The Universal Magnetic Structure of Black Hole Accretion Disk Winds

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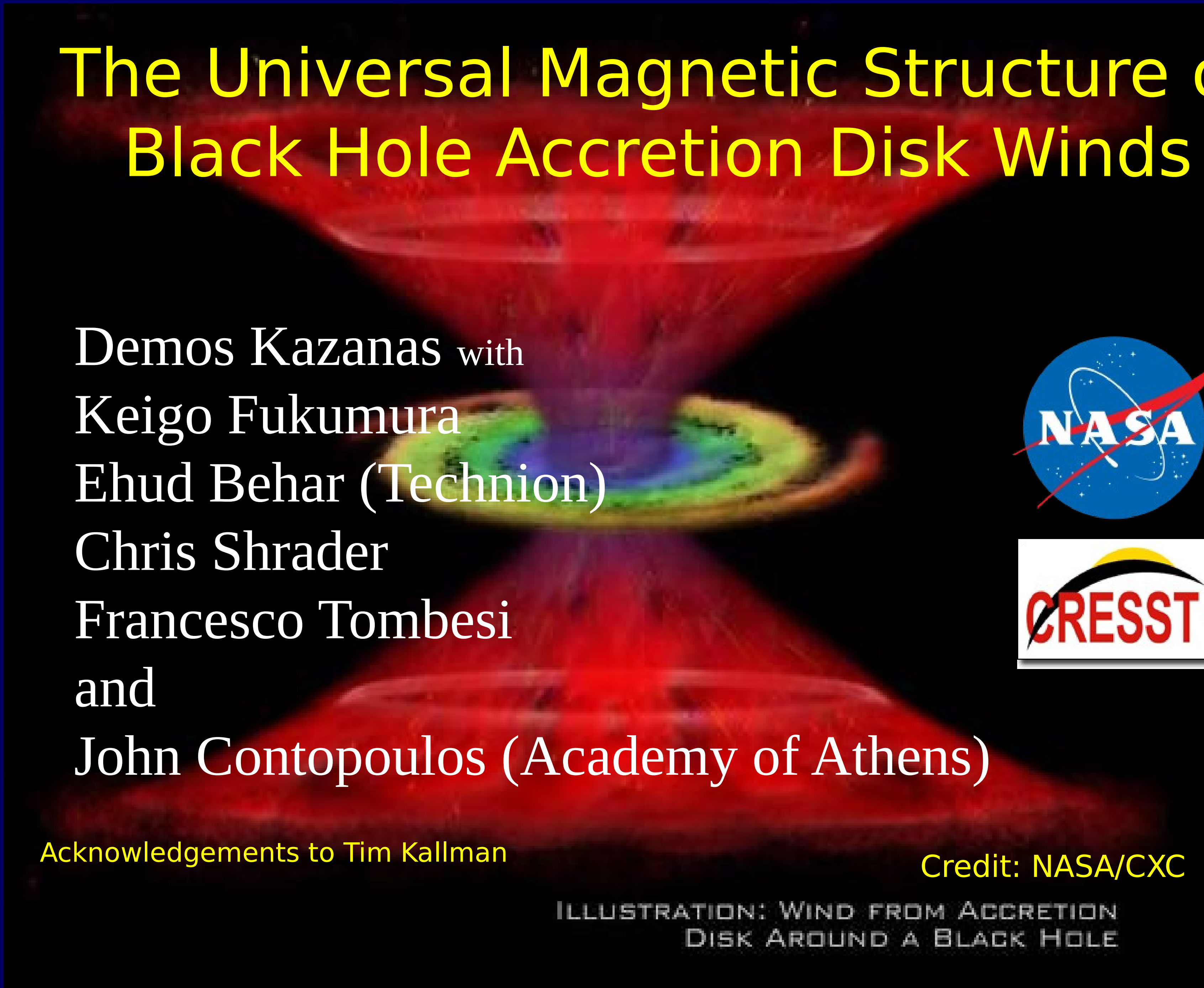
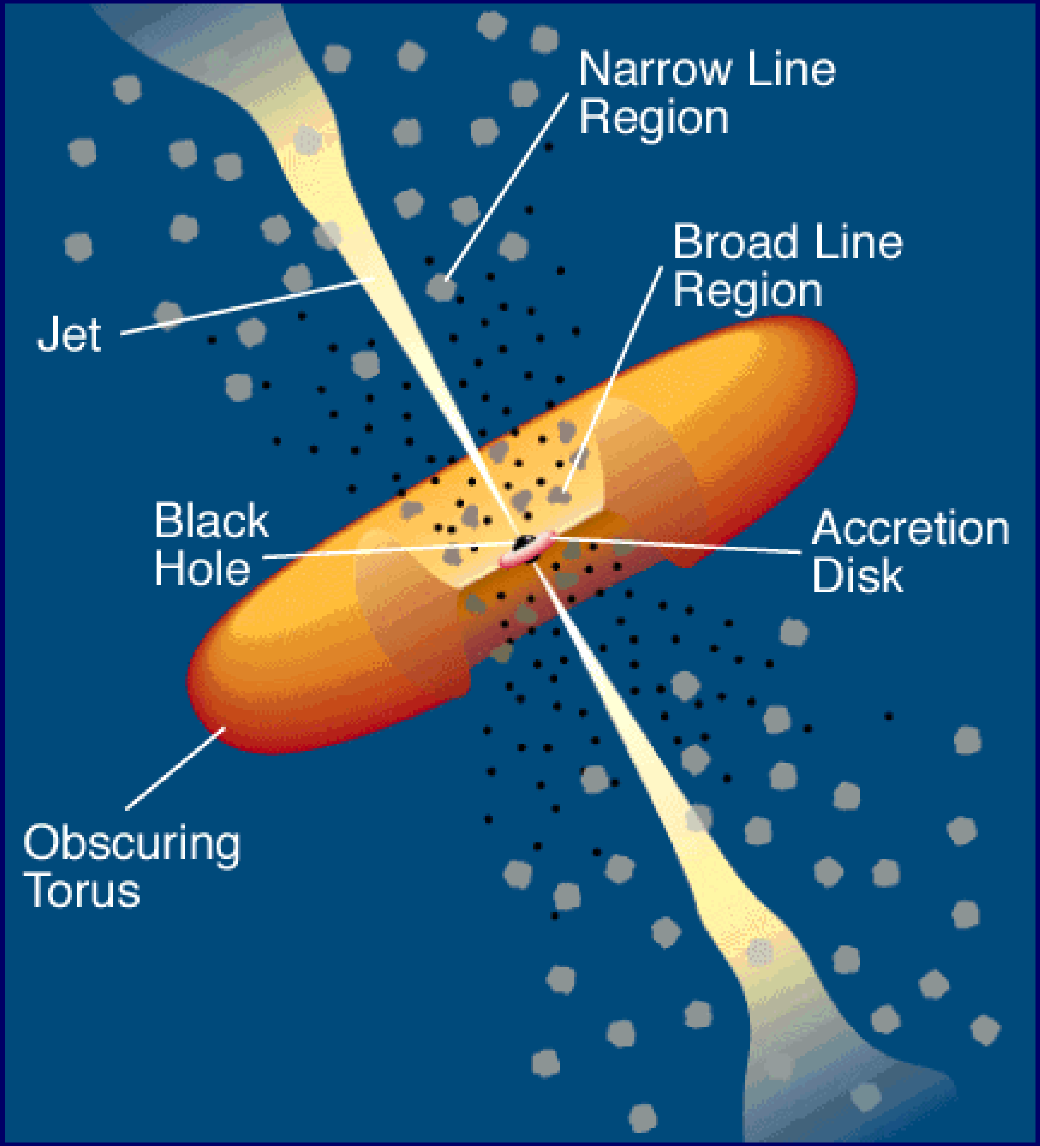
Acknowledgements to Tim Kallman



Credit: NASA/CXC

Radiation Emission from Accreting Black Holes

- **Accretion onto Black Holes proceeds with the formation of accretion disks.**
- **Their structure, still not well understood, relies on comparison of models with observed features.**
- **The ubiquitous spectral features of these objects comprise:**
  - **A multicolor disk component consistent with themal emission by an accretion disk that extends to ~100 R_S.**
  - **X-ray emission, presumably by a corona.**
  - **Broad (and Narrow) emission lines consistent with isotropic velocity of the emitting gas.**
  - **Blue-shifted absorption lines indicating *OUTFLOWS* (*not accretion !!!*)**



Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus

Outflows are Ubiquitous in AGN

(originally discovered in their UV spectra)

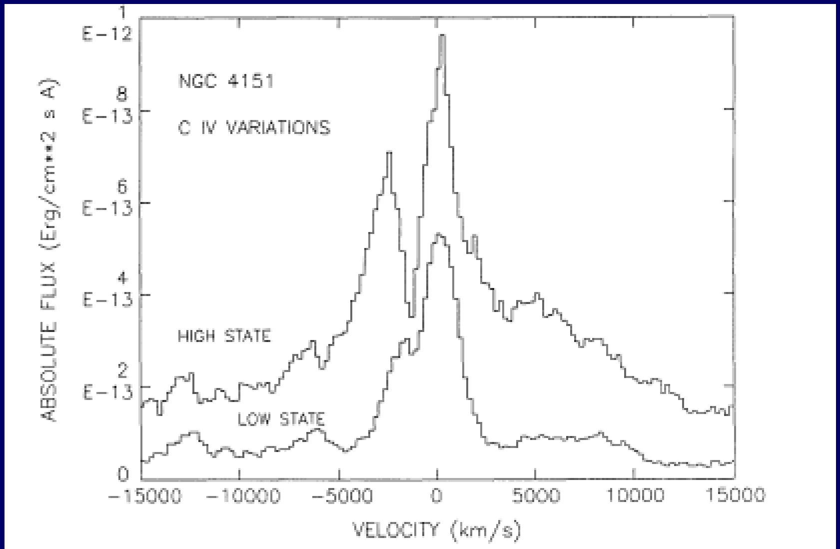
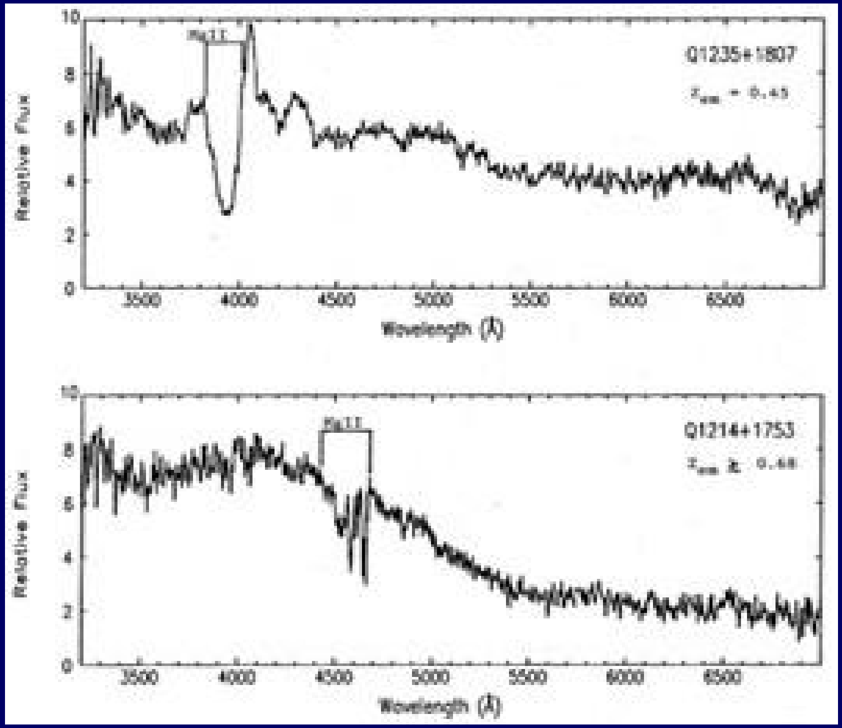


FIG. 1.—Representative C IV line profiles of NGC 4151 obtained in a low state (SWP 21578, 120 minute exposure, day = 82051), and in a high state (SWP 18490, 45 minute exposure, day = 82310). The spectra are plotted on the same absolute intensity scale and are shown in velocity space corrected for redshift.



X-ray Absorbers

- *Chandra* and *XMM-Newton* discovered a host of absorption features in the X-ray band of wide ionization state and velocities, hinting of much richer wind structures than thought before.

