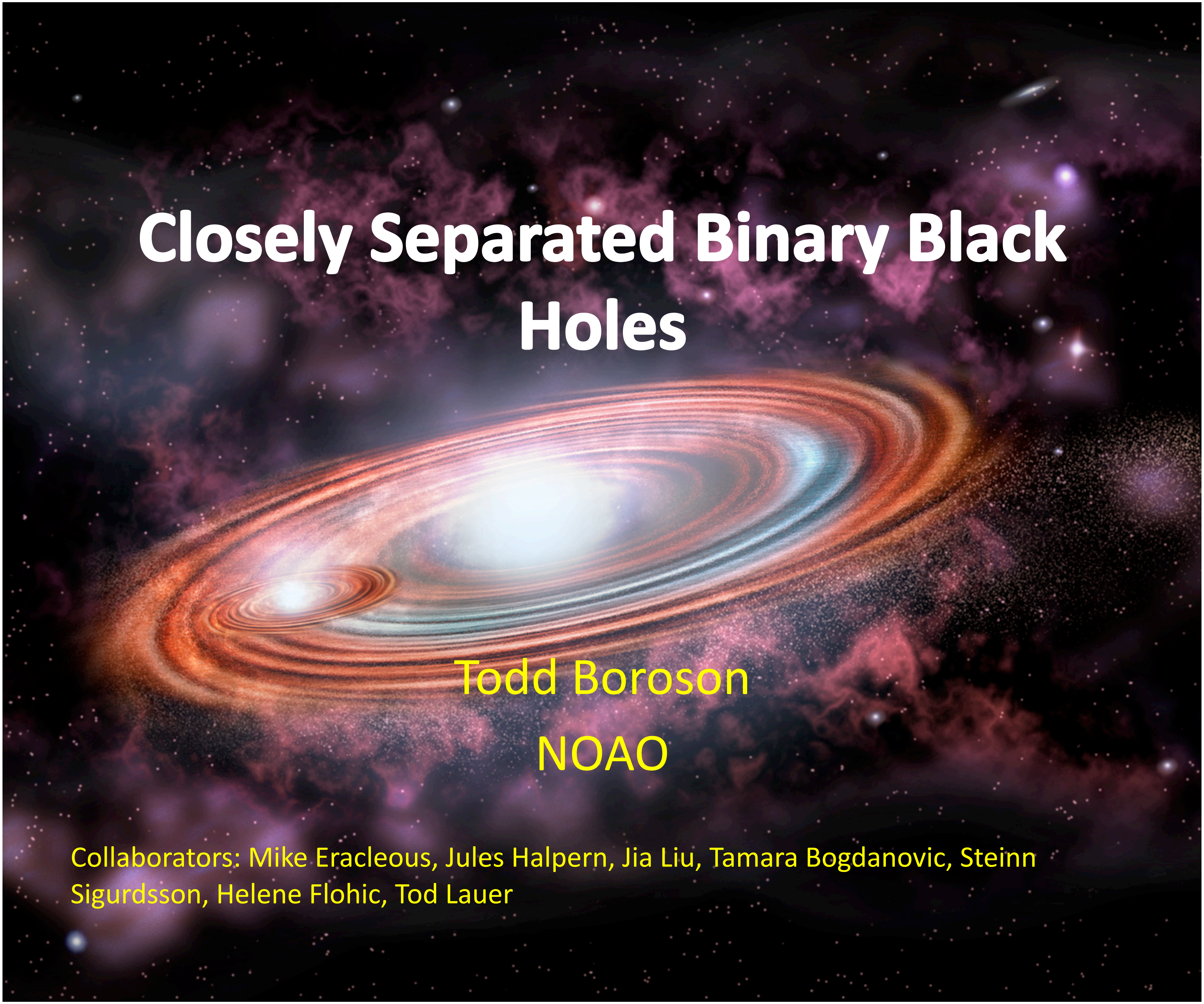

# Closely Separated Binary Black Holes


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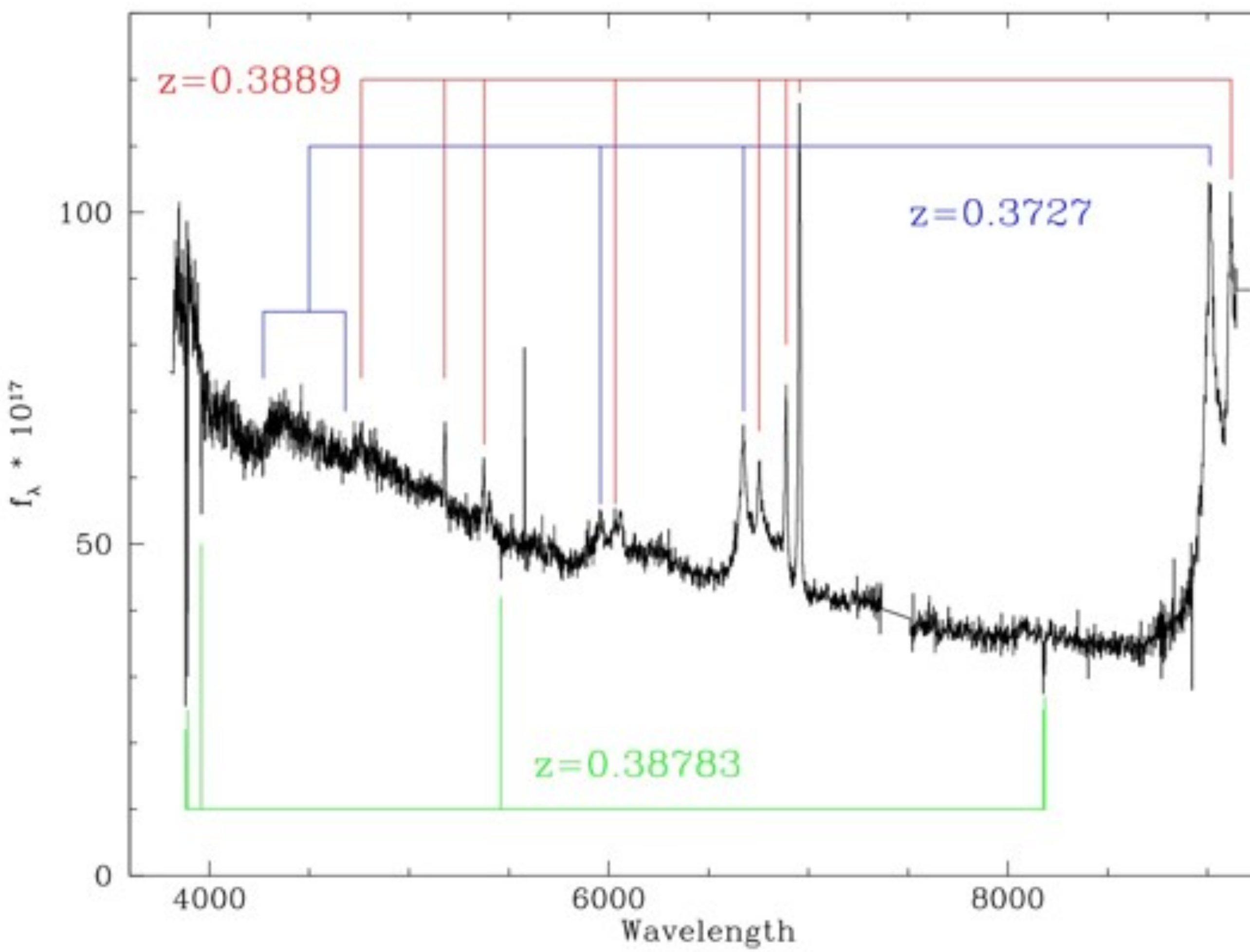
# Background

- Finding bound, merging SMBH binaries of interest for:
  - Better estimates of merger rates
  - Better understanding of growth of SMBHs
  - Better understanding of physics governing SMBH mergers (final parsec problem)
  - Predictions of GW event statistics
- Methodology (Active objects)
  - Too close to be resolved by imaging
  - Variability difficult to interpret (OJ 287)
  - Spectroscopic signature – similar to (stellar) spectroscopic binaries
    - Find objects in which broad emission lines are offset from systemic redshift. Monitor them over (part of) period as they trace orbital motion by "moving" to other side of systemic lines and back.

# Inspiration – SDSS J1536+0441



# Premise

- Find objects in which broad emission lines are offset from systemic redshift. Monitor them over (part of) period as they “move” to other side of systemic lines and back.
- Candidates are defined by unusual broad line profile with shifted peak
- Caveats
  - BL components centered on primary, secondary, or both?
    - Are all of these represented in nature?
  - Bound orbits vs. recoil/ejection
  - Physical connection vs. chance superposition
  - Differentiation from double-peaked emitters and other peculiar line profiles
  - Permitted/preferred regions of parameter space
    - Significant shifts mean that we tend to pick systems at quadrature

