PENNSTATE 1855

Observational searches for close supermassive binary black holes

by Mike Eracleous

Massive Black Holes:Birth, Growth and Impact
KITP, Aug 5-8, 2013

Close SBHBs worth fnding becuse...

- They are the penultimate link in the SBHB evolutionary chain

    census allows us to track the “flow” of systems through different evolutionary phases

- They have been invoked to explain a number of other phenomena

    formation and subsequent erosion of stellar cusps in galaxy cores (e.g., Milosavljević & Merritt 2001; Sesana et al. 2008; Kormendy & Bender 2009)

    precessing radio jets and X-shaped radio sources e.g., Roos (1987, ApJ, 334, 95); Merritt (2002, Sci, 297, 1310)

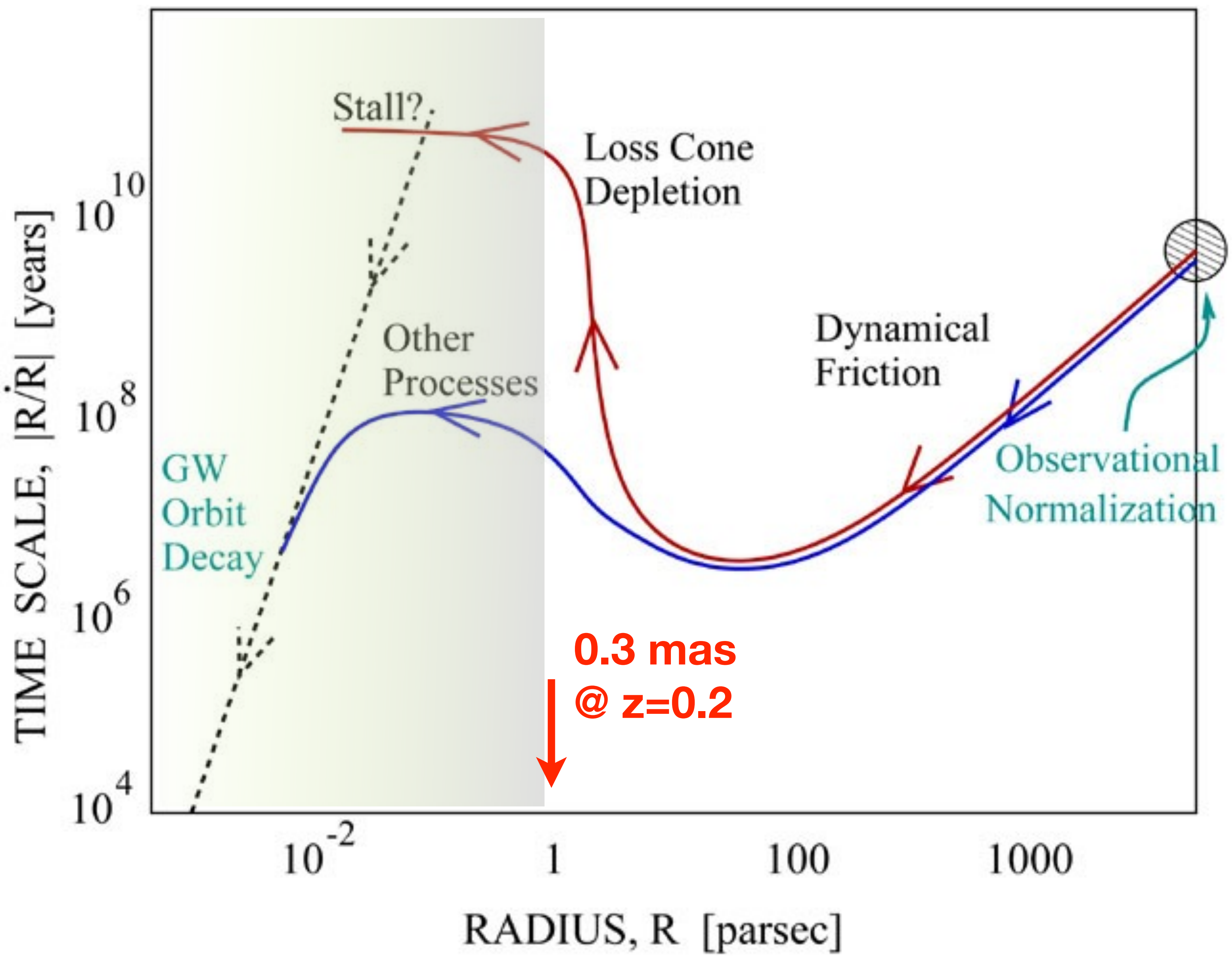


figure from Backer et al. (2003), based on the work of Begelman et al. (1980)

SBHBs @ 0.1 pc within circumbinary disk

- Direct imaging via radio interferometry
  talk by Sarah Burke-Spolaor, Wednesday morning
- Indirect detection via radial velocity changes
  Tsalmantza et al. 2011, ApJ, 738, 20
  Decarli et al. 2013, MNRAS, in press, arXiv:1305.4941
  Eracleous et al. 2012, ApJS, 201, 23
  Ju et al. 2013 (arXiv:21306.4987)
  Shen et al. 2013 (arXiv: 1306.4330)
- Relative intensities and profiles of broad lines
  Montuori et al. 2011, MNRAS, 412, 26

At even shorter separations...

- Predicted Fe Kα line and SED signatures of SBHBs
  Saavik Ford, Wednesday morning
  Gükltekin & Miller 2012, ApJ, 761, 90
- Detecting SBHBs via pulsar timing
  Alberto Sesana, Wednesday morning
- Periodic X-ray emission during inspiral
  Bode et al. 2010, ApJ, 715, 1117
  Bode et al. 2012, ApJ, 744, 45

Conspicuously missing from this talk:
Life after merger...

- Recoiling BHs
  Laura Blecha, Tuesday afternoon

The hypothesis: two BHs within disk

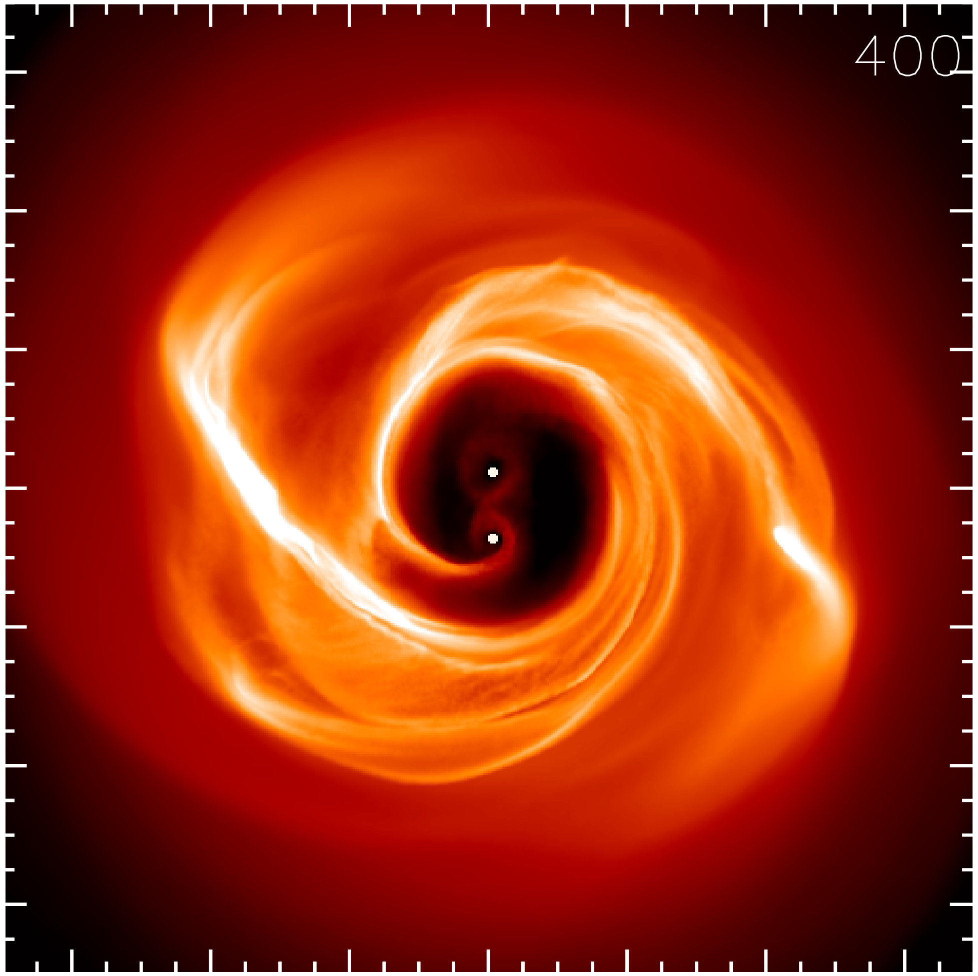


Figure from Cuadra et al. 2009, MNRAS, 393, 1423
see also Hayasaki et al. 2007, PASJ, 59, 427

