Evidence for a shocked outflow in NGC 4051

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Status quo on powerful winds from radio quiet AGN

• best evidence from blue-shifted Fe K absorption lines
velocities high, typically v~0.1c, and column densities > 10^{23} cm^{-2}
(Tombesi et al 2010)

• covering factor only directly measured for PG1211+143 (b~0.3-0.5)
(Pounds and Reeves 2009)
while recent XMM archival survey suggests b~0.2

• however most believed to be sub_Eddington

• implication: BH masses over-estimated and/or intermittent super - Eddington accretion in Tombesi sample

But does the energy in a fast outflow reach into the galactic bulge?

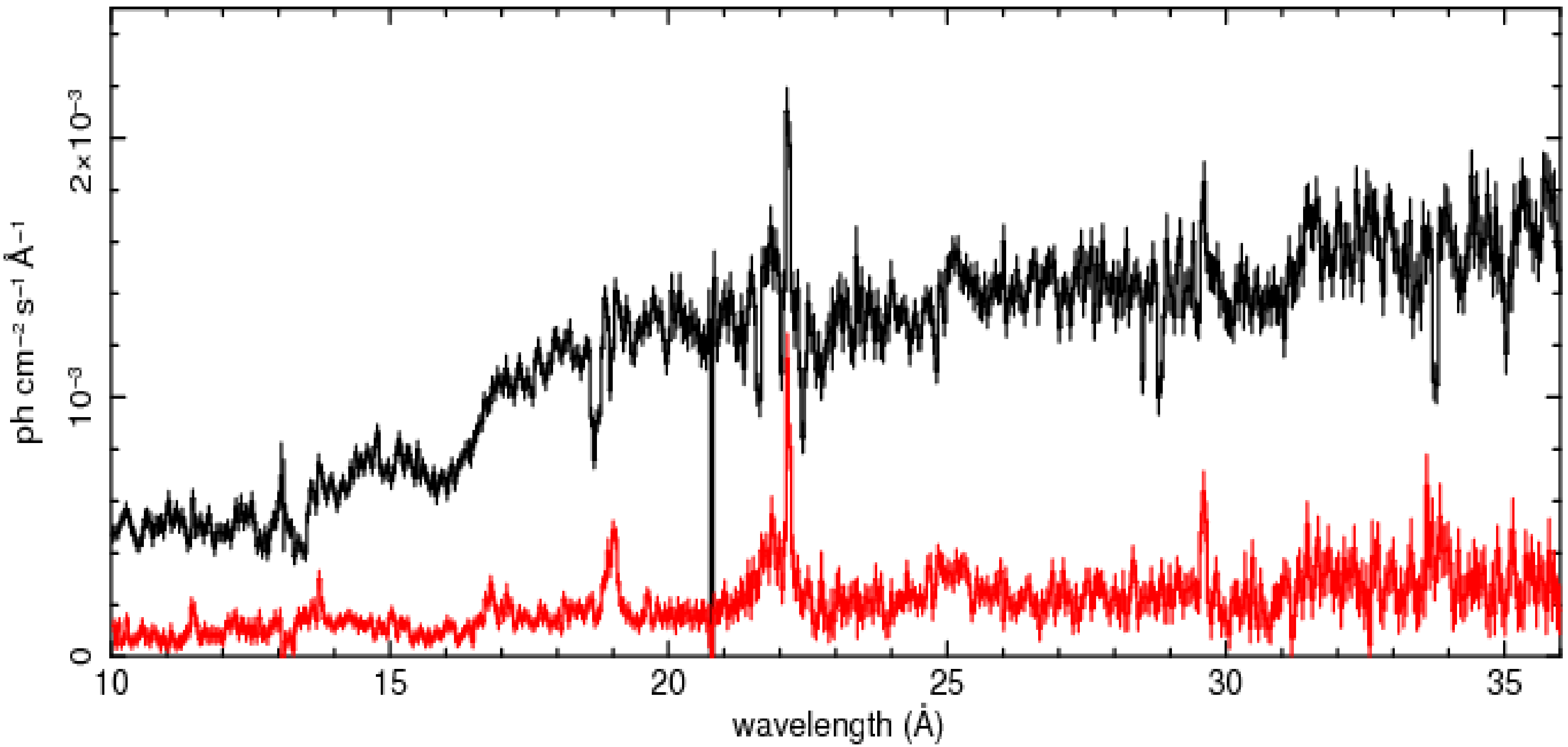
• PG1211 rate may in fact be too high if maintained for >> 10^8 years, unless coupling of wind energy to galactic baryons is inefficient

• King (2010) has discussed interaction of a fast AGN wind with the ISM, finding that much of the mechanical energy is lost in strong cooling after a resulting strong shock

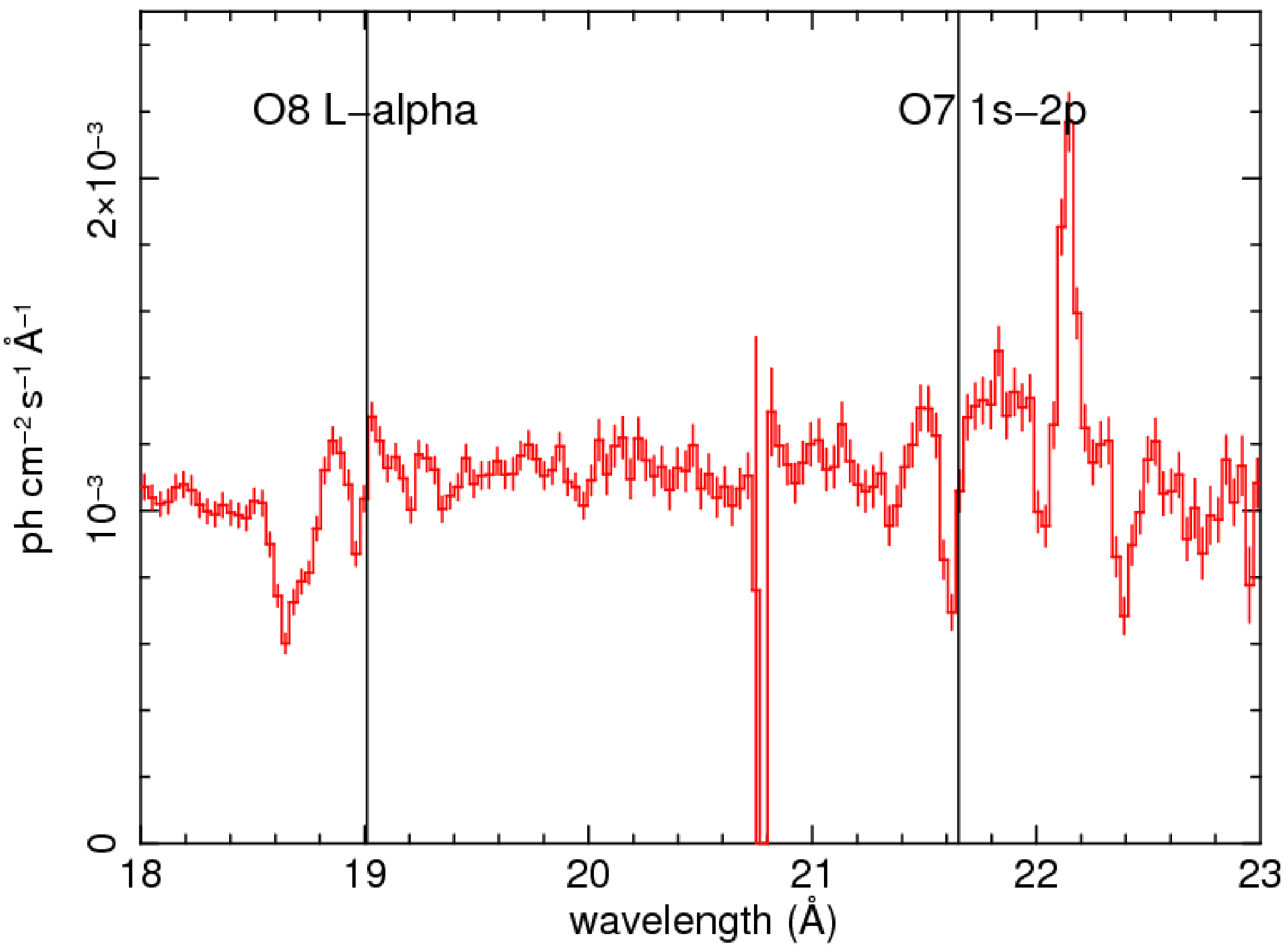
• new spectral data from NGC 4051 now show intriguing evidence for such a shocked outflow

