Quasars: Some Answers, More Questions

Pat Hall (York University)

- Background
- Broad Emission Lines
- Accretion Disk Winds
- Broad Absorption Line Variability

Disclaimer: I should really use the term 'AGN' (Active Galactic Nucleus) herein instead of 'quasar', because 'quasar' usually refers to only luminous AGN. However, I prefer to spend my career working on a made-up word rather than on an acronym.

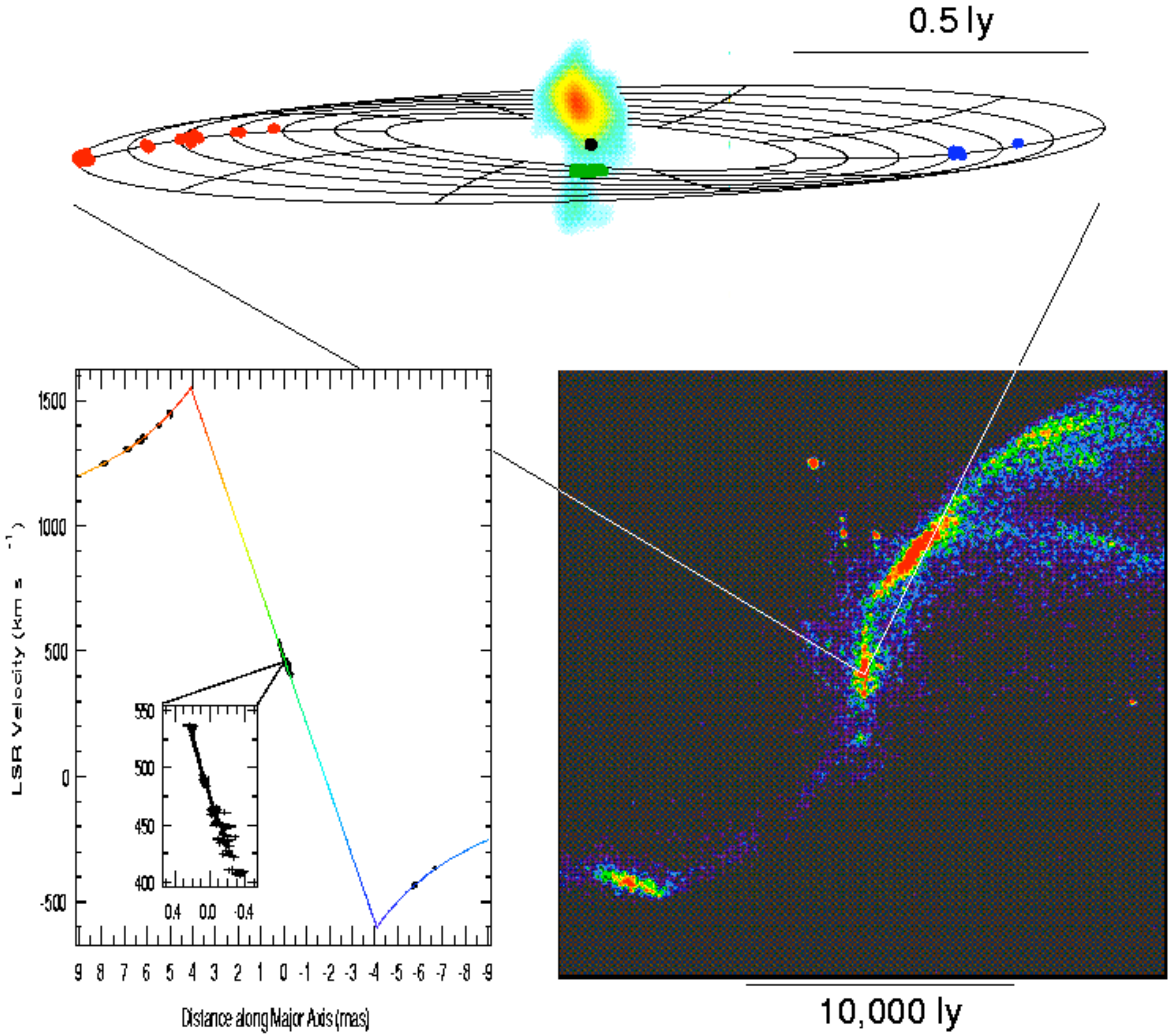
Quasars: do we understand them?

- A quasar is a process, not a thing. It's what happens when matter spirals into a supermassive black hole through an accretion disk. The matter heats up through a kind of friction. Different annuli in the disk emit thermal radiation at different temperatures, with blackbody peaks ranging from the far-ultraviolet to the mid-infrared. (X-ray, radio emission arise from different mechanisms.)

Evidence for an accretion disk: NGC 4258

- Nucleus of NGC 4258 shows water masers
- Certain rotational states of the water molecule are easily populated, leading to population inversions and masing
- Masing generates very strong, pointlike emission at a very specific frequency, yielding very accurate position and velocity maps of the nuclear region...

Evidence for an accretion disk: NGC 4258



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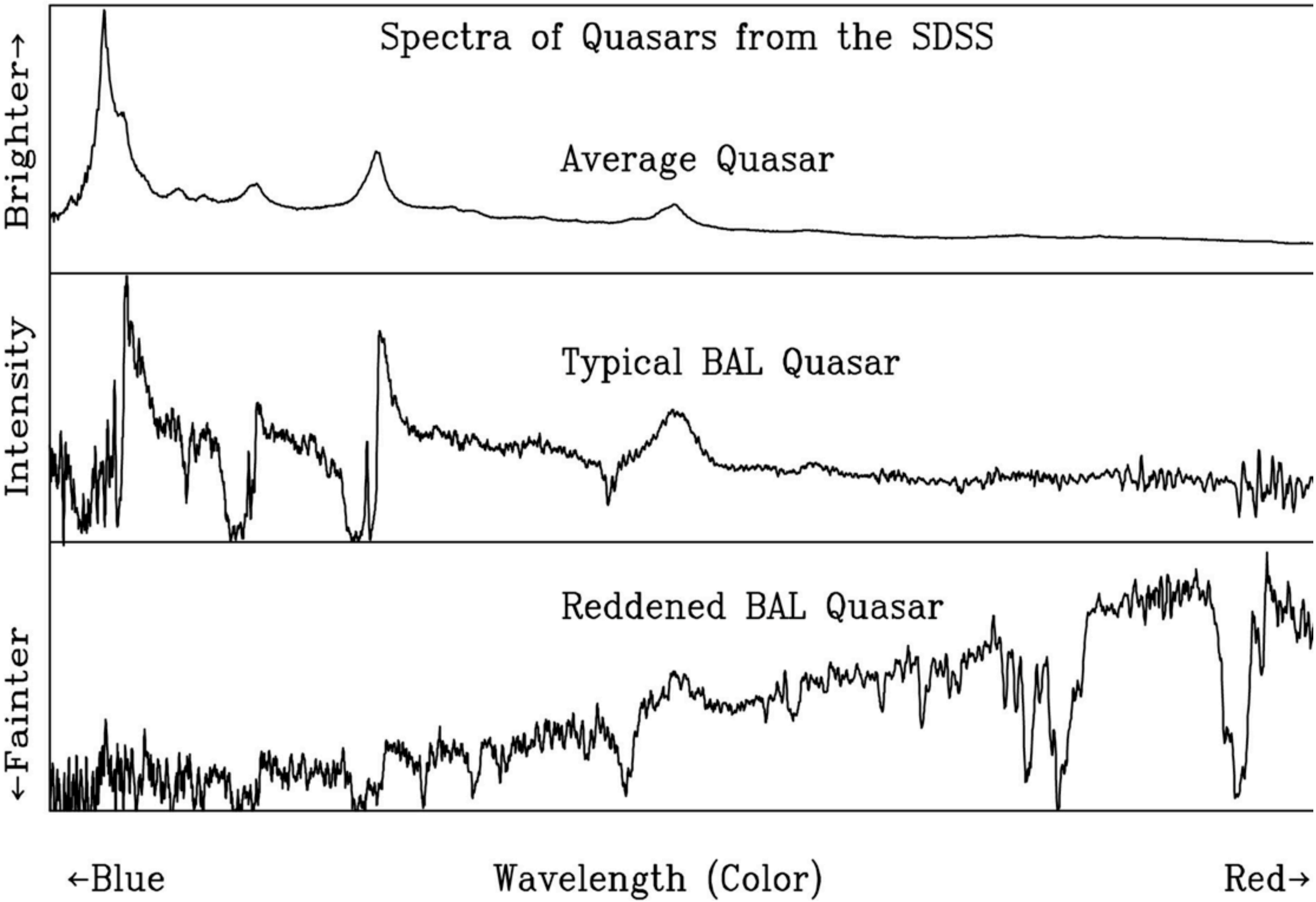
- The resulting UV-through-optical quasar spectrum is a power-law continuum w/broad (10^4 km/s) emission lines sometimes w/outflowing broad absorption lines (BALs).


Spectra of Quasars from the SDSS
Average Quasar
Typical BAL Quasar
Reddened BAL Quasar
Brighter→
Intensity
←Fainter
←Blue
Wavelength (Color)
Red→

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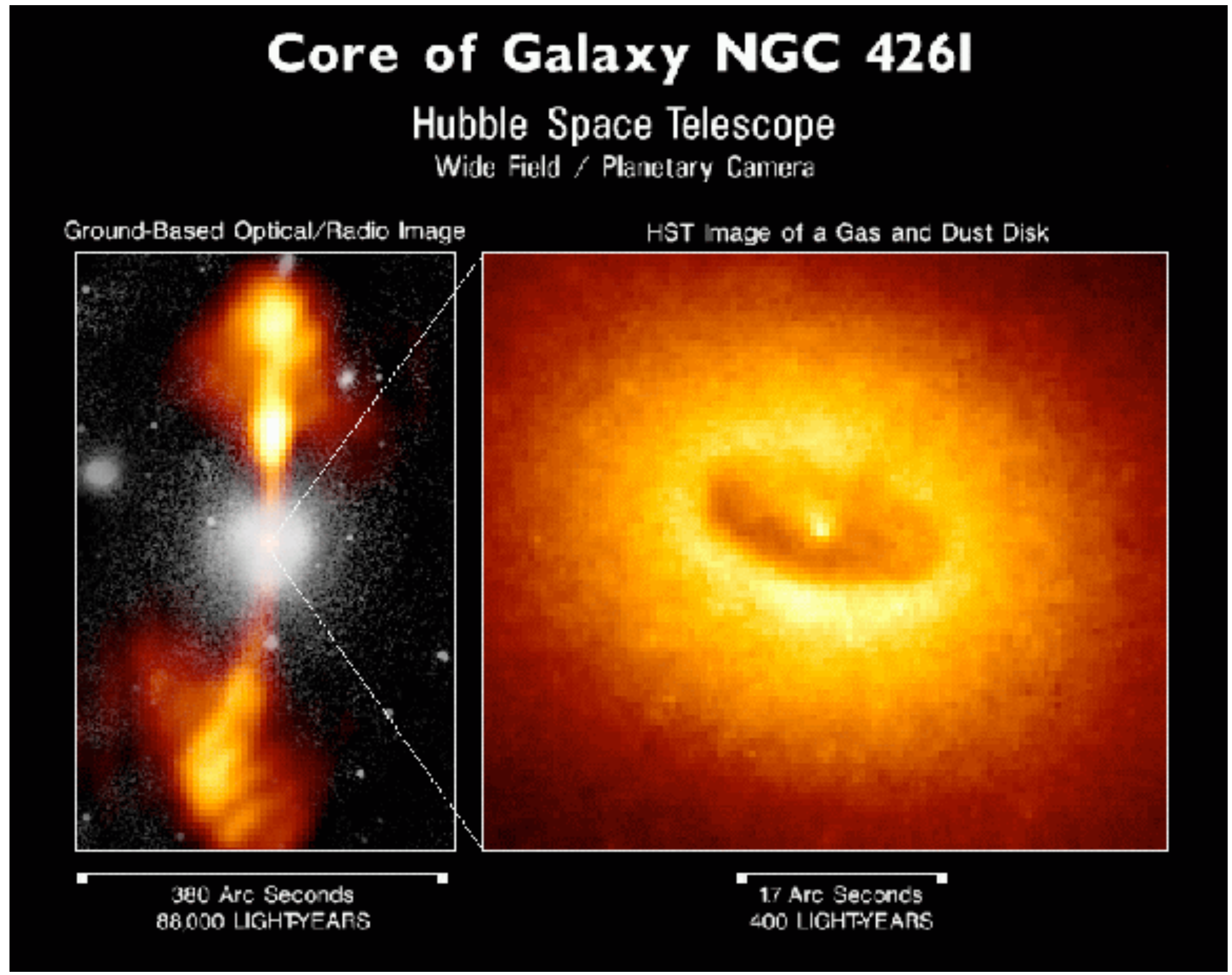
- *The resulting UV-through-optical quasar spectrum is a power-law continuum plus broad (10^4 km/s) emission lines.*

- Quasars cannot (yet) be resolved at optical/UV/X-ray wavelengths. What we know about their structure at such wavelengths is by inference (e.g., from spectra).

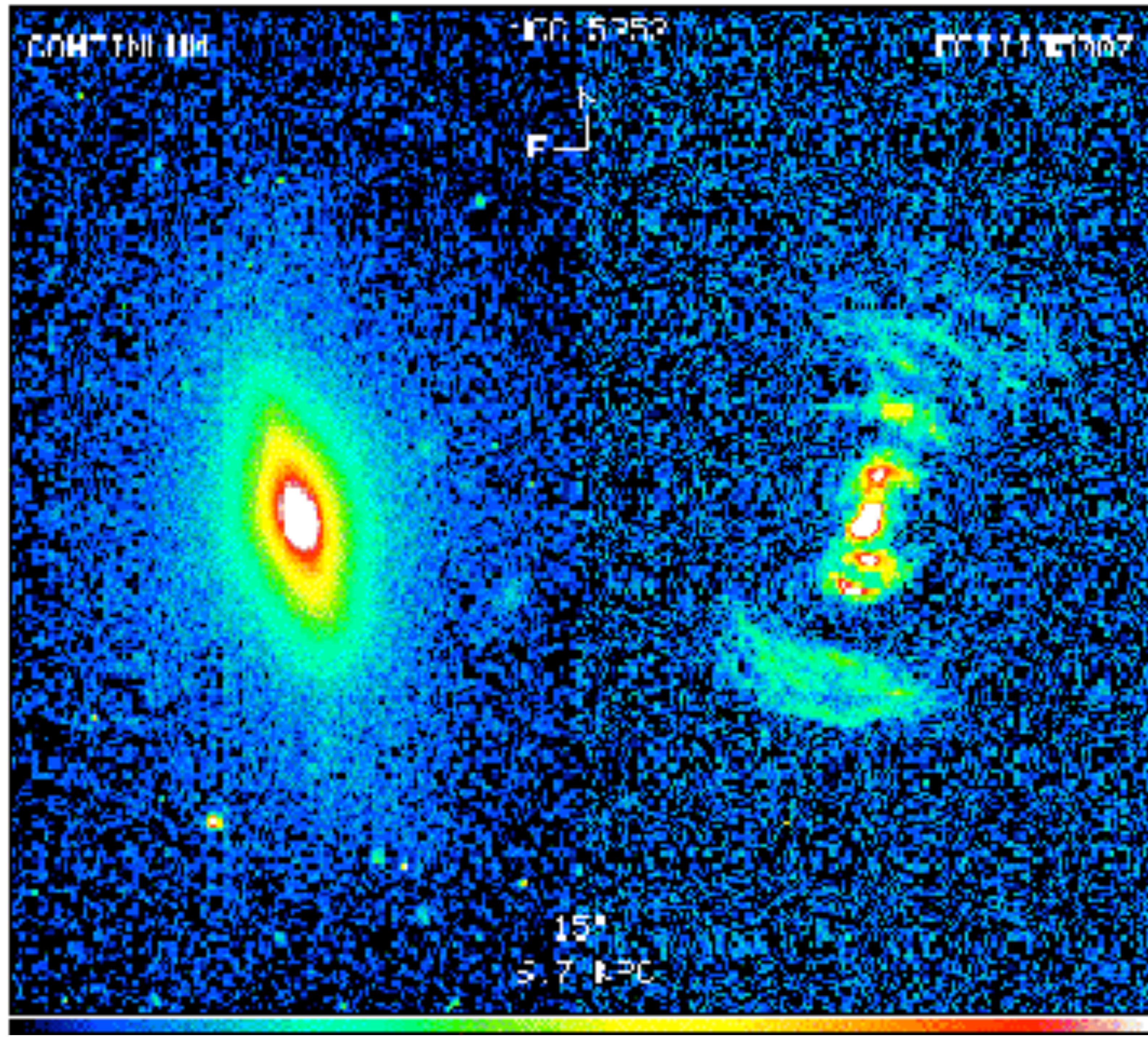
OK, but why should we care?

- Black hole environments are laboratories for testing general relativity
- Complicated physics of accretion disks is relevant to the formation of solar systems
- Quasars affect galaxy formation



Inferred Quasar Structure

- Opaque accretion disk (with inner X-ray-emitting region)
- Polar radio jets
- UV-absorbing outflows at a range of latitudes
- 'Torus' (equatorial obscuration by gas and dust, *right*)



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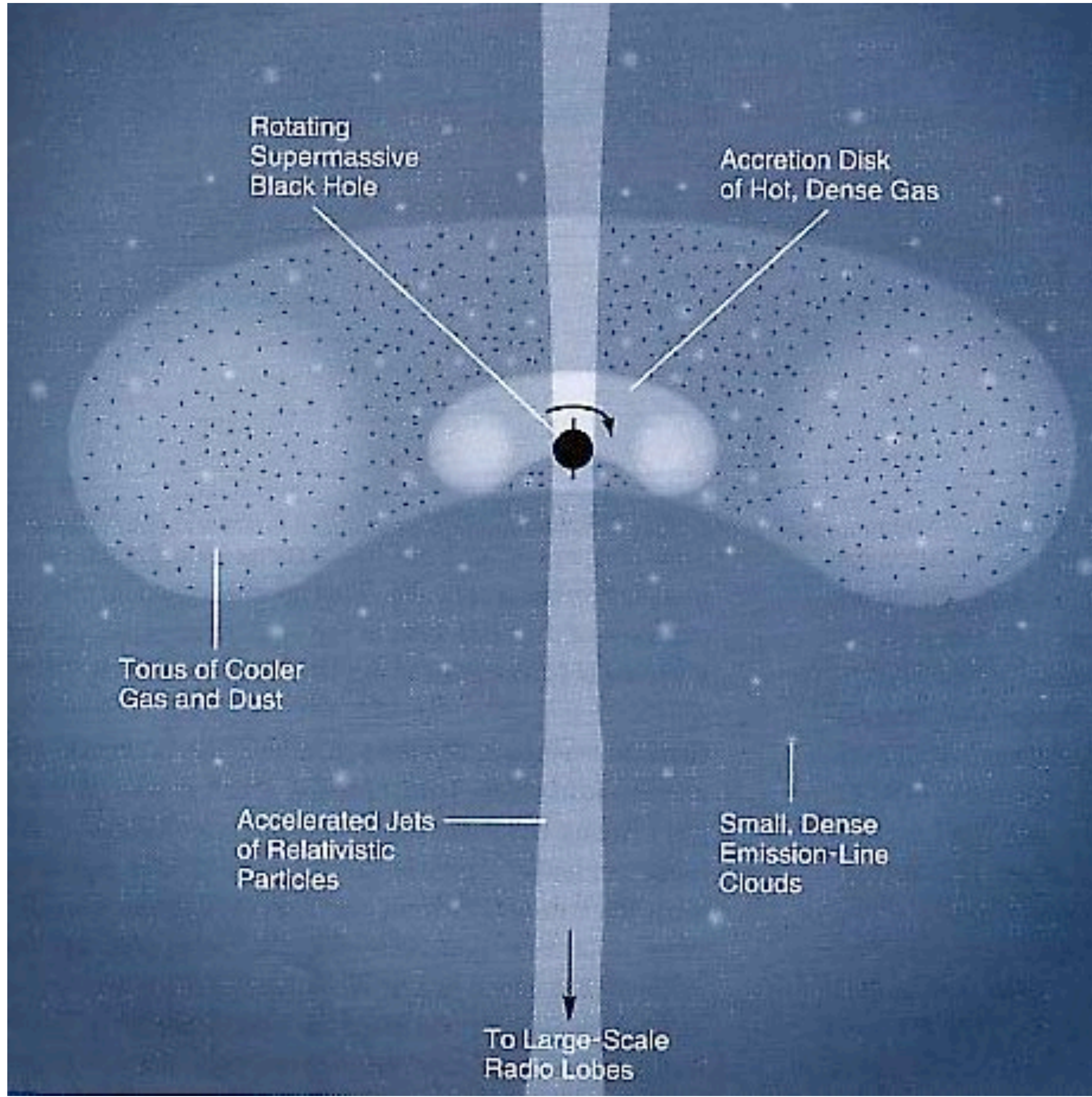
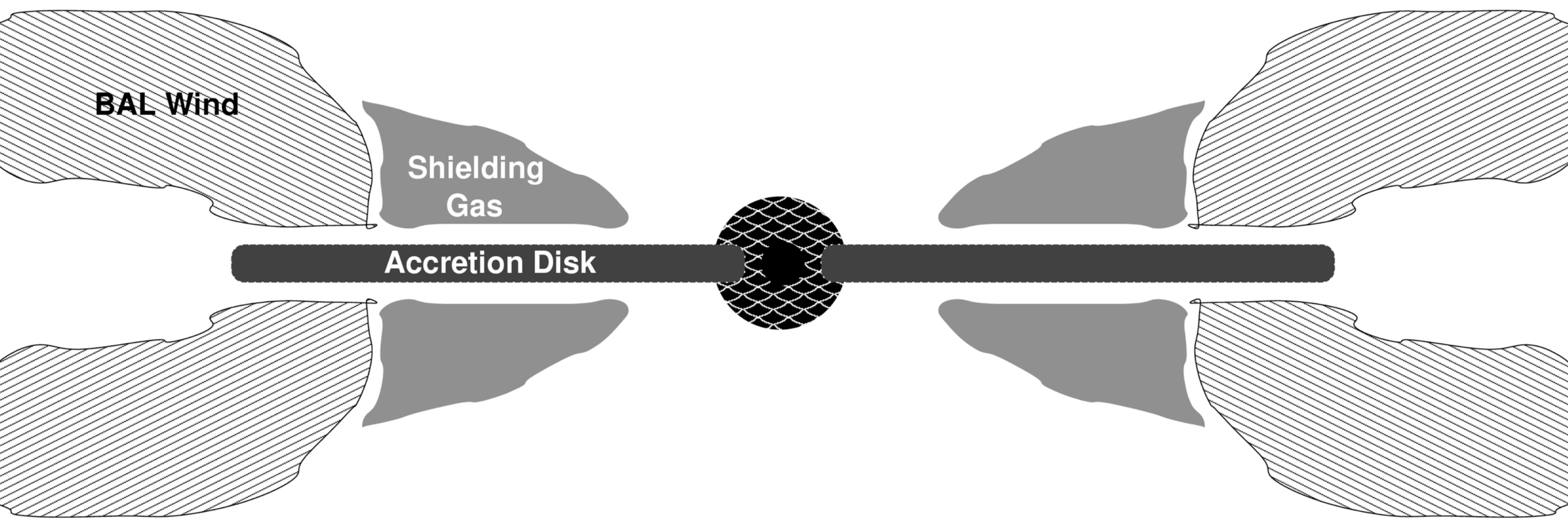


