A Contemporaneous *Chandra* HETG and *Suzaku* Observation of NGC 4051

Andrew Lobban

Milano, Italy, 05/04/2011

Keele University,

United Kingdom

In collaboration with:

- James Reeves; Keele University, UK
- Lance Miller; University of Oxford, UK
- Jane Turner; University of Maryland Baltimore County, USA
- Valentina Braito; University of Leicester, UK
- Mike Crenshaw; Georgia State University, USA
- Steve Kraemer; The Catholic University of America, USA

A deep study of NGC 4051 with *Chandra* and *Suzaku*

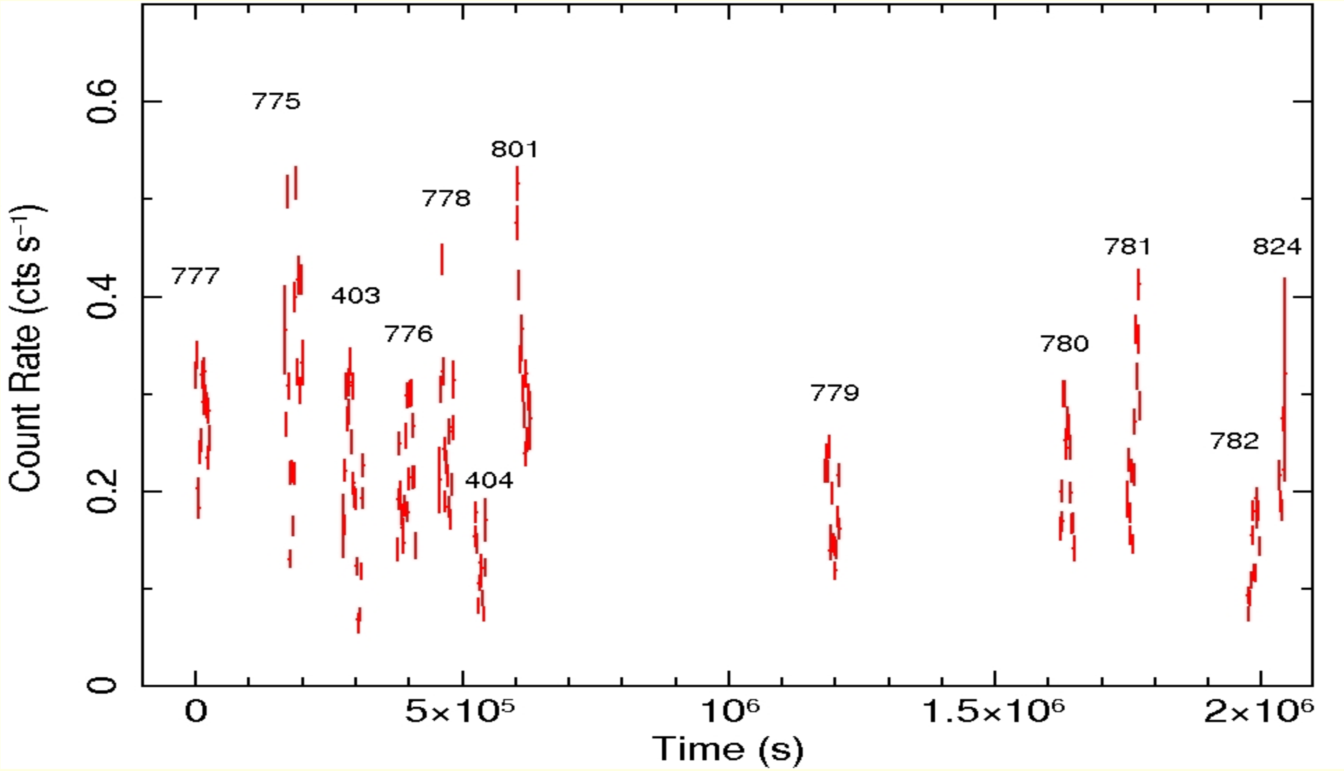
- Narrow-line Seyfert Type 1
- $M_{BH} = (1.7 \pm 0.5) \times 10^6 M_\odot$ (Denney et al. 2009)
- $z = 0.002336$ (nearby)
- 15.2 Mpc (Tully-Fisher)
- $L_{bol} \sim 7 \times 10^{43}$ erg s^{-1} (Ogle et al. 2004)
- $L / L_{EDD} \sim 30\%$

- Warm absorber (Collinge et al. 2001; Ogle et al. 2004; Krongold et al. 2007; Steenbrugge et al. 2009)
- Extreme X-ray variability on short and long timescales (occasionally falls into extended period of low flux)
- Observed X-ray spectrum hardens as source flux drops (also see NGC 5506; Lamer, Uttley & McHardy 2000 and MCG-6-30-15; Vaughan & Edelson 2001)

Chandra HETG Light Curve

- November 2008 (exp. ~300 ks)
- 1.0-6.0 keV energy range
- 2ks bins

- MEG: $\Delta\lambda$ = 0.01Å;
  HEG: $\Delta\lambda$ = 0.005Å
- Galactic absorption: N_H = 1.35 x 10^{20} cm^{-2}