# What could we hope to see?

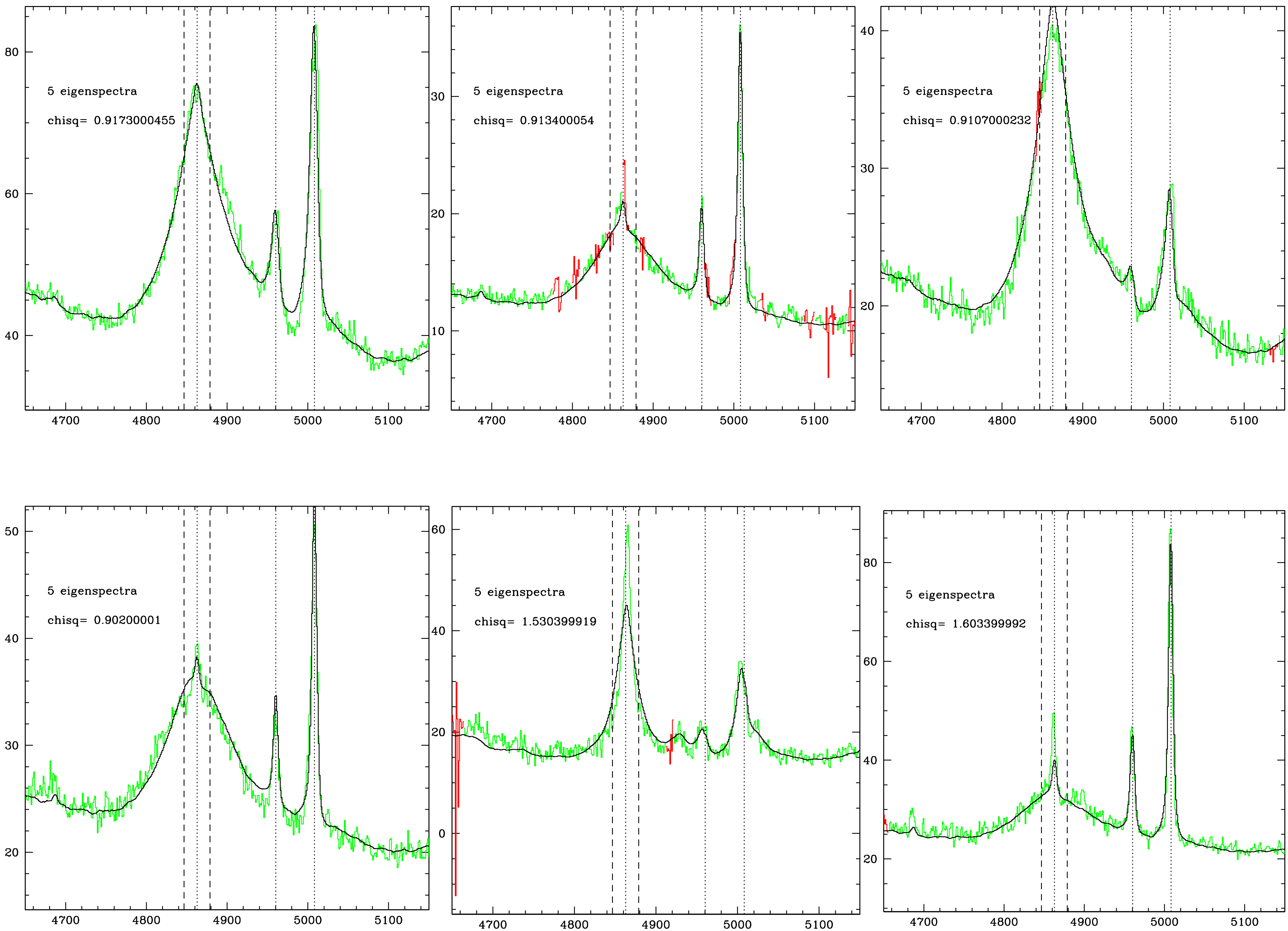
- Offset of ≥1000 km $s^{-1}$ is easily distinguishable

| | $M_1+M_2 = 10^7$ | $M_1+M_2 = 10^8$ | $M_1+M_2 = 10^9$ |
|---|---|---|---|
| v = 1000 km $s^{-1}$ | r = 0.04 pc<br>P = 260 yr<br>$\langle dv/dt \rangle$ =<br>15 km $s^{-1}$ $yr^{-1}$ | r = 0.43 pc<br>P = 2600 yr<br>$\langle dv/dt \rangle$ =<br>1.5 km $s^{-1}$ $yr^{-1}$ | r = 4.3 pc<br>P = 26000 yr<br>$\langle dv/dt \rangle$ =<br>0.15 km $s^{-1}$ $yr^{-1}$ |
| v = 3000 km $s^{-1}$ | r = 0.005 pc<br>P = 10 yr<br>$\langle dv/dt \rangle$ =<br>1200 km $s^{-1}$ $yr^{-1}$ | r = 0.05 pc<br>P = 100 yr<br>$\langle dv/dt \rangle$ =<br>120 km $s^{-1}$ $yr^{-1}$ | r = 0.50 pc<br>P = 1000 yr<br>$\langle dv/dt \rangle$ =<br>12 km $s^{-1}$ $yr^{-1}$ |

