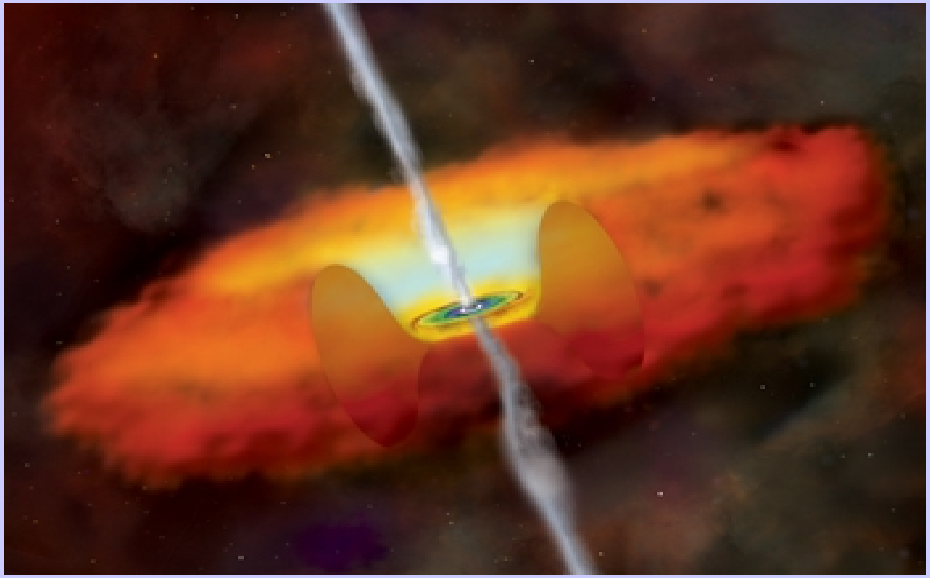
X-ray evidence for ultra-fast outflows in local AGNs



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AGN Winds in Charleston, SC, Oct. 15-18 2011

Outline

- **Spectral analysis of the radio-quiet AGNs sample**
(Tombesi et al. 2010a)

- **Photo-ionization modeling and global parameters**
(Tombesi et al. 2011a)

- **Location and energetics of ultra-fast outflows**
(Tombesi et al. 2011c, MNRAS submitted)

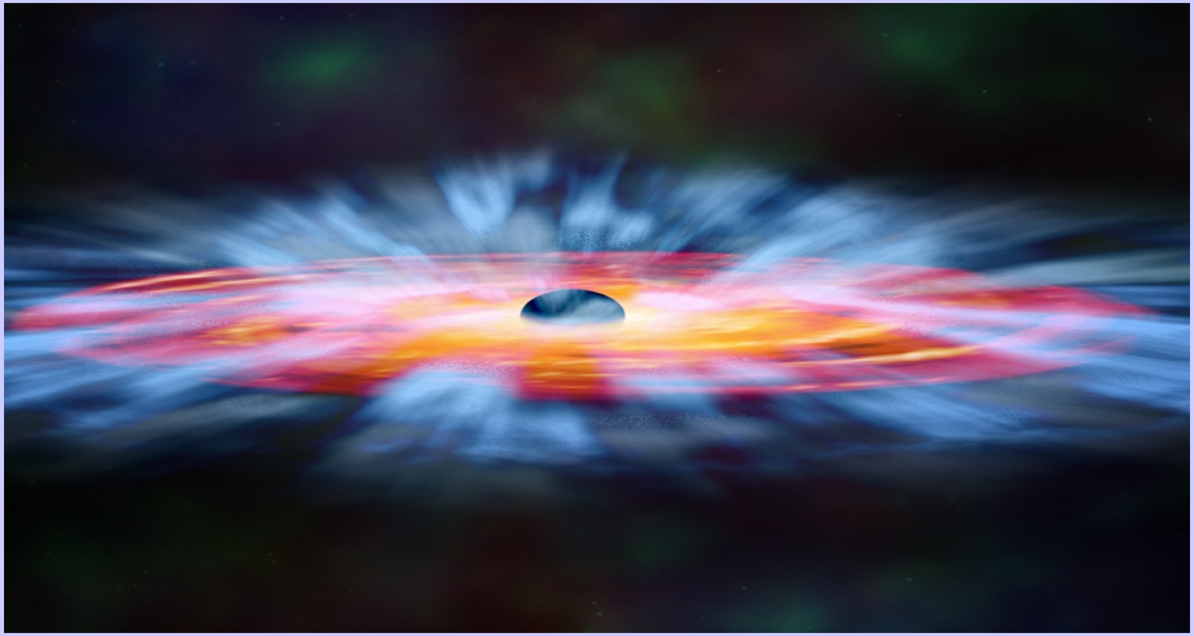
- **Ultra-fast outflows in radio-loud AGNs** (Tombesi et al. 2010b)

- **Follow-up on 3C 111** (Tombesi et al. 2011b)

- **Astro-H simulations**

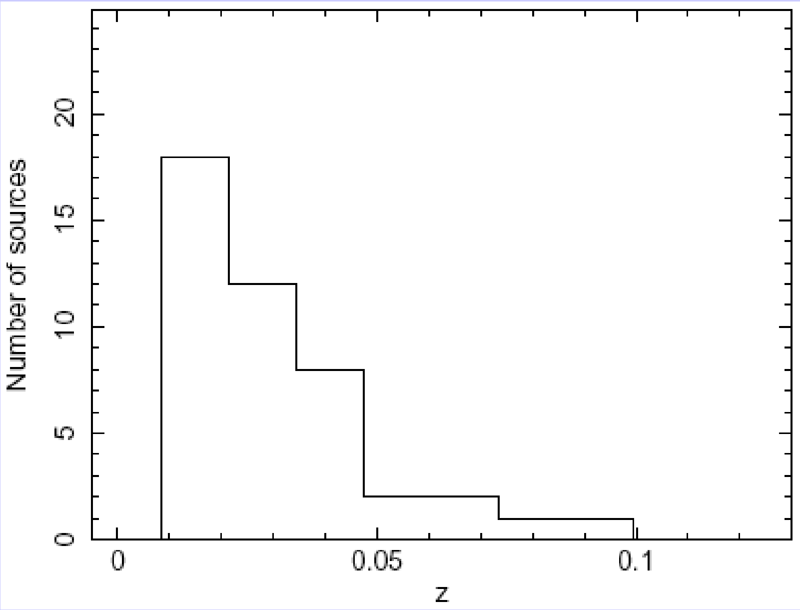
- **Conclusions**

X-ray evidence for fast outflows in radio-quiet AGNs

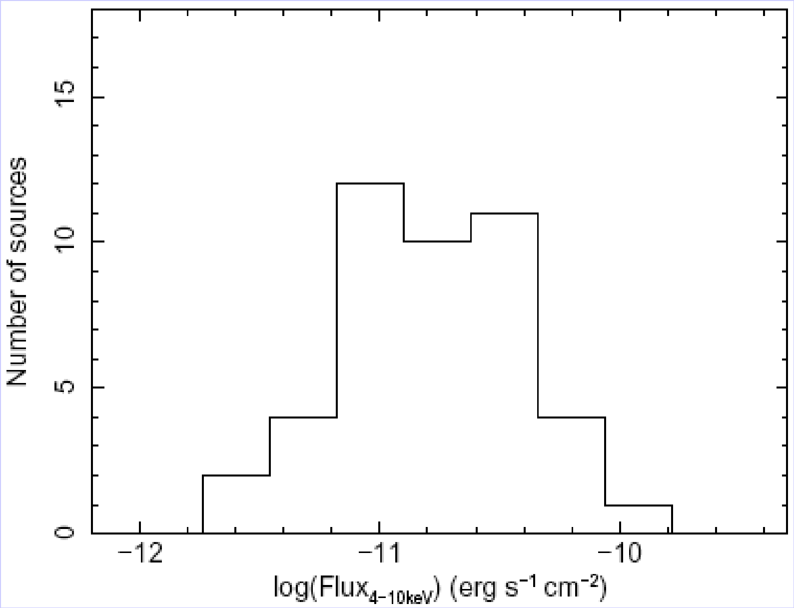


- **Blue-shifted Fe XXV/XXVI absorption lines suggest presence of highly ionized and mildly relativistic X-ray outflows in radio-quiet AGNs** (e.g. Chartas et al. 2002, 2003; Pounds et al. 2003; Dadina et al. 2005; Markowitz et al. 2006; Braito et al. 2007; Turner et al. 2008; Cappi et al. 2009; Reeves et al. 2009, …)
- **Possible direct connection with accretion disk winds/outflows and important contribution on AGN feedback**
- **Need for a systematic analysis on a large sample of sources**

The sample of local radio-quiet AGNs



Cosmological red-shifts of sources



4-10keV flux of the sources

- Selection of all NLSy1, Sy1 and Sy2 ($N_H < 10^{24} cm^{-2}$) in RXTE All-Sky Slew Survey Catalog (complete at 90% at 4σ limiting flux 10^{-11} erg s^{-1} cm^{-2} in 4-10keV; Revnivtsev et al. 2004)
- Cross-correlation with XMM-Newton Accepted Targets Catalog (as of October 2008)
- Total of 42 sources for 101 pointed XMM-Newton observations
- Local ($z<0.1$)
- X-ray bright ($F_{4-10keV}=10^{-12}-10^{-10}$ erg s^{-1} cm^{-2})

(Tombesi et al. 2010a)

Fe K-shell absorption lines search

Ultra-Fast Ouflows (UFOs): highly ionized X-ray absorbers with outflow velocities v≥10,000 km/s

