Tomography of Accreting Black Holes and Its Implications on Their Global Properties

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- Accretion onto a black hole proceeds through the formation of a disk.
- The standard disk model is that of **Shakura and Sunyaev** (SS73) which assumes the viscous **stresses** needed to remove the fluid's angular momentum is proportional to the local pressure $t_{r\varphi} = \alpha P$

$$2ht_{r\phi} = \frac{\dot{M}}{2\pi r^2}(GMr)^{1/2}\left[1-\zeta\left(\frac{r_I}{r}\right)^{1/2}\right] = \frac{\dot{M}}{2\pi r^2}(GMr)^{1/2}J(r)$$

- We also have hydrostatic equilibrium in the z-direction

$$\frac{dP}{dz} = -\rho\frac{GM}{r^2}\frac{z}{r} \quad \text{or} \quad \frac{P}{h} \simeq \rho\frac{GM}{r^2}\frac{h}{r}$$

$$\frac{P}{\rho} \simeq c_s^2 \simeq \frac{GM}{r}\frac{h^2}{r^2} = v_K^2\frac{h^2}{r^2} \simeq \Omega^2 h^2$$

- The energy release per unit surface area is ($\sigma_{r\phi} = (3/4)\Omega = (3/4)(GM/r^3)^{1/2}$)

$$2h\dot{\varepsilon} = (2ht_{r\phi})(2\sigma_{r\phi}) = 2Q = \frac{3\dot{M}}{4\pi r^2}\frac{GM}{r}J(r)$$

- The energy released from infinity to r_isco = r_1 is

$$2Q_{tot}(r_1) = \int_{r_1}^{\infty} 2h\dot{\varepsilon}\, 2\pi r\, dr \simeq \frac{3}{2}\dot{M}\frac{GM}{r_1}$$

- The potential energy release to r_1 is V = $GM\dot{M}\frac{1}{r_1}$

However because 2T+V=0 only half of it is available for heat. The rest remains as kinetic energy T = V/2

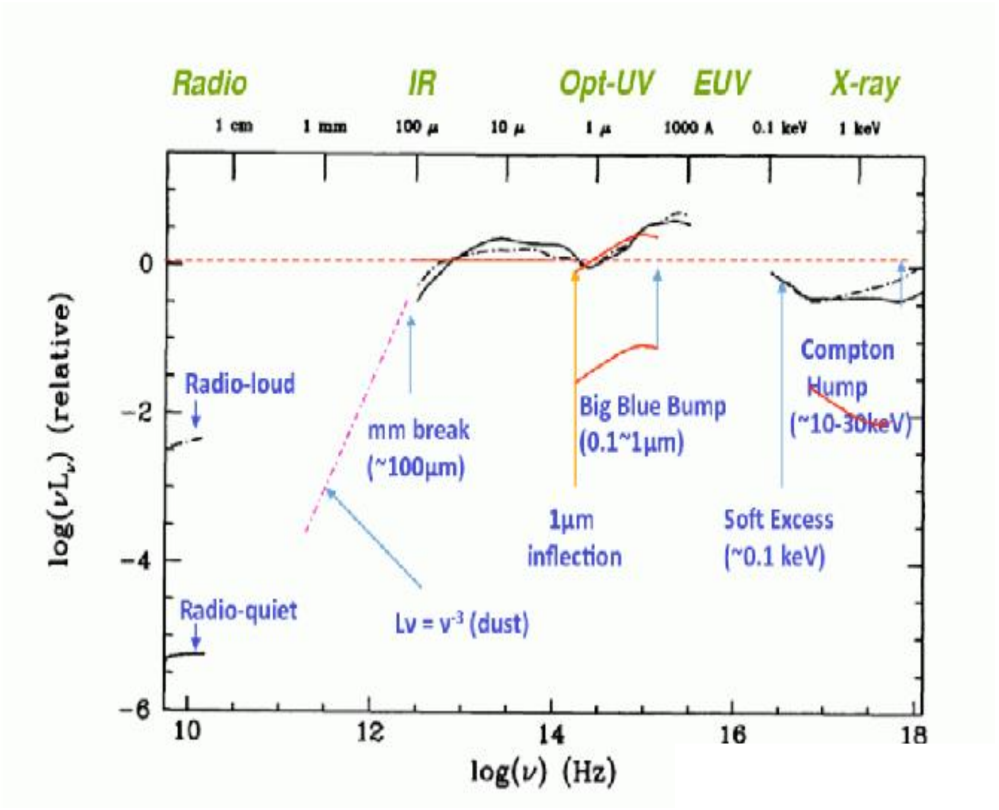
- What about the factor (3/2) in $2Q_{tot}(r_1) = \int_{r_1}^{\infty} 2h\dot{\varepsilon}\, 2\pi r\, dr \simeq \frac{3}{2}\dot{M}\frac{GM}{r_1}$?

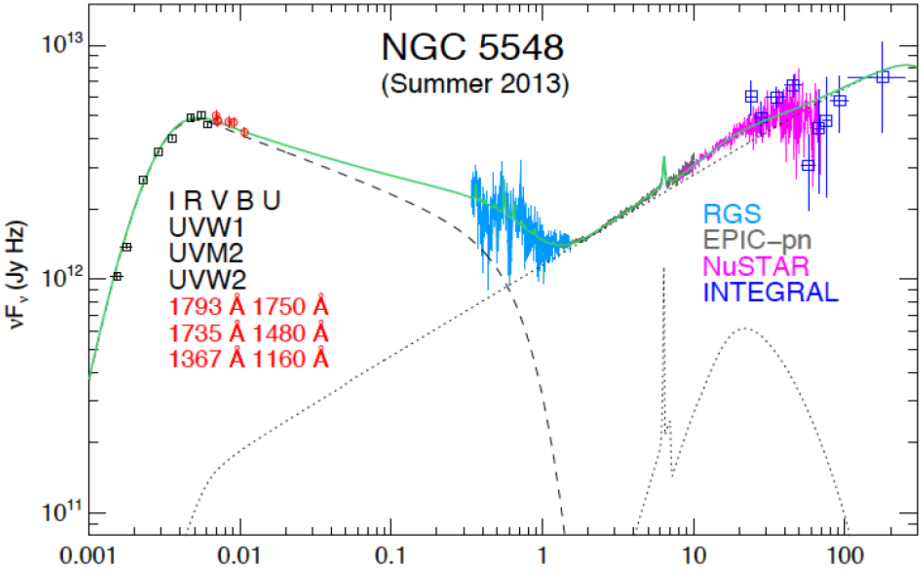
- This extra energy is due to the energy transferred by the viscous torques!

$$\dot{E} = \Omega \mathscr{T} = \Omega 2\pi r^2\, 2h t_{r\phi} = \frac{GM\dot{M}}{r_1} J(r_1) \simeq \frac{GM\dot{M}}{r_1} \quad (r \gg r_I) .$$

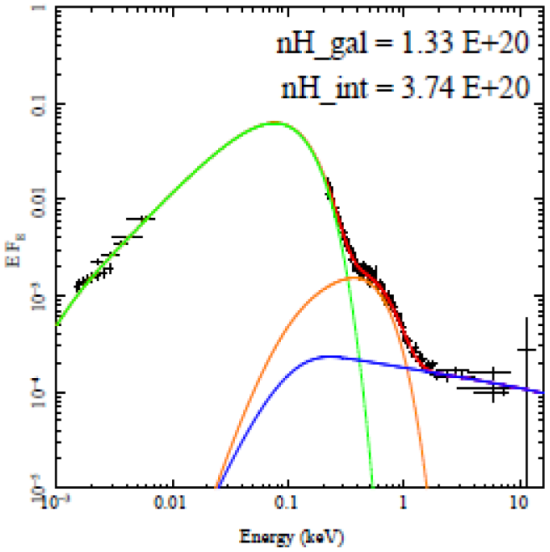
- *It is important to bear in mind that besides ang. momentum viscous forces transfer also energy. This can make the local energy E>0. Loss of excess energy in winds across entire disk* (Blandford & Begelman 99).
- It is generally assumed that *all this energy is dissipated locally!*
- Setting this equal to $r^2 \sigma T^4$ we infer that $T \sim r^{-3/4}$

The disk temperature is then $T \sim 10^{6.5} (M/Mo)^{(-1/4)}$. For quasars $M \sim 10^8$ Mo, *T ~ 30,000 K*, and the emission represents the so called Big Blue Bump (BBB).