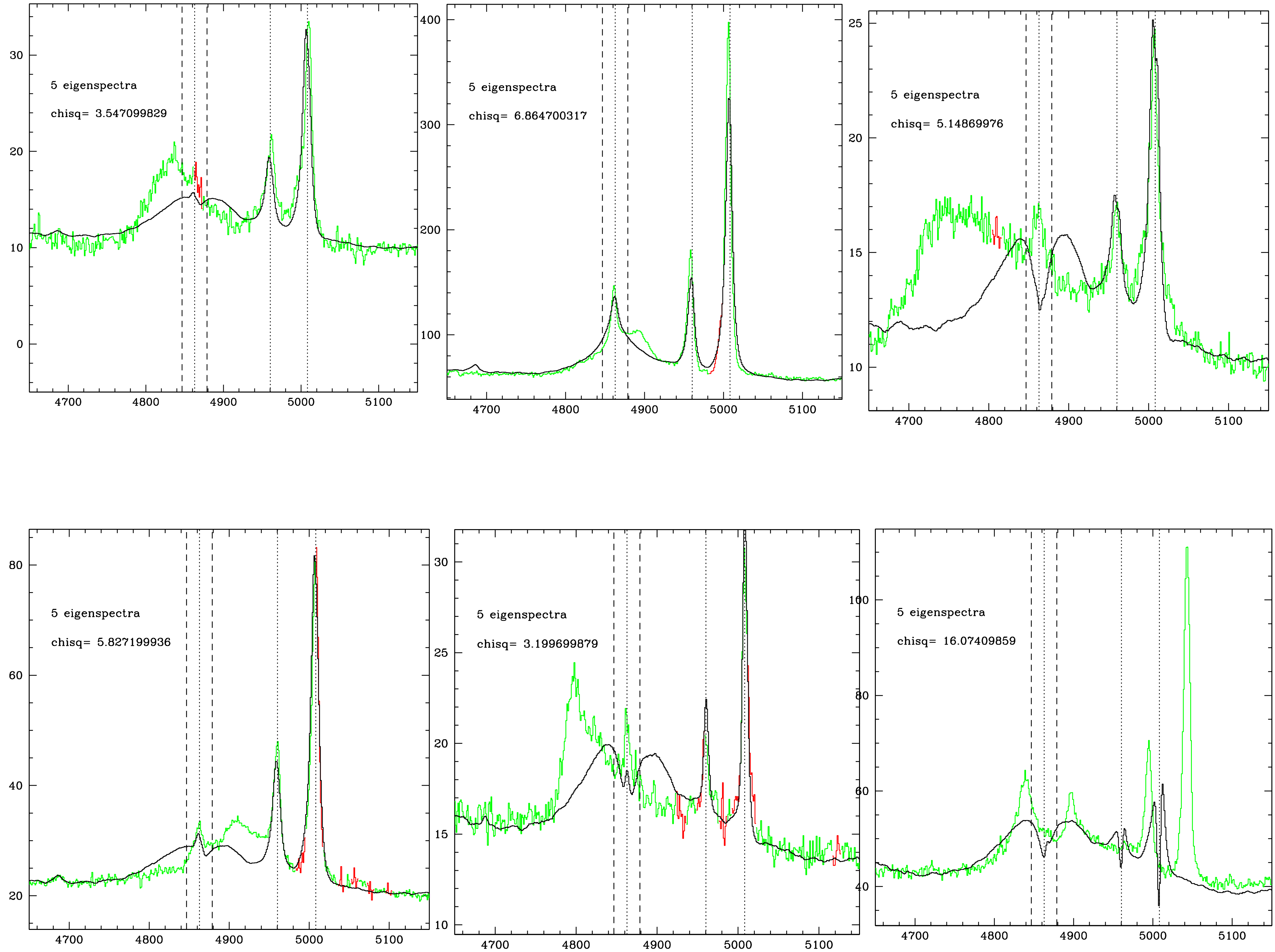
These numbers are all averages over orbit. Instantaneous values will be much larger/smaller.

# Sample of candidates

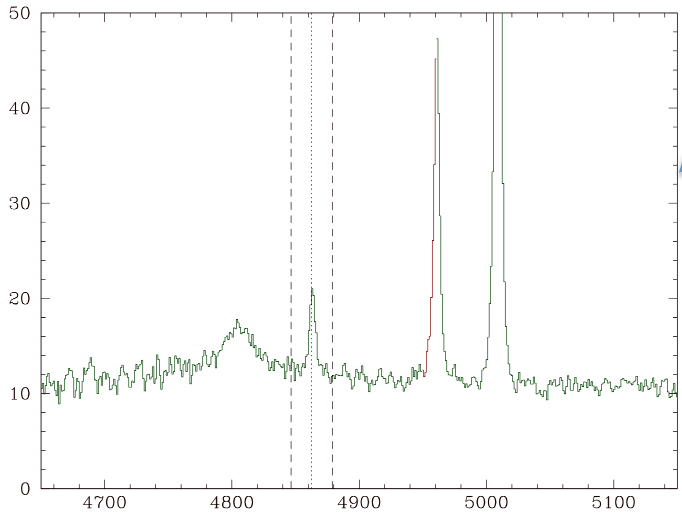
- Concentrate on Hβ
- SDSS archive contains 15,900 QSOs w/ $z<0.7$
- Use spectral PCA to identify objects with unusual Hβ emission line profiles
  - Fit λλ4300-5400 region
  - Limit fit to first 5 eigenspectra
  - Examine objects with $\chi^2 > 3$
- Inspect visually to find objects with:
  - Peak of line offset from systemic redshift (as determined from [O III]) by > 1000 km $s^{-1}$
    - Subsequent systematic measurements of peaks left some with v<1000
  - Exclude typical double-peaked emitters
- 88 candidate objects



