Anatomy of an outflow: mapping the Mrk 509 warm absorber

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Collaborators

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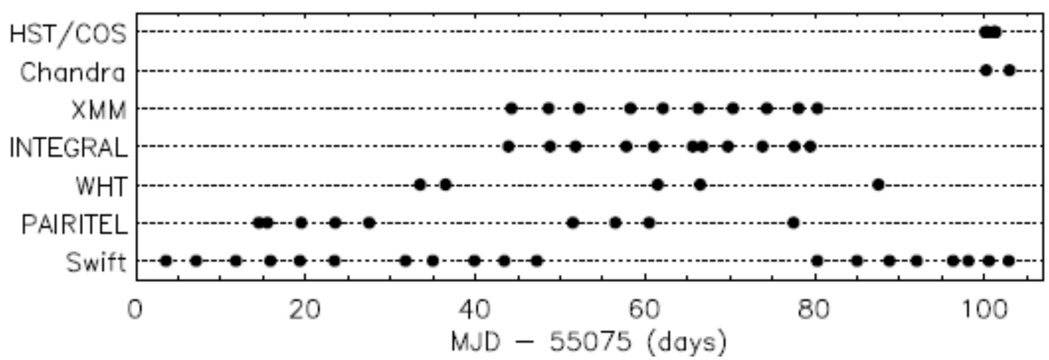
Main goal campaign

- Characterise warm absorber by stacked, high S/N, high-resolution RGS spectrum
- Measure / constrain any variability of the absorber by med-resolution, highly sensitive EPIC spectra
- From (lack of) variability, determine distance absorption components

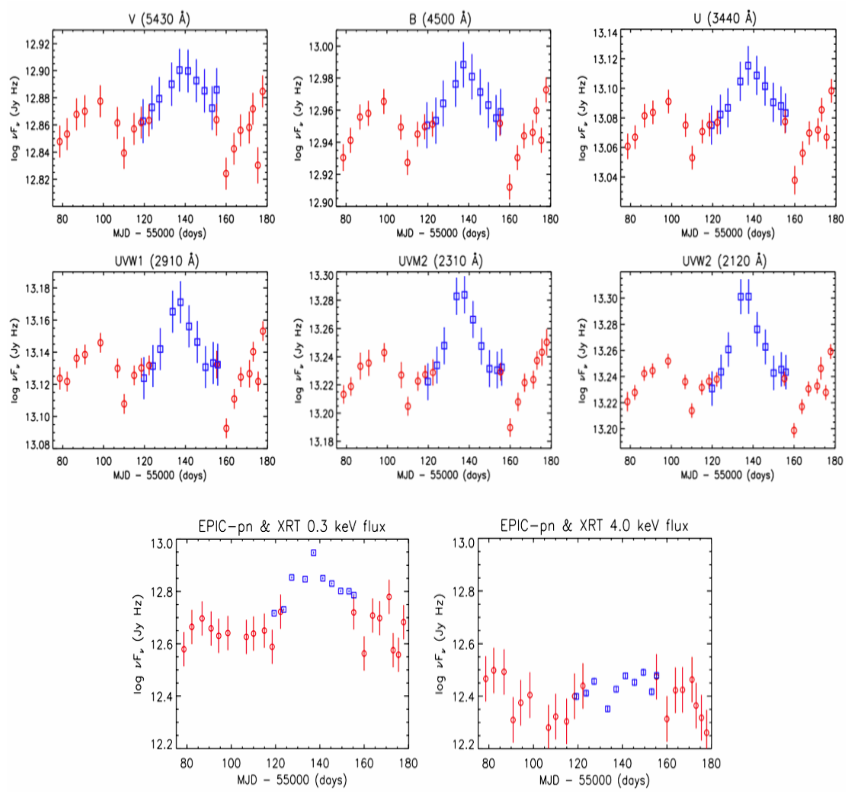
Observation campaign Mrk 509

- Core: 10 x 60 ks XMM, spaced 4 days (RGS, EPIC & OM all used!)
- Simultaneous Integral 10 x 120 ks
- Followed by 180 ks Chandra LETGS, simultaneous with 10 orbits COS (HST)
- Preceded with Swift (UVOT, XRT) monitoring
- Supplemented with ground-based (WHT, Pairitel) photometry & grism
- Period: 4 Sept – 13 Dec 2009 (100 days)
- 7 papers published, 8 submitted/ in progress



Lightcurve during 100 days

- Intense monitoring with XMM & Swift gives continuous ~4d sampling
- Outburst in middle XMM monitoring ➔ ideal for reverberation
- Strong correlation UV & Soft X-ray ➔ comptonisation soft excess (Mehdipour et al. 2011)



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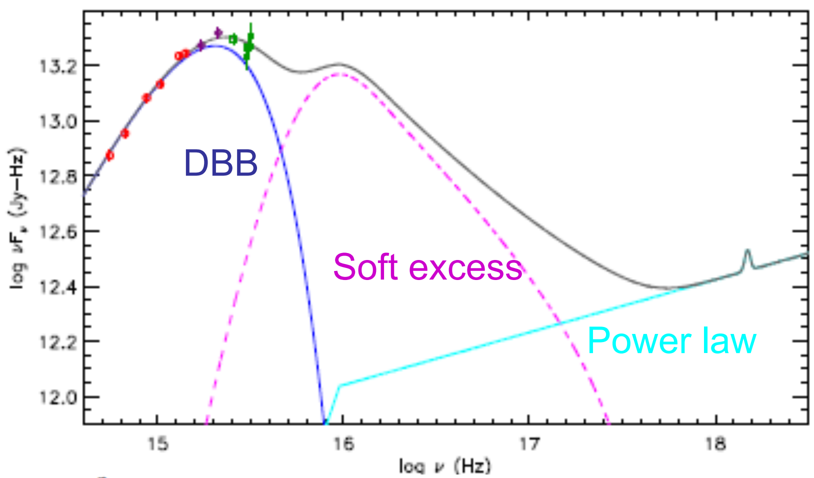
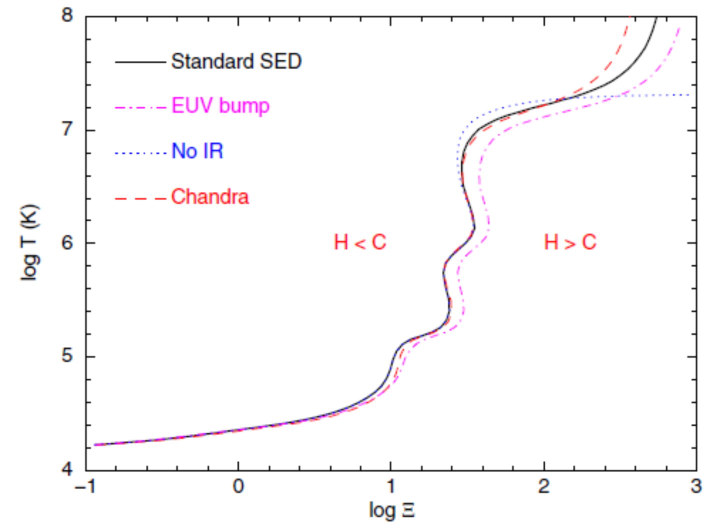
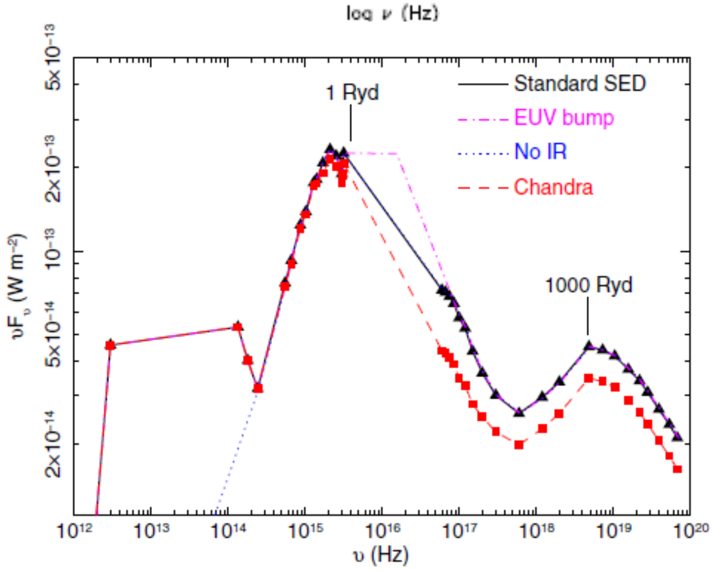
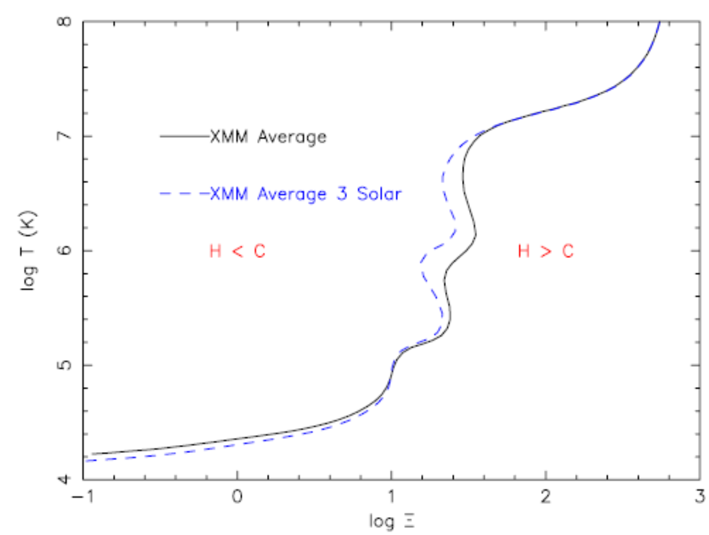
Spectral energy distribution









