Magnetic View of AGN Disk-Winds

Keigo Fukumura
(James Madison University, USA)
fukumukx@jmu.edu

Demos Kazanas (NASA/GSFC)
Chris Shrader (NASA/GSFC)
Francesco Tombesi (NASA/UMD)
Ehud Behar (Technion, Israel)
Ioannis Contopoulos (Academy of Athens, Greece)

6/26/17 AGN winds in GA

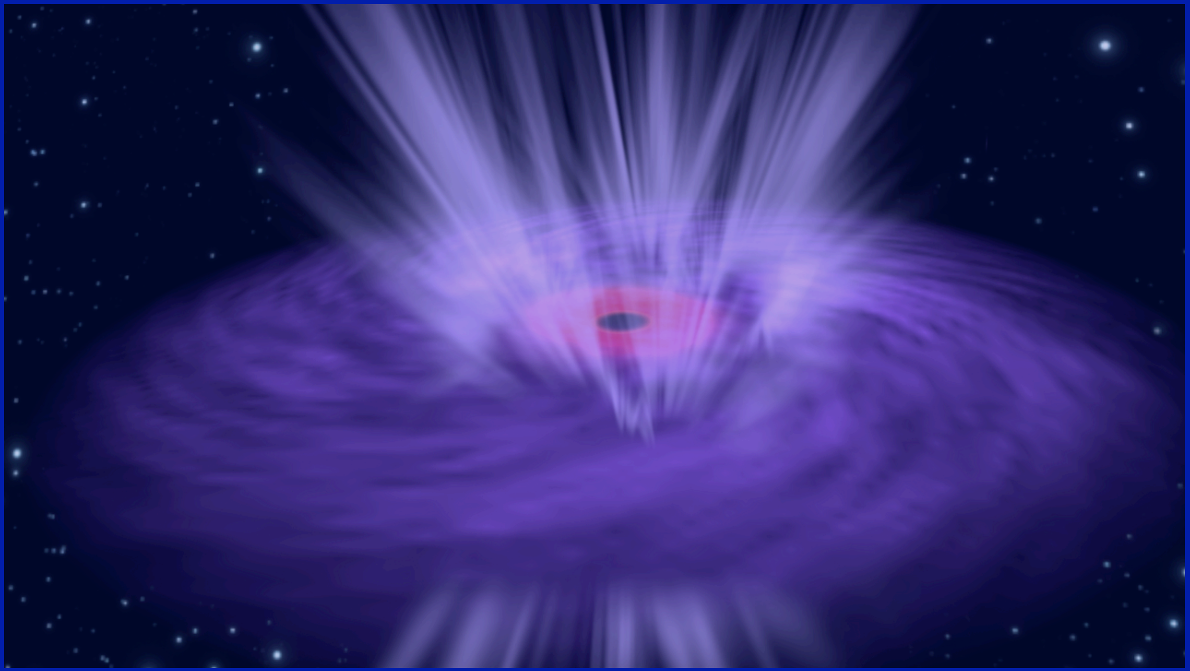
Outline

1) X-Ray Absorbers ~ AGN Disk-Winds

2) Generic Features of MHD-driven Outflows

3) Observables

4) Summary



Credit: The European Space Agency (ESA)

AGN Disk-Winds (WAs + UFOs)

➔ Ubiquitous across diverse Seyferts/QSOs populations

➔ Can learn

[1] column: N_H

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

[3] LoS velocity: v_{LoS}

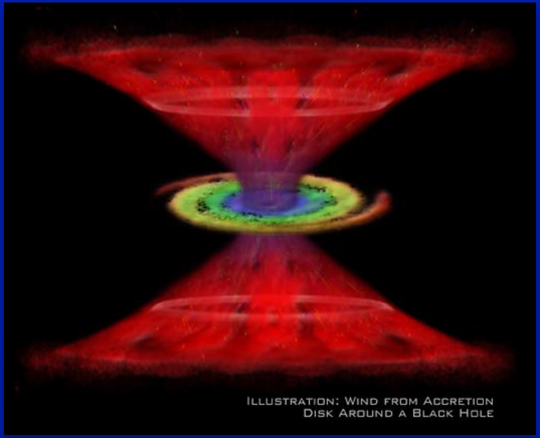
[4] geometry, global property, disk physics, AGN feedback…

~ WAs ~

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

~ UFOs (soft + Fe K) ~

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



General Review: e.g.
Blustin+05, Reynolds+97, Laor&Brandt02, Crenshaw+03, Crenshaw&Kraemer12, Tombesi+13, Laha+(14,16)…etc.

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

Ionized X-ray Absorbers

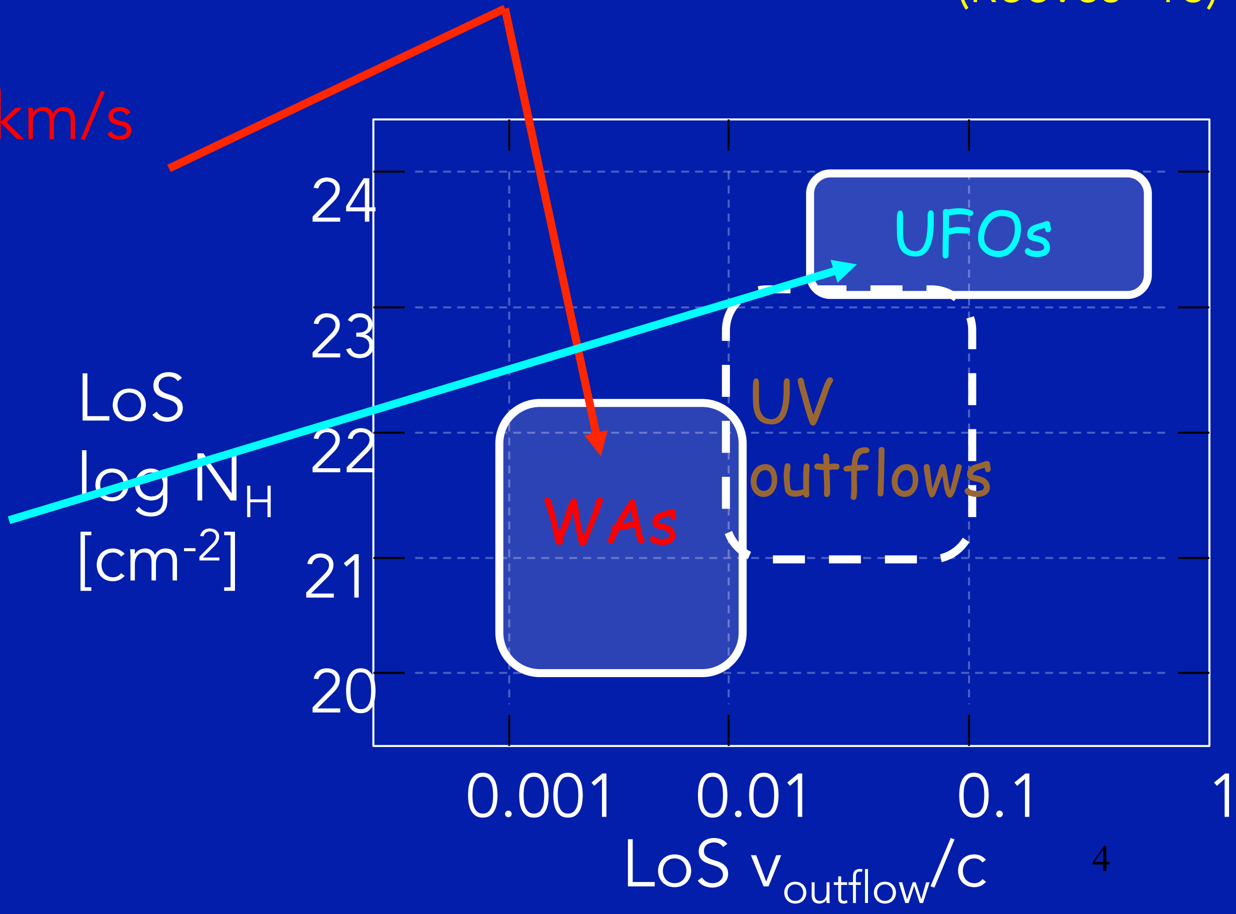
(i.e. Warm Absorbers & Ultra-Fast Outflows)

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

* *Also soft X-ray UFOs (e.g. Mg, Ne)*
(Reeves+16)

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

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



Outstanding Questions

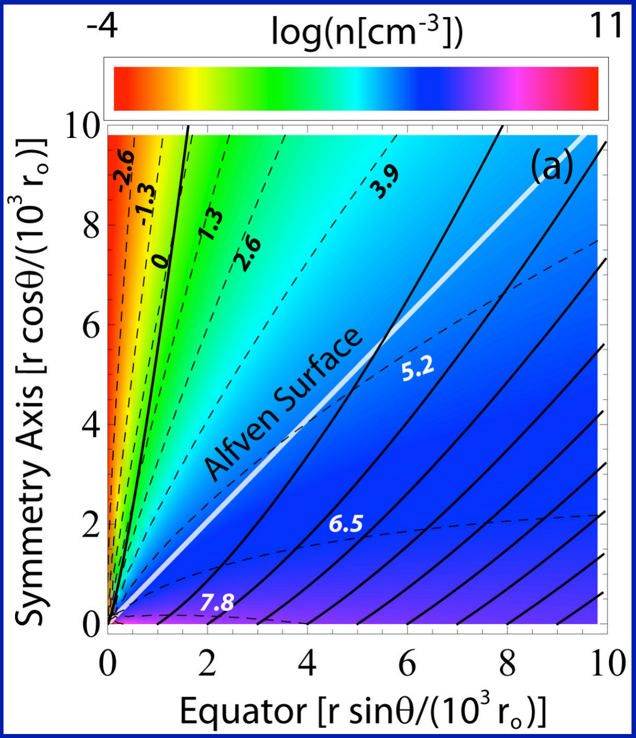
- ✓ Flow Geometry?
- ✓ Continuous or patchy?
- ✓ Defining quantities?
- ✓ How are they launched?

