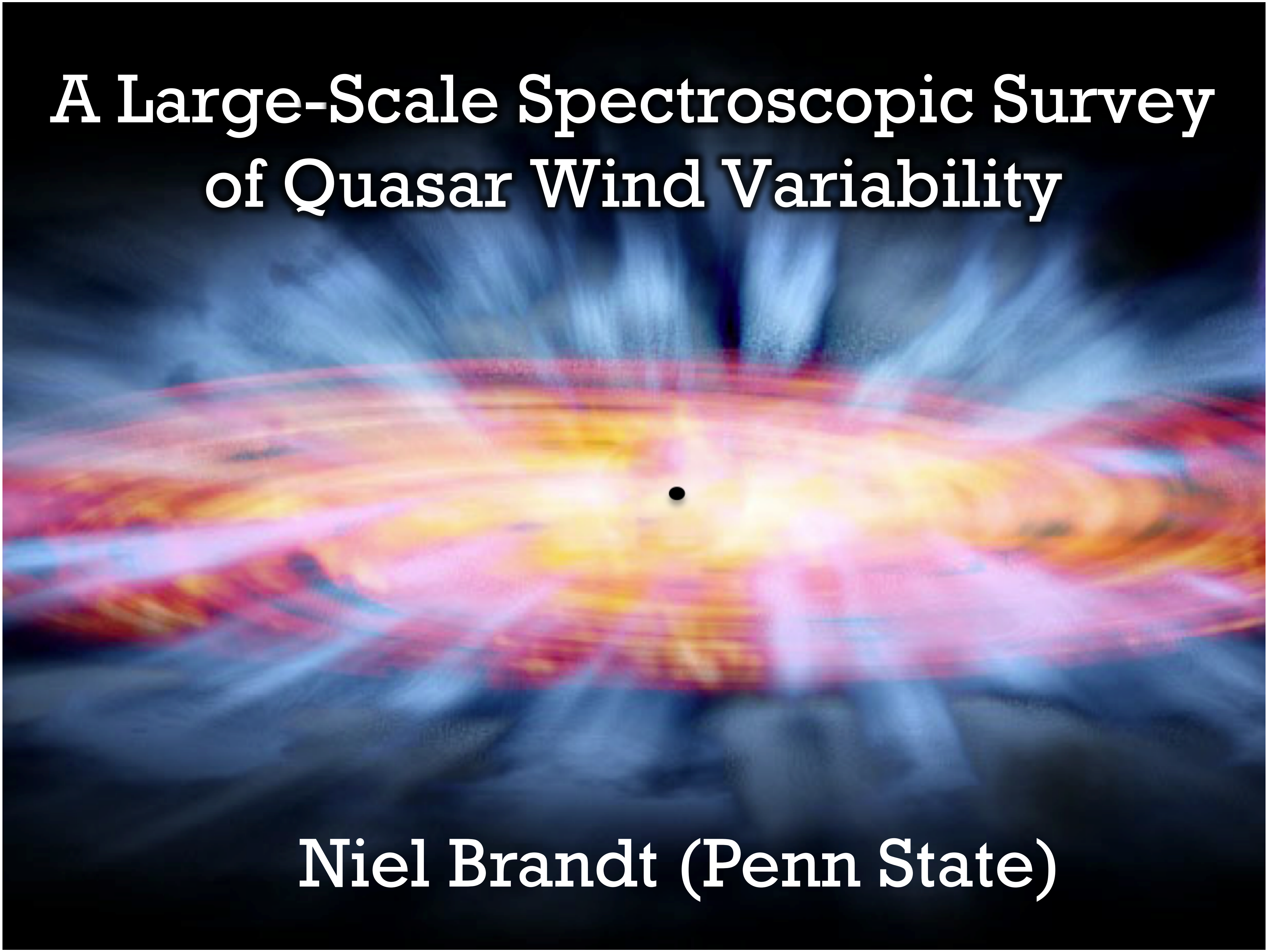
A Large-Scale Spectroscopic Survey of Quasar Wind Variability



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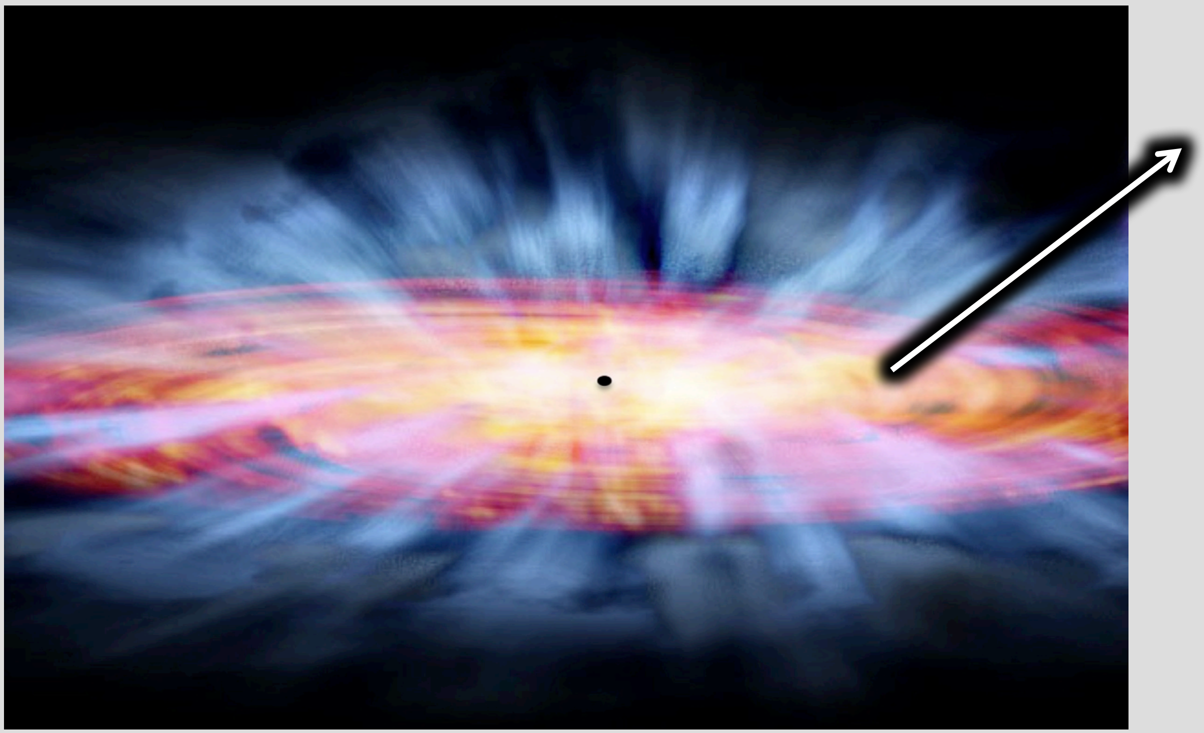
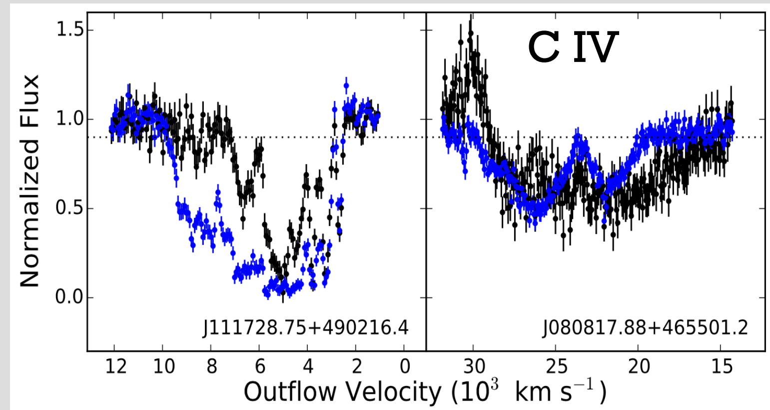
SDSS-III BOSS
Quasars Team
and
SDSS-IV TDSS Team

Absorption-Trough Variability

Radiatively Driven Accretion-Disk Wind
with Wind Velocities of ~ 1000-60000 km s^{-1}





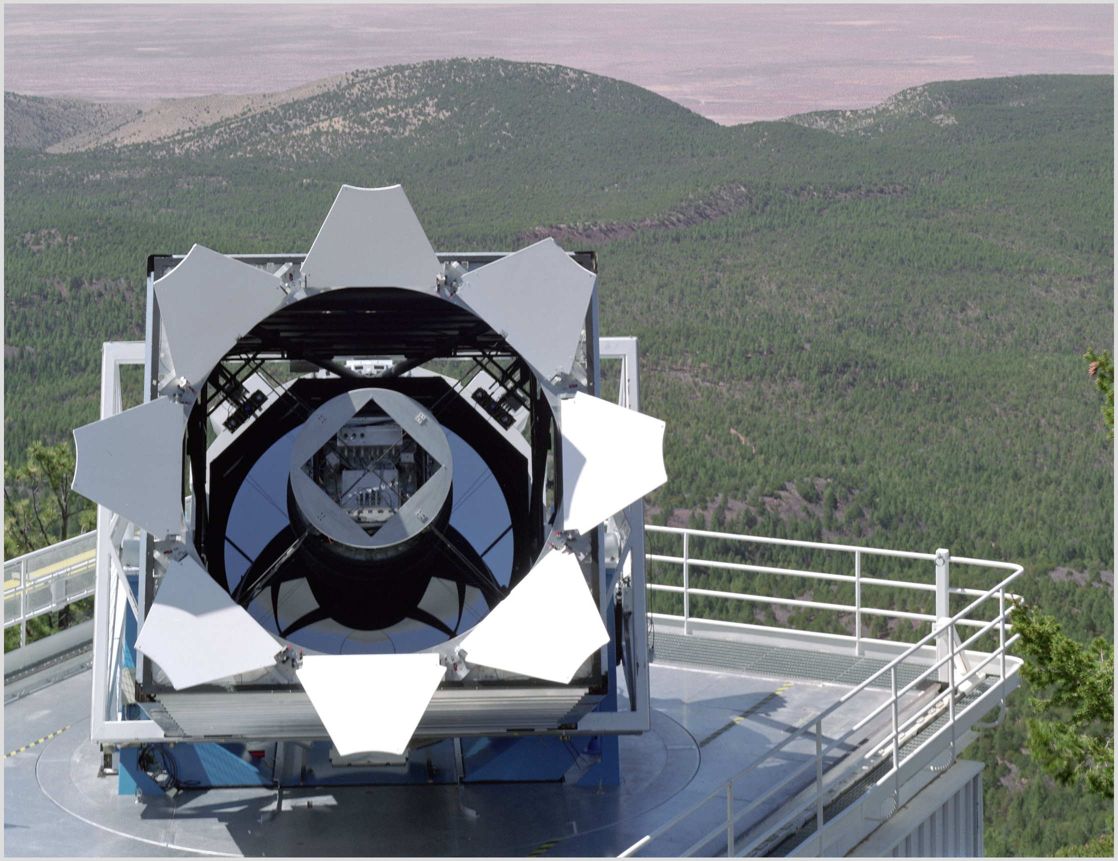
Grier et al. (2016)

Having ~ 1 line-of-sight is both
an advantage and a disadvantage.

Possible causes of absorption trough variations:

- Motion of material in / out of line-of-sight (e.g., disk rotation)
- Ionization changes
- Background source geometry changes

SDSS-III BOSS and SDSS-IV TDSS



SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS)

5-year program (2009-2014)

Covered 10,000 deg^2

Ancillary BOSS project on BAL variability

SDSS-IV Time-Domain Spectroscopic Survey (TDSS)

6-year program (2014-2020)

Covering 7,500 deg^2

Main Goal - Obtain spectra for classification of variables

About 10% of fibers allocated for repeat obs. - e.g., BAL quasars

Spectra from 3600-9800 Å with resolution ~ 2000.

Main Goal of SDSS BAL Variability Project

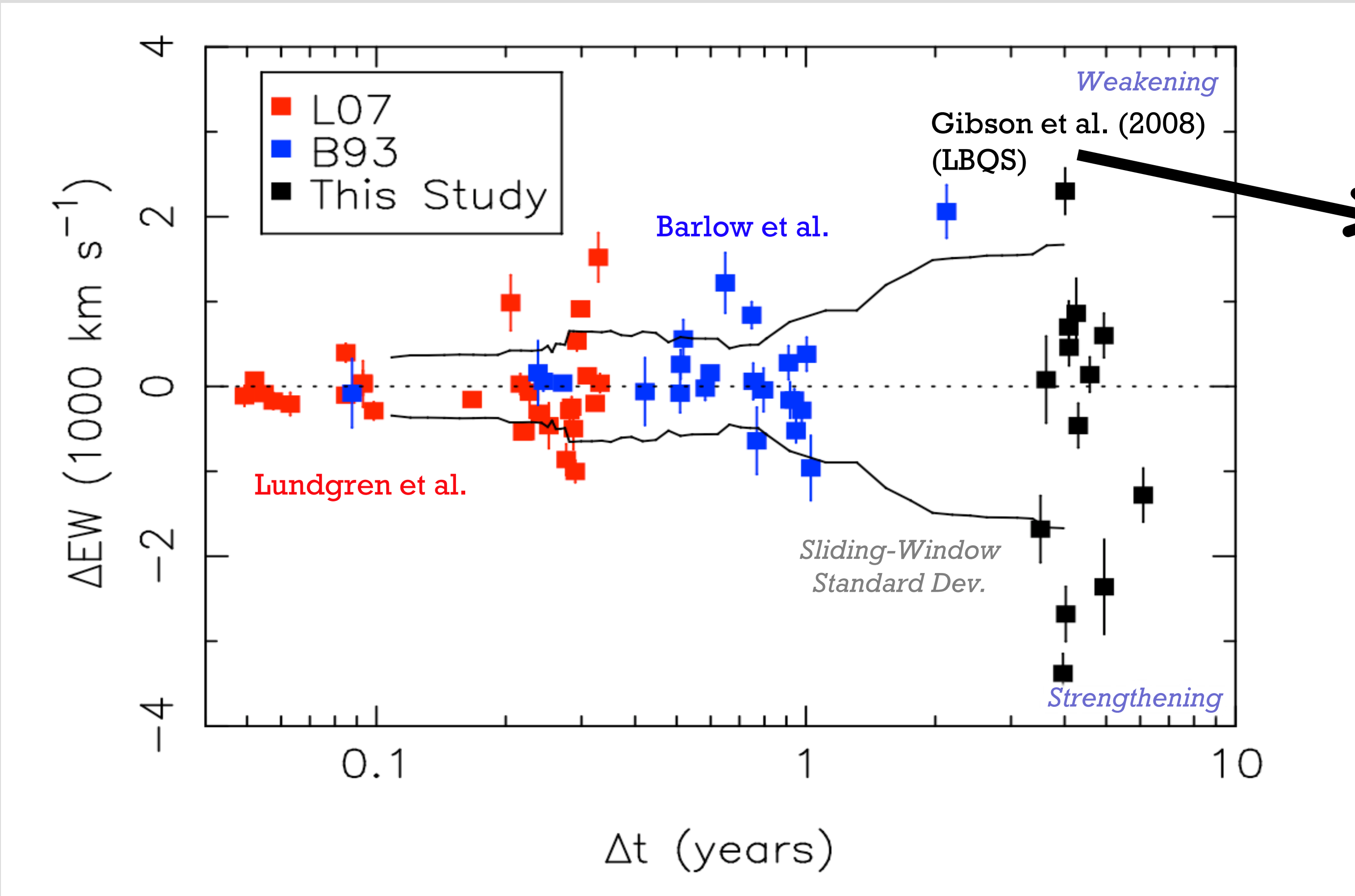
Move from small-sample and single-object studies of multi-year BAL variability

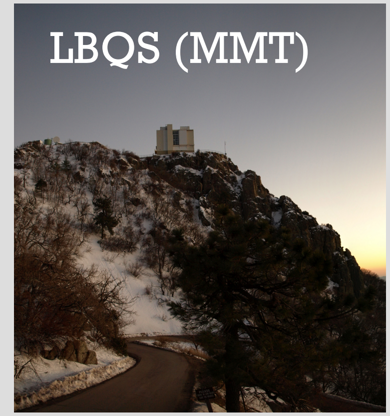
to

statistically powerful, large-sample constraints on quasar winds.

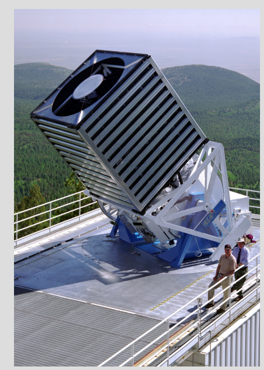
Need for Multi-Year Timescales

C IV BAL EW Changes vs. Rest-Frame Timescale





vs.



In small and heterogeneous samples, C IV BALs appear to vary substantially more strongly on multi-year timescales.