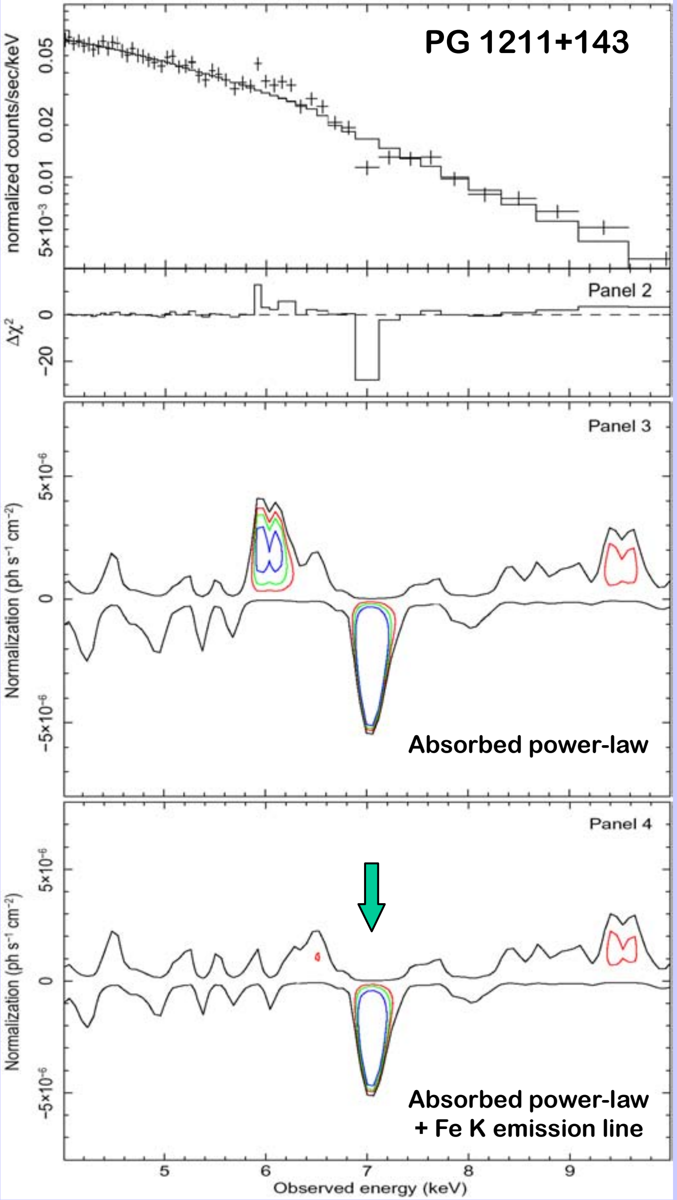
(soft X-ray warm absorbers v<1000km/s)

Uniform spectral analysis of EPIC pn:

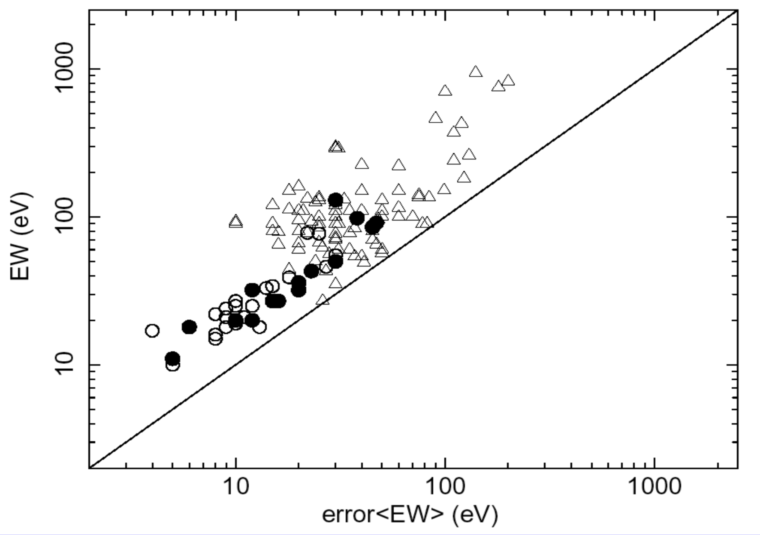
- Phenomenological baseline model in the 4-10keV: absorbed power-law + Gaussian Fe K emission lines
- Checked consistent results including more complex spectral components (e.g., reflection, warm absorption)

Blind absorption/emission lines search:

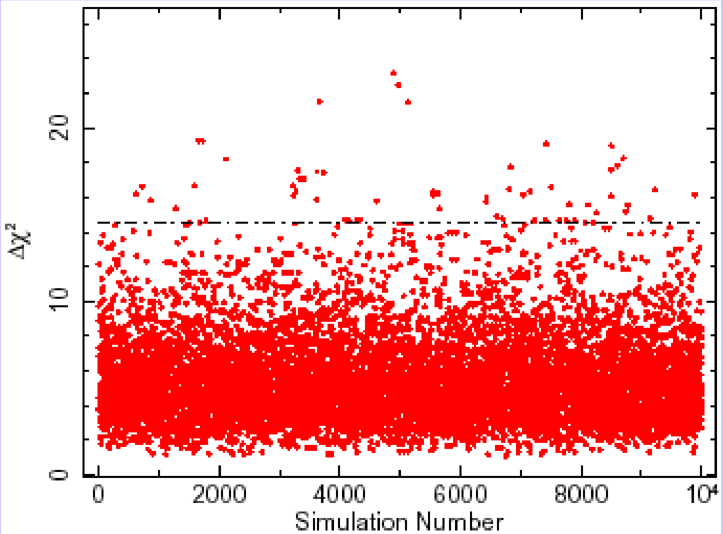
- Addition of narrow line to baseline model stepping energy in 4-10keV and recording $\Delta\chi^2$ deviations
- Visualization on energy-intensity contour plots (F-test significance >68% red, >90% green, >99% blue)
- Initial selection of narrow (σ<100eV) lines with F-test confidence levels >99%
- 14 absorption lines E=6.4-7.1keV and 22 at E≥7.1keV
- Identification with Fe XXV/XXVI 1s-2p/1s-3p transitions and derived relative velocity shift



Global blue-shifted absorption lines significance



Blue-shifted lines (open circles v<0.05c filled circles v>0.05c) and Fe Kα emission at 6.4keV (open triangles)



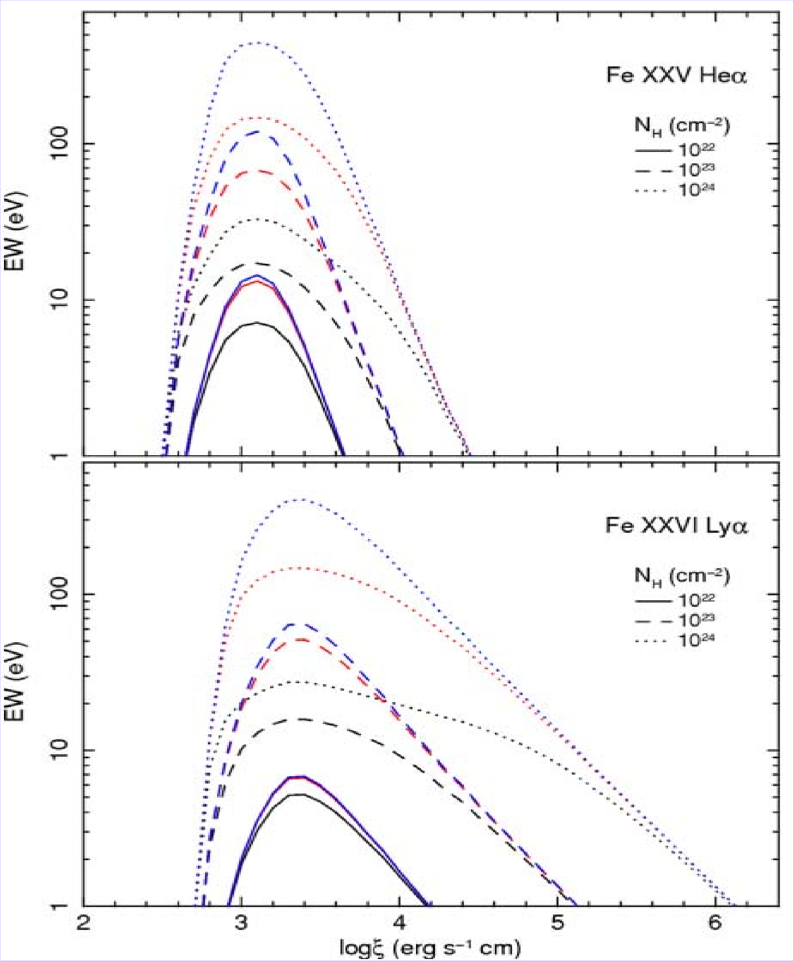
Extensive Monte Carlo simulations

- Additional significance test on lines at E=7.1-10 keV with Monte Carlo simulations
- Selection of 22 with MC confidence level >95%
- Checked no contamination from EPIC pn background and calibration
- Only marginal model dependence results
- Detection of lines with blue-shift >10,000km/s (UFOs) in ~40%-60% of the sources
- Random probability detection in 21 observations out of 101 is $<10^{-8}$ ($>5\sigma$)
- Consistency check and confirmation of 12/22 detections (>90%) with MOS, global random probability $<10^{-7}$
- Solved the claimed publication bias (Vaughan & Uttley 2008)

Photo-ionization modeling Fe XXV/XXVI absorption lines

Ion	ID	Transition	<E> (eV)	Line	E (eV)	f_{lu}	A_{ul}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Fe XXV	Heα	1s^2–1s2p	6697	(r)	6700	7.04×10^{-1}	4.57×10^{14}
				(i)	6668	6.87×10^{-2}	4.42×10^{13}
	Heβ	1s^2–1s3p	7880	(r)	7881	1.38×10^{-1}	1.24×10^{14}
				(i)	7872	1.70×10^{-2}	1.00×10^{13}
	Heγ	1s^2–1s4p	8295	(r)	8295	5.07×10^{-2}	5.05×10^{13}
				(i)	8292	6.00×10^{-3}	2.00×10^{12}
	Heδ	1s^2–1s5p	8487	(r)	8487	2.44×10^{-2}	2.54×10^{13}
				(i)	8485	2.90×10^{-3}	1.00×10^{12}
Fe XXVI	Lyα	1s–2p	6966	(r_1)	6973	2.80×10^{-1}	2.96×10^{14}
				(r_2)	6952	1.40×10^{-1}	2.93×10^{14}
	Lyβ	1s–3p	8250	(r_1)	8253	5.32×10^{-2}	7.86×10^{13}
				(r_2)	8246	2.65×10^{-2}	7.83×10^{13}
	Lyγ	1s–4p	8701	(r)	8701	1.95×10^{-2}	3.20×10^{13}
	Lyδ	1s–5p	8909	(r)	8909	9.35×10^{-3}	1.61×10^{13}

