Overview of Observational Searches for Binary Supermassive Black Holes

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1855

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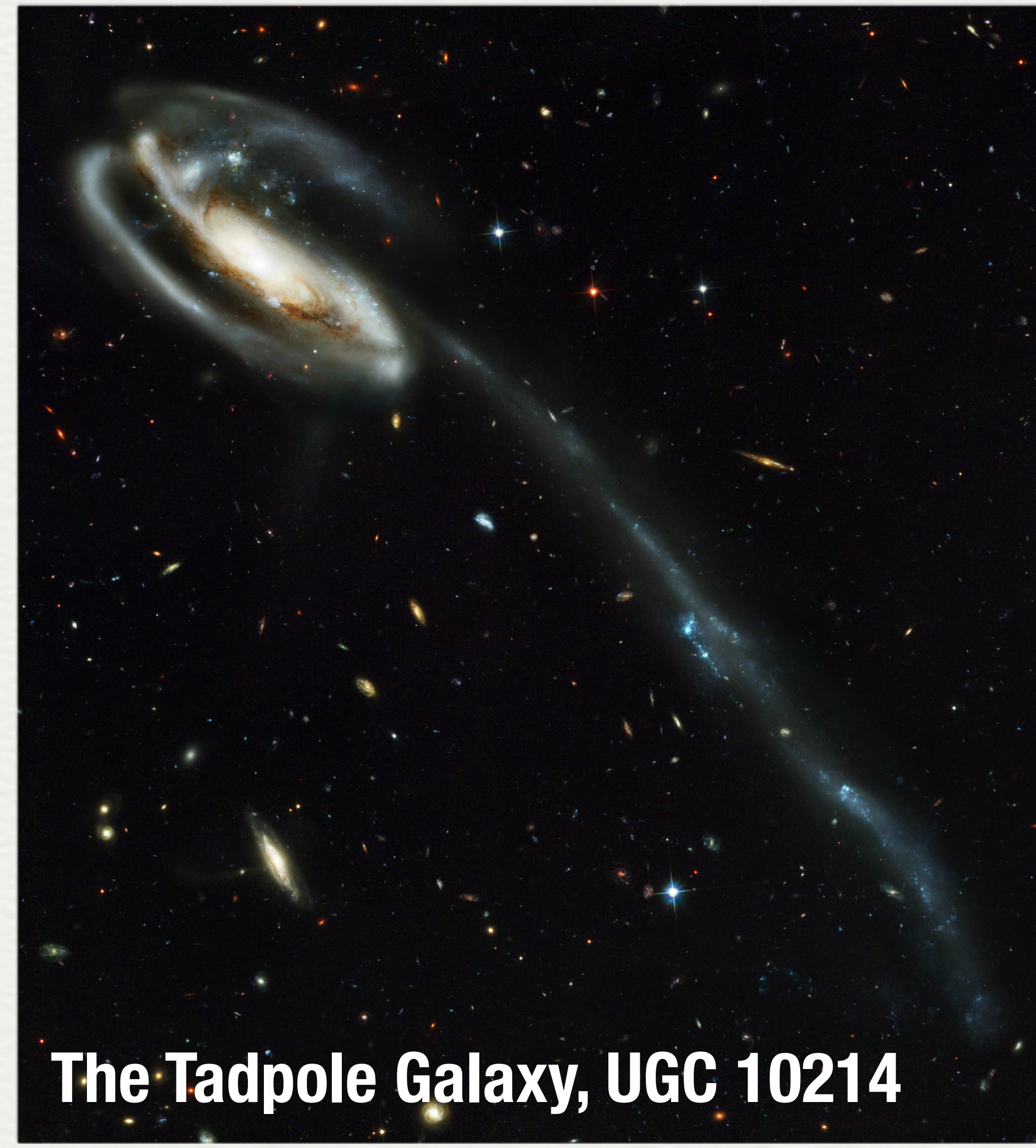
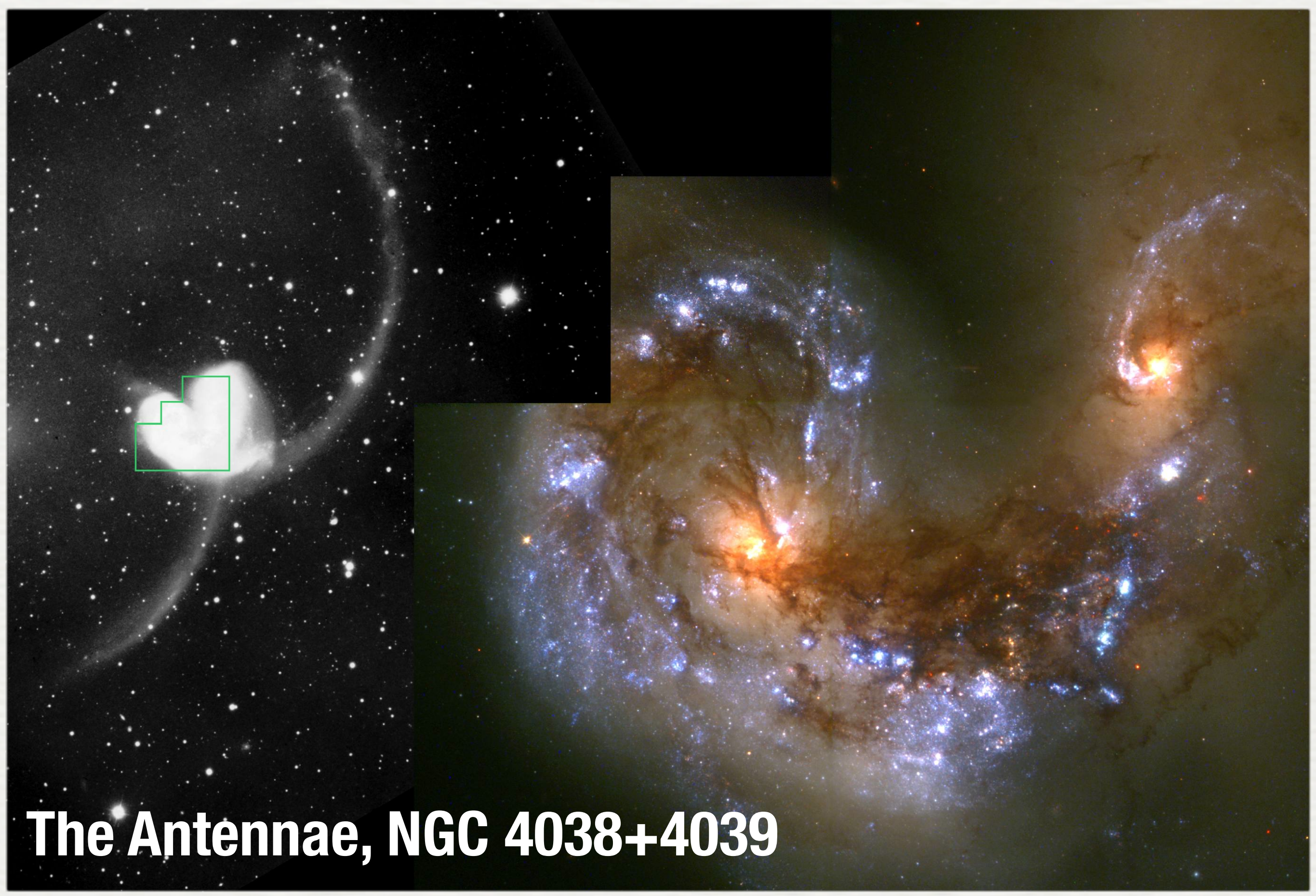
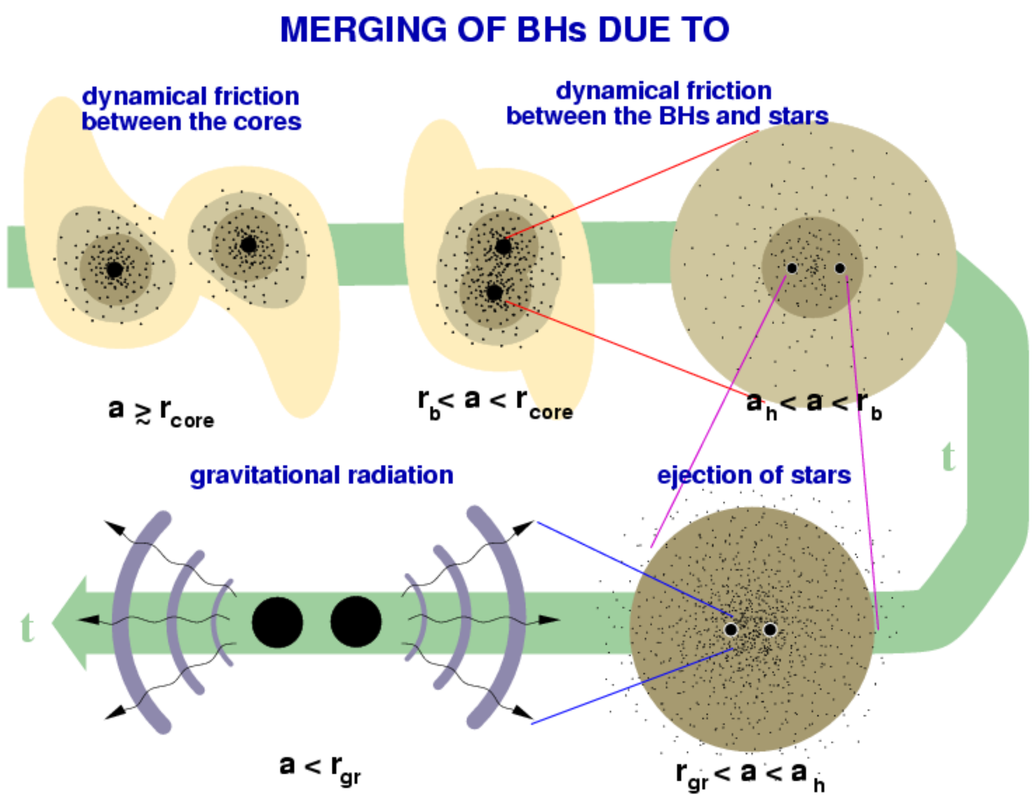
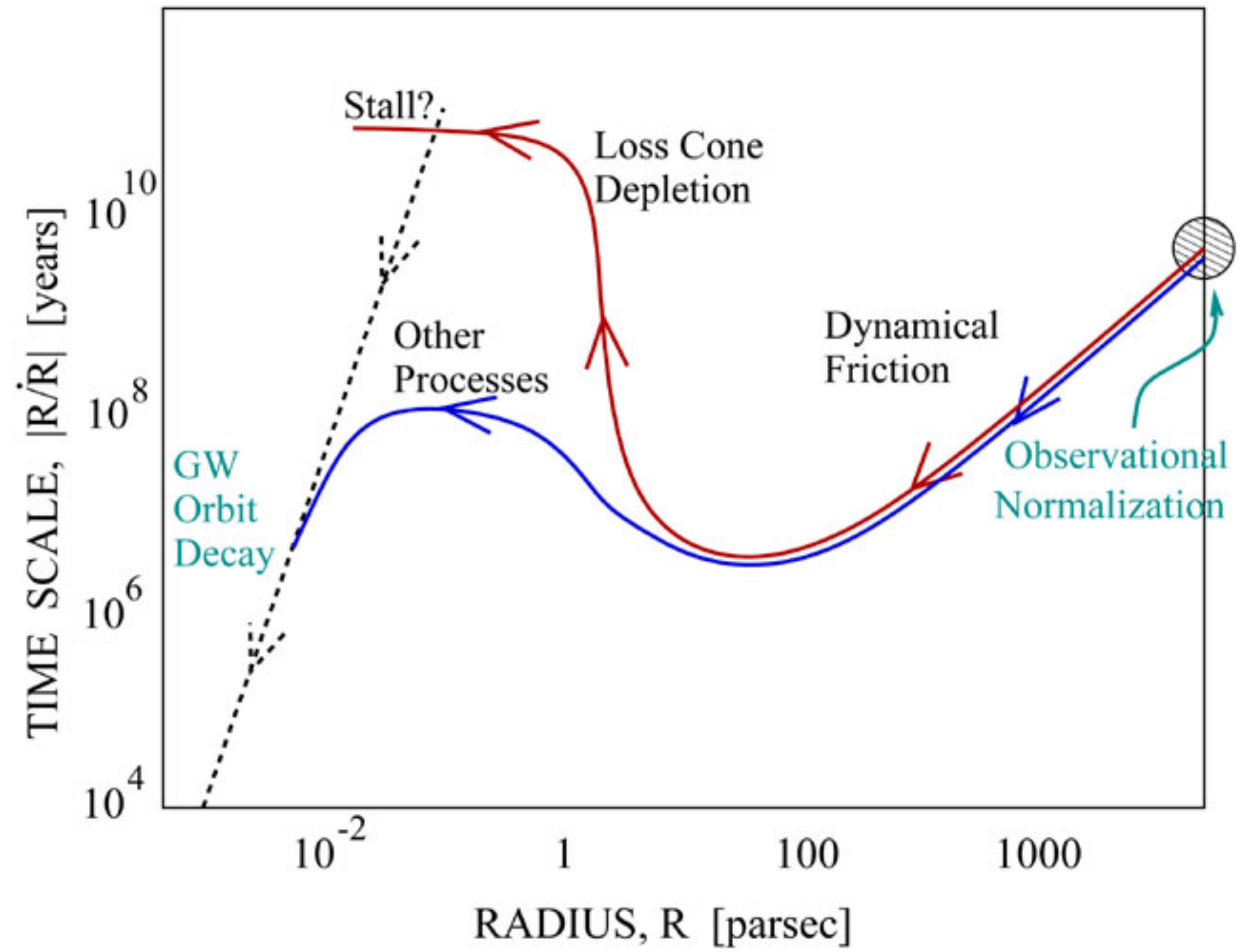
The Mice, NGC 4676