(1) Moderate Outflows ~ various charge state (~100-1,000 km/sec; N_H ~10^{21-22} cm^{-2})

 Many charge state from X-ray-bright AGNs

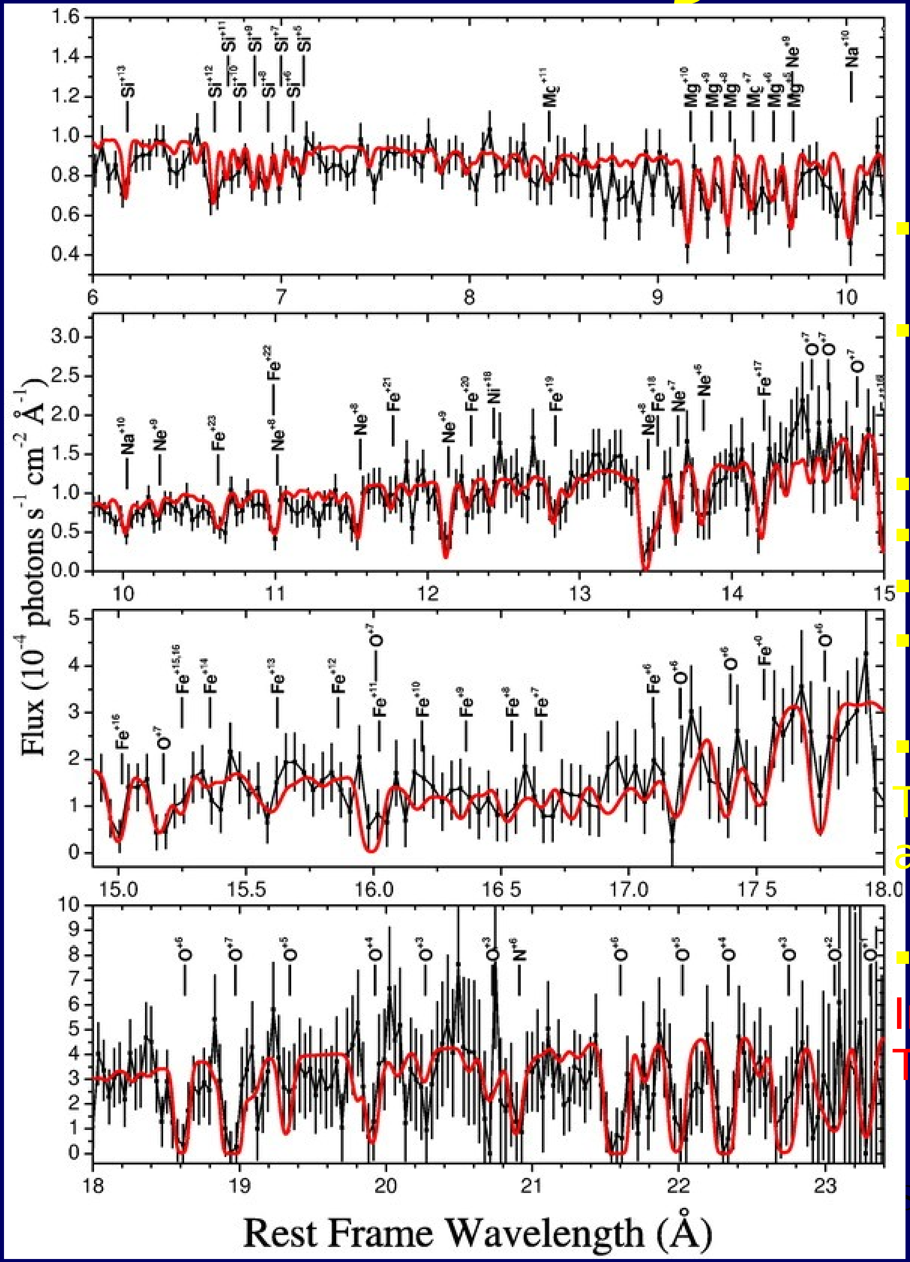
e.g. *MCG-6-30-15*, *IRAS 13349+2438*

(2) Fast Outflows ~ K-shell resonance (v/c~0.1-0.7; N_H ~10^{23-24} cm^{-2})

 H/He-like ions from hard-X-ray-weak AGNs

e.g. *PDS 456*, *PG 1211+143*, *APM 08279+5255*

X-ray-Bright AGNs



QSO: **IRAS 13349+2438:**
(z = 0.10764)

- X-ray bright, IR-loud/radio-quiet QSO
- X-ray obs. with *ROSAT*, *ASCA*, *Chandra*, *XMM-Newton*

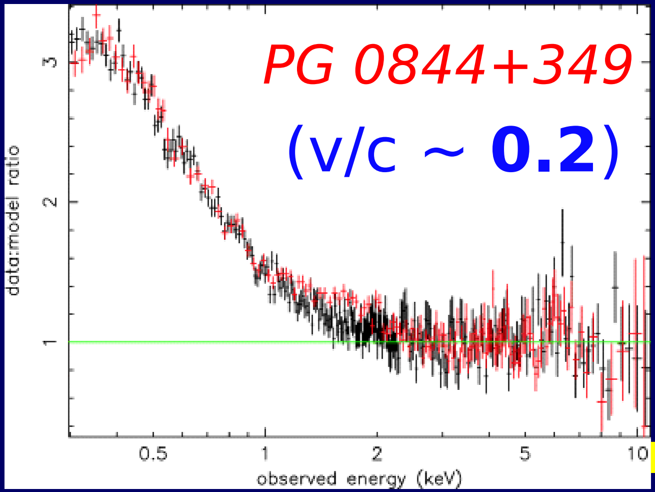
- Ions with various charge state
- Fe XVII ~ 300 km/sec
- Fe XXV ~ 3000 km/sec
- Integrated N_H ~ 1.2×10^{22} cm^{-2}

- Absorption lines are characterized by Their ionization state (ξ=L/nr^2), velocity v and column N_H .

- Importance of X-ray Spectroscopy: In 1.5 decades of E covers transitions That span 5 decades in ξ

Chandra data
Holczer+(07)

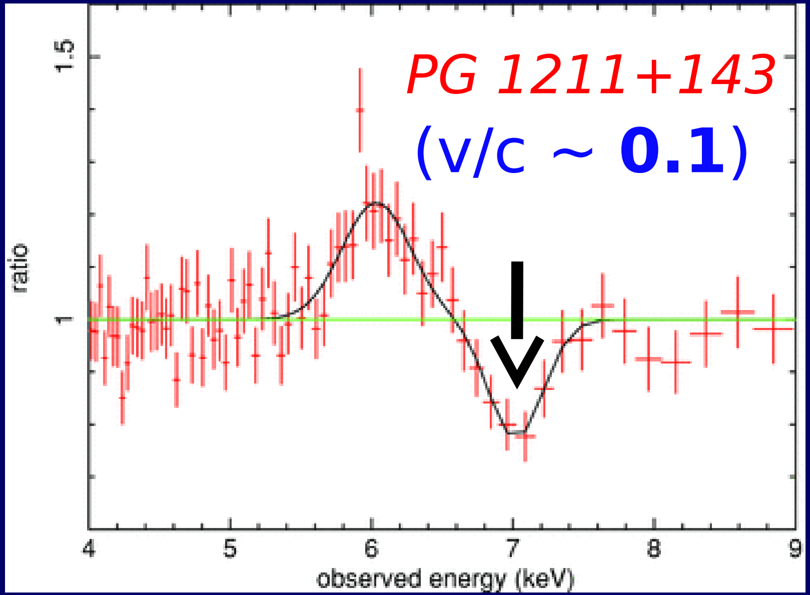
Narrow-Line Seyferts

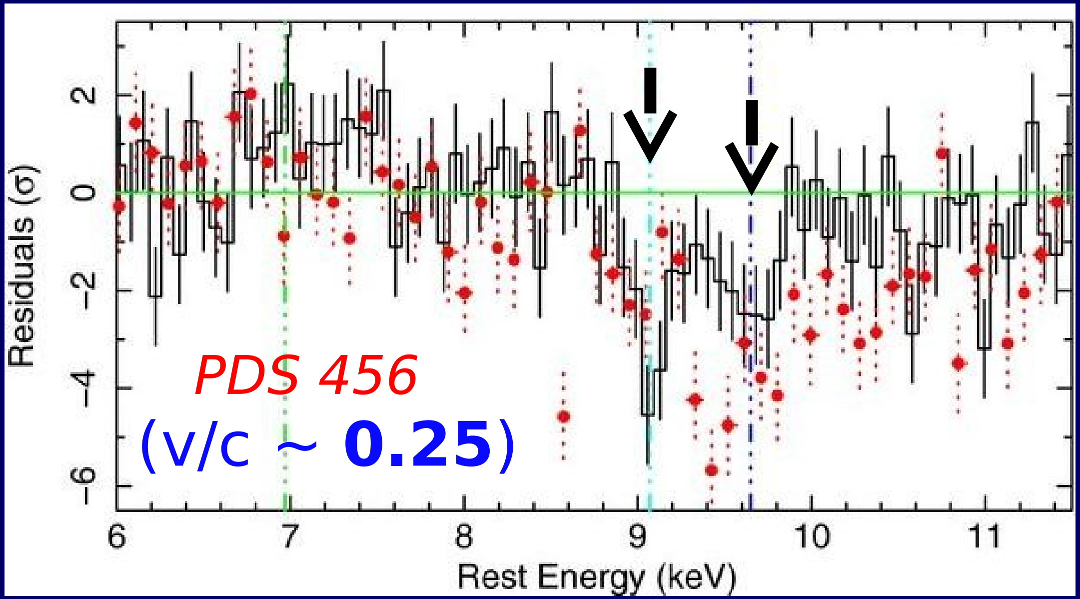


- "Narrow" Hβ line < 2,000 km/sec
- Weak O III/Hβ ratio
- Strong "Soft X-ray Excess"
- Highly-blueshifted absorption lines

Chandra/XMM-Newton data

Pounds+(03)





Pounds+Reeves(09)

Reeves+(09)

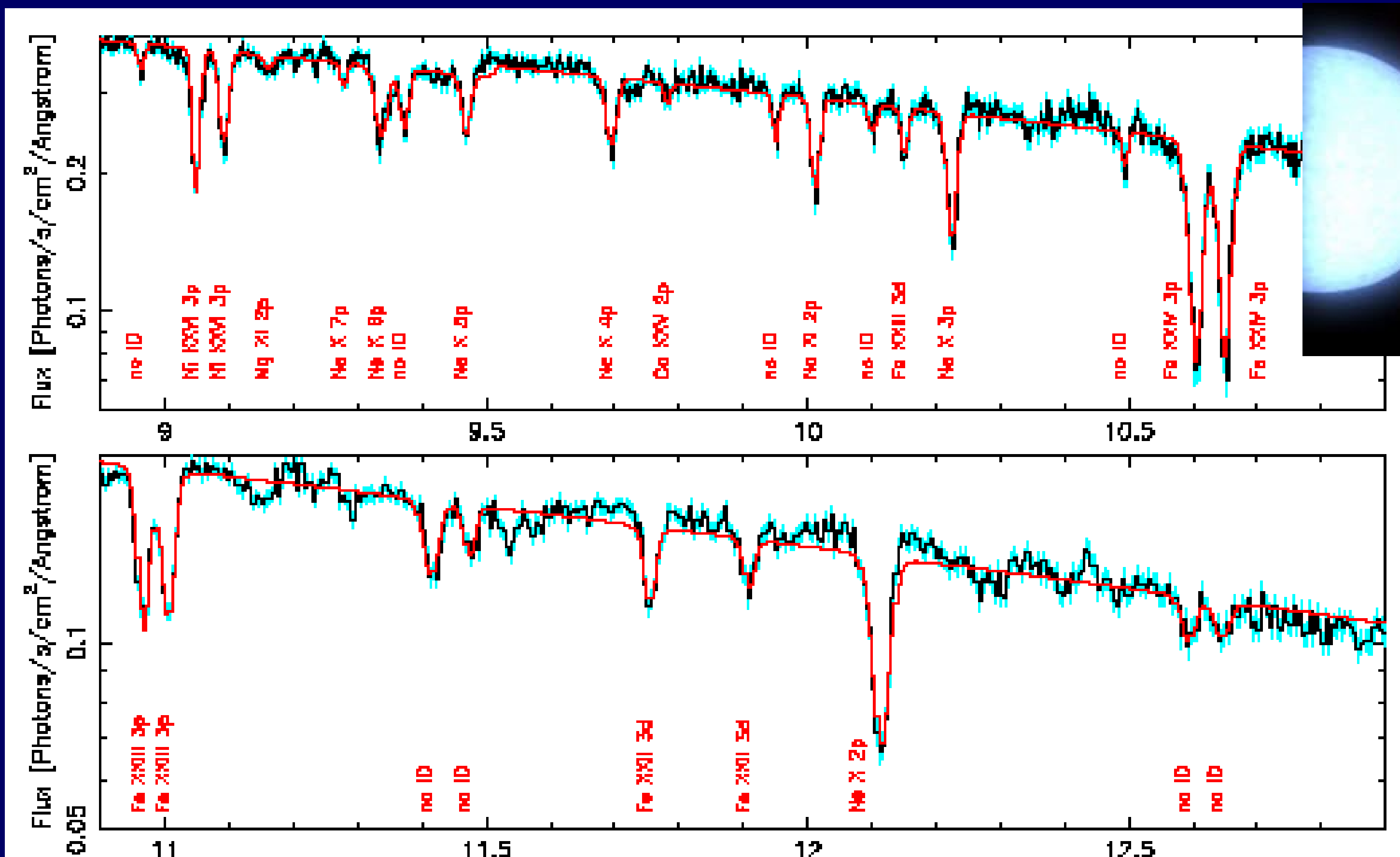
Galactic Black Hole Candidates (GBHC)