Possible Accretion Disk Structure

- Circle represents inner accretion disk, source of X-ray emission; UV emission from radii just beyond that
- Shielding gas (failed wind) overionized by X-rays
- Broad Absorption Line (BAL) Wind accelerated by scattering of UV photons



Quasar spectra: what we know

- Typical quasar spectrum is a non-thermal continuum plus broad emission lines (10^3-10^4 km/s FWHM) from various ions Ly-α, Si IV, C IV, C III], Mg II, H-β, H-α, etc.
- Broad absorption lines (BALs) seen in ~23% of quasars; similar range of widths, outflow velocities up to 0.2c.
- Broad emission lines (BELs) usually single-peaked.

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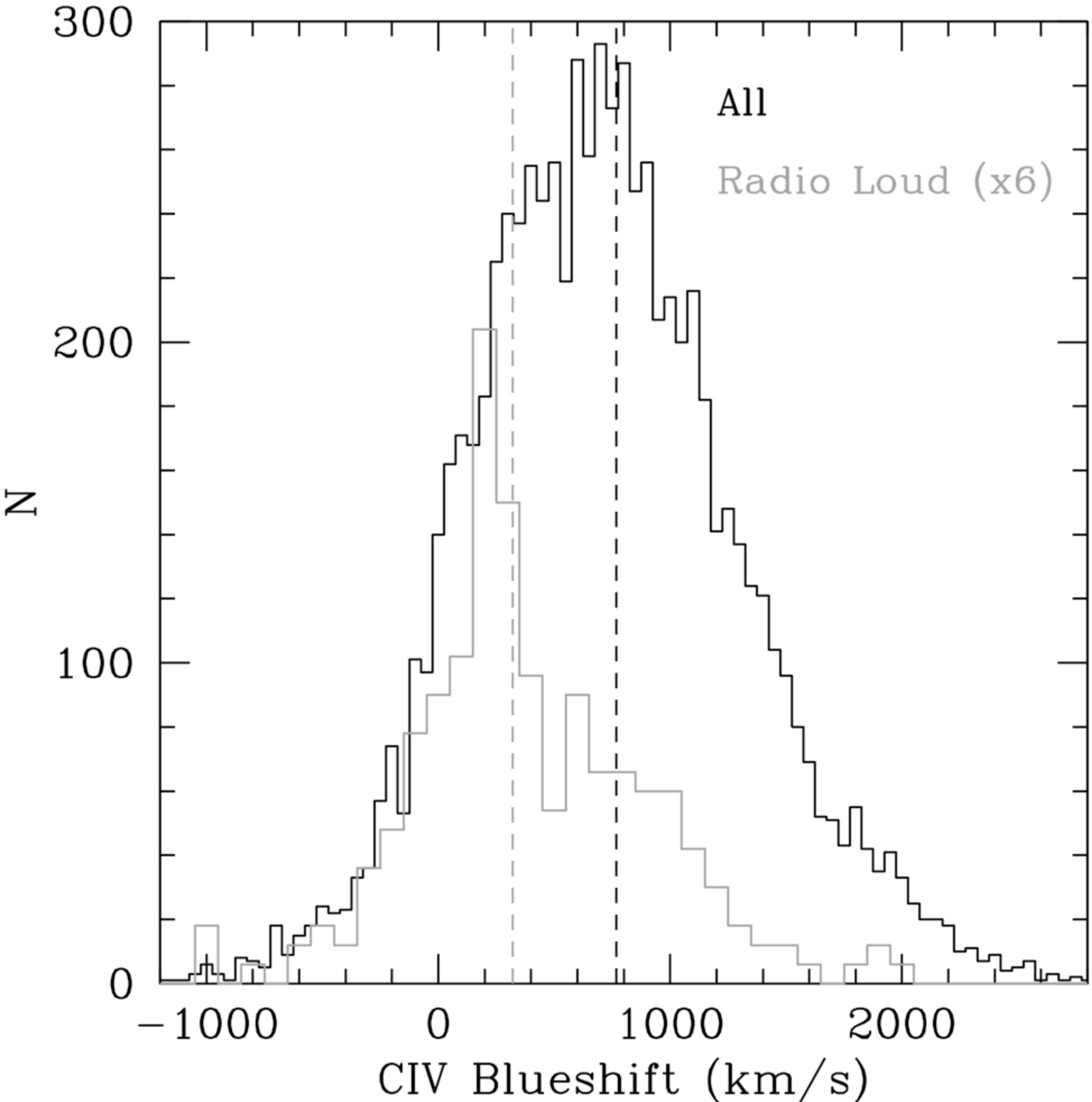
- *Broad absorption lines (BALs) seen in ~23% of quasars; similar range of widths, outflow velocities up to 0.2c.*
- *Broad emission lines (BELs) usually single-peaked.*
- Higher-ionization lines are emitted closer to the ionizing continuum source, and are broader
- Higher-ionization emission lines usually blueshifted from the quasar host galaxy redshift (≈ the Mg II redshift)

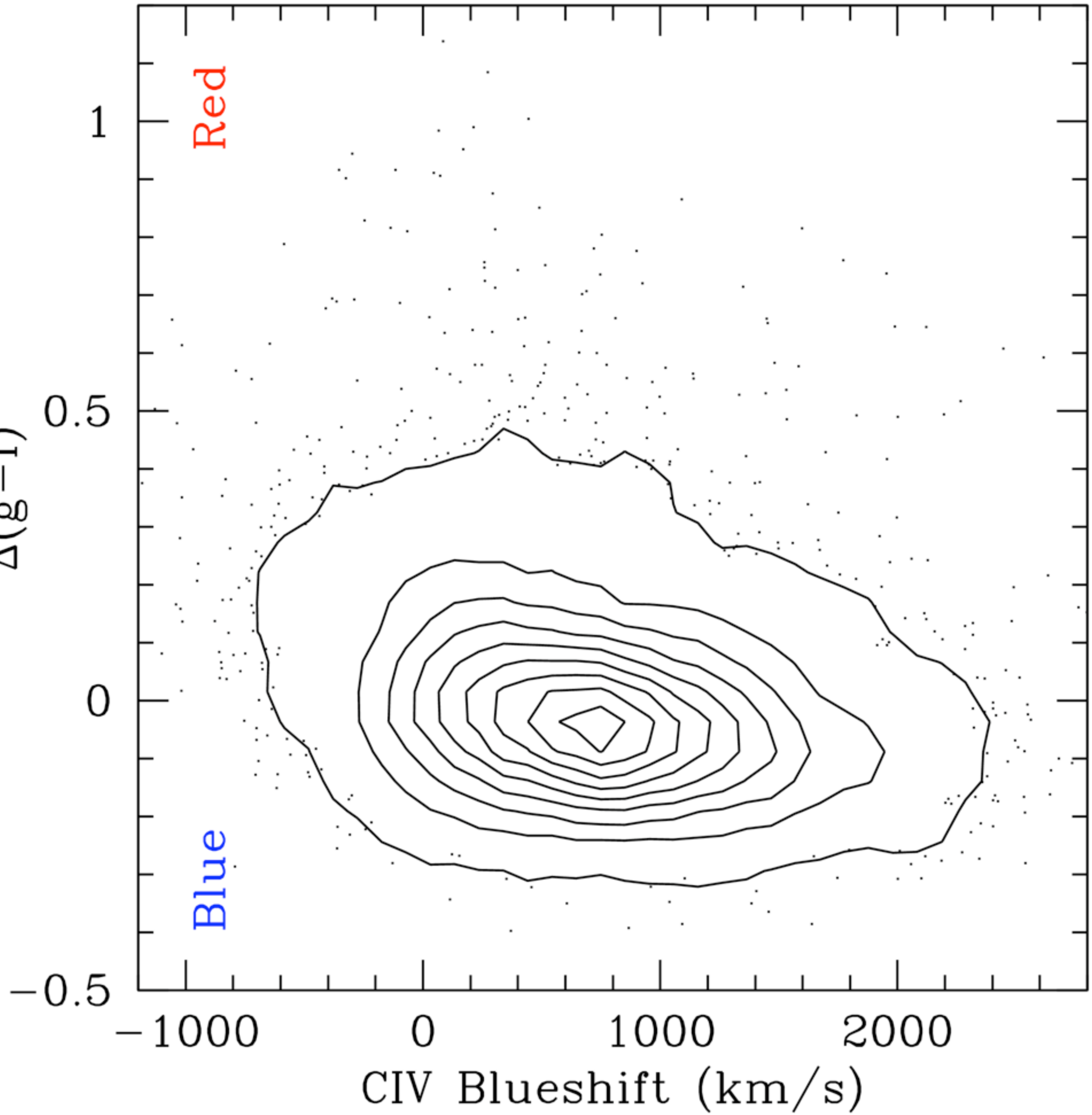
Sloan Digital Sky Survey Data

- 2.5m diameter telescope
- Digital survey of 20% of the sky in 5 wavelength bands
- Spectroscopy of 1 million galaxies and 100,000 quasars
- Now operating as SDSS-III

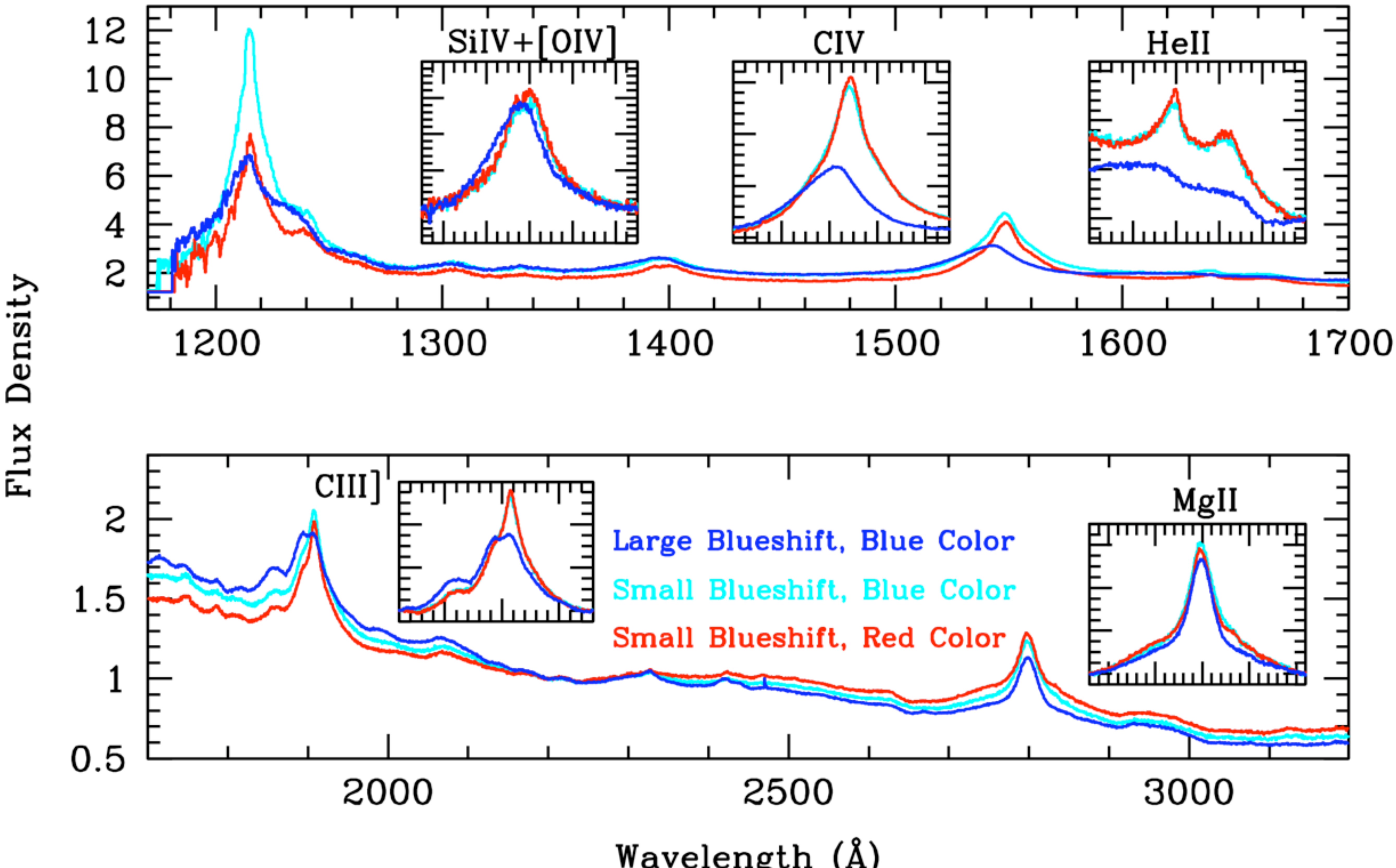


C IV emission line peak is usually blueshifted from the Mg II peak. Average blueshift is ~800 km/s.

- Quasars with large C IV blueshifts tend to have bluer than average continuum colors



Red
Blue
Δ(g−i)
1
0.5
0
−0.5
−1000
0
1000
2000
CIV Blueshift (km/s)



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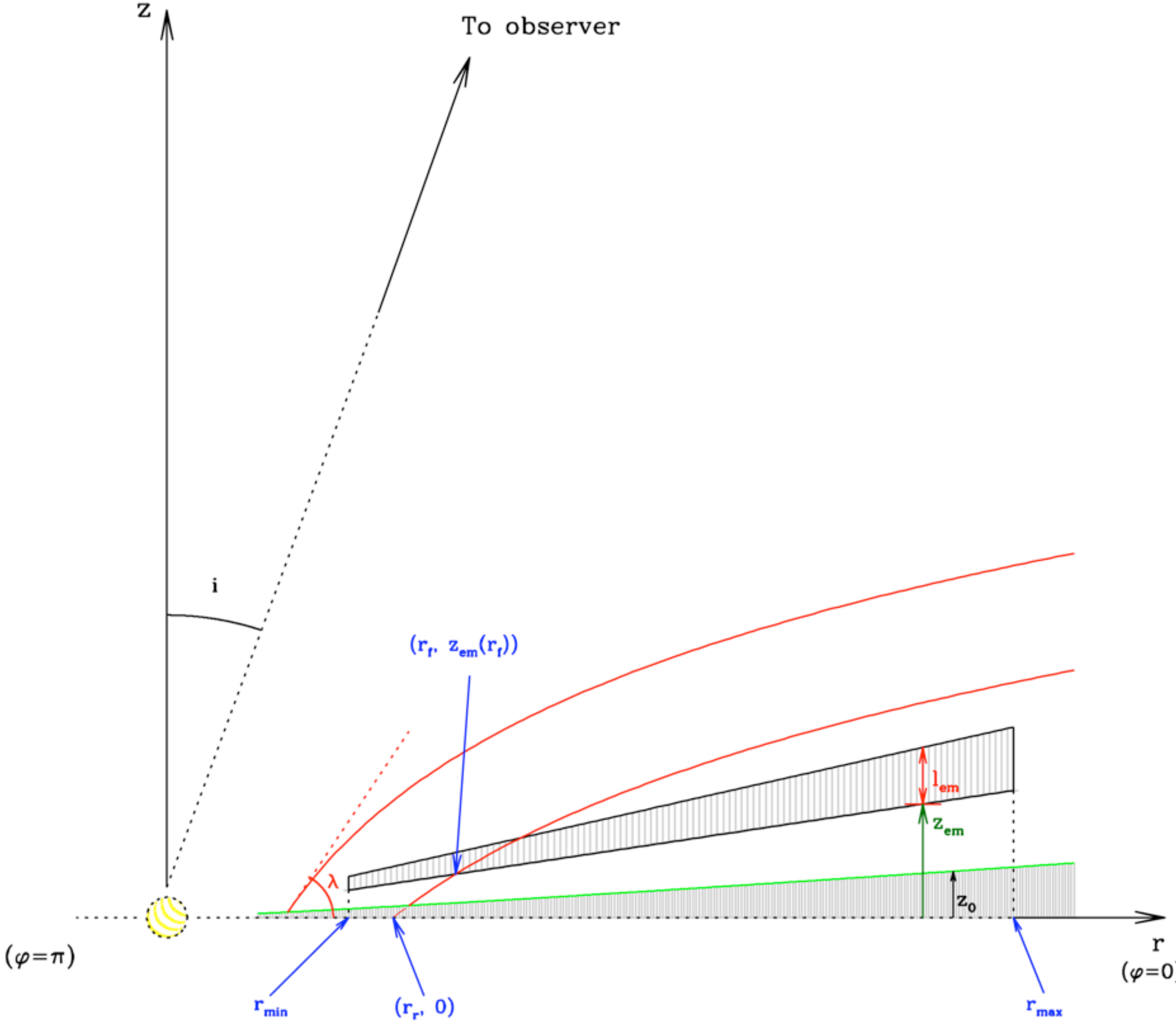
- *Quasars with large C IV blueshifts tend to have bluer than average continuum colors*
- Emission-line properties (usefully?) connected to accretion disk properties

BEL region = Accretion Disk?