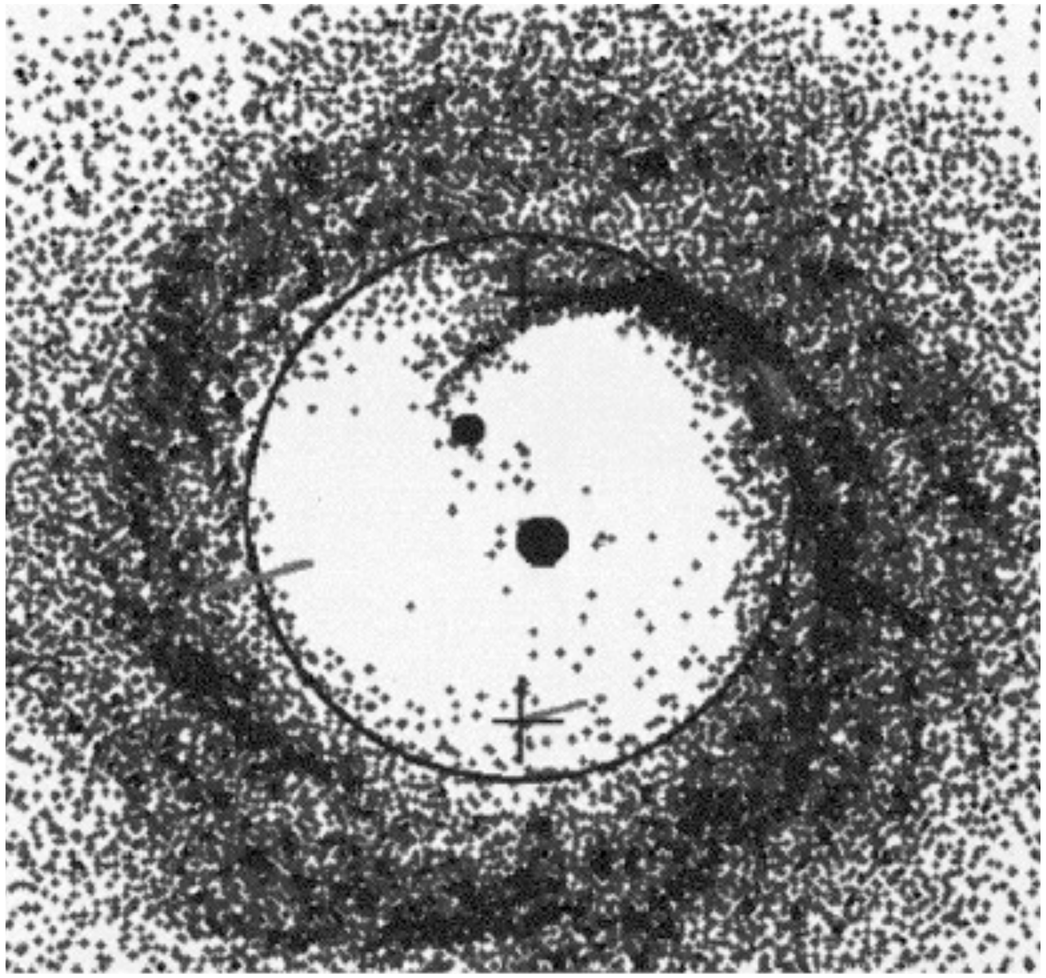
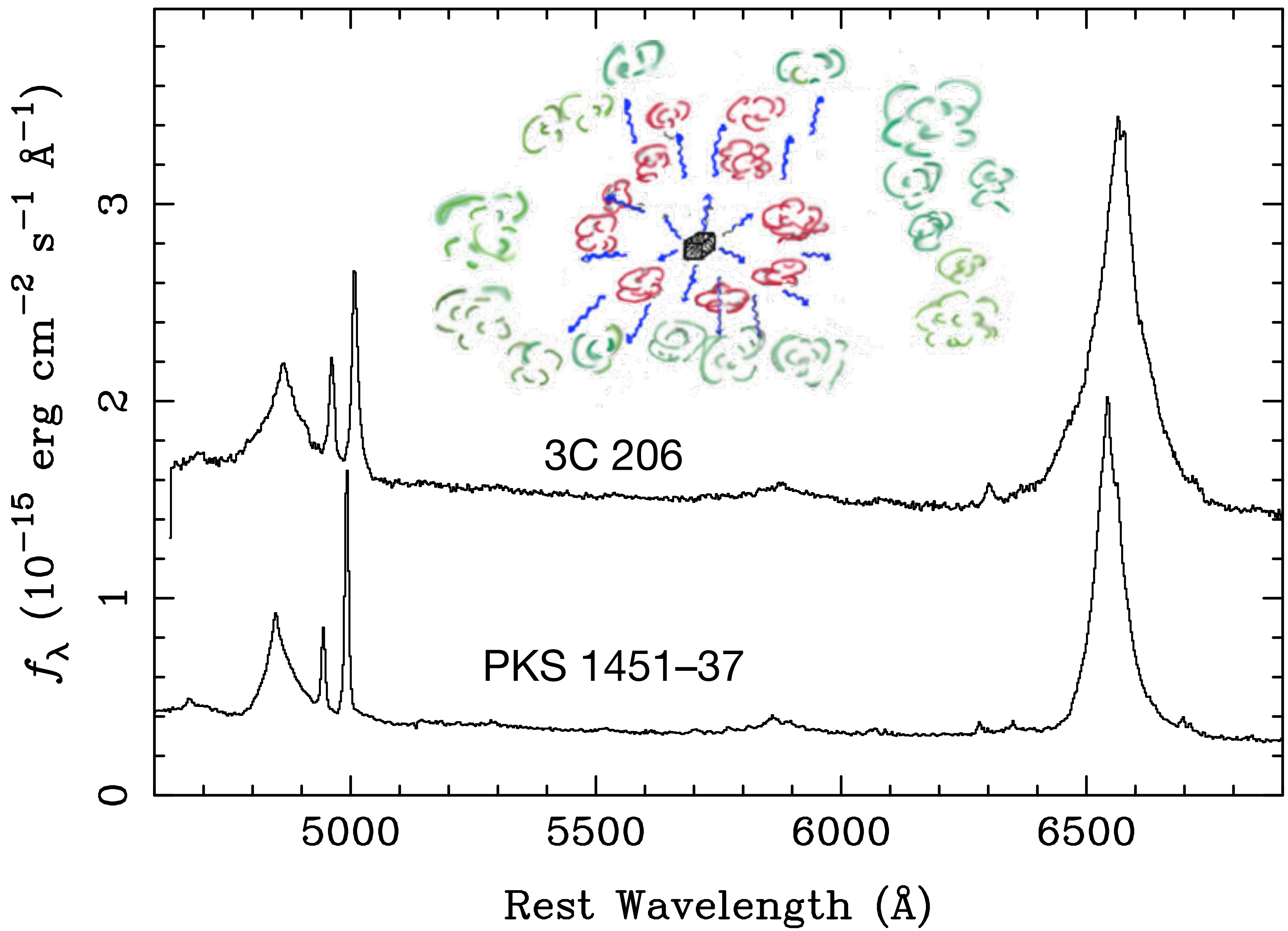


Figure from
Artymowicz & Lubow 1996, ApJ, 467 L77

Quasar optical spectra: up close and personal



Both black holes active: double-peaked lines

Tested and rejected

- Separation of peaks must be less than width
- Variation of peak velocities over 30 years inconsistent with binary
- Reverberation mapping: both sides respond together

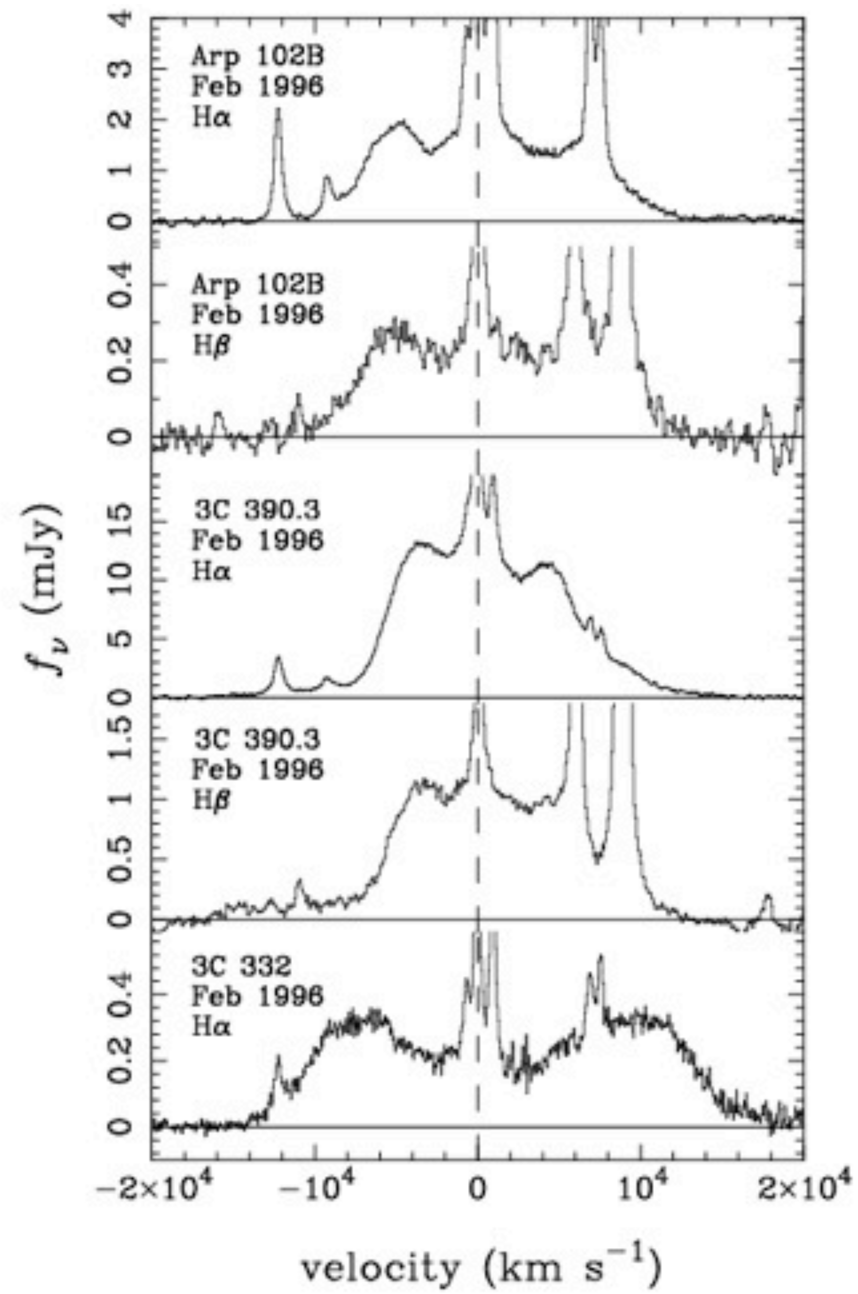
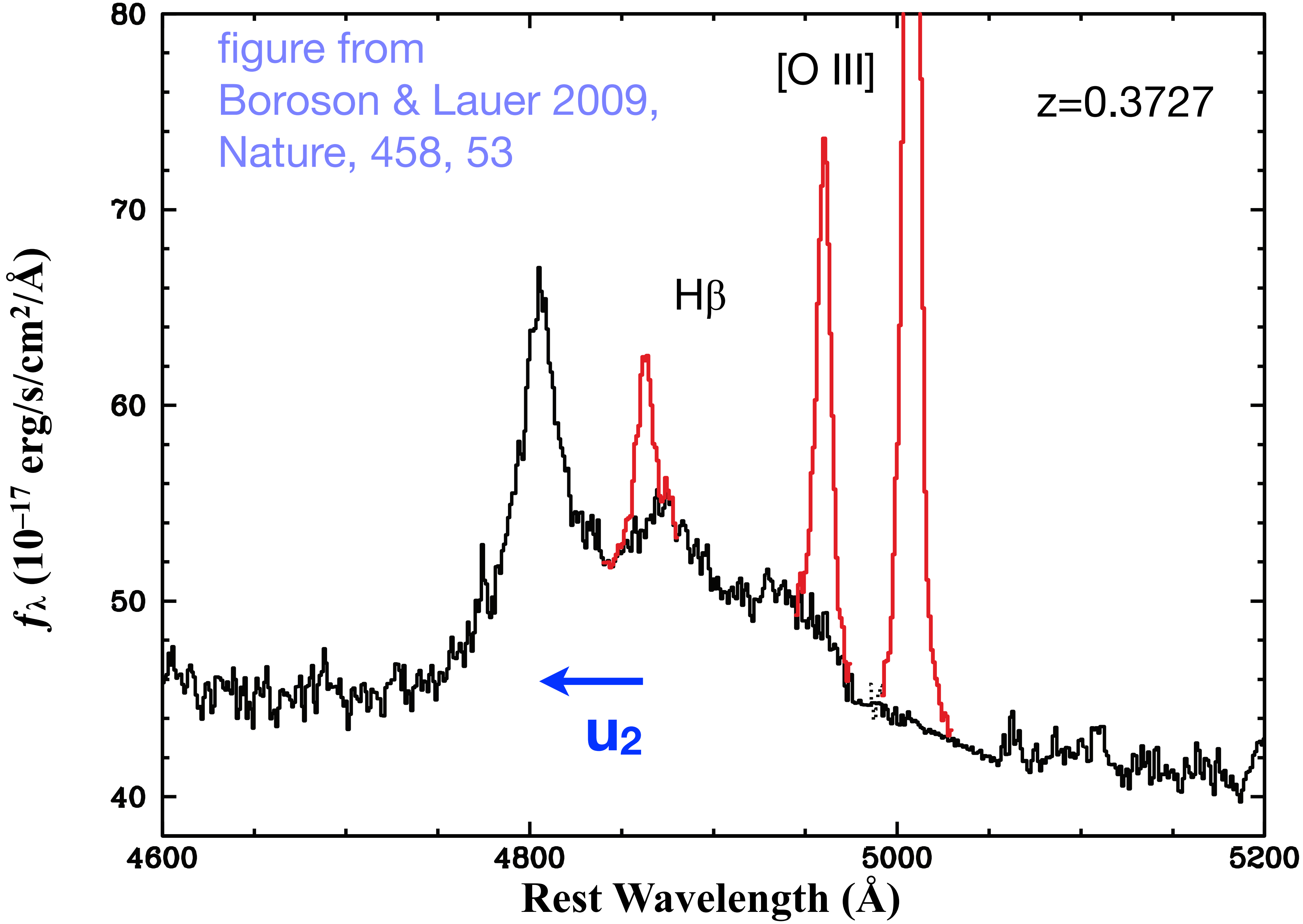
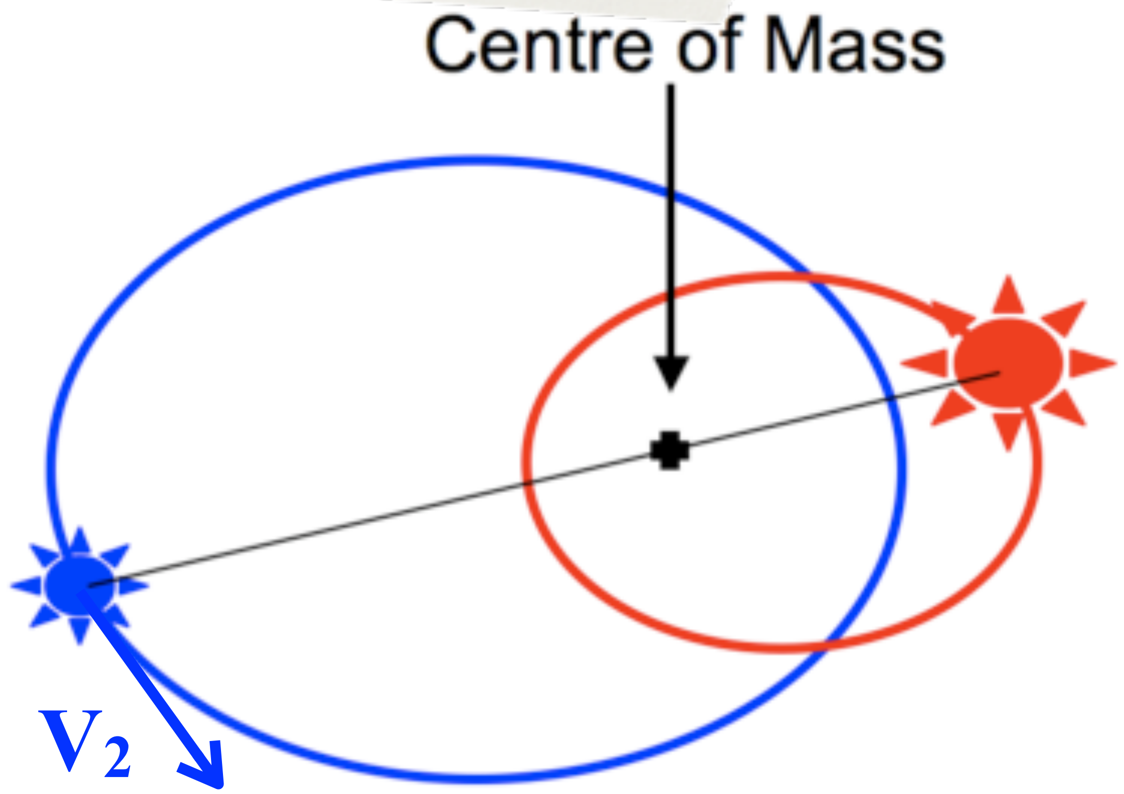


