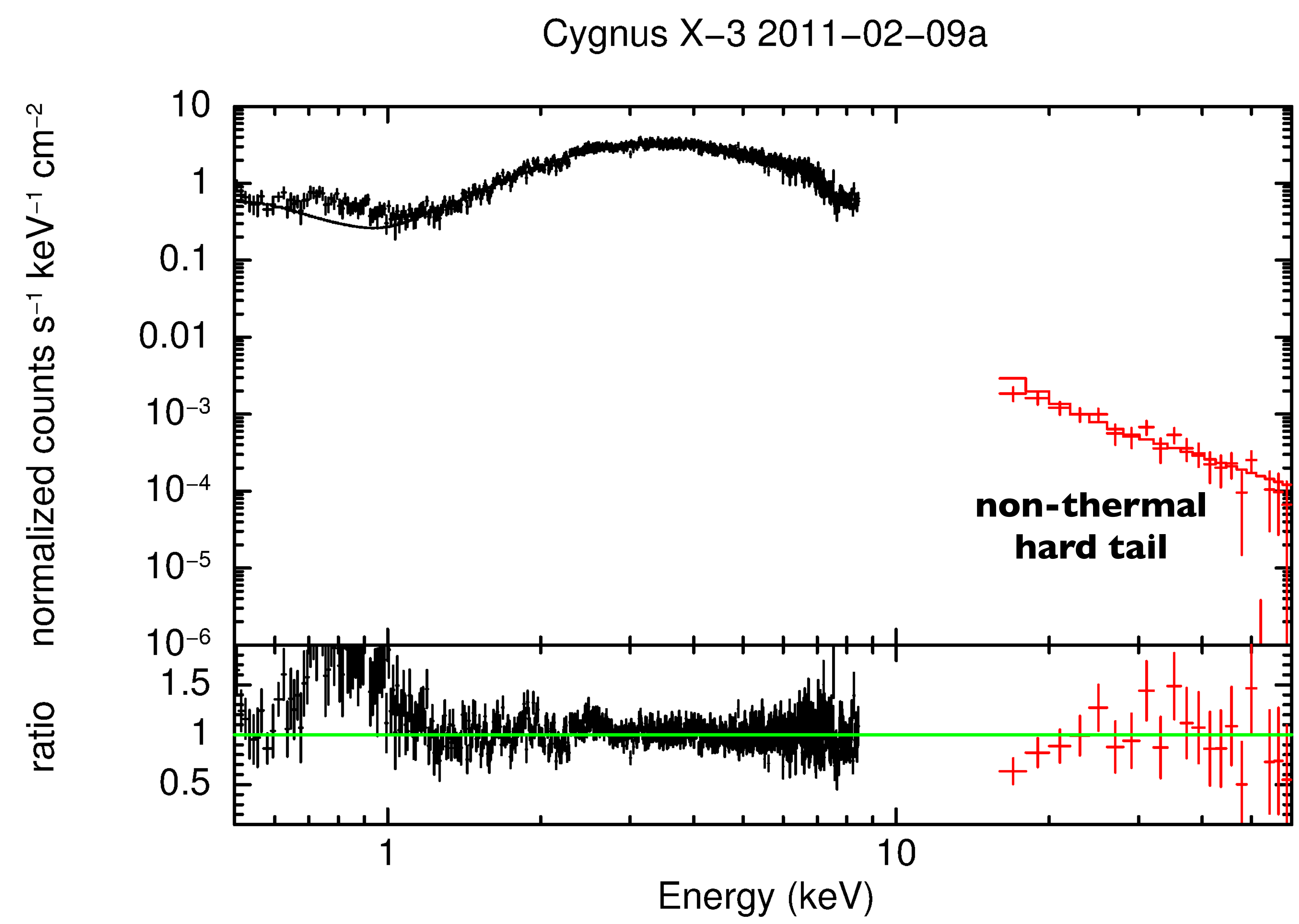
- Interstellar absorption $n_H \sim 2 \cdot 10^{22}$ cm^{-2}, variable partial covering absorption $n_H \sim 5–10 \cdot 10^{22}$ cm^{-2}

- Iron absorption edges around 7 keV and 9 keV

- CompPS free parameters: kT_{bb}, kT_e, τ, normalization (+ power law index, minimum Lorenz factor at times when thermal Comptonization is insufficient for a fit)

Most parameters depend mainly on *Swift*/XRT data

A soft excess remains below 1 keV



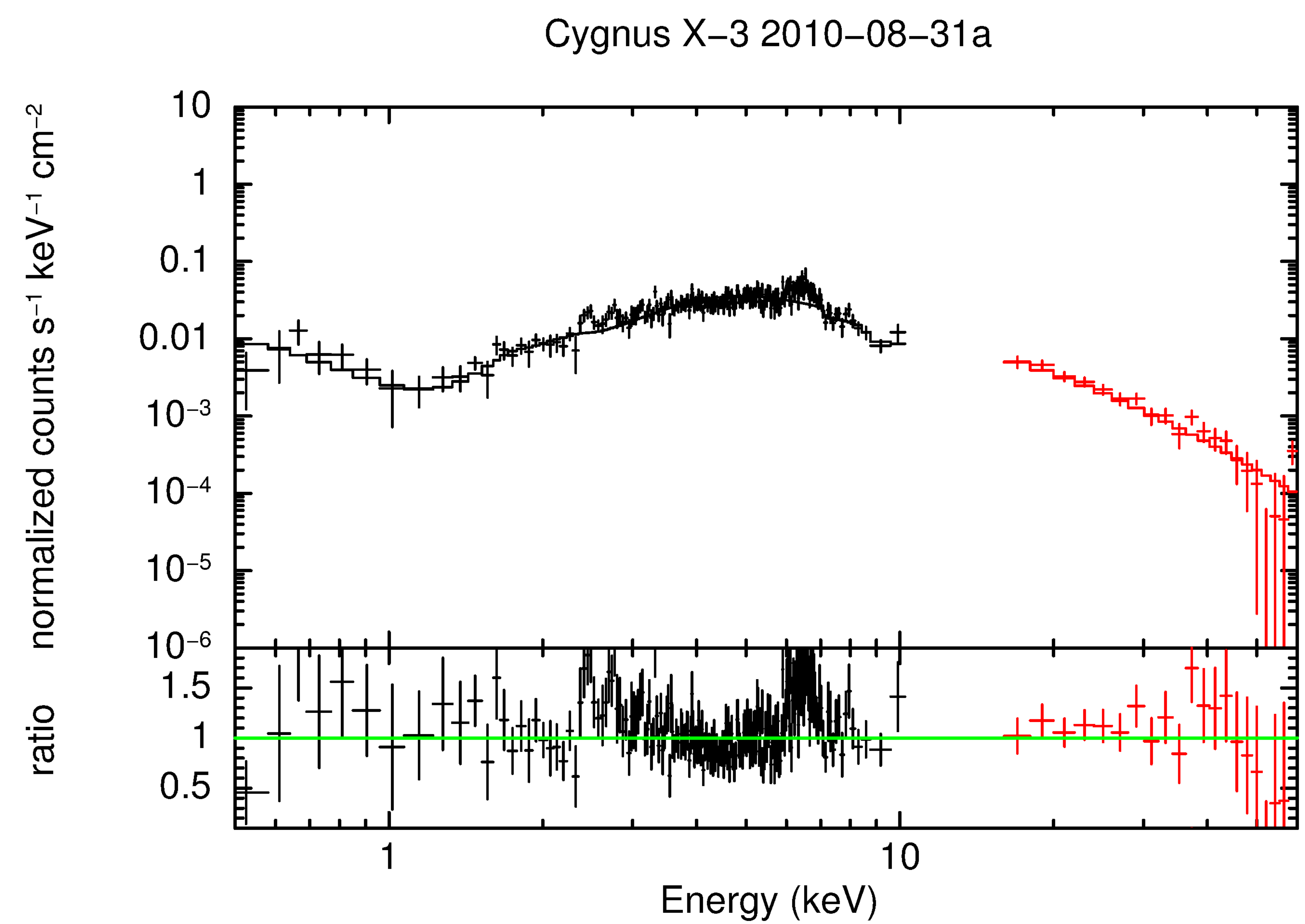
Suppressed / soft state before the quenching

Continuum model, extended to 0.5 keV

- The following continuum was fit between 0.5–60 keV:
  `constant*TBabs*pcfabs*edge*edge*CompPS`
  `+ TBabs*bbody`
- Cross-calibration / timing difference factor
- Interstellar absorption $n_H \sim 2 \cdot 10^{22} cm^{-2}$,
  variable partial covering absorption $n_H \sim 5\text{–}10 \cdot 10^{22} cm^{-2}$
- Iron absorption edges around 7 keV and 9 keV
- CompPS free parameters: kT_{bb}, kT_e, τ, normalization
  (+ power law index, minimum Lorenz factor at times when thermal Comptonization is insufficient for a fit)
- A soft blackbody component with the interstellar n_H tied was added to account for excess below 1 keV

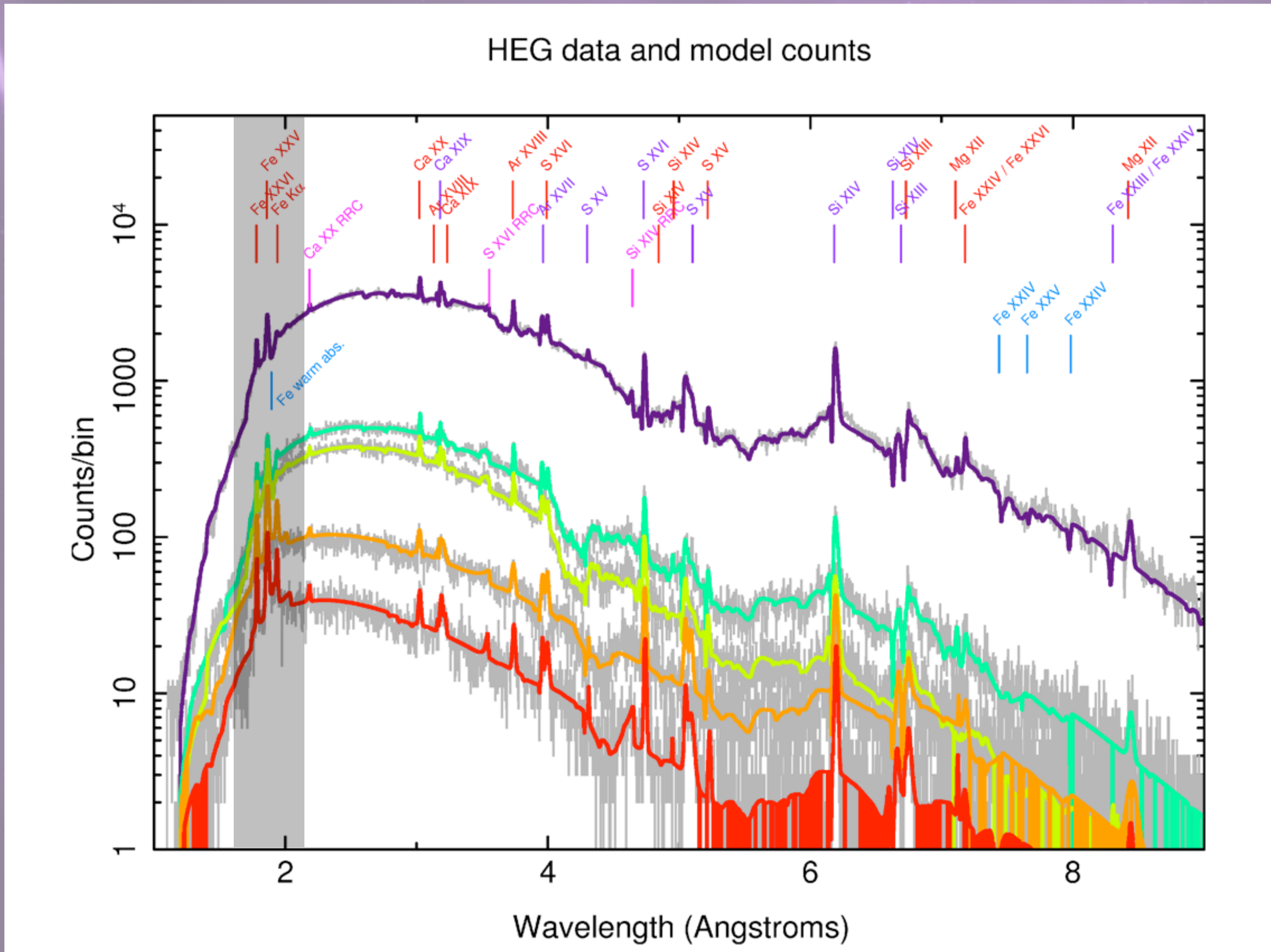
Most parameters depend mainly on *Swift*/XRT data

