Updates on Emergent and Redshifted BAL Quasars

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…

AGN Winds on the Georgia Coast 2017

But first… accretion disks of unusual size

- AGN accretion disks produce UV emission out to radii 2 to 3 times larger than expected from thin disk models
- (As inferred from quasar microlensing - e.g., Morgan et al. 2010 - and disk reverberation - e.g., Jiang et al. 2016)
- At each radius, disks can emit at shorter average wavelengths if scattering prevents perfect blackbody emission; see Hall, Sarrouh & Horne arXiv:1705.05467
- We need to understand accretion disk emission because it can (help) drive outflows.

Conclusions

- We see UV broad absorption line troughs in quasars out to 60,000 km/s - as far out in velocity as we've looked.
- At least 50% of trough variability is ionization variability, which can help constrain the density in an outflow.
- Coordinated trough variability is velocity-dependent.

- There exist BAL quasars with **redshifted** troughs (by up to 10,000 km/s at least).
- They are probably rotating disk winds, but verifying that and ruling out infalling gas will take more work.

- Maunakea Spectroscopic Explorer = awesome.

Maunakea Spectroscopic Explorer

The **11.25-meter** MSE will efficiently obtain very large numbers (>1,000,000) of

- **low- (R~2000), medium- (R~6500) and high-resolution (R=40,000) spectra**
- for faint ($20 < g < 24$) science targets, **3200 fibers at a time** (800 med/high-res)
- over large areas of the sky (1000 – 10,000 sq.deg, **1.5 sq.deg. at a time**)
- spanning blue/optical to near-IR wavelengths, **0.37 – 1.8 micron** (R~3000)
- at the highest resolutions, with velocity accuracy of <<1 km/s
- at low resolution, with complete wavelength coverage in a single observation

- **Unique science cases for MSE stem from:**
  - **11.25 m diameter aperture on the CFHT site (same building, new scope and dome)**
  - **Operation at a range of spectral resolutions**
  - **Dedicated operations, producing stable, well-calibrated and characterised data**
  - **Long lifetime (allows for upgrades such as IFUs and R=90,000 modes)**

- *Natural path from 4m-class facilities (KPNO4m+DESI, WHT+WEAVE, 4MOST, AAT+HERMES...) and 8m-class, shared-time, small-FOV instruments (Subaru/PFS, VLT/MOONS) to MSE*
- ***MSE design phase participation from Canada, France, China, Spain, India, and Australia***
- *ESO is thinking along similar lines, with the report of the working group led by Richard Ellis*

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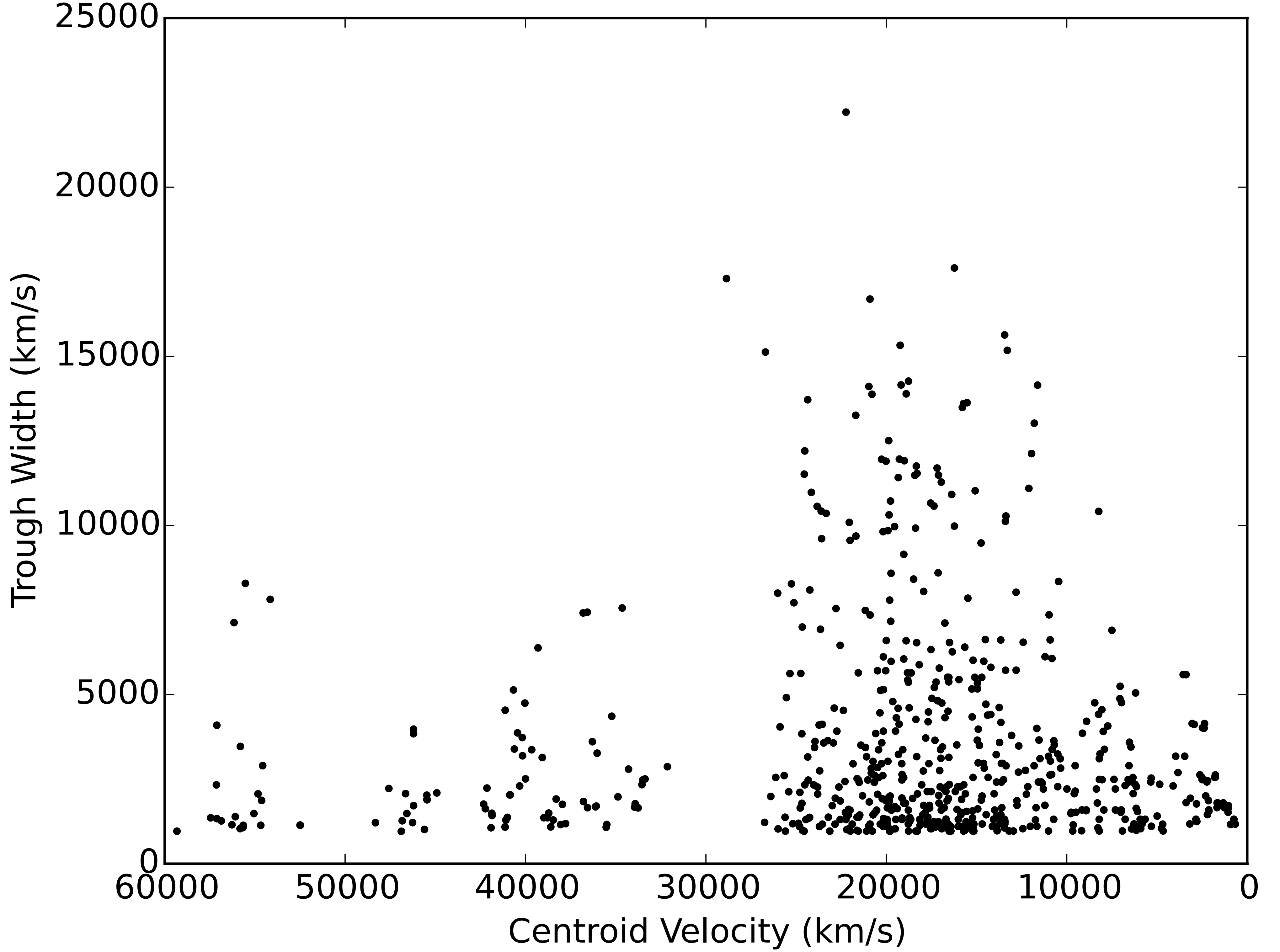
J0230: The Fastest UV-Absorbing Outflow Yet

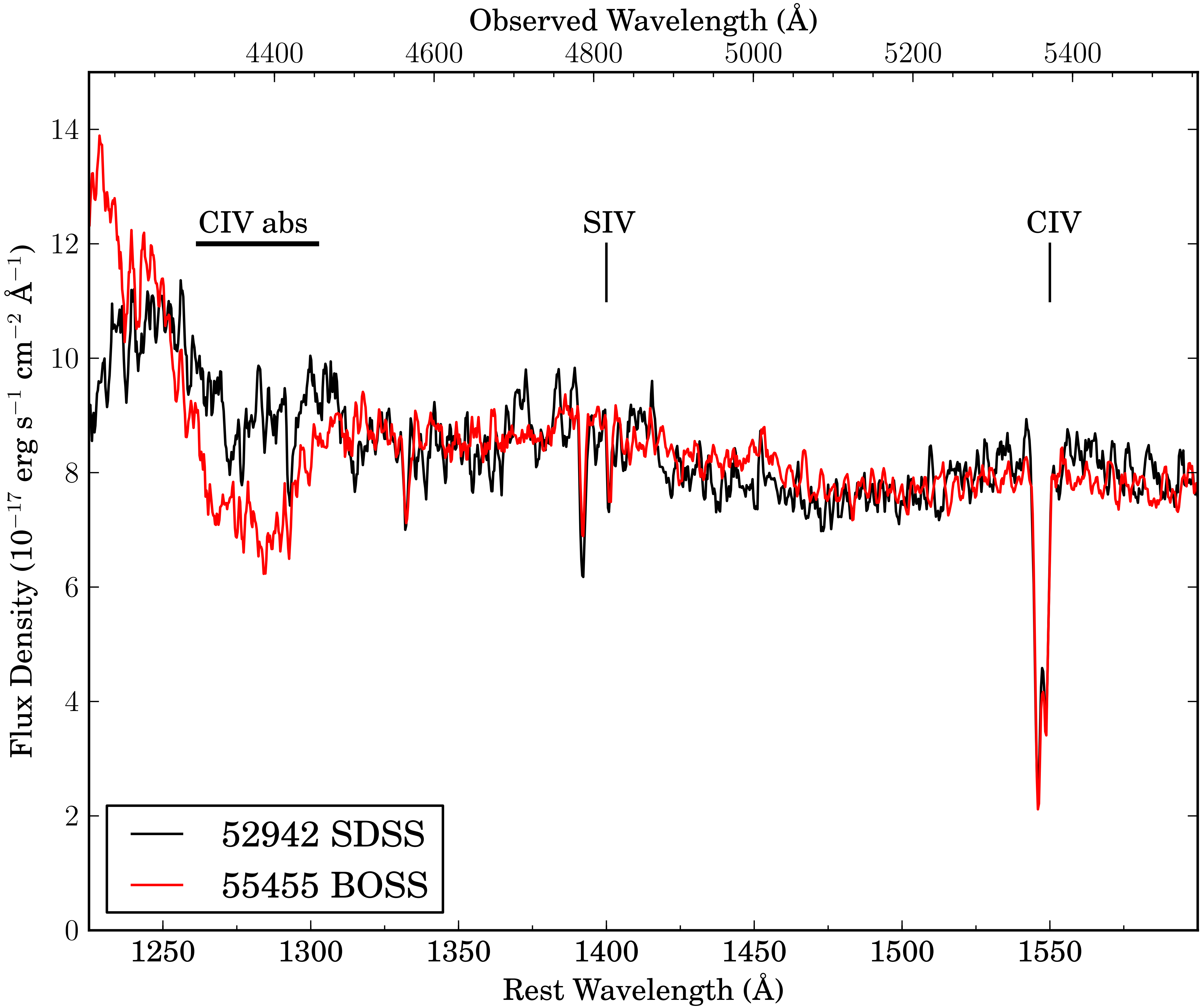
- Compared 8,317 objects with spectra in both SDSS and BOSS, a few rest-frame years apart.
- Looked for emergent broad absorption line troughs.