NGC 4051 Warm Absorber

- 21 statistically significant absorption lines (O VI, O VII, O VIII, Ne VIII, Ne IX, Ne X, Mg XI, Mg XII, Si XIII)
- Plus L-shell transitions from Fe XVII-XXII
- Some appear to be resolved (FWHM ~ 600 km s^{-1}); mean FWHM = 581 ± 59 km s^{-1}; σ = 211 km s^{-1}
- All appear to be outflowing (v_{out} < -1000 km s^{-1}); mean v_{out} = -(617 ± 34) km s^{-1}; σ = 152 km s^{-1}
- 7 narrow emission lines ([O VII], O VIII, [Ne IX], Ne IX, Ne X, Mg XII, [Si XIII])
- O VIII and Mg XII appear to be P-Cygni-like in appearance
- All lines significant at >99.9 % for two parameters of interest

NGC 4051 Warm Absorber

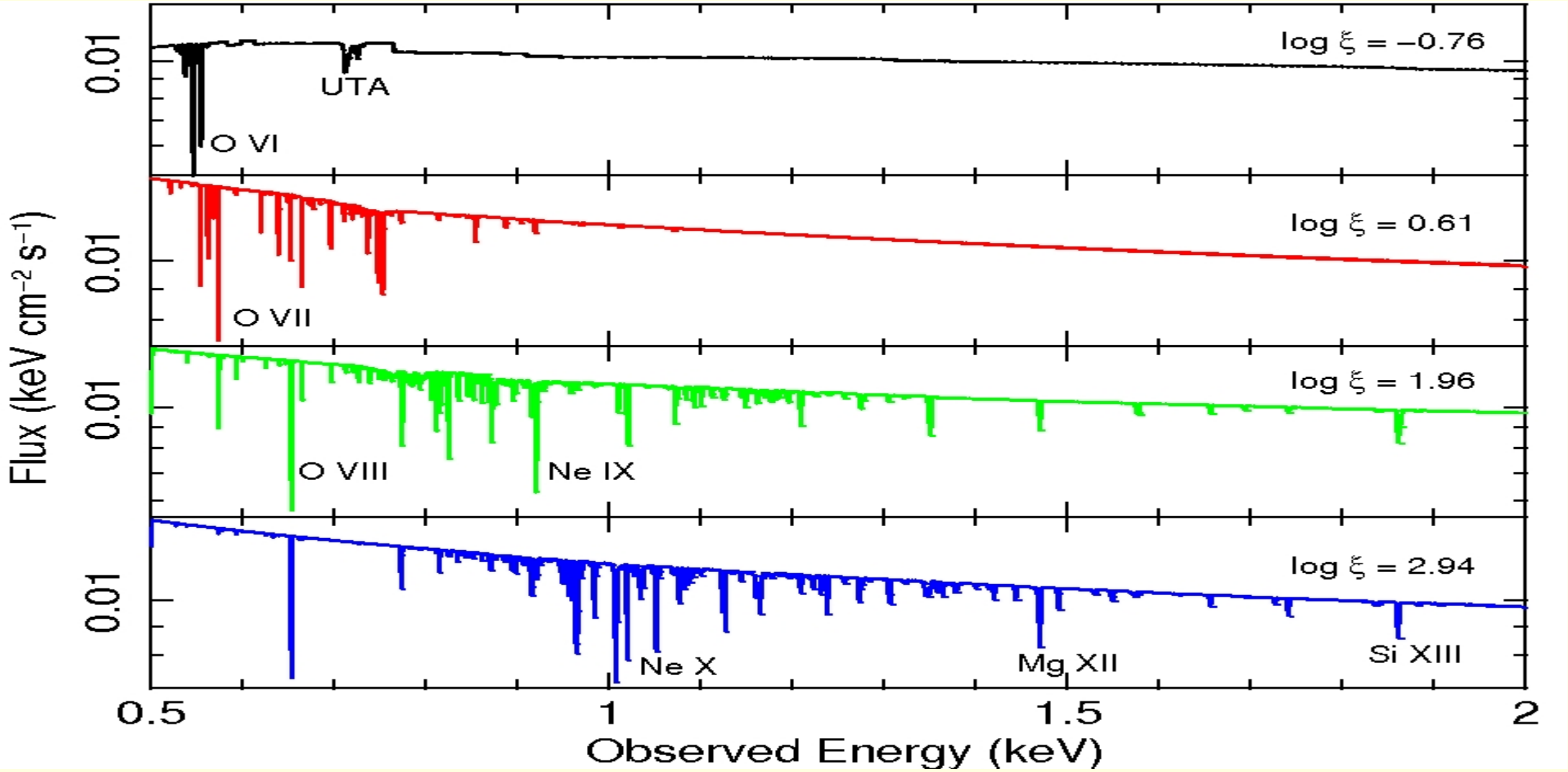
- Attempt to model the warm absorber using XSTAR (Kallman & Bautista 2001)
- Assumes thin shells of absorbing gas and self-consistently models zones of absorption parameterised by column density, N_H, and ionisation parameter: $\xi = L_{ion} / nR^2$

- Require four individual ionisation zones of absorption:
- Zone 1: log ξ = -0.76; v_{out} = -(180 ± 30) km s^{-1}
- Zone 2: log ξ = 0.61; v_{out} = -(200 ± 50) km s^{-1}
- Zone 3a: log ξ = 1.96; v_{out} = -(820 ± 40) km s^{-1}
- Zone 3b: log ξ = 2.09; v_{out} = -(550 ± 30) km s^{-1}
- Zone 4: log ξ = 2.94; v_{out} = -(710 ± 60) km s^{-1}

