Quasar Outflow Properties from UV/Optical Spectroscopy

Fred Hamann

University of California, Riverside

ASTRONOMY UCR

Dan Capellupo
Hanna Herbst
Emily Moravec
Sylvain Veilleux
Todd Tripp
David Rupke
Nadia Zakamska
Nic Ross
Isabelle Paris
Rachael Alexandroff
BOSS SDSS3 quasar team

Observational Puzzles:

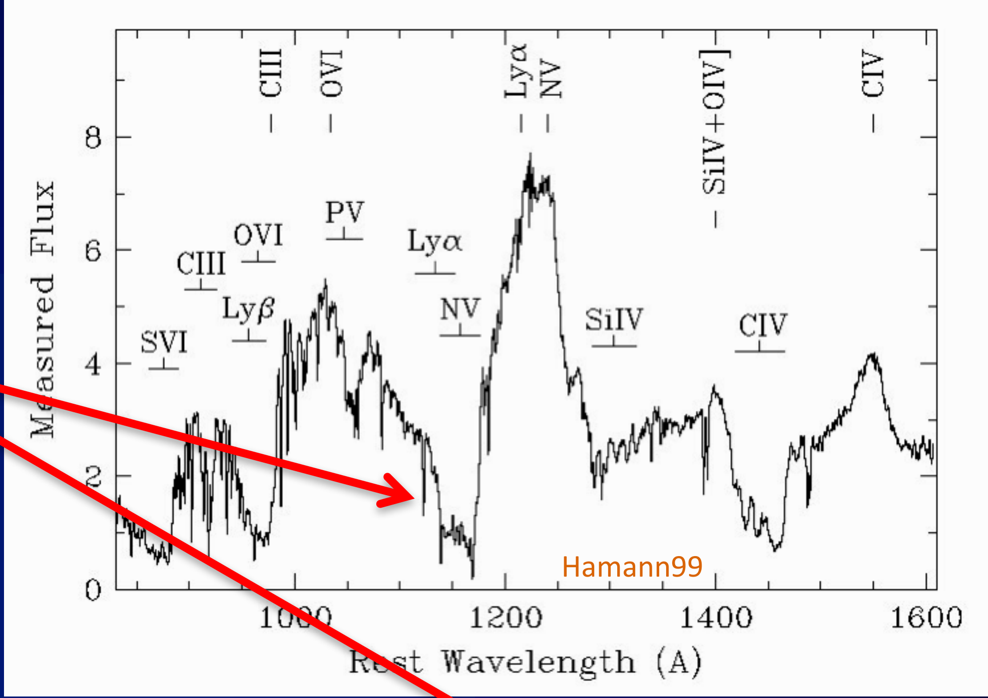
Relating BALs, mini-BALs, NALs

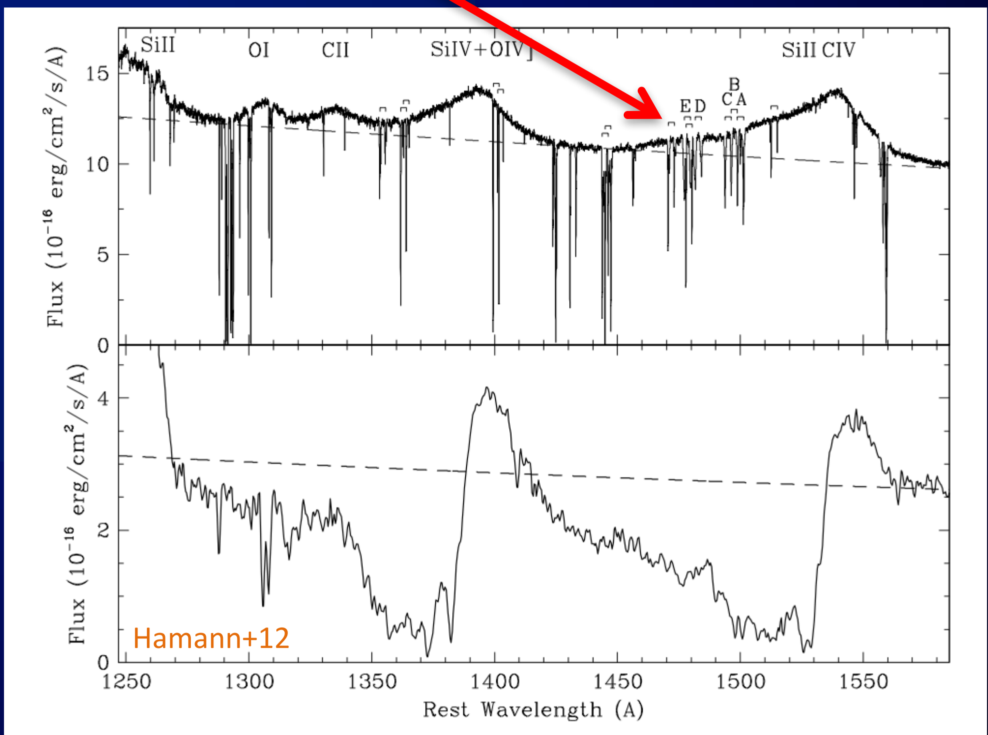
…and UV to X-ray outflows

Total column densities

Spatial structure, Location, Energetics

- PV BALs
- A BLR cloud crossing our LOS?
- CIV at ~0.3c in PDS 456?
- ERQs are outflow monsters





PV BAL Quasars

BALs are often(?) saturated but not "black"

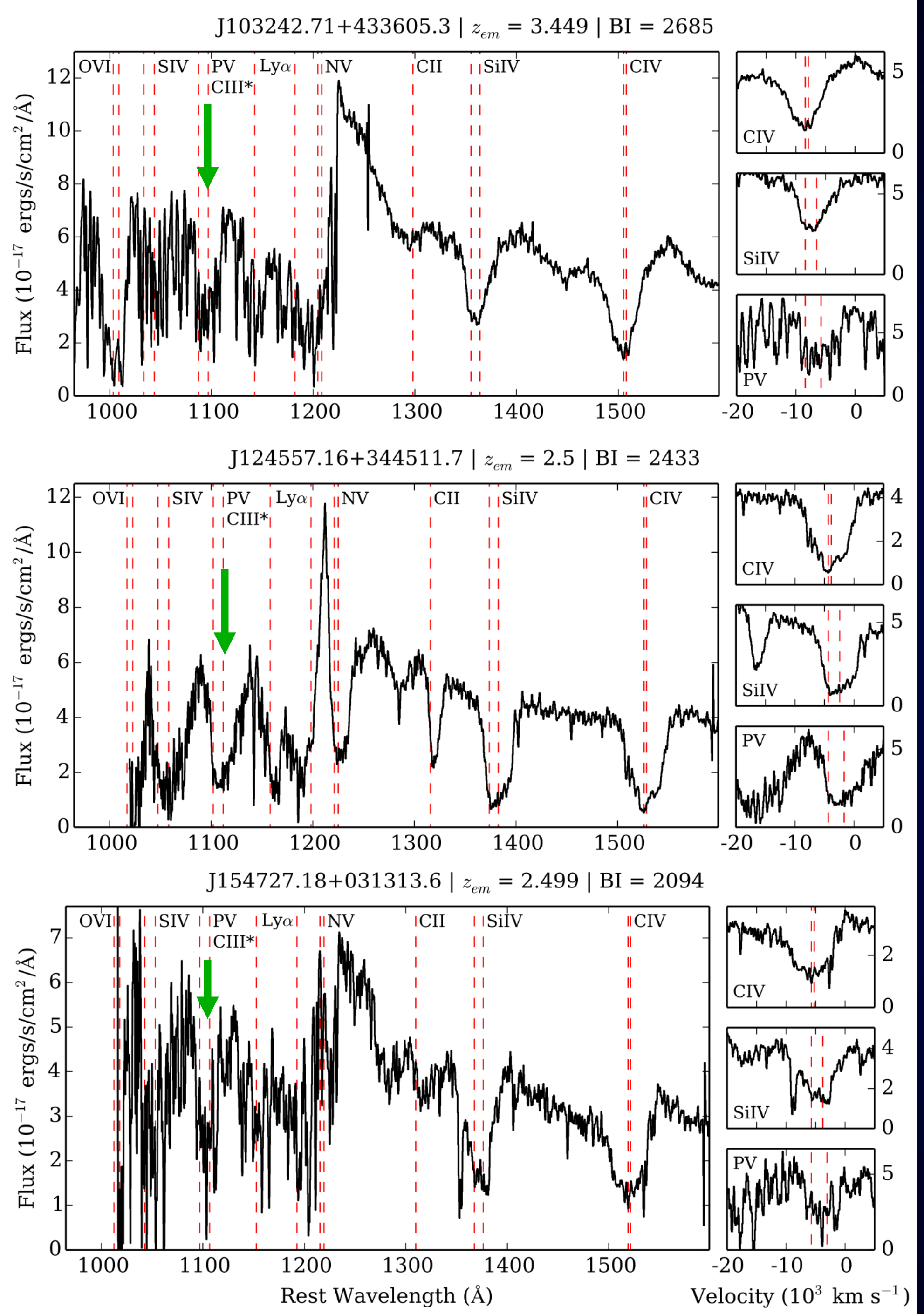
because the absorber partially covers background light source

Low-abundance ions like PV 1118,1128 (Hamann 1998) or excited-state HeI* 3889 & 10830 (Leighly+11) yield larger lower limits on τ, N_H, L_K

Select BALs with PV from BOSS DR9

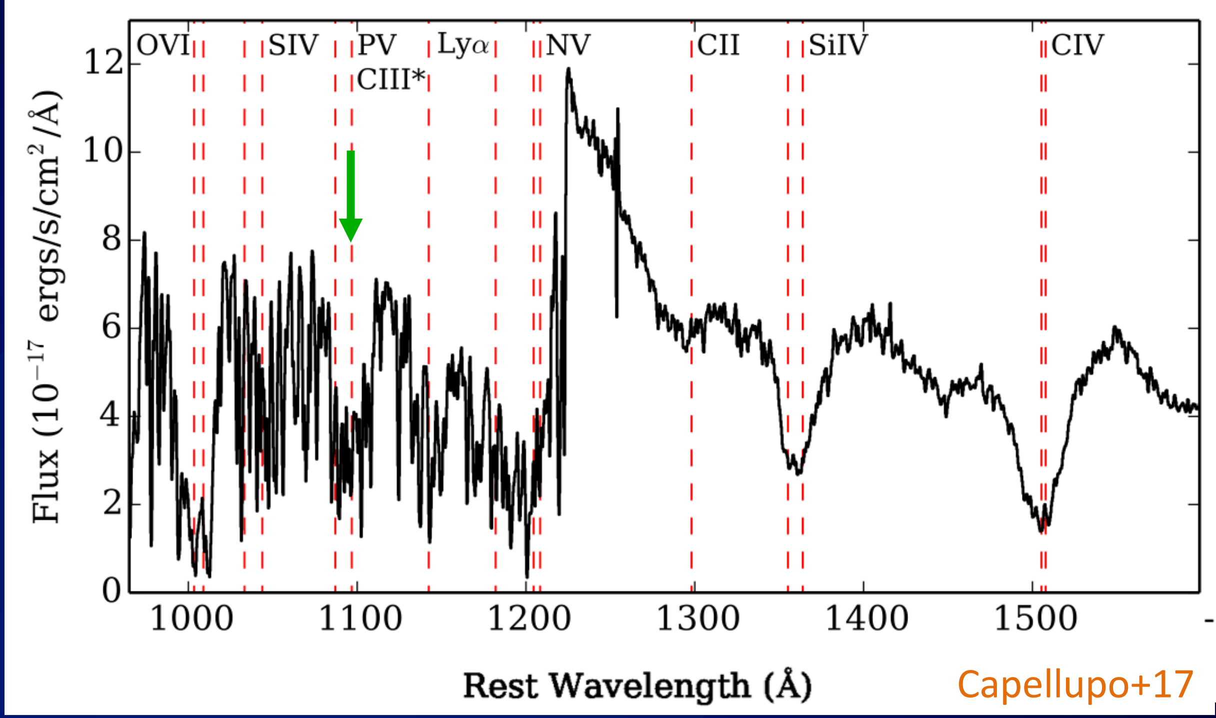
6% of BAL quasars have "strong" PV

Capellupo+17



PV BAL Quasars

Capellupo+17



If P/C ~ solar, then

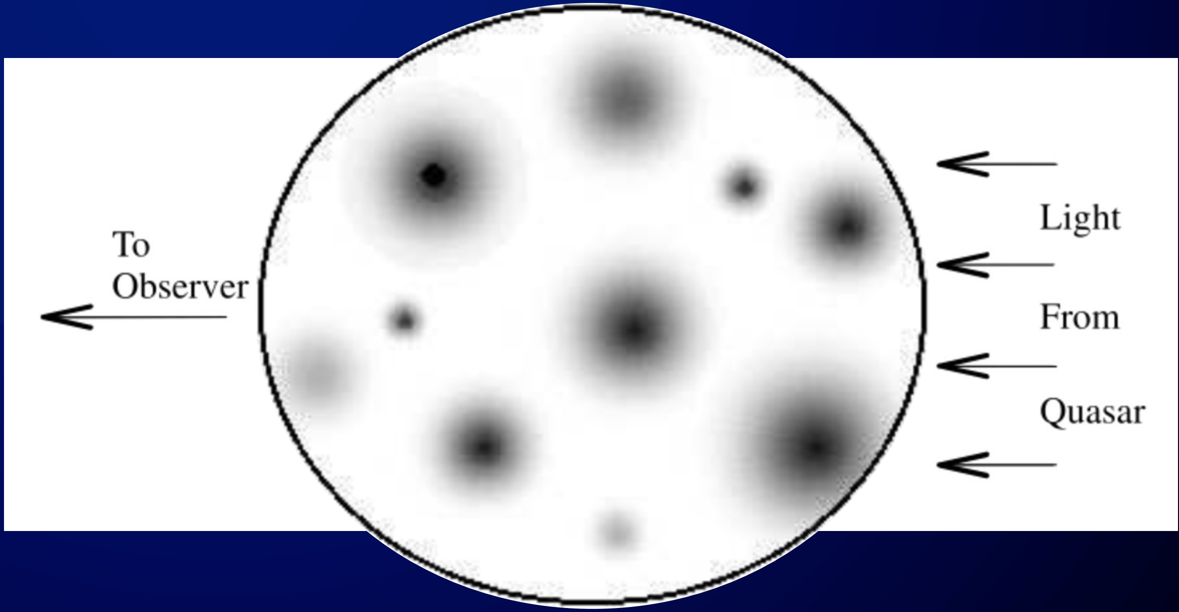
τ(CIV) >~ 1000 τ(PV) >> 1

but CIV often not "black"

Different depths in different lines, all with τ >> 1

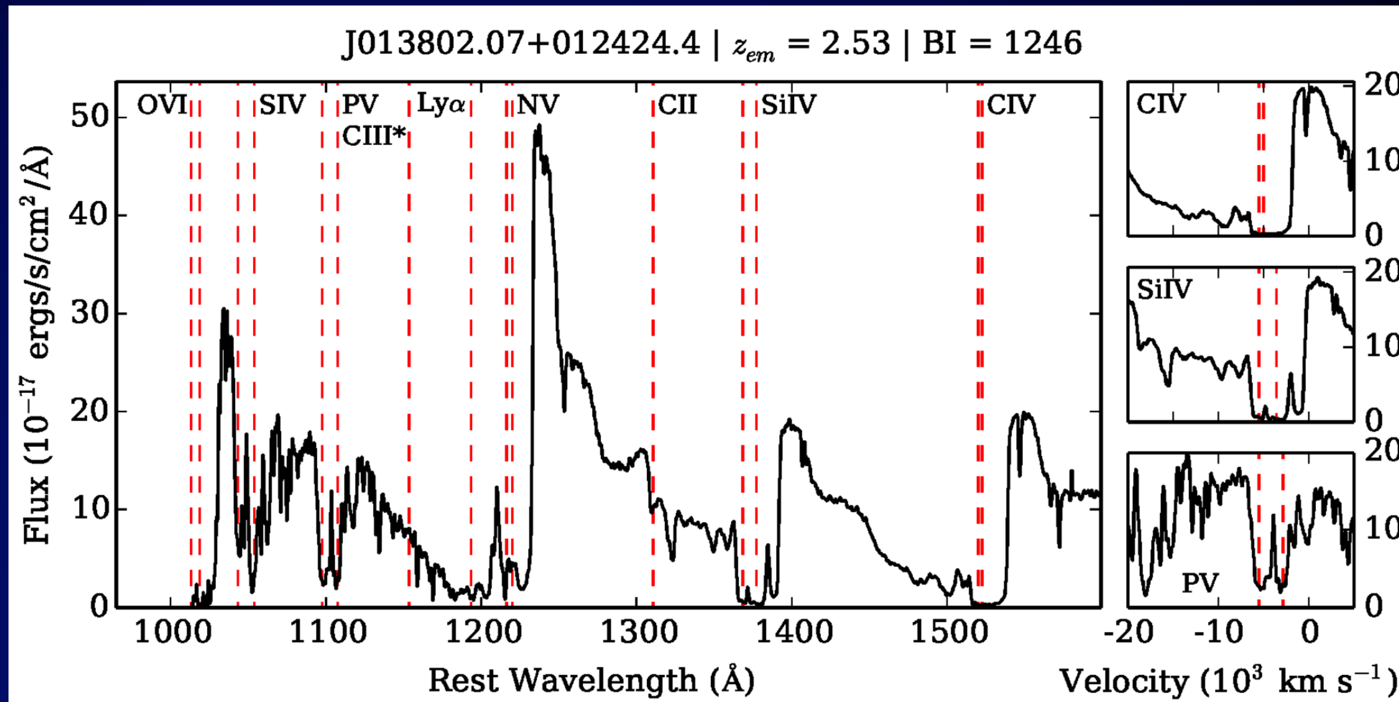
Inhomogeneous partial covering

(Hamann+01,04, Arav+05)



What are the column density lower limits?

Assume solar abundances to get N_H
Hamann+98, Leighly+11



Capellupo+17

τ(PV) > 3 indicates $N_H > 4 \times 10^{22}$ cm^{-2} in ionized gas.

Covering factor in PV: ~85%

Velocities: ~4500 to 6500 km/s (compared to CIV at 1500 to 23,000 km/s)

If R ~ 3 pc (from variability with evidence for $\tau >> 1$) and Q ~ 15%
then dM/dt > 12 Mo/yr and $L_K > 4 \times 10^{44}$ ergs/s ~ 2% L_{bol}