Troughs found out to 60,000 km/s



J0230: The Fastest UV-Absorbing Outflow Yet

- *Compared 8,317 objects with spectra in both SDSS and BOSS, a few rest-frame years apart.*
- *Looked for emergent broad absorption line troughs.*
- One of the sample's most interesting emergent BAL quasars was 'J0230' (Rogerson et al. 2016, MNRAS).
- We obtained follow-up spectra with the Gemini telescopes of this object and many others (Rogerson et al., submitted).



Observed Wavelength (Å)
4400
4600
4800
5000
5200
5400
CIV abs
SIV
CIV
Flux Density (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
14
12
10
8
6
4
2
0
52942 SDSS
55455 BOSS
1250
1300
1350
1400
1450
1500
1550
Rest Wavelength (Å)

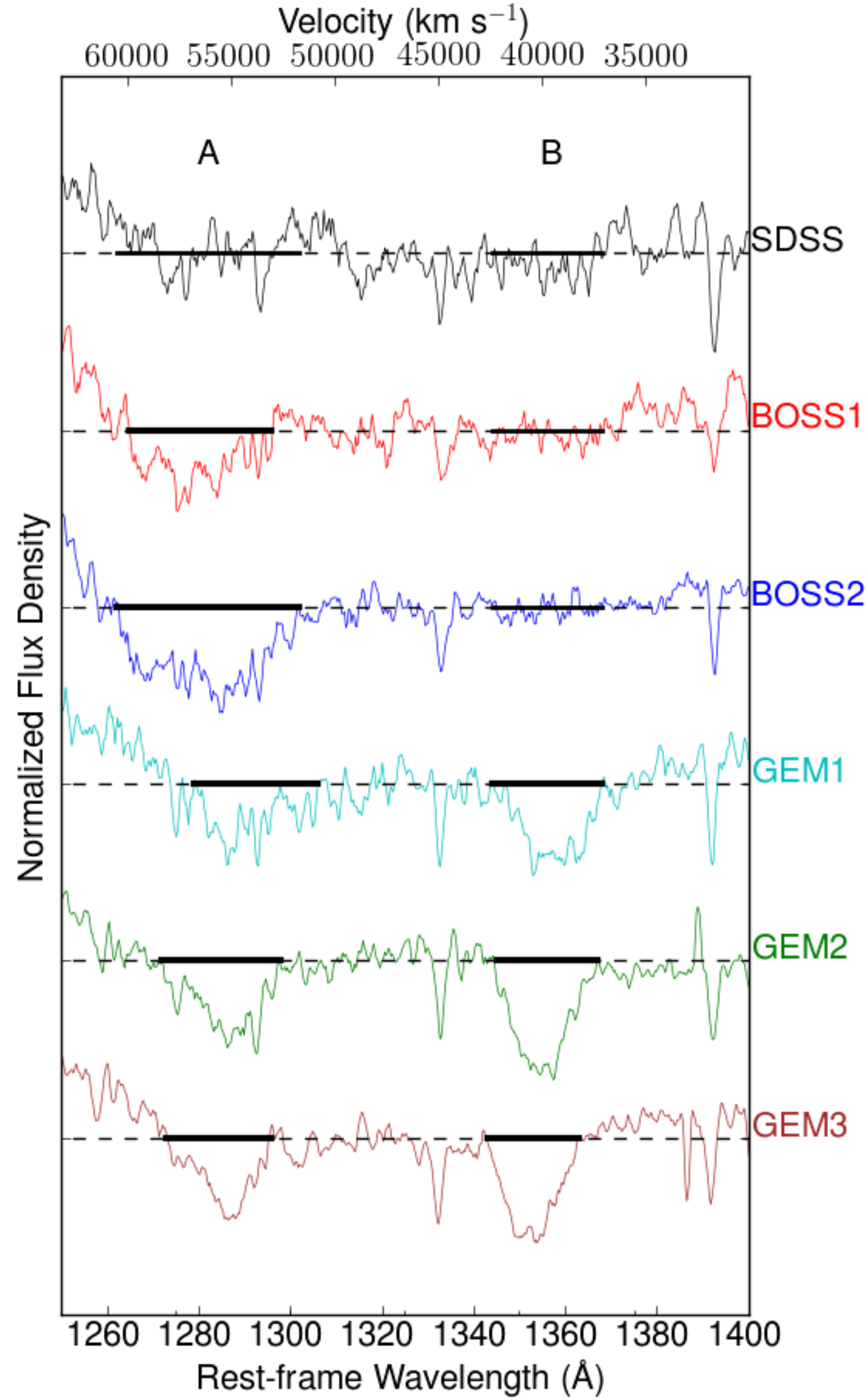
Absorption region of each spectrum is plotted at right.

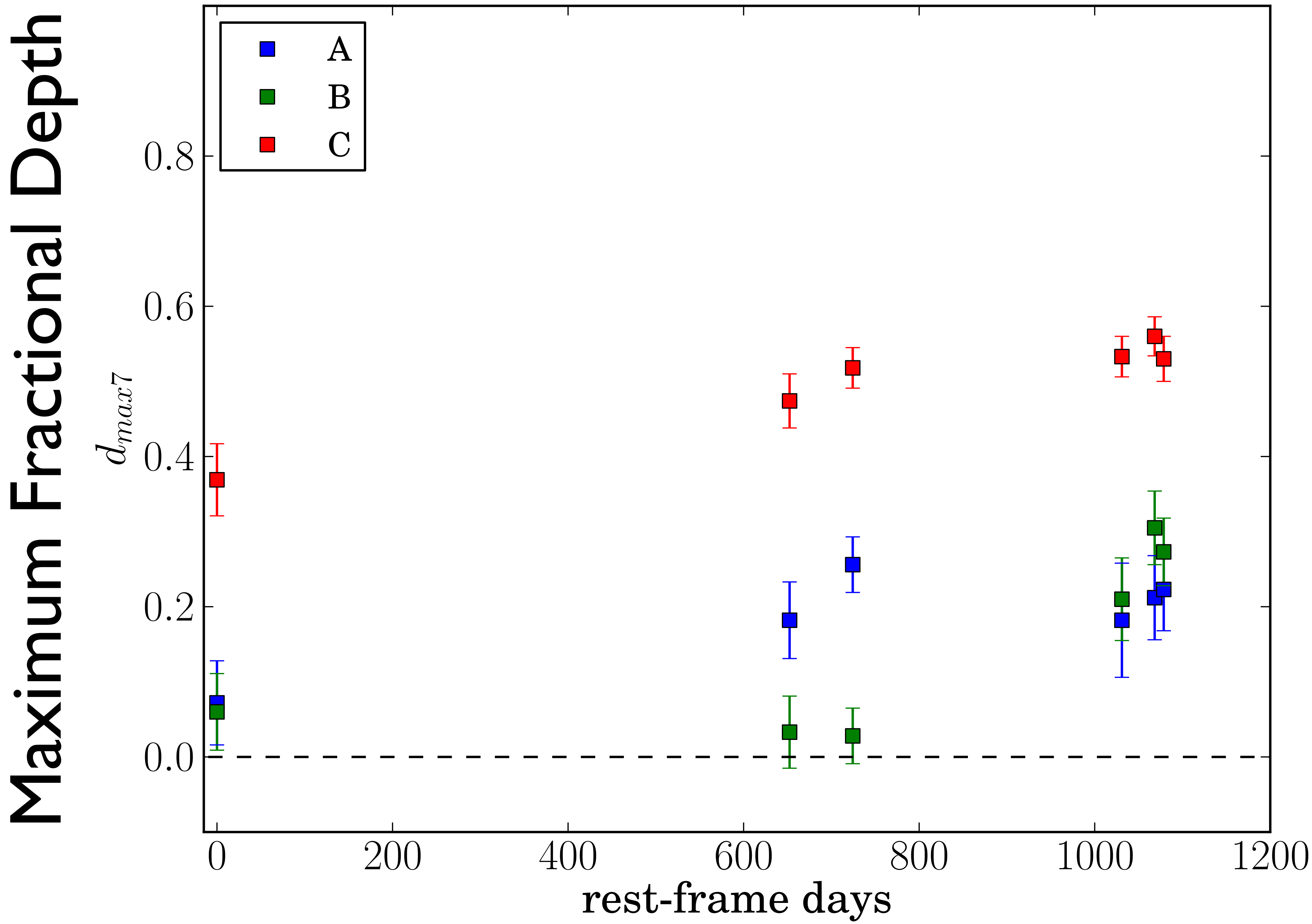
Earliest spectrum is at top; later spectra are shown below, in sequence.

Highest-velocity trough is A (55,000 km/s); next-highest is B (40,000 km/s).

Trough at systemic redshift (not shown) is C.

Variability seen on timescales from ~10 days to 3 years.





- How to explain absorption troughs whose depth changes with time (see above)?
- Ionization variability, transverse motion, or both?

Ionization variability … ?

- Perhaps the absorbing gas is always present, but with a changing amount of C IV along our sightline.
- Filiz Ak et al. (2013) showed that <u>this explanation is correct at least half the time</u>, because troughs widely separated in velocity tend to show coordinated variability.

Ionization variability … or transverse motion?

- Perhaps the absorbing gas is always present, but with a changing amount of C IV along our sightline.

