Ultra-Fast Outflows in Seyfert I AGN

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March 11th, 2019

Galaxy Group Meeting, U. Michigan, Ann Arbor , MI

Outline

- Introduction
  - AGN Unified Model
  - X-ray Ionized Absorbers in Seyfert I AGN
- X-ray Ionized Absorbers
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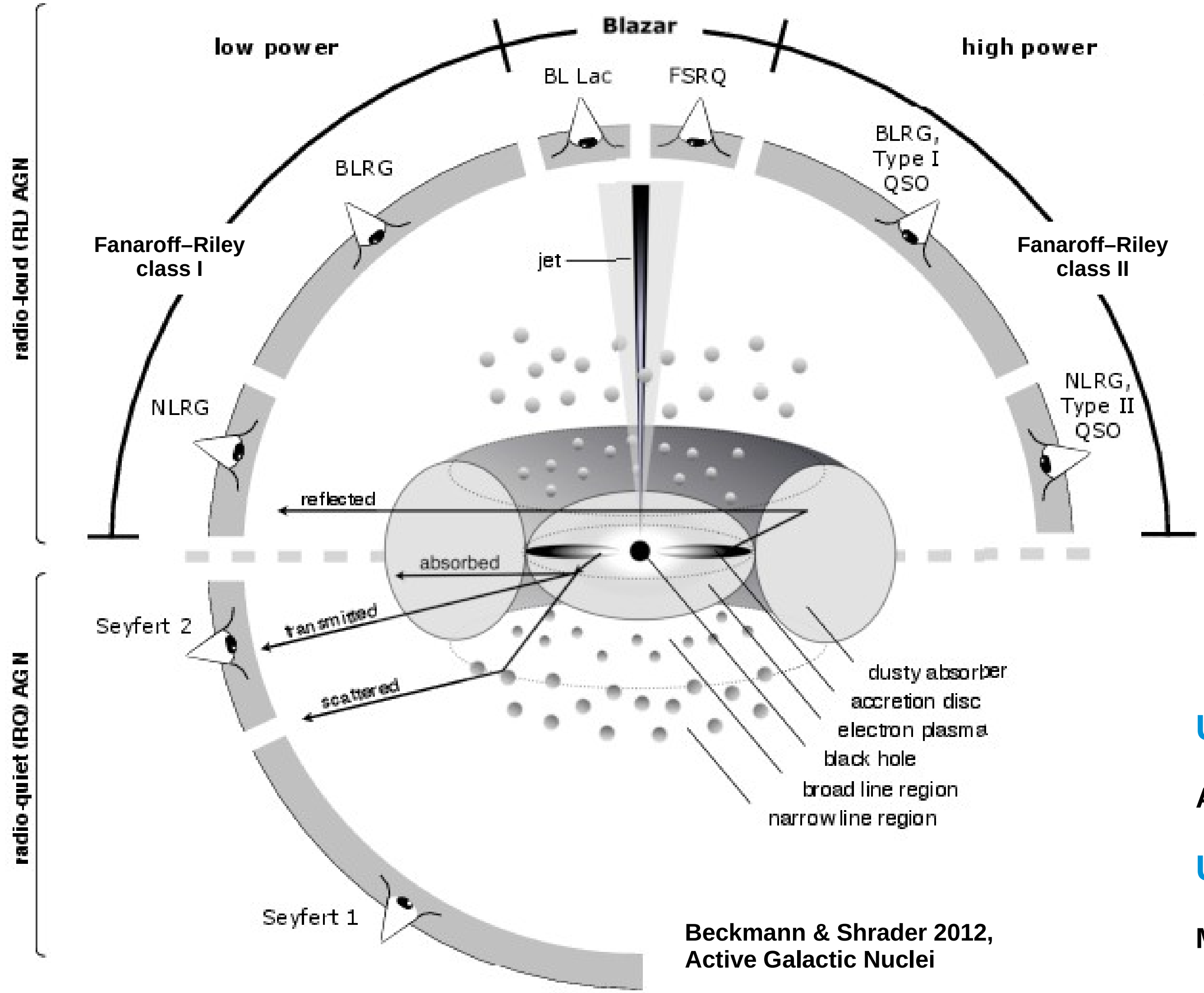
- Photoionization Modeling of Ionized Absorbers
- UFOs in the Seyfert I Galaxy PG 1211+143
- UFOs in other Seyfert I AGN
- Unified AGN Outflow Model
  - Absorber Density Profile
  - Unification of WAs and UFOs
- Conclusion

Introduction

AGN Unified Model (radio-loud & -quiet AGN, Seyfert I & II Galaxies)



Beckmann & Shrader 2012, Active Galactic Nuclei

AGN Unified Model

- Radio-Quiet AGN
  - Seyfert I
  - Seyfert II
- Radio-Loud AGN
  - FR I
  - FR II
  - Blazar

Unified Models for AFNs

Antonucci, ARA&A, 1993, 31, 473

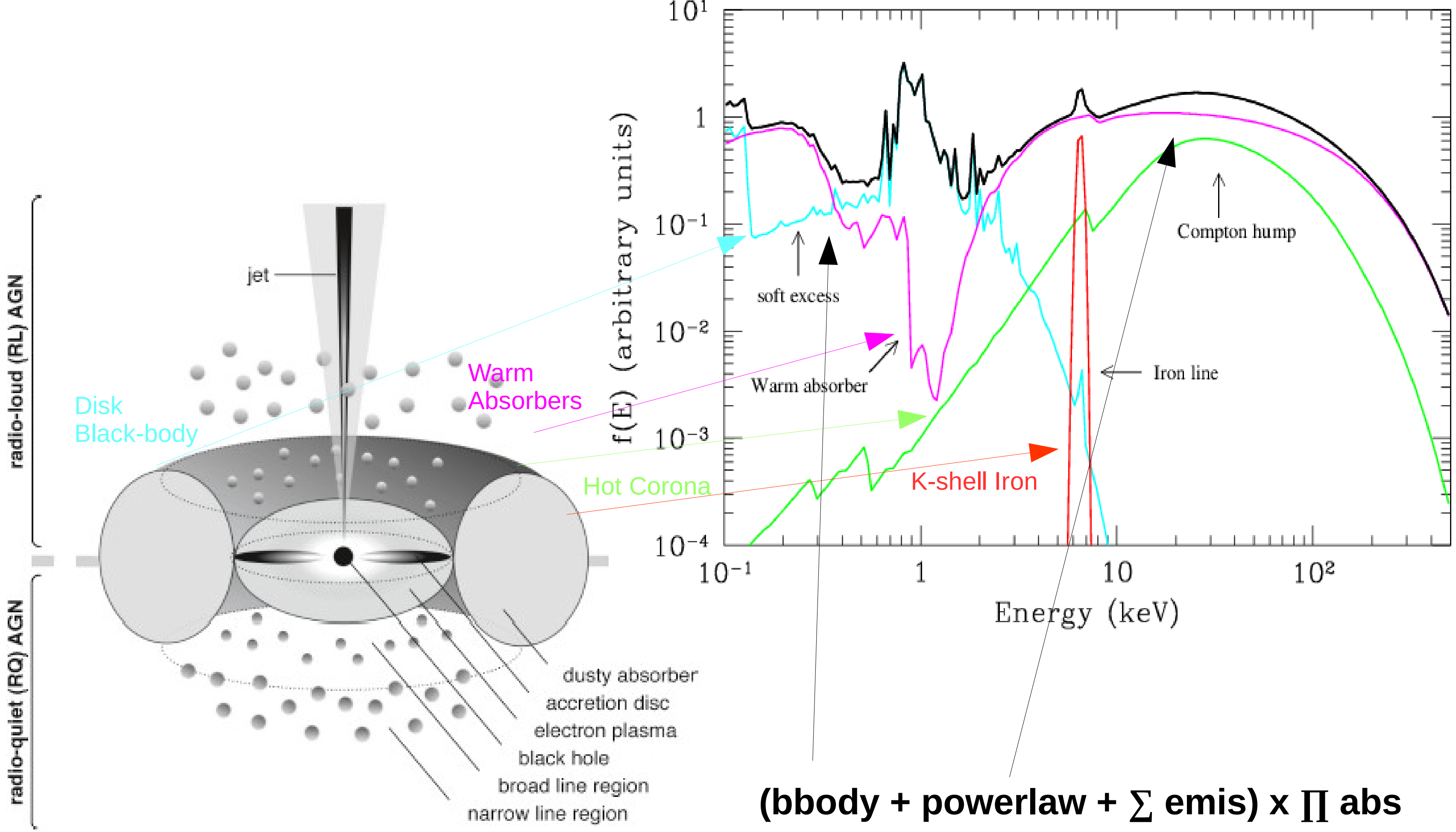
Unified Schemes for AGNs

Megan Urry & Padovani, 1995, PASP, 107, 803

Introduction

X-ray Ionized Absorbers in Seyfert I AGN

Risaliti & Elvis 2004

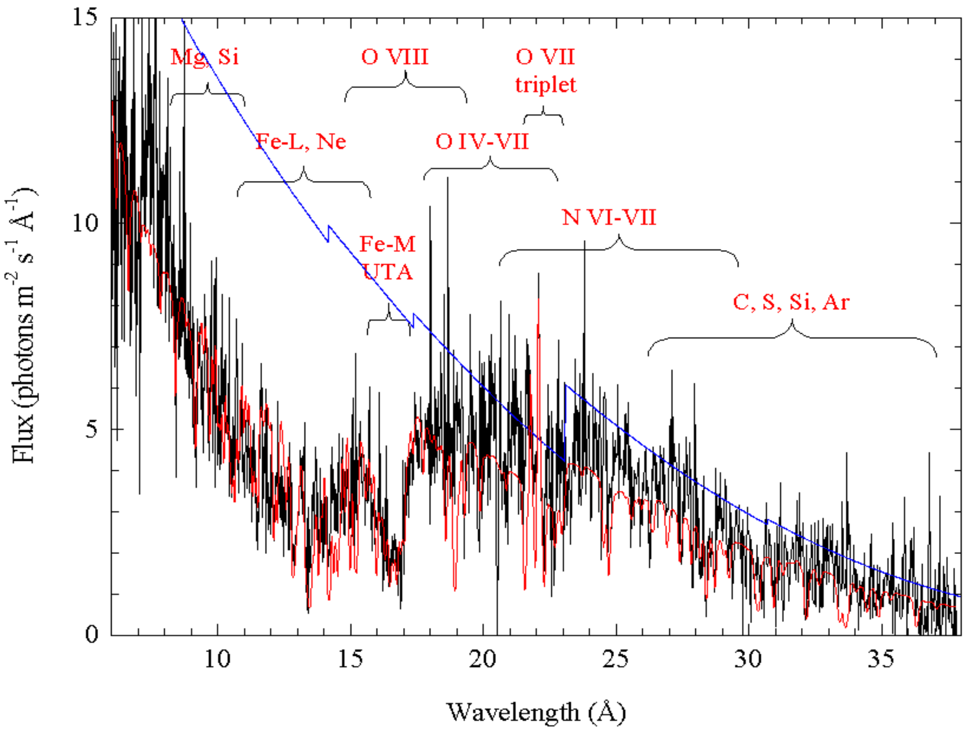


(bbody + powerlaw + ∑ emis) x ∏ abs

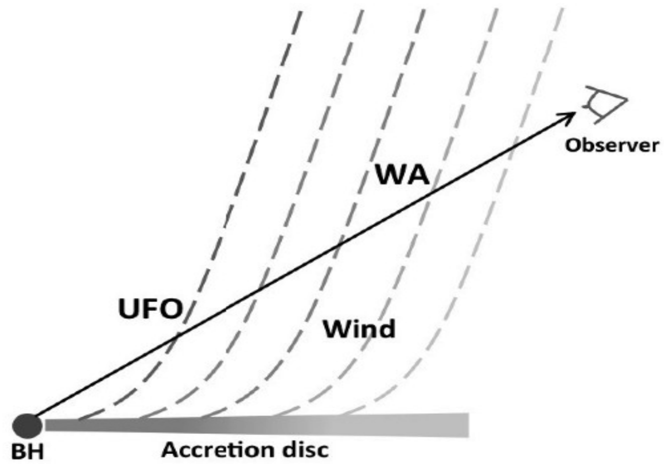
Beckmann & Shrader 2012

X-ray Ionized Absorbers

- **Warm Absorbers (WAs):**
  - *soft* X-ray blue-shifted absorption lines
  - H-like & He-like O, Ne, Mg, Si, S Ions
  - Velocity < 10,000 km/s (0.03*c*)
  - Observed in 50% of Seyfert I galaxies
  - (Reynold & Fabian 1995, Reynold 1997, George + 1998)



- **Ultra-fast Outflows (UFOs):**
  - *hard* X-ray blue-shifted absorption lines
  - H-like & He-like Fe Ions
  - Velocity > 10,000 km/s (0.03*c*)
  - high velocity ~ 0.1– 0.4*c*
  - (Pounds + 2003, Cappi 2006, Braito + 2007)
  - Recently observed in 30% of radio-quite and -loud AGN
  - (Tombest + 2010,2011,2012,2014)



X-ray Ionized Absorbers

Blue-shifted Fe lines

Name	Type	z	$E_{\rm rest}$ (keV)	v/c	$\log N_{\rm H}$ ($\rm cm^{-2}$)	$\log \xi$ ($\rm erg\ cm\ s^{-1}$)
NGC1365	Sey1.8	0.0055	6.7-7.2 (Kα) 7.8-8.3 (Kβ)	0.016	23-23.7	3.7
MCG-6-30-15	Sey1.2	0.0077	6.74 and 7	0.007	23.2	3.6
MCG-5-23-16	Sey1.9	0.0085	7.7	0.1	22.9	3.6
NGC3783	Sey1	0.0097	6.7	0.003	22.7	3
IC4329a	Sey1	0.0160	7.7	0.1	22.1	3.7
IRAS13197-1627	Sey1.8	0.0165	7.5	0.11	23.7	$\gtrsim$3
Mrk509	Sey1	0.034	8.2	0.1-0.2	23.1	3.5
PG0844+349	Sey1	0.064	8.7	0.2	23.6	3.7
PG1211+143	NLSey1	0.081	7.6	0.13	22.3	2.9

Red-shifted Fe lines

Name	Type	z	$E_{\rm rest}$ (keV)	v/c	$\log N_{\rm H}$ ($\rm cm^{-2}$)	$\log \xi$ ($\rm erg\ cm\ s^{-1}$)
Mrk335	Sey1	0.026	5.9	0.15	22.4	3.6
Mrk509	Sey1	0.034	5.4-5.5	0.21	22.8	3.5
PG1211+143	NLSey1	0.081	4.56 and 5.33	0.4 and 0.26	23.6	3.9

Cappi 2006

Photoionization Modeling of Ionized Absorbers

XSTAR (Kallman + 1996, 2004) or CLOUDY (Ferland + 1998)

- **Photo-emission, Ionized absorption**

- **(bbody + powerlaw + ∑ photemis) x ∏ warmabs**
- **XSTARDB & XSTAR2XSPEC**
- **Set parameters**
  - **Number density (log *n* ~12)**
  - **Ionizing SED (Radio+IR+Opt+UV+X-ray)**
- **Physical Conditions (*free parameters*):**
  - **Column density (N_H)**
  - **Ionization parameter (ξ)**

Photoionization Modeling of Ionized Absorbers

Photoionization Code XSTAR (Kallman + 1996, 2004)