BALs to mini-BALs

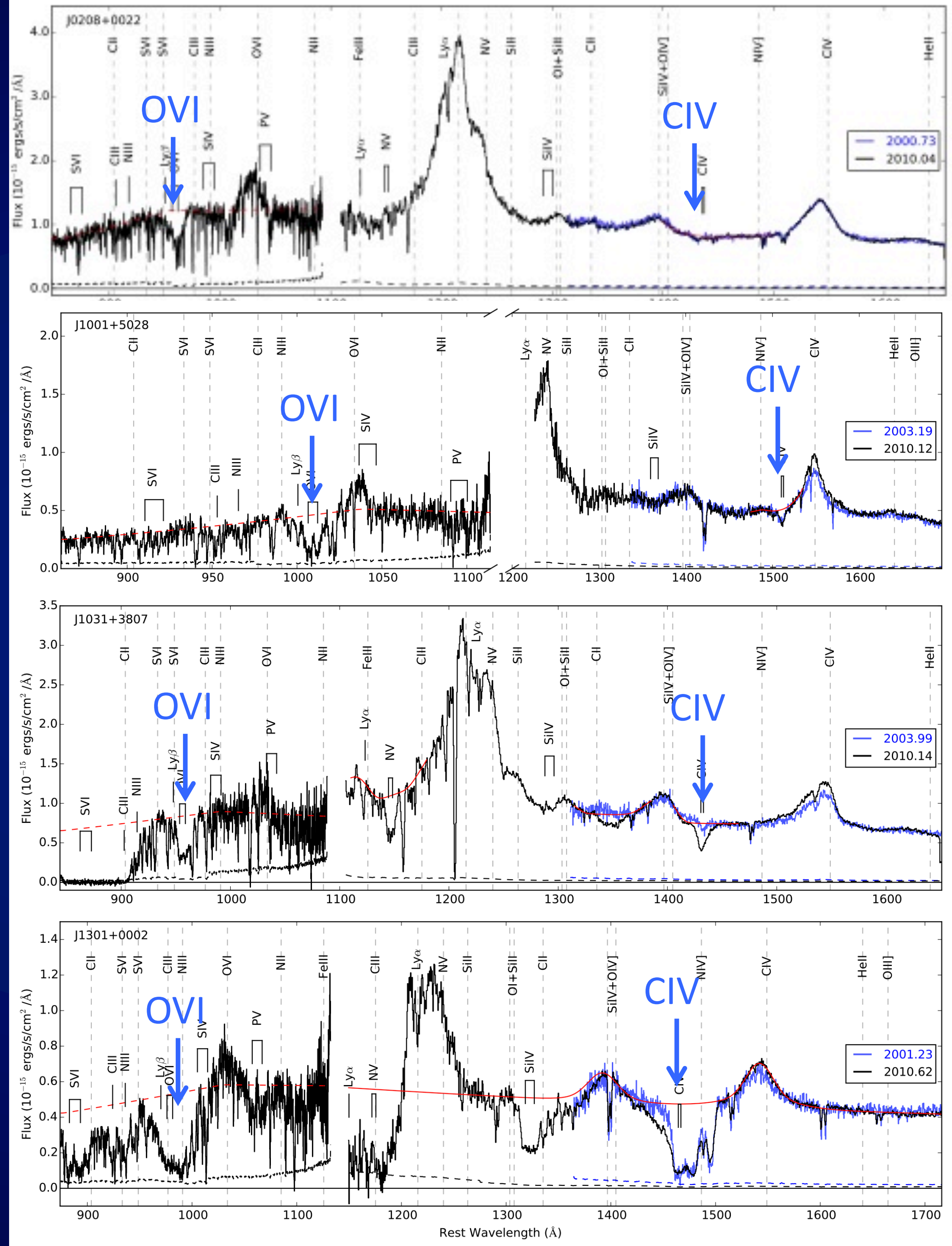
Moravec+17

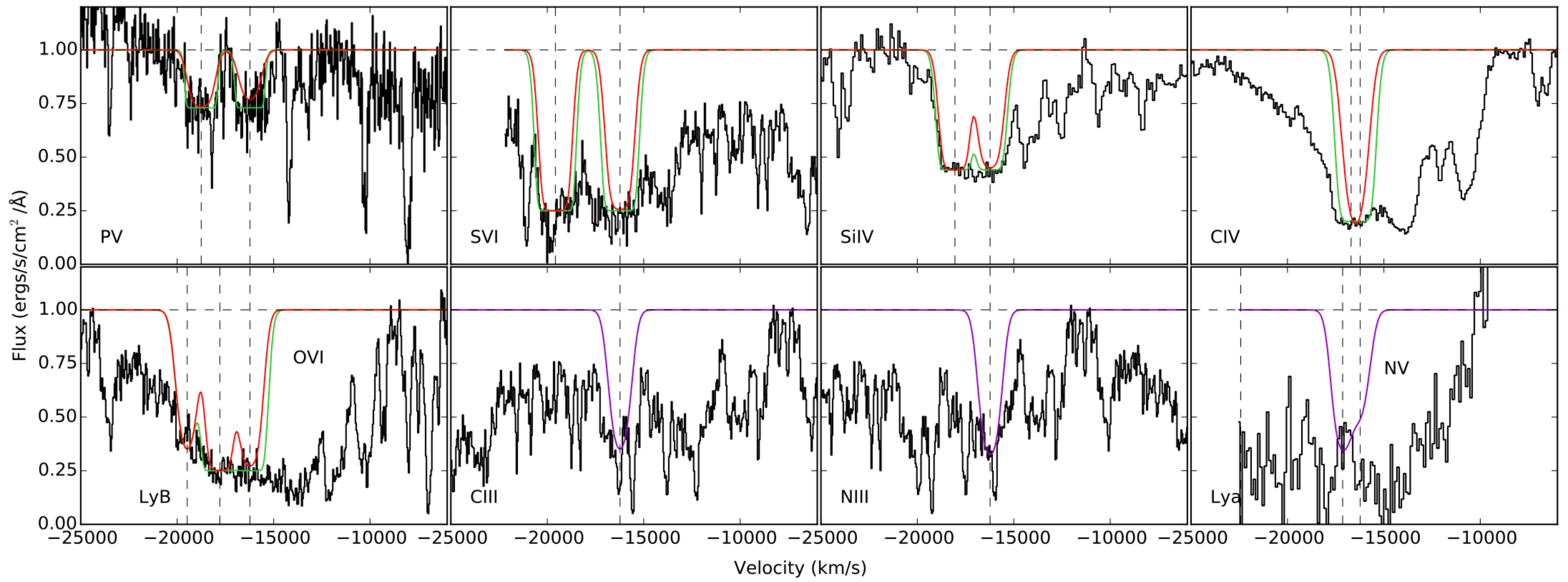
OVI > CIV

1:1 ratios in OVI

All varied in < 1.9 yrs

PV mini-BAL
embedded in a BAL



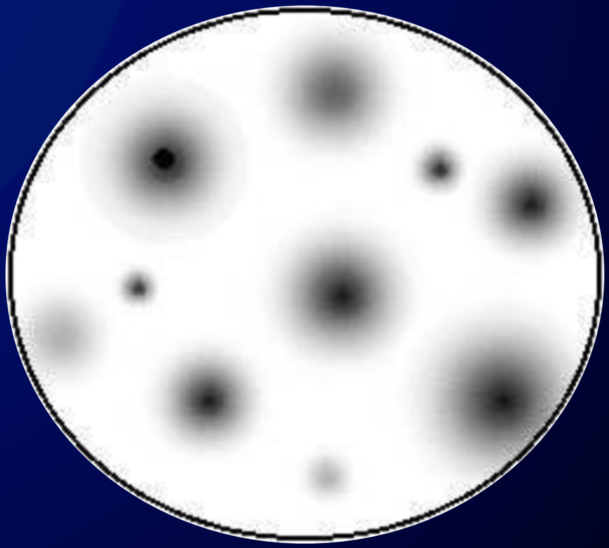


PV mini-BAL in a BAL outflow:

First fit PV: v = 16230 km/s, b = 600 km/s, $\tau > 3$, $C_0 = 0.27$

Move this fit to other lines to identify $\tau >> 1$ gas

Range in covering factors: $0.27 < C_0 < 0.8$



$N_H > 2 \times 10^{22}$ cm^{-2} (based on PV, solar P/H, Leighly+11)

If R ~ 2 pc (from variability) -> $L_K \sim 0.7\% \, L_{bol}$

Case	Δt (yrs)	ΔA	Crossing speed (km/s)	~ Location (pc)
"Typical" mini-BAL	1.1	0.12	3500	2.5
Shortest Δt in mini-BALs (J1001+5028)	0.29	0.063 ± 0.008	7640	0.4
Largest ΔA in mini-BALs (J1031+3807)	0.81	0.22 ± 0.015	3750	0.7
Shortest Δt in BAL	0.33	0.039 ± 0.008	4690	0.8
Largest ΔA in BAL	4.29	0.38 ± 0.018	1110	14

< 1 kpc (from recomb. time)

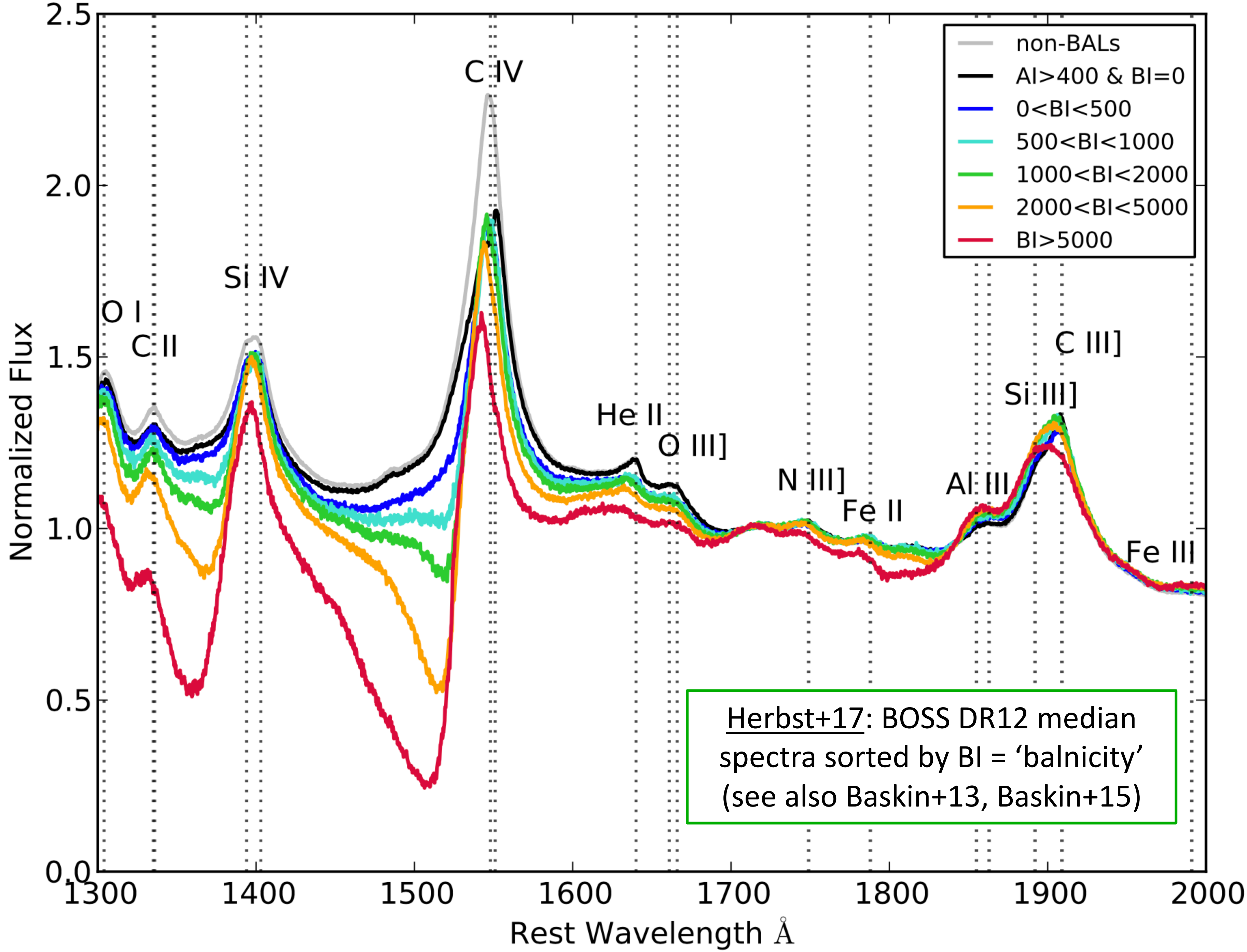
$$M \approx 4100 \left(\frac{Q}{15\,\text{per cent}}\right)\left(\frac{N_H}{2\times10^{22}\,\text{cm}^{-2}}\right)\left(\frac{R}{3.5\,\text{pc}}\right)^2 \text{M}_\odot,$$

$$K \approx 4\times10^{54} \left(\frac{M}{4100\,\text{M}_\odot}\right)\left(\frac{v}{10\,000\,\text{km s}^{-1}}\right)^2 \text{erg}.$$

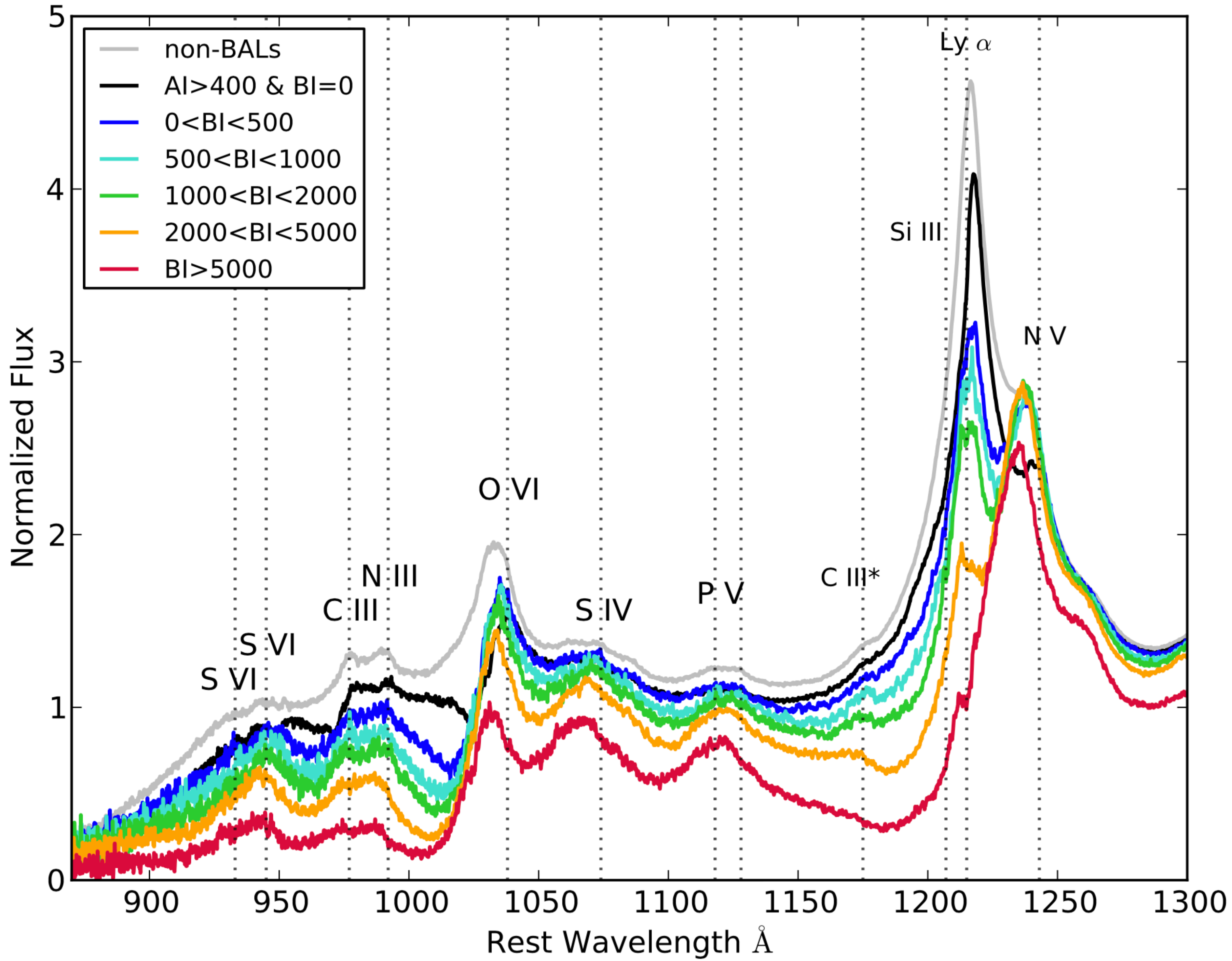
Bottom line:

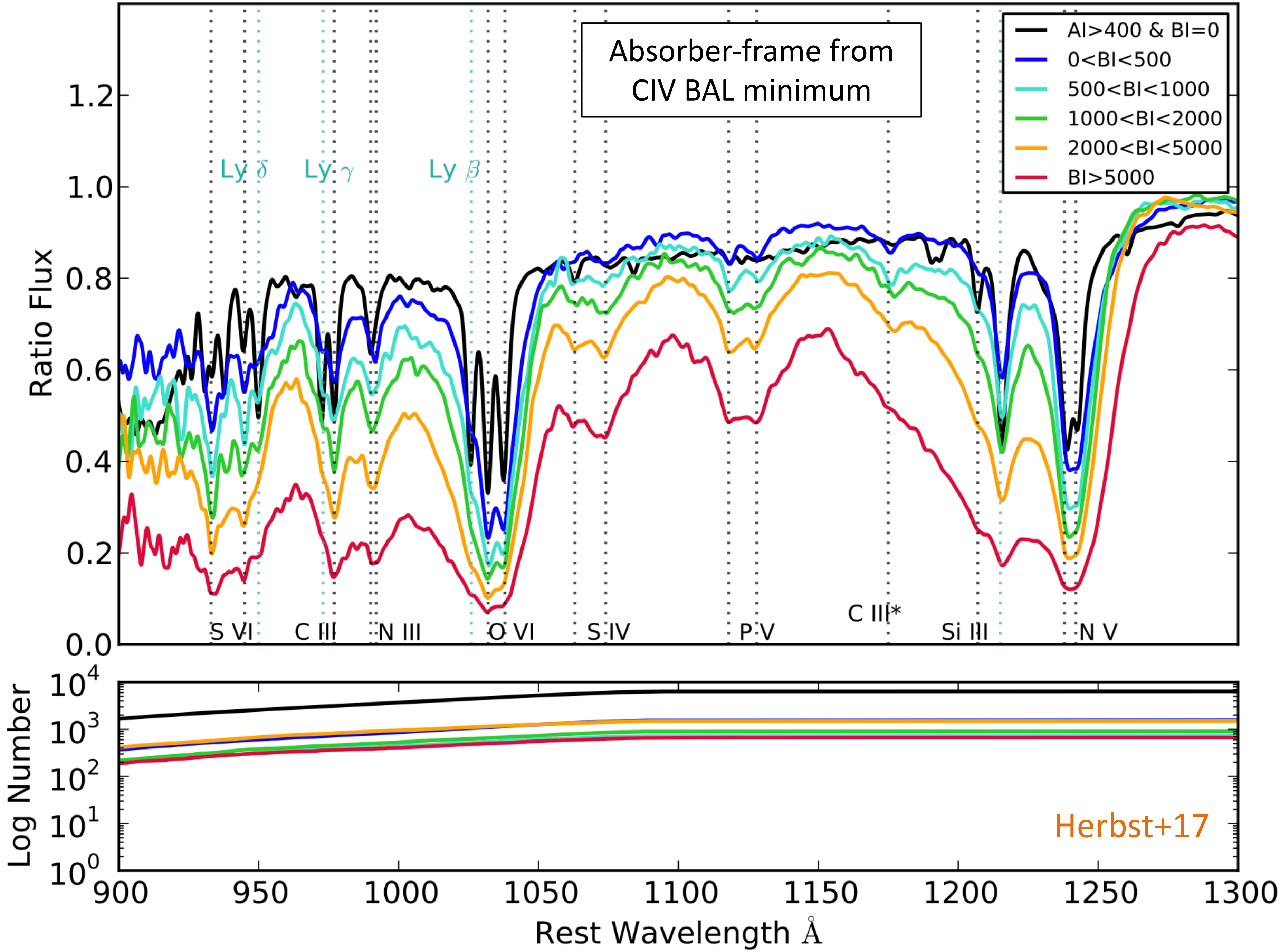
Even at "small" pc-scale distances: 0.2% < L_K < 2% L_{bol} for BAL outflows with PV

How common are the large N_H indicated by PV?

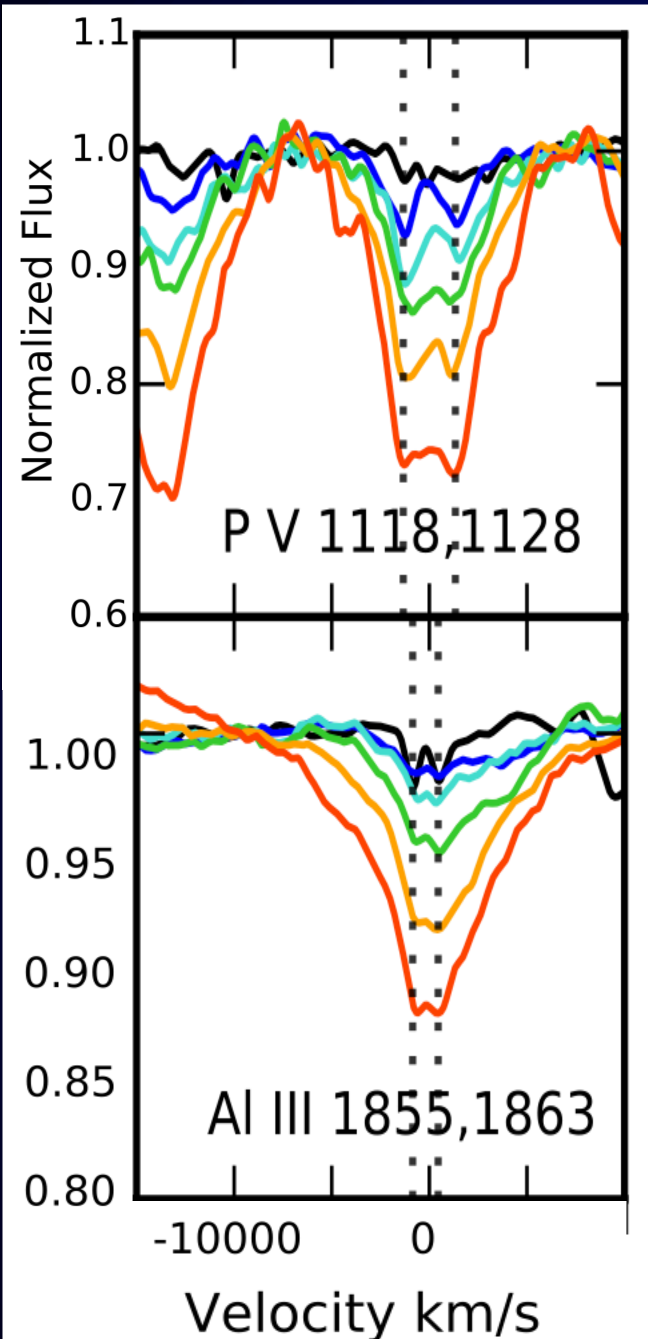


2.5
2.0
1.5
1.0
0.5
0.0
1300
1400
1500
1600
1700
1800
1900
2000
Normalized Flux
Rest Wavelength Å
O I
C II
Si IV
C IV
He II
O III]
N III]
Fe II
Al III
Si III]
C III]
Fe III
non-BALs
AI>400 & BI=0
0<BI<500
500<BI<1000
1000<BI<2000
2000<BI<5000
BI>5000
Herbst+17: BOSS DR12 median spectra sorted by BI = 'balnicity'
(see also Baskin+13, Baskin+15)


non-BALs
AI>400 & BI=0
0<BI<500
500<BI<1000
1000<BI<2000
2000<BI<5000
BI>5000
Ly α
Si III
N V
O VI
N III
C III
S VI
S VI
S IV
P V
C III*
Normalized Flux
Rest Wavelength Å
0
1
2
3
4
5
900
950
1000
1050
1100
1150
1200
1250
1300