- All column densities on the order of 10^{20} – 10^{21} cm^{-2}

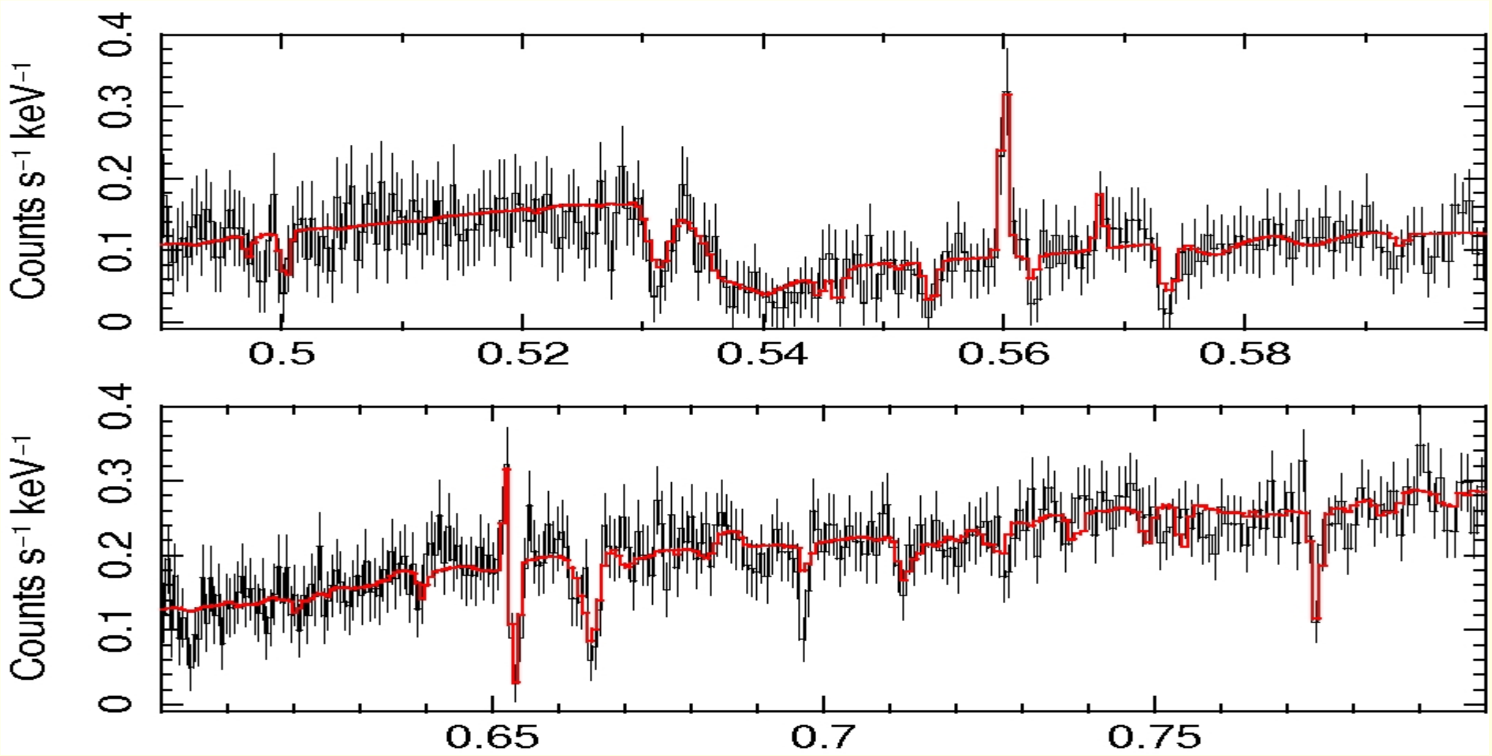
HETG XSTAR Zones

- Contribution of each individual zone
- Zones 1 and 2 may coincide with UV zones observed with HST (Kraemer et al. 2011 in prep.)