Luminosity (13.6 eV-13.6 keV)

$$\xi \equiv \frac{L}{nR^2}$$

Ionization parameter

Gas density

Radius

$$N = n\Delta R$$

Column density

Shell thickness

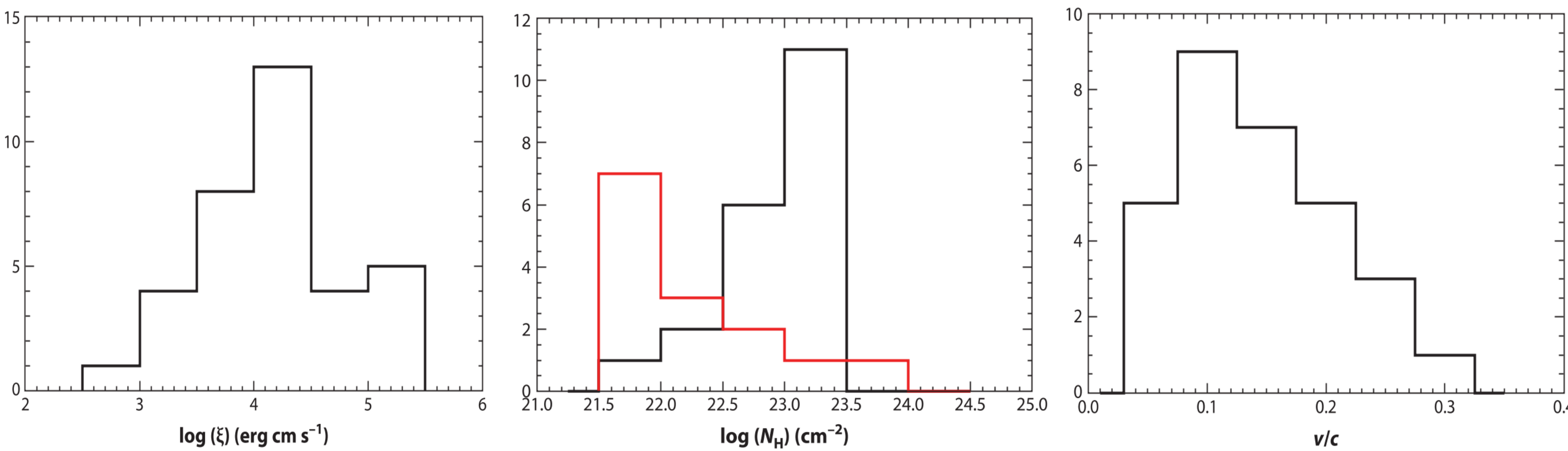
Photoionization Code XSTAR (Kallman + 1996, 2004)

$$R < \frac{L}{N\xi}$$

$$R > 2\,G M_{\rm BH} / v_{\rm out}^2$$

BH mass

Outflow velocity

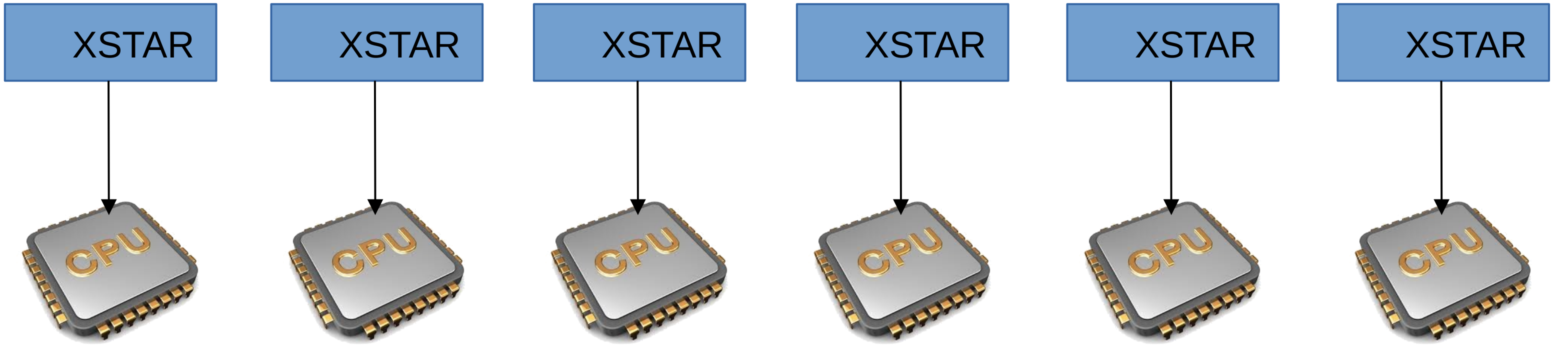


King & Pounds 2015; XMM-Newton & Suzaku (42 radio-quiet, Tombesi et al 2011; 51 AGN, Gofford et al. 2013)

Photoionization Modeling of Ionized Absorbers

XSTAR (Kallman + 1996, 2004)

- **MPI_XSTAR Parallelization: github.com/xstarkit/mpi_xstar (Danehkar + 2018)**



- **produce table model files:**
  - **absorption spectrum imprinted onto continuum (xout_mtable.fits)**
  - **reflected emission spectrum in all directions (xout_ain.fits)**
  - **emission spectrum in transmitted direction of the absorpter (xout_aout.fits)**

Seyfert I Galaxy PG 1211+143

- **A Narrow-line Quasi-Stellar Object (QSO)**

- **In a Seyfert I nearby galaxy (*z* = 0.0809)**

- **Strong soft excess**

- **Reported to have mildly relativistic outflows – 0.07*c* (*XMM-Newton*)**

- **Might be variable outflows (*appeared and disappeared!*)**
  - **No Ultra-fast outflow in *NuSTAR* observation!**

- **Also shows redshifted aborbers at 0.2-0.4*c*: infall to the black hole**

Seyfert I Galaxy PG 1211+143

Blue-shifted Fe lines

Name	Type	z	E_{rest} (keV)	v/c	$\log N_H$ (cm^{-2})	$\log \xi$ (erg cm s^{-1})
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Cappi 2006

UFOs in the Seyfert I Galaxy PG 1211+143

XMM-Newton Observations

- **UFOs v_{out} ~ -0.07c (Pounds + 2003)**
- **H- and He-like C, N, O, Ne, Mg, S and Fe ions**

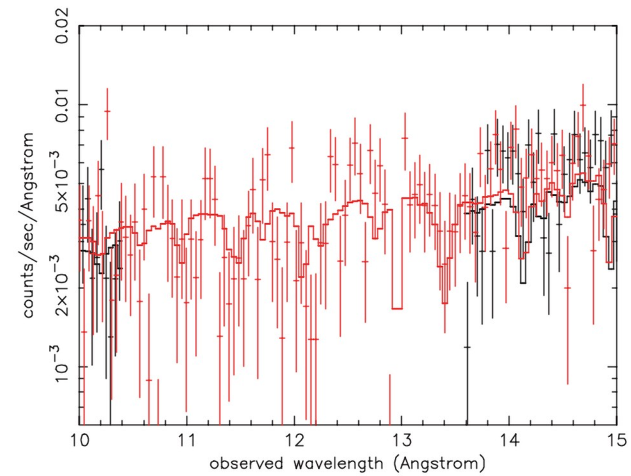


Figure 9. RGS spectrum from 10–15 Å showing absorption lines at 13.40 Å (Ne IX 1s–2p) and 12.17 Å (Ne X Lyα). Several Fe L lines are also indicated and we note that both Ne lines are probably blended with lines of Fe XVII–XXI, limiting their present value in characterizing the outflow from PG1211+143.

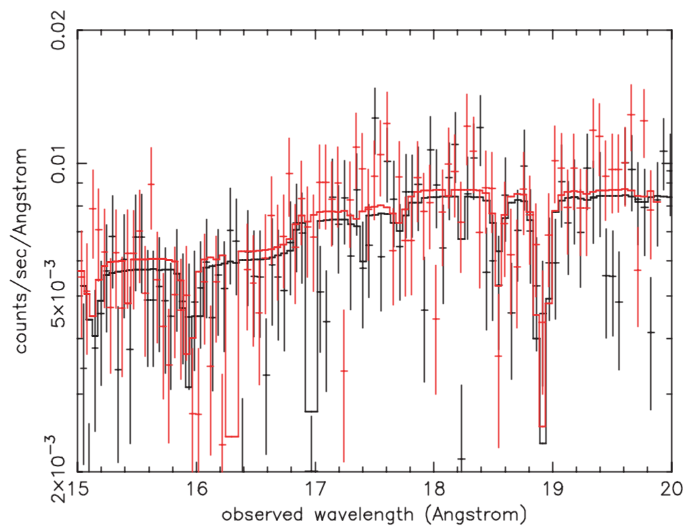


Figure 8. RGS spectrum from 15–20 Å showing resonance absorption lines at 18.90 Å (O VIII Lyα), 18.60 Å (O VII 1s–3p) and 15.98 Å (O VIII Lyβ).

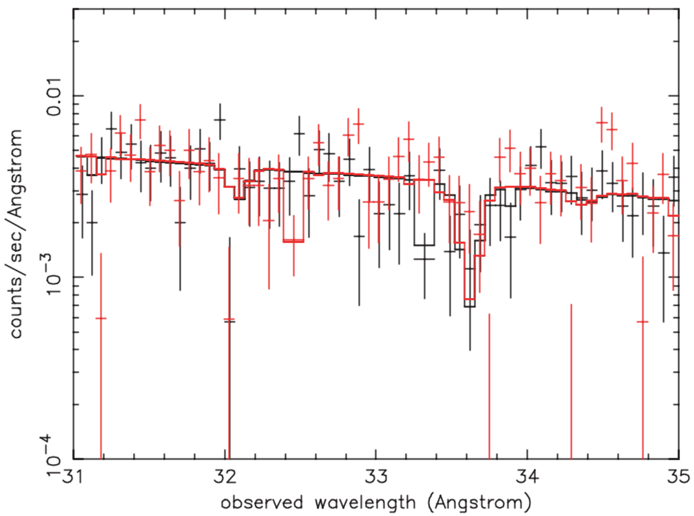
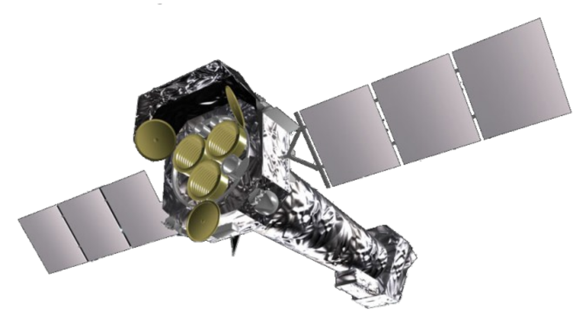


Figure 6. RGS spectrum from 31–35 Å fitted with the photoionized model described in Section 3.5. The C VI Lyα absorption line is observed at 33.62 Å.



UFOs in the Seyfert I Galaxy PG 1211+143

XMM-Newton Observations

- FOs v_{out} ~ -0.13*c* (Pounds + 2006,2007,2009)
- H- and He-like Ne, Mg, Si, S, Ar and Fe ions

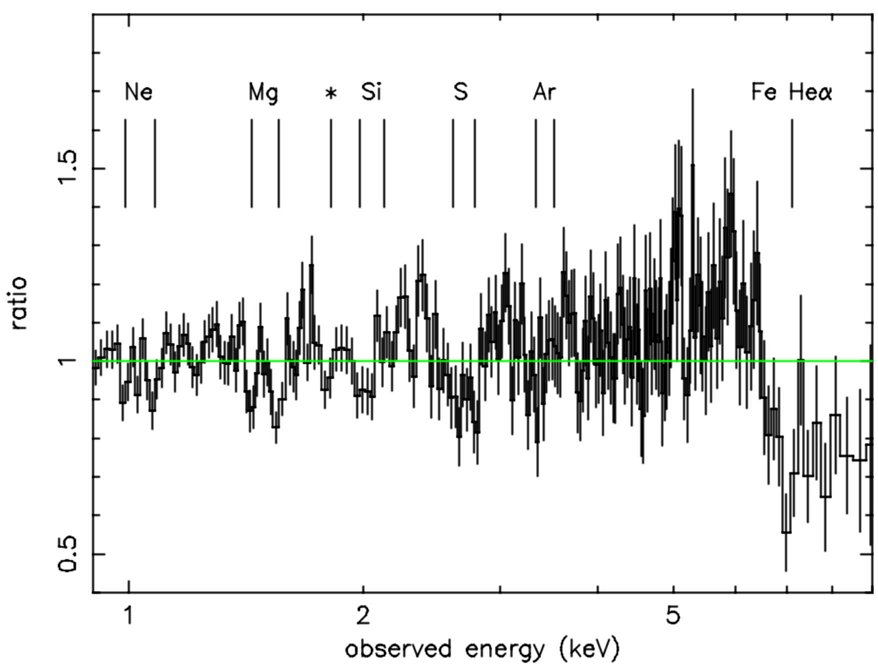


Figure 2. EPIC MOS camera data from the observation of PG1211+143 in 2001 compared with a simple power-law fit over the energy band 1–10 keV. Narrow spectral features and their proposed identification with K-shell absorption lines of Ne, Mg, Si, S, (Ar?) and Fe are indicated.

- UFOs v_{out} ~ -0.06*c* and -0.13*c* (Pounds + 2016)

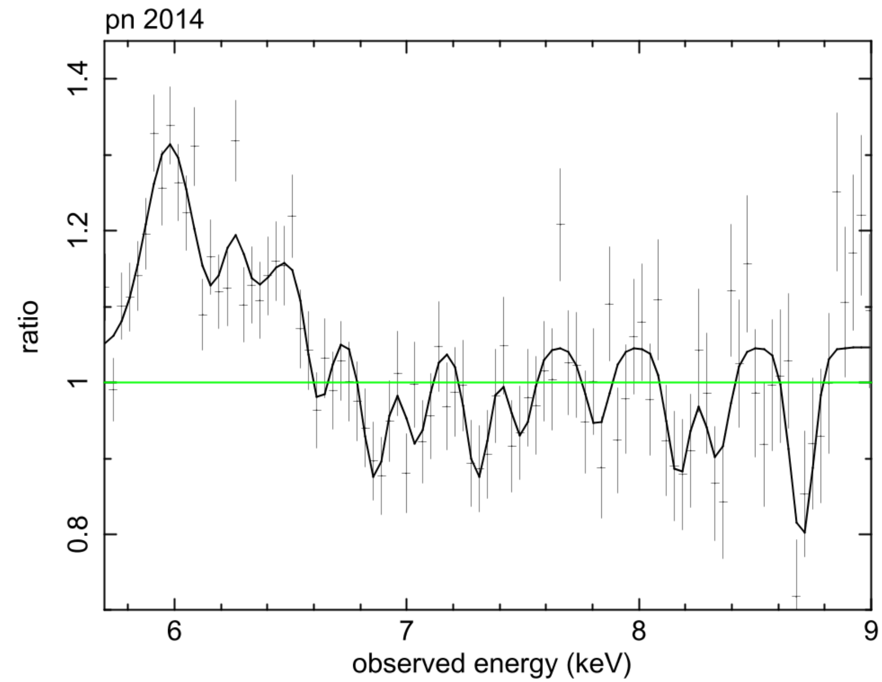
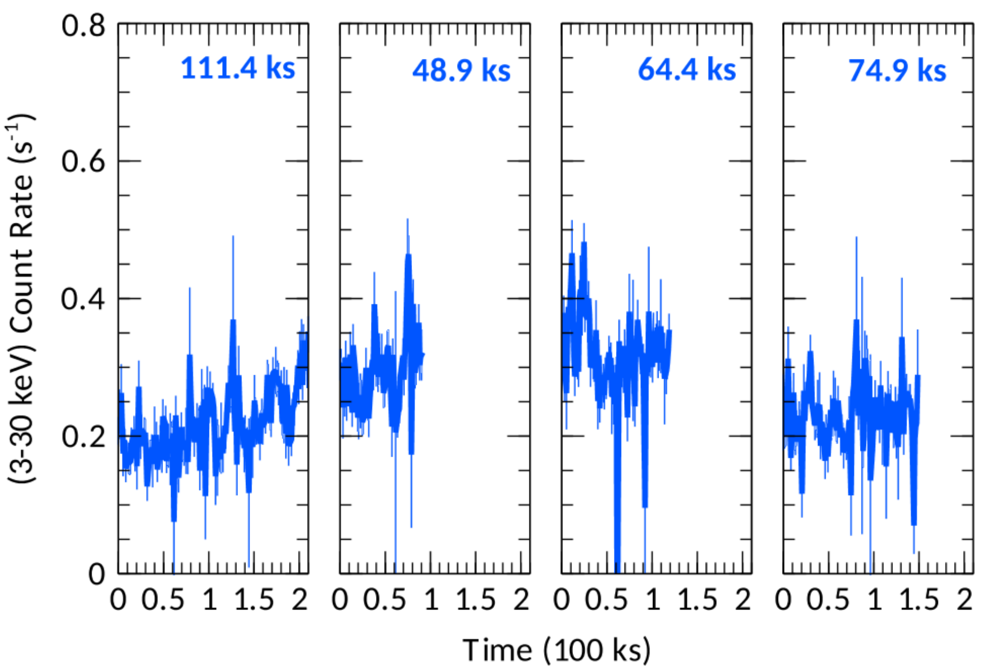


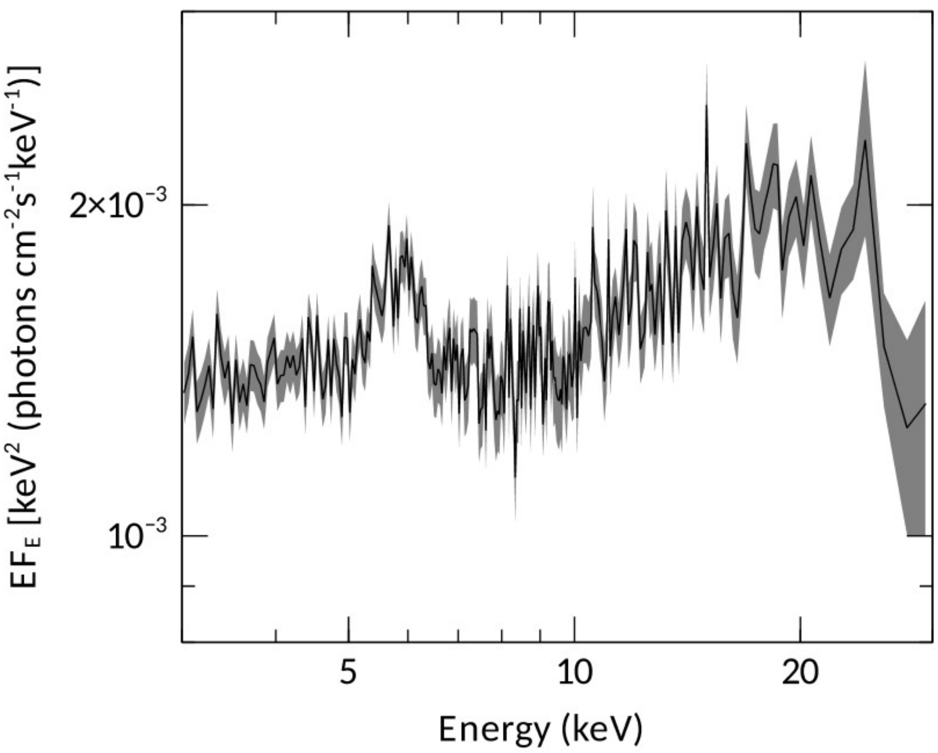
Figure 6. Gaussian line fitting to spectral structure in the stacked pn data from the *XMM-Newton* observation of PG1211+143 in 2014. In this plot data binning has been relaxed with the removal of the limit of 3 data points per resolution element to provide smoother Gaussian profiles. Nine possible absorption lines are detected, numbered from left to right as abs1 – abs 9 in Table 2, where the measured energy, proposed identification and outflow velocity are listed