600 ks observation of NGC 4051 with XMM-Newton

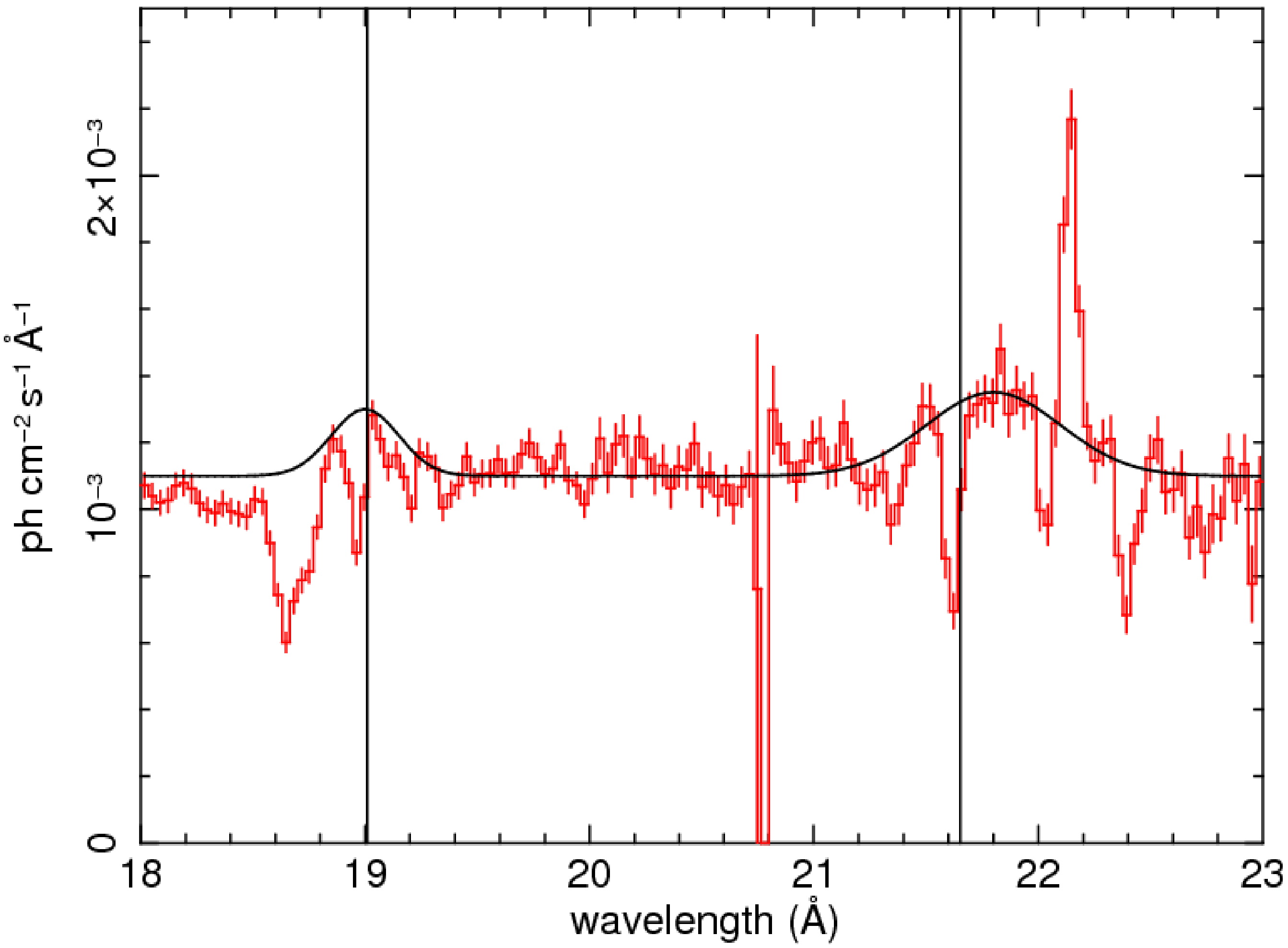
Contrasting RGS spectra in high and low flux states