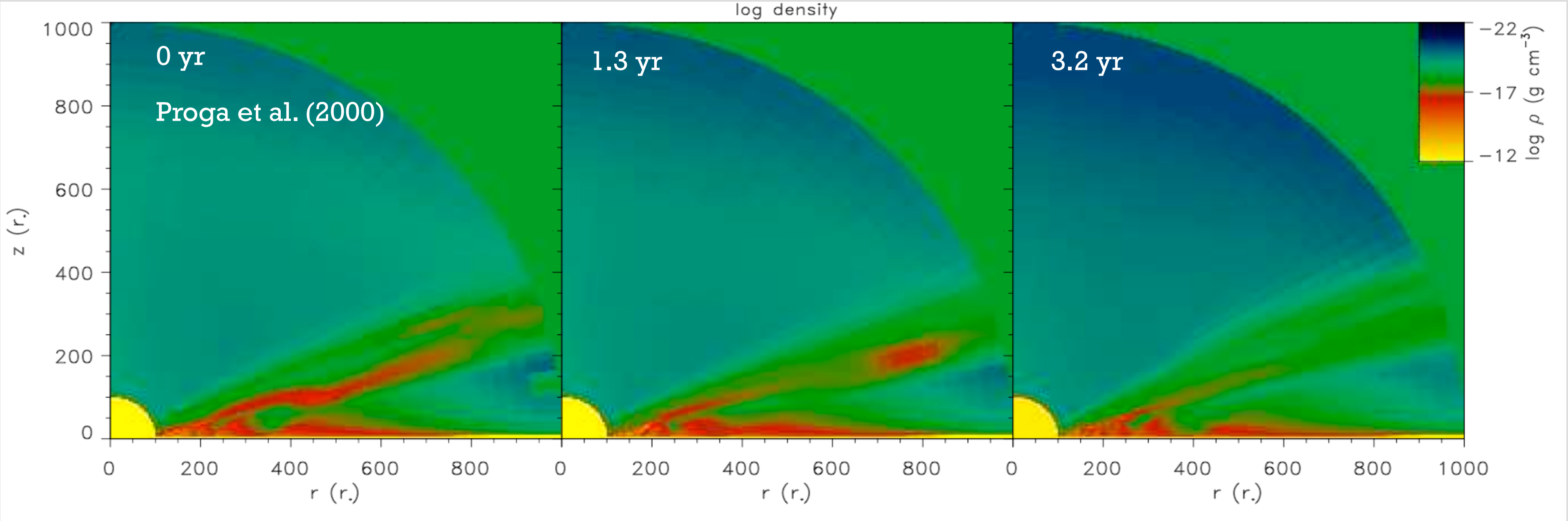
Need for Multi-Year Timescales

Launching radius is typically thought to be ~ 10 light days.

Years is characteristic timescale for BAL-material crossing and disk rotation.

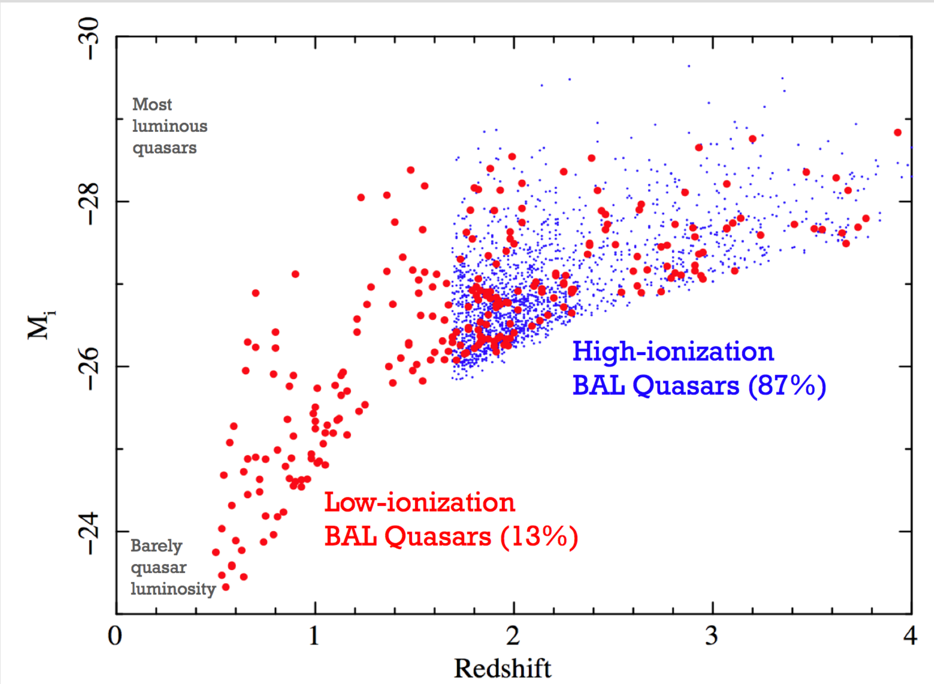
This can turn into observed 10+ years due to (1 + z) time dilation > t_{PhD}.

Density Maps from BAL Quasar Wind Simulation



BAL Variability Project - Experimental Design

Luminosity vs. Redshift for Main Sample



Some BAL Variability Samples

Sample-based Studies of BAL Quasar Variability

Reference	No. of Quasars	Δt Range (yr)	No. of Epochs
Barlow (1993)	23	0.2–1.2	2–6
Lundgren et al. (2007)	29	0.05–0.3	2
Gibson et al. (2008)	13	3.0–6.1	2
Gibson et al. (2010)	14	0.04–6.8	2–4
Capellupo et al. (2011, 2012, 2013)	24	0.02–8.7	2–13
Vivek et al. (2012)[a]	5	0.01–5	4–14
Haggard et al. (2012)	17	0.001–0.9	6
Filiz Ak et al. (2012)[b]	19	1.1–3.9	2–4
Welling et al. (2013)[c]	46	0.2–16.4	2–6
This study	291	0.0006–3.7	2–12
Full BOSS Ancillary	2105	0.0006–6	2–12

Notes.
[a] Fe low-ionization BAL quasars.
[b] Quasars with disappearing BAL troughs.
[c] Radio-loud BAL quasars.

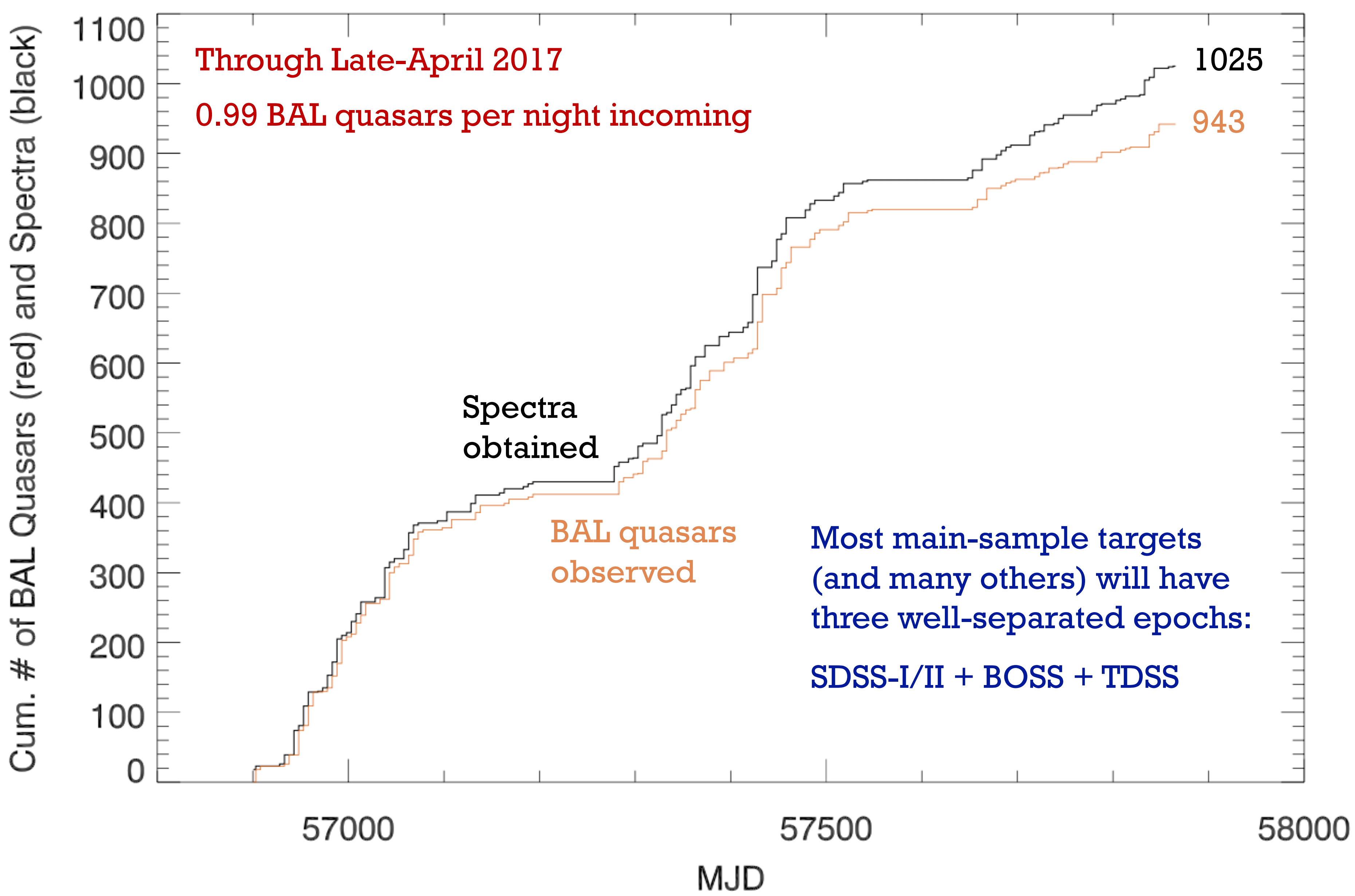
Focus is on the C IV, Si IV, Mg II, and Al III transitions.

Main sample is 2005 representative BAL quasars from Gibson et al. (2009) catalog that are bright (i = 16.5-19.2) and have good BAL coverage - observed by SDSS-I/II from 2000-2008.

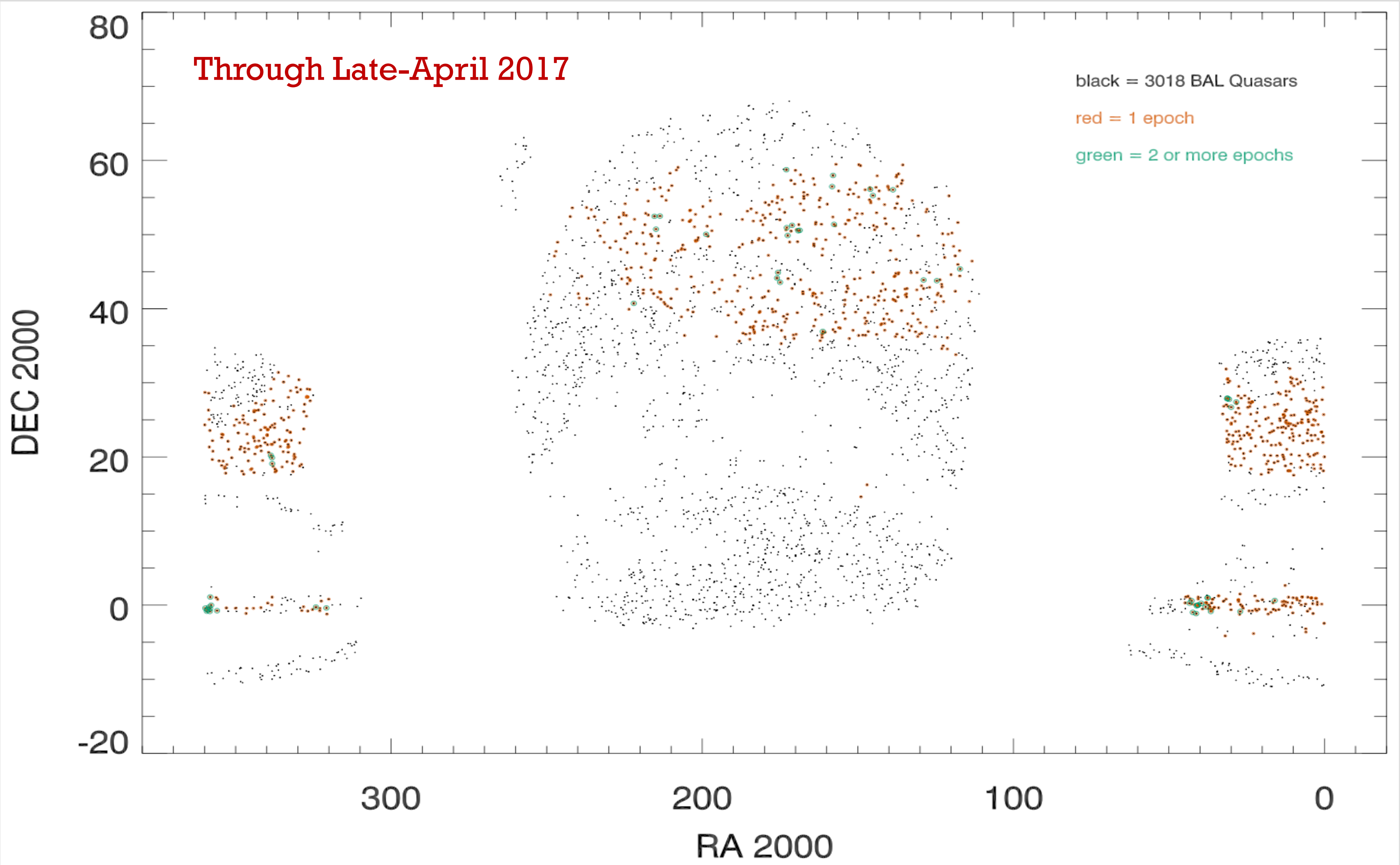
Additional samples - Exceptional BALs, LBQS/FBQS, 2-epoch regions. 3018 targets in total.

Sample is <u>100 times larger</u> than other samples and will reach <u>15-20 observed-frame years.</u>