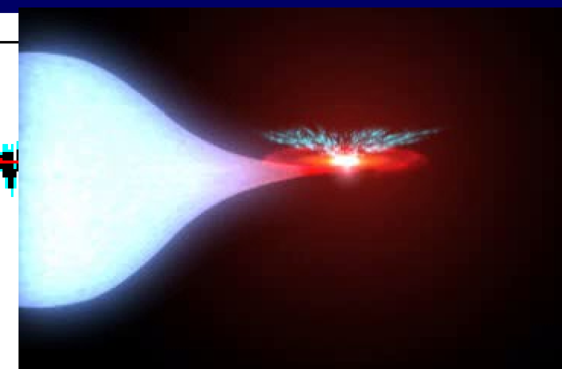
GRO J1655-40:

- M(BH)~7Msun
- M(2nd)~2.3Msun

- High ionization: log(ξ[erg cm s^{-1}]) ~ 4.5 - 5.4
- Small radii: log (r[cm]) ~ 9.0 - 9.4
- High density: log(n[cm^{-3}]) ~ 14

Miller+(06)





NASA/CXC/A.Hobart

Chandra Data
Miller+(08)

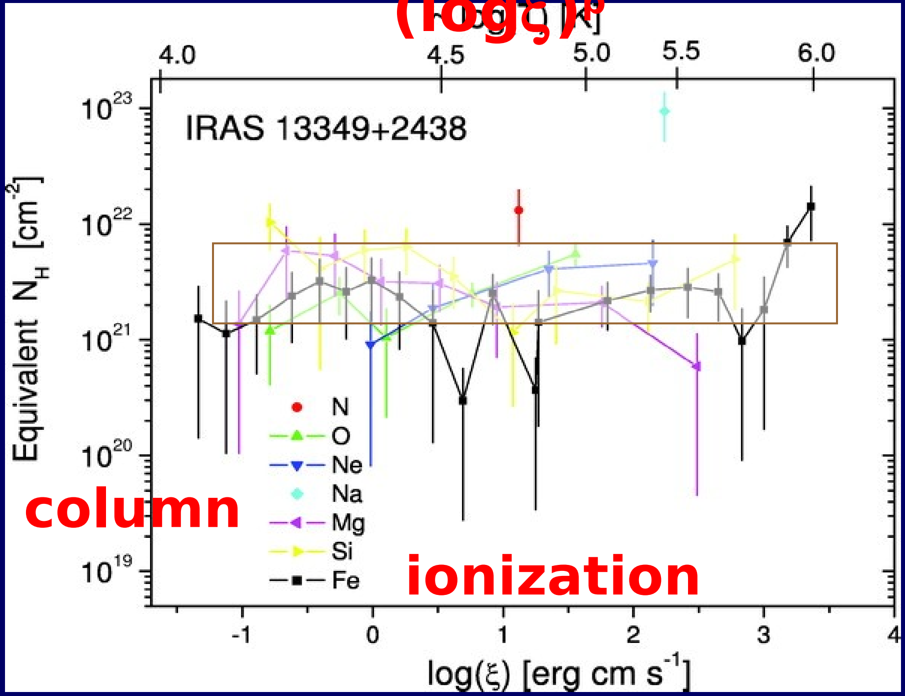
Can we make sense of all these diverse Observations?

Fundamental Questions:

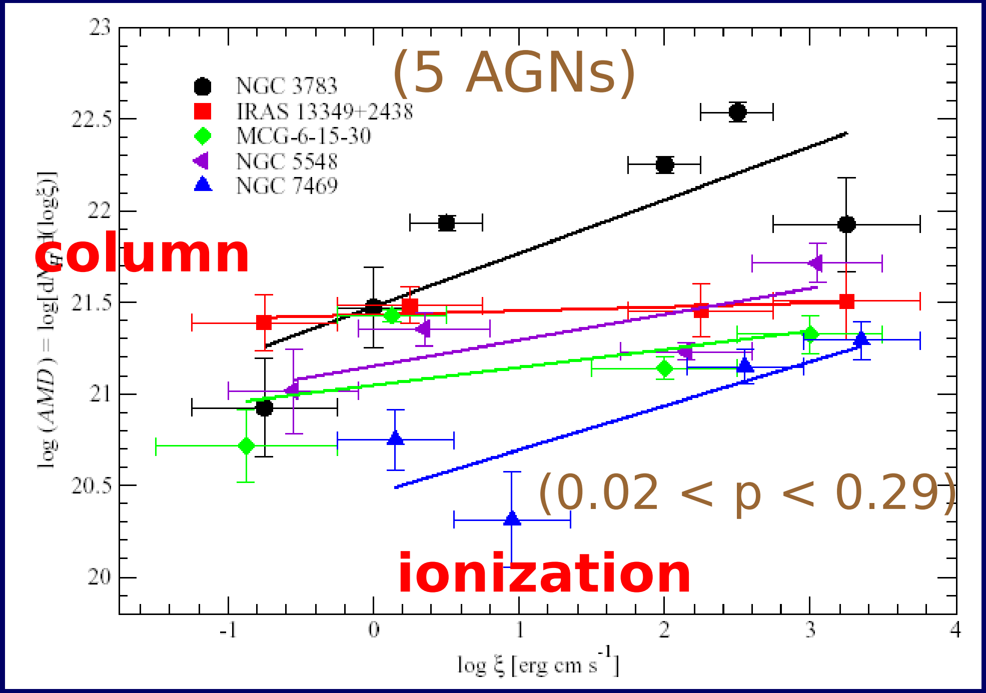
- Geometry?
- Spatial location?
- Properties?
- Physical origin?

Absorption Measure Distribution (AMD)

$AMD(\xi) = dN_H / d\log\xi \sim (\log\xi)^p$ where $\xi = L/(n\,r^2)$



Holczer+(07)

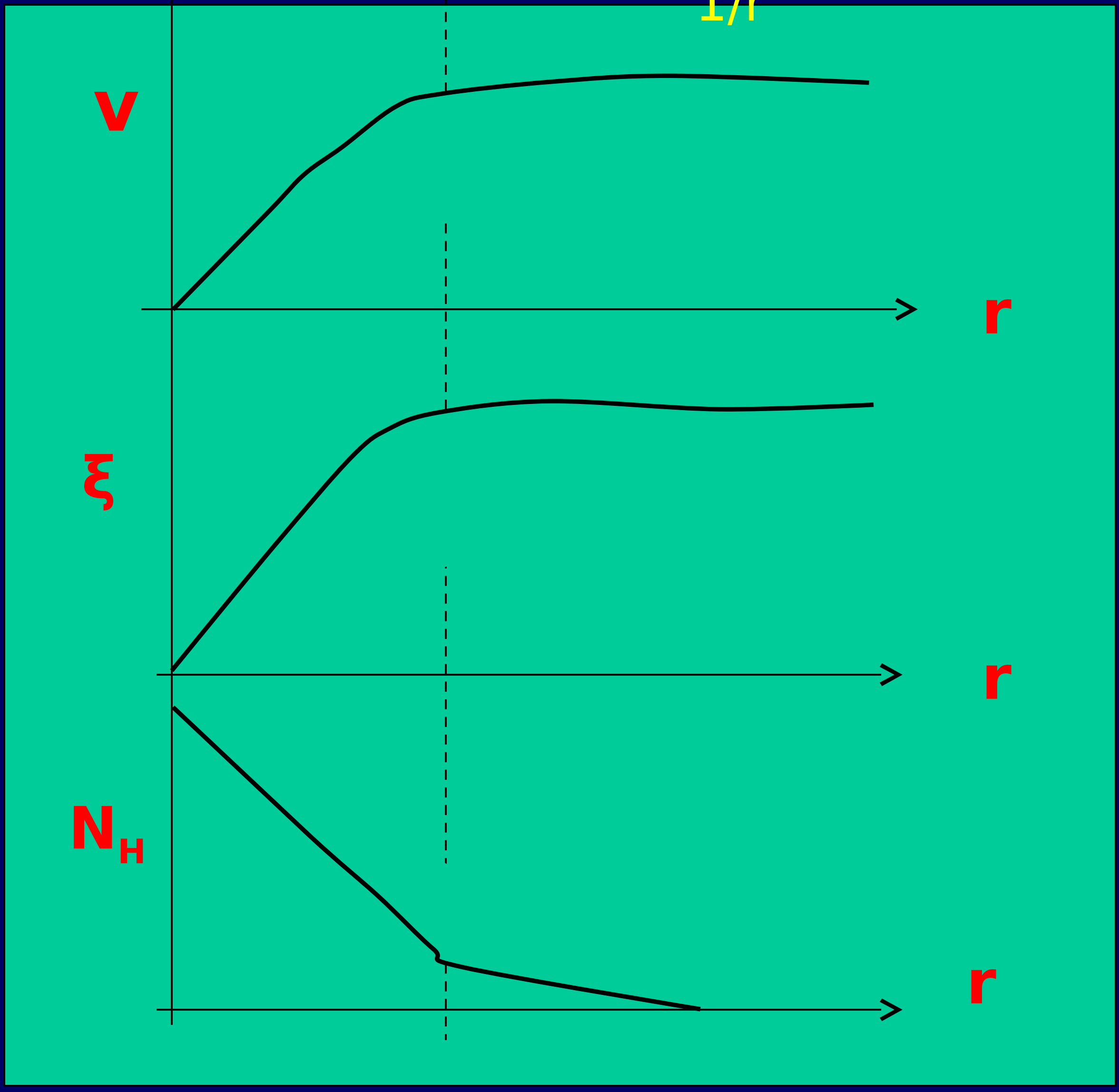


Behar(09)

 presence of nearly equal N_H over ~4 decades in ξ (p~0.02)

Schematic run of v, ξ, $\mathbf{N_H}$, for radiation driven outflow

V~r, n(r) ~$1/r^3$, N_H~ $1/r^2$ then V~ const, n(r) ~$1/r^2$, N_H~ 1/r



Low V, low ξ

High V, high ξ

N decreases with ξ

N decreases with V

N independent of V,ξ

Some Simple Estimates/Conclusions

$$\xi = \frac{L}{nr^2} \approx \frac{L}{rN_H} \Rightarrow N_H \approx \frac{L}{r\xi}$$

$$\frac{dN_H}{d\log\xi} \approx \frac{L}{r\xi} \approx const. \Rightarrow$$

$$r\xi \approx const. = \xi \approx \frac{1}{r} \approx \frac{L}{nr^2} \Rightarrow n \approx \frac{1}{r}$$

Not $n \sim 1/r^2$!!