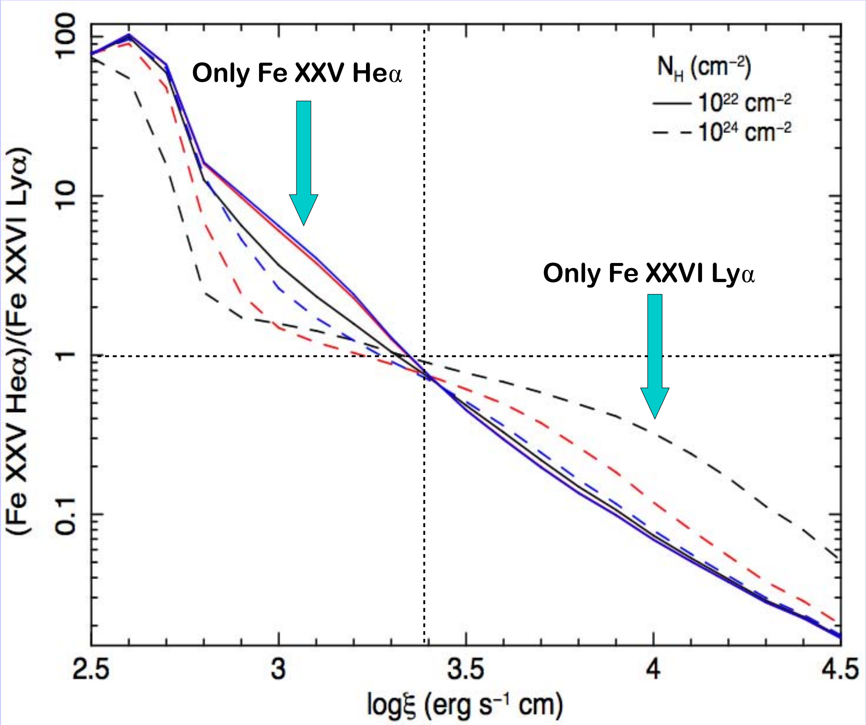
from NIST atomic database



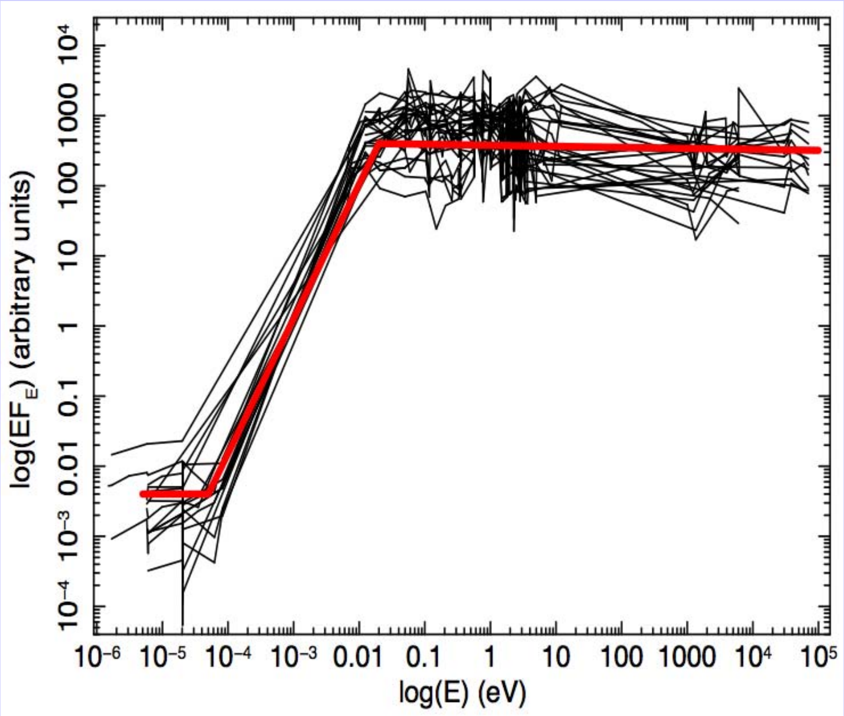
b=100 (solid), 1000 (dashed), 5000 km/s (dotted)

- Curve of growth analysis of Fe XXV/XXVI absorption lines: EW vs. N_H, logξ, b (km/s)
- Fe ions populations derived from Xstar simulations and lines Voigt profile integration (Tombesi et al. 2011a)

Photo-ionization modeling Fe XXV/XXVI absorption lines



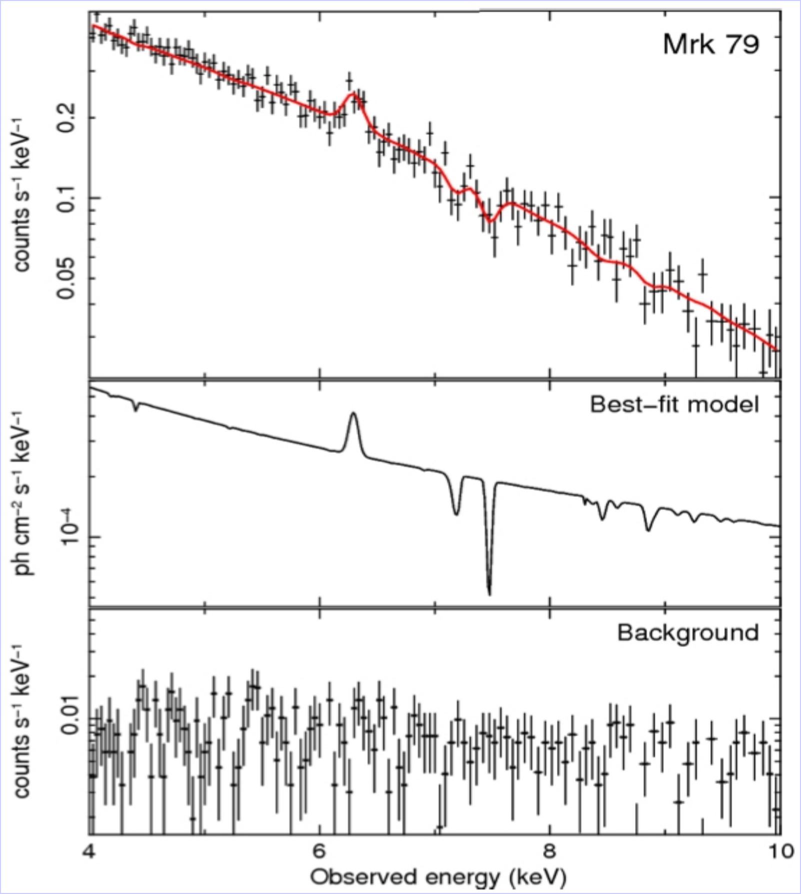
b=100 (black), 1000 (red), 5000 km/s (blue)



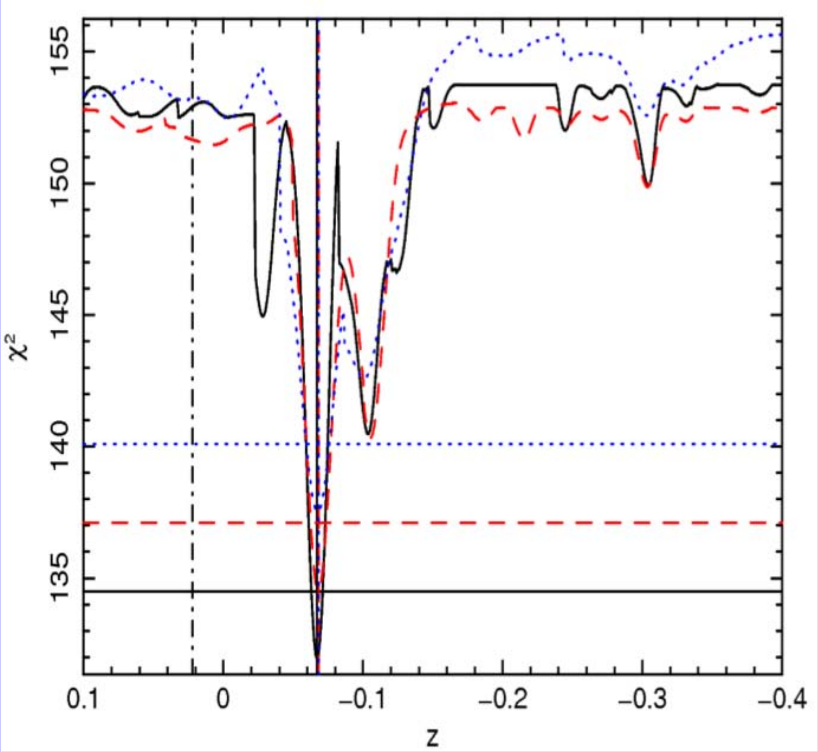
Average SED of Seyfert 1s from NED

- Fe XXV dominates for logξ=2.5-3.5, Fe XXVI dominates for logξ>3.5 erg cm/s
- Calculated average Seyfert 1 SED from NED, Γ=2 and cut-off E~100keV
- Calculated Xstar photo-ionization grids with Solar abundances and turbulent velocities of 1000, 3000, 5000km/s
- Four absorption lines resolved with width σ ~5000km/s, others only upper limits