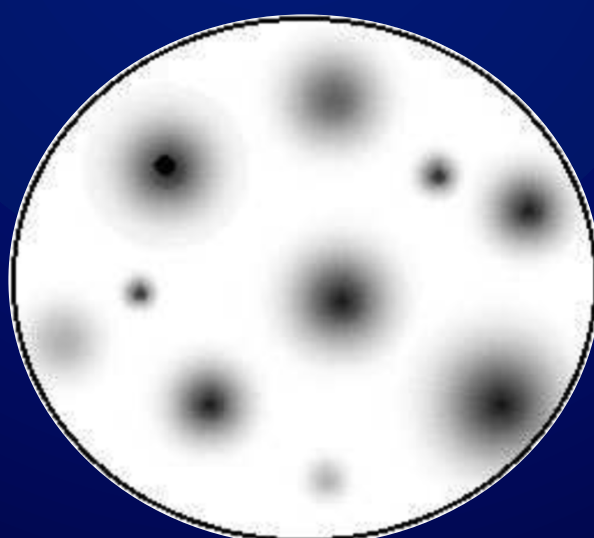
Absorber-frame from
CIV BAL minimum
AI>400 & BI=0
0<BI<500
500<BI<1000
1000<BI<2000
2000<BI<5000
BI>5000
Ly δ
Ly γ
Ly β
S VI
C III
N III
O VI
S IV
P V
C III*
Si III
N V
Ratio Flux
Log Number
Herbst+17
Rest Wavelength Å

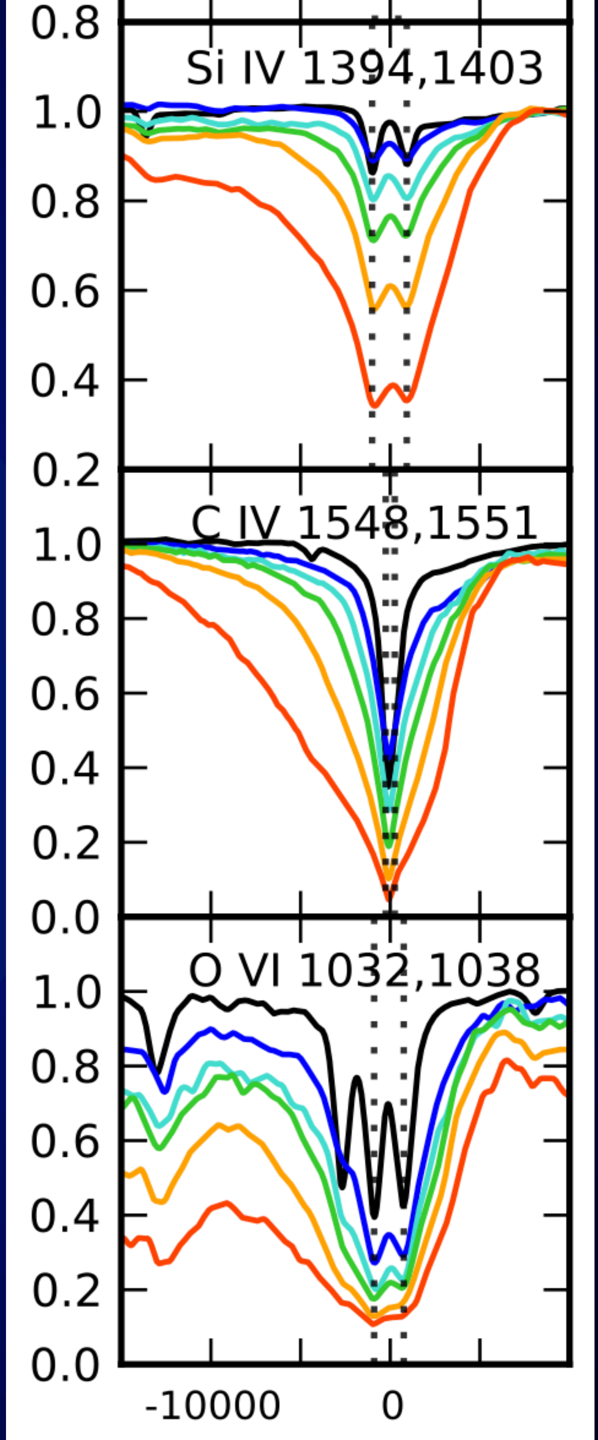


PV is present in all BAL (BI > 0) composites

Median 1:1 doublet ratios regardless of BAL strength $\tau >> 1$

BAL strength is mostly LOS covering fraction (projected area with $\tau > 1$) not column density



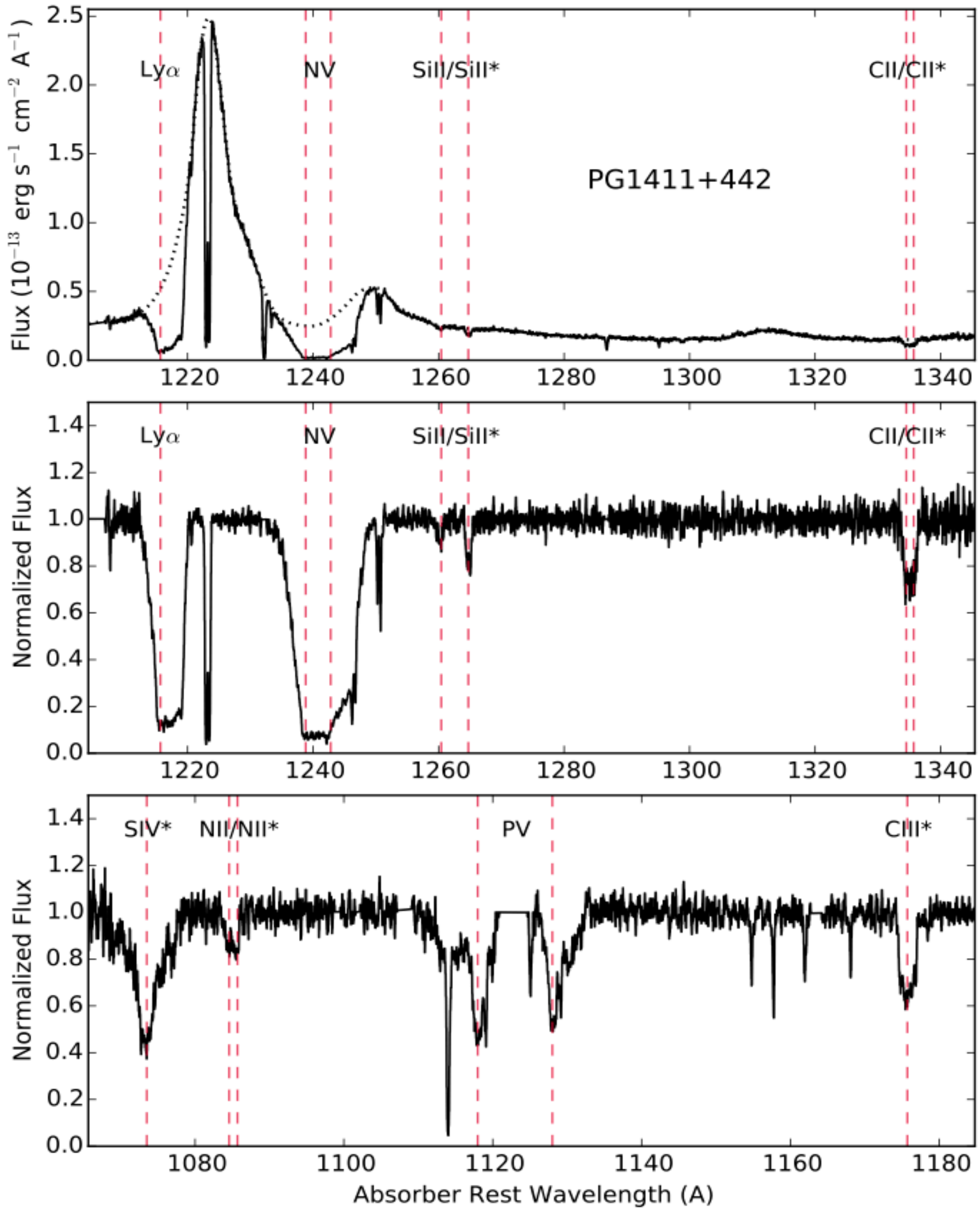


PG 1411+442

HST/COS – Oct 2011

(Sylvain Veilleux - QUEST)

Selected for follow-up because of many mini-BALs including PV and excited-state lines…



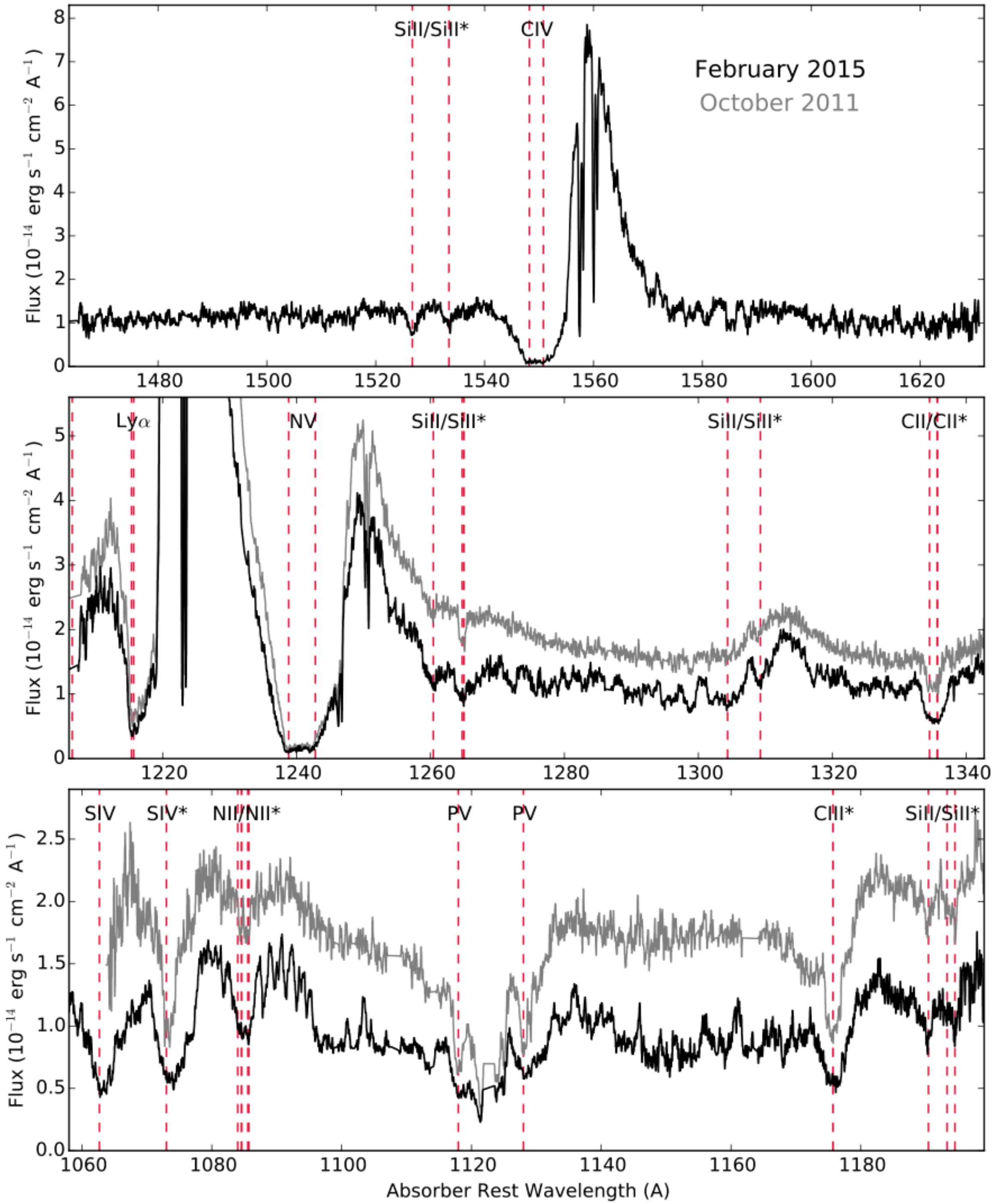
PG 1411+442

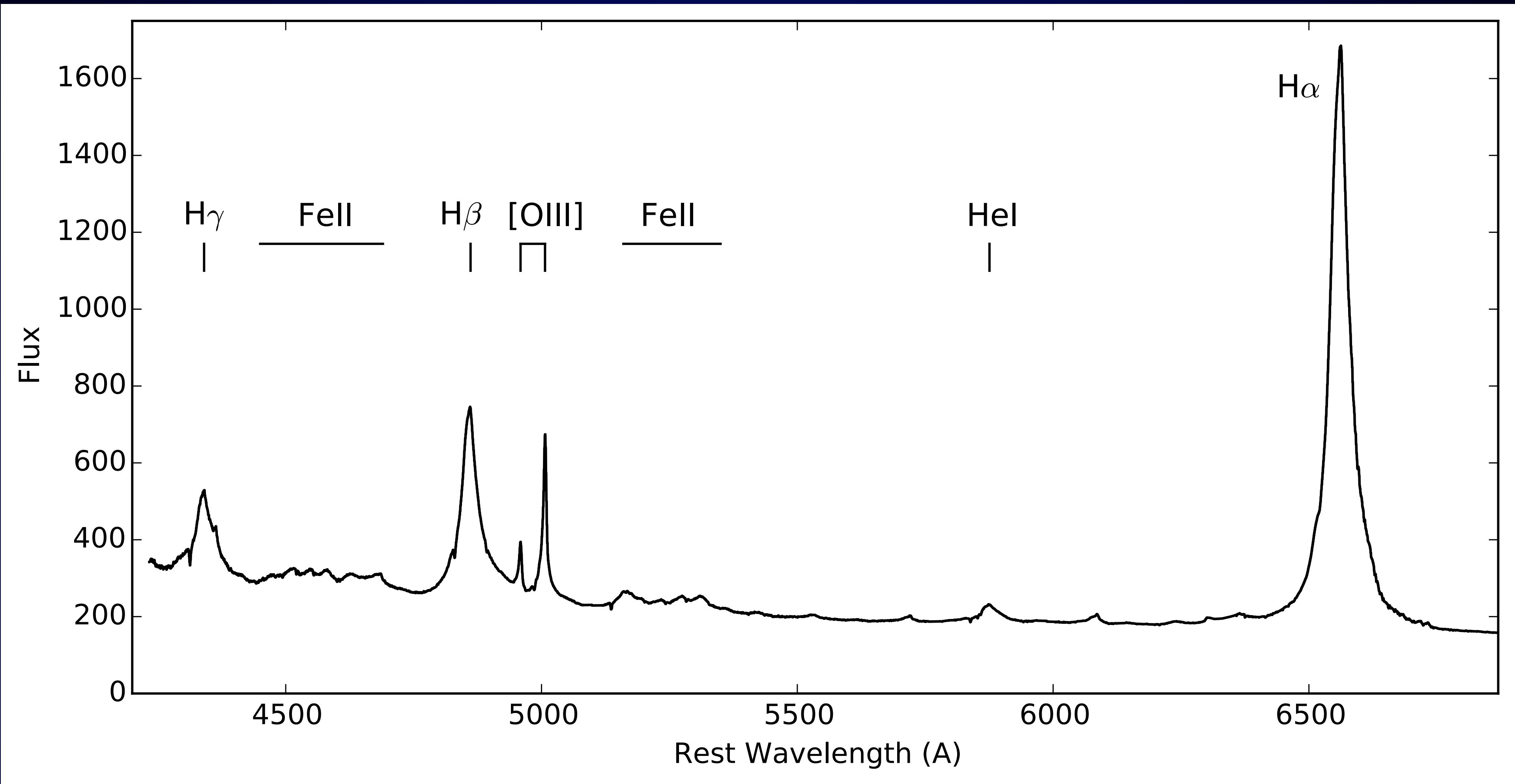
HST/COS – Oct 2011
HST/COS – Feb 2015

20-40% ripples!!??!

Problems with COS or the pipeline?

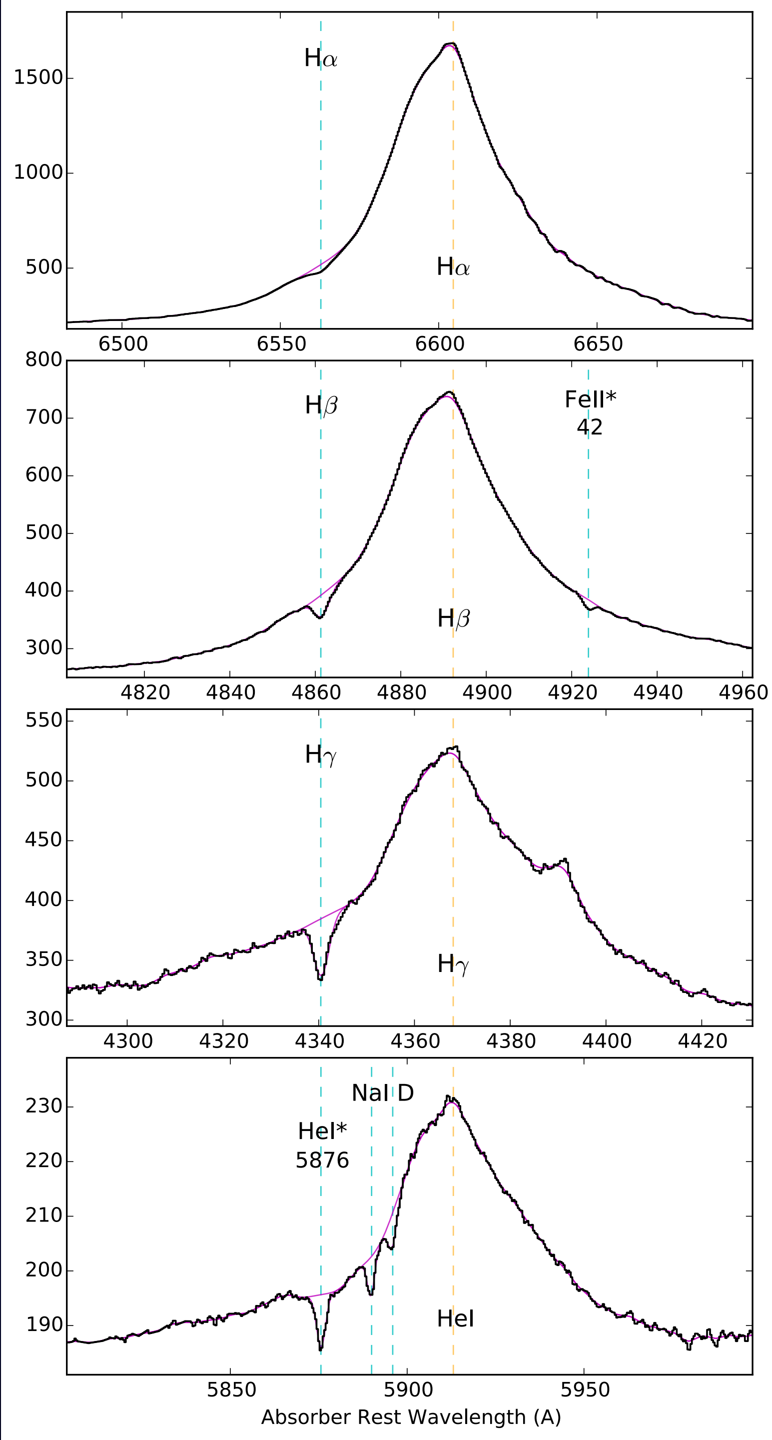
NO!