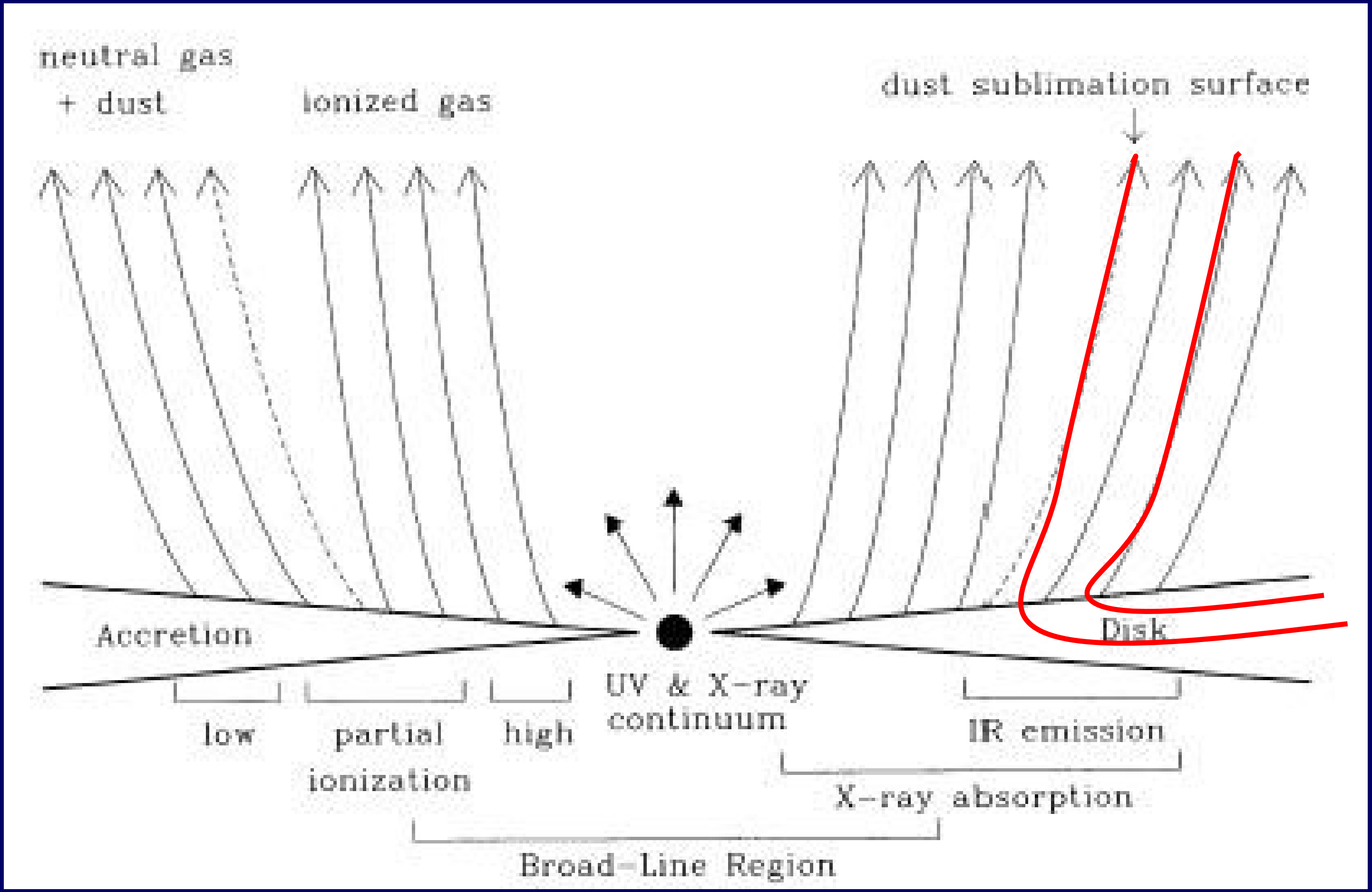
$$\dot{M} \approx nr^2 v \approx r^{-1} r^2 r^{-1/2} \approx r^{1/2}$$

Mdot not constant! (ADIOS Blandford . Begelman 1999)

The flow is 2 dimensional! (Blandford+Payne 82, Contopoulo and Lovelace 94 AGN Unification: Torus = MHD Wind)

Mdot ~ $r^{1/2}$, Edot ~ Mdot $v^2 \sim r^{-1/2}$, Pdot ~ Mdot v ~ r^0

Flow line geometry



From Konigl+Kartje (94), based on the models of Contopoulos + Lovelace (94)

With the above density scaling we get the following relation for ξ

$$\dot{m} \approx \frac{\dot{M}}{\dot{M}_{Edd}} \qquad \dot{M}_{Edd} = \frac{L_{Edd}}{c^2} \propto M, \qquad x = \frac{r}{R_S} \Rightarrow r = xM$$

$$L \propto \dot{M} = \frac{\dot{M}}{\dot{M}_{Edd}} \dot{M}_{Edd} \cong \dot{m} M, \qquad n = \frac{\dot{m}}{M} \frac{1}{x}$$

$$\xi = \frac{L}{nr^2} \Rightarrow \xi = \frac{const.}{x}$$

ξ is independent of the mass M of the BH!!. The models are equally well applicable to AGN and galactic XRBs.

Their difference lies in the fraction of the bolometric emission that comprise the X-rays.

The larger the X-ray content the more ionized the high V segments of the wind and the lower the absorber velocities.

BAL QSOs: V ~ 10,000 – 100,000 km/s

GRO J1655-40: V ~ 300-1200 km/s

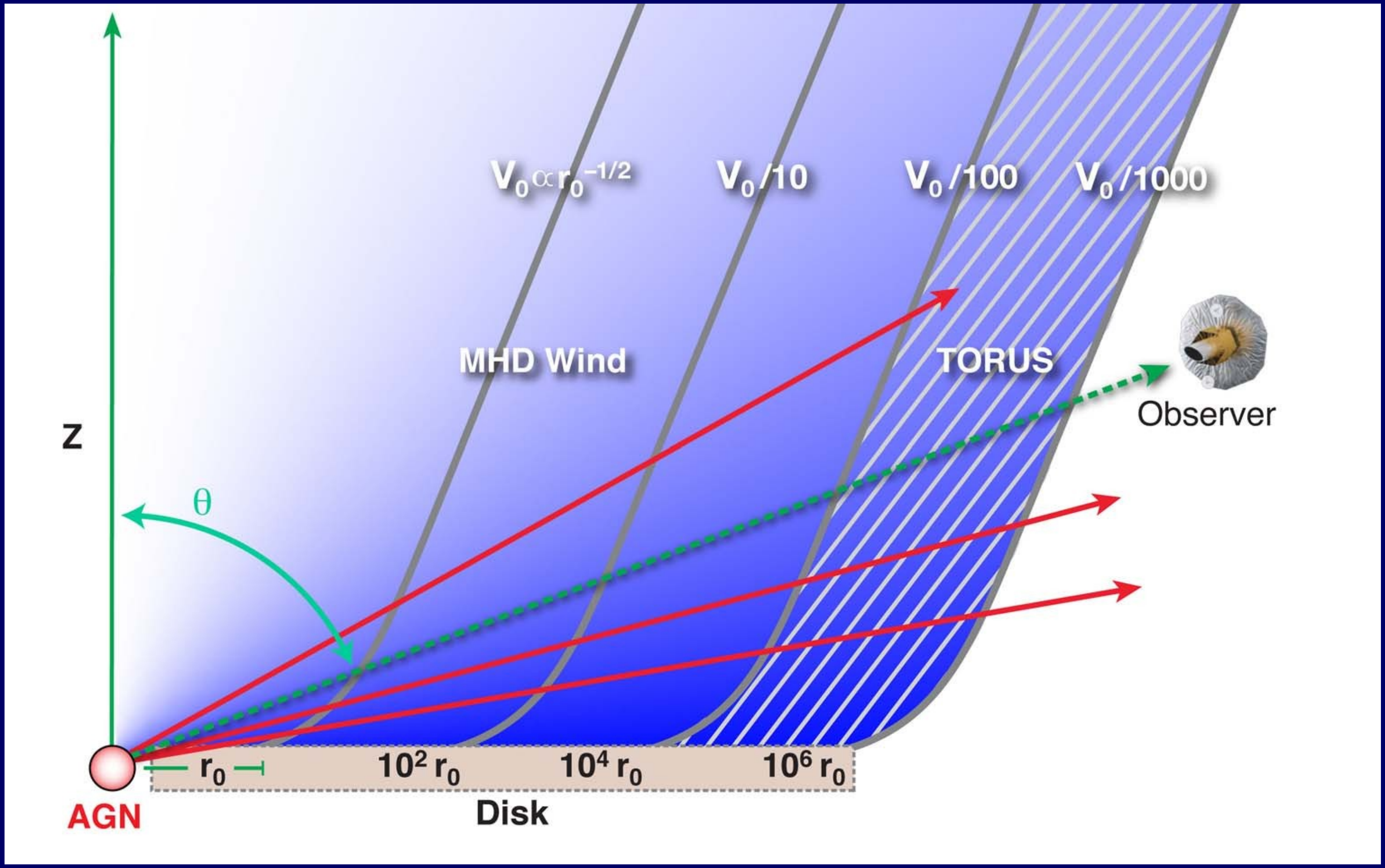
- ***Basic Dogma:***

- **All winds have the same velocity ($v \sim 1/r^{1/2}$) and density ($n \sim 1/r$) all the way to ~ (a few) ISCO**

- **Their overall normalization is given by mdot at r ~ 1**

- **The observed diversity is due to their ionization status and the observer's inclination angle.**

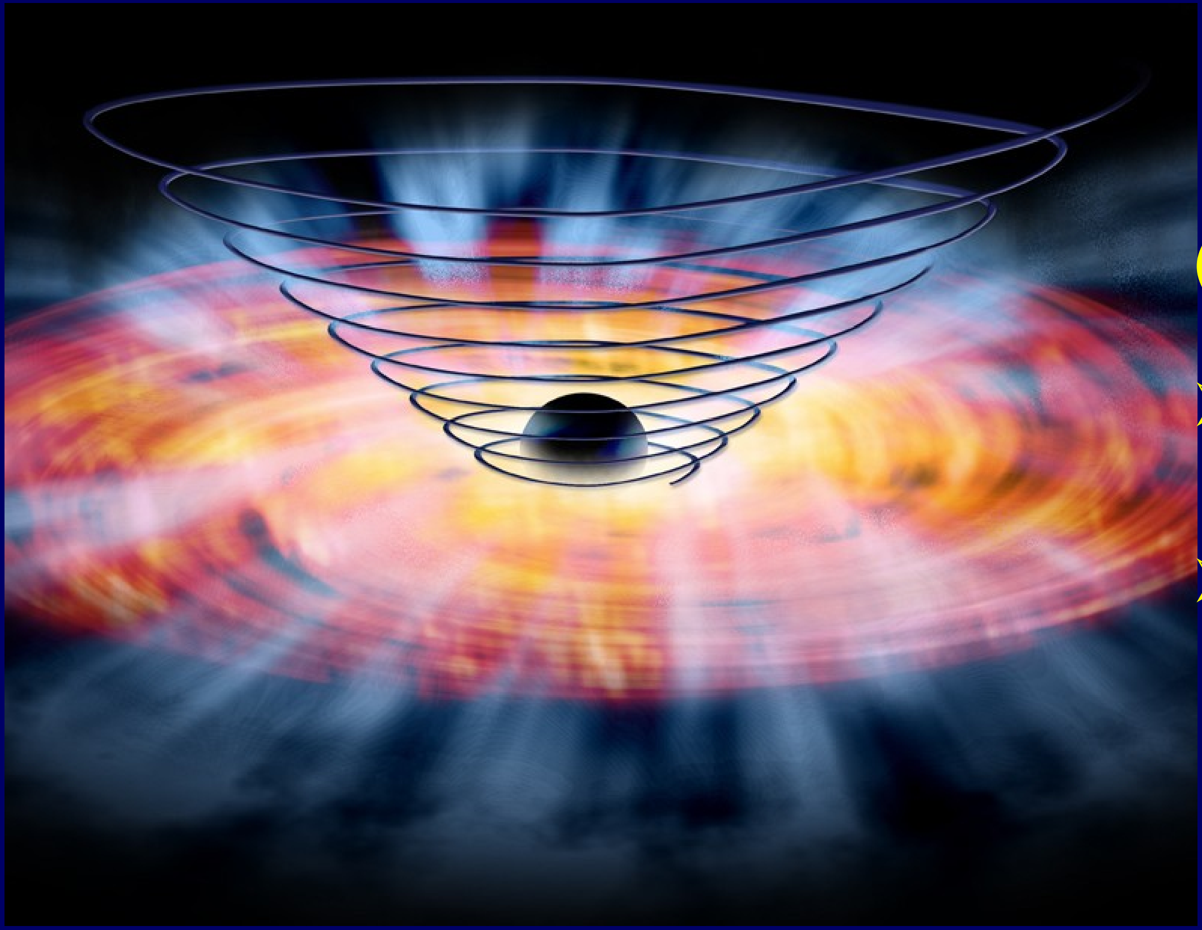
- **The X-ray contribution to their spectra most important for the appearance of their spectral / kinematic structure (broad-narrow lines**



The velocities and size of the winds measured in v/c and r/R_S scale directly from those of AGN to those of XRBs.