UFOs in the Seyfert I Galaxy PG 1211+143

NuSTAR Observations

- **Exposure time: 300 ks (2014 Feb-July)**
- **Covering 3-30 keV**
- **No UFO (Zoghbi + 2015)**

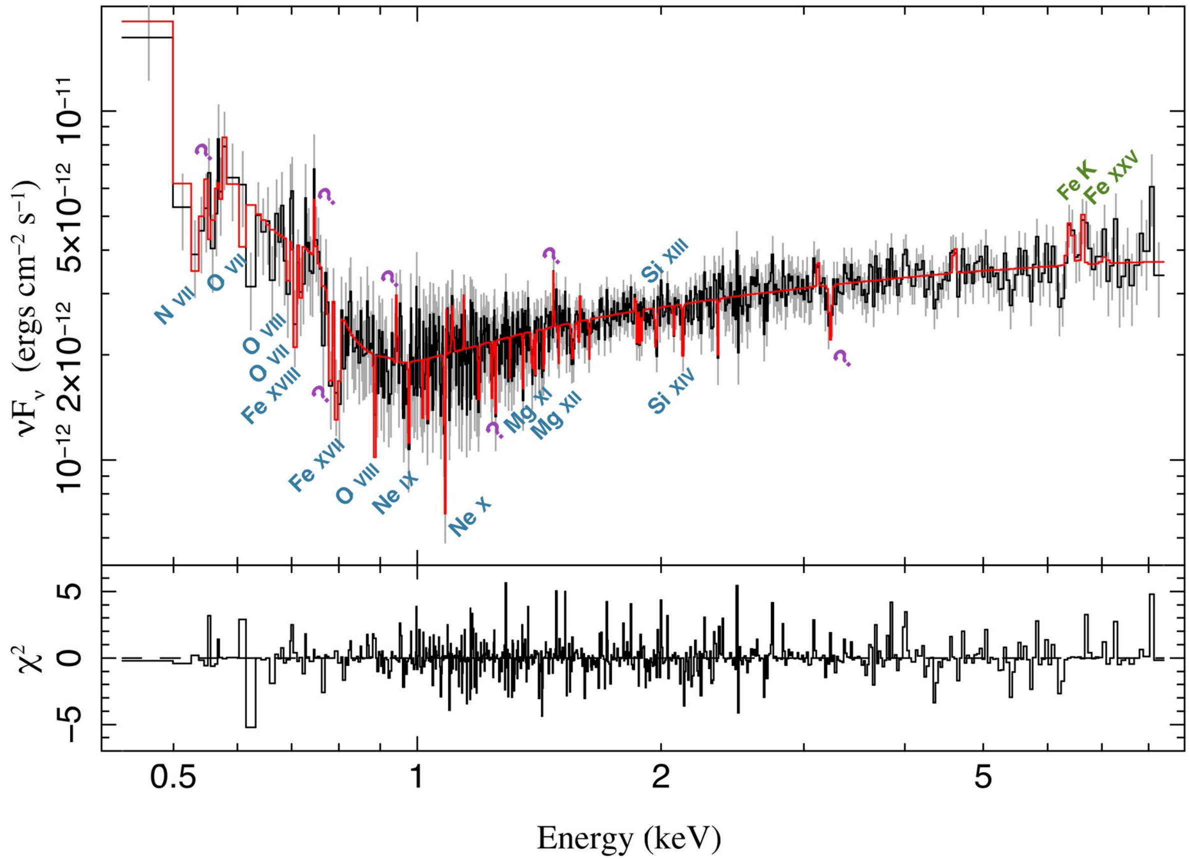




UFOs in the Seyfert I Galaxy PG 1211+143

Chandra Observations

- **High Energy Transmission Grating (HETG; PI: J.C. Lee, 2015 April)**
- **6 observations over 9 days ~ 433 ks**
- **H- and He-like Ne, Mg, S ions: -0.06*c***

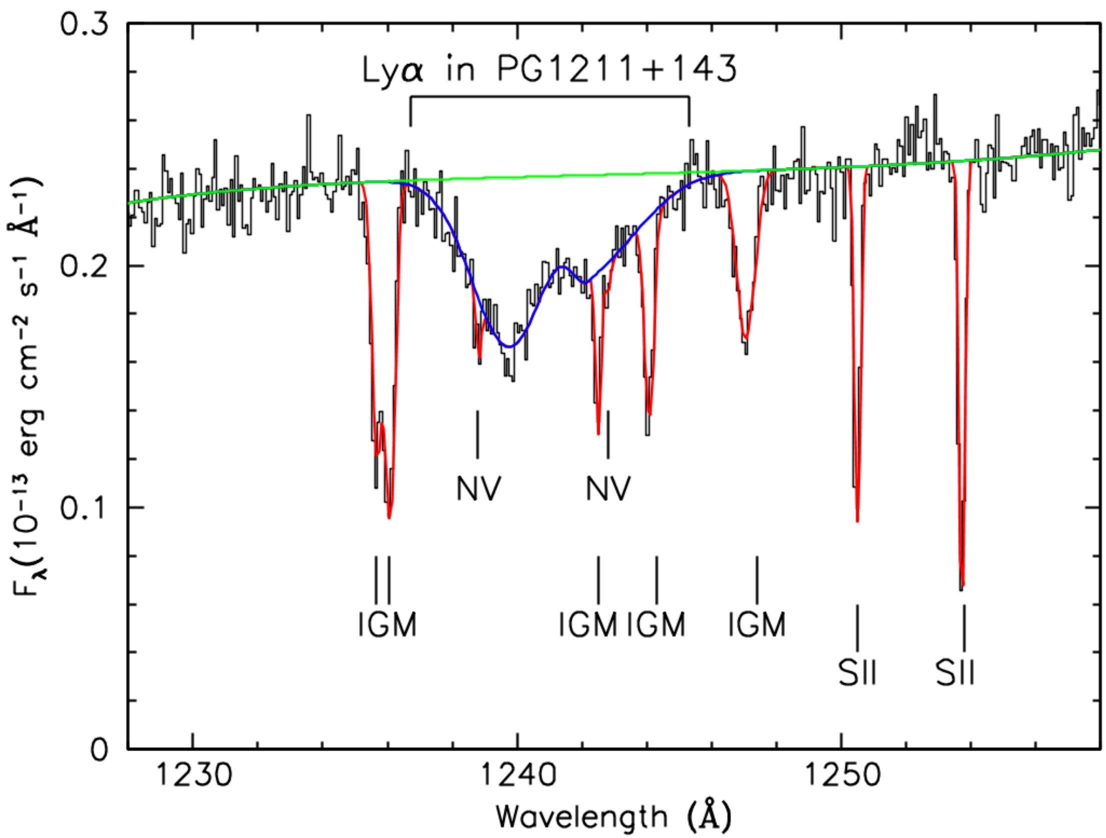


PG 1211+143 *Chandra* Observations (PI J.C. Lee)

UFOs in the Seyfert I Galaxy PG 1211+143

Hubble UV Observations

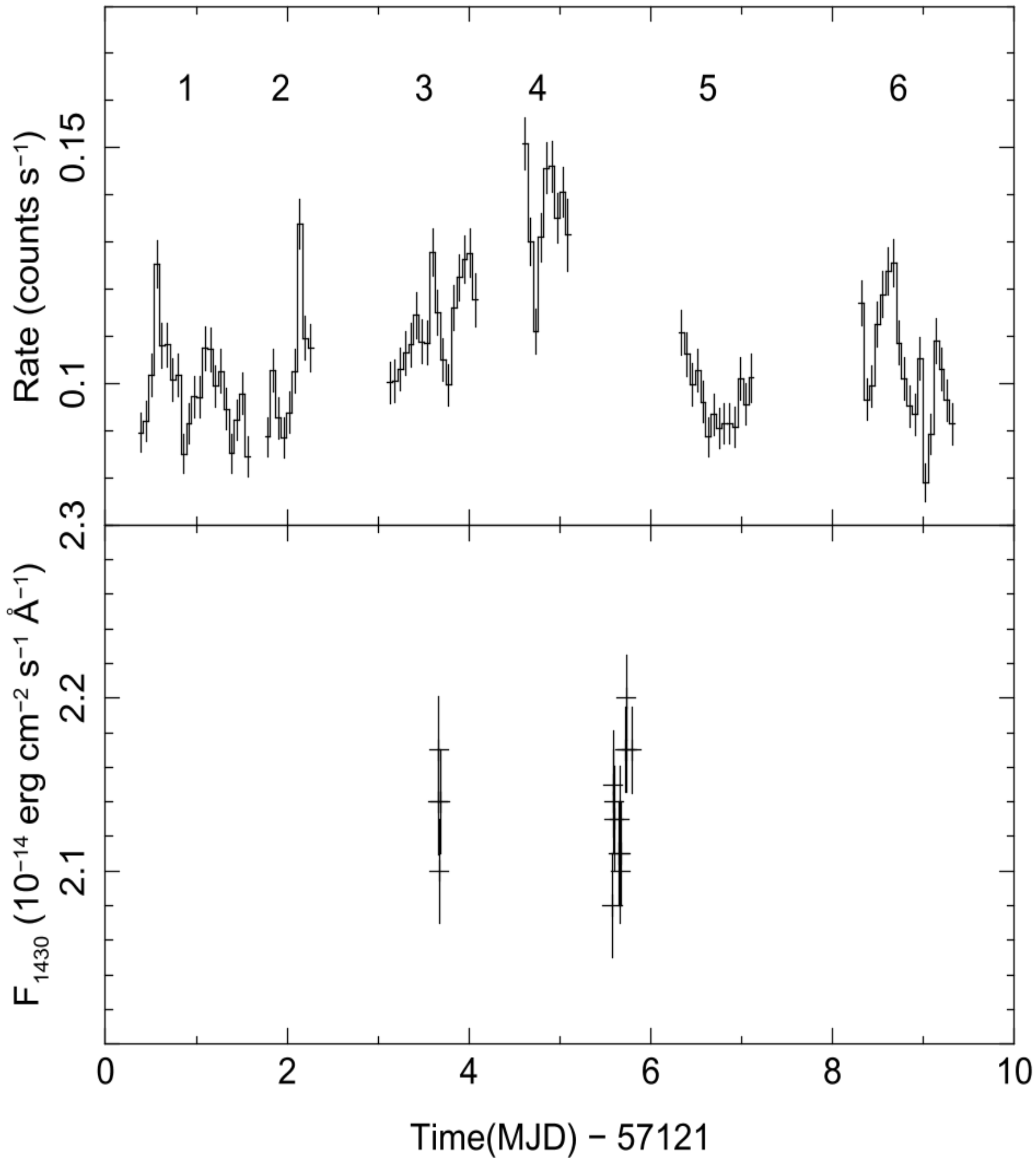
- **Cosmic Origins Spectrograph (COS)**

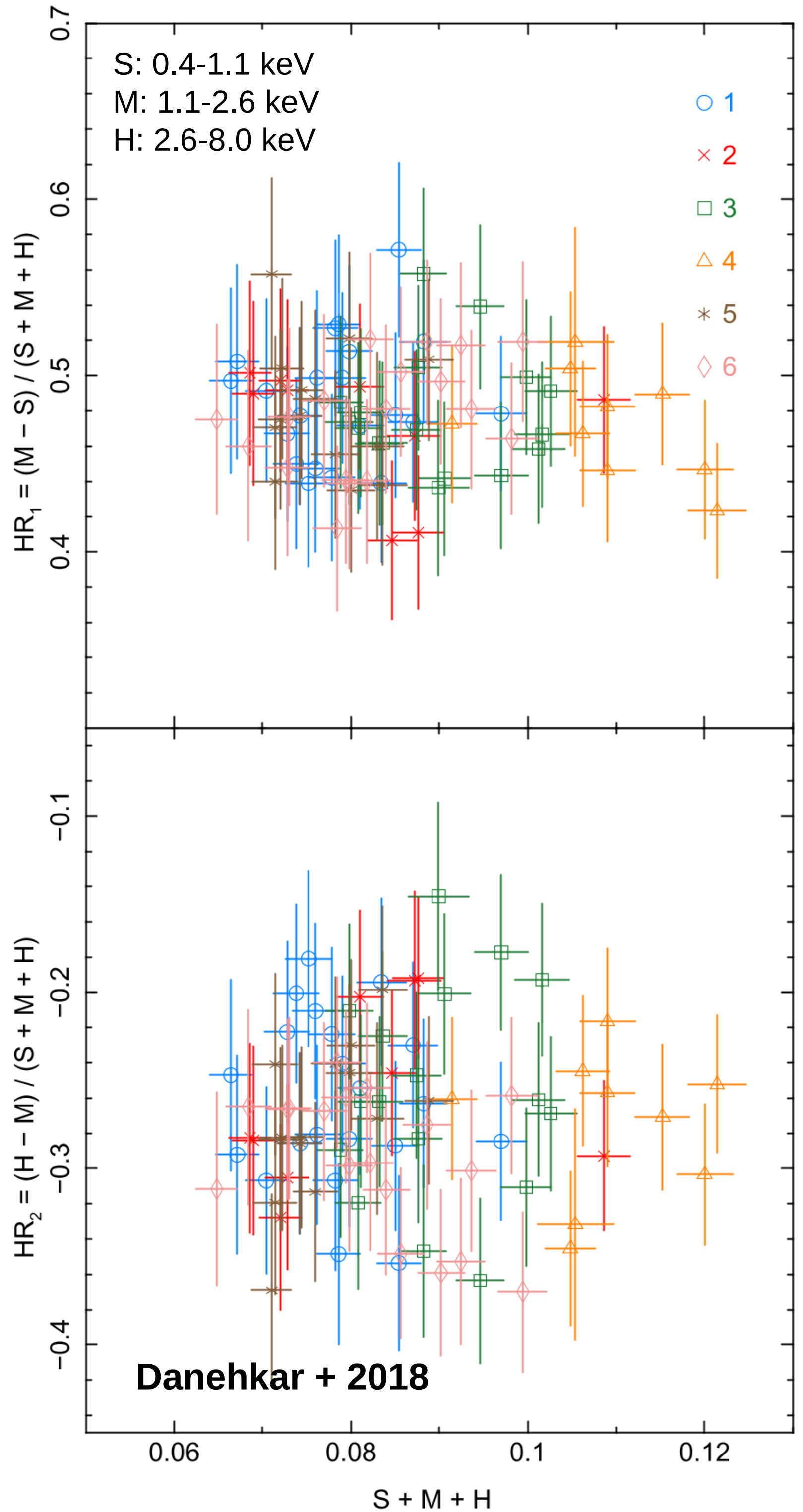


- **PG 1211+143 *Chandra* Observations (PI J.C. Lee)**

UFOs in the Seyfert I Galaxy PG 1211+143

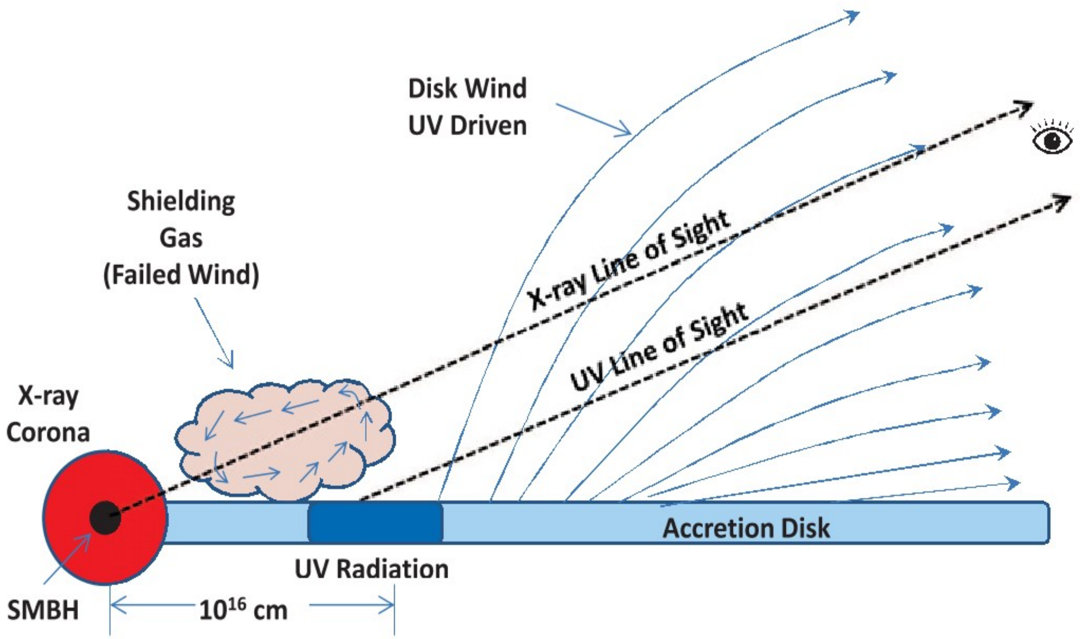
Chandra and *Hubble* Variabilities over 10 days