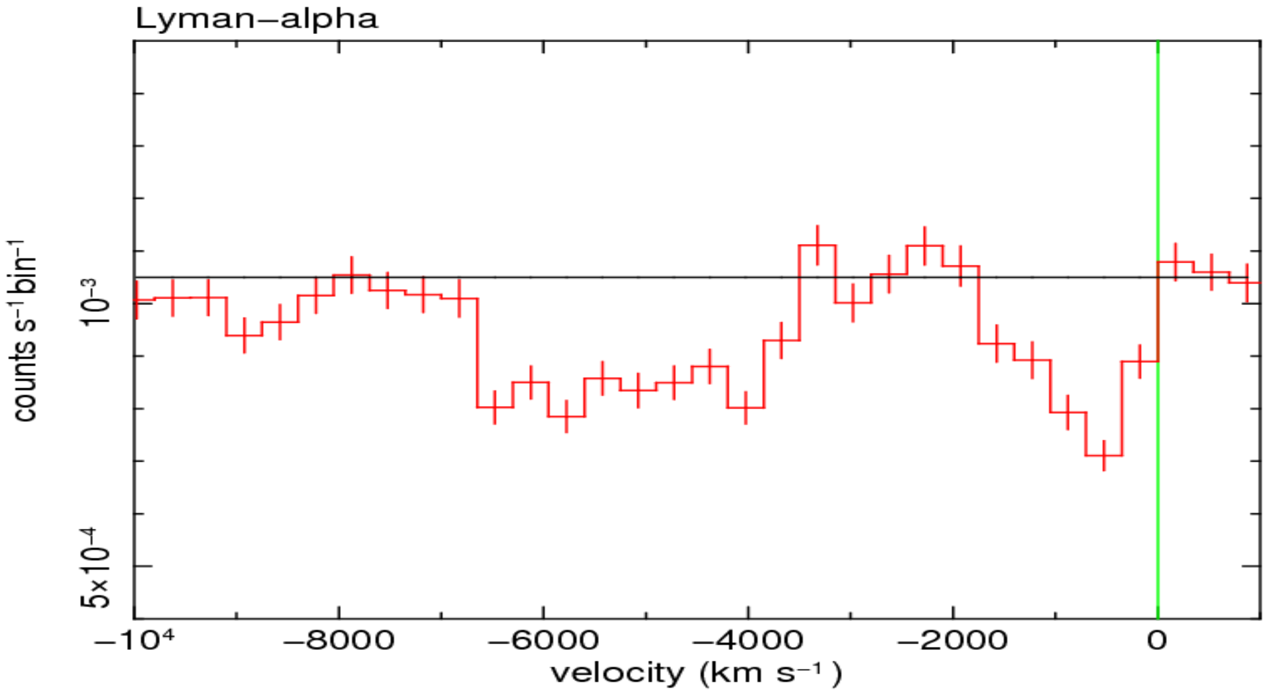
Multiple velocities in absorption



Broad line emission – recombining post-shock flow ?