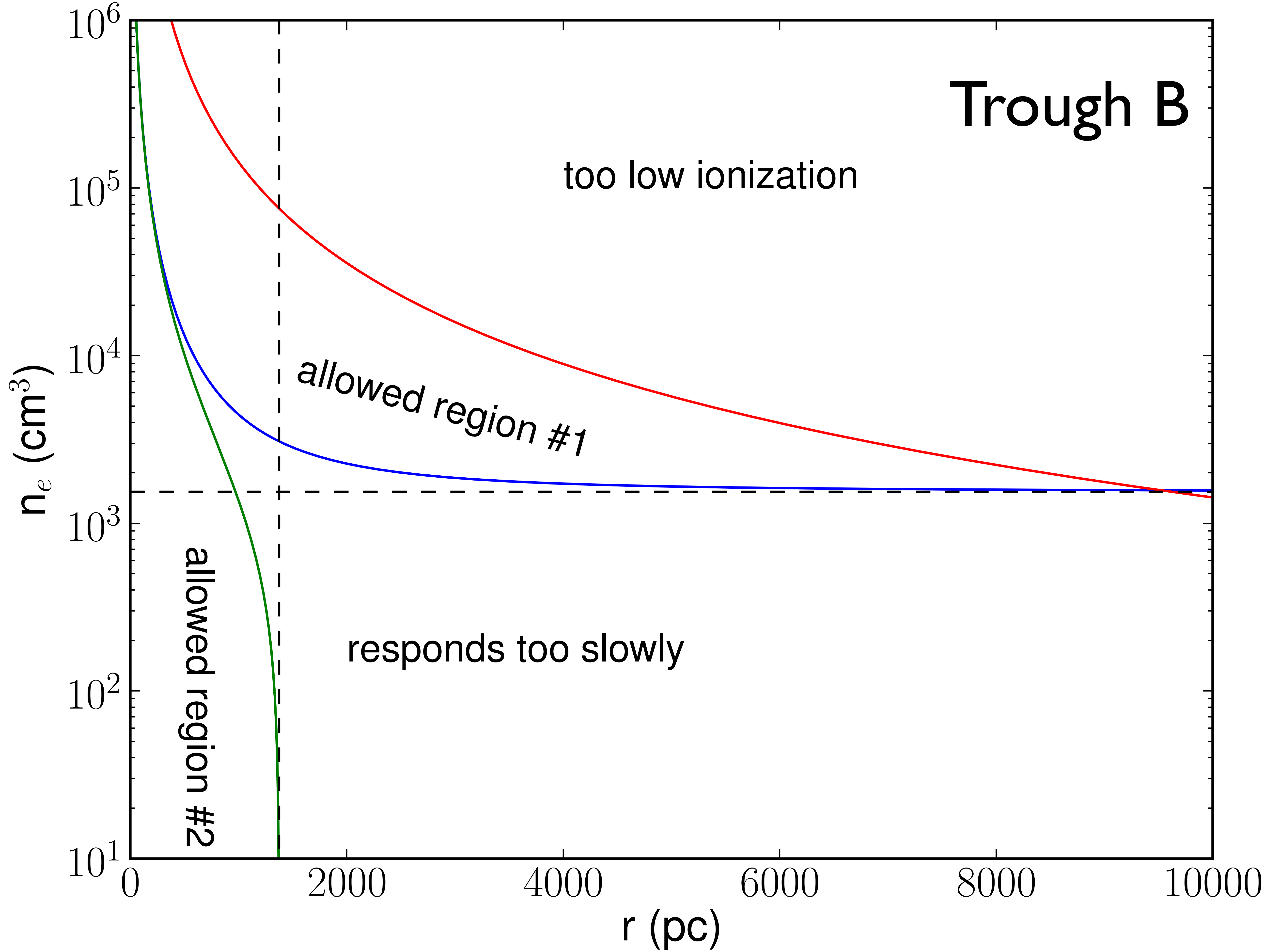
- Filiz Ak et al. (2013) showed that this explanation is correct at least half the time, because troughs widely separated in velocity tend to show coordinated variability.

- A wind launched from a rotating disk will exhibit rotation and outflow, leading to transverse motion of absorbing gas across our line of sight.

- Transverse motion thus **will** occur in part of the flow. If it is to explain J0230, the required v=14,000 km/s (trough A) to v=36,000 km/s (trough B) imply $d < 400\ r_g$ for the absorbers, and changes in absorption in new data in hand.

Ionization variability

- In equilibrium, amount of C IV along sightline is set by balance between photoionization (C III→C IV; C IV→C V) and recombination (C IV→C III; C V→C IV).
- If ionizing flux changes, the amount of C IV changes on a timescale set by F_{ion} and the carbon number density (e.g., Hamann+1997, Arav+2012, Wang, Yang, Wang & Ferland 2015, He+2017; Grier+2015, Rogerson+2016).
- For conditions where rates of C III↔C IV = C IV↔C V, the initial response to ionizing flux changes is very slow.
- Observing changes in C IV on a given timescale constrains density and distance from the quasar of optically thin gas.



Trough B
too low ionization
allowed region #1
responds too slowly
allowed region #2
n_e (cm^3)
r (pc)
10^6
10^5
10^4
10^3
10^2
10^1
0
2000
4000
6000
8000
10000

Ionization variability

- Observing changes in C IV on a given timescale constrains the gas density and distance from the quasar.
- <u>If ionization variability away from photoionization equilibrium caused the observed changes…</u>
- The gas producing trough B is located 1.4 to 9.6 kiloparsecs from the quasar (4000-32,000 light-years) with density >1540 cm^-3, or is located <1.4 kpc from the quasar with little constraint on its density.
- The gas producing trough A is located 2 to 14 kpc from with quasar with density >720 cm^-3, or <2 kpc from the quasar with little constraint on its density.
- More detailed modeling justified if more data available.

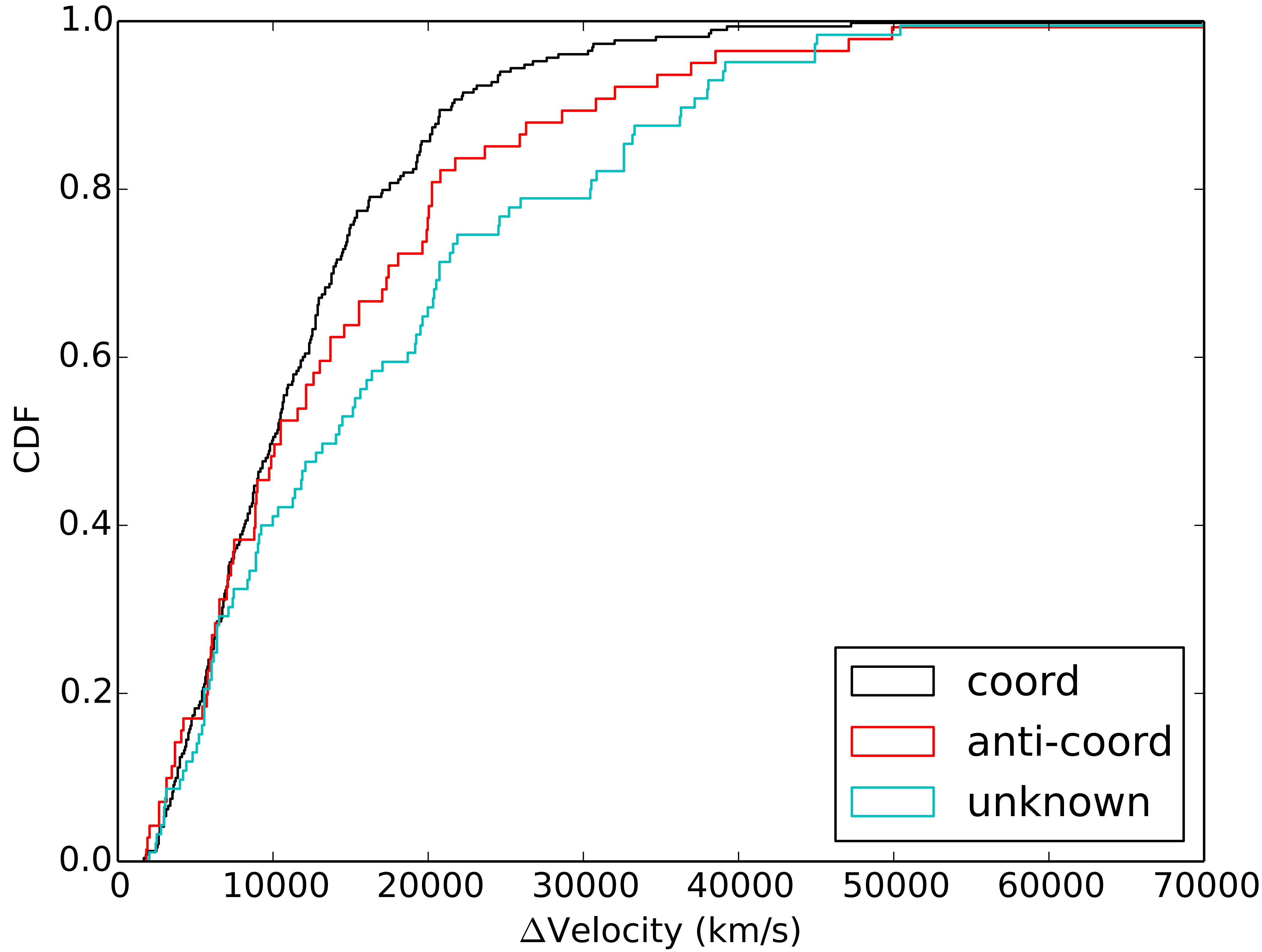
v-dependent Coordinated Variability

- Rogerson et al. 2017, submitted
- Compared SDSS-I/II DR7 spectra to SDSS-III/ BOSS DR9+DR10 spectra
- Identified 292 quasars with candidate emergent BAL troughs, out to 60,000 km/s
- Followed up 105 targets with Gemini spectroscopy
- Identified absorption complexes using multi-epoch spectra (the same absorption complex might be seen as one trough in some epochs and two troughs in other epochs, due to variability)

v-dependent Coordinated Variability

- From spectra in two epochs, measure the direction of variability of an absorption complex (strengthen, weaken, or no change [< 3 sigma variation in EW])
- Compare to next absorption complex at a higher outflow velocity in same quasar: are the changes in the same direction (coordinated) or opposite (anti-coordinated), or indeterminate (unknown)?
- Repeat for all pairs of complexes and plot the three cumulative distribution functions.

Coordinated variability (black line) is relatively less common at higher velocities.



v-dependent coordinated variability

- **p=0.017 chance that coordinated and anti-coordinated variability in our sample are drawn from the same parent distribution**
  - p=0.0001 that coordinated and unknown variability drawn from same parent distribution
  - p=0.15 that anti-coordinated and unknown variability drawn from same parent distribution
- **<u>Troughs closer in velocity are more likely to vary in a coordinated manner.</u>** If outflows decrease in density as they are accelerated, then outflows at similar velocities are more likely to vary in concert, since ionization variability response is ρ-dependent.