5 eigenspectra
chisq= 0.9173000455
5 eigenspectra
chisq= 0.913400054
5 eigenspectra
chisq= 0.9107000232
5 eigenspectra
chisq= 0.90200001
5 eigenspectra
chisq= 1.530399919
5 eigenspectra
chisq= 1.603399992

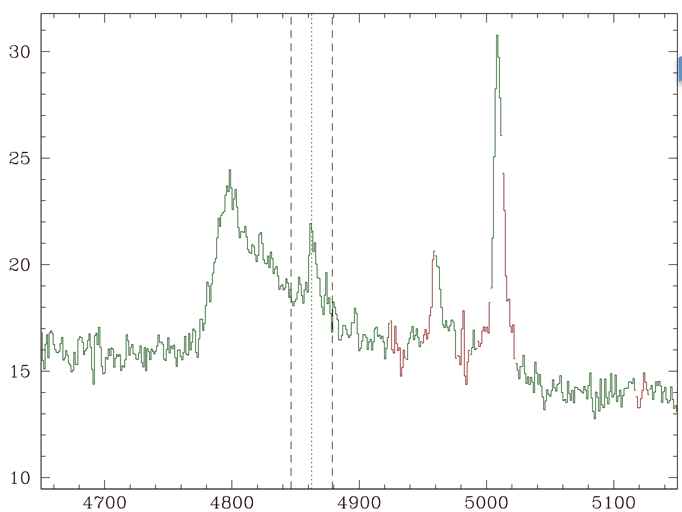

5 eigenspectra
chisq= 3.547099829
5 eigenspectra
chisq= 6.864700317
5 eigenspectra
chisq= 5.14869976
5 eigenspectra
chisq= 5.827199936
5 eigenspectra
chisq= 3.199699879
5 eigenspectra
chisq= 16.07409859
4700
4800
4900
5000
5100

