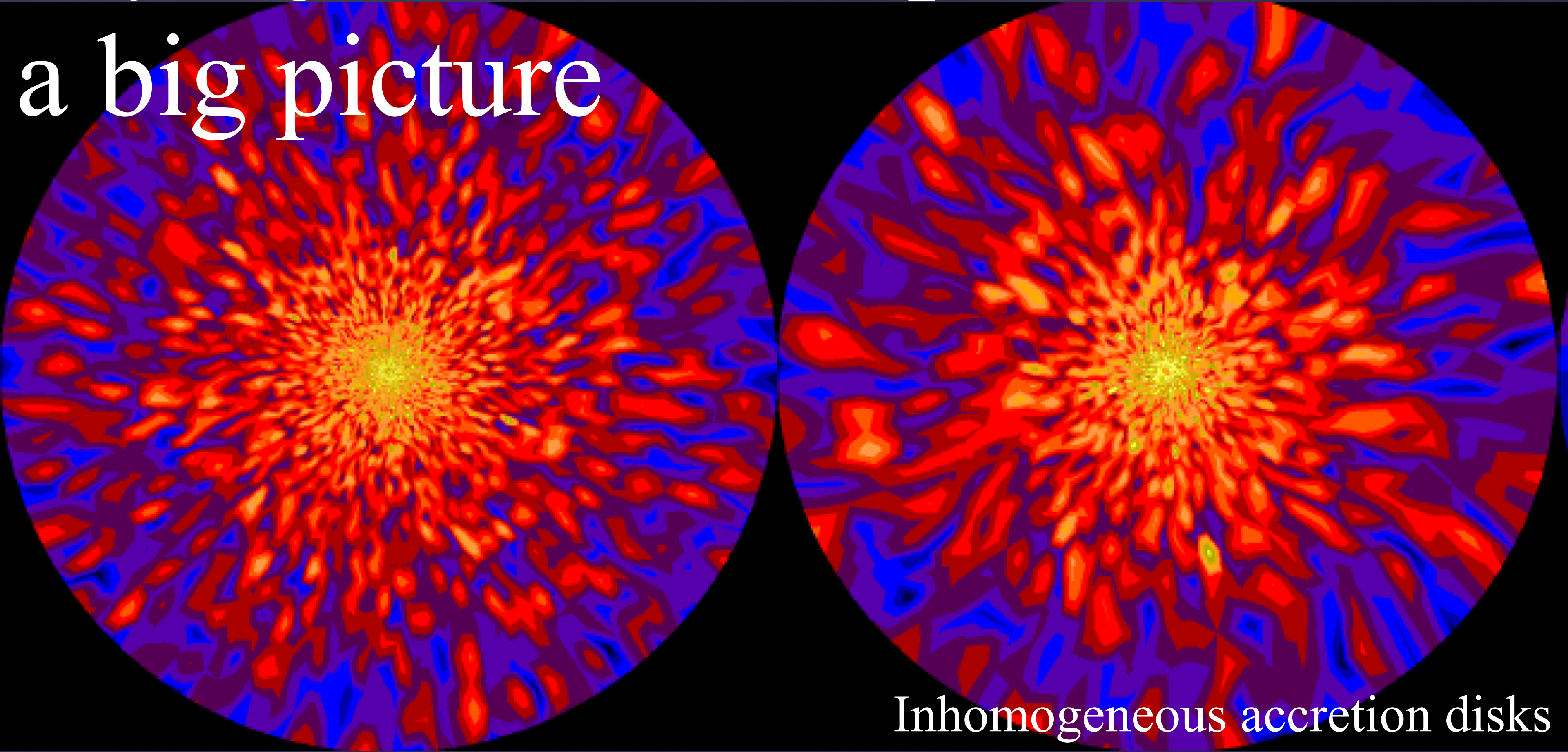
Trying to fit BAL quasars into a big picture



Inhomogeneous accretion disks
(Dexter & Agol)

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Paola Rodriguez Hidalgo, Jesse Rogerson
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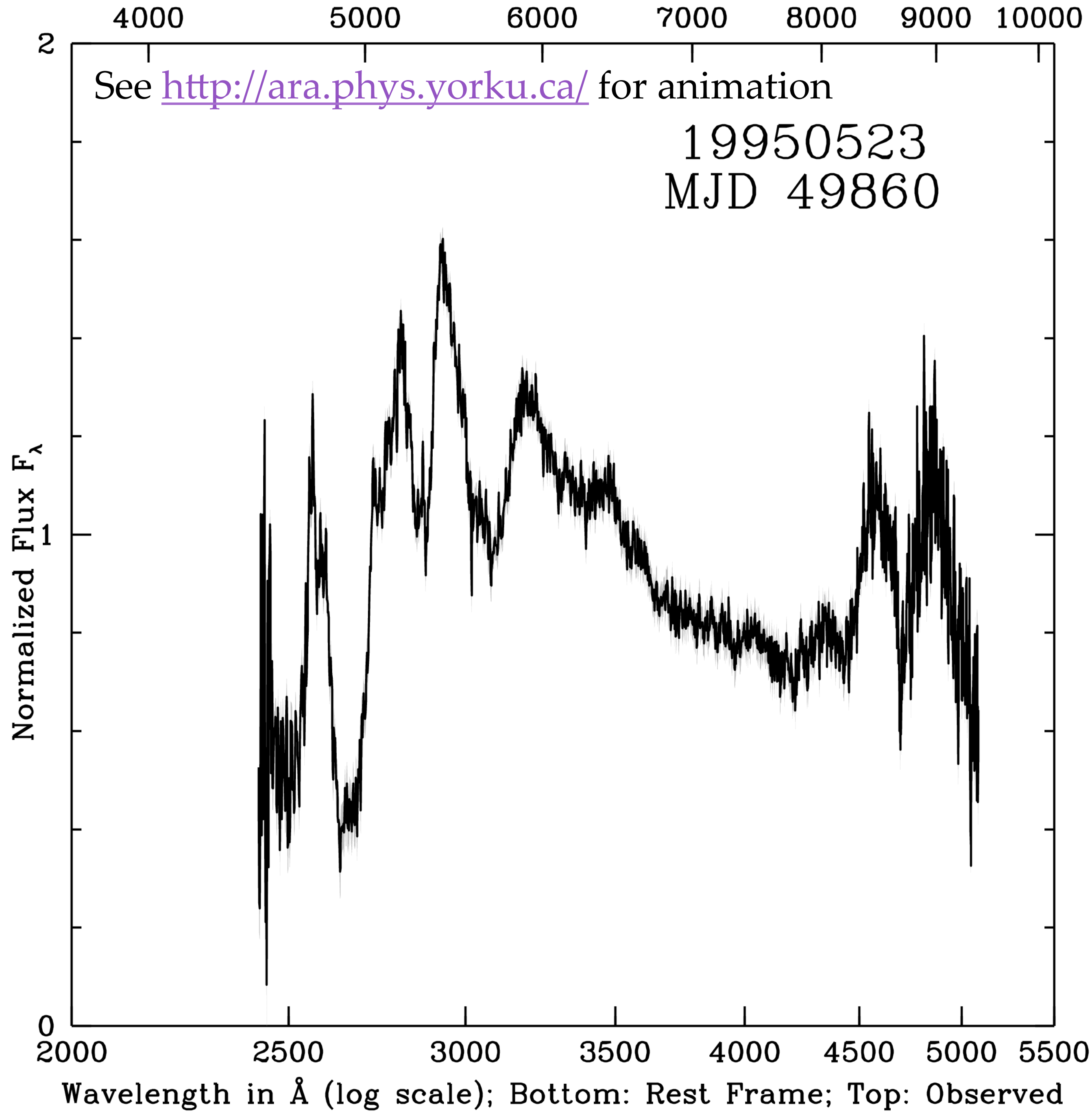
WillsFest 2014

BAL big picture ingredients

- Accretion disk inhomogeneous (Dexter & Agol, …)
- Accretion disk launches wind (Laor & Davis)
- Wind (e.g. C IV absorbers) will be inhomogeneous
- Troughs can be saturated w/o fully covering source
- Absorbers radially thin ($dr/r \sim 10^{-3}$), up to kpc away
- No more than 2/3 of BALs have X-ray shielding
- Ionizing SED ➔ BAL properties (Baskin+2013)
- Variable troughs: bulk motion? ionization changes? Latter from change in ionizing flux or shielding gas; BAL illuminated by $F_{\nu,ion}(x,y) \times \exp[-\tau_\nu(x,y)]$.

Extreme Fe II BAL Variability

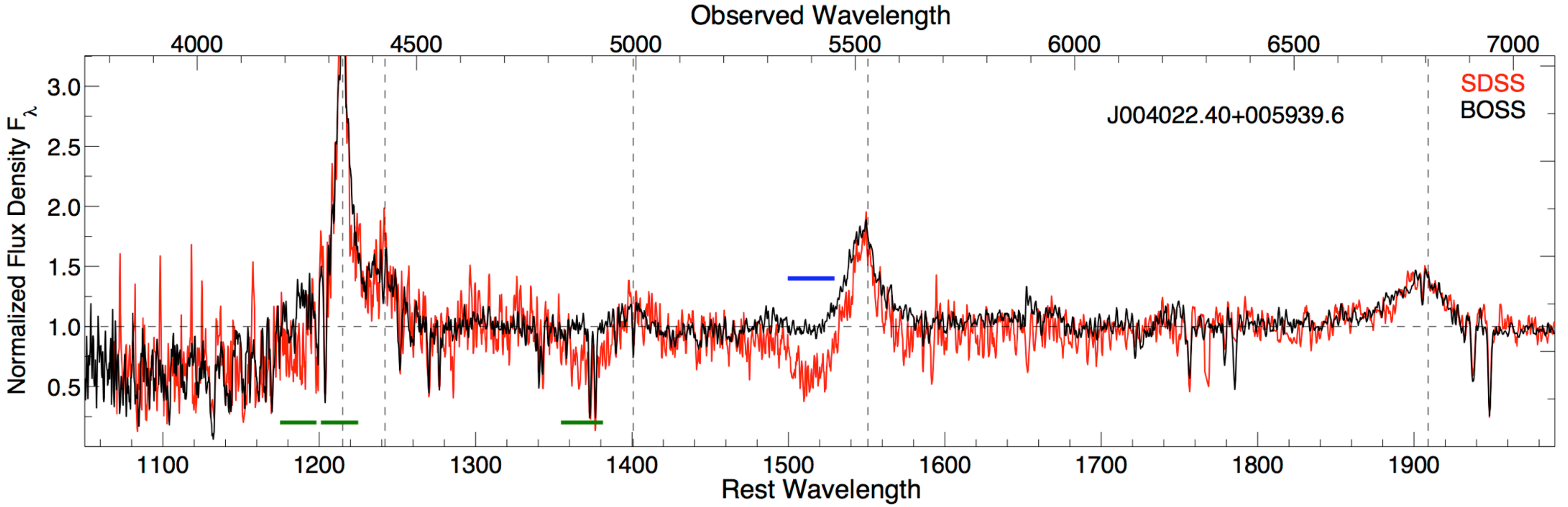
- Hall et al. 2011
- z=0.848 ‘overlapping-trough’ FeLoBAL
- Fe II absorption nearly vanishes
- Mg II weakens by >60%
- All over 946 rest-frame days
- Let’s watch an animation of the spectral evolution; dark spectra are data, light spectra are interpolated, with damped-random-walk uncertainties.
- Dates are given at upper right.



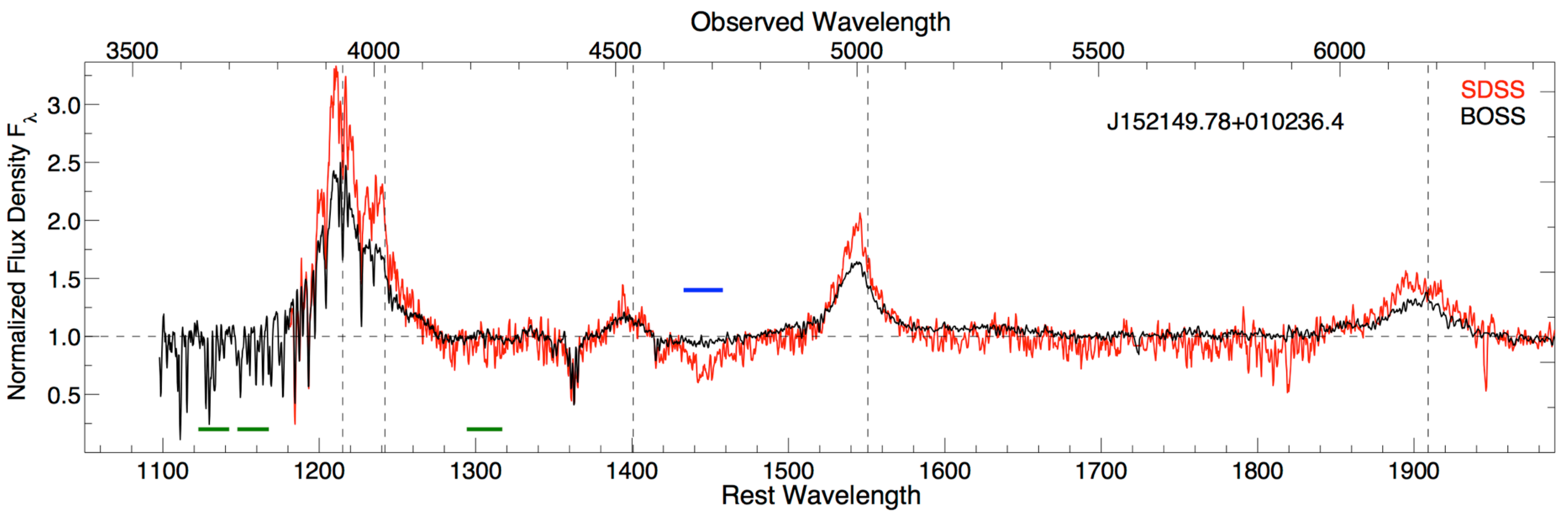
See http://ara.phys.yorku.ca/ for animation
19950523
MJD 49860
Normalized Flux F_λ
Wavelength in Å (log scale); Bottom: Rest Frame; Top: Observed
4000
5000
6000
7000
8000
9000
10000
2000
2500
3000
3500
4000
4500
5000
5500
0
1
2

The Iron Giant

- If from bulk motion, continuum region size plus timescale & geometric wind model give kinematic distance estimate of 1.7-13 pc from the black hole, 10-85 times the distance of the Hβ BELR
- Can't rule out ionization variation alternative, but it must have been due to varying obscuration (a la NGC 5548 recently; Kaastra+2014), not just varying ionizing flux, insofar as there was no significant 3000 Å continuum variability in this source
- If Fe II vanished due to bulk motion, then not all FeLoBALs are galaxy-wide ULIRG→QSO outflows

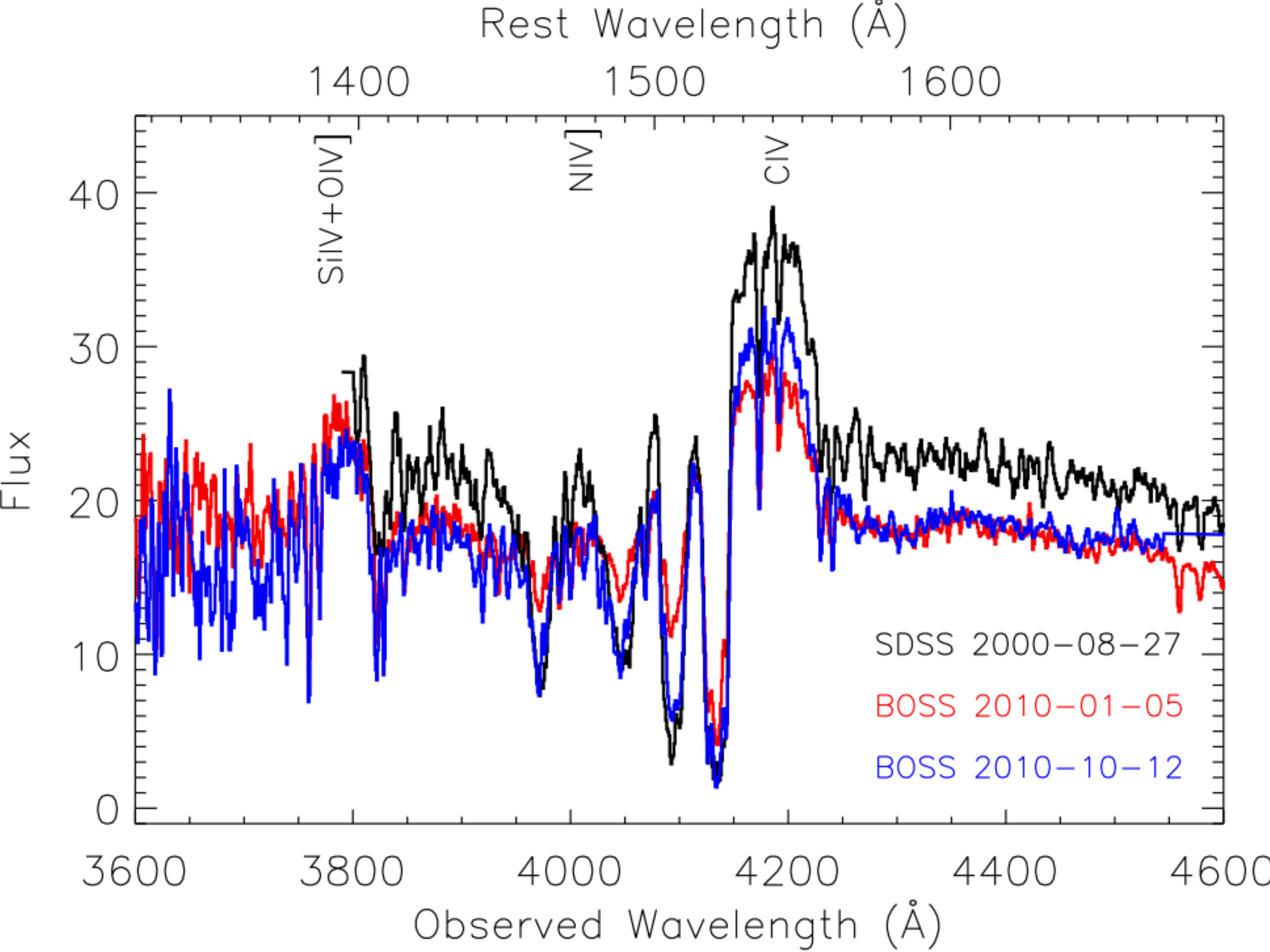


Other Disappearing Troughs (Filiz Ak+2012)