figure from Eracleous et al. (1997)

One black hole active: single, displaced line



Expected Binary Properties



We observe:

$$u_2 = V_2 \sin i \sin \phi$$

$$u_{2,3} = \frac{V_2 \sin i \sin \phi}{10^3 \text{ km/s}}$$

$$P = \frac{332\ M_8}{(1+q)^3\, u_{2,3}^3} \left(\frac{\sin i}{\sin 45^\circ}\ \frac{|\sin \phi|}{\sin 45^\circ} \right)^3 \ \mathrm{yr}$$

$$a = \frac{0.11\, M_8}{(1+q)^2\, u_{2,3}^2} \left(\frac{\sin i}{\sin 45^\circ}\ \frac{|\sin \phi|}{\sin 45^\circ} \right)^2 \ \mathrm{pc.}$$

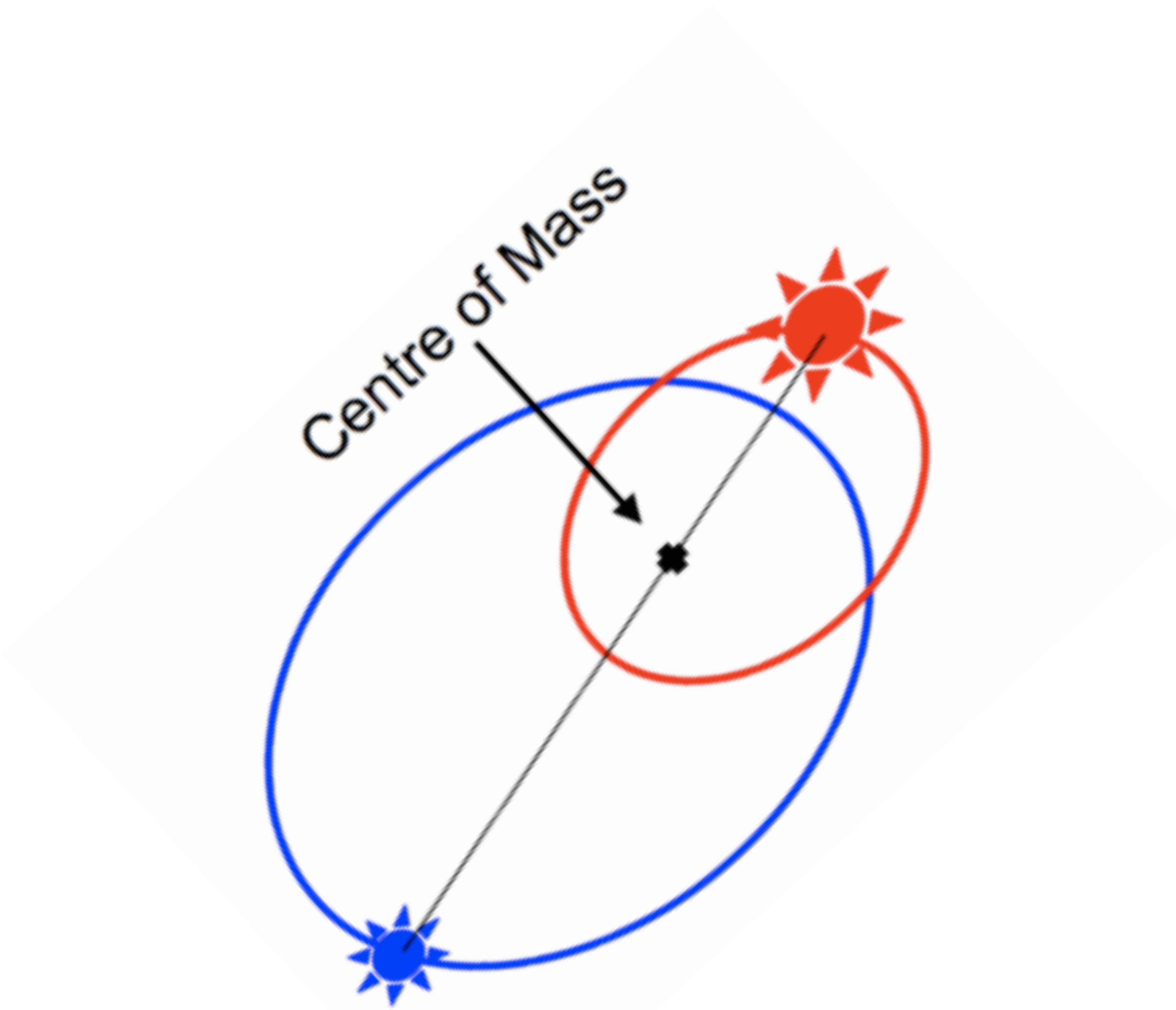
$$\left| \frac{du_2}{dt} \right| = 2.4\ \frac{u_{2,3}^4\, (1+q)^3}{M_8\ \sin^3 i} \left| \frac{\cos \phi}{\sin^4 \phi} \right| \ \mathrm{km/s/yr}$$

$$= 19\ \frac{u_{2,3}^4\, (1+q)^3}{M_8} \left(\frac{\sin 45^\circ}{\sin i} \right)^3 \frac{|\cos \phi|}{\cos 45^\circ} \left(\frac{\sin 45^\circ}{\sin \phi} \right)^4 \ \mathrm{km/s/yr}$$

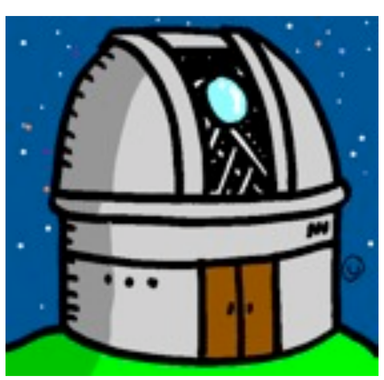
Recent searces for radial velocity variations:

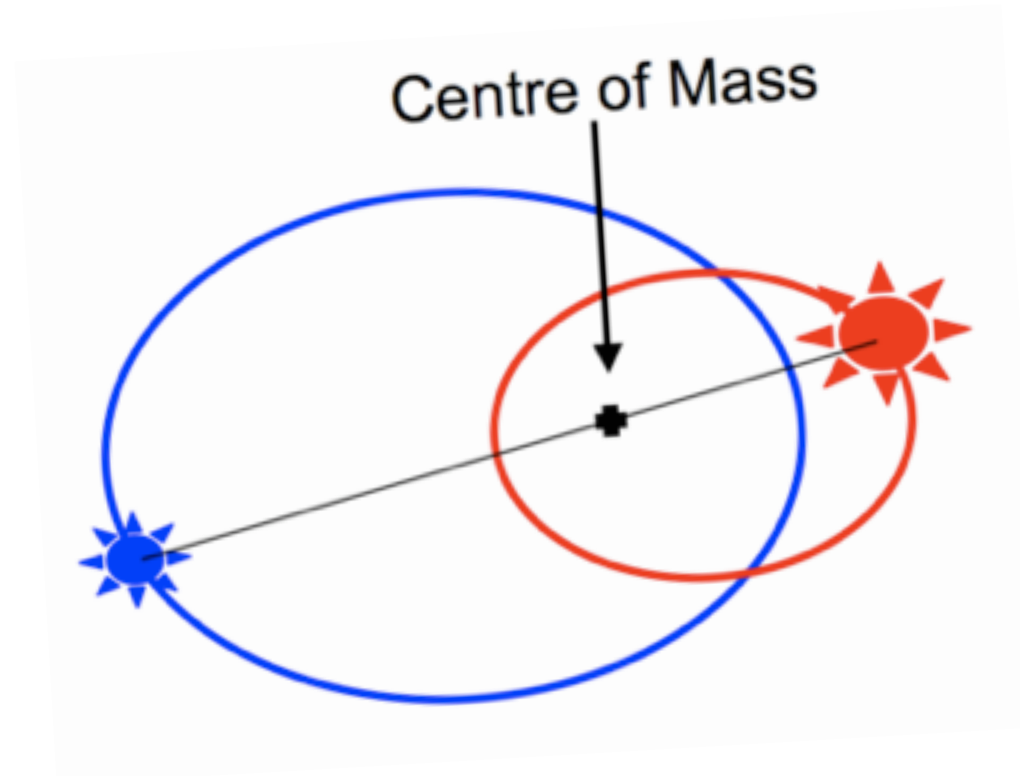
- Type I
  Tsalmantza et al. 2011, ApJ, 738, 20
  Decarli et al. 2013, MNRAS, in press, arXiv:1305.4941
  Eracleous et al. 2012, ApJS, 201, 23

- Type II
  Ju et al. 2013 (arXiv:1306.4987)
  Shen et al. 2013 (arXiv: 1306.4330)