Photo-ionization modeling Fe XXV/XXVI absorption lines



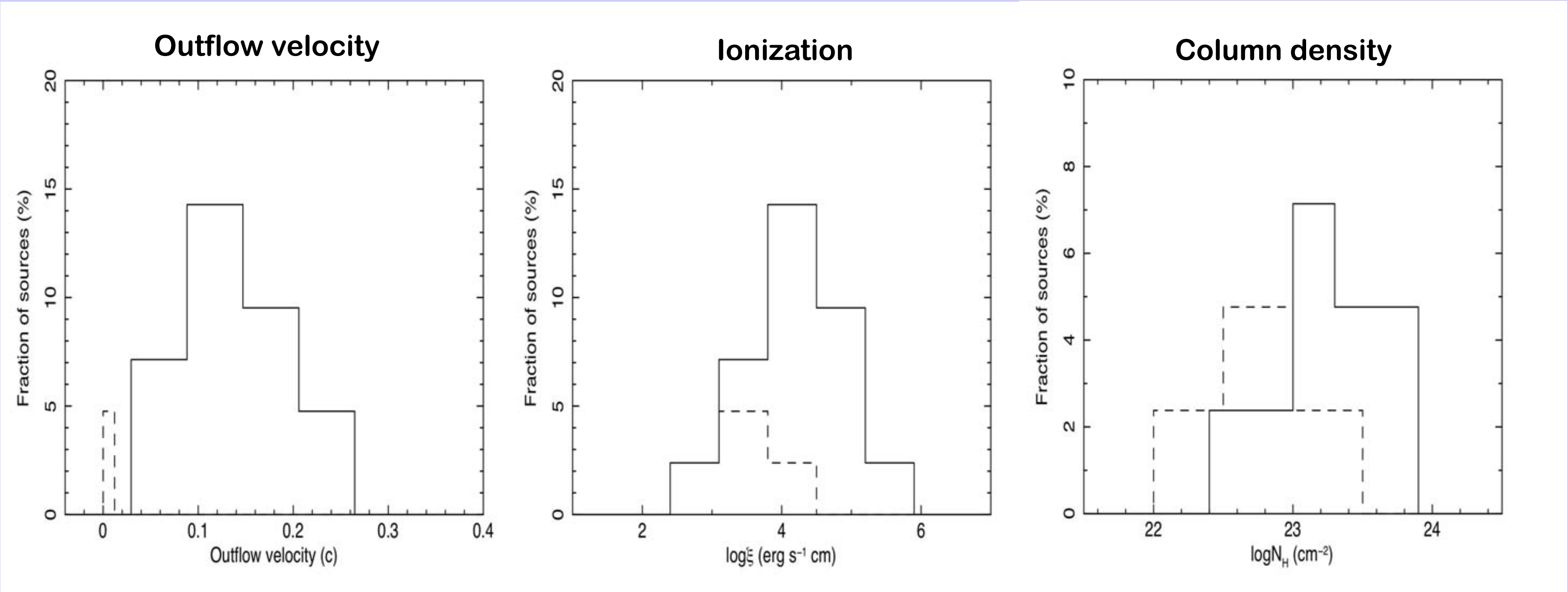
v=0.092±0.04c, logξ=4.19±0.23, N_H=(1.9±1.2)x$10^{23}$$cm^{-2}$



χ^2 statistics vs. Xstar absorber redshift, P_F=99.97%

- Blind search for Xstar solution(s) stepping redshift between 0.1 and -0.4, min χ^2
- Fits self-consistently take into account lines and edges from ions of all elements
- If two equivalent solutions, averaged parameters and included identification errors
- Fits significance >99% and only one Xstar component needed each time

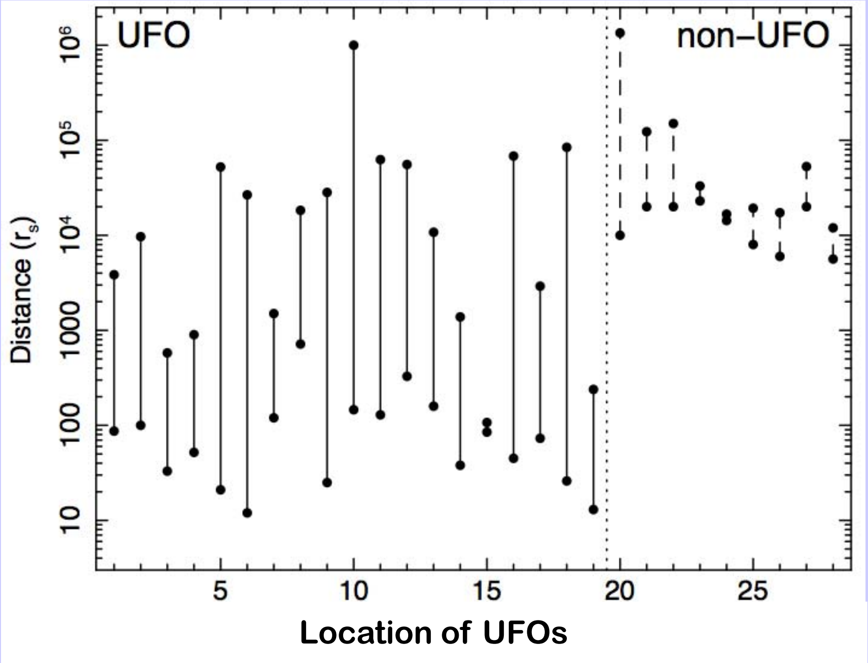
Global parameters of UFOs in radio-quiet AGNs

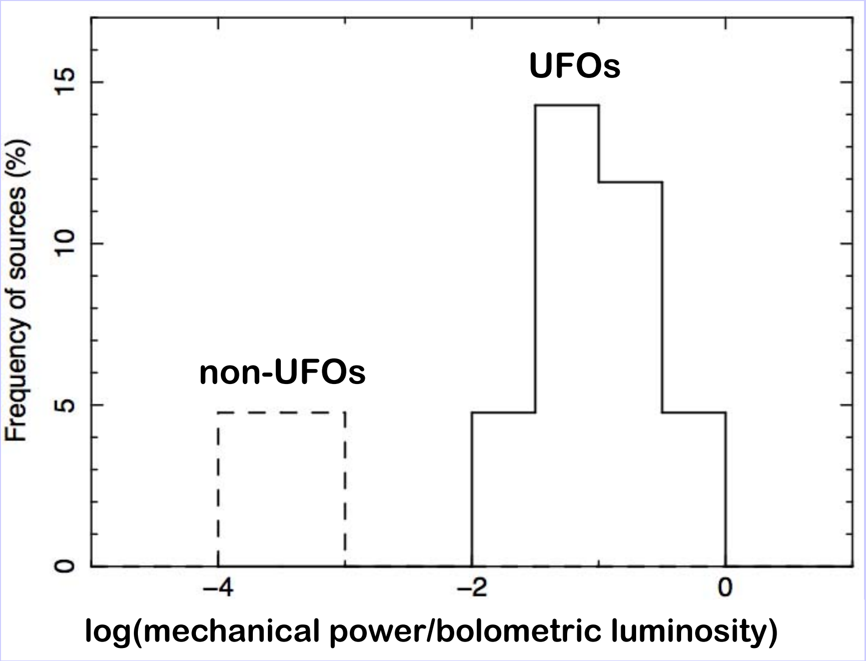


- UFO detected in **>40%** of the sources, large covering fraction ~0.5
- Variability in EW and velocity on time-scales even of **~days**, compact absorbers
- Mildly-relativistic outflow velocities, distribution ~0.03-0.3c, with mean **~0.14c**
- Highly ionized, logξ~2.5-6 erg s^{-1}cm, with mean **~4.2 erg s^{-1}cm**
- Large column densities, N_H~10^{22}-$10^{24}$$cm^{-2}$, with mean **~$10^{23}$$cm^{-2}$**

(Tombesi et al. 2011a)