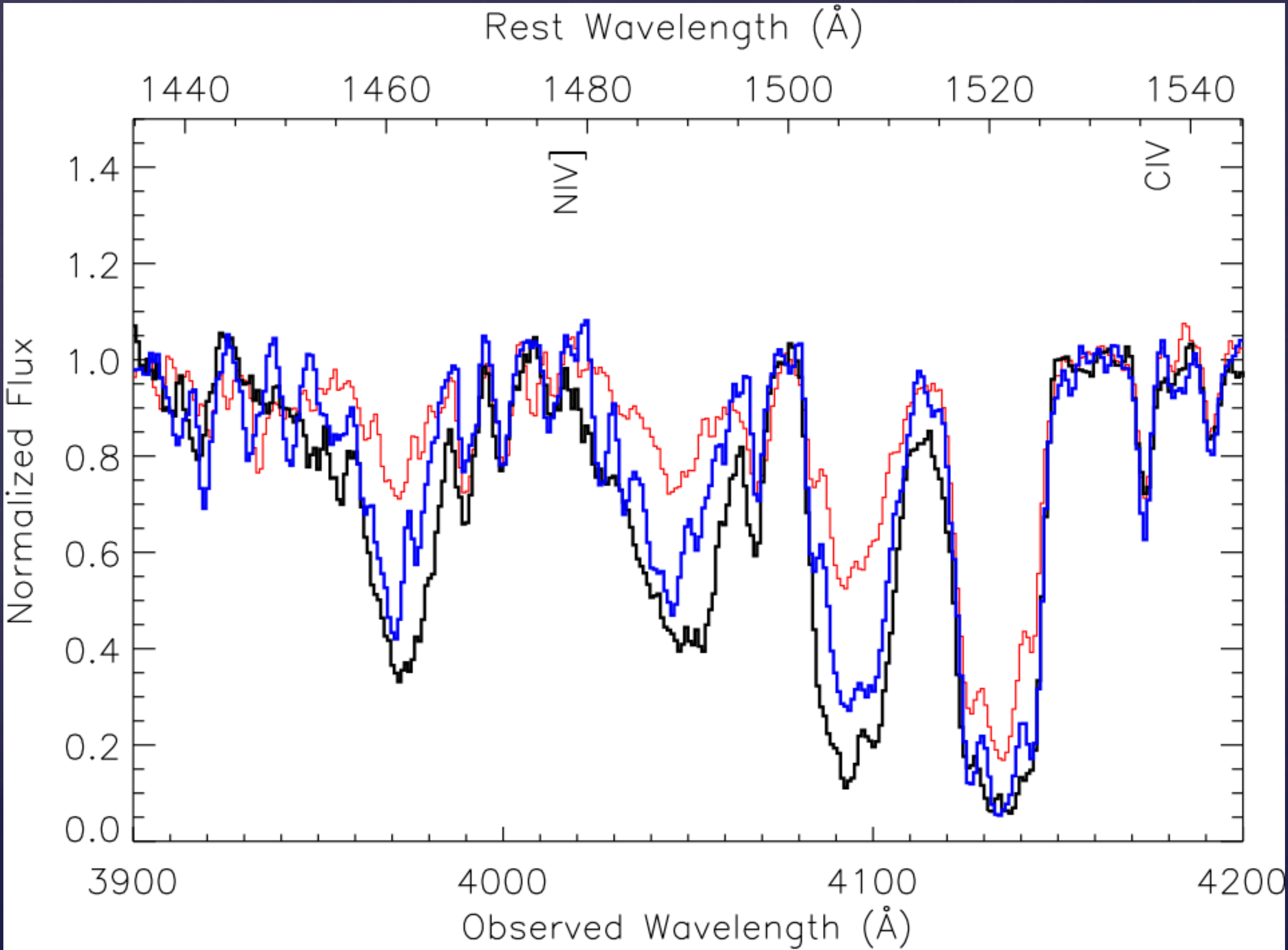
Variability and Inhomogeneity

- z=1.703 HiBAL, noticed by Paola Rodriguez H.
- 3.5 years between SDSS and BOSS, then a second BOSS spectrum 104 days later.
- Absorption weakened significantly over 3.5 years, but back almost to where it started 104 days later; see black, red, blue spectra in next slide:



Rest Wavelength (Å)
1400
1500
1600
SiIV+OIV]
NIV]
CIV
Flux
0
10
20
30
40
SDSS 2000−08−27
BOSS 2010−01−05
BOSS 2010−10−12
3600
3800
4000
4200
4400
4600
Observed Wavelength (Å)

Black: SDSS; Red: BOSS #1; Blue: BOSS #2



There And Back Again

- *z=1.703 HiBAL, noticed by Paola Rodriguez H.*
- *3.5 years between SDSS and BOSS, then a second BOSS spectrum 104 days later.*
- *Absorption weakened significantly over 3.5 years, but back almost to where it started 104 days later;* ionization variability seems most likely explanation.
- But: fainter continuum➔troughs weaken…
- …no change in continuum➔ troughs strong again.
- Return to the previous trough levels puzzling...

There And Back Again

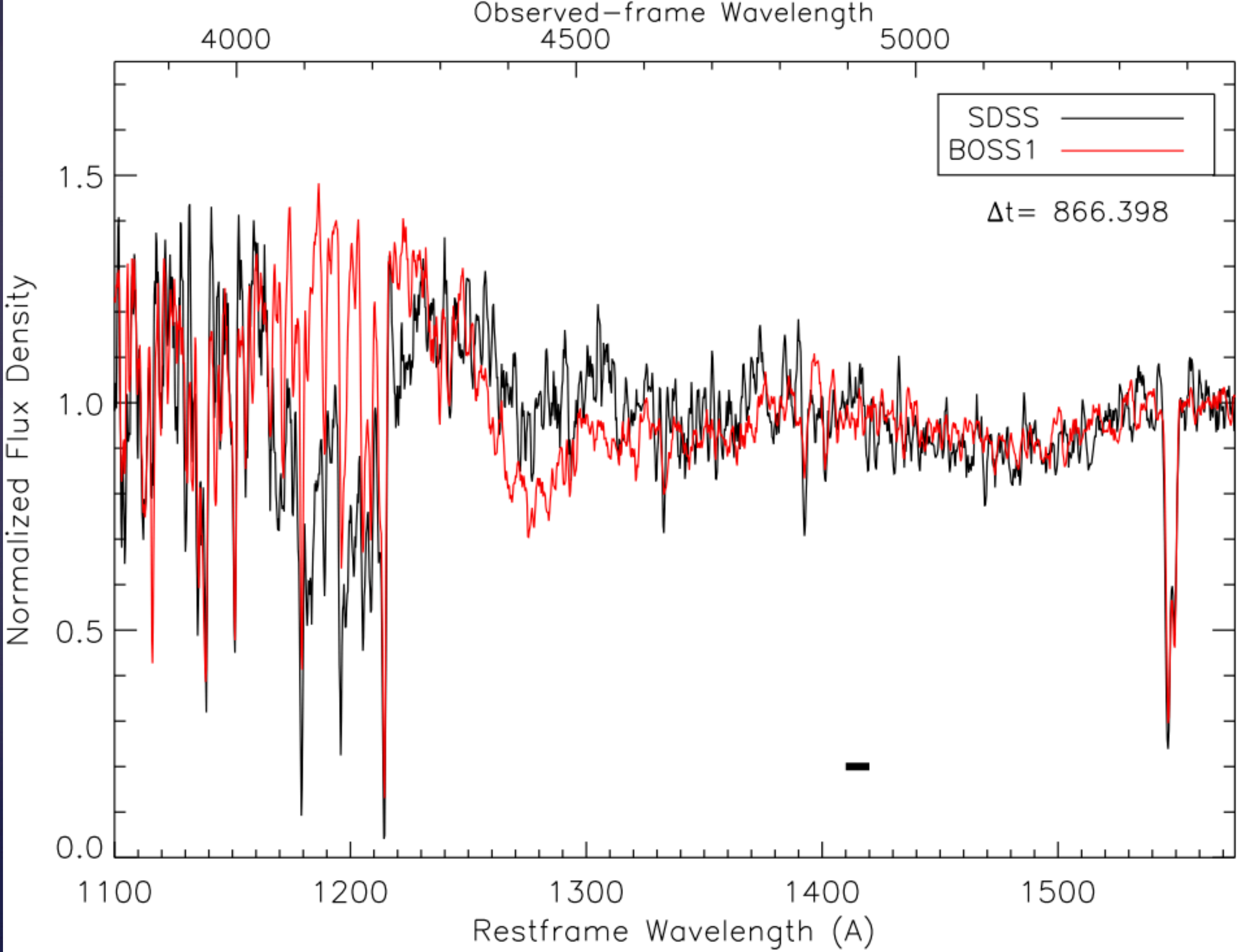
- Troughs that strengthen then return to previous strength could be response to a shield cloud crossing our LOS (reduction in F_{ion} leads to increased C IV), or to a disk hotspot moving behind an absorber.
- Troughs that weaken (indicating increase in F_{ion} or decrease in shielding) then return to previous strength with no accompanying continuum variability much tougher to understand! Maybe varying intrinsic shape of the ionizing spectrum?
- Accurate (spectro)photometry needed to move beyond normalized trough profile studies.

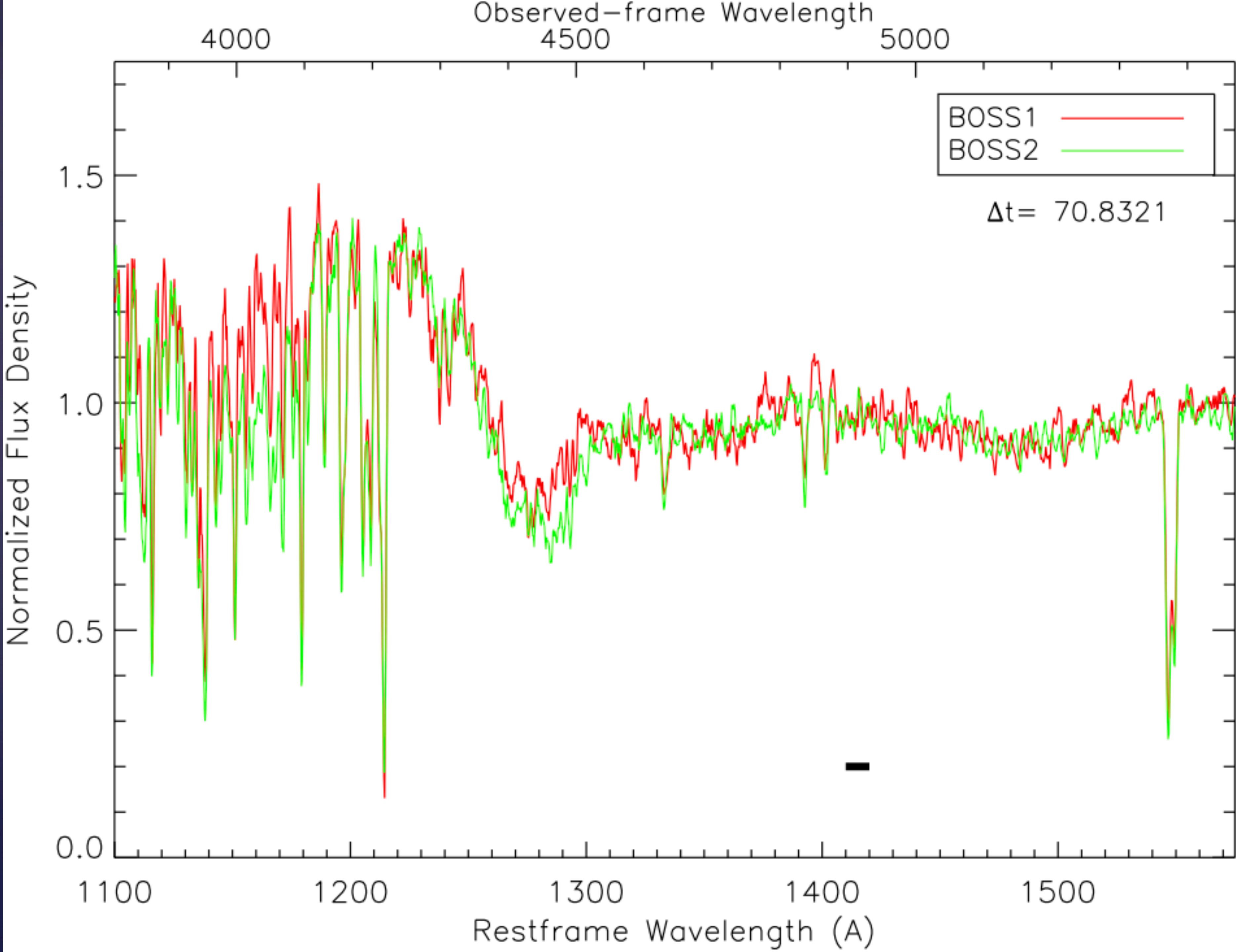
Coordinated Trough Variability

- Filiz Ak et al. (2012, 2013): in BAL quasars with multiple troughs, 107 of 137 troughs (78±8%) vary in same direction between SDSS & BOSS spectra.
- If a mixture of uncorrelated transverse-motion and perfectly correlated ionization variability, 56±7% of trough variations due to ionization variations.
- Actual fraction higher? Ionization variations can be uncorrelated if densities sufficiently different … high-density gas responds to recent average ionizing flux, low-density gas to a longer-term average.

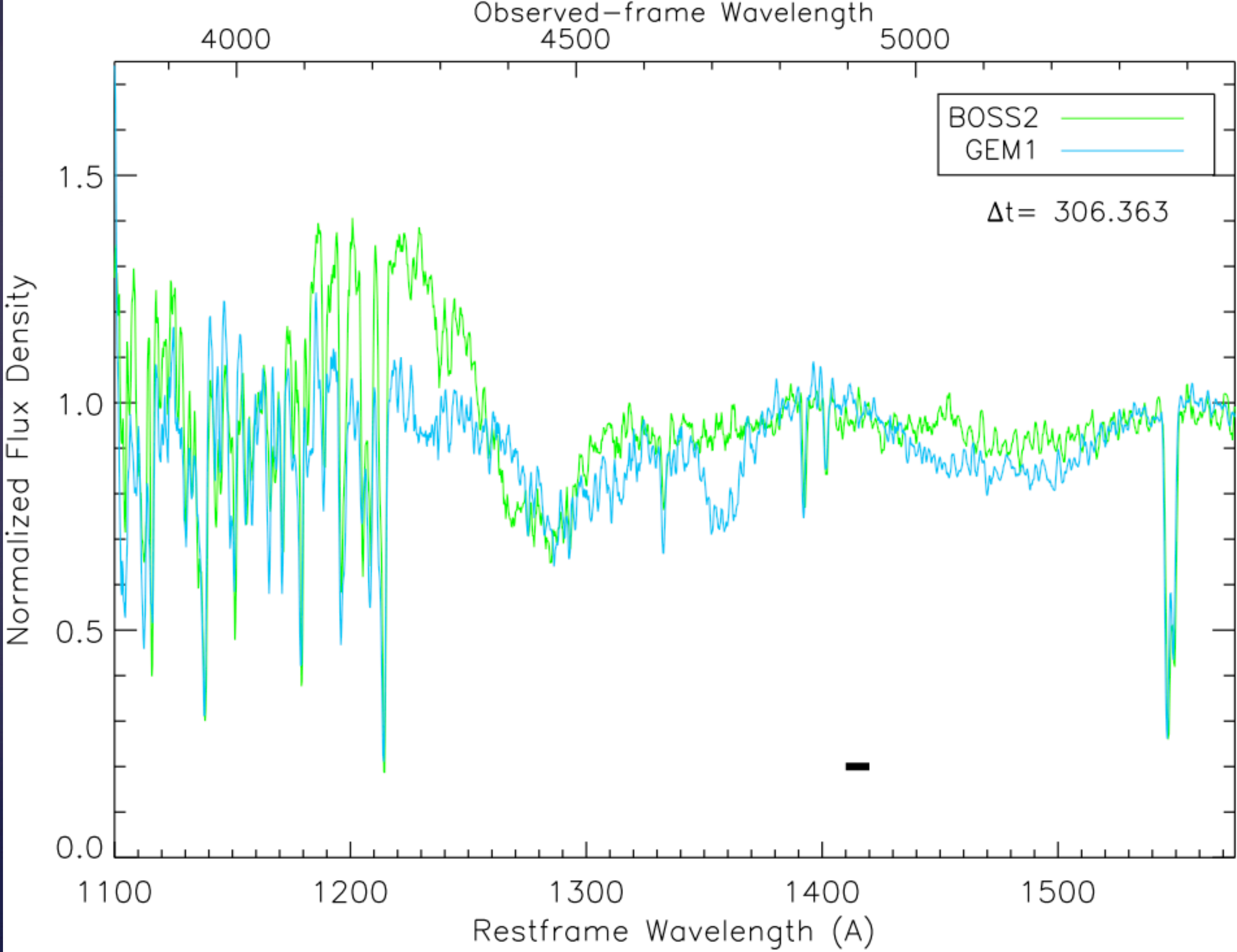
Very High Velocity Variability

- SDSS J023011+005913 (z=2.473)
- Varying C IV absorption at up to 60,000 km/s, record high velocity for C IV (Rogerson+ in prep)
- Found in a (successful) search for emergent BAL troughs between SDSS and BOSS
- Variability down to timescales of 10 days
- Will show pairs of normalized spectra, with rest-frame timesteps given at upper right; narrow C IV absorption at systemic redshift seen on right…

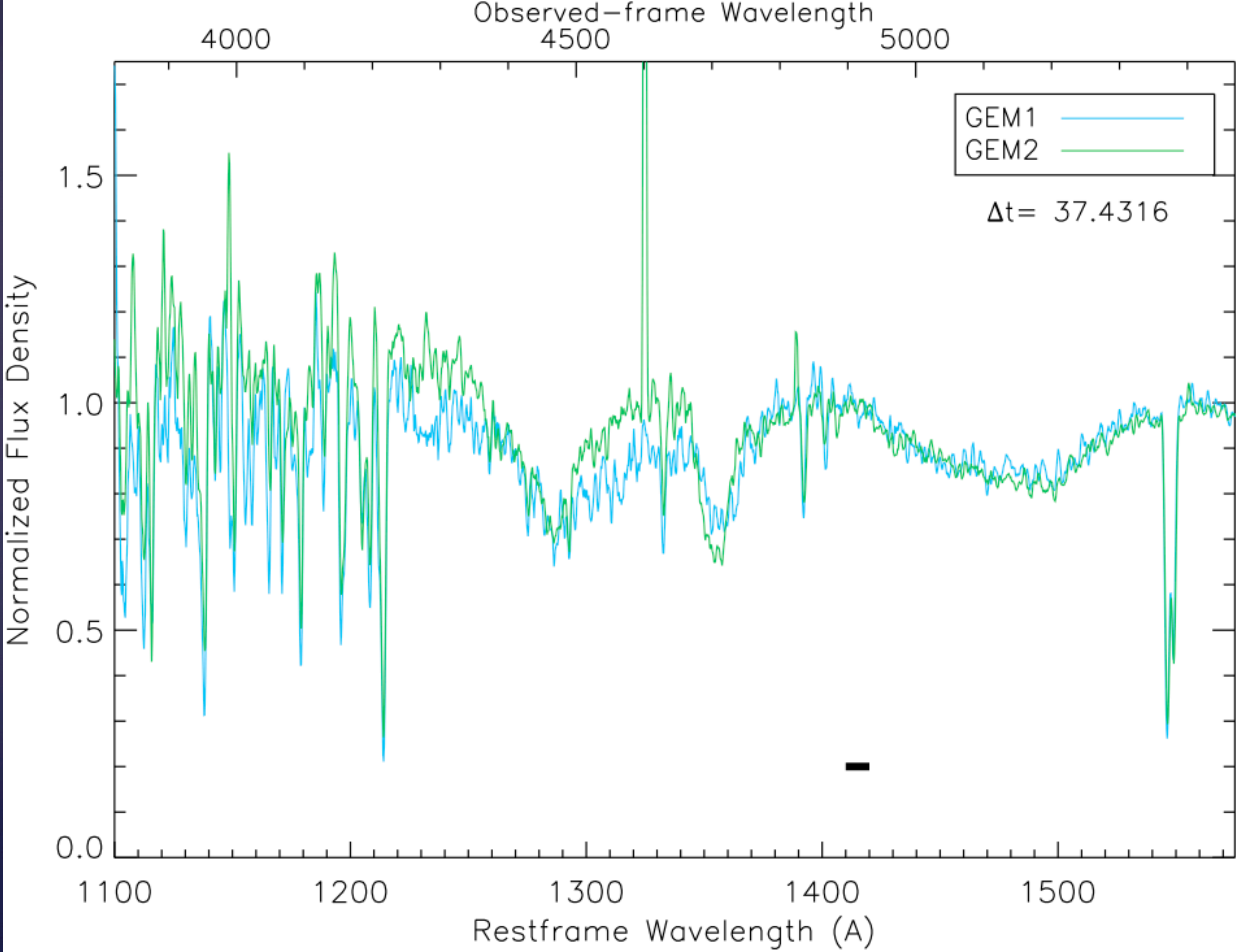

Observed−frame Wavelength
4000
4500
5000
SDSS
BOSS1
Δt= 866.398
1.5
1.0
0.5
0.0
Normalized Flux Density
1100
1200
1300
1400
1500
Restframe Wavelength (A)



