Magnetic View of AGN-Driven Winds

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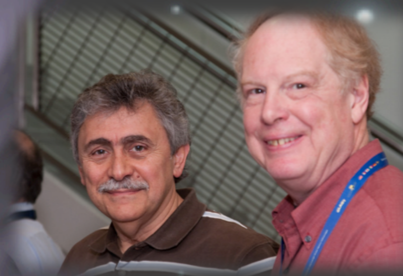


Outline

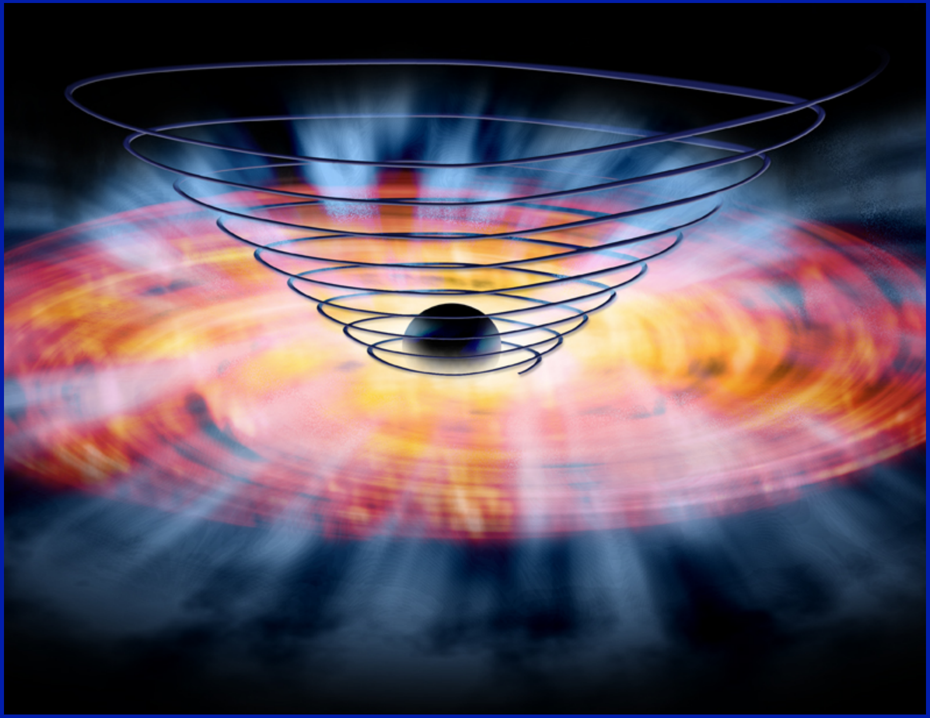
1) X-ray ionized winds in AGNs

2) What can motivate MHD-driven?

3) Observables

4) Implications

5) Summary



AGN-driven outflows

➔ Ubiquitous across diverse Seyferts/QSOs populations

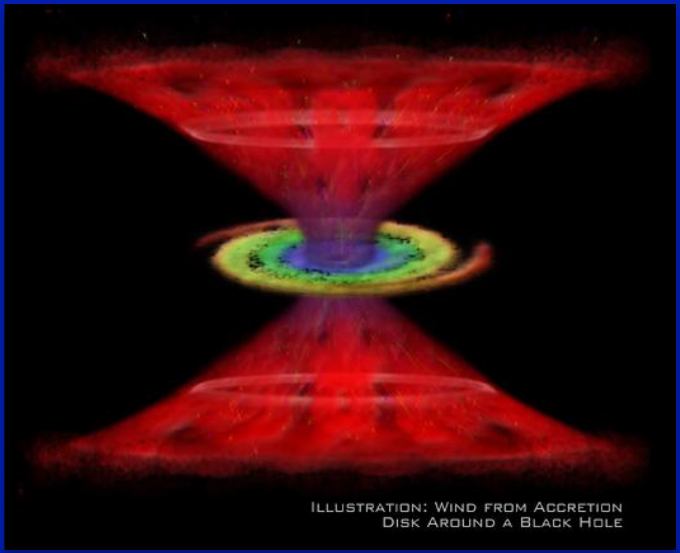
➔ can learn

[1] column density: N_H

[2] ionization parameter: $\xi = L_{ion}/(nr^2)$

[3] wind velocity: v_{LoS}

[4] geometry, global property, AGN feedback…etc.



General Review:
Blustin+(05), Reynolds+(97)
Laor&Brandt (02)
Crenshaw&Kraemer(12)
Crenshaw+(03)

Classical MHD Models: e.g.
Blandford+Payne82 (BP82), Contopoulos
+Lovelace94 (CL94),
Konigl+Kartje94 (KK94)…etc.

Ionized X-ray Winds

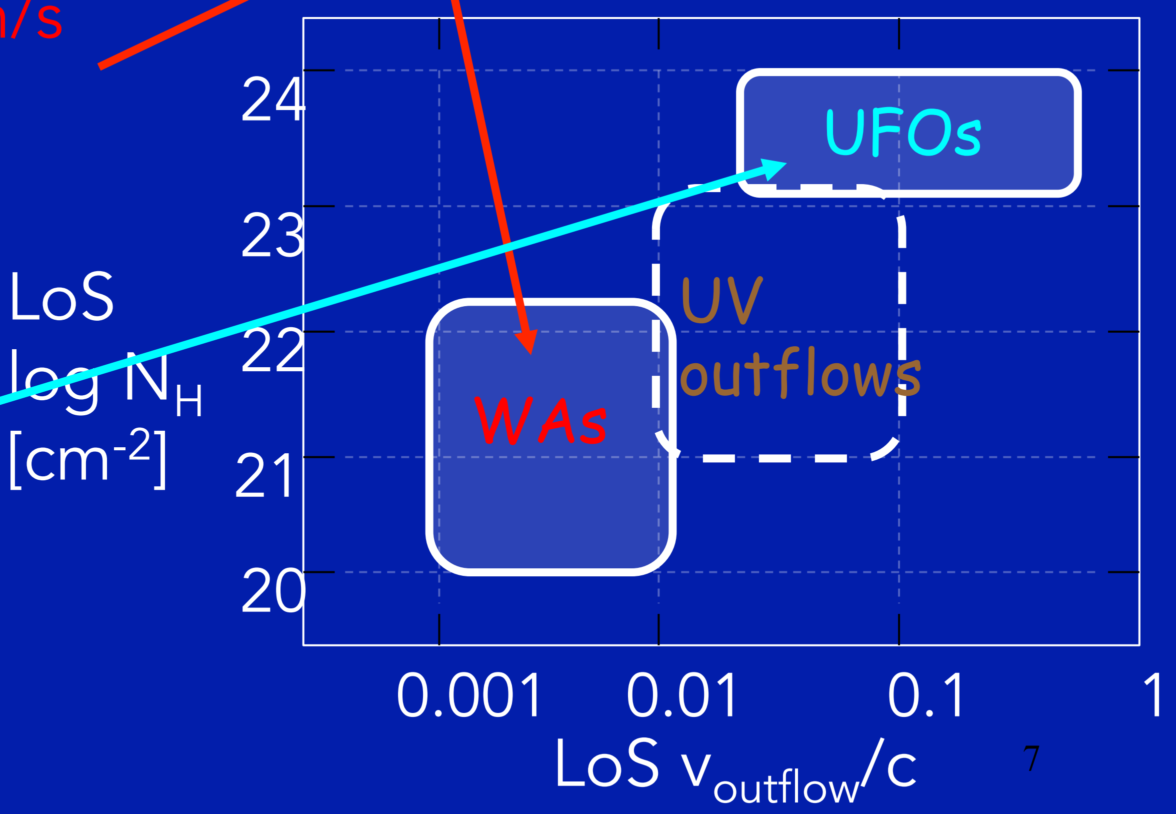
(i.e. Warm Absorbers & Ultra-Fast Outflows)

- WAs in Soft X-ray
- UFOs* in Fe K band

* *Also soft X-ray UFOs (?)*

- v_{out} ~100 - 1,000 km/s
- log ξ ~ -1 to 4
- N_H ~ 10^{20-22} cm^{-2}

- v_{out}/c~0.1 – 0.7
- log ξ ~ 3-6
- N_H ~ 10^{23-24} cm^{-2}



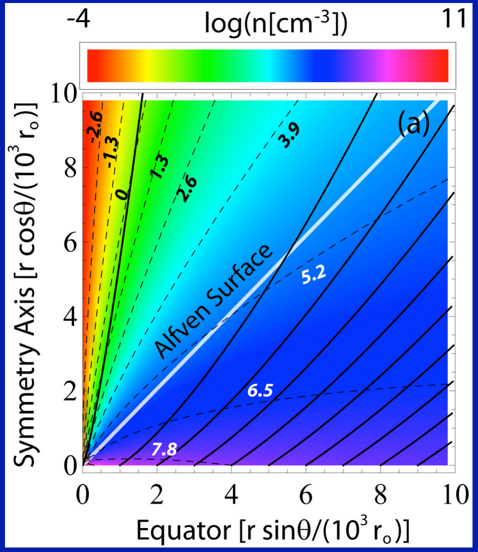
Outstanding Questions

- ✓ Flow Geometry?
- ✓ Continuous/Patchy flows?
- ✓ Defining quantities?
- ✓ How are they launched?