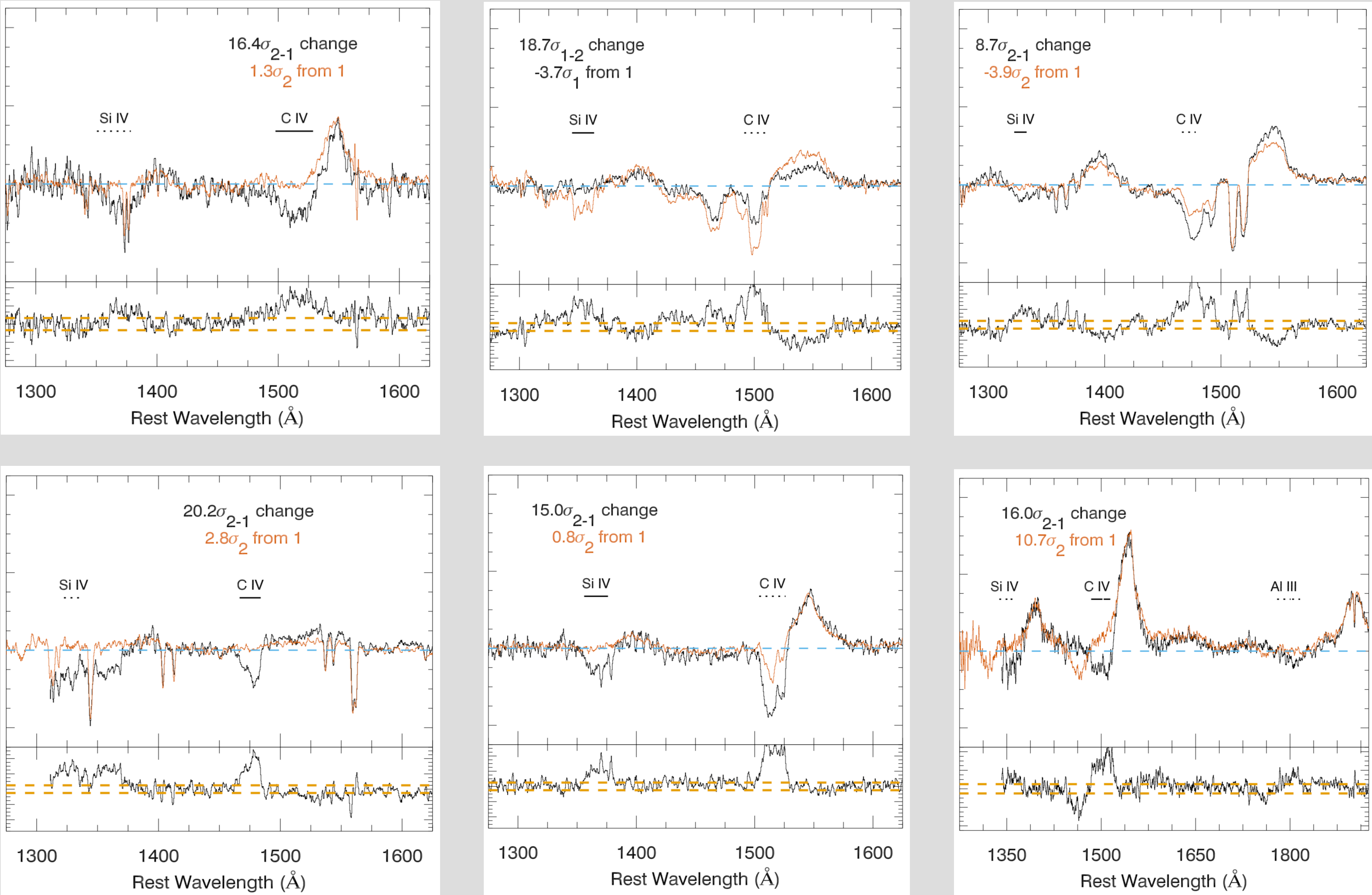
TDSS Observations vs. MJD



TDSS Targets on the Sky

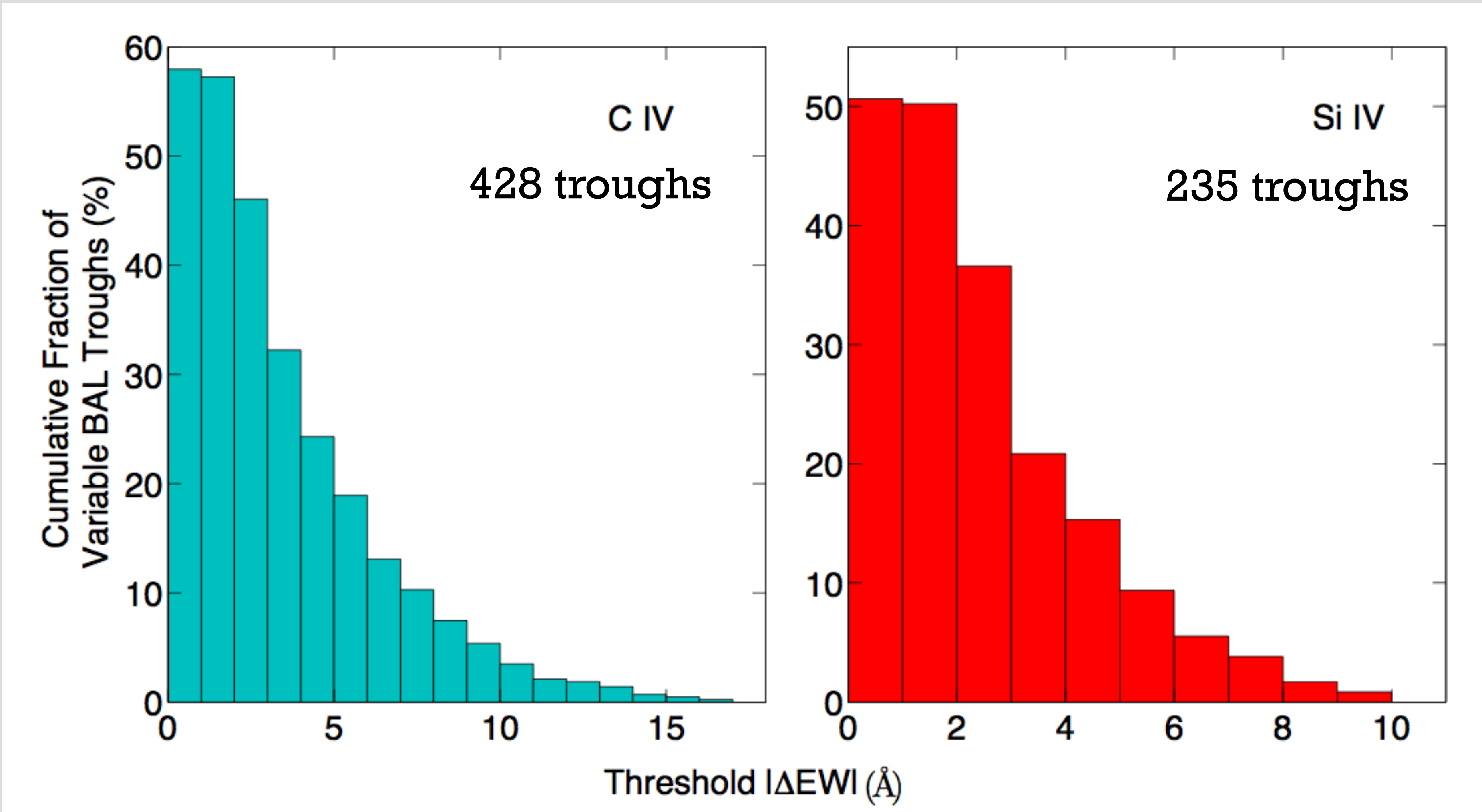


Examples of Strong BAL Variability



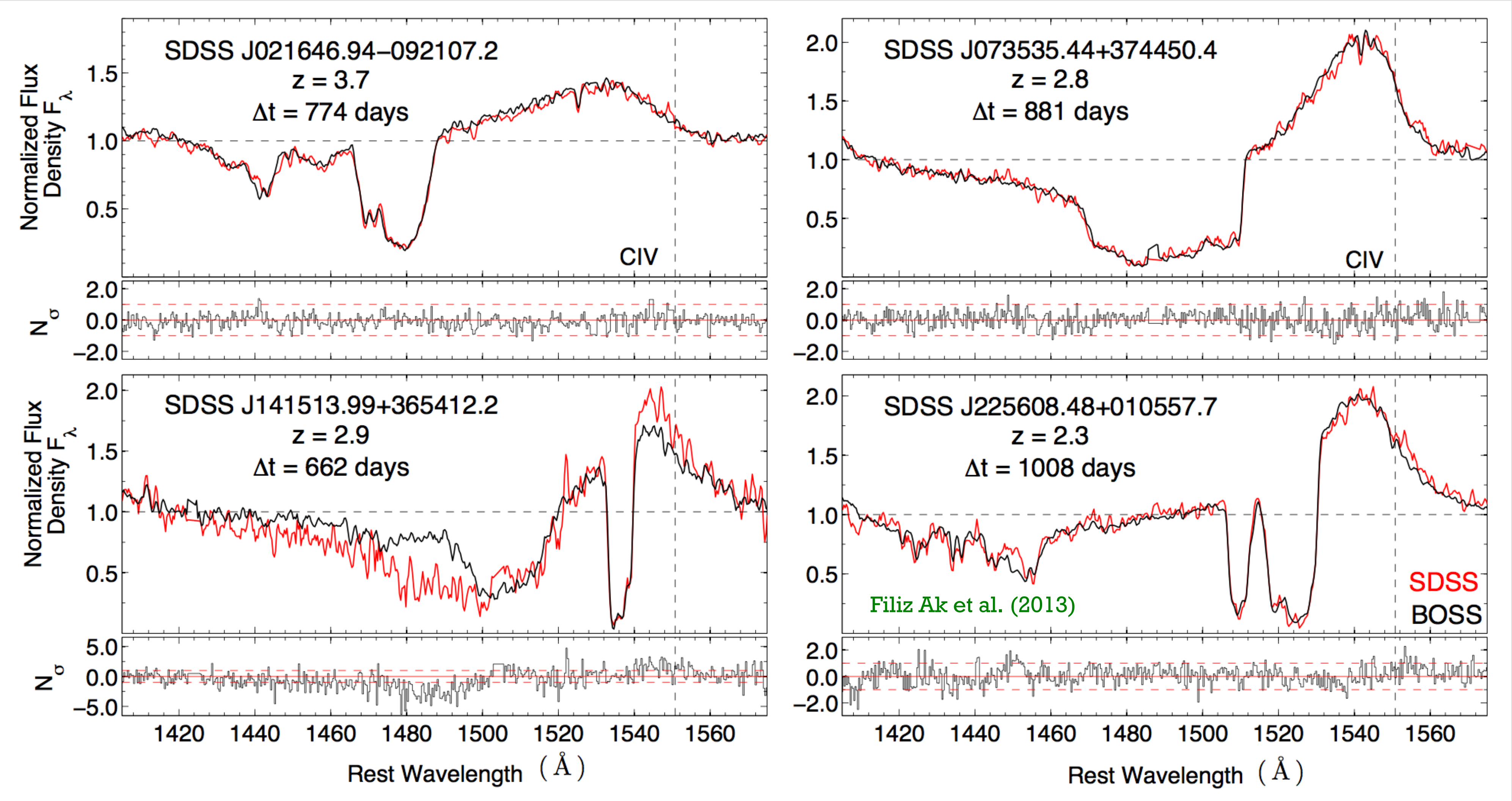
McGraw et al. (2017) – Many more where these came from!

BAL Variability is Common on Multi-Year Timescales



Filiz Ak et al. (2013)

But Some BALs Remarkably Stable



BALs may be formed over a wide range of scales, out to ~ kpc distances.

Can see both variable and remarkably stable in the same object.

Main Science Papers to Date

Filiz Ak et al. (2012) – First BAL Disappearance Results

Filiz Ak et al. (2013) – Statistical Characterization of C IV and Si IV Variability

Filiz Ak et al. (2014) – Coordinated Ionization Levels, Kinematics, Column Densities

Grier et al. (2015) – Rapid C IV BAL Variability (data from SDSS-RM)

Grier et al. (2016) – C IV BAL Acceleration Study

Rogerson et al. (2016) – Extremely High-Velocity Emergent Absorption

McGraw et al. (2017) – BAL Disappearance and Emergence with Multiple Epochs

Rogerson et al. (2017) – Large BAL Emergence Study

Additional Papers

Spin Off Papers

Hall et al. (2013) – Redshifted BAL Troughs

Zhang et al. (2017) – X-ray Properties of Quasars with Redshifted BAL Troughs

Examples of Other Uses

McGraw et al. (2015) – FeLoBAL Variability

Welling et al. (2014) – BAL Variability in Radio-Loud Quasars

Rafiee et al. (2016) – Vanishing Absorption in FeLoBAL Quasars

Stern et al. (2017) – Extreme BAL Variability

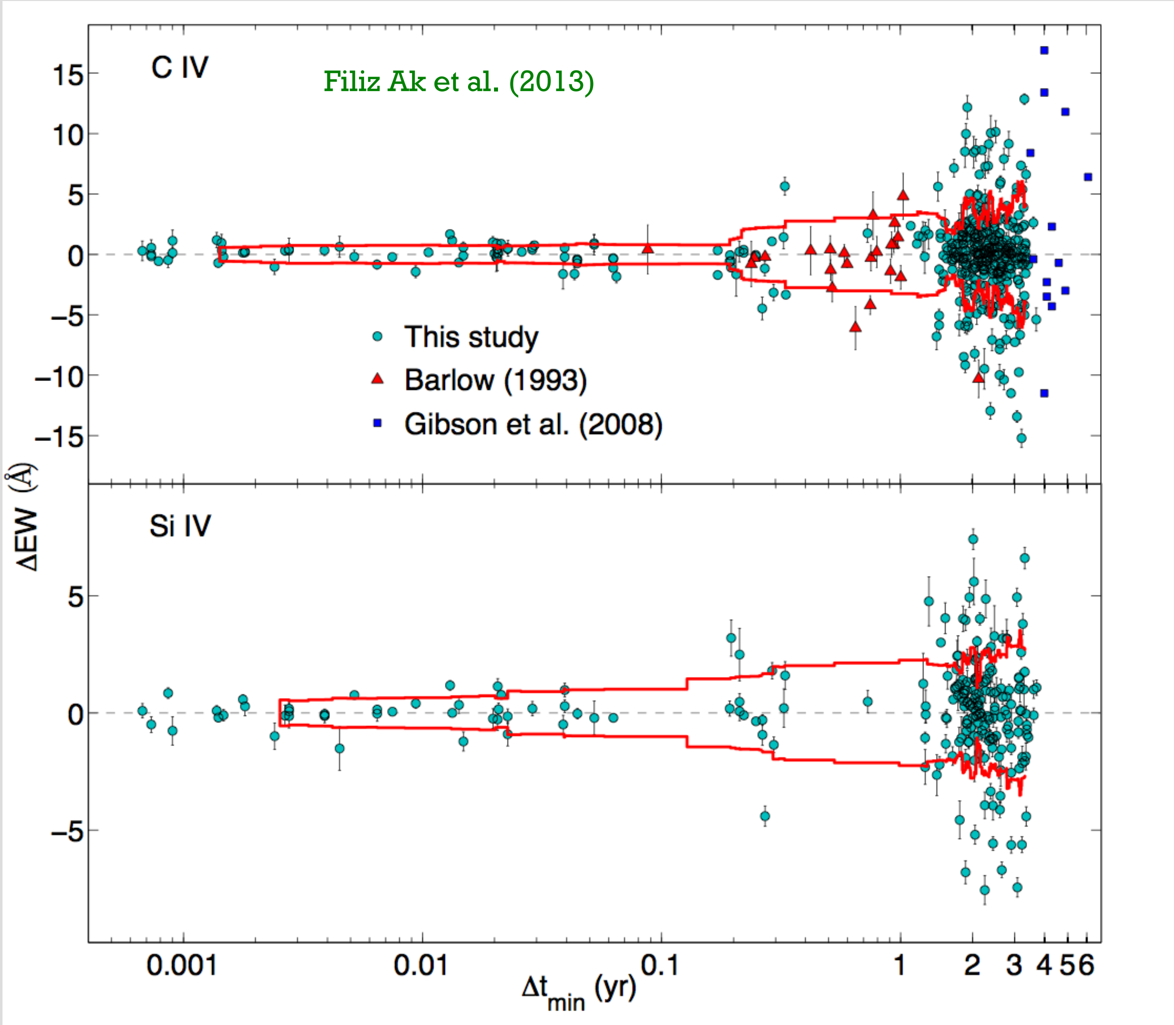
More Papers in Progress

Quick Overview of Some General Results

Filiz Ak et al. (2013)
Rogerson et al. (2017)

Effects of Rest-Frame Timescale

C IV and Si IV BAL EW Changes vs. Rest-Frame Timescale

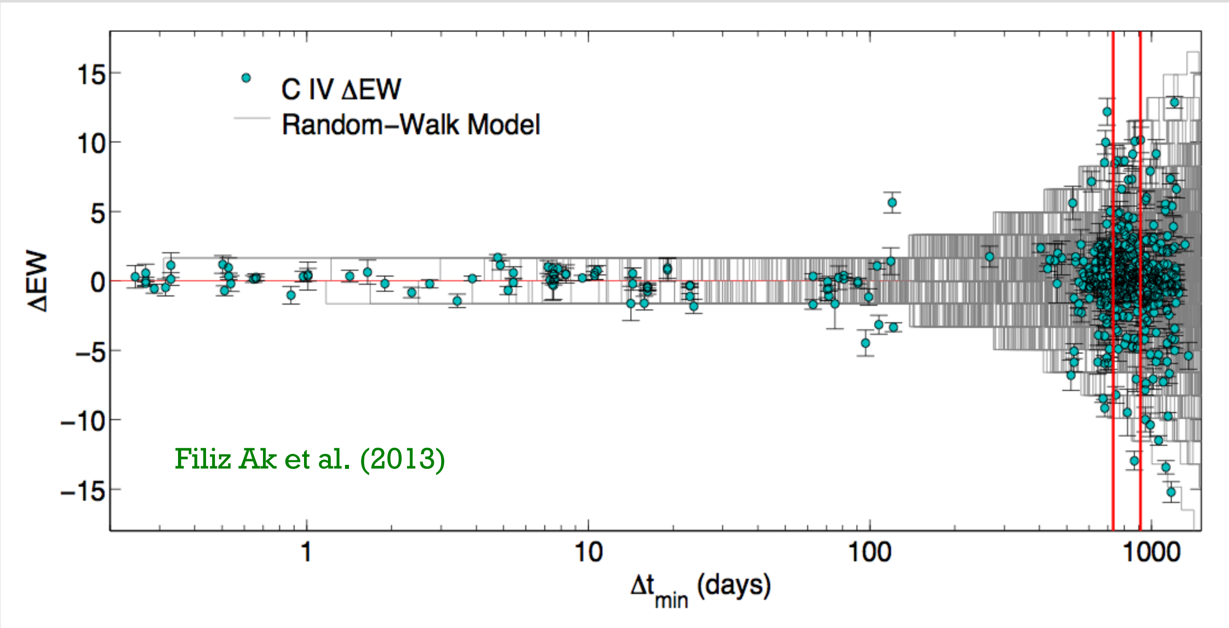


Magnitude of BAL EW variability increases out to longest timescales sampled.

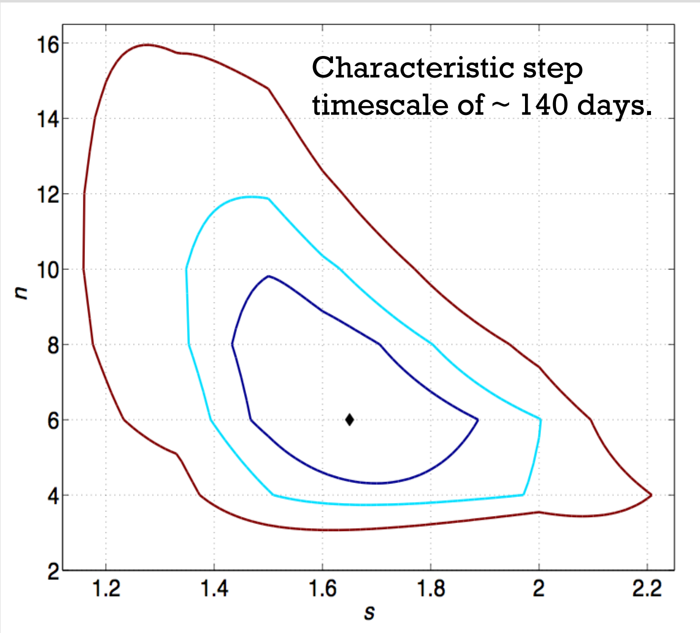
Generally do not strengthen or weaken monotonically (months vs. years).