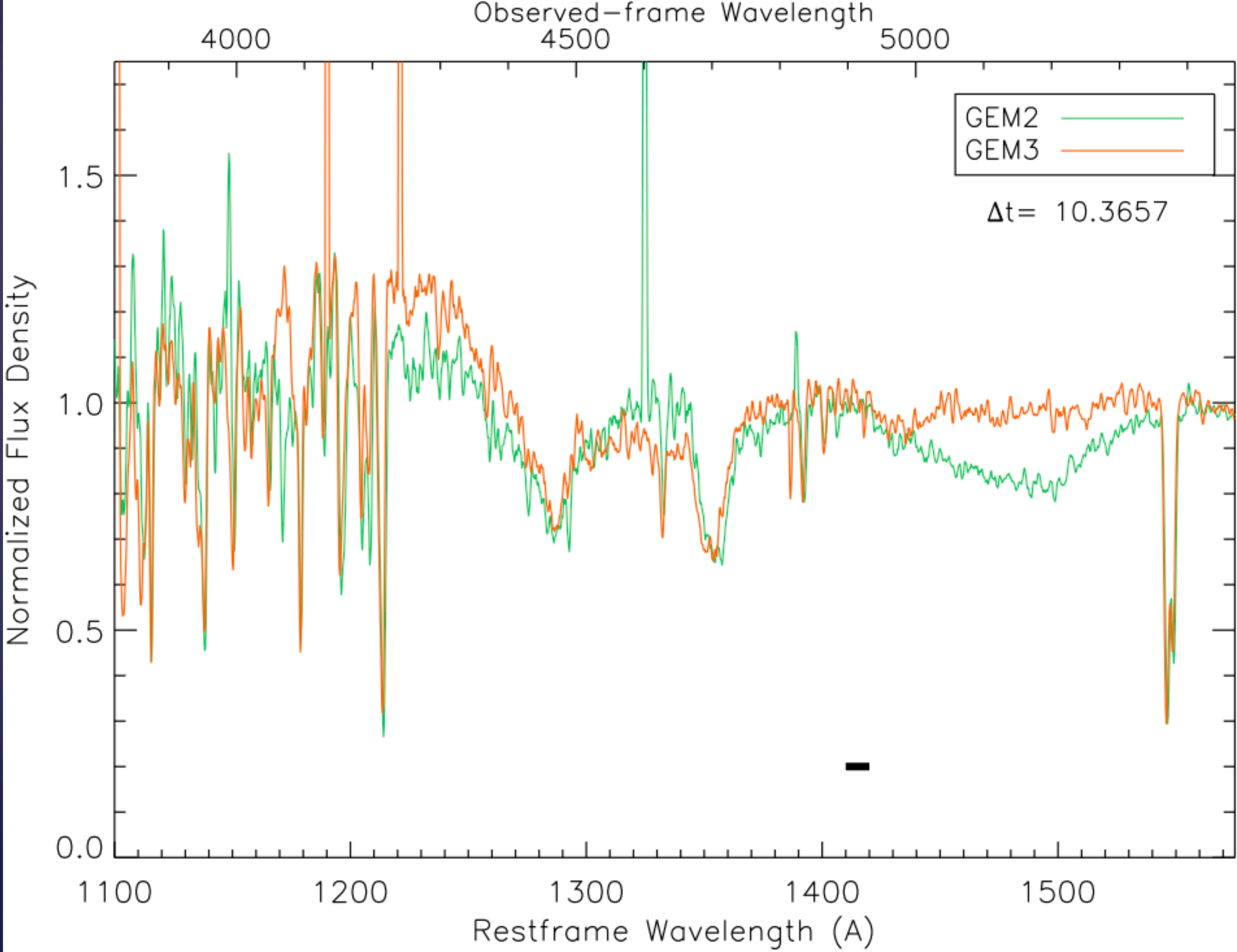
Observed−frame Wavelength
4000
4500
5000
BOSS1
BOSS2
Δt= 70.8321
Normalized Flux Density
1.5
1.0
0.5
0.0
1100
1200
1300
1400
1500
Restframe Wavelength (A)



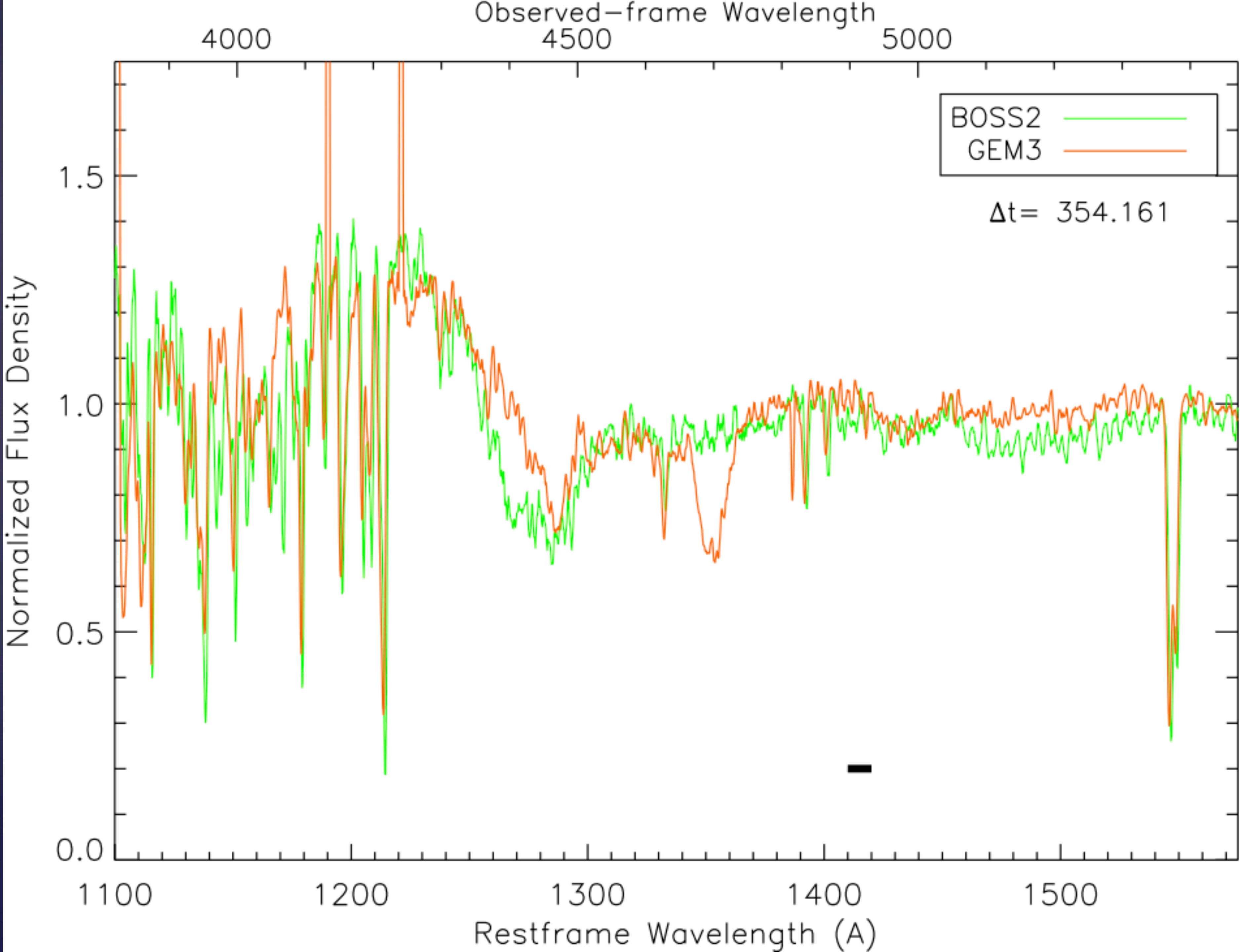
Observed−frame Wavelength
4000
4500
5000
BOSS2
GEM1
Δt= 306.363
Normalized Flux Density
1.5
1.0
0.5
0.0
1100
1200
1300
1400
1500
Restframe Wavelength (A)



Observed−frame Wavelength
4000
4500
5000
GEM1
GEM2
Δt= 37.4316
Normalized Flux Density
1.5
1.0
0.5
0.0
1100
1200
1300
1400
1500
Restframe Wavelength (A)



Observed−frame Wavelength
4000
4500
5000
GEM2
GEM3
Δt= 10.3657
1.5
1.0
0.5
0.0
Normalized Flux Density
1100
1200
1300
1400
1500
Restframe Wavelength (A)



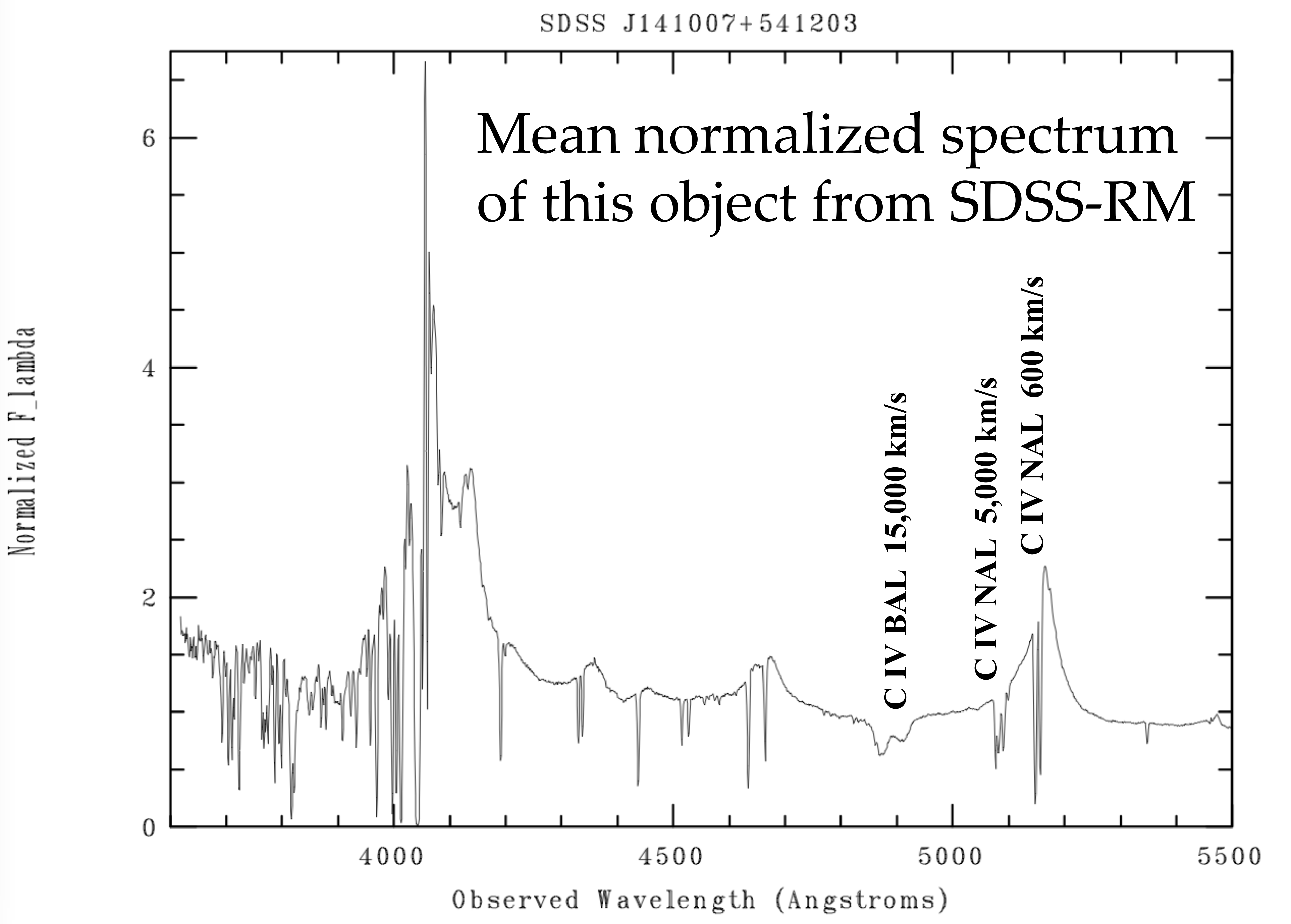
Observed−frame Wavelength
4000
4500
5000
BOSS2
GEM3
Δt= 354.161
Normalized Flux Density
1.5
1.0
0.5
0.0
1100
1200
1300
1400
1500
Restframe Wavelength (A)

The Need for Speed

- *Variability down to timescales of 10 days*
- Pure ionization variability unlikely for 60,000 km/s trough, whose high-velocity half appeared with the low-velocity half but then disappeared; differential saturation or transverse motion also involved?
- If 40,000 km/s trough due to bulk motion, velocity of 1000 to 5000 km/s across sightline; equating that with the circular velocity, $r<0.3\pm0.1$ pc. (But…)
- Ongoing followup with Gemini: if further changes in absorption are detected, we will trigger multiple followup spectra on short timescales.

Intensive BAL Trough Monitoring

- SDSS J141007+541203 at z=2.34, with g=18.4
- 1 of 850 SDSS-RM AGN (Shen+:1408.5930)
- 30 epochs over 53 rest-frame days
- C IV NALs at 600 km/s and 5000 km/s (Si II 1526 from former blends with C IV from latter)
- C IV BAL at 14000-18250 km/s (N V, weak Si IV)
- BAL varies on timescales down to 1.2 to 3 days (previous record 8 to 10 days; Capellupo+2013; but see Haggard+2012 unpublished ~1 day variation)



SDSS J141007+541203
Mean normalized spectrum
of this object from SDSS-RM
Normalized F_lambda
Observed Wavelength (Angstroms)
0
2
4
6
4000
4500
5000
5500
C IV BAL 15,000 km/s
C IV NAL 5,000 km/s
C IV NAL 600 km/s

C IV region

All 30 epochs

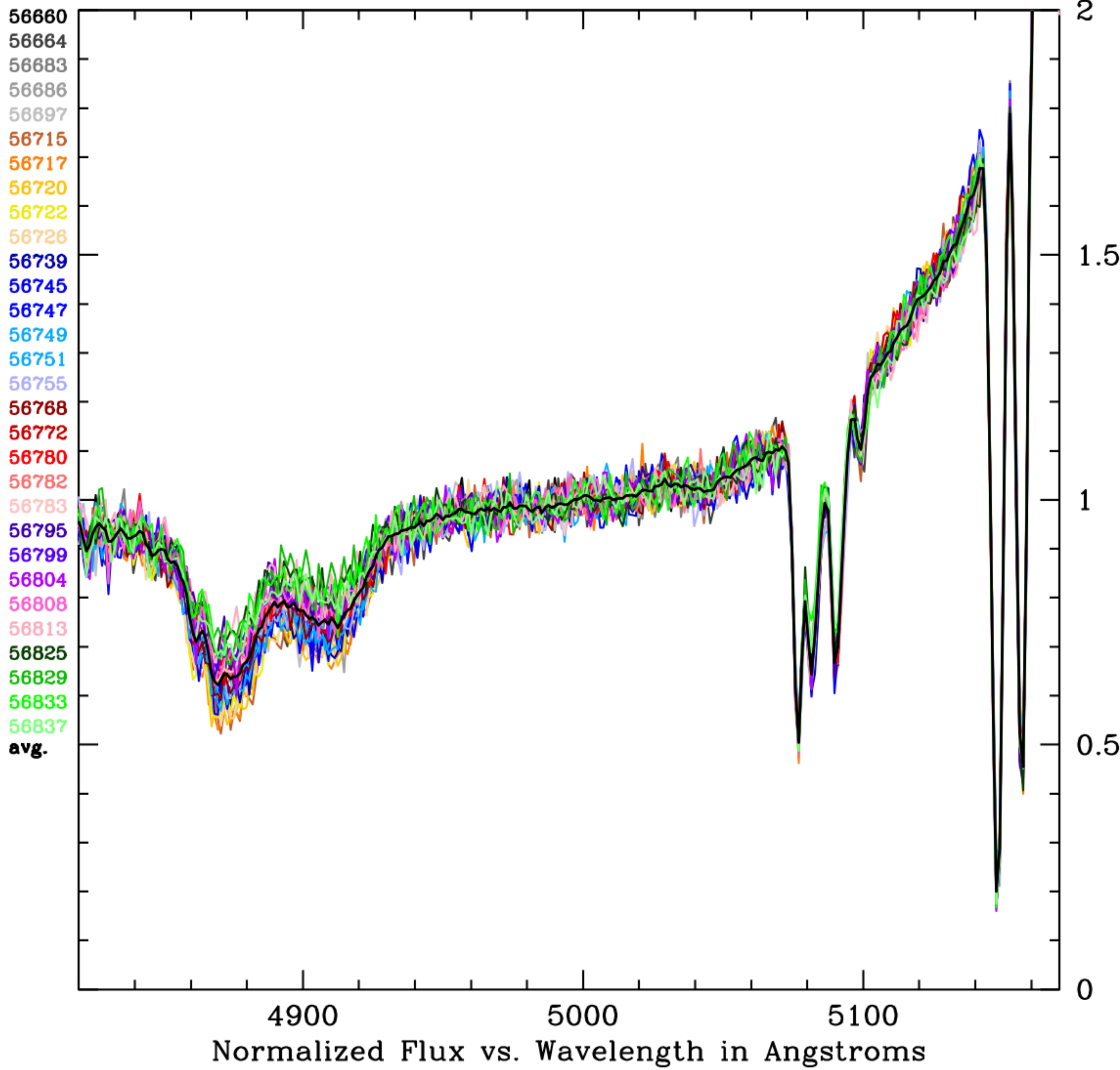
Normalized at 4950-5050 Ang.