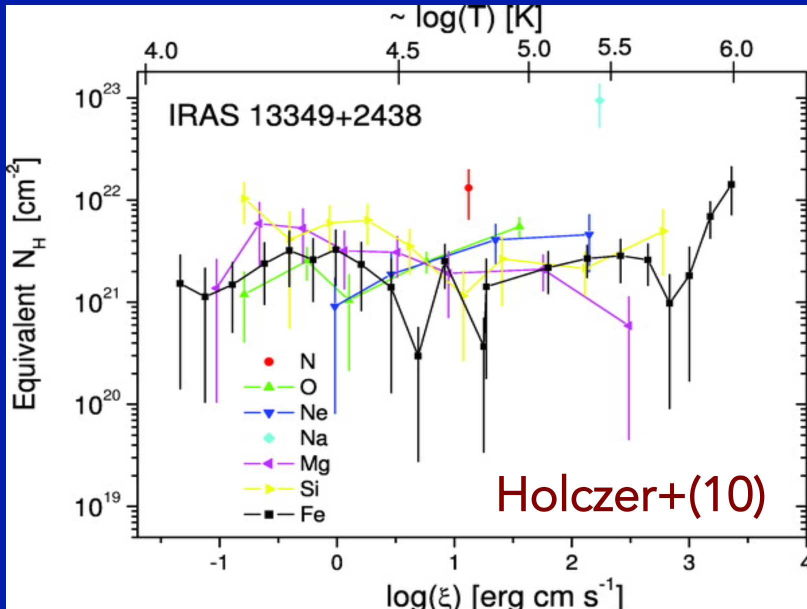
Some "good" indicators for MHD-driven winds…

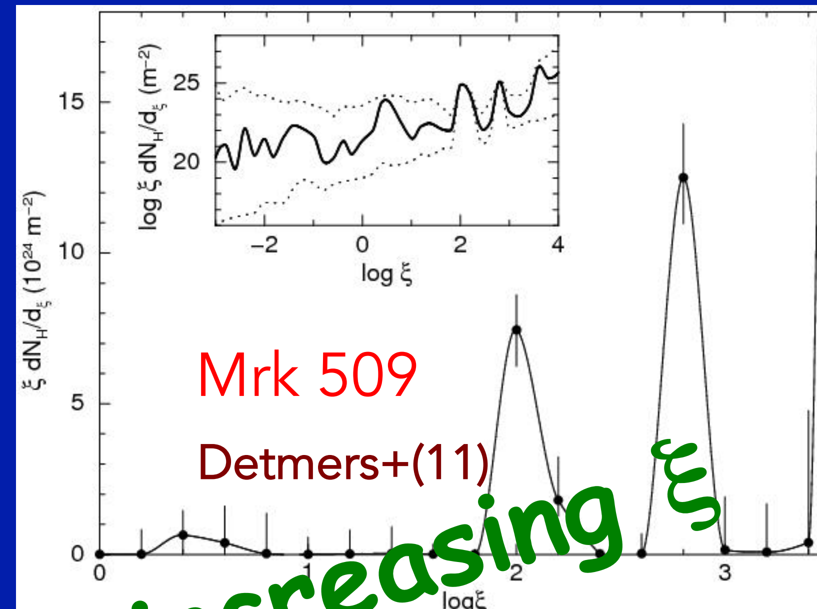
- ❑ High ξ, v, N_H (UFOs) w/ gratings
- ❑ Flat (or slightly varying) AMD
- ❑ Insufficient Force Multiplier argument
- ❑ Process of elimination by "R" and "ξ"…

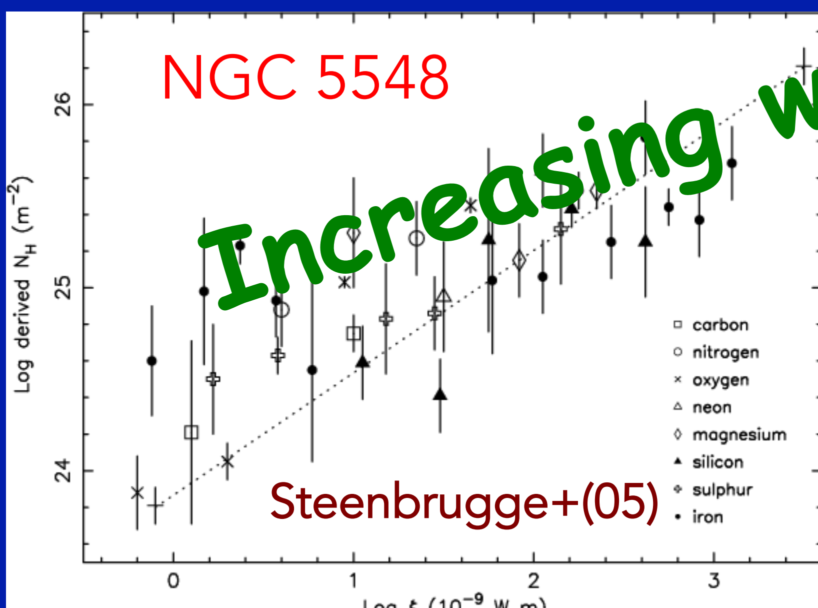
FKCB(10b)

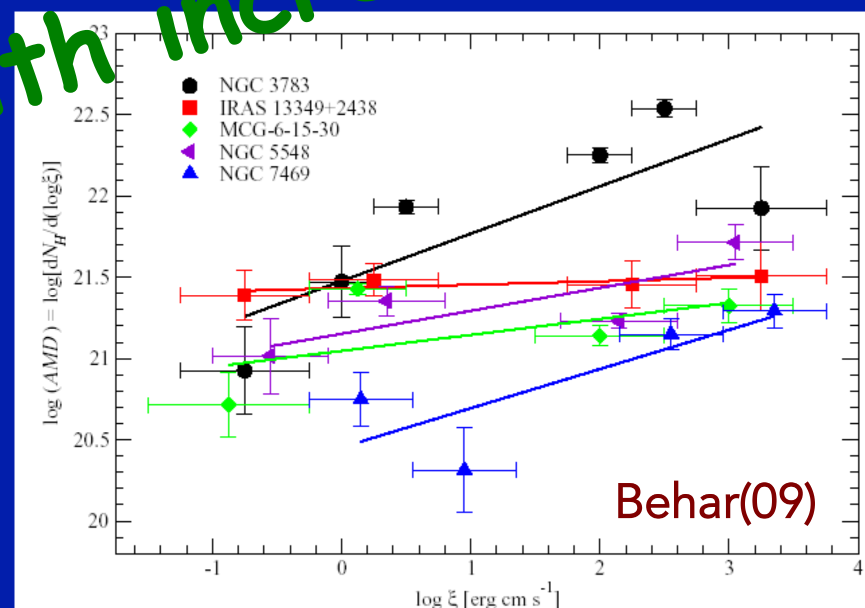


Absorption Measure Distribution (AMD)









Increasing with increasing ξ

What does AMD tell us?

$$n \propto r^{-p}, \qquad \xi \equiv \frac{L}{nr^2} \propto r^{p-2} \Rightarrow r \propto \xi^{\frac{1}{p-2}} \qquad \therefore \Delta N_H = n \cdot \Delta r \propto \xi^{-\frac{2p-3}{p-2}} \Delta\xi$$

$$AMD \equiv \frac{\Delta N_H}{\Delta(\log \xi)} = \xi \frac{\Delta N_H}{\Delta \xi} \propto \boxed{\xi^{-\frac{p-1}{p-2}}}$$

Behar(09)

Hence, p~1 wind

- shows AMD ~ const ➔ n ~ r $^{-1}$
- is favored by minimization argument of B-energy (B_ϕ~ r $^{-1}$) in the disk. e.g. CL94, KK94

$$N_H \equiv \int_{in}^{out} n(r)\,dr \propto \ln\left(r_{out}/r_{in}\right)$$

As toroidal rotation efficiently converted into poloidal motion,

- Plasma accelerated along a field line while V_{LOS} ~ V_{esc} ~ r $^{-1/2}$
- N_H ~ const per decade in radius
- ξ ~ r $^{-1}$ ~ v^2