Magnetically-Driven Outflows

Magnetohydrodynamics (MHD)



(At least) 2 candidates

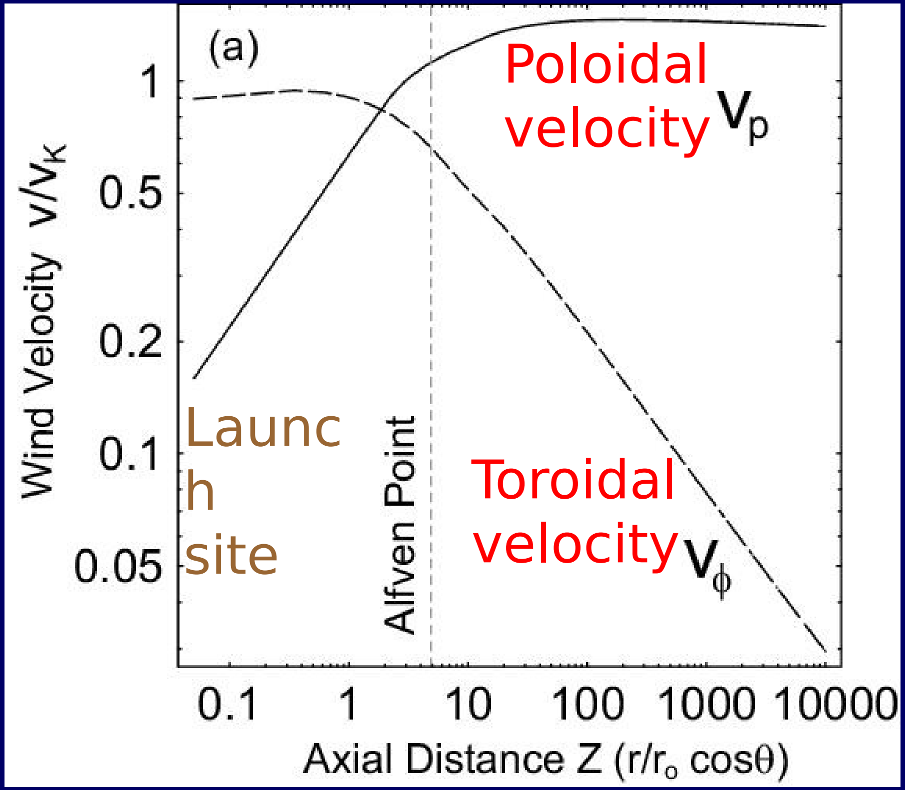
- GRO J1655-40
  Miller+(06,08)
- NGC 4151
  Kraemer+(05)
  Crenshaw+Kraemer(07)

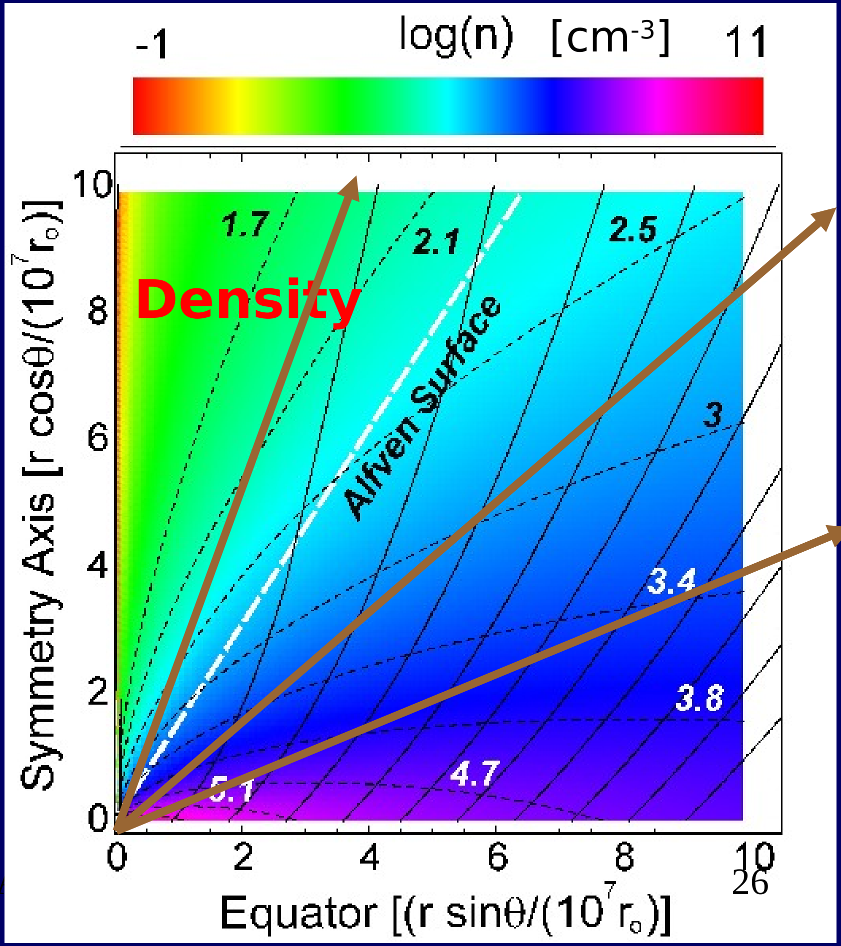
Simple Wind Solutions with $n \sim 1/r$

(q=1)

Assume:

M(BH) = 10^6 Msun, **Γ** ~ 2 (single power-law), **L_X** ~ 10^{42} erg/s,
mdot ~ 0.5, **rad. eff.** ~ 10%, **n(in)** ~ 10^{10} cm^{-3}





(Fukumura+10a)

Simple Wind Solutions with n~1/r

(q=1)

Assume:

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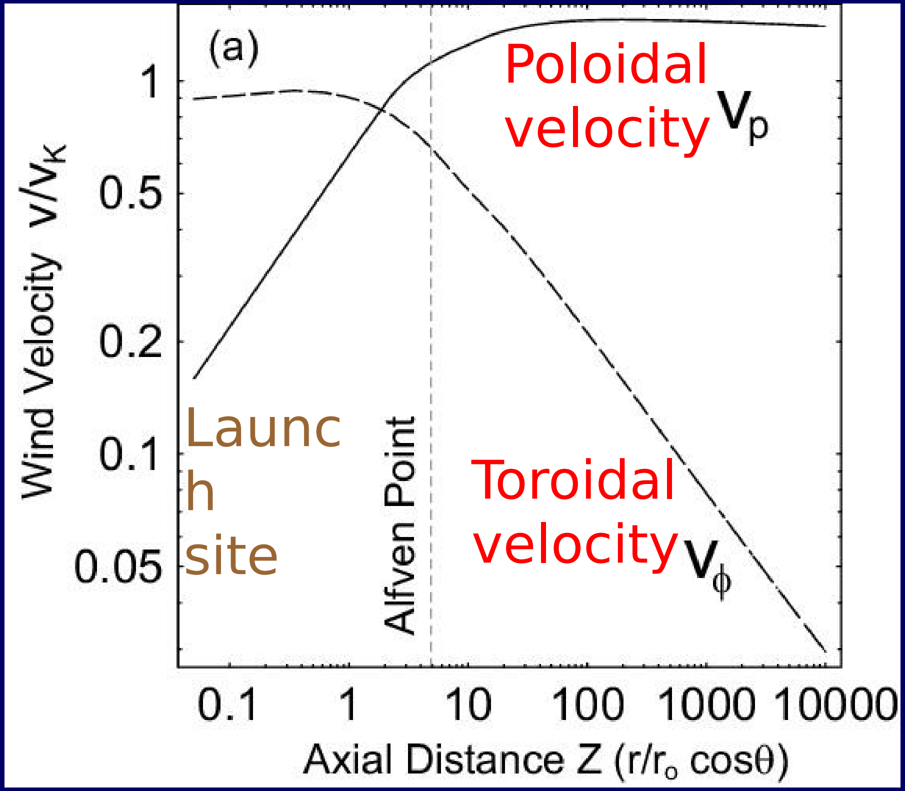
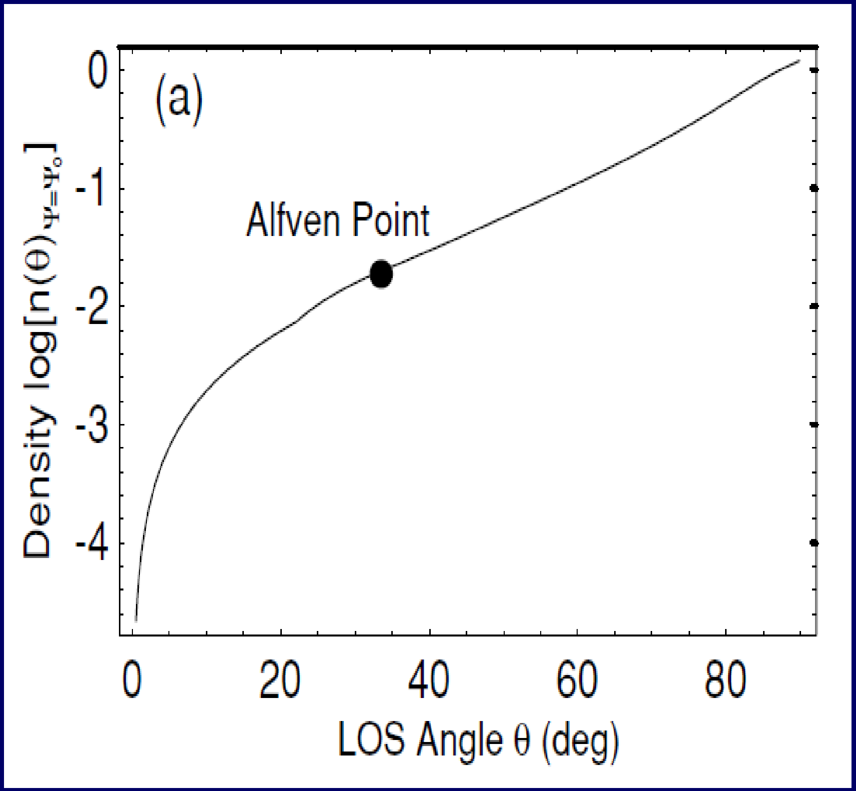


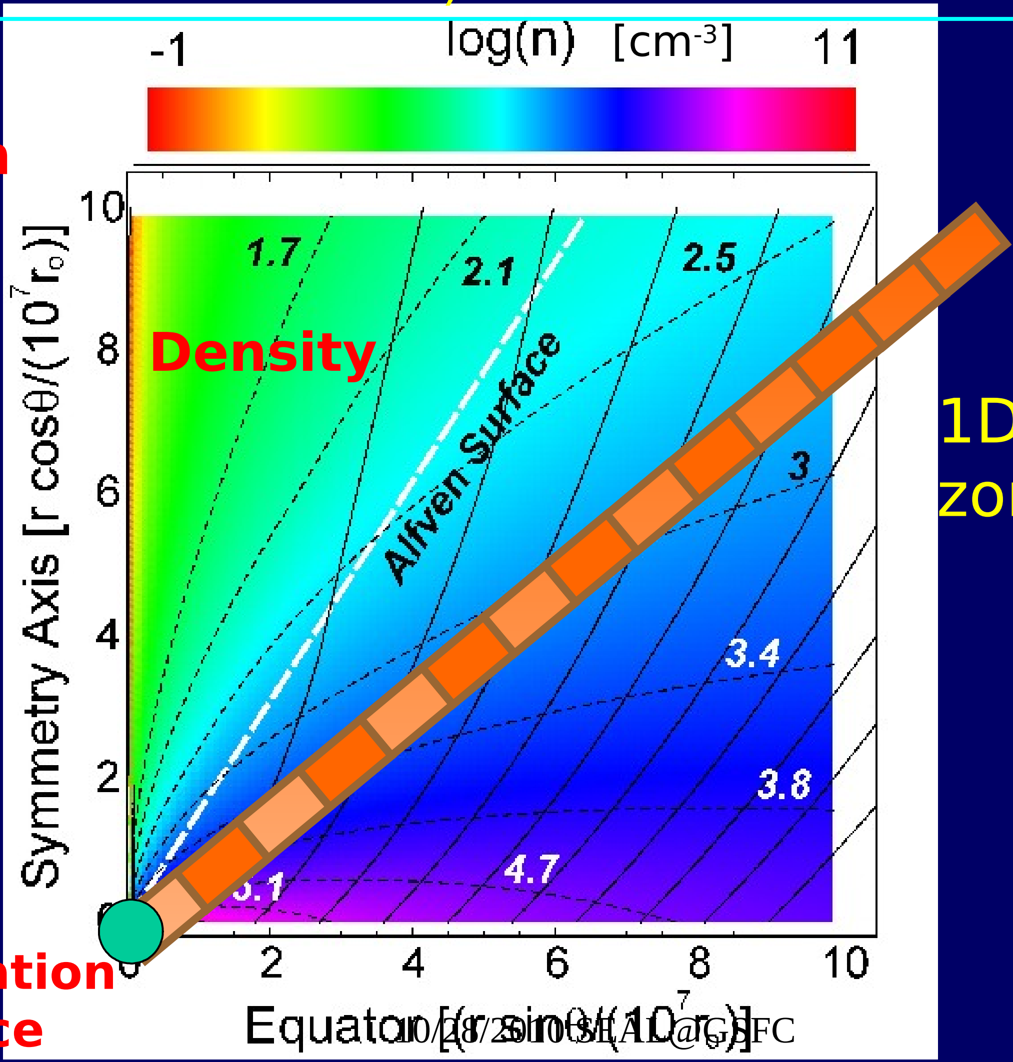


(Fukumura+10a)