Some "good" indicators for MHD-driven winds…

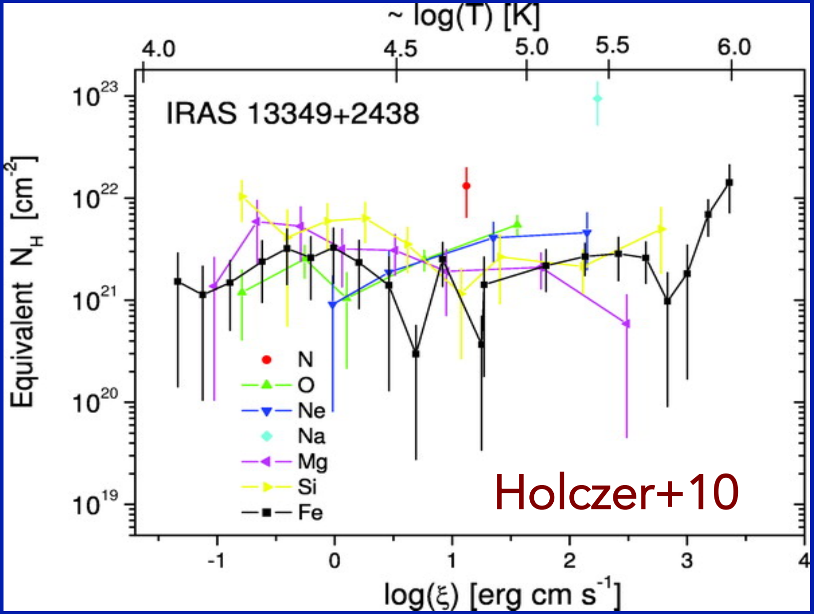
w/ gratings

- ☐ High ξ, v, N_H (UFOs)
- ☐ Flat (or slightly varying) AMD
- ☐ Insufficient force multiplier
- ☐ Process of elimination by "R" and "ξ"…

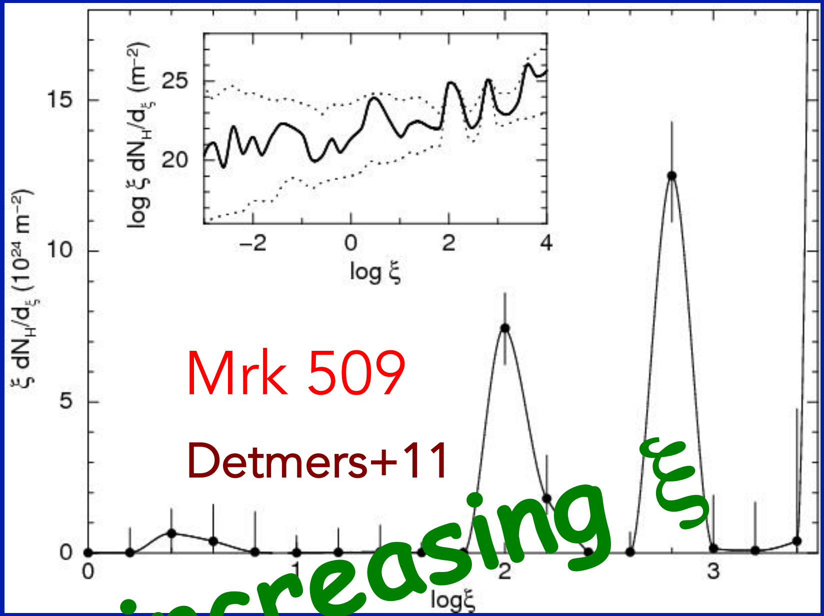
Fukumura+10



Absorption Measure Distribution (AMD)

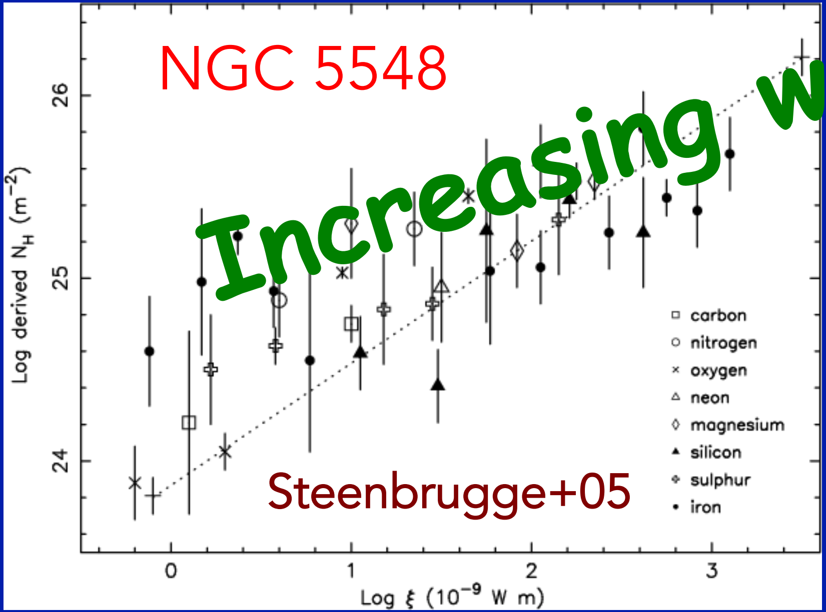


Holczer+10



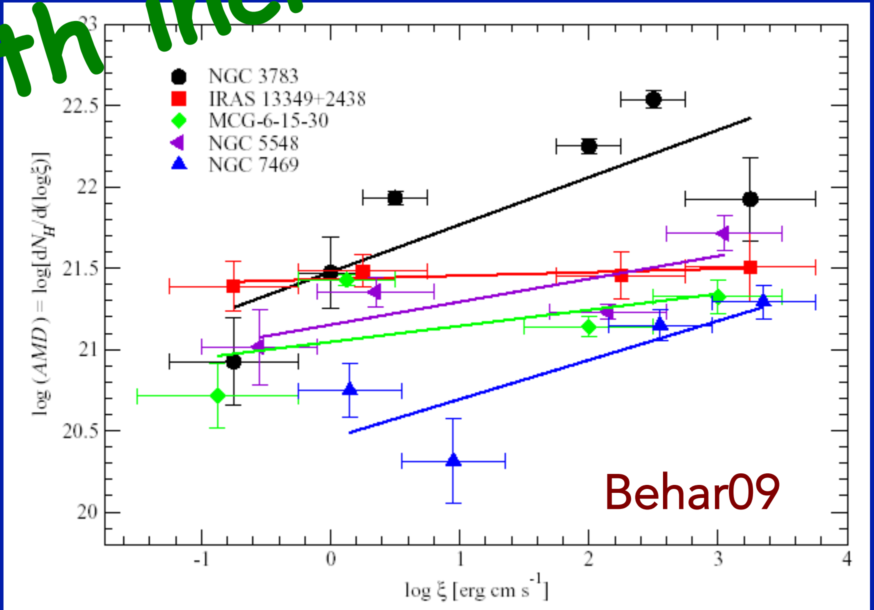
Mrk 509

Detmers+11



NGC 5548

Steenbrugge+05



Behar09

Increasing with increasing ξ

What does AMD tell us?

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

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

Behar09
Kazanas+12

Hence, p~1 wind

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

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

Toroidal rotation efficiently converted into poloidal motion,

- ☐ Plasma accelerated along a field line while V_{base} ~ V_{esc} ~ r $^{-1/2}$
- ☐ N_H ~ const per decade in radius
- ☐ v_{out} ~ $\xi^{1/2}$

Kazanas+12

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

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

outflow rate ← exterior kinetic power ← interior

What does AMD tell us?

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

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

Behar09
Kazanas+12

What about other slope?

☐ p=3/2 for BP82 MHD winds

➔ AMD~ξ , $\xi \sim r^{-1/2}$, $v_{out} \sim \xi$, $N_H \sim r^{-1/2}$ (slowly dropping)

☐ p=2 for spherical winds & asymptotically coasting radiative winds

As soon as wind reaches $v \sim v_{coast}$, ionization freezes at $\xi \sim \xi_o$

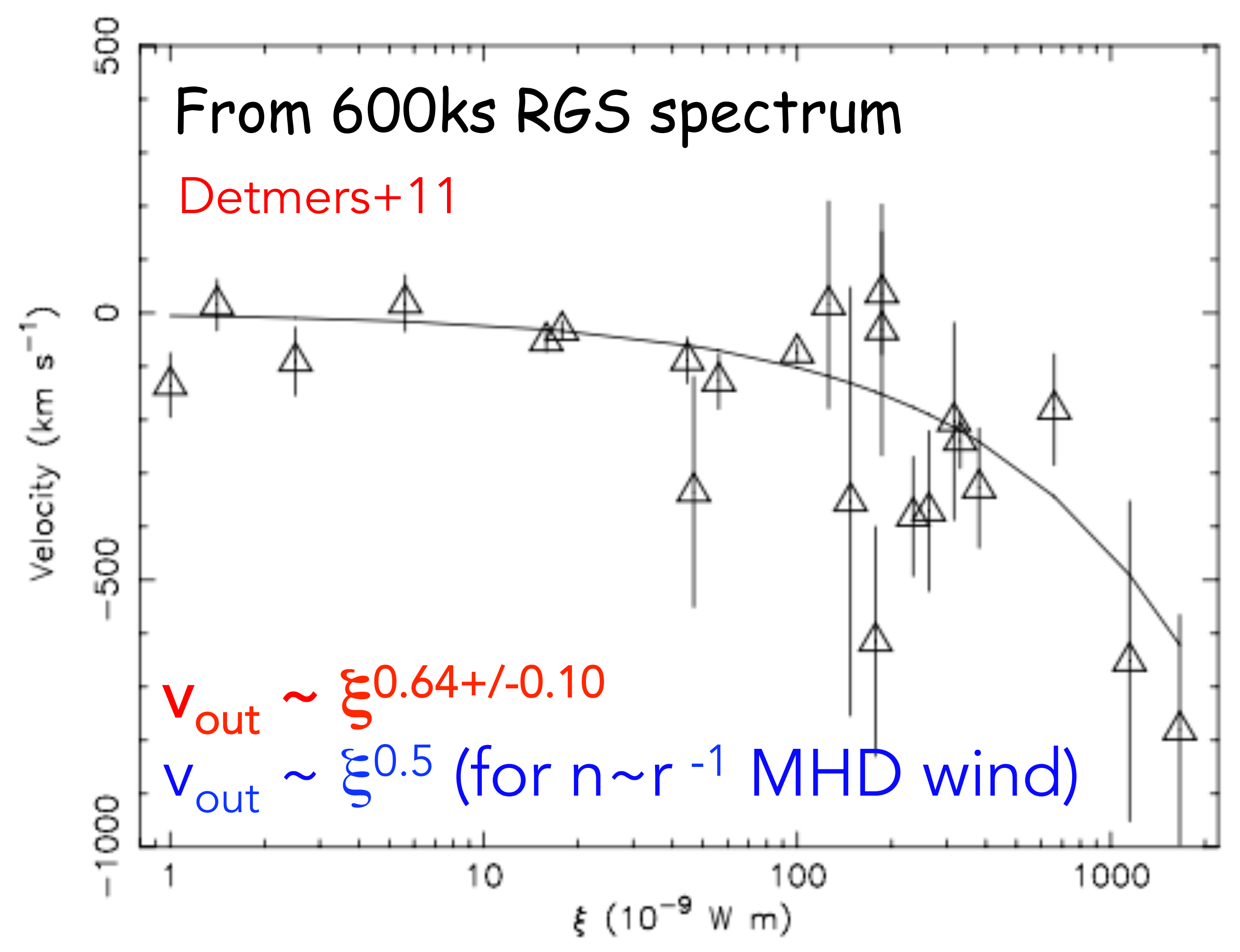
➔ singular blueshift, monochromatic ξ

➔ $N_H \sim r^{-1}$ (rapidly dropping)

➔ AMD not a function of ξ (i.e. very narrow)

Are we seeing MHD-driven winds???