The Tadpole Galaxy, UGC 10214


The Antennae, NGC 4038+4039

The basics of SBHB evolution





a ≤ 0.01 pc   a ~ few pc

figure from Christian Zier's web site
Max-Planck-Institut für Radioastronomie

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

Time Scale for Orbital Decay by Emission of Gravitational Waves

Kepler's 3rd law gives...

$$\left(\frac{a}{10^{-2}\ \mathrm{pc}}\right)^3 = \left(\frac{M_\bullet}{10^8\ \mathrm{M}_\odot}\right)\left(\frac{P}{10\ \mathrm{yr}}\right)^2$$

$$t_{\mathrm{gw}} = 6.7 \times 10^6\ \frac{(1+q)^2}{q}\ \left(\frac{M_\bullet}{10^8\ \mathrm{M}_\odot}\right)^{-5/3}\left(\frac{P}{10\ \mathrm{yr}}\right)^{8/3}\ \mathrm{years}$$

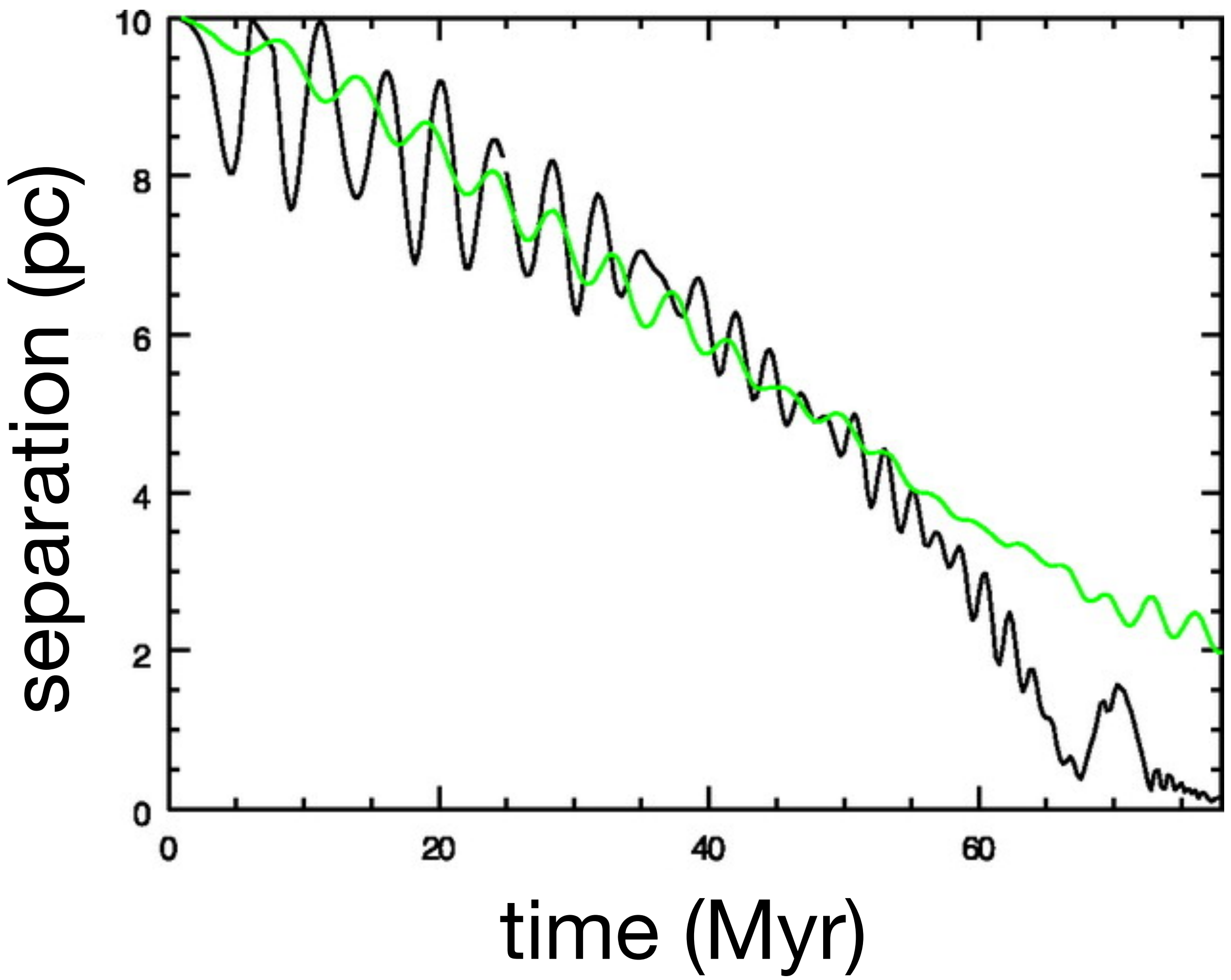
$$= 5.7 \times 10^6\ \frac{(1+q)^2}{q}\ \left(\frac{M_\bullet}{10^8\ \mathrm{M}_\odot}\right)^{-3}\left(\frac{a}{10^{-2}\ \mathrm{pc}}\right)^{4}\ \mathrm{years}$$

Solutions to the final parsec problem

STELLAR PROCESSES

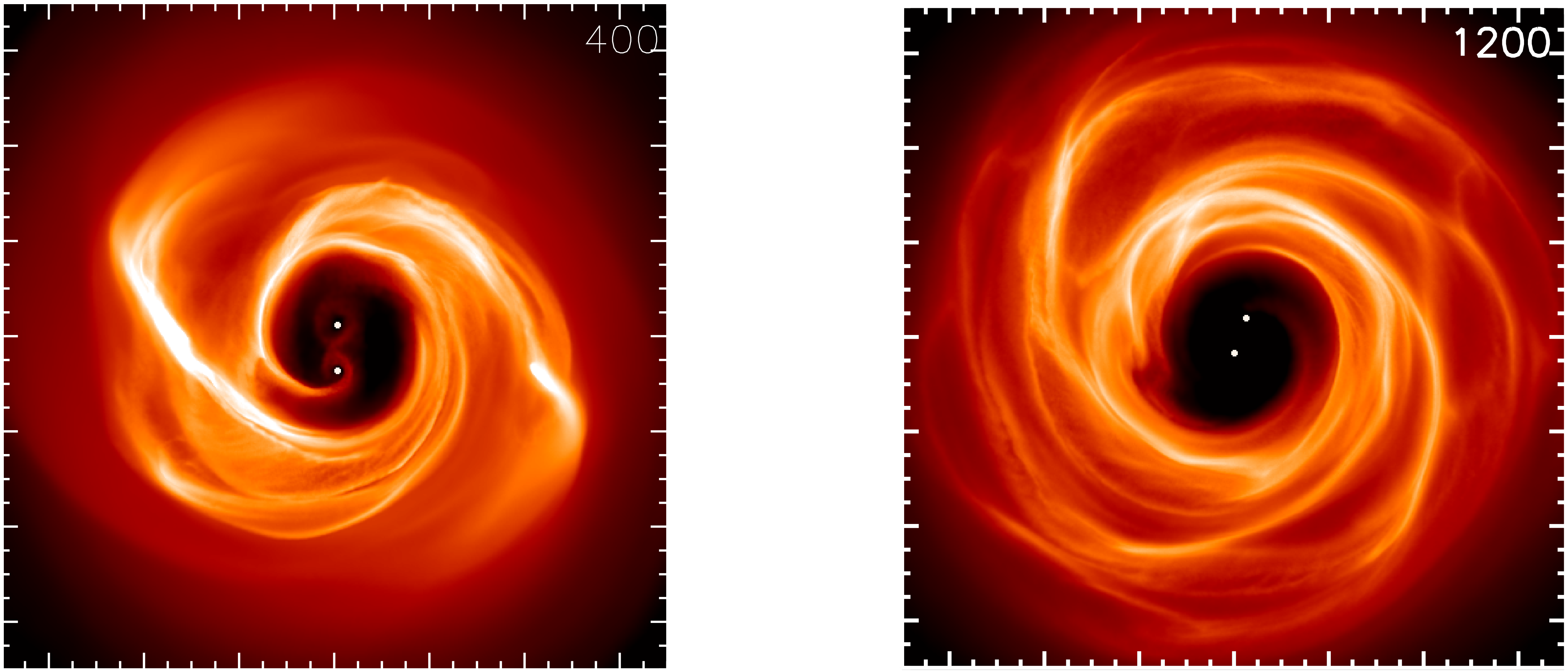
- Efficient re-filling of the loss cone or repeated ejections of stars on eccentric orbits
  (e.g., Milosavljević & Merritt 2003, ApJ, 596, 860)
- Triaxial or axisymmetric potential or galaxy rotation
  (e.g., Berczik et al. 2006, ApJ, 642, L21; Khan et al. 2013, ApJ, 773, 100)
- Eccentricity increases and t_{GR} decreases
  (e.g., Iwasawa et al. 2011, ApJ, 731, L9)