No smoothing

Low-v NAL: No variation

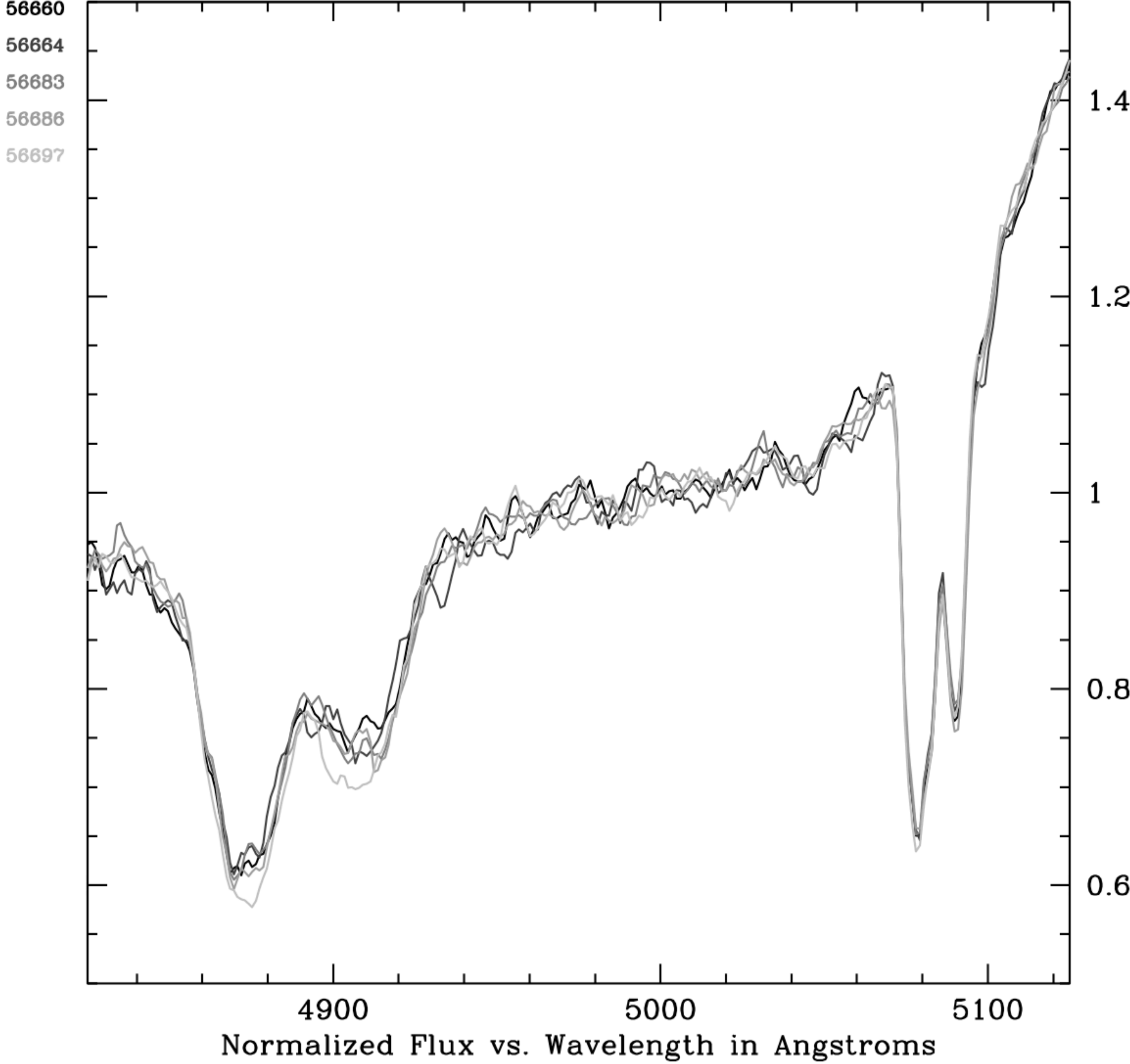
Med.-v NAL: Some variation?

BAL: clearly more variable than continuum



5-pix smoothing

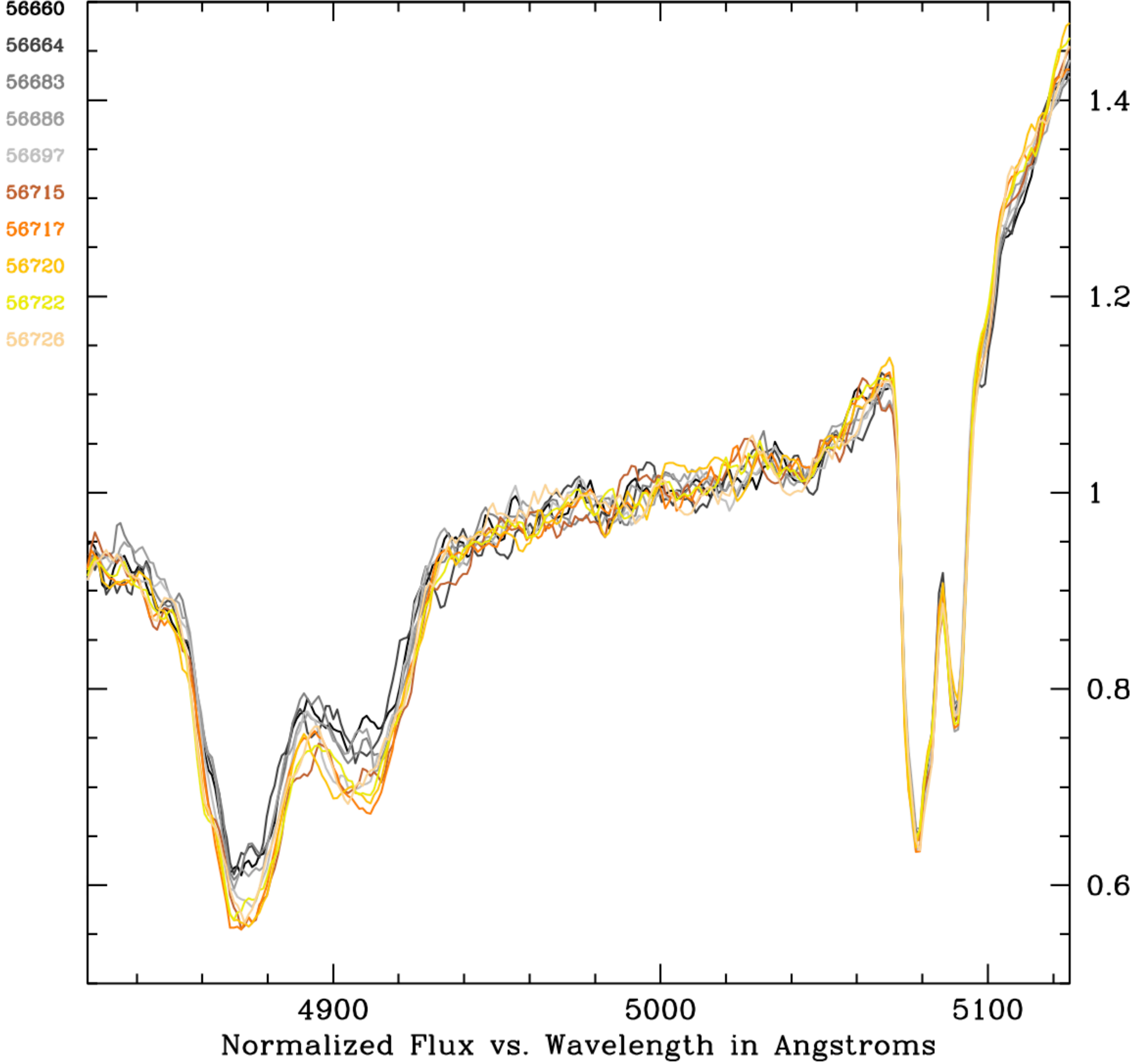
Constant REW for 7.9 days, then trough deepens over <3.1 days between epochs 4 and 5.



5-pix smoothing

Constant REW for 7.9 days, then trough deepens over <3.1 days between epochs 4 and 5.

Stays that deep for the next 8.9 rest frame days.

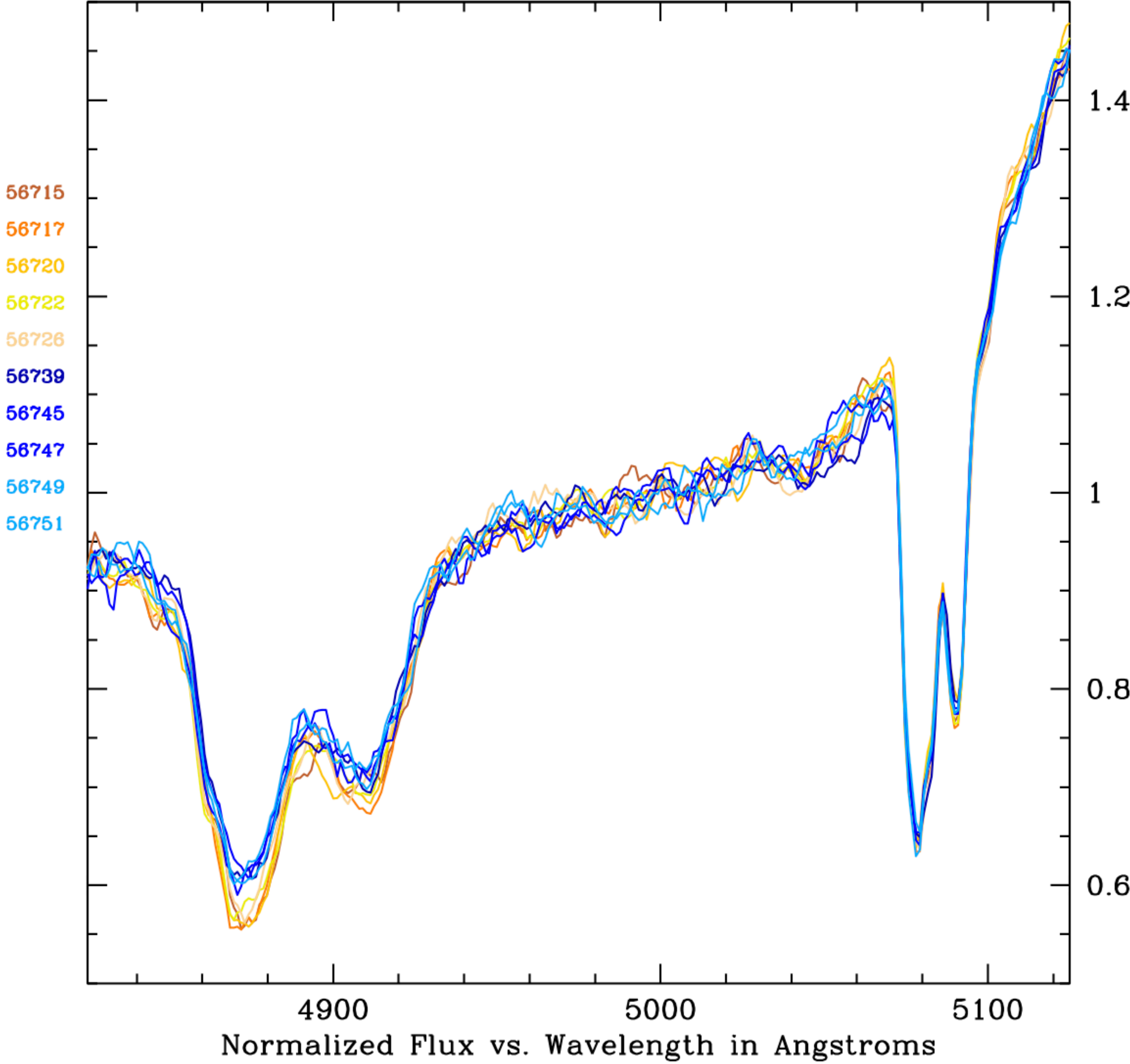


5-pix smoothing

Constant REW for 7.9 days, then trough deepens over <3.1 days between epochs 4 and 5.

Stays that deep for the next 8.9 rest frame days.

In less than 3.9 days, returns to depth similar to starting epoch.



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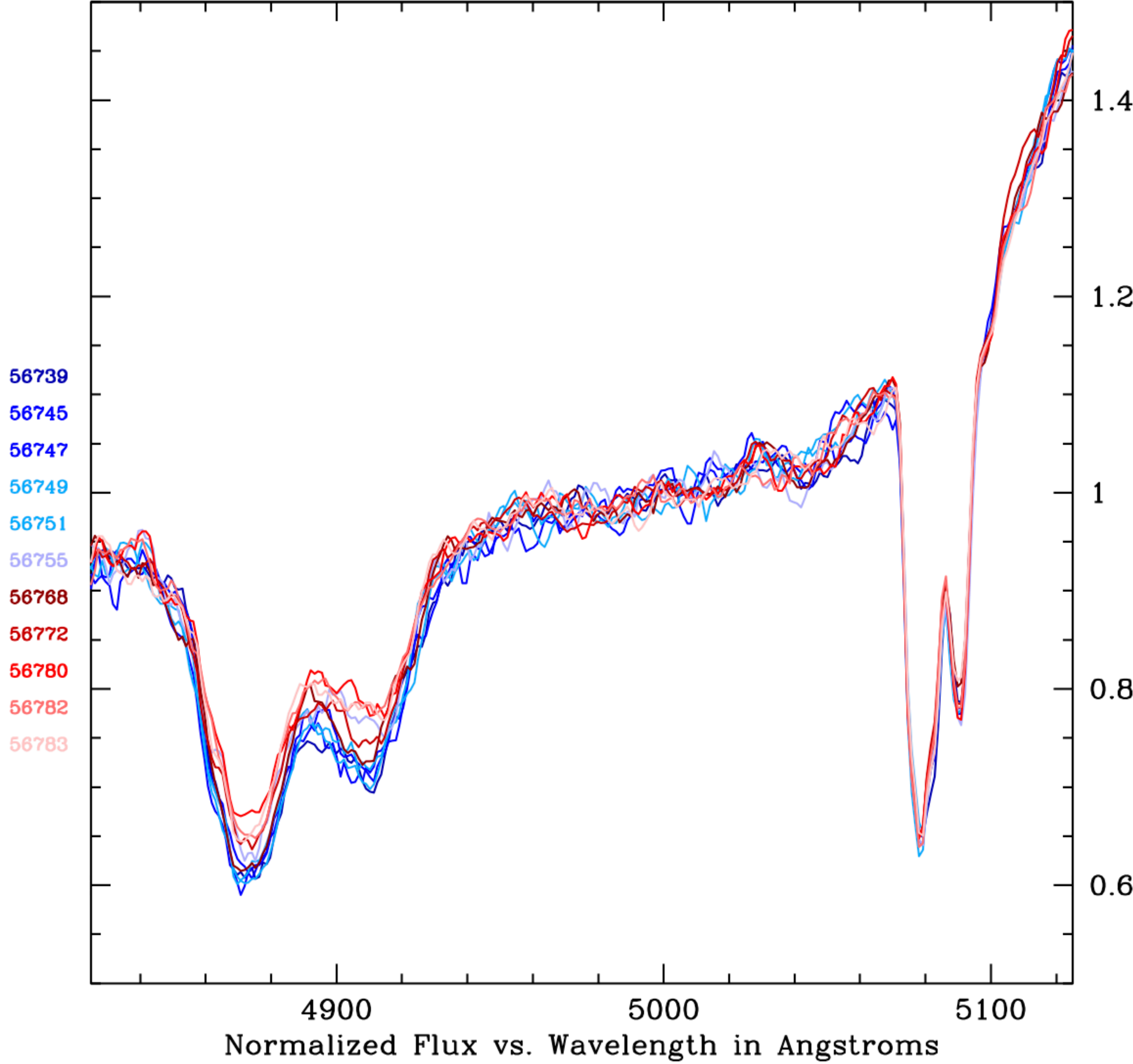
In less than 3.9 days, returns to depth similar to starting epoch.

After 8.6 days, trough weakens on 1.2 and 2.4 day timescales.



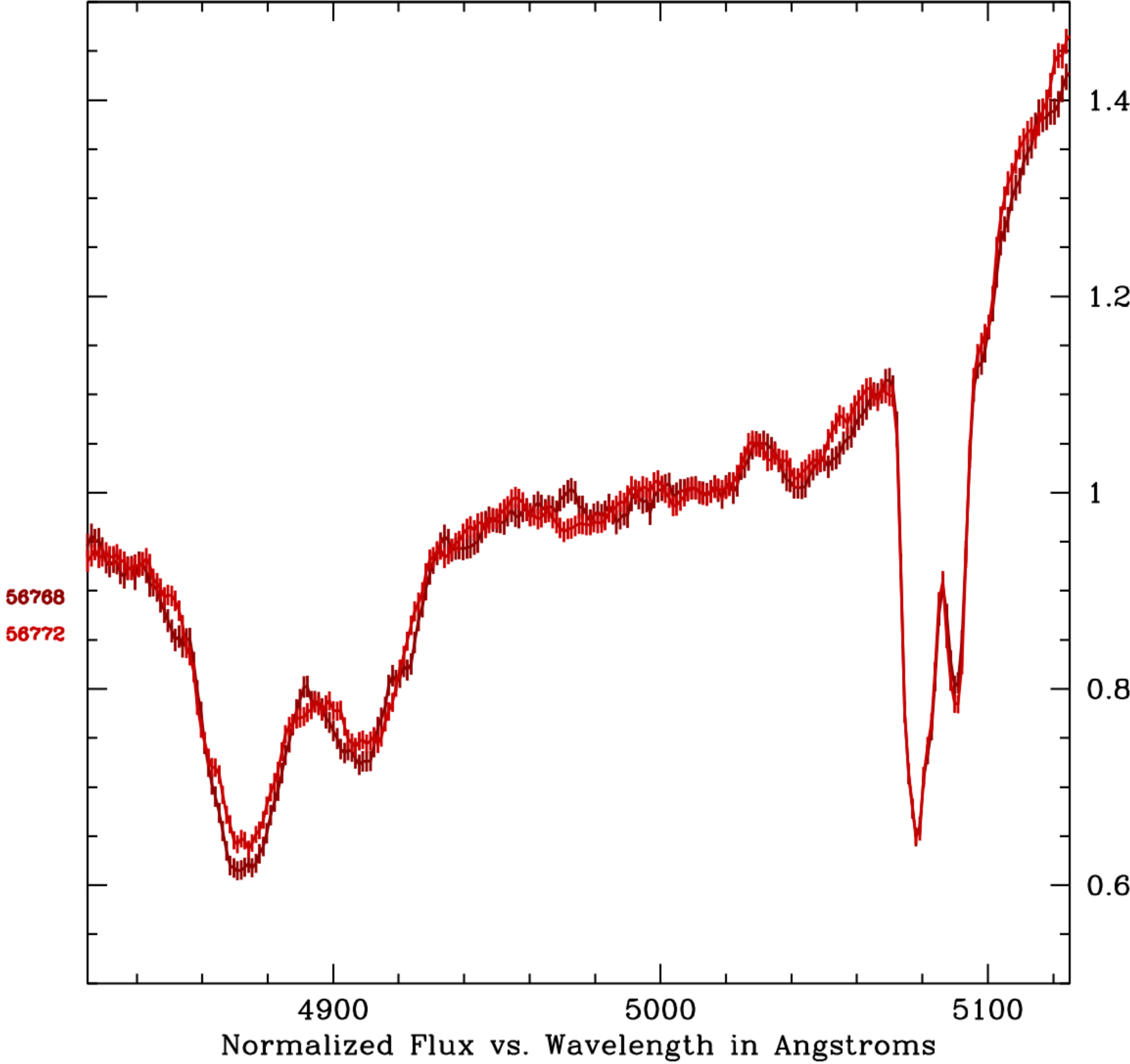
5-pix smoothing

Constant REW for 7.9 days, then trough deepens over <3.1 days between epochs 4 and 5.