- Outflowing gas above an accretion disk is called a disk wind.
- Gas in the atmosphere of a flared accretion disk can be ionized by the inner disk. The gas initially shares the rotational velocity of the disk, but is subject to acceleration by radiation pressure and magnetic field effects (magnetohydrodynamics).
- One quadrant of a disk + wind + BEL region, seen in cross-section:



z
To observer
i
$(r_f,\ z_{em}(r_f))$
λ
l_{em}
z_{em}
z_0
$(\varphi=\pi)$
r
$(\varphi=0)$
r_{min}
$(r_r,\ 0)$
r_{max}

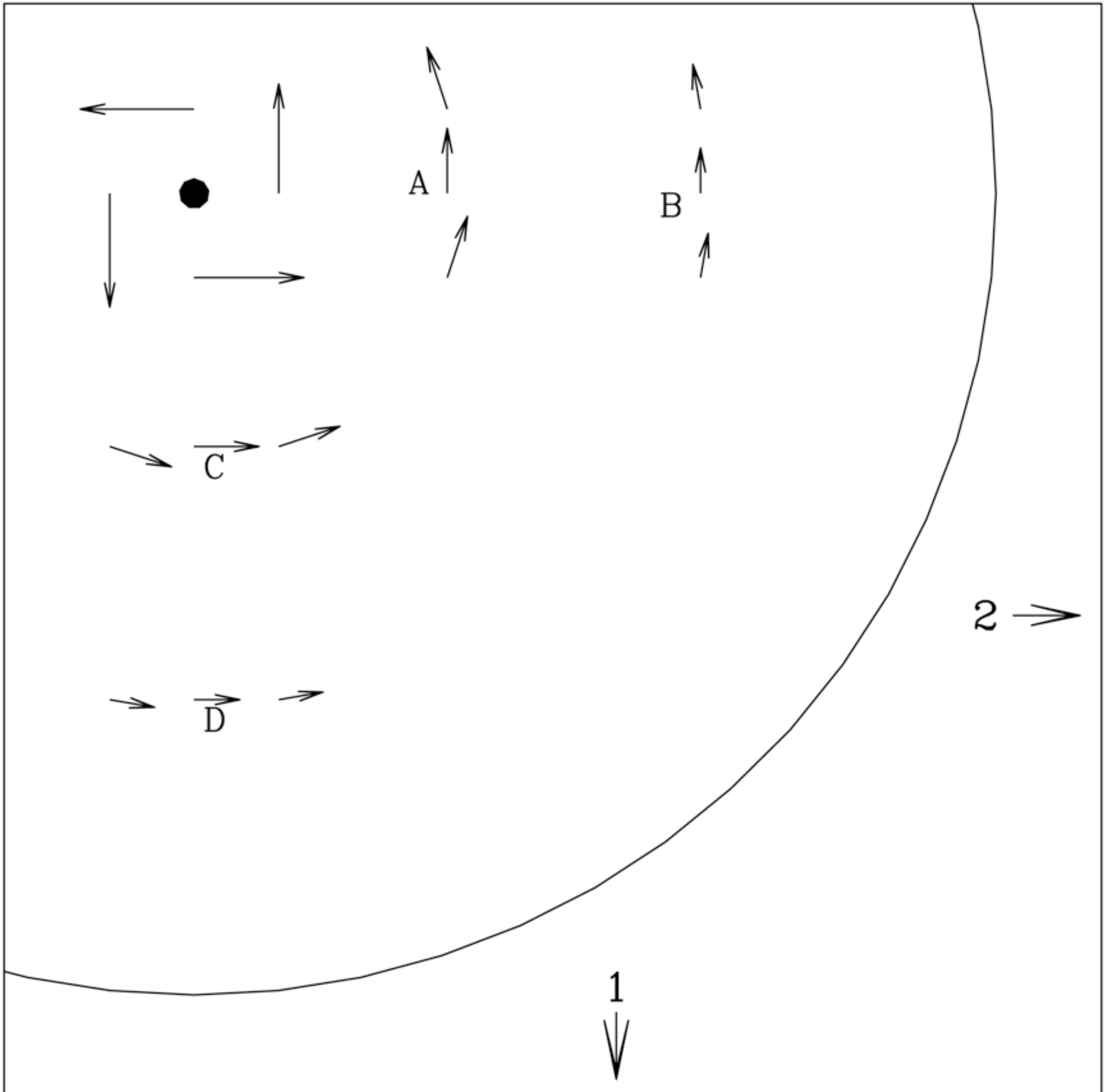
BEL region = Accretion Disk?

- *Outflowing gas at low latitudes above an accretion disk is called a disk wind.*
- *Gas in the atmosphere of a flared accretion disk can be ionized by the inner disk. The gas initially shares the rotational velocity of the disk, but is subject to radiative and magnetohydrodynamic acceleration.*
- But if the BELs come from a rotating disk, why don’t we see redshifted & blueshifted peaks in each line?

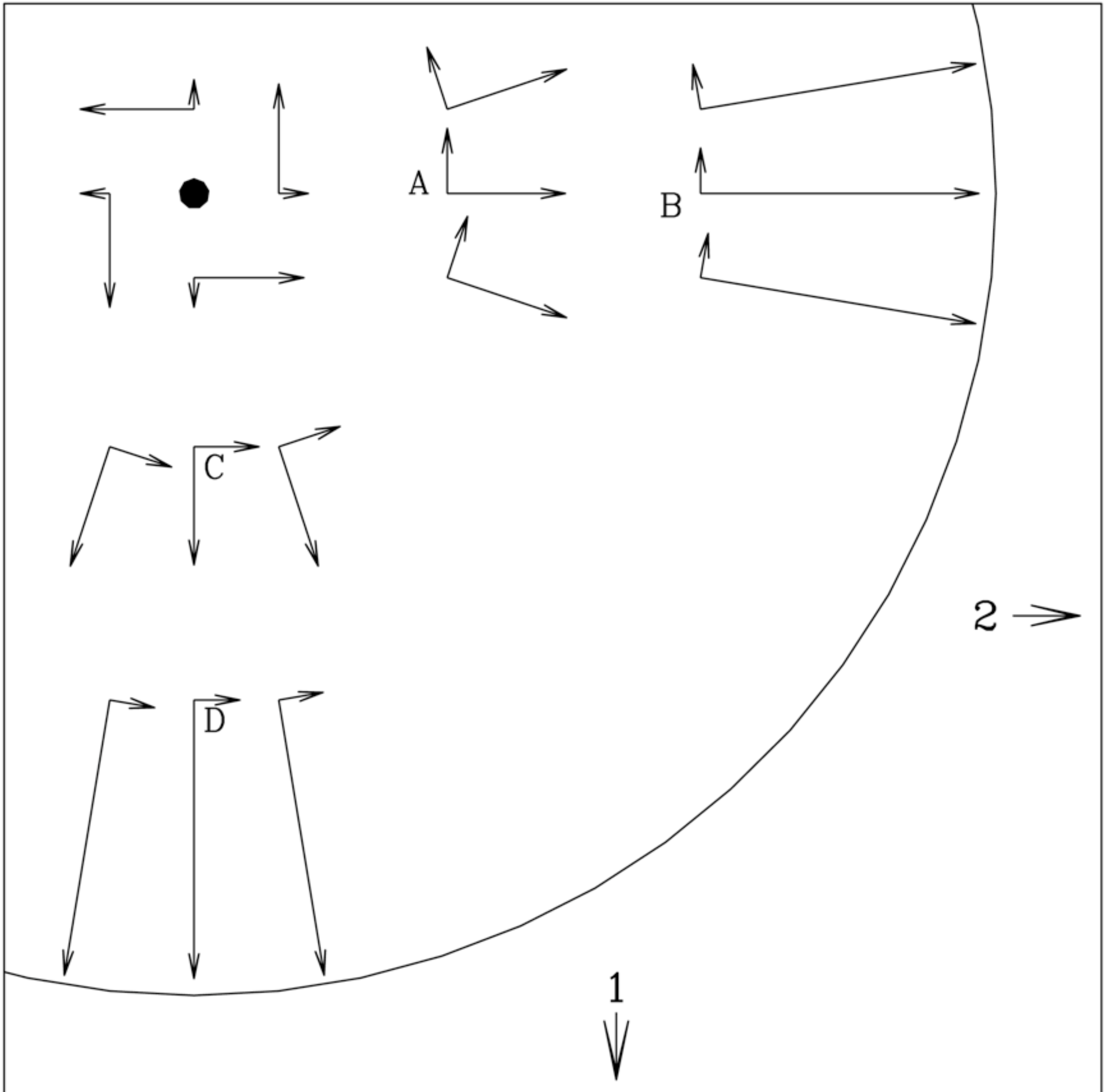
- Answer derives from the fact that line photons (with their specific wavelengths) are much more easily absorbed or scattered than continuum photons with different wavelengths, unless the velocity gradient of the gas is large.

BEL region = Accretion Disk?

- *Gas in the atmosphere of a flared accretion disk can be ionized by the inner disk. The gas initially shares the rotational velocity of the disk, but is subject to radiative and magnetohydrodynamic acceleration.*
- *But if the BELs come from a rotating disk, why don't we see redshifted & blueshifted peaks in each line?*
- Murray & Chiang & collaborators (1995,1997,1998): the base of a radially accelerating disk wind optically thick in a line produces single-peaked emission lines: <u>most line photons escape in directions where the velocity gradient is large</u> (green arrows in following):



A
B
C
D
2
1



A
B
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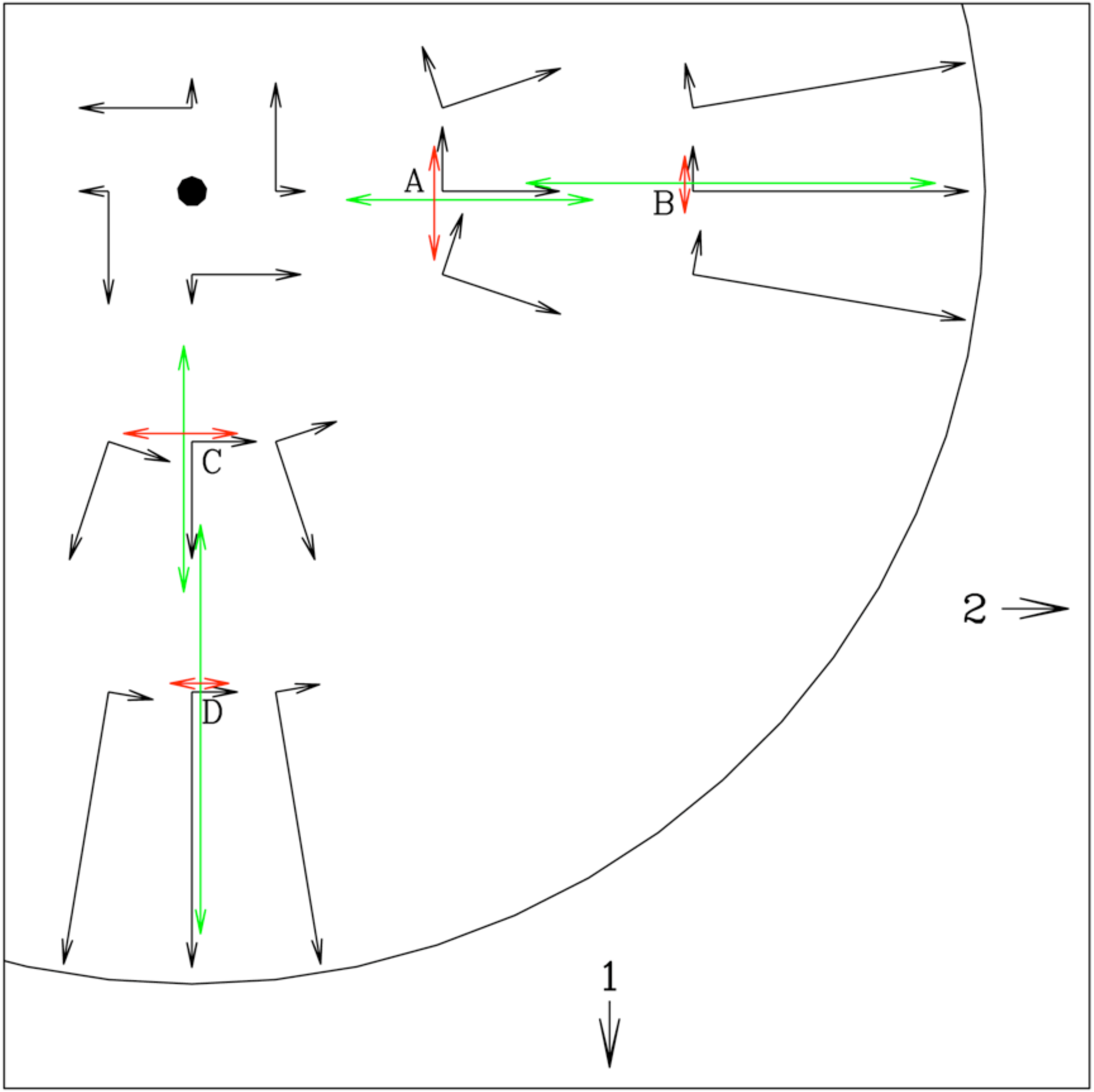
D
2
1



A
B
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BEL region = Accretion Disk?

- *Murray & Chiang & collaborators (1995,1997,1998) showed that the base of a radially accelerating disk wind which is optically thick to line photons produces single-peaked emission lines. We see line photons primarily from directions with a large line-of-sight gradient of the line-of-sight velocity.*
- However, their lines had blueshifts of only ~80 km/s.
- We have corrected and extended the MC formalism to allow for non-negligible radial and vertical velocities.

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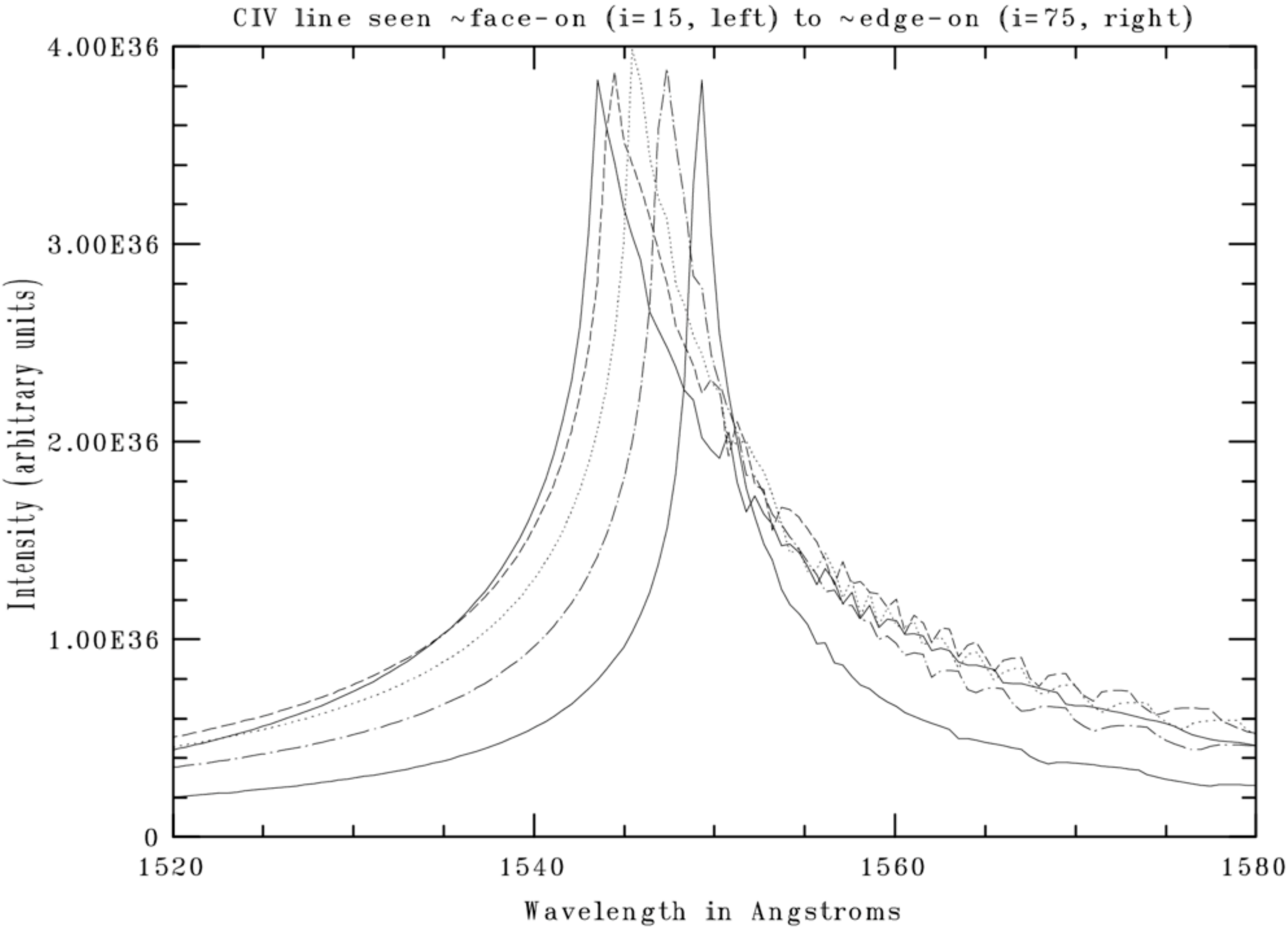
- *However, their lines had blueshifts of only ~80 km/s.*
- *We have corrected and extended the MC formalism to allow for non-negligible radial and vertical velocities.*
- Our goal is to find regions of parameter space which produce emission lines matching those of real quasars.

Matching Observations

- We can produce large blueshifts.


CIV line seen ~face-on (i=15, left) to ~edge-on (i=75, right)
4.00E36
3.00E36
2.00E36
1.00E36
0
Intensity (arbitrary units)
1520
1540
1560
1580
Wavelength in Angstroms

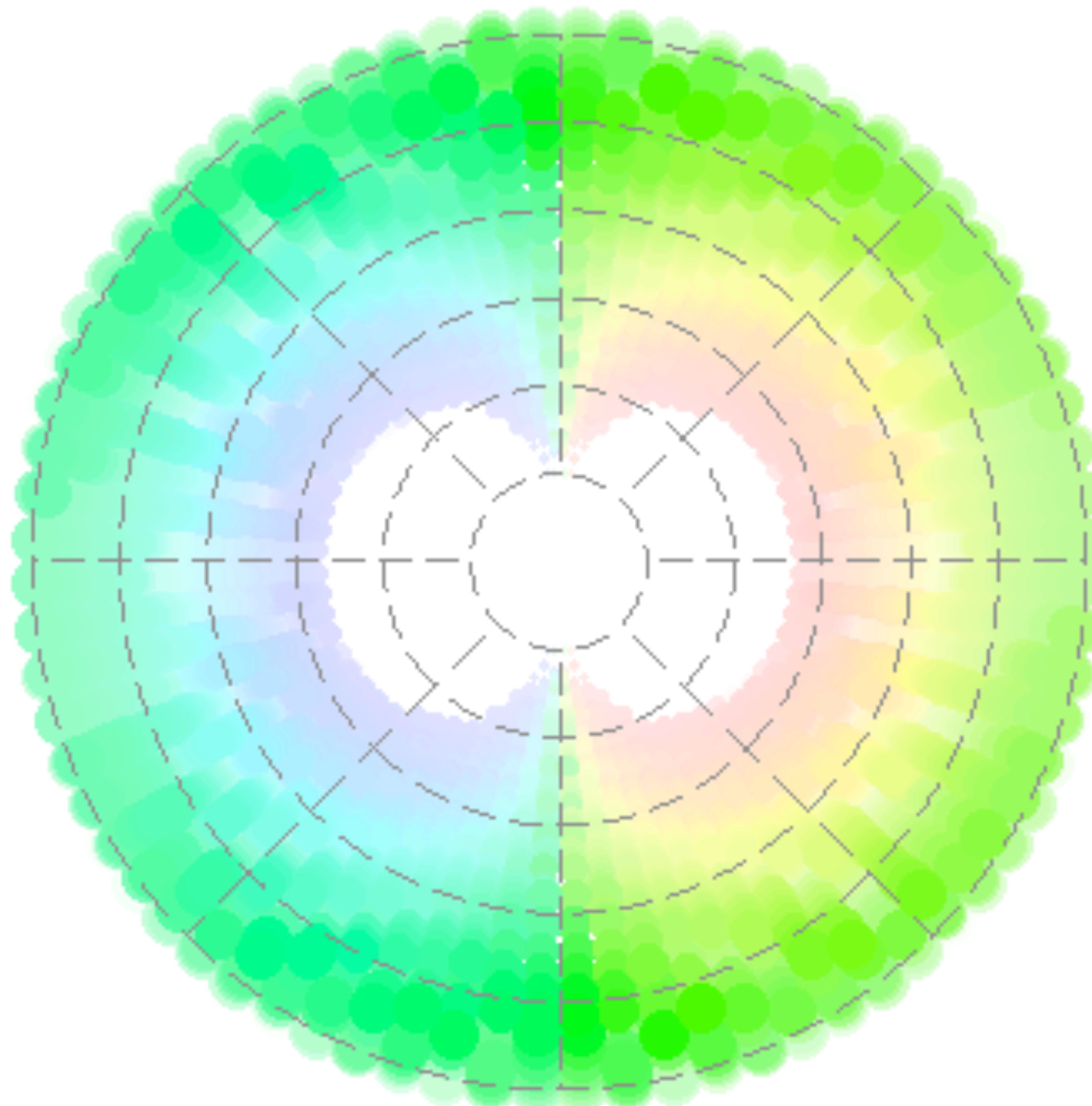
Matching Observations

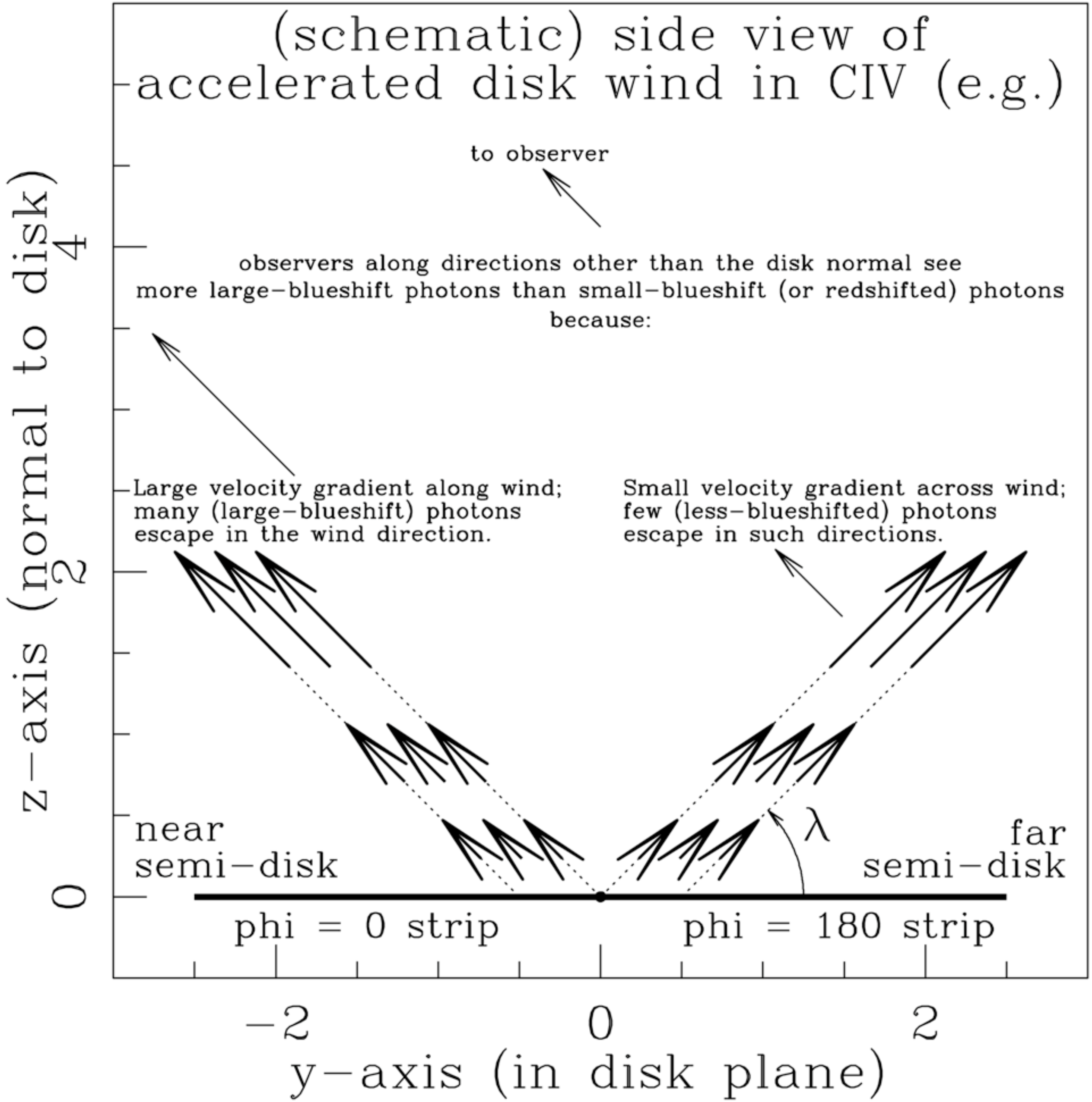
- *We can produce large blueshifts.*
- For a proof of concept we want to simultaneously match line profiles.
- Lots of parameter space to investigate!