A Random-Walk Toy Model

Comparison of Data vs. Random-Walk Model



C IV Model Confidence Contours

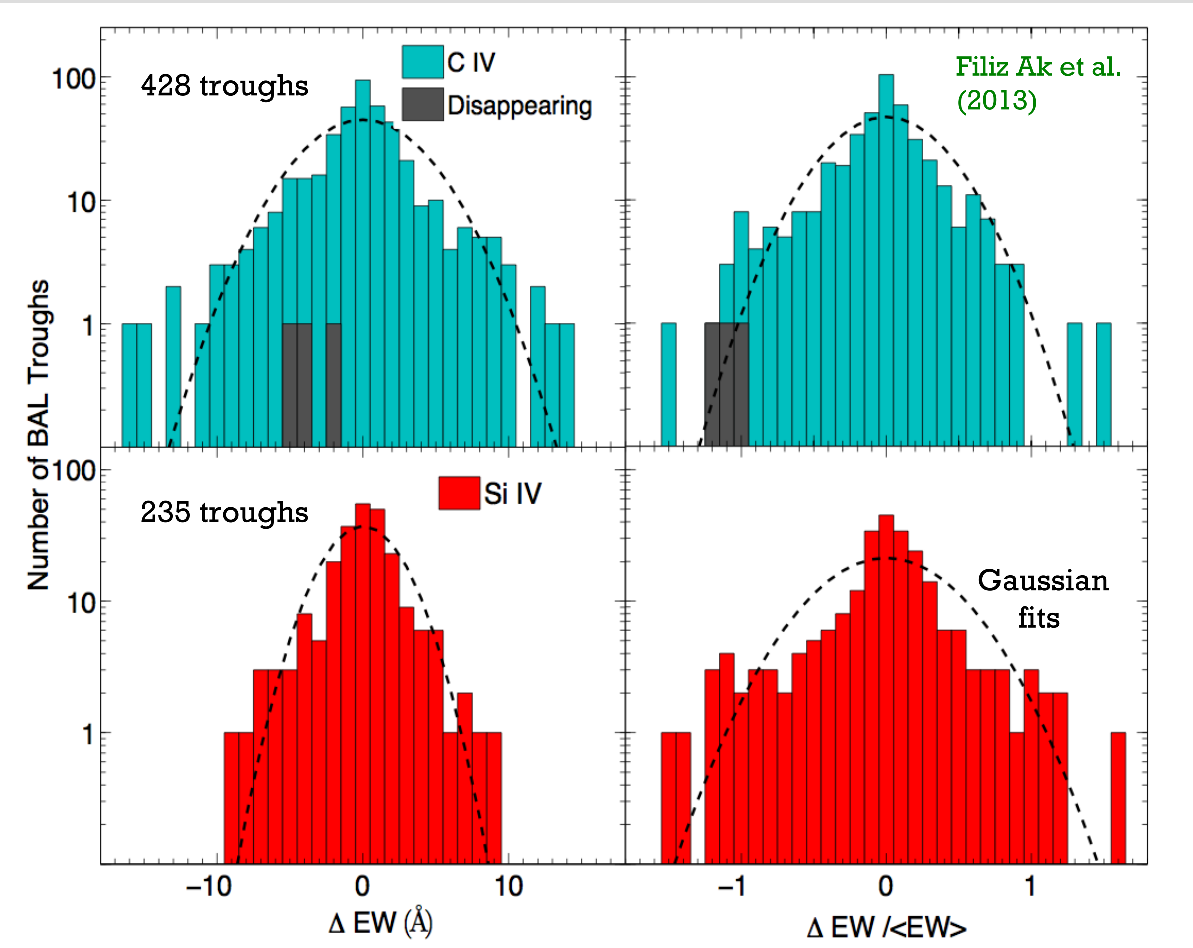


A random-walk toy model, giving a binomial distribution of ΔEW, fits the observed C IV behavior acceptably with a relatively small number of steps (about 5-9) over 2.0-2.5 yr.

Si IV troughs independently give almost the same random-walk model parameters.

Distribution of EW Variability

Distributions of EW and Fractional EW Variations for Timescales of 1-3.7 yr



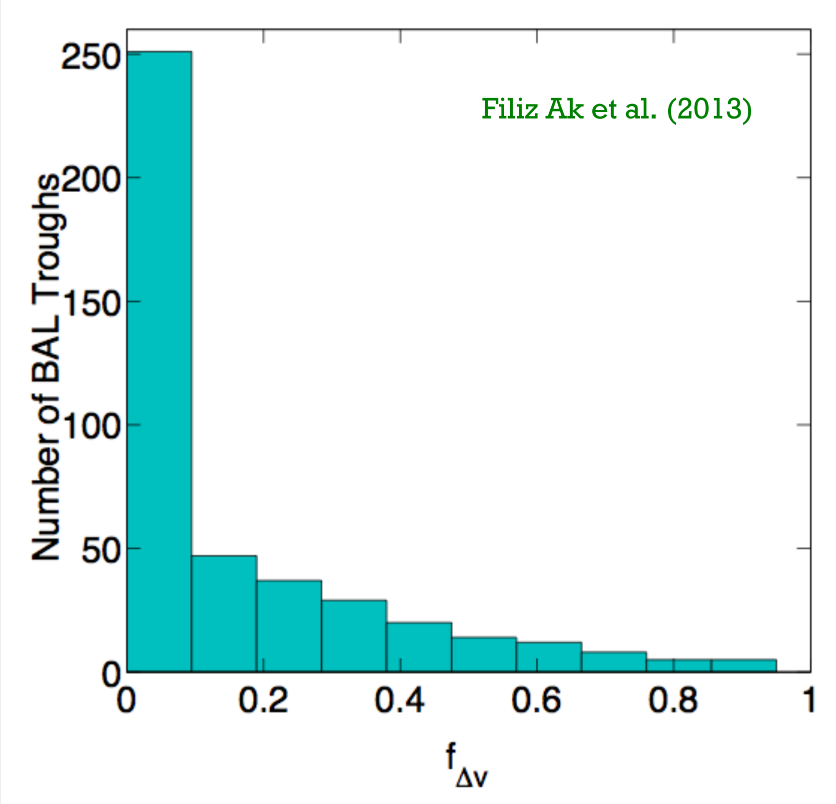
Distributions are zero-centered and symmetric.

Strengthening and weakening of BAL troughs occur at similar rates (e.g., no evidence for fast onset and slow decay).

Distributions can be characterized well with a binomial distribution, but are non-Gaussian.

Multi-Year BAL Profile Variability

Fraction of a BAL Trough's Width in Variable Regions



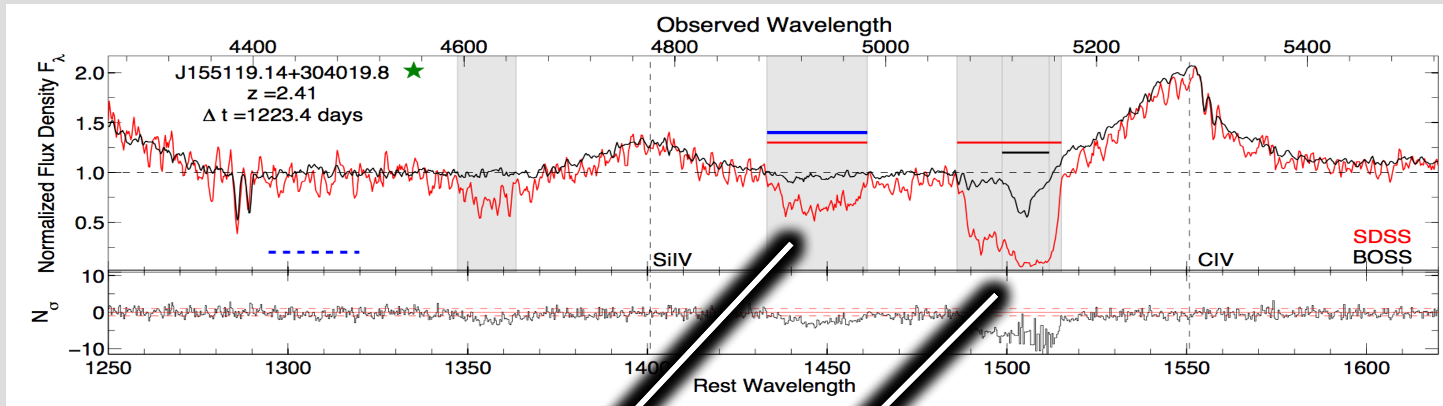
On multi-year timescales, BALs typically vary in discrete regions (1000-3000 km s^{-1} wide) rather than monolithically.

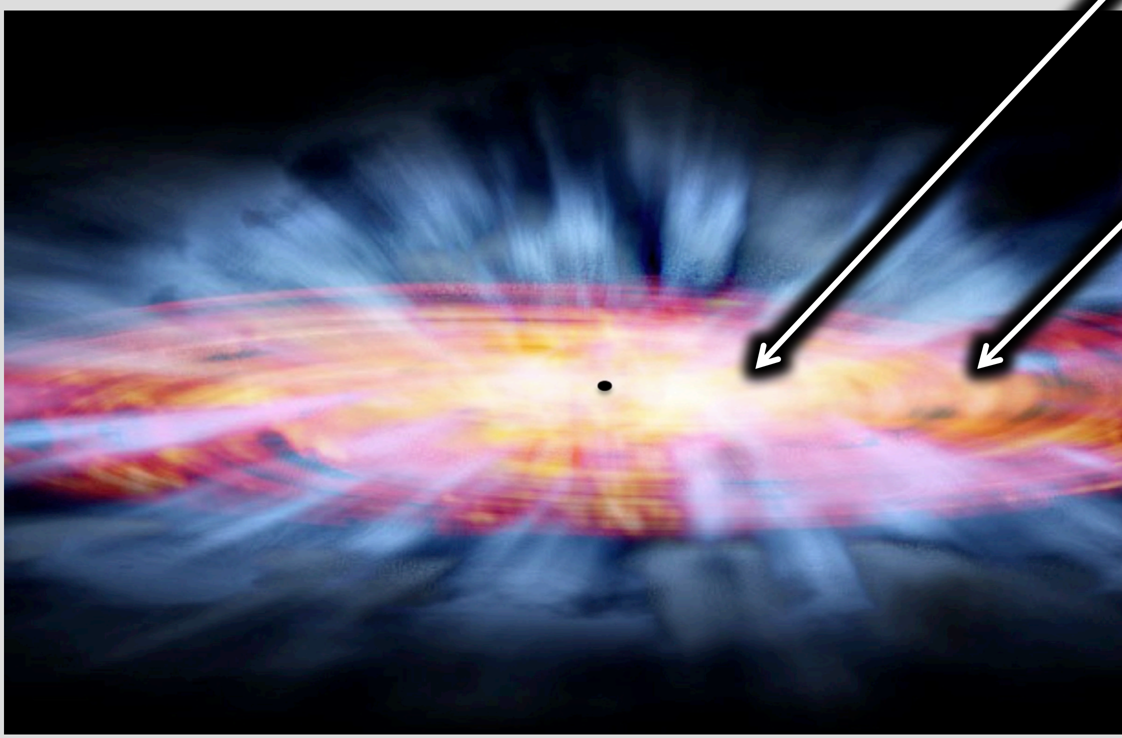
But there are notable exceptions to the rule.

Substructure of BALs.

Regions spread uniformly across a trough.

A Somewhat Surprising Result

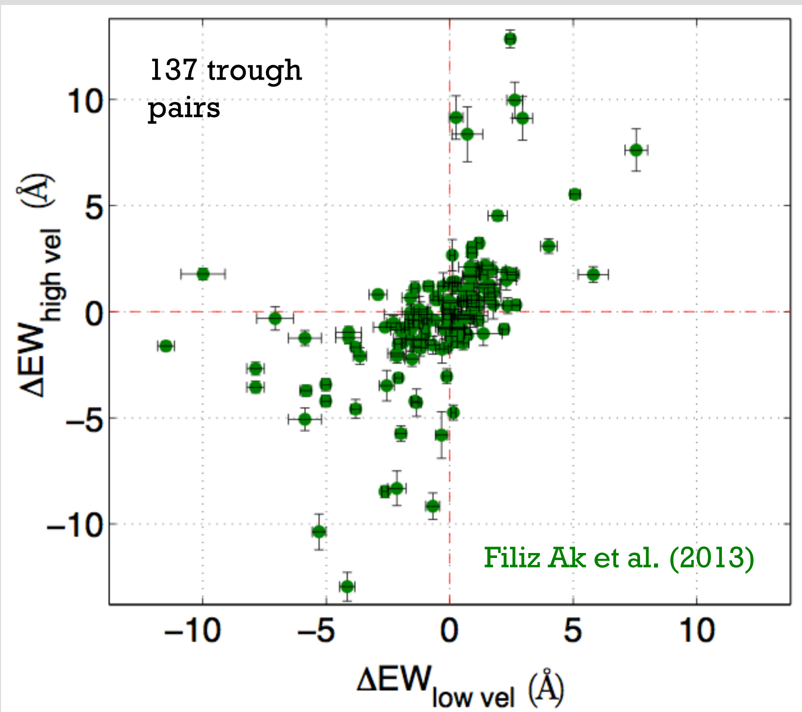




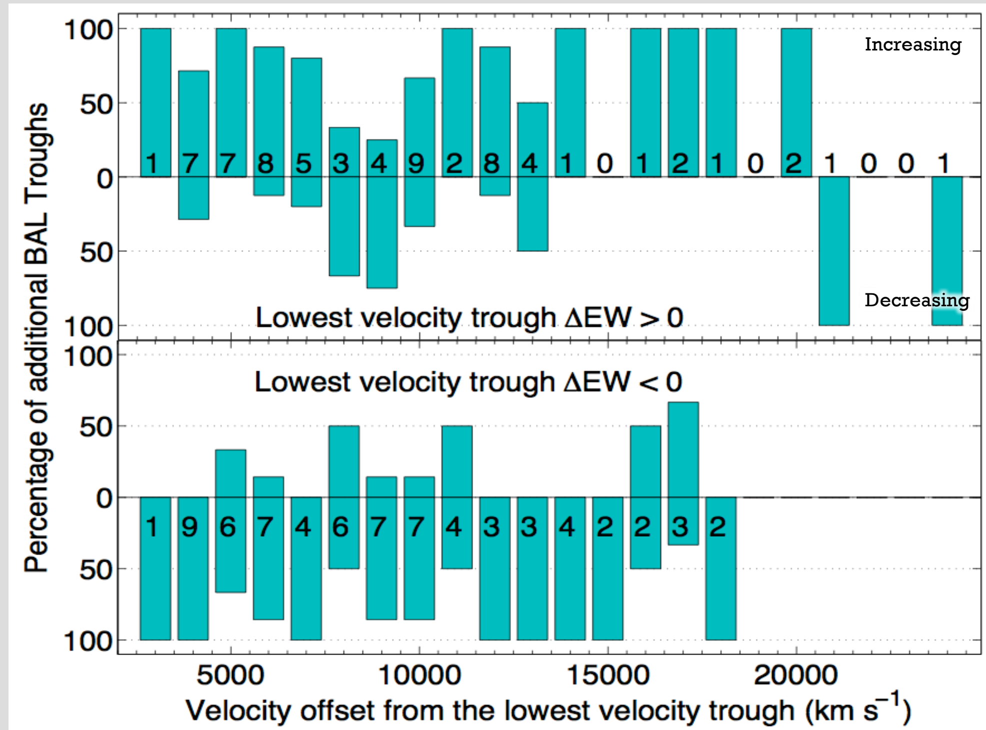
Components at different velocities likely have different launching radii and should be largely independent.

Coordinated Trough Variations

EW Variations of Lowest Velocity Versus Higher Velocity C IV Troughs



Coordinated Trough Variations across Wide Velocity Spans



Variations of distinct troughs are clearly correlated, though with scatter in correlations.

Need some agent to enforce coordinated variability - ionization-driven variability.

Could be intrinsic changes of EUV continuum or changes in shielding gas.

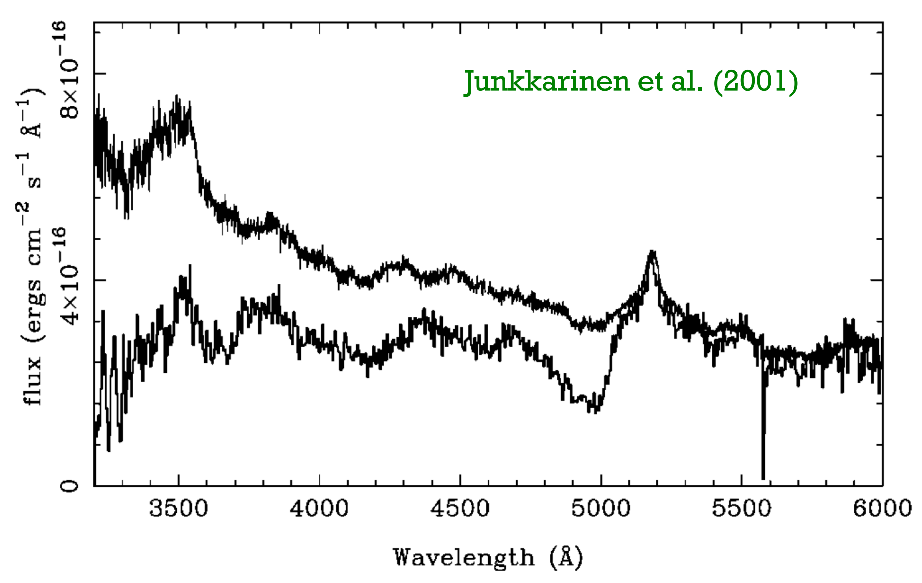
Rogerson et al. (2017) find that degree of coordination drops off with velocity separation.