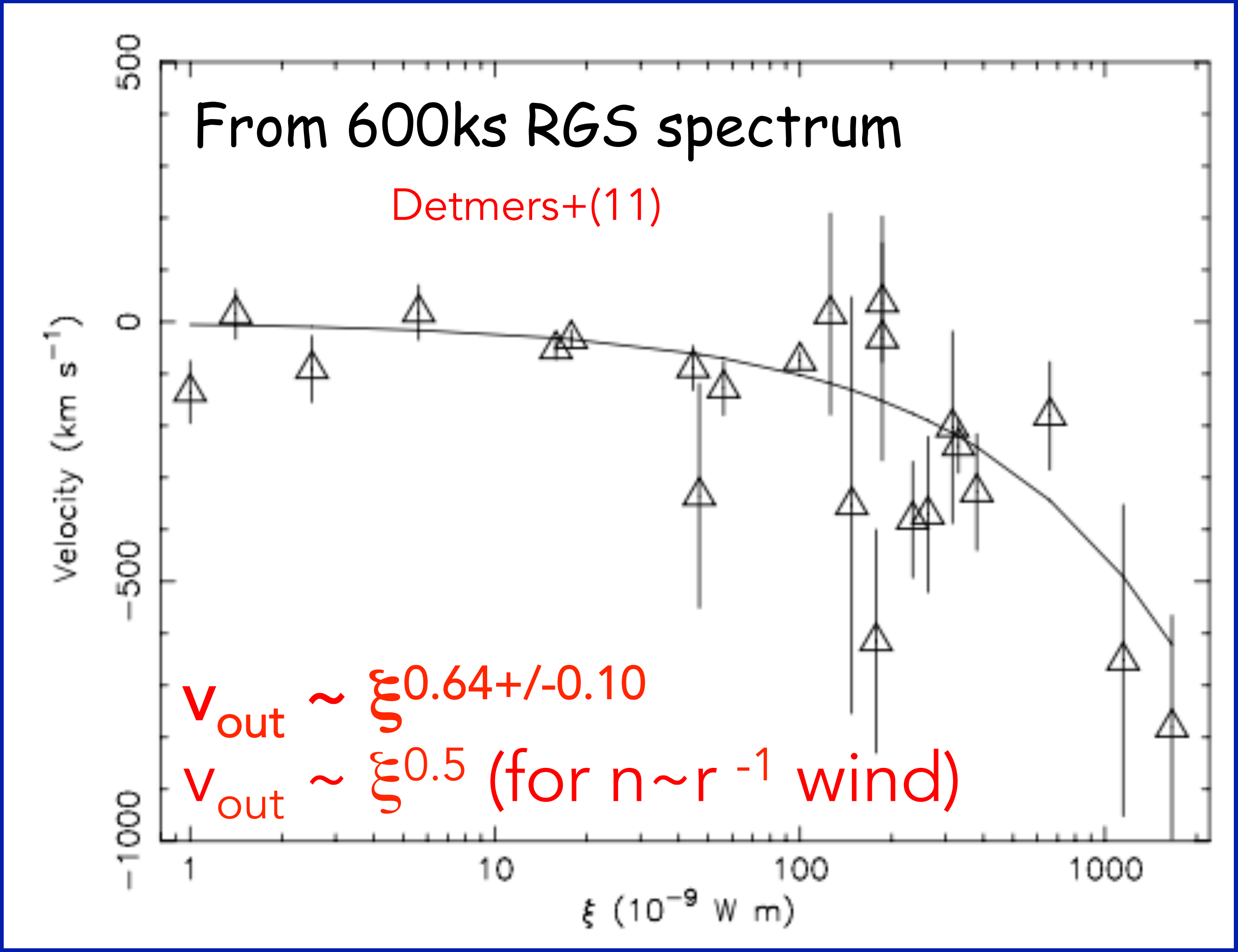
$$\dot{M} \approx nr^2 v \approx r^{-1} r^2 r^{-1/2} \approx \boxed{r^{1/2}}$$

$$\dot{E}_k = \dot{M} v^2 \propto \boxed{r^{-1/2}}, \dot{P} = \dot{M} v = \boxed{const.}$$

Kazanas+(2012)

outflow rate ← exterior kinetic power ← interior

Multi-λ campaign of Mrk 509



Indicating magnetic-origin?

What does AMD tell us?

$$n \propto r^{-p}, \qquad \xi \equiv \frac{L}{nr^2} \propto r^{p-2} \Rightarrow r \propto \xi^{\frac{1}{p-2}} \qquad \therefore \Delta N_H = n \cdot \Delta r \propto \xi^{-\frac{2p-3}{p-2}} \Delta\xi$$

$$AMD \equiv \frac{\Delta N_H}{\Delta(\log \xi)} = \xi \frac{\Delta N_H}{\Delta \xi} \propto \xi^{-\frac{p-1}{p-2}}$$

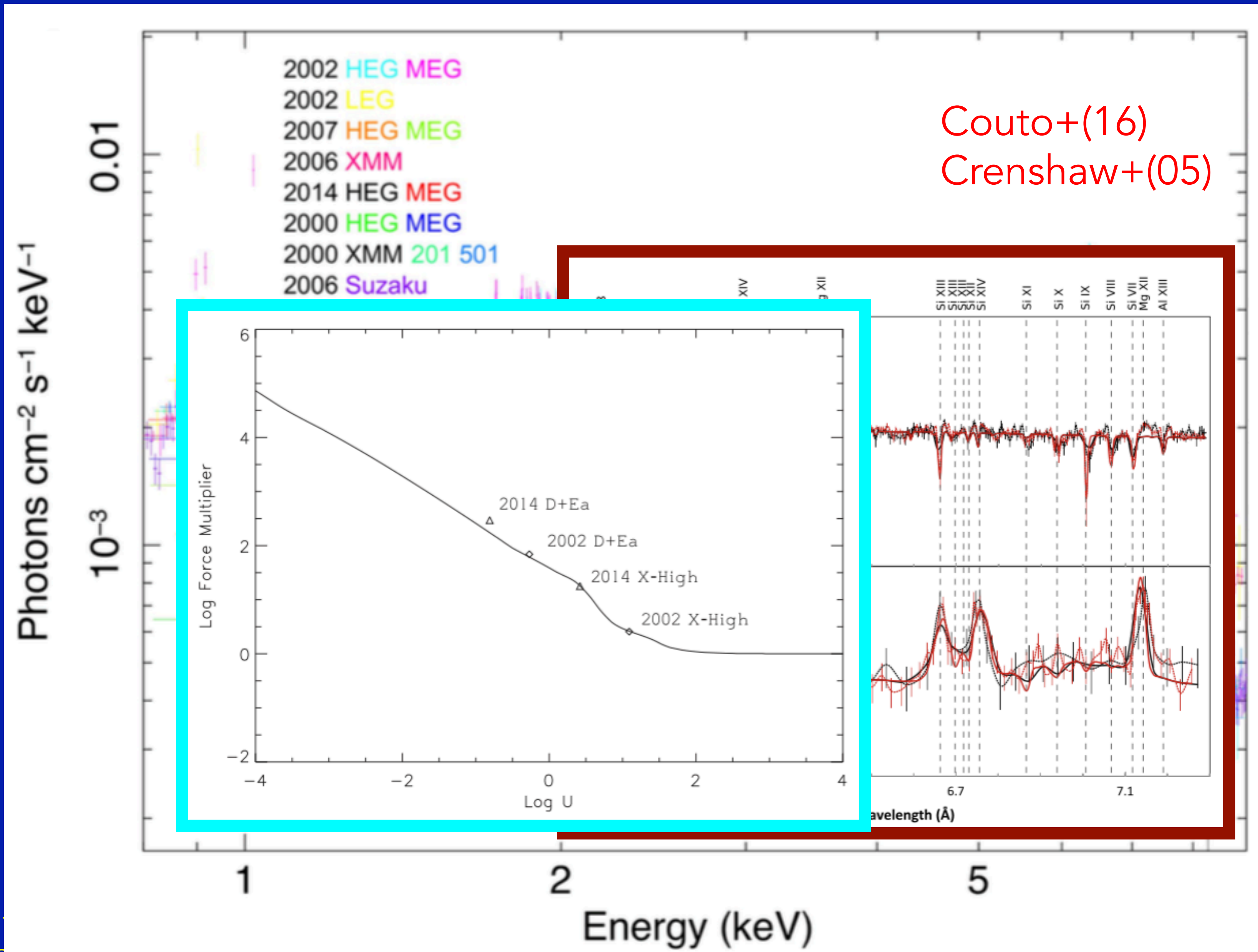
Behar(09)

What about other slope?