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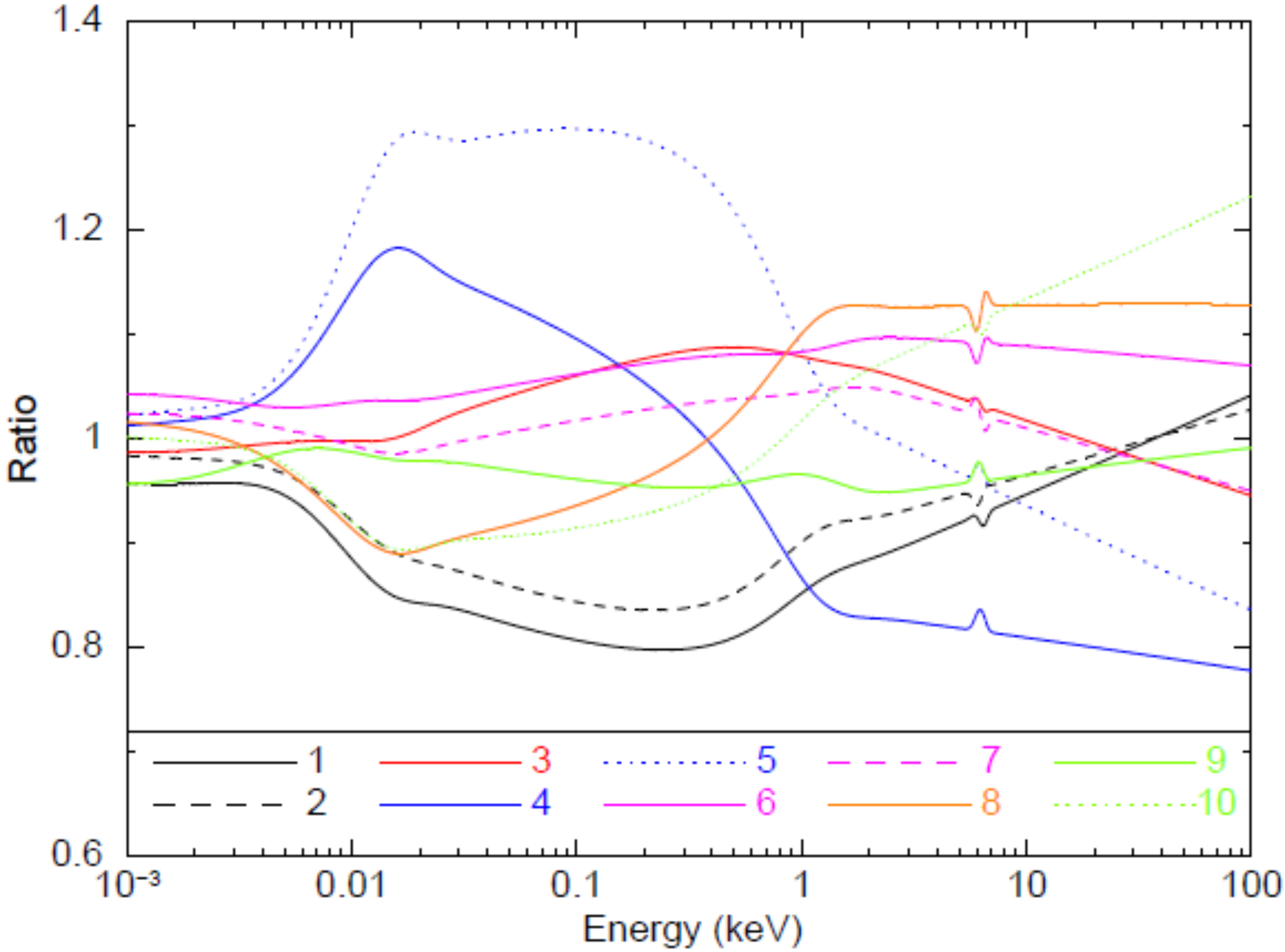
Time-dependent SEDs



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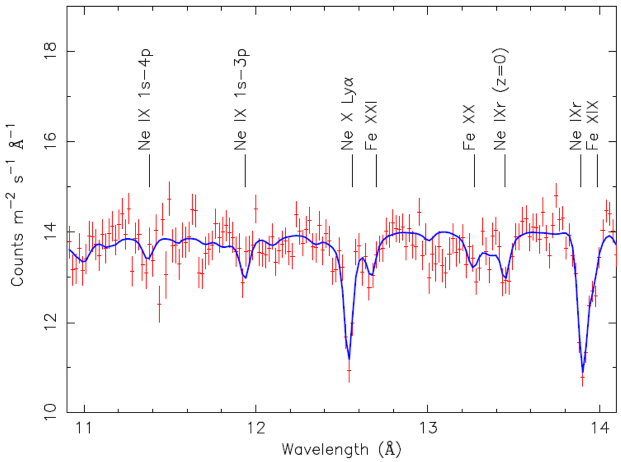
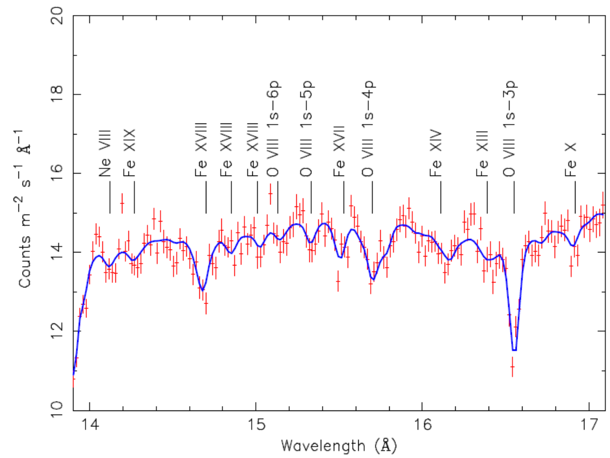
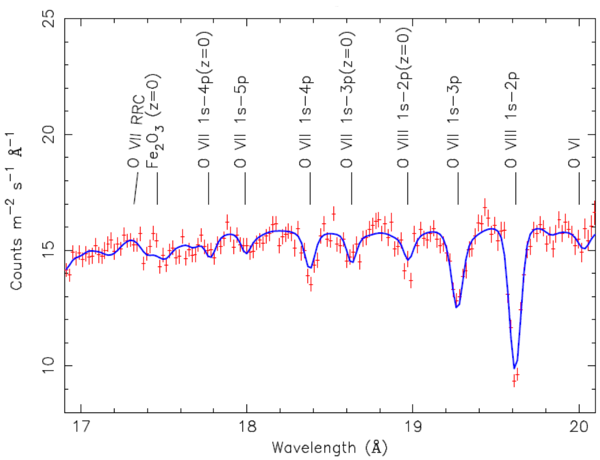
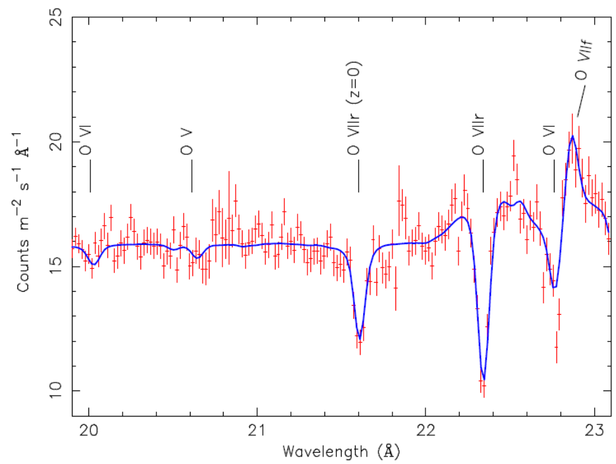
Sample high-resolution spectra