Gemini/GMOS – June 2015

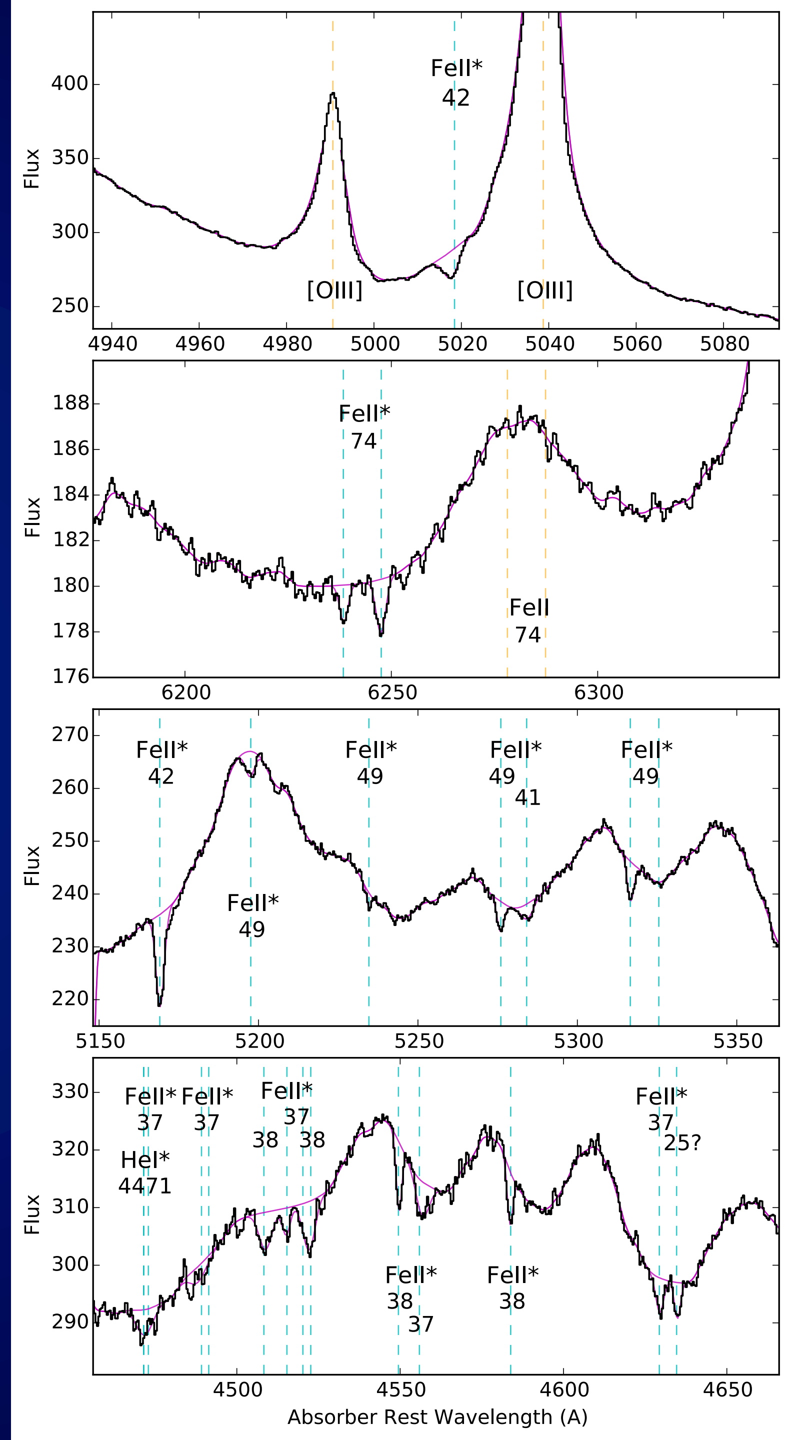
(David Rupke)

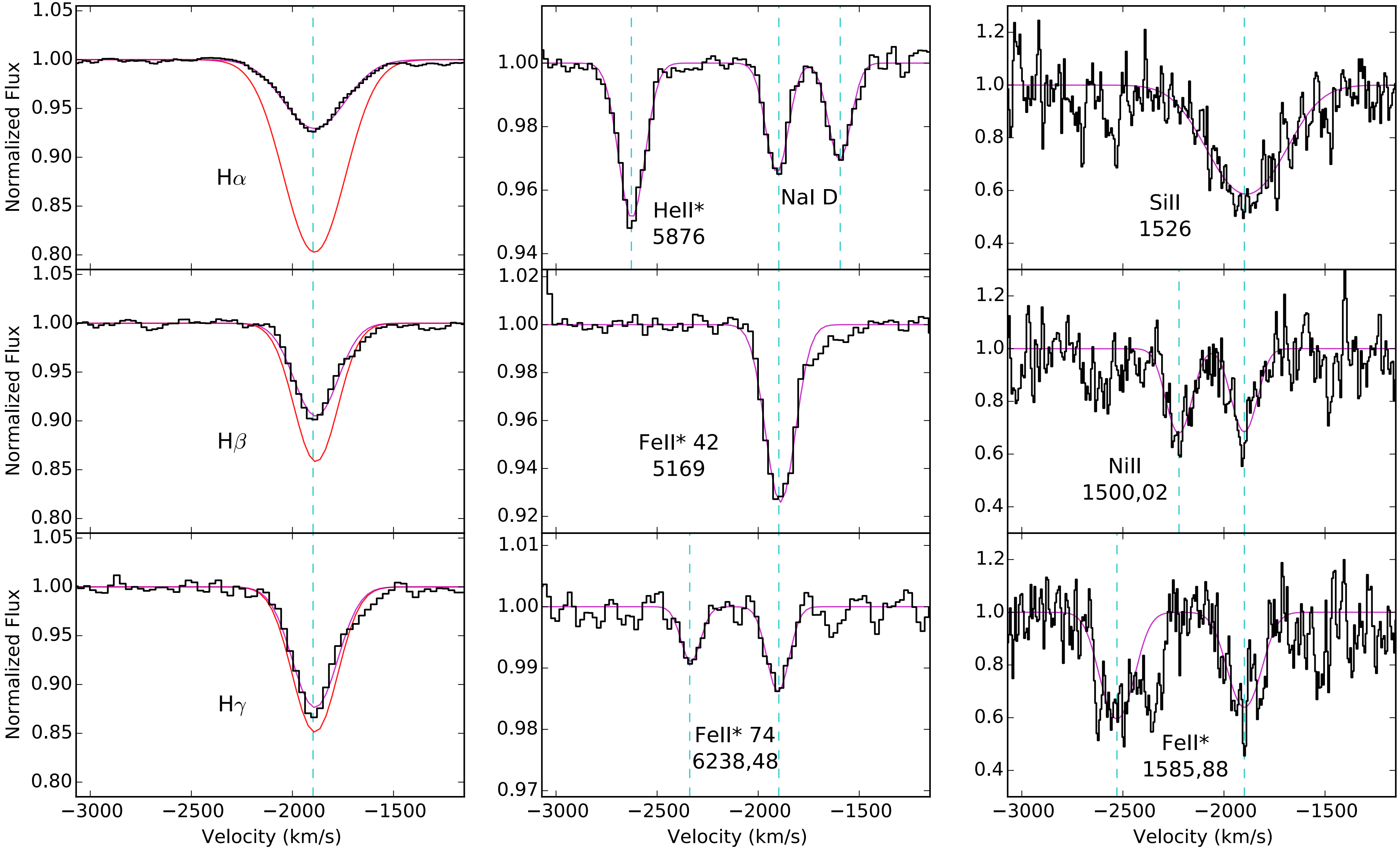


narrow outflow lines with

v ~ 1900 km/s

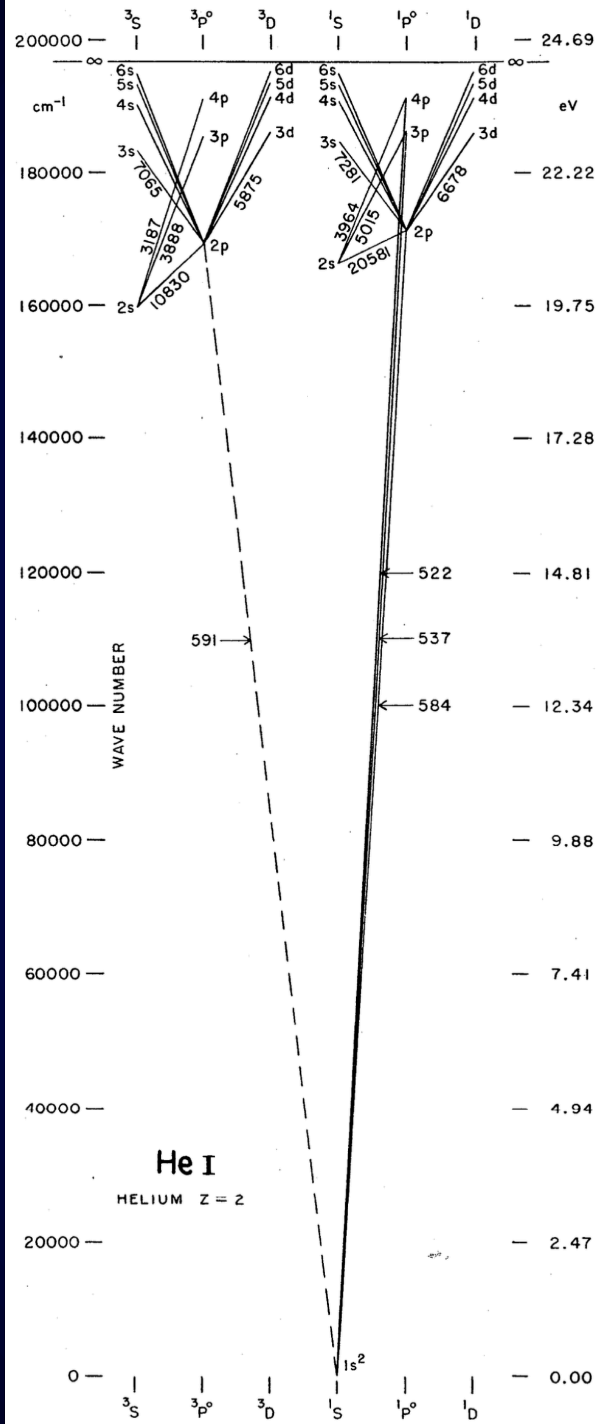
b ~ 100 km/s



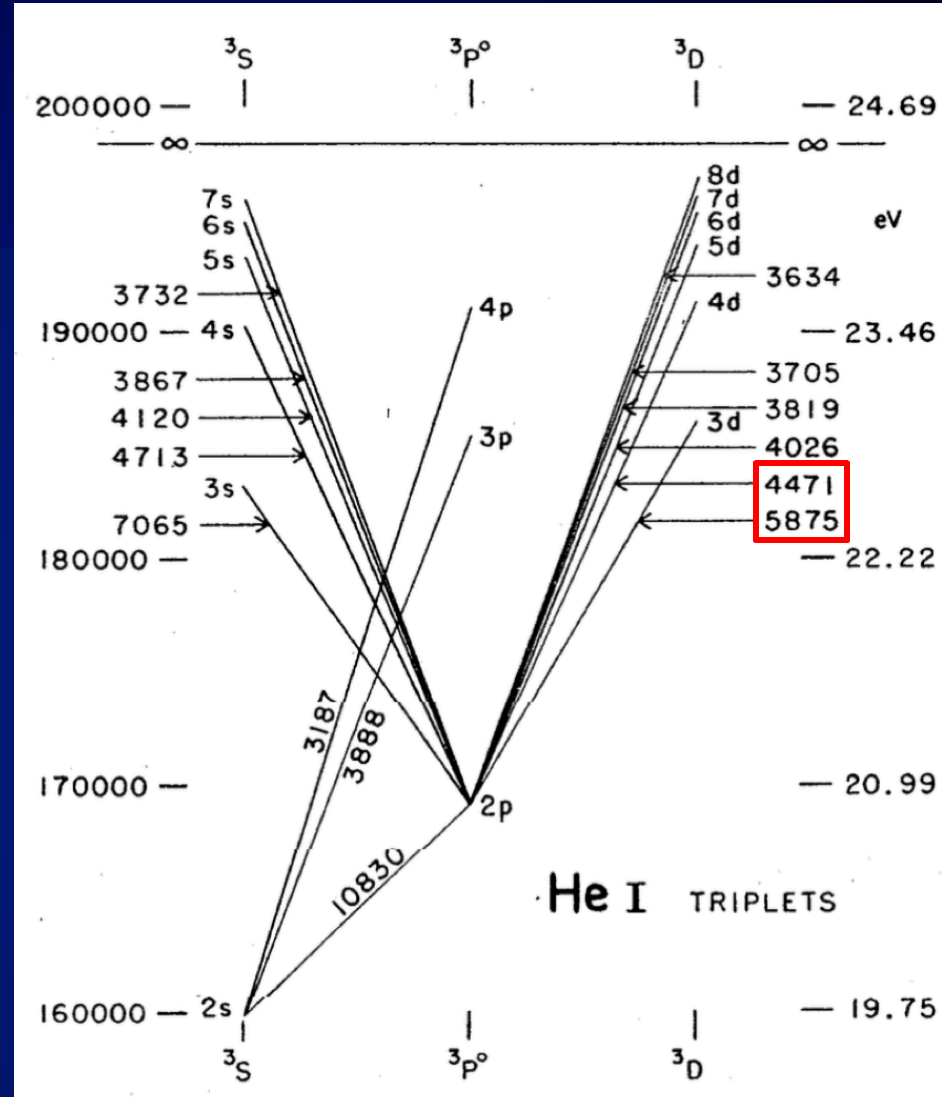


narrow outflow lines with: v ~ 1900 km/s, b ~ 100 km/s, C_0 ~ 5% (visible) to 40% (UV)

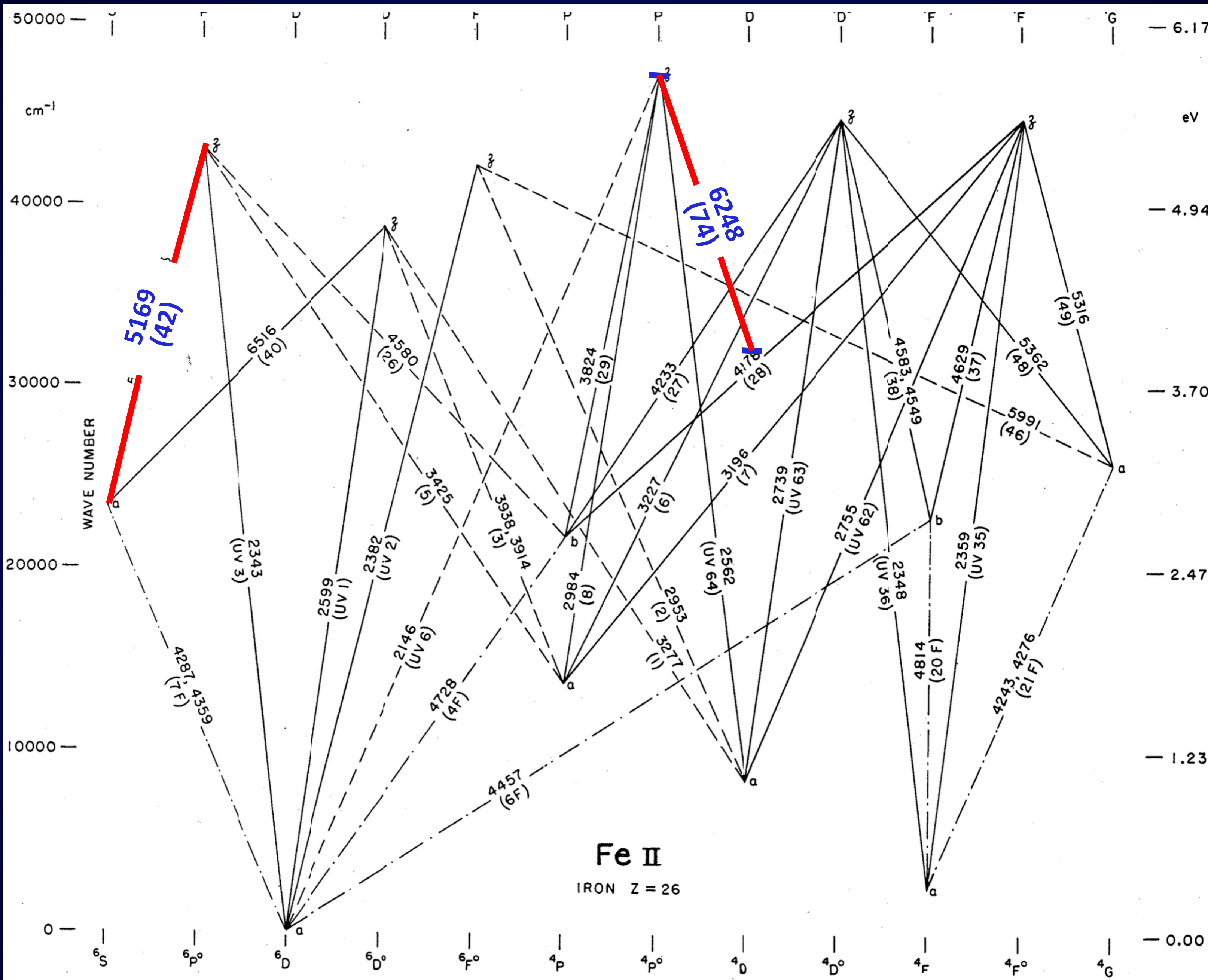
(Hα < Hβ means absorber does not cover Balmer-line BLR)



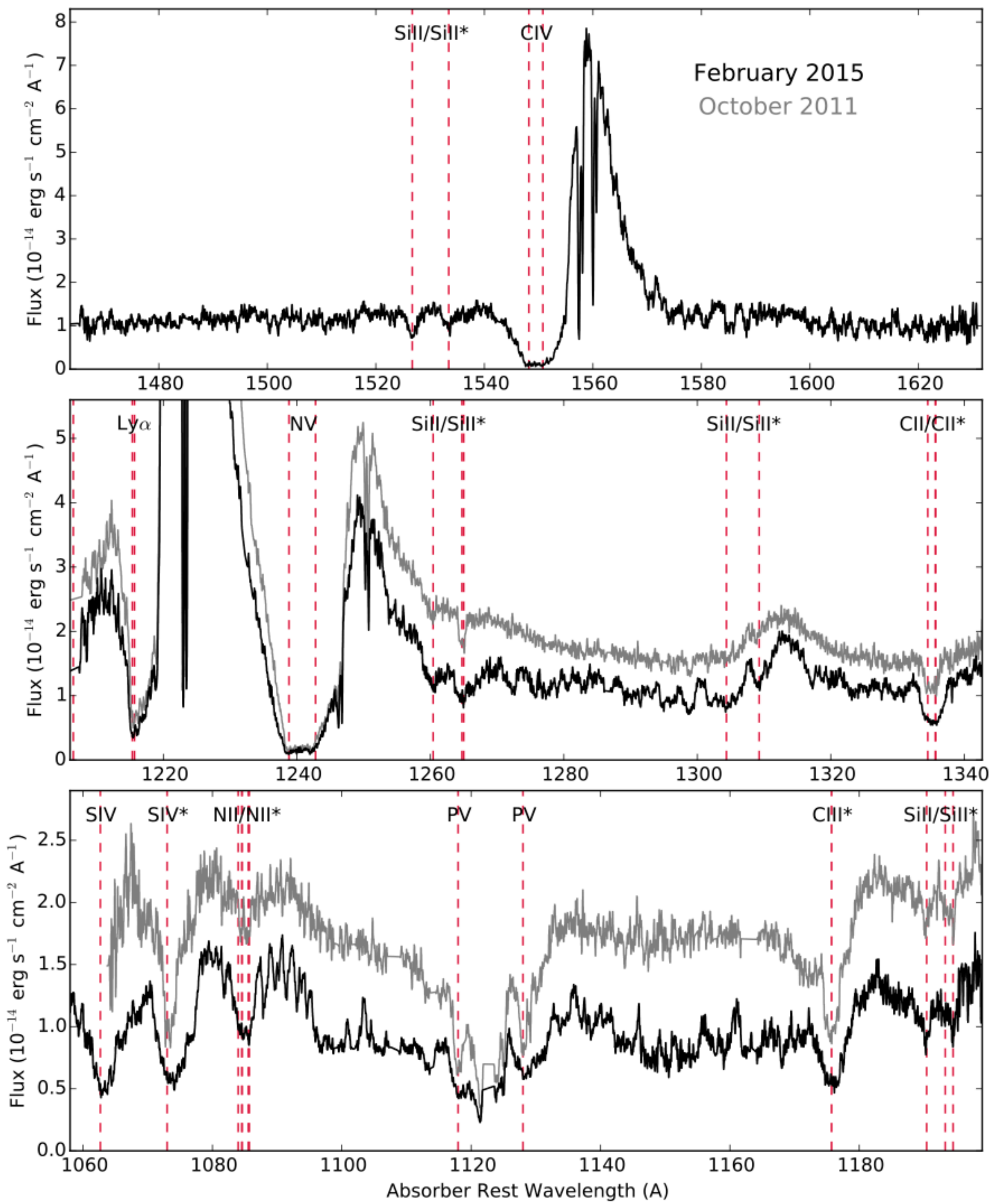
cm⁻¹
WAVE NUMBER
eV
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
24.69
22.22
19.75
17.28
14.81
12.34
9.88
7.41
4.94
2.47
0.00
^3S $^3P^o$ ^3D ^1S $^1P^o$ ^1D
∞
6s 5s 4s 3s 2s
4p 3p 2p
6d 5d 4d 3d
1s²
7065 3187 3888 10830 5875
7281 3964 5015 20581 6678
591
522
537
584
He I
HELIUM Z = 2



^3S $^3P^o$ ^3D
200000
190000
180000
170000
160000
24.69
23.46
22.22
20.99
19.75
eV
∞
7s 6s 5s 4s 3s 2s
4p 3p 2p
8d 7d 6d 5d 4d 3d
3732
3867
4120
4713
7065
3634
3705
3819
4026
4471
5875
3187
3888
10830
He I TRIPLETS


50000
40000
30000
20000
10000
0
cm⁻¹
WAVE NUMBER
eV
6.17
4.94
3.70
2.47
1.23
0.00
5169 (42)
6248 (74)
6516 (40)
2343 (UV 3)
4580 (26)
2599 (UV 1)
2382 (UV 2)
3425 (5)
3938, 3914 (3)
3824 (29)
4233 (27)
4178 (28)
4583, 4549 (38)
4629 (37)
5362 (48)
5316 (49)
5991 (46)
3227 (6)
3196 (7)
2739 (UV 63)
2755 (UV 62)
2562 (UV 64)
2348 (UV 36)
2359 (UV 35)
2984 (8)
2953 (2)
3277 (1)
2146 (UV 6)
4728 (4F)
4287, 4359 (7F)
4457 (6F)
4814 (20F)
4243, 4276 (21F)
Fe II
IRON Z = 26
6S
6P°
6D
6D°
6F°
4P
4P°
4D
4D°
4F
4F°
4G