Multi-λ campaign of Mrk 509



From 600ks RGS spectrum

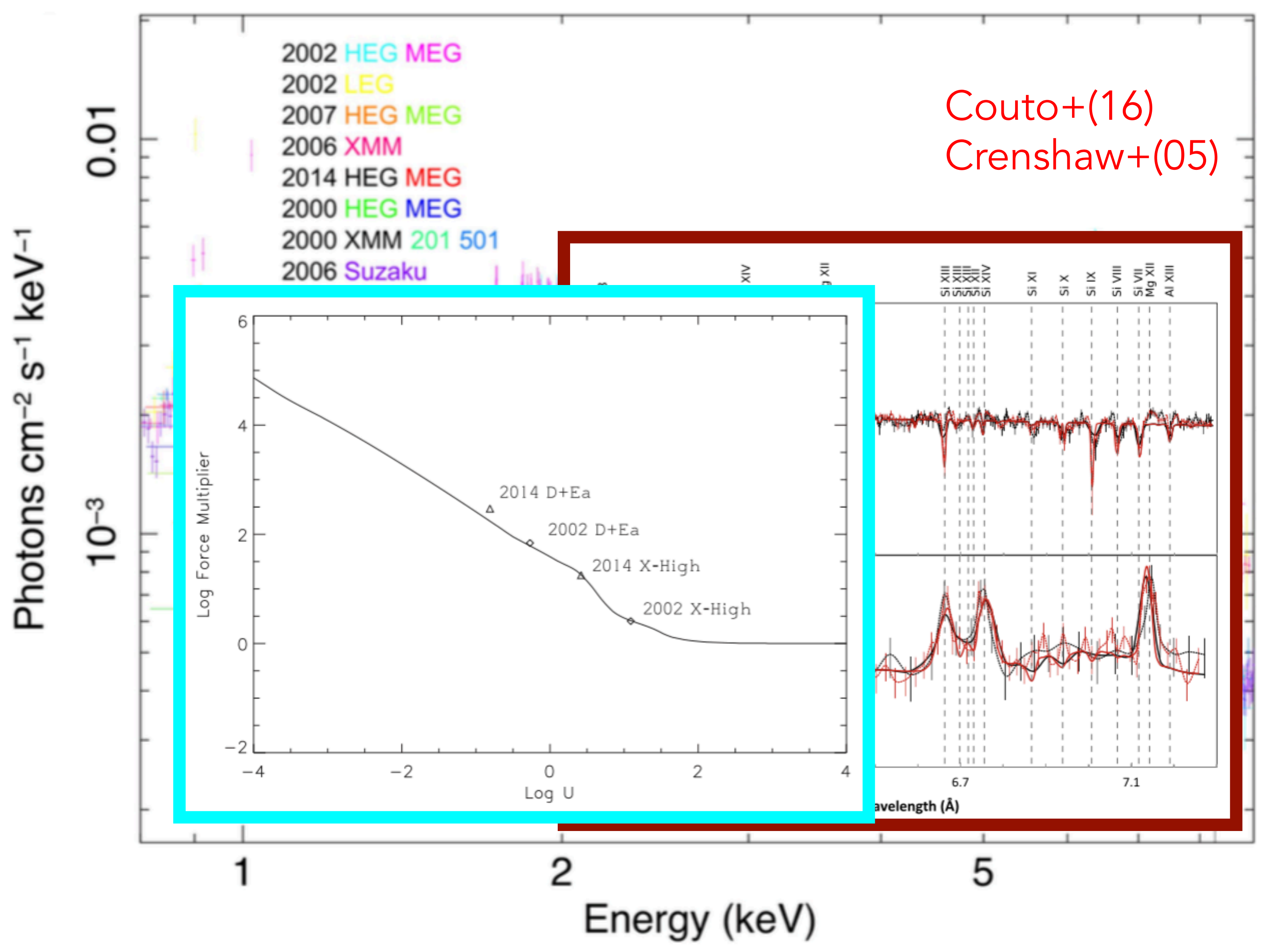
Detmers+11

$v_{out} \sim \xi^{0.64+/-0.10}$

$v_{out} \sim \xi^{0.5}$ (for $n \sim r^{-1}$ MHD wind)

Indicating magnetic-origin?

WAs in NGC 4151



Couto+(16)
Crenshaw+(05)

Magnetized Disk-Wind Models

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

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

Disk treated as BC

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

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

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

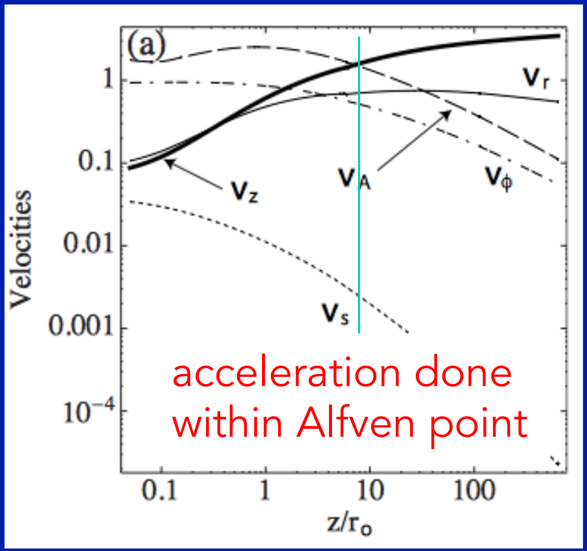
$$\nabla \times \mathbf{E} = 0 \quad \text{(Faraday's law)} ,$$

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

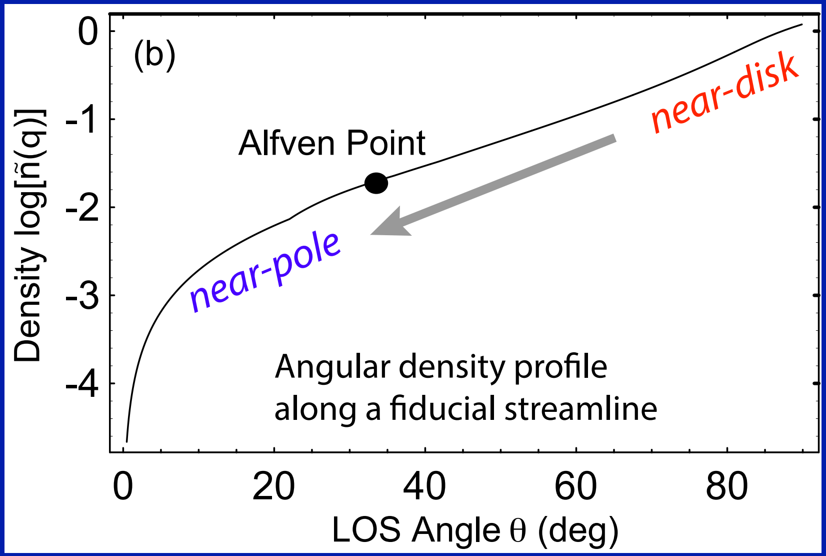
$$n(r,\theta) \equiv \frac{\rho(r,\theta)}{\mu m_p} = n_o x^{2q-3} \mathcal{N}(\theta)$$

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

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



acceleration done within Alfven point



Alfven Point

near-disk

near-pole

Angular density profile along a fiducial streamline

MHD wind is 2D!

Solving Grad-Shafranov eqns. with self-similar radial profiles.

➔ Toroidal (Keplerian) to poloidal motion transition.

Magnetic Disk-Wind Models

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

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

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

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

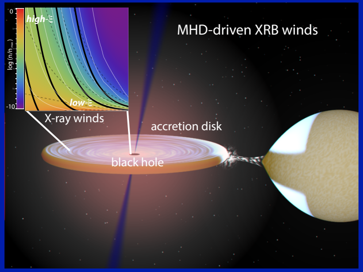
$$\Psi(r,\theta) = (r/r_o)^q \psi(\theta) \Psi_o ,$$

Generic MHD-Wind Properties

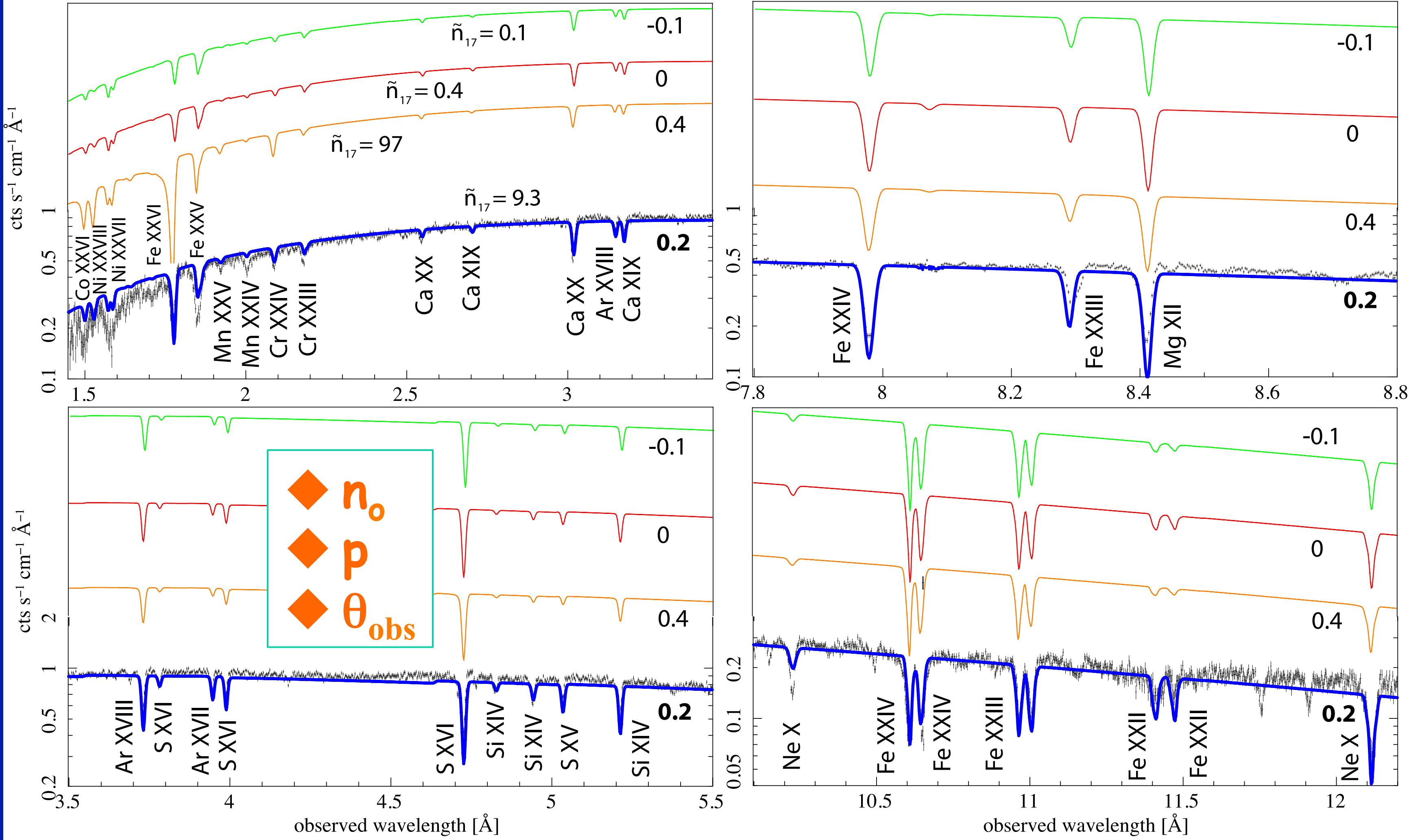
- ❖ Mass-invariant (across XRBs and AGNs)
- ❖ Inner part of the wind is inherently near-relativistic
- ❖ Accommodate both UFOs (inner) and WAs (outer)
- ❖ SED (e.g. Γ and α_{OX}) "breaks" mass-invariant!