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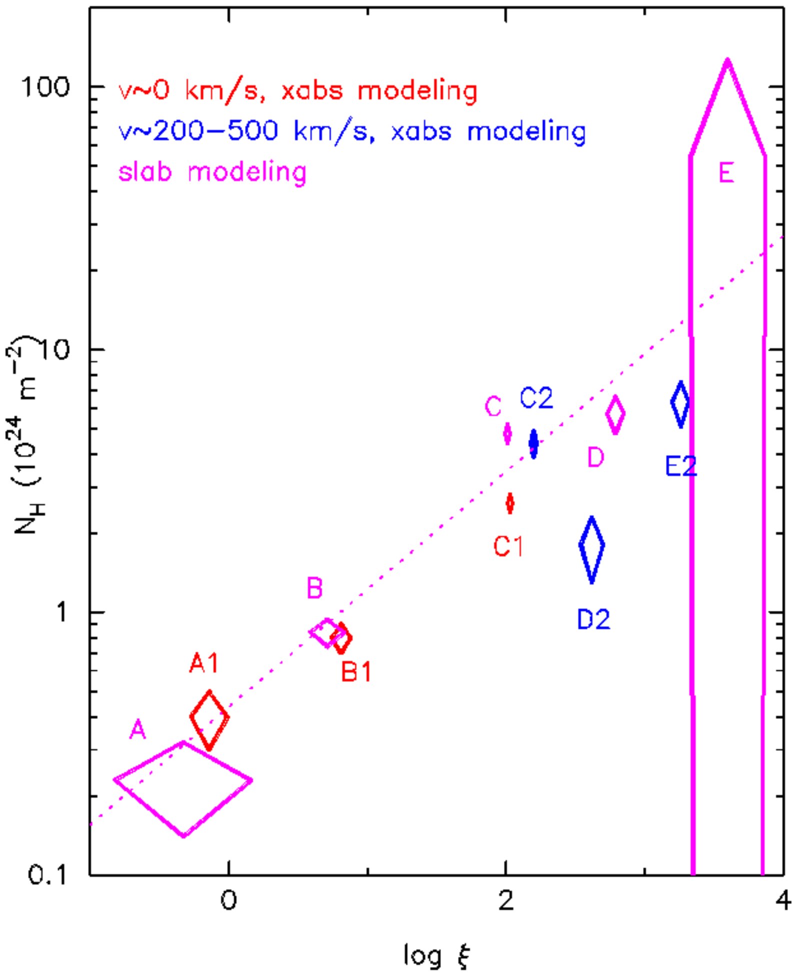
Discrete ionisation components?

- Fitting RGS spectrum with 6 discrete WA components (A1-C1, C2-E2)
- Alternative: fit individual column densities, then decompose that into discrete components A-E (integrated over v)



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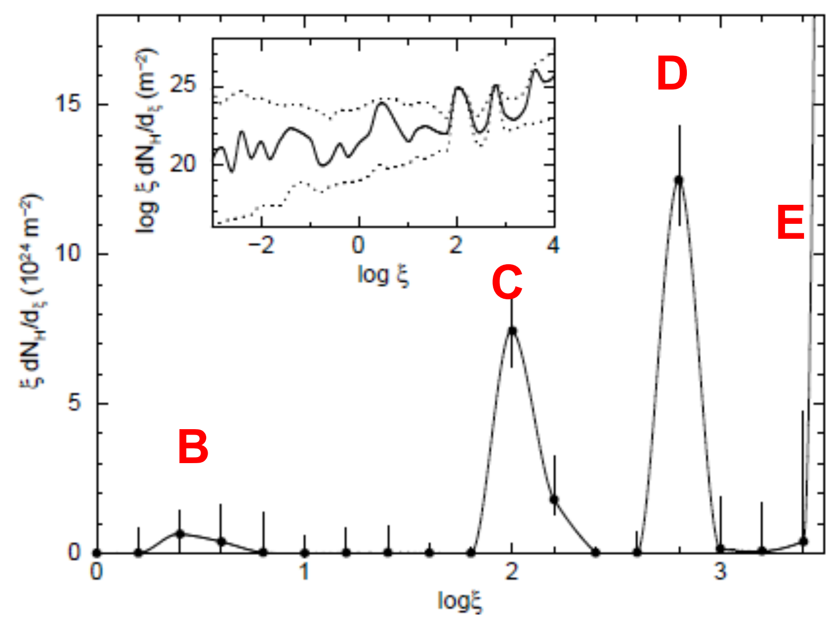
Continuous AMD model

- Fitted columns with continuous (spline) model
- Surprise: comps C & D pop-up as discrete components!
- Upper limits FWHM 35 & 80 %
- Component B (& A) too poor statistics to prove if continuous
- Component E also poorer determined: correlation ξ and N_H
- ➔ Discrete components



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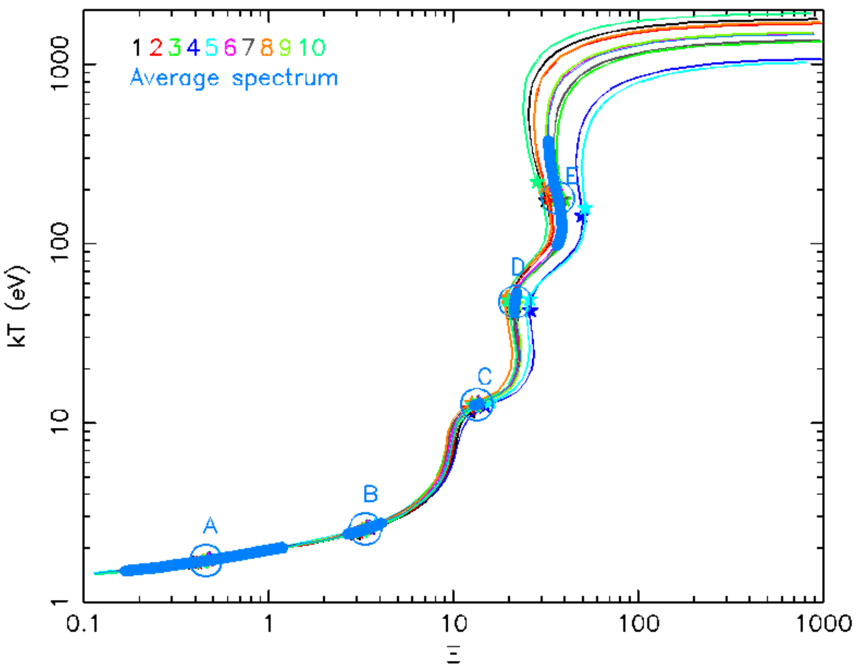
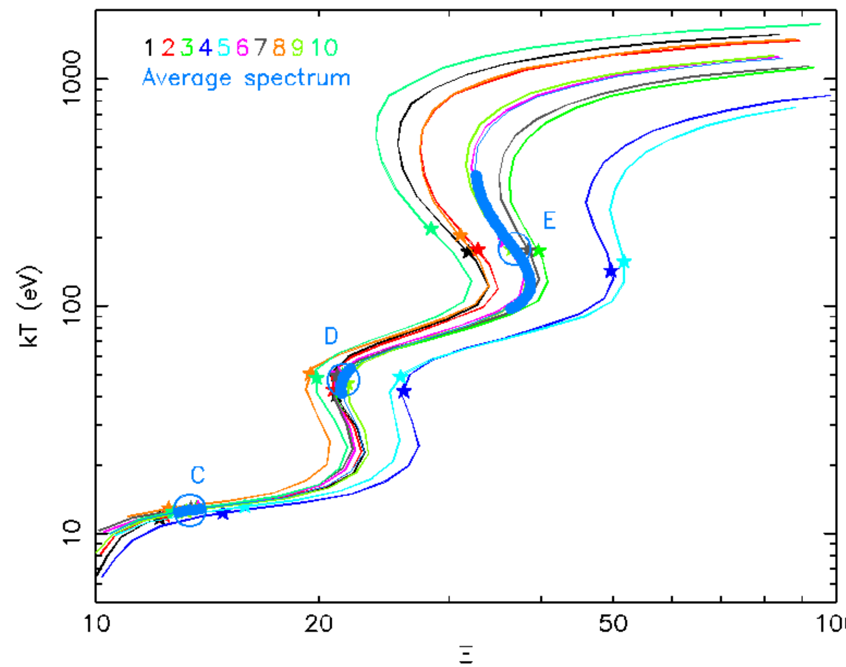
Pressure equilibrium? No!