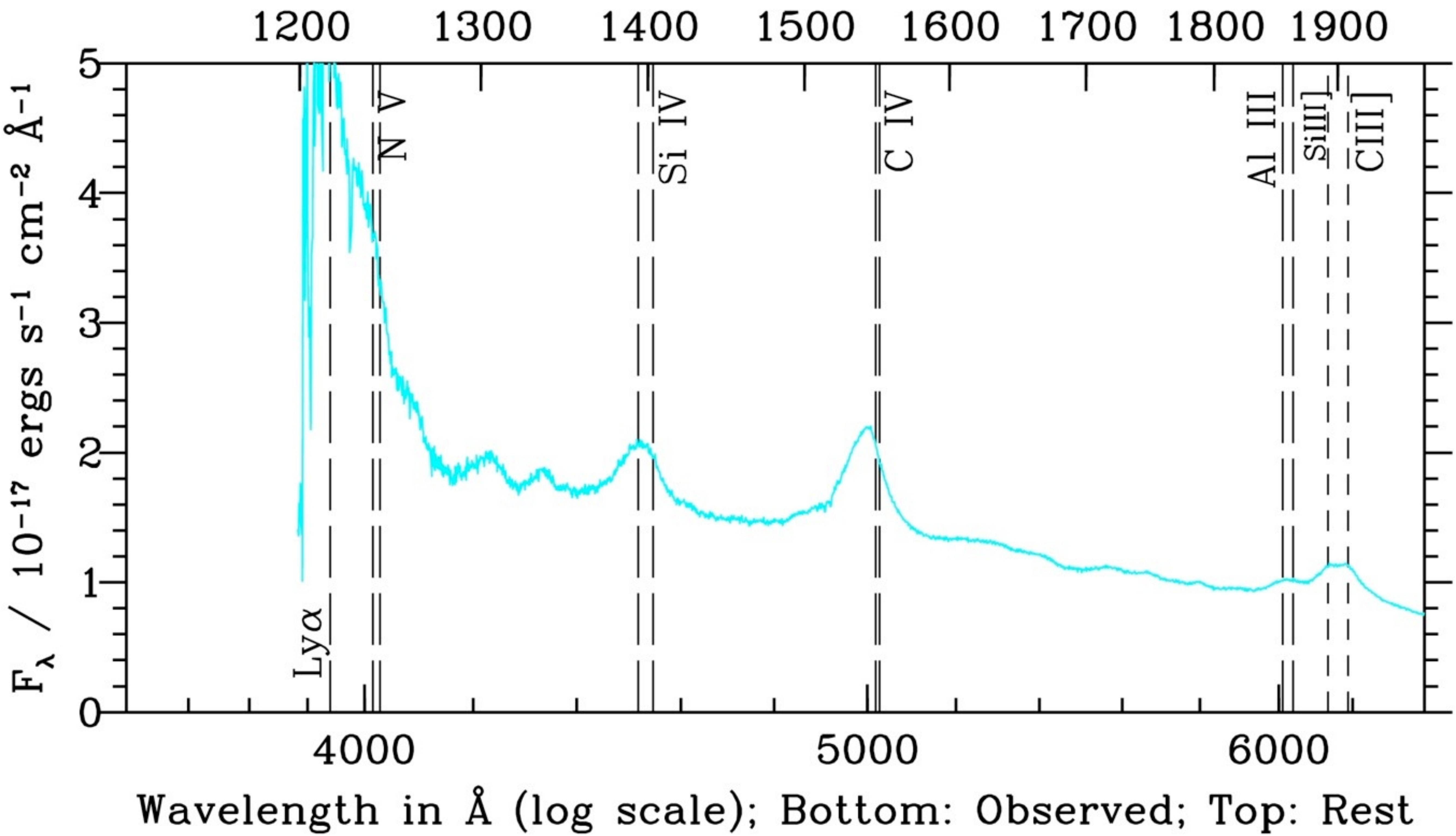
Redshifted Broad Absorption Troughs in Quasars

- Hall et al. (2013)
- There exist BAL quasars with **redshifted** troughs (by up to 10,000 km/s at least)
- They are likely rotating disk winds, but confirming that and ruling out infalling gas will take more work

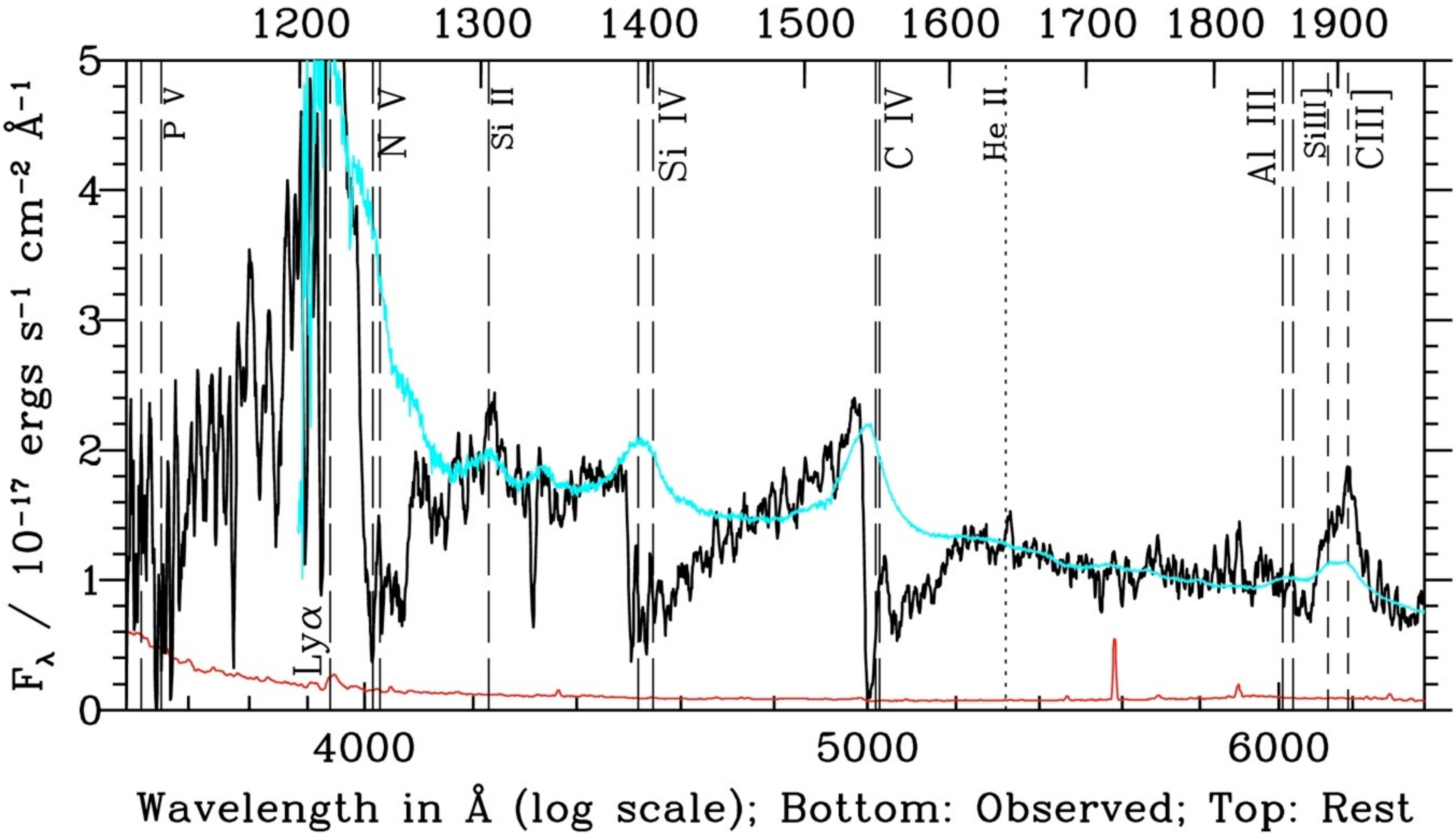
Redshifted-Trough BAL Quasars

- Work in the quasar rest frame, so that redshifted refers to gas that appears to be moving in the direction away from us, and blueshifted to gas that appears to be moving towards us.
- Among ~12,000 BAL quasars we studied in SDSS-III, 17 found with *redshifted* absorption in C IV and other ions of similar ionization state, from gas that appears to be moving in the direction away from us.
- Seven additional high-ionization candidates.
- Two cases of redshifted Mg II at low redshift (Hall et al. 2002), and one candidate.

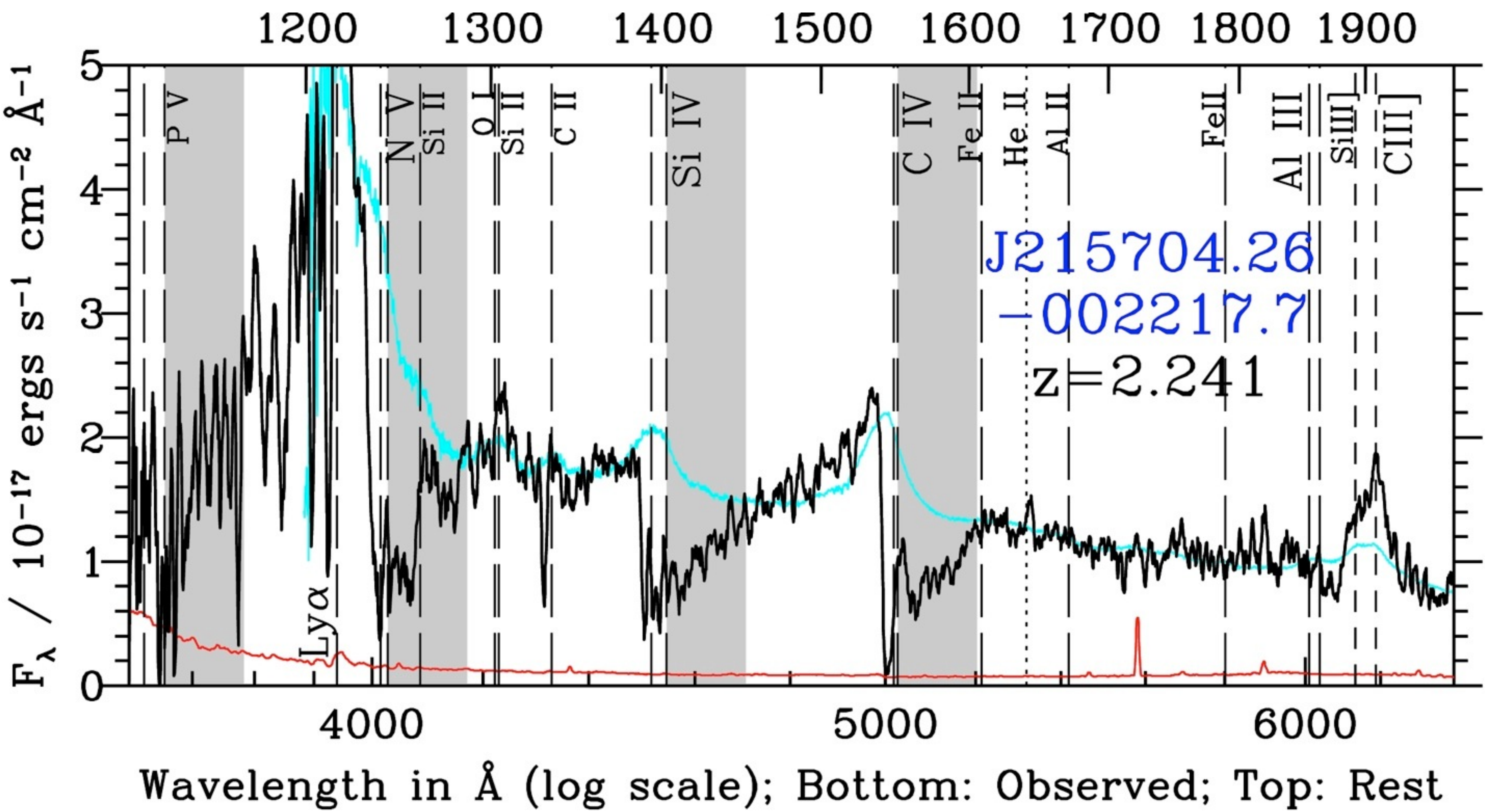
Unabsorbed quasar spectrum



Unabsorbed quasar vs. quasar with redshifted absorption



Gray regions indicate velocity ranges of strongest (~saturated) redshifted absorption