➔ allows for diverse ionization structure!

WAs in XRB GRO J1655-40



density slope: $n \sim r^{-1.2}$ ➔ control global feature

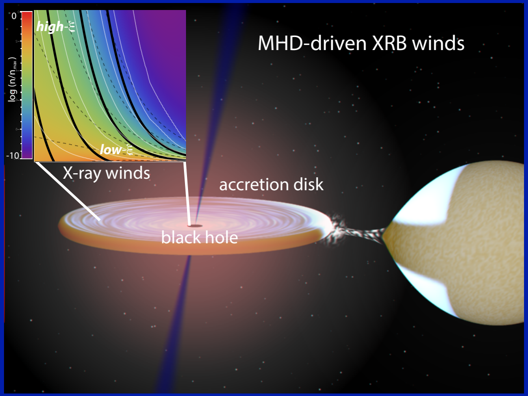


- ◆ n_o
- ◆ p
- ◆ θ_{obs}

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

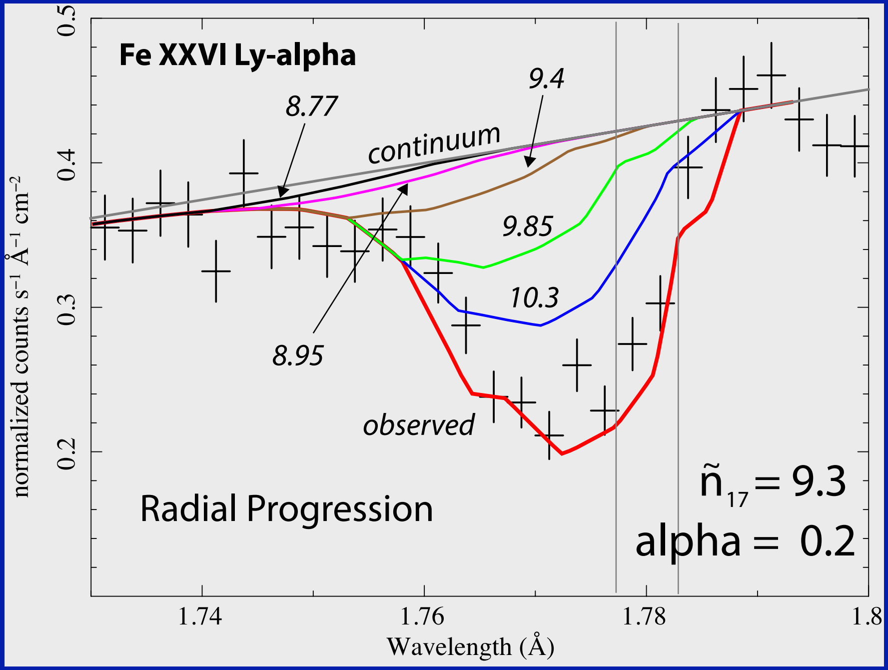
Magnetic WAs in XRB GRO J1655-40

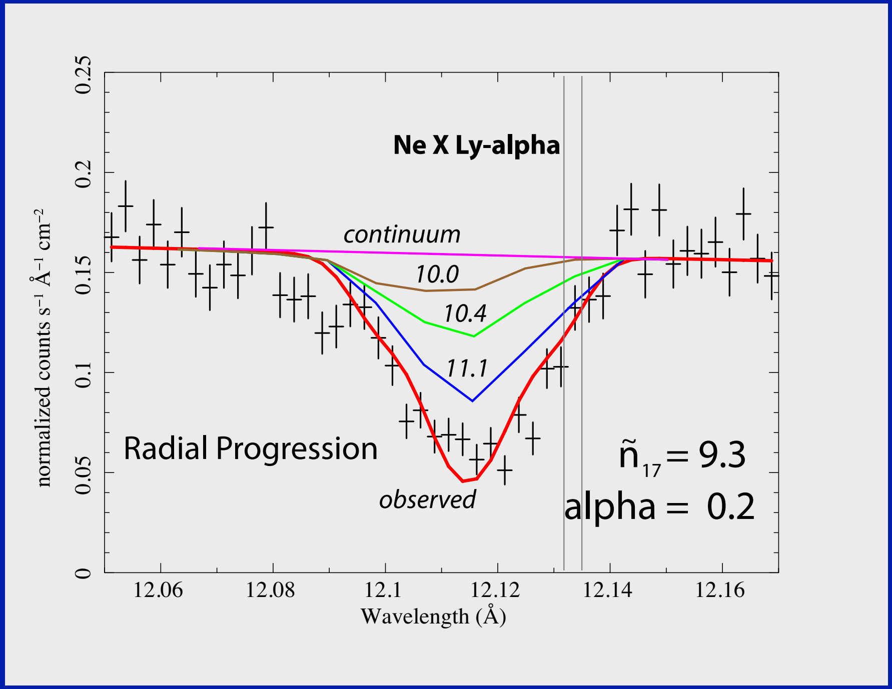
density slope: $n \sim r^{-1.2}$ ➔ control global feature



We calculate *progressive spectra* along LoS

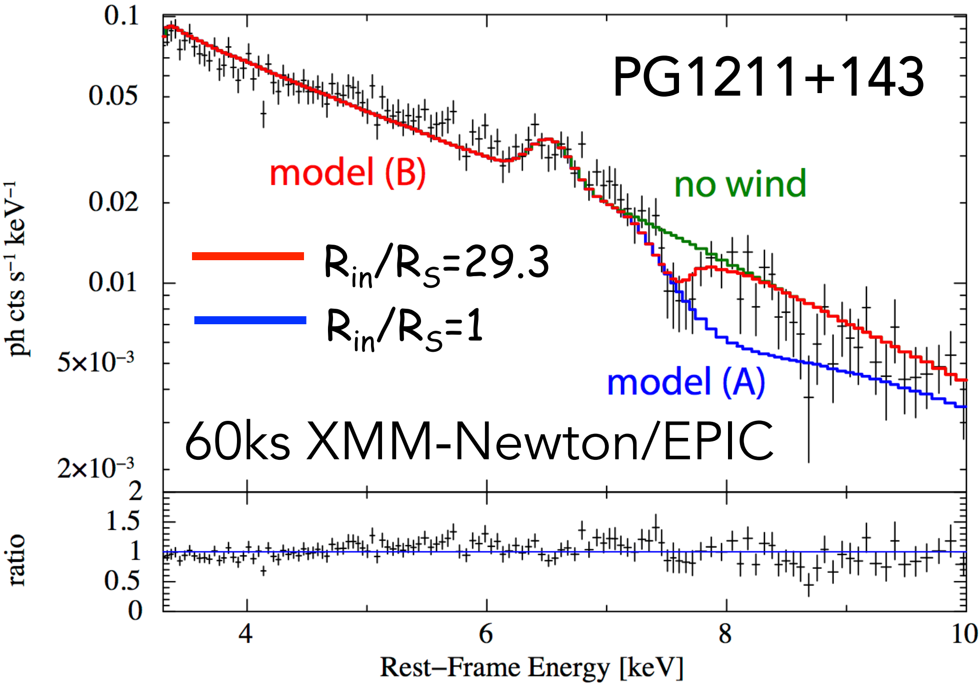
- $n_o = 9.3e17\ cm^{-3}$
- $\theta_{obs} = 80^o$

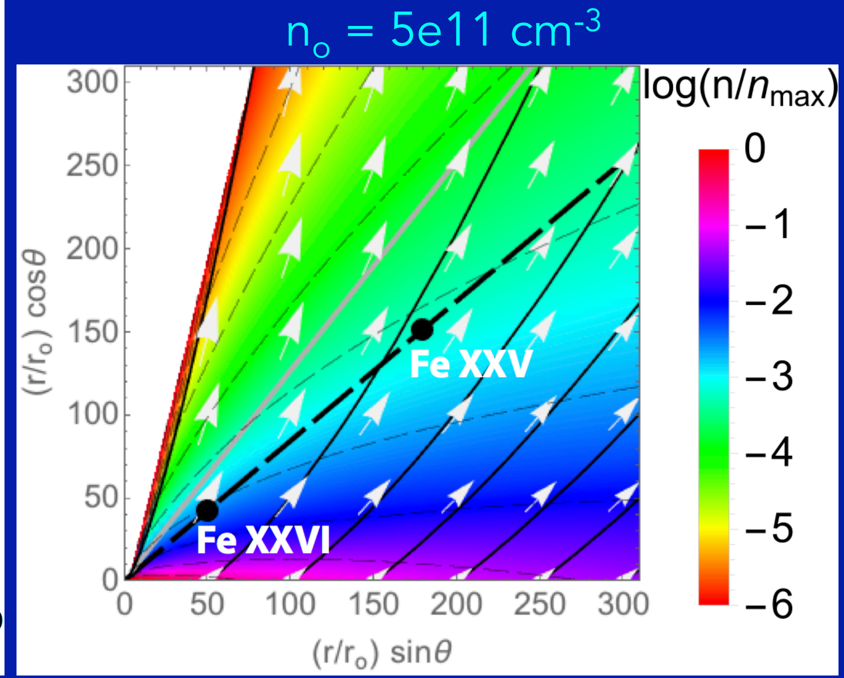




Fukumura+17, Nature Astronomy,
230th AAS Press Release (Texas)