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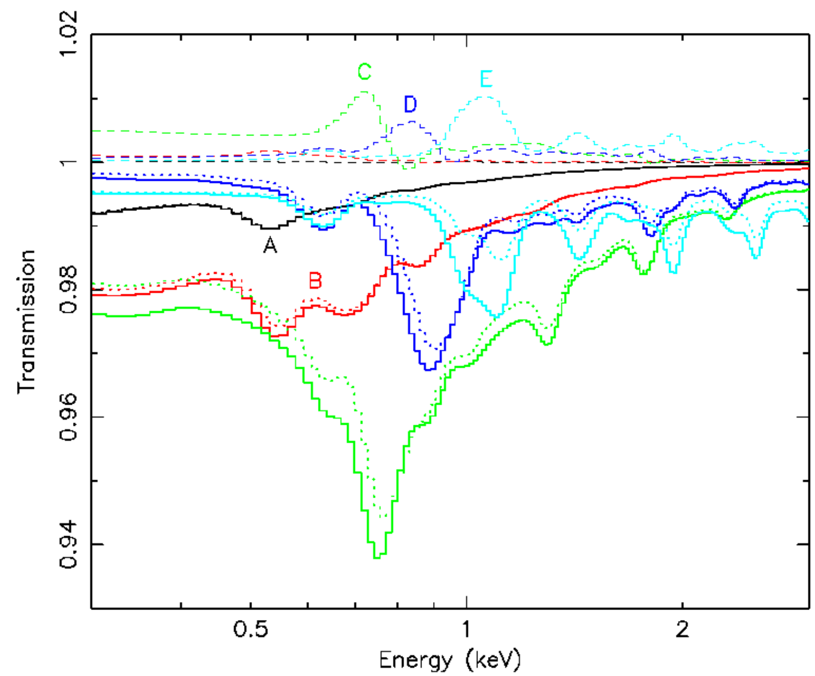
Time-dependent photoionisation

- SED changes in complex way
- Absorber adjusts on timescale $t_{rec} \sim 1/n$
- Solve t-dependent equations:
- $dn_i/dt = A_{ij}(t)\ n_j$
- $A_{ij}(t)$ contains t-dependent ionisation & recombination rates

Simplified case: predicted change transmission for 0.1 dex increase L, At spectral resolution EPIC/pn



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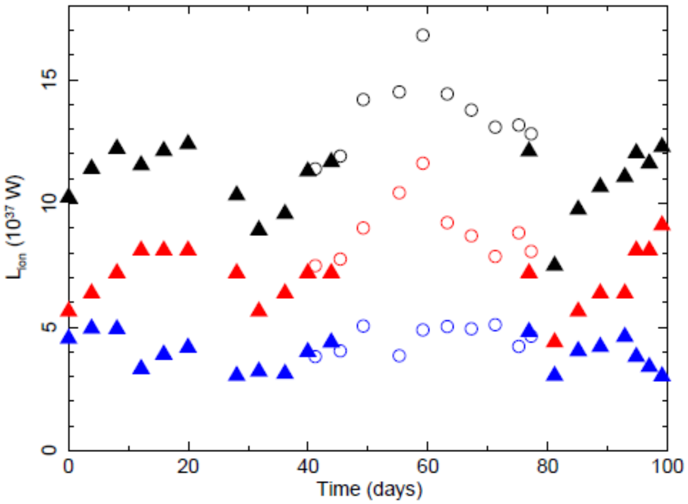
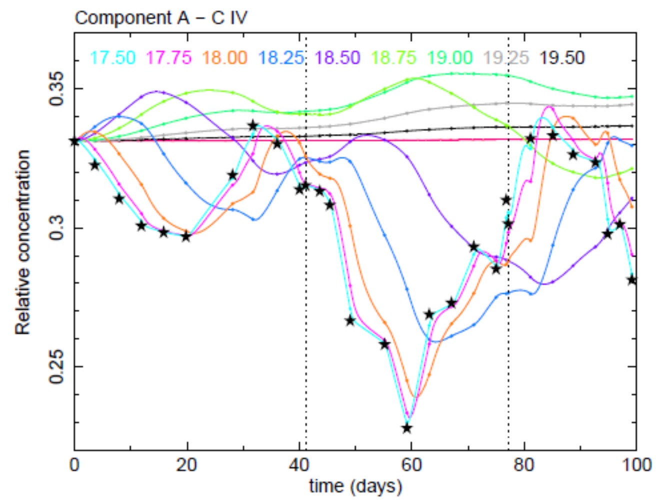
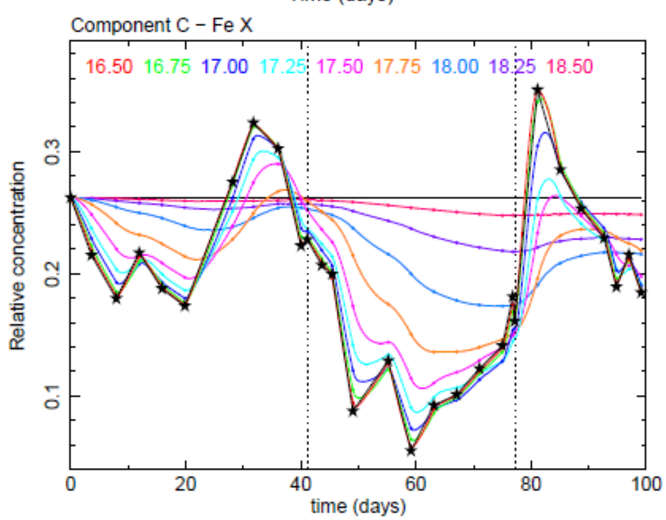
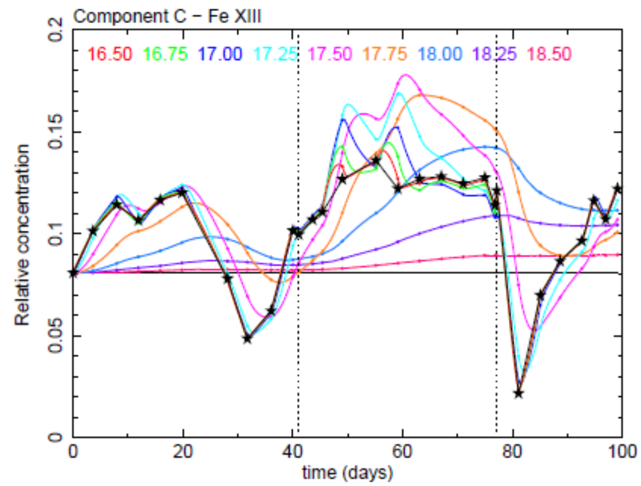
Example of time-dependent calculation