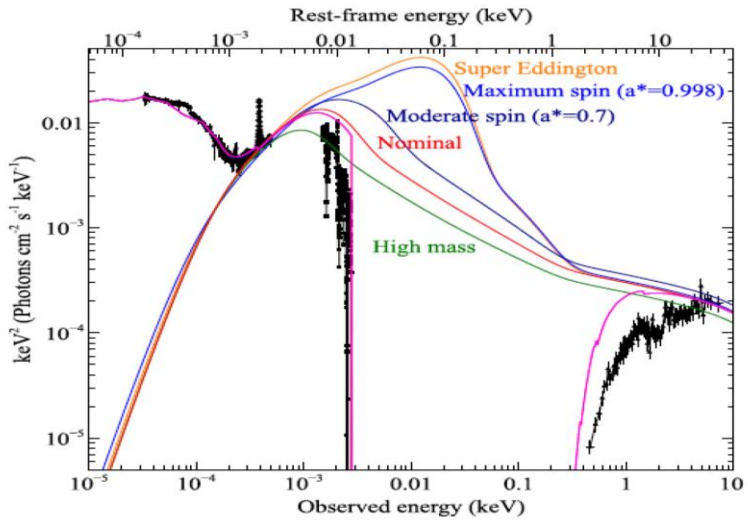




Besides the BBB there are other components too, most prominently the X-rays. Their relative contribution can vary by a factor of 100!. X-ray emission generally attributed to a corona.



APM08279+5255



Some questions concerning the AGN SEDs

- Why such a large difference in α_{ox}?
- If the disk is BB emission from a disk extending to ISCO, why such a large range in X-ray emission?
- It appears that the *BBB/X-ray ratio* depends on the accretion rate (in Eddington units).
- Microlensing indicates that the X-ray emitting plasma is smaller than that of the UV emitting one (Patchy Corona?).
- If X-ray emission is due to a corona, is this a free parameter to be adjusted?
- The corona (in most cases) should not cover the entire (inner segment) of the disk (Haardt & Maraschi 92).

Winds !!!

- **50% of all AGN** are observed to have **UV absorbers**, blue shifted by up to 10,000 km/s.
- **50% of all AGN X-ray** spectra have **X-ray absorption features**, blue shifted by up to c/2 and as low as 200-300 km/s.

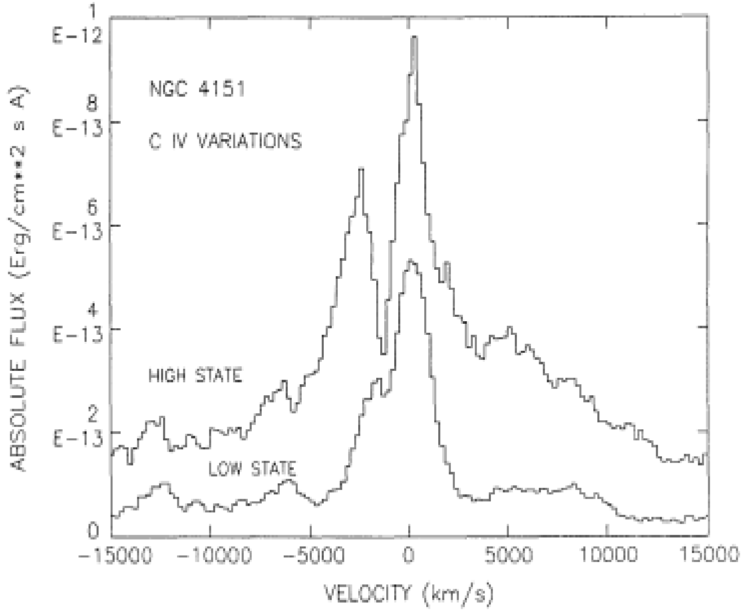
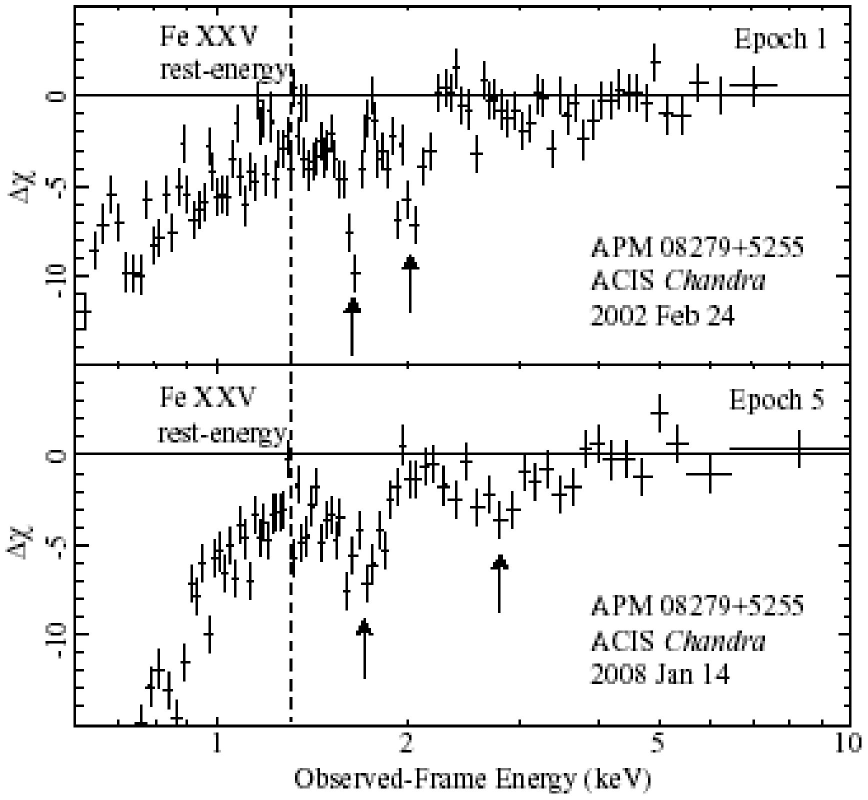
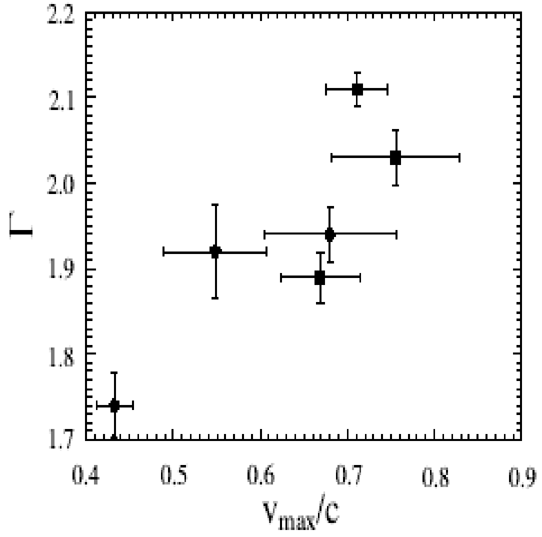
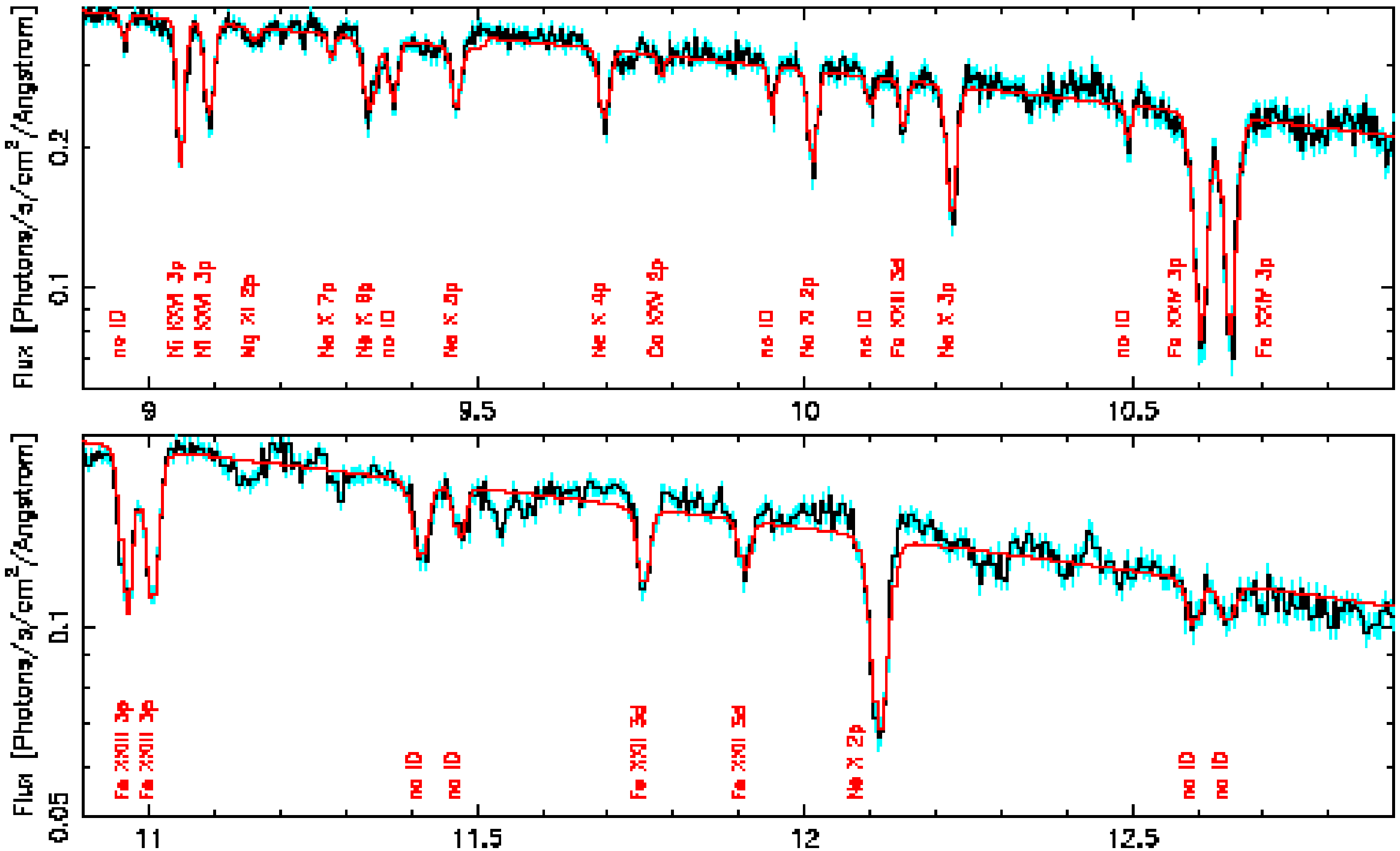