# Three classes of profile

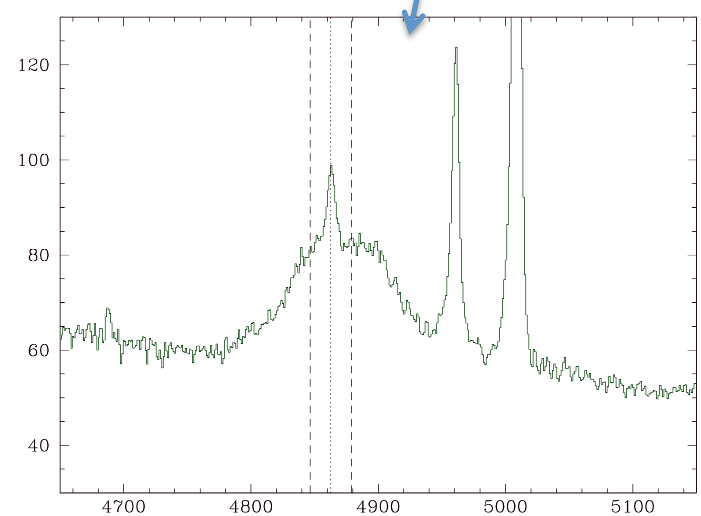



Narrow, symmetric

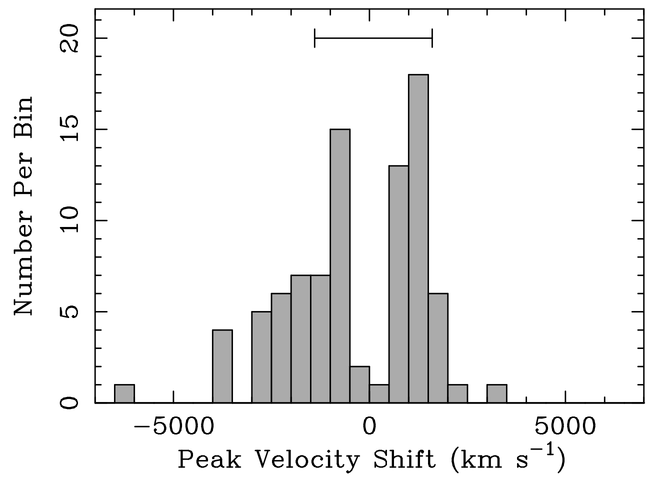
Broad, skewed



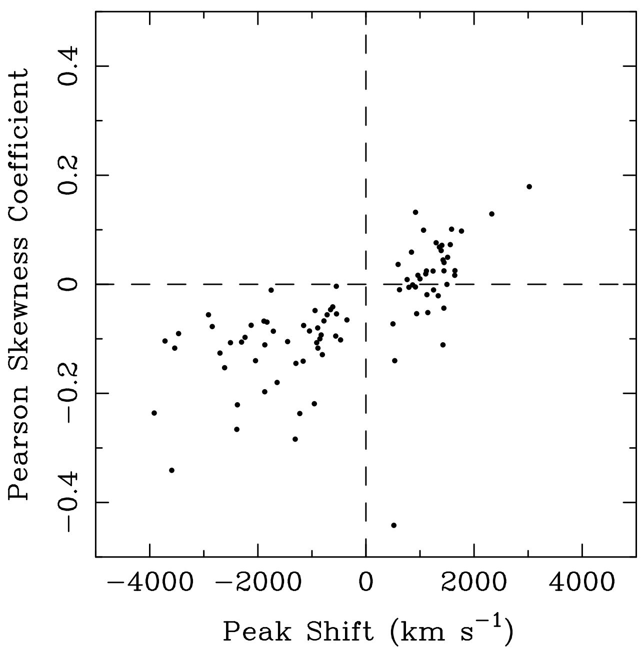

Broad, flat-top



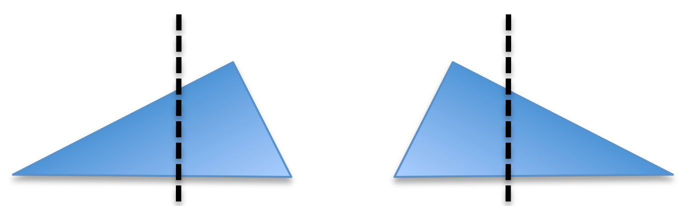
# Properties of candidates




Error bar shows range of peak shifts found by Bonning et al. 2007




Lines tend to be skewed such that they are "centered" close to systemic redshift, even though peak is offset:



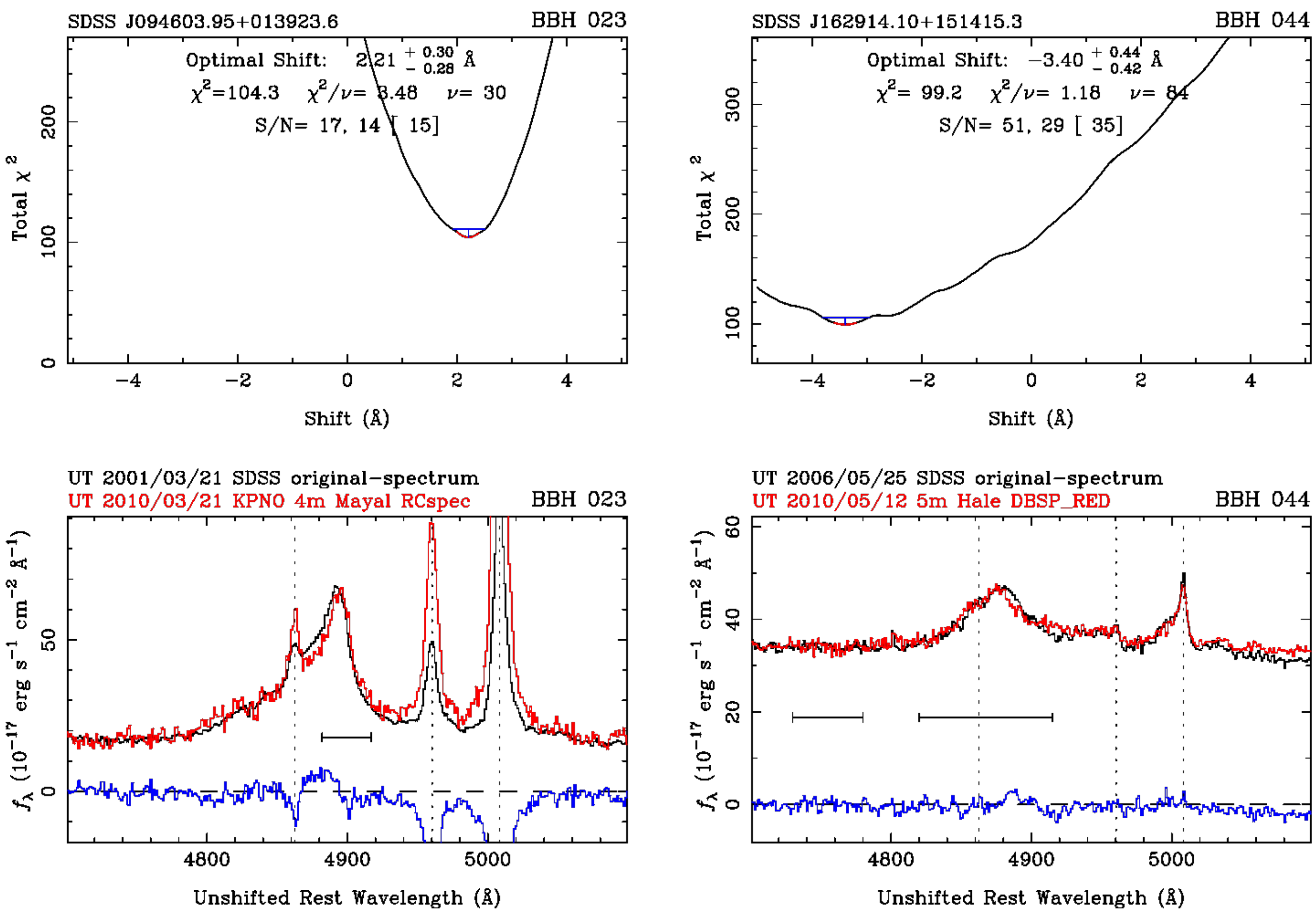
# Second Epoch Observations

- SDSS spectra taken between 2000 and 2008
- Second epoch spectra of 68 objects in sample taken between Jan 2009 and June 2010:
  - MDM – 2.4m Hiltner telescope – 7.6 Å resolution
  - KPNO – 4m Mayall telescope – 3.1 Å
  - Palomar – 5m Hale telescope – 4.0 Å (b); 3.1 Å (r)
  - Hobby-Eberly telescope – 5.6 Å