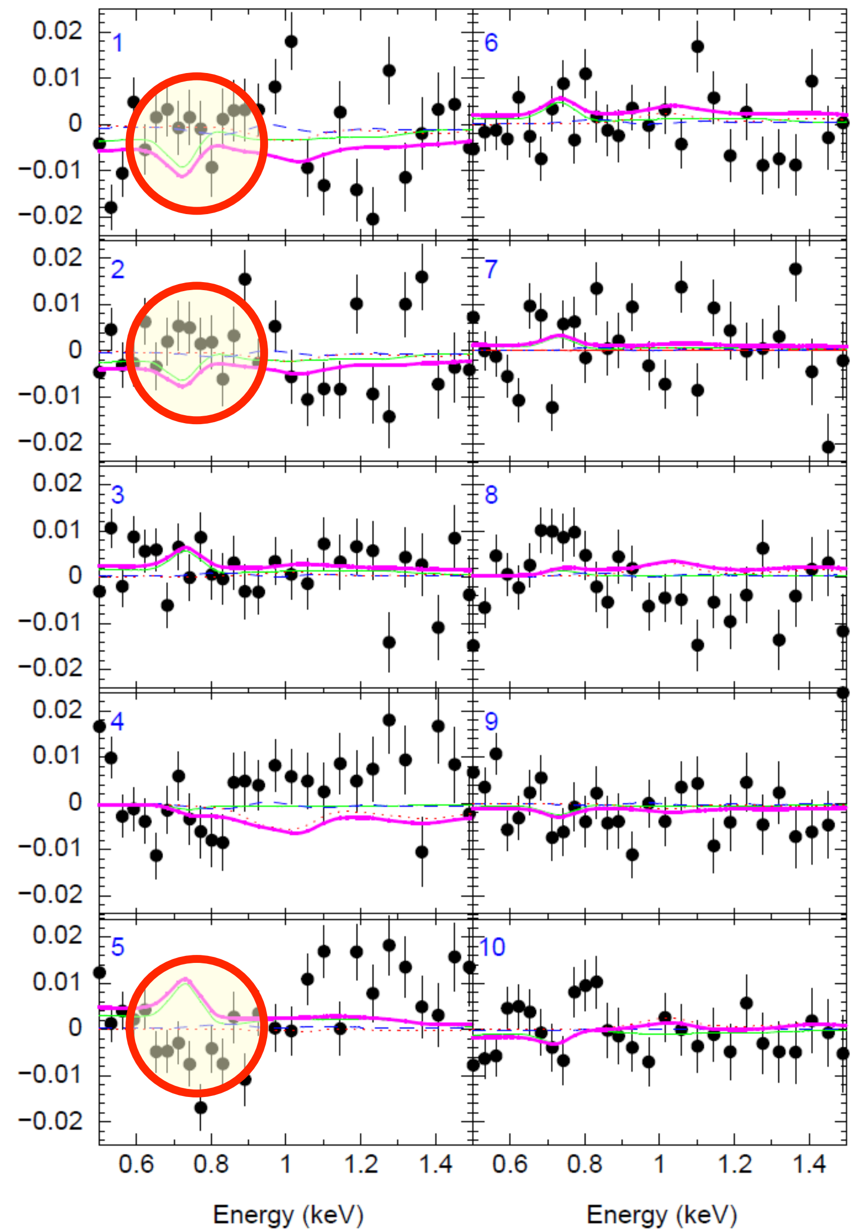








- Models for instantaneous response:
- No sign of predicted signal
- ➔ lower density
- RGS gives similar constraints



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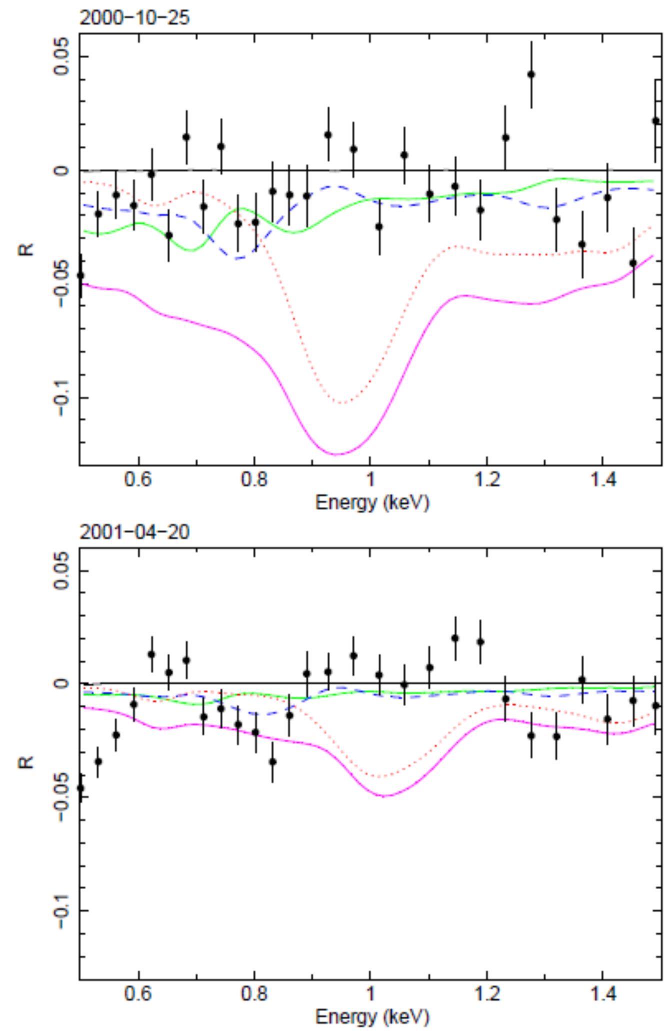
Long term variability

- Compare archival spectra to our 2009 spectrum
- Predictions for change in components C, D and E
- Only change seen for component D



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Upper limits distance

- Recombination time scale yields density n
- Using $\xi = L/nr^2 \rightarrow r = \sqrt{(L/\xi n)}$
- Using measured column density $N = n\Delta r$ with Δr the thickness of the layer and $\Delta r < r$ $\rightarrow$ $r < L/N\xi$

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Summary distance limits

Component	Lower limit (pc)	Method	Upper limit (pc)	Method
A	~3000	Direct imaging [O III]	~3000	Direct imaging [O III]
B	?		?	
C	71	pn & RGS, Fe blend	9000	$\Delta r/r<1$
D	4.7	RGS O VIII	33	Long-term pn
E	4.6	pn, Fe blend	21-400	$\Delta r/r<1$

Physical parameters

- The mass outflow rate is very large:
- using $Mdot = \Omega m_p n r^2 v$ with $nr^2=L/\xi$ gives:
- $Mdot/\Omega$ = 2000, 25, 22, 2.1 and 0.6 Msun/yr for components A-E
- Compare to accretion rate of about 0.5 Msun/yr
- ➔ either small filling factor, super-Eddington or small solid angle
- Kinetic luminosity is very small (at most 10^{-4} x the ionising luminosity)

Other highlights

- Excellent UV spectra with COS (see talk Jerry Kriss)
- Accurate abundances of the outflow (Steenbrugge et al.)
- Fe-K studies (Ponti et al.)
- Continuum emission modeling, including soft excess (Mehdipour et al., Petrucci et al.)
- Broad X-ray emission lines (Costantini et al.)
- Interstellar foreground absorption (Pinto et al.)
- Etc.

Conclusions

- Deep, multi-wavelength monitoring campaigns (AGN) are rewarding:
- High quality spectra, not limited by statistics
- “Continuous” light curves, allowing to monitor the variations

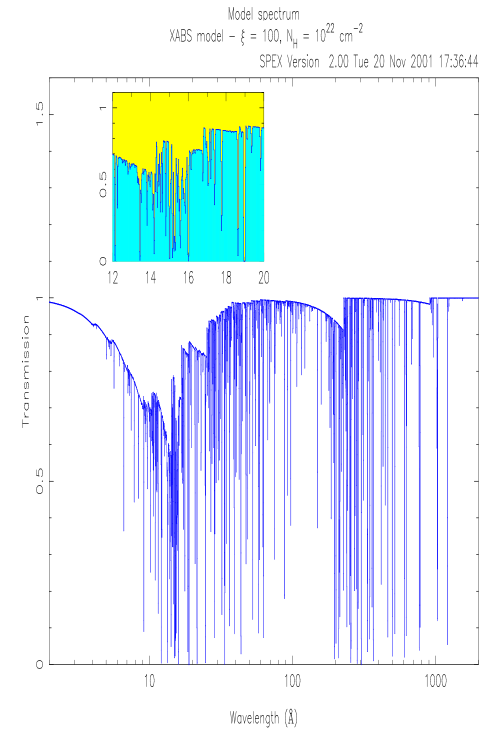
Spare slides

Photoionisation modelling

- Radiation impacts a volume (layer) of gas
- Different interactions of photons with atoms cause ionisation, recombination, heating & cooling
- In equilibrium, ionisation state of the plasma determined by:
  - *spectral energy distribution* incoming radiation
  - chemical *abundances*
  - *ionisation parameter* $\xi = L/nr^2$ with L ionising luminosity, n density and r distance from ionising source; ξ essentially ratio photon density / gas density

Photoionisation models

- Models for transmission of a thin slab
- Continuum & line absorption calculated
- slab model: ion columns independent
- xabs model: ion columns coupled through xstar/ cloudy runs
- warm model: continuous distribution of $N_H(\xi)$



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X-ray analysis

- Fit spectra using a power law + modified blackbody (or even a spline) continuum
- Where needed, add emission lines: relativistic, BLR or NLR X-ray lines
- Fit warm absorber using a model (see previous slide) → ionic or total column densities
- Using photo-ionisation model, derive N_H and ξ distribution
- Spectral fits done with SPEX, global fits