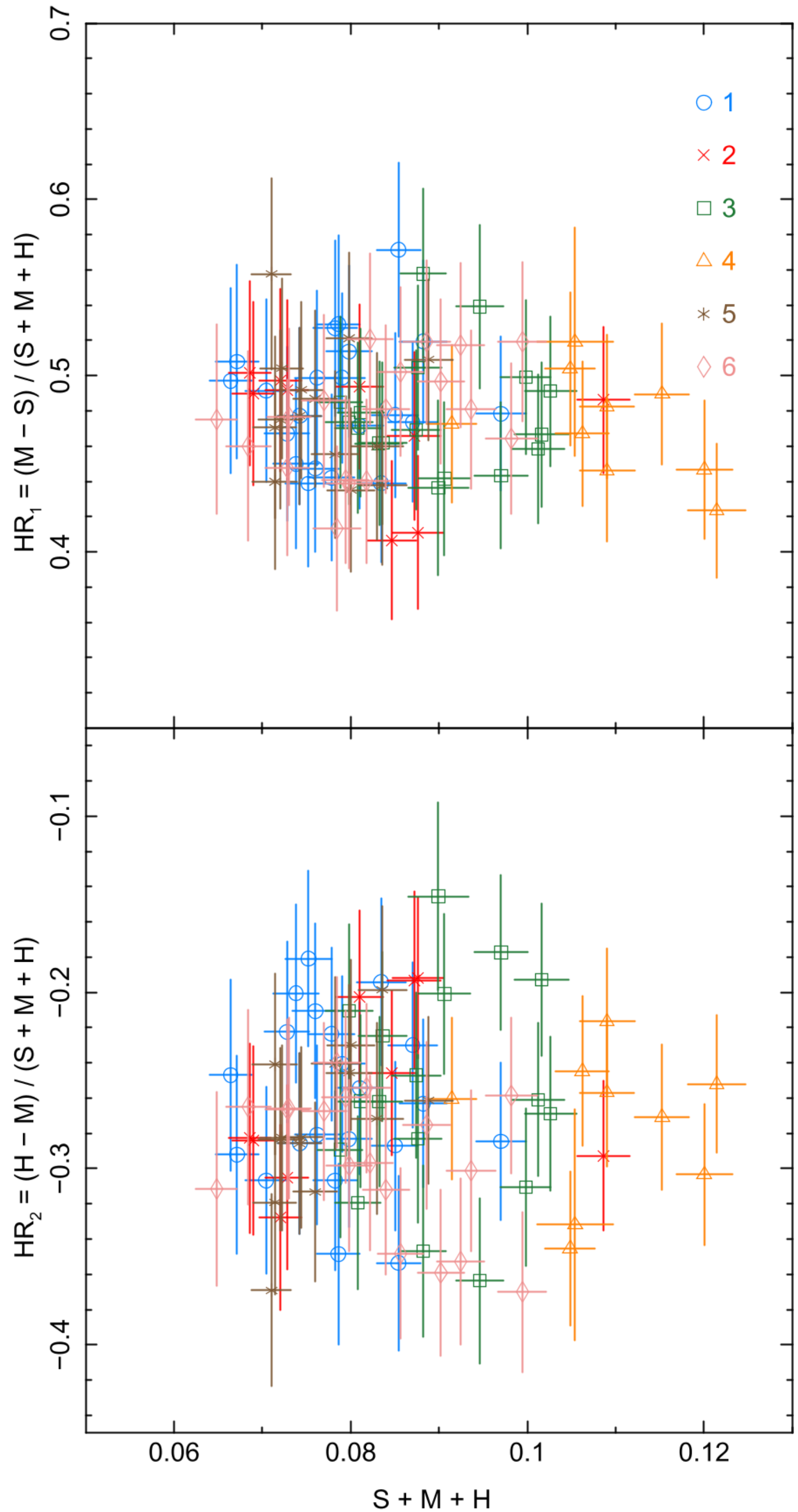


UFOs in the Seyfert I Galaxy PG 1211+143

Time-Variability

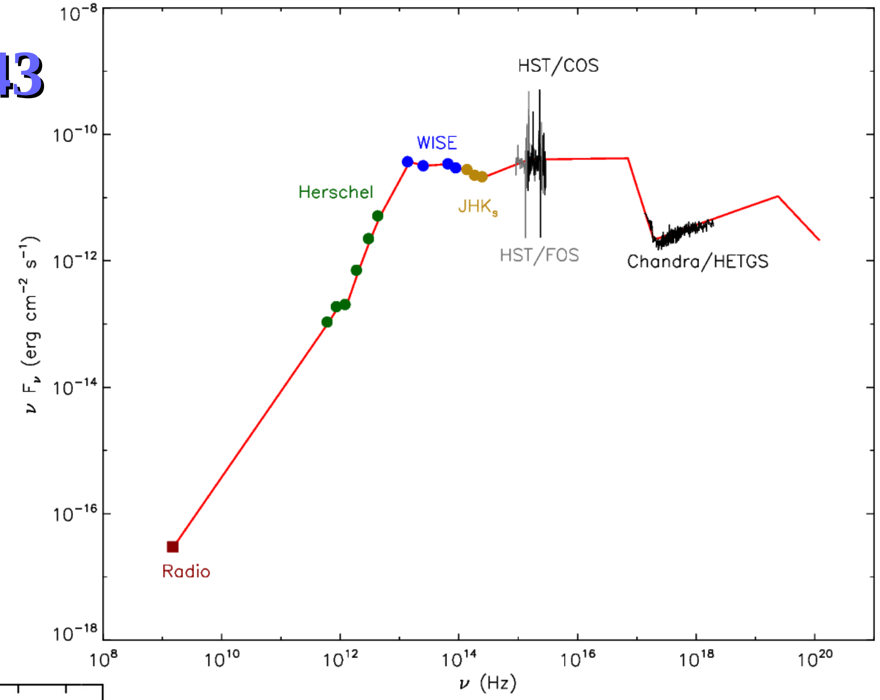


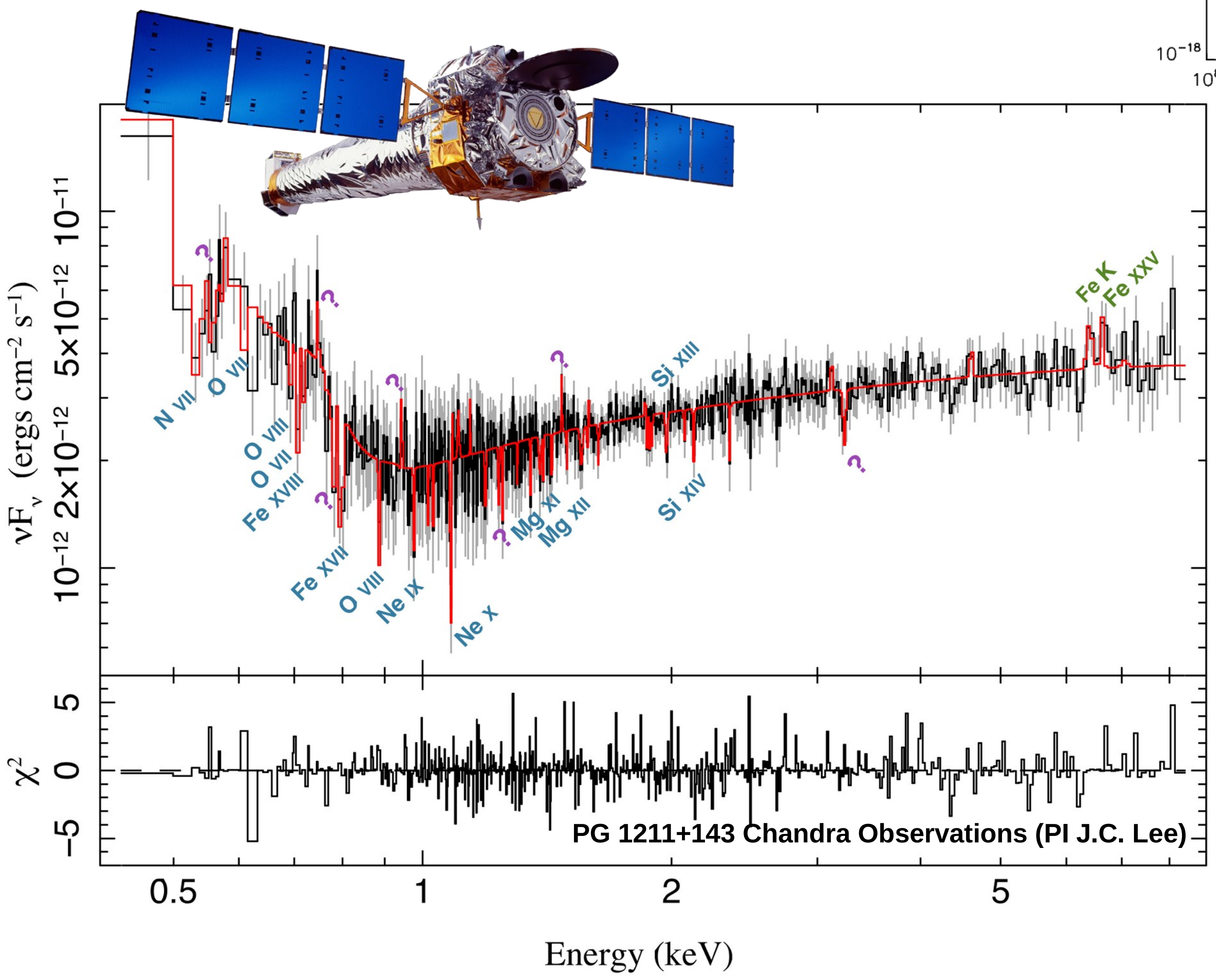
Luo et al, 2013, ApJ 772, 153



UFOs in the Seyfert I Galaxy PG 1211+143

$$\mathrm{zdust} \times \mathrm{ztbabs} \times \mathrm{highecut} \times (\mathrm{diskbb} + \mathrm{powerlaw} + \sum_{i=1}^{M} \mathrm{emis}_i) \times \prod_{i=1}^{N} \mathrm{abs}_i.$$



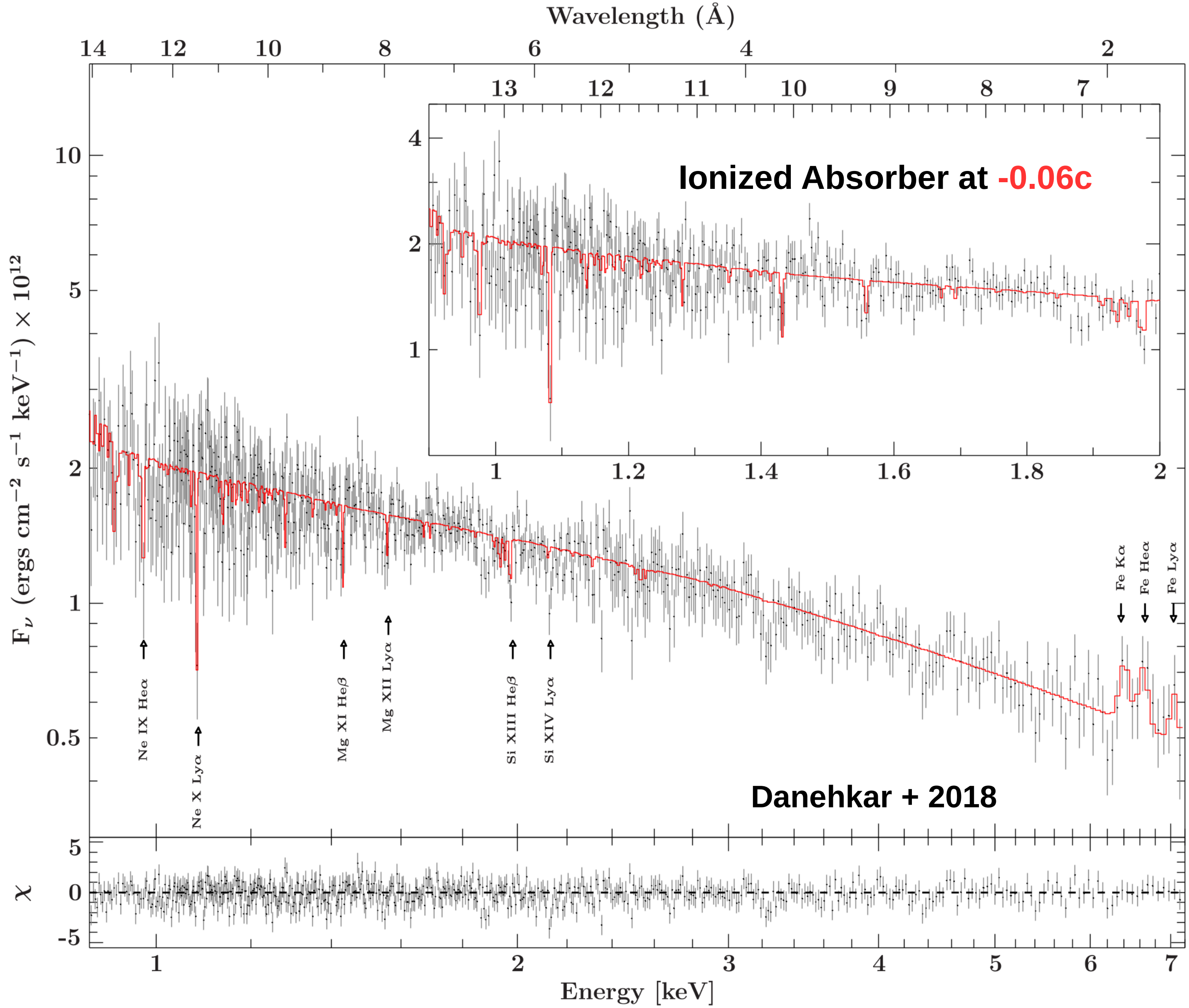


Plausible detection at -0.06c but further analysis needed

UFOs in the Seyfert I Galaxy PG 1211+143

$$\text{zdust} \times \text{ztbabs} \times \text{highecut} \times (\text{diskbb} + \text{powerlaw} + \sum_{i=1}^{M} \text{emis}_i) \times \prod_{i=1}^{N} \text{abs}_i$$

Ionized Absorber



March 11th, 2018

UFOs in the Seyfert I Galaxy PG 1211+143

Luminosity (13.6 eV-13.6 keV)

$$\xi \equiv \frac{L}{nR^2}$$

Ionization parameter

Gas density

Radius

$$N = n\Delta R$$

Column density

Shell thickness

Photoionization Code XSTAR (Kallman + 1996, 2004)

$$R < \frac{L}{N\xi}$$

$$R > 2\,G M_{\rm BH}/v_{\rm out}^2$$

BH mass

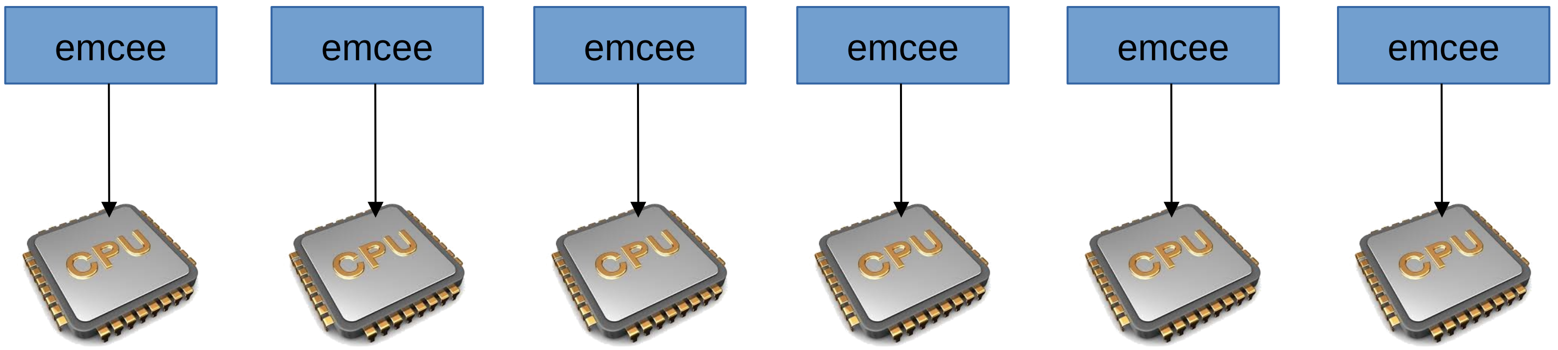
Outflow velocity

Parameter	Value
$L_{\rm ion}$ (10^{38} erg s^{-1})	1.587×10^7
$T_{\rm init}$ (10^4 K)	100
$\log n$ (cm^{-3})	$8 \cdots 14$
$\log N_{\rm H}$ (cm^{-3})	$18 \cdots 25$
$\log \xi$ (erg cm s^{-1})	$-2 \cdots 5$
$v_{\rm turb}$ (km s^{-1})	$100 \cdots 1000$
$A_{\rm Fe}$	1.0
$C_f = \Omega/4\pi$	0.5