Location and energetics of UFOs in radio-quiet AGNs



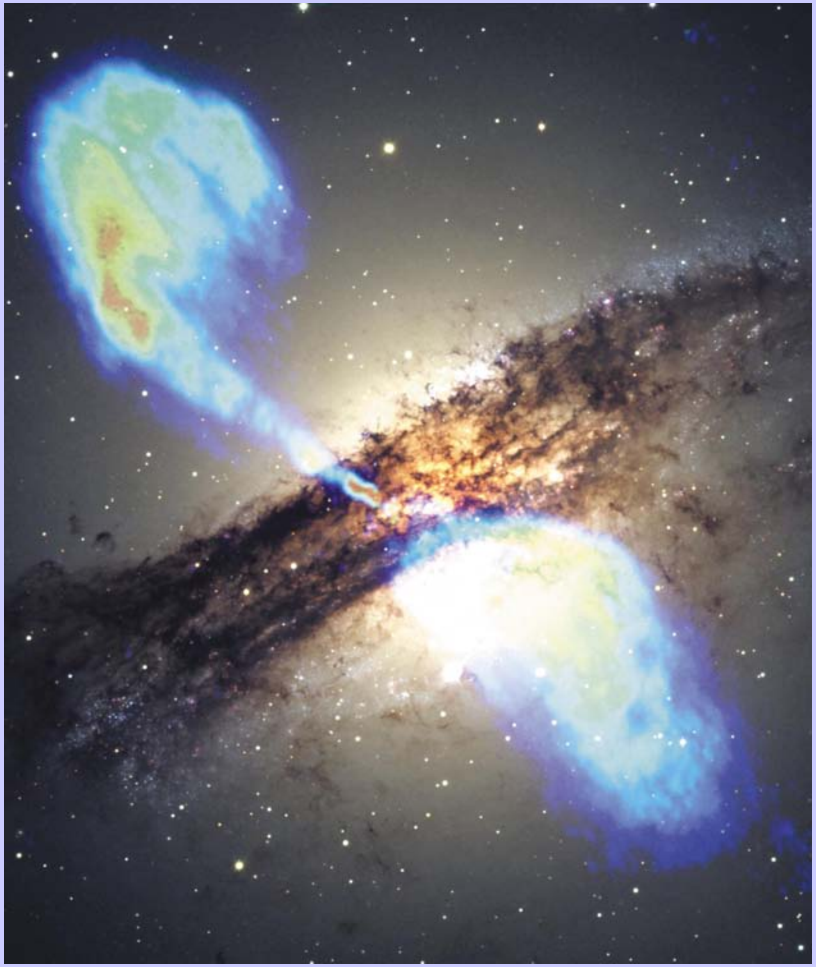


- $r_{max}=L_{ion}/\xi N_H$, $r_{min}=2GM_{BH}/v^2$, d~0.0005-0.05pc (~10^2-$10^4 r_s$), **accretion disk outflows**
- $M_{out}/C > M_{acc}$. For M_{out}~M_{acc}~$0.2M_{sun}$/yr, filling factor ~10-20%, **clumpy and/or intermittent**
- Mechanical power ~10^{43}-10^{44}erg/s ~ L_X **~5-10% L_{bol}**, integrated ~10^{59}-10^{60}erg
- Potentially important for AGN energetic budget and cosmological **feedback**
- Comparable/**higher feedback than jets?** UFOs massive, mildly-relativistic, wide angles, mechanical power ~jets, >40% sources and also in radio-loud AGNs

(Tombesi et al. 2011c, MNRAS sub.)

Ultra-fast outflows in radio-loud AGNs

- **Broad Line Radio Galaxies are the <u>radio-loud counterpart of Seyfert 1s</u>**
- **<u>Show relativistic radio jets</u>, but i~20° allows observation of the inner disk**
- **Limited long observations in X-ray archives to five local (z<0.1) sources**
- **3C 111, 3C 390.3, 3C 120, 3C 382, 3C 445**

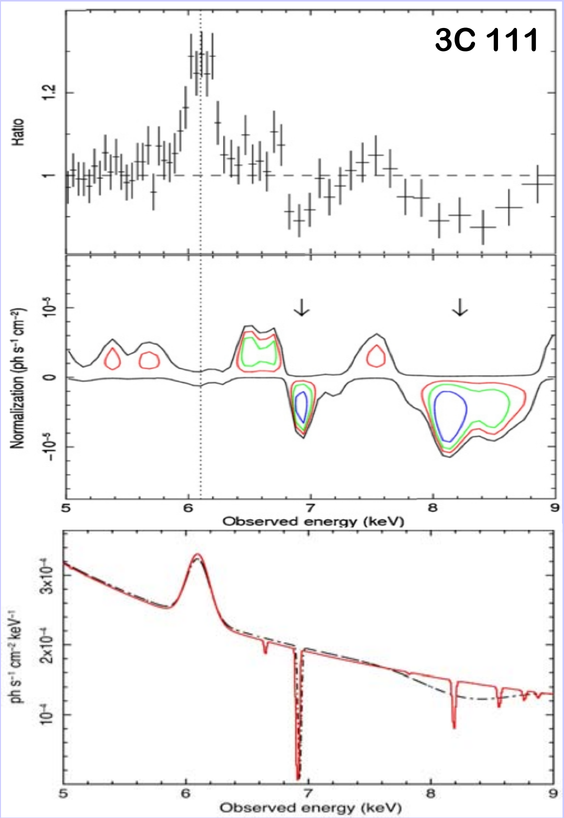


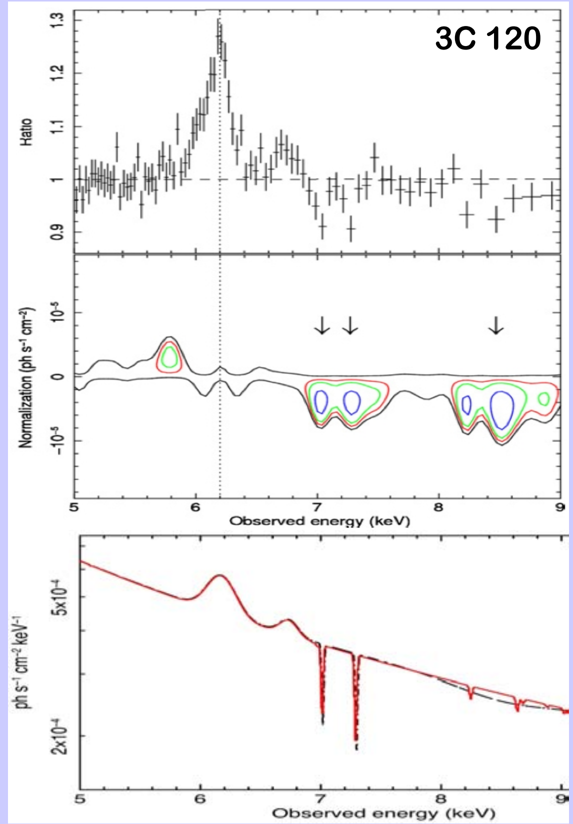
Centaurus A

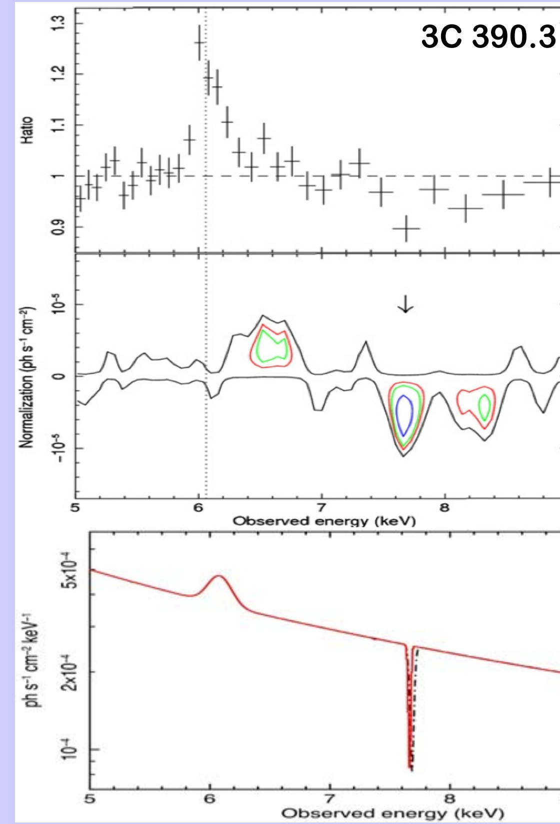
(Tombesi et al. 2010b)

- **Systematic 4-10keV spectral analysis Suzaku**
- **Same method for radio-quiet with XMM-Newton**
- **Search for blue-shifted Fe K absorption lines**
- **Blue-shifted Fe K lines at E>7keV in 3/5 sources**
- **Each absorption line significant at >99% with F-test and Monte Carlo simulations**
- **Background and XIS consistency checks**
- **Check broad-band XIS+PIN (0.5-50keV) including reflection and warm absorption**

Ultra-fast outflows in radio-loud AGNs





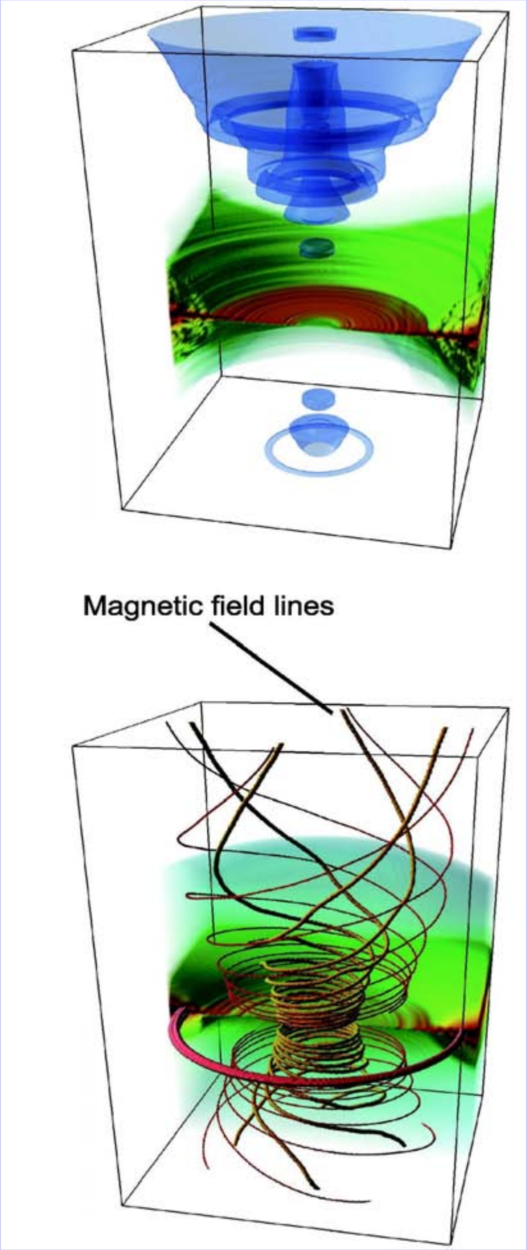


- **3C 111**: Fe XXVI Lyα, Lyβ, Lyγ, Lyδ series, v=0.041±0.004c. Random probability ~10^{-8}
- **3C 120**: Fe XXV Heα + Heβ and Fe XXVI Lyα + Lyβ, v=0.076±0.003c. Random probability ~10^{-4}
- **3C 390.3**: Fe XXVI Lyα, v=0.146±0.004c. Random probability ~10^{-3}
- Physically self-consistent photo-ionization modeling with Xstar, lines rations suggest saturation
- High ionization $\log\xi$=4-6 erg s^{-1}cm, mildly-relativistic v=0.04-0.15c, high columns $N_H > 10^{22}$ cm^{-2}