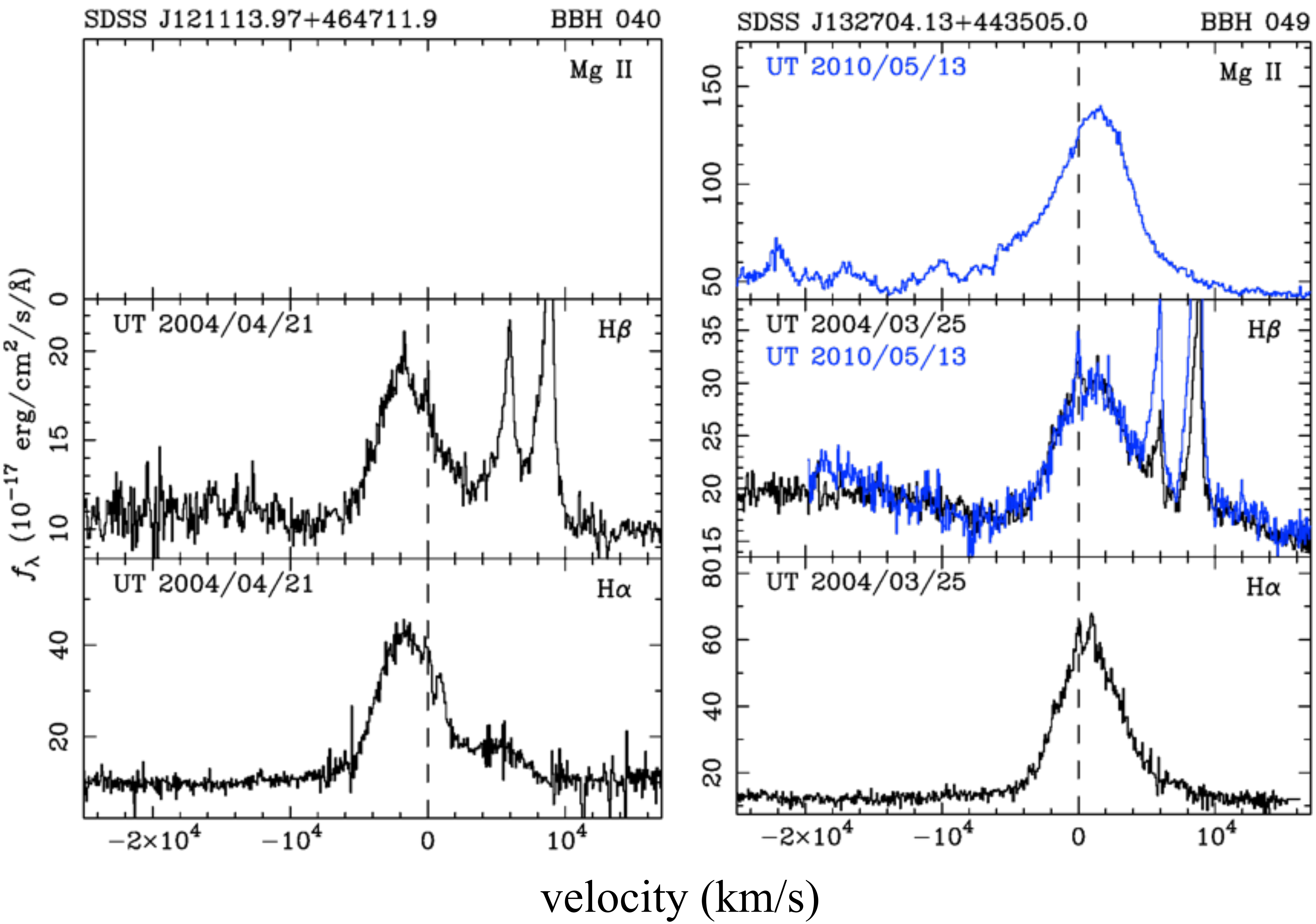


$\varphi = 0$



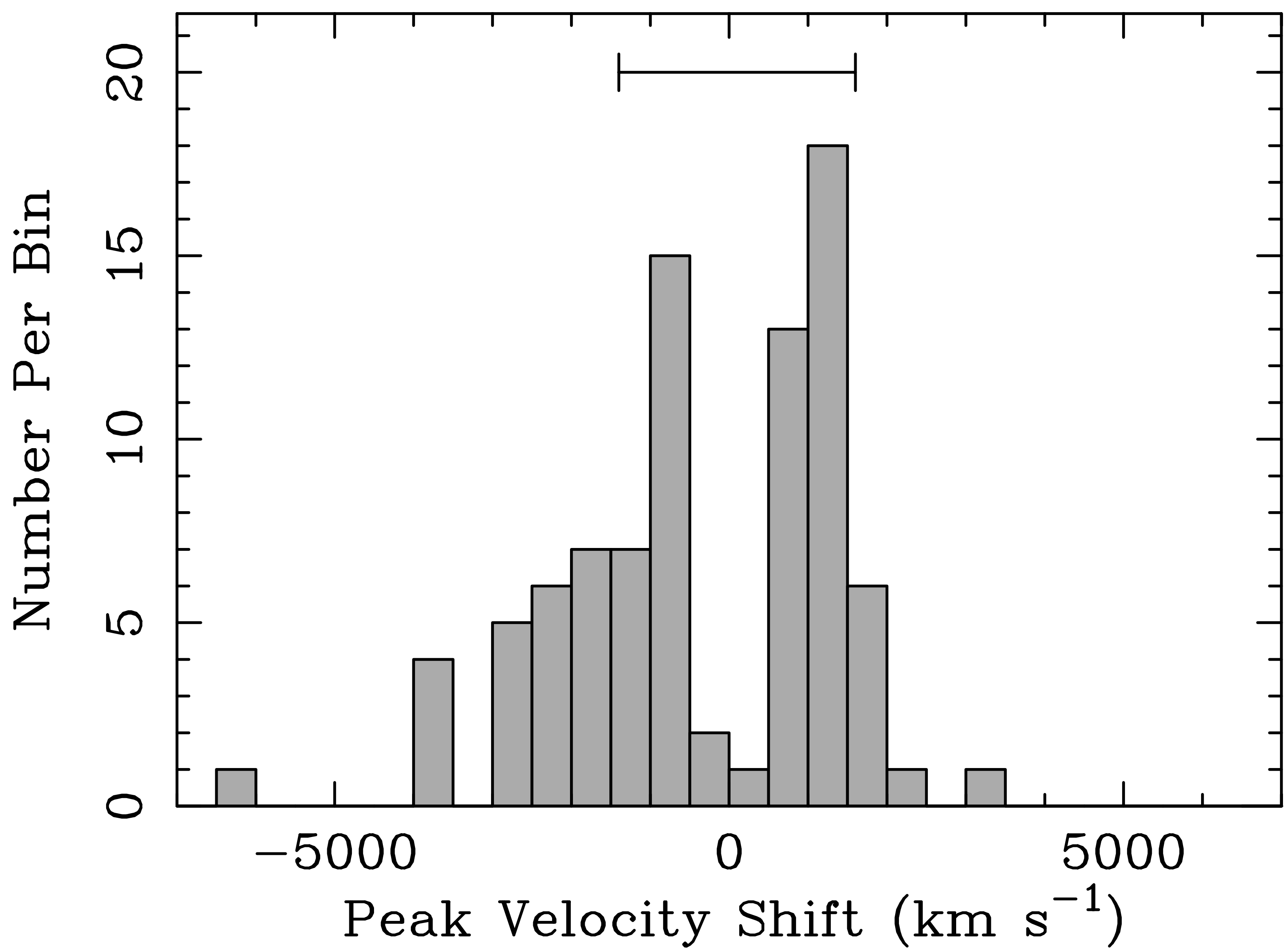


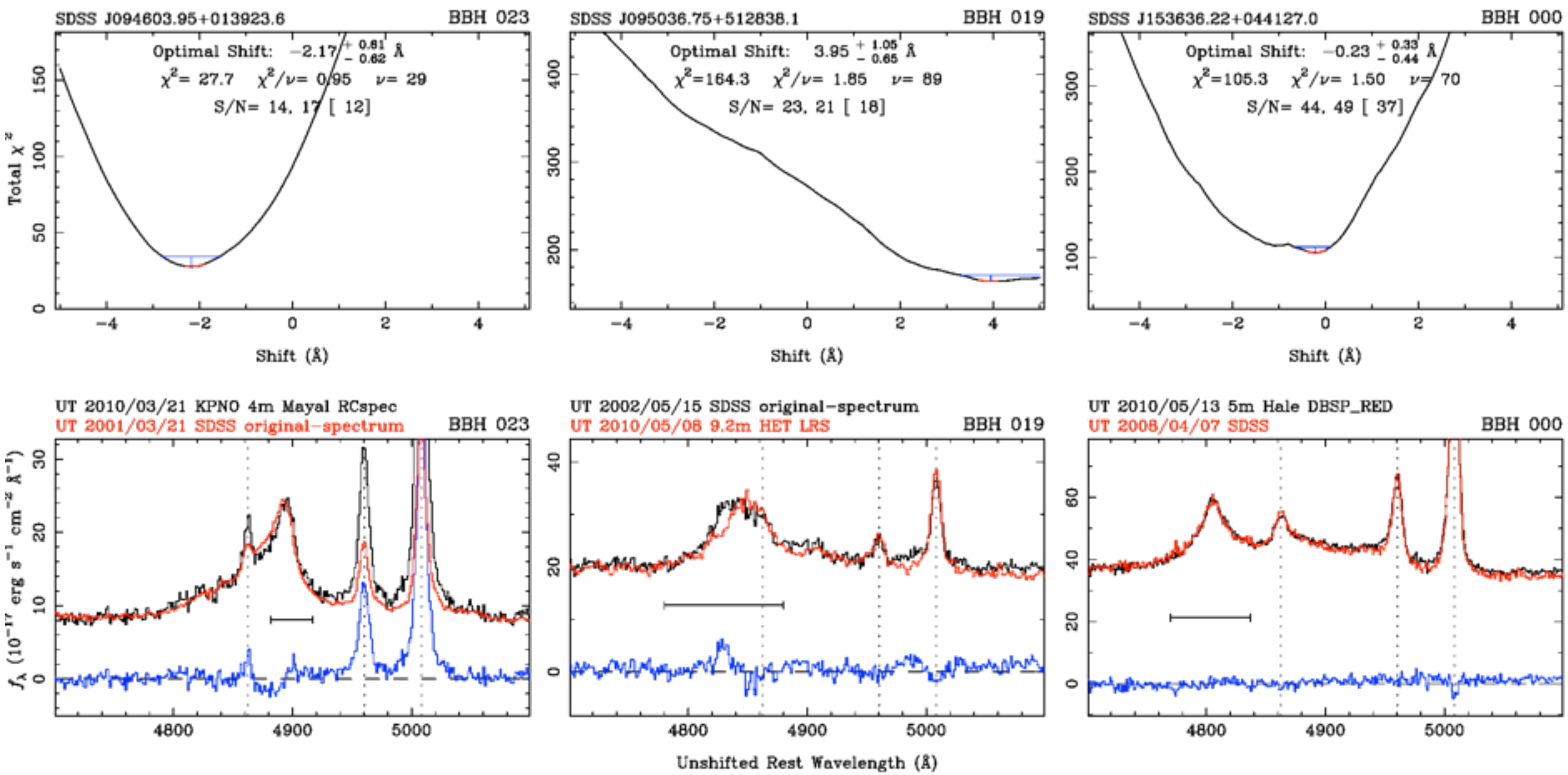
$\varphi \neq 0$



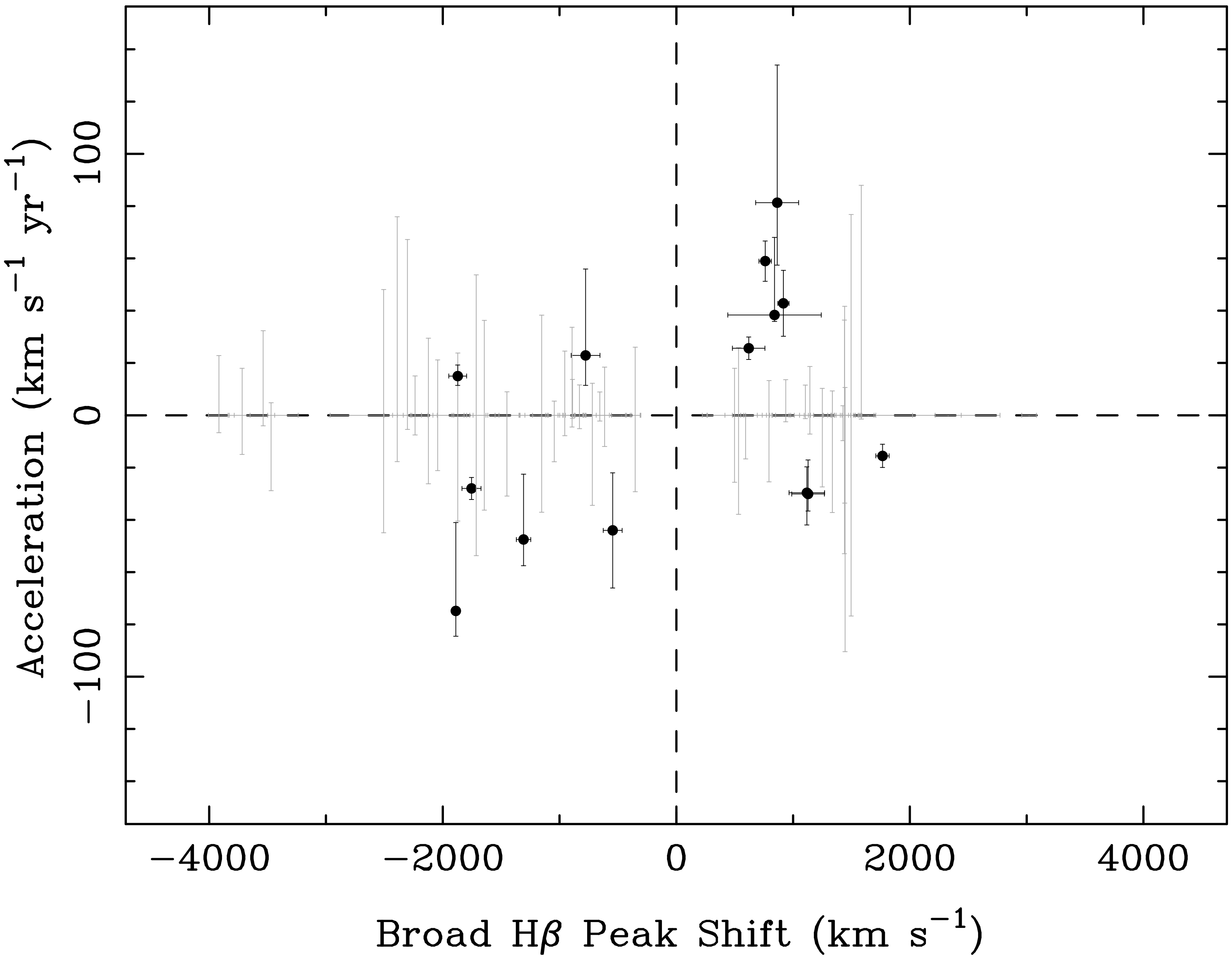
SDSS J121113.97+464711.9
BBH 040
Mg II
UT 2004/04/21
Hβ
UT 2004/04/21
Hα
f_λ (10^{-17} erg/cm^2/s/Å)
SDSS J132704.13+443505.0
BBH 049
UT 2010/05/13
Mg II
UT 2004/03/25
UT 2010/05/13
Hβ
UT 2004/03/25
Hα
-2×10^4
-10^4
0
10^4
velocity (km/s)

Distribution of Velocity Offsets

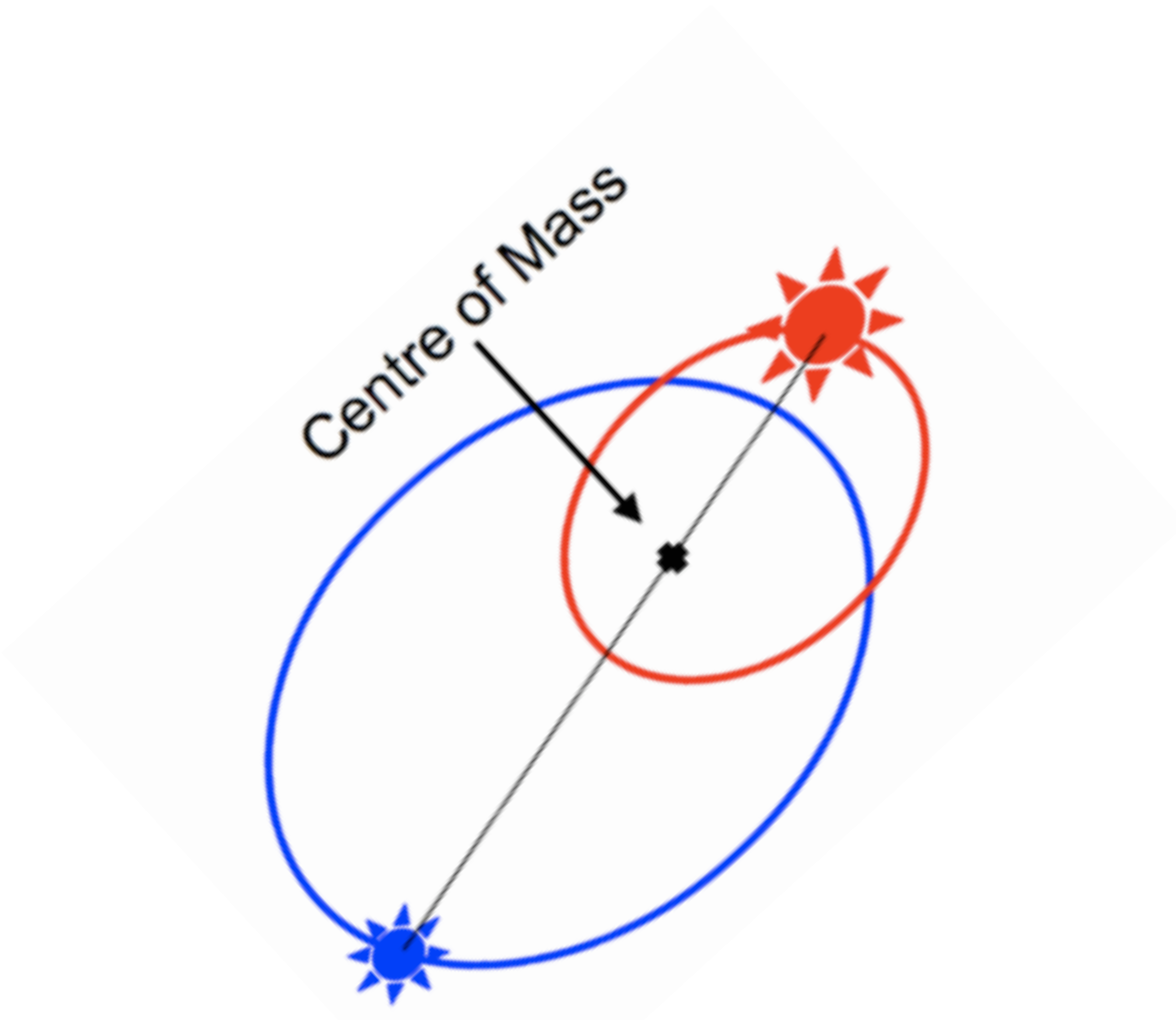




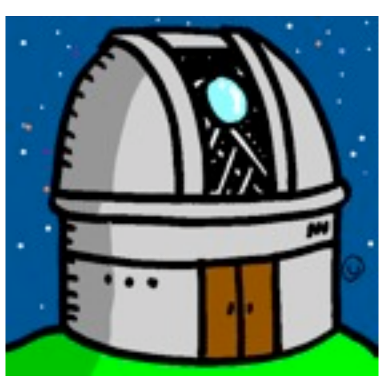
SDSS J094603.95+013923.6
BBH 023
Optimal Shift: −2.17 + 0.81 − 0.62 Å
χ²= 27.7 χ²/ν= 0.95 ν= 29
S/N= 14, 17 [12]
Total χ²
Shift (Å)
SDSS J095036.75+512838.1
BBH 019
Optimal Shift: 3.95 + 1.05 − 0.65 Å
χ²=164.3 χ²/ν= 1.85 ν= 89
S/N= 23, 21 [18]
SDSS J153636.22+044127.0
BBH 000
Optimal Shift: −0.23 + 0.33 − 0.44 Å
χ²=105.3 χ²/ν= 1.50 ν= 70
S/N= 44, 49 [37]
UT 2010/03/21 KPNO 4m Mayal RCspec
UT 2001/03/21 SDSS original−spectrum
UT 2002/05/15 SDSS original−spectrum
UT 2010/05/08 9.2m HET LRS
UT 2010/05/13 5m Hale DBSP_RED
UT 2008/04/07 SDSS
f_λ (10⁻¹⁷ erg s⁻¹ cm⁻² Å⁻¹)
Unshifted Rest Wavelength (Å)