GAS PROCESSES



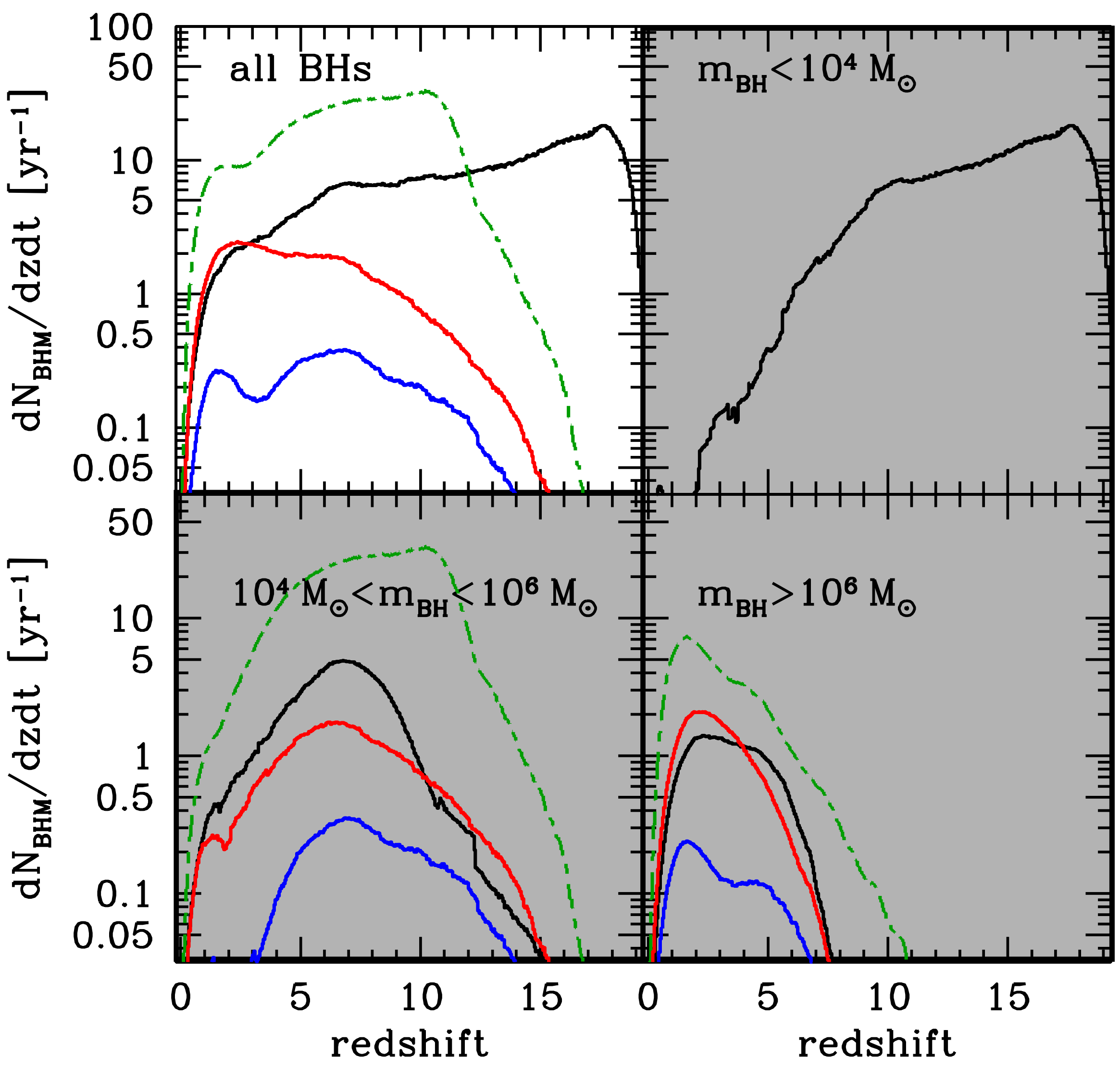
from Escala et al. 2005, ApJ, 630,152
also Dotti et al. 2007, MNRAS, 379, 956