Stays that deep for the next 8.9 rest frame days.

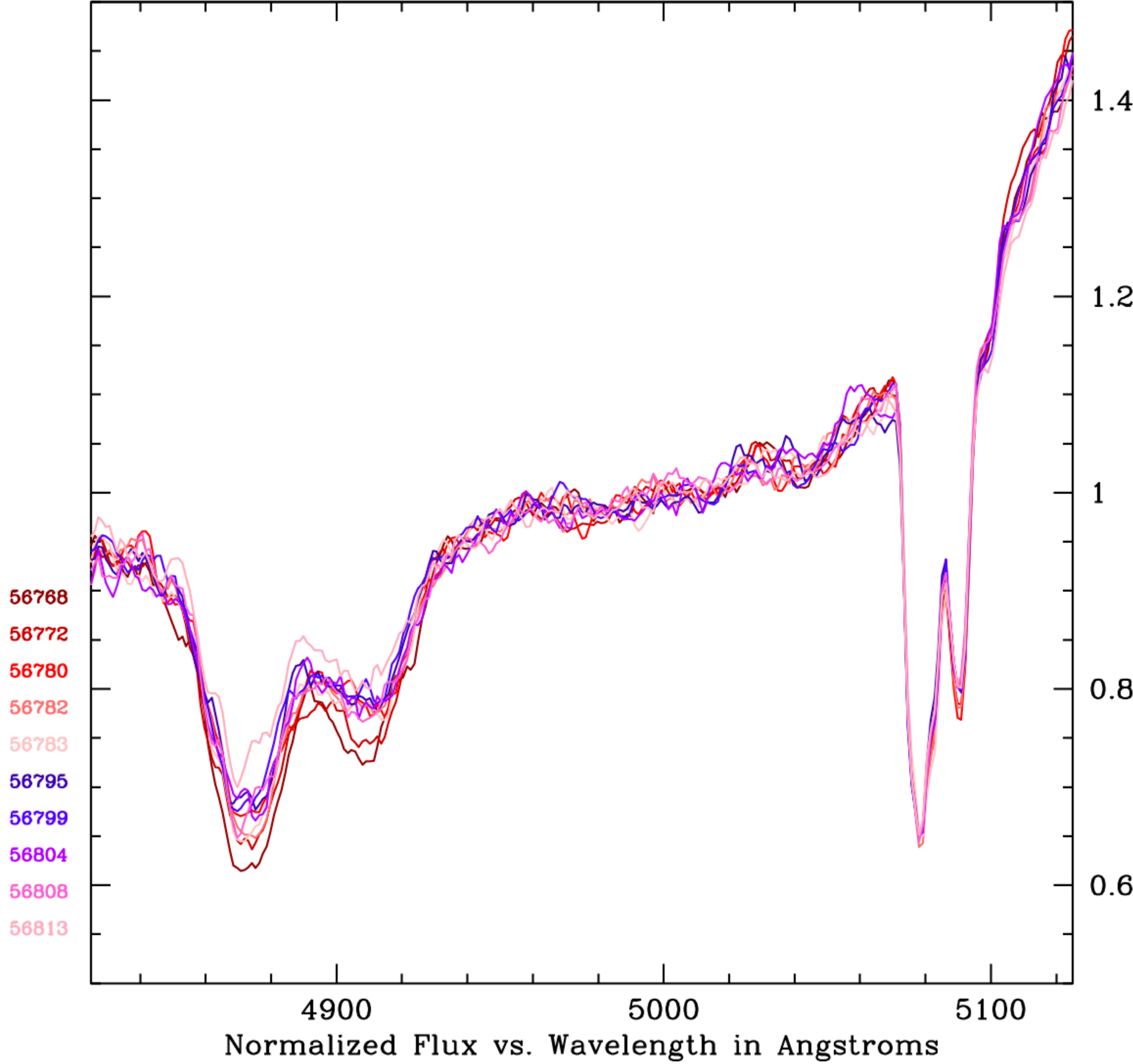
In less than 3.9 days, returns to depth similar to starting epoch.

After 8.6 days, trough weakens on 1.2 and 2.4 day timescales. **(Shown: 1.2 day variation+errors)**



5-pix smoothing

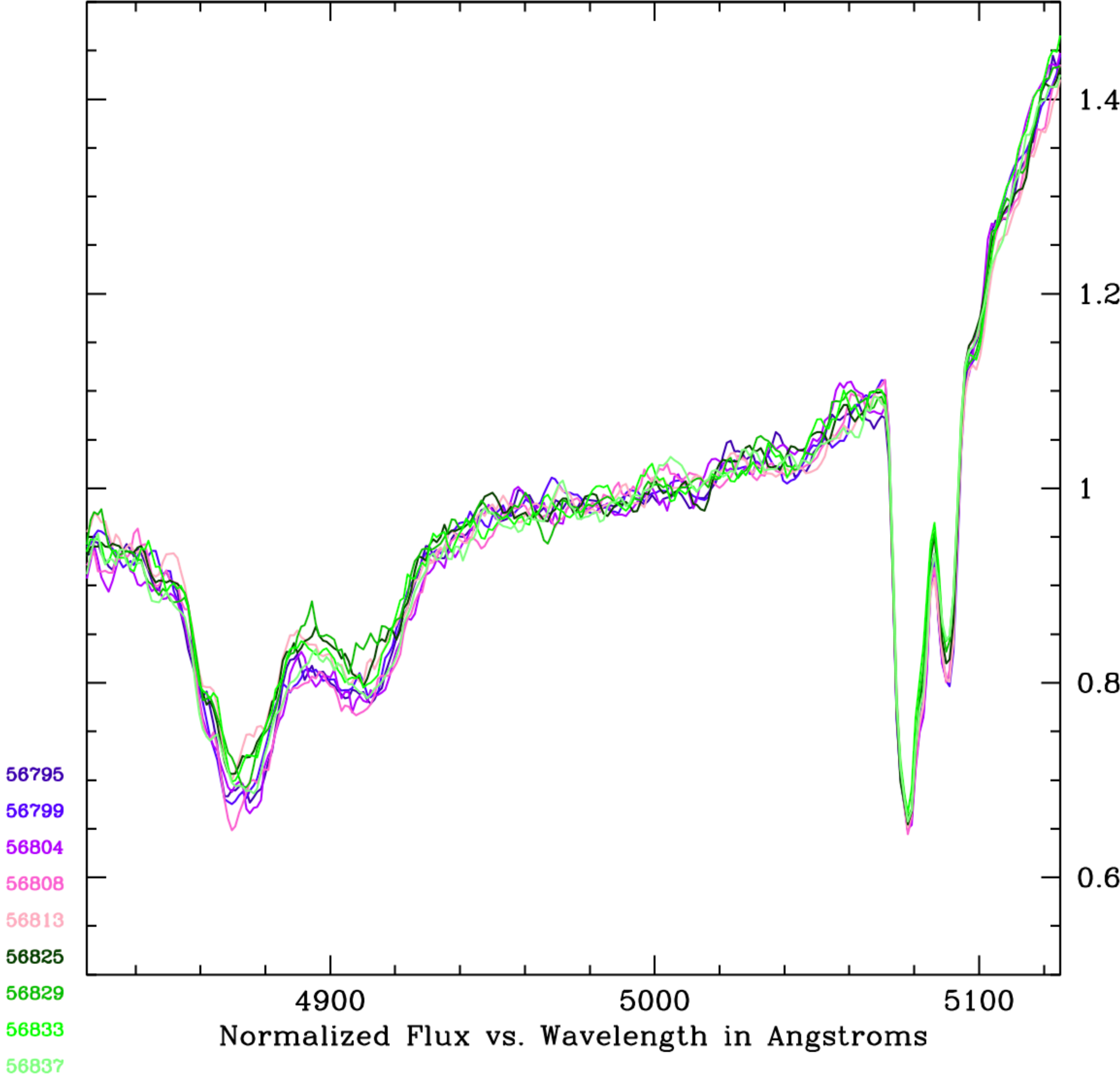
Trough stays at same REW for 8.4 days, then weakens over 1.5 days.



5-pix smoothing

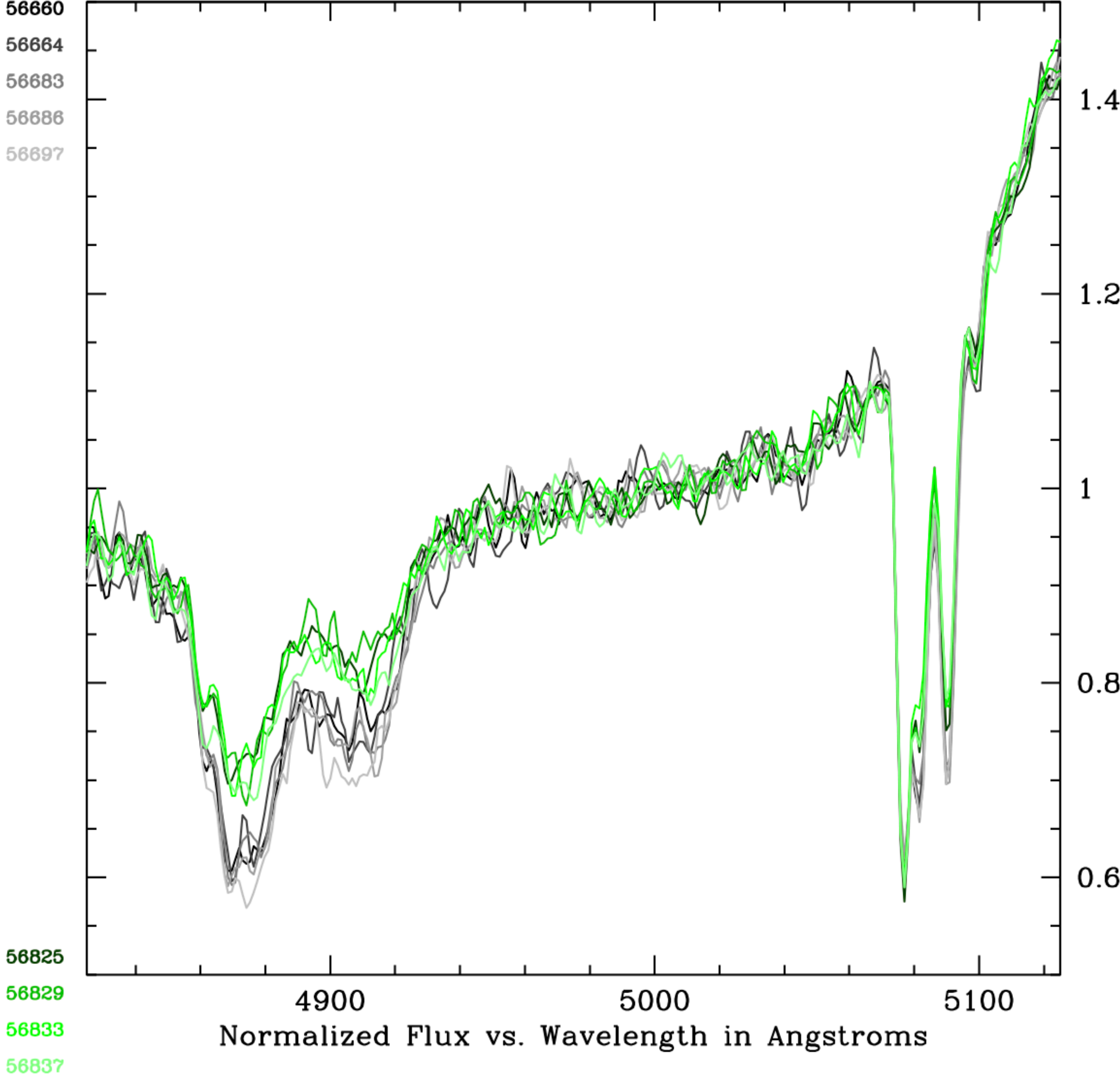
Trough stays at same REW for 8.4 days, then weakens over 1.5 days.

Stays at same level for 7.2 days until end of observations for 2014.



3-pix smoothing

Comparing first five and last four epochs shows that the narrow C IV outflow at 5000 km/s has also weakened!



Fast and Furious

- *BAL varies on timescales down to 1.2 to 3 days (previous record 8 to 10 days; Capellupo+2013; but see also Haggard+2012 ~1 day, unpublished),* with variability ~consistent over entire trough.
- NAL separated by >9000 km/s varies in concert!
- Ionization variability seems likeliest explanation
- "Punctuated equilibrium" (rapid shifts between ~stable states): movement of X-ray absorbers?
- Will be able to compare spectroscopic variations with independent photometric measurements

Explaining rapid column variations

- Consider ionization variability scenario.
- Changes in BAL N_{ion} from changes in quasar's ionizing luminosity or in a shielding gas column.
- Sufficiently large & rapid N_{ion} changes seem to favor the latter, but for completeness I'll mention another possibility:
- If the observed C IV arises from trace amounts of C^{+3} in gas which is mostly C^{+5} or C^{+6}, variations in the C IV column will go as the square or cube of the ionizing flux variations (see next slide).

Column variability of trace ions

- Consider densities of ions with charges i and i+1.
- In photoionization equilibrium $n_i I_i = n_{i+1} R_i$ where I & R are ionization & recombination rates; $R_i = \alpha_i n_e$.
- We can write $n_{i+1}/n_i = Y_i = I_i/R_i$ in equilibrium.

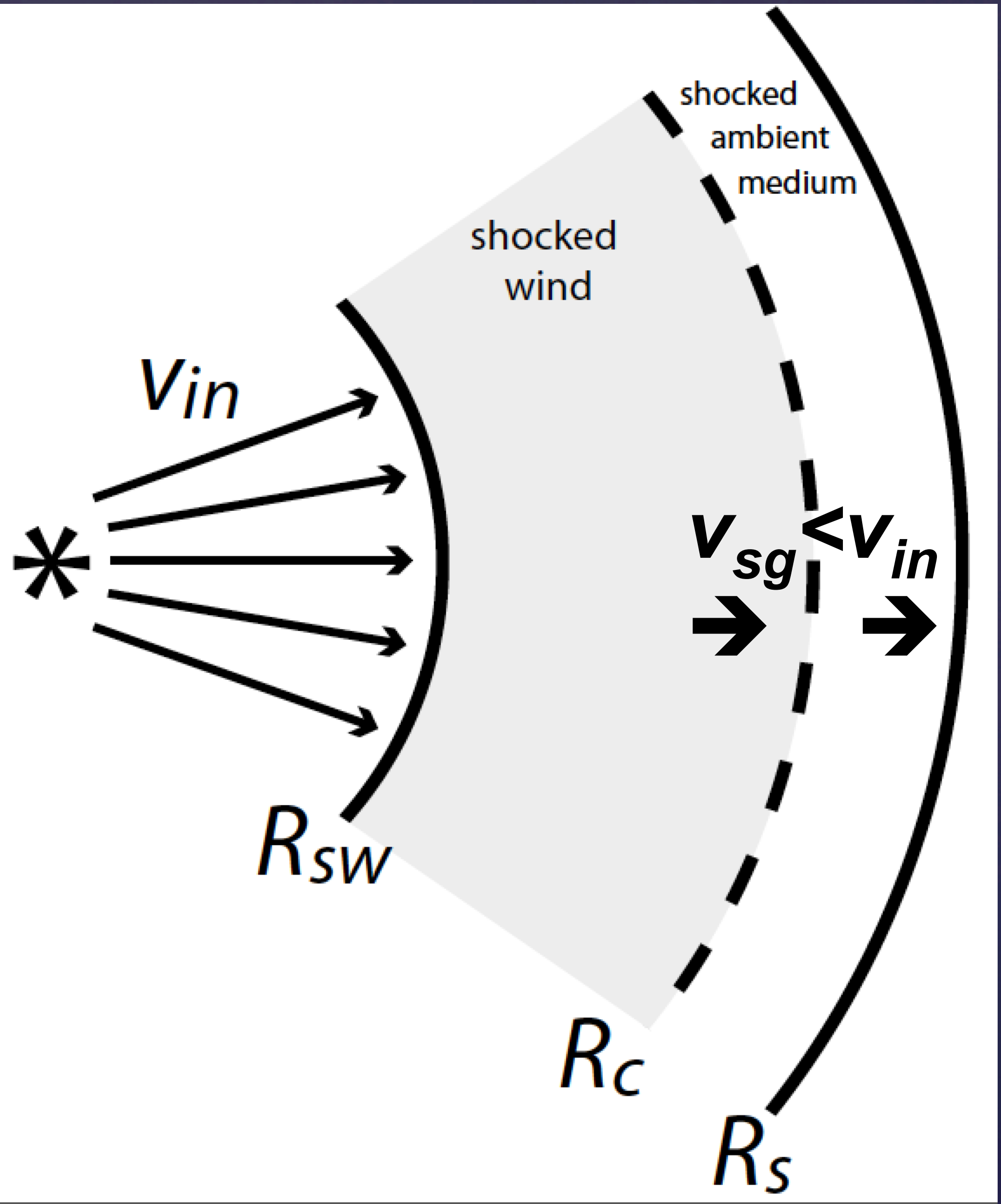
- Consider highly ionized limit, where most carbon is fully ionized: $n_C \approx n_6$, $n_5 = n_6/Y_5$ and $n_3 = n_6/Y_5Y_4Y_3$.
- Similarly, $n_3 = n_5/Y_4Y_3$ if most carbon is C^{+5}.

Column variability of trace ions

- In highly ionized limit, where most carbon is fully ionized: $n_C \approx n_6$, $n_5 = n_6/Y_5$ and $n_3 = n_6/Y_5Y_4Y_3$.
- If ionizing flux incident on BAL goes up by factor (1+f), then $I_{new} = (1+f)I_{old}$ and $Y_{new} = (1+f)Y_{old}$.
- Still have $n_C \approx n_6$, but now $n_{3new} = n_{3old}/(1+f)^3$, so the C IV column changes by 33% for a 10% change in F_{ion} (pure flux variations with no SED change), or by 21% if most C IV is in the C^{+5} stage.
- Of course, reaching n_{3new} takes time.
- Testable via prediction of high U / large N_H.

Where can absorption arise?