Fe K UFO in PG 1211+143





<u>Best-fit MHD wind model with r^{-1}:</u> α_{OX} = -1.5 assumed

θ_{obs} = 49°

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

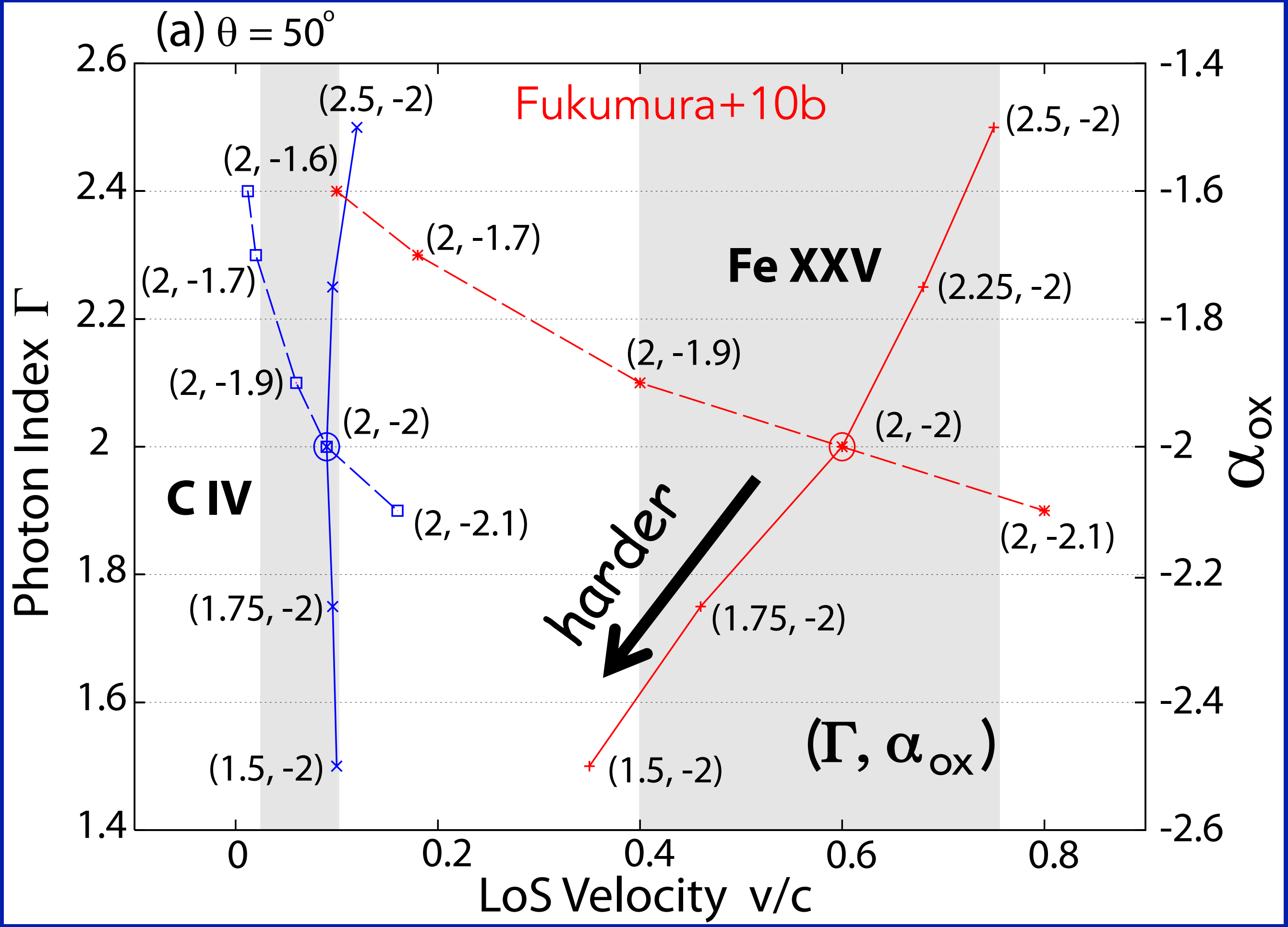
R(FeXXV) = 235 R_S , R_{trunc} = 29.3 R_S

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

Fukumura+15

Faster layer of MHD-winds (at smaller radii) is inherently present regardless of L/L_{edd} ➔ Outflow velocity Func(F_ν and θ)

QSO: Velocity vs. Ionizing SED

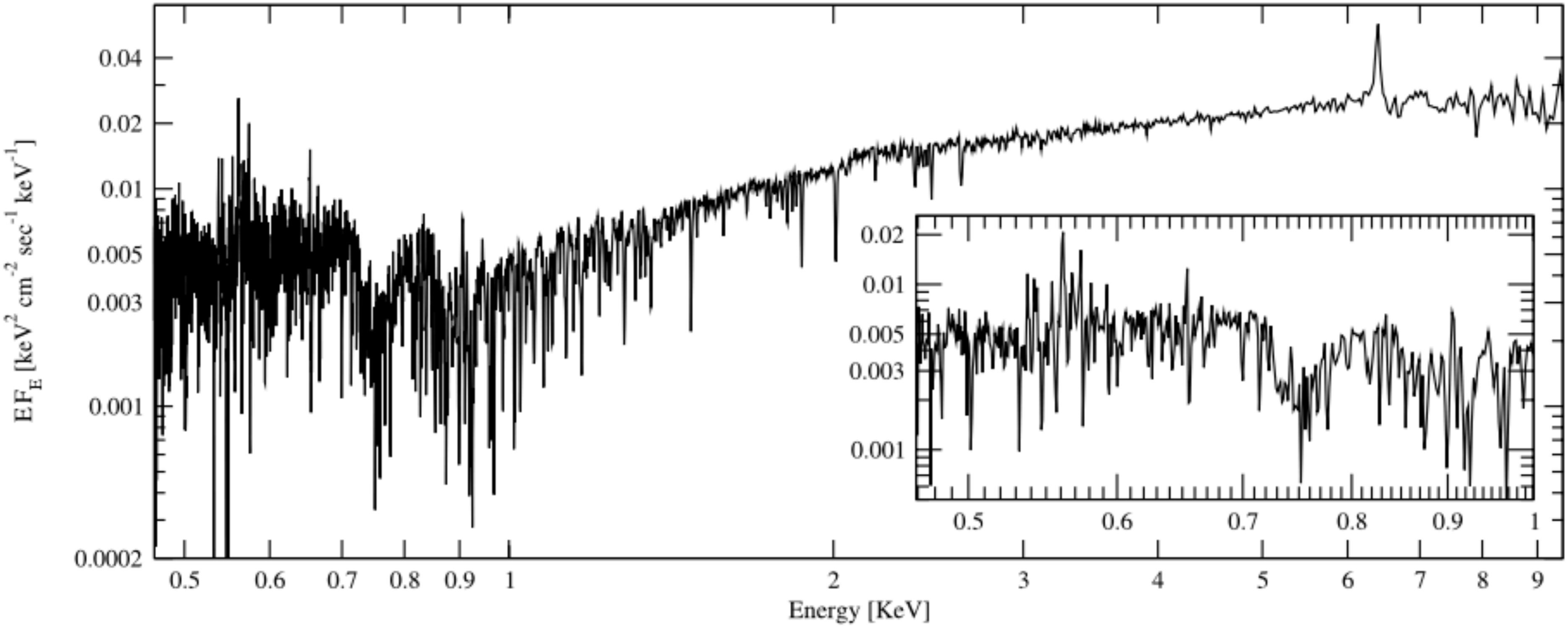


Faster layer of MHD-winds (at smaller radii) can be "visible"
➔ Outflow velocity depends on SED hardness