LoS Radiation Transfer

Photoionization with XSTAR (e.g. Kallman+Bautista01)

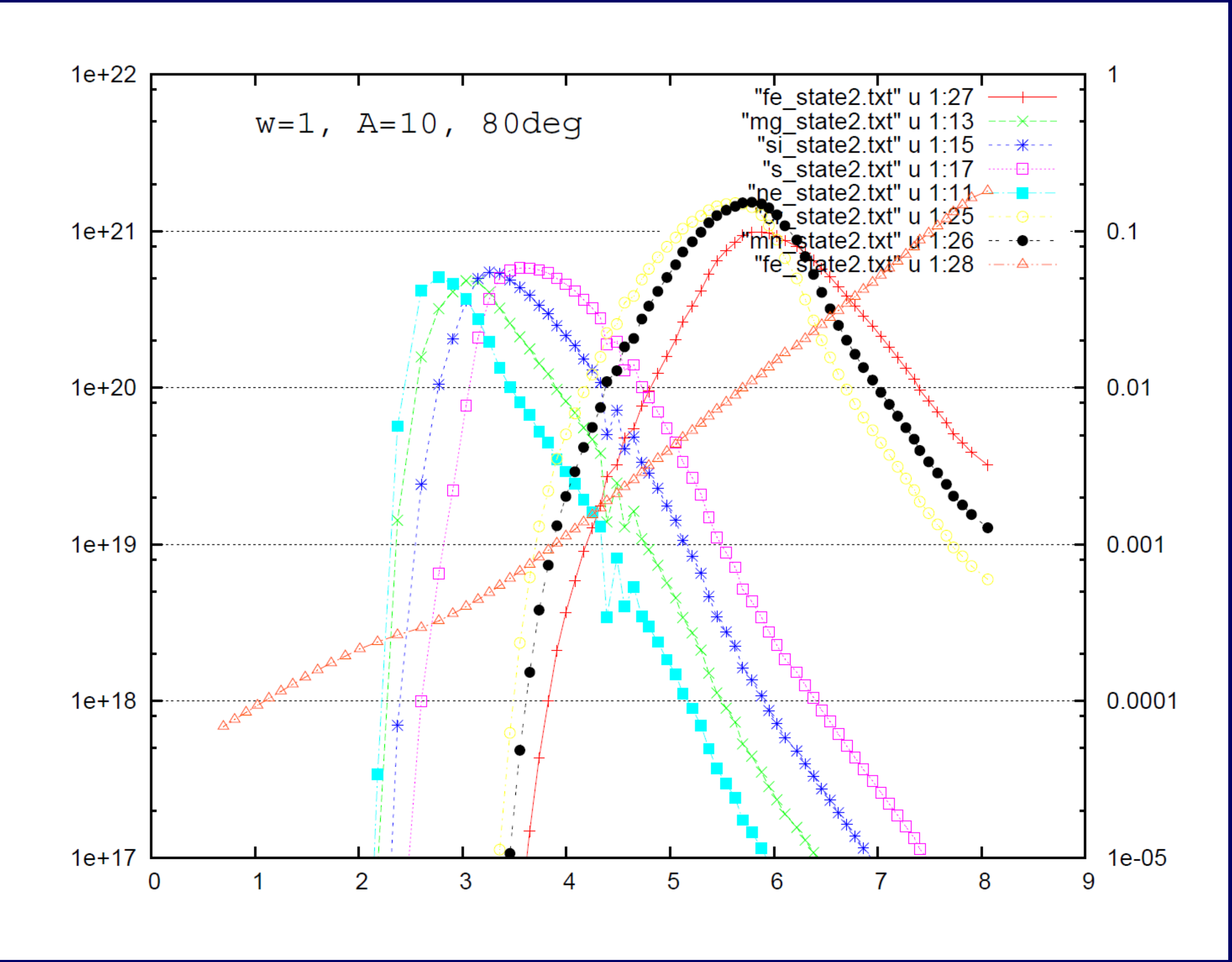
Ionization Distribution



LoS

1D computational zones

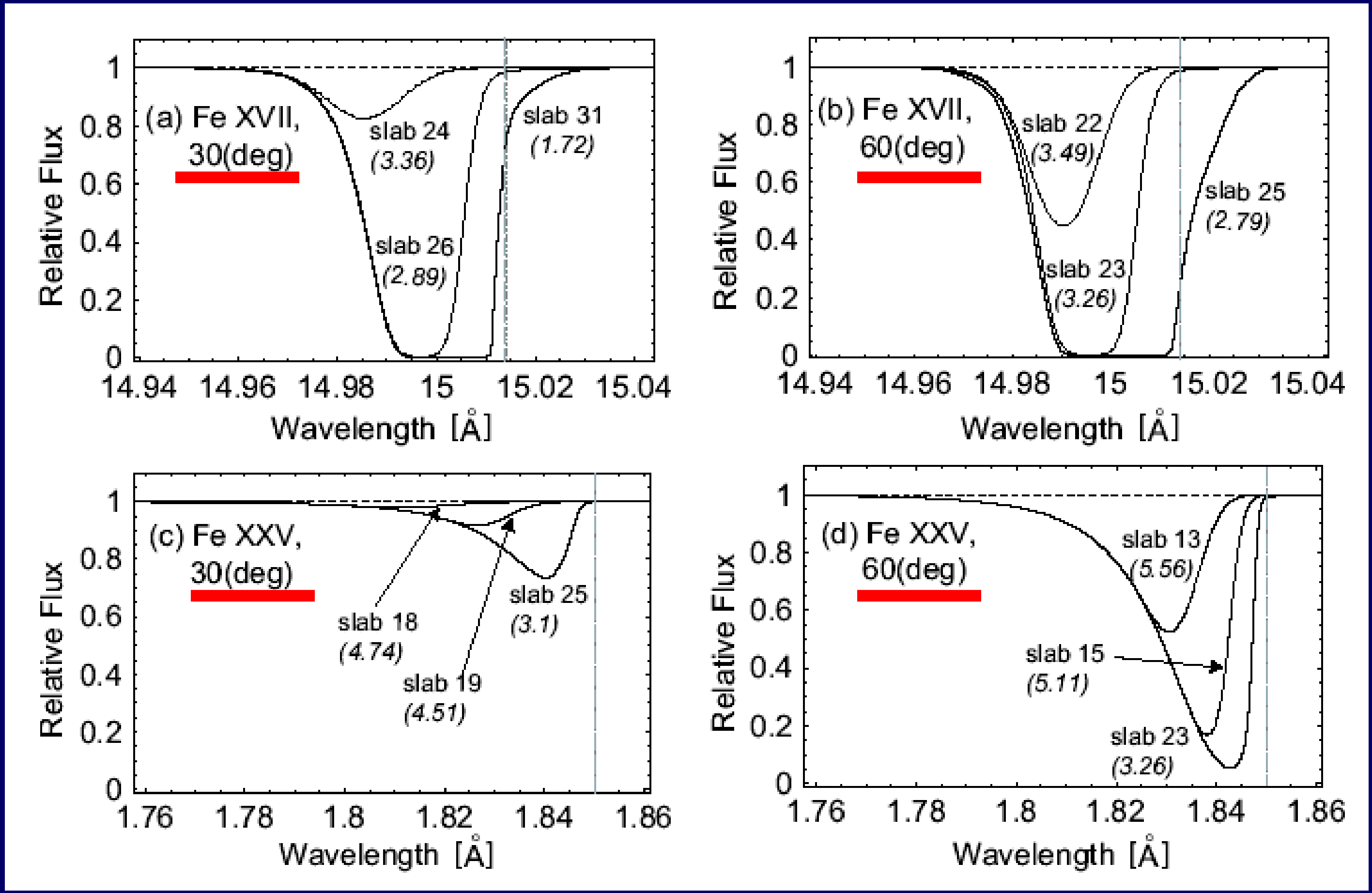
Radiation Source


w=1, A=10, 80deg
"fe_state2.txt" u 1:27
"mg_state2.txt" u 1:13
"si_state2.txt" u 1:15
"s_state2.txt" u 1:17
"ne_state2.txt" u 1:11
"ar_state2.txt" u 1:25
"mn_state2.txt" u 1:26
"fe_state2.txt" u 1:28
1e+22
1e+21
1e+20
1e+19
1e+18
1e+17
0 1 2 3 4 5 6 7 8 9
1
0.1
0.01
0.001
0.0001
1e-05

Modeling Absorption Spectra

Wind optical depth $\tau(\nu) = \sigma(\nu) N_H(\nu)$

Line photo-absorption cross-section $\sigma = 0.01495 (f_{ij}/\Delta\nu_D) H(a,u)$



f_{ij} = oscillator strength

$\Delta\nu_D$ = broadening factor

H(a,u) = Voigt function

(e.g. Mihalas78)

We need not use the Parameter vturb of XSTAR; we use the Velocity gradient of The wind.

Table 2. Summary of our best-fit **mhdwind** model parameters for PG 1211+143.

Parameter/Model	Model (A) Fe XXV/Fe XXVI	Model (B) Fe XXV/Fe XXVI
θ [degree]	40.0 ◇	$49.8^{+3.27}_{-6.52}$
$kT_{\rm bbb}$ [eV]	$30.1^{+9.01}_{-2.56}$	$38.1^{+4.55}_{-9.01}$
$E_{\rm Fe}$ [keV]	$6.54^{+0.097}_{-0.080}$	$6.52^{+0.10}_{-0.073}$
$\tau_{\rm max}$	$0.095^{+0.014}_{-0.0105}/0.019^{+0.0023}_{-0.0031}$	$0.235^{+0.073}_{-0.124}/0.052^{+0.018}_{-0.024}$
$\log(r_c/R_S)^\flat$	$2.96^{+0.116}_{-0.161}/2.51^{+0.11}_{-0.16}$	$2.37^{+0.48}_{-0.35}/1.82^{+0.54}_{-0.25}$
$\log(\xi_c[\rm erg\ cm\ s^{-1}])$ △	$5.21^{+0.149}_{-0.104}/5.62^{+0.147}_{-0.105}$	$5.31^{+0.13}_{-0.15}/5.80^{+0.084}_{-0.17}$
v_c/c △	$0.099^{+0.023}_{-0.008}/0.165^{+0.038}_{-0.013}$	$0.115^{+0.016}_{-0.021}/0.208^{+0.018}_{-0.043}$
$\mathcal{N}_\mathcal{H}$ [cm^{-2}] /10^{22} ♯	$4.04^{+0.224}_{-0.178}/5.94^{+0}_{-0.182}$	$12.1^{+5.30}_{-7.56}/16.7^{+5.72}_{-8.63}$
$\log(R_t/R_S)$	0 ♣	$1.48^{+0.065}_{-0.27}$
χ^2/ν (with `mhdwind`)	200.84/129	198.54/128
$\Delta\chi^2$ (from `phabs*(po+zga)`)	-34.1	-36.4

◇ The value is pegged.

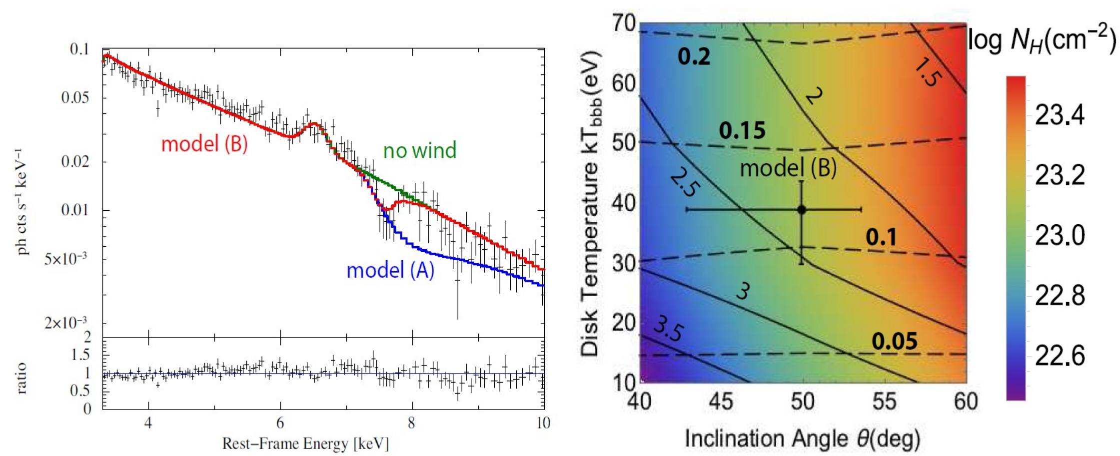
♭ The characteristic LoS radius r_c where wind Fe XXV opacity τ_ν (see eqn. (9)) is maximum along a given LoS angle.