Line-like residuals at 2.5–4, 6–7 keV



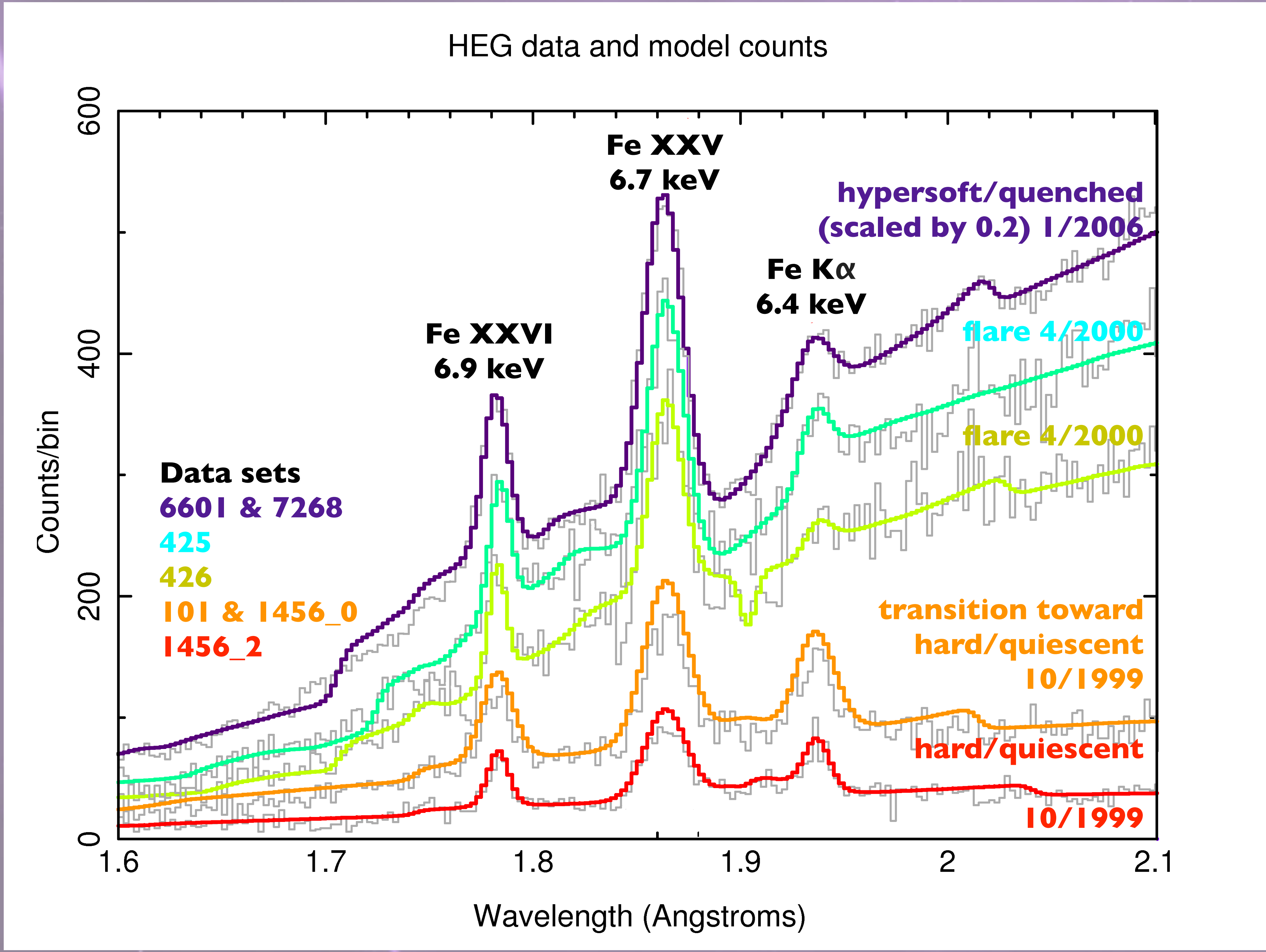
Quiescence / hard state

Line model from *Chandra* HETG spectra



Highly photoionized lines from Ar, Ca, Fe, Mg, S & Si

Chandra HETG spectra, iron region



Our other project looks at how the lines change with state and phase

Continuum model with lines

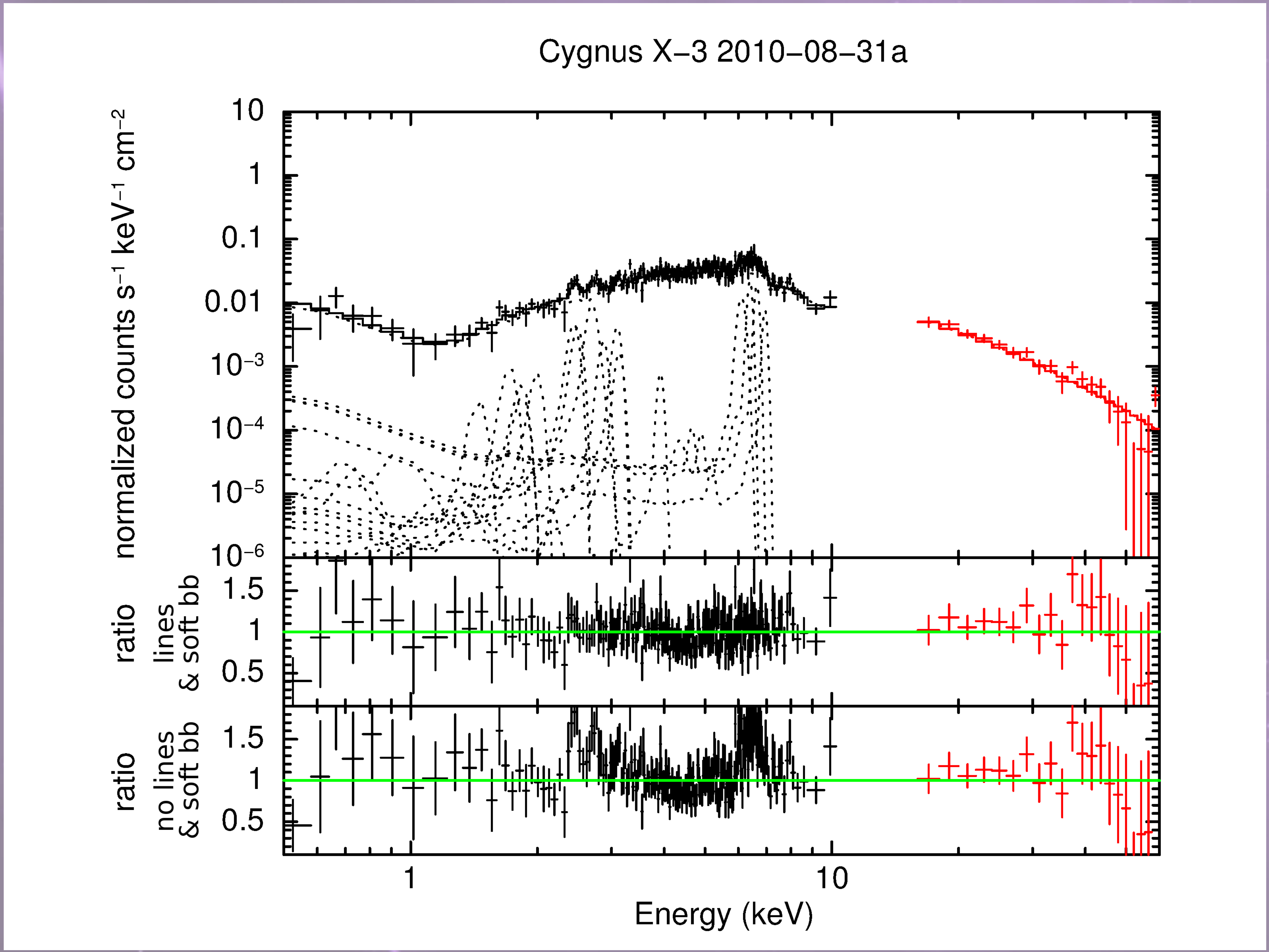
- With line components added, the model becomes:

```
constant*TBabs*pcfabs*edge*edge(compPS*gabs
*gabs*gabs*gabs*gabs*gabs*gabs*gabs*gabs*gabs*
gabs*gabs*gabs + gaussian + gaussian +
gaussian + gaussian + gaussian + gaussian +
gaussian + gaussian + gaussian + gaussian +
gaussian + gaussian + gaussian + gaussian +
gaussian + gaussian + gaussian + gaussian +
gaussian + gaussian + gaussian + gaussian +
redge + redge + redge) + TBabs*bbody
```

- The locations and widths of the line components were frozen to typical *Chandra* values
- ~55 free parameters, most of which only depend on a tightly limited range of energy channels