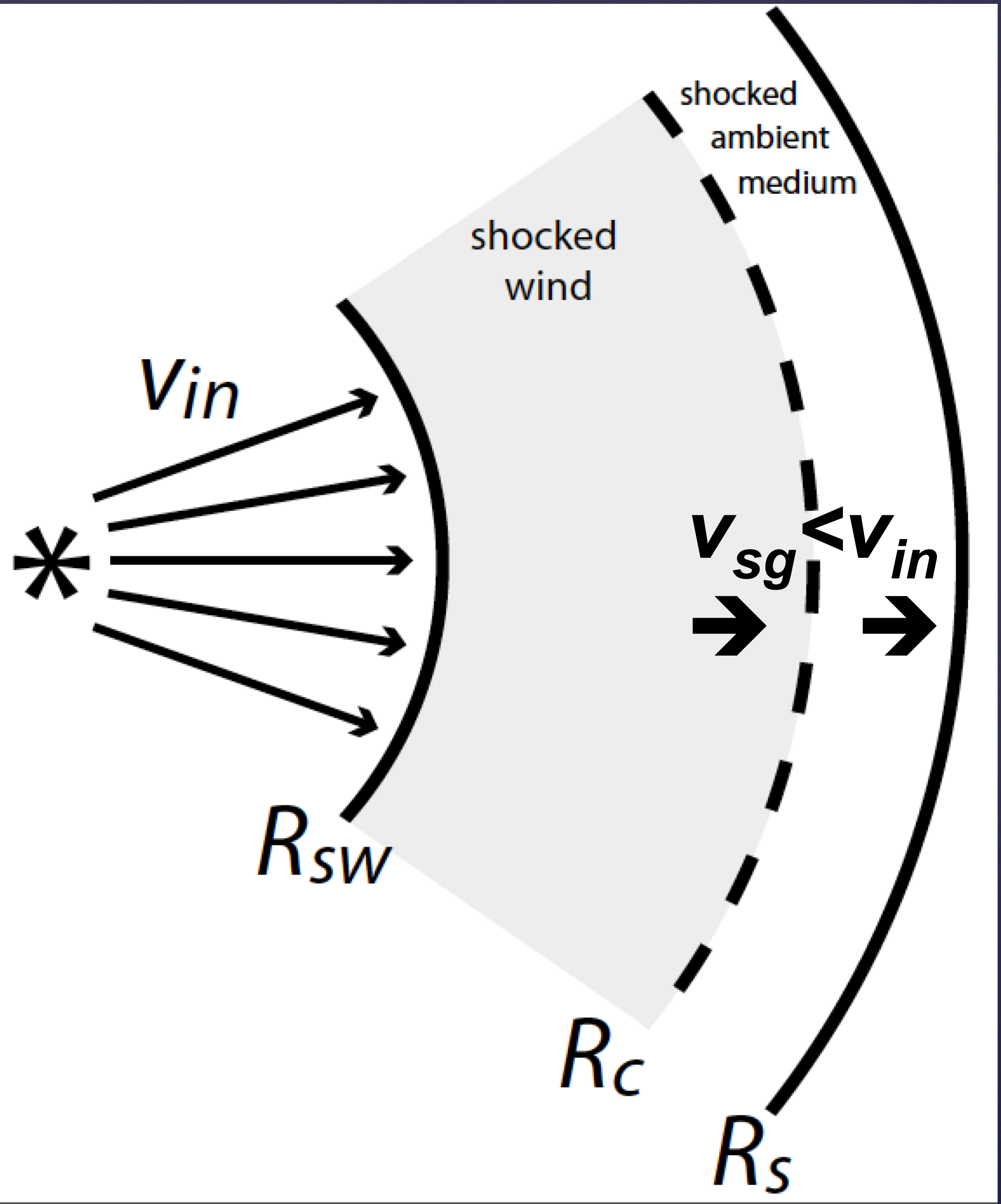
Where can absorption arise?



- Wind acceleration & coasting zone ($v \leq v_{in}$; e.g., Murray+1995).
- Faucher-Giguere & Quataert 2012 energy-conserving model: wind shocks, accelerates ISM to $v_{sg}<v_{in}$, shell expands.
- v_{sg} decreases with time for constant v_{in}.
- v(r) as a f(time)...

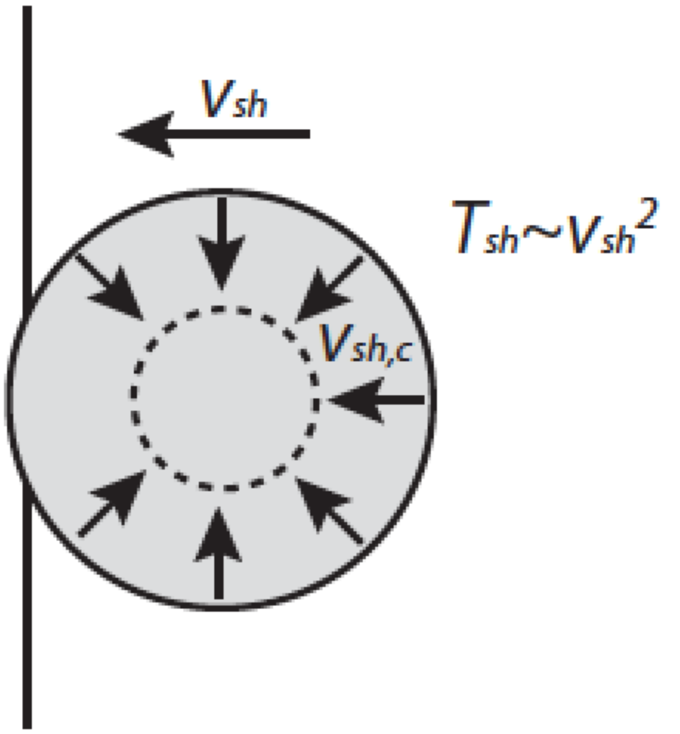
See http://ara.phys.yorku.ca/ for animation

Where can absorption arise?

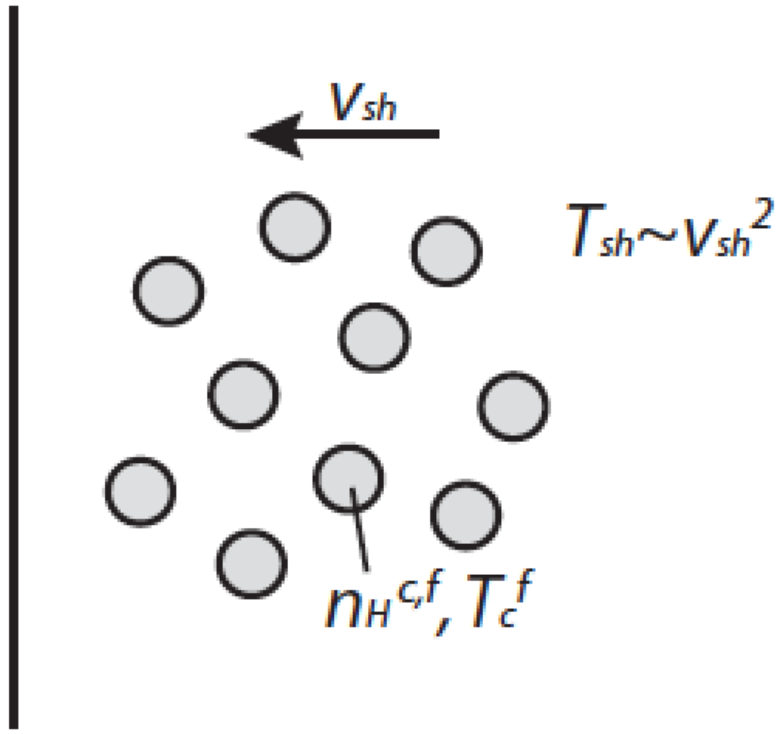


- *Wind acceleration & coasting zone ($v \leq v_{in}$; e.g., Murray+1995).*
- *Faucher-Giguere & Quataert 2012 energy-conserving model: wind shocks, accelerates ISM to $v_{sg}<v_{in}$, shell expands.*
- *v_{sg} decreases with time for constant v_{in}.*
- **Wind seen at $r<R_{sw}$...**

- Faucher-Giguere, Quataert & Murray 2012: preexisting gas clouds **at R_s** can be accelerated to v_{sg} if compression and destruction timescales are longer than acceleration timescale: FeLoBAL absorbers?

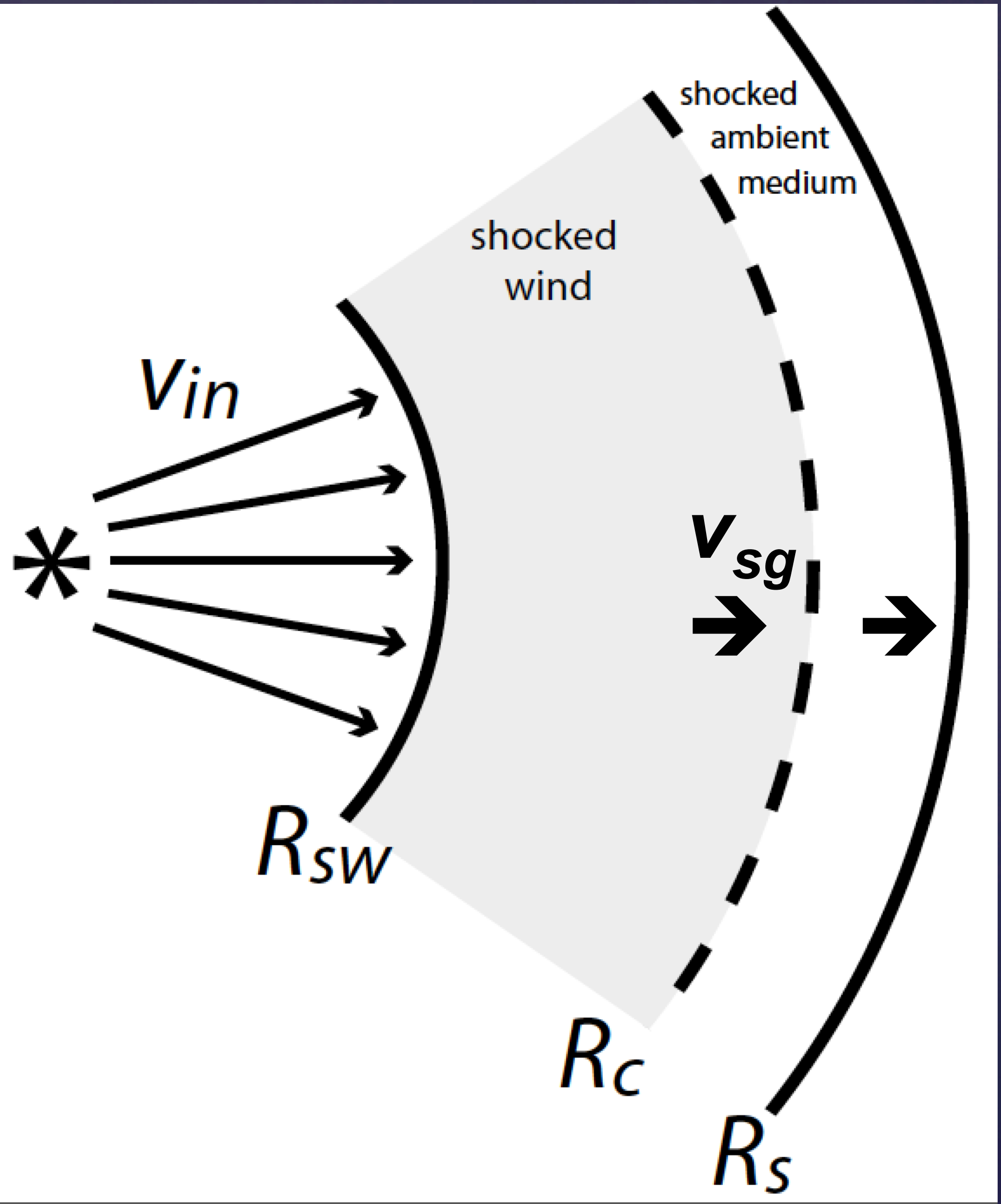


Shock wave propagates in cloud on crushing time t_{cc}, cloud is destroyed by K-H in $t_{KH} \sim 20 t_{cc}$, and is accelerated to $\sim v_{sh}$ in t_{drag}.



At $t > t_{KH}$, t_{drag}, original cloud is shredded into cloudlets traveling at $\sim v_{sh}$ and compressed by hot post-shock gas.

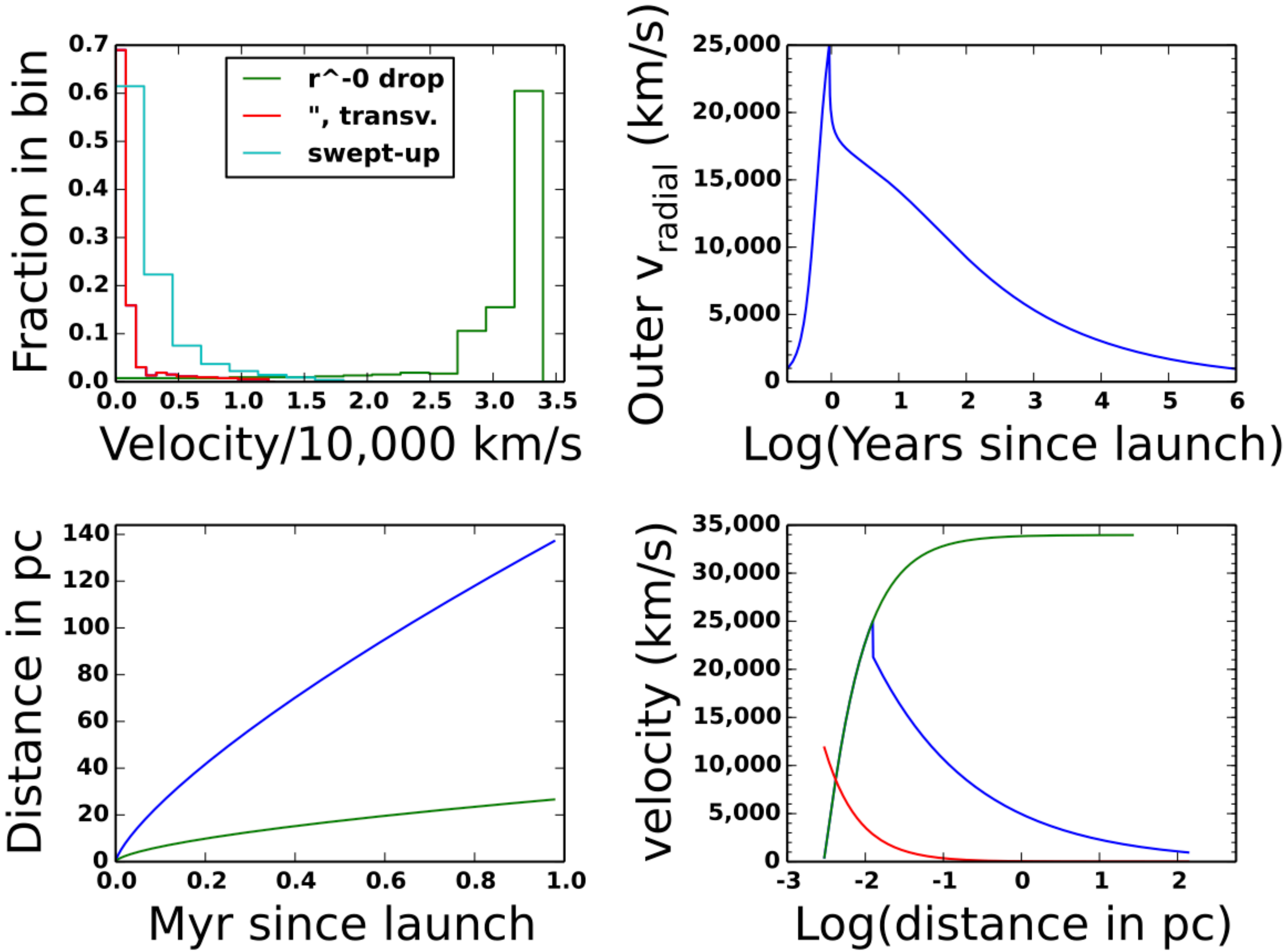
Where can tranverse motion arise?



- If absorption is distributed randomly in radius inside R_{sw}, and also occurs at R_s...
- Then we can calculate the distribution of absorption velocities expected at a given time, or <u>integrated over a given wind lifetime.</u>

In the plots I'm about to show:

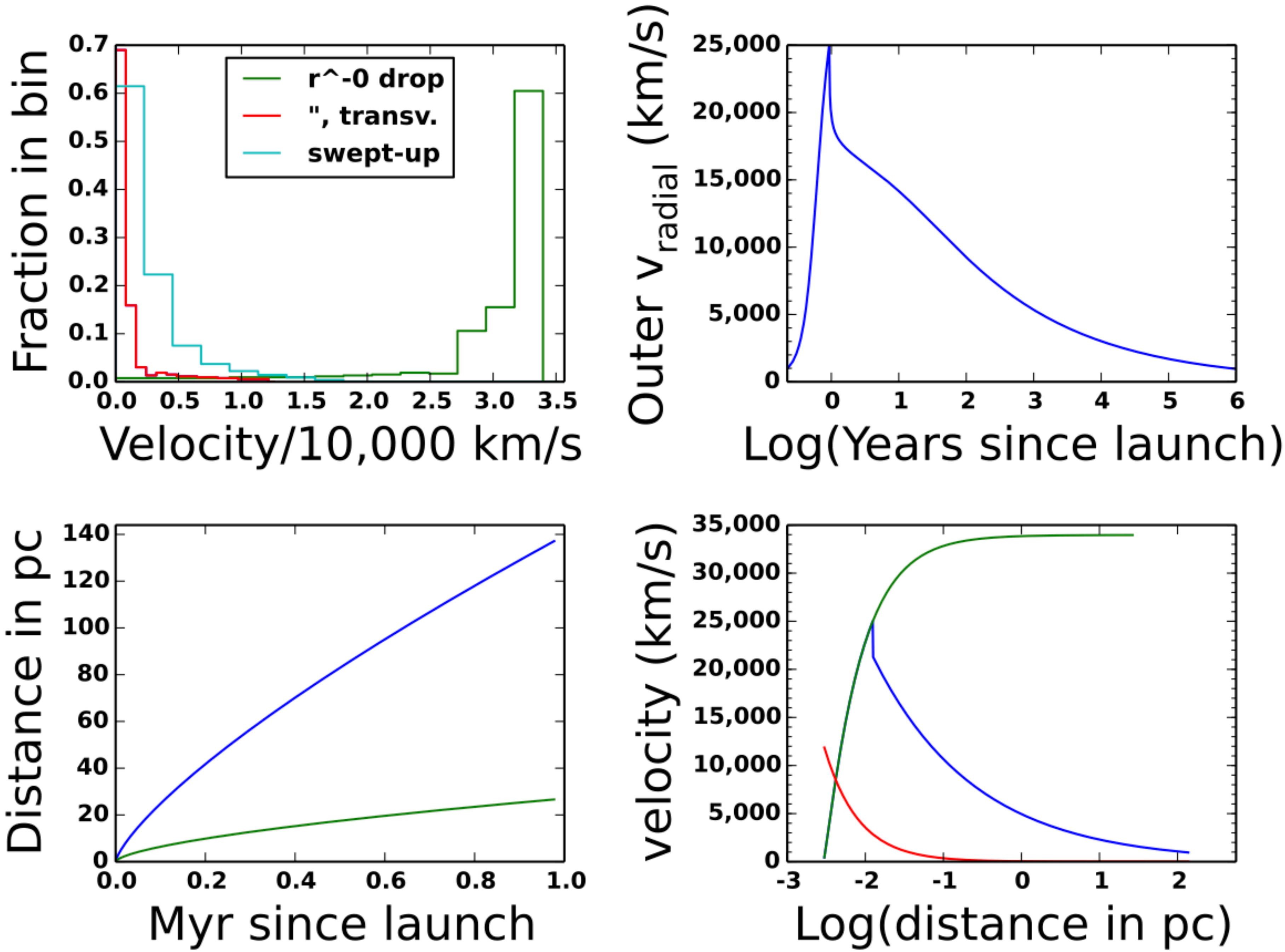
- Upper right: outer radial velocity vs. log(time)
- Lower left: distance to outer edges of shocked shell (blue) and of wind zone (green) vs. time
- Lower right: radial v at shell edge (blue) and in wind zone (green) vs. log(distance), along with transverse velocity in wind zone (red). The full radial v profile at time t is the green curve at small radii, abruptly switching to the blue curve in the shell between inner & outer shocks (animation).
- Upper left: histogram of absorber radial and transverse velocities over the quasar lifetime