△ The characteristic value ("c") is evaluated at the LoS position $r = r_c$.

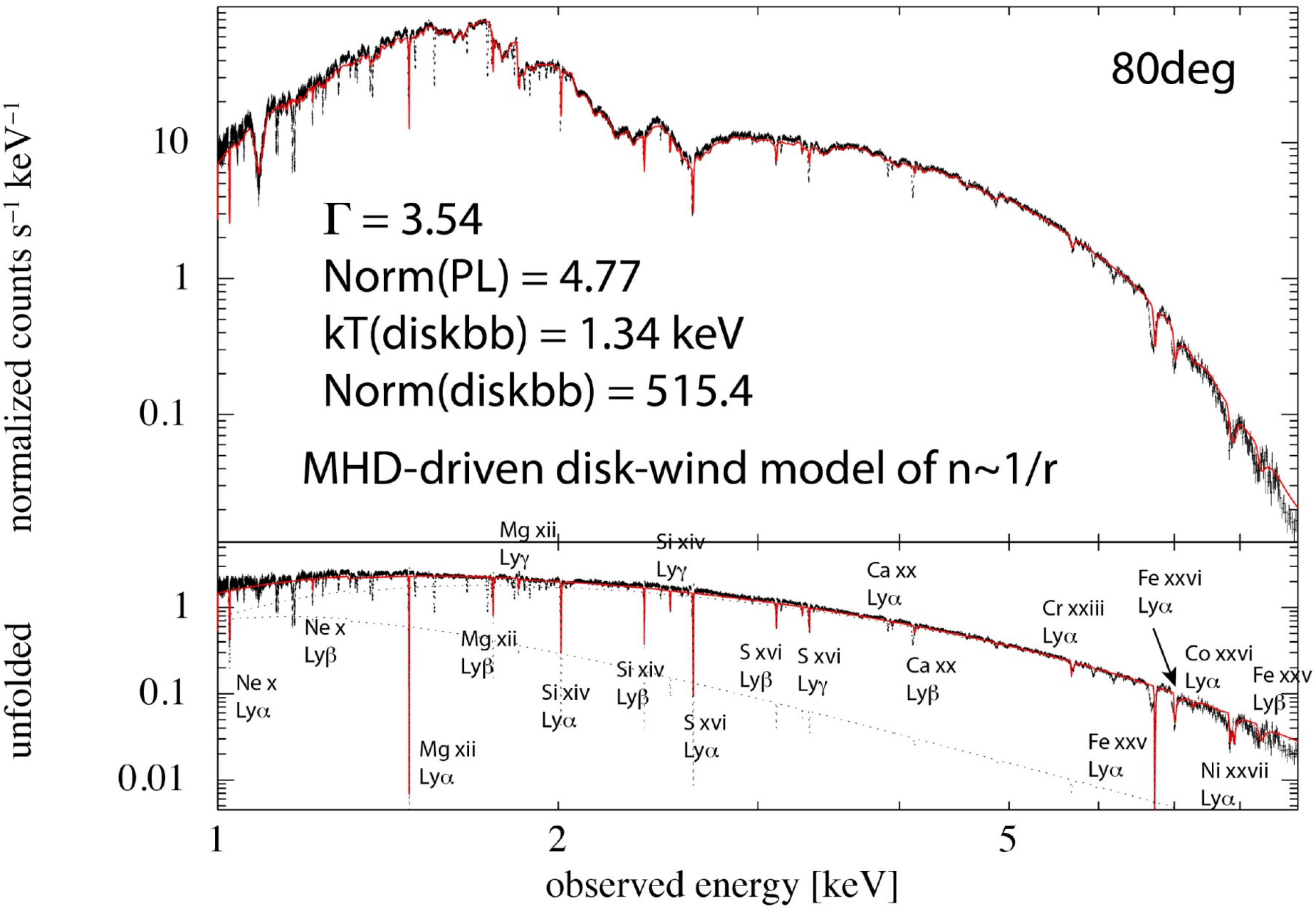
♯ LoS-integrated total Fe XXV column density.

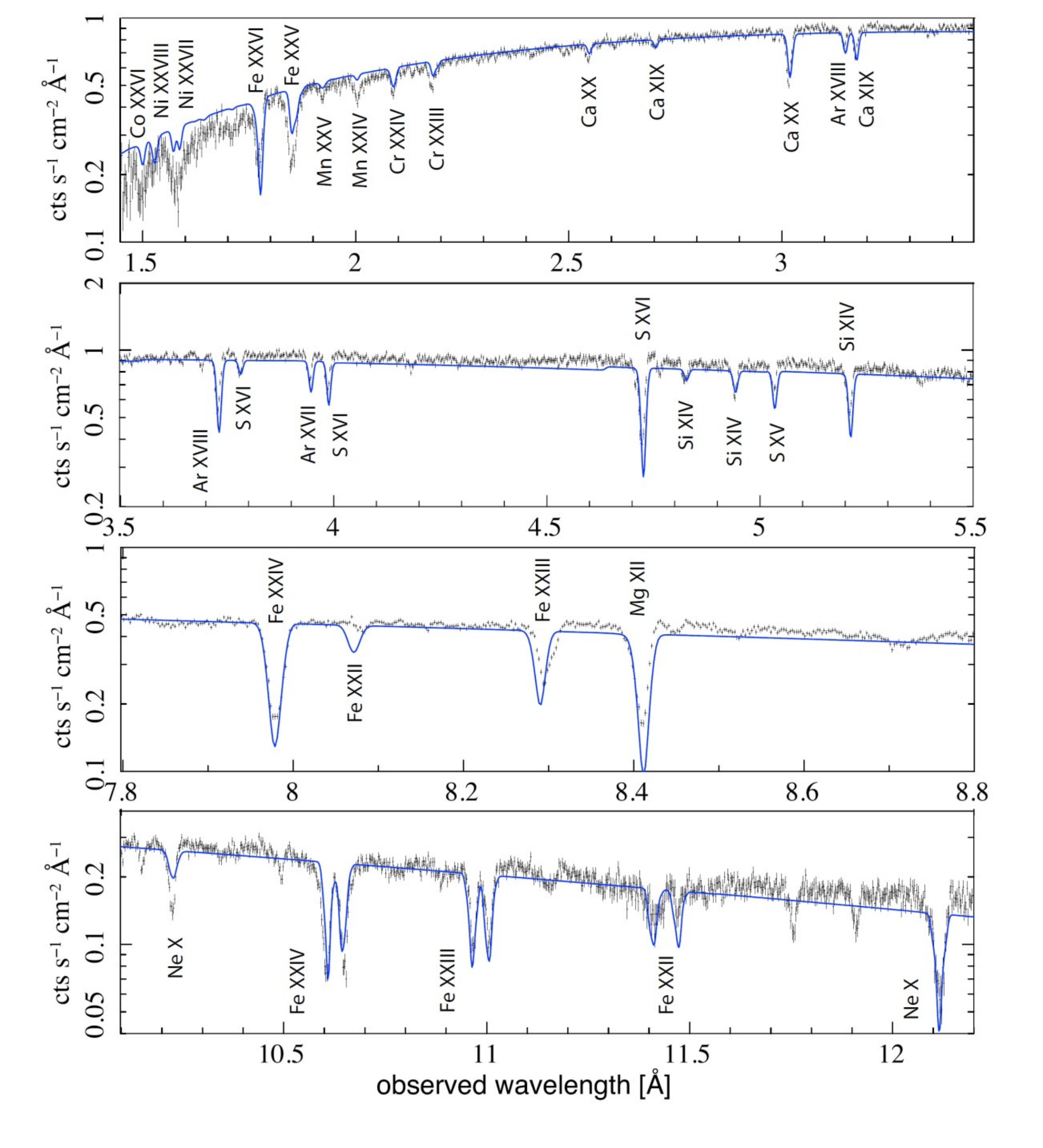
♣ The value is fixed.

PG 1211+143



45ks *Chandra*/HETGS spectrum of GRO J1655−40

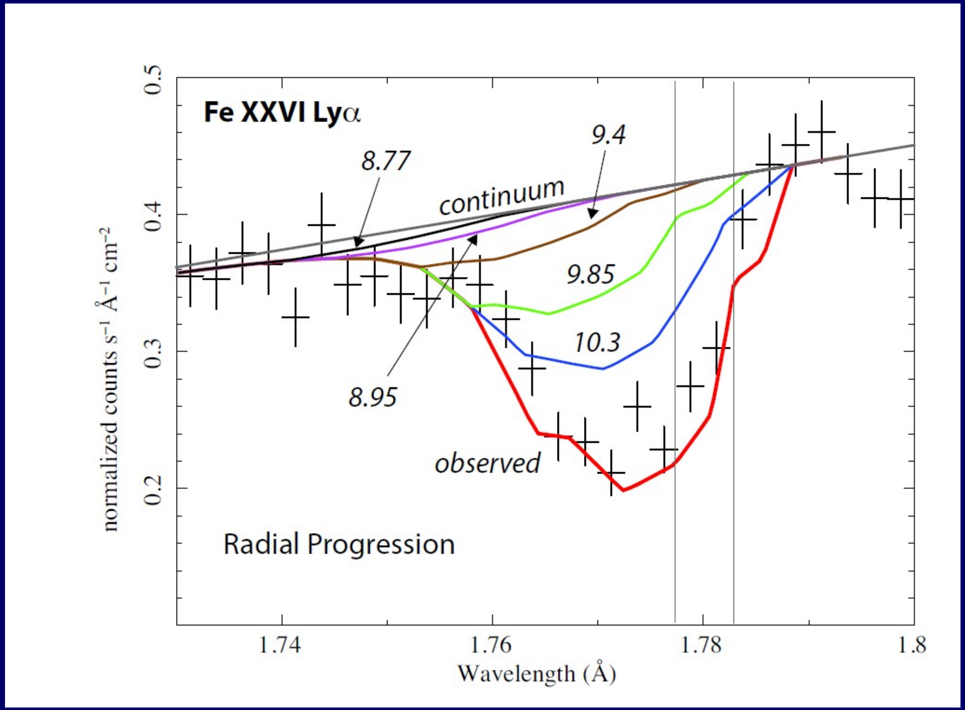


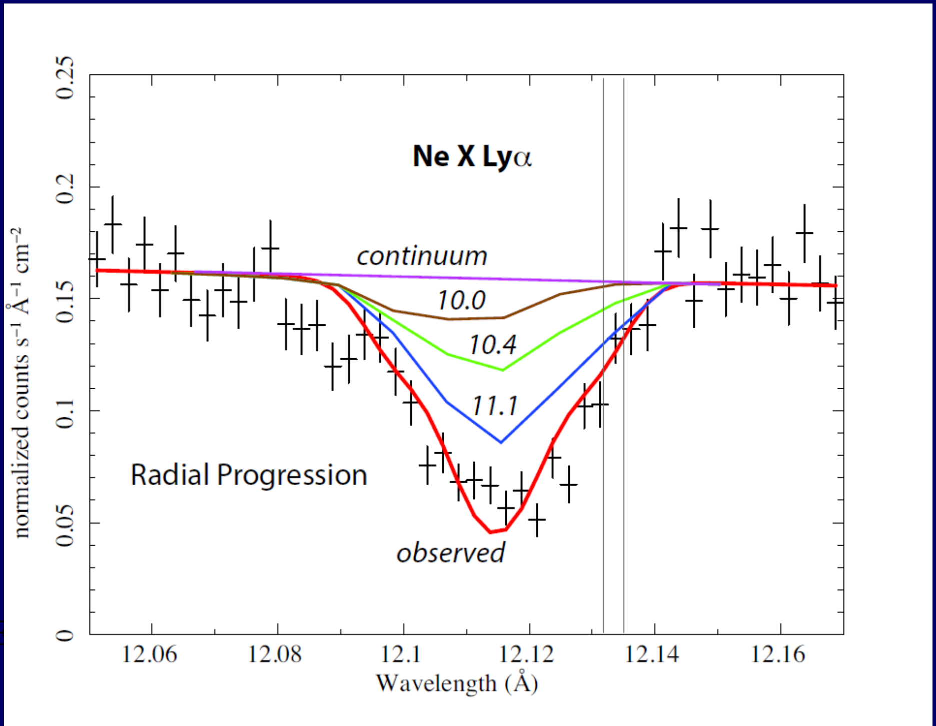


n ~ 1/r$^{1.2}$

Θ =80 deg

Development of the Fe XXVI Lyα and Ne X Lyα profiles





Summary

MHD disk-winds provide a promising unified account of the entire absorber phenomenology. This can serve a basic benchmark for further development and refinenent.