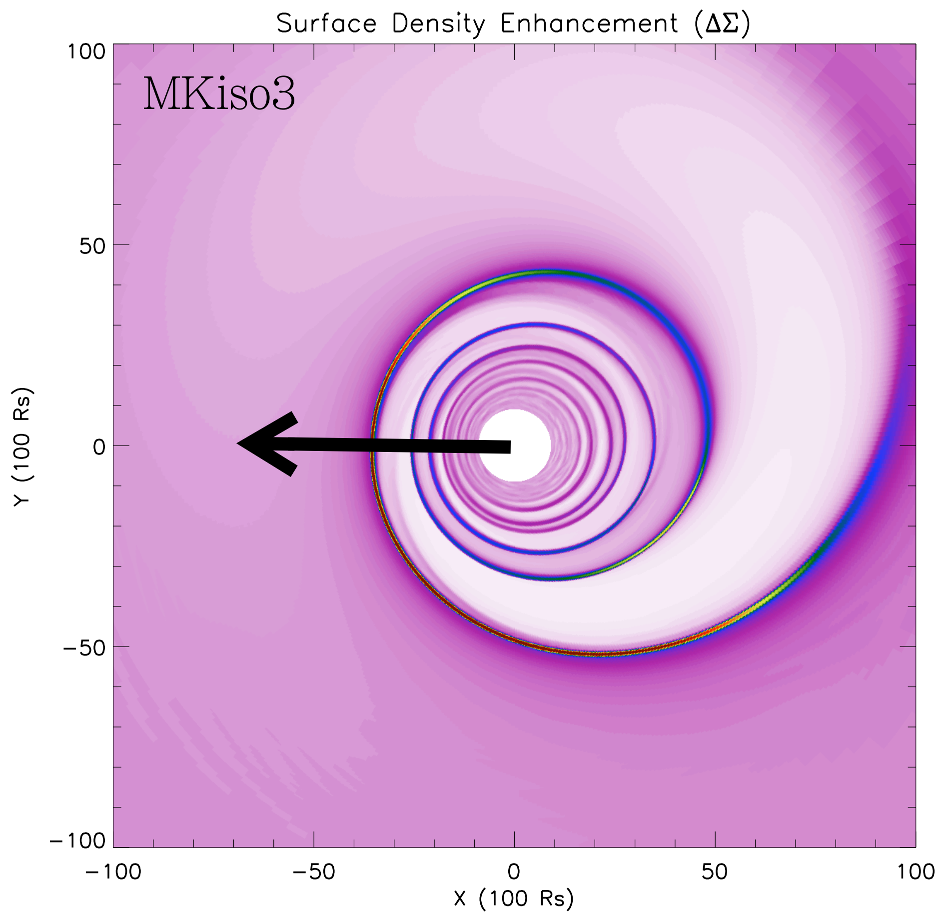
SBHB evolution inside a gaseous disk



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

Coalescence and beyond:
Event rates and observational consequences





$t = 210$ d, $r_{in} = 10^3\ R_s$

$\upsilon_k = 530$ km/s, $M_\bullet = 10^6\ M_\odot$

$L \sim 2 \times 10^{43}$ erg/s

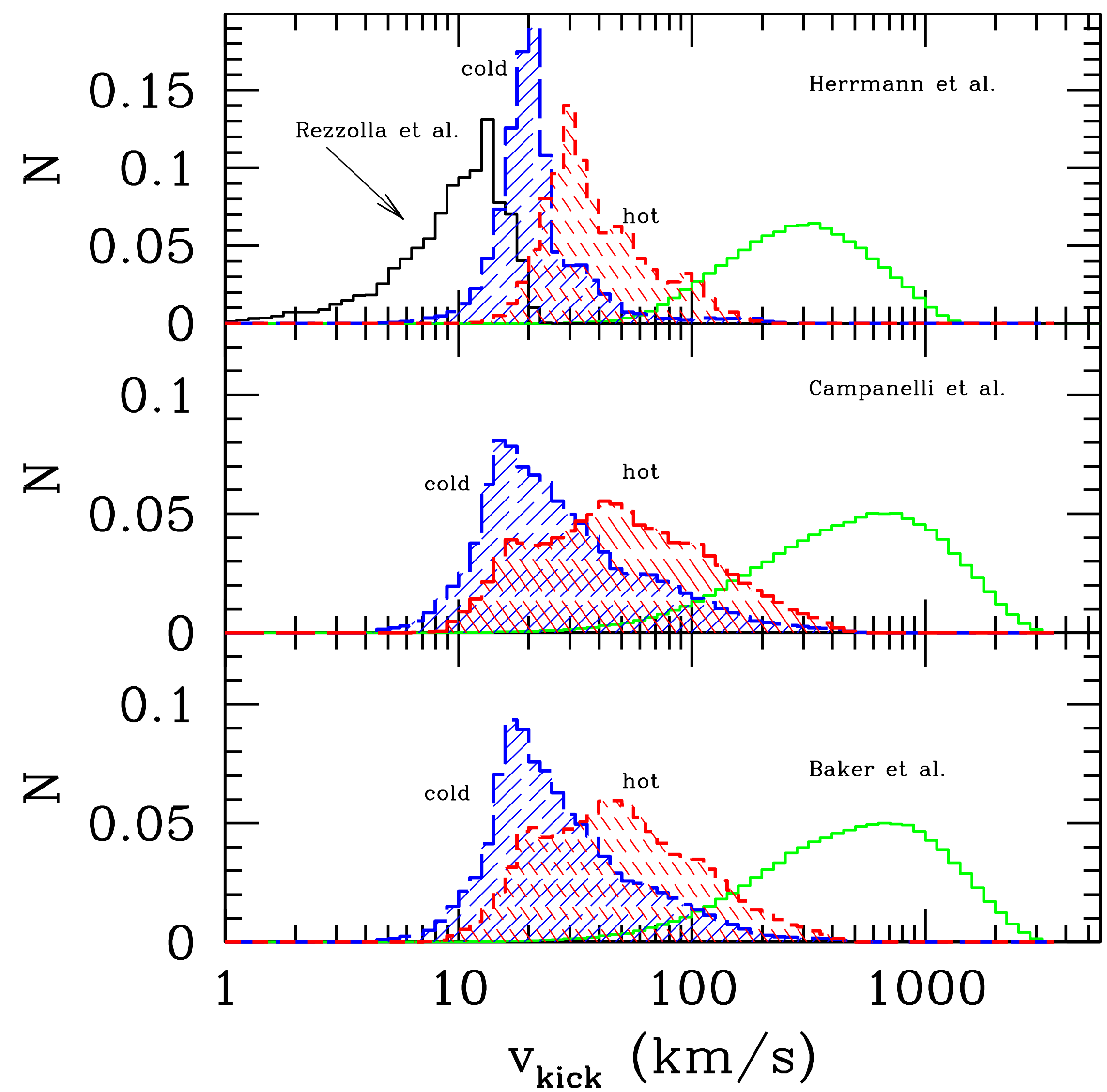
LISA rate: 10 – 100 yr $^{-1}$???

from Sesana et al. 2009,