Magnetic 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

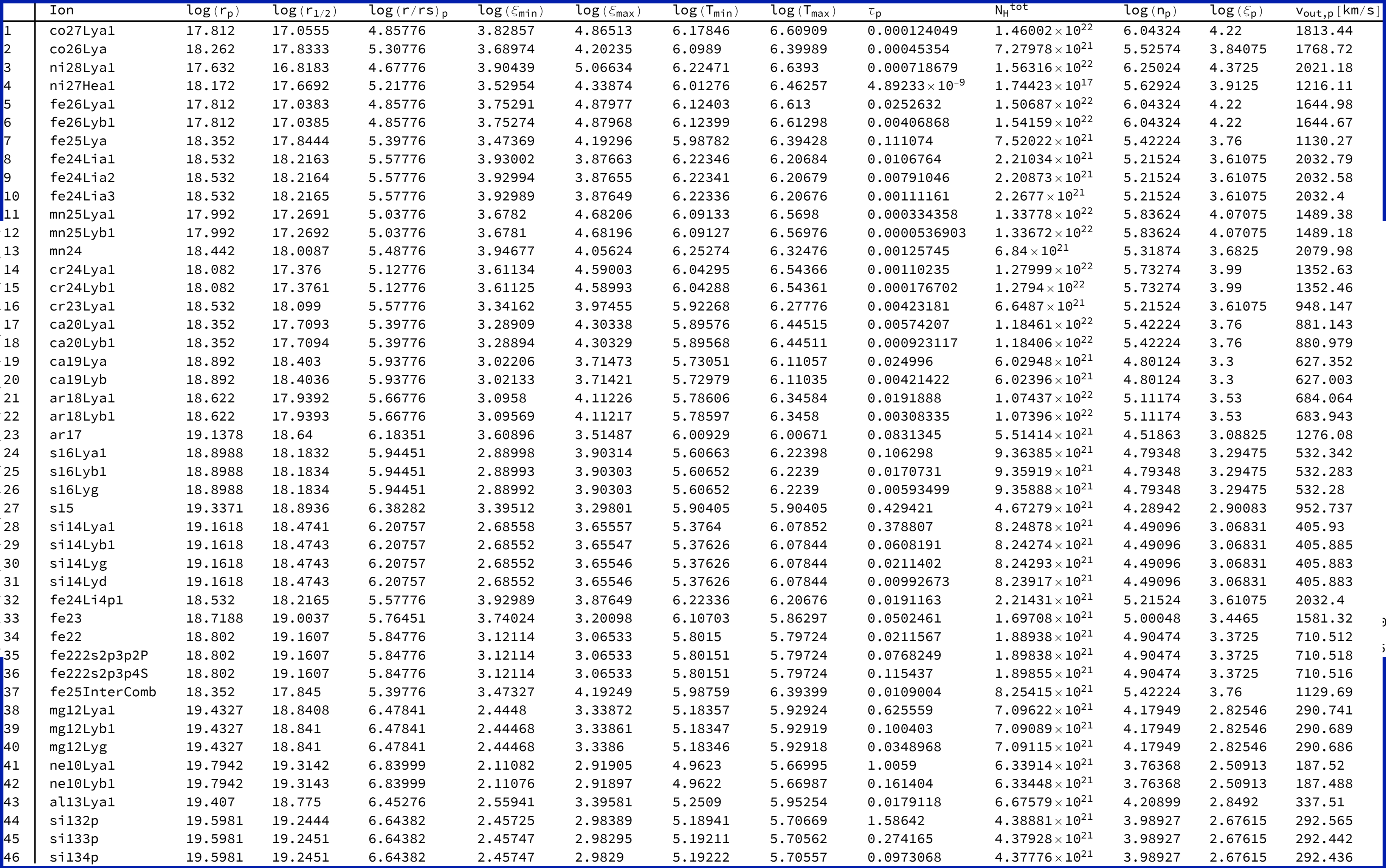
Kaspi+01

n~ $r^{-1.15}$ to $r^{-1.29}$ derived from AMD

Behar+09

WAs in NGC 3783

(MHD-wind solutions) + (AMD) + (xstar) ➔ spectra



	Ion	$\log(r_p)$	$\log(r_{1/2})$	$\log(r/rs)_p$	$\log(\xi_{min})$	$\log(\xi_{max})$	$\log(T_{min})$	$\log(T_{max})$	τ_p	N_H^{tot}	$\log(n_p)$	$\log(\xi_p)$	$v_{out,p}$ [km/s]
1	co27Lya1	17.812	17.0555	4.85776	3.82857	4.86513	6.17846	6.60909	0.000124049	1.46002×10^{22}	6.04324	4.22	1813.44
2	co26Lya	18.262	17.8333	5.30776	3.68974	4.20235	6.0989	6.39989	0.00045354	7.27978×10^{21}	5.52574	3.84075	1768.72
3	ni28Lya1	17.632	16.8183	4.67776	3.90439	5.06634	6.22471	6.6393	0.000718679	1.56316×10^{22}	6.25024	4.3725	2021.18
4	ni27Hea1	18.172	17.6692	5.21776	3.52954	4.33874	6.01276	6.46257	4.89233×10^{-9}	1.74423×10^{17}	5.62924	3.9125	1216.11
5	fe26Lya1	17.812	17.0383	4.85776	3.75291	4.87977	6.12403	6.613	0.0252632	1.50687×10^{22}	6.04324	4.22	1644.98
6	fe26Lyb1	17.812	17.0385	4.85776	3.75274	4.87968	6.12399	6.61298	0.00406868	1.54159×10^{22}	6.04324	4.22	1644.67
7	fe25Lya	18.352	17.8444	5.39776	3.47369	4.19296	5.98782	6.39428	0.111074	7.52022×10^{21}	5.42224	3.76	1130.27
8	fe24Lia1	18.532	18.2163	5.57776	3.93002	3.87663	6.22346	6.20684	0.0106764	2.21034×10^{21}	5.21524	3.61075	2032.79
9	fe24Lia2	18.532	18.2164	5.57776	3.92994	3.87655	6.22341	6.20679	0.00791046	2.20873×10^{21}	5.21524	3.61075	2032.58
10	fe24Lia3	18.532	18.2165	5.57776	3.92989	3.87649	6.22336	6.20676	0.00111161	2.2677×10^{21}	5.21524	3.61075	2032.4
11	mn25Lya1	17.992	17.2691	5.03776	3.6782	4.68206	6.09133	6.5698	0.000334358	1.33778×10^{22}	5.83624	4.07075	1489.38
12	mn25Lyb1	17.992	17.2692	5.03776	3.6781	4.68196	6.09127	6.56976	0.0000536903	1.33672×10^{22}	5.83624	4.07075	1489.18
13	mn24	18.442	18.0087	5.48776	3.94677	4.05624	6.25274	6.32476	0.00125745	6.84×10^{21}	5.31874	3.6825	2079.98
14	cr24Lya1	18.082	17.376	5.12776	3.61134	4.59003	6.04295	6.54366	0.00110235	1.27999×10^{22}	5.73274	3.99	1352.63
15	cr24Lyb1	18.082	17.3761	5.12776	3.61125	4.58993	6.04288	6.54361	0.000176702	1.2794×10^{22}	5.73274	3.99	1352.46
16	cr23Lya1	18.532	18.099	5.57776	3.34162	3.97455	5.92268	6.27776	0.00423181	6.6487×10^{21}	5.21524	3.61075	948.147
17	ca20Lya1	18.352	17.7093	5.39776	3.28909	4.30338	5.89576	6.44515	0.00574207	1.18461×10^{22}	5.42224	3.76	881.143
18	ca20Lyb1	18.352	17.7094	5.39776	3.28894	4.30329	5.89568	6.44511	0.000923117	1.18406×10^{22}	5.42224	3.76	880.979
19	ca19Lya	18.892	18.403	5.93776	3.02206	3.71473	5.73051	6.11057	0.024996	6.02948×10^{21}	4.80124	3.3	627.352
20	ca19Lyb	18.892	18.4036	5.93776	3.02133	3.71421	5.72979	6.11035	0.00421422	6.02396×10^{21}	4.80124	3.3	627.003
21	ar18Lya1	18.622	17.9392	5.66776	3.0958	4.11226	5.78606	6.34584	0.0191888	1.07437×10^{22}	5.11174	3.53	684.064
22	ar18Lyb1	18.622	17.9393	5.66776	3.09569	4.11217	5.78597	6.3458	0.00308335	1.07396×10^{22}	5.11174	3.53	683.943
23	ar17	19.1378	18.64	6.18351	3.60896	3.51487	6.00929	6.00671	0.0831345	5.51414×10^{21}	4.51863	3.08825	1276.08
24	s16Lya1	18.8988	18.1832	5.94451	2.88998	3.90314	5.60663	6.22398	0.106298	9.36385×10^{21}	4.79348	3.29475	532.342
25	s16Lyb1	18.8988	18.1834	5.94451	2.88993	3.90303	5.60652	6.2239	0.0170731	9.35919×10^{21}	4.79348	3.29475	532.283
26	s16Lyg	18.8988	18.1834	5.94451	2.88992	3.90303	5.60652	6.2239	0.00593499	9.35888×10^{21}	4.79348	3.29475	532.28
27	s15	19.3371	18.8936	6.38282	3.39512	3.29801	5.90405	5.90405	0.429421	4.67279×10^{21}	4.28942	2.90083	952.737
28	si14Lya1	19.1618	18.4741	6.20757	2.68558	3.65557	5.3764	6.07852	0.378807	8.24878×10^{21}	4.49096	3.06831	405.93
29	si14Lyb1	19.1618	18.4743	6.20757	2.68552	3.65547	5.37626	6.07844	0.0608191	8.24274×10^{21}	4.49096	3.06831	405.885
30	si14Lyg	19.1618	18.4743	6.20757	2.68552	3.65546	5.37626	6.07844	0.0211402	8.24293×10^{21}	4.49096	3.06831	405.883
31	si14Lyd	19.1618	18.4743	6.20757	2.68552	3.65546	5.37626	6.07844	0.00992673	8.23917×10^{21}	4.49096	3.06831	405.883
32	fe24Li4p1	18.532	18.2165	5.57776	3.92989	3.87649	6.22336	6.20676	0.0191163	2.21431×10^{21}	5.21524	3.61075	2032.4
33	fe23	18.7188	19.0037	5.76451	3.74024	3.20098	6.10703	5.86297	0.0502461	1.69708×10^{21}	5.00048	3.4465	1581.32
34	fe22	18.802	19.1607	5.84776	3.12114	3.06533	5.8015	5.79724	0.0211567	1.88938×10^{21}	4.90474	3.3725	710.512
35	fe222s2p3p2P	18.802	19.1607	5.84776	3.12114	3.06533	5.80151	5.79724	0.0768249	1.89838×10^{21}	4.90474	3.3725	710.518
36	fe222s2p3p4S	18.802	19.1607	5.84776	3.12114	3.06533	5.80151	5.79724	0.115437	1.89855×10^{21}	4.90474	3.3725	710.516
37	fe25InterComb	18.352	17.845	5.39776	3.47327	4.19249	5.98759	6.39399	0.0109004	8.25415×10^{21}	5.42224	3.76	1129.69
38	mg12Lya1	19.4327	18.8408	6.47841	2.4448	3.33872	5.18357	5.92924	0.625559	7.09622×10^{21}	4.17949	2.82546	290.741
39	mg12Lyb1	19.4327	18.841	6.47841	2.44468	3.33861	5.18347	5.92919	0.100403	7.09089×10^{21}	4.17949	2.82546	290.689
40	mg12Lyg	19.4327	18.841	6.47841	2.44468	3.3386	5.18346	5.92918	0.0348968	7.09115×10^{21}	4.17949	2.82546	290.686
41	ne10Lya1	19.7942	19.3142	6.83999	2.11082	2.91905	4.9623	5.66995	1.0059	6.33914×10^{21}	3.76368	2.50913	187.52
42	ne10Lyb1	19.7942	19.3143	6.83999	2.11076	2.91897	4.9622	5.66987	0.161404	6.33448×10^{21}	3.76368	2.50913	187.488
43	al13Lya1	19.407	18.775	6.45276	2.55941	3.39581	5.2509	5.95254	0.0179118	6.67579×10^{21}	4.20899	2.8492	337.51
44	si132p	19.5981	19.2444	6.64382	2.45725	2.98389	5.18941	5.70669	1.58642	4.38881×10^{21}	3.98927	2.67615	292.565
45	si133p	19.5981	19.2451	6.64382	2.45747	2.98295	5.19211	5.70562	0.274165	4.37928×10^{21}	3.98927	2.67615	292.442
46	si134p	19.5981	19.2451	6.64382	2.45747	2.9829	5.19222	5.70557	0.0973068	4.37776×10^{21}	3.98927	2.67615	292.436