- p=3/2 for BP82 MHD winds
  - ➔ AMD~ξ , ξ~r $^{-1/2}$, N_H ~ r $^{-1/2}$ (slowly dropping)
- p=2 for spherical winds & asymptotically coasting radiative winds
  - As soon as wind reaches $V \sim V_{coast}$, ionization freezes at $\xi \sim \xi_o$
  - ➔ singular blueshift, monochromatic ξ
  - ➔ N_H ~ r $^{-1}$ (rapidly dropping)
  - ➔ AMD not a function of ξ or very narrow

Are we seeing MHD-driven winds??? YES!

WAs in NGC 4151



Model Description

(e.g. Fukumura+10a,b,14,15)

(1) Steady-state, axisymmetric ideal MHD eqns. (P_{rad}=0)

Disk treated as BC

$$\nabla \cdot (\rho \mathbf{v}) = 0 \quad \text{(mass conservation)} ,$$

$$\nabla \times \mathbf{B} = \frac{4\pi}{\mathbf{c}} \mathbf{J} \quad \text{(Ampere's law)} ,$$

$$\mathbf{E} + \frac{\mathbf{v}}{\mathbf{c}} \times \mathbf{B} = 0 \quad \text{(ideal MHD)} ,$$

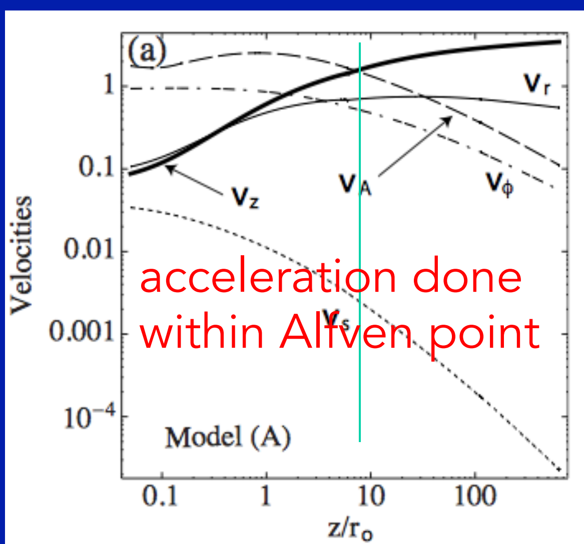
$$\nabla \times \mathbf{E} = 0 \quad \text{(Faraday's law)} ,$$

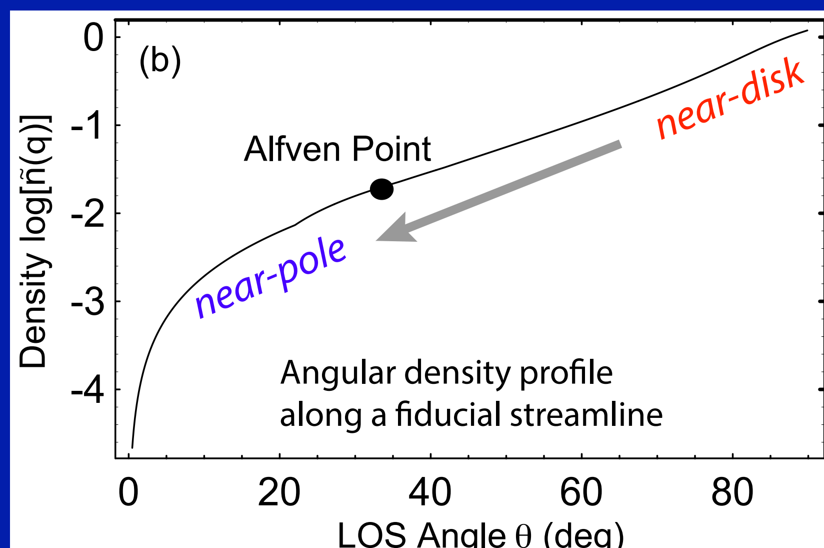
$$\rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla \mathbf{p} - \rho \nabla \Phi_{\mathrm{g}} + \frac{1}{\mathbf{c}} (\mathbf{J} \times \mathbf{B}) \quad \text{(momentum conservation)} ,$$

$$n(r,\theta) \equiv \frac{\rho(r,\theta)}{\mu m_p} = n_o x^{2q-3} \mathcal{N}(\theta)$$

$$N_H(\Delta r, \theta) \equiv \int_{\Delta r} n(r,\theta) dr$$

$$\Psi(r,\theta) = (r/r_o)^q \psi(\theta) \Psi_o ,$$



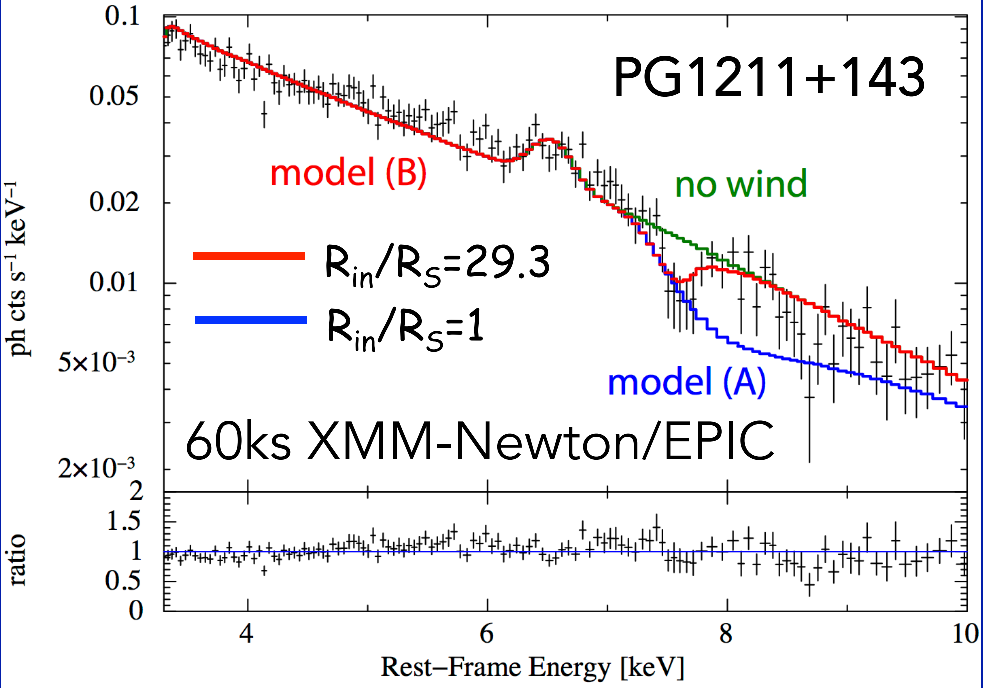


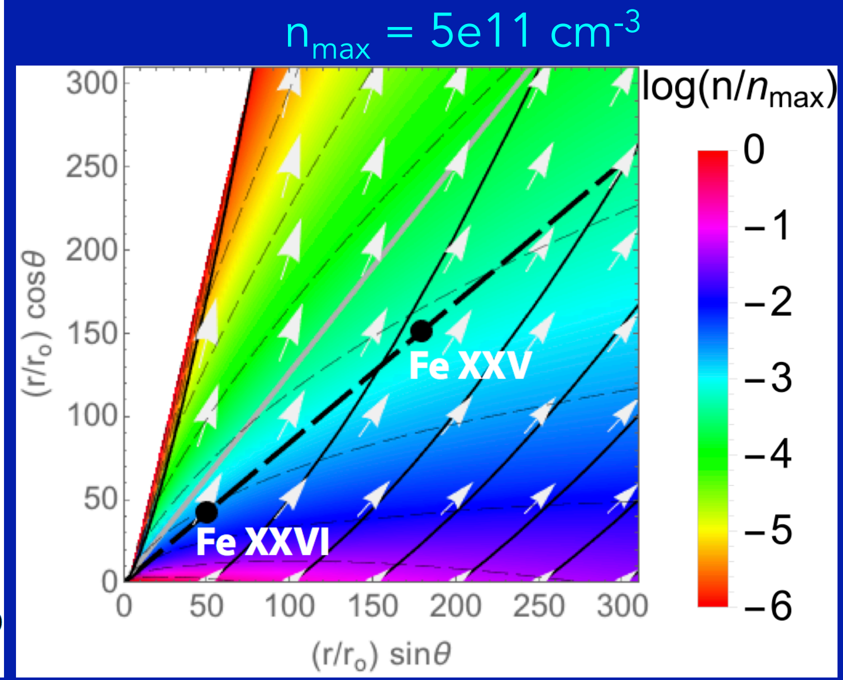
MHD wind is 2D!