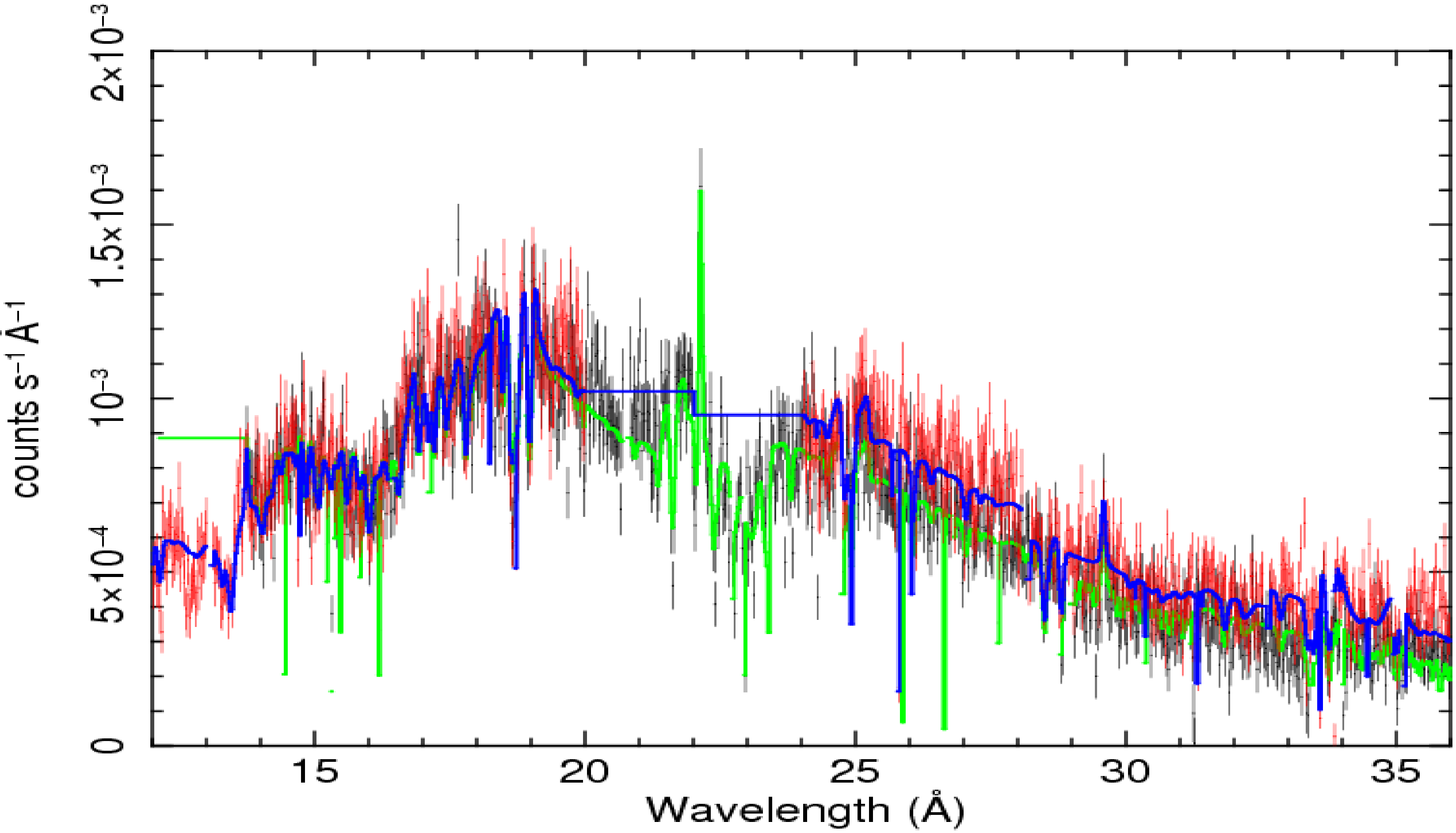


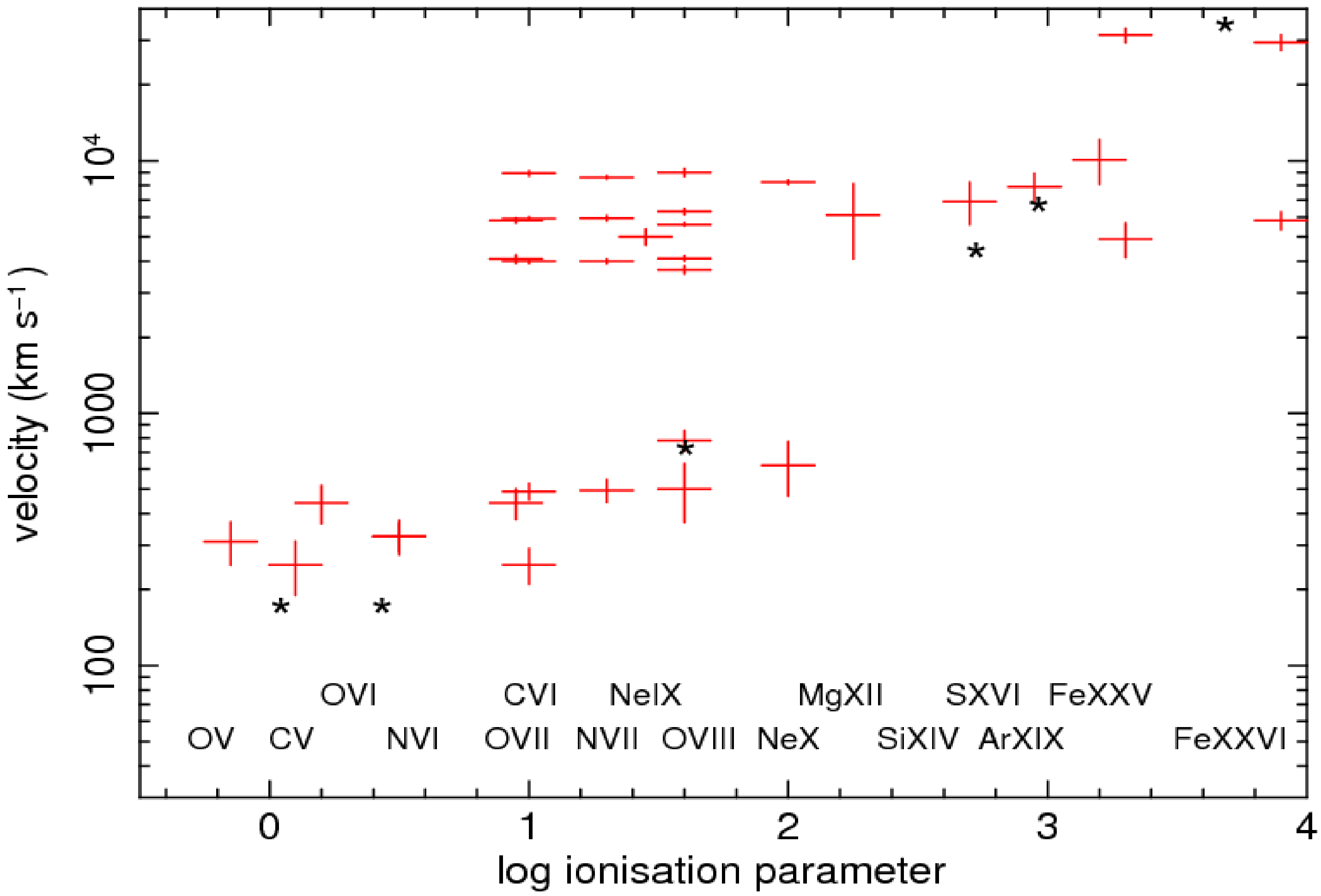
Velocity profile in combined Lyman alpha lines maps post-shock flow



- opacity increase at ~ 7000 km/s suggests shock front where v~0.1c wind hits ISM or slower moving ejecta
- reduced opacity below ~3000km/s coincides with enhanced recombination from OVII, OVIII, etc
- opacity increases again as flow slows ahead of contact discontinuity

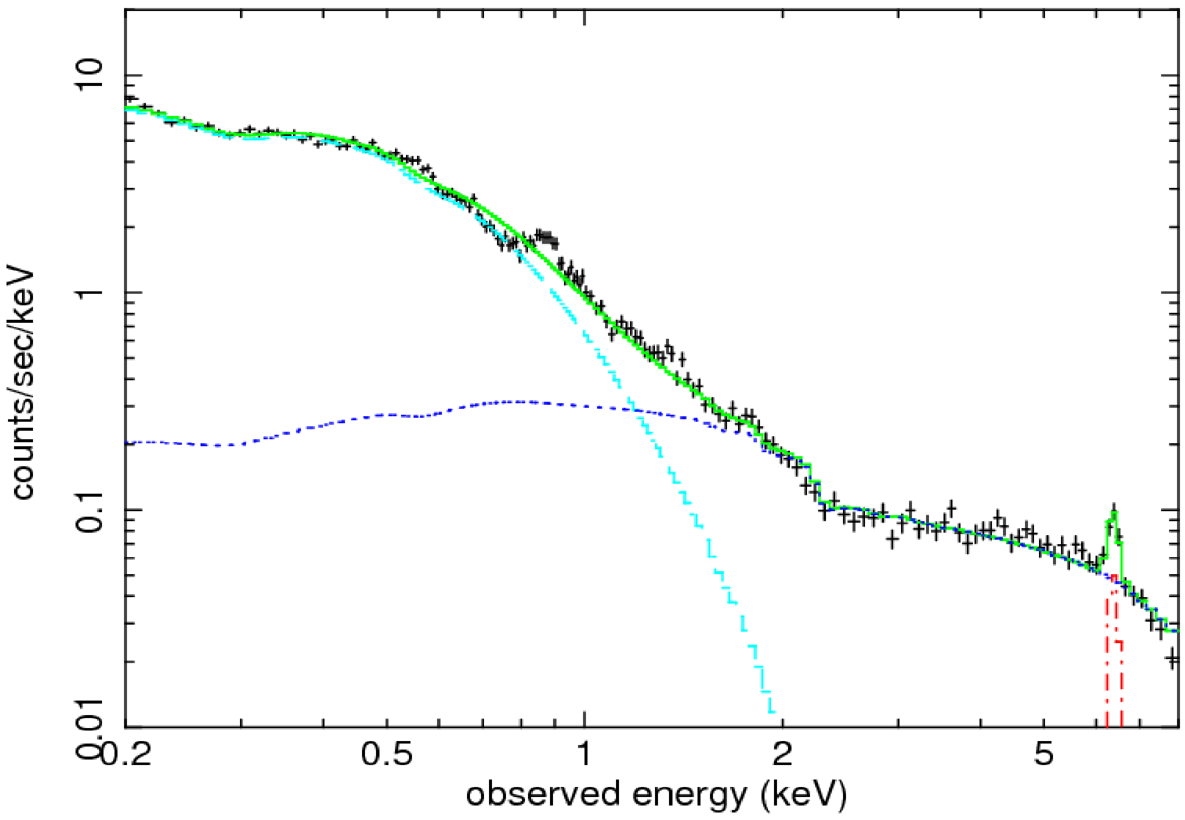
Modelling with XSTAR
- 5 photoionised absorbers to fit RGS data





- correlation of velocity and ionisation parameter consistent with narrow post-shock region
- lowest data points linked with forward shock?