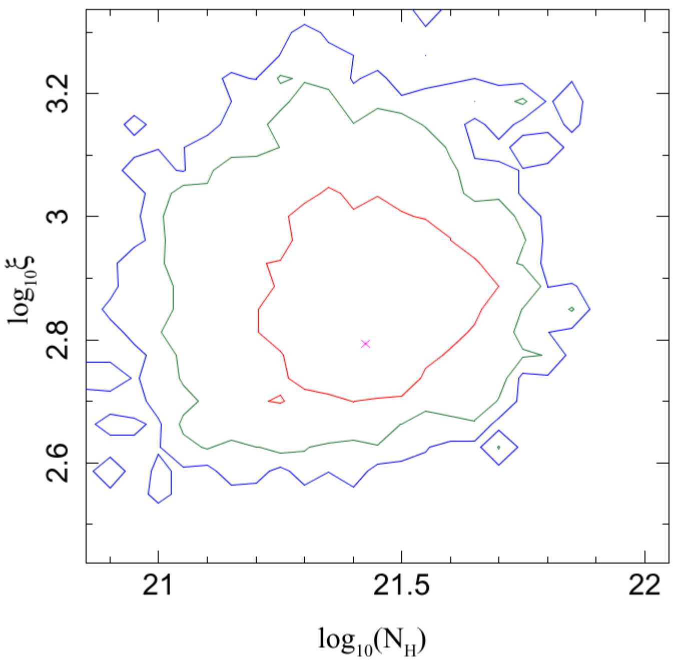
UFOs in the Seyfert I Galaxy PG 1211+143

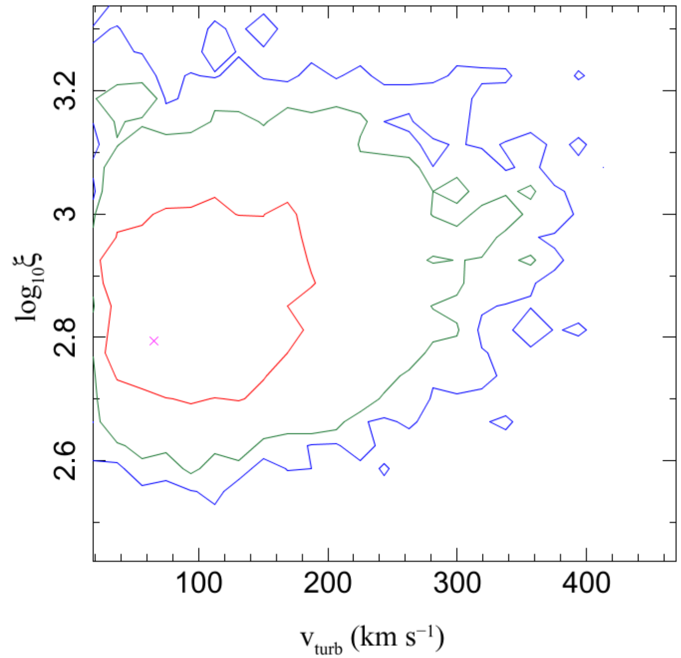
isis_emcee (Nowak + 2016)

- isis_emcee: S-Lang Markov Chain Monte Carloe (MCMC) Hammer
- Based on MCMC algorithm (Goodman & Weare 2010)
- Python implemented (Foreman-Maxkey + 2013)
- slmpi_emcee: Parallelization: github.com/mcfit/slmpi_emcee (Danehkar + 2017)
- S-Lang MPI Interface (Dauser & Schwarm)
- isis_emcee and lsmpi_emcee used with warmabs for confidence maps



UFOs in the Seyfert I Galaxy PG 1211+143





Luminosity (0.0136-13.6 keV)

$$\xi \equiv \frac{L}{nR^2}$$

Ionization parameter

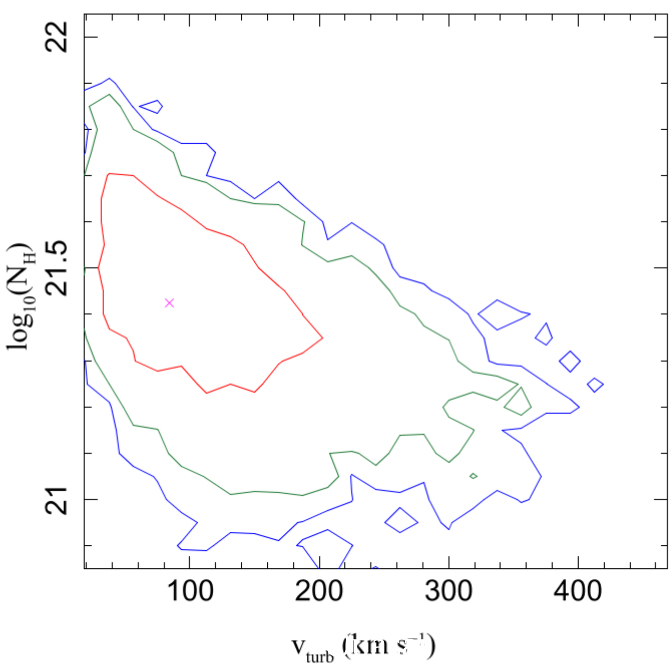
Gas density

Radius

$$N = n\Delta R$$

Column density

Shell thickness



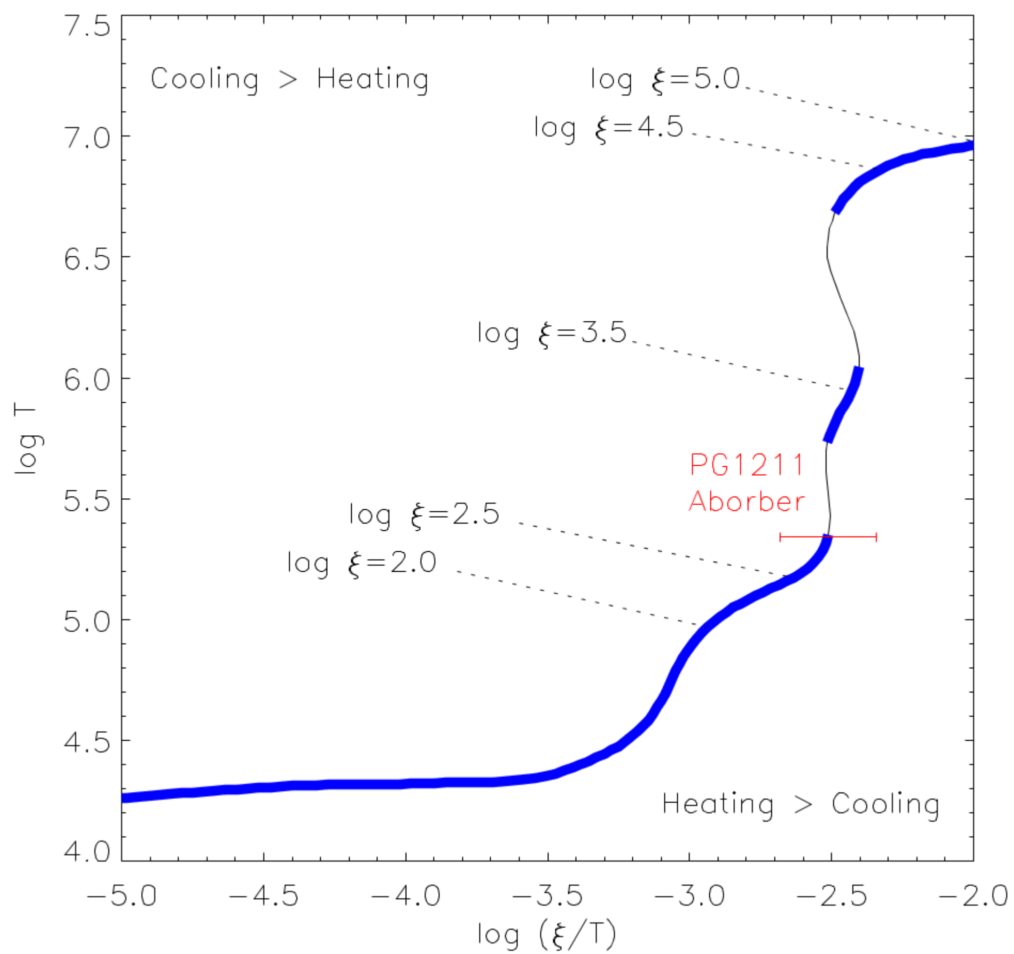
Component	Parameter	Value
warmabs	$\log n$ (cm^{-3})	12.0
	$\log N_{\rm H}$ (cm^{-2})	$21.47^{+0.15}_{-0.39}$
	$\log \xi$ (erg cm s^{-1})	$2.81^{+0.26}_{-0.13}$
	$\Delta v_{\rm shift}$ (km s^{-1})	-17246^{+117}_{-181}
	$v_{\rm turb}$ (km s^{-1})	57^{+192}_{-26}
	$A_{\rm Ne}$	$1.00^{+2.44}_{-0.42}$
	$A_{\rm Mg}$	$1.45^{+1.84}_{-0.78}$
	$A_{\rm Si}$	$2.03^{+2.27}_{-0.75}$
	$A_{\rm S}$	$0.27^{+3.01}$