Solving Grad-Shafranov eqns. with self-similar radial profiles in MHD framework.

➔ Toroidal (Keplerian) to poloidal motion transition.

Fe XXV UFO in PG 1211+143





Best-fit MHD wind model with p = 1.1:

Fukumura+(15)

θ_{obs} = 49°

N_H(FeXXV) = 1.2x10^{23} cm^{-2}, log ξ_c = 5.3, v/c = 0.115

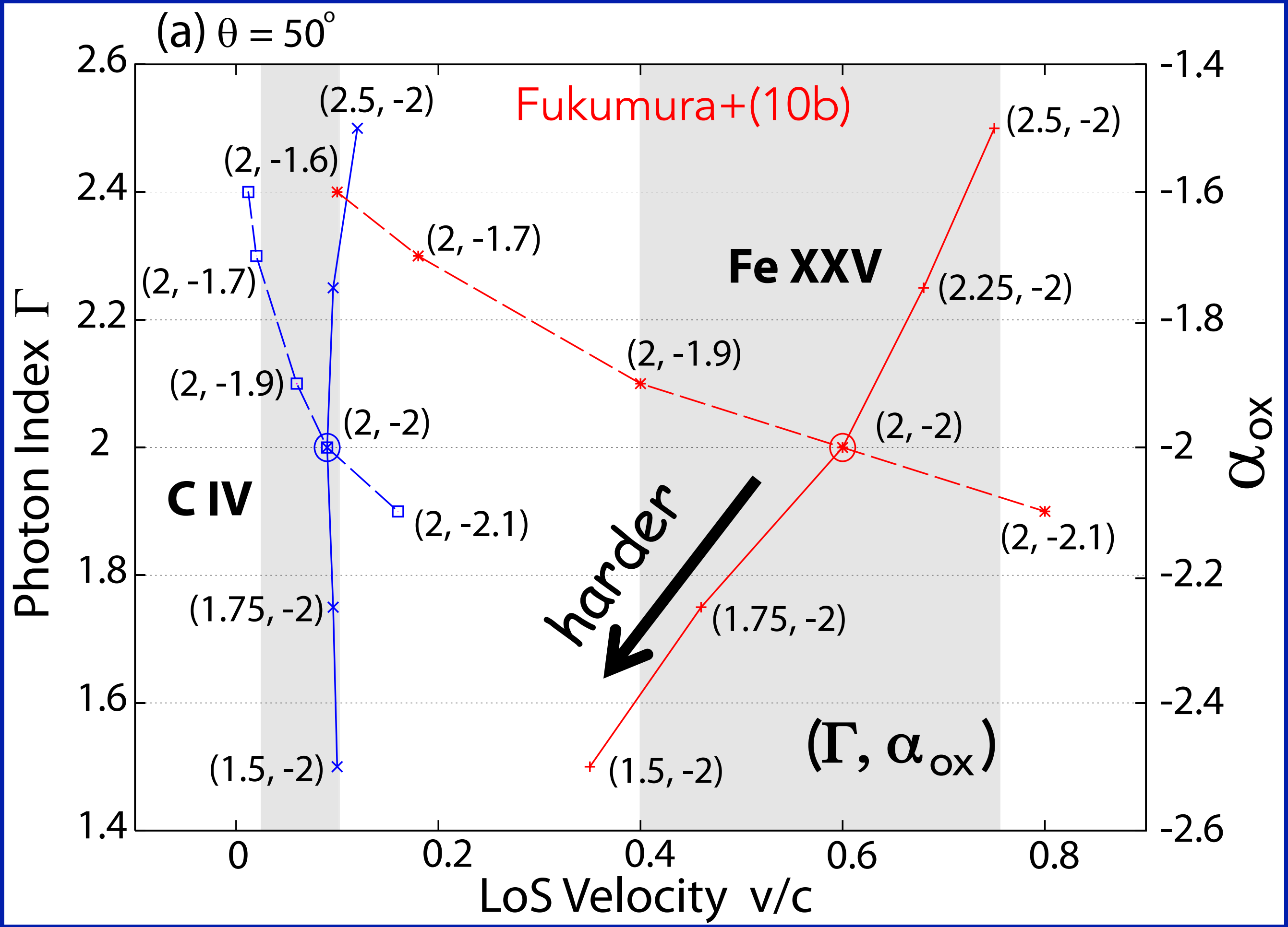
R(FeXXV) = 235 R_S , R_{trunc} = 29.3 R_S

M_{out}(FeXXV) = 2.56Msun/yr, χ^2/dof = 198.54/128

Faster layer of MHD-winds (at smaller radii) can be "visible"

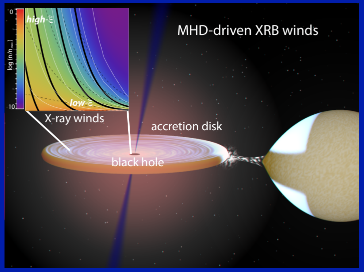
➔ Outflow velocity depends on SED hardness

QSO: Velocity vs. Ionizing SED

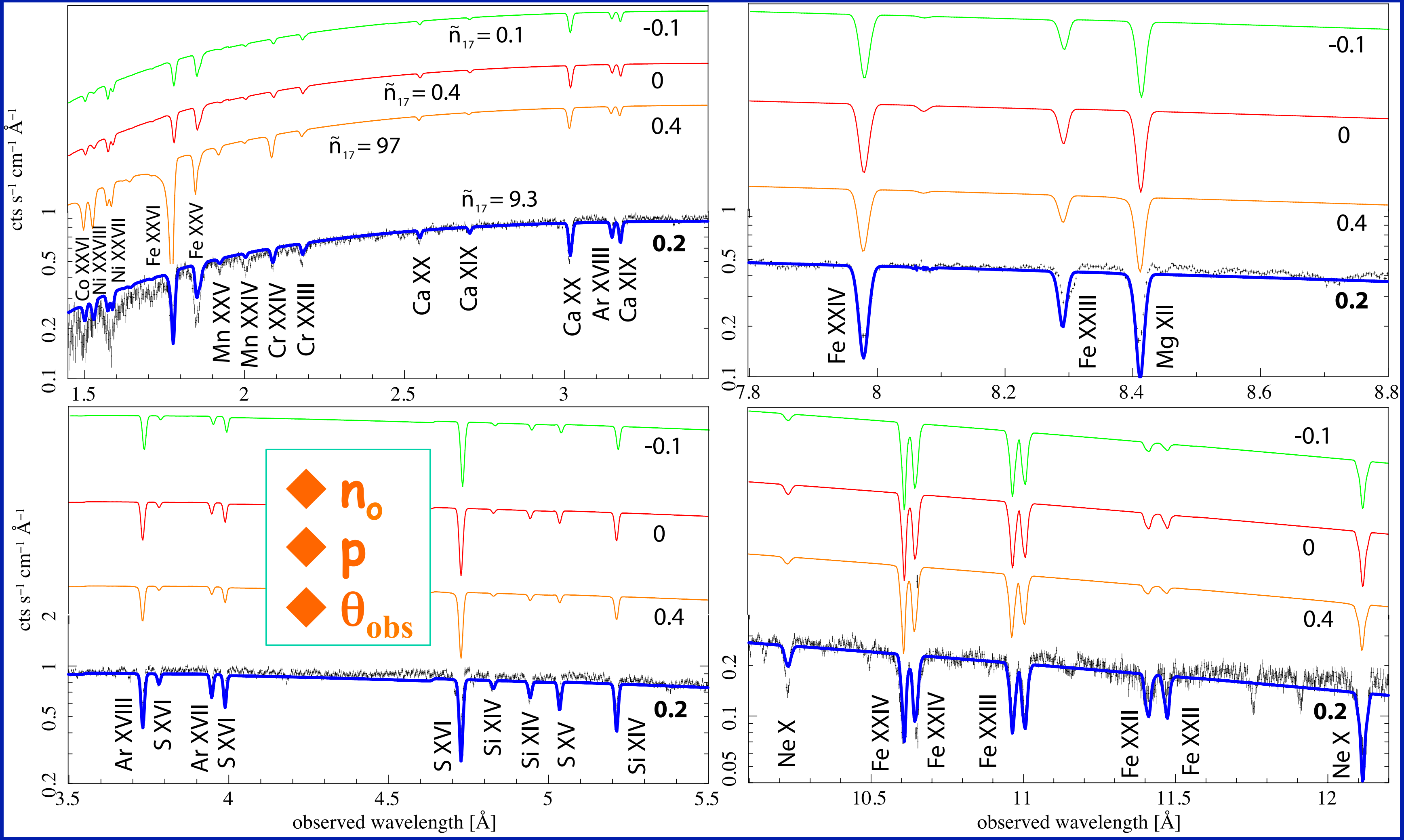


Faster layer of MHD-winds (at smaller radii) can be "visible"
➔ Outflow velocity depends on SED hardness