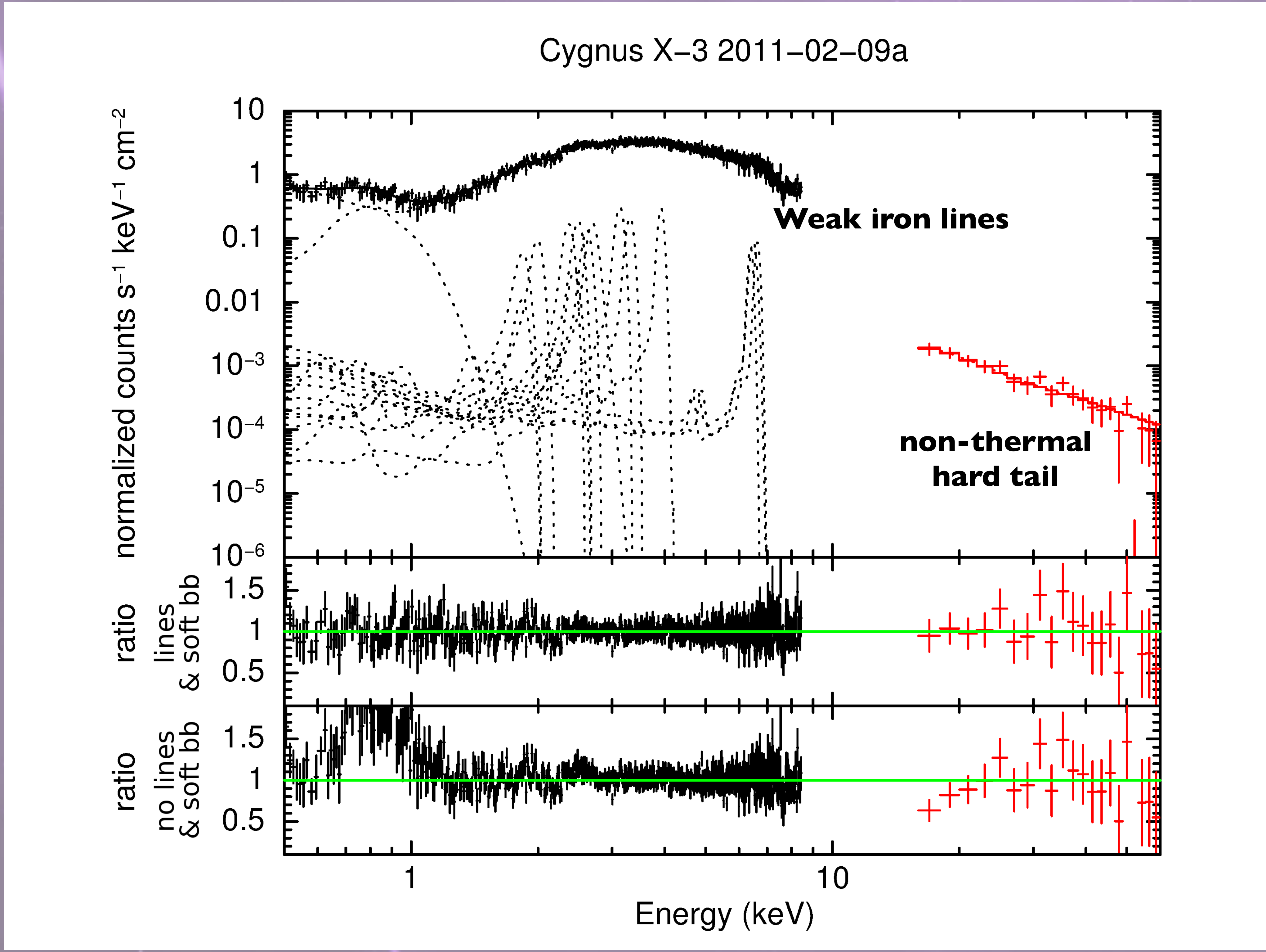
Most parameters depend mainly on *Swift*/XRT data

Inclusion of lines evens the residuals



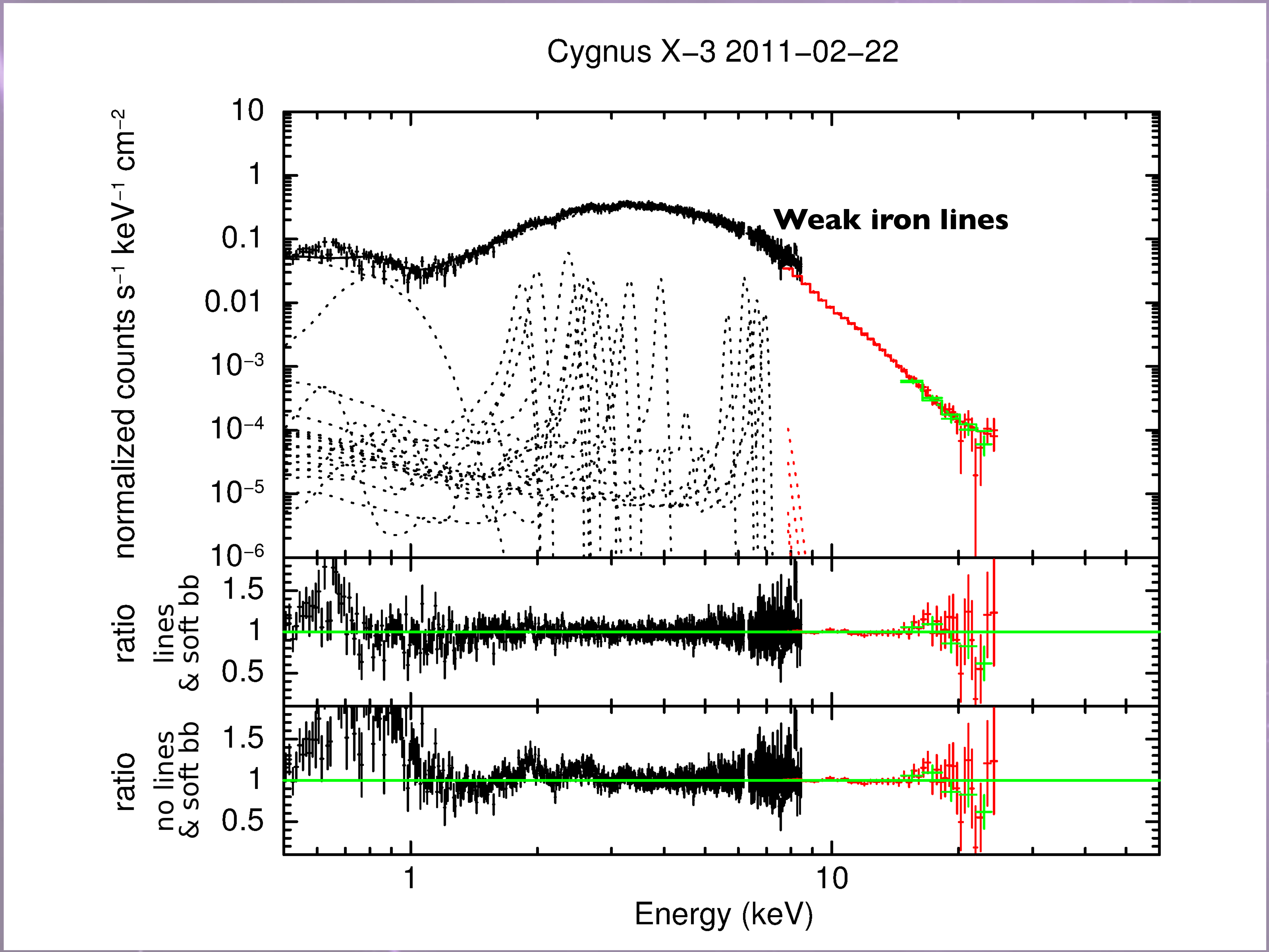
Quiescence / hard state

Soft blackbody and lines added



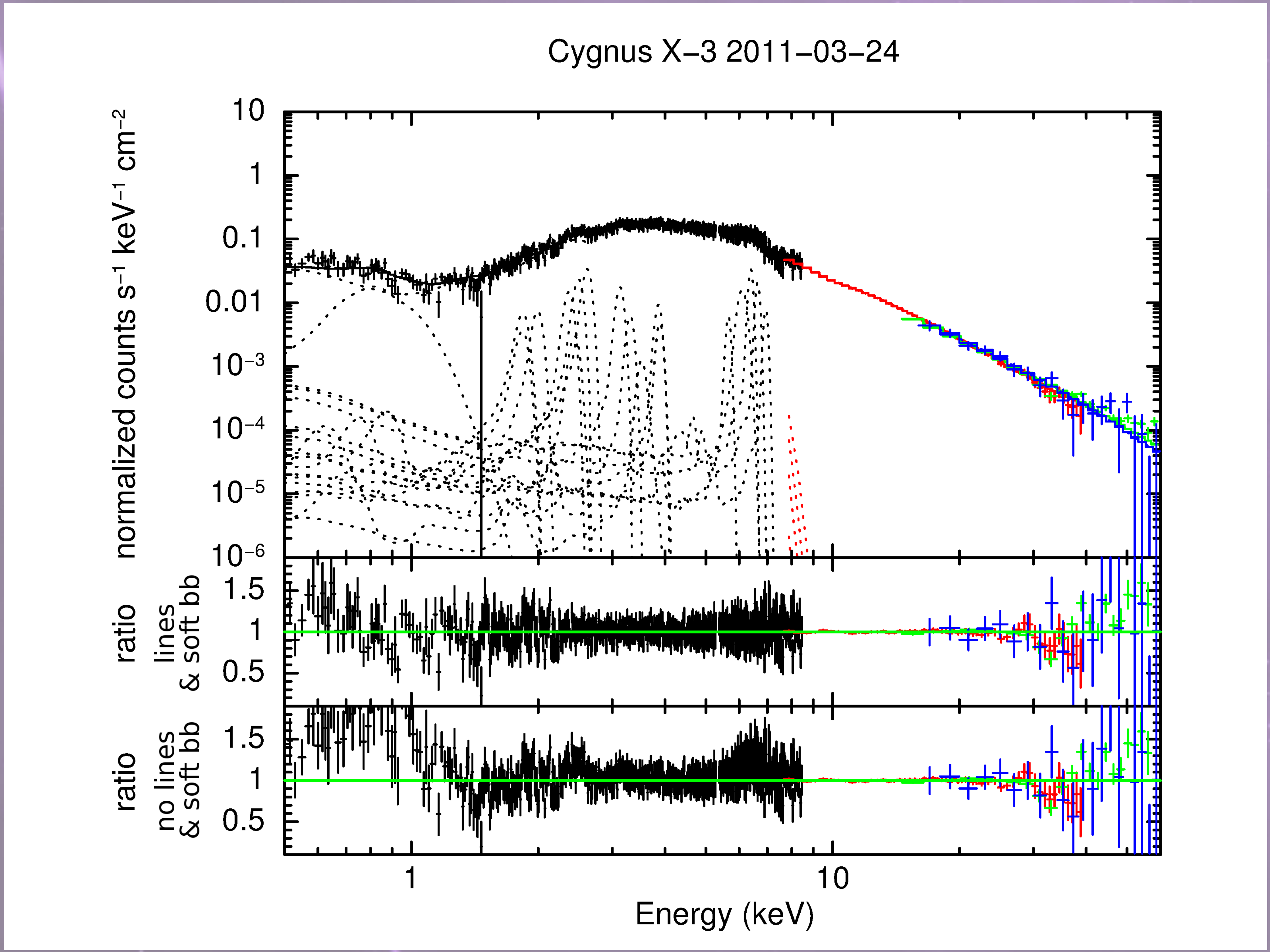
Suppressed / soft state before the quenching