HST/COS – Feb 2015



HST/COS – Feb 2015

IDs:

red = non-FeII

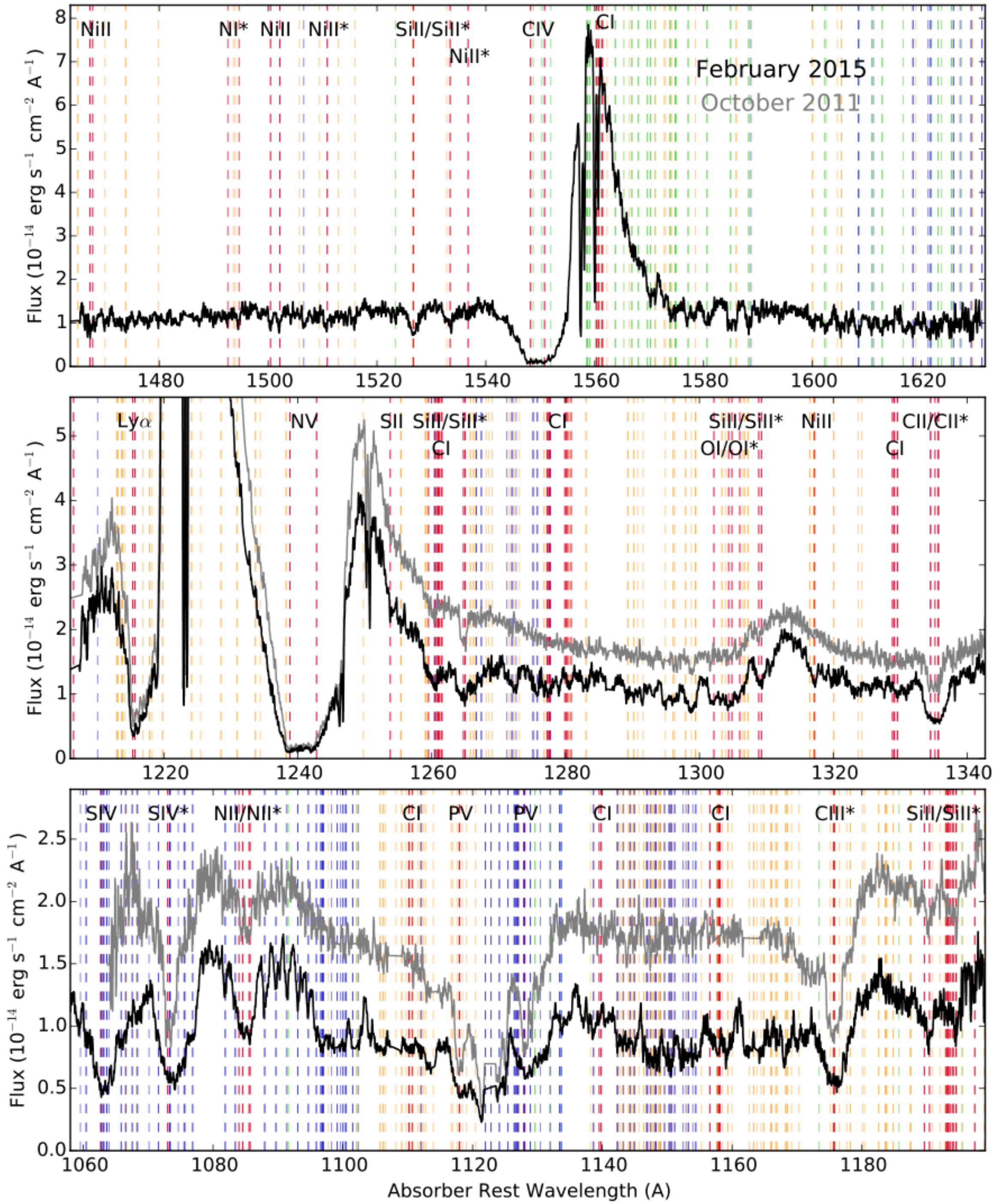
FeII:

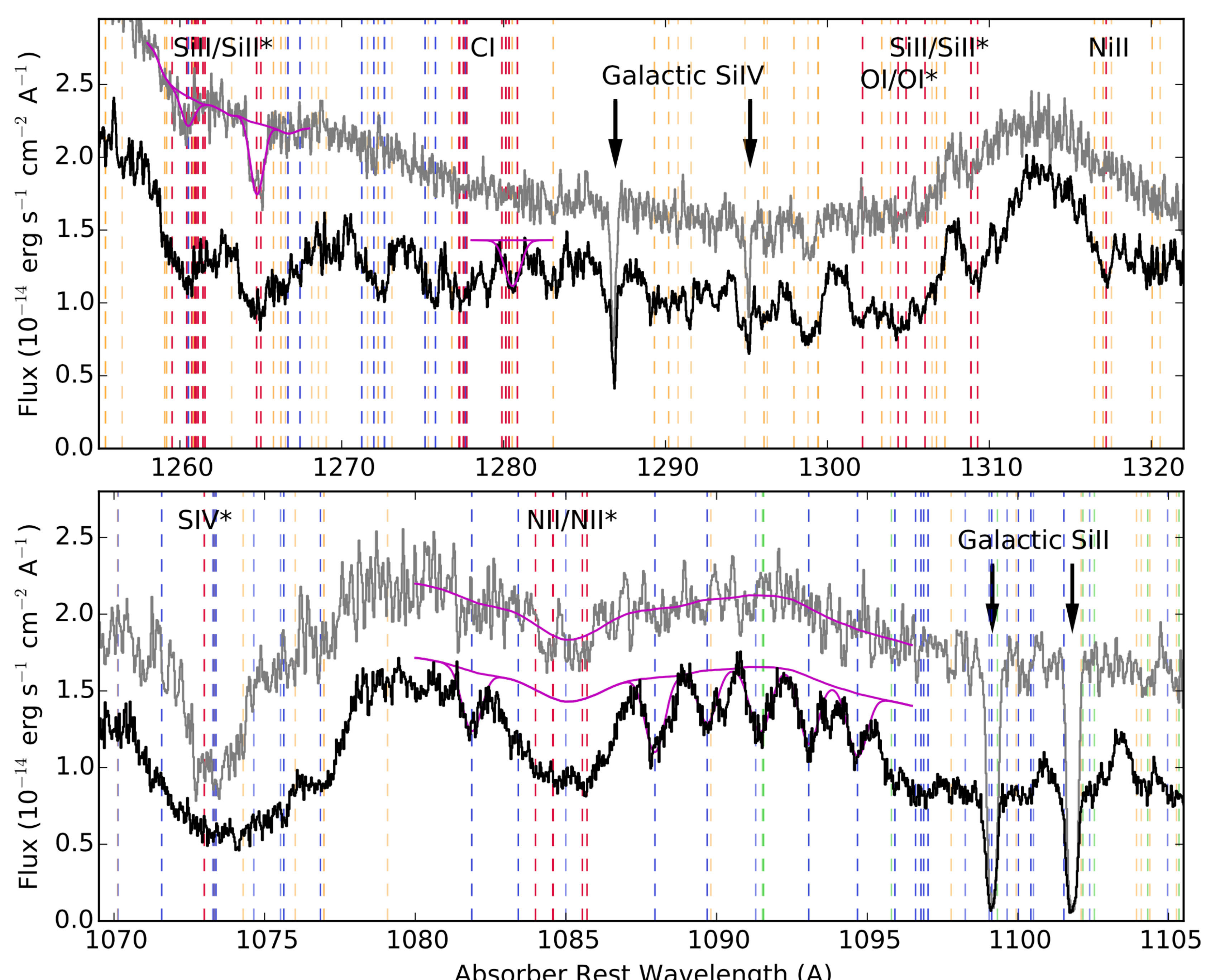
blue = ground multiplet a^6D

green = a^4F

orange = up to 3.0 eV

- Line blanketing absorption
- "emission" spikes are gaps between absorption lines

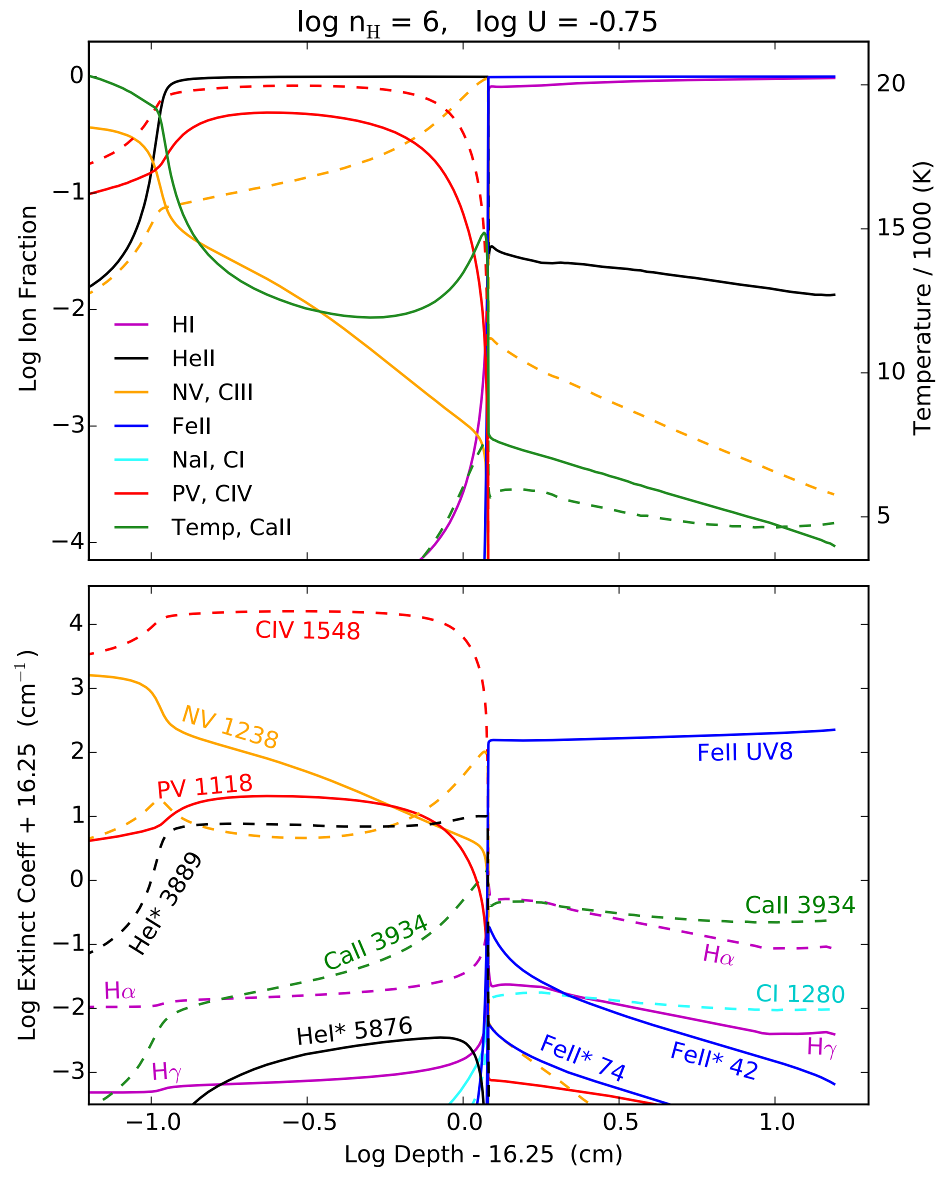


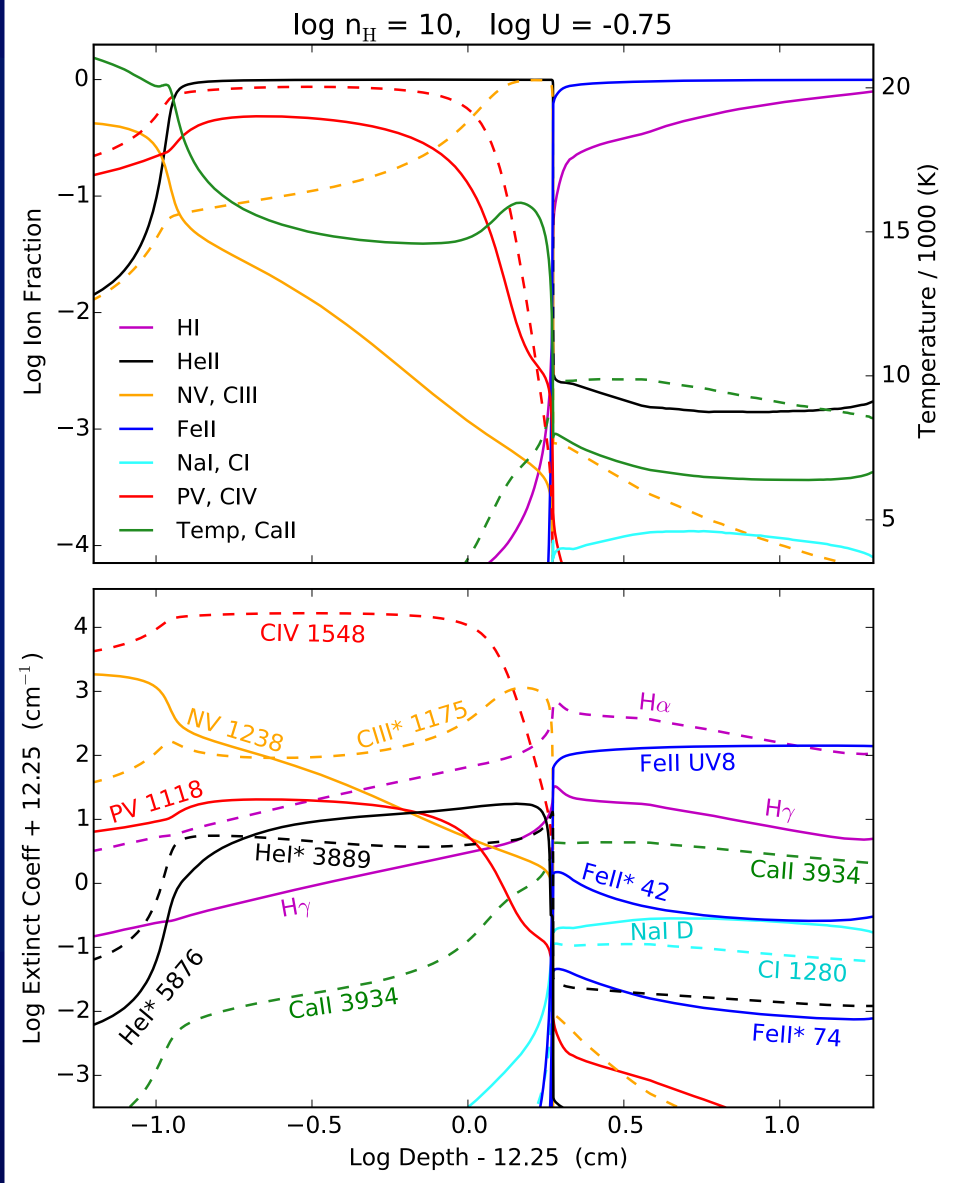


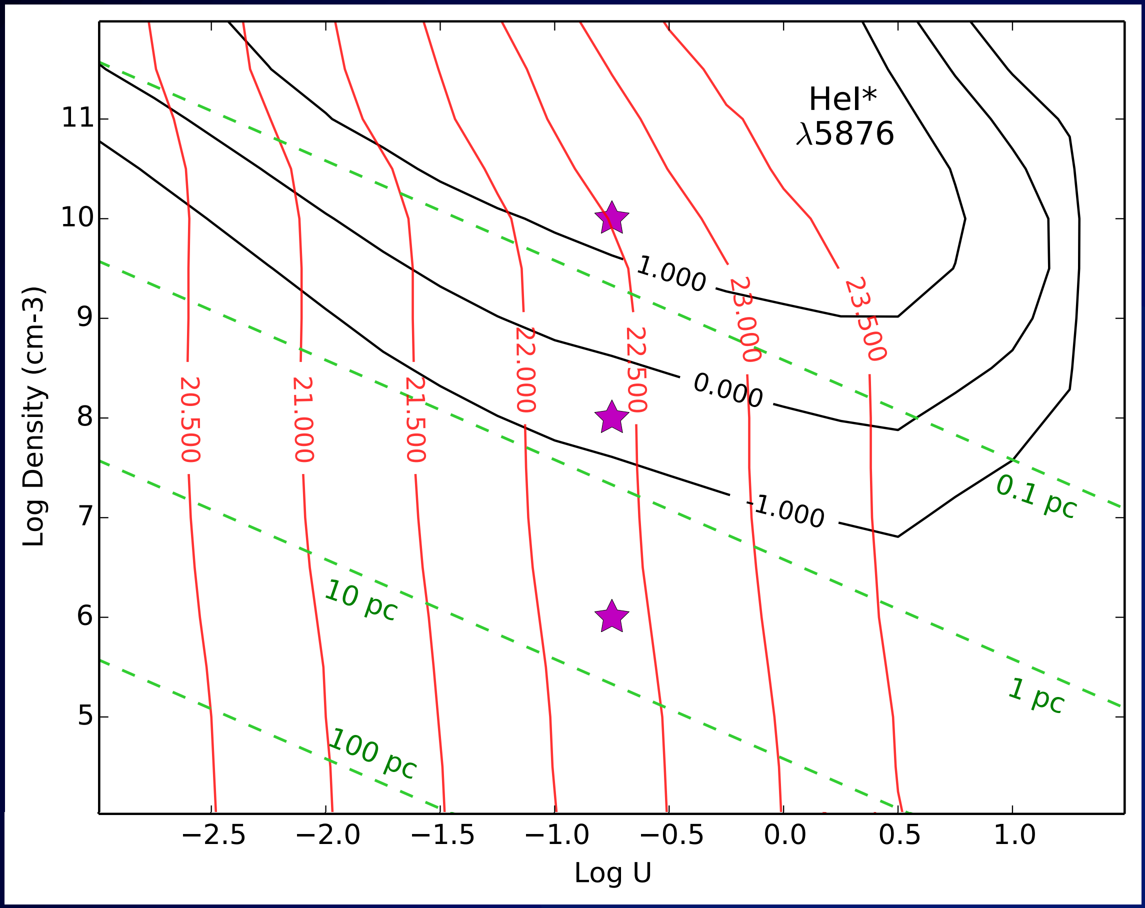
SiII/SiII*
CI
Galactic SiIV
SiII/SiII*
OI/OI*
NiII
Flux (10^{-14} erg s^{-1} cm^{-2} A^{-1})
SIV*
NII/NII*
Galactic SiII
Absorber Rest Wavelength (A)

Cloudy simulations:

solar metallicities, turbulence b=100 km/s, constant density,
Excited states: Cloudy HI + HeI, FeII with 371 levels, Chianti data







Fully-ionized (HII, HeII) gas

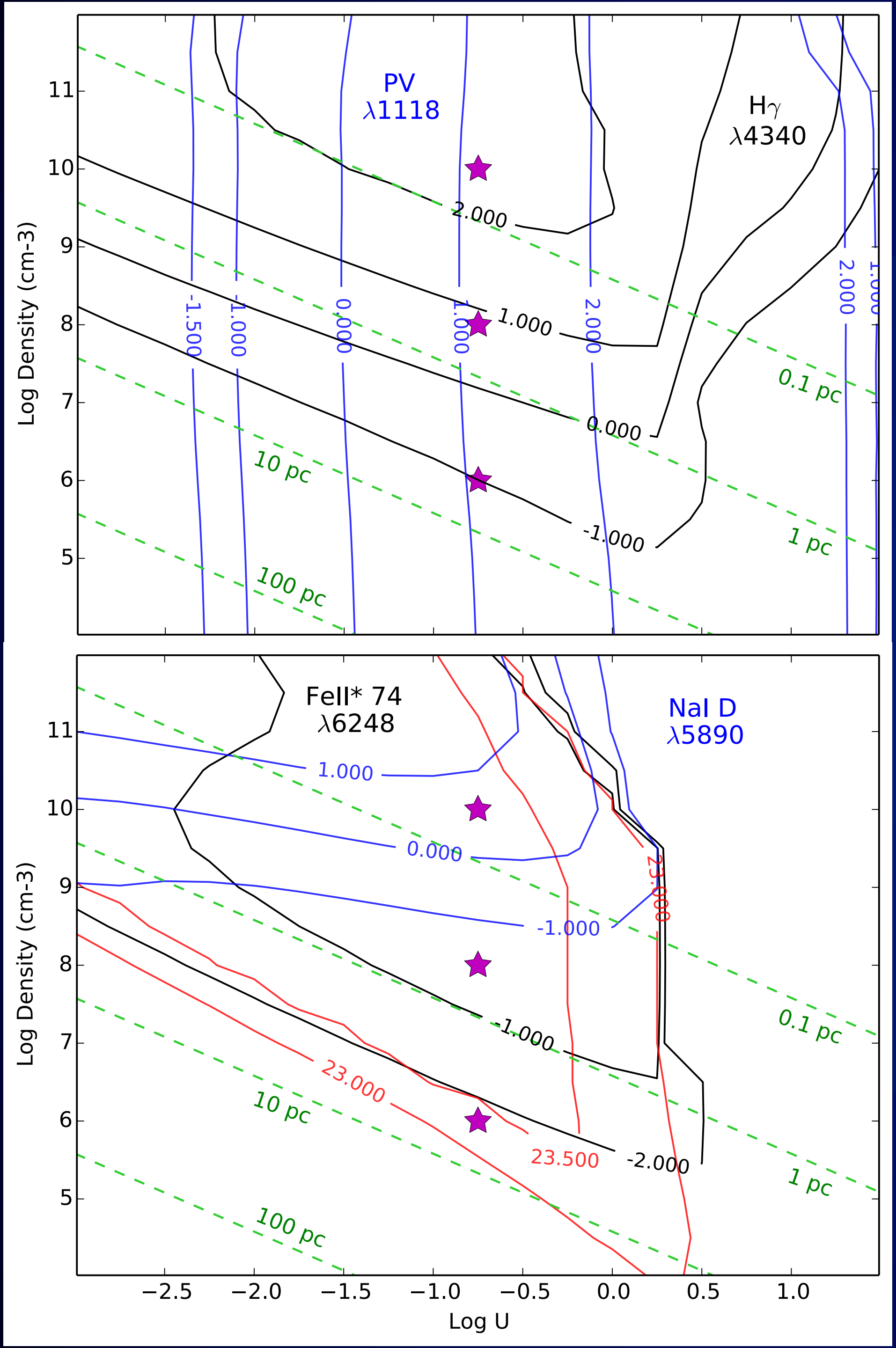
He I 5876

τ > 0.1 requires:

log n_H > 8 (cm^{-3})

log N_H > 22 (cm^{-2})