Class. Quant. Grav. 26 094033

from Corrales et al. (2010)
see also Rossi et al. (2010)

Distribution of post-merger kick speeds

- Kick magnitude very sensitive to spin orientations
- Aligned spins from previous evolution lead to very small kicks (Bogdanović et al. 2007, ApJ, 661, L147; and others)



kick predictions from Dotti et al. 2010, MNRAS, 402, 682

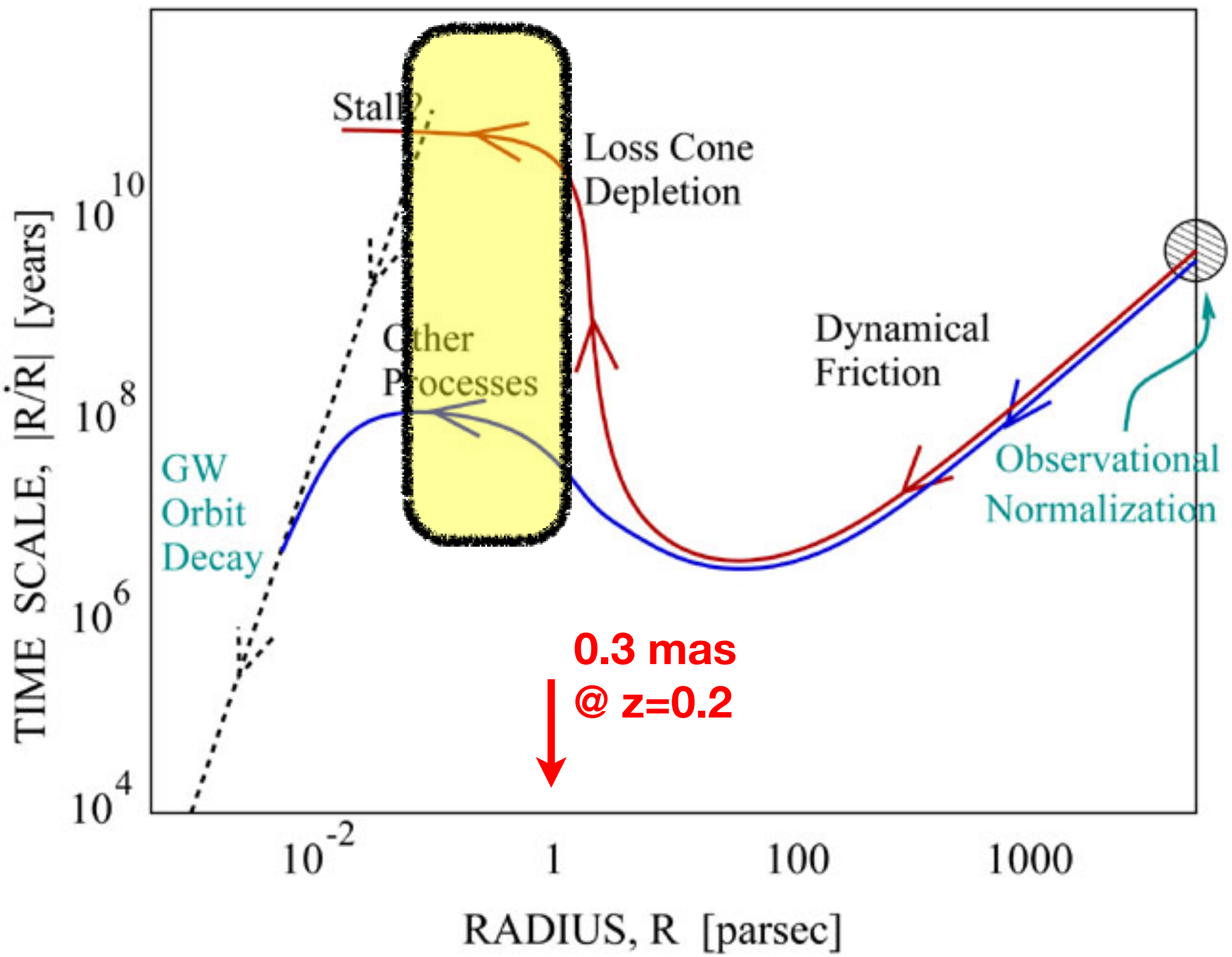
SBHBs are worth finding because...