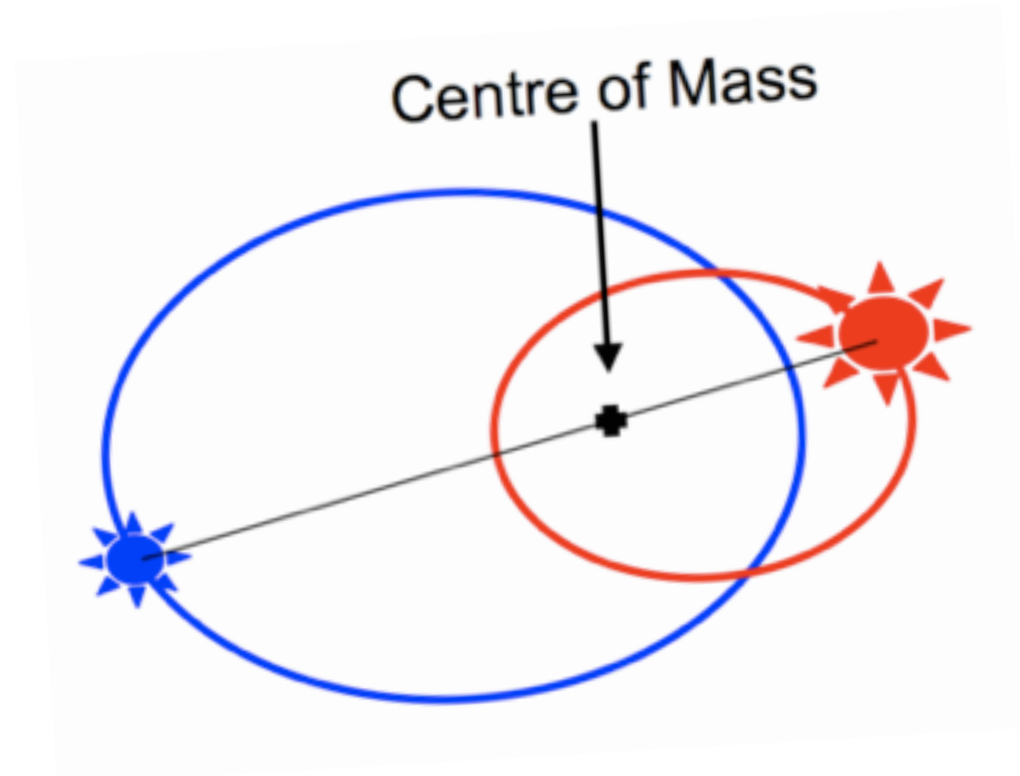


Acceleration (km s^{-1} yr^{-1})
100
0
−100
−4000
−2000
0
2000
4000
Broad Hβ Peak Shift (km s^{-1})



$\varphi = 0$

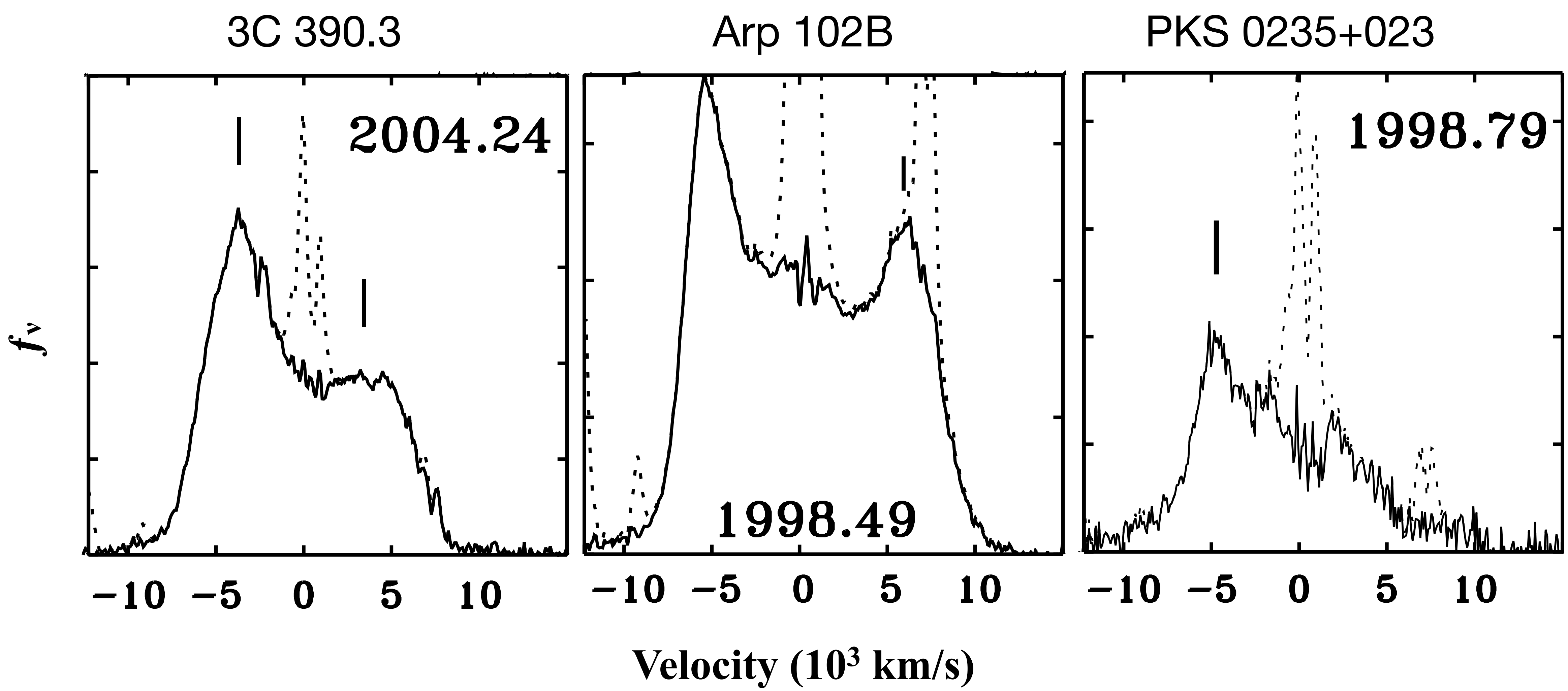




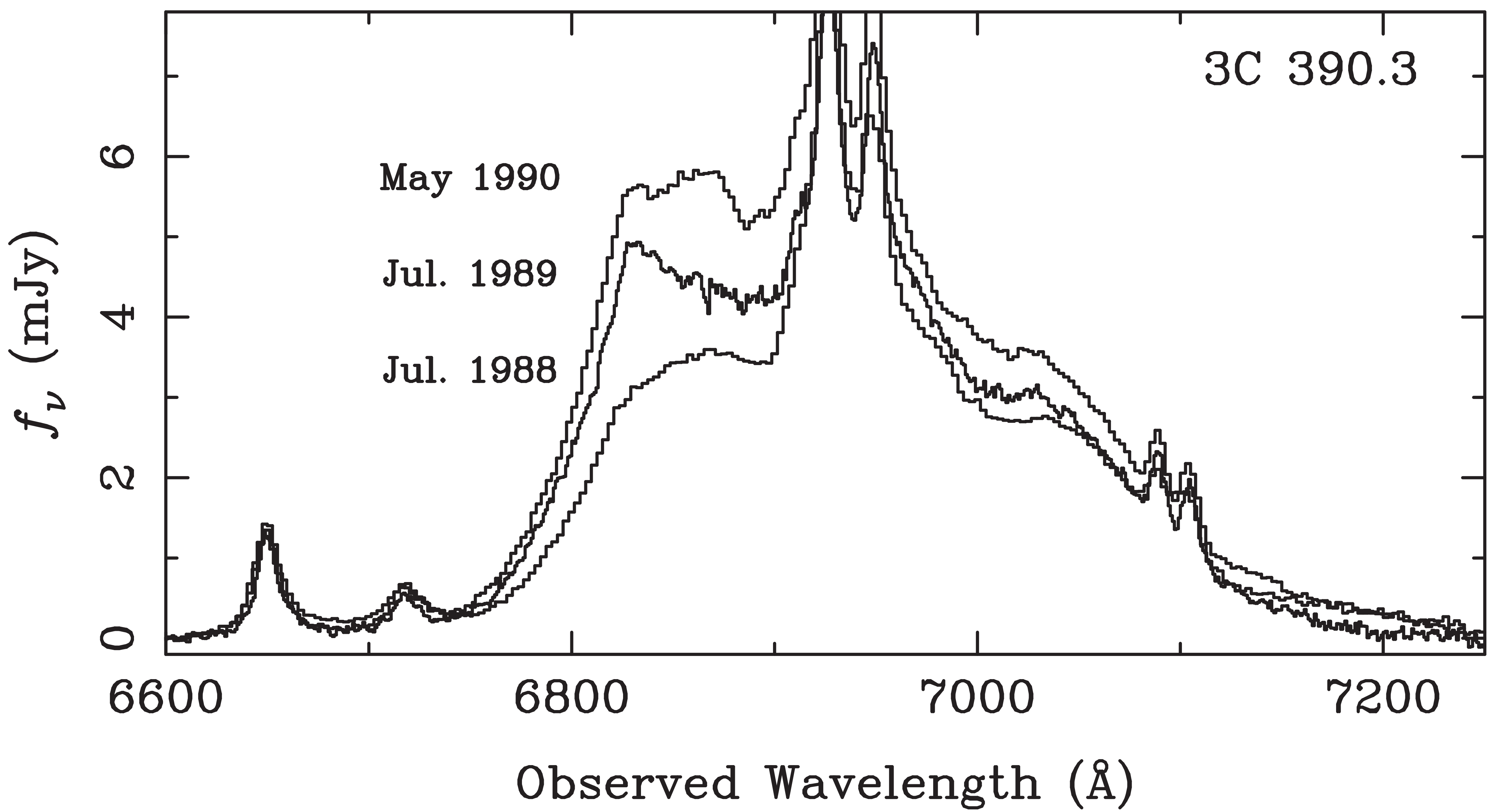
$\varphi \neq 0$

Caveats:

Displaced Peaks Do NOT Always Mean Binaries!