Soft blackbody and lines added



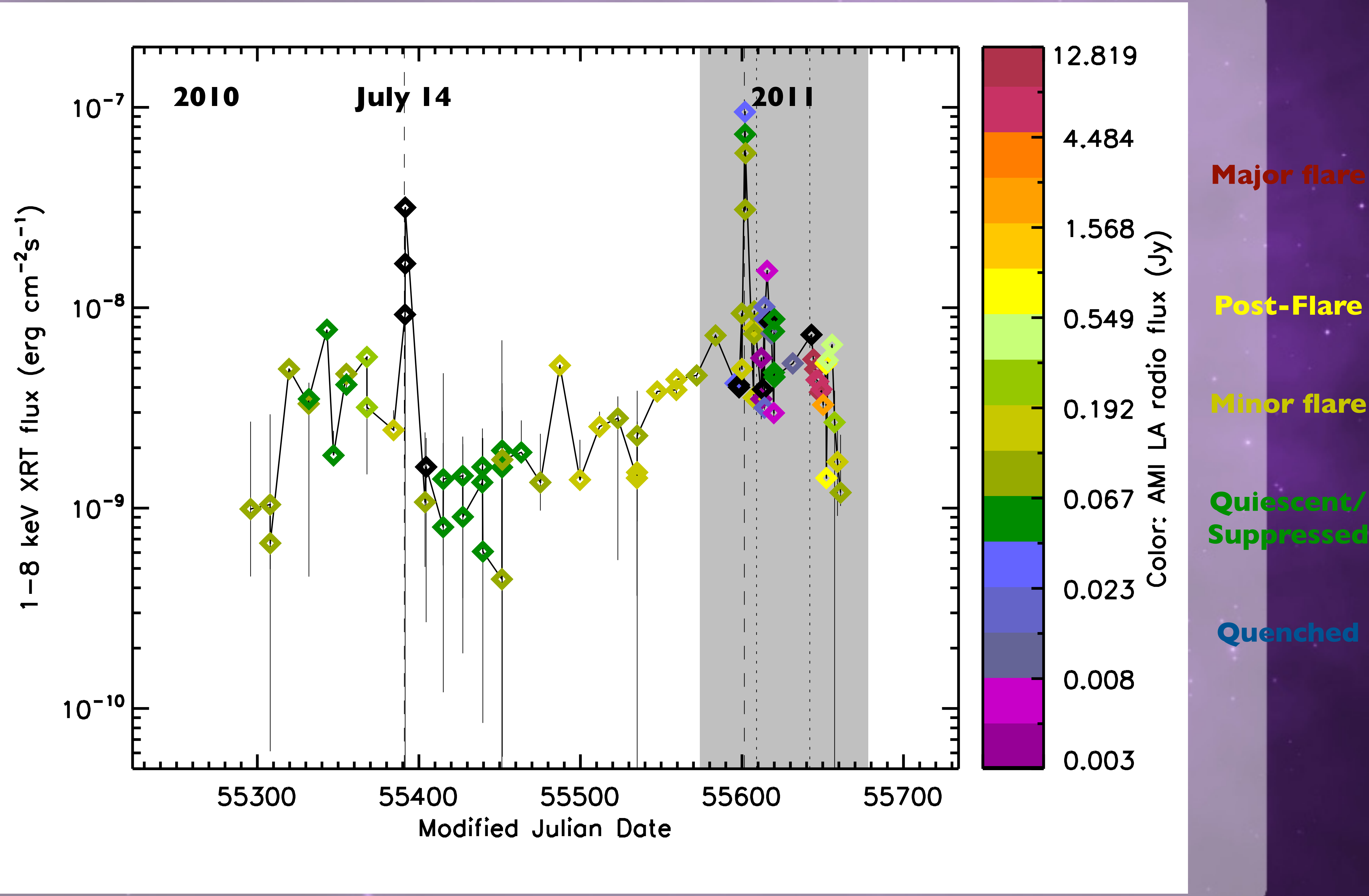
Quenching / hypersoft state

Soft blackbody and lines added



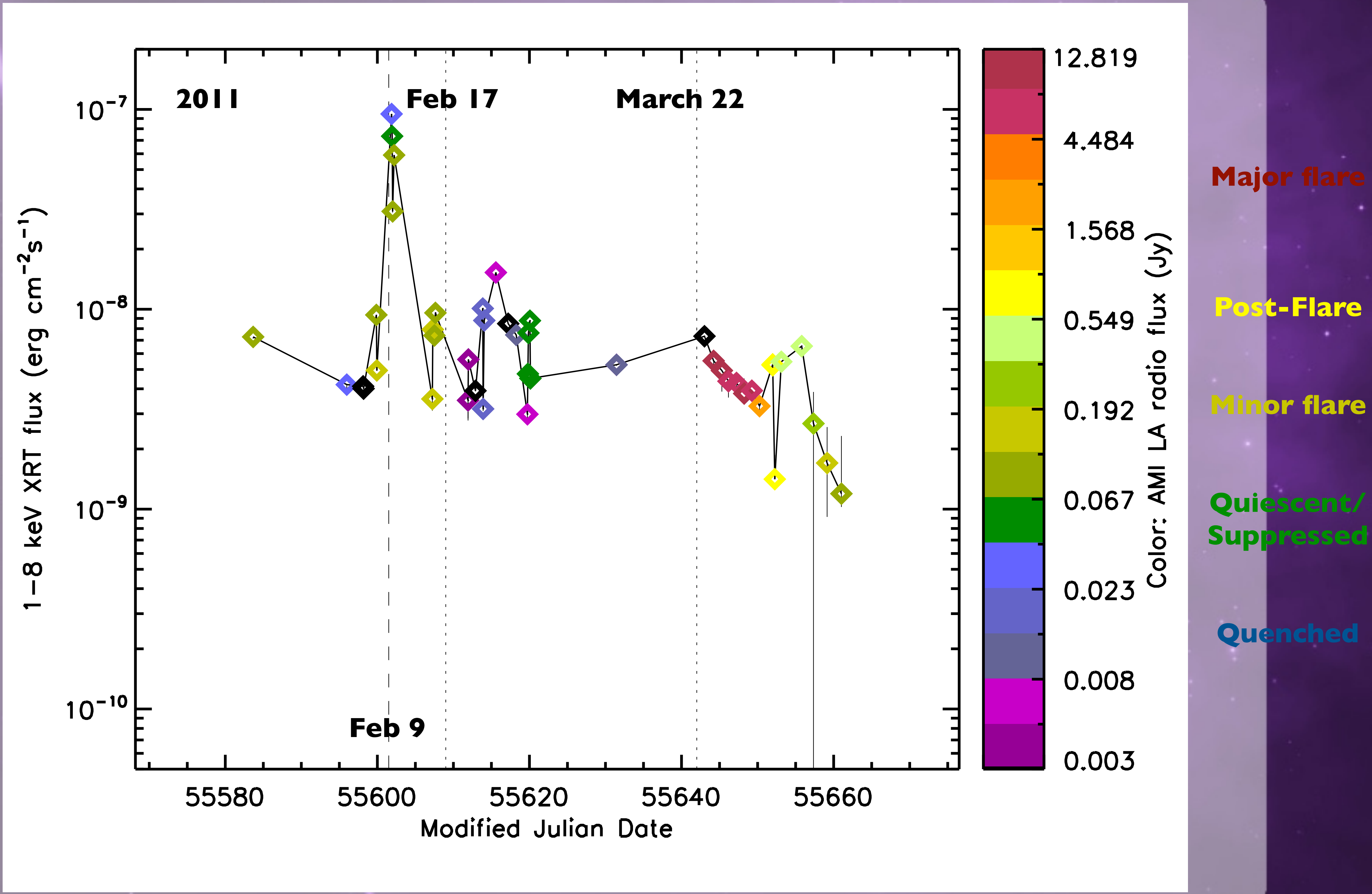
Near the peak of the major radio flare / soft state

XRT 1–8 keV flux vs. time



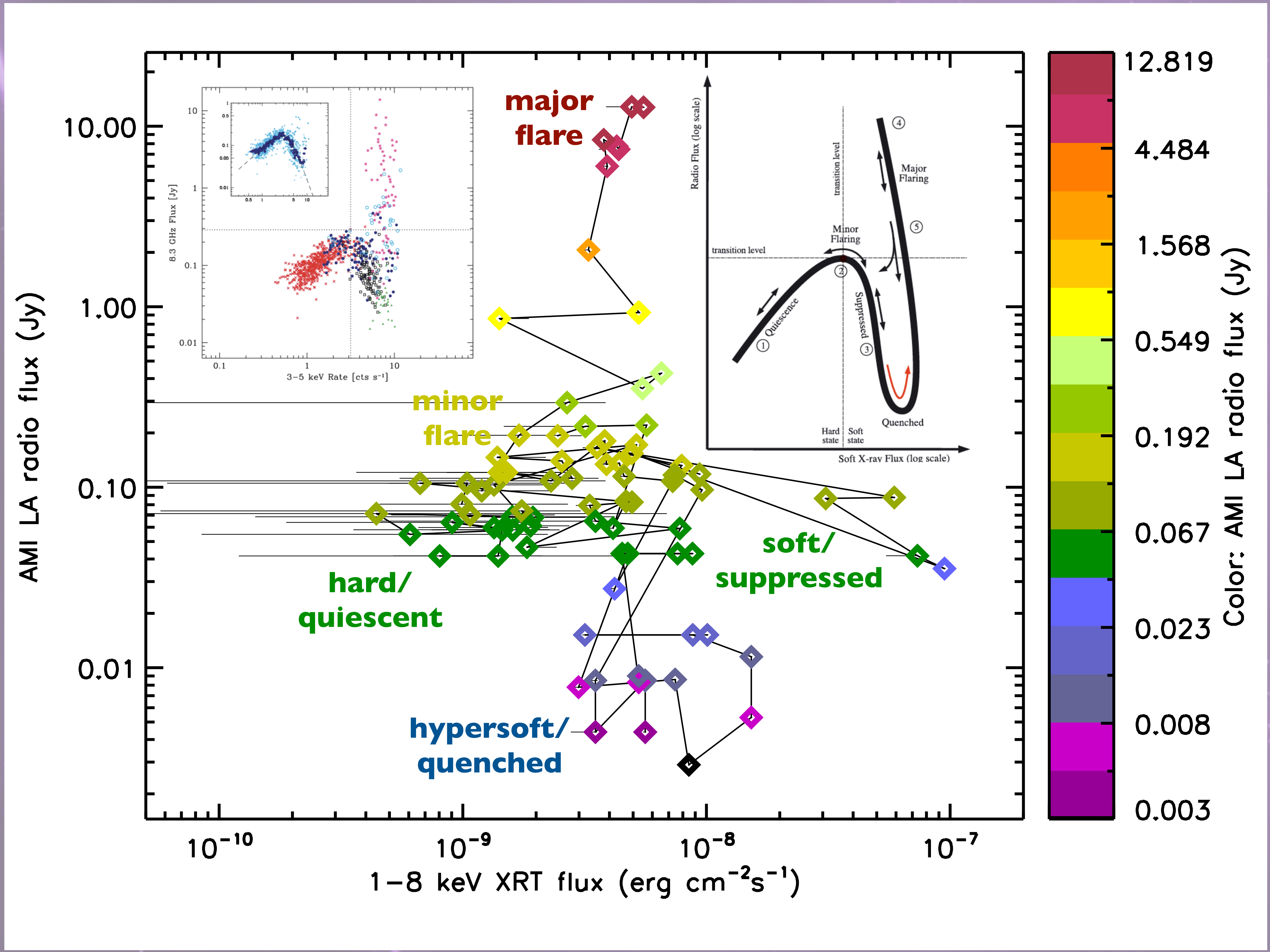
Soft X-ray flux peaked on July 14 and Feb 9