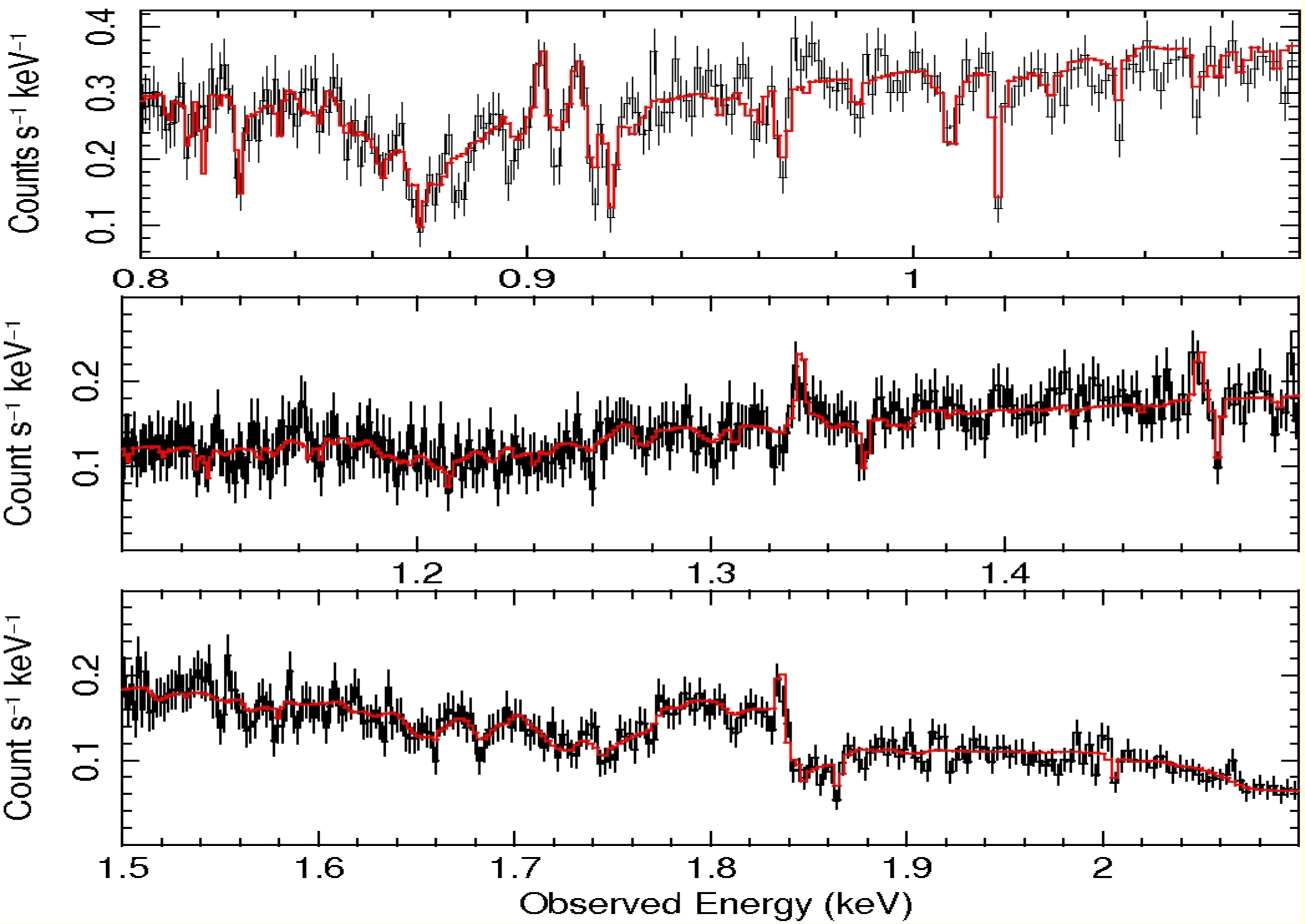


HETG Warm Absorber Model

- Also allow for the presence of a partial-coverer (continuum shape; additional power-law component absorbed by XSTAR zone; Γ tied; norm. free to vary): $N_H \sim 10^{23}$ cm-^{2}; log ξ < 2.4
- $f_{cov} \sim 30\%$