Redshifted BAL Quasars

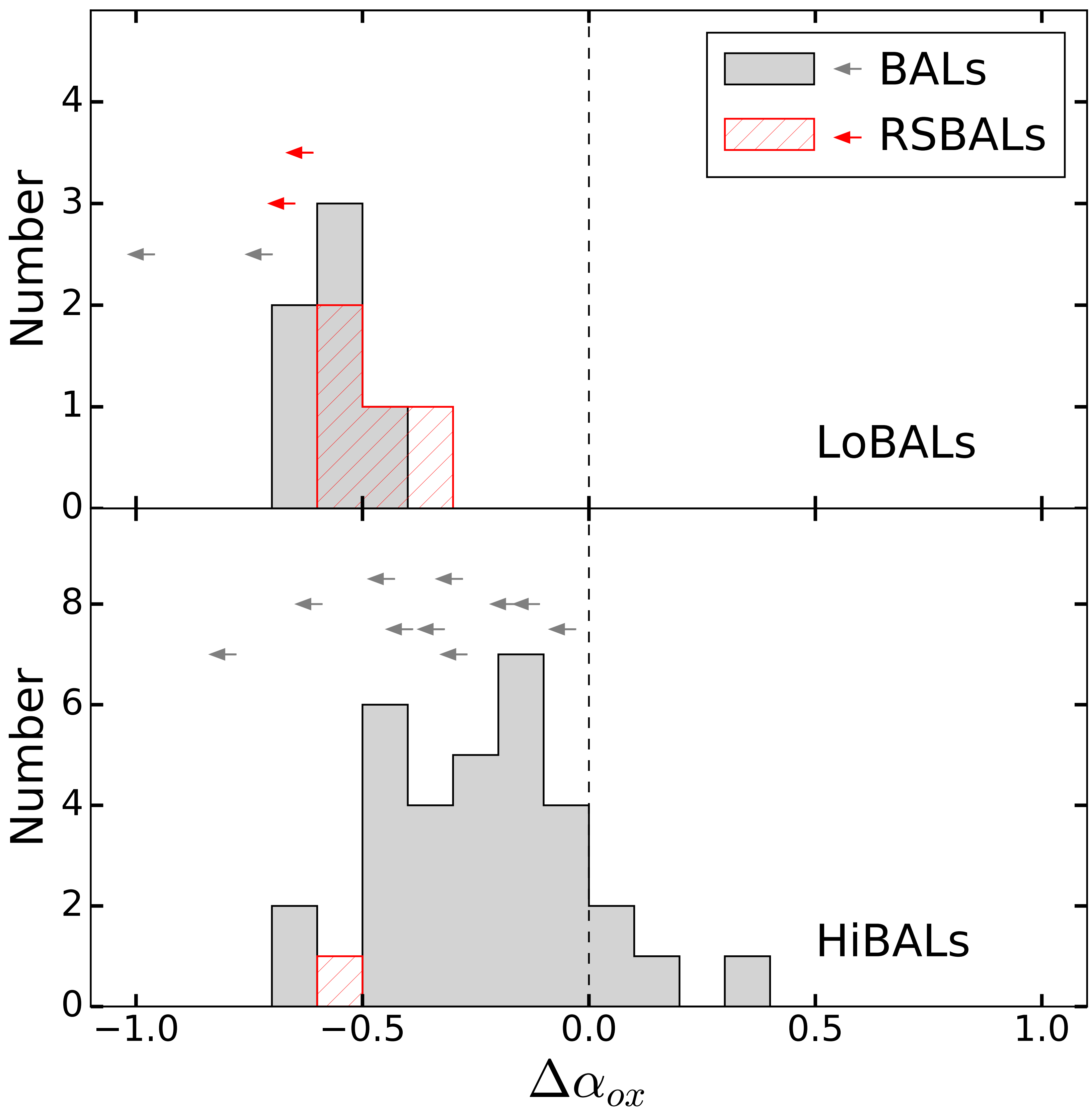
- Sometimes only redshifted absorption is seen
- Sometimes seen in conjunction with blueshifted absorption (continuous or not)
- Velocity ranges -13,000 km/s (blueshift) to +13,000 km/s (redshift), in different objects
- C IV equivalent width distribution consistent with normal BAL quasars (not with LoBALs)
- C IV saturated in many cases (high column)
- LoBAL absorption 10 times more common

Possible Explanations

- **Infall or Fallback**
- **Rotating wind + extended continuum source**
- Binary quasars + silhouetted BAL outflow
- Relativistic Doppler shift might contribute
- Some combination of the above
- Ruled out: gravitational redshift alone (requires infalling gas absorbing in C IV at few tens of r_g, 10x smaller radii than the C IV BELR)

Follow-up Studies of RSBALs

- Near-infrared spectra (7 Gemini+GNIRS, 1 X-Shooter, 1 FIRE):
  - confirm our systemic redshifts were accurate to +-1000 km/s, via detection of [O III]/Balmer lines.
  - no evidence for binary quasars in the form of double narrow-emission-line redshifts.
- Chandra X-ray snapshots of 7 RSBALs (Zhang+2017), chosen to have stronger redshifted than blueshifted absorption.
  - Accompanying Gemini+GMOS optical spectroscopy



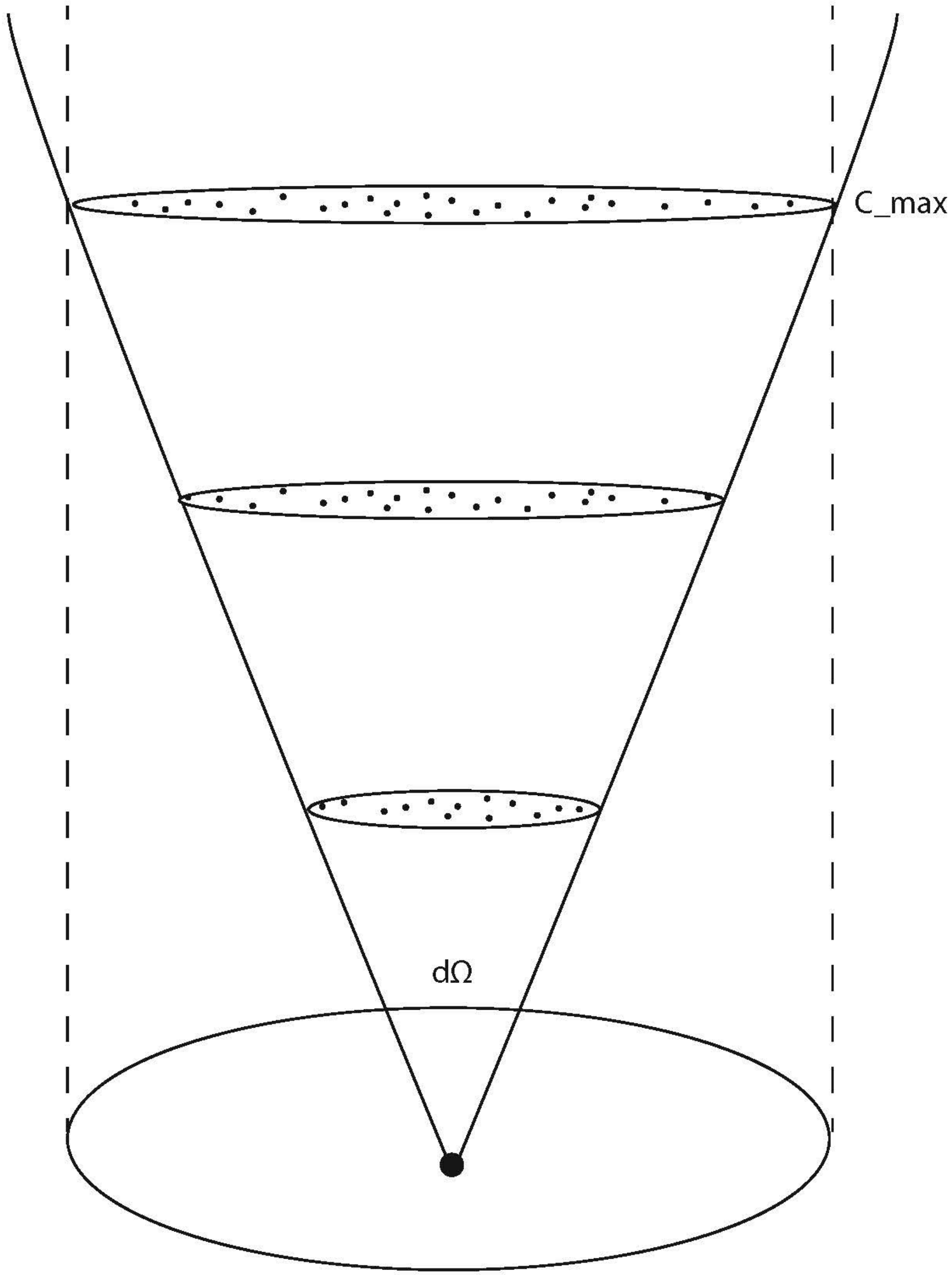
Zhang et al. 2017: RSBALs have alpha_ox distribution consistent with normal BAL quasars; i.e., <u>similar X-ray absorption levels</u>

Binary Quasars + silhouetted BAL outflow?