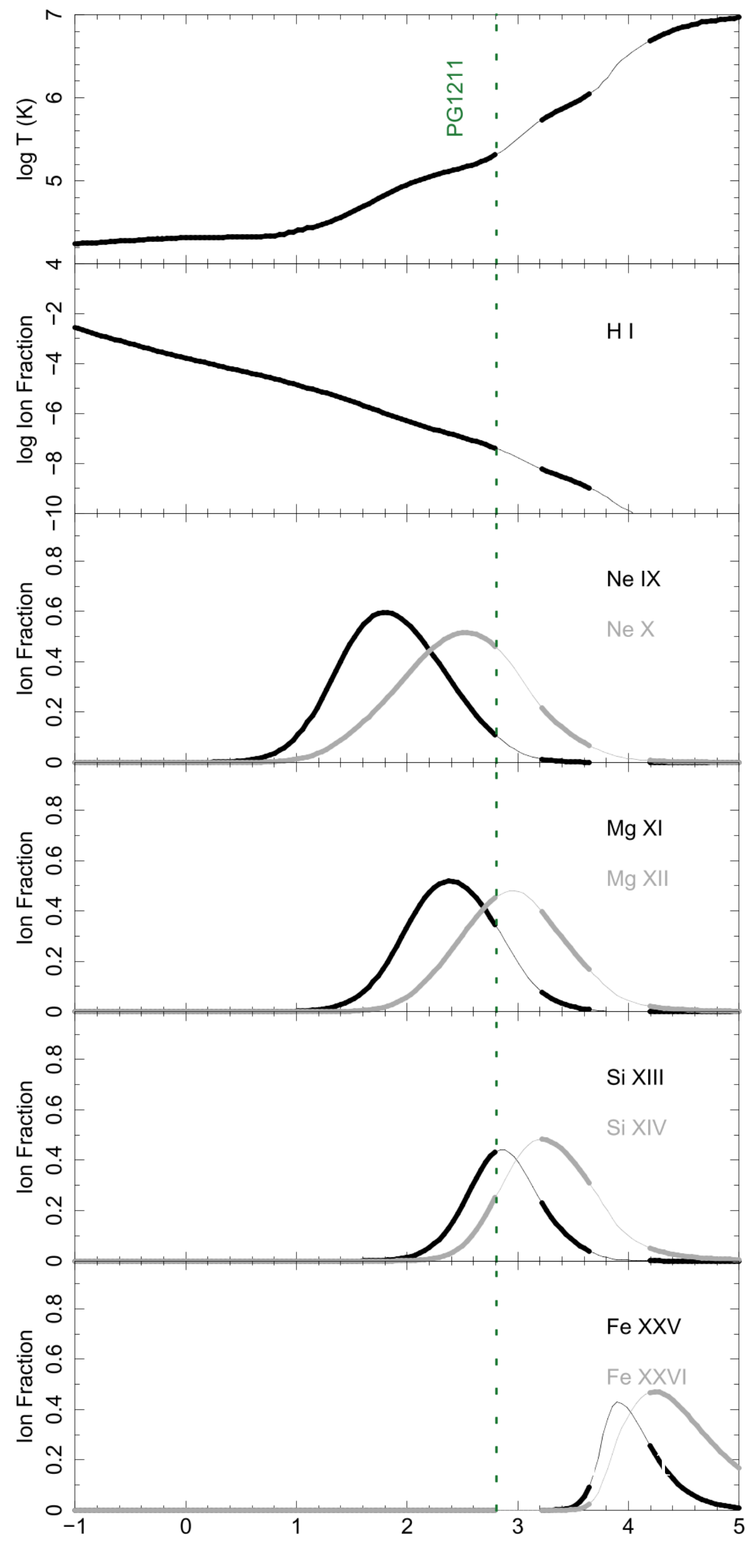
~ **-0.06c**

Danehkar + 2018

PG 1211+143: Photoionization Modeling

- **Thermal Stability Curve and Ion Fraction Plots**

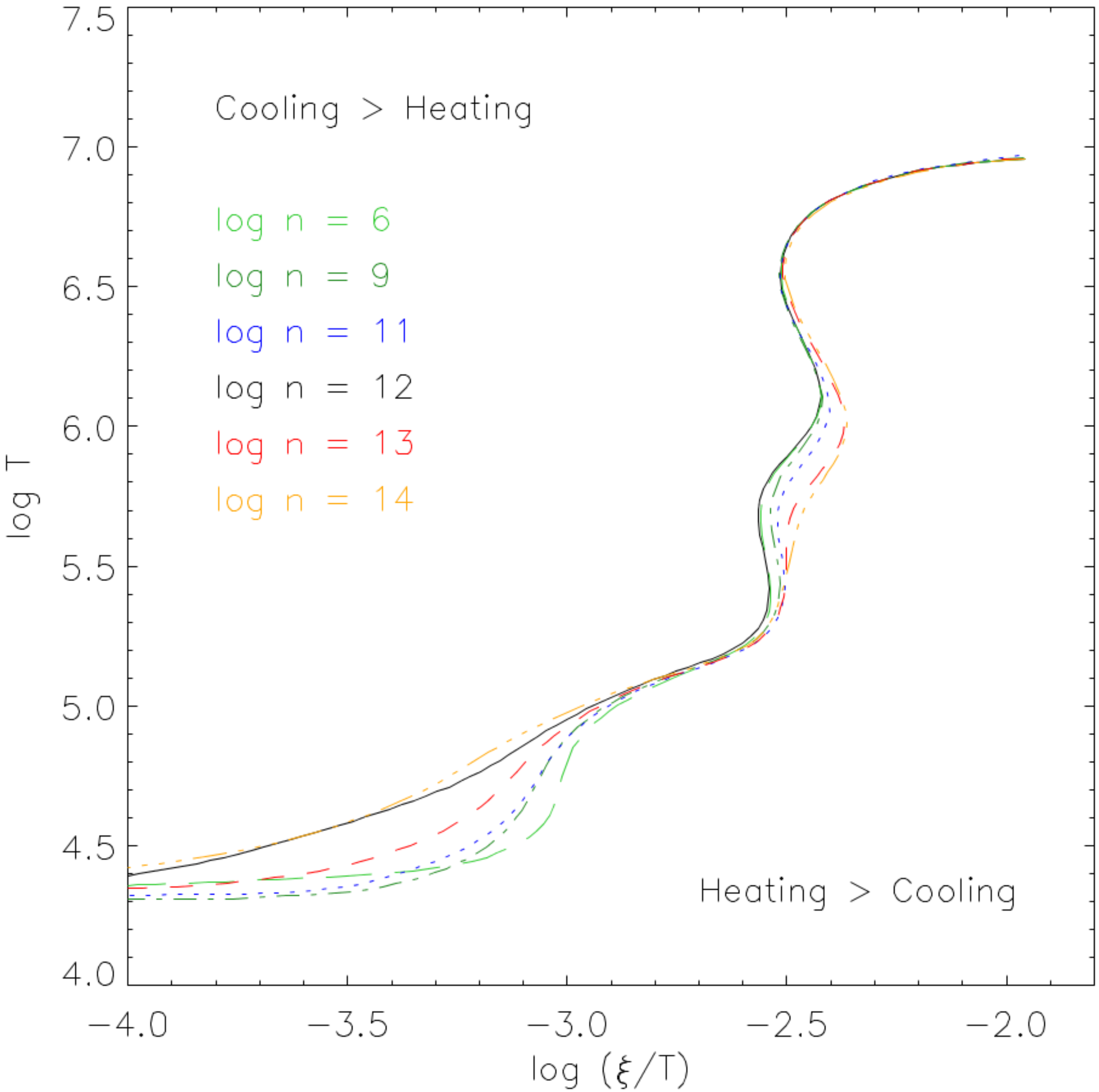


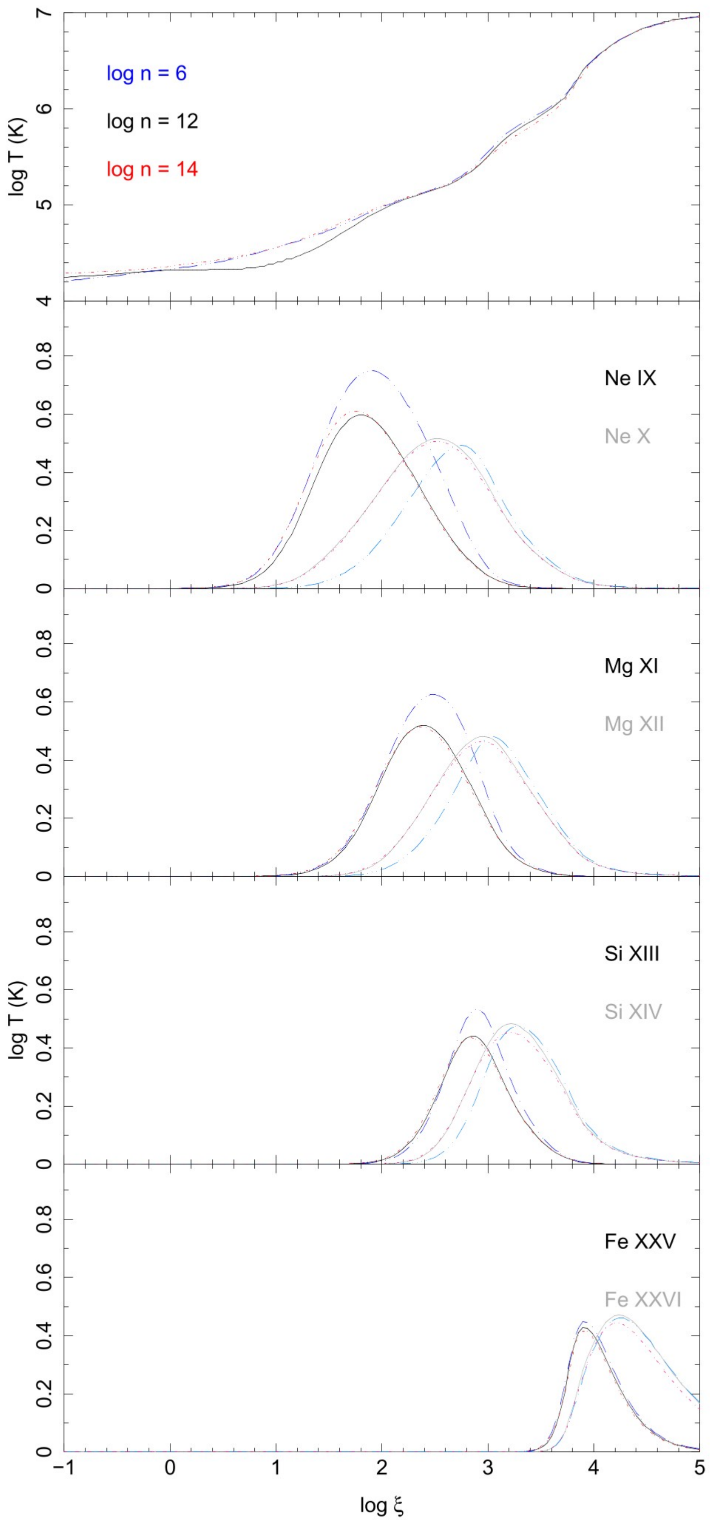


Danehkar + 2018

PG 1211+143: Photoionization Modeling

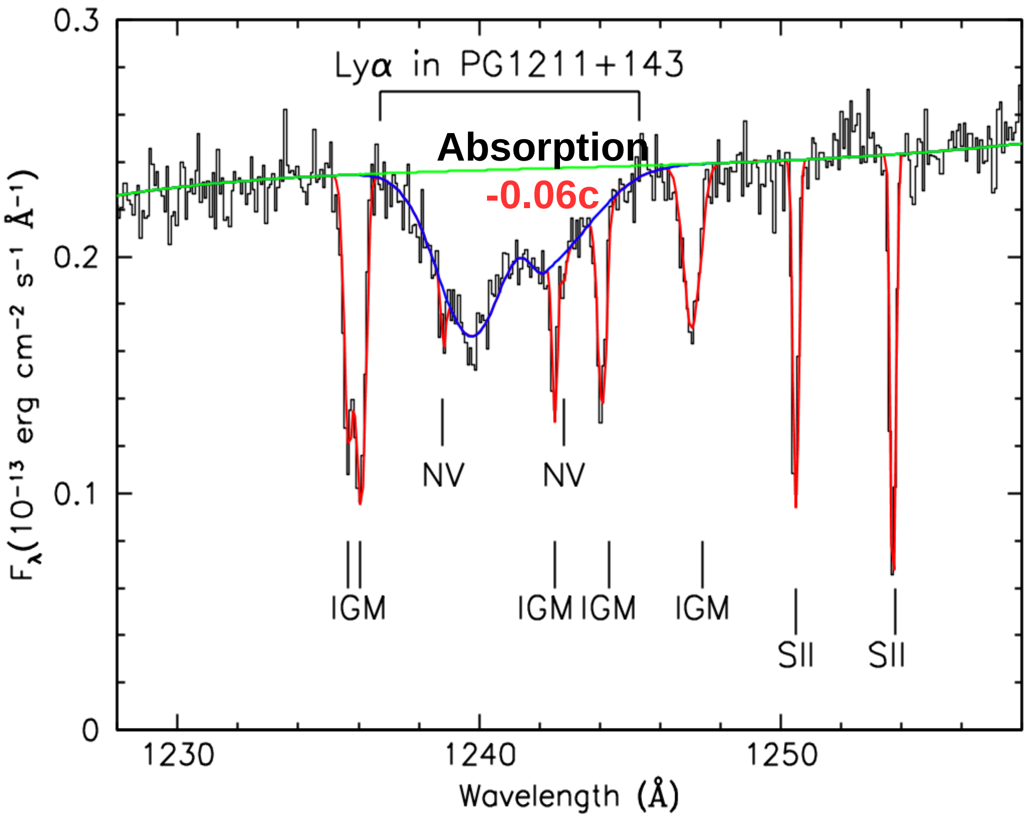
Thermal Stability Curves of Ionized Absorbers:





UFOs in the Seyfert I Galaxy PG 1211+143

- *HST* Cosmic Origins Spectrograph (COS)
- UV Lyα wide absorption line,
  possible counterpart to X-ray absorber
- The same outflow velocity (-0.06c)
- log $N_{H\,I}$ > 14.5 (log N_H ~ 21)
- log ξ ~ 2.9

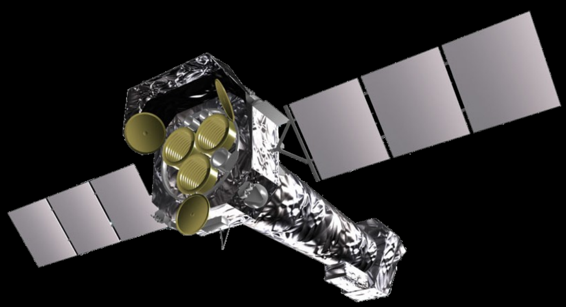


Kriss + 2018

PG 1211+143: Observation Summary

XMM-Newton Observations

- UFOs v_{out} ~ -0.07*c* (Pounds + 2003, Pounds & Page 2006; Pounds + 2016)
- H- and He-like C, N, O, Ne, Mg, S and Fe ions (Pounds + 2003)
- A second component outflow
  - -0.14*c* (Pounds 2014; Pounds et al. 2016)



NuSTAR Observations

- No UFO (Zoghbi + 2015)

Chandra Grating Observations

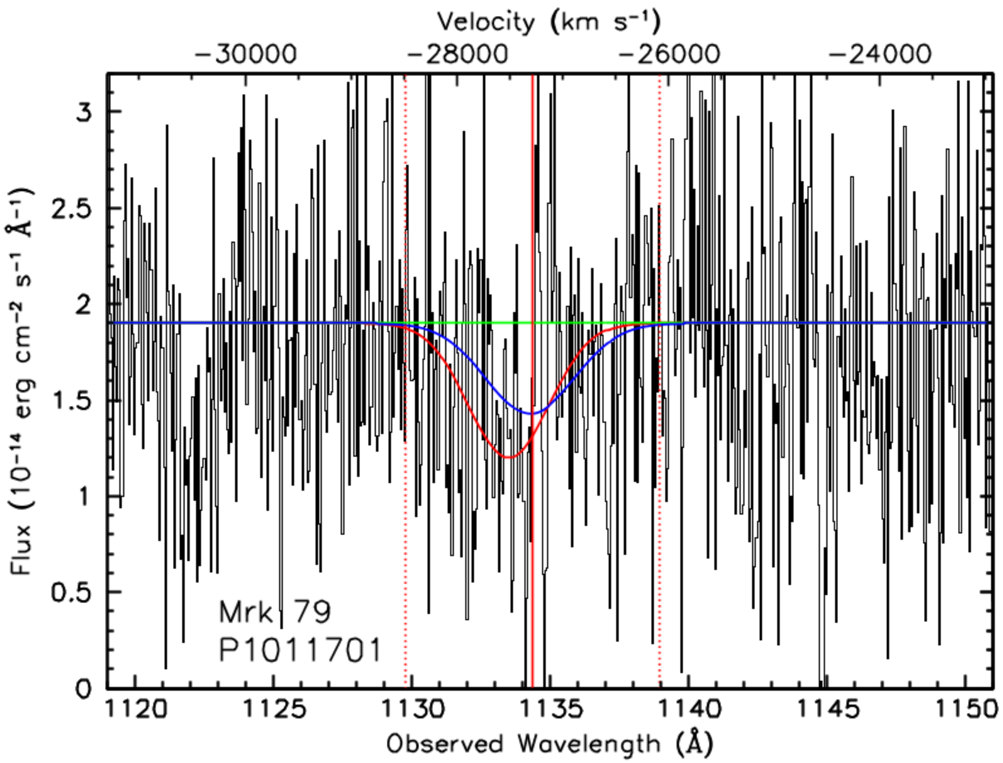
- High Energy Transmission Grating (HETG; PI: J.C. Lee)
- 6 observations over 9 days ~ 433 ks
- H- and He-like Ne, Mg, S ions: -0.06*c*

- UV *HST* COS: Lya with -0.06c

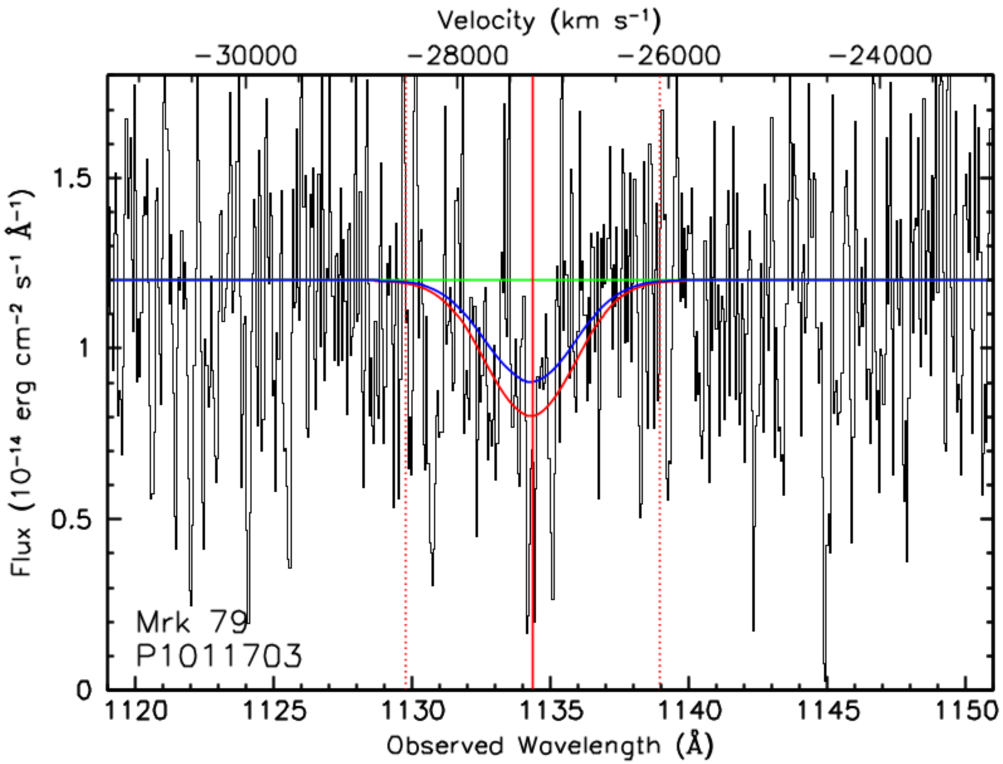
UFOs in Seyfert I AGN

Search for UV Counterpart of X-ray UFOs

- **Checking UV archives of 16 AGN with X-ray UFO**
  - **Only Mrk 79 show broad Lya absorption**