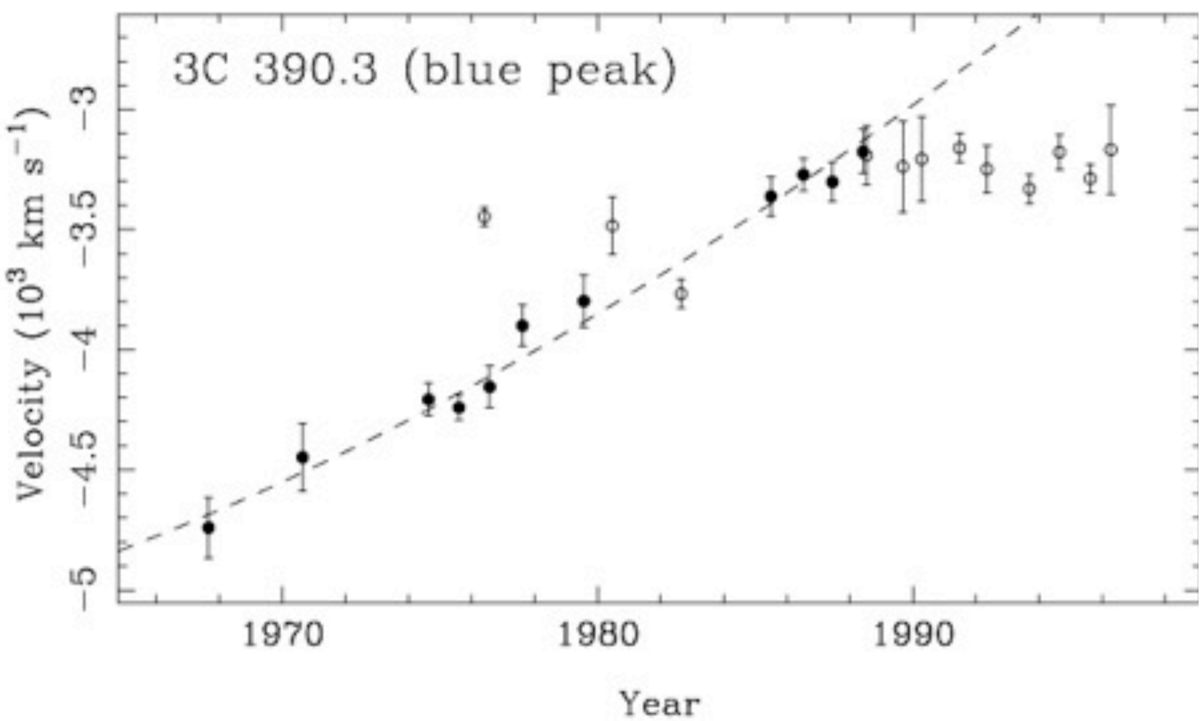


from Gezari, Halpern & Eracleous (2007)

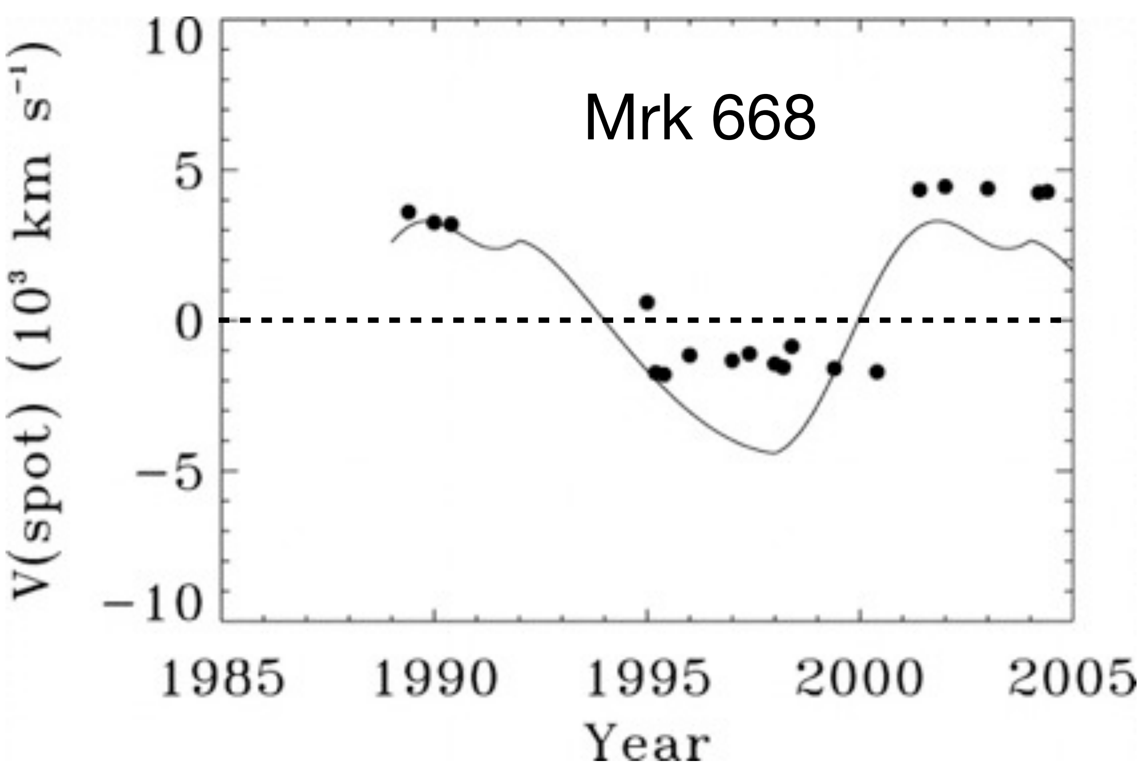


from Eracleous et al. (1997)

Nor Do Displaced Peaks that Move!



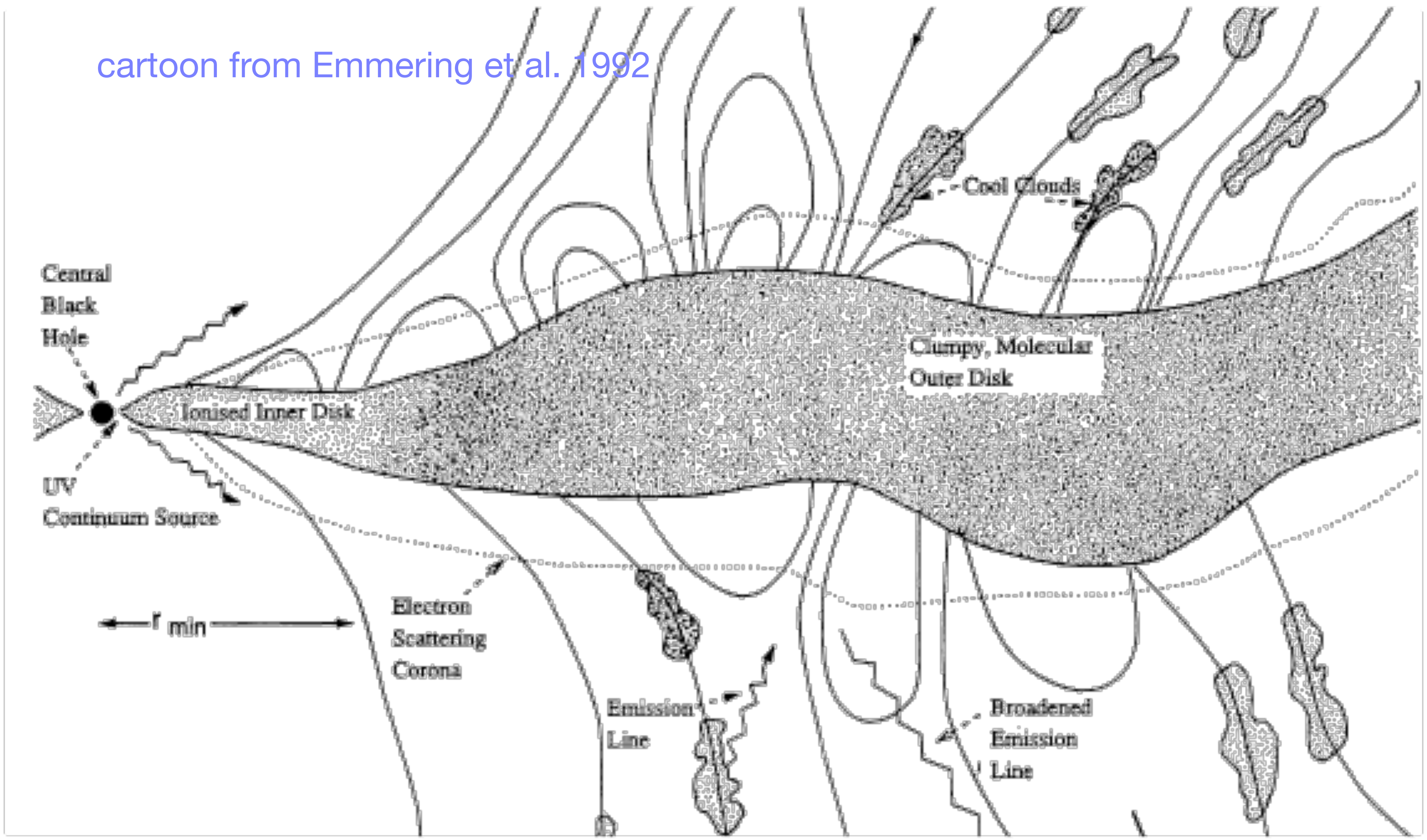
from Eracleous et al. (1997)
including data from Gaskell (1996)



Gezari, Halpern & Eracleous (2006)
see also Marziani et al. (1996)