- BAL outflow from one quasar, silhouetted against the light from another quasar.
- Requires a spatially unresolved quasar pair where the background quasar is the more optically luminous one, and produces the broad emission lines we see.
- But in that case, expect normal X-ray properties.
- <u>Our Chandra data rules this model out as an explanation for the population, if not for all individual objects.</u>

Model: Infall or Fallback

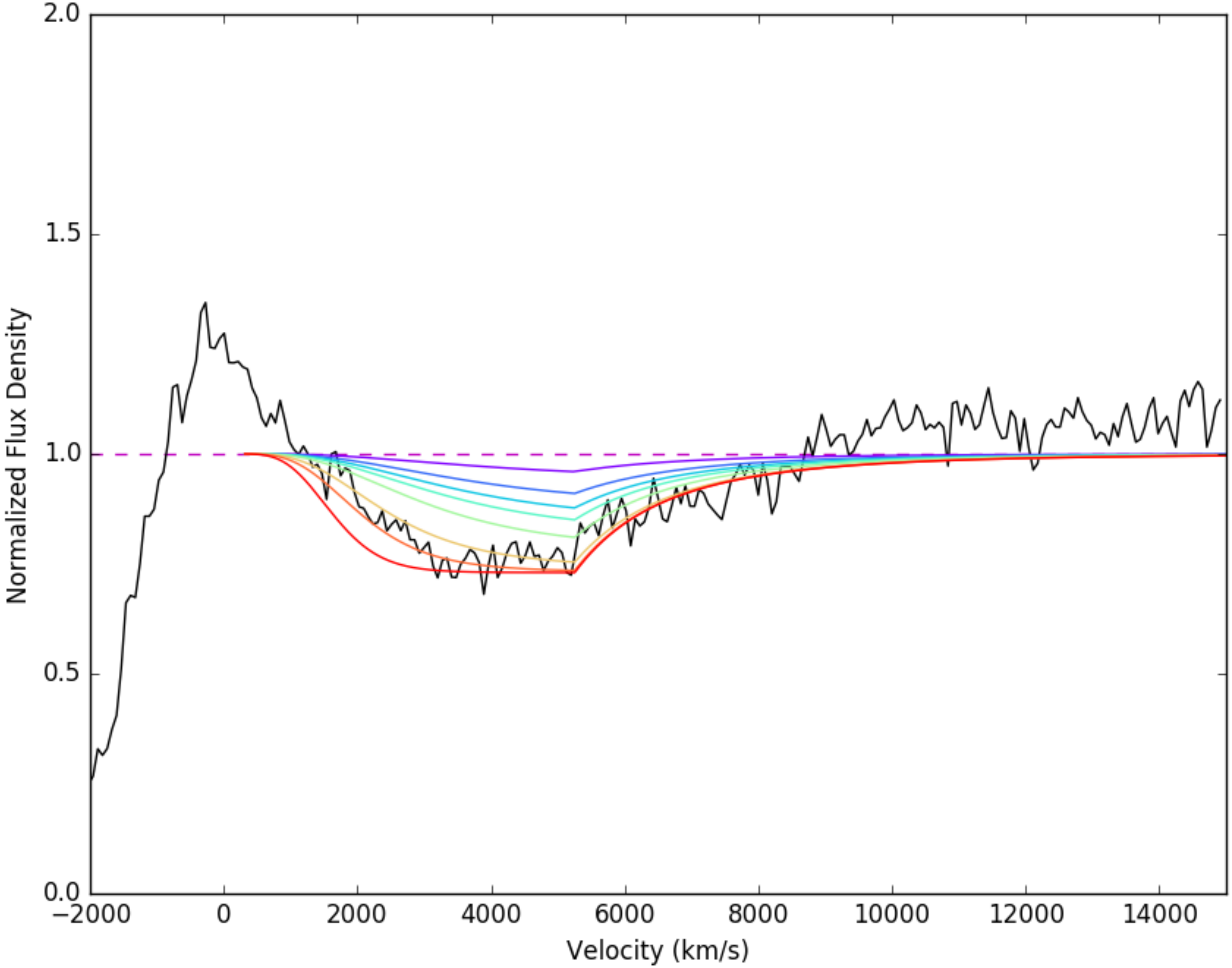
- Infalling gas not far out in galaxy; must be close to BH. Infall to radius r from the BH will generate velocities up to the escape velocity from that radius: $v=(2GM_{BH}/r)^{1/2}$
- Matching RSBAL velocities requires infall to 1000 r_g (outer BLR). Seen in some simulations (Proga+2008; Kurosawa+Proga 2009) which may not simultaneously reproduce large observed optical depths in C IV.
- <u>Parabolic infall can't match observations. Simple radial infall model can, in some cases.</u>
- <u>But infall doesn't readily explain high LoBAL fraction or X-ray data</u> (why don't X-ray weak objects with only redshifted absorption also have blueshifted absorption?)



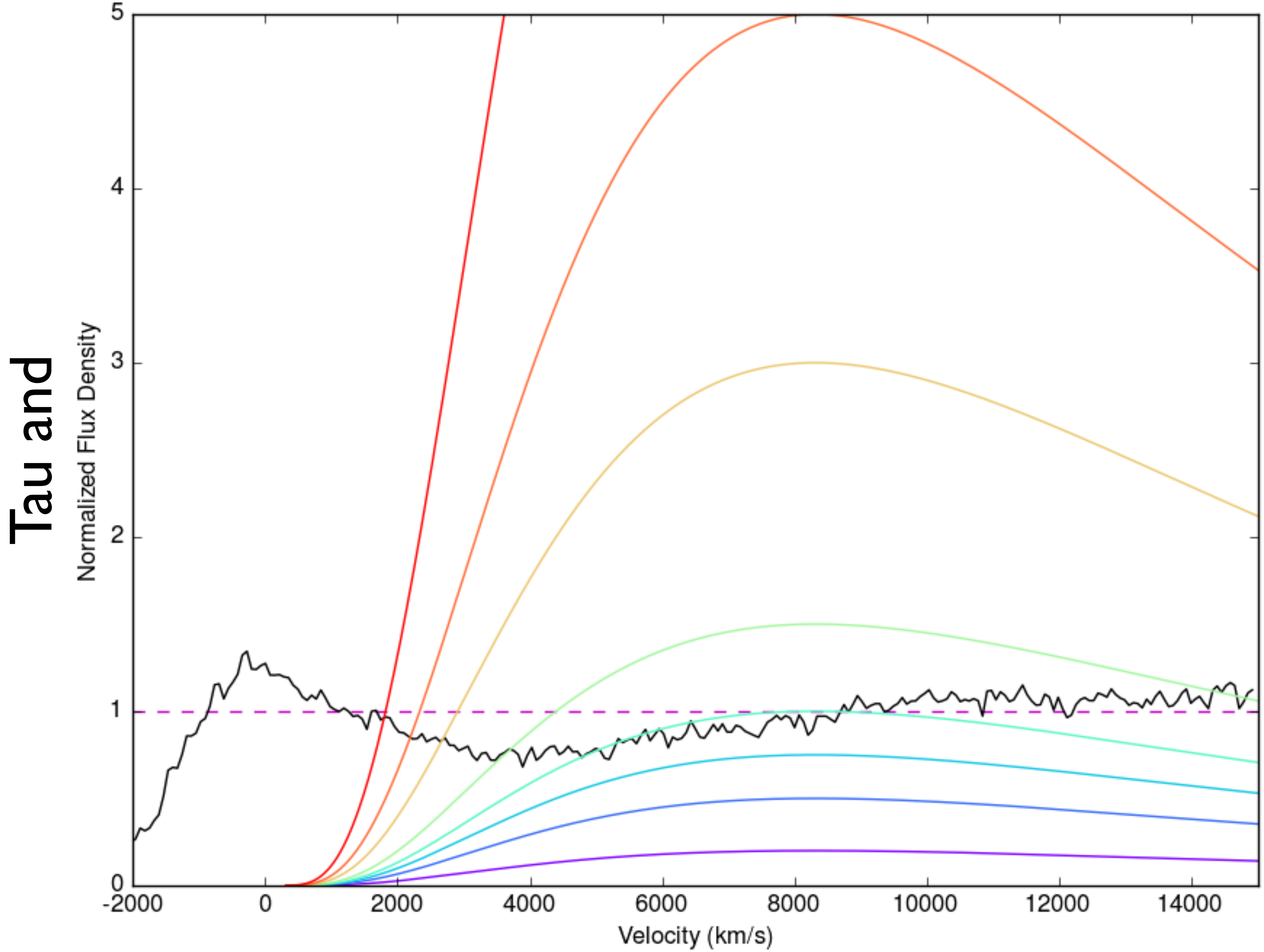
Radial infall of distinct clumps along fixed solid angle can reasonably reproduce some objects.

Model accounts only for C IV ionization fraction and radial acceleration due to gravity.

J1034 infall fits to trough in Gemini epoch.