Ultra-fast outflows in radio-loud AGNs

Ultra-fast outflows in BLRGs:

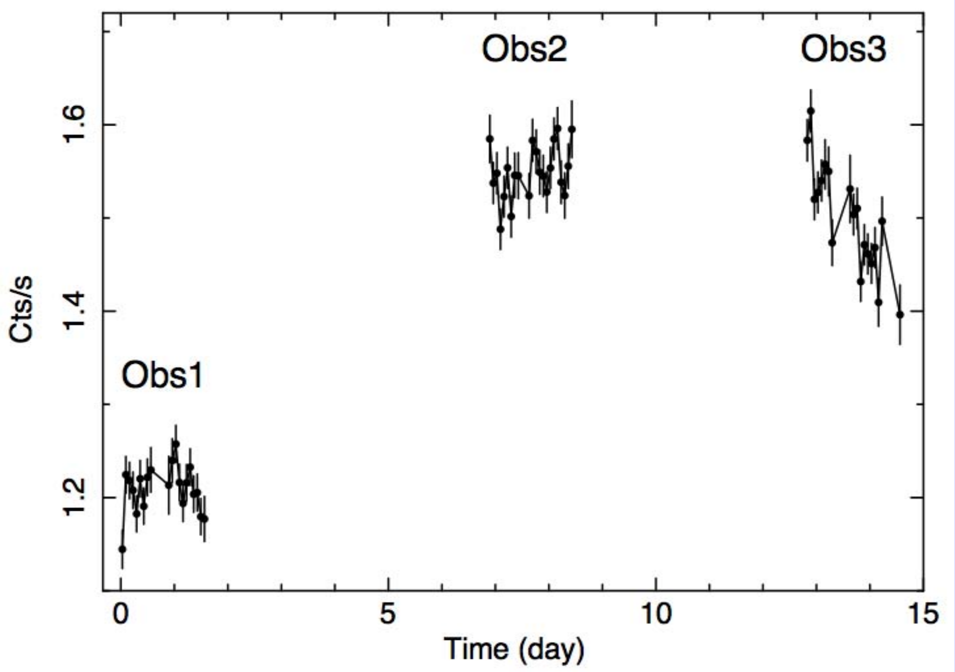
- Common, detected in 3/5 sources
- Compact and close to the BH, d<0.01-0.1pc
- Covering fraction roughly ~0.5, similar to Seyferts
- Mildly relativistic, v~0.1c
- Massive, $M_{out} \sim 1 M_{Sun} yr^{-1} \sim M_{acc}$
- Powerful, $E_K \sim 10^{44}$-10^{45}erg/s ~ radio jet power
- Energetically significant, $E_K \sim L_X \sim 0.1 L_{bol}$
- Possibly important contribution to AGN feedback
- $L_{bol}/L_{Edd} \sim 0.1$-0.5, wind/photon momenta $(M_{out} v_{out})/(L_{bol}/c) \geq 1$
- Acceleration through radiation and/or magnetic forces?
- Connection with ejection of knots in the jet? Outbursts?



(Ohsuga et al. 2009)

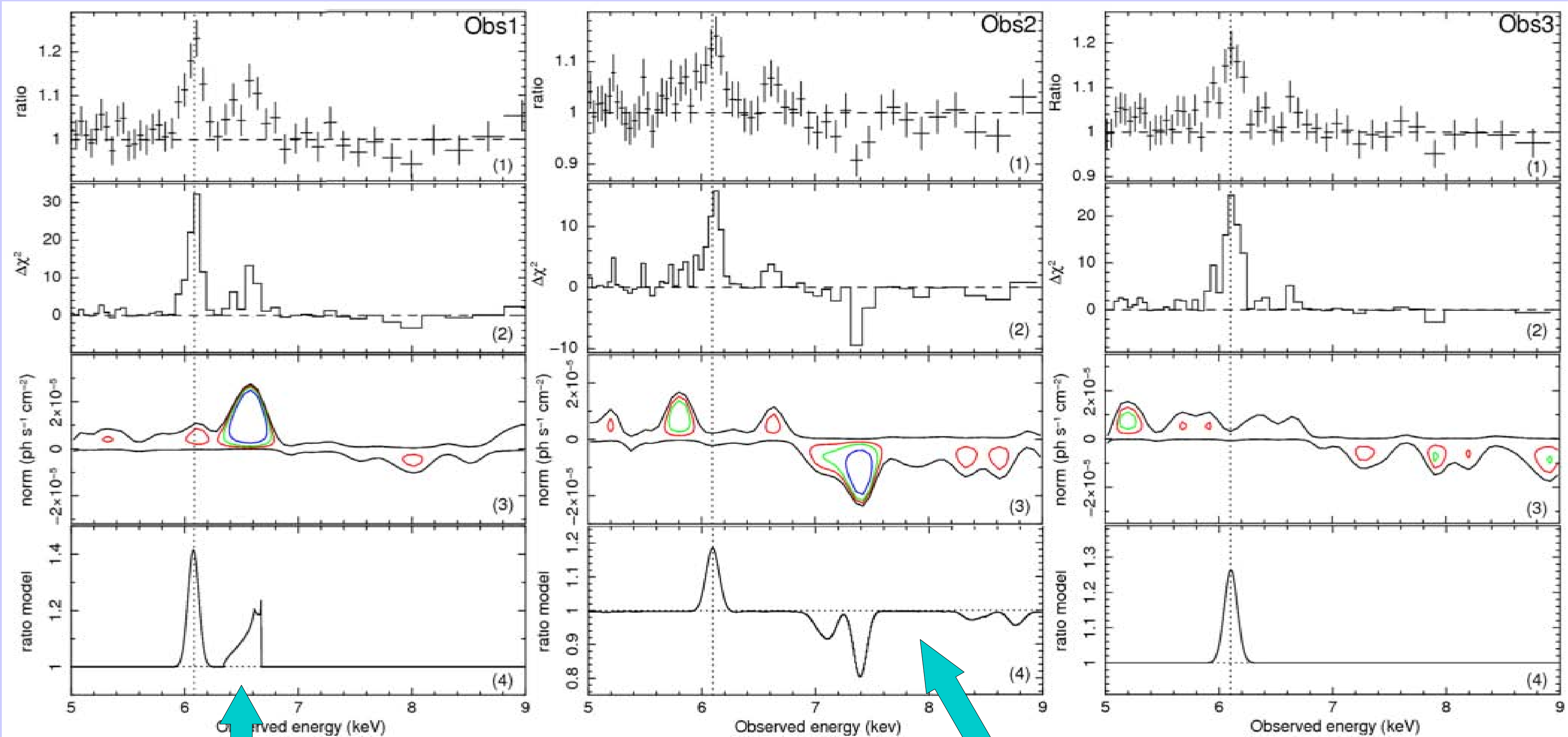
Accretion disk-outflow connection in 3C 111 with Suzaku

Follow-up on 3C 111: 3x60ks Suzaku observations in Sep. 2010 to monitor predicted UFO variability on ~7 days (Tombesi et al. 2011b)



- 30% flux variability between Obs1 and Obs2
- 4-10 keV XIS spectral analysis, power-law continuum Γ~1.7 and 6.4keV Fe K
- Detection emission line E=6.88keV in Obs1, absorption line E=7.75keV in Obs2
- High significance, >99.9% from F-test and Monte Carlo simulations
- Constancy emission/absorption lines excluded at 99.7% and 99.9%

Accretion disk-outflow connection in 3C 111 with Suzaku



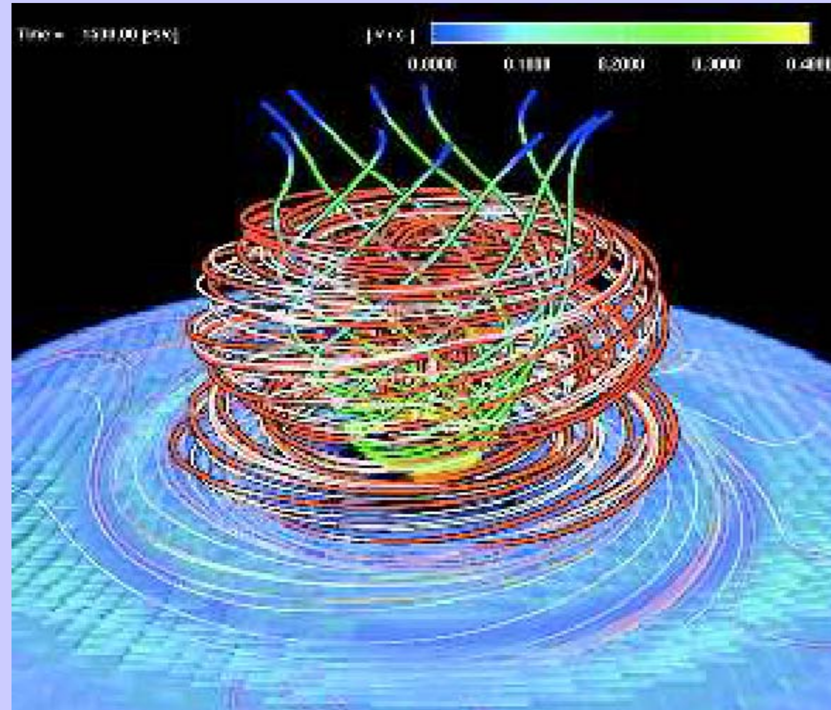
Obs1

- Ionized relativistic disk line (relline profile)
- Emission from Fe XXV/XXVI
- Bulk reflection accretion disk at ~20-100r_g
- Inclination ~18^o

Obs2

- Ultra-fast Outflow (Xstar modeling)
- Velocity v_{out}=0.106±0.006c
- logξ=4.32±0.12 erg s^{-1}cm, Fe XXV/XXVI
- N_H=(7.7±2.9)x10^{22} cm^{-2}

Accretion disk-outflow connection in 3C 111 with Suzaku


Magnetic tower jet (Kato et al. 2004)

- Variability ~7days, d<0.006pc (compact absorber)
- Ionized reflector, ~20-100r_g, Compton-thick
- Ultra-fast Outflow v~0.1c, M_{out}~ 1$M_{Sun}$$yr^{-1}$ ~M_{acc}
- E_K~5x10^{44}erg/s~0.5L_X~0.06L_{bol} ~radio jet power
- L_{bol}/L_{Edd}<0.3, ($M_{out}v_{out}$)/(L_{bol}/c) ~ 1

Evidence accretion disk-outflow connection

- Disruption/over-ionization inner accretion disk
- Outflow lifted at ~100r_g, acceleration by radiation pressure?
- Superluminal and ~18°, possible plasma additional magnetic acceleration?