Detecting the cooling radiation ?



- low flux spectrum - similar to offset in rms-flux relation
- major part in continuum - Compton cooling dominant
- but 2-body cooling significant for later stages

Summary

- new XMM-Newton spectra show photoionised outflow with structured velocity and ionisation profiles

- consistent with scenario where a high velocity wind launched during intermittent super-Eddington episodes shocks with ISM or slower moving ejecta.

- post-shock radius ~few x 10^{17} cm and thickness ~ 10^{16} cm

- mechanical energy lost in efficient post-shock cooling

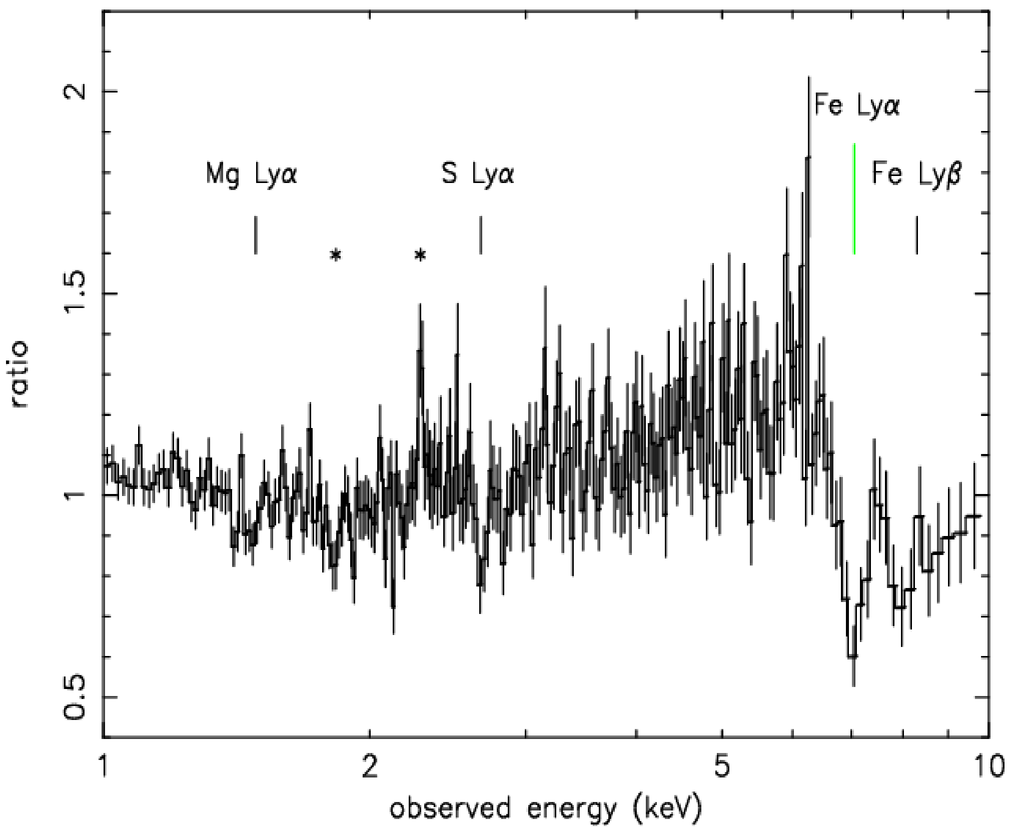
- low flux state soft X-ray spectrum evidence of cooling radiation

- total momentum in swept-up ISM replaces as feedback mechanism

• 2001 pn spectrum* showed absorption lines at ~7.1, 2.7 and 1.5 keV

• identified with Ly-alpha of Fe, S, Mg (del chi-sq: 69/3, 17/2, 16/2)

• >>> high velocity outflow (0.09+/-0.01c) in highly ionised gas

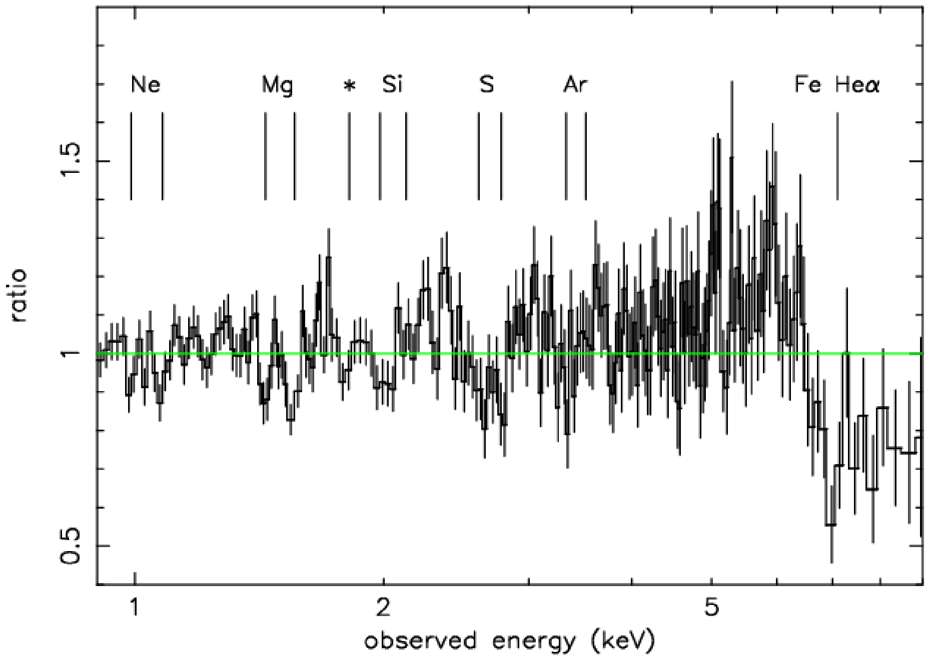


initial caveats re significance for feedback :