Visualizing Line Emission

- I'm going to show deprojected maps of optically thick line emission from the base of a particular disk wind
- Blue colors indicate blueshifts, reds indicate redshifts
- A pixel's brightness gives its emission strength on a logarithmic scale (emissivities as a function of radius taken from photoionization simulations done by MC97)
- The observer is off the bottom of the page
- Radial contours are logarithmically spaced by factors of ten; innermost contour is at 10^{15} cm (around a black hole of 4 billion solar masses)

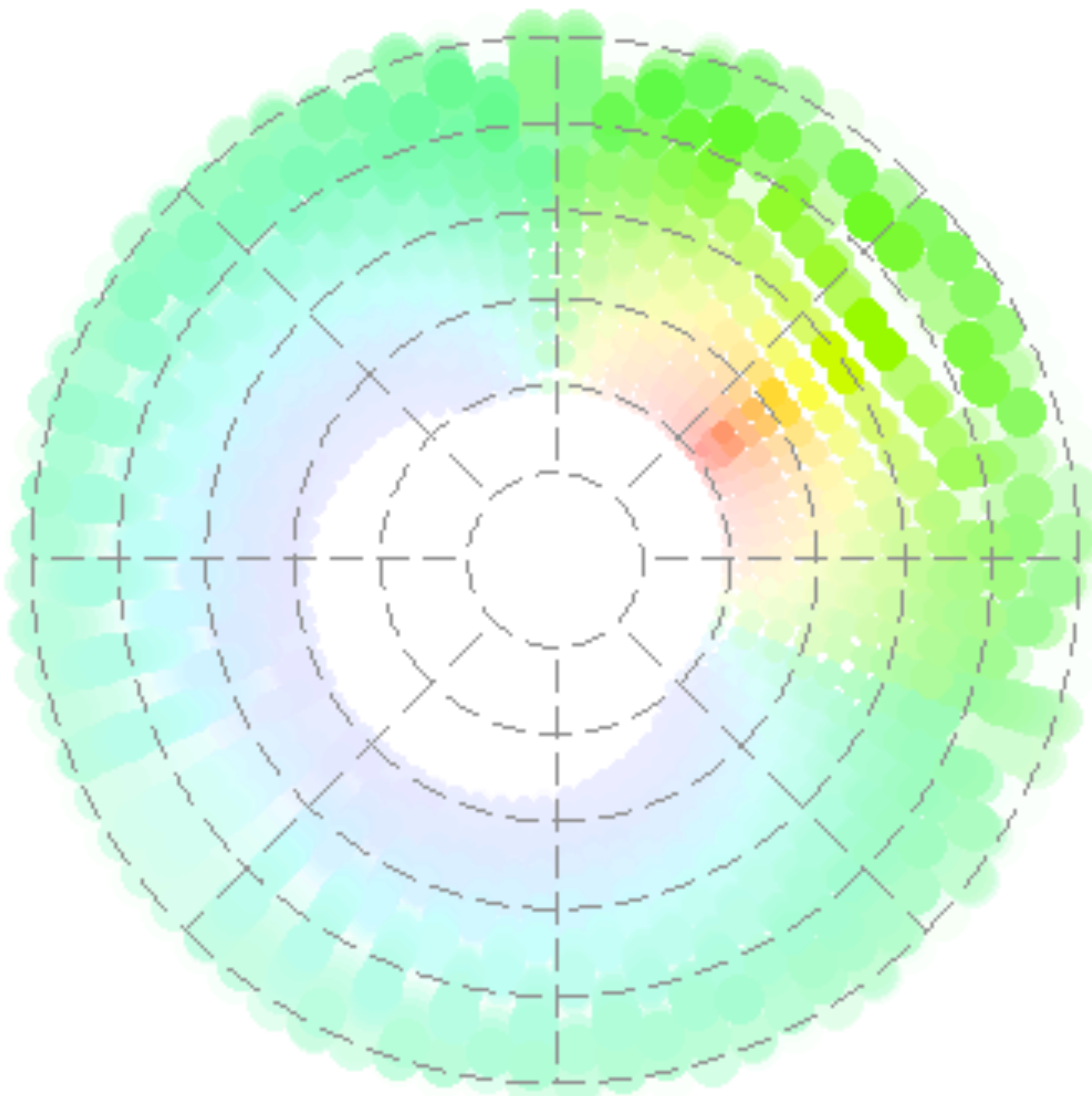
Low-velocity, optically thin wind with observer nearly edge-on

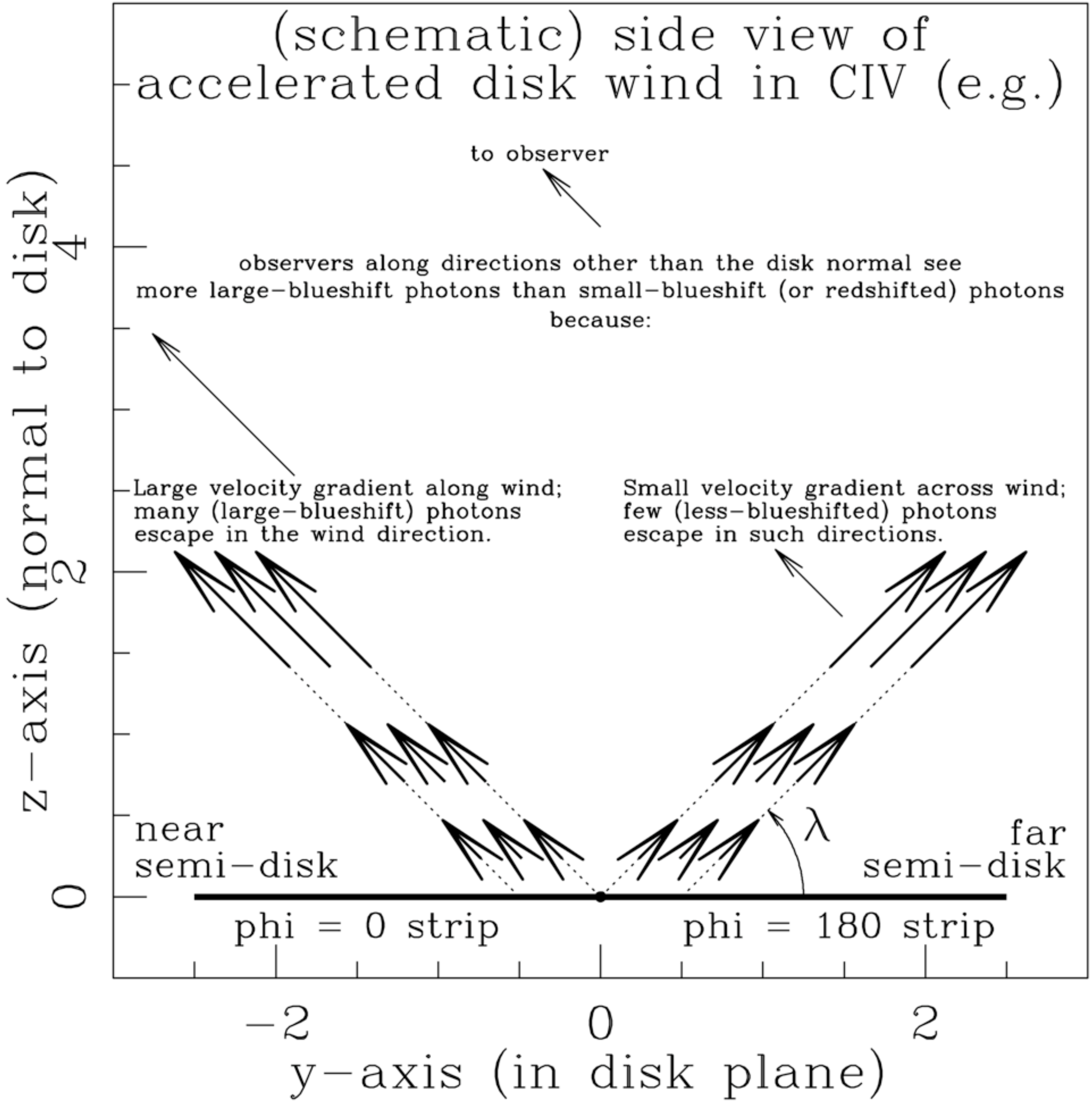




(schematic) side view of
accelerated disk wind in CIV (e.g.)
to observer
observers along directions other than the disk normal see
more large−blueshift photons than small−blueshift (or redshifted) photons
because:
Large velocity gradient along wind;
many (large−blueshift) photons
escape in the wind direction.
Small velocity gradient across wind;
few (less−blueshifted) photons
escape in such directions.
λ
near
semi−disk
far
semi−disk
phi = 0 strip
phi = 180 strip
z−axis (normal to disk)
0
2
4
−2
0
2
y−axis (in disk plane)

λ=45° degree wind, with v_{wind}=$v_{rotation}$, observer at i=45°

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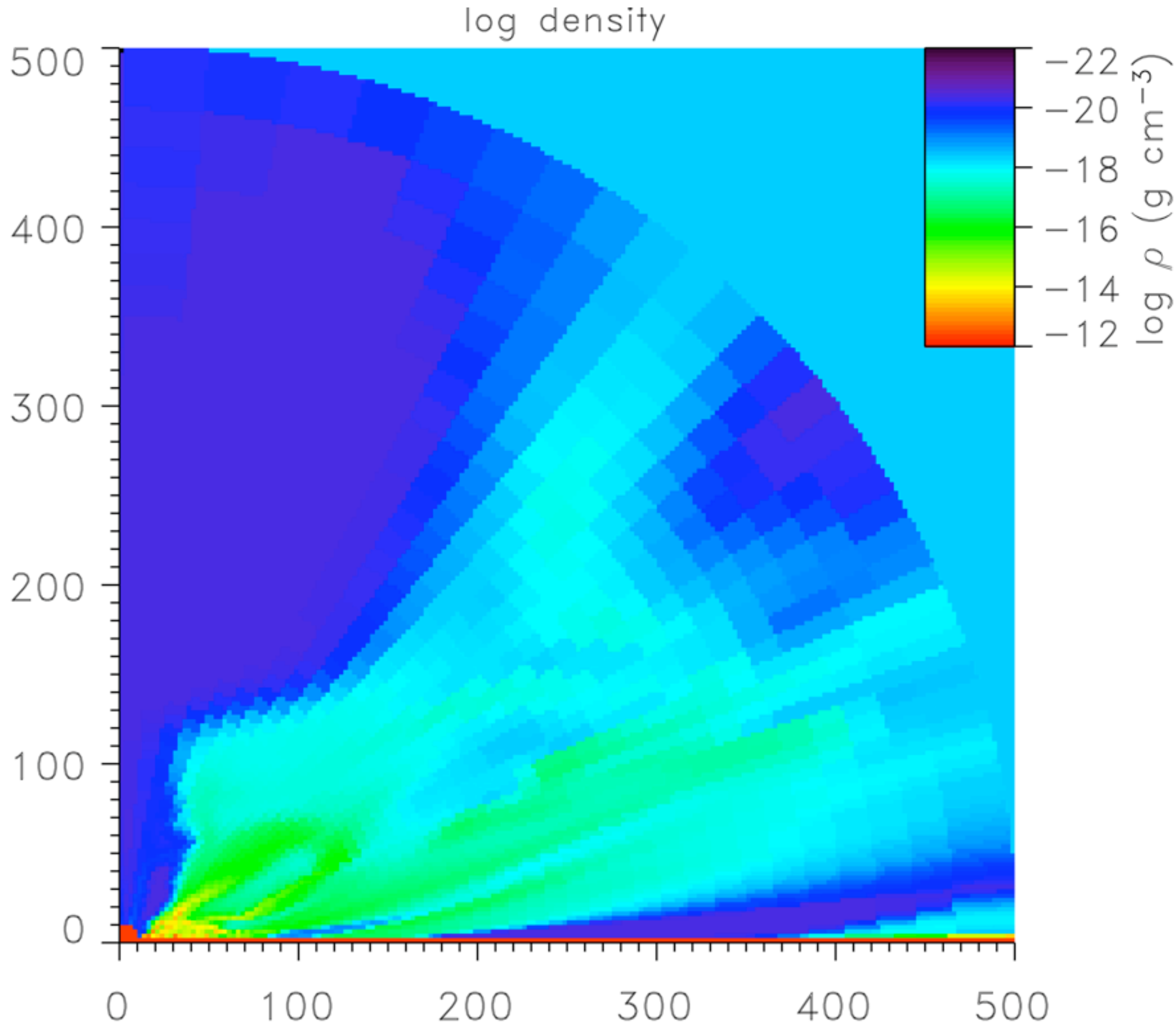
Accretion disk wind simulations

Proga & Kallman (2004)

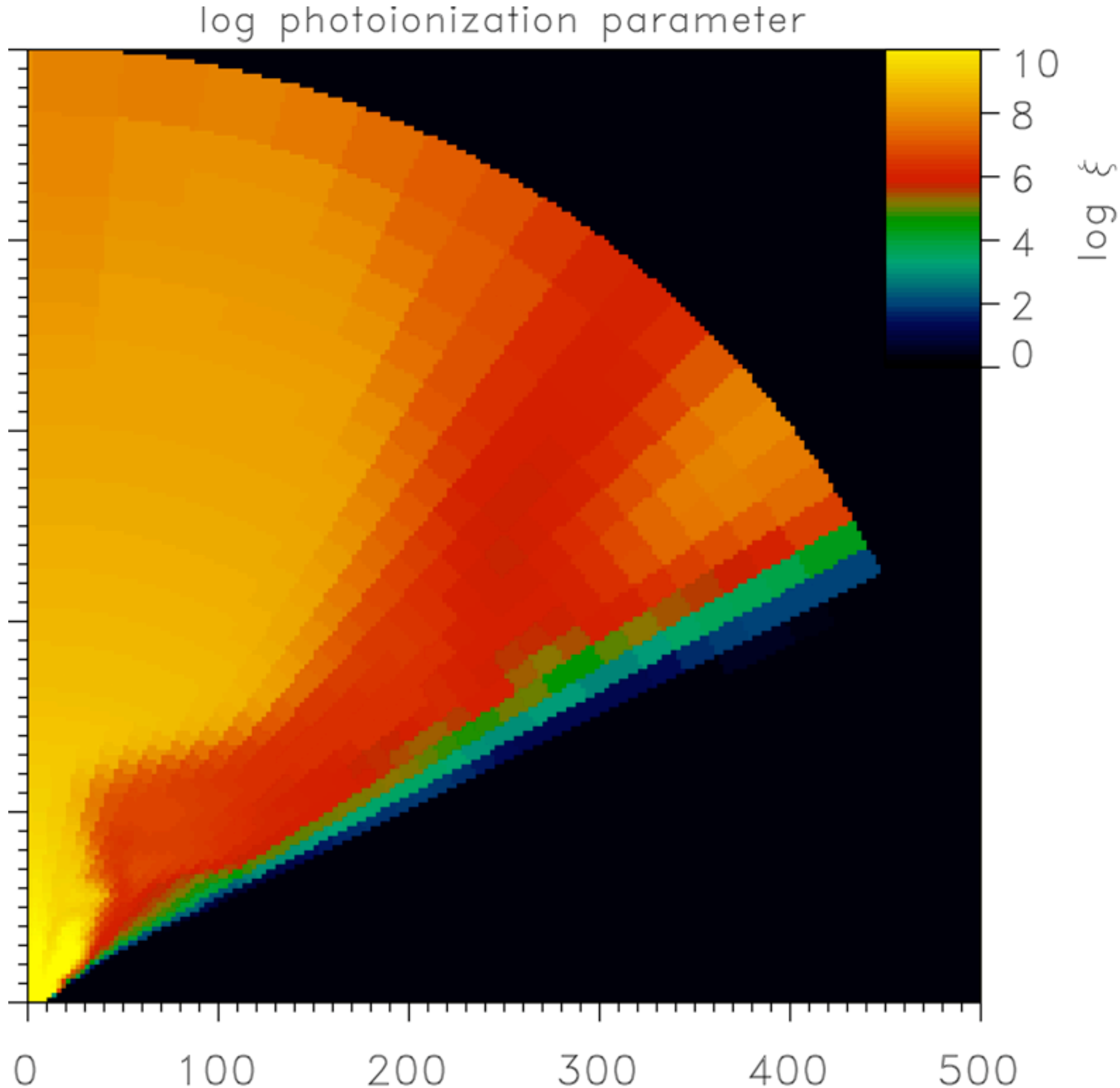
Cross section of density in one quadrant of a disk + wind (2-D simulation)



Accretion disk wind simulations

Proga & Kallman (2004)

Cross section of ionization level in one quadrant of a disk + wind (2-D simulation)