Under investigation

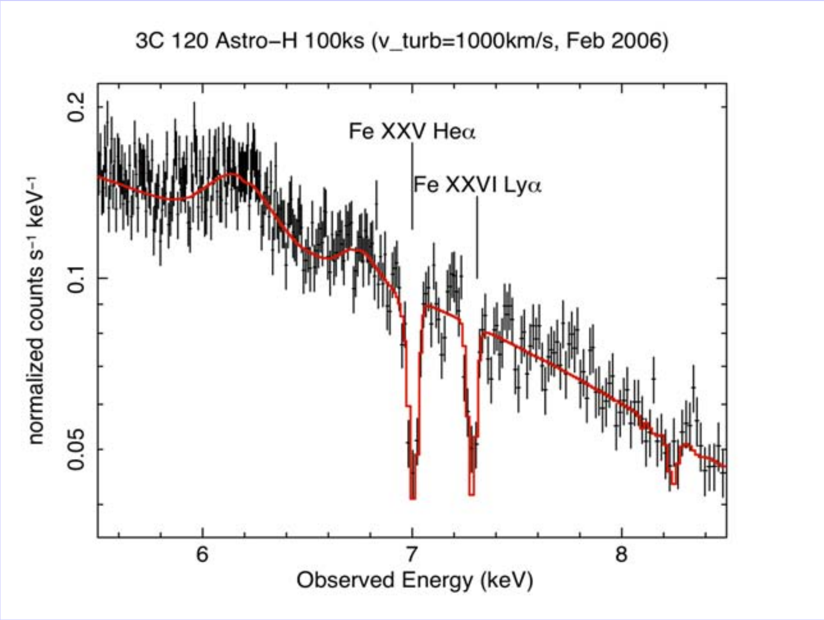
- Connection with radio jet? External layers, collimation, shocks? (e.g., Chattergee et al. 2011)

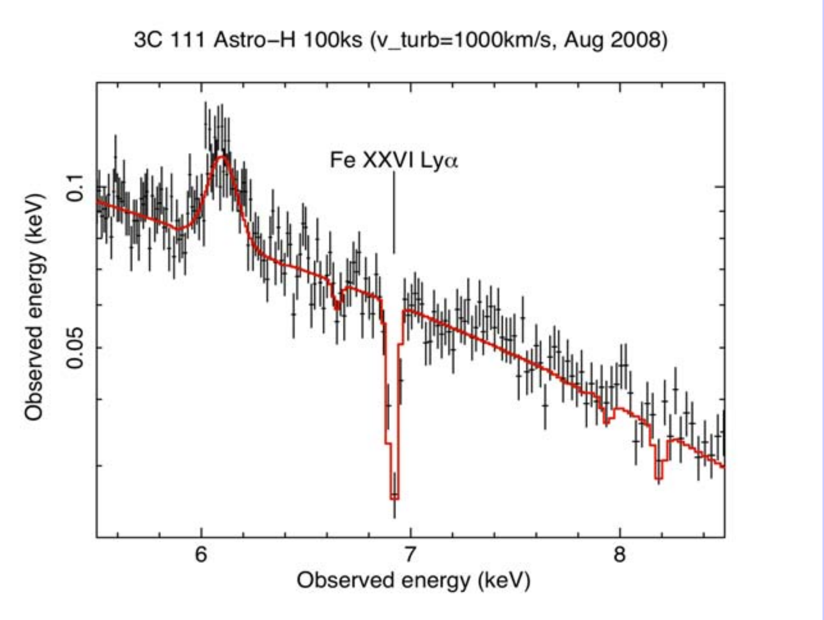
(X-ray spectroscopy potentially capable study jet related phenomena on distances <0.1milliarcsec resolution of VLBA images)

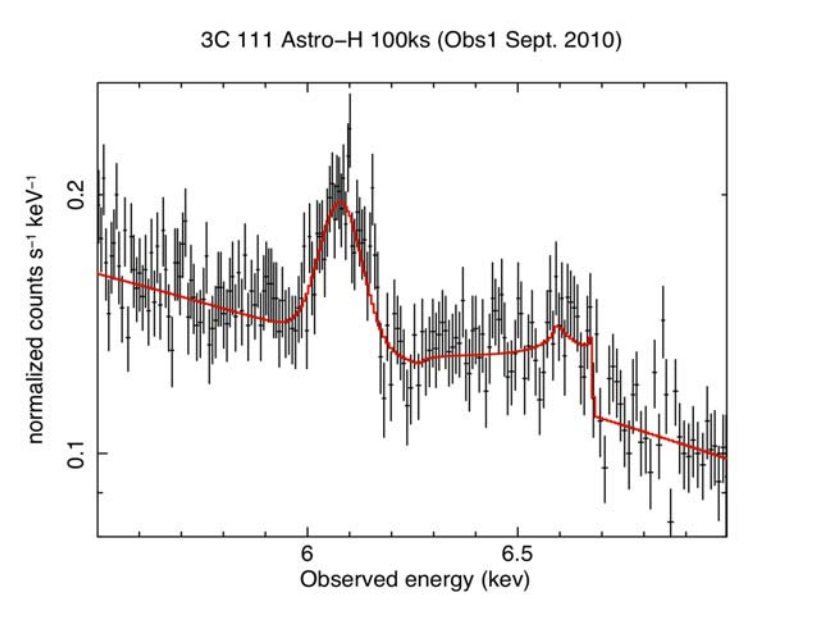
- Coupling between accretion disk, outflows and jets? (e.g., GRS 1915+105 Neilsen & Lee 2009)
- Role on AGN cosmological feedback?

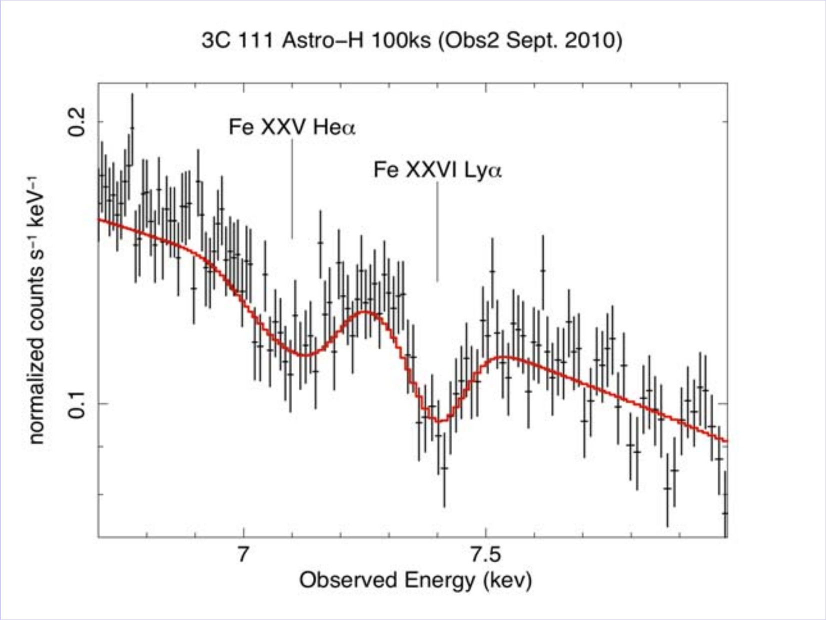
Additional monitoring required!

Astro-H micro-calorimeter simulations









Conclusions

• Highly ionized and mildly-relativistic outflows are common (>40%) in both radio-quiet and radio-loud AGNs

• Directly connected with accretion disk winds

• High outflow rate suggest a synergy between accretion and ejection processes

• Large covering fraction (~0.5), clumpy and/or intermittent (filling factor ~10-20%)

• Mechanical power ~5-10% L_{bol}, potentially important for AGN feedback

• Important improvements from higher effective area and energy resolution in Fe K band from Astro-H and especially Athena

Several still open questions, such as:

• What is the duty cycle and actual filling factor of UFOs?

• What triggers the ejection of UFOs? Similar to jets? Need long-term monitoring and different wavebands, X-ray, Optical-UV, radio (e.g., Chatterjee et al. 2011)

• What is their main acceleration process, radiation and/or magnetic? The same in RL and RQ?