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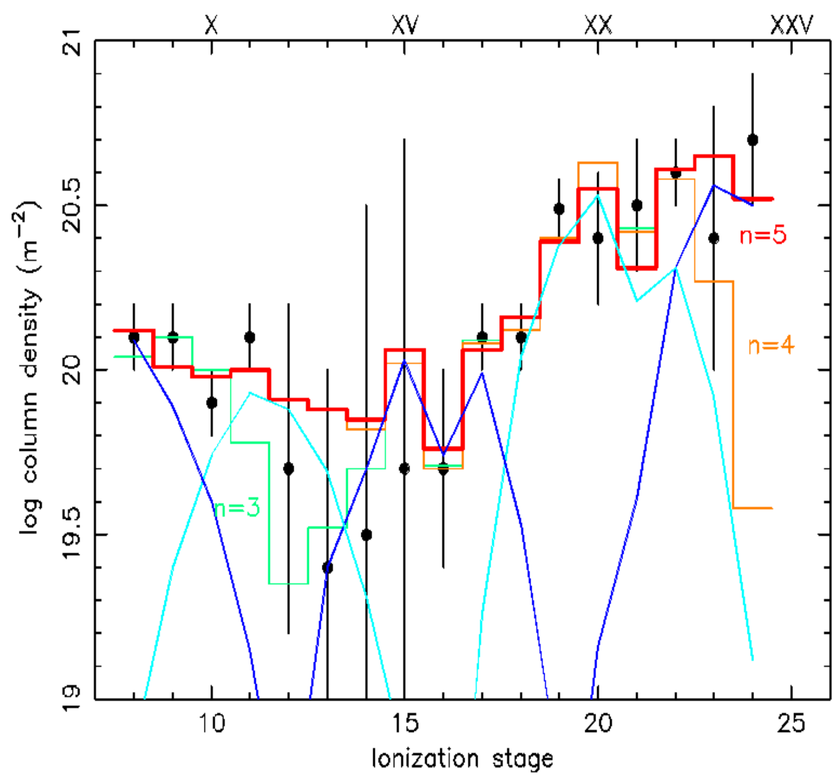
Decomposition into separate ξ: evidence for 5 components

- Use column densities Fe ions from RGS data
- Measured N_{ion} as sum of separate ξ components
- LETGS results similar
- Need at least 5 components



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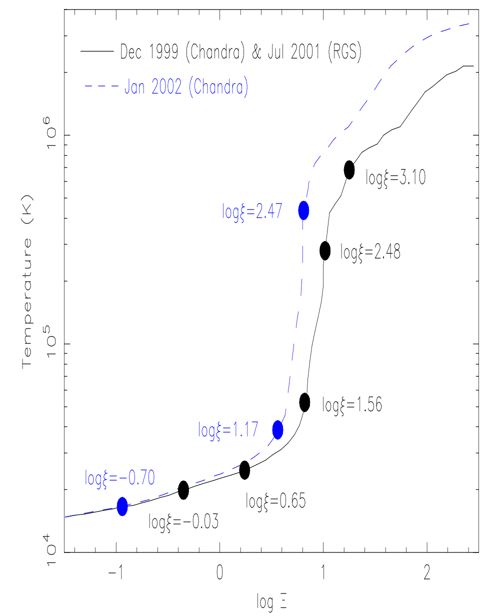
Separate components in pressure equilibrium?

- Not all components in pressure equilibrium (same $\Xi \sim \xi/T \sim F/p$)
- Division into ξ comps often poorly defined
- ➔ Continuous $N_H(\xi)$ distribution: see next slide



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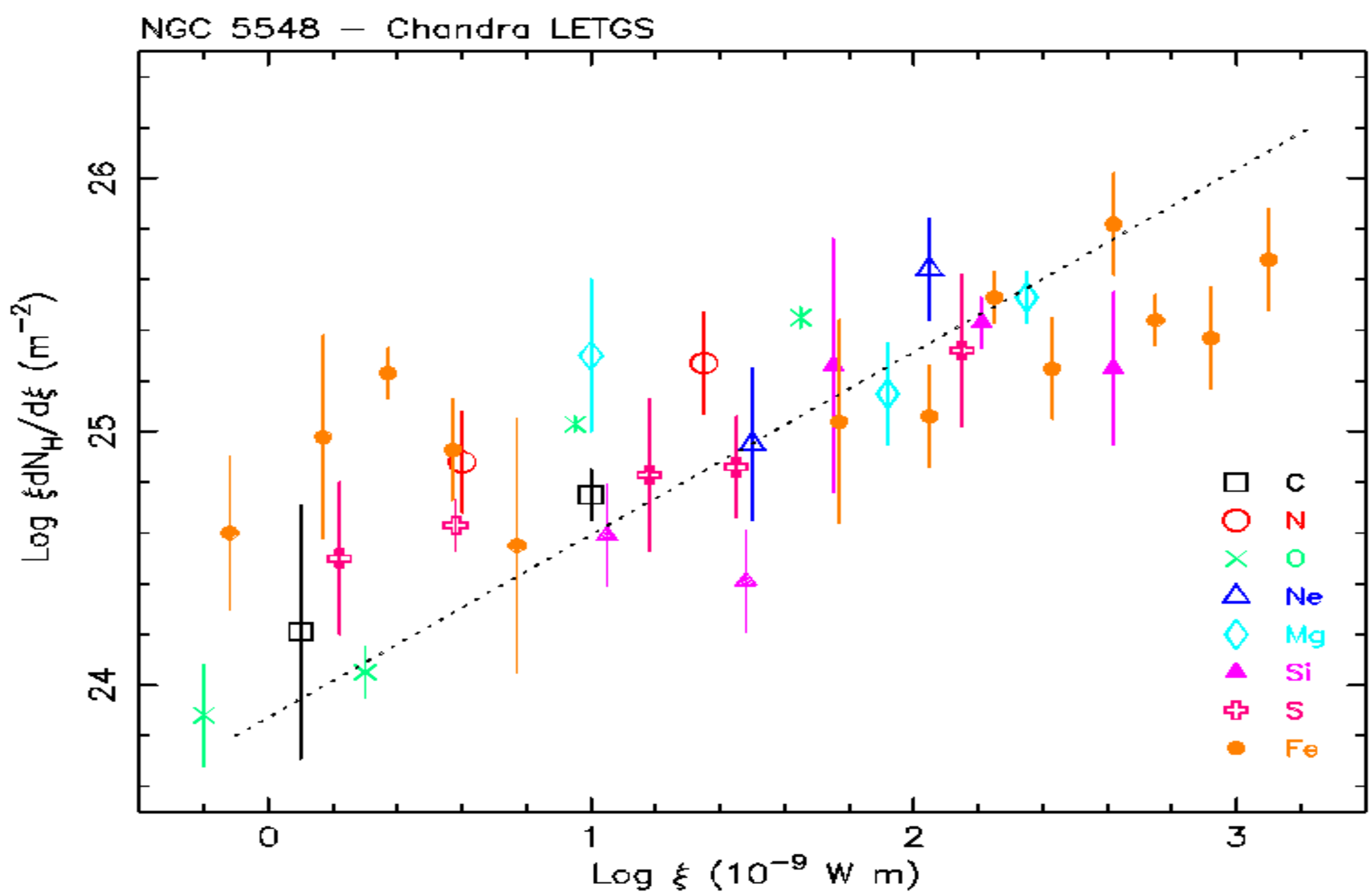
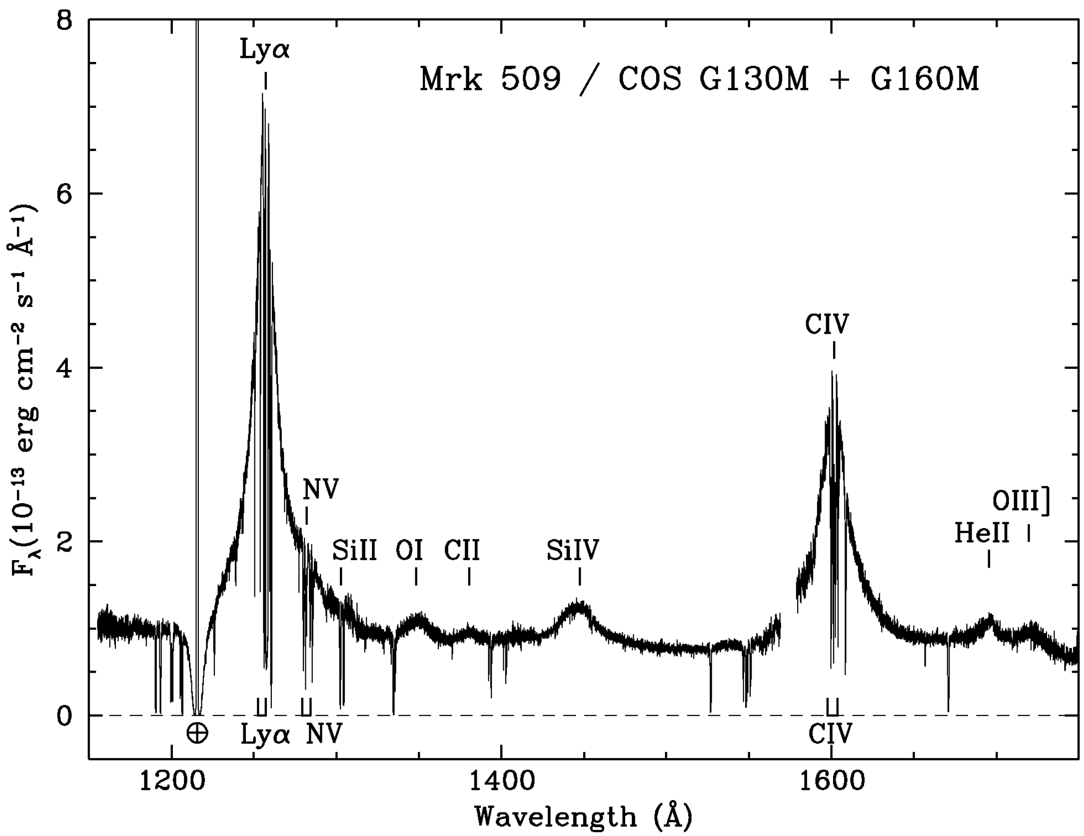
Column density versus ξ