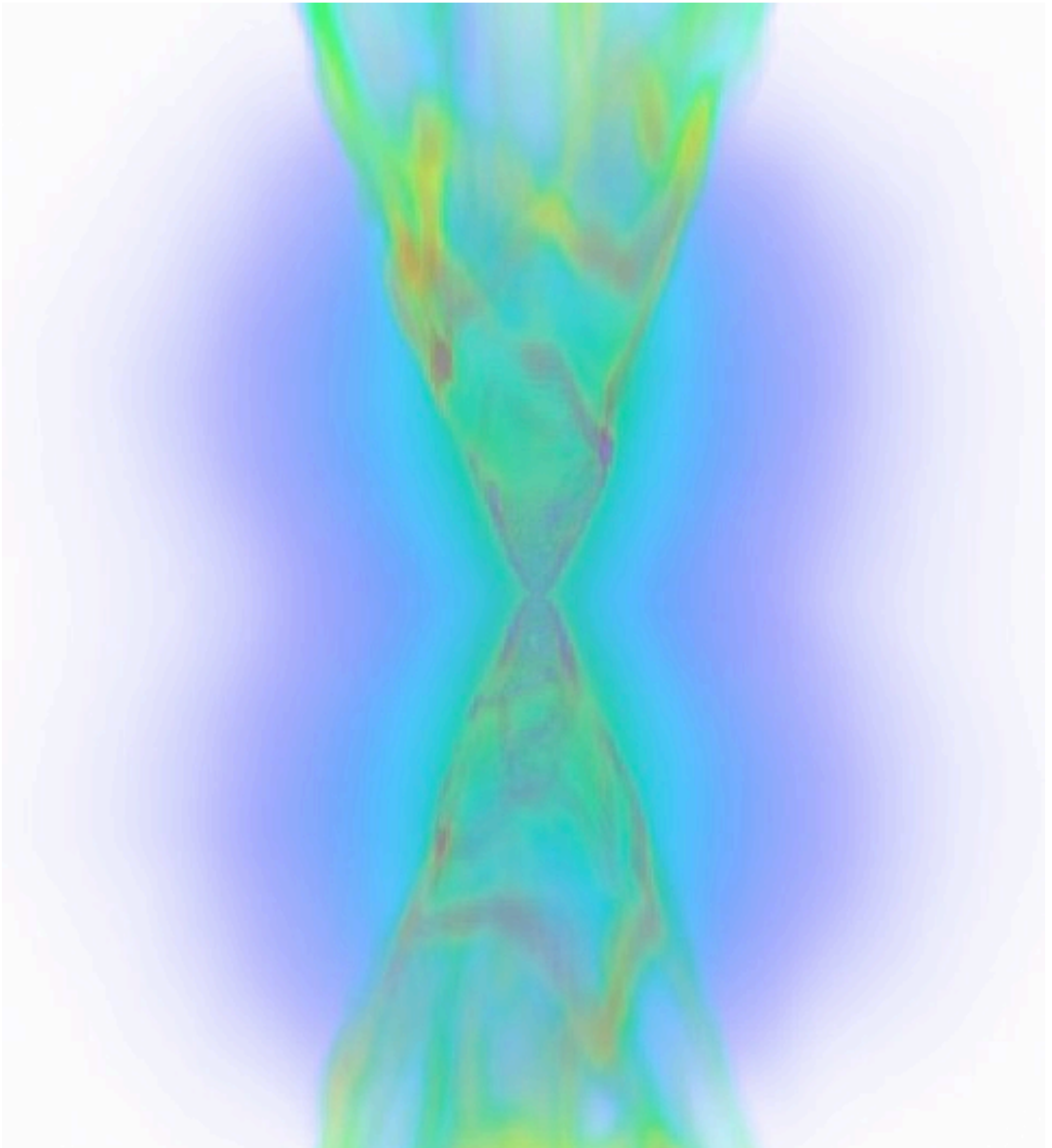


Accretion disk wind simulations

Kurosawa & Proga (2009)

Volume rendering of density in a 3-D disk + wind simulation

Simulations resemble reality; e.g., the Red Square Nebula (next)



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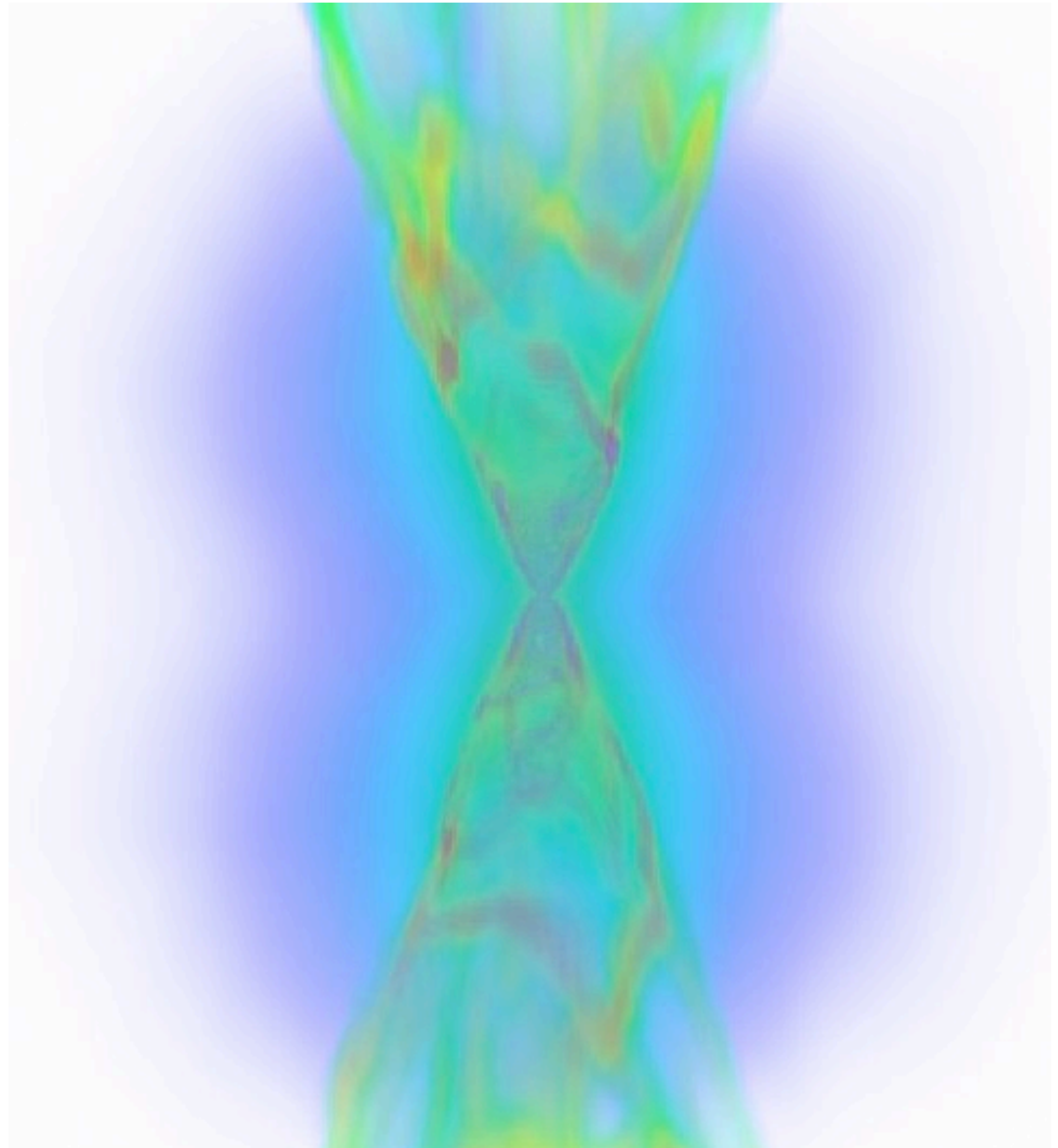
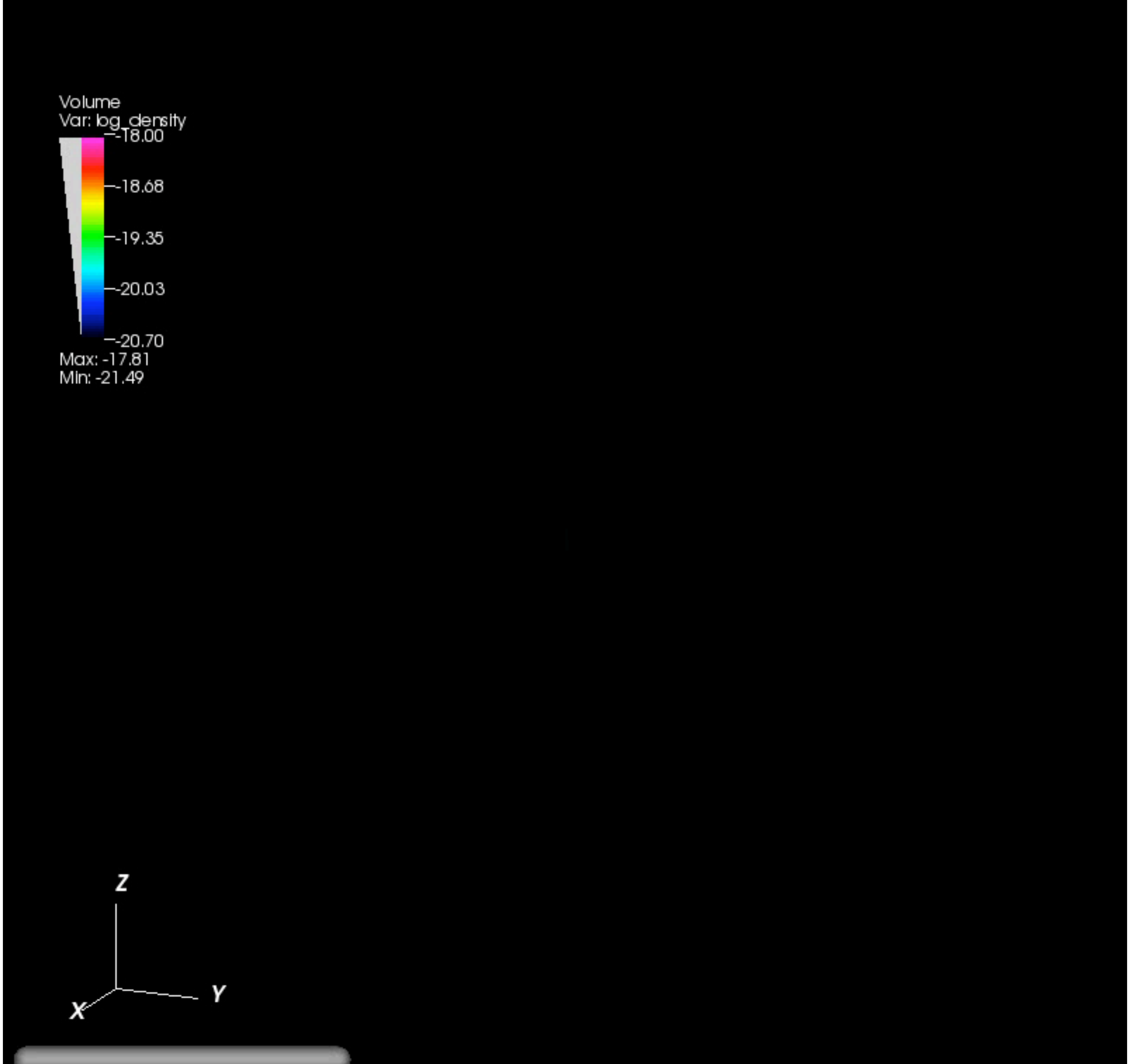
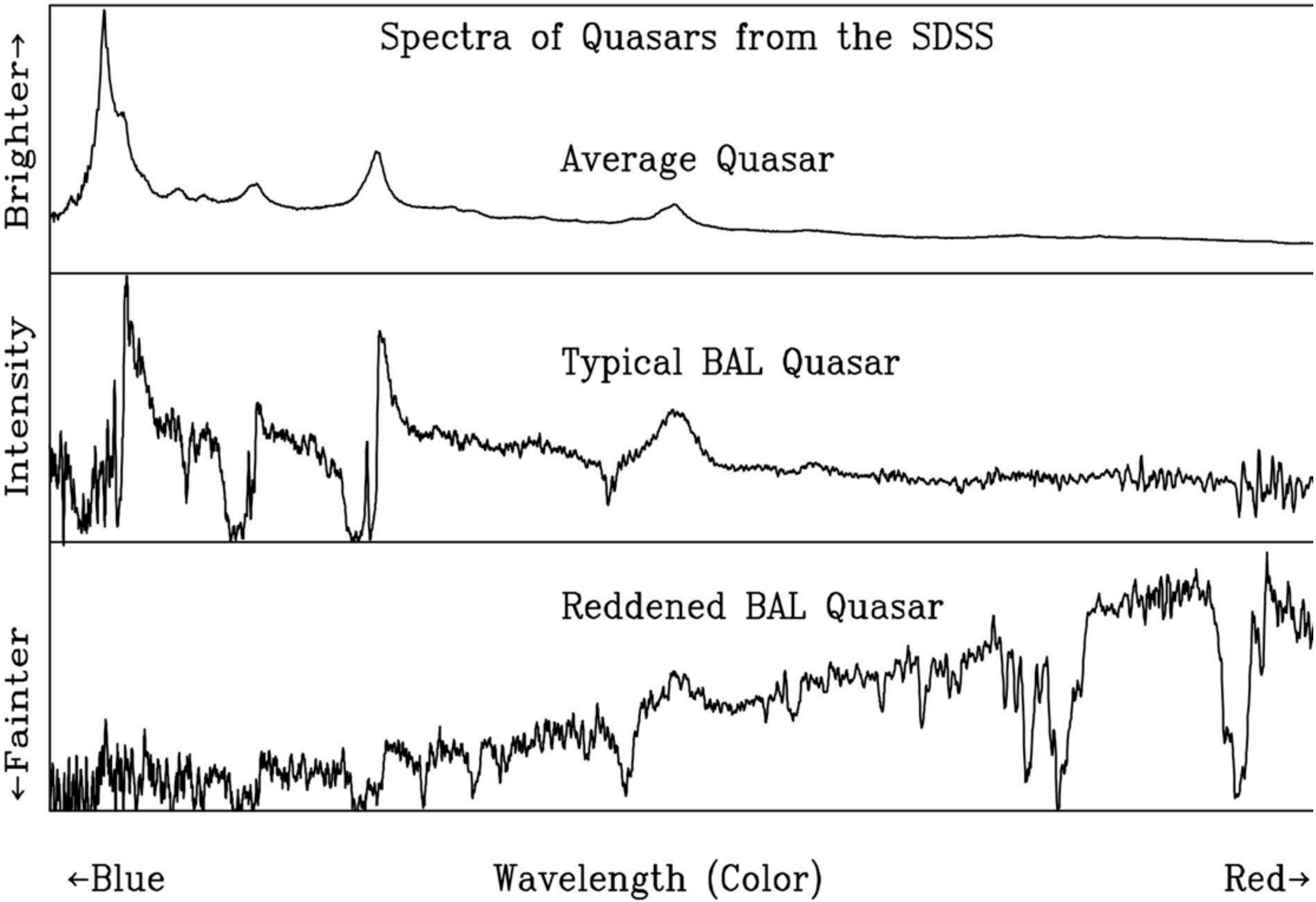
Movie of 3-D simulation shows rotation and outflow:




Volume
Var: log_density
-18.00
-18.68
-19.35
-20.03
-20.70
Max: -17.81
Min: -21.49
Z
Y
X

Can we detect this rotation and outflow in Broad Absorption Line Quasars?

- Blueshifted absorption in quasar rest frame indicates outflowing gas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Average Quasar
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Red→

Types of BAL quasars

- Imagine outflowing BAL gas cloud exposed to ionizing radiation from the quasar.
- At inward surface, carbon is mostly C^{+3}, producing C IV absorption troughs (along with Si IV, N V, O VI, etc.).

- Known as HiBALs

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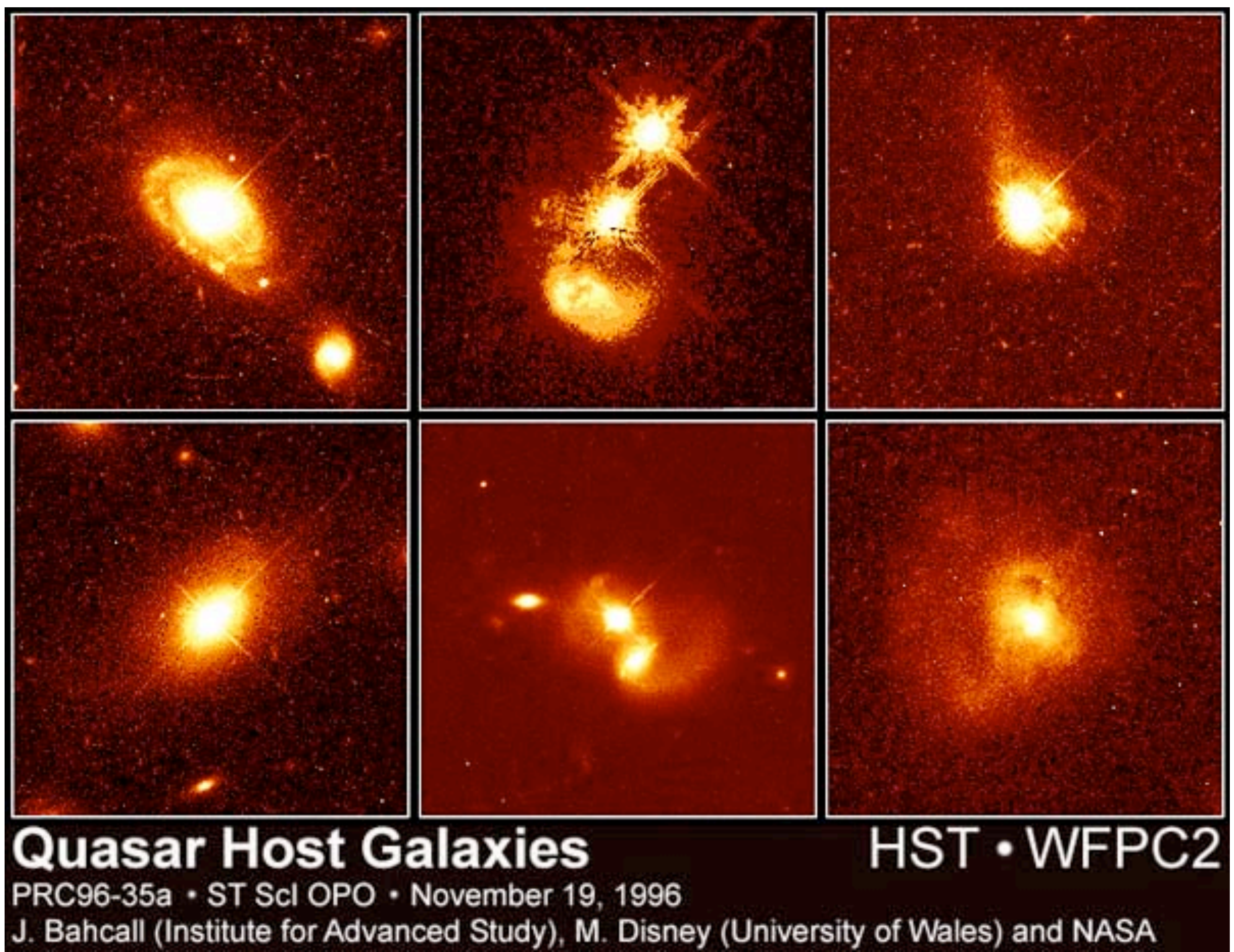
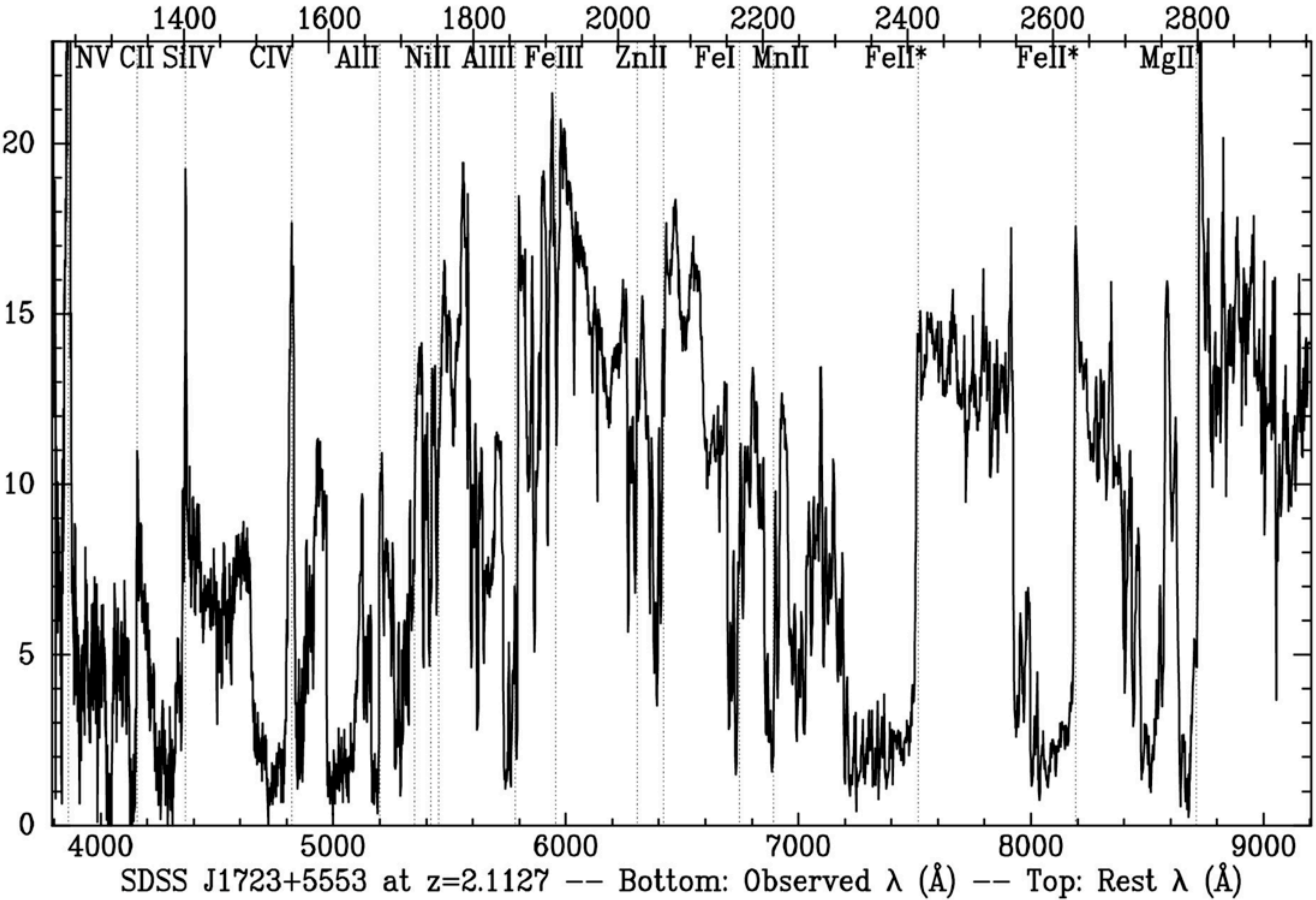
- If cloud is thick enough, deeper inside there will be absorption from lower ionization species: Al III, Mg II.
- If cloud is even thicker, there can be absorption from ground-state and excited-state Fe II (+ H I Balmer).
- Known as HiBALs, LoBALs, FeLoBALs respectively.