FIG. 1.—Representative C IV line profiles of NGC 4151 obtained in a low state (SWP 21578, 120 minute exposure, day = 82051), and in a high state (SWP 18490, 45 minute exposure, day = 82310). The spectra are plotted on the same absolute intensity scale and are shown in velocity space corrected for redshift.





Winds from Galactic Black Holes !!!



- How can we have winds with different velocities along the line of sight? (1. we observe the acceleration of the wind; 2. winds are inherently 2D, LoS cuts through segments of different velocities)
- We do see ions (along the line of sight) at very different values of their ionization parameter **ξ**.
- Radiatively, or thermally driven winds achieve asymptotically velocities $v \sim 1/r^2$, at which point **ξ** is constant. => Lower **ξ** segments should be associated with the wind acceleration, i.e. they should have smaller velocity **v** and higher column N_H (assuming nearly spherical geometry).
- Considering that ***$\xi = L / nr^2$*** and that ***Mdot ~ $v\, nr^2 \sim (L/\xi)\, v$*** , measuring ξ, v we can estimate the mass flux associated with a given ion. *This is found to be greater than that necessary to power the BH!*
- *Most available mass never reaches the BH; it escapes in the wind!*

Why X-Ray Spectroscopy?

- The presence or not of a specific ion depends on the ionization parameter $\boldsymbol{\xi = L / nr^2 = L/N_H r}$.

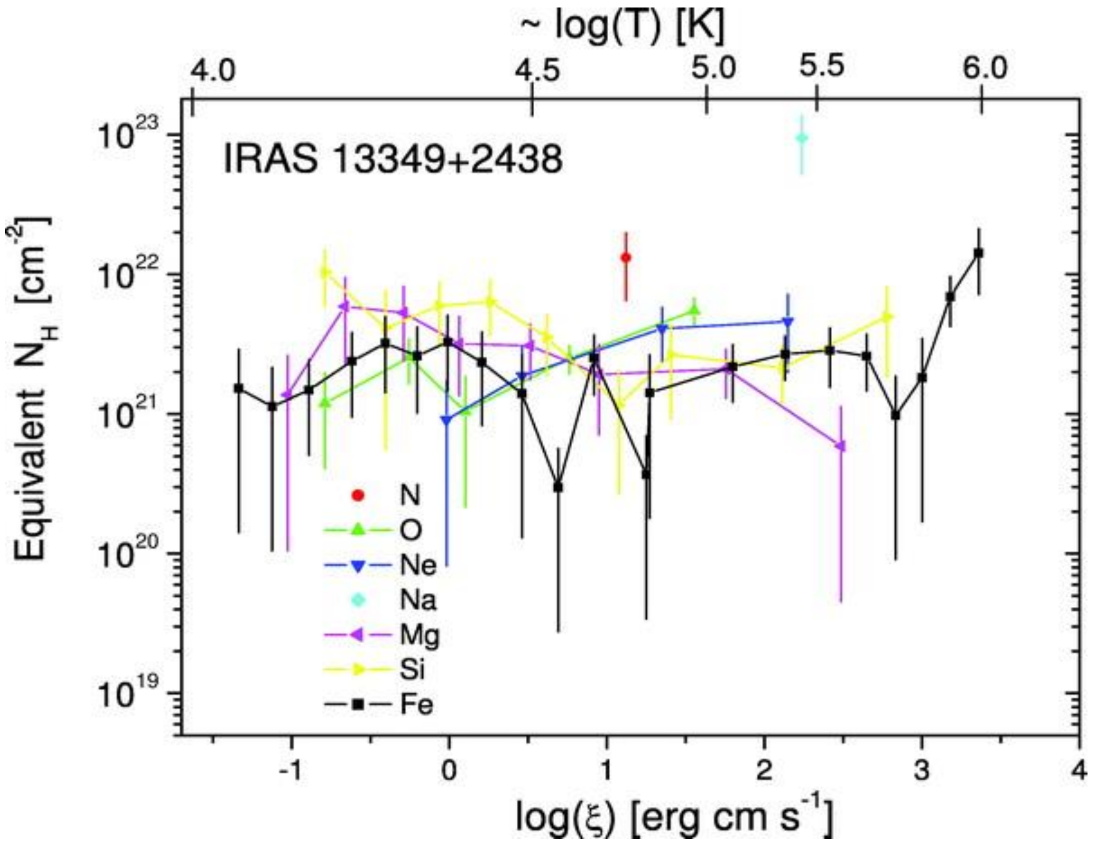
- The advantage of X-ray spectroscopy is that it can access all states of ionization (5-6 decades in ξ) within a factor of 20 in X-ray energy.

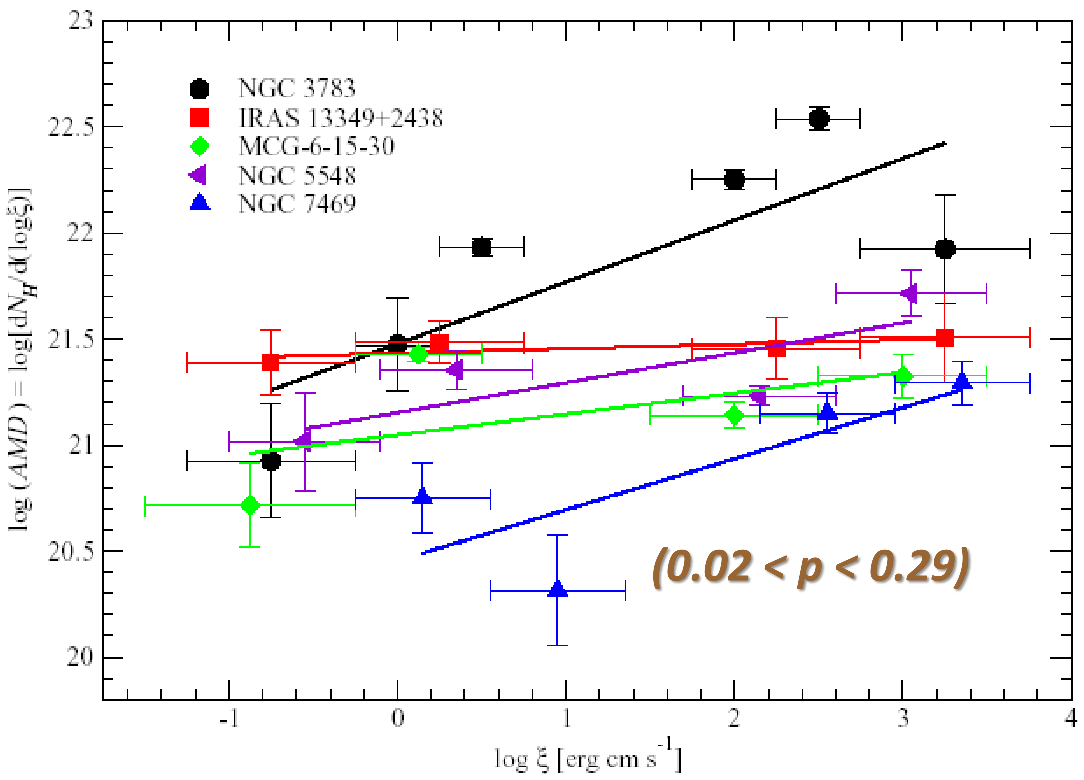
- By measuring the absorption depth (column) of widely spaced in **ξ** ionic species we can then obtain a good estimate of the absorber density along our lines of sight

- $AMD(\xi) = dN_H / d\log\xi \sim (\log\xi)^p$
- Distribution of column with logξ (AMD)

Absorption Measure Distribution (AMD)

$AMD(\xi) = dN_H / d\log\xi \sim (\log\xi)^p$





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~1/r^2 !!