< 1 pc from the quasar



Partially-ionized (FeII) gas

Fe II (74) 6248

τ > 0.2 requires:

log n_H > 8 (cm^{-3})

log N_H > 23.2 (cm^{-2})

Na I D 5890

τ > 3 requires:

log n_H > 9.7 (cm^{-3})

log N_H > 23.3 (cm^{-2})

Large N_H requires large U behind a front (not isolated low-U clouds)

Balmer HI BLR not covered:
R < 0.1 pc, log n_H > 9 (cm^{-3})

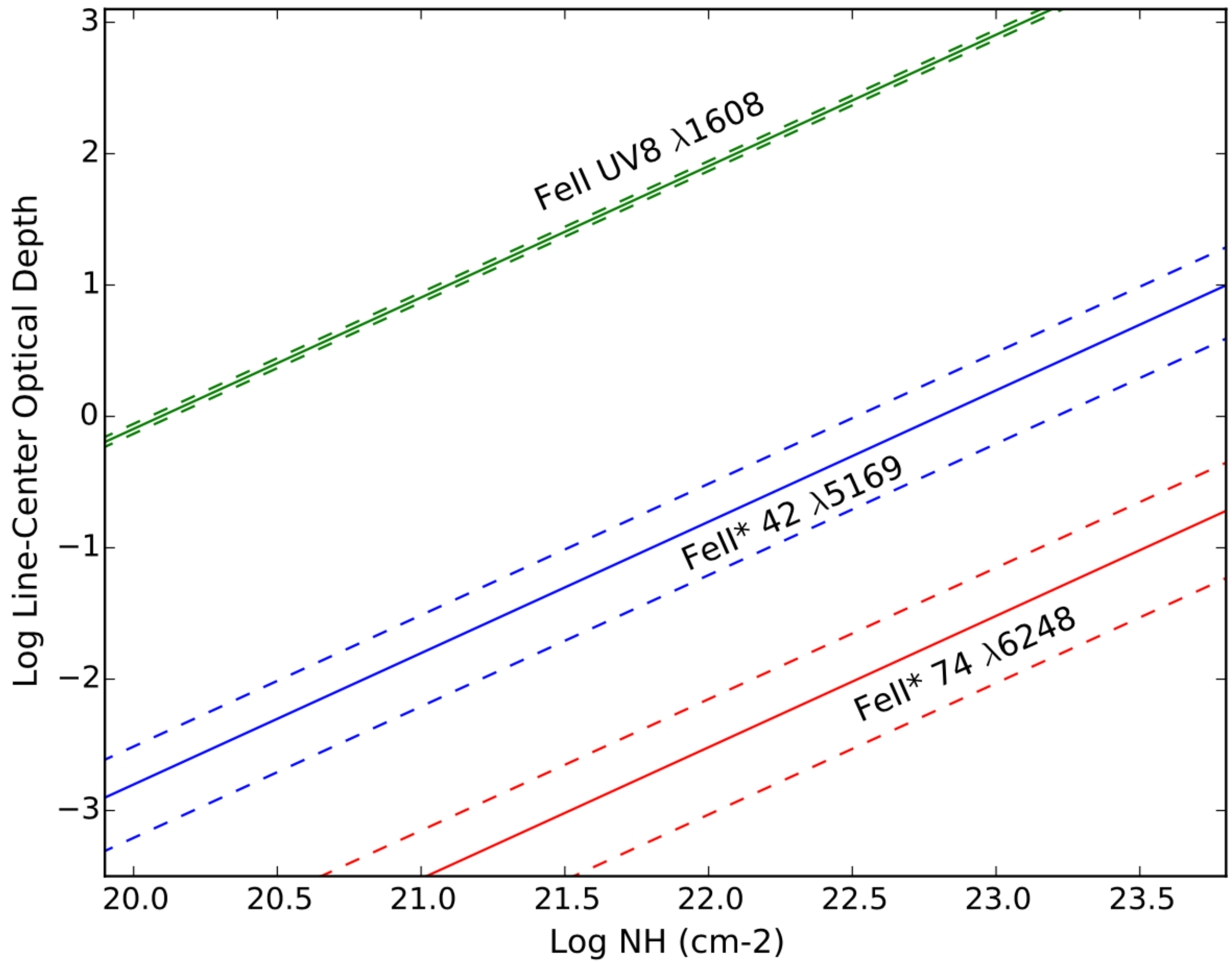
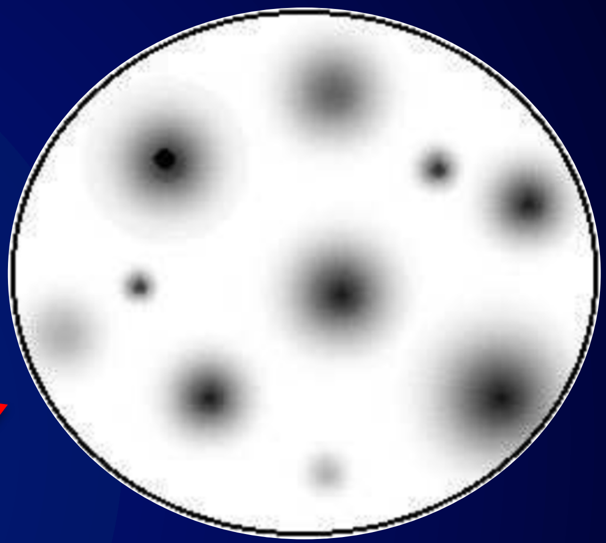


Figure 7. Theoretical line-center optical depths in three Fe II lines as a function of total column density, log N_H (cm^{-2}), in clouds with solar abundances, velocity dispersions characterized by b = 100 km s^{-1}, level populations in thermal equilibrium, and ionization fraction $N(\text{Fe II})/N(\text{Fe})$ = 1 throughout. The three different curves for each absorption line (dashed, solid, dashed) indicate temperatures T = 5500, 6500, and 7500 K (respectively, from bottom to top for multiplets 42 and 74 but the opposite for the resonant UV8 line).

PG 1411+442

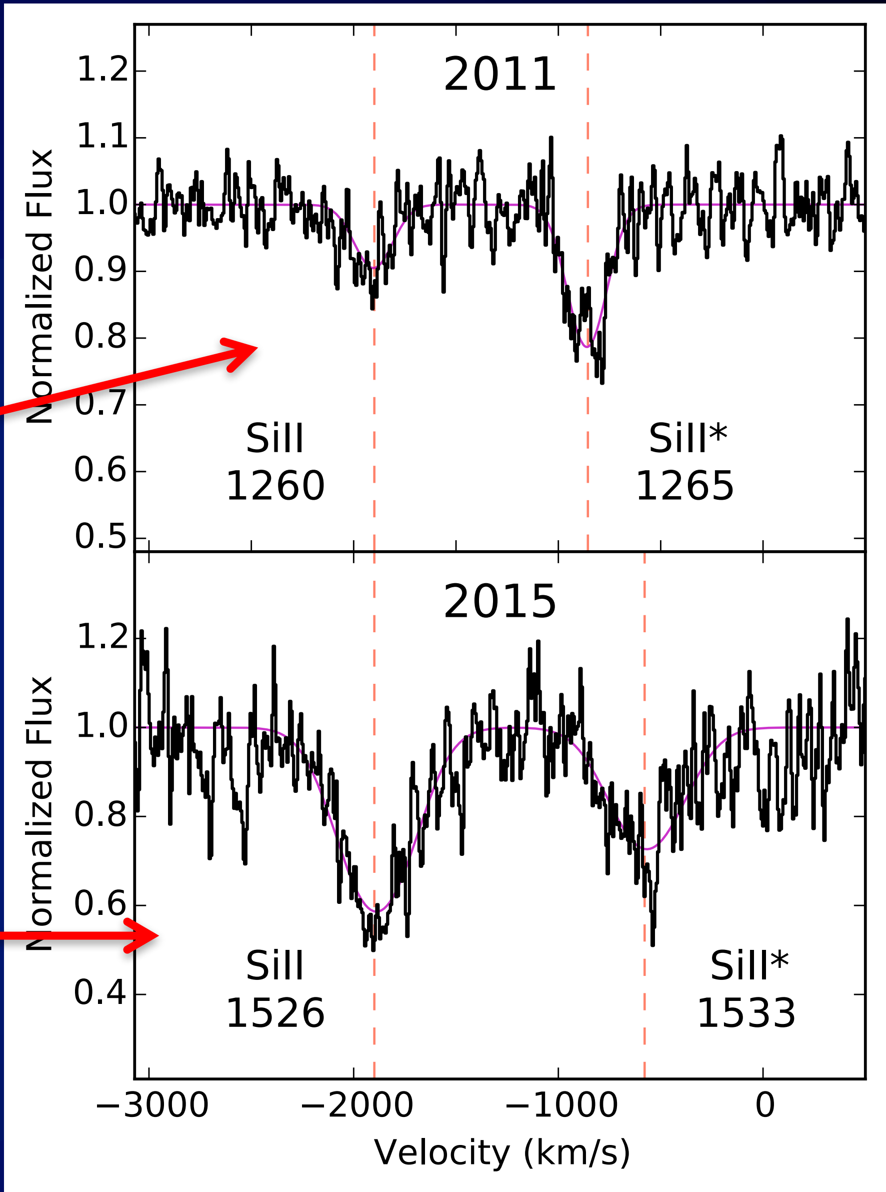
- Appeared in < 3 years (now fading)
- Velocity ~1900 km/s, dispersion b ~ 100 km/s
- Total column density $\log N_H > 23.3$ (cm^{-2})
- Likely R < 0.1 pc, $\log n_H > 9$ (cm^{-3})
- $\tau >> 1$ multiplets show $\tau <\sim 1$ signatures
- Consistent with BLR cloud(s) crossing our lines of sight
- Related (somehow) to the mini-BAL outflow at <u>same speed</u>
- Like other high-column density outflows (LoBALs, FeLoBALs), but with narrower/resolved lines?



Distances and variability

Mini-BAL gas has high densities:
log n_H (cm^{-2}) > 4

Oh wait, no, low densities:
log n_H (cm^{-2}) < 3

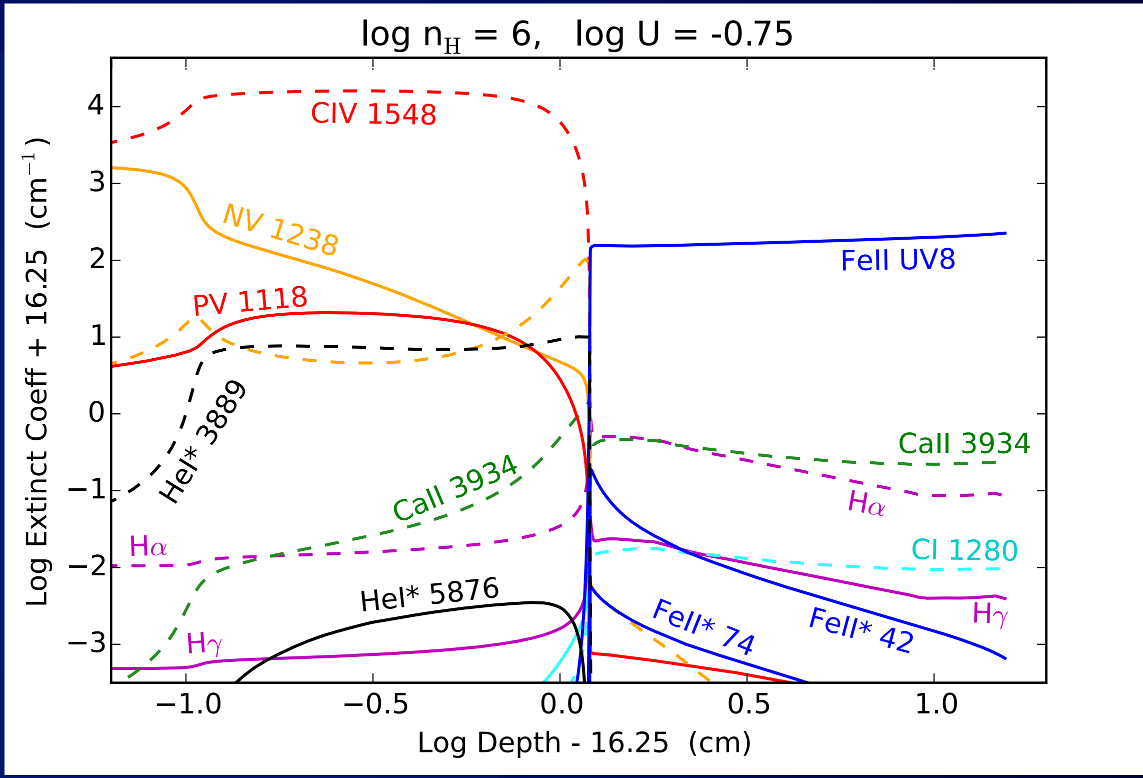


Distances and variability

If log N_H (cm^{-2}) > 22 or 23:

Absorption spectra with are not (very) responsive to changes in U

Ions like CIV, SIV can survive at very large U



PDS 456

z = 0.184
L ~ 10^{47} ergs/s

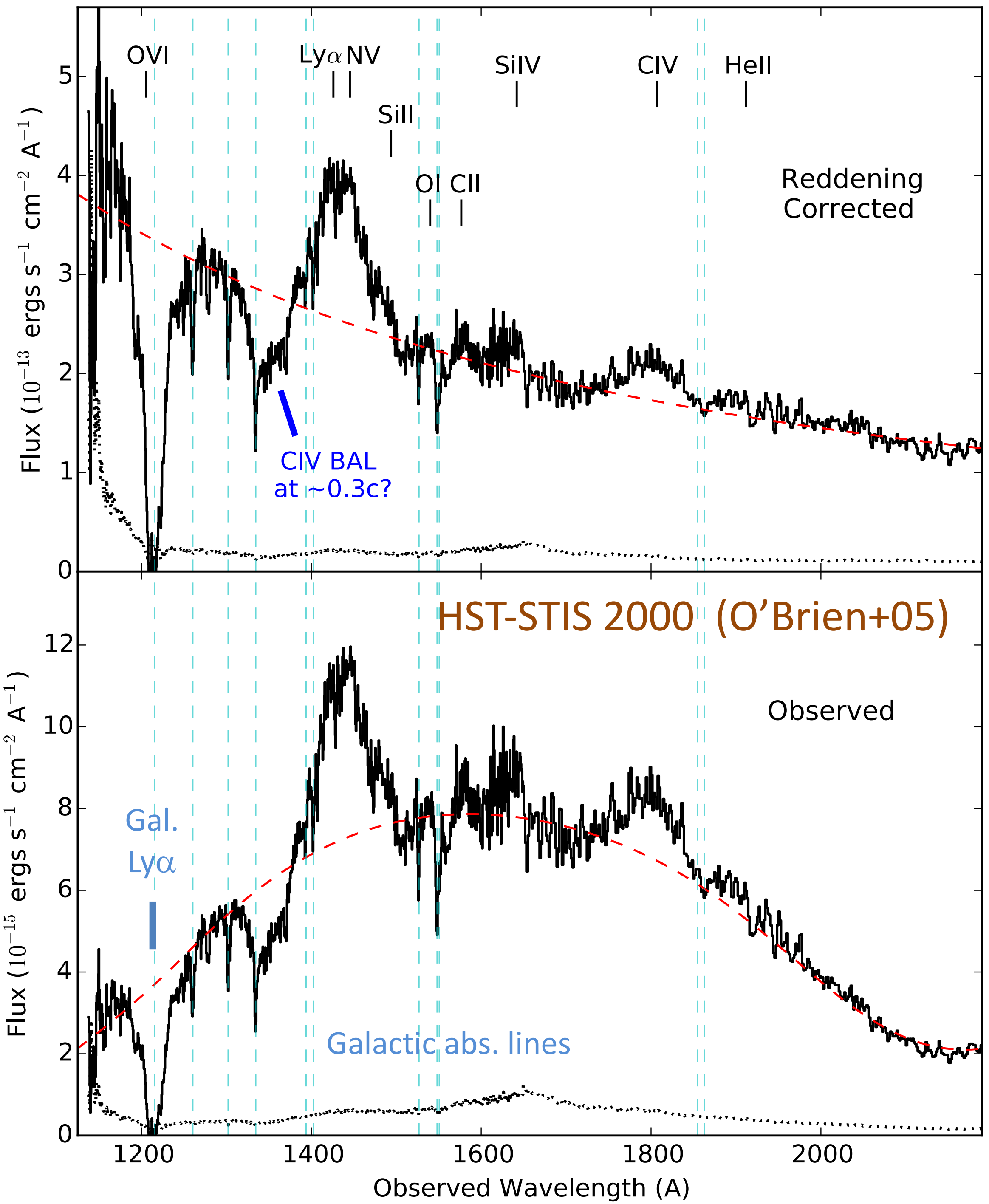
X-ray UFO (Reeves+16):
- v ~ 0.25-0.31c
- log $N_H(cm^{-2}) > 23$
- log $\xi > 5$

UV BAL identified as Lyα at v ~ 18,000 km/s

...is probably CIV at ~0.3c

Problems with Lyα:

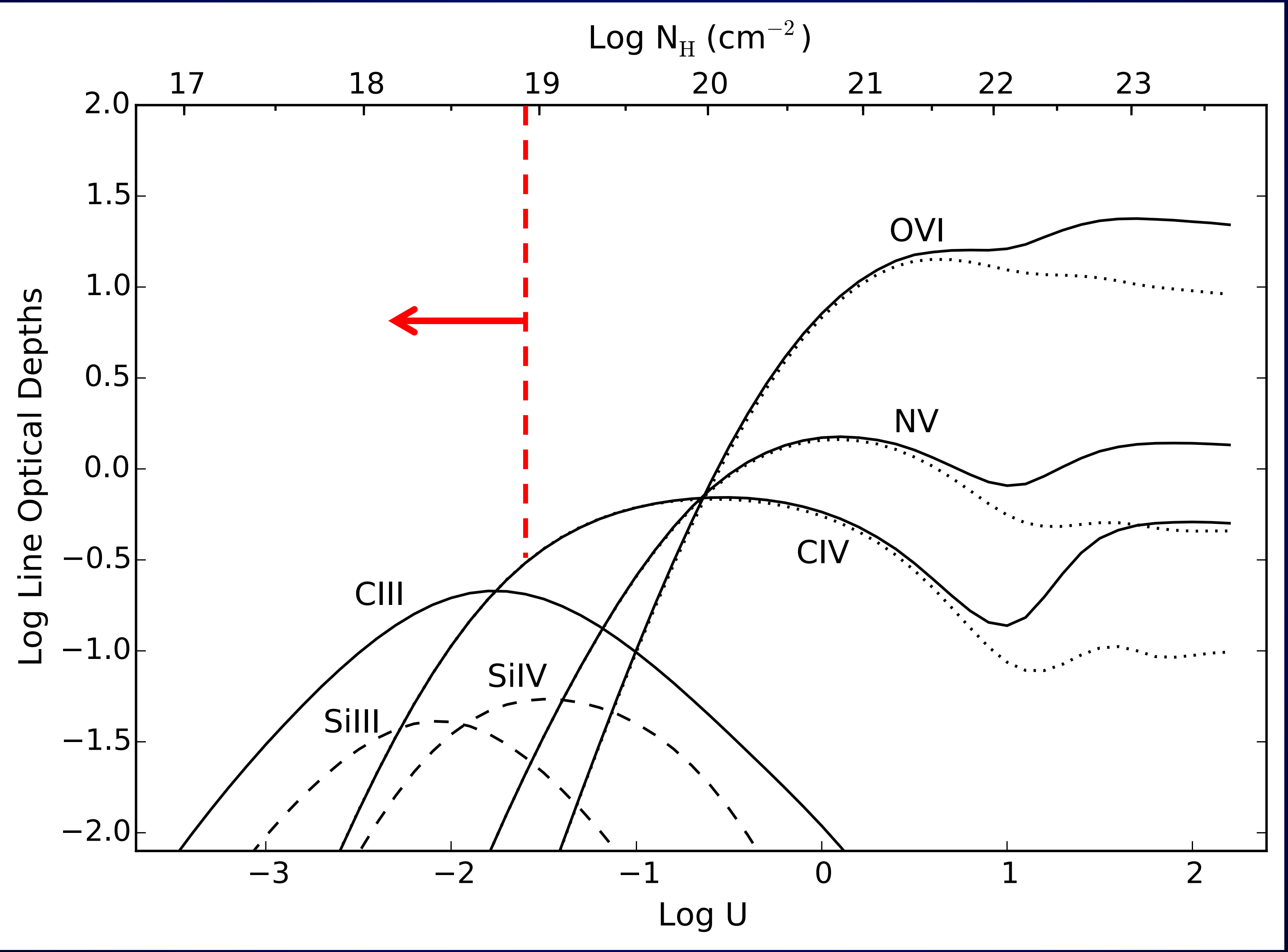
- Lyα-only is unprecedented
  known BALs have
  OVI >= CIV > Lyα
- Where is CIV at
  v ~ 18000 km/s?