XRT 1–8 keV flux vs. time



Soft X-ray flux remained steady in quenching, then decayed

Radio flux vs. soft X-ray flux



Major flare

Post-Flare

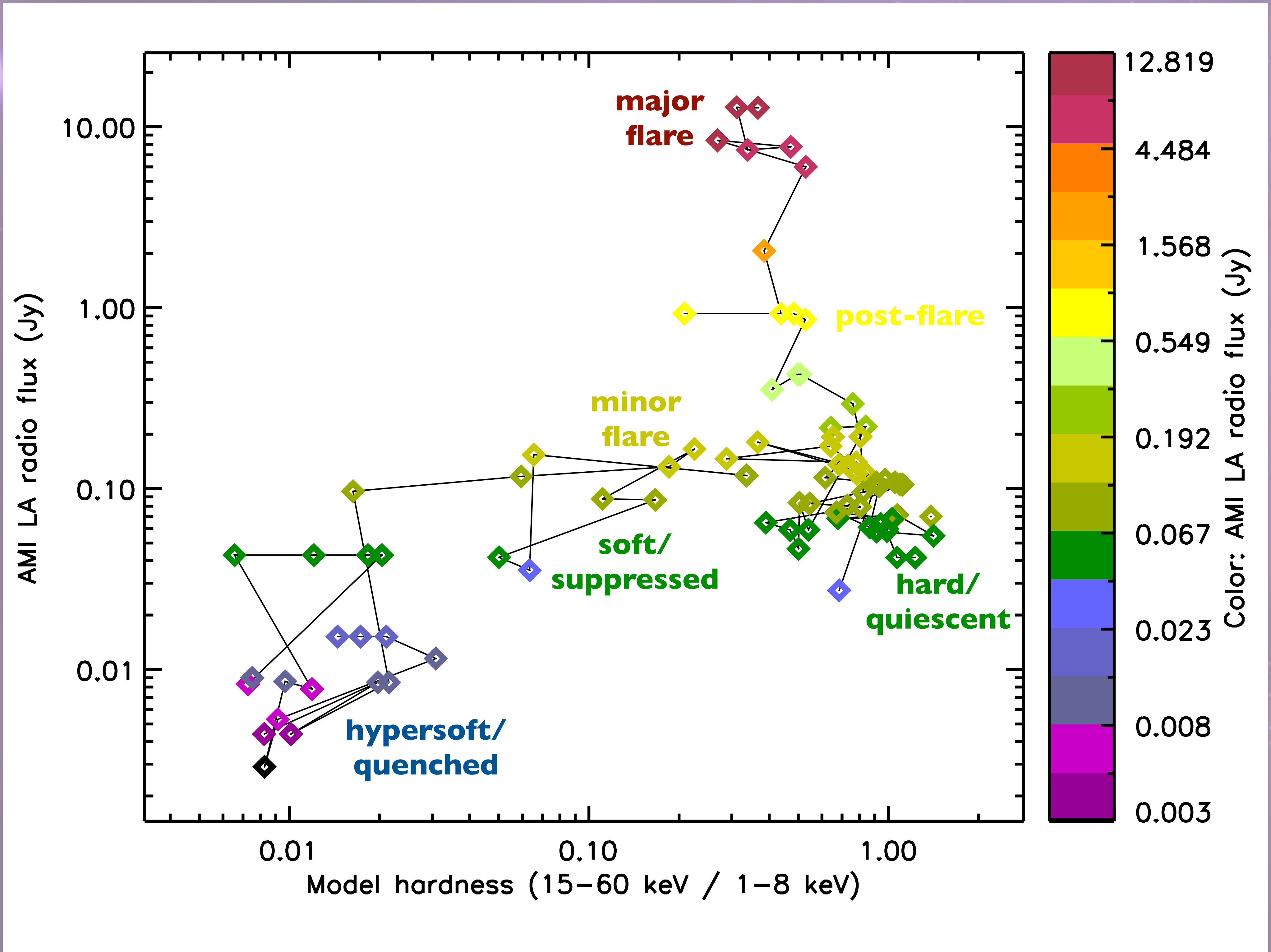
Minor flare

Quiescent/ Suppressed

Quenched

Comparison to Szostek, Zdziarski & McCollough 2008

Radio flux vs. X-ray hardness



Major flare

Post-Flare

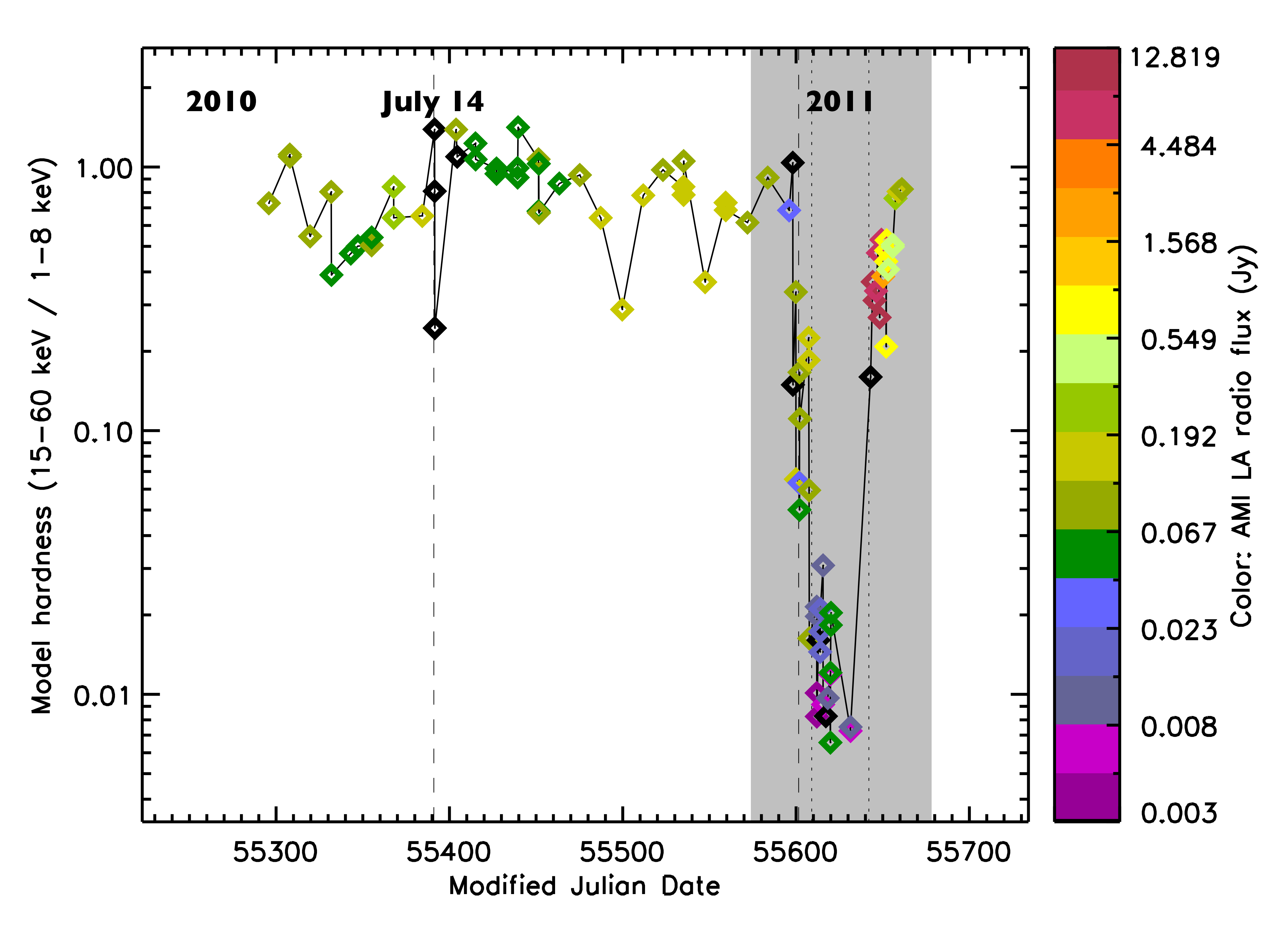
Minor flare

Quiescent/ Suppressed

Quenched

Another way of drawing the state diagram