BAL Disappearance and Emergence

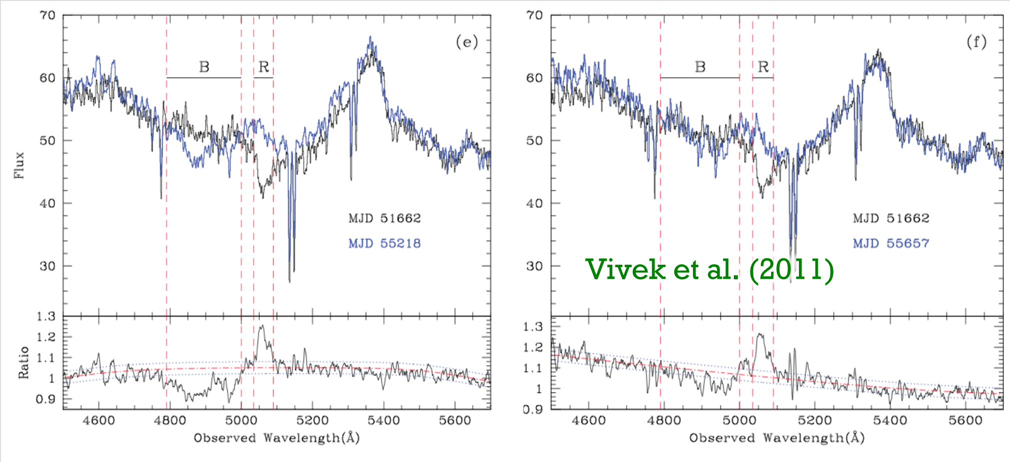
Filiz Ak et al. (2012)
McGraw et al. (2017)
Rogerson et al. (2017)

Gone with the Wind: BAL Disappearance

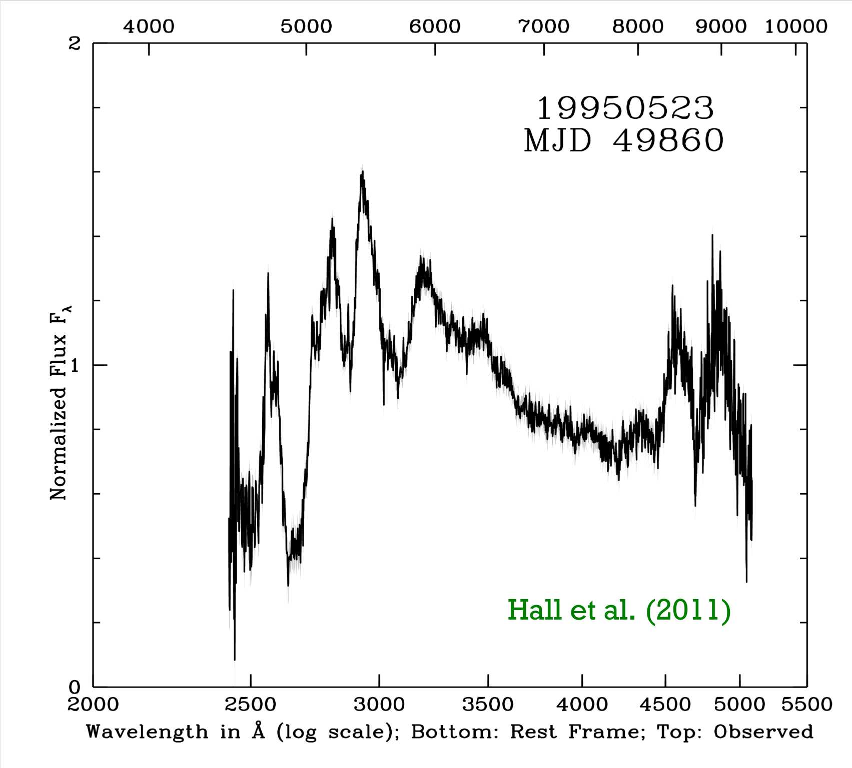
Mg II BAL Disappearance in LBQS 0103-2753



Mg II BAL Disappearance in SDSS J1333+0012



Fe II BAL Disappearance in FBQS J1408+3054

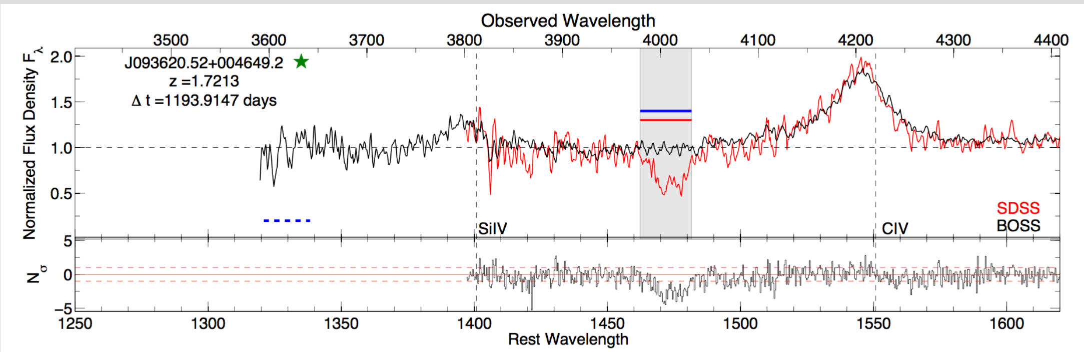


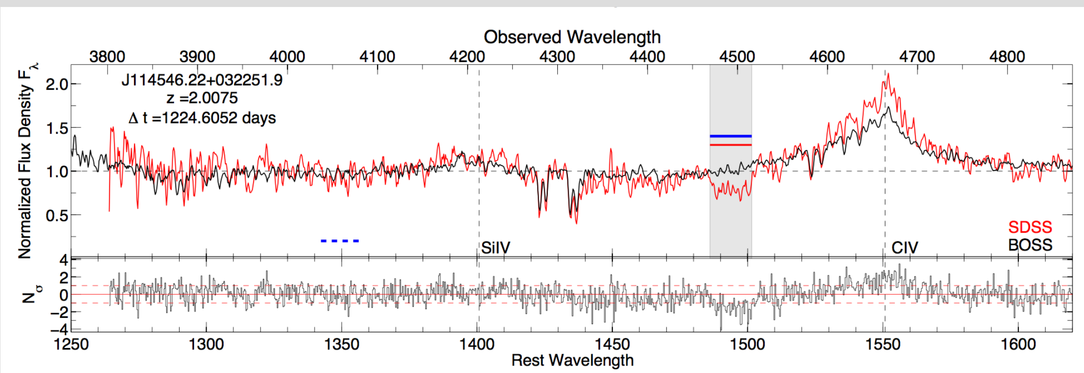
Early studies of BAL disappearance were typically in low-ionization lines.

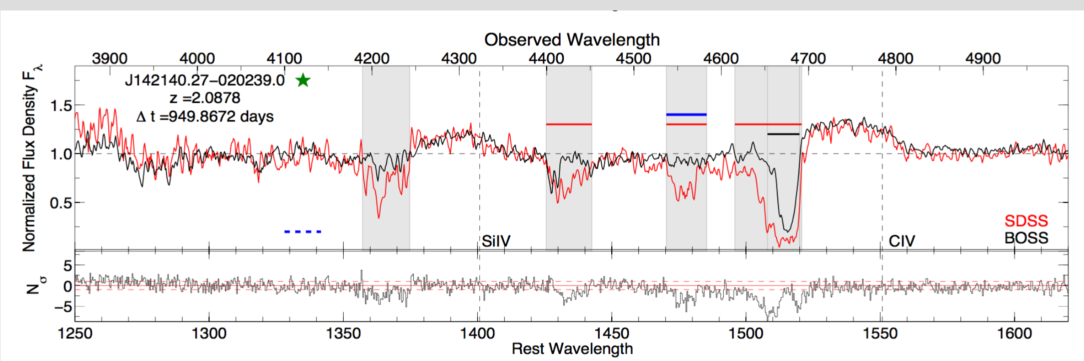
Did not involve BAL quasar to non-BAL quasar transformations (i.e., other BALs remained).

C IV BAL Disappearance Survey

Filiz Ak et al. (2012)







Sample: 582 BAL quasars with 925 C IV troughs in SDSS-I/II and BOSS.

21 examples of BAL disappearance in 19 quasars – first C IV examples.

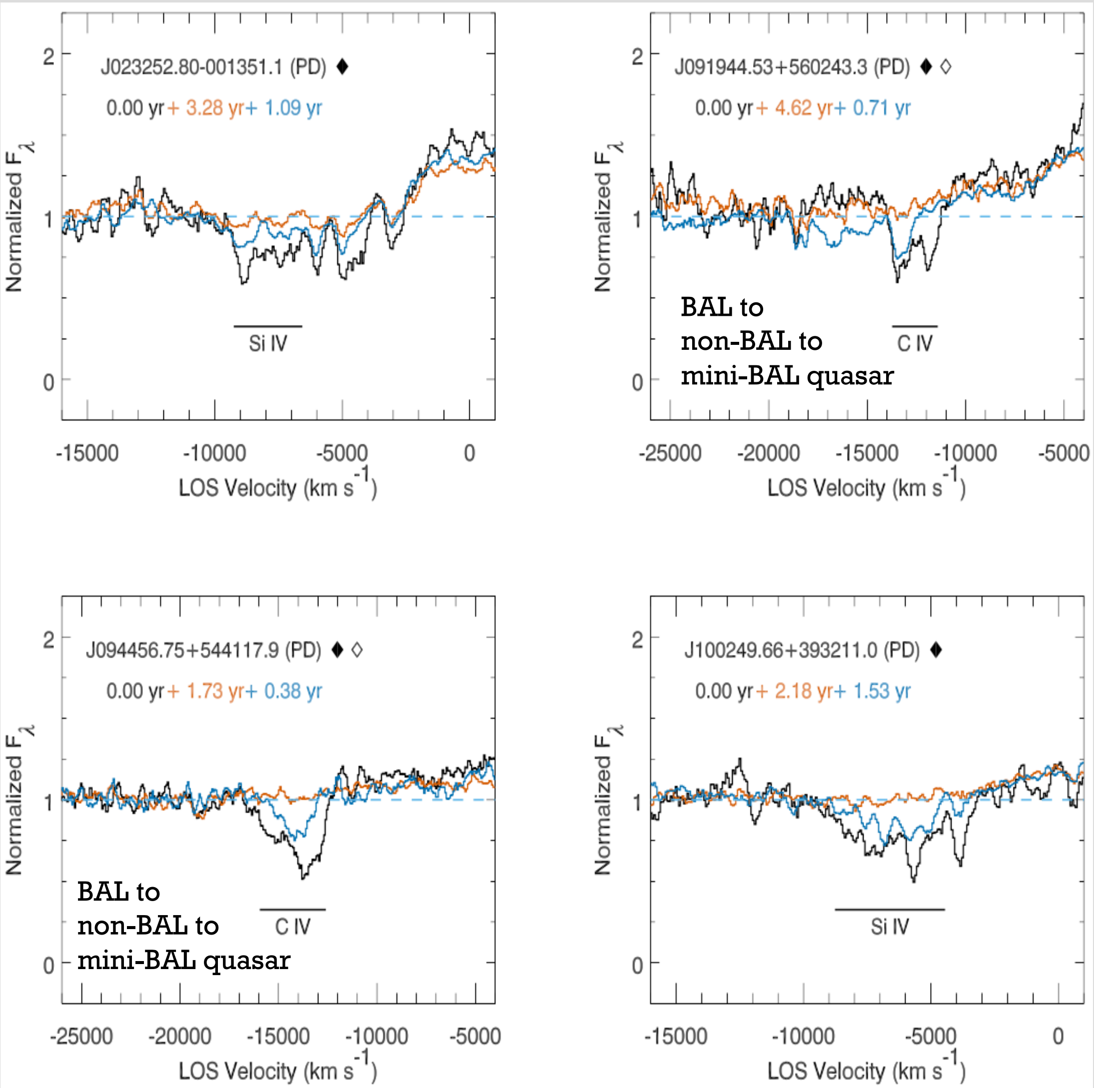
On 1-4 yr rest-frame timescales, 2.3% of C IV troughs disappear and 3.3% of BAL quasars show at least one disappearing trough.

Suggests average C IV BAL lifetime of about a century.

BAL disappearance occurs mainly for weak or moderate-strength absorption troughs, as well as for those at relatively high outflow velocities.

Three-Epoch Disappearance Follow-Up

Re-Emergence After Disappearance



McGraw et al. (2017)

Focused on sample with SDSS-I/II + BOSS + TDSS coverage – 470 BAL quasars.

14 new pristine cases of disappearing C IV and/or Si IV BALs.

Four mini-BALs re-emerge in the third-epoch TDSS data – encore!

Re-emerge at roughly same velocity and with notable kinematic similarities.

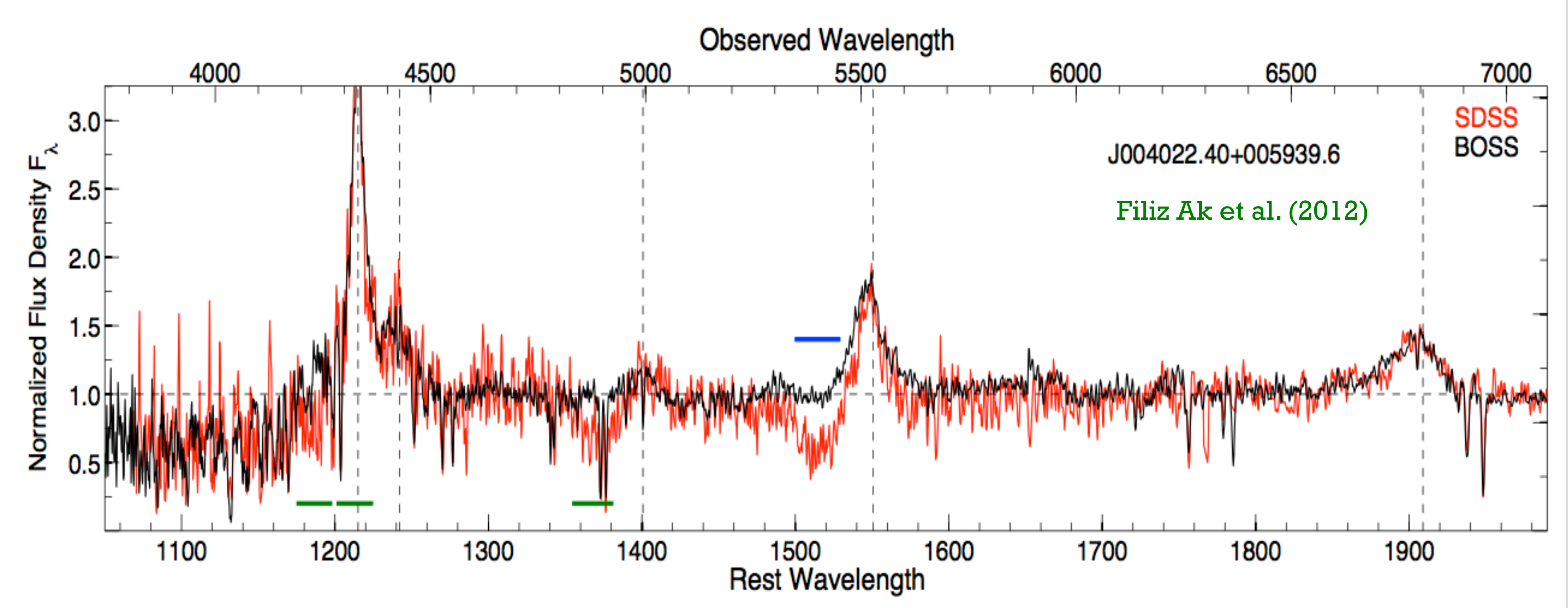
Evidence for ionization changes causing the variability.

BAL to Non-BAL Quasar Transformation

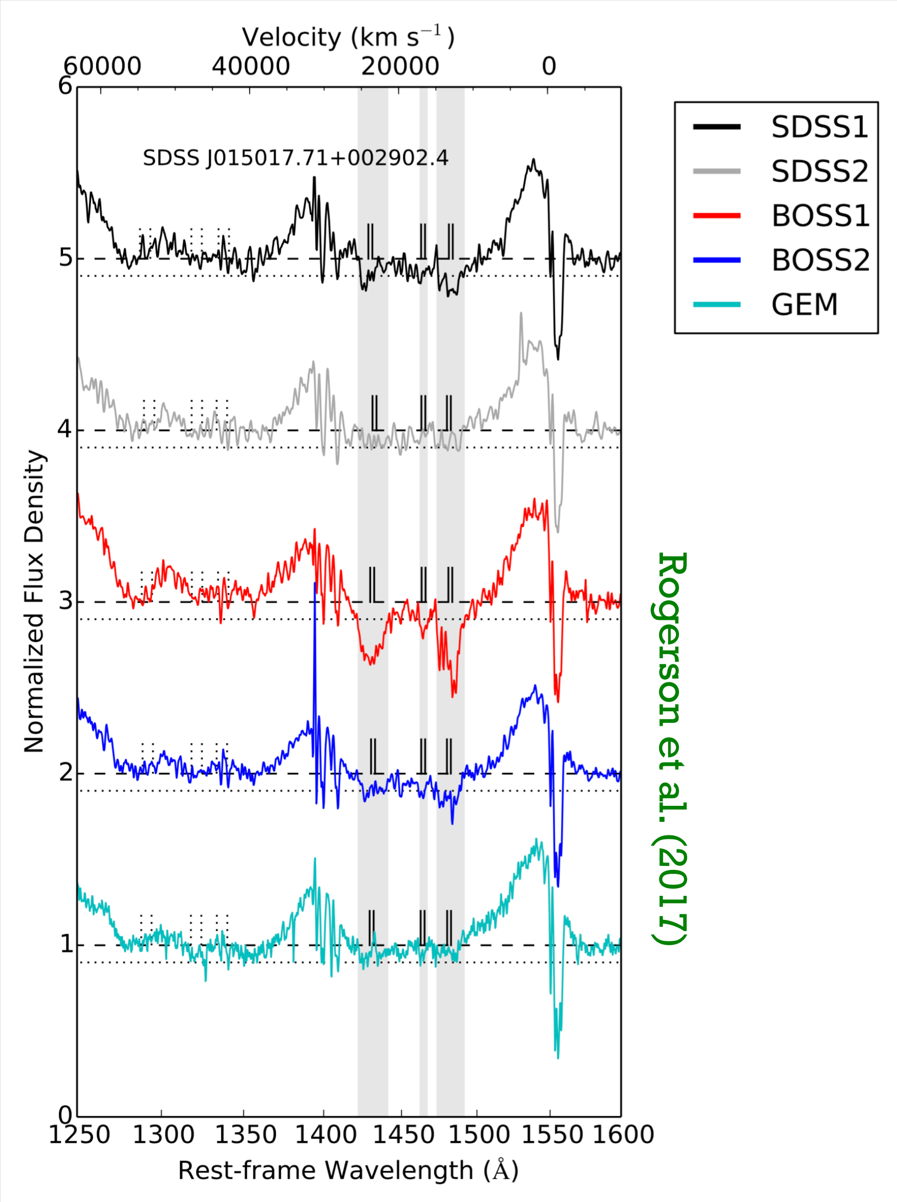
We have found examples of BAL to non-BAL quasar transformations.