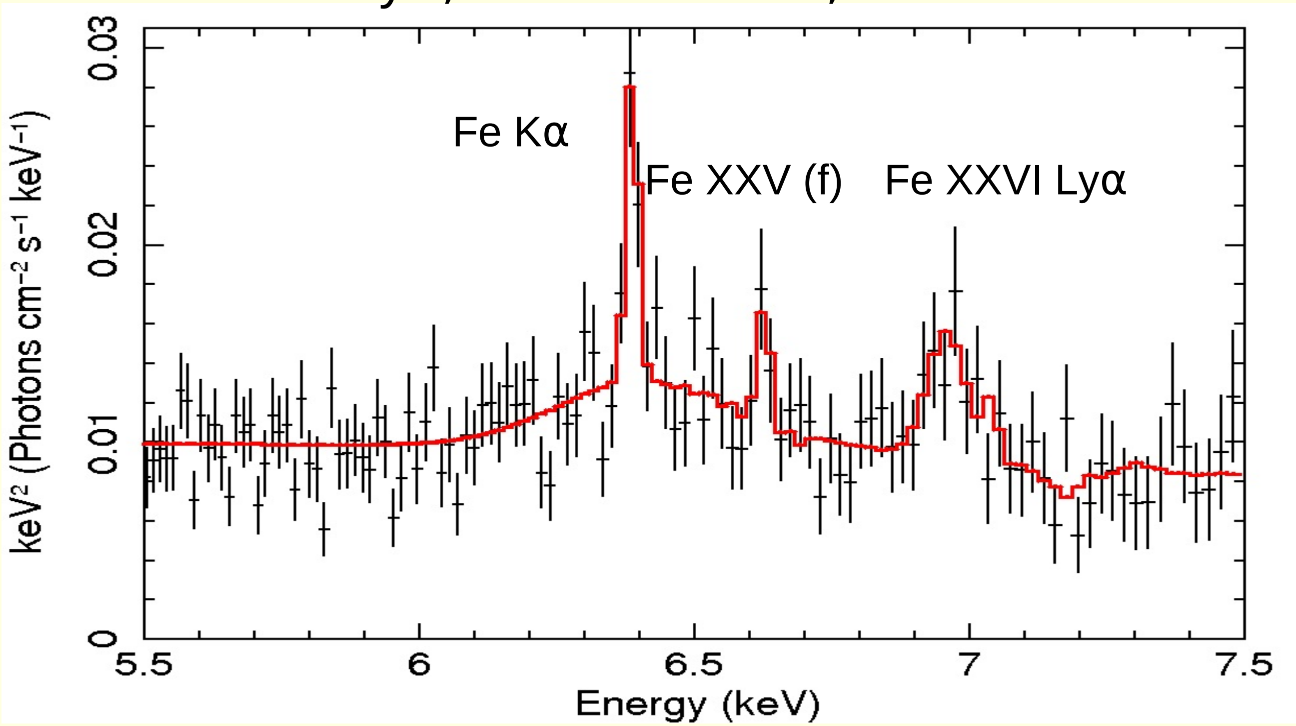


HETG Warm Absorber Model



Chandra HETG Fe Line Profile

- Fe Kα; *E* = 6.40 keV; EW = 50 eV (σ = 10 eV) – plus moderately broad component (EW ~ 160 eV; FWHM ~ 16,000 km s^{-1}); ~100 R_g if associated with transverse Doppler broadening
- Fe XXV (f); *E* = 6.64 keV; EW = 19 eV
- Fe XXVI Lyα; *E* = 6.97 keV; EW = 63 eV



- Final *Chandra* HETG model

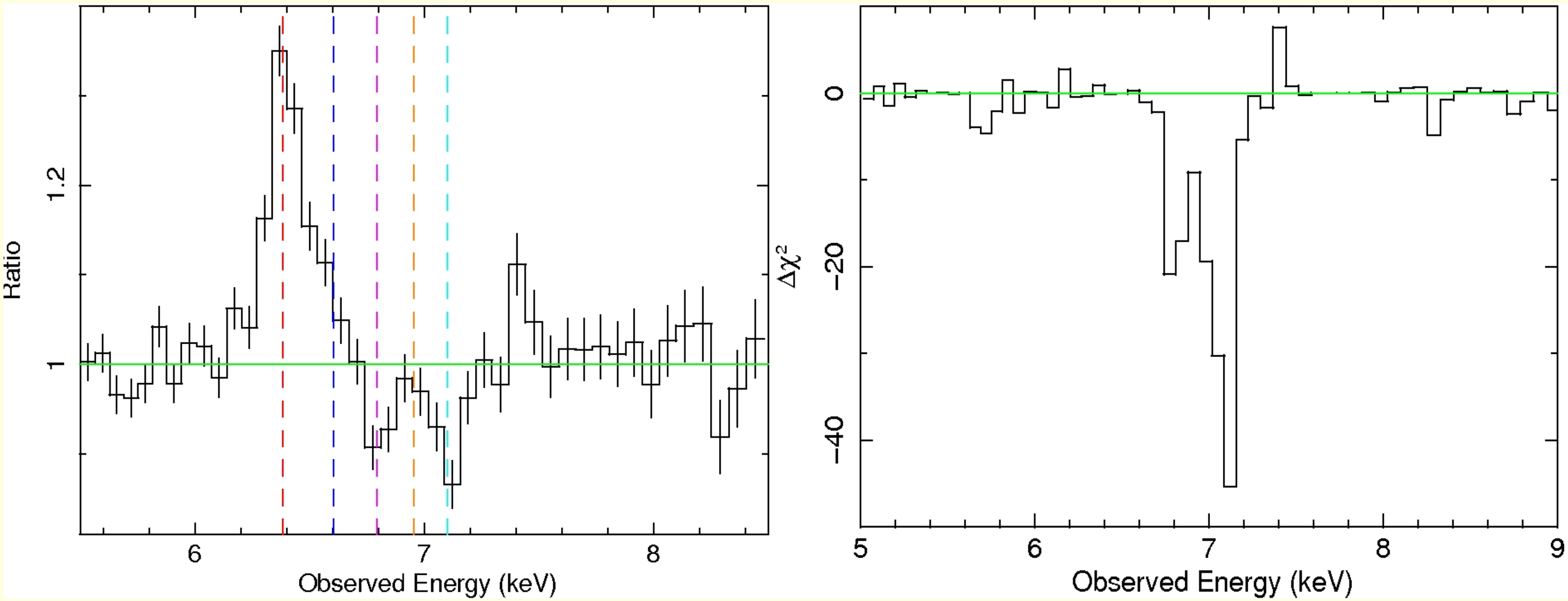
Contemporaneous *Suzaku* Data

- Contemporaneous broad-band *Suzaku* data (November 2008)
- Exposure time ~ 350 ks (split into two observations; ~275 ks and ~80ks)
- $F_{0.5\text{-}10}$ = 5.03 x 10^{-11} erg cm^{-2} s^{-1} (XIS)
- $F_{15\text{-}50}$ = 3.06 x 10^{-11} erg cm^{-2} s^{-1} (HXD)

- Apply best-fit *Chandra* HETG model
- - including 4 fully-covering warm absorber zones fixed at best-fit values from HETG (contemporaneous data) and partial-coverer

- Significant Fe line profile:
- Fe Kα: ~6.41 keV; EW ~ 75 eV
- Fe XXV: ~6.62 keV; EW ~ 25 eV
- Fe XXVI: ~6.97 keV; EW ~ 10 eV

Suzaku Fe Line Profile



- Plus highly ionised absorption...
- E_{line} = 6.81 keV and E_{line} = 7.12 keV (EW ~ -28 eV and ~-43 eV)
- Fe XXV resonance line (6.70 keV) and Fe XXVI Lyα (6.97 keV) line...?