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

Mdot in wind **increasing with radius!!** (Contopoulos Lovelace 94; Blandford Begelman 1999)

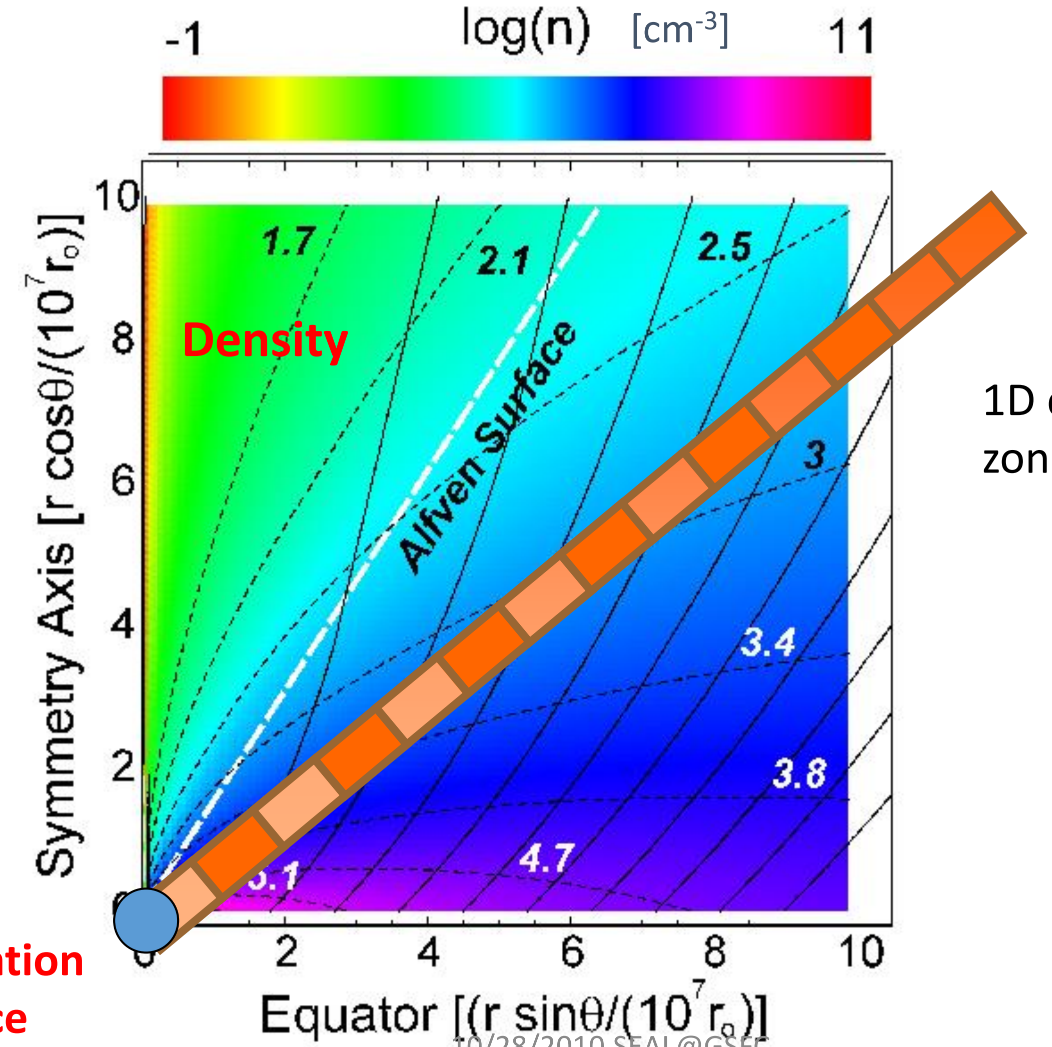
The flow is 2 dimensional! (Blandford+Payne 82, Contopoulos and Lovelace 94; Konigl+Kartje 94 → AGN Unification: Torus = MHD Wind)