To maintain population equilibrium, indicates that non-BAL quasars must be turning into BAL quasars via BAL emergence:

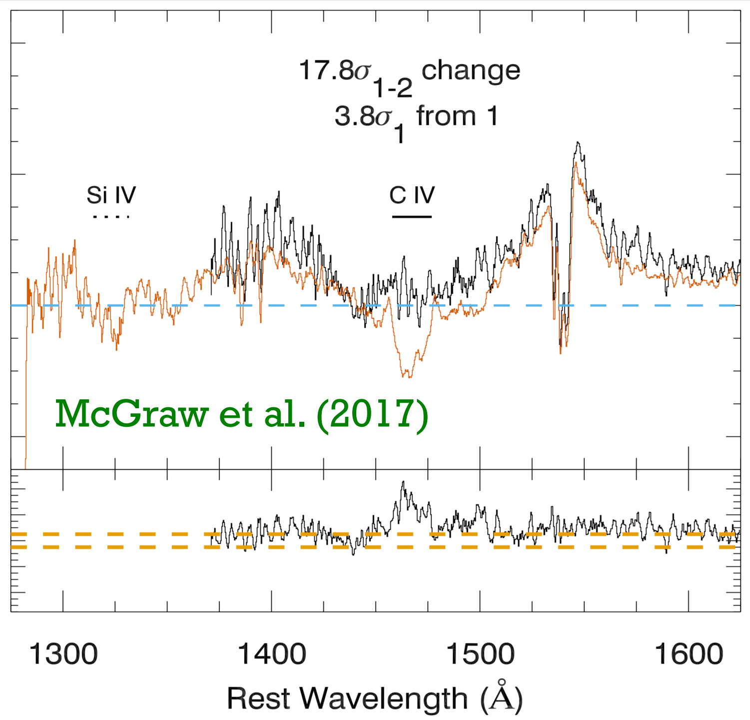
$$R_{\mathrm{Disappear}}\, N_{\mathrm{BAL}} = R_{\mathrm{Emerge}}\, N_{\mathrm{NonBAL}}$$



BAL Emergence



Rogerson et al. (2017)

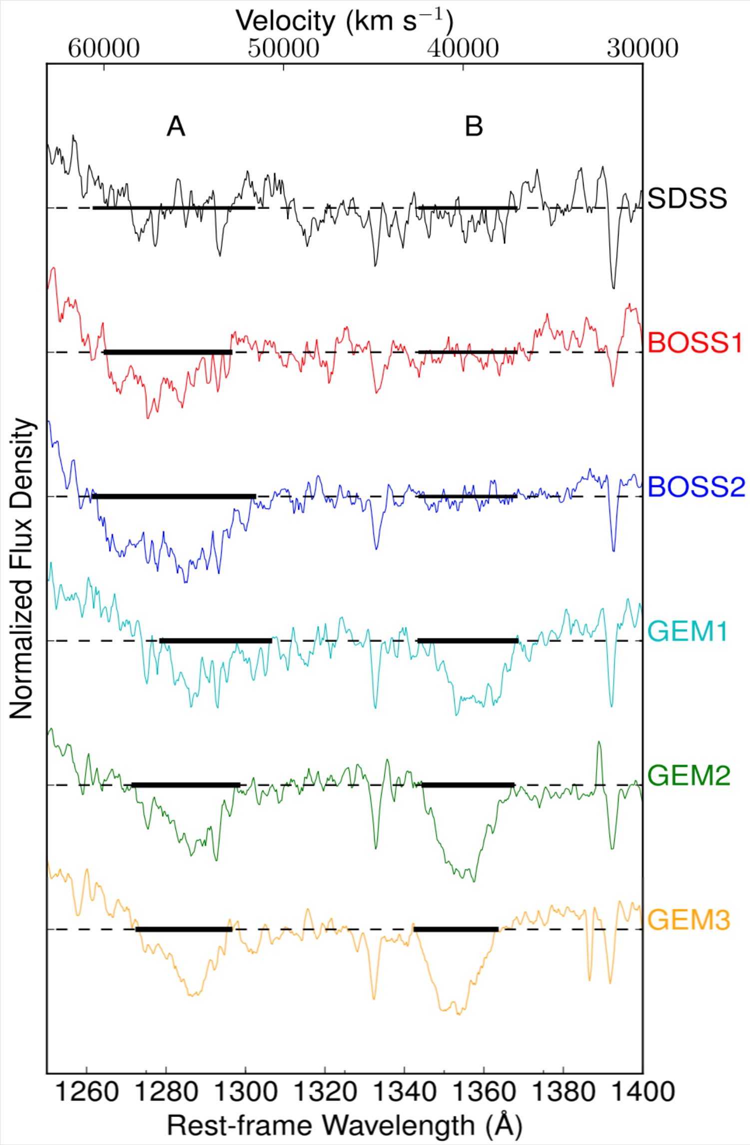


~ 120 confirmed examples

~ 180 additional strong candidates

Plausibly balances disappearance rate; see Rogerson et al. (2017)

Emergent Absorption at 56,000 km s^{-1}



Rogerson et al. (2016)

Highest velocity C IV trough to date.

Second emerging trough at 40,000 km s^{-1}

York University / Penn State Press Release:

Crazy fast winds escape black hole 'like a bat out of hell'

Posted by Barbara Kennedy-Penn State | March 22nd, 2016

Share Article

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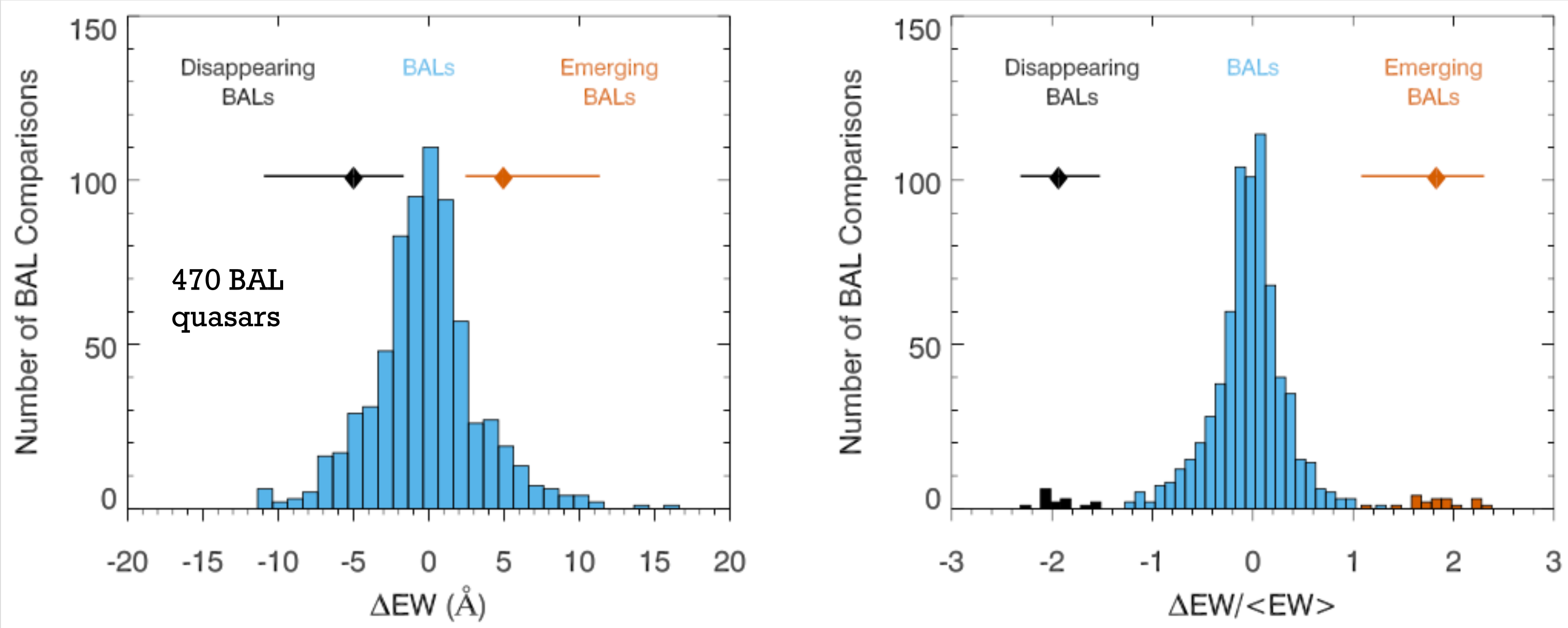
The fastest winds ever seen at ultraviolet wavelengths have been discovered near a supermassive black hole.

"This new ultrafast wind surprised us when it appeared at ultraviolet wavelengths, indicating it is racing away from the ravenous black hole at unprecedented speeds—almost like a bat out of hell," says William Nielsen (Niel) Brandt, professor of astronomy and astrophysics and a professor of physics at Penn State.

"We're talking wind speeds of more than 200 million miles an hour, equivalent to a category 77 hurricane," says Jesse Rogerson, who led the research as part of his efforts toward earning a PhD in the physics and astronomy department at York University in Canada.

Disappearance/Emergence in Context

Distributions of EW and Fractional EW Variations for C IV and Si IV



McGraw et al. (2017)

Disappearance and emergence events represent stronger than average changes in ΔEW – though not atypical of population.

They are more exceptional in ΔEW / EW and are suggestively more common than extrapolation of overall distribution – different mode?

BAL Acceleration and Deceleration

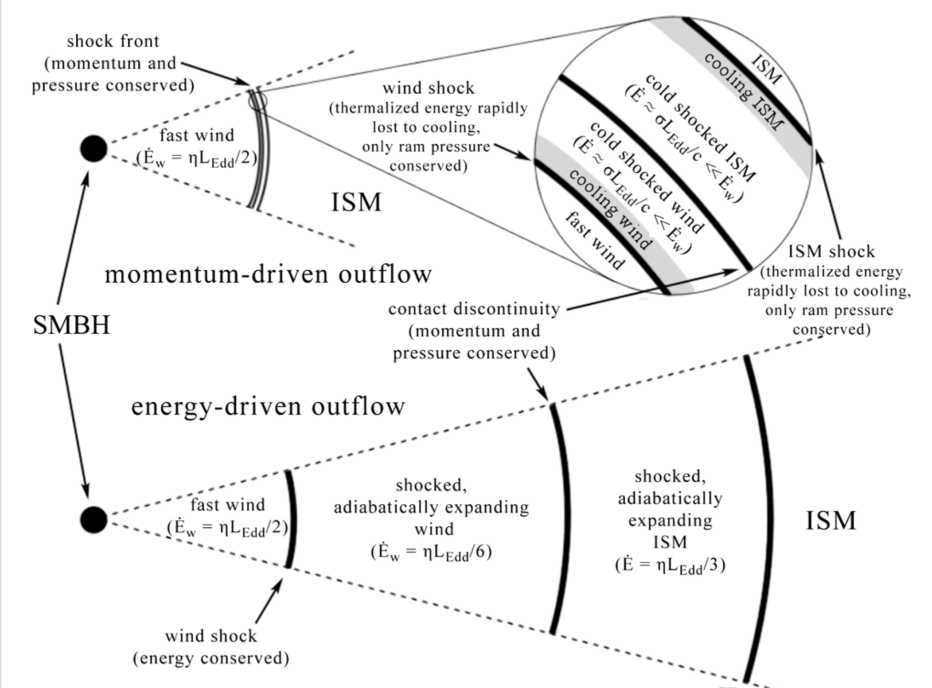
Grier et al. (2016)

Possible Causes

BALs could accelerate due to an actual increase in the speed of material from an (intermittent) outflow.

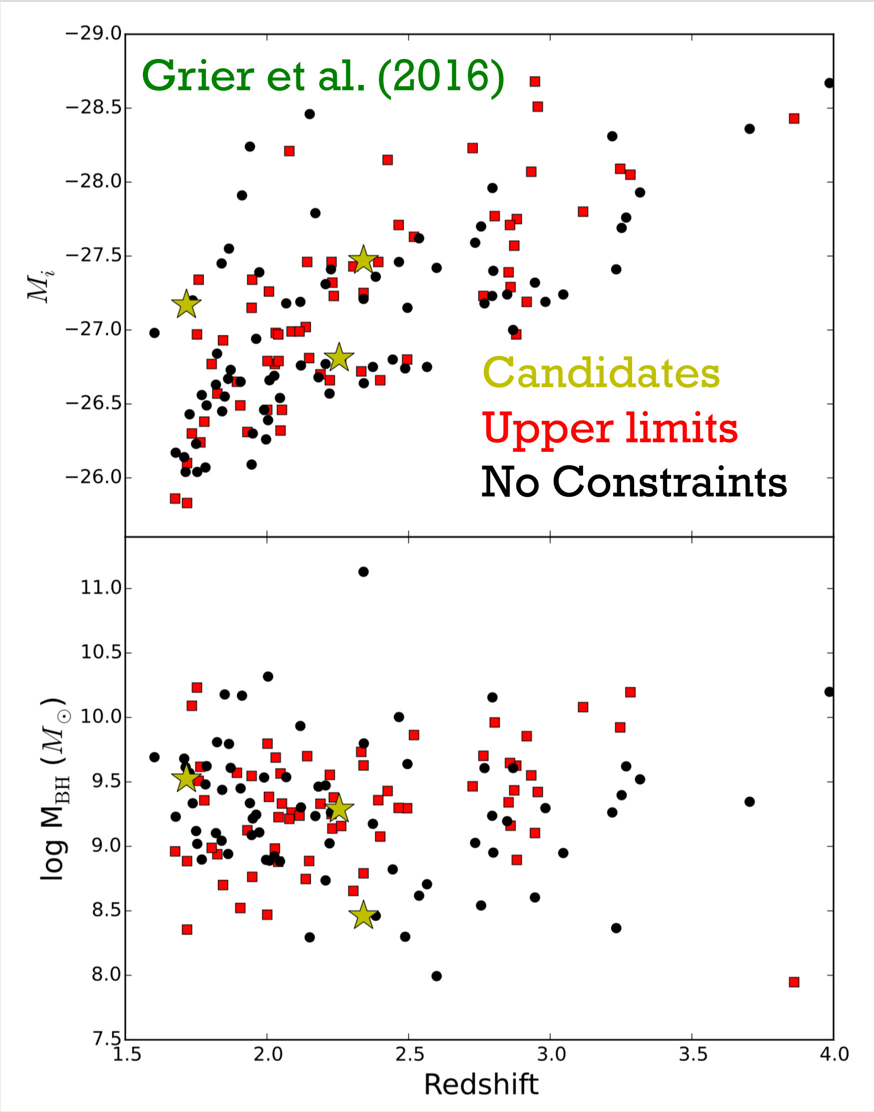
Or directional shift in an outflow changing LOS velocity; e.g., due to disk rotation.

Deceleration plausibly expected in galactic feedback models, when wind interacts with ambient host material.



Zubovas & King (2012)

Systematic Search for BAL Acceleration



Few measurements of BAL acceleration in the literature (e.g., Vilkoviskij & Irwin 2001; Rupke et al. 2002; Gabel et al. 2003).

Available sample-based constraints use small samples with unclear methodology.

First systematic, large-scale search to constrain this phenomenon.

Long timescales help since velocity shifts from acceleration accumulate.

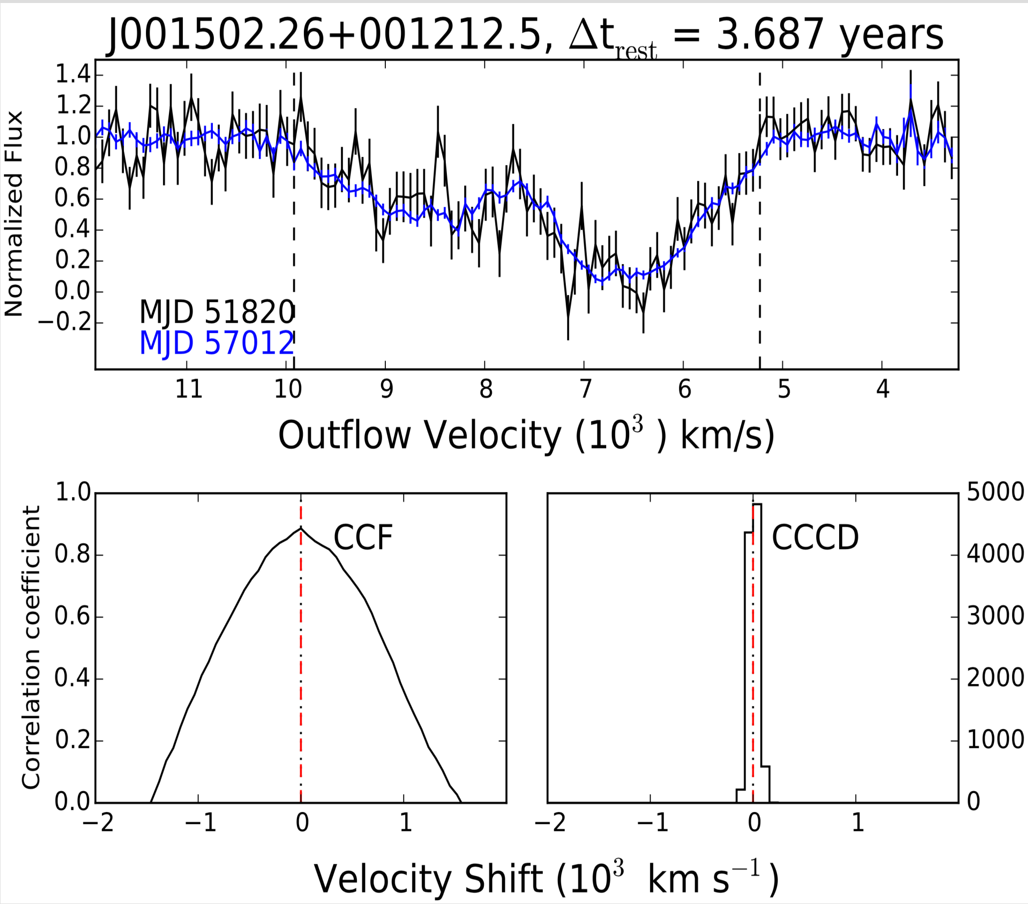
Search for acceleration by looking for ~ monolithic velocity shifts of C IV BALs.