Highly Ionised Absorption

- Parameterise absorption lines with single XSTAR zone (Kallman & Bautista 2001)
- v_{turb} = 3000 km s^{-1} (so as not to saturate absorption lines)
- $N_H \sim 8 \times 10^{22}$ cm^{-2}; log $\xi \sim 4.1$
- Blueshift implies $v_{out} \sim -6000$ km s^{-1} (~0.02*c*; consistent with Pounds et al. 2004 and Terashima et al. 2009)
- No other zones required by data
- Perhaps the highly ionised signature of the same high velocity components detected by Collinge et al. (2001) and Steenbrugge et al. (2009) (LETG) ?

- For consistency, attempt to model high velocity absorption lines in *Chandra* HETG data
- EW < 21 eV and EW < 41 eV respectively (consistent with *Suzaku*)

High Velocity Outflow

- $R_{in} = L_{ion} / N_H \xi$ (integrating through a homogeneous radial wind from infinity); may extend inwards if $R >> \Delta R$
- Lower limit ($v_{esc} = (2GM / R)^{1/2}$; assuming material escapes to ∞)
- $0.5 \lesssim R \lesssim 5$ light-days
- Well within the 10-15 l-d dust sublimation radius (Krongold et al. 2004) – i.e. no toroidal origin
- Located within BELR -> accretion disc wind?

- Assuming homogeneous, radial flow: $\dot{M}_{out} \sim 0.2b\ M_{\odot}\ yr^{-1}$
- *b* likely to be appreciable fraction of 1 and not highly collimated (Tombesi et al. 2010 -> global covering fraction of 0.4-0.6 from sample of 17/42 RQ AGN)
- Kinetic output ~ 10^{42} erg s^{-1}; could perhaps deposit ~10^{56-57} erg (if wind persists); comparable with binding energy of Galactic bulge, ~5 x 10^{56} erg
- Perhaps a low mass analogue of QSOs PG 1211+143 (Pounds & Reeves 2009) and PDS 456 (Reeves et al. 2009) -> 10^{60} erg