X-ray hardness vs. time



Major flare

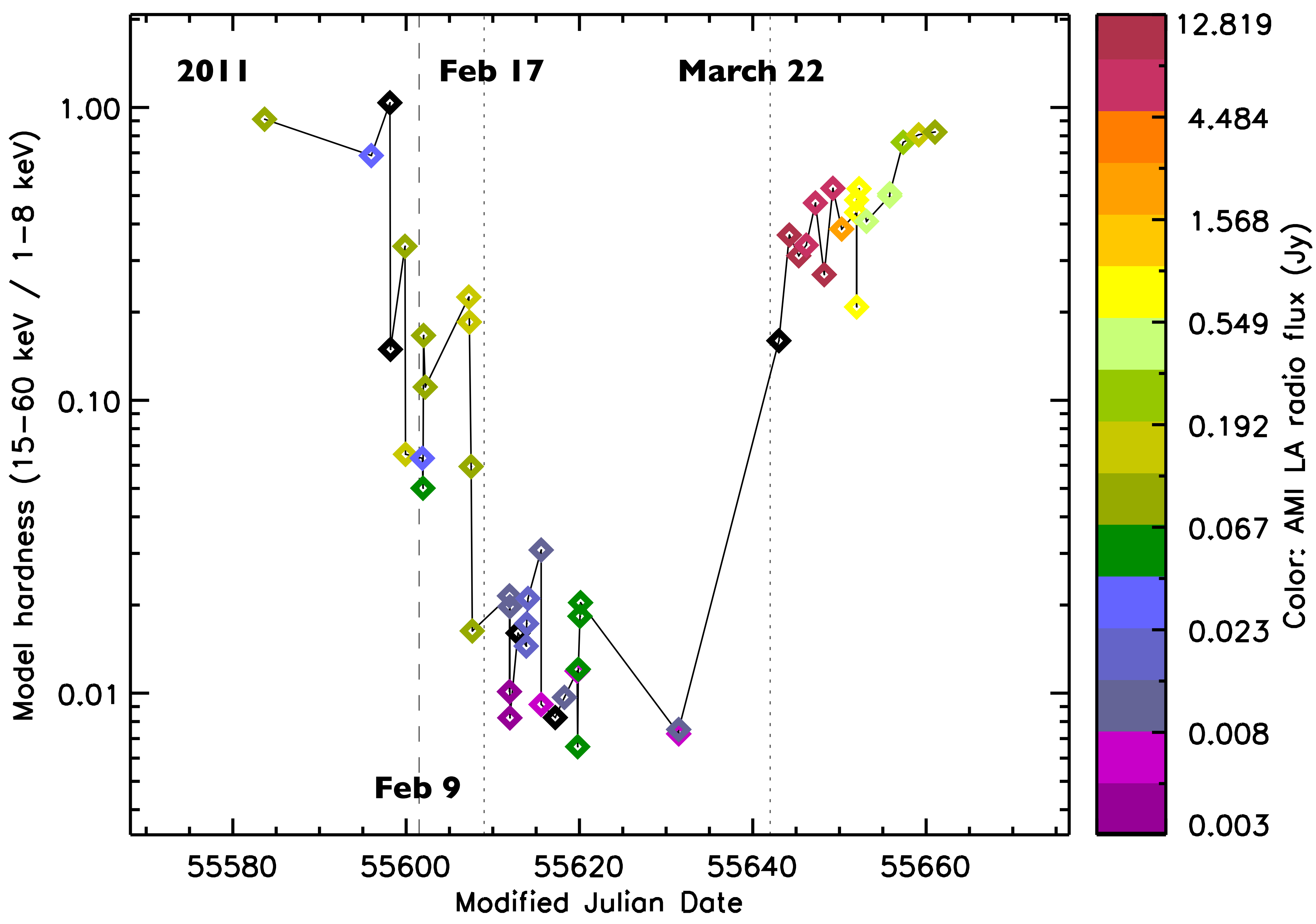
Post-Flare

Minor flare

Quiescent/ Suppressed

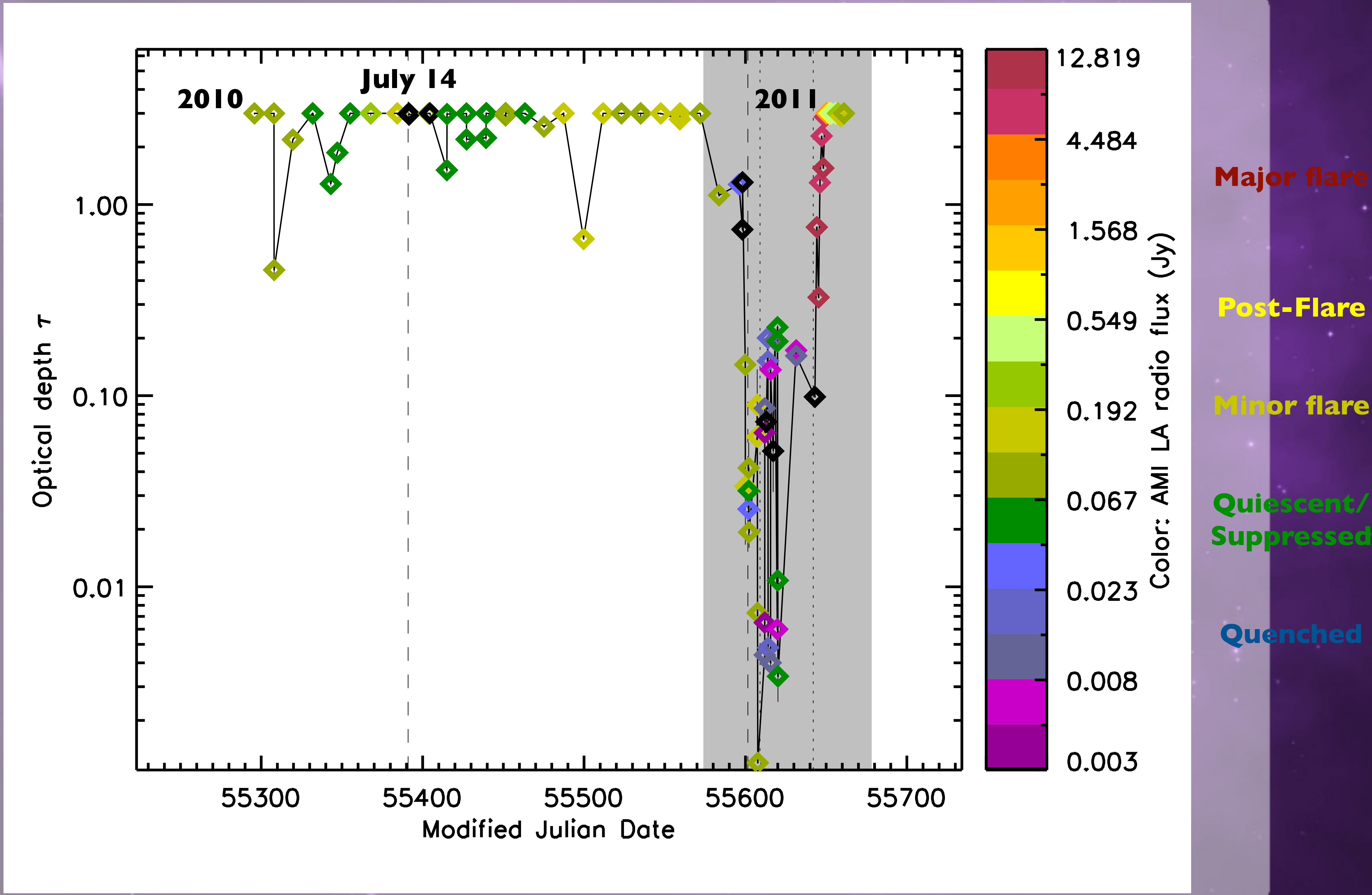
Quenched

X-ray hardness vs. time



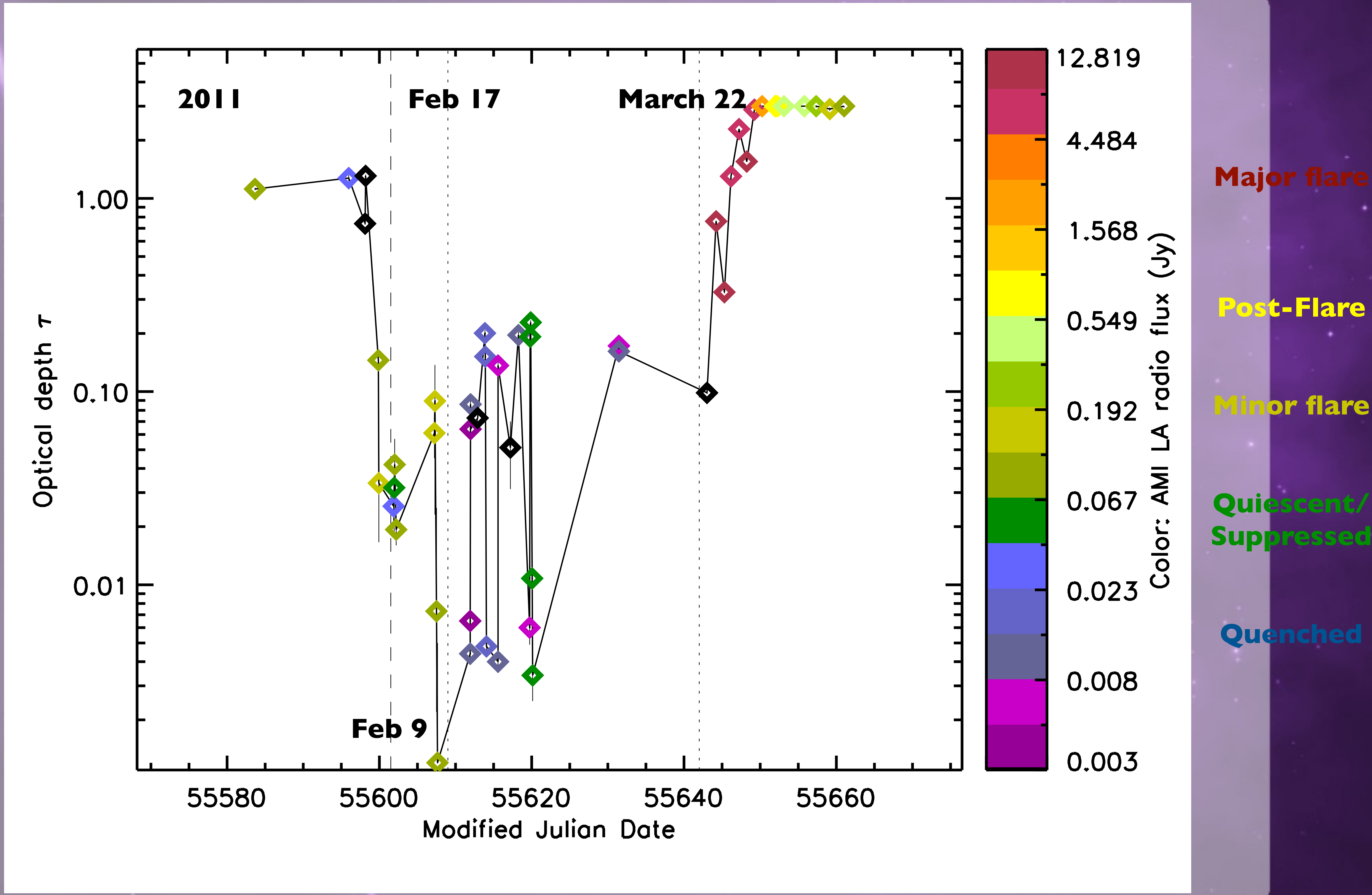
Hardness ratio kept increasing as the radio flare decayed

Compton optical depth vs. time



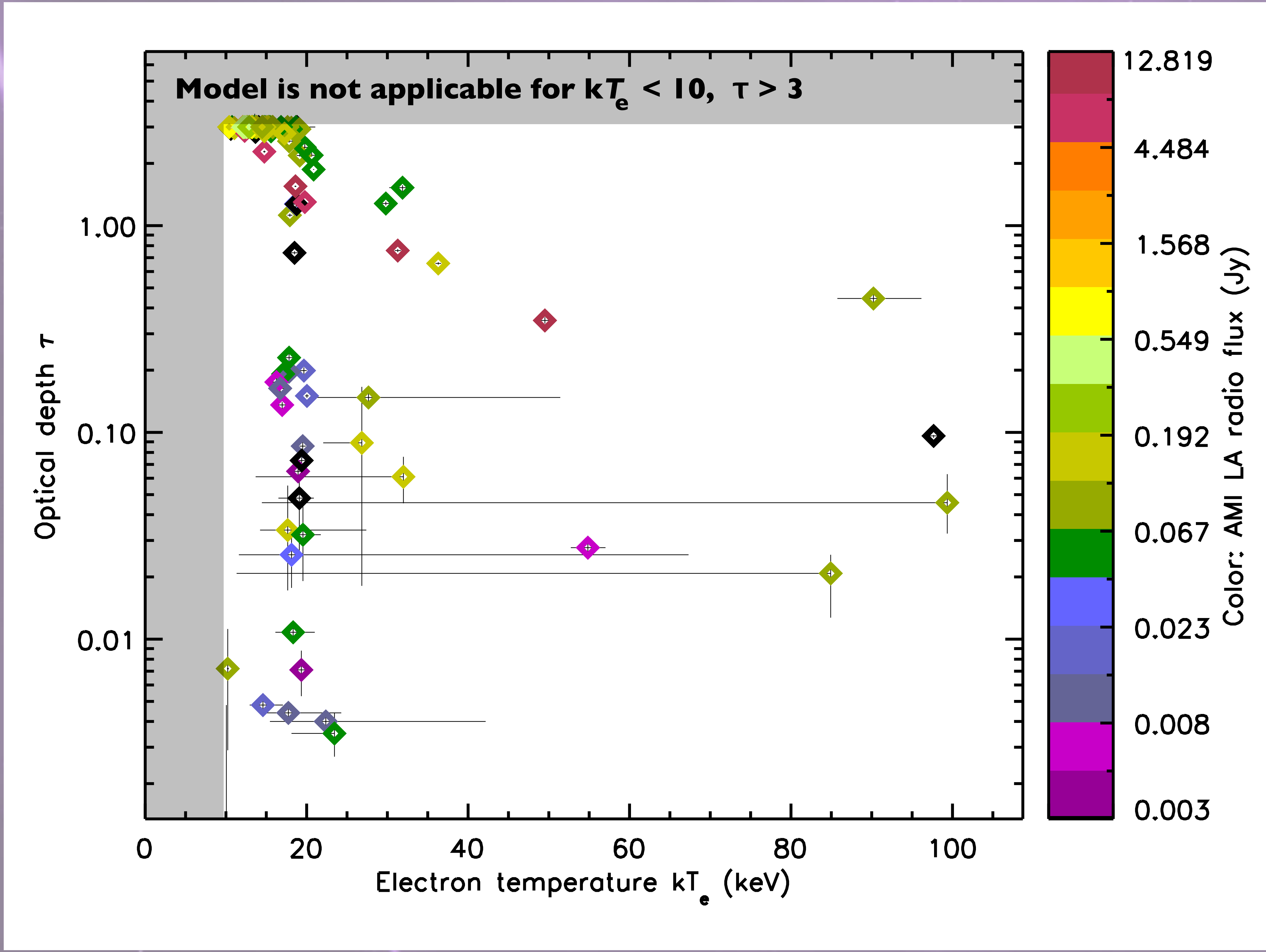
τ is the parameter mainly accounting for the hardness changes