140 representative BAL quasars with <u>3-epoch data</u> spanning 2.5-5.5 years.

151 distinct C IV BAL-trough complexes.

Constraining Velocity Shifts

Example of Stable, Non-Shifting BAL



Grier et al. (2016)

In addition to improved sample, also improved search methodology.

Look for BALs that don't very in shape much, or only in small parts, so can obtain velocity lock.

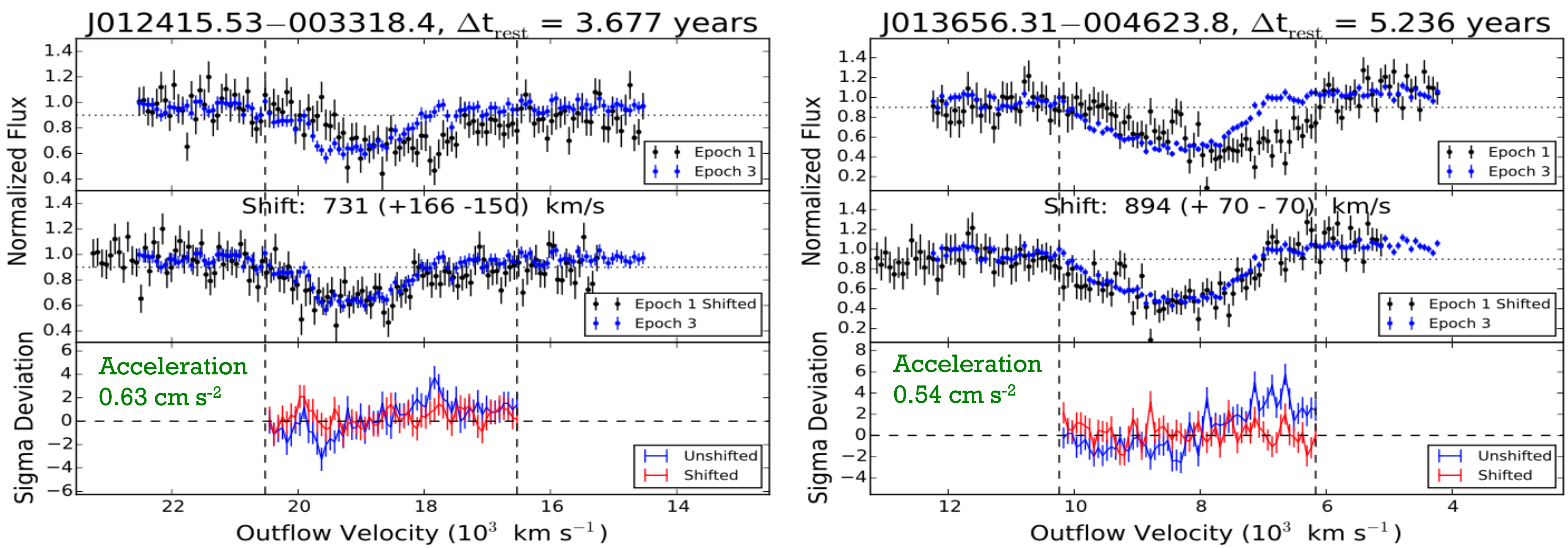
85 BALs passed this test, while 66 varied too strongly.

Use cross-correlation methodology from RM to identify velocity shifts.

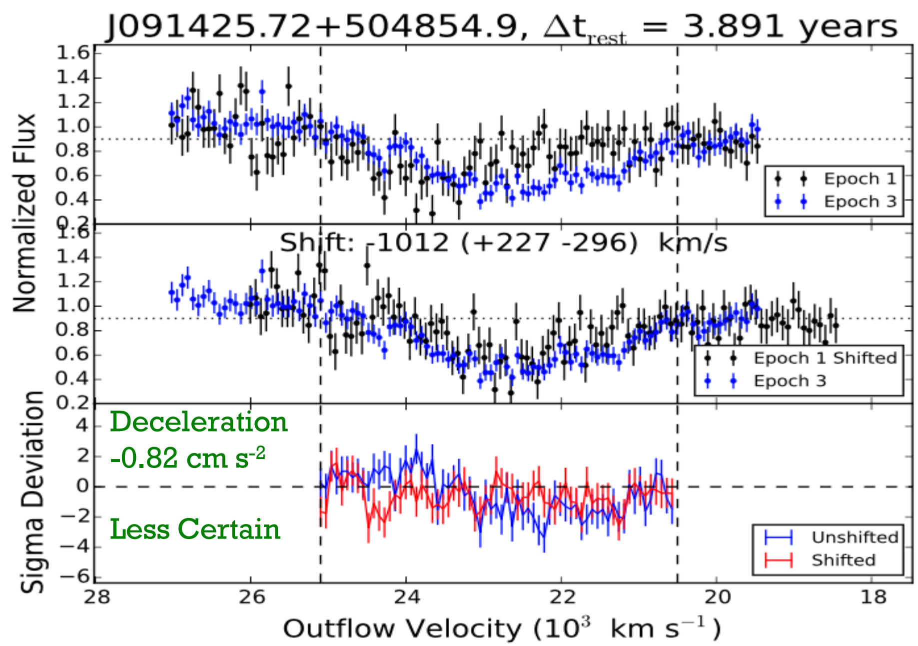
Can reach 0.1-2 pixel shift limits - median is 0.5 pixels, about 33 km s^{-1}.

Over 2.5-5.5 years, this translates into a sensitive acceleration search.

2-3 Acceleration / Deceleration Candidates



Large negative "jerk" values suggest acceleration events may be short lived (~ decade).



No extreme photometric variability.

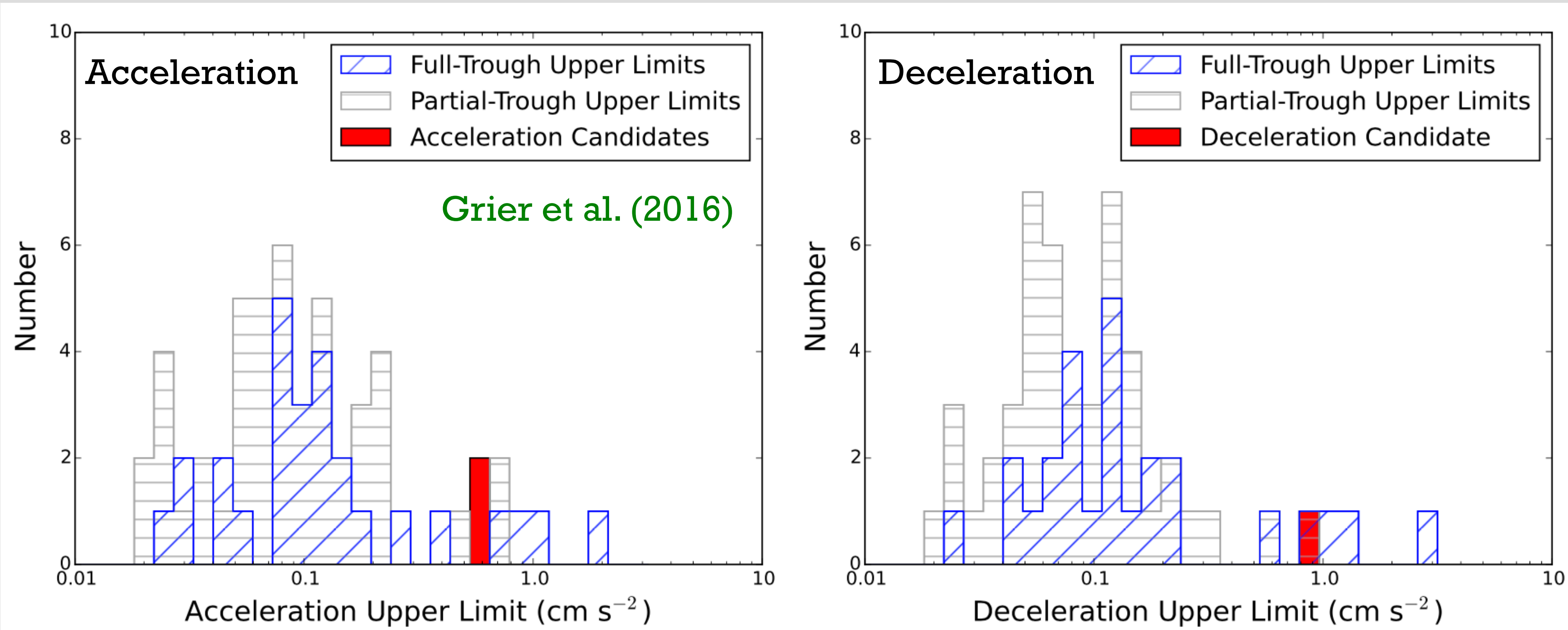
These need further follow-up.

Expect ~ 35 cases in full sample.

Grier et al. (2016)

Most BALs Remarkably Velocity Stable

Upper Limits on Acceleration and Deceleration



Most of our sample have 3σ upper limits of 0.5 cm s^{-2} or better.

Most BALs are stable to within 3% of their outflow velocities over years.

Some Implications

For <u>acceleration candidates</u>, Murray et al. (1995) model can plausibly match observed velocities and accelerations. But "jerk" magnitudes are problematic.

For <u>acceleration upper limits</u>, might explain if gas is in "standing pattern" outflow.

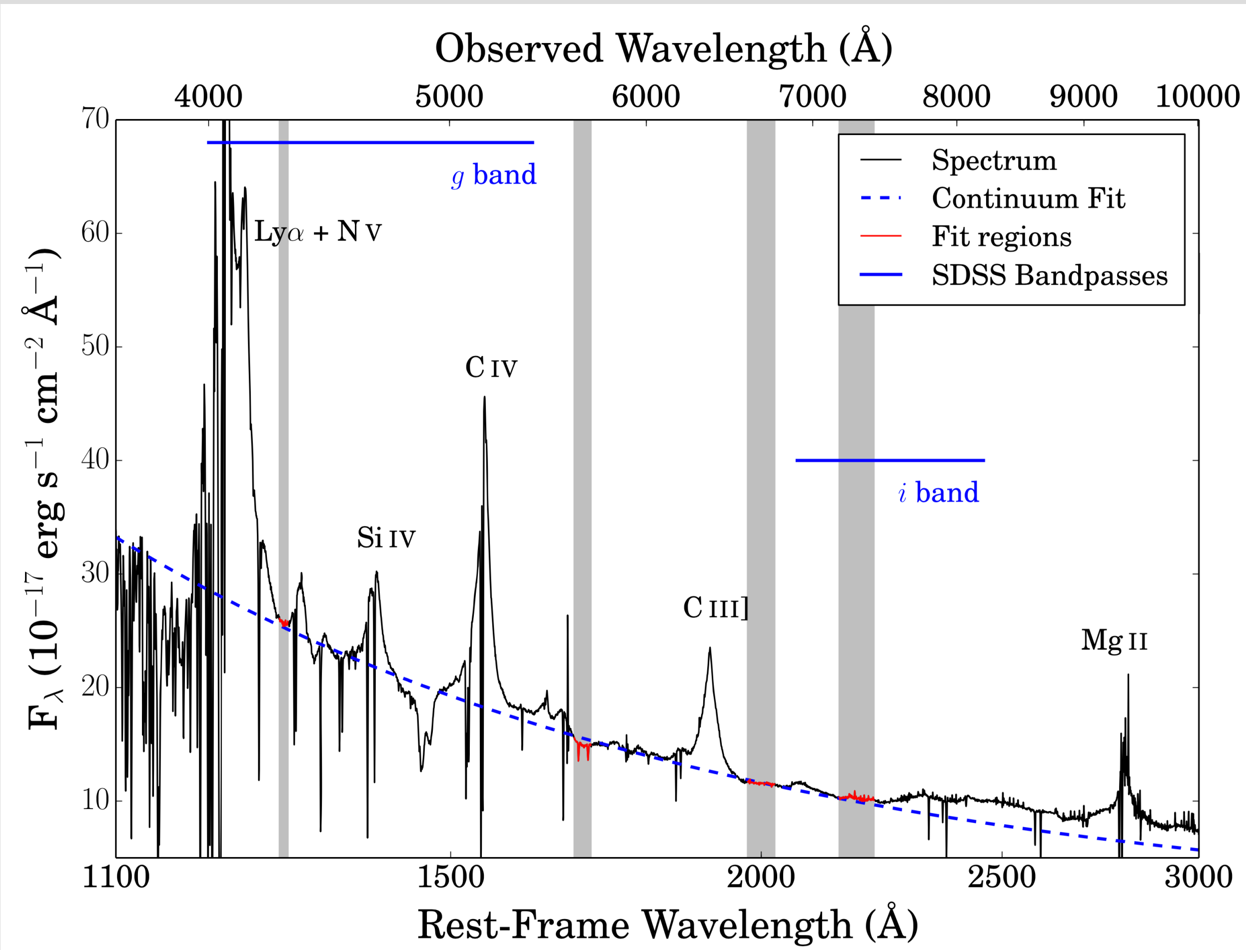
But, are sampling a significant fraction of $t_{\rm orbit}$ at $r_{\rm launch}$, so need azimuthally symmetric outflow. Larger radii help.

For <u>deceleration upper limits</u>, need quantitative predictions of deceleration from feedback models for comparison.

Rapid BAL Variability

Grier et al. (2015)

Quasar Showing Rapid C IV BAL Variations



Grier et al. (2015)

SDSS J1410+5412

z = 2.337
m_i = 18.1
M_i = -27.69

Fairly typical BAL quasar.

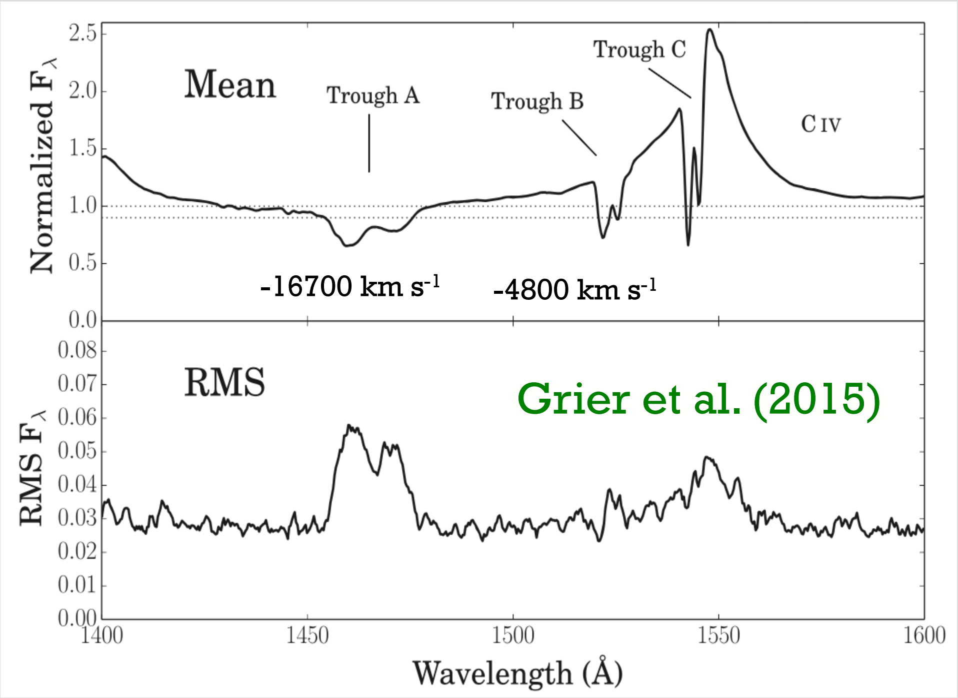
Known to show UV absorption since 1991.

Observed intensively as part of SDSS-RM. Part of sample of 849.