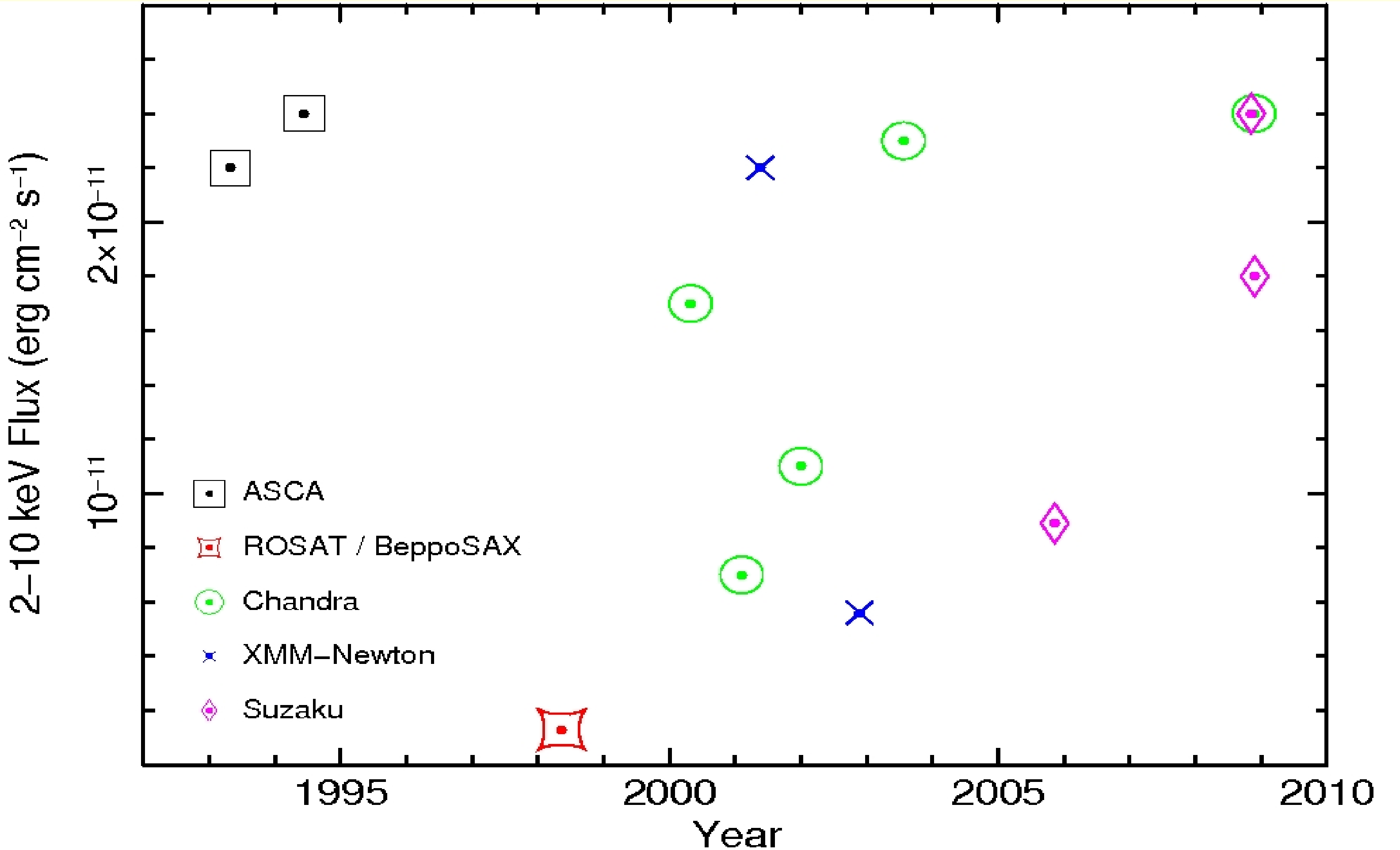
Broad-band *Suzaku* Model

- Able to model the hard excess (> 10 keV), curvature in soft band and Fe emission with two absorbed reflectors (one near-neutral and one ionised) (REFLIONX; Ross & Fabian 2005)

- Full model then consists of fully-covering warm absorber (HETG), intrinsic power-law, partial-coverer and two reflectors

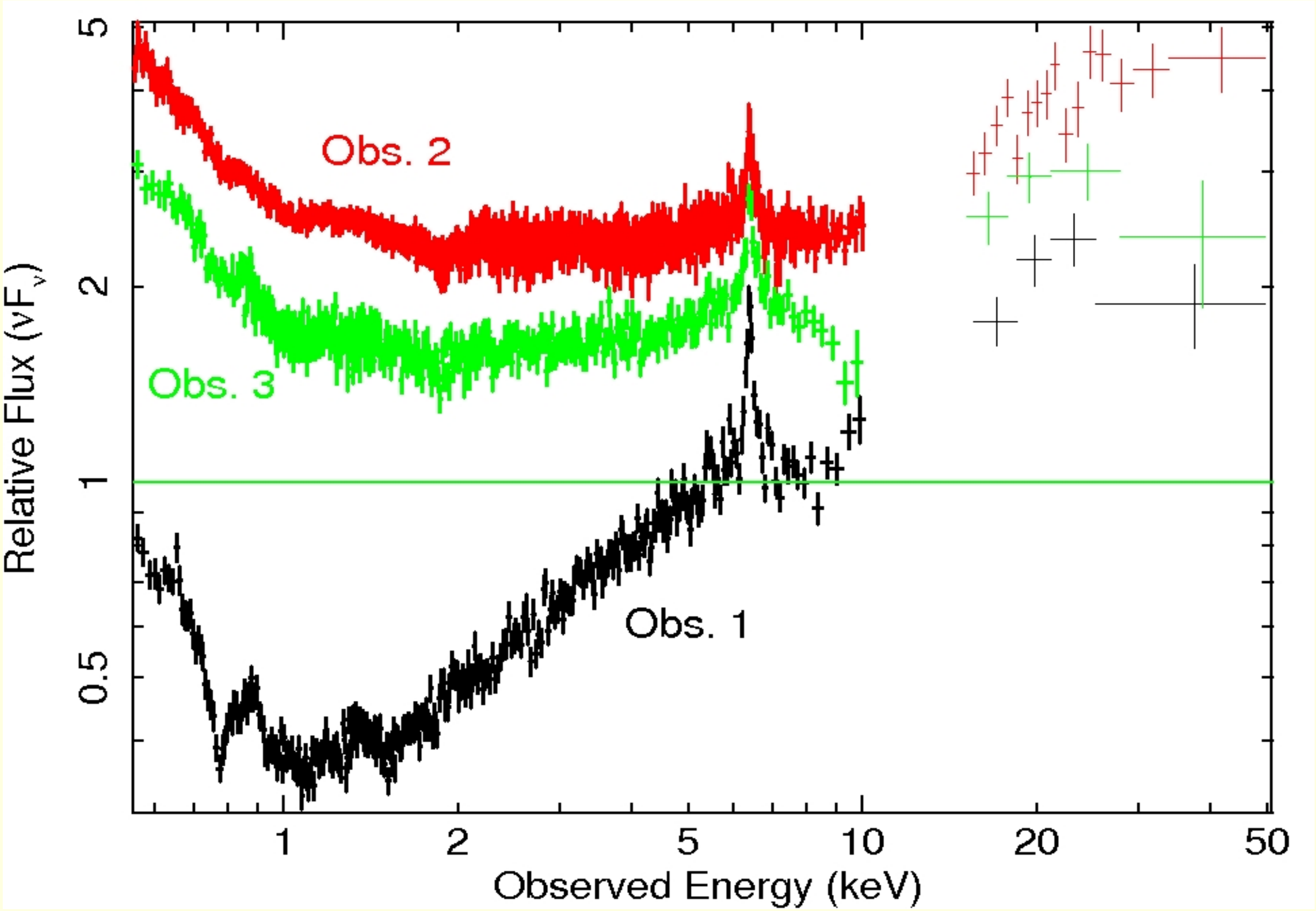
- Include 2005 data (when the source fell into an extended period of low flux with significant hard excess, R ~ 7; Terashima et al. 2009) to model long-term spectral variability...