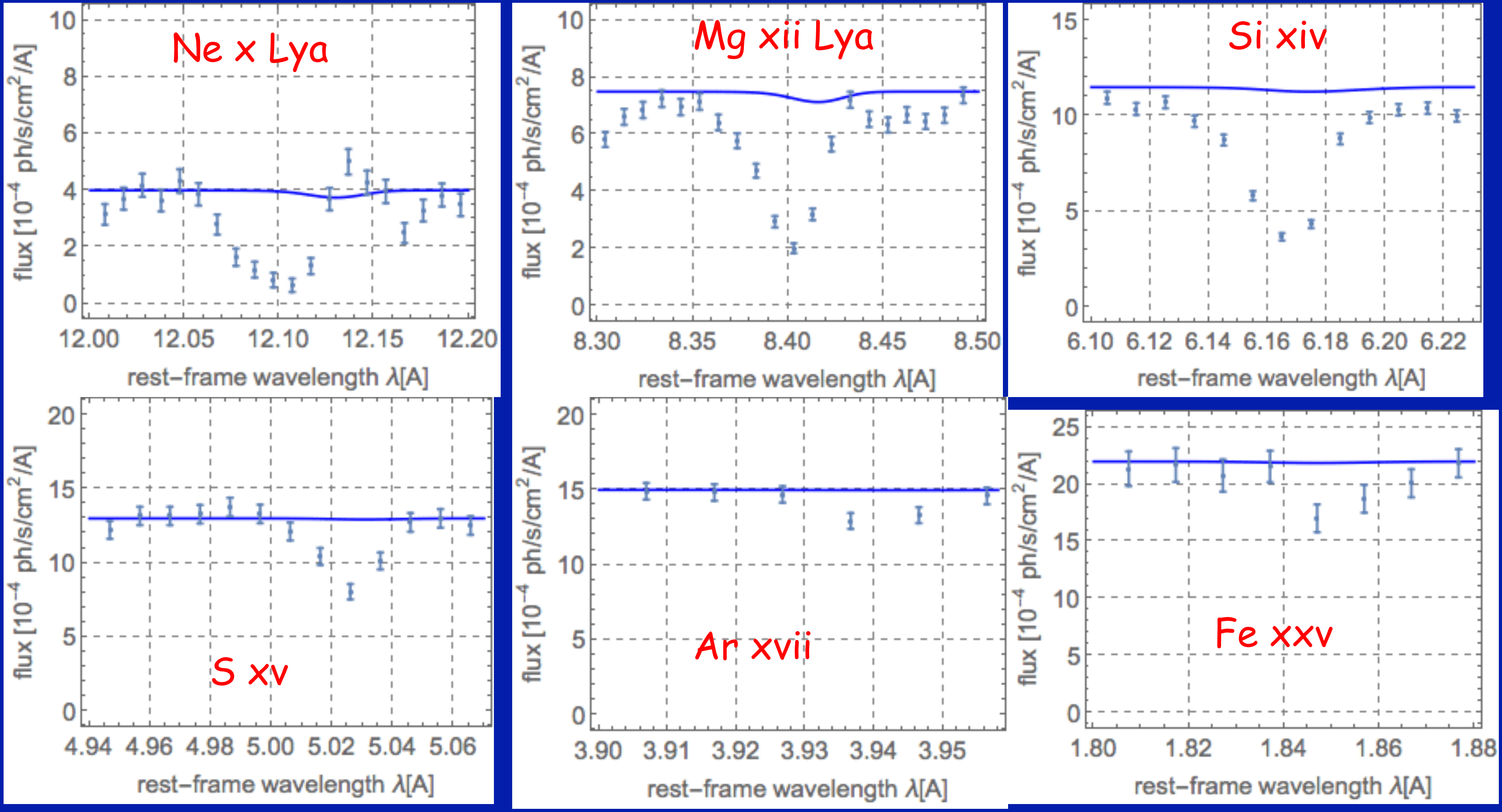
WAs in NGC 3783

preliminary

Kaspi+01 SED
n~ r $^{-1.15}$ wind

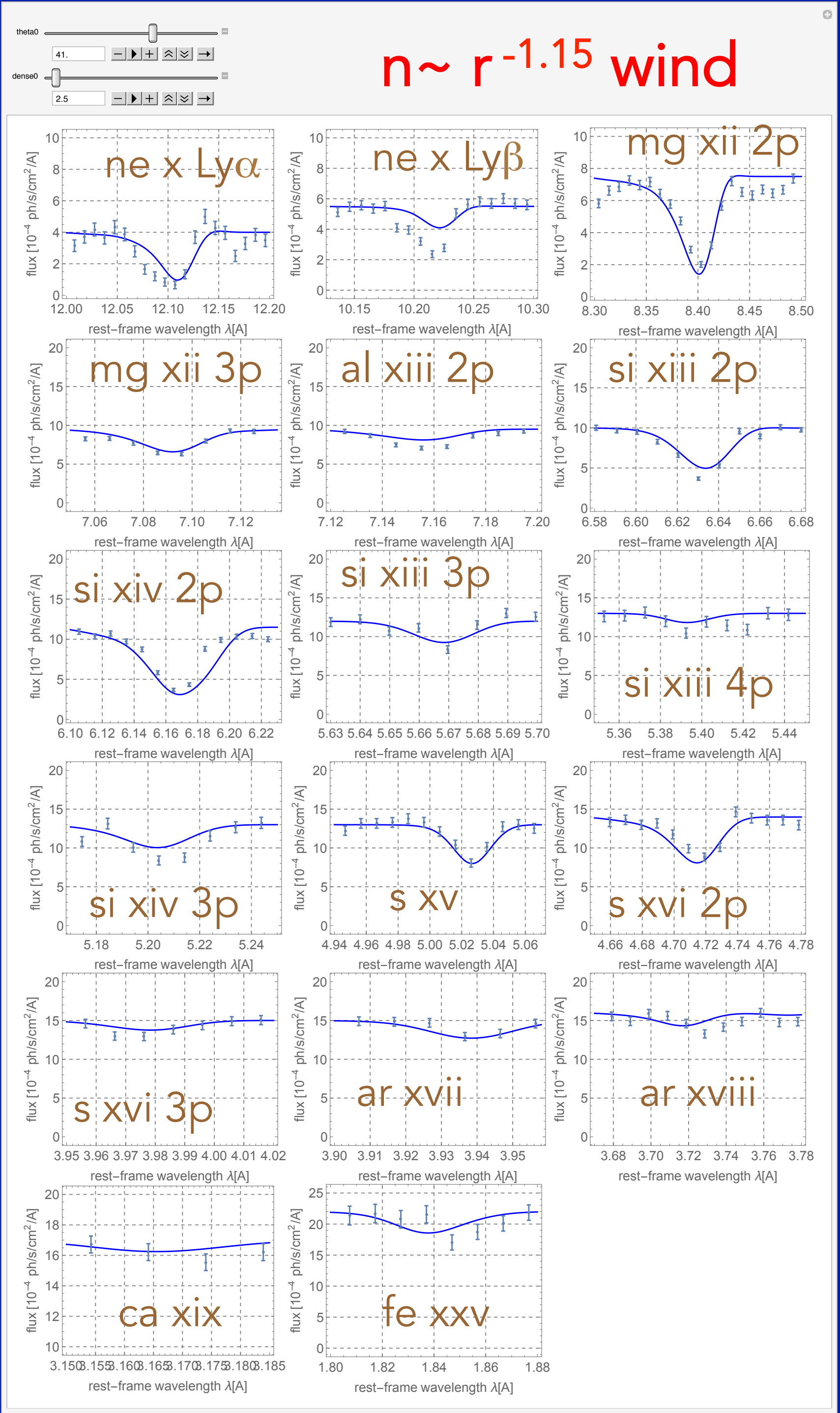
wind density at base: 1.7e11 – 1.1e13 [cm^{-3}]
Inclination: 30° – 50°

Fukumura, in prep.



Bestfit: n_o = 6.8e11 cm^{-3} , θ_{obs} = 41°

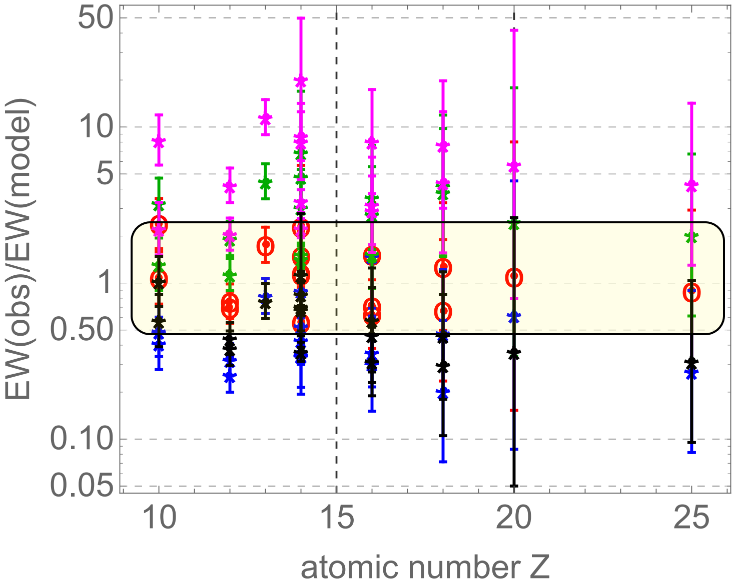
EW ratio (model vs. data)



theta0 41.