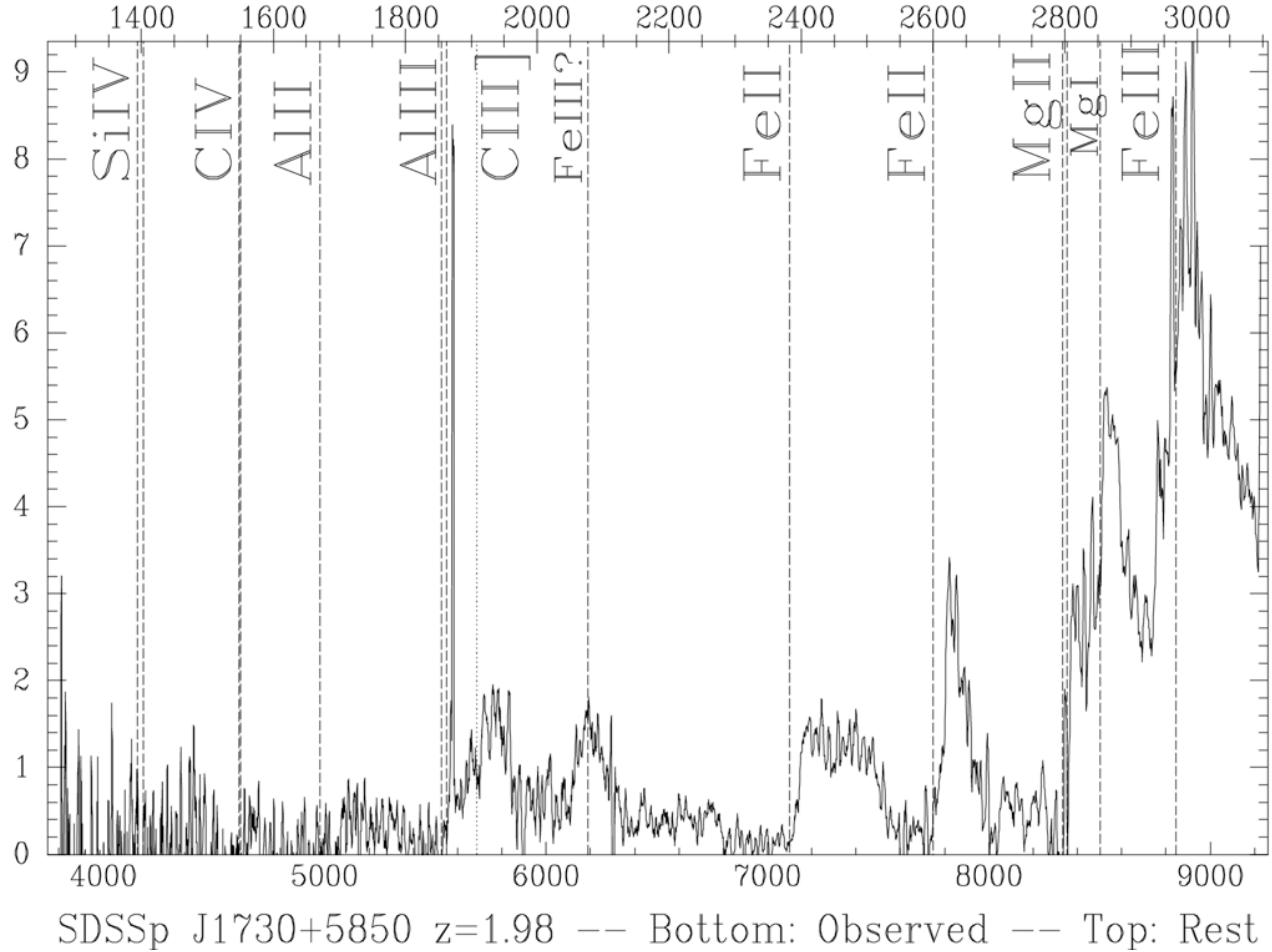
- Some FeLoBAL quasars have far-infrared properties distinct from other quasars; one FeLoBAL appears to have a star formation rate of 2700 solar masses/year!
- Do FeLoBAL troughs trace the late stages of galaxy mergers, where the quasar is at last unshrouded by dust?



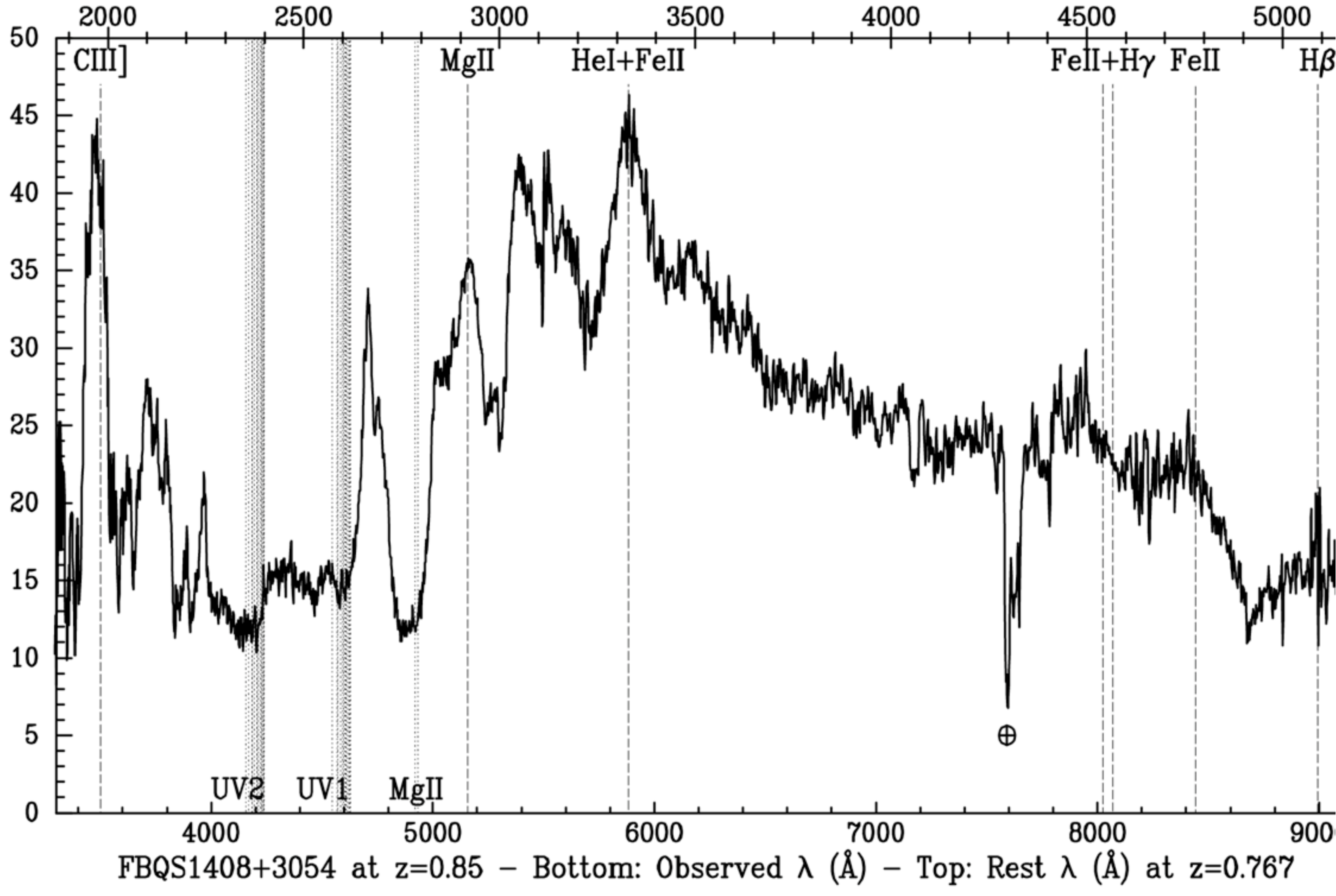
FeLoBAL quasar with narrow troughs



FeLoBAL quasar with broad troughs



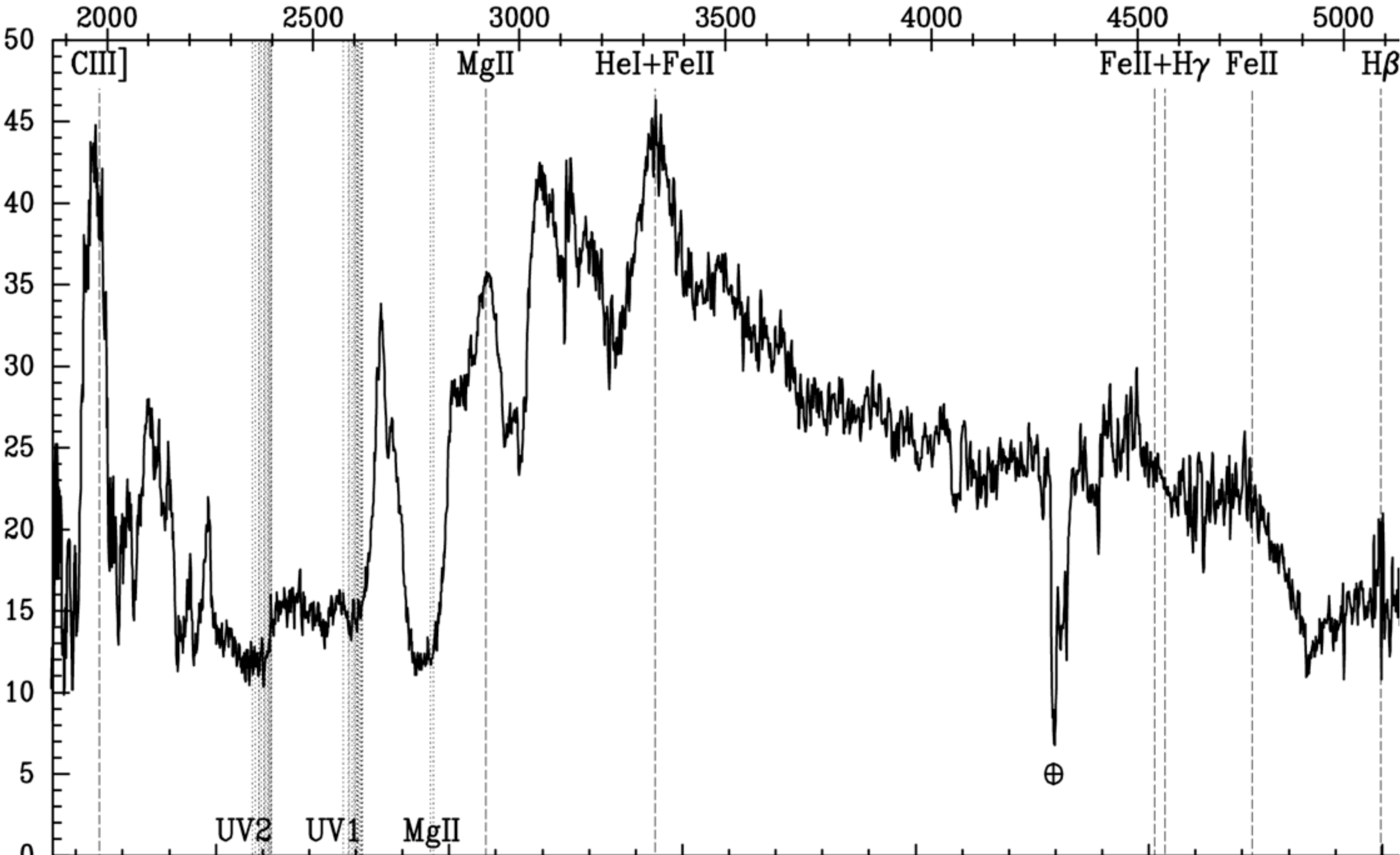
Example: FBQS J1408+3054 (in 2000)



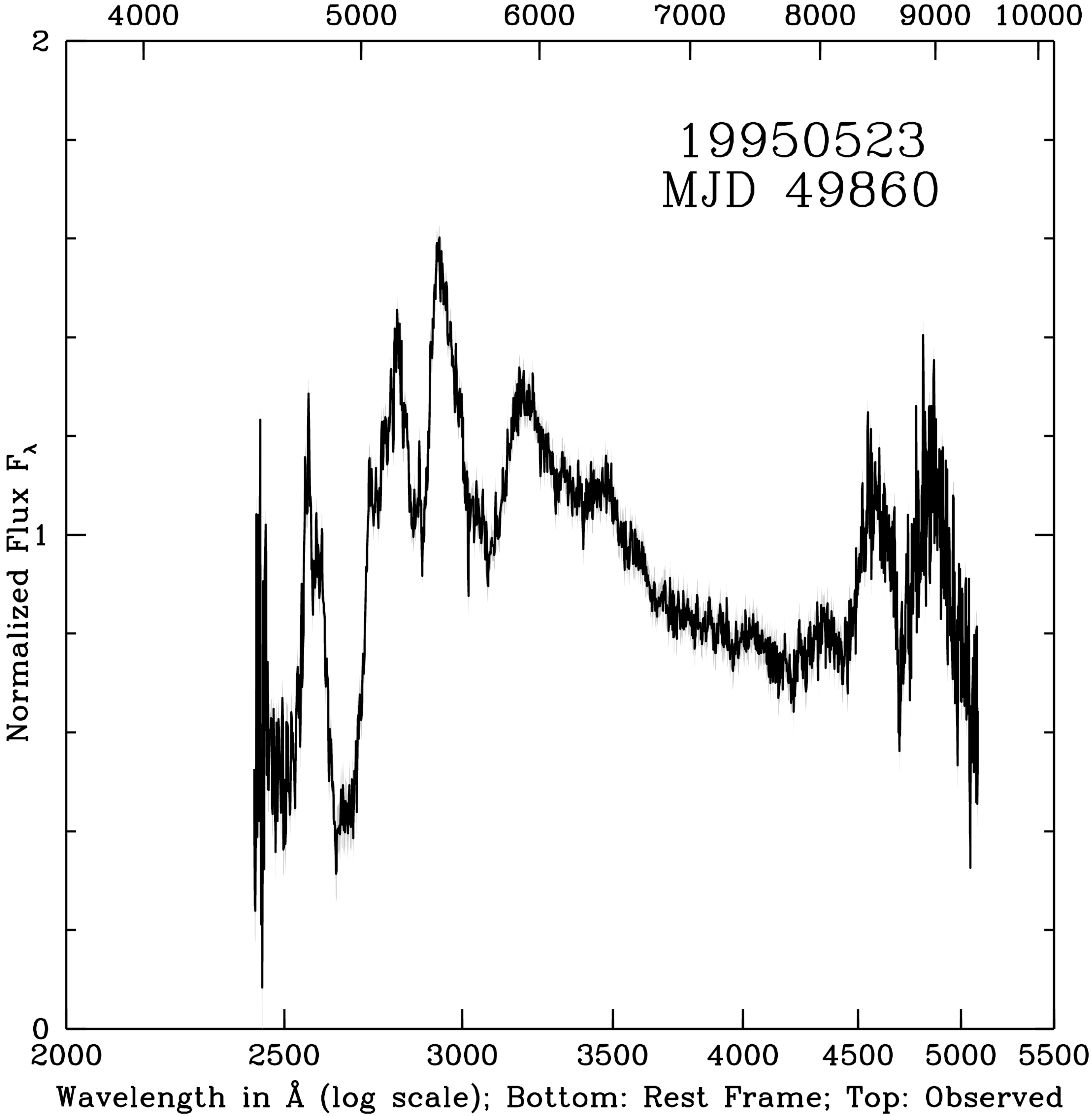
Variability of FBQS J1408+3054

- FBQS J1408+3054 observed by SDSS in March 2006
- Change in spectrum noticed in April 2009
- HET spectrum obtained in July 2009
- Collaboration with FIRST Bright Quasar Survey group yielded access to spectra from 1995 to 2005
- Paper (Hall et al. arXiv:1010.3728) accepted Oct. 2010
- Movie of all spectral variability from 1995 to 2009 includes uncertainties scaled using a damped random walk (MacLeod et al. arXiv:1004.0276)

Reminder: FBQS J1408+3054 in 2000



FBQS1408+3054 at z=0.85 – Bottom: Observed λ (Å) – Top: Rest λ (Å) at z=0.767



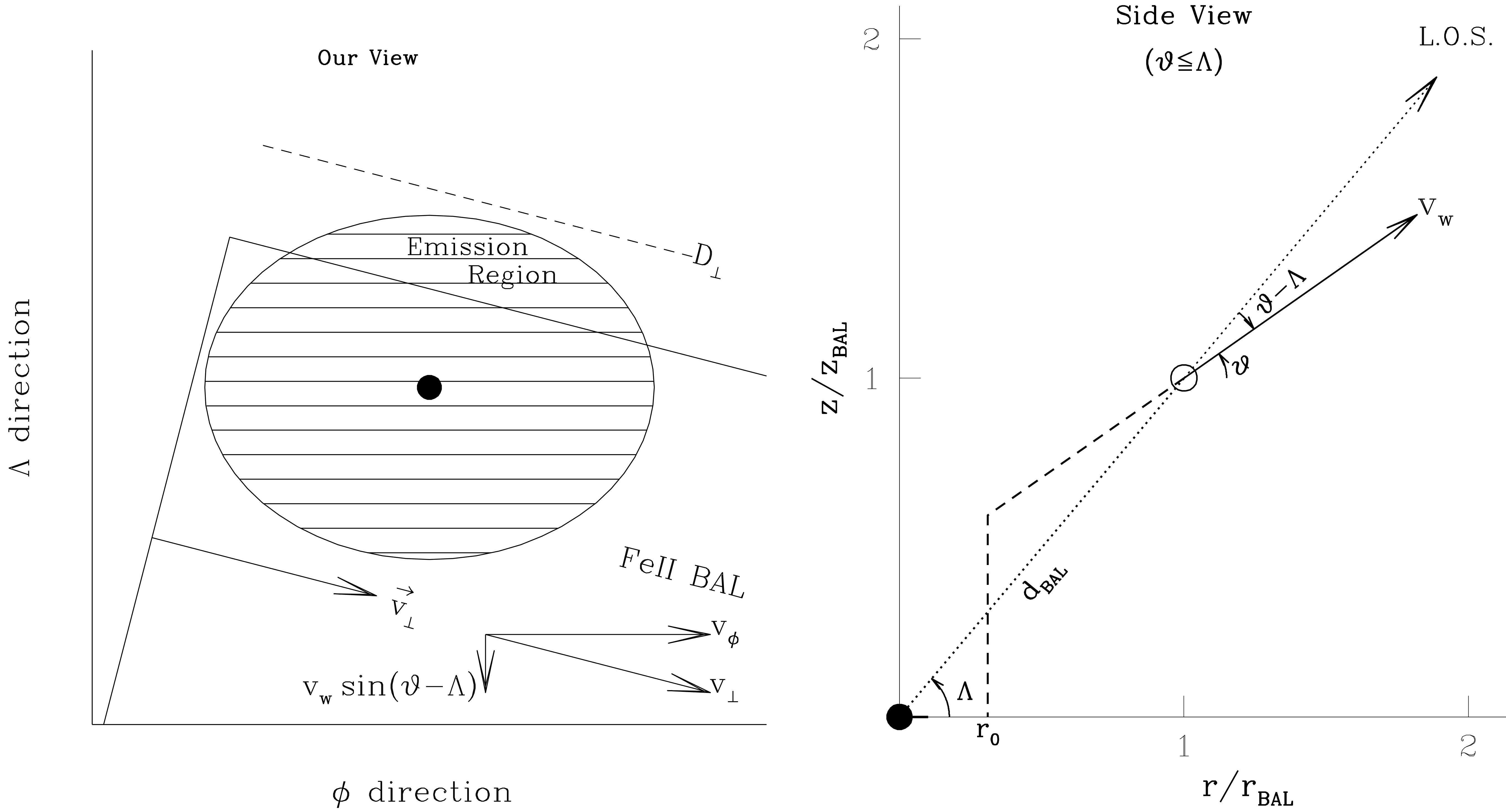
19950523
MJD 49860
Normalized Flux F_λ
Wavelength in Å (log scale); Bottom: Rest Frame; Top: Observed
4000
5000
6000
7000
8000
9000
10000
2000
2500
3000
3500
4000
4500
5000
5500
0
1
2

Variability of FBQS J1408+3054

- 3000 Angstrom flux of FBQS J1408+3054 changed by <10% during the 1 to 5 year span over which the Fe II BAL trough disappeared
- Suggests that the variability was due to transverse motion of BAL gas across our line of sight

Variability constrains geometry

Left: our view of Fe II BAL cloud passing over continuum emission region. Right: side view of same; cloud is at (1,1).