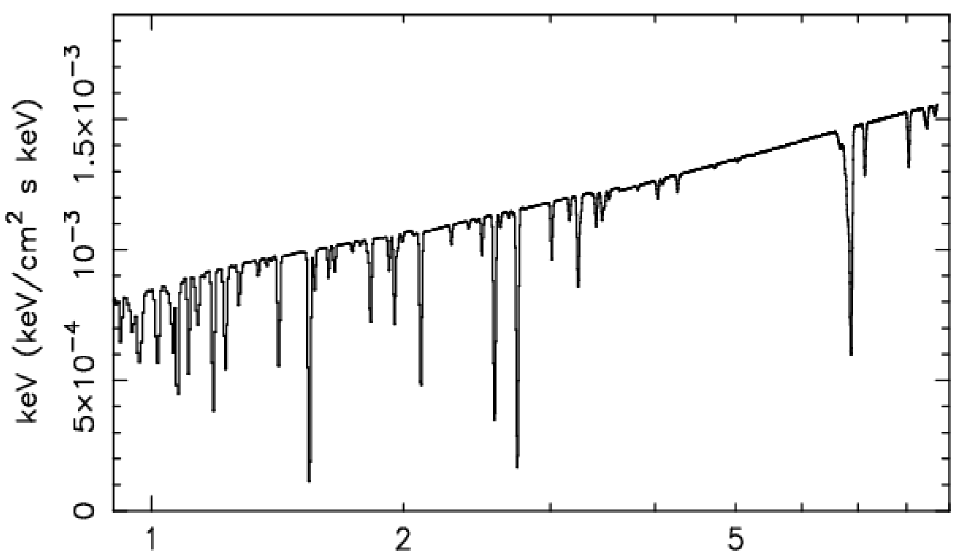
velocity depends on correct i.d.

and flow collimation or CF unknown

Pounds et al (2003) MNRAS, 345, 705



higher resolution XMM MOS data removed FeK absorption line ambiguity, confirming (a higher) velocity



fitting with XSTAR photoionised absorber found ionisation parameter Xi ~ L/nr^2 ~ 1000

K-shell absorption from H- and He-like ions of Ne, Mg, Si, S and Fe

and v~0.13+/-0.01c

Pounds and Page (2006) MNRAS, 372, 1275

quantitatively :

in a radial outflow, with b the fractional solid angle of the flow the mass rate is

$$\dot{M}_{out} = 4b\pi r^2 n v m_p$$

with mechanical energy $\dot{M}_{\rm out}\frac{v^2}{2}$

measure v directly and obtain nr^2 from L_{ion} / xi

- a direct measure of the collimation angle, or the covering factor can be obtained from emission (scattering or recombination) from the ionised outflow

this has now been done for PG1211+143 (5) by

i) quantitative modelling of the broad-band X-ray spectrum

ii) resolving the PCygni profile in FeK

yielding a value of b ~ 0.5-1

(5) Pounds and Reeves (2009) MNRAS, 397, 249

taking b ~0.5 for the highly ionised outflow in PG1211+143,

we find both the mass outflow rate and associated mechanical energy to be high:

outflow mass rate ~ 3 M_{sun} / yr (M $_{acc}$ ~ 2 M_{sun} / yr)

with mechanical energy ~ 10^{45} ergs/s (L_{Edd} ~ 6 x 10^{45} ergs/s)

consistent with a state of super-Eddington accretion where BHWmodel (*)

predicts flow energy ~ v/c . L_{Edd}

over 10^{8} years this rate would carry ~ 3 x 10^{60} ergs into the host galaxy

* King and Pounds (2003) MNRAS, 345, 657

BUT how much mechanical energy in the outflow actually reaches the bulge gas?

It seems quite likely that the sub-relativistic flow:

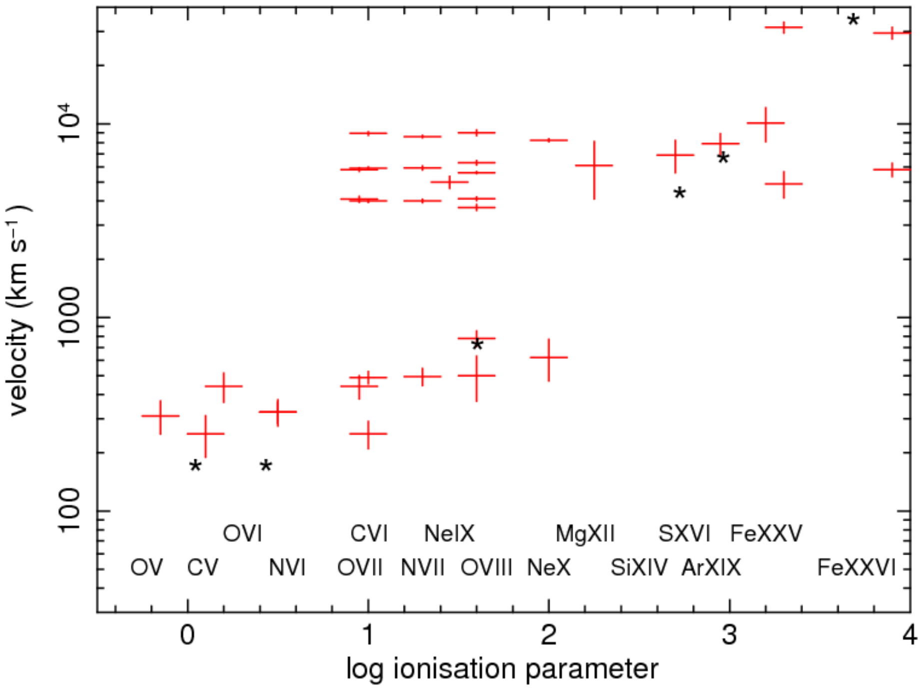
- will shock when hitting the ISM, the shocked gas then being cooled to its Compton temperature by thermal radiation from the AGN

- cooling time then critical in determining how much of the initial outflow energy is radiated away (probably as UV or soft X-rays)

The intriguing case of NGC4051

- new XMM observations (PI: Simon Vaughan) reveal a complex absorption spectrum with a wide range of velocities and ionisation parameter
- Ms exposure for combined RGS and MOS >> blue shifted absorption lines from 23 ions ranging from OIV to FeXX , with multiple lines (velocities) in mid-range ions such as OVIII.
- provisional interpretation in terms of shocked outflow suggests a short (10 years) Eddington episode which ended ~30-50 years ago
- low state soft X-ray component may be cooling radiation from shock