Density estimates: reverberation

- If L increases for gas at fixed n and r, then $\xi = L/nr^2$ increases
- → change in ionization balance
- → column density changes
- → transmission changes
- Gas has finite ionization/recombination time t_r (density dependent as $\sim 1/n$)
- → measuring delayed response yields $t_r \rightarrow n \rightarrow r$

COS spectrum Mrk 509



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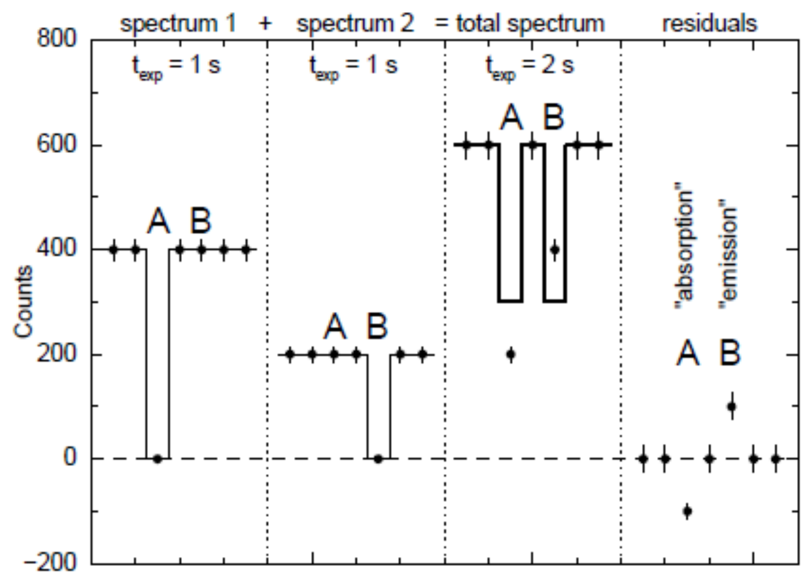
RGS analysis

- Because of excellent quality, many new steps developed
- *Example*: combining spectra with variable hot pixels
- Several other instrumental issues resolved (separate paper) (λ-scale, effective area, response 2Gb➔8 Mb, rebinning…)



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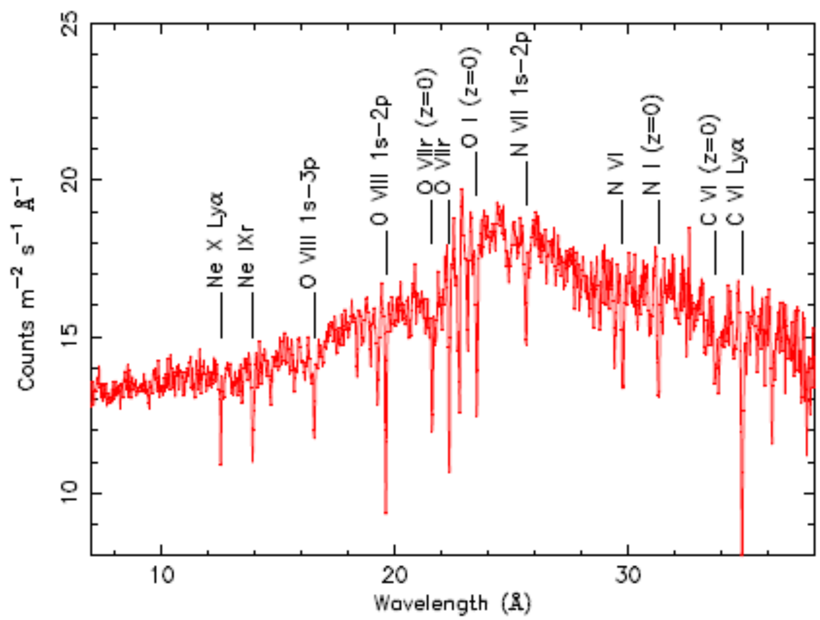
Stacked RGS spectrum

- See Galactic O I edge
- Several narrow absorption lines



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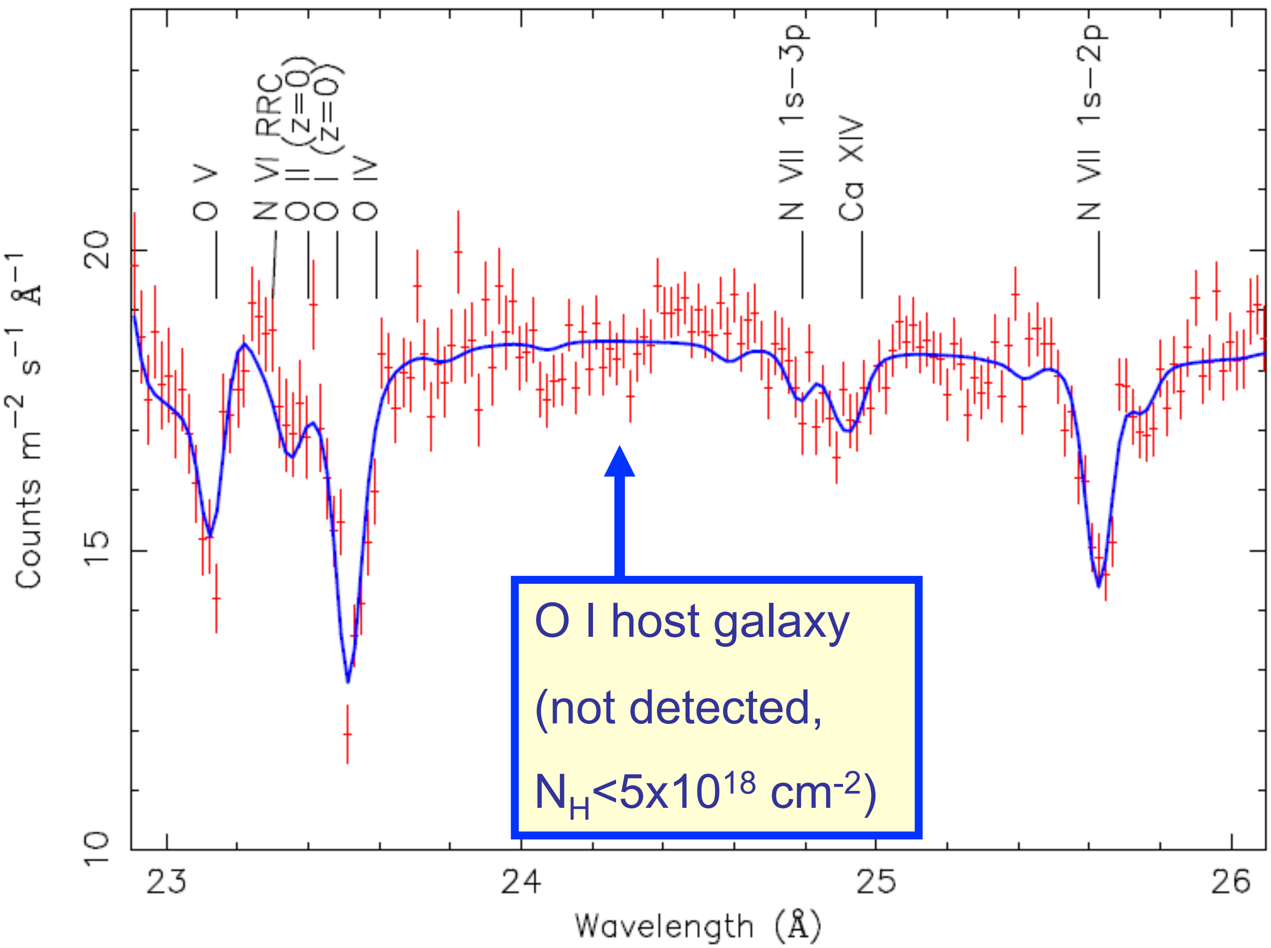
No O I from host galaxy