Compton optical depth vs. time



Plasma went optically thin in suppressed state, thickened during flare

Compton optical depth vs. kT_e



Major flare

Post-Flare

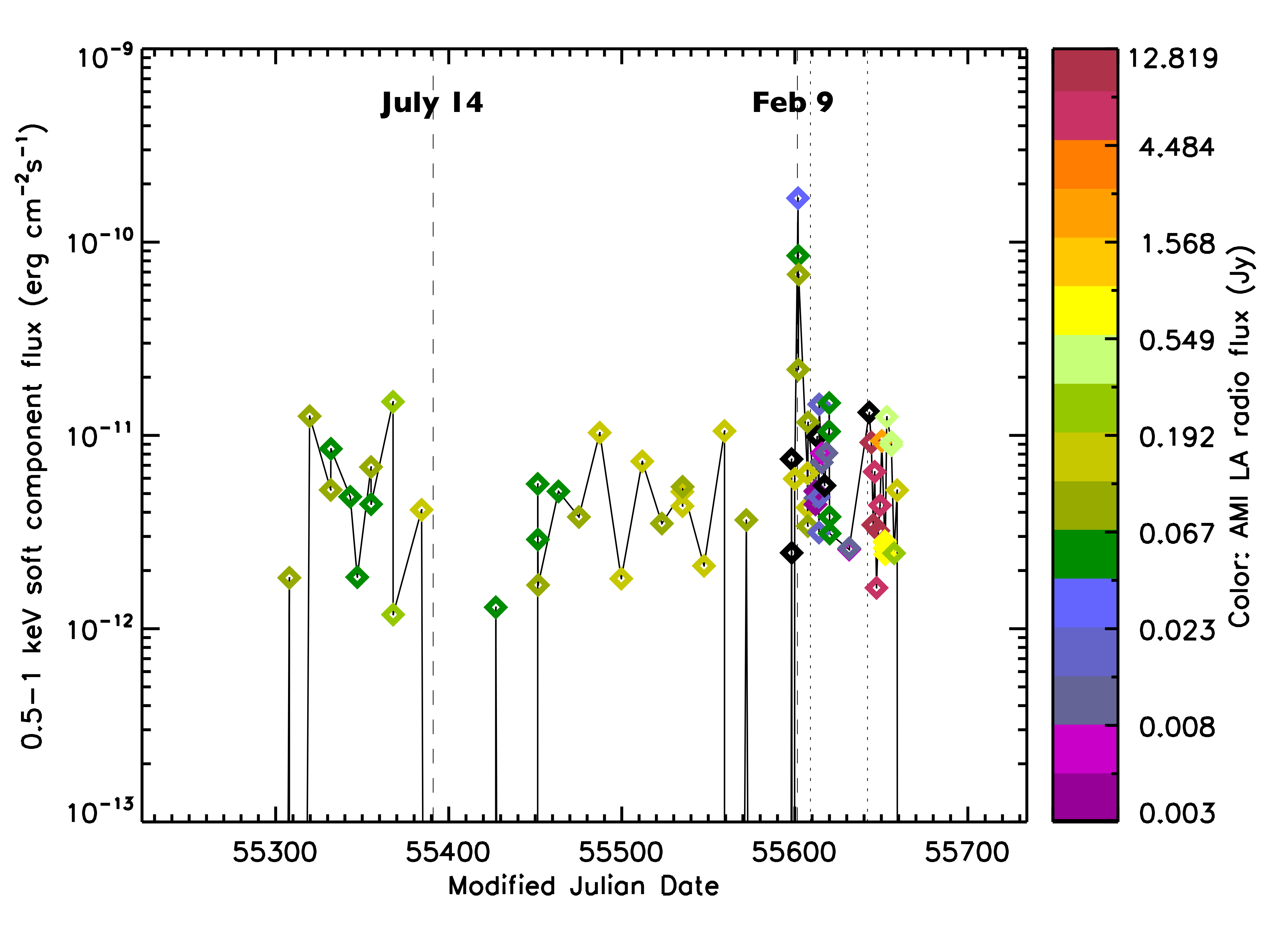
Minor flare

Quiescent/ Suppressed

Quenched

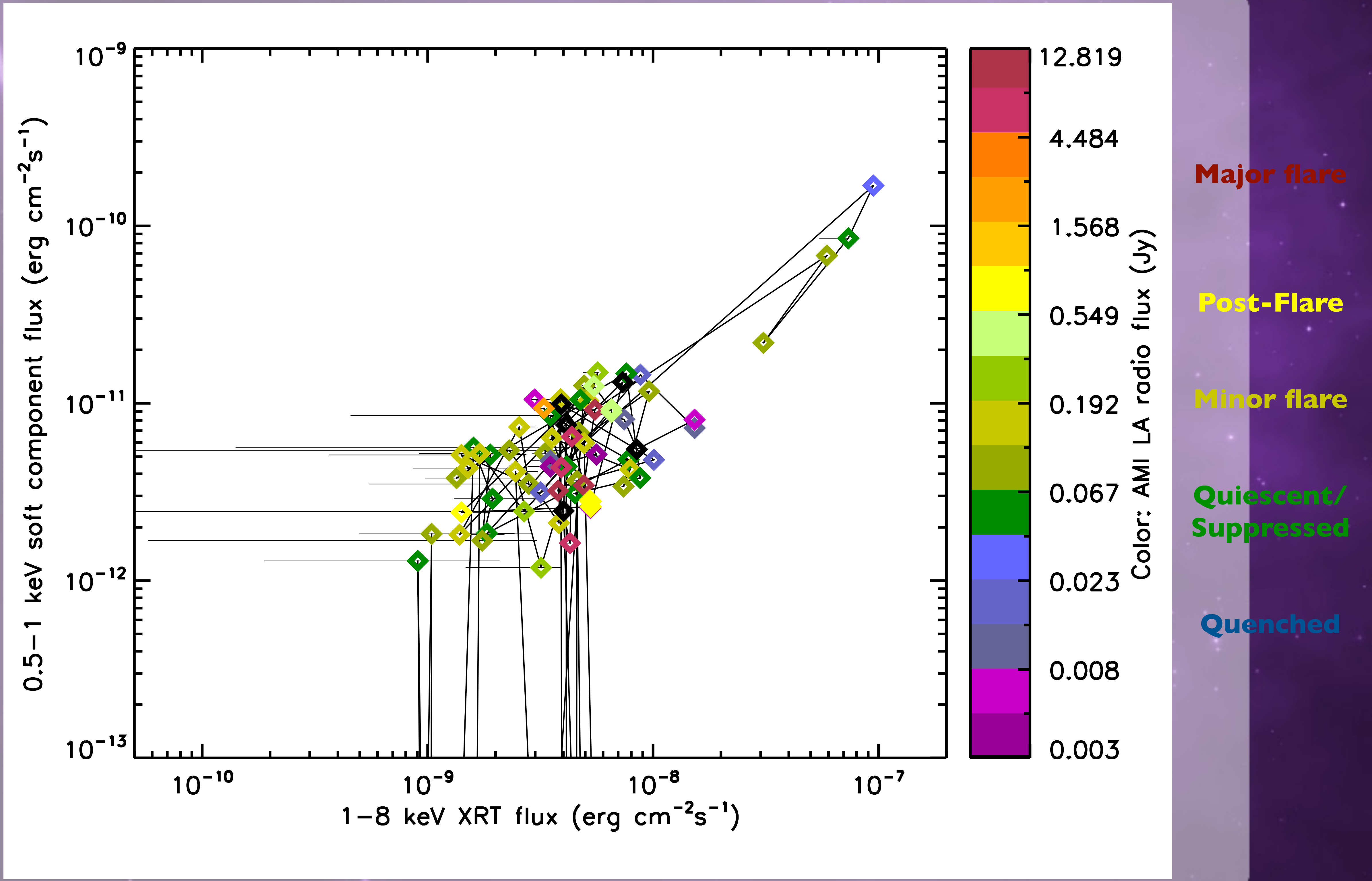
Comptonizing kT_e ~10–25 keV, state-independent