they are the penultimate link in the SBHB evolutionary chain

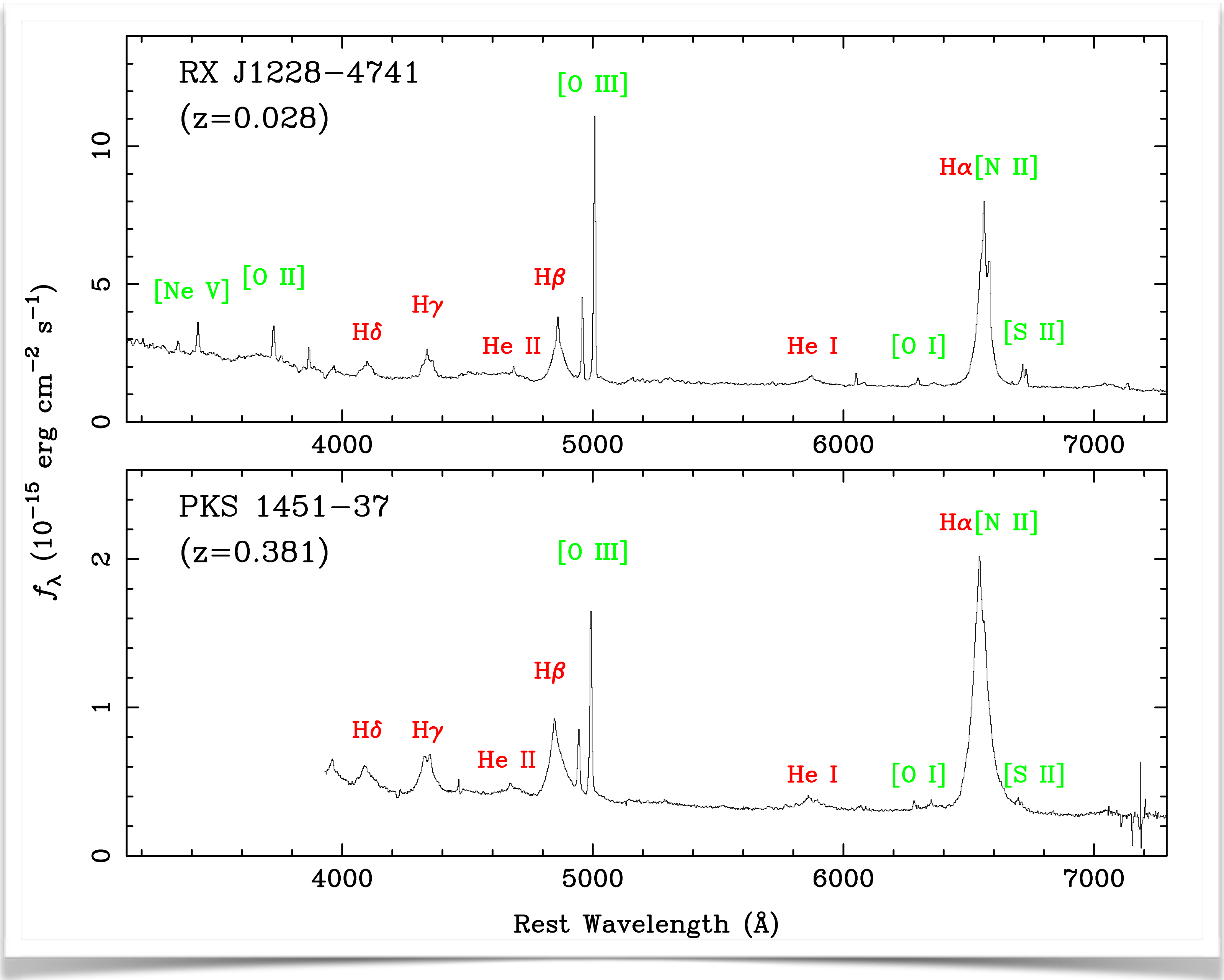
- ✦ census allows us to track the “flow” of systems through different evolutionary phases and address “final parsec problem”
- ✦ progenitors of strong gravitational wave sources and transients