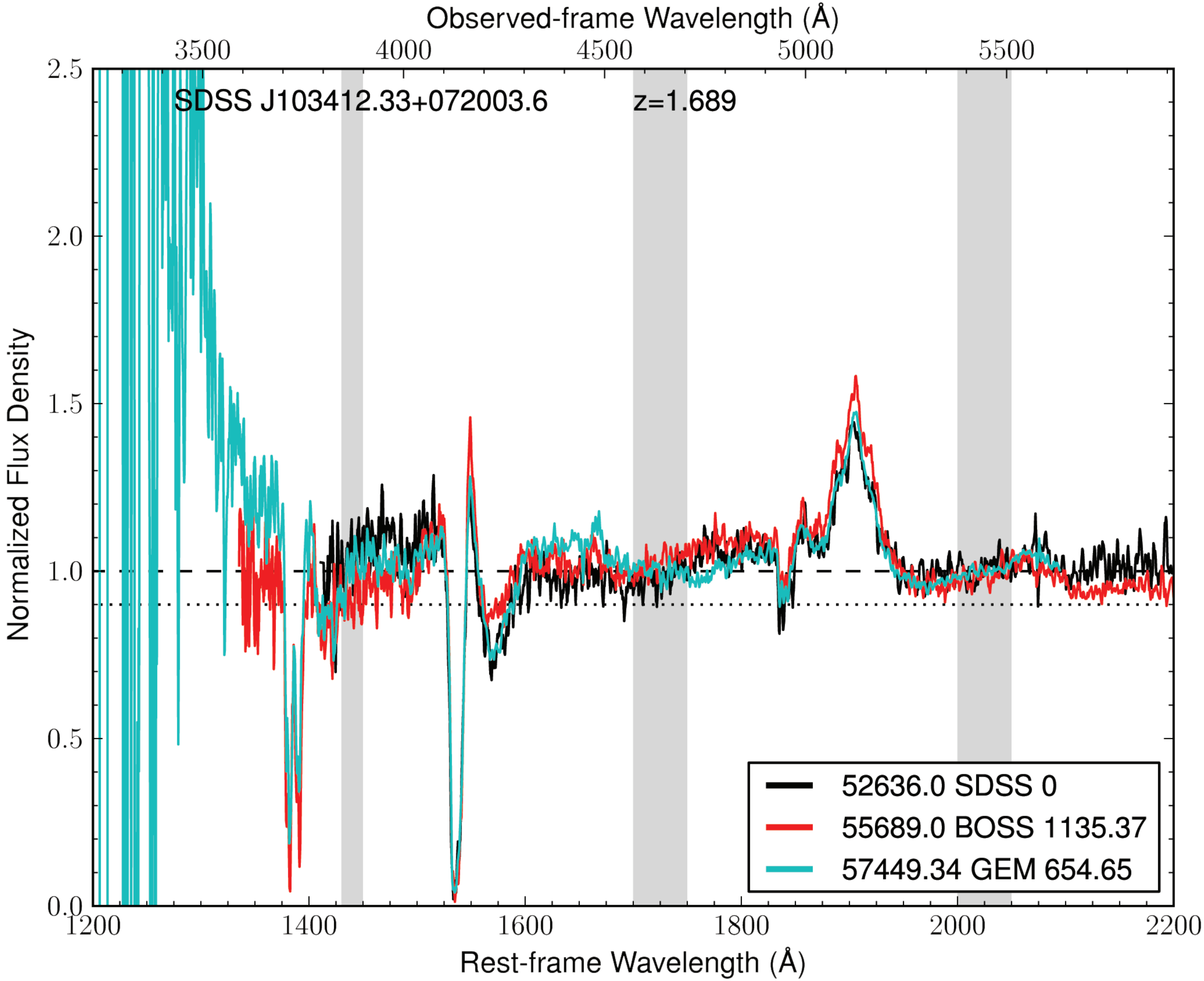


J1034 model tau values for infall fits.



Optical Spectral Variability

- Changes in object J1034 consistent with ionization variability over 2 to 4 rest-frame years (epochs 1,2,3 shown in black,red,blue)



Observed-frame Wavelength (Å)
3500
4000
4500
5000
5500
SDSS J103412.33+072003.6
z=1.689
2.5
2.0
1.5
1.0
0.5
0.0
Normalized Flux Density
52636.0 SDSS 0
55689.0 BOSS 1135.37
57449.34 GEM 654.65
1200
1400
1600
1800
2000
2200
Rest-frame Wavelength (Å)

Optical Spectral Variability

- For infall model, factor of ~4 range in velocity in J1034 corresponds to a factor of ~16 in radius and a factor of ~64 in density. Troughs should vary more rapidly at large redshifted velocities in this model. Need better time sampling to test.
- (Variability might also test disk wind model, but azimuthally smooth disk winds won't show transverse motion variations.)
- Overall, spectral variability results to date are inconclusive.

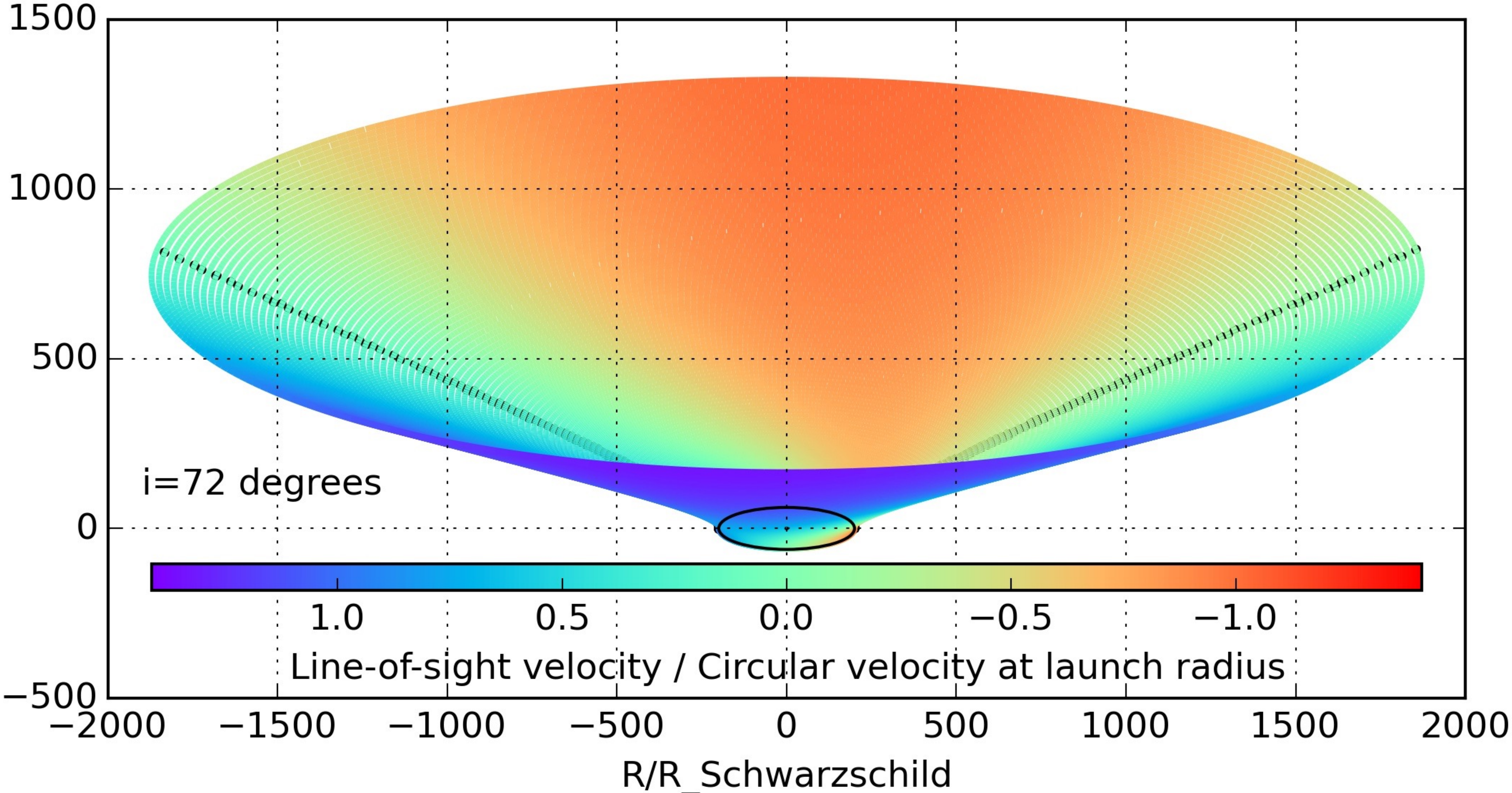
Model: Rotating wind plus extended continuum source

- *This effect originally proposed in Hall et al. (2002) to explain two cases of low-ionization (Mg II) absorption extending to redshifts of ~1,000 km/s; see also Ganguly et al. (1999).*
- Both rotational and outflow velocity components in wind.

Rotating wind + extended continuum source?

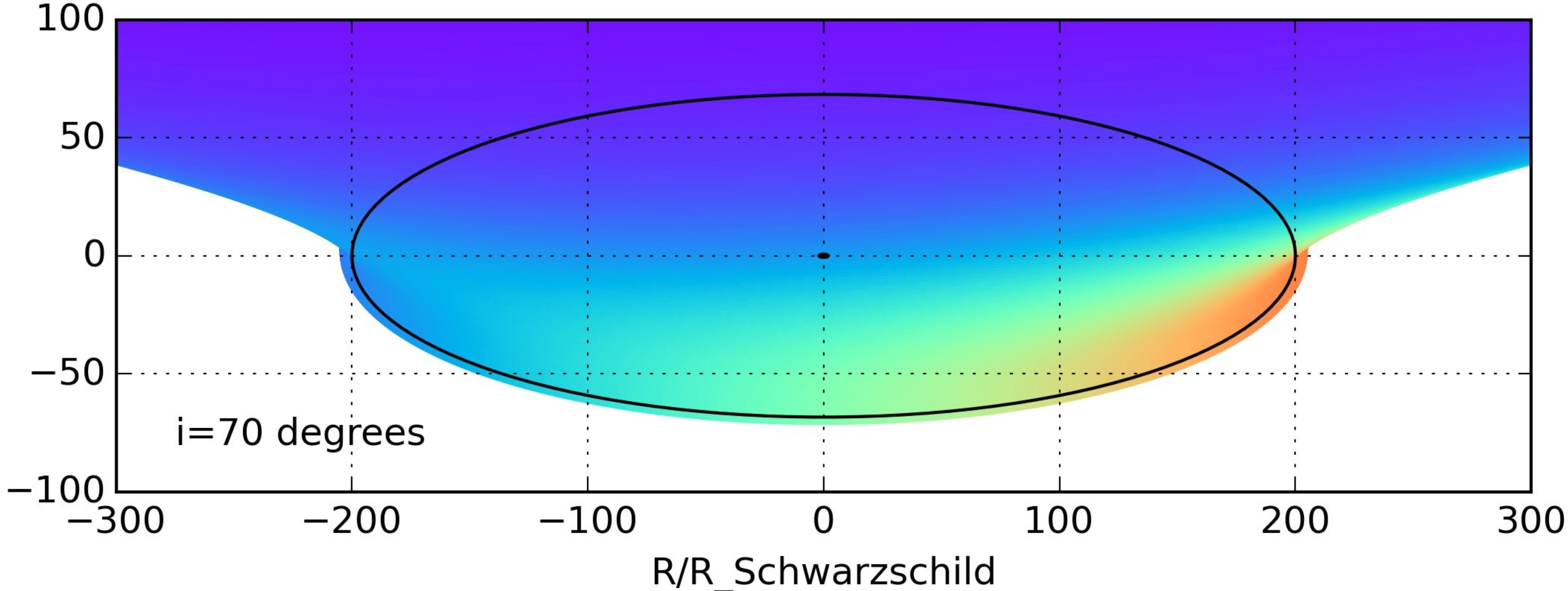
- *This effect originally proposed in Hall et al. (2002) to explain two cases of low-ionization (Mg II) absorption extending to redshifts of ~1,000 km/s; see also Ganguly et al. (1999).*
- Both rotational and outflow velocity components in wind.
- If the wind originates close enough to the extended continuum source, then parts of the wind rotating away from us will contribute to the absorption.
- If rotational velocity is large enough, net radial velocity vector from those parts of the wind will be redshifted.