How variability constrains geometry

- We can estimate the mass M of the quasar's black hole and the size D of the 2700 Angstrom continuum emission region around a black hole of that mass.

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- *We can estimate the mass M of the quasar's black hole and the size D of the 2700 Angstrom continuum emission region around a black hole of that mass.*
- The time t required for Fe II absorption to disappear constrains the BAL's transverse velocity: $v_{\perp} \sim D / t$.
- The BAL has poloidal velocity v_w along angle ϑ above the disk, and azimuthal velocity v_Φ.

Variability constrains geometry

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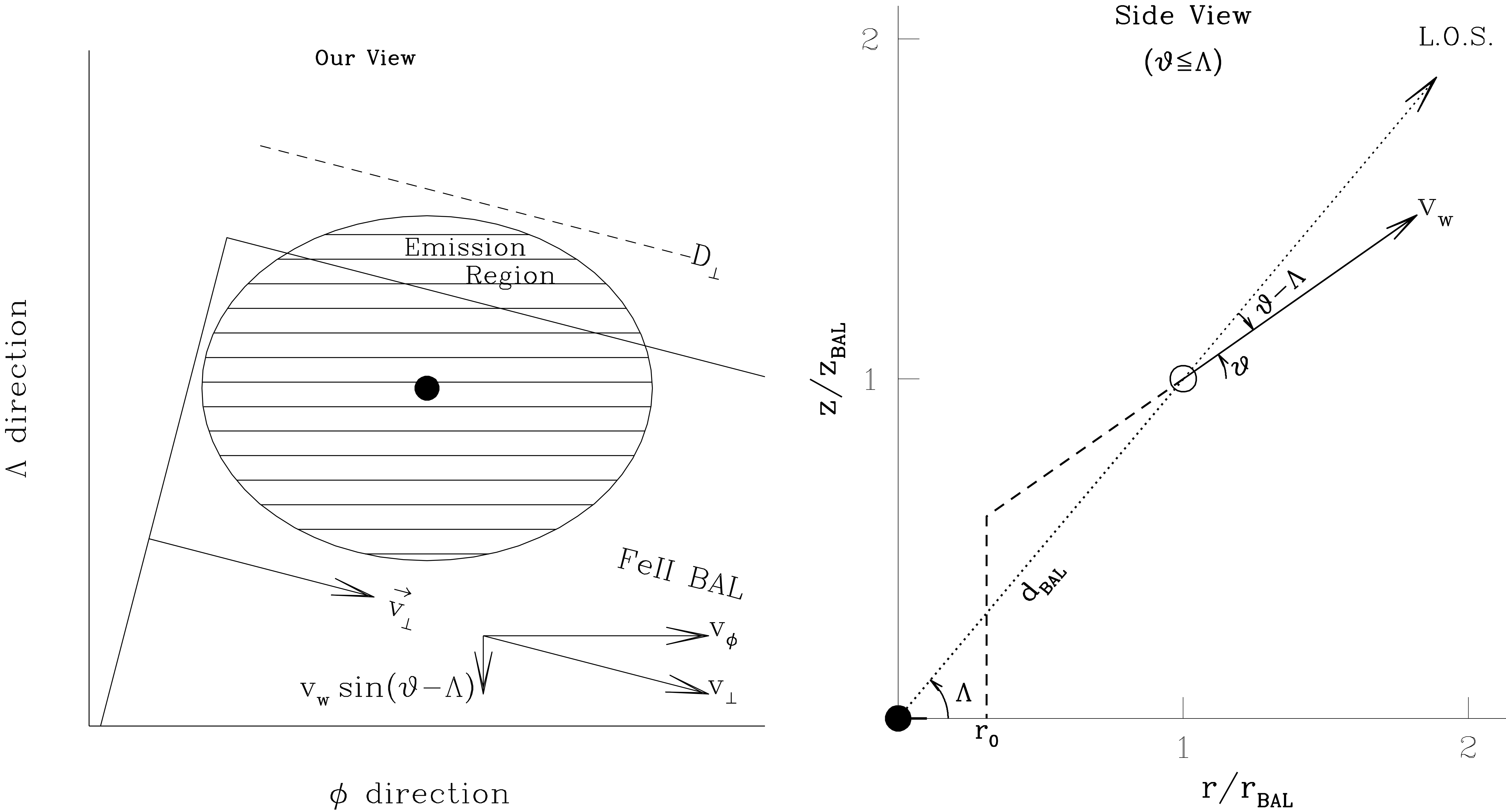

How variability constrains geometry

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- *The time t required for Fe II absorption to disappear constrains the BAL's transverse velocity: $v_\perp \sim D / t$.*

- *The BAL has poloidal velocity v_w along angle ϑ above the disk, and azimuthal velocity v_Φ.* Assuming the BAL outflow conserves angular momentum, $v_\Phi = v_0 r_0 / r_{BAL}$, where v_0 is the circular velocity at the launch radius r_0. We assume terminal wind velocity: $v_w = (3.6 \pm 1.1) v_0$.

- With those assumptions, we constrain d_{BAL} and ψ_{LOS}.

Resulting constraints

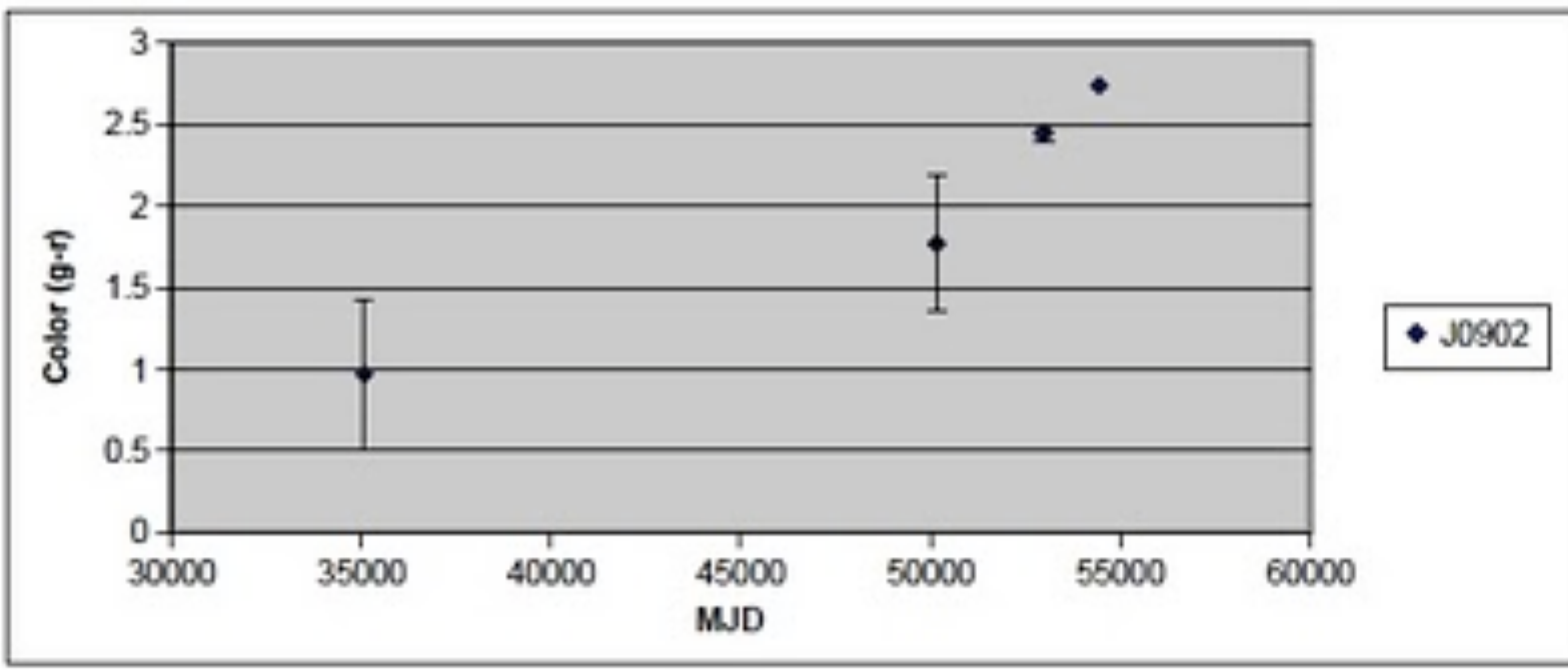
- What we do not know are ϑ and Λ. So we calculate d_{BAL} for all combinations of our line of sight angle $\Lambda<73$ degrees (set by the quasar's radio lobe separation) and wind angle $5<\vartheta<85$ degrees, and average.
- The Fe II BAL is located between 7300 and 73,000 Schwarzschild radii from the black hole. That is 2.2 to 22 parsecs, 14 to 140 times the radius of the Hβ BLR.
- The angle between the BAL wind and the line of sight, ψ_{LOS}, is on average 18 ± 3 degrees for parameter choices that match the observations. (Hamann et al. (2010) find $\psi_{LOS} <16$ degrees for a NAL system.)

Are these constraints interesting?

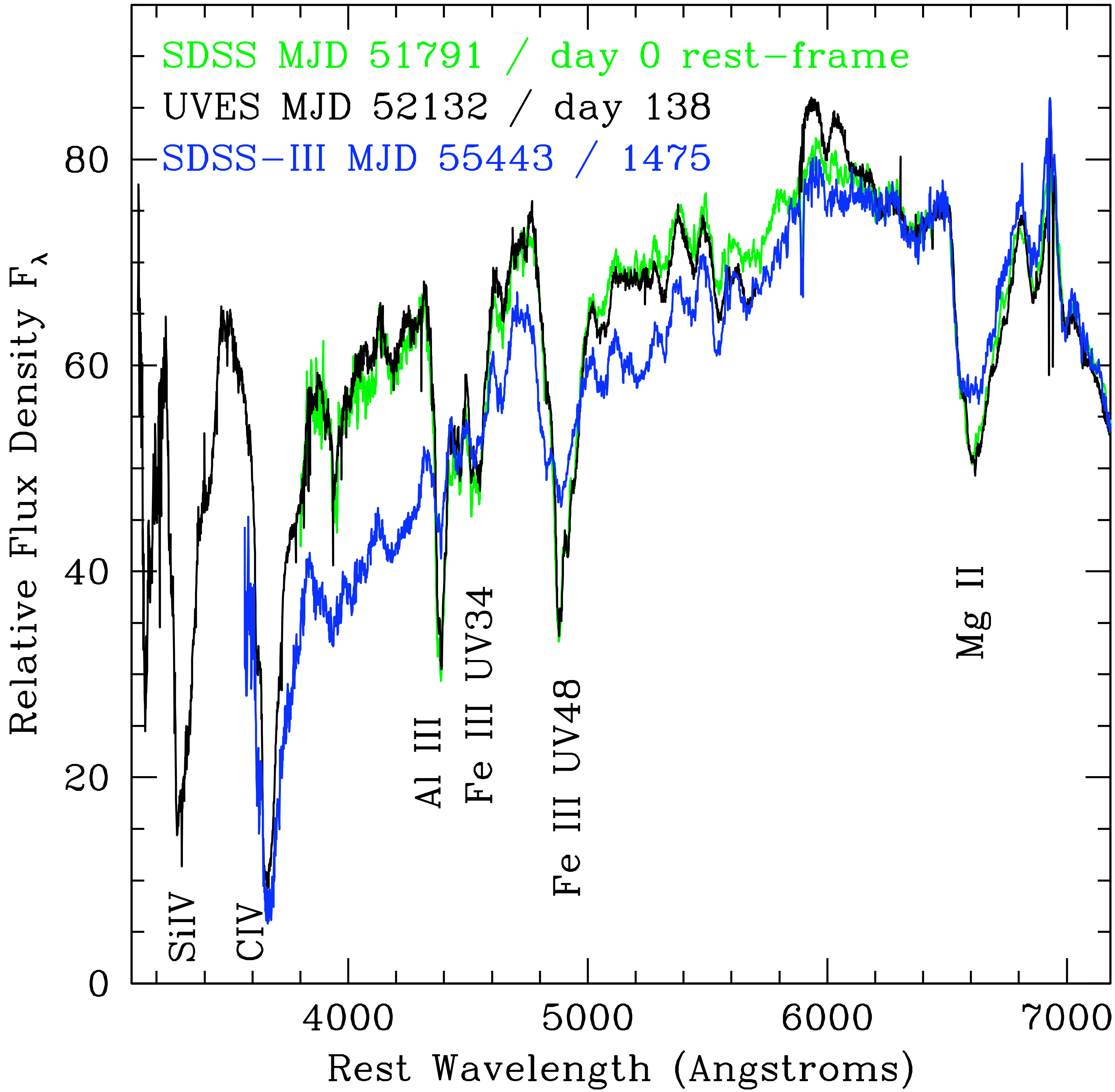
- The Fe II BAL is located between 2.2 to 22 parsecs from the black hole. Also, its outflow velocity is between 12,000 and 16,000 km/s.
- That means the Fe II absorption is associated with the black hole, not (directly) with nuclear star formation.
- <u>Not all FeLoBALs can signal galaxy-scale outflows in IR luminous galaxies transitioning to unobscured quasars.</u>
- Given that this quasar transitioned from an FeLoBAL to a LoBAL, if some FeLoBAL quasars have IR properties distinct from HiBAL quasars, then some LoBAL quasars might share those properties.

More long-term BAL variability

- Variations as strong as those in J1408 are detectable as color variations; spectroscopy not needed initially.
- POSS provides photometry going back decades. J0902, another FeLoBAL quasar, got more absorbed w/time:



Are FeLoBALs more variable?



Summary

- Quasar broad emission lines may come from an accelerating wind optically thick in those lines (explains virialized, single-peaked lines), whose photosphere is at or near the surface of the accretion disk.
- We are exploring disk wind parameter space to see what's needed to produce emission line shapes and blueshifts like those of real quasars. We hope to explain observed blueshifts and broad-line width distributions.
- BAL troughs arise farther out in the wind. Variability can be strong (or negligible) over timescales of years; SDSS-III will provide largest BAL variability sample yet.

Questions?

Disk Winds and BELs

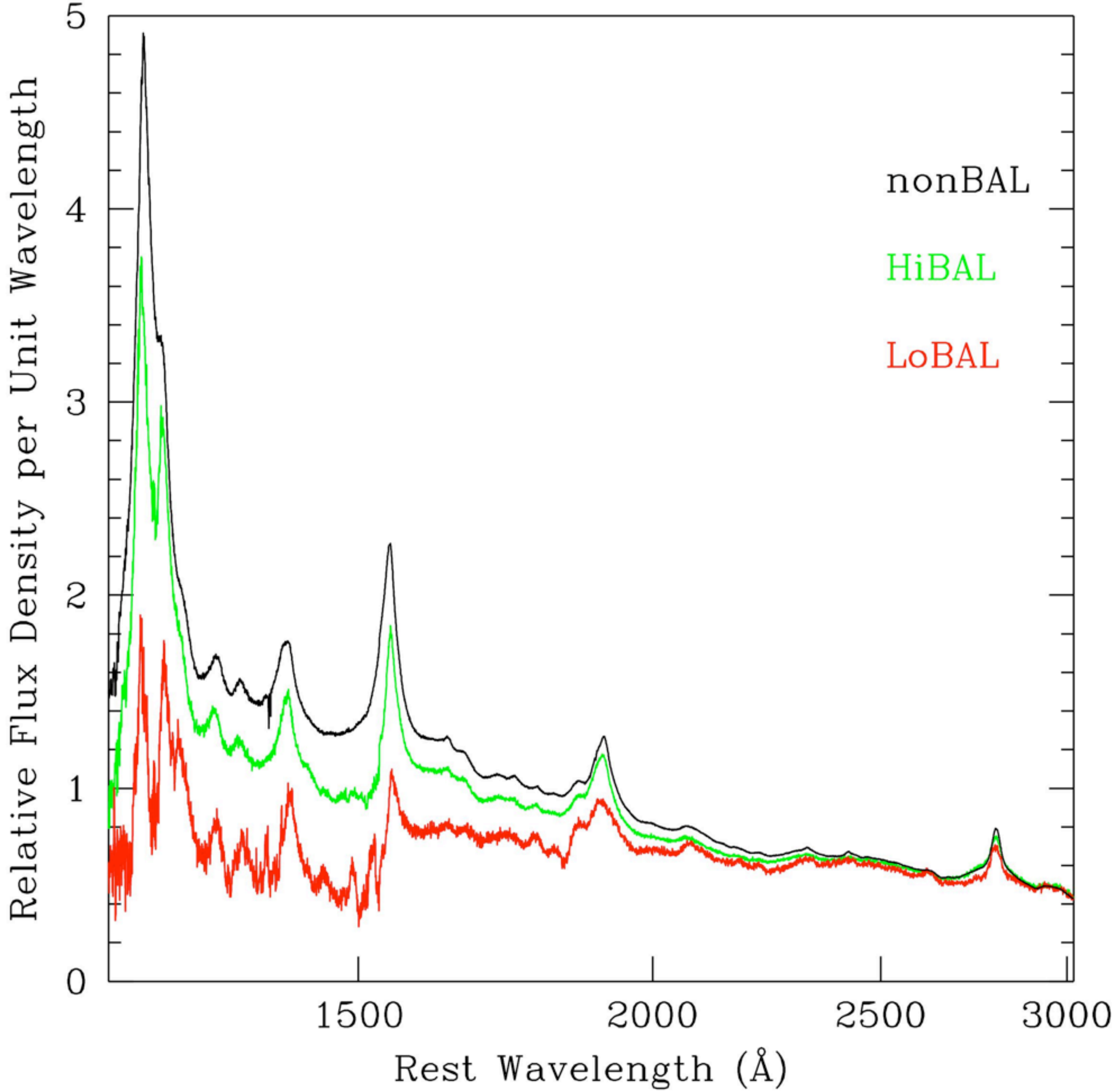
- Another constraint comes from the distribution of broad-line widths (Fine et al. 2008).
- If all BEL regions were perfectly planar, rotating distributions of clouds, BEL linewidths would vary as (sin i), where i=0 is face-on.

Disk Winds and BELs

- *Another constraint comes from the distribution of broad-line widths (Fine et al. 2008, in press).*
- *If all BEL regions were perfectly planar, rotating distributions of clouds, BEL linewidths would vary as (sin i), where i=0 is face-on.*
- Very few luminous narrow-line quasars are known, so there must be a polar component to BEL velocities.
- A polar velocity dispersion for BEL clouds is often invoked, but is unlikely to be stable. Accretion disk winds with radially varying vertical velocities naturally provide a range of velocities in the polar direction.

Broad Absorption Line Quasars

- Quasars with BAL troughs in their spectra often have red continua ... intrinsic, or dust reddening?