Mrk 79, FUSE observation P1011701



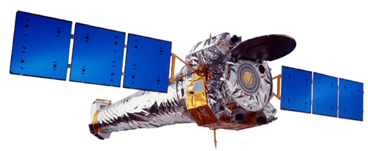
Mrk 79, FUSE observation P1011703

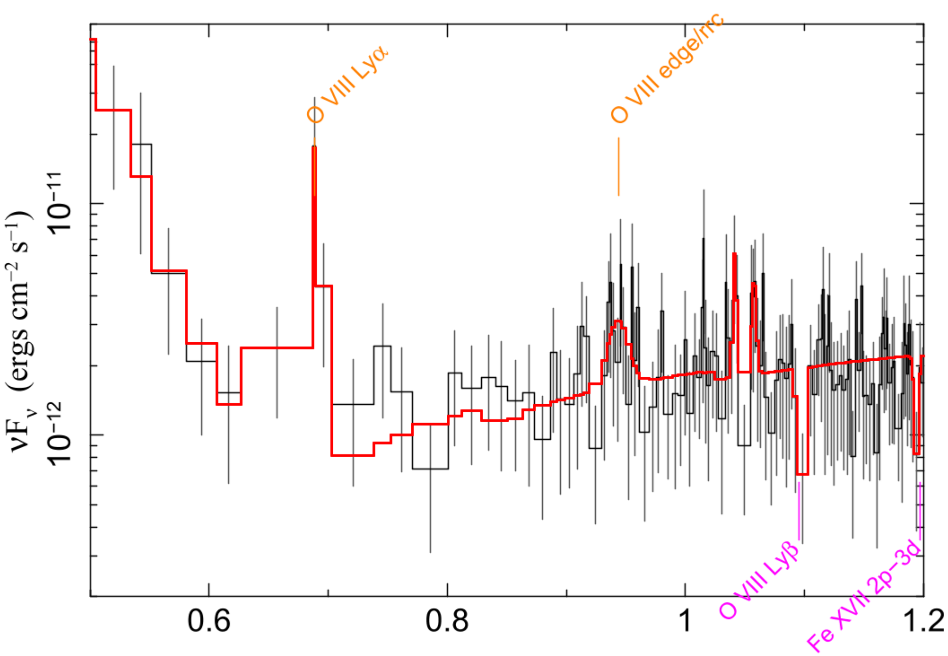
Kriss + 2018

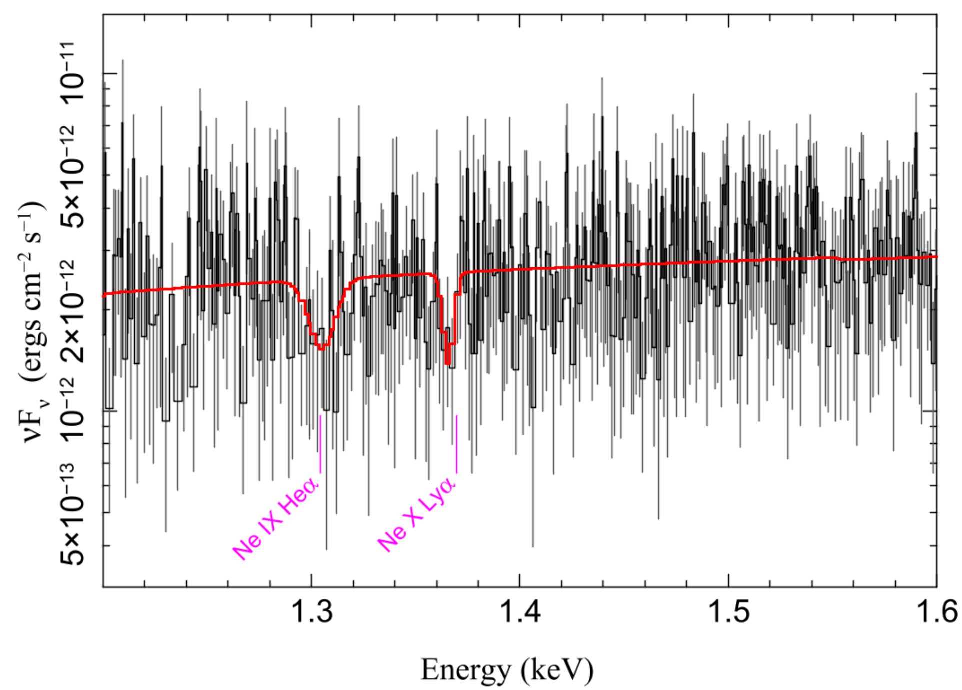
UFOs in the Seyfert I Galaxy PDS 456

Chandra, NuSTAR, and XMM-Newton

- **Two-component UFO:**
  - **-0.24 *c* to -0.29 *c***
  - **-0.48 *c***







Boissay-Malaquin + 2019

UFOs in the Seyfert I Galaxy PDS 456

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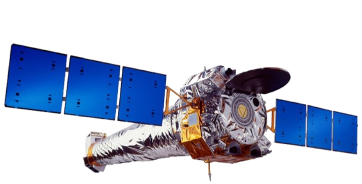
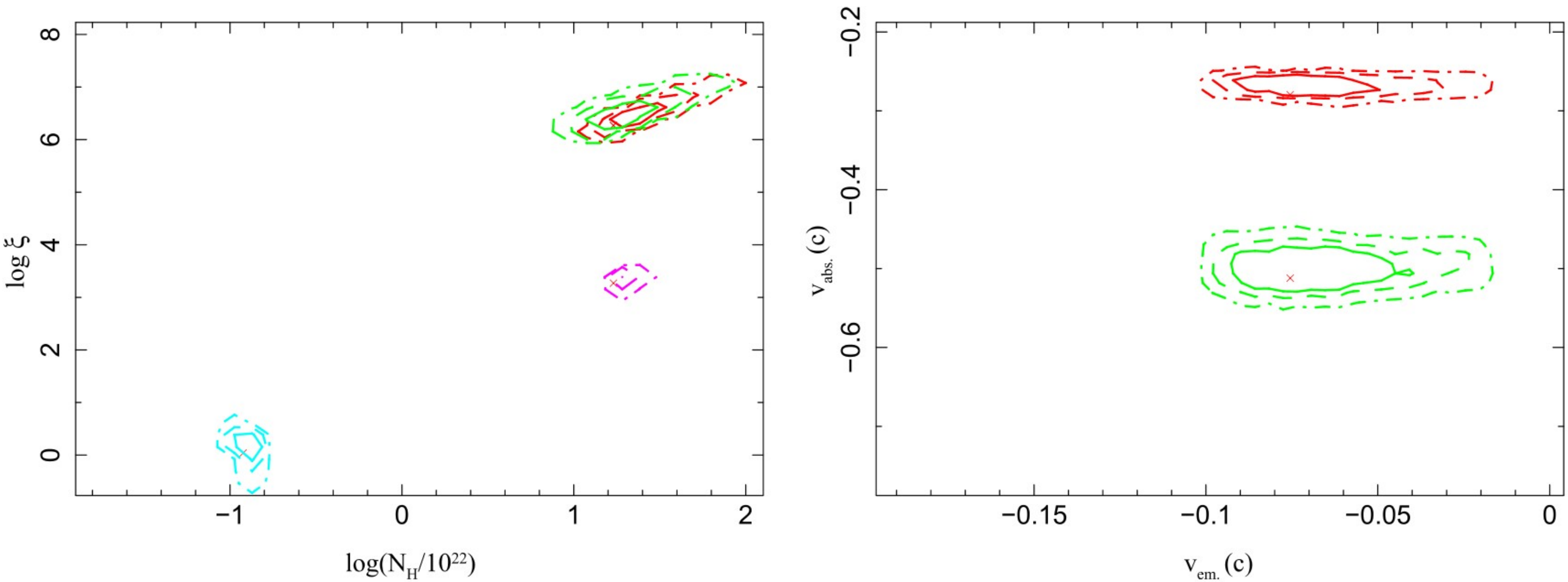
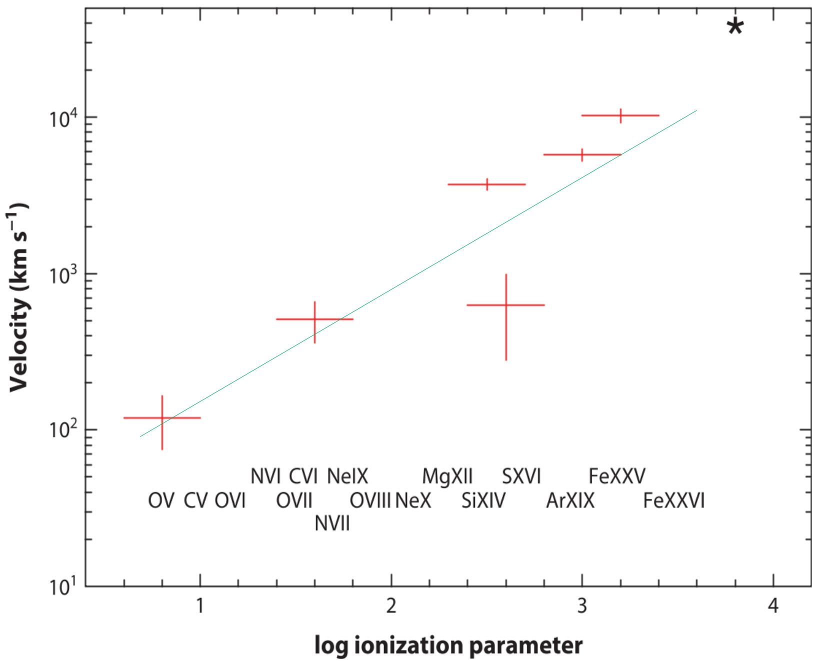


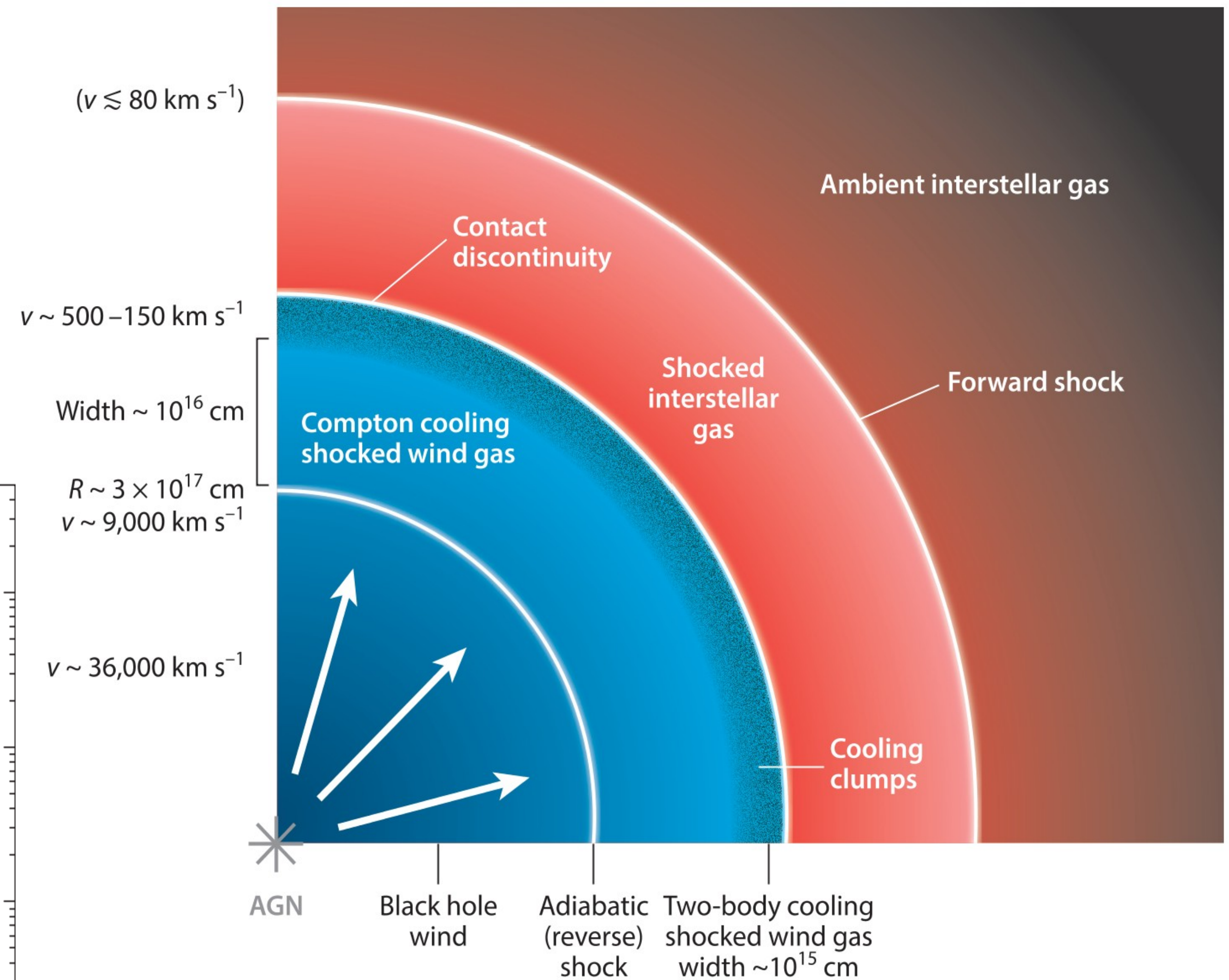


Boissay-Malaquin + 2019

Future Prospects: A Unified AGN Outflow Model



NGC 4051 (six XSTAR absorbers)
Pounds & King 2013



Schematic view of the shocked wind model
Pounds & King 2013

Future Prospects: A Unified AGN Outflow Model

Absorption Measure Distribution (AMD): similar to Emission Measure Distribution (EMD)

$$\mathrm{AMD} = |dN_\mathrm{H}/d(\log\xi)|$$

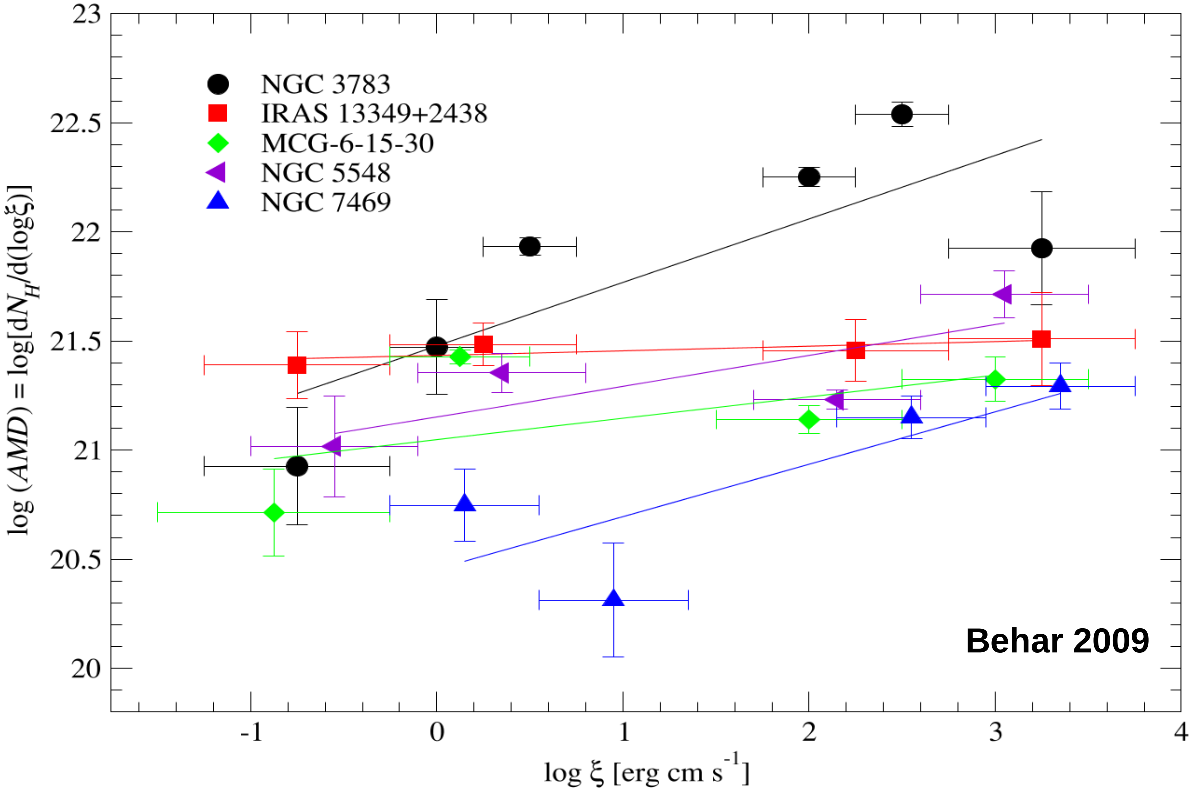
$$n(r) \propto r^{-\alpha}$$

$$\longrightarrow \quad \mathrm{AMD} = \left|\frac{dN_\mathrm{H}}{d\log\xi}\right| \propto \xi \left|\frac{dN_\mathrm{H}}{d\xi}\right| \propto \xi^{-\frac{\alpha-1}{\alpha-2}} \equiv \xi^a$$

$a = 0.7$

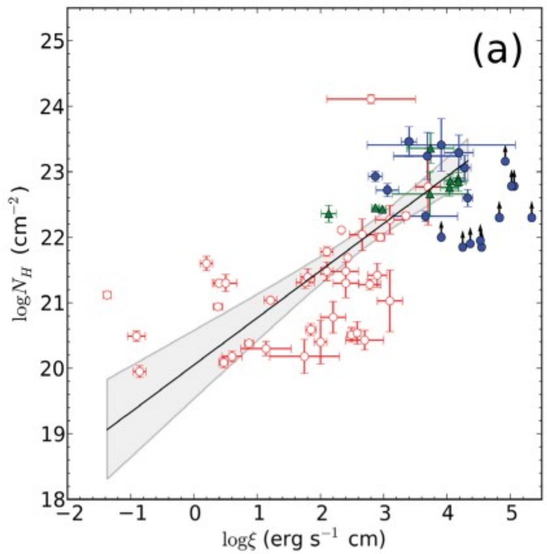
$\alpha = (1+2a)/(1+a) \simeq 1.4$

$n(r) \sim r^{-1.4}$ density profile



Future Prospects: A Unified AGN Outflow Model

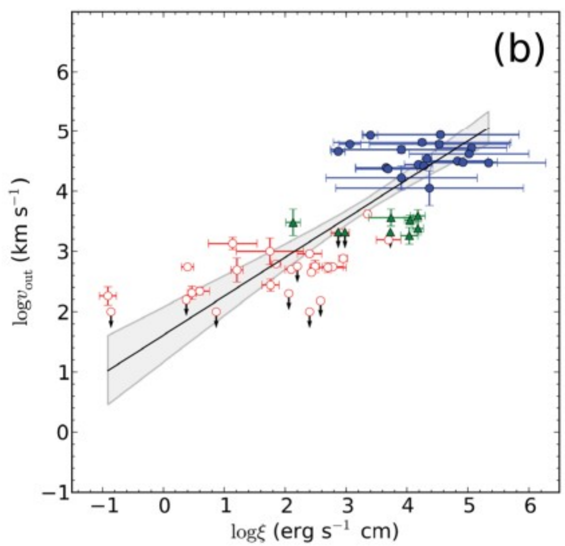
Unification of UFOs and WAs

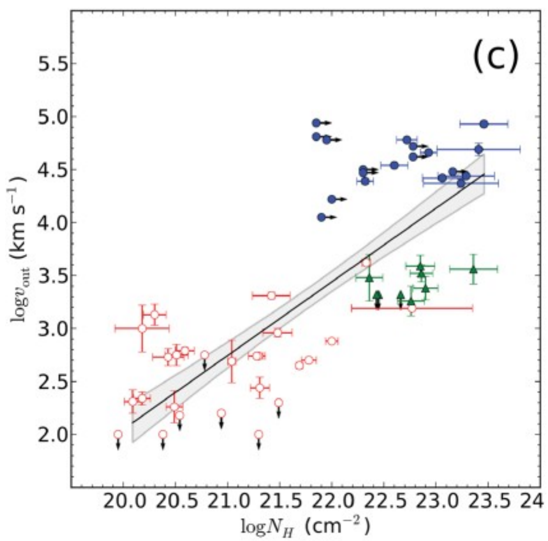


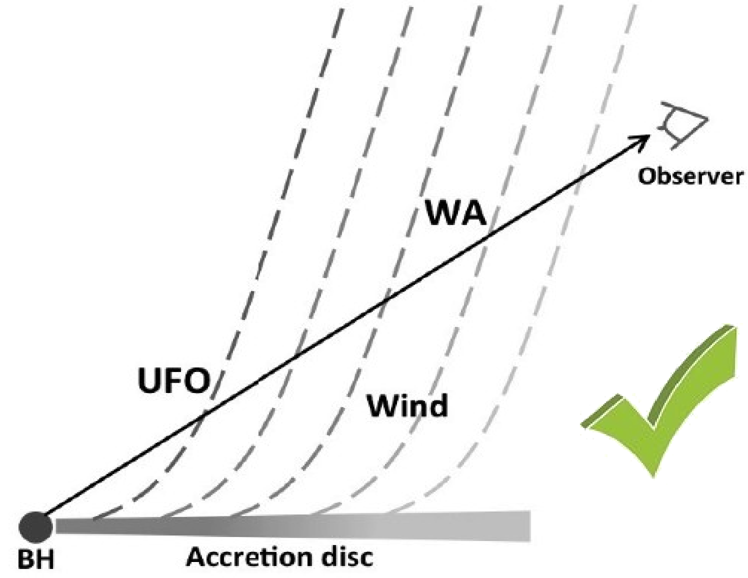
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **430,** 1102–1117 (2013) doi:10.1093/mnras/sts692

Unification of X-ray winds in Seyfert galaxies: from ultra-fast outflows to warm absorbers