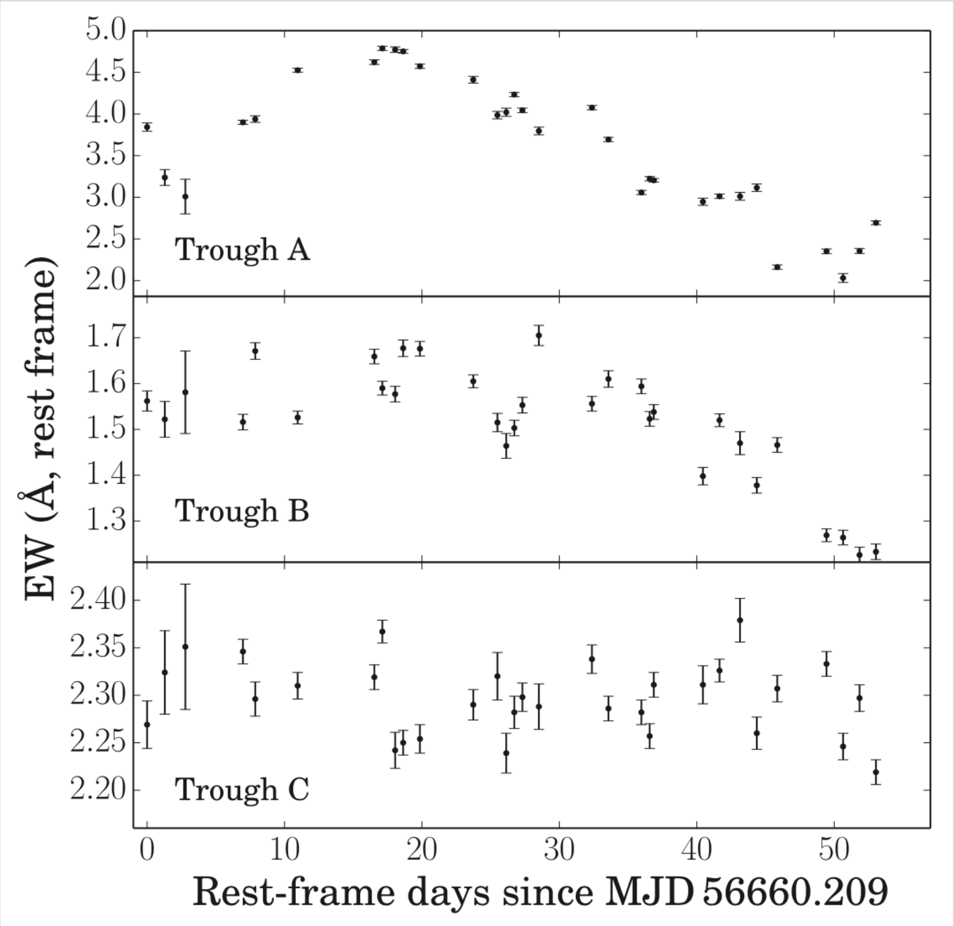
32 epochs in 6 months in 2014.

Observed General BAL Variability

Mean and RMS Spectra



Trough Light Curves



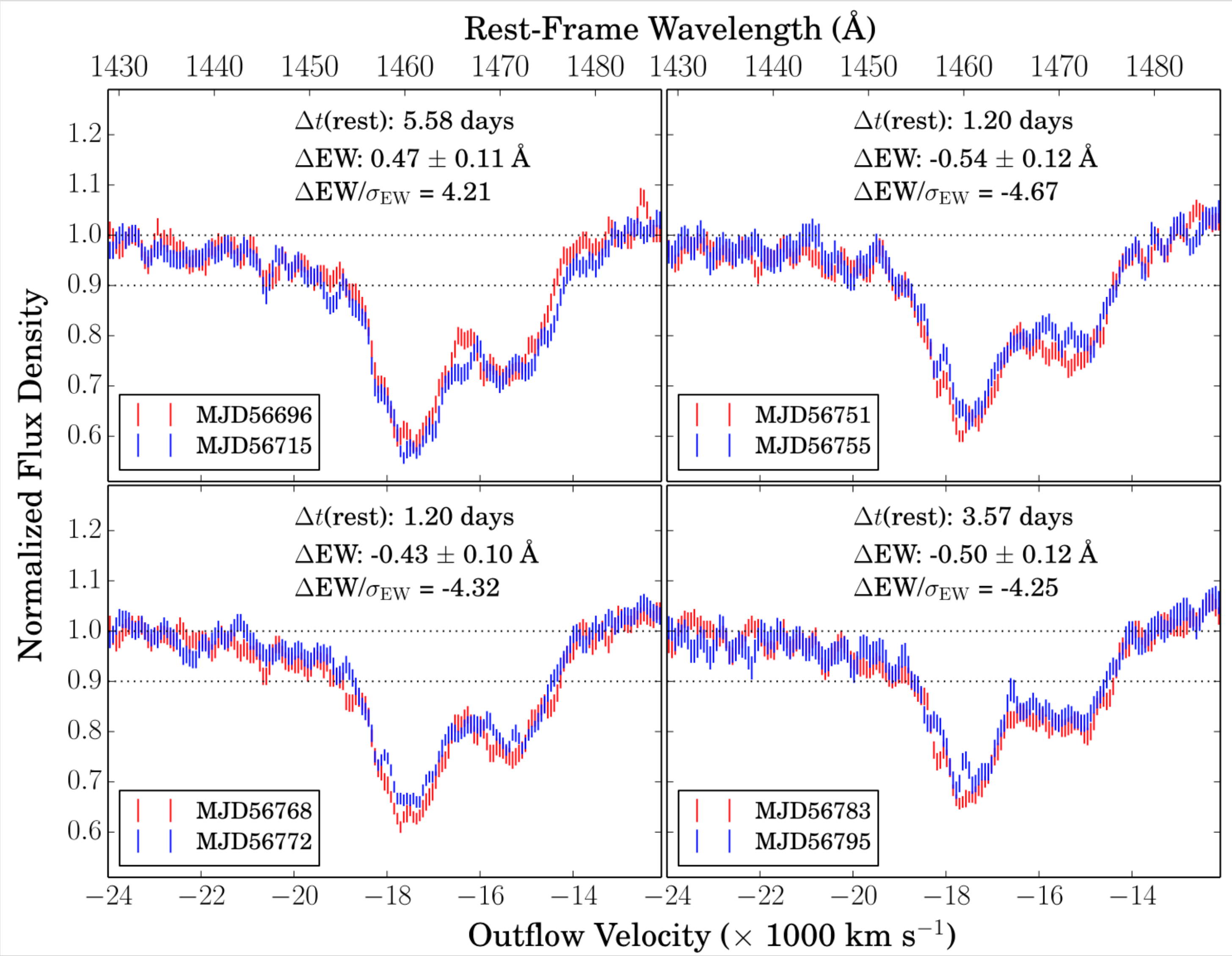
Trough A varies strongly; factor of ~ 2.

Troughs A and B correlated.

Also signs of variable absorption in N V, Al III, Si IV.

Observed rest-frame UV continuum varies by only ~ 10%.

Fastest Observed Variability



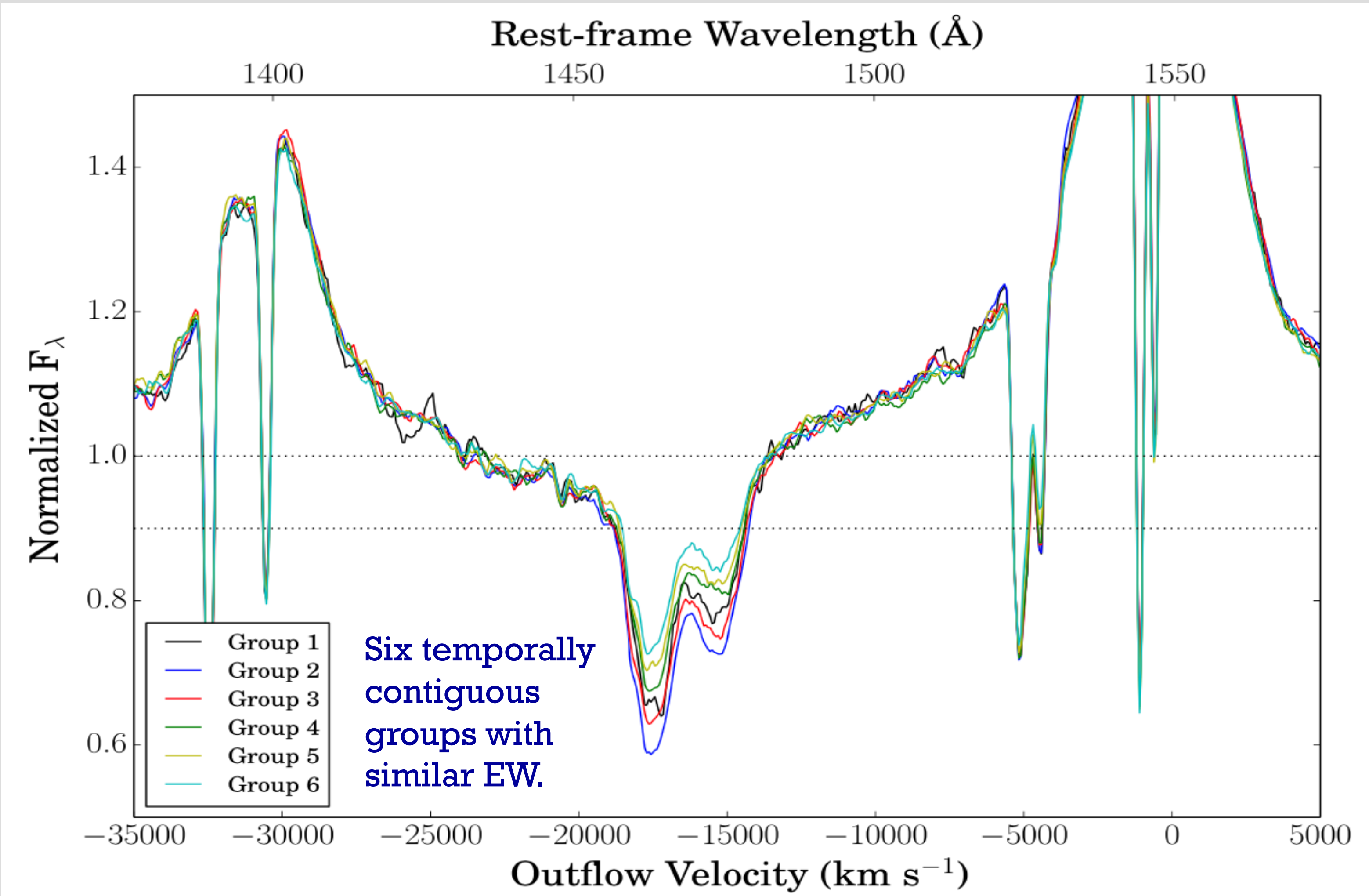
Grier et al. (2015)

Require EW variations significant at 4σ level.

EW variations seen down to 1.2 days (29 hrs) at 10% level.

Compare with 8-10 days in Capellupo et al. (2013).

Trough Profile Shape



Trough A changes in coordinated manner across its entire velocity span.

Interpretation and Ongoing Work

Ionization changes appear the likely variability driver:

- Global variations across entire trough (4340 km s^{-1} wide)
- Troughs A and B show coordinated variability

EUV continuum must be much more variable than rest-frame UV continuum – intrinsic changes or shield changes.

Hemler et al. investigating rapid BAL variability in the SDSS-RM field systematically.

Future Prospects

Lots More Variability Work to Do in the Short Term!

BAL vs. continuum, emission-line, and reddening variability.

Large-sample studies of low-ionization BAL variability.

Further constraints on BAL acceleration, and follow-up of acceleration candidates.

Systematic survey of rapid BAL variability.

X-ray and multiwavelength follow-up of remarkable BAL variability events – e.g., disappearance and emergence.

After SDSS-IV – AS4

AS4[1] Executive Summary

Juna Kollmeier (AS4 Director) and the AS4 Science Management Team

AS4 is the ***first all-sky, time-domain spectroscopic survey***, with observational capabilities that will remain unmatched for the foreseeable future. This unique survey facility is poised to transform broad areas of astrophysics, in particular: understanding the formation of our Milky Way and other galaxies, along with the astrophysics of stars and of supermassive black holes.

In one flagship program, AS4 will provide spectroscopic data for stars across the Milky Way. This survey is unrivaled in its combination of sky coverage, time sampling, and systematic target selection throughout our Galaxy, enabled by dual-hemisphere, wide-field infrared spectroscopy. From this, we will:

- Understand the **genesis of our Galaxy** by acquiring
  - a first **global** picture of Milky Way structure and dynamics, placing our Galaxy precisely in the overall realm of galaxies,
  - comprehensive constraints on the evolutionary processes that shaped our Milky Way and other galaxies, and
  - a map of when and where the broad range of chemical elements were created in our Galaxy.
- Take the understanding of fundamental **stellar physics**, the pillar upon which much of astrophysics rests, to a new level. In combination with the *Gaia*, *Kepler* and TESS space missions, AS4 will transform our understanding of
  - the origin of supernovae,
  - the difference between planet-hosting and non-hosting stars,
  - binary stars across the Hertzsprung-Russell diagram -- as witnesses to star-formation physics, as drivers of stellar evolution and as laboratories to test stellar evolution, and
  - young, massive stars, through a vast sample of (near-IR) spectra.

At the same time, AS4 will open new frontiers in extragalactic astrophysics: it will enable us to understand **quasars as dynamical phenomena** -- through both reverberation mapping and direct black hole mass estimates from multi-epoch spectroscopy that samples time-scales from days to more than a decade. In addition, AS4 will be the only dual-hemisphere spectroscopic complement to the eROSITA mission, unveiling the nature of **X-ray sources** that shine brightly across the sky.

All-sky, time-domain spectroscopic survey (about 2020-2025).

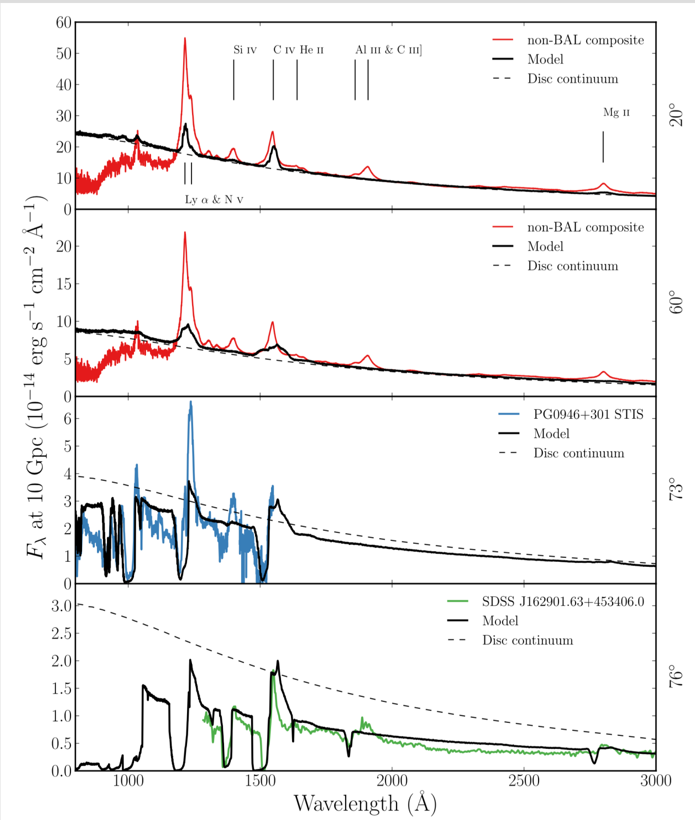
A key component is quasars as dynamical phenomena:

- Reverberation mapping
- General multi-epoch spectroscopy

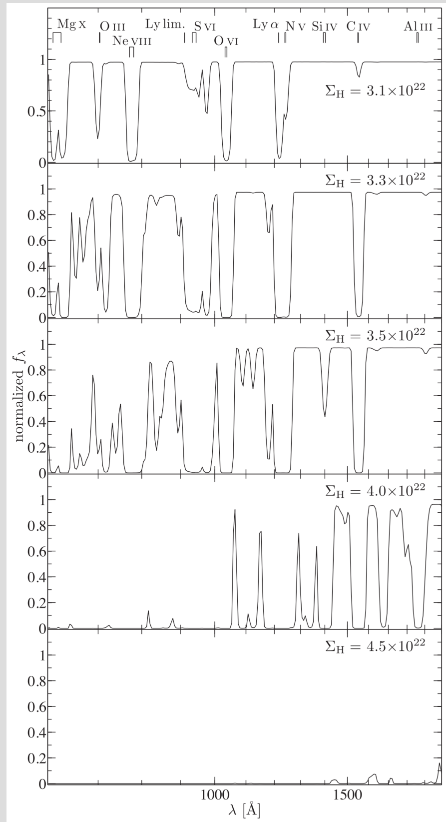
May 31 is the deadline for full bonus credit on project contributions.

Better Variability Simulations

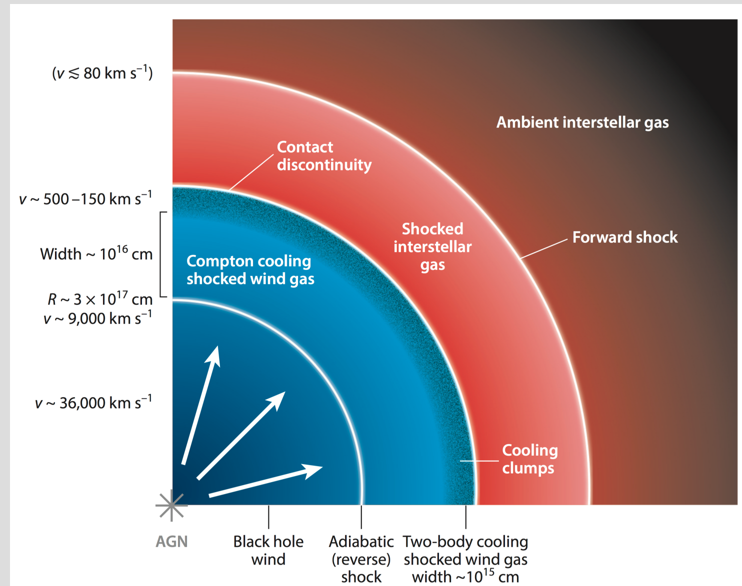
Matthews et al. (2015)



Baskin et al. (2014)



King & Pounds (2015)



Corresponding improvements in BAL variability simulations needed to utilize the flood of new variability data most effectively.

Especially need simulations making *observationally testable* predictions.

The End