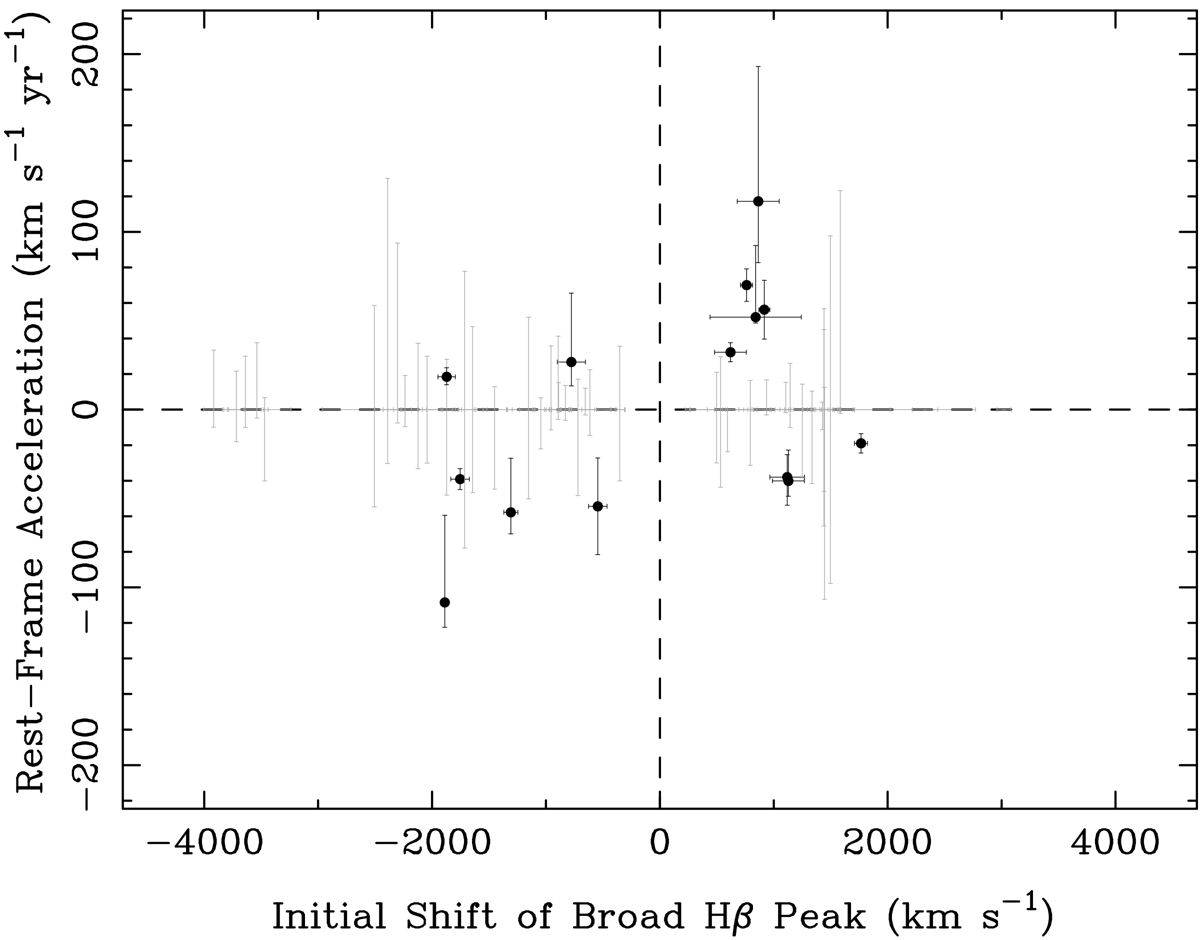
# Procedure & Results

- Set zero point of velocity shift using [O III] lines
- Apply flux density transformation (linear scaling + constant) to match continuum and broad Hβ emission line
- Compute $\chi^2$ as fn of relative shift, using only clean regions of Hβ profile
- 14 objects show shifts significant at > 99% confidence level
  - $<|v_{shift}|>= 200 \pm 26$ km/s (1 σ)
  - Accelerations in range ±120 km $s^{-1}$ $yr^{-1}$
- 13 objects show profile variations
- 38 objects show no significant shift (±58 km/s)
- 3 objects had insufficient S/N to say anything meaningful
- Objects with significant shifts – no statistically significant difference in properties from those with no shift

# Objects with shifts



# Accelerations



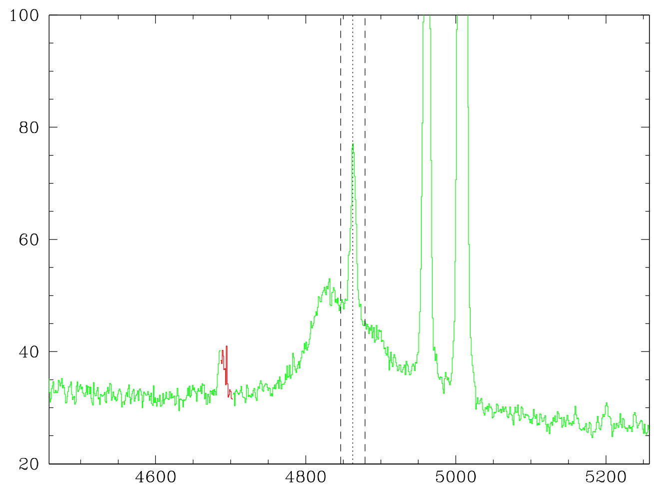
# Interpretations

- Relative motion
  - Binary black holes (peak velocity traces orbit)
  - Recoils (shift, but no acceleration)
    - Might expect narrow line peculiarities
  - other accretion disk or BLR structure (might accelerate)
    - Might or might not appear to rotate
  - Superposed objects (no acceleration)
    - Expect narrow lines corresponding to offset peak
- Not relative motion
  - Disk emission (might change)
    - Off-axis illumination?
  - Line profile variations

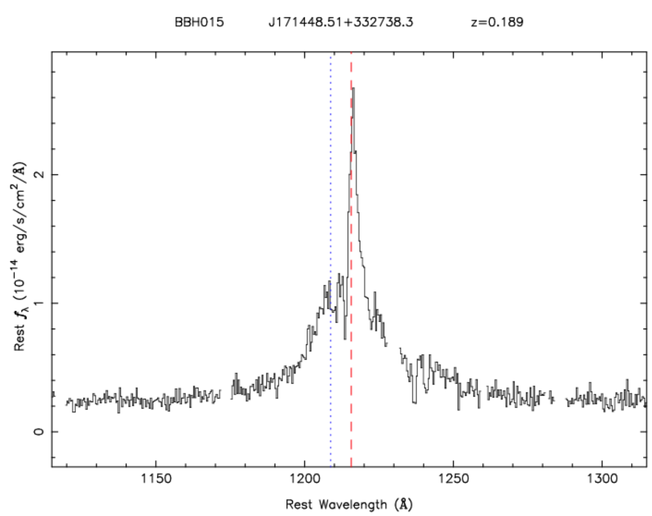
# Next Steps

- Monitor long enough to observe unequivocal orbital motion
  - Several examples of DPEs with peaks that seemed to mimic orbital motion temporarily
  - Have finished $2^{nd}$ epoch observations and started third
- Observe UV lines
  - In DPEs, high ionization lines show single peak
  - Have obtained HST (COS or STIS) spectra of 13 objects in our sample, covering Lyα and Mg II
- HST or AO images to rule out superposed objects
- VLBI observations could resolve in some cases

# One interesting candidate




Hβ, showing ±1000 km $s^{-1}$




Lyα, showing systemic (narrow line) redshift

# Open Questions

- Observational:
  - Can hot spots in disk ever (within a fraction of an orbit) be distinguished from binary objects?
- Theoretical:
  - Refine numbers and lifetimes for binaries with close separations
  - Model gas motions and ionization structure to better understand expected spectroscopic properties
  - What fraction of merging binaries is expected to be active, half-active?