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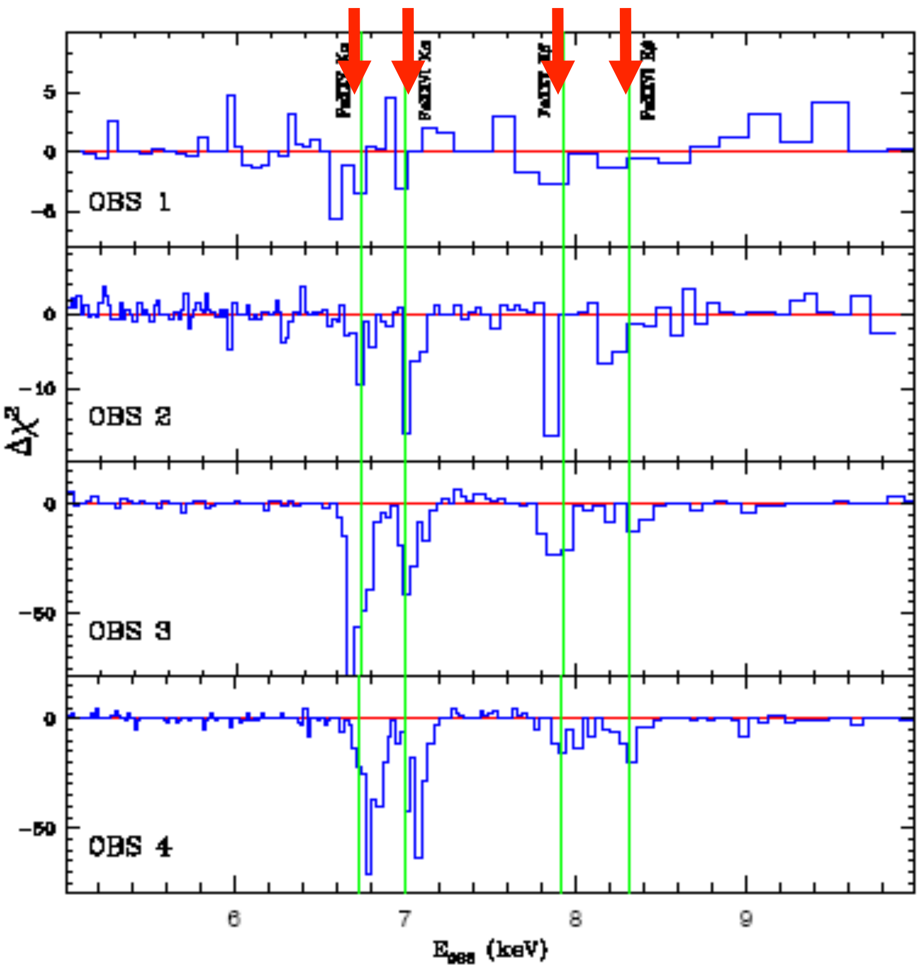
Ejection/outflows: Blue-shifted absorption lines/edges - **Variability**

Absorbers **variability** on timescales 1000-10000s

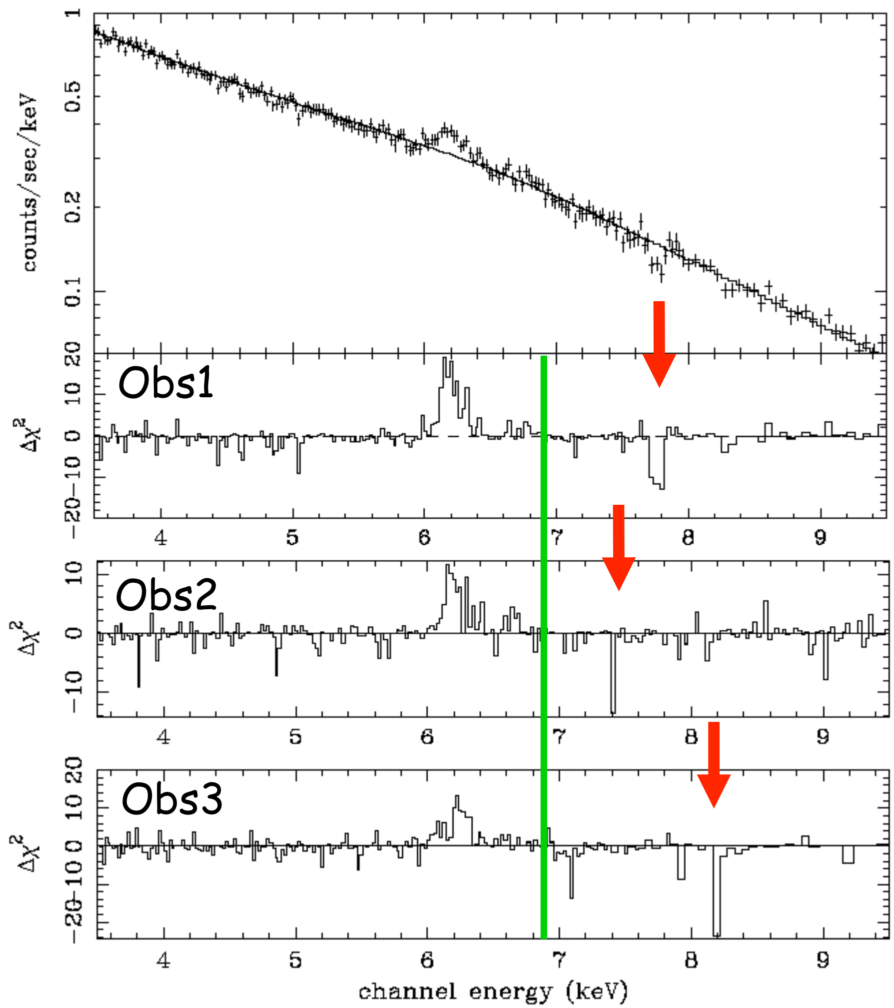
NGC1365



Risaliti et al. 2005

(See also Krongold et al. 2007 on NGC4051)

Mrk 509 (long-look, 200ks)



Cappi et al., 2009
Dadina et al. '05

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Mass loss through the wind

$$\dot{M}_{loss} = \Omega m_p n r^2 v$$

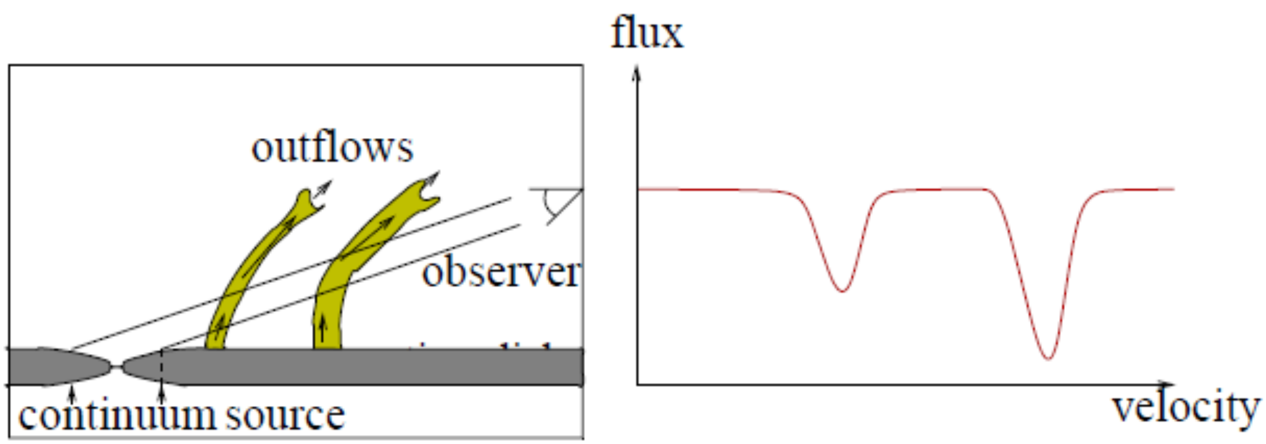
$$n r^2 \cdot v = (L/\xi) \cdot v$$

$$\dot{M}_{loss} < \dot{M}_{acc}$$

$$L = \eta \dot{M}_{acc} c^2$$

$$\Omega < \frac{(\xi / v)}{\eta m_p c^2}$$

v (km/s)	-166	-1040
ξ=1	0.0007	0.0001
ξ=1000	0.7	0.1


outflows
observer
continuum source
flux
velocity