Outflow velocity v. (optimum) ionisation parameter

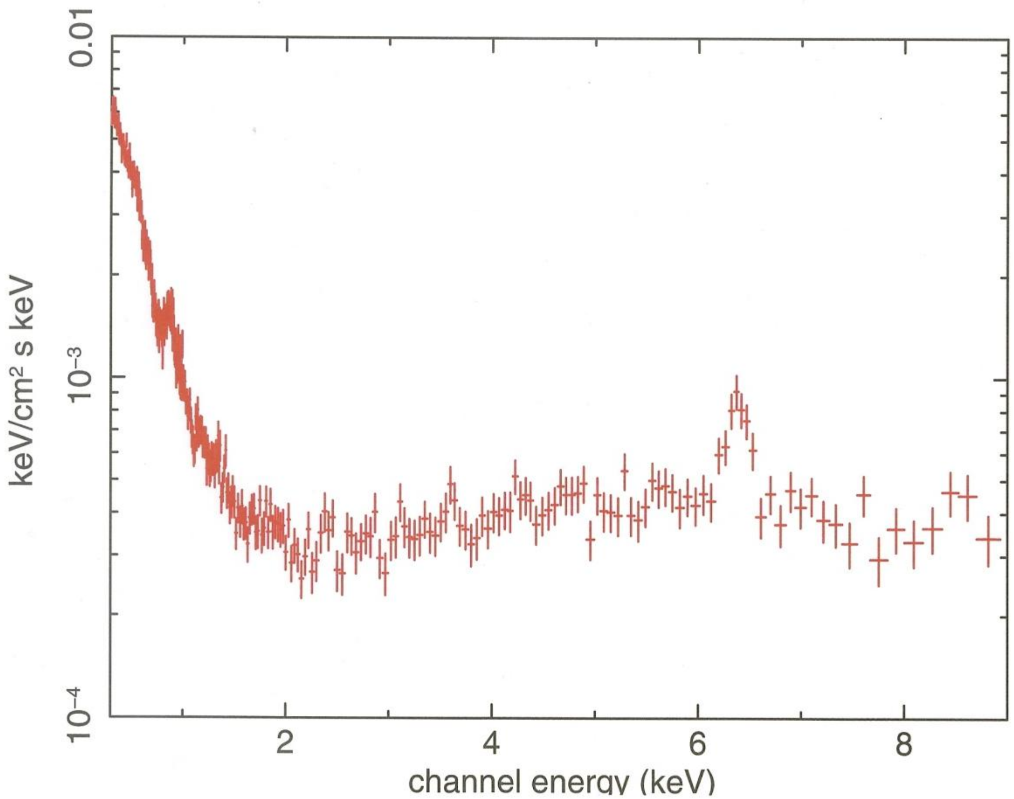


pre-shock high velocity/ highly ionised wind

Cooling post-shock flow, slowing and recombining

low velocity/low ionisation matter ahead of CD

has the cooling shock already been detected ?



residual soft component seen by Chandra during 6-week low state (*)

almost identical to soft component in 2009 XMM low state

few percent of BBB luminosity

* Uttley et al 2003

Summary

- high velocity/highly ionised outflows in several bright radio quiet AGN could be the feedback linking the growth of SMBH and their host galaxies

- the association of high velocities with high ionisation state delayed discovery of such energetic outflows until new X-ray Observatories provided sensitivity to detect absorption lines in the Fe K band

- as the high speed wind collides with the ISM, it will shock, efficient cooling by Comptonisation causing most of the mechanical energy to be lost

- however the flow momentum will be conserved, with ram pressure building to eventually unbind the bulge gas if continued through a major merger event (or multiple Eddington episodes)

- a new observation of NGC4051 offers evidence of a minor Eddington episode that may have ended some tens of years ago. Such episodes could be common.

NB King has previously shown that the ram pressure of a momentum driven outflow leads naturally to the observed M-sigma relationship circumstantial evidence for the importance of shocks

consider a merger event for PG1211+143 which doubles the mass of the black hole and the bulge

accretion at the Eddington rate for 10^8 years will inject total mechanical energy into the bulge $E_{mech} \times 10^8\ yr \sim 3 \times 10^{60} \eta_{mech}\ erg$

the bulge mass increases by $\sim M_b \sim 10^3 M_{BH}$

with binding energy $E_{bind} \sim M_b \sigma^2 \sim 8 \times 10^{58}\ erg$

taking $\sigma = 200\ \mathrm{km/s}$ from the M-sigma relation

the coupling of outflow energy to the galaxy must be highly inefficient to avoid premature destruction of the bulge

BHW model* offers a physical framework for an ‘Eddington wind’

since a radial outflow of the measured column density will have an electron scattering optical depth (tau~1) within the launch radius we expect single scattering of each photon, providing an outflow momentum

$$\dot{M}_{out}.v \simeq \frac{L_E}{c}$$

Since $L_E = \eta \dot{M}_E c^2$ we expect $\frac{v}{c} \simeq \frac{\eta \dot{M}_E}{\dot{M}_{out}} \sim 0.1$

while the mechanical energy in the outflow is of order

$$\dot{M}_{out}.v^2 \simeq \frac{v L_E}{c}.$$

* King and Pounds (2003) MNRAS, 345, 657

for an Eddington wind we also expect * :

the ionisation parameter to be high, since $\xi = \frac{L_i}{NR^2}$

combining $\dot{M}_{out}.v \simeq \frac{L_E}{c}$ and $\dot{M}_{out} = 4b\pi r^2 n v m_p$

we find $\xi = 3 \times 10^4 \eta_{0.1}^2 l_2 \dot{m}^{-2}$,

where $l_2 = l_i/10^{-2}$, and $\eta_{0.1} = \eta/0.1$

hence fast X-ray outflows are best seen in Fe K band

* King (2010) MNRAS in press (also astro-ph/0911282)

Ultra fast outflows in radio quiet AGN

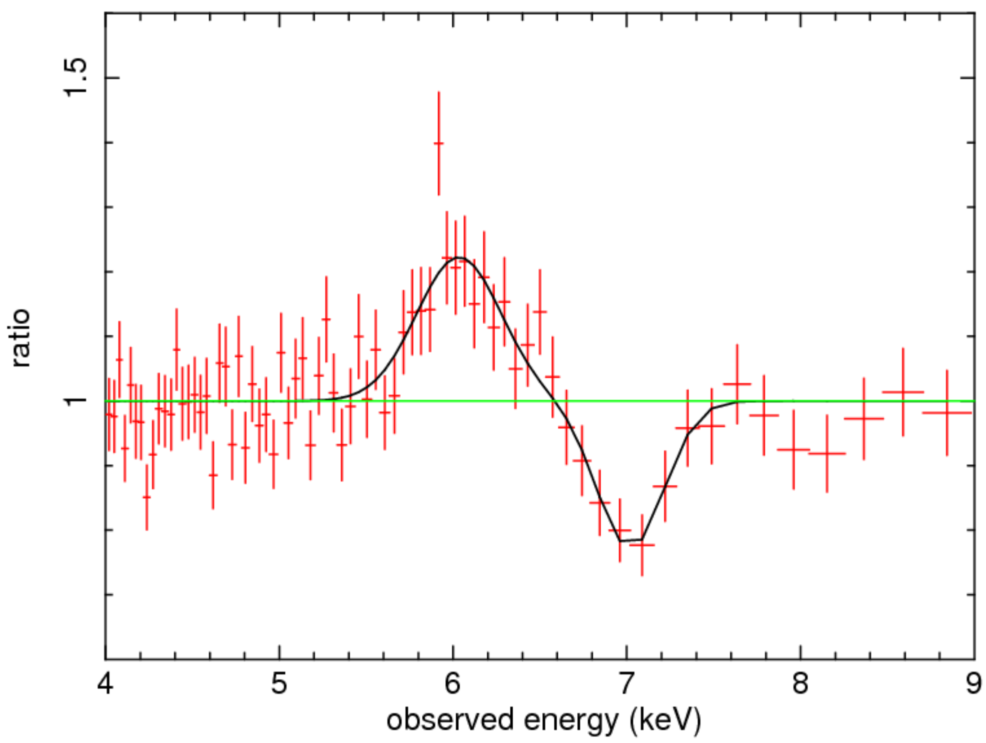
‘warm absorbers’ are found in ~ 50% of AGN but the low velocities (~ 200-500 km/s) and column densities (~ 10^{21}-10^{22} cm^{-2}) carry little energy