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

LoS Radiation Transfer

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

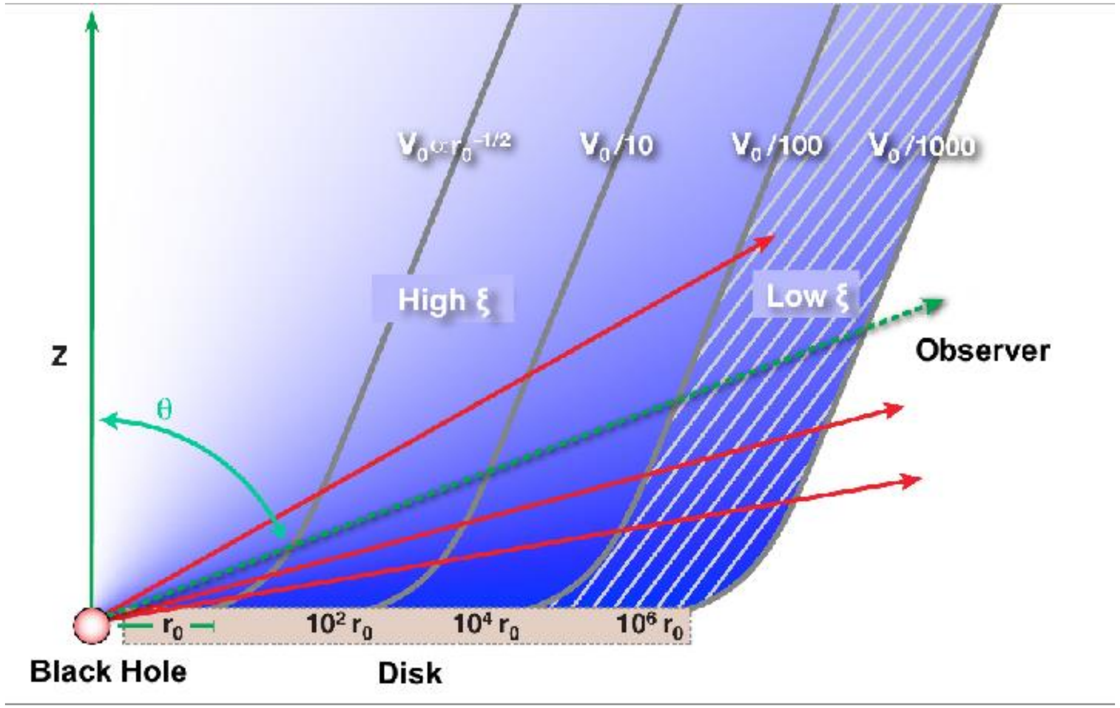
Ionization Distribution

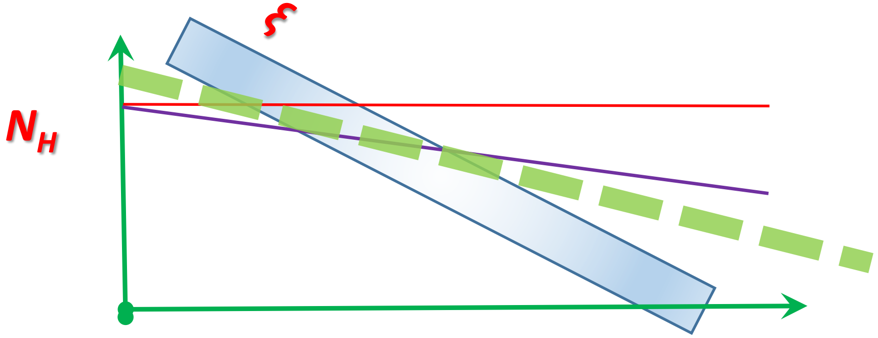


LoS

1D computational zones

Radiation Source





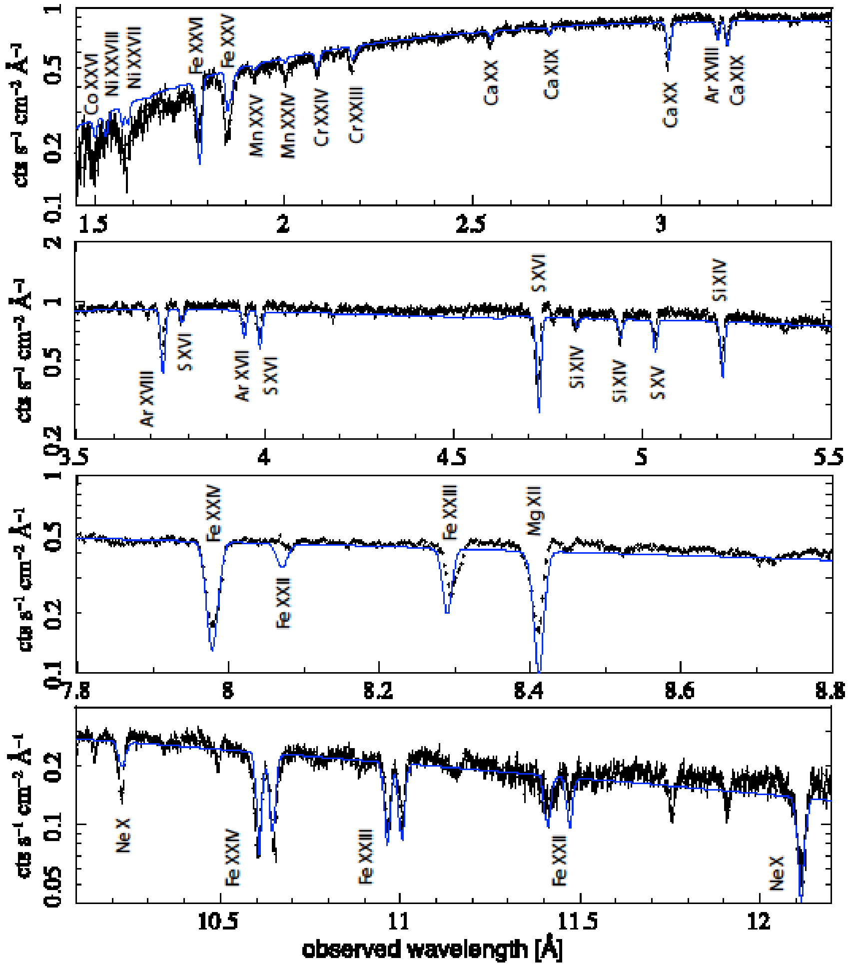
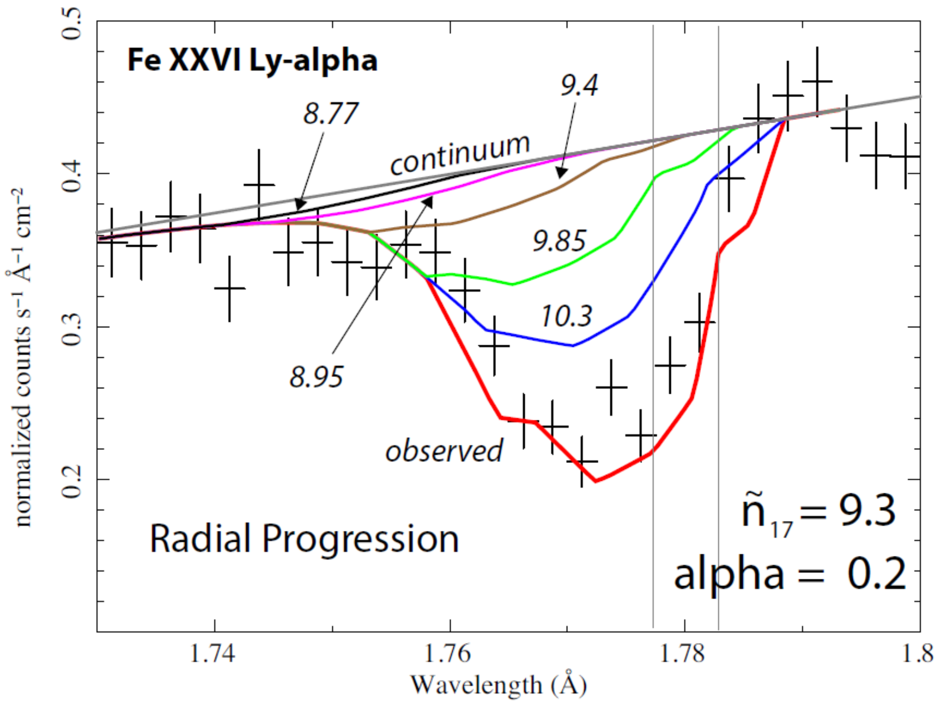
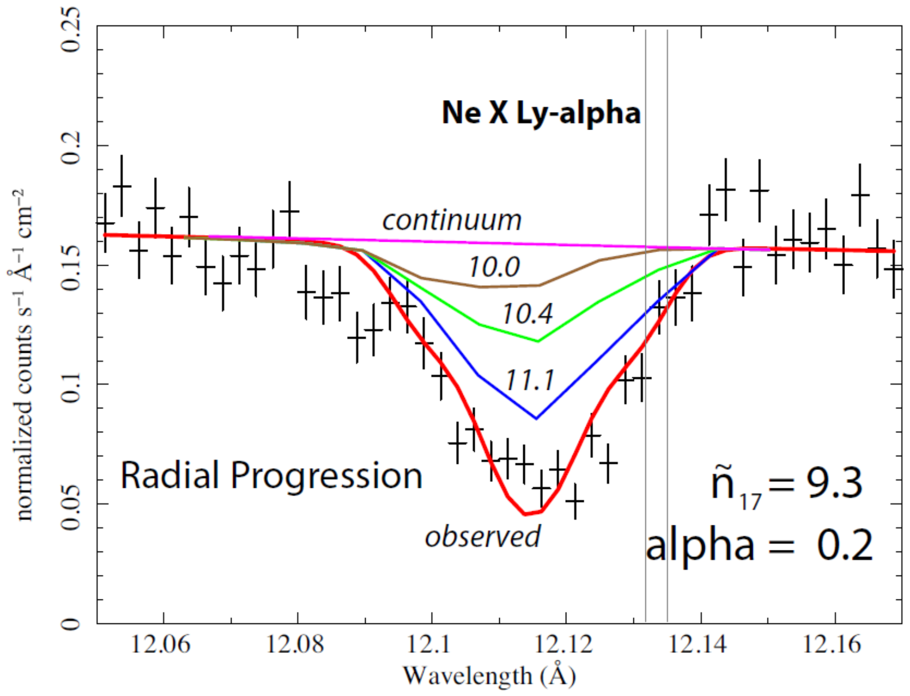


Fig. 2. A model X-ray absorption line spectrum of the Galactic black hole GRO J1655-40 (blue lines) overlaid on the *Chandra* data. The line widths and depth are all obtained from a single wind model and not modeled individually.

The model – the same we employed to model AGN - provides also the velocity structure of the absorption lines.
We find that the wind density profile that fits the data best is proportional to $1/r^{1.2}$



V ~ 2500 km/s



V ~ 500 km/s

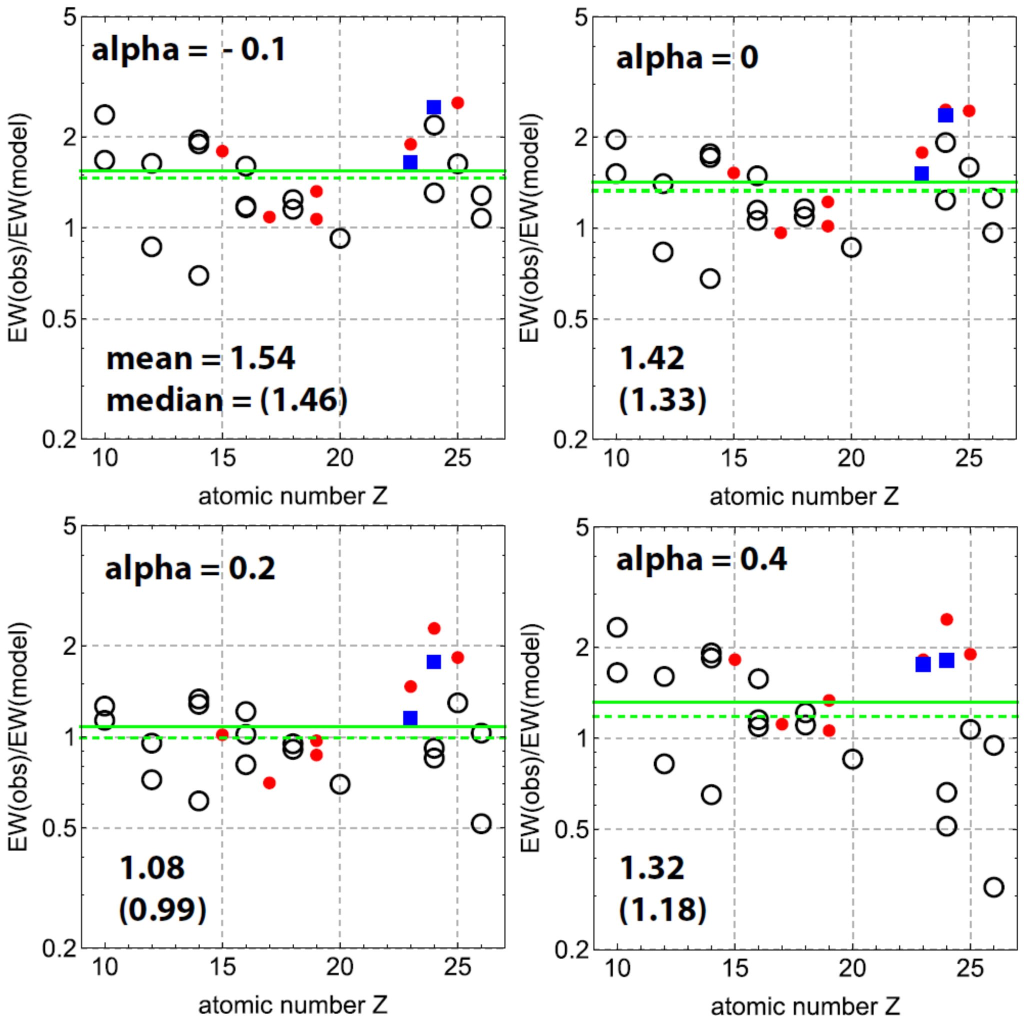
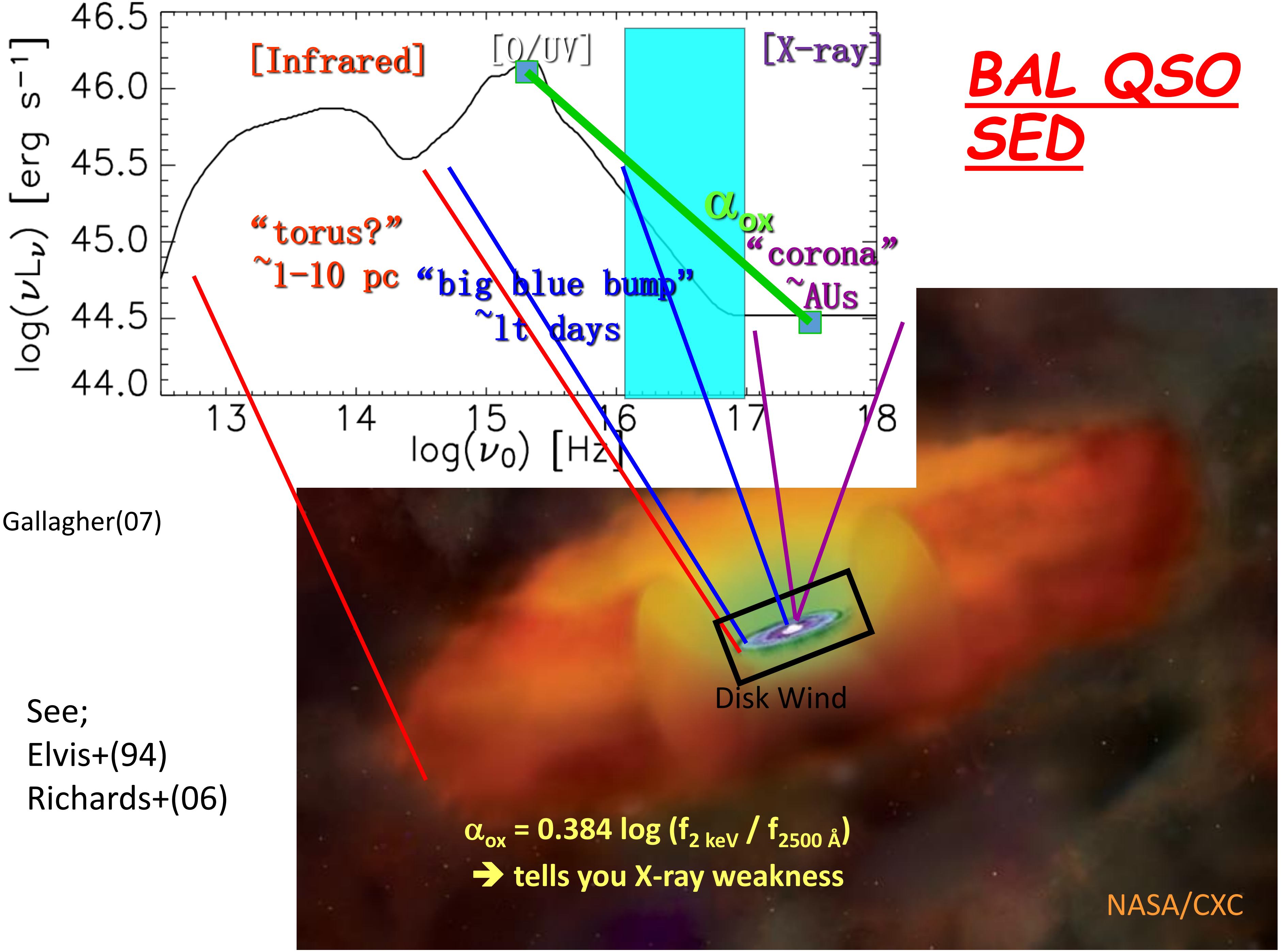


Figure S4 EW ratios between our model and data for $\alpha = -0.1, 0, 0.2$ and 0.4.

General Model Assumptions

- The winds are two dimensional (2D axisymmetric).
- We have assumed self-similarity, so all parameters run as power-laws of the radius with the same dependence on the polar angle **θ,** with velocity $\mathbf{V \sim 1/r^{(1/2)}}$
- They extend across the entire disk domain (to the point that the Keplerian velocity $\mathbf{V_K}$ is comparable to the velocity dispersion **σ** of the overlying spheroid (half the distance to the companion in XRBs).
- Their inner segements are fully ionized with the highest **ξ** ions (Fexxvi-Fexxv) having the highest velocities. These depend on the ionizing radiation of their SEDs (***low X-rays → high velocity V – BAL QSO, high X-rays → low V, XRBs***)

BAL QSO SED



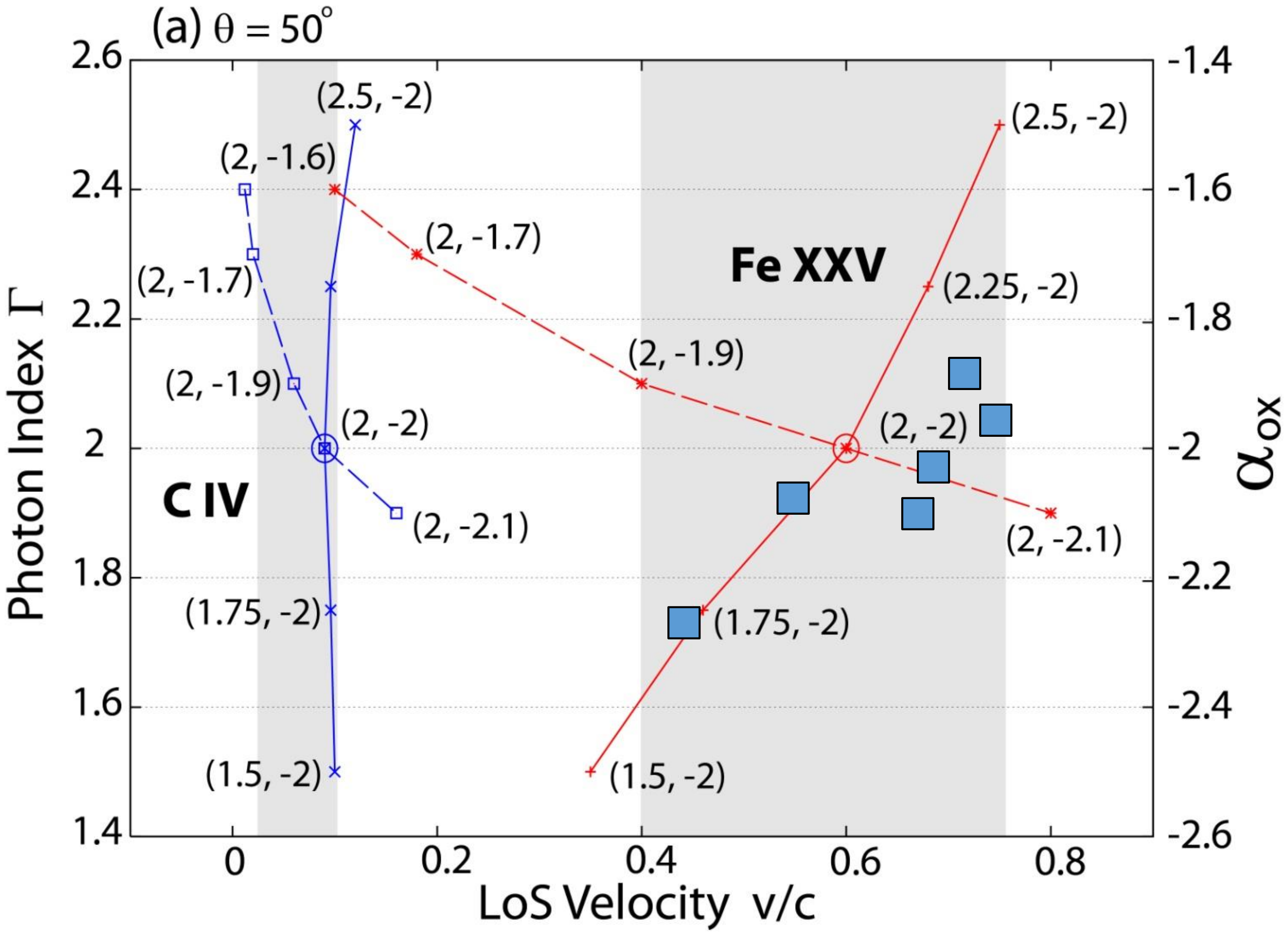
Gallagher(07)

See;
Elvis+(94)
Richards+(06)

Correlations with Outflow Velocity

Increased X-ray fraction in the spectrum implies more small-r ionization hence lower velocities

Velocity Dependence on SED (X-ray Slope)



- X-ray data of APM 08279+5255 from Chartas+(09)
- Model from Fukumura+(10b)

Application to GRO J1655-40

- GRO J1655-40 is a Galactic BH low mass binary. It exhibits the entire suit of states that these objects do as a function of time and mdot (q-diagram).
- In its soft state it exhibited a large number of high S/N absorption features that make it ideal for applying our variable mdot models.
- The model has 3 parameters: the wind mass flux, its radial dependence (assuming to be a power law) and the observer inclination angle.
- We compute the entire wind ionization and choose the parameters that provide the best agreement with the data *(Fukumura, DK, Shrader, Behar, Tombesi, Contopoulos, 2017, **Nature Astronomy, 1**, 62)*

Implications of Global Wind Structure

- There is mounting evidence that the accretion disk winds mass flux increases with distance ***r.***
- Therefore the disk ***accretion rate must decrease with r!***
- Therefore *mdot* will become sufficiently small that would support an ADAF disk, ***interior to some radius r_t.***
- As the overall mass accretion rate Mdot increases (relative to that of Eddington) ***r_t decreases.*** Then, ***the BBB flux relative to the X-rays increases. The X-rays are emitted by the ADAF segment of the flow interior to r_t.***

- Assume that we do have a wind density profile close to **n(r) ~ 1/r**
- Then, the wind and accretion disk mass fluxes will be of the form ***mdot ~ mdot$_0$ x$^{1/2}$.***
- Assume that at ***x <~ x$_t$ = rt/R$_S$ mdot ~ mdot$_0$ x$_t^{1/2}$ < α^2***
- Then the flow reverts to a less efficient ADAF (ADIOS).
- Then

$$L(x > x_{tr}) \propto \int_{x_{tr}}^{\infty} \frac{\dot{m}(x)}{x} J(x) dlnx \sim \frac{\dot{m}_0}{x_{tr}^{1/2}}$$

BBB disk emission

$$L(x < x_{tr}) \propto \int_{x_I}^{x_{tr}} \frac{\dot{m}(x)^2}{x} J(x) dlnx \sim \dot{m}_0^2 \left[ln\left(\frac{x_{tr}}{x_I}\right) - 2\zeta + 2\zeta \left(\frac{x_I}{x_{tr}}\right)^{1/2} \right]$$

X-ray emission

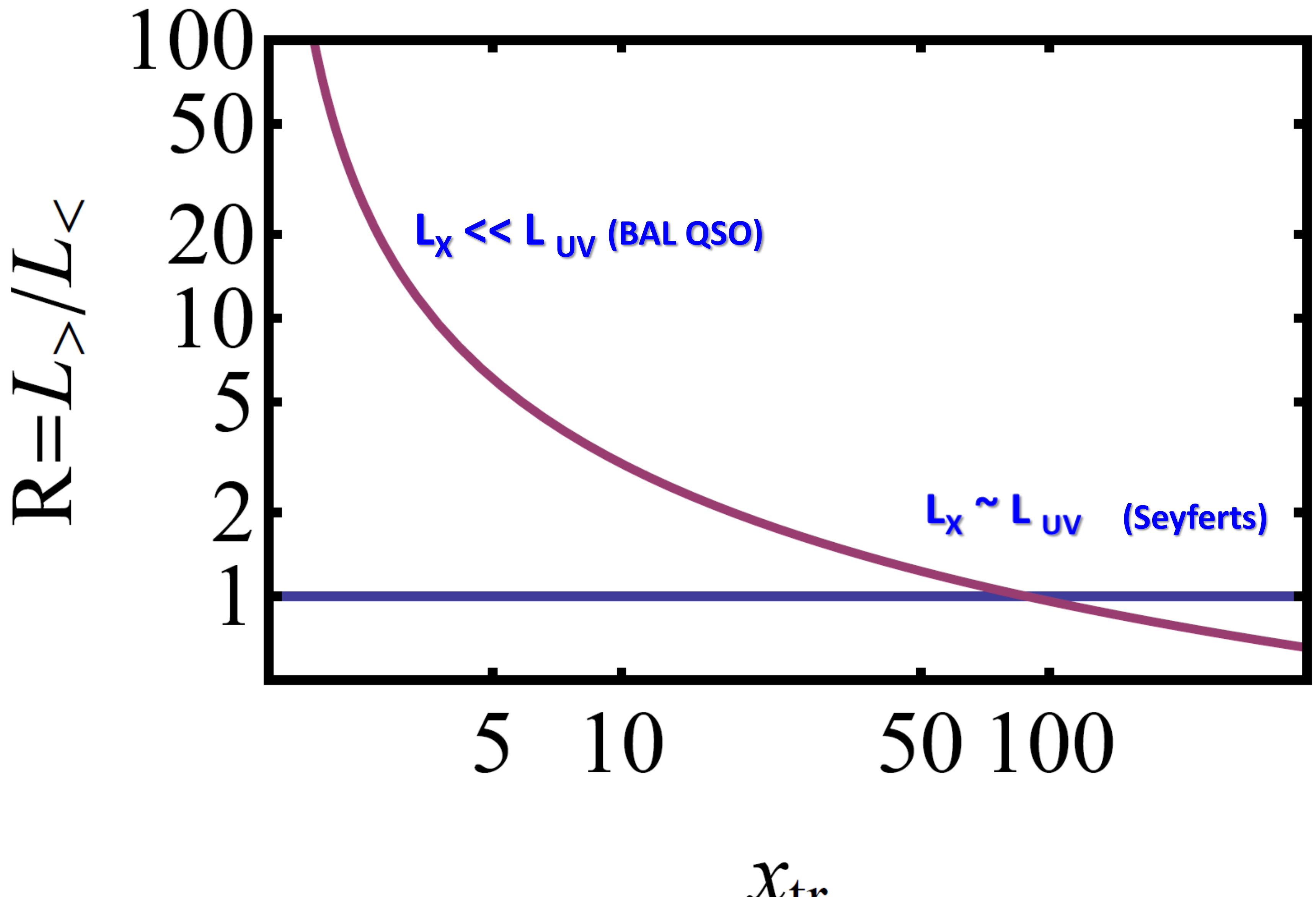
The ratio of luminosities emitted at radii larger (BBB) and smaller (X-rays) to the transition radius is given by

$$R = \frac{L(x > x_{tr})}{L(x < x_{tr})} = \frac{1}{\dot{m}_0 \, x_{tr}^{1/2}} \, \frac{1}{P2} = \frac{1}{\alpha^2} \, \frac{1}{P2}$$

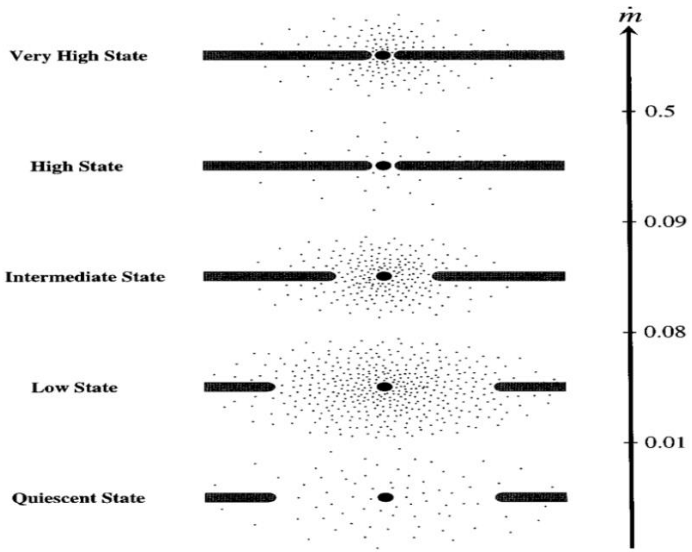
where

$$P2 = \left[ln\left(\frac{x_{tr}}{x_I}\right) - 2\zeta + 2\zeta \left(\frac{x_I}{x_{tr}}\right)^{1/2} \right]$$