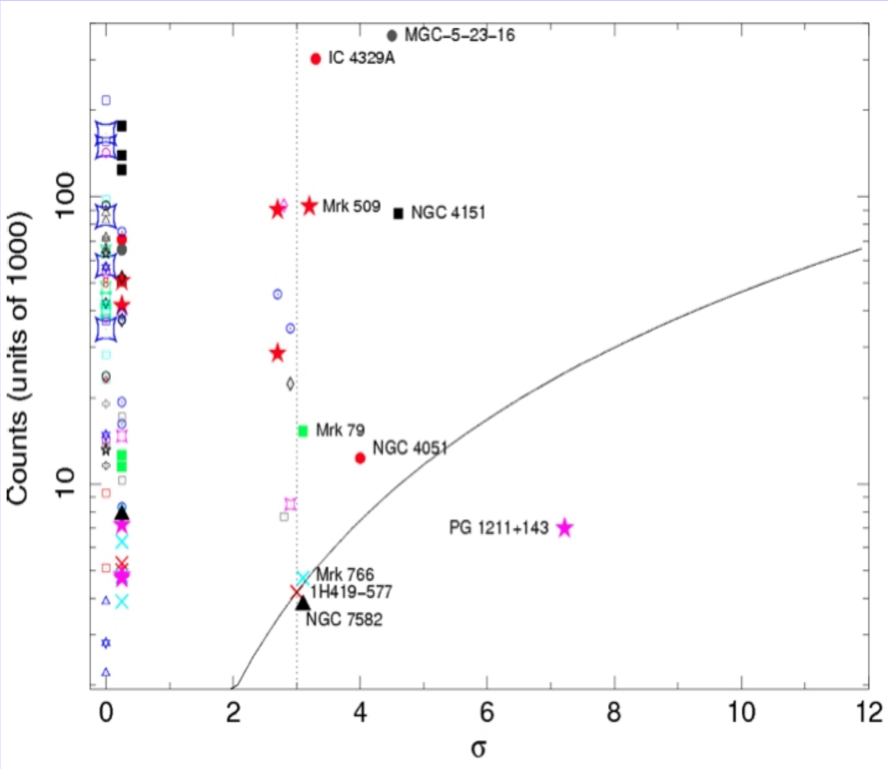
• What is their connection with the jet in radio-loud sources?

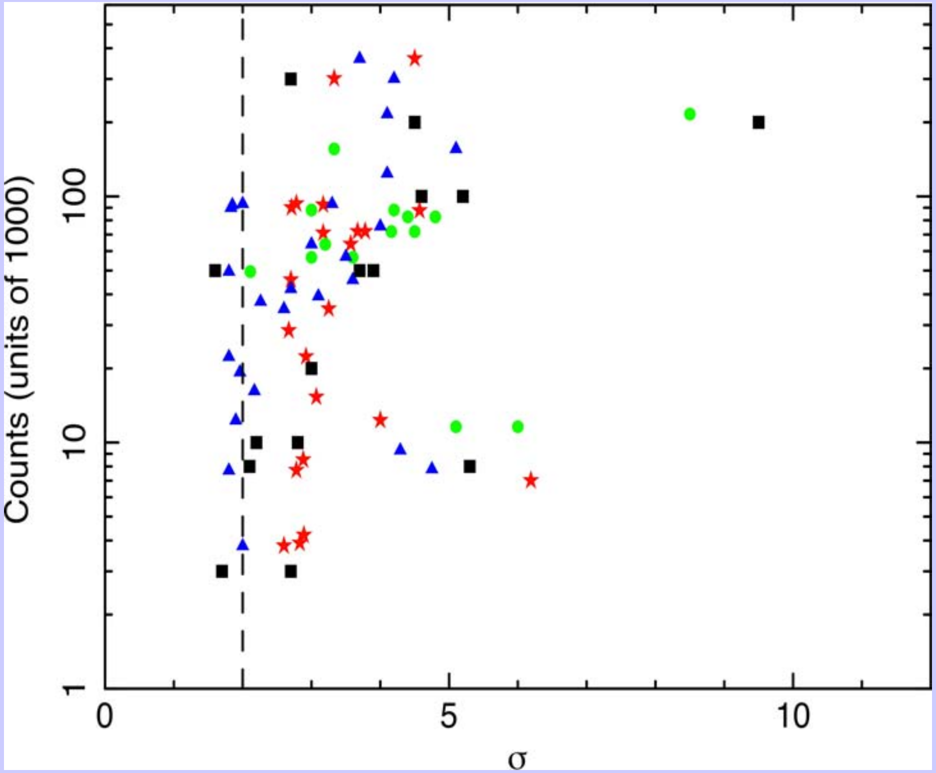
• What is their detailed feedback impact on the surrounding environment?

• What is the possible connection with outflows in other bands? e.g., Soft X-ray, UV

Thank you

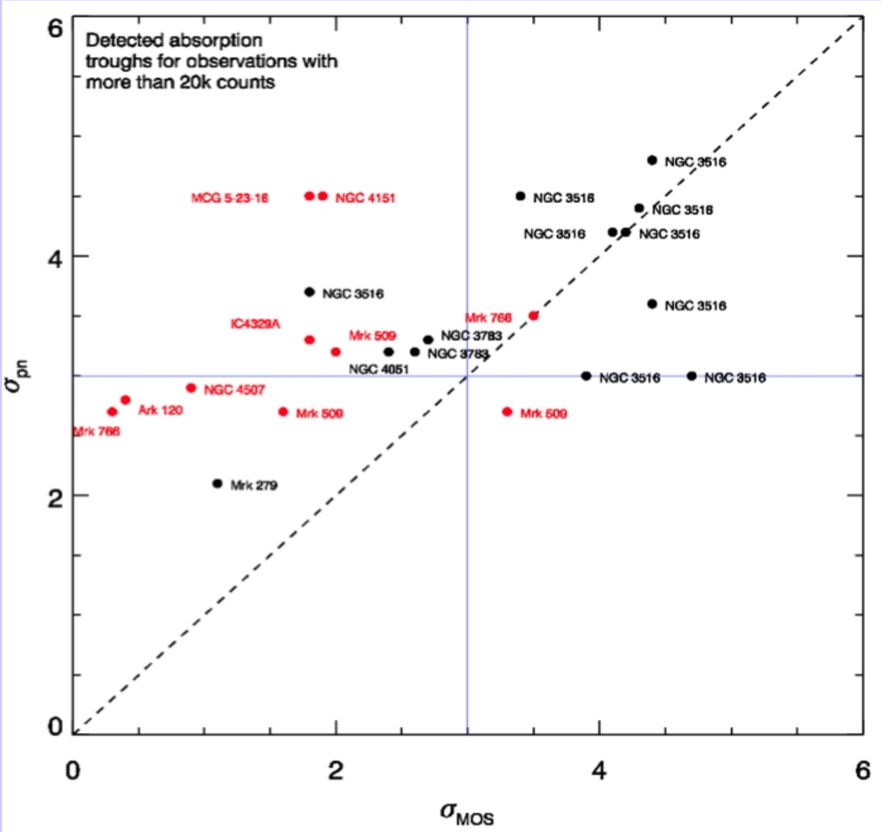
Check on EPIC pn absorption lines significance

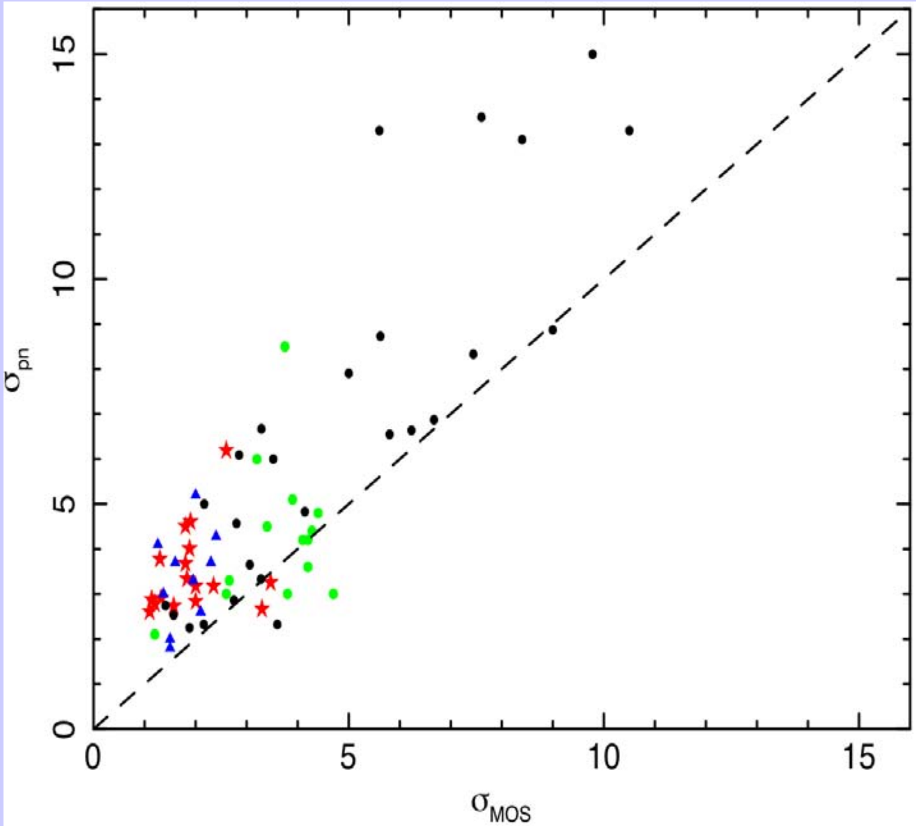




- Sigma vs. counts distribution UFO absorption lines means they are fake? (Assuming constant EW) (LEFT)
- Abs E=6.4-7.1keV (green dots), E>7.1keV (red stars), Emi ionized E=6.5-7keV (blue triangles)
- Simulation 4-10keV counts 3-300x10^3, randomly variable EW=20, 40, 60eV and E=7,8,9keV (black squares)
- The three distributions are consistent and agree with the simulations! (RIGHT)
- No problem with E>7.1keV (UFO) absorption lines, it means they are variable in EW and E, as observed.

Consistency check on EPIC pn and MOS





- Systematic more significant detection UFO abs lines in EPIC pn w.r.t. MOS means they are fake? (LEFT)
- Abs 6.4-7.1keV (green dots), >7.1keV (red stars), Emi 6.4keV (black dots), ionized 6.5-7keV (blue triangles)
- <u>All the four distributions are consistent and show more significant pn detections compared to MOS!</u> (RIGHT)
- No problem with E>7.1keV (UFO) absorption lines.
- MOS lower effective area: combined effective area MOS 1+2 is ~20% pn at E>7keV
- MOS higher background: background/source ratio MOS is ~10x higher pn at E>7keV