an XMM observation (1,2) of the narrow line QSO PG1211+143 found an outflow with v~0.1c and column density ~ $5x10^{23}$ but this was disputed after the high velocity was not detected in RGS data (3)

more examples have now been seen (4), and a search in the XMM data base of a complete sample of 44 radio quiet AGN (5) has found 11 with evidence of a highly ionised outflow with v ~ 0.1c

(1) Pounds et al (2003) MNRAS, 345, 705
(2) Pounds and Page (2006) MNRAS, 372, 1275
(3) Kaspi and Behar (2006) ApJ, 636, 674
(4) Cappi (2006) Astron. Nachr., 327, 1012
(5) Tombesi et al (2010) A&A, submitted

P Cygni profile of Fe K absorption and emission identified with FeXXV

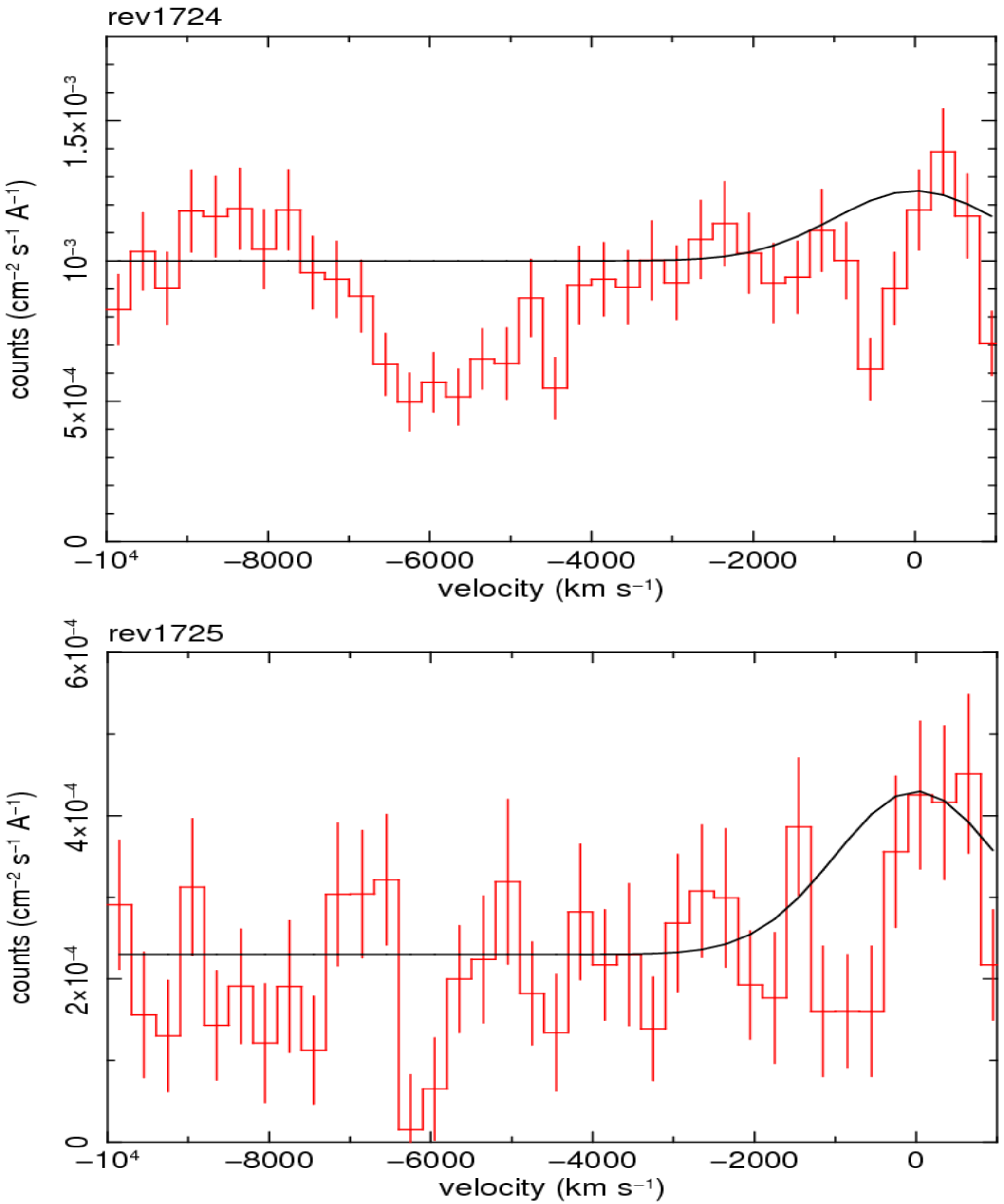


FeXXV absorption line at ~7.6 keV (rest frame) yields v ~ 0.12c
width ~ 150 eV (1 sigma) >> velocity spread ~ 0.11- 0.13c

FeXXV emission line at ~6.7 keV (rest frame), mean v ~ 0
width ~ 300 eV (1 sigma)
>> velocity broadening ~ 27000 km/s FWHM

>> wide angle outflow/ C.F. ~ 0.5-1

scaling the shock



recombination in high velocity post-shock gas as flux level falls by factor 5 between successive orbits

>> > density ~ $10^{\mathbf{6}}$ cm$^{\mathbf{-3}}$

from modelled ionisation parameter then

shock radius ~ $10^{\mathbf{17}}$ cm

(t~1 year at 0.1c)

a few parameters of the post shock flow

	post-shock	pre-CD	forward shock
mass rate	0.015 M_{sun}/yr (0.3M_{Edd})		
mass		0.75 M_{sun} (t ~ 50 years)	
mech. energy	2.5 x 10^{41} erg/s (0.1% L_{Edd})		
mass			850 M_{sun} (1% of virial ISM for r~10^{18} cm)