F. Tombesi,[1,2]★ M. Cappi,[3] J. N. Reeves,[4] R. S. Nemmen,[1] V. Braito,[5] M. Gaspari[6] and C. S. Reynolds[2]



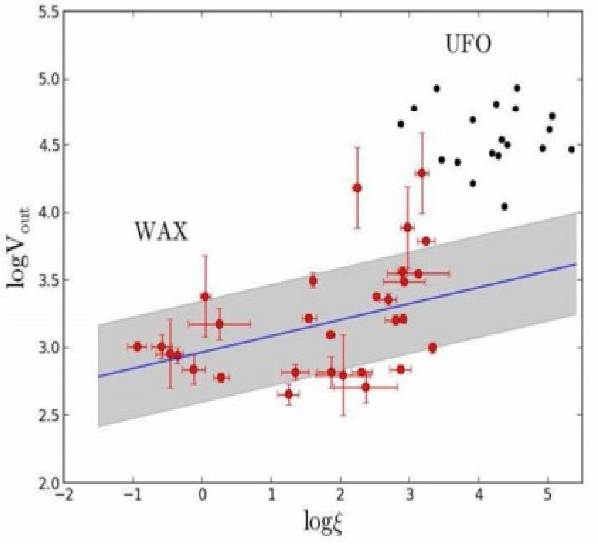




Tombesi + 2013

Future Prospects: A Unified AGN Outflow Model

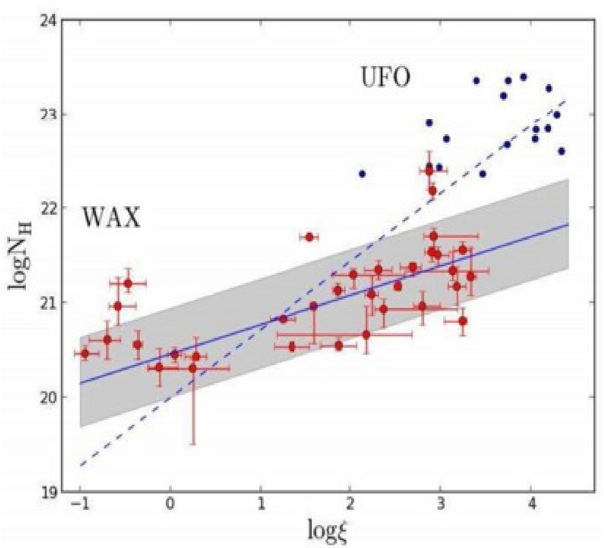
Non-Unification of UFOs and WAs

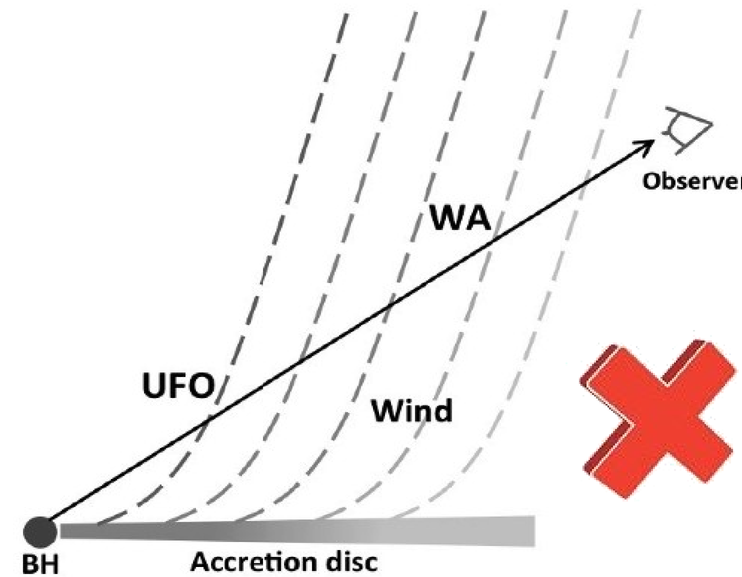


Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **441,** 2613–2643 (2014) doi:10.1093/mnras/stu669

Warm absorbers in X-rays (WAX), a comprehensive high-resolution grating spectral study of a sample of Seyfert galaxies – I. A global view and frequency of occurrence of warm absorbers.

Sibasish Laha,[1★] Matteo Guainazzi,[2] Gulab C. Dewangan,[1] Susmita Chakravorty[3] and Ajit K. Kembhavi[1]





Tombesi + 2013

Future Prospects: A Unified AGN Outflow Model

Unification of UFOs and Spins?

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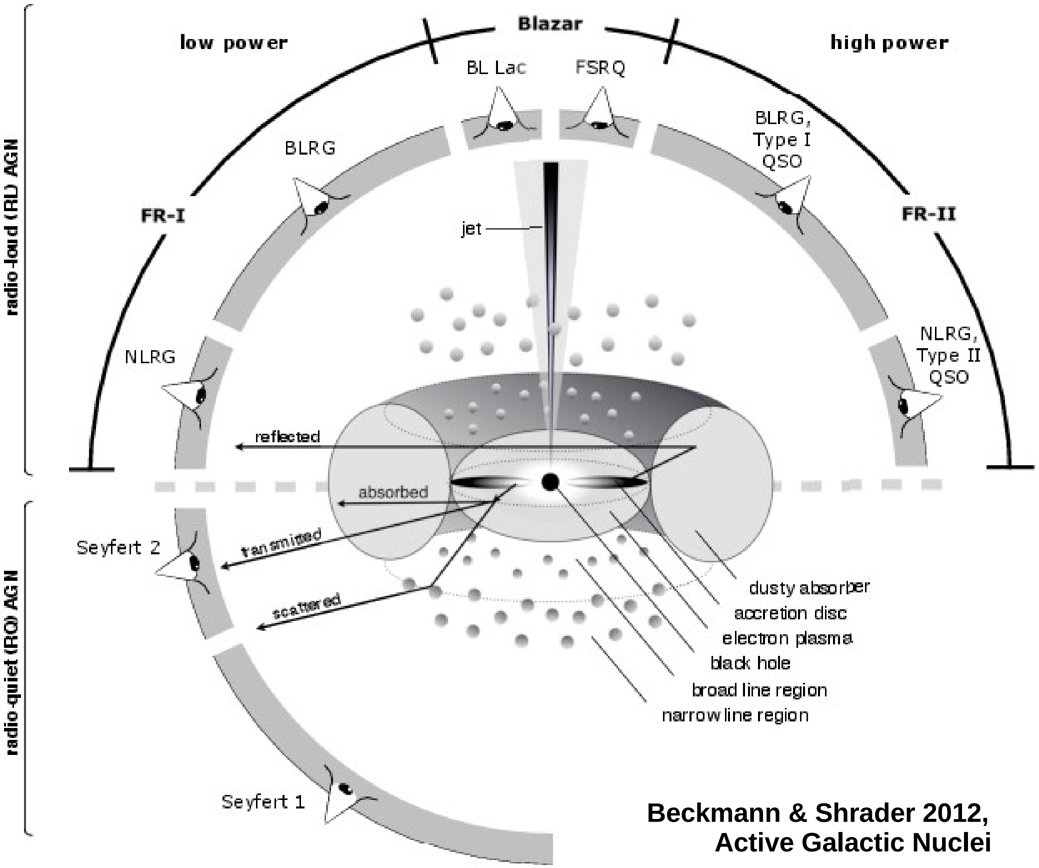


Beckmann & Shrader 2012, Active Galactic Nuclei

Garofalo + 2010

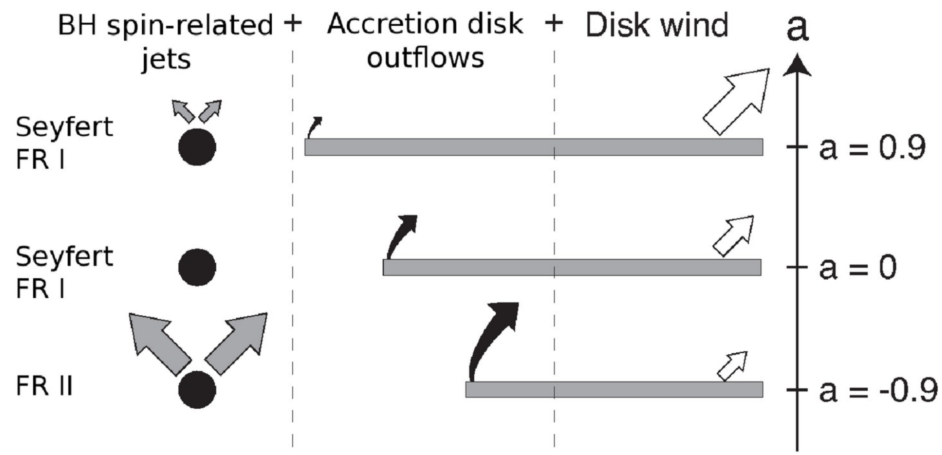


FIGURE 3. A schematic view of the dependence of accretion disk outflows and black hole spin-related jets on spin (Garofalo et al. 2010). Radio-loud FR II AGNs have retrograde spins, whereas radio-loud FR I and radio-quiet Seyfert AGNs have prograde spins. Fast outflows and jets (near the BH) could be due to spin-energy extraction from the black hole via the Blandford–Znajek mechanism, while slow wind outflows could be mass-loss from the accretion disk via the Blandford–Payne mechanism.

Future Prospects: A Unified AGN Outflow Model

Unification of UFOs and Spins?

- **A possible correlation between UFO and angular momentum?**
- **Spin from relativistic Fe Kα line**
- **UFOs from blue-shifted H-like and He-like Fe absorption lines**
- **BH Mass from reverberation-mapping**

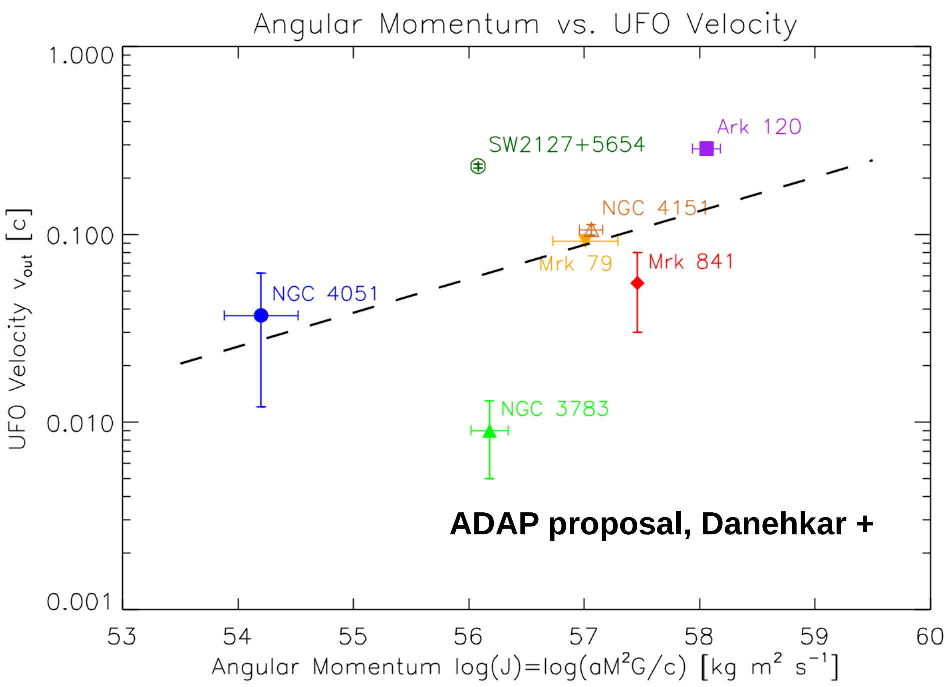


FIGURE 4. The black hole angular momentum ($J = aM^2G/c$ [kg m^2 s^{-1}]) versus the ultra fast outflow velocity ($v_{\rm out}[c]$) for 7 radio-quiet AGNs. The black hole spins (a) are adopted from Brenneman (2013) and Brenneman et al. (2014), black hole masses (M) are chosen from Bentz & Katz (2015), and ultra-fast outflow (UFO) velocities ($v_{\rm out}$) are from Tombesi et al. (2010, 2011, 2012). A linear fit to the 5 points in the figure (the dashed line) yields $\log(v_{\rm out}[c]) = -(11.36 \pm 0.62) + (0.18 \pm 0.01)\log(J[{\rm kg\,m^2\,s^{-1}}])$ suggesting that the kinematics of highly-ionized outflow may be a function of the black hole angular momentum. Further studies of a larger sample of radio-quiet AGNs are required to decide whether there is a strong correlation between the black hole angular momentum and the UFO proprieties (velocity, density, and density profile).

Future Prospects: A Unified AGN Outflow Model

Toward an AGN Outflow Unification

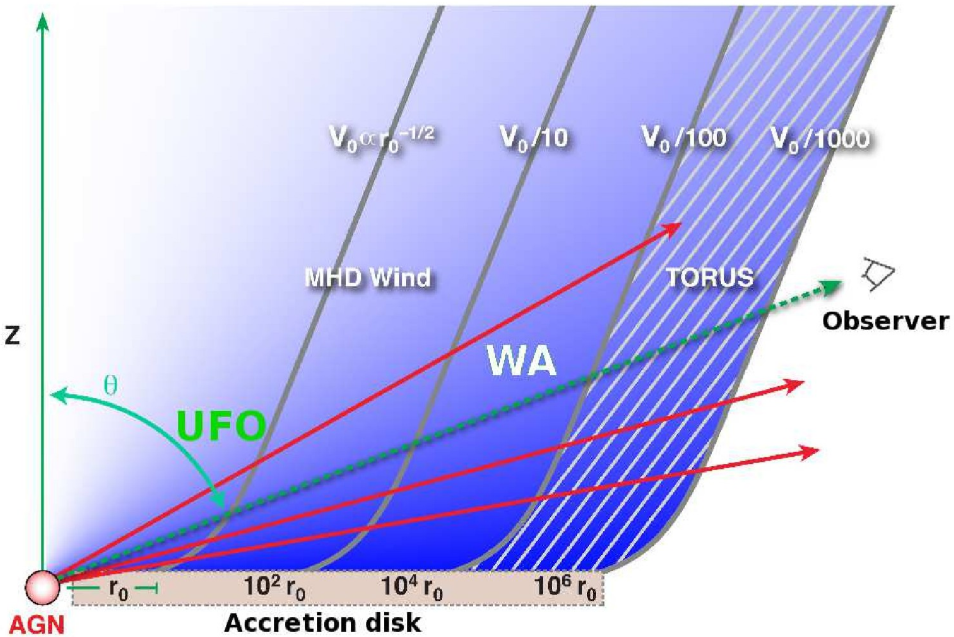
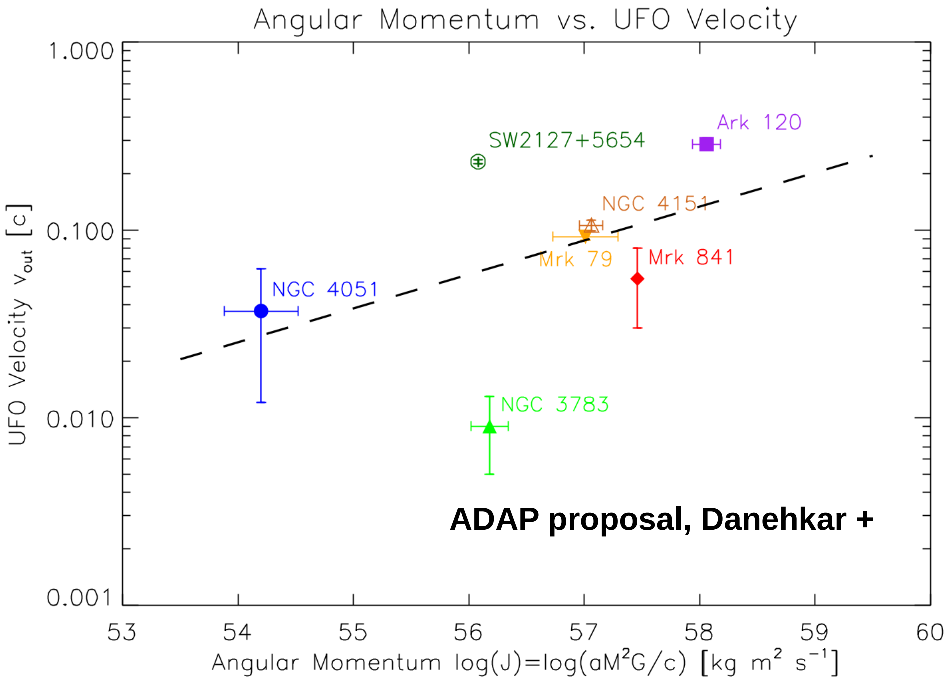


FIGURE 1. A schematic representation of stratified layers of the unified AGN outflow model (Kazanas et al. 2012; Tombesi et al. 2013). UFOs and WAs are associated with different locations of a single large-scale stratified outflow in the AGN.



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Summary

- **X-ray ionized Absorbers**
  - **WAs: typically H-like & He-like O, Ne, Mg, Si & S ions, low velocity < 10,000 km/s**
  - **UFOs: typically H-like & He-like Fe, high velocity > 10,000 km/s, usually ~ 0.1– 0.4c**
- **Photoionization Code XSTAR (XSTAR Grids, xstardb)**
  - ***Physical Conditions*: ionization parameters, column density, & gas density**
- **Seyfert I Galaxy PG 1211+143**
  - ***XMM-Newton* observations: UFOs vout ~ -0.06*c* and -0.13*c***
  - ***Chandra* observations over 9 days ~ 433 ks**
  - ***Hubble* UV observations, radio observations with VLA**
- **Photoionization Modeling of PG1211+143**
  - **X-ray ionized absorber (log ξ ~ 2.8, log N_H ~ 21.5, V_{out} ~ -0.06c)**
  - **UV Lyα absorption: outflow velocity -0.06*c*, counterpart to X-ray absorber**
- **UV counterpart to X-ray UFO in AGN?**
  - **Only in Mrk 79 among 16 AGN**
- **Other AGN with two-component UFO:**
  - **PDS 456: -0.25*c* and -0.48*c***
- **Future Prospects: A Unified AGN Outflow Model**
  - **N_H - ξ , V_{out} - ξ and N_H - V_{out} correlations (Tombesi + 2013)**
  - **A possible correlation between UFO and angular momentum?**