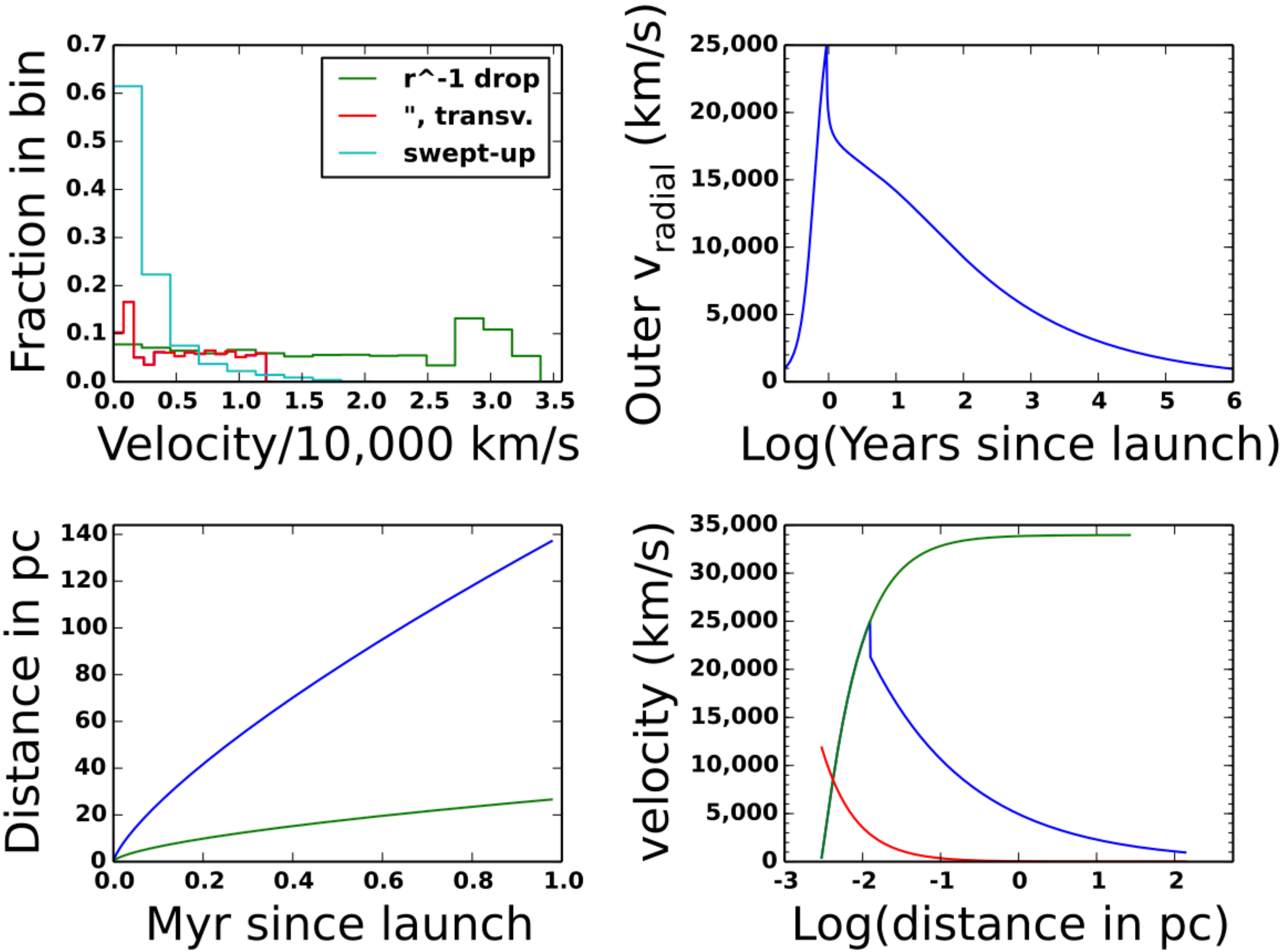
Fraction in bin
Velocity/10,000 km/s
r^-0 drop
", transv.
swept-up
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Outer v_{radial} (km/s)
Log(Years since launch)
0
5,000
10,000
15,000
20,000
25,000
0
1
2
3
4
5
6
Distance in pc
Myr since launch
0
20
40
60
80
100
120
140
0.0
0.2
0.4
0.6
0.8
1.0
velocity (km/s)
Log(distance in pc)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
-3
-2
-1
0
1
2

Where can tranverse motion arise?

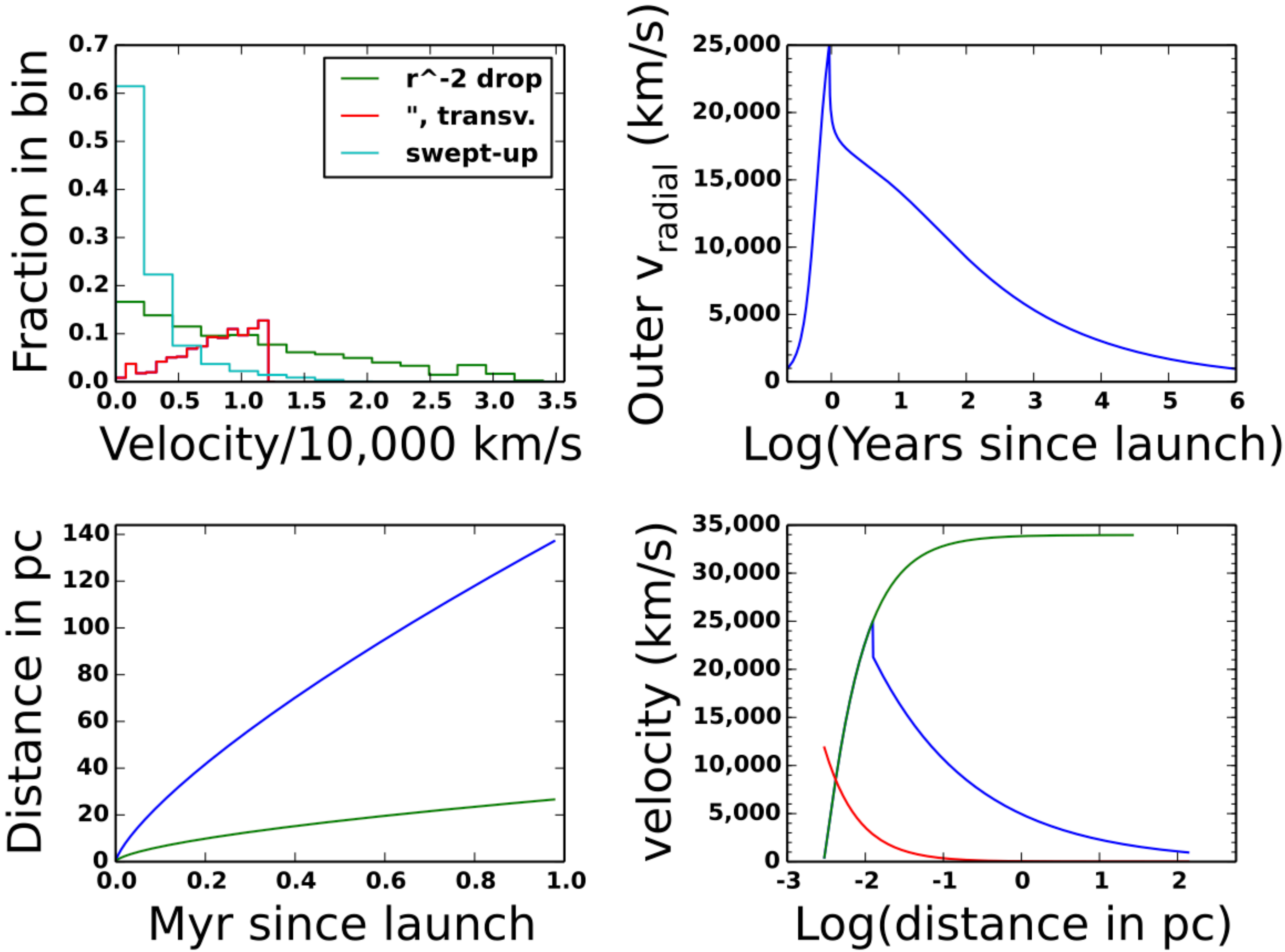
- Assuming absorbers randomly populate the outflow yields radial velocity histograms unlikely to match observations when ensemble of outflows considered
- Too many high-velocity absorbers, so try a rate of absorber occurrence that drops off with r.



Fraction in bin
Velocity/10,000 km/s
r^-0 drop
", transv.
swept-up
Outer v_radial (km/s)
Log(Years since launch)
Distance in pc
Myr since launch
velocity (km/s)
Log(distance in pc)



Fraction in bin
r^-1 drop
", transv.
swept-up
Velocity/10,000 km/s
Outer v_{radial} (km/s)
Log(Years since launch)
Distance in pc
Myr since launch
velocity (km/s)
Log(distance in pc)



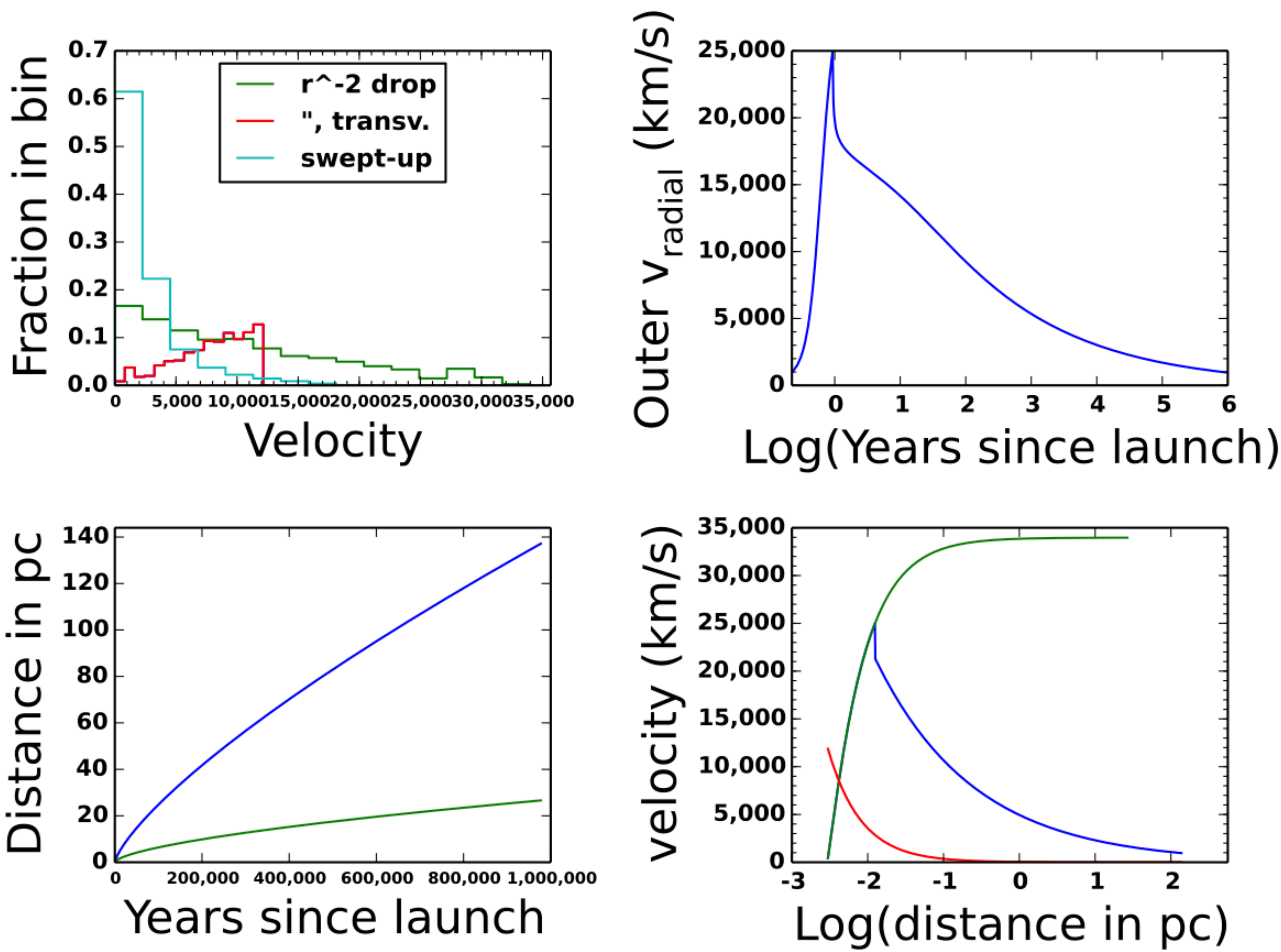
Fraction in bin
Velocity/10,000 km/s
r^-2 drop
", transv.
swept-up
Outer v_{radial} (km/s)
Log(Years since launch)
Distance in pc
Myr since launch
velocity (km/s)
Log(distance in pc)

Absorbers and tranverse motion

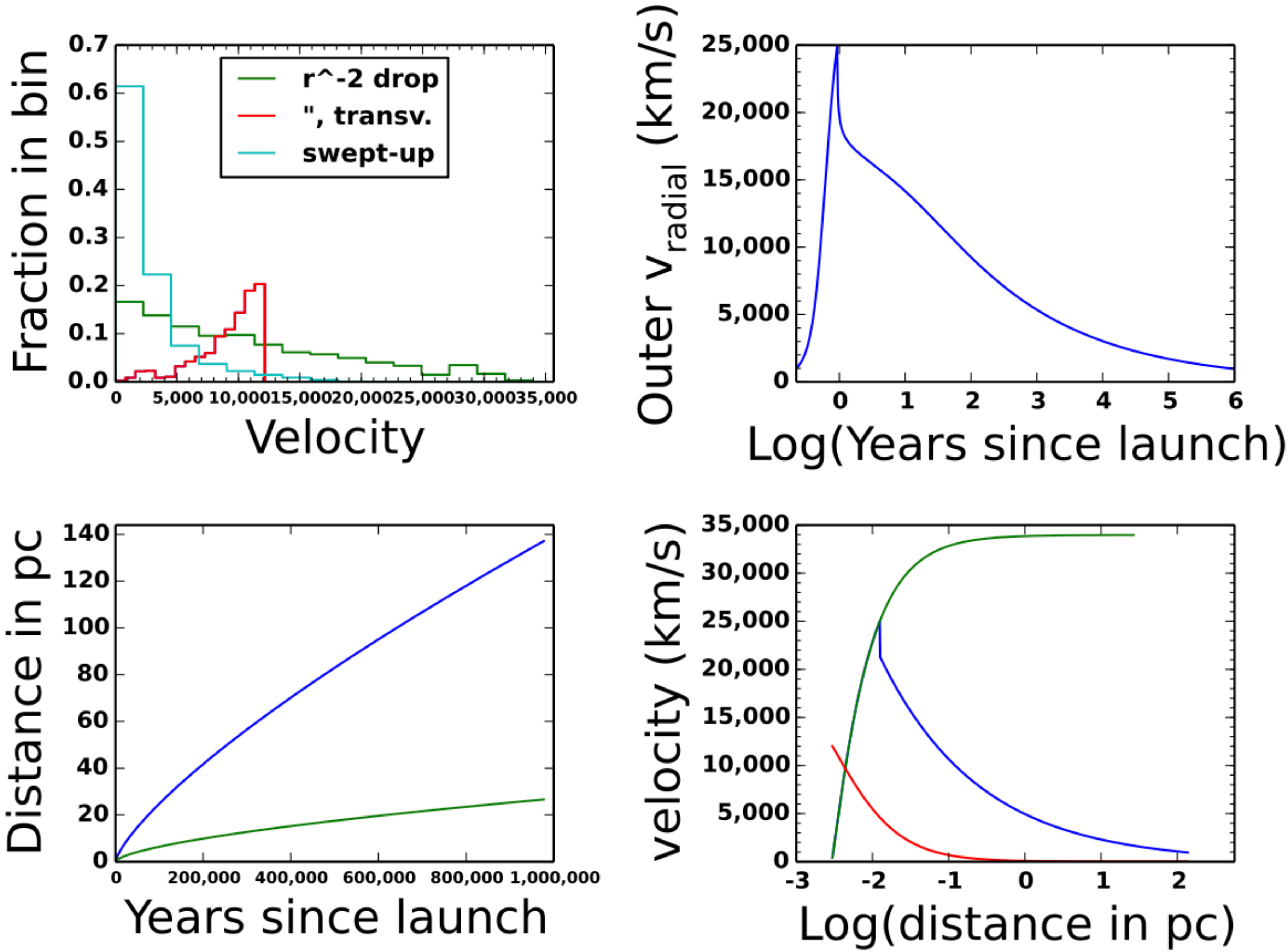
- *Assuming absorbers randomly populate the outflow yields radial velocity histograms unlikely to match observations when ensemble of outflows considered*
- Rate of absorber occurrence must drop off as $\mathbf{r}^{-2}$ for trough velocity distribution (green histogram, upper left) to qualitatively match observations.
- For such a dropoff, many troughs will have large transverse velocities (red histogram, upper left), anticorrelated with their radial velocities.
- Population of low-v absorbers (cyan histogram): swept-up gas, not structures in free-flowing wind.

Caveat Emptor – Caveats Galore!

- All plots shown are for one fiducial ISM density, density profile, launch radius, 6° launch angle… 60° launch angle only alters transverse velocities.