- Key ingredients **mdot** (overall column normalization)
  SED (Γ, **mainly α_{ox}**)
  θ (Inclination angle)

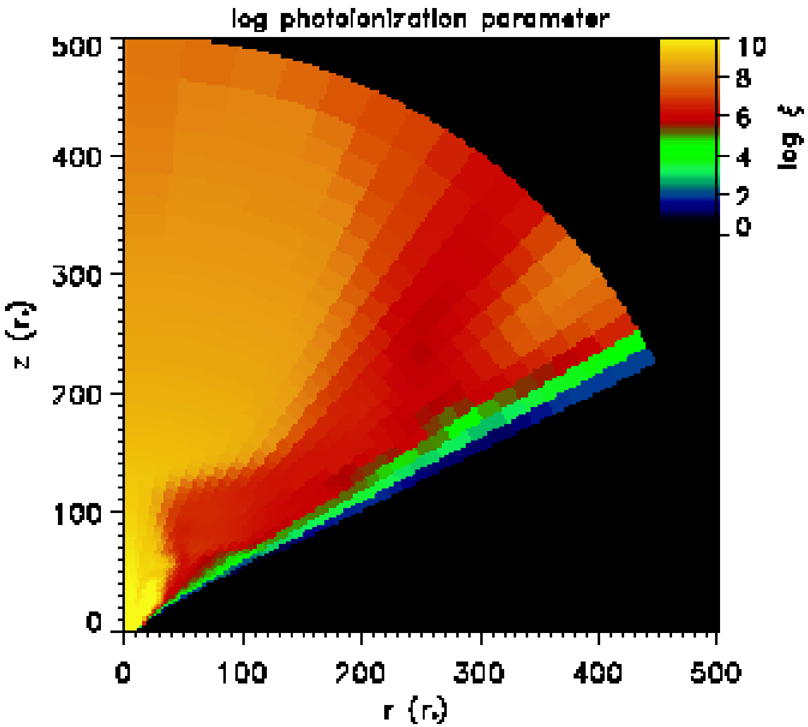
(these are not all independent parameters – correlation of L- α_{ox})

- The model implies that AGN and XRB winds are multiscale objects, governed (basically) by magnetic forces.

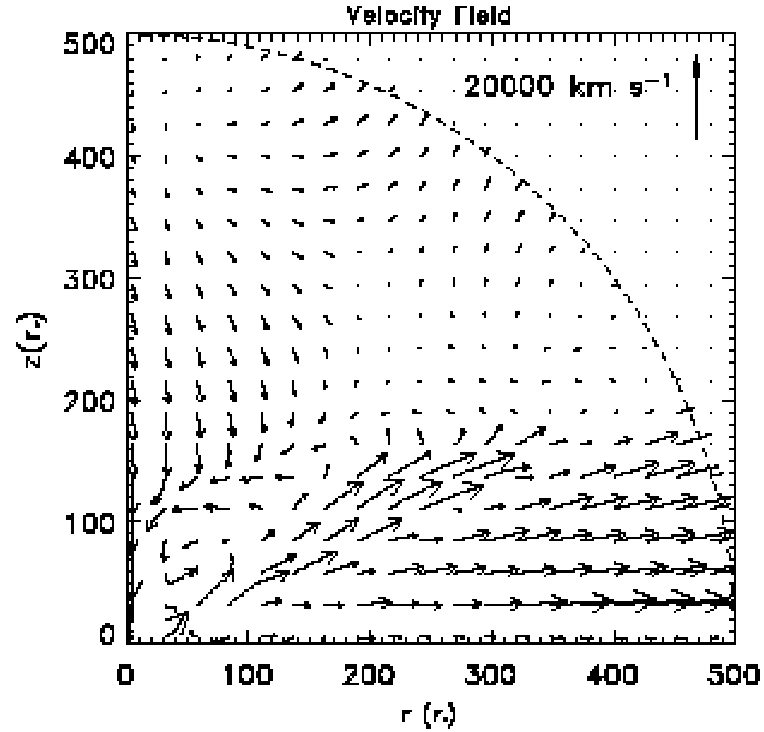
- ***An instrument with higher throughput and resolution would be able to probe also the detailed velocity structure of these features and their variability to provide the density – velocity structure of the entire AGN flow. (Hitomi 2 ? Athena)***

THE END

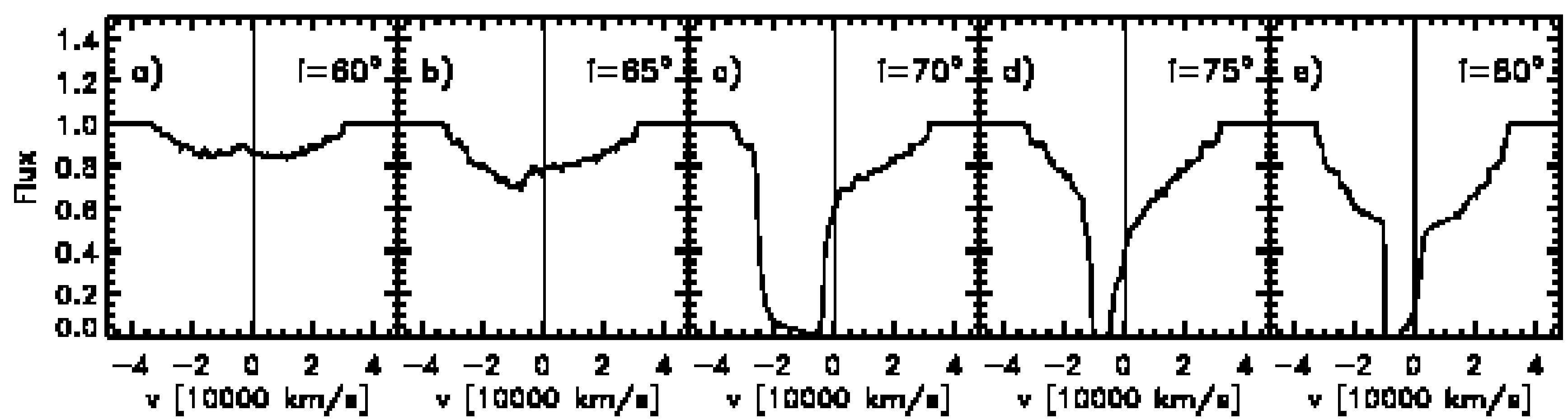
Thank you



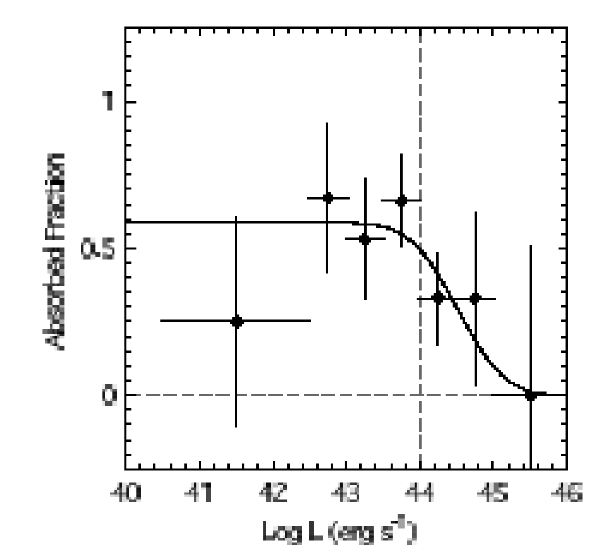
log photoionization parameter
log ξ
z (r_s)
r (r_s)

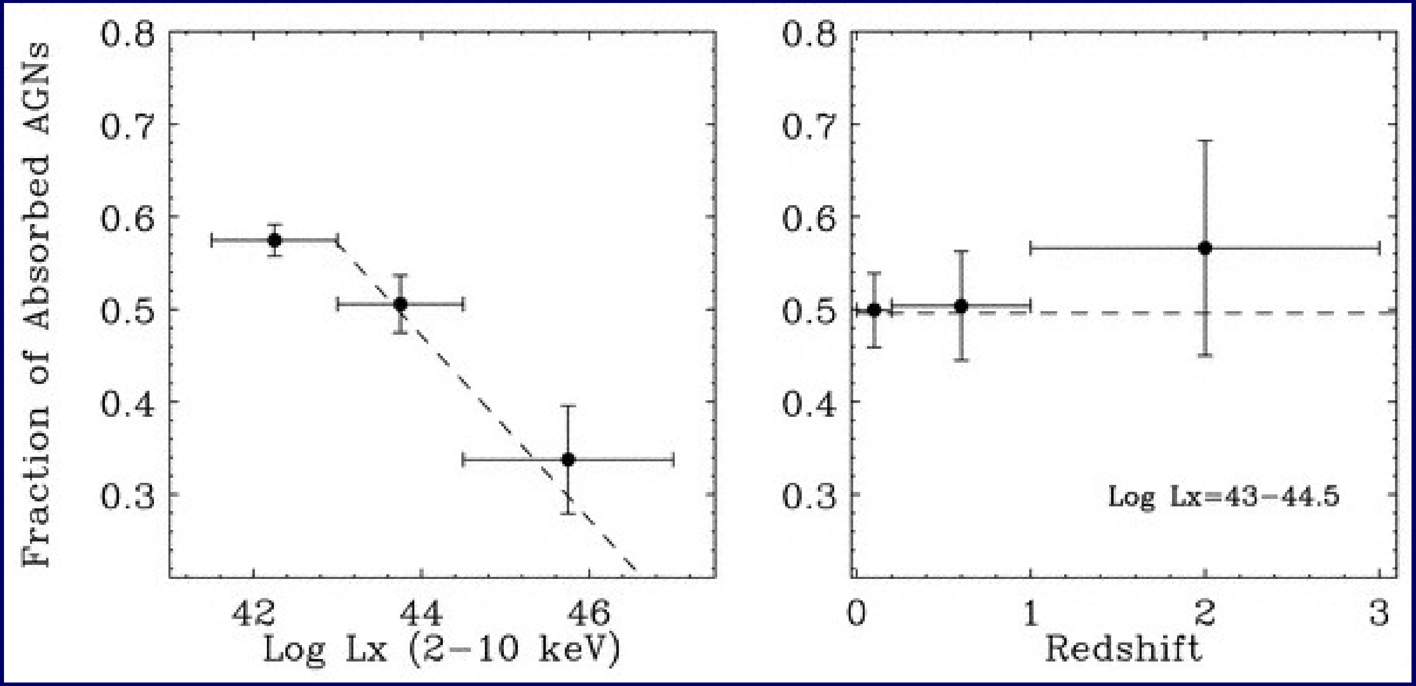


Velocity Field
20000 km s⁻¹
z(r_s)
r (r_s)



Flux
a) i=60°
b) i=65°
c) i=70°
d) i=75°
e) i=80°
v [10000 km/s]


Absorbed Fraction
1
0.5
0
40
41
42
43
44
45
46
Log L (erg s^{-1})


Fraction of Absorbed AGNs
0.8
0.7
0.6
0.5
0.4
0.3
42
44
46
Log Lx (2–10 keV)
0
1
2
3
Redshift
Log Lx=43–44.5

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What is Dark Energy?

News Feature

Image Credit: Z. Paragi, Joint Institute for VLBI in Europe (JIVE) .

Newborn Black Holes Boost Explosive Power of Supernovae

An international team of scientists, including two astronomers from NASA's Marshall Space Flight Center in Huntsville, Ala., have observed a supernova with peculiar radio emission. In the Jan. 28 issue of

Current Missions

- Advanced Composition Explorer (ACE)
- Fermi Gamma-ray Space Telescope (formerly GLAST)
- Galaxy Evolution Explorer (GALEX)
- Hubble Space Telescope (HST)
- Internation al Gam ma-Ray Astrophysics Laboratory (INTEGRAL)
- Rossi X-ray Timing Explorer (RXTE)
- Spitzer