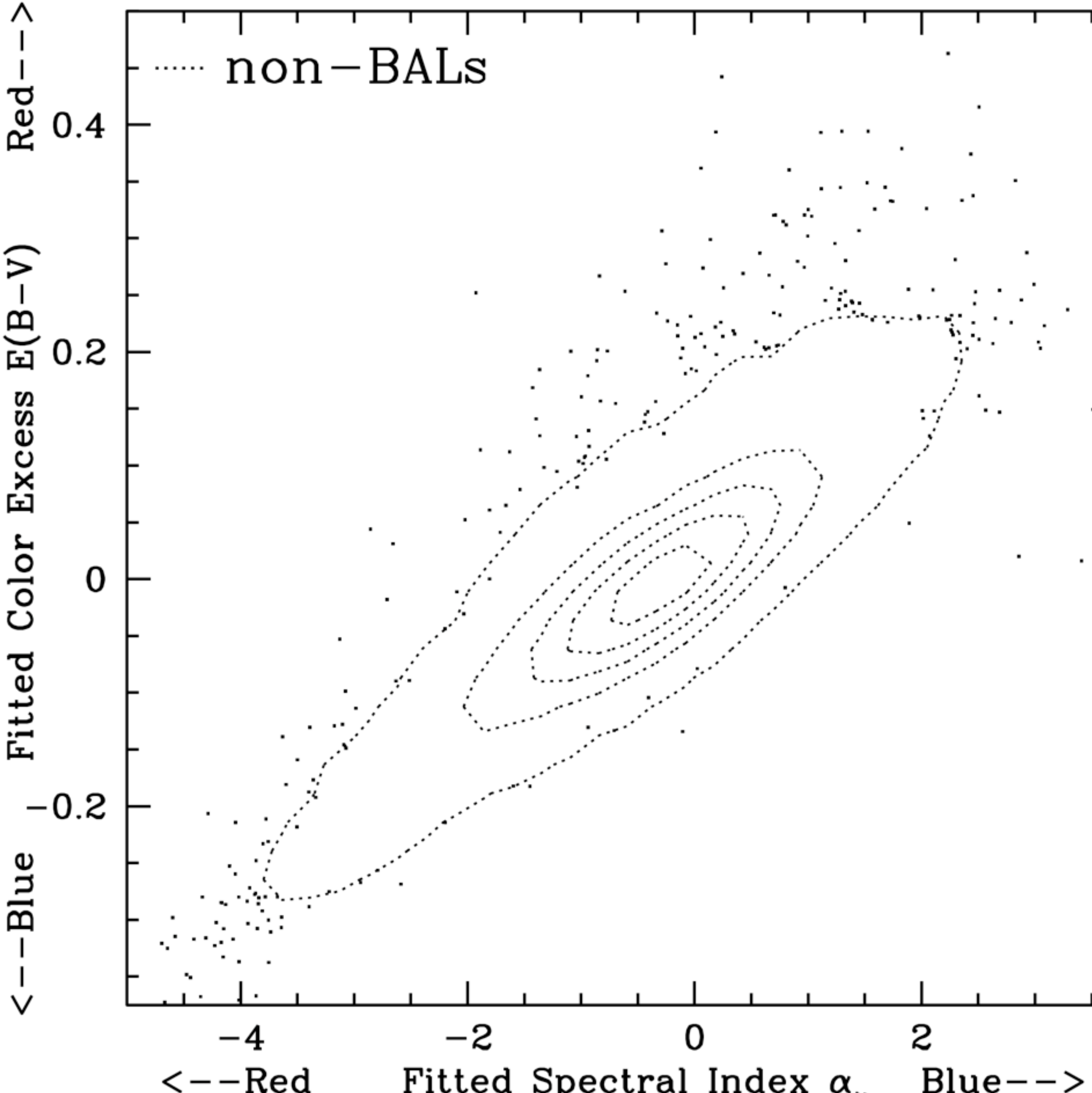
nonBAL
HiBAL
LoBAL
Relative Flux Density per Unit Wavelength
Rest Wavelength (Å)
0
1
2
3
4
5
1500
2000
2500
3000

BAL Quasars

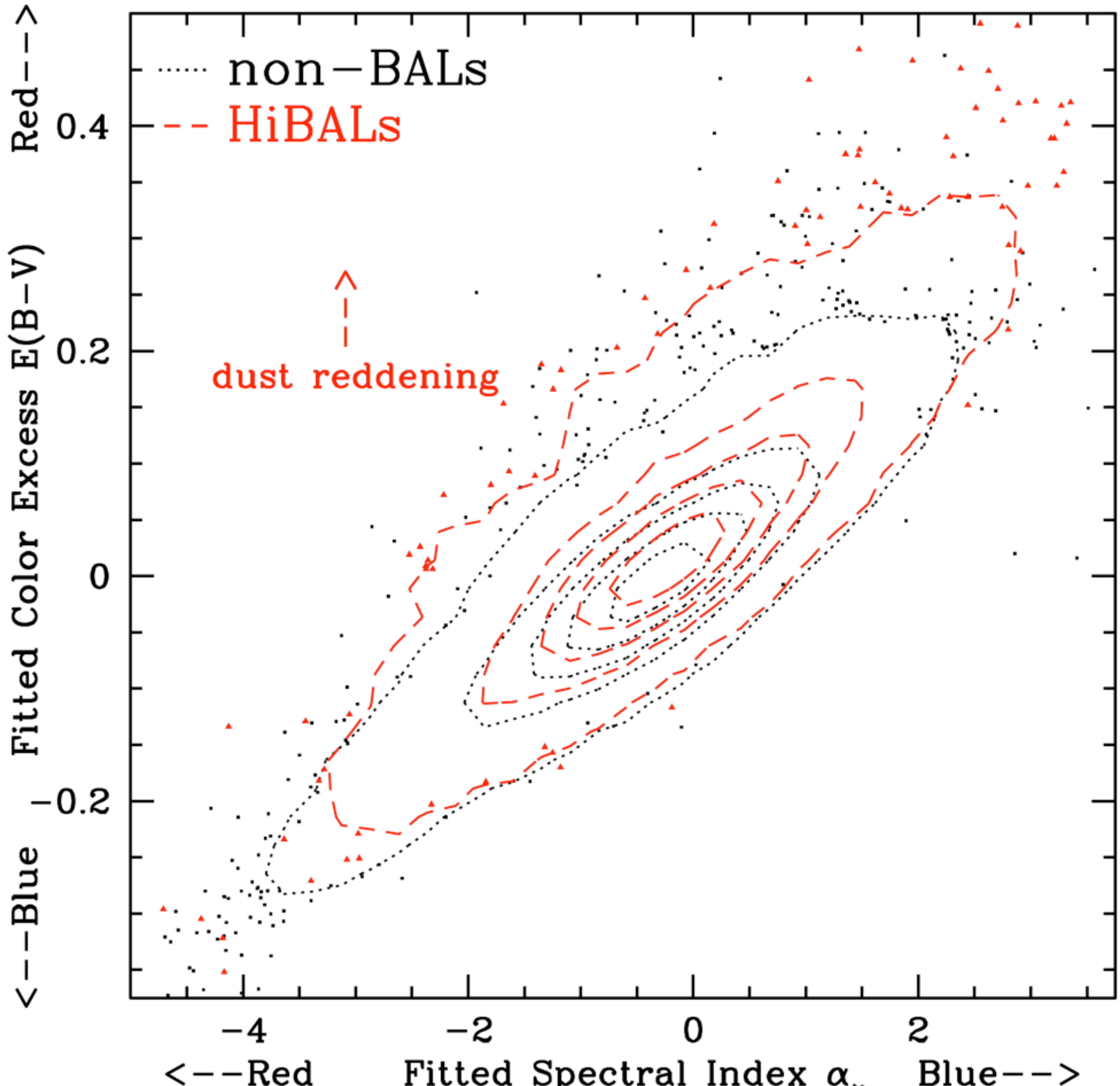
- *Quasars with BAL troughs in their spectra often have red continua ... intrinsic, or dust reddening?*
- In Reichard et al. 2003ab, we developed a technique for statistically untangling dust reddening from continuum slope variations
- Fit non-BAL quasar composite spectra to appropriate spectral regions of BAL quasars, allowing both continuum spectral index and reddening to vary

BAL Quasars

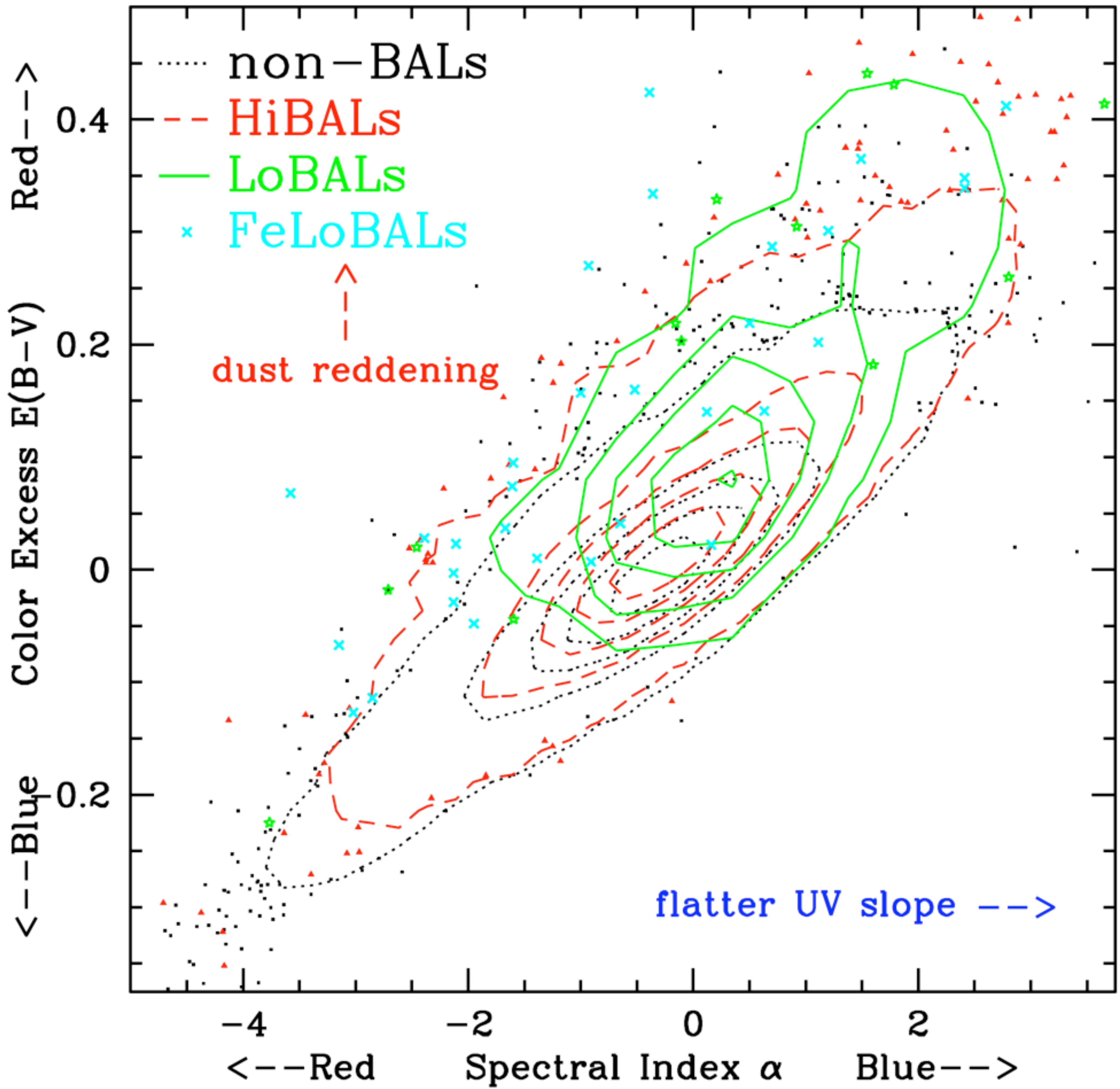
- *Quasars with BAL troughs in their spectra often have red continua ... intrinsic, or dust reddening?*
- *In Reichard et al. 2003ab, we developed a technique for statistically untangling dust reddening from continuum slope variations*
- *Fit non-BAL quasar composite spectra to appropriate spectral regions of BAL quasars, allowing both continuum spectral index and reddening to vary*
- Fitted spectral index and E(B-V) are quite degenerate, but may still be statistically useful. In any case, the fitting's 'smearing' doesn't wipe out the effects of dust



non−BALs
0.4
0.2
0
−0.2
<−−Blue
Fitted Color Excess E(B−V)
Red−−>
−4
−2
0
2
<−−Red
Fitted Spectral Index α_ν
Blue−−>



non−BALs
HiBALs
dust reddening
<--Blue
Fitted Color Excess E(B−V)
Red-->
0.4
0.2
0
−0.2
−4
−2
0
2
<--Red
Fitted Spectral Index α_ν
Blue-->



non−BALs
HiBALs
LoBALs
FeLoBALs
dust reddening
flatter UV slope -->
0.4
0.2
0
-0.2
-4
-2
0
2
<--Blue   Color Excess E(B−V)   Red-->
<--Red   Spectral Index α   Blue-->

BAL quasars: a framework

- 1) Broad absorption lines are more common among intrinsically bluer quasars
- 2) Broad absorption line quasars are on average more dust-reddened than non-BAL quasars

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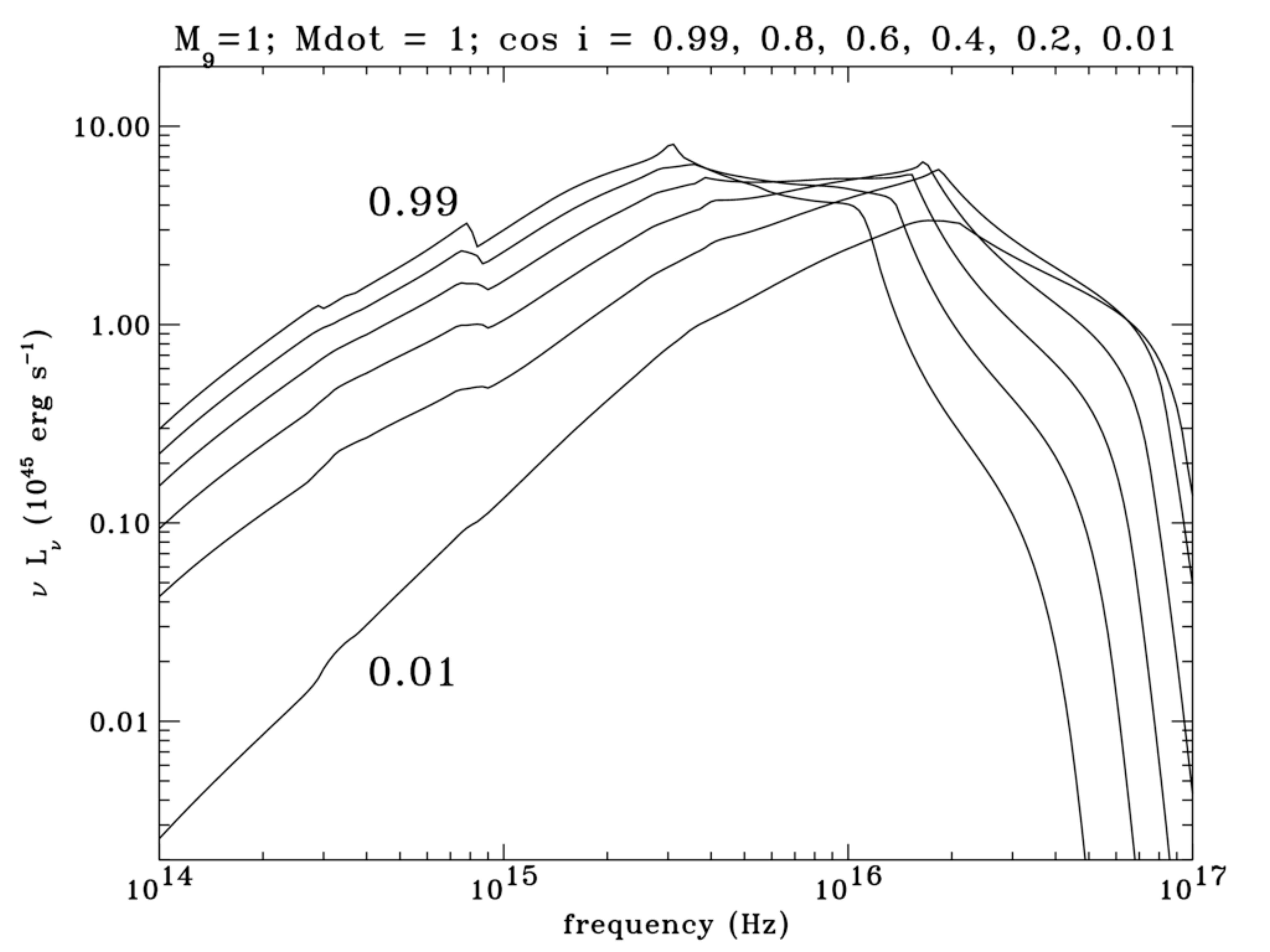
BAL quasars: a framework

- *1) Broad absorption lines are more common among intrinsically bluer quasars*
- *2) Broad absorption line quasars are on average more dust-reddened than non-BAL quasars*
- *Point 2) consistent with BALs being preferentially found along low-latitude sightlines where encountering a dusty torus or wind is more likely*
- That hypothesis also explains point 1). According to the accretion disk models of Hubeny et al. (2000), relativistic effects make edge-on disks bluer. Inclination is i=0 when face-on, i=90 for edge-on:



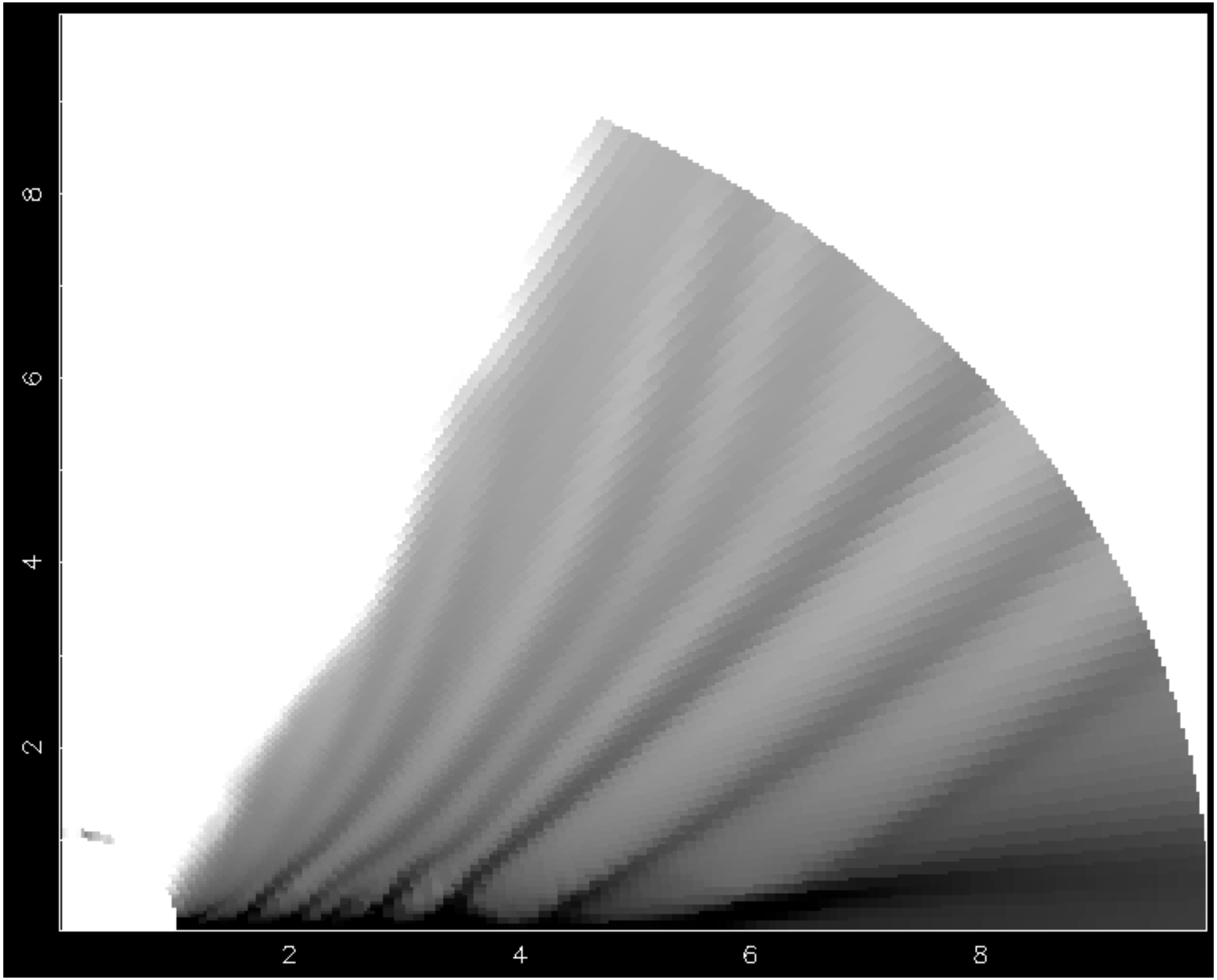
M_9=1; Mdot = 1; cos i = 0.99, 0.8, 0.6, 0.4, 0.2, 0.01
0.99
0.01
10.00
1.00
0.10
0.01
ν L_ν (10^45 erg s^-1)
10^14
10^15
10^16
10^17
frequency (Hz)

Accretion disk winds

- Hypothesis: BALs are preferentially found along low-latitude sightlines above an accretion disk, sightlines along which the accretion disk looks bluer
- Outflowing gas at low latitudes above an accretion disk is called a disk wind.

Accretion disk winds

- *Hypothesis: BALs are preferentially found along low-latitude sightlines above an accretion disk, sightlines along which the accretion disk looks bluer*
- *Outflowing gas at low latitudes above an accretion disk is called a disk wind.*
- The accretion disk + wind is a plausible source of gas for both BALs and BELs. If the disk flares, its atmosphere can be ionized by the inner disk. The relatively hard low-latitude continuum actually helps explain quasar He II emission (Korista et al. 1997).



2
4
6
8
2
4
6
8