WAs in XRB GRO J1655-40

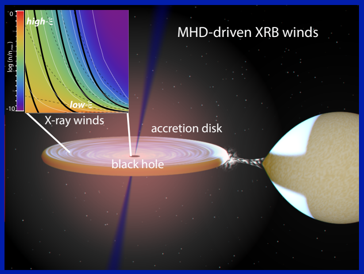


density slope: “p − 1” ➔ control global feature



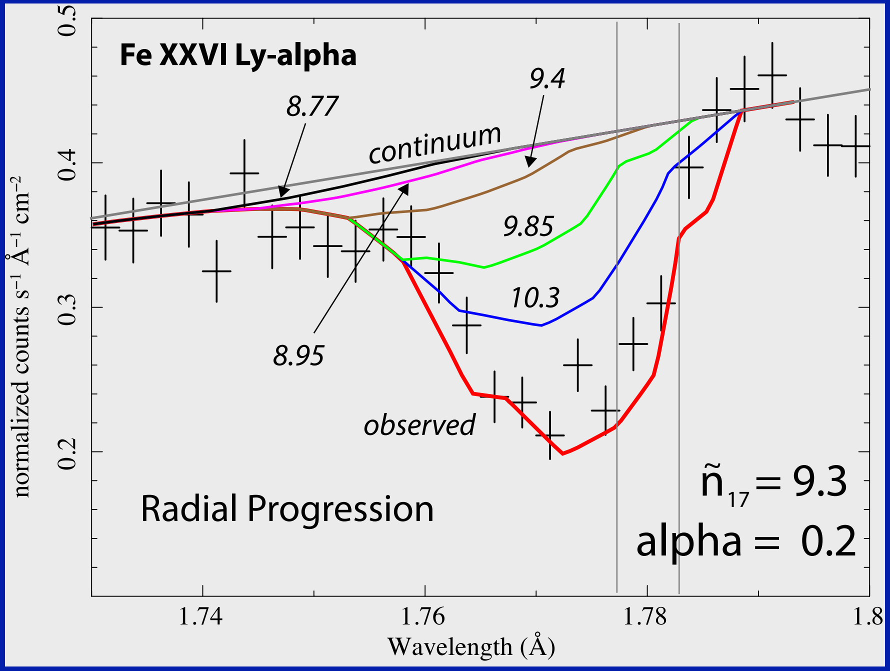
Fukumura+(17), Kallman+(09), Miller+(06,08)

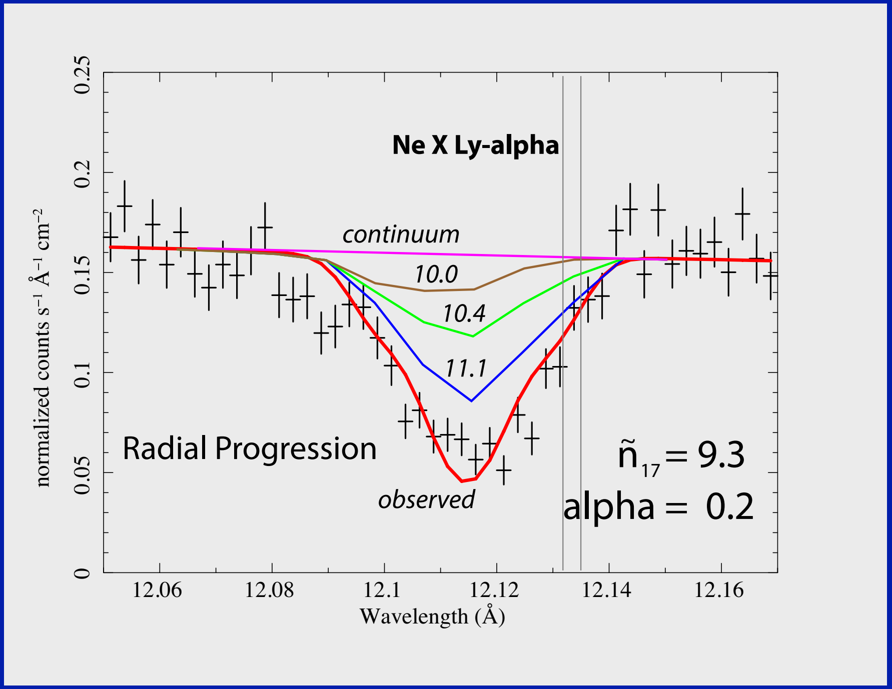
WAs in XRB GRO J1655-40



density slope: "p − 1" ➔ control global feature

- n_o = 9.3e17 cm^{-3}
- p = 1.2
- $\theta_{obs} = 80^o$



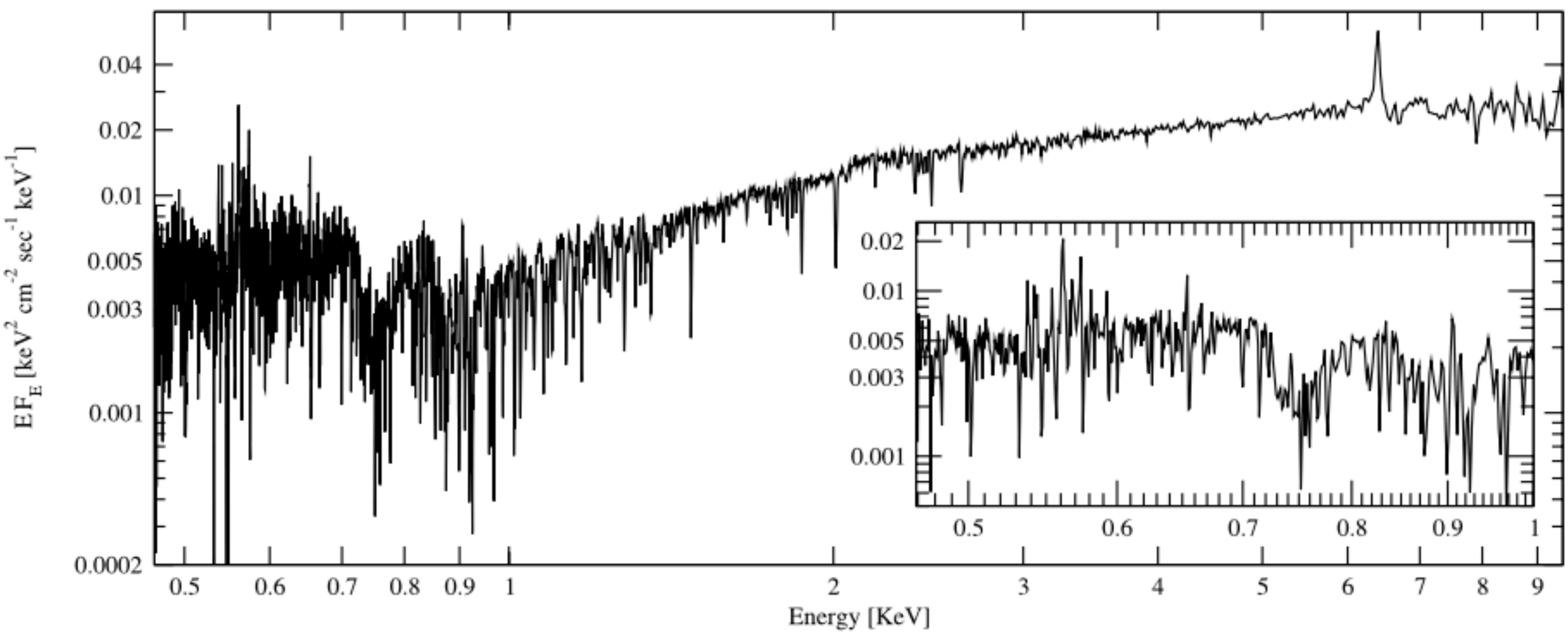


Fukumura+, Nature Astronomy (2017)

WAs in NGC 3783

900 ks (stacked) Chandra/HETG/METG spectrum

Kaspi+(02)