Historical Light Curve of NGC 4051



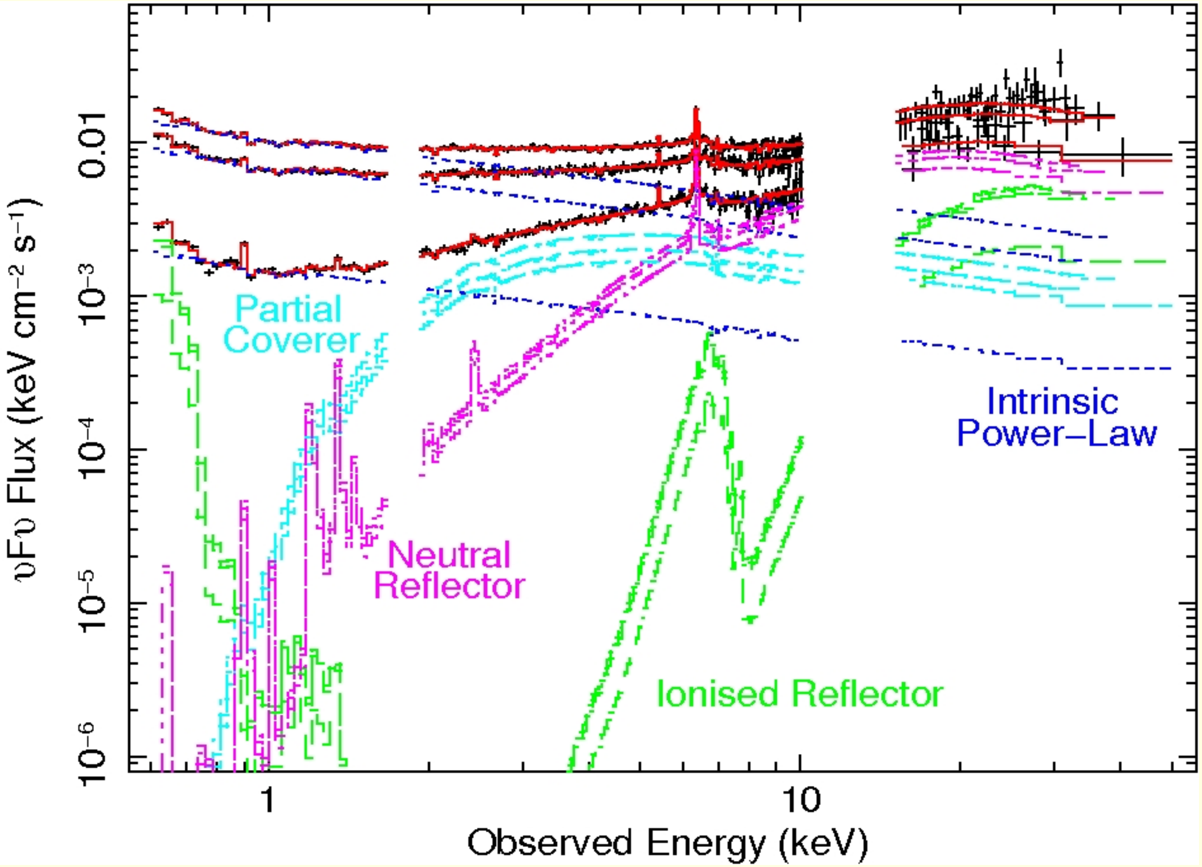
Suzaku Observations of NGC 4051

- $F_{0.5\text{-}10}$ varies by a factor ~5 between 2005 and 2008



Long-term Spectral Variability

- Apply broad-band model to 2005 and 2008 data
- No variability of the warm absorber detected between 2005 and 2008



Long-term Spectral Variability

- Primary power-law continuum disappears in low-flux state
  Quasi-constant, hard spectral component remains
- Anti-correlation between f_{cov} and L? Varying corona? Ionised clouds?
- Alternatively, changes in L are not intrinsic...
  Perhaps changes in line-of-sight f_{cov} of C-thick obscuring material (same system as partial-coverer?); solution used to model other AGN, e.g. 1H 0419-577 (Pounds et al. 2004) and NGC 3516 (Turner et al. 2008)
- Low ξ reflector and near-neutral Fe Kα emission constant in flux over time despite *apparent* (observed) changes in continuum flux; distant material receiving invariant ionising flux?
- Variable component of hard excess (high ξ) with associated moderately broad Fe Kα component (responding to continuum changes on 20 ks timescale); perhaps scattering off a disc wind (Sim et al. 2010)?
- See PCA analysis of Miller et al. (2010) (optically-thick material: $C_G > 0.4$; $r \sim 100R_g$)

Summary

- Zones of outflowing absorption ranging from log ξ = -0.76 to log ξ = 4.1 ($N_H \sim 10^{20} - 10^{23}$ cm^{-2})
- High ξ zone outflowing at ~-0.02*c* (perhaps influential in terms of affecting host galaxy environment)
- Broad-band *Suzaku* data modelled with variable partial-coverer, absorbed reflectors and fully-covering warm absorber zones
- Long-term spectral variability could be accounted for by changes in line-of-sight covering fraction of partial-coverer leading to significant observed (but not intrinsic) changes to the continuum shape