Predicted BAL tau's (Cloudy) for clouds with log N_{HI} (cm^{-2}) = 15.2

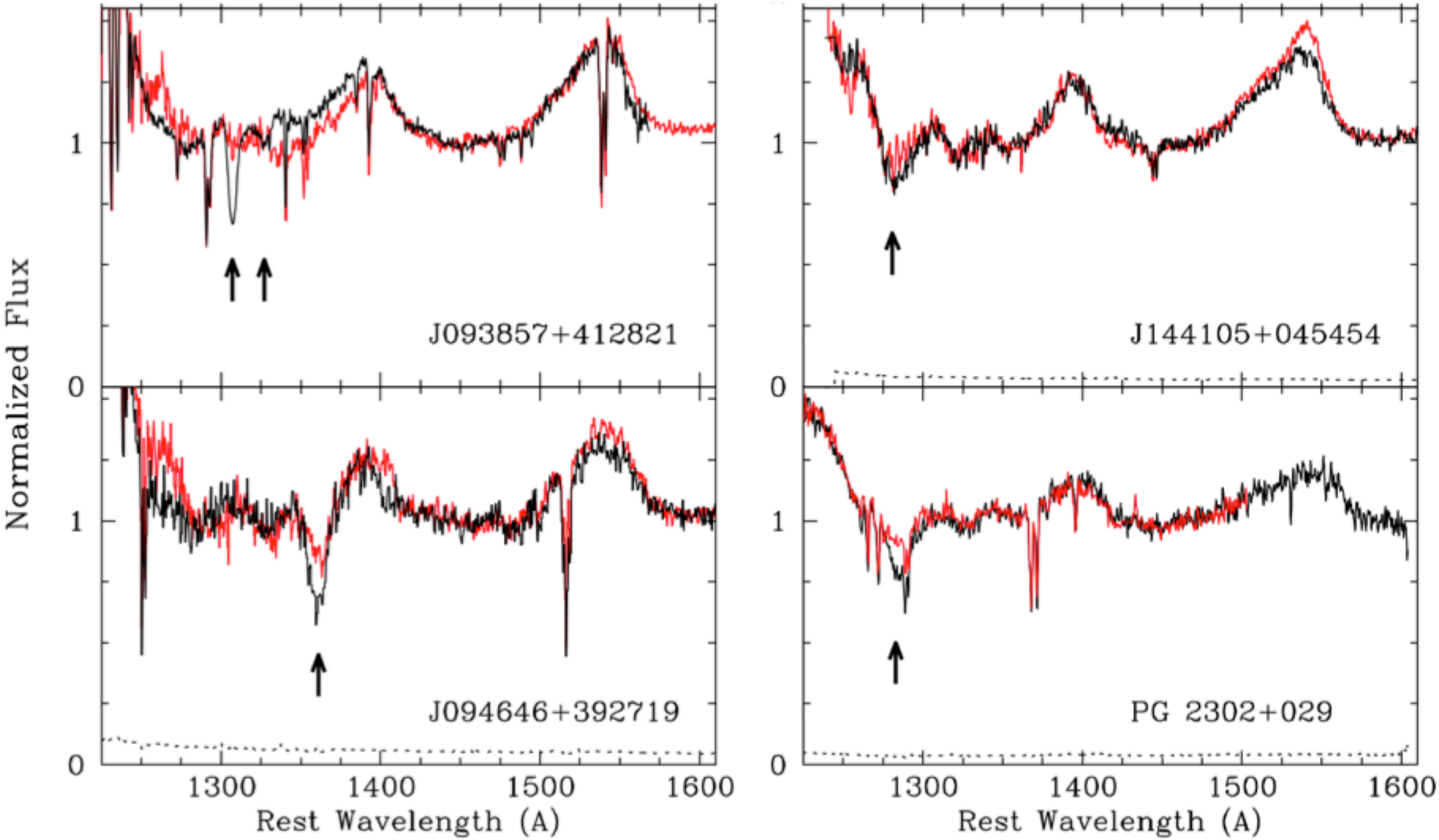
Lyα-only BAL would require unusually low U and N_H

Cloudy13 (Ferland+13)



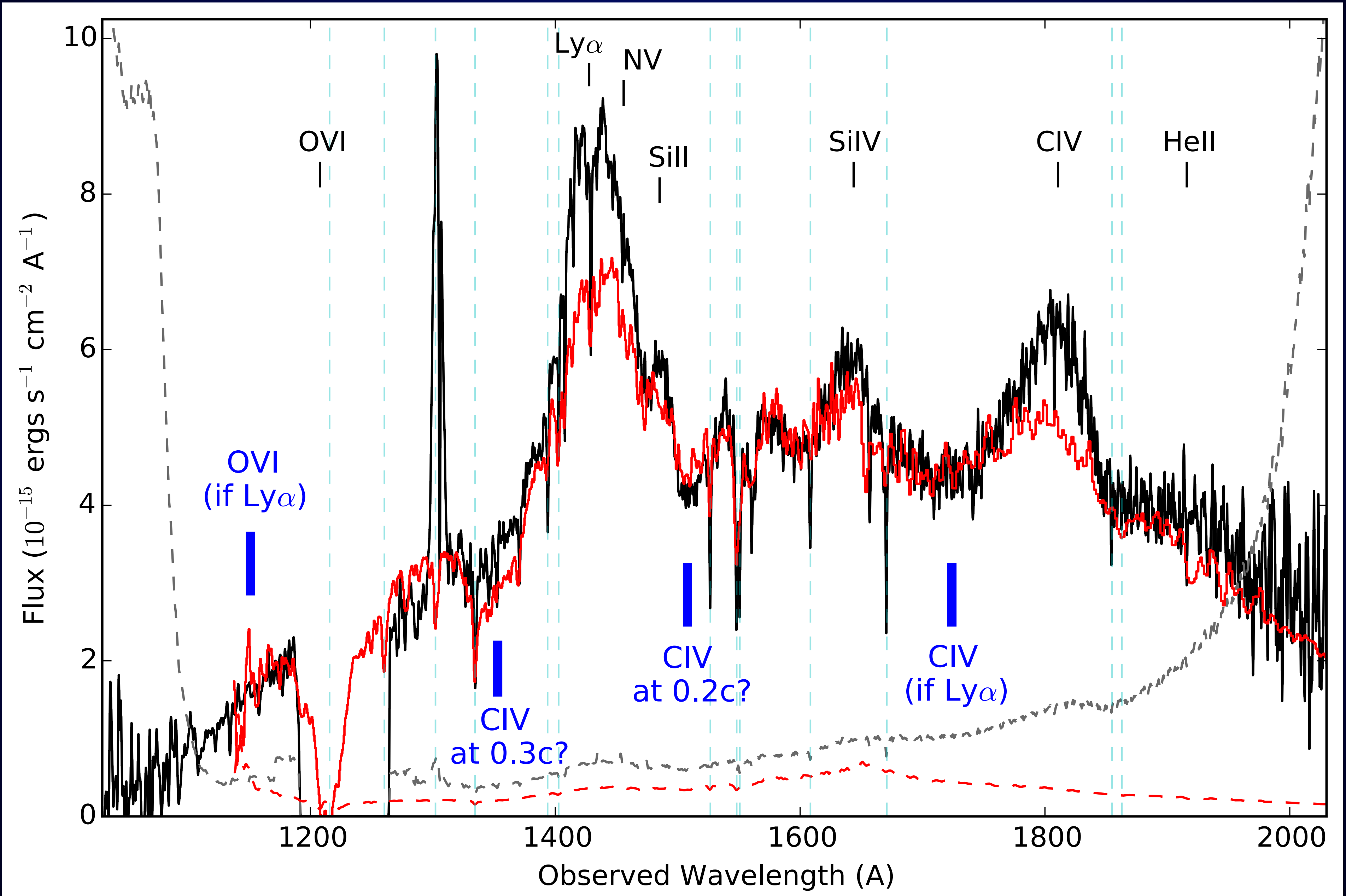
High-velocity CIV is (perhaps) more likely…

Hamann+13

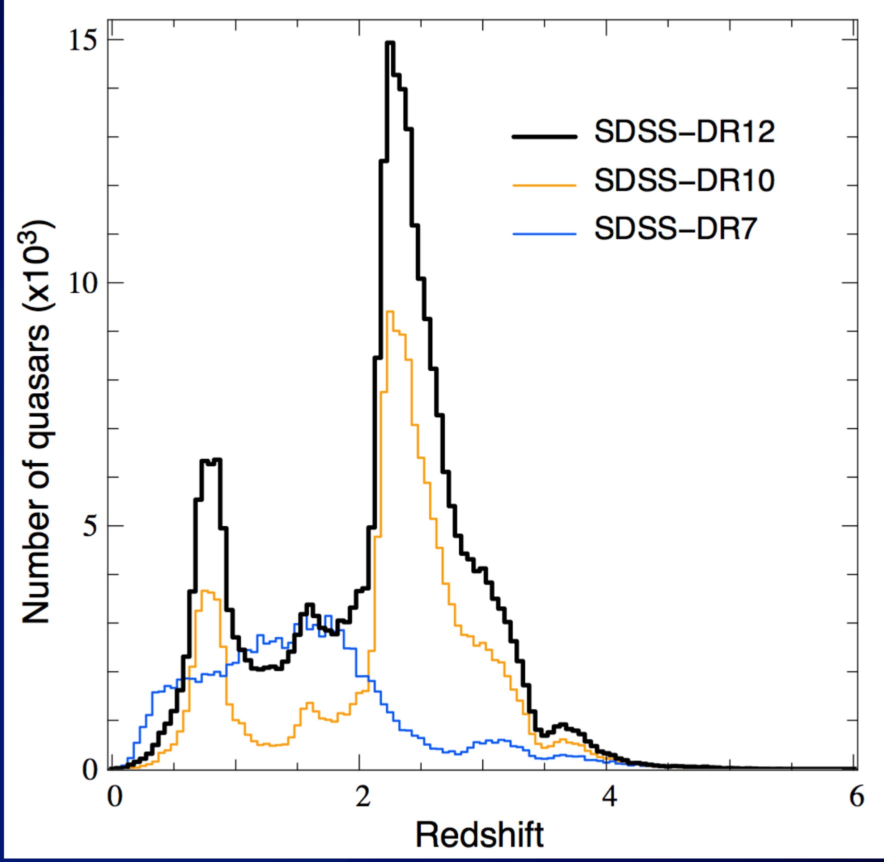


…requiring only log N_H (cm^{-2}) > 19 compared to log N_H (cm^{-2}) > 23 from X-ray lines

PDS 456: 2000 (red) vs 2014 (black)



Extremely Red Quasars (ERQs)



SDSS-III/BOSS:

Sloan Digital Sky Survey-III / Baryon acoustic Oscillation Spectroscopic Survey

Spectra of 297,301 quasars at 3600A – 1μm

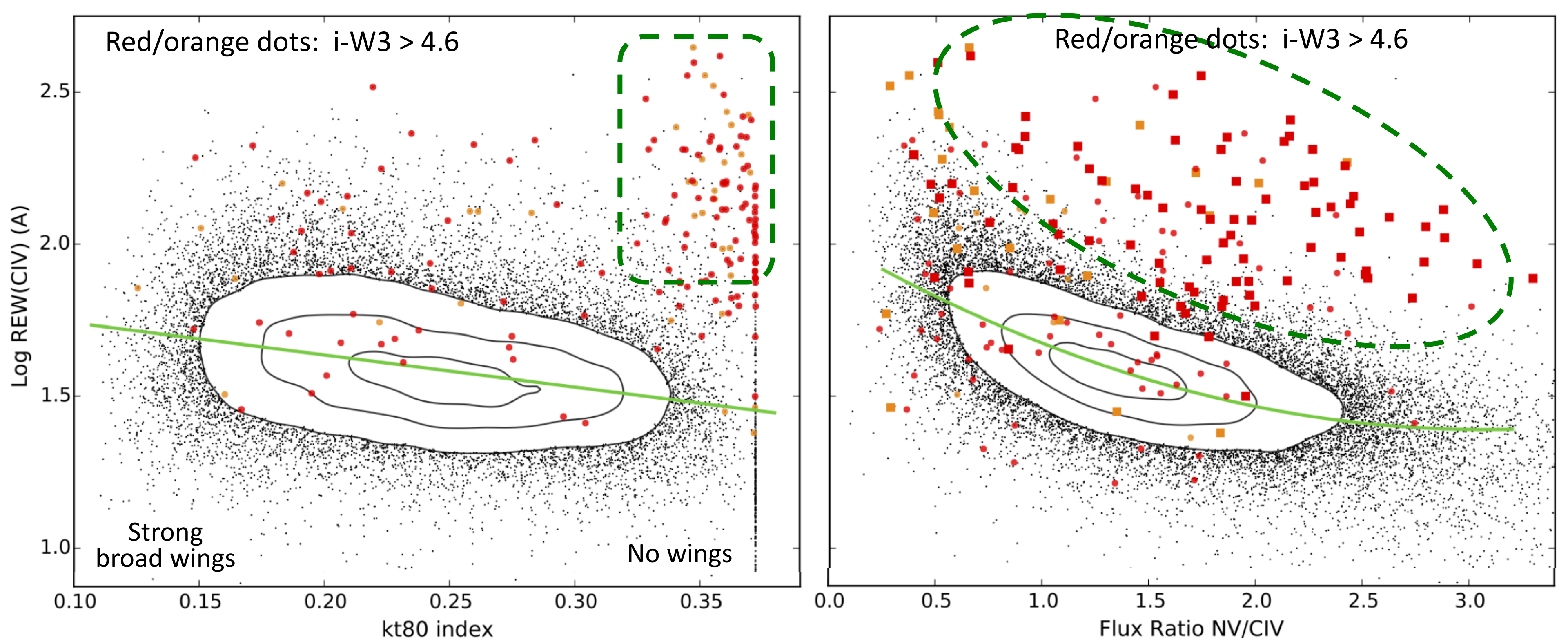
Fainter, redder & higher z than previous

WISE:

Wide-field Infrared Survey Explorer

W1, W2, W3, W4 at 3.4, 4.6, 12, and 22 μm

96,000 detected in W3 at SNR > 3



Define ERQ by i – W3 > 4.6
(0.2 – 3.5 μm rest)

Also "core" ERQs: REW(CIV) > 100A

→ A unique population
with unique *exotic* physical conditions

<u>Extremely red colors AND</u>:

Large REWs

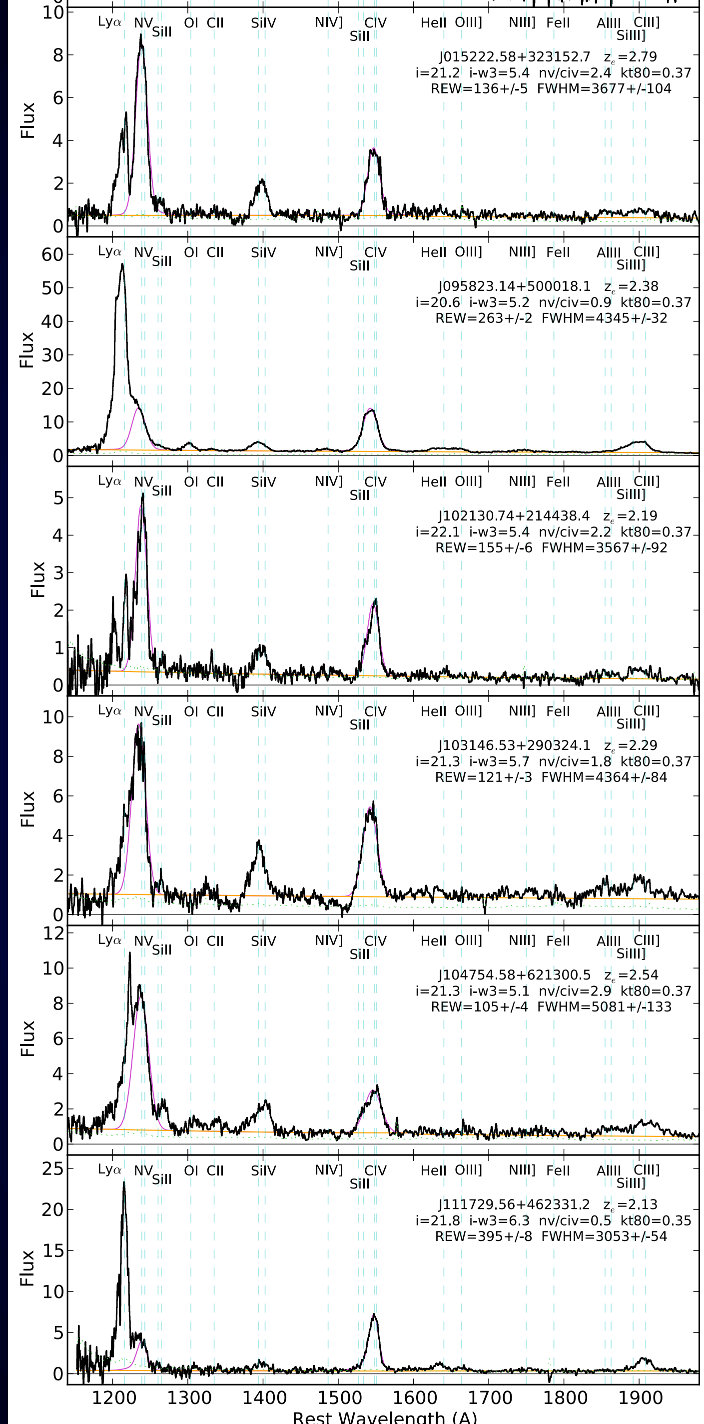
Wingless profiles

Exotic line ratios

Frequent large BEL blueshifts

Frequent BALs, mini-BALs

Broad blueshifted [OIII]

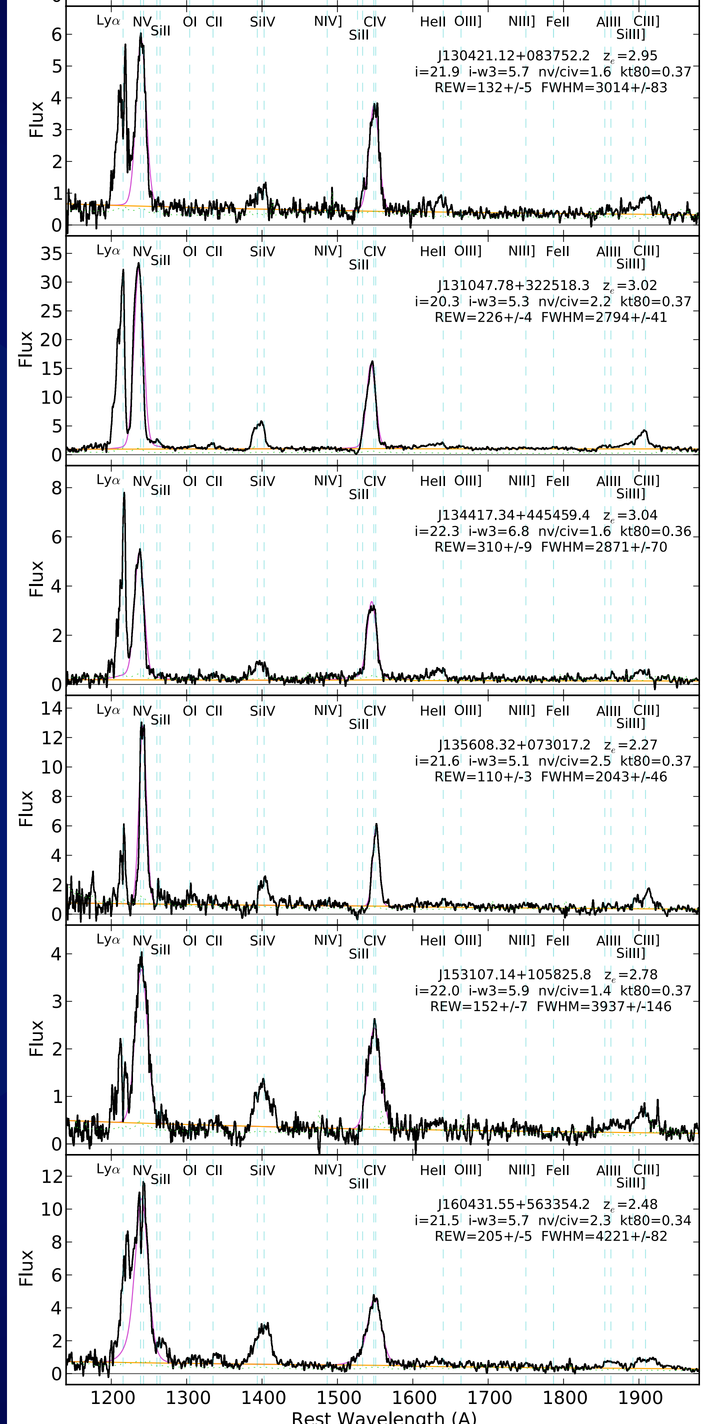


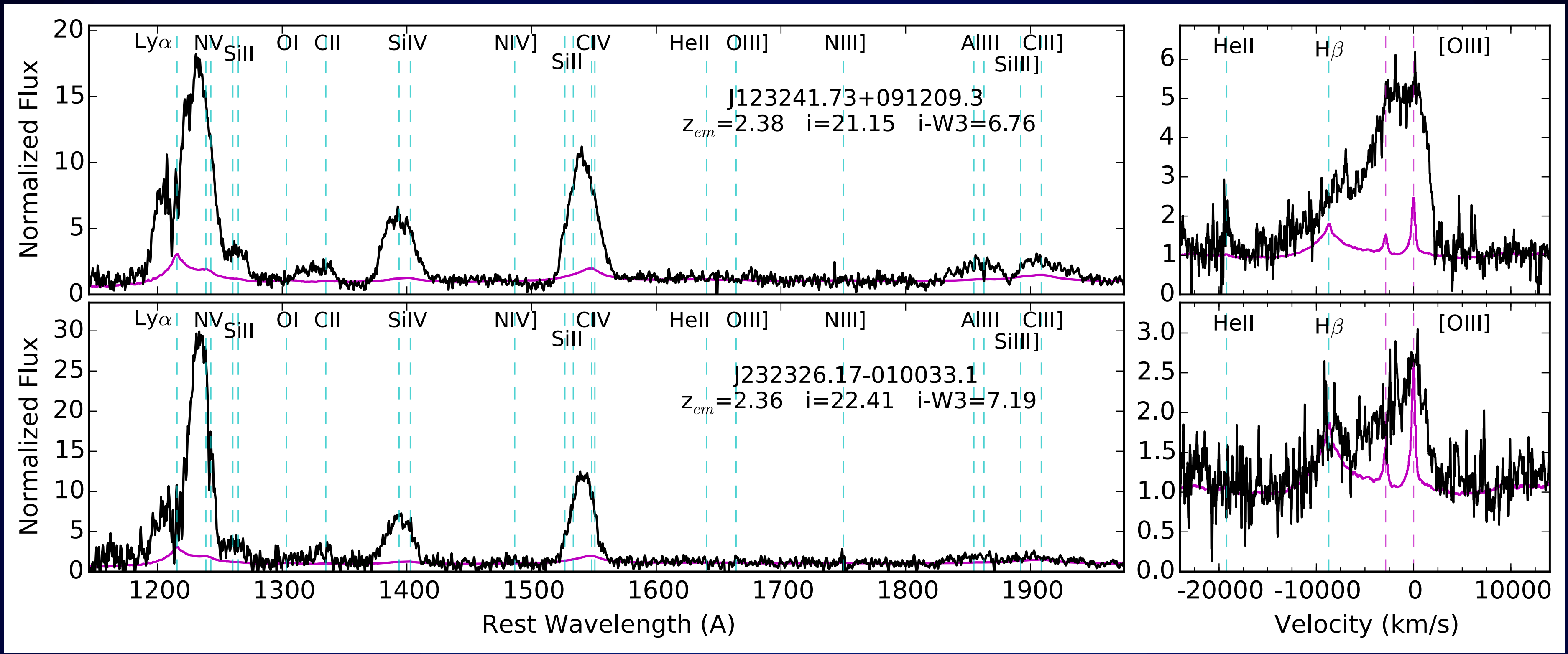
Several hundred ERQs:

i-W3 > 4.6

2.0 < z < 3.4

$L_{bol} \sim 10^{47}$ ergs/s





[OIII] FWHMs and blueshifted wings up to 5000 km/s

Extended (>1 kpc) quasars-driven <u>outflows</u>

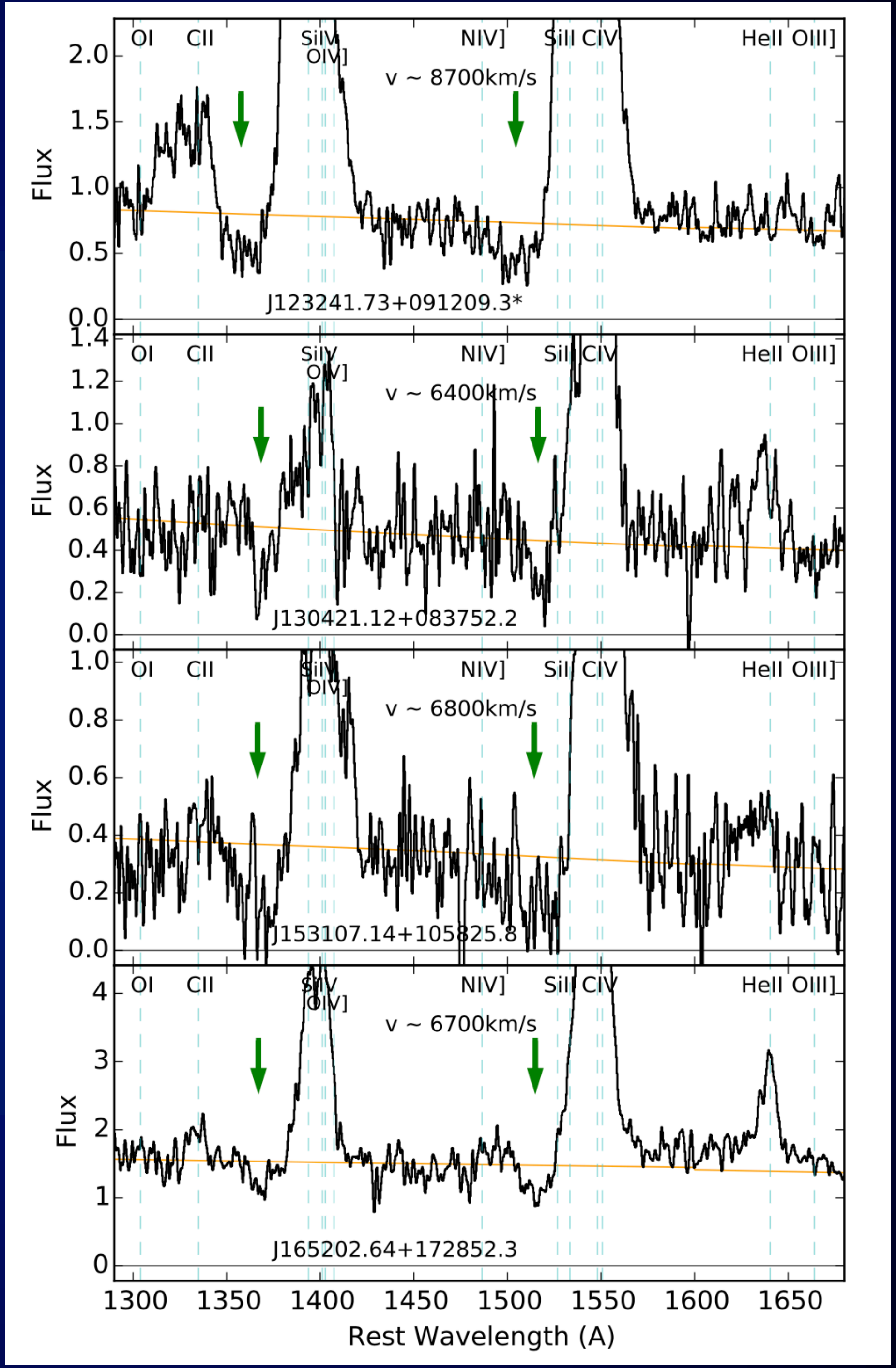
(Zakamska+16, Hamann+17, Perrotta+17)

Outflow Evidence 2:

35-75% have BAL outflow lines

3–6x greater than other BOSS quasars

Like other red quasar samples (Urrutia+09)



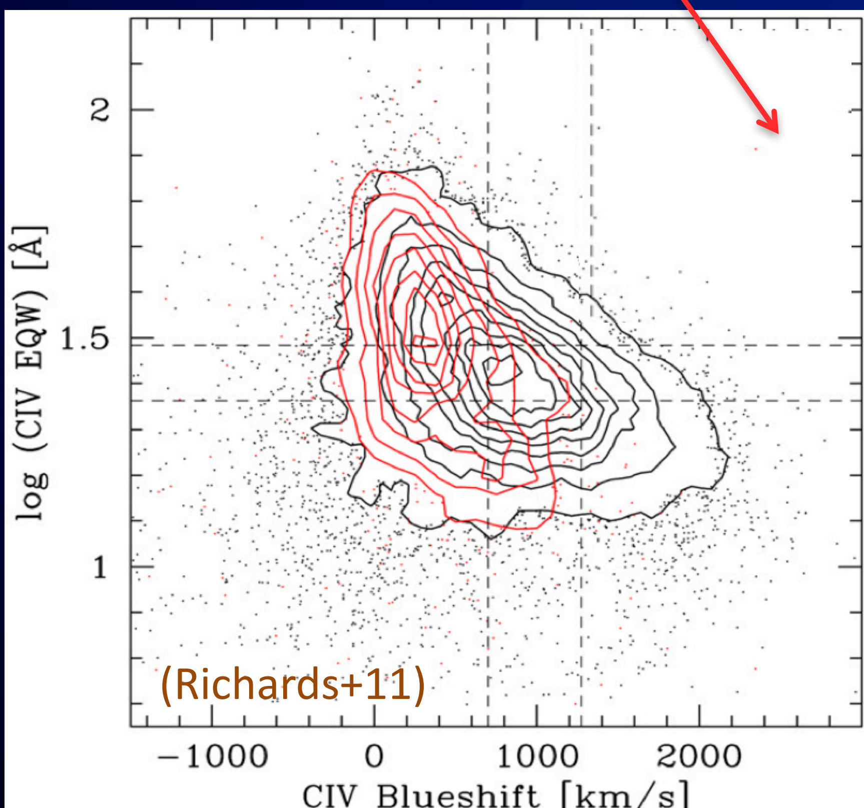
Outflow Evidence 3:

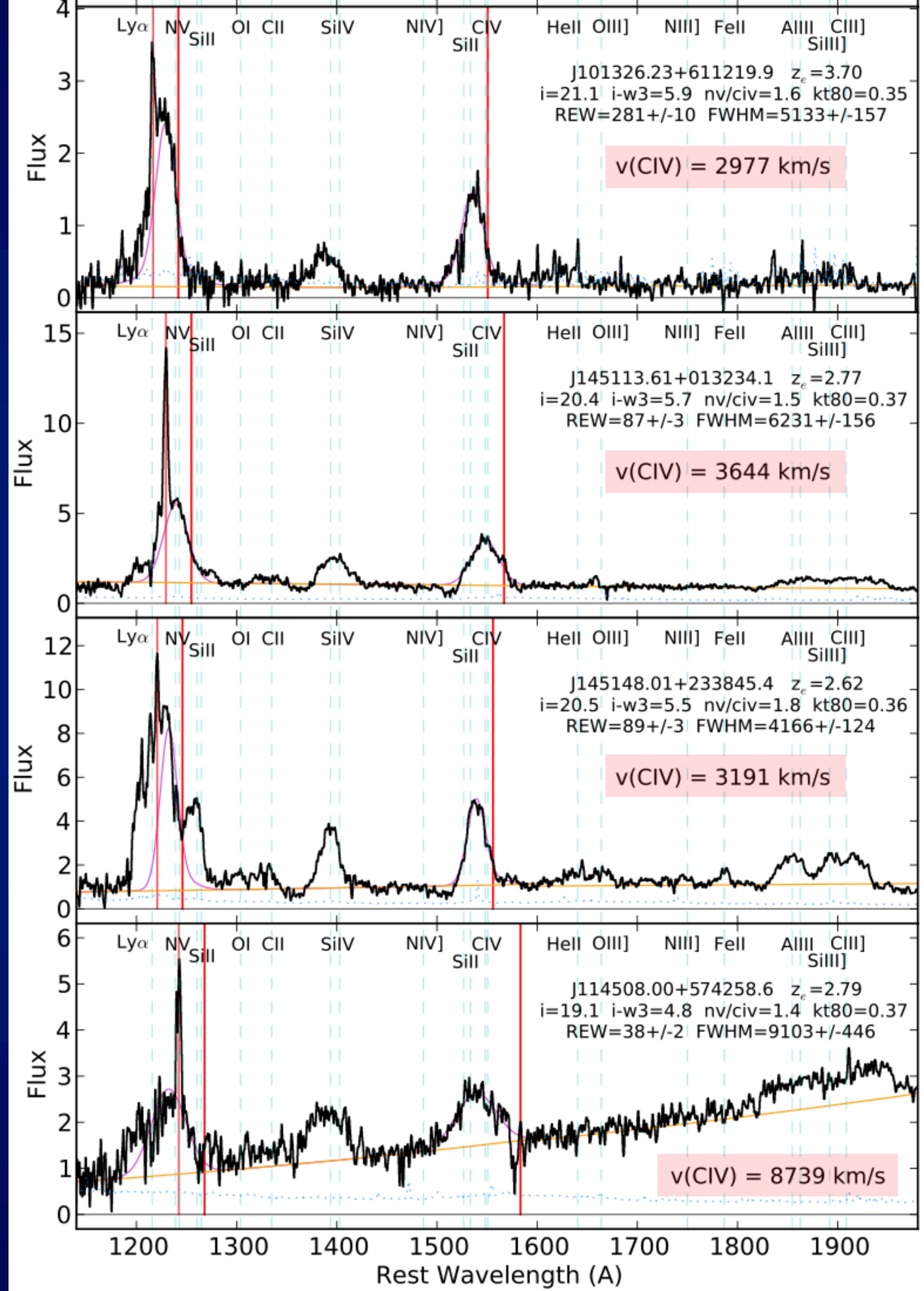
Common *large* CIV blueshifts

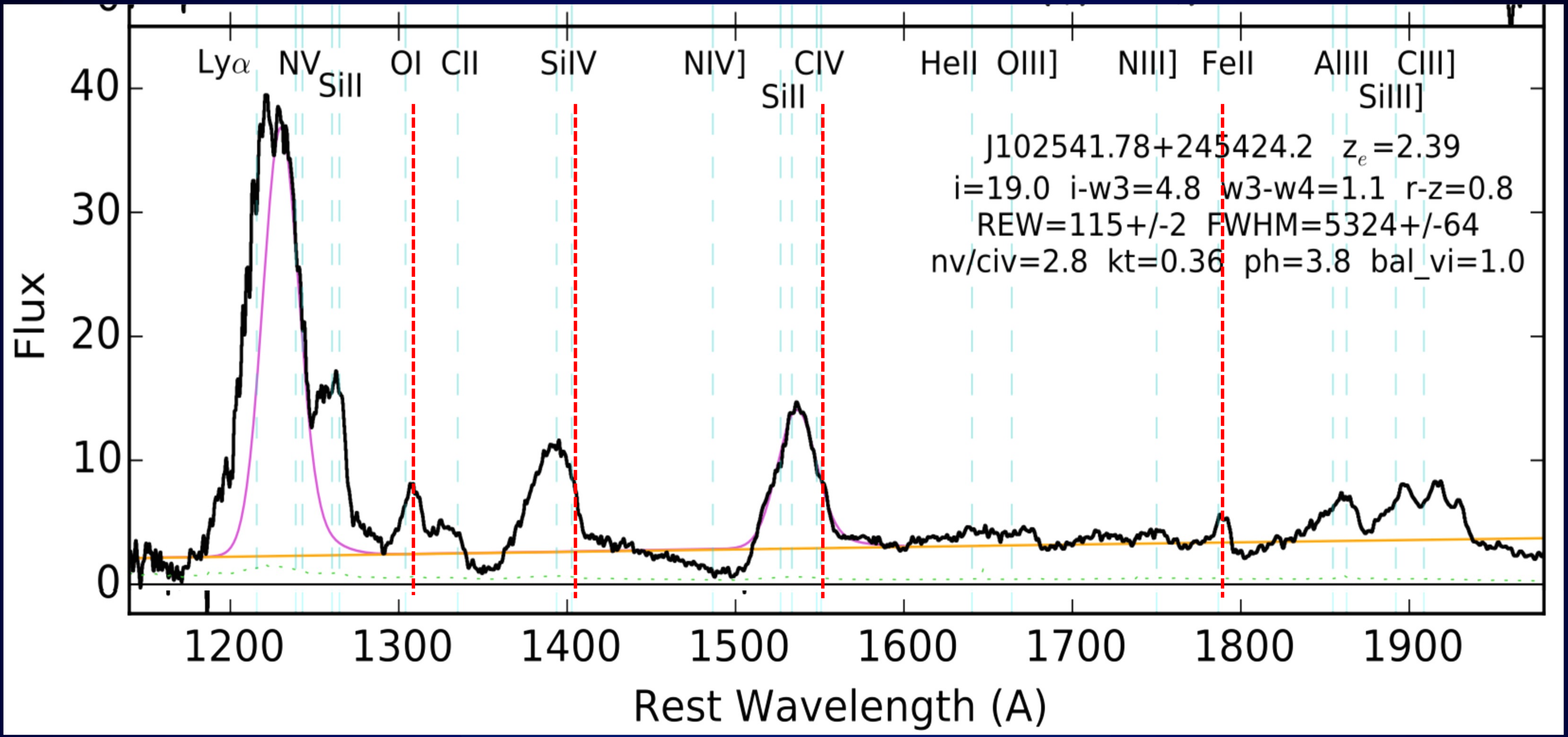
Spikes are Lyα at v=0 (also OI, SiII, FeII)

~7% of ERQs have blueshifts >2500 km/s compared to <0.1% in SDSS overall

Outflow-dominated BLRs







CIV emission-line blueshift v ~ 3900 km/s

Powerful ERQ Outflows

across scales

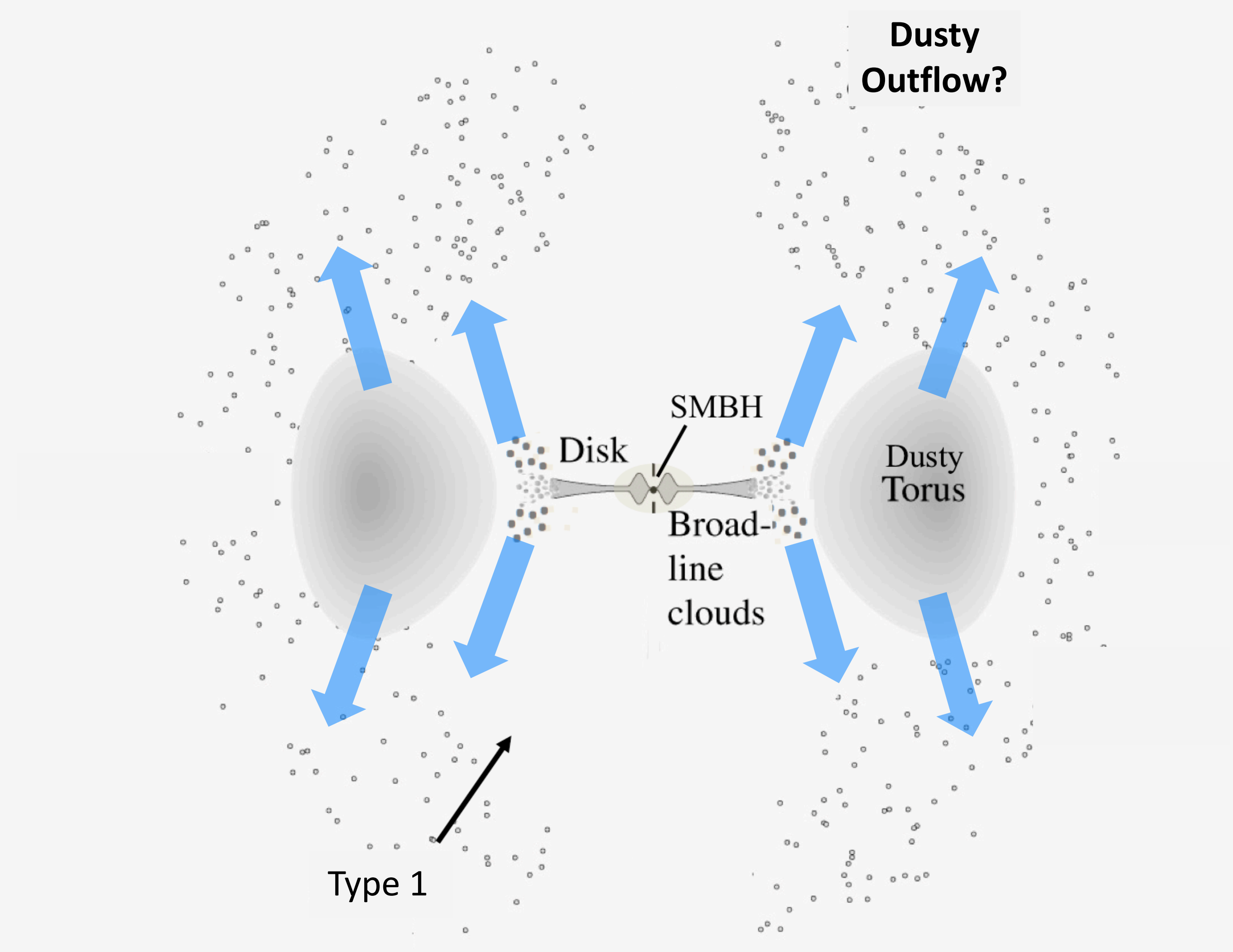
<1 pc to >1 kpc

BAL/mini-BAL outflows

Broad blueshifted
CIV 1549A

Broad blueshifted
[OIII] 5007

+ Extremely red colors (dust)



Outflows enhanced by high accretion rates?
high “metal” content?

Obscuration by outflowing
dusty clumpy torus?