Soft component flux vs. time



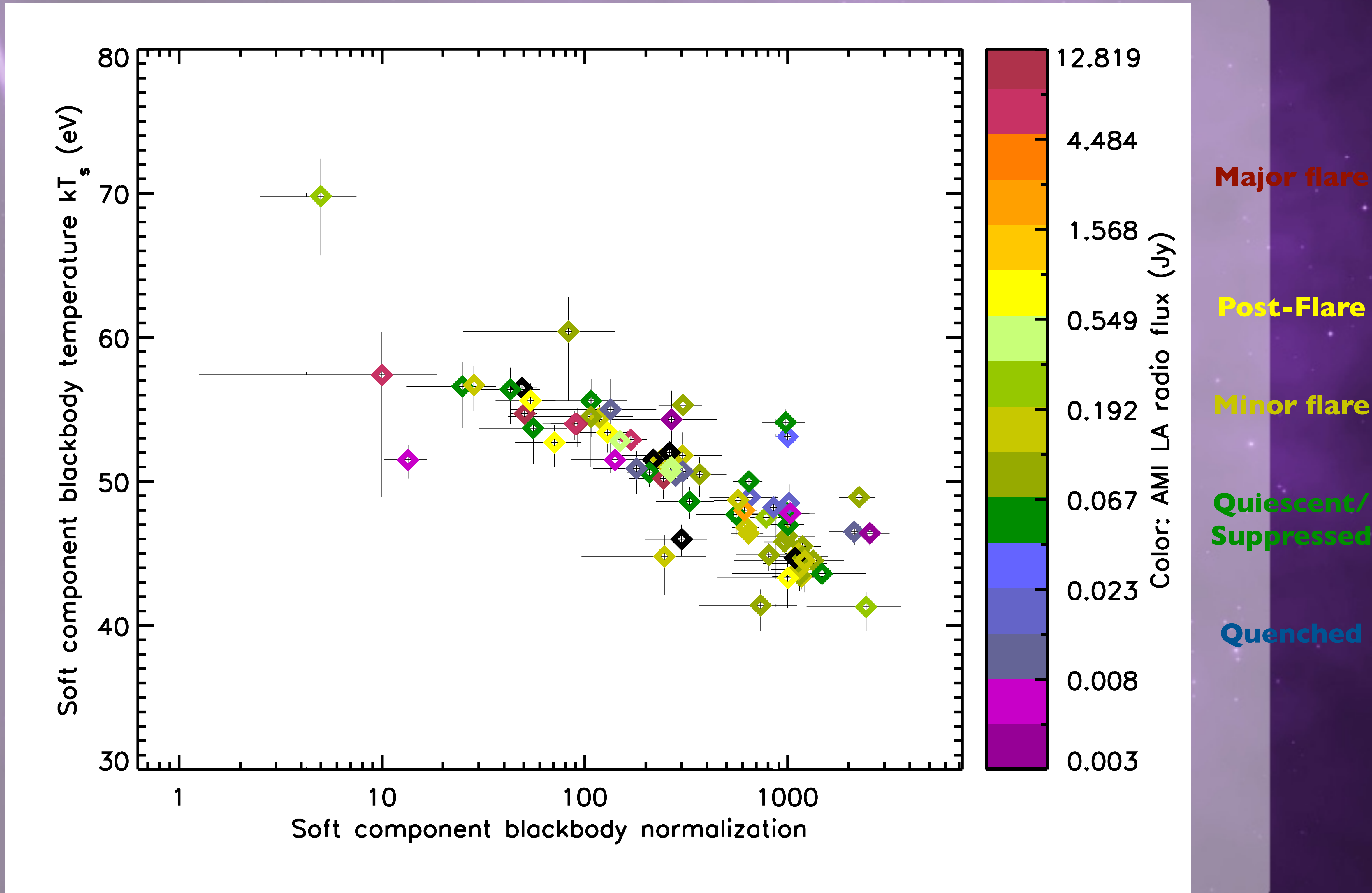
Often gone in quiescence, strong in suppressed state, otherwise stable

Soft component flux vs. 1–8 keV flux



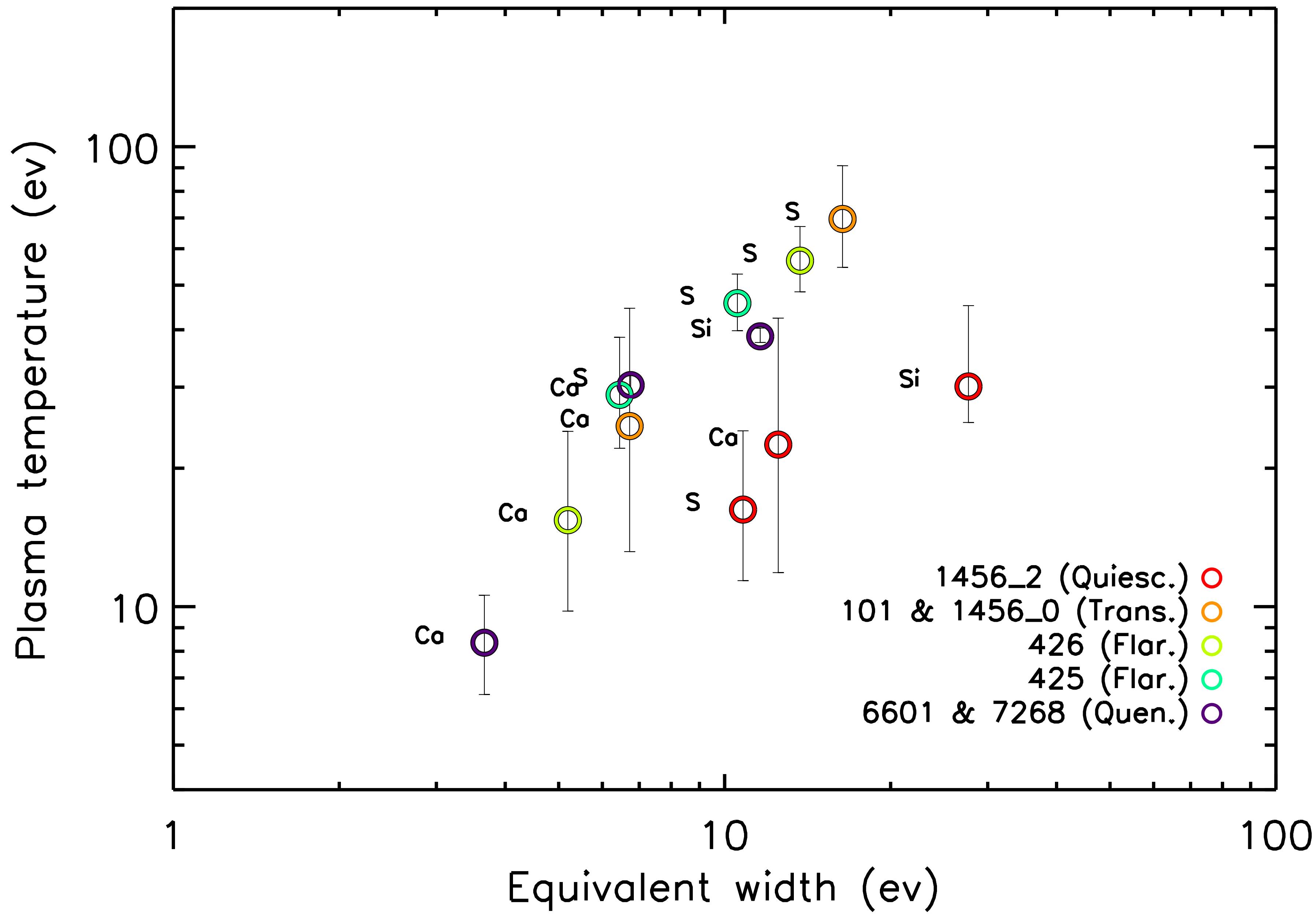
Strong correlation in the soft/suppressed state, weaker otherwise

Soft component parameters



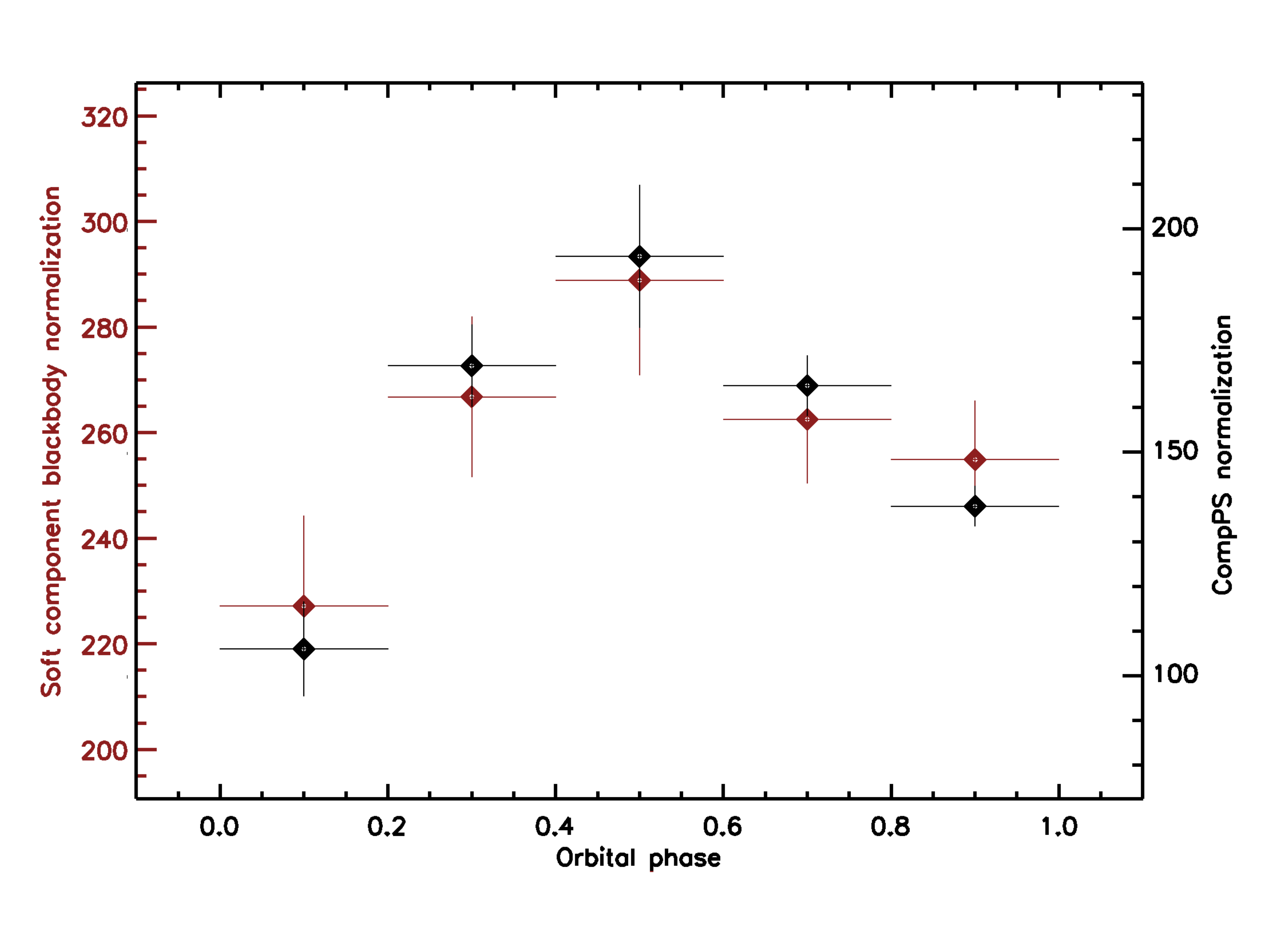
Soft component temperature was consistently at ~40–60 eV

Plasma k*T* from *Chandra* RRC fits



RRCs reveal that photoionized plasma at k*T* ~10–100 eV is present

Soft bb norm is orbitally modulated



The soft component comes from the inner part of the system

Summary (I)

- We have observed and modeled the X-ray spectrum of Cygnus X–3 over a full year of activity, during which the source went through the complete pattern of spectral states
- The X-ray continuum emission of Cygnus X–3 up to 60 keV can be successfully modeled with a disk blackbody Comptonized by a thermal electron plasma of kT_e ~20 keV, optically thick during quiescence and minor flaring, thinning as the source approaches the quenched state and thickening during major flares. Non-thermal emission was occasionally present. Reflection, while by no means excluded, is not necessary for our model
- The fits are improved by taking into account the presence of unresolved line features

Summary (2)

- **This study is the first extensive study of Cygnus X–3 to include the 0.5–3 keV energy range, essential for constraining the absorption components, the disk blackbody temperature, and the soft emission**
- **Most XRT spectra of Cygnus X–3 contain a soft excess at 0.5–1 keV, which can be modeled with a 40–60 eV blackbody or Bremsstrahlung. This temperature range is consistent with the RRCs seen in *Chandra* spectra**
- **The soft component is modulated in phase and correlated with the main continuum component**
- **We conclude that the soft component originates from blackbody or Bremsstrahlung emission in the Wolf-Rayet wind, in the vicinity of the compact object**