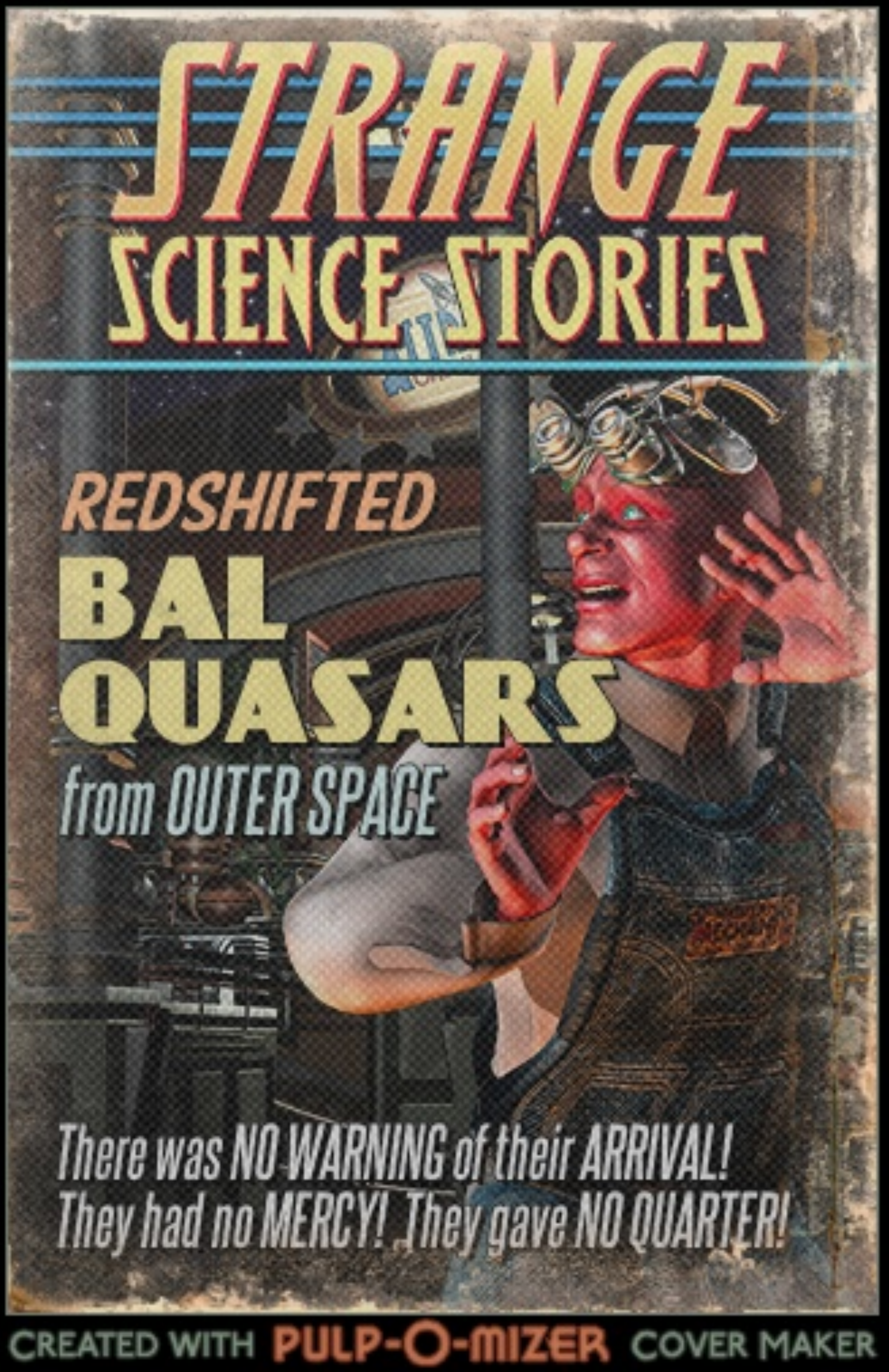


Fraction in bin
r^-2 drop
", transv.
swept-up
Velocity
Outer v_{radial} (km/s)
Log(Years since launch)
Distance in pc
Years since launch
velocity (km/s)
Log(distance in pc)


r^-2 drop
", transv.
swept-up
Fraction in bin
Velocity
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
Outer v_{radial} (km/s)
Log(Years since launch)
0
5,000
10,000
15,000
20,000
25,000
0
1
2
3
4
5
6
Distance in pc
Years since launch
0
20
40
60
80
100
120
140
0
200,000
400,000
600,000
800,000
1,000,000
velocity (km/s)
Log(distance in pc)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
-3
-2
-1
0
1
2

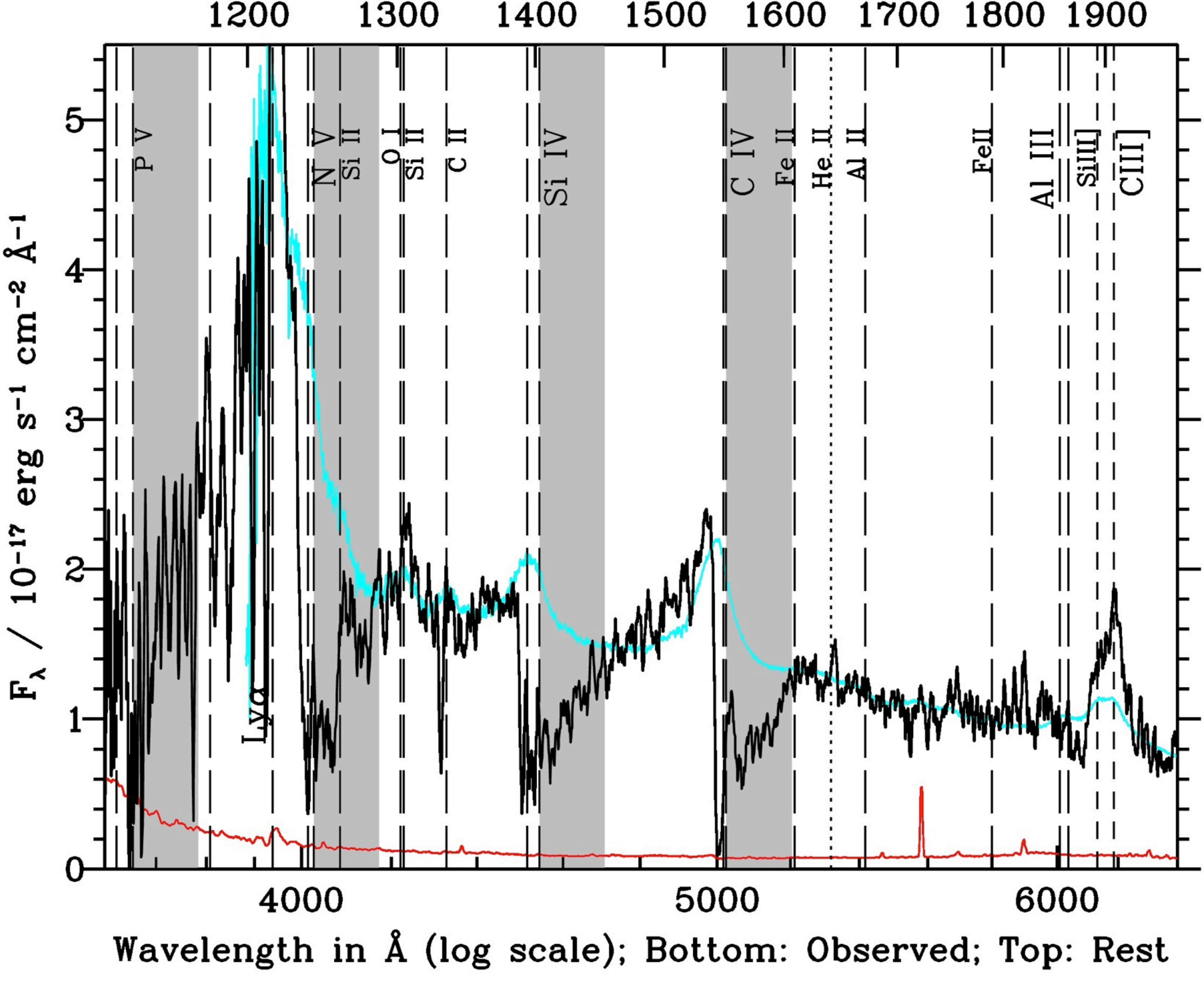
Caveat Emptor – Caveats Galore!

- All plots shown are for one fiducial ISM density, density profile, launch radius, 6° launch angle… 60° launch angle only alters transverse velocities.
- FGQ12 assumes (eventual) spherical symmetry; plots assume you're looking down the outflow.
- Murray+1995: OK to use for clumpy outflow?
- Your objection here!
- Number of absorbers vs velocity could be used to test if population of hi-v clouds condensing out of hot shocked gas is needed (Voit+1409.1598 & r.t.)



Redshifted BAL quasars

- Hall et al. (2013)
- 17 examples (1 in 1000)
- Troughs unexceptional, except for redshifting & LoBALs overrepresented
- Redshifted velocities reach 12,000 km/s
- Sometimes see both red- & blue-shifted absorption



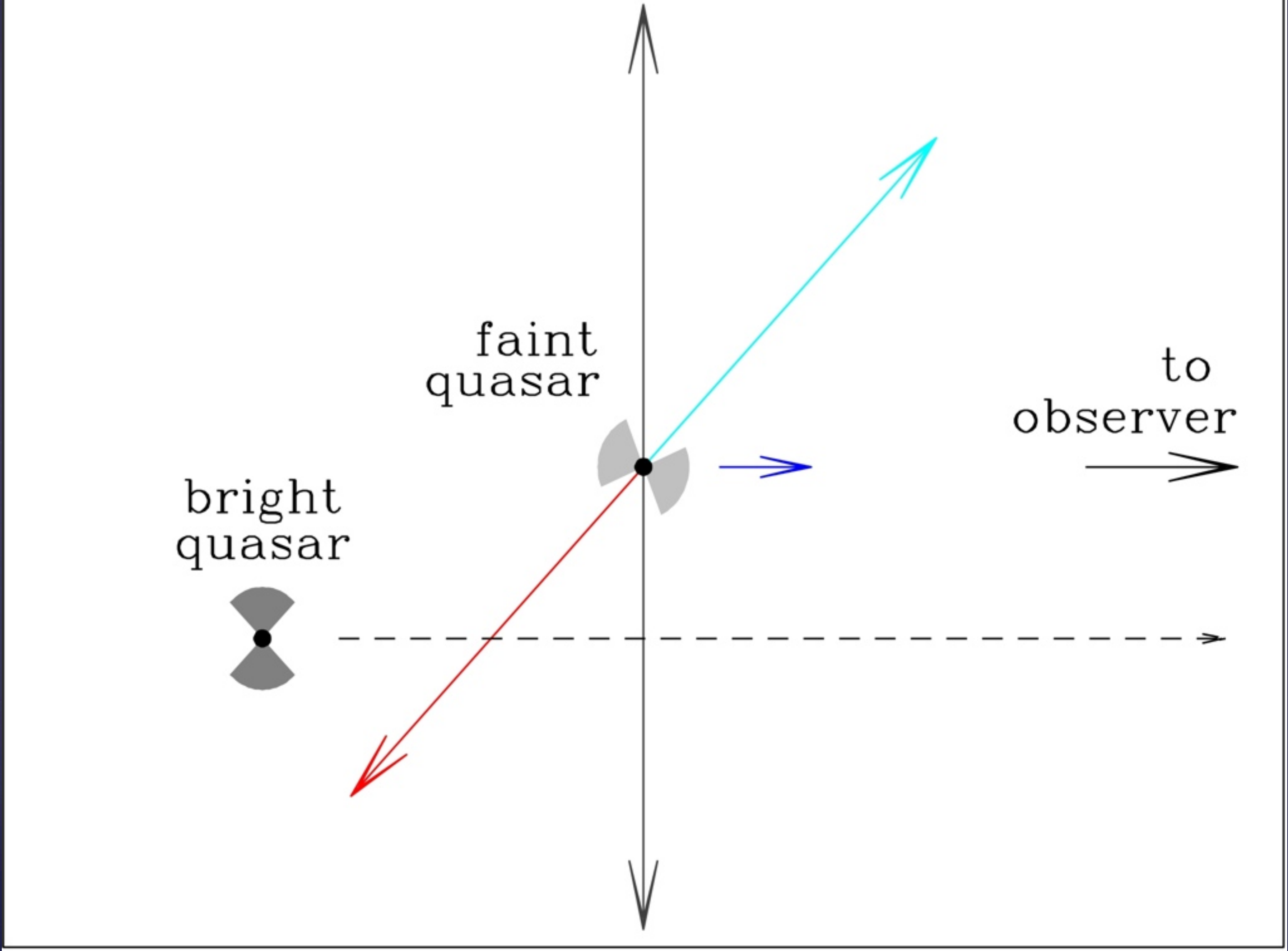
1200
1300
1400
1500
1600
1700
1800
1900
P V
N V
Si II
O I
Si II
C II
Si IV
C IV
Fe II
He II
Al II
FeII
Al III
SiIII]
CIII]
Lyα
F_λ / 10^{-17} erg s^{-1} cm^{-2} Å^{-1}
0
1
2
3
4
5
4000
5000
6000
Wavelength in Å (log scale); Bottom: Observed; Top: Rest

Least Unlikely Explanation

- Infall of relatively dense clouds down to 400 R_{Sch} can in principle explain observations, but how to explain the survival of gas down to such radii?
- Remember, these clouds infall to high velocity against the outward push of radiation pressure.
- Relative numbers of red- and red+blue-shifted troughs suggest fallback more likely than infall.
- Infalling clouds must radially elongate by ~10× for every ~10× decrease in radius to match covering factor decrease with increasing redshifted velocity.

Other Possible Explanations

- Rotation-dominated base of wind? [driven to extreme parameter choices to make it work, but objects are rare, so…]
- Binary quasars with silhouetted BAL outflows? Predicted numbers of such objects seem lower than observed, but there are many uncertainties.
- Near-IR spectroscopy in hand, confirming z's.
- Exploratory X-ray observations pending; will obtain new optical spectra to check for variability.

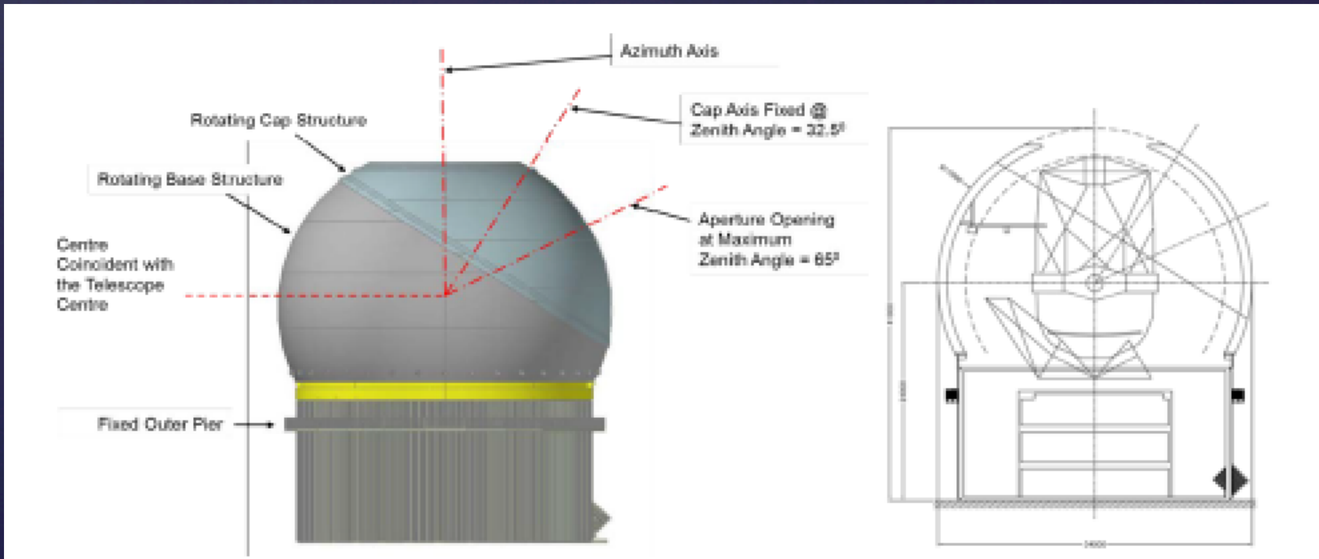


Binary Quasar Scenario for Redshifted Absorption Troughs

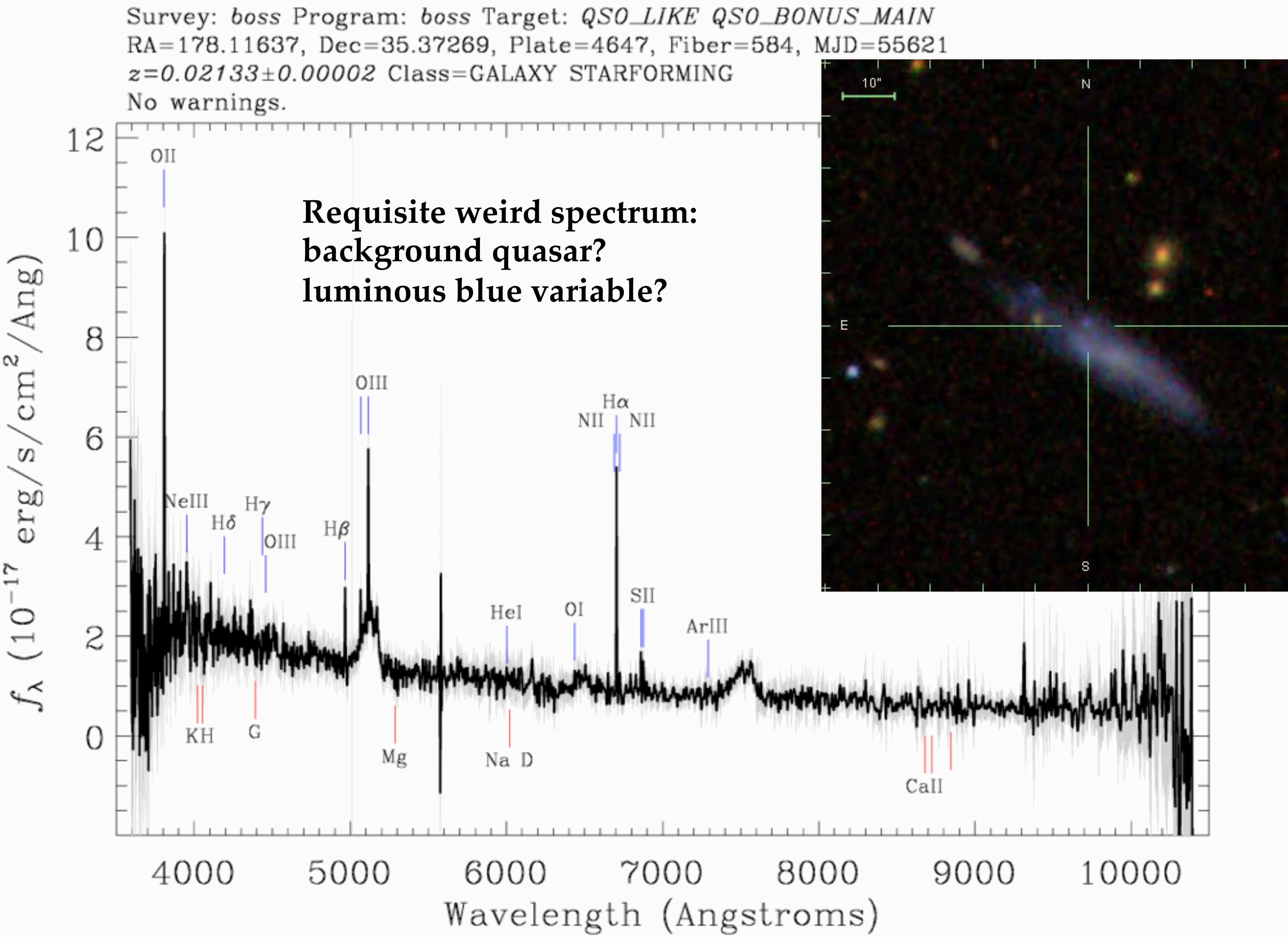
BAL Quasars: Conclusions

- Very few firm ones! Still many questions.
- Variability from both ionization and bulk motion; can be rapid! Punctuated equilibrium?
- Absorption likely spans close in to far out.
- Future data: Maunakea Spectroscopic Explorer?

(replace CFHT with a 10-m spectroscopic telescope)



Requisite weird spectrum:
background quasar?
luminous blue variable?



Extra Slide: Multiple Ions

- Cases where new BAL quasars observed between SDSS and BOSS in C IV, Si IV, N V and O VI simultaneously. Bulk motion into sightline?