dense0 2.5

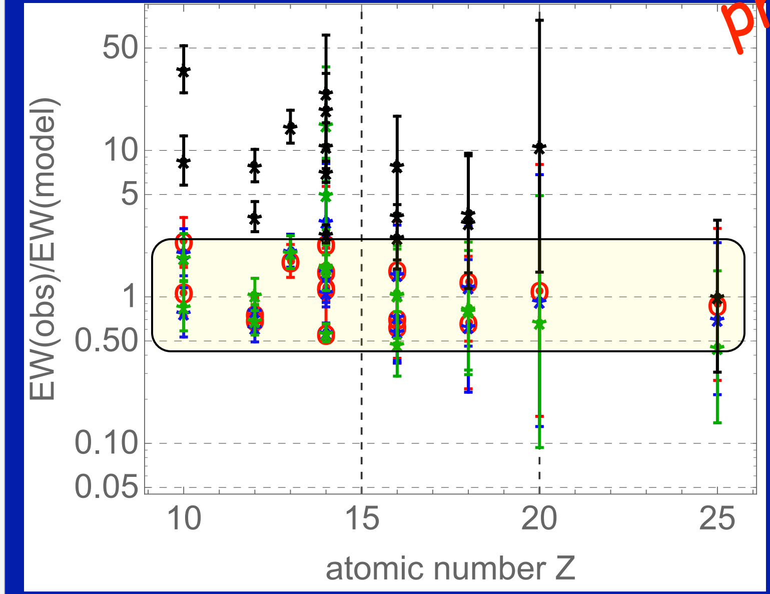
$n \sim r^{-1.15}$ wind



$n_o=10^9-10^{13}$

θ_{obs}=30°-50°

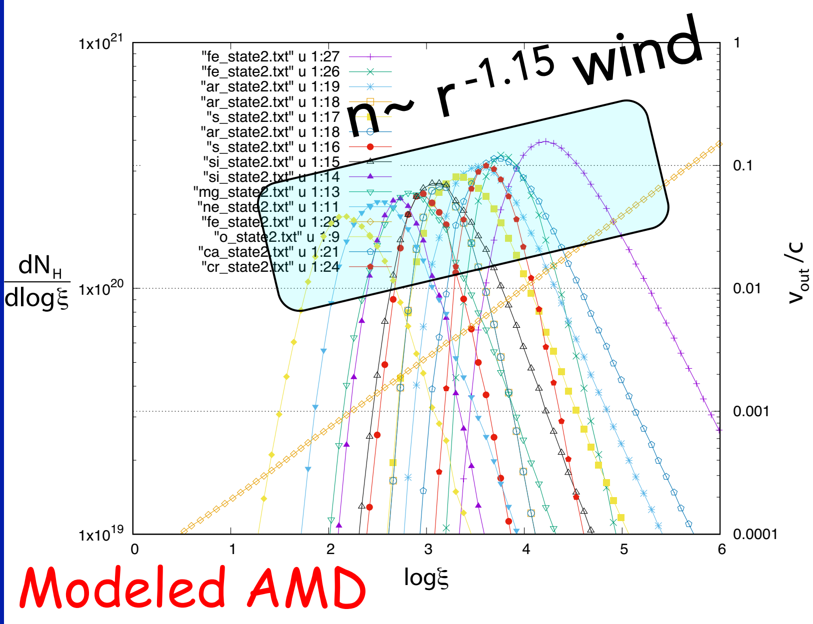
preliminary



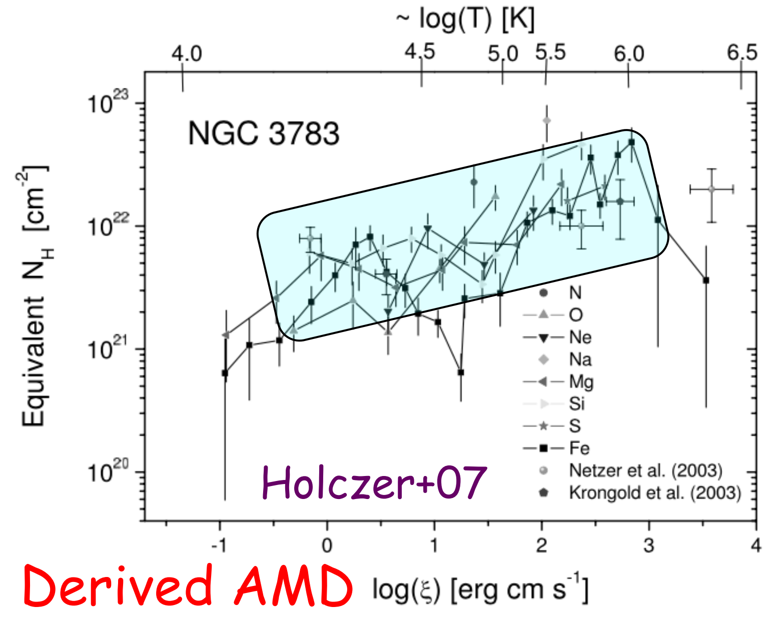
p=1.15,
1.22,
1.29.
1.5

More about NGC 3783

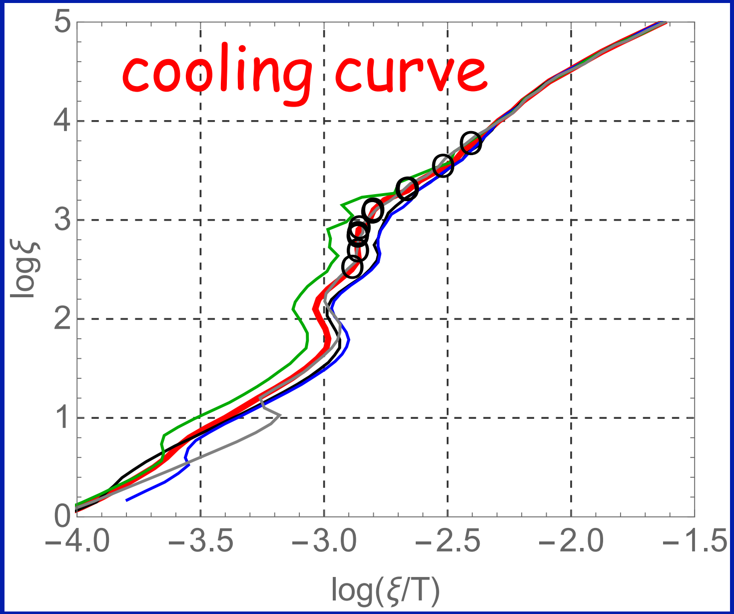
preliminary

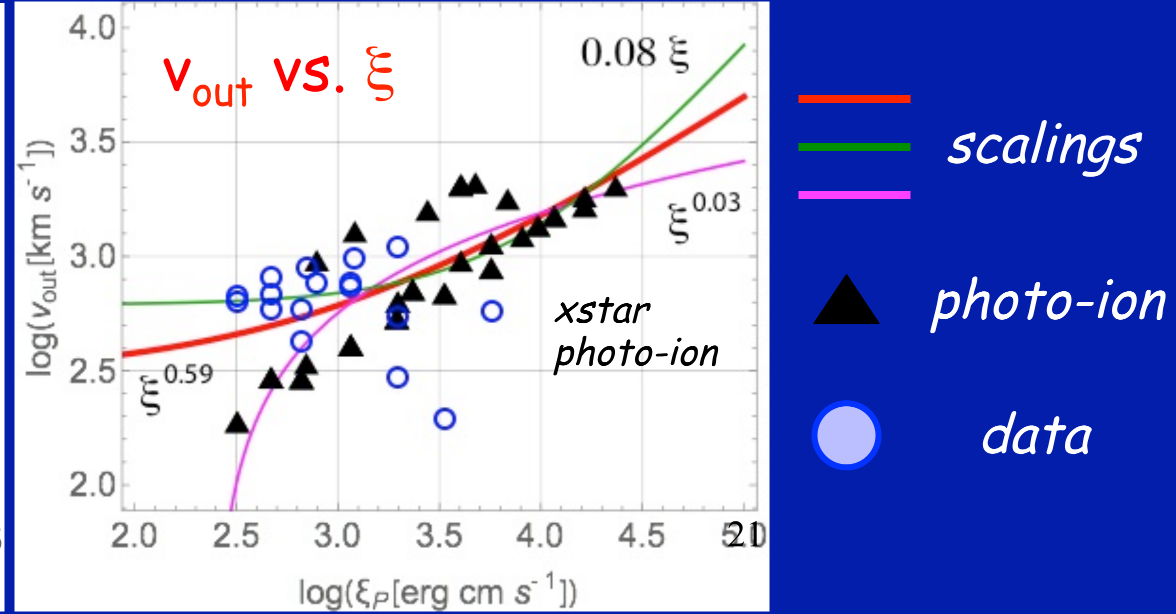


Modeled AMD



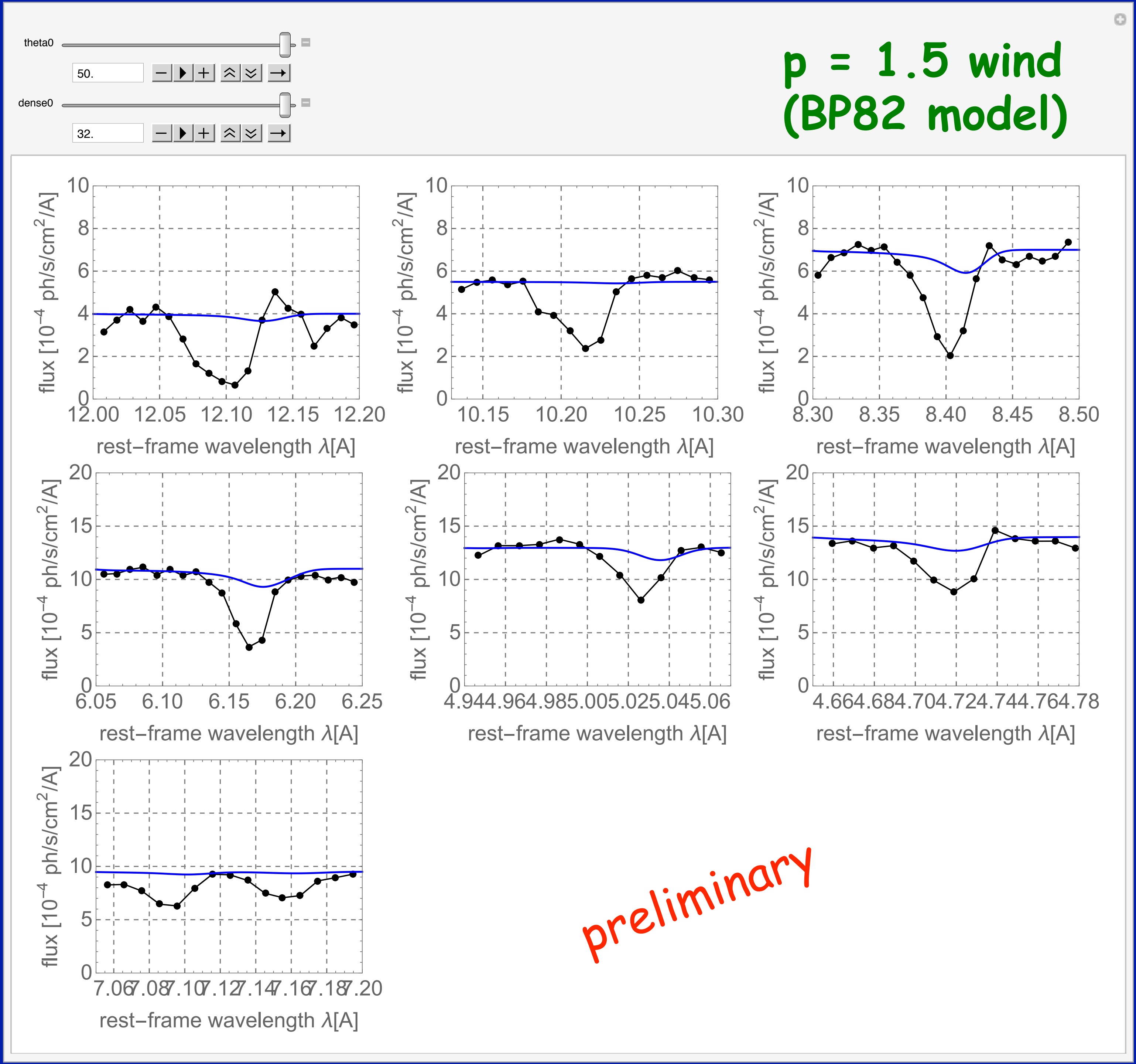
Derived AMD





p = 1.5 wind (BP82 model)

Out[1949]=



theta0 50.

dense0 32.

preliminary

Summary

Why magnetic-origin?

- ✧ Generic ability to launch ionized winds
  - UFOs @ smaller radii (~ hundreds of R_S)
  - WAs @ larger radii (~ sub pc to pc scale)

- ✧ Can describe global outflow conditions
  - Radial (LoS) density distribution ➔ AMD
  - Helical motion ➔ Transverse motion

- ✧ Can explain observable (non-)correlations
  - AMD, $V_{out}(\xi)$, $N_H(\xi)$, spectral shape
  - V_{out}(UFO) vs. L/L_E , SED dependence…etc.

END