The Broad-Line Region Revisited

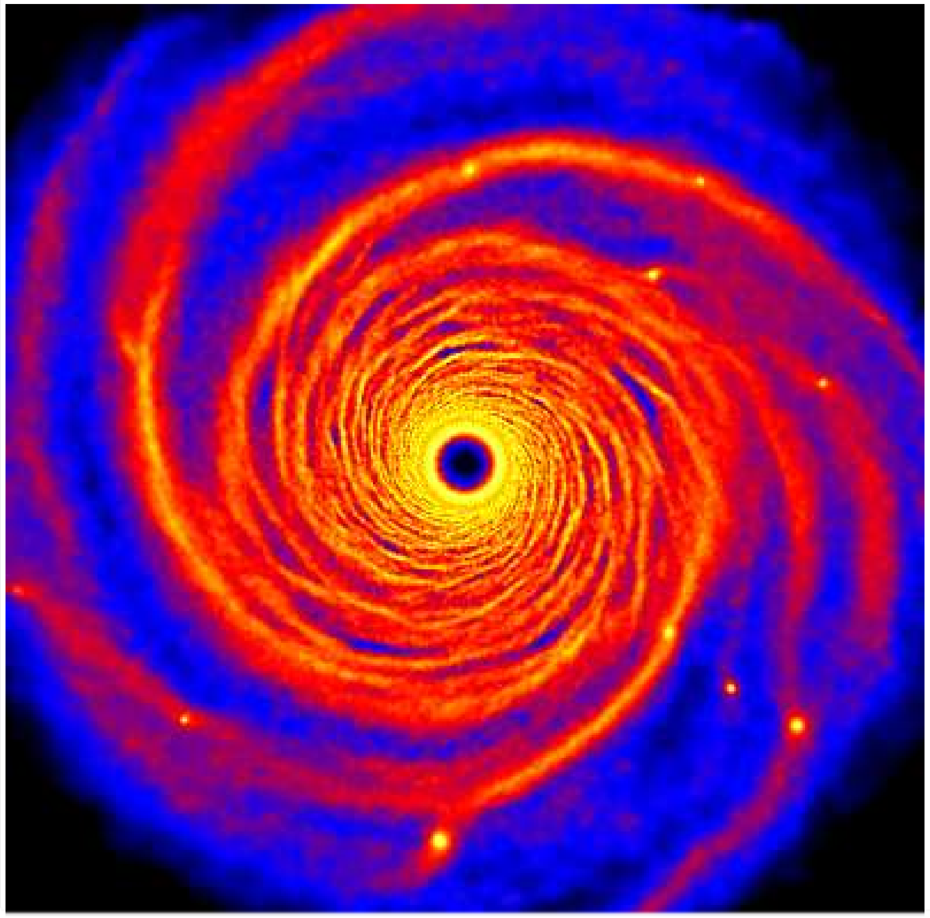
cartoon from Emmering et al. 1992



Spiral structure and fragmentation

Low-Mass Disk

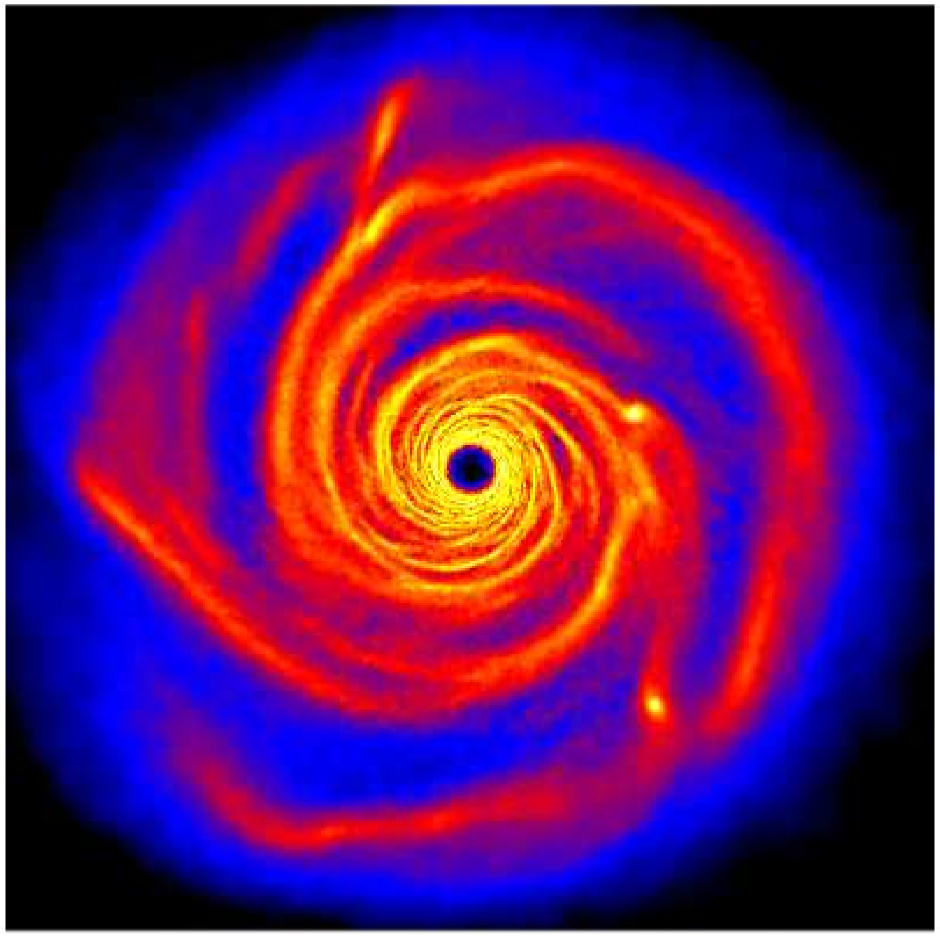
$t_{cool} \sim t_{Kep}$

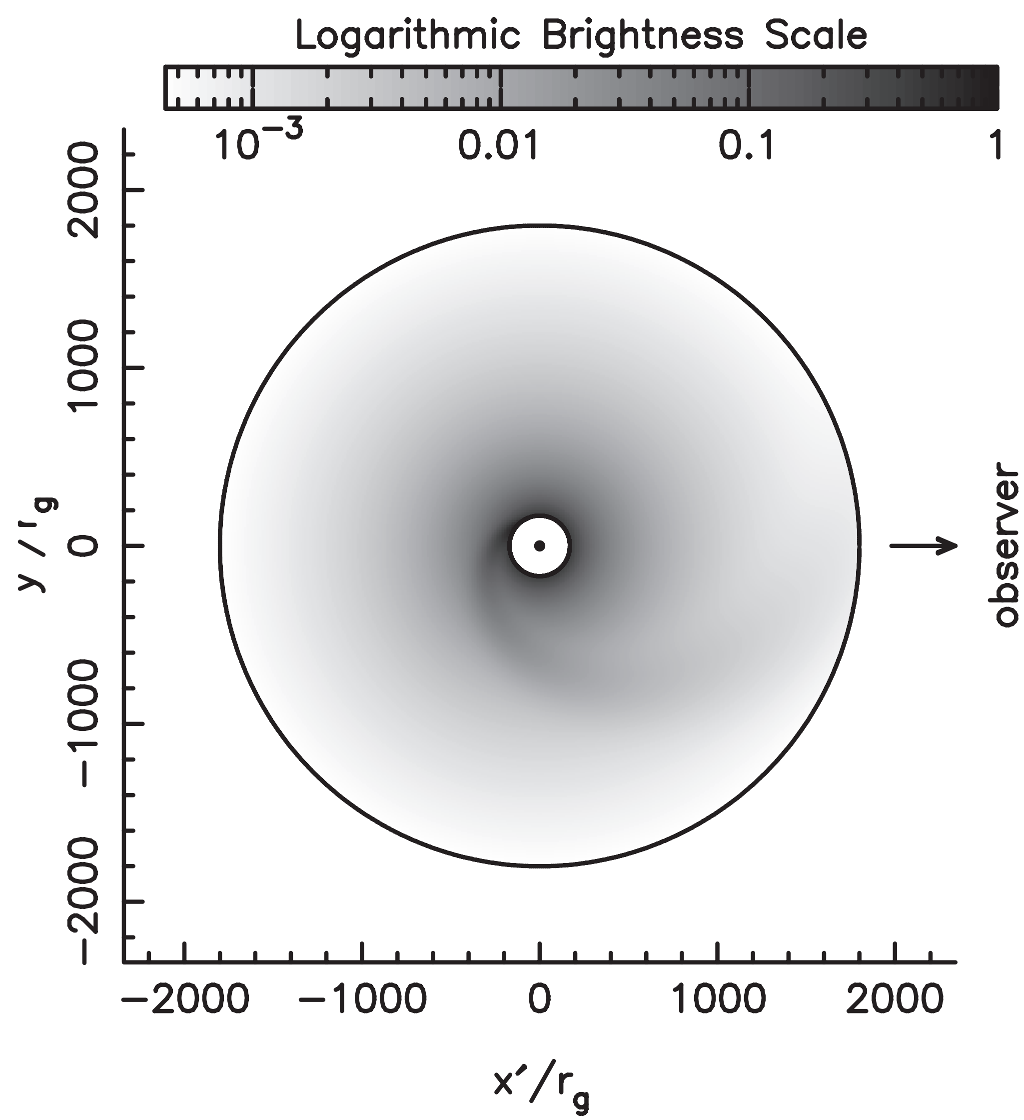


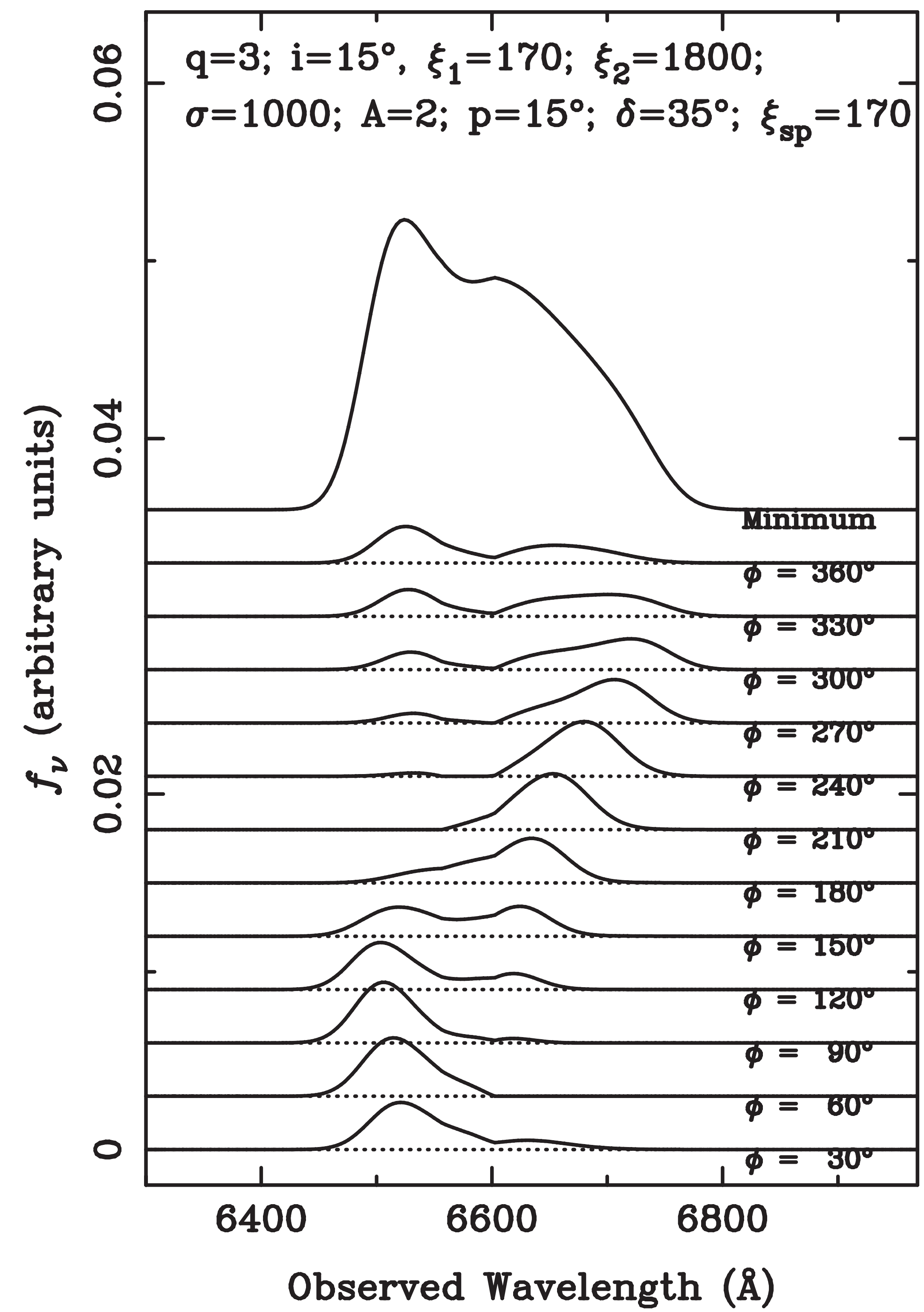
Rice, Lodato, & Armitage (2005, MNRAS, 364, L56)

Massive Disk

$t_{cool} \sim 2\ t_{Kep}$







from Lewis, Eracleous, &
Storchi-Bergmann (2010)

Implications and Future Prospects

Reasons to be (cautiously) optimistic...

- Theoretical predictions of population size in broad agreement with observed numbers.
- We can pick out the short-period binaries (P~10–20 yr) from repeating patterns, even though these will be short-lived.
- We will learn a lot about the dynamics of the gas in the broad-line region in the process.