Funnel-shaped rotating outflow: blue/red for blueshift/redshift



(near side velocities only)

Funnel-shaped rotating outflow: blue/red for blueshift/redshift



Black ellipse=continuum emission region; i=70 degrees

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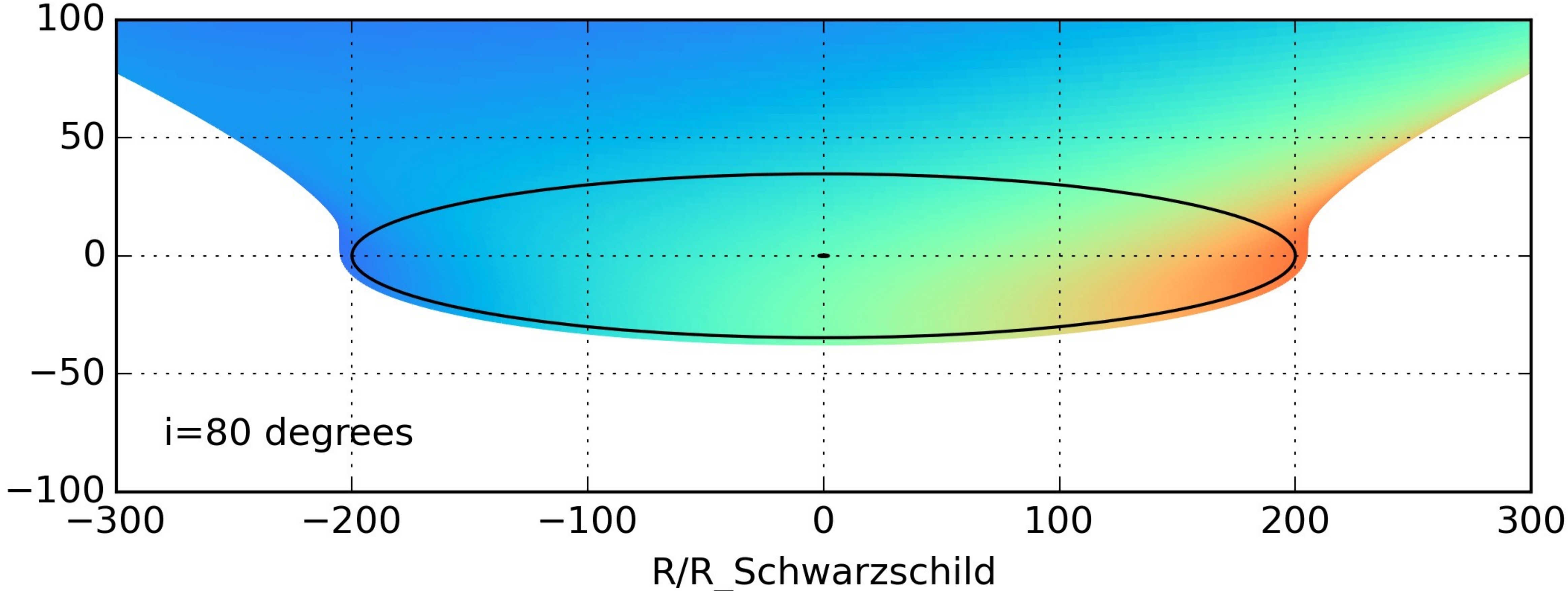
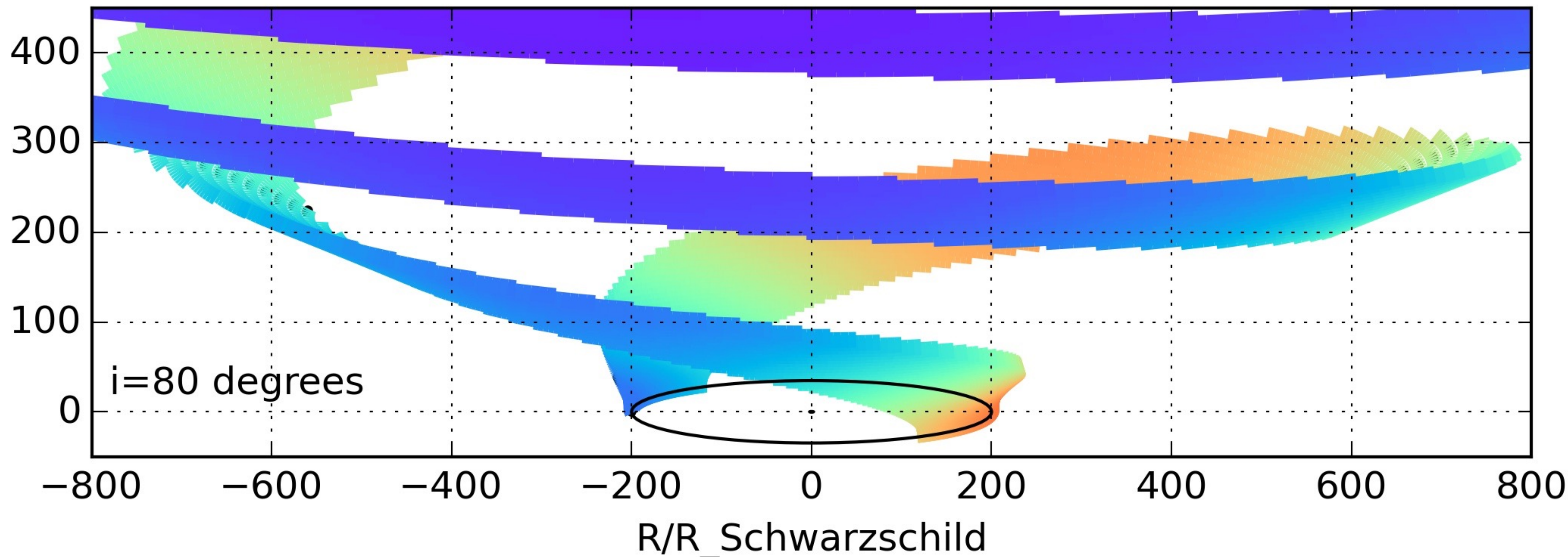


Black ellipse=continuum emission region; i=80 degrees

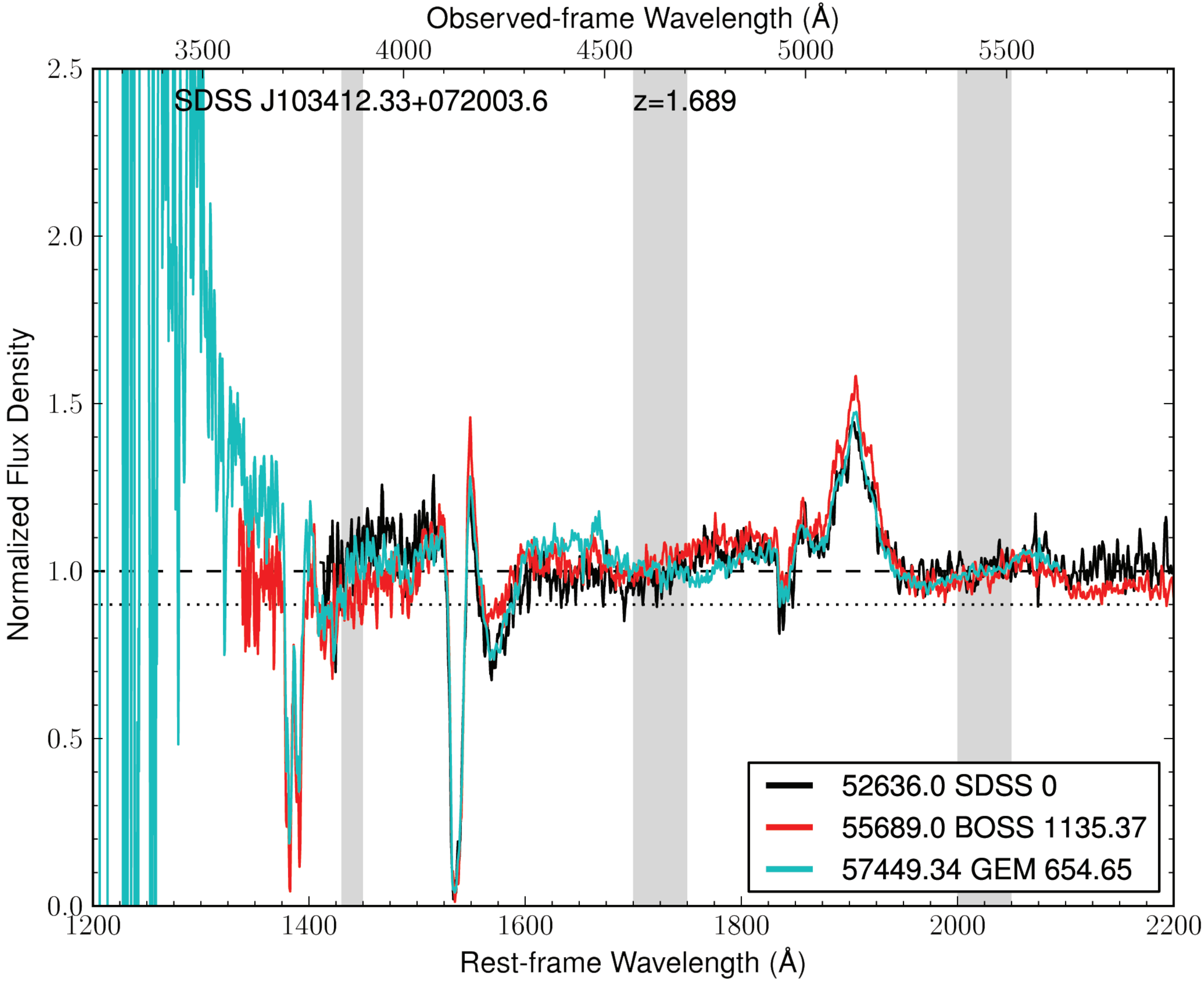
Rotating wind + extended continuum source?

- Applies to quasars with both blue- and redshifted troughs (though only redshifted absorption could be present at times if azimuthal symmetry of outflow is broken).
- Absorption must originate at radii not much larger than that of the extended continuum source.
- Disk must be viewed close to edge-on at launch radii; requires torus misaligned to that disk plane, or gappy.
- Required circumstances are not impossible. They would be uncommon, but so are these quasars...

Azimuthal asymmetries can yield cases of just redshifted absorption



(absorption seen only in front of black ellipse); i=80 degrees



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Rest-frame Wavelength (Å)

RSBALs: Summary

- About 1 in 1200 BAL quasars has redshifted absorption
- Not due to gravitational redshifts
- NIR spectra: no evidence to support binary hypothesis
- X-rays: suggest same (disk wind) origin as normal BALs
- Any due to binaries=new lines of sight through outflows
- Need to consider detailed predictions for rotating disk wind outflows, and more realistic infall models, and compare to (more and better) observations.

Questions?