SED (PL: $\Gamma_X \sim 1.8$)
L_{ion} = 1.5e43 erg/s

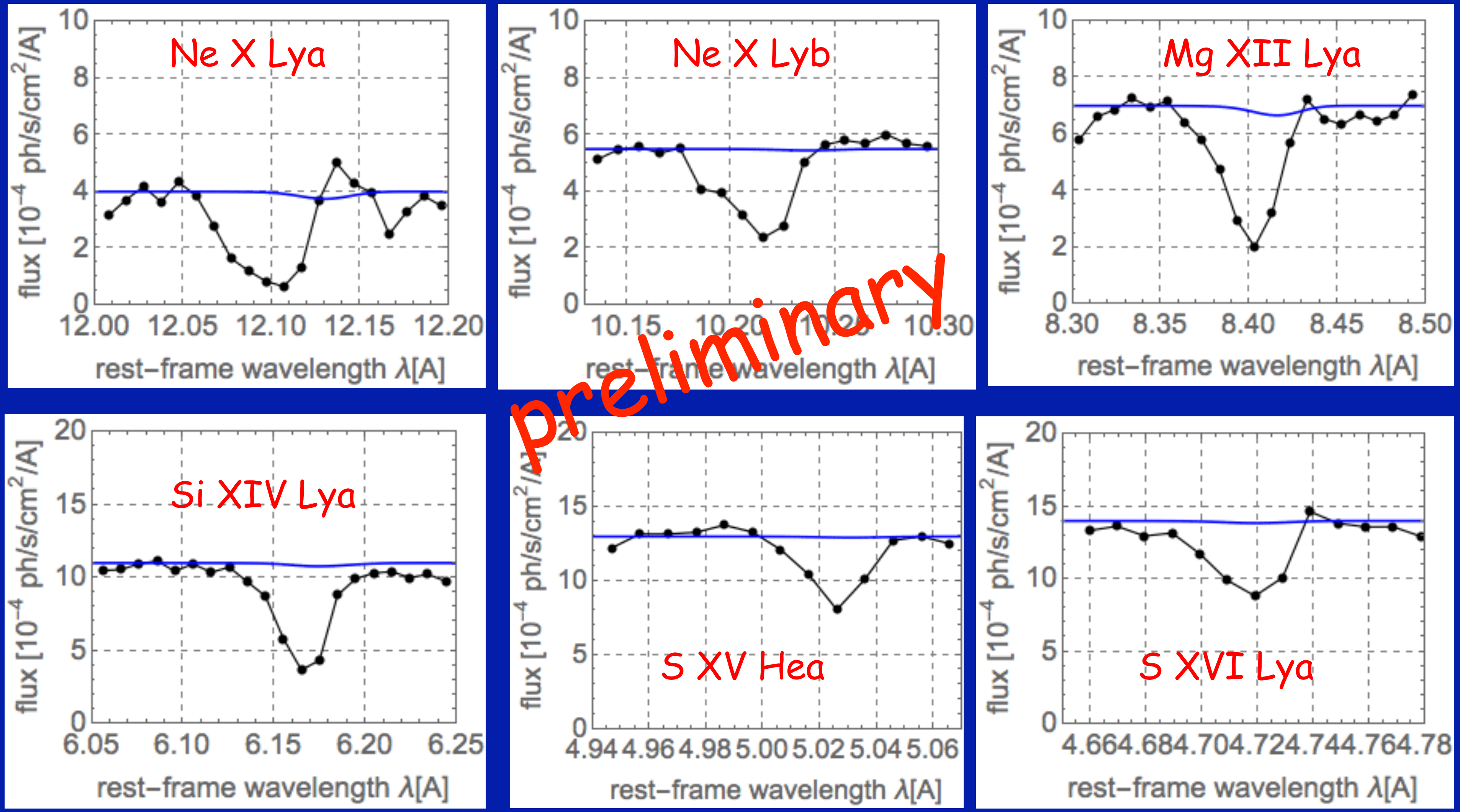
Kaspi+(01)

WAs in NGC 3783

p = 1.15 wind

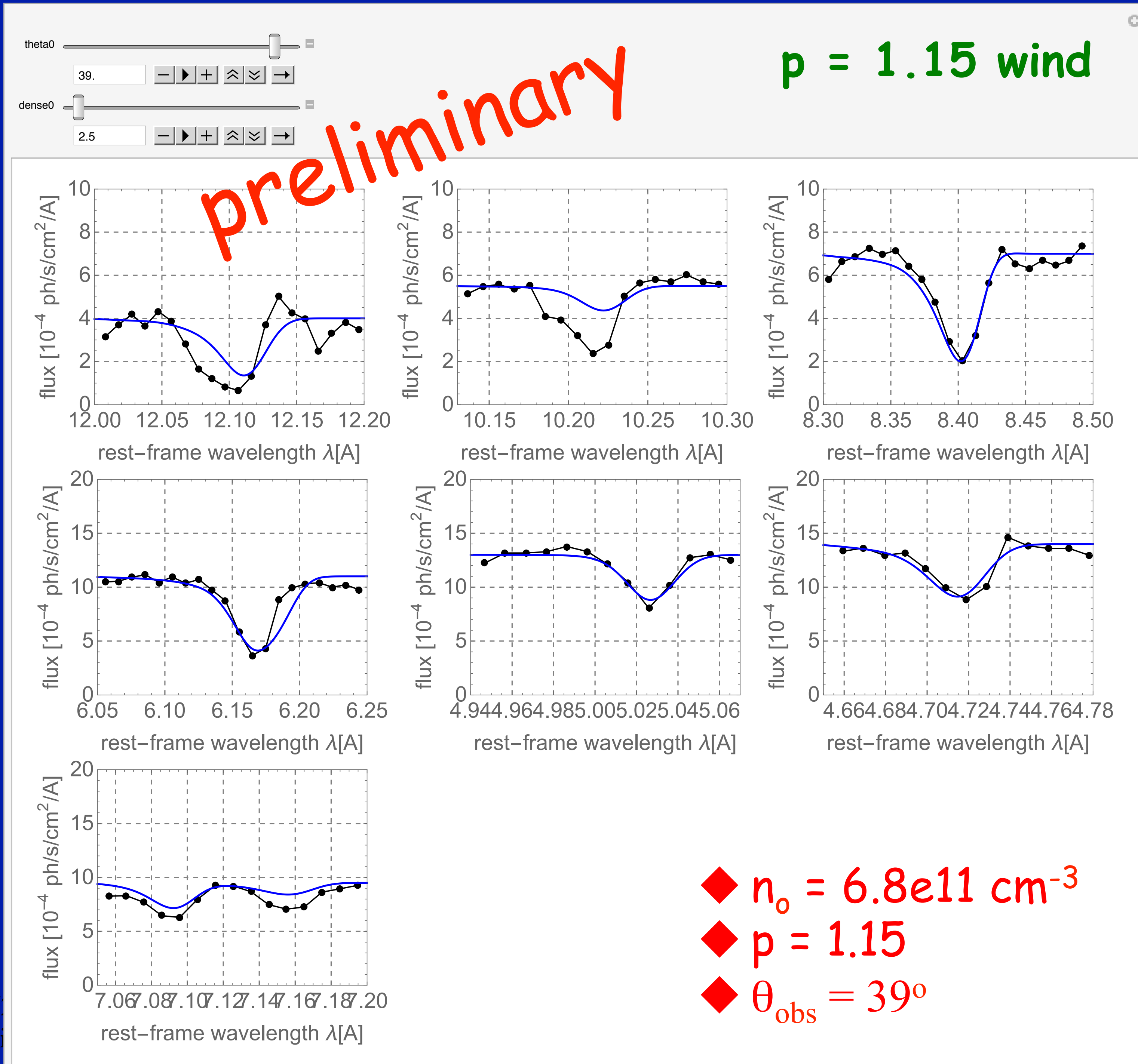
wind density at base: 1.7e11 – 1.1e13 [cm^{-3}]