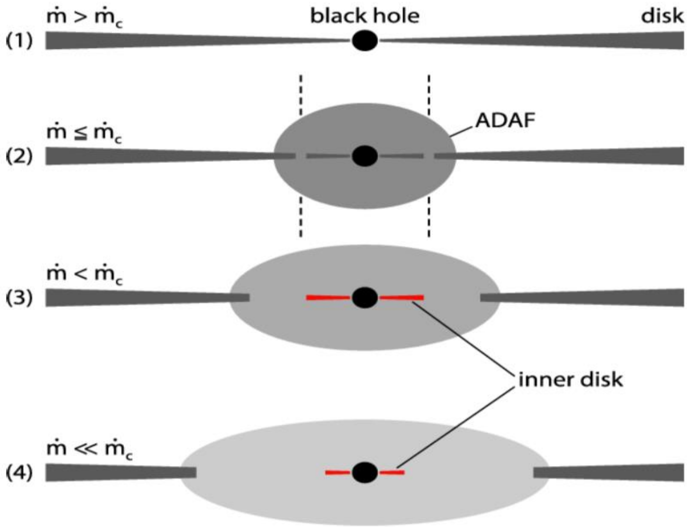
This ratio is given graphically by the next figure



Still need to understand the precise spectral distribution between the BBB and the X-Rays



Esin et al. (1997)



Meyer-Hofmeister et al. (2009)

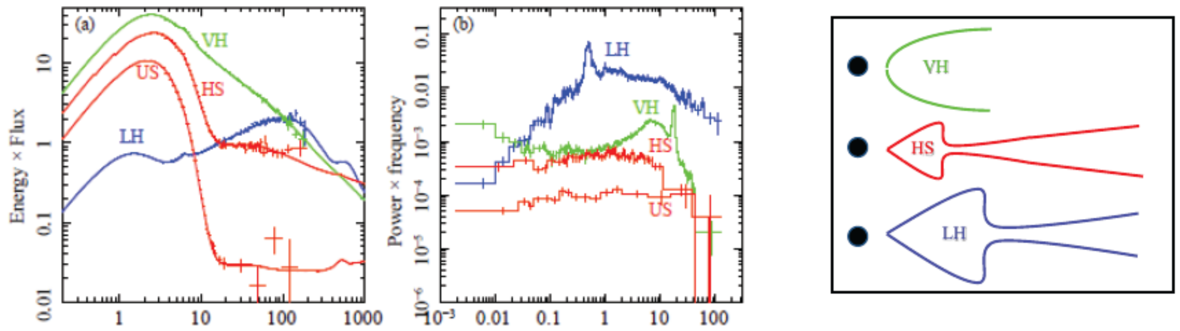


Fig. 2 *Left:* The νF_ν spectra of GRO 1655-40 at its different states: Blue Low Hard, red High Soft, green Very High. *Middle:* The corresponding timing properties corresponding the these energy spectra, color coded for correspondence. *Right:* Schematic depiction of the disk structure corresponding to the spectral states of the same color as the figure to the left.

Kazanas ’15 in “Formation …Jets” Contopoulos, Gabuzda, Kylafis eds.

Variation of properties, phenomenology with increasing global accretion rate (q-diagram)

At r=10rg…

t_{dyn} = 1.5ms

t_{th} ~ 15ms

t_{visc} ~ 1.5s

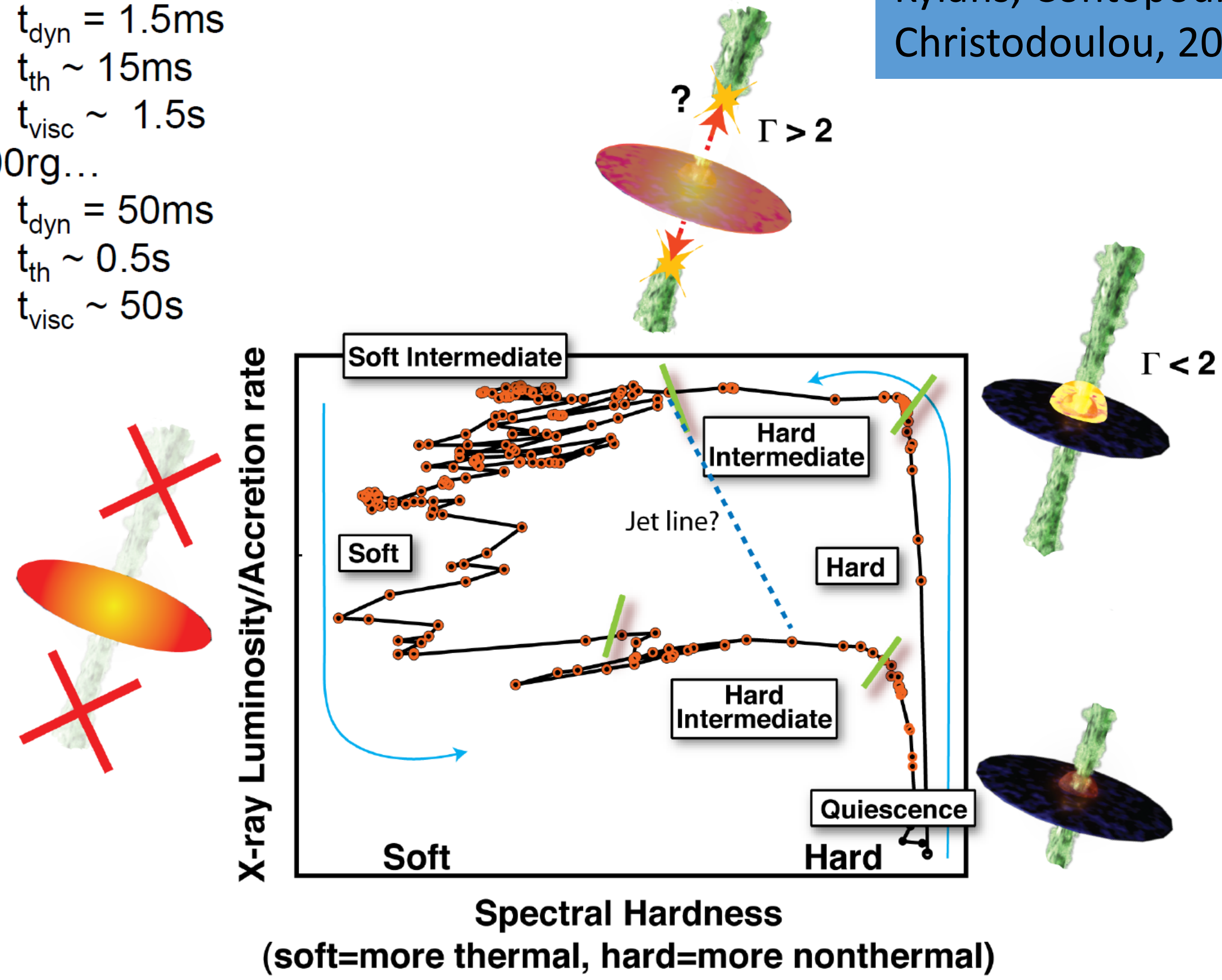
At r=100rg…

t_{dyn} = 50ms

t_{th} ~ 0.5s

t_{visc} ~ 50s

Kylafis, Contopoulos, Kazanas, Christodoulou, 2012



Summary - Conclusions

- There is mounting evidence of the ubiquitous presence of *outflows* associated with accreting black holes.
- The broad range of ionized species and their velocities imply a broad range of launching radii, inconsistent with radiatively driven winds.
- The distribution of absorbing columns with ξ provides a measure of the wind density with *r*. This implies that the *wind mass flux increases with distance* from the black hole! → *MHD launching.*
- It also implies the *disk mass flux decreases with decreasing r (ADIOS)!* As a result there exists a radius *below which the disk makes a transition to an ADAF, a region where the entire X-ray emission is located. This makes X-ray emission integral part of dynamics of accretion, rather a corona with arbitrary geometry and properties.*
- The transition radius, which determines the relative importance of the X-ray to BBB emission, depends on the global (normalized) mass flux.

Summary – Conclusions (continued)

- The wind ionization properties, in turn, depend on the amount of X-rays in the spectrum:
- *Low X-ray content* implies little ionization, even very close to the BH → *High velocities absorption features (BAL).*
- *High X-ray content* (transition to ADAF at large r), implies highly ioninzed inner wind regions → *Lower velocity absorbers (UFO, Seyfert Warm Absorbers).*
- *The BBB of Galactic sources is in X-rays → Low Absorber Velocities.*
- Motivated by the X-ray absorber properties we have produce a general framework that reproduces the global, broad-brush-stroke properties of accreting black holes, in general, across the 10 – 10^9 mass scale with main fundamental parameter the (normalized) mdot.
- It suggests that *AGN* and *Galactic accreting BH systems extend over many scales in radius (~10^6 R_{Schw})* and are *largely driven by magnetic forces*, which *expel their excess angular momentum needed to achieve accretion in MHD winds.*

- ***What is the origin of these magnetic fields? (Cosmic Battery?)***