Inclination: 30° – 50°



p = 1.15 wind

preliminary

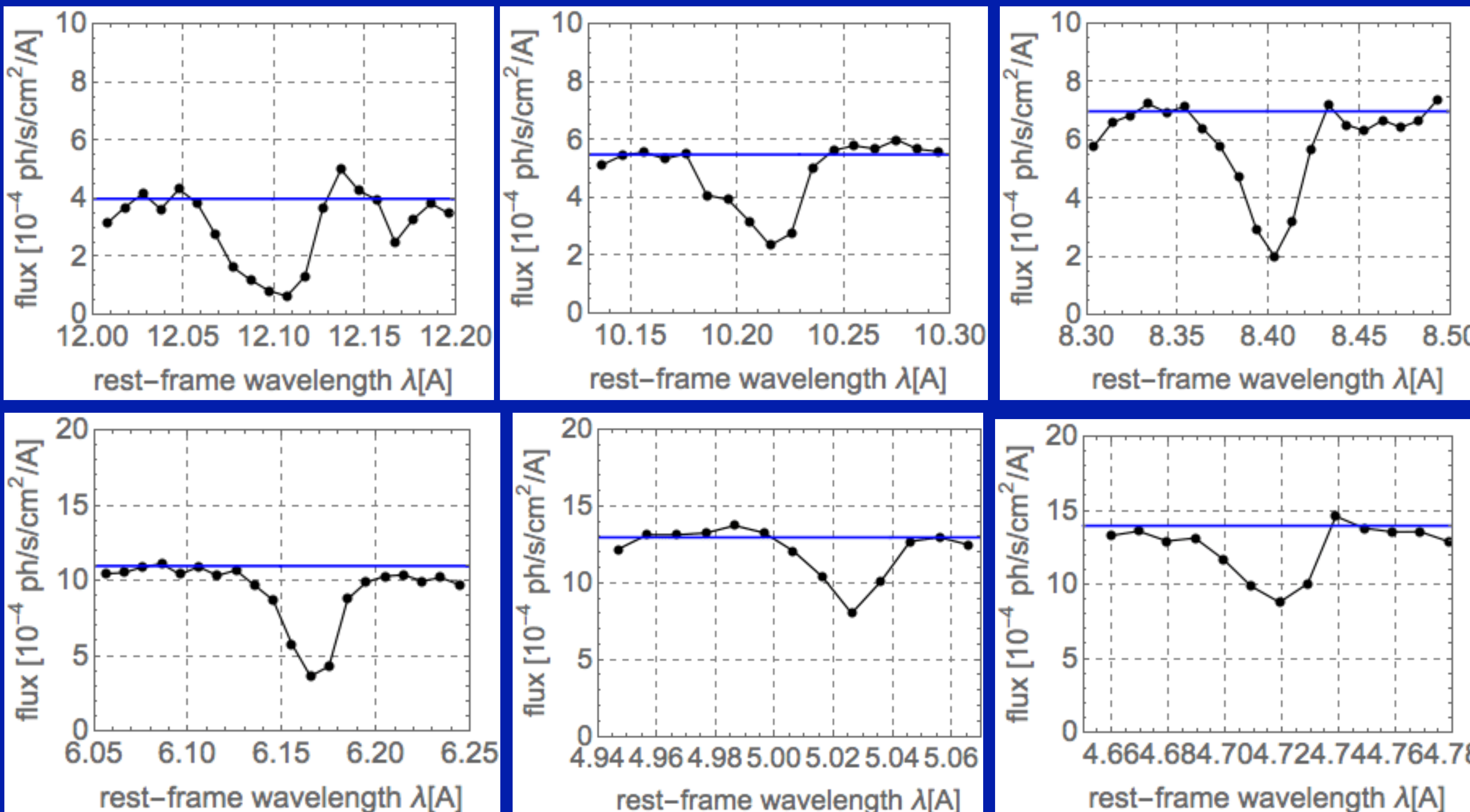


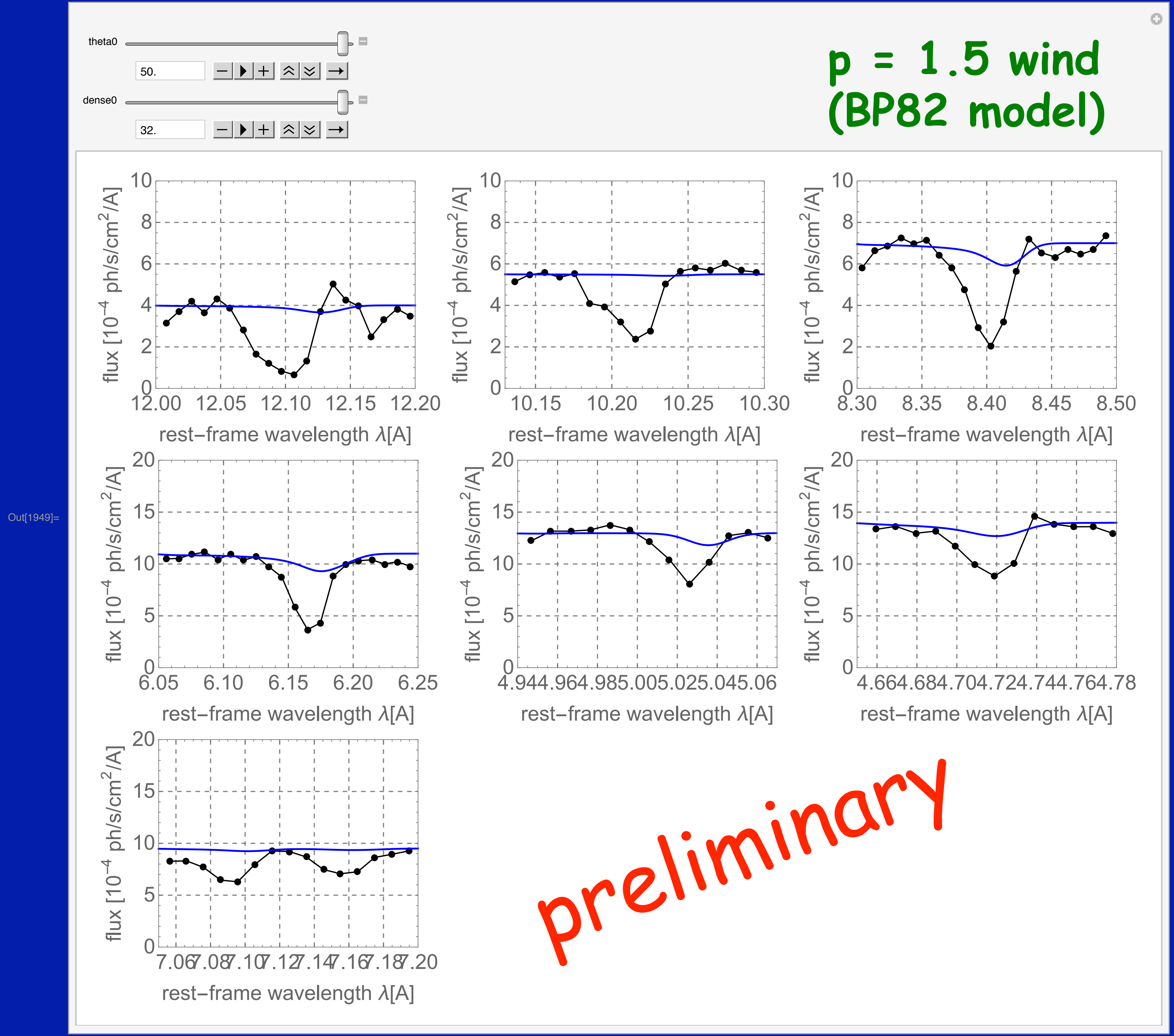
- n_o = 6.8e11 cm^{-3}
- p = 1.15
- $\theta_{obs} = 39^o$

WAs in NGC 3783

p = 1.5 wind
(BP82 model)

wind density at base: 1.7e11 – 1.1e13 [cm^{-3}]
Inclination: 30^{o} – 50^{o}





theta0
50.
dense0
32.
p = 1.5 wind
(BP82 model)
Out[1949]=
flux [10^{-4} ph/s/cm^2/A]
rest–frame wavelength λ[A]
preliminary

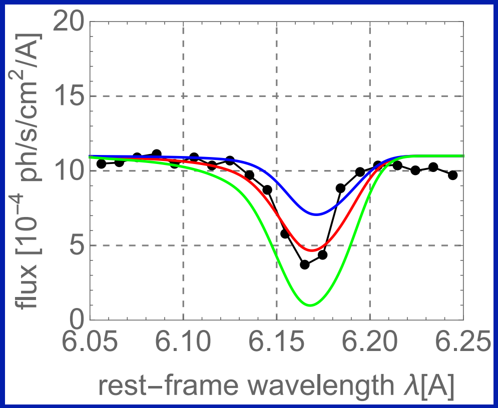
Summary

- Ability to launch H/He-like high-columns

- Global scaling (2D):
  - LoS dependence ➔ AMD
  - (θ,ϕ) dependence ➔ Transverse motion?

- Correlations for a given source
  - AMD, $V_{LOS}(\xi)$, $FM=\sigma_{abs}/\sigma_{Thomson}$, SED-dependence…

non-Gaussian/Voigt



- Asymmetric spectral shape due to ∇V

Potential AGNs for meaningful AMD diagnostics:
NGC 3516, Ark 564, NGC 4051, Mkn 509, Mkn 766, NGC 4151, NGC 3783, NGC 3227, NGC 4507, PG 1211+143, MCG 6-30-15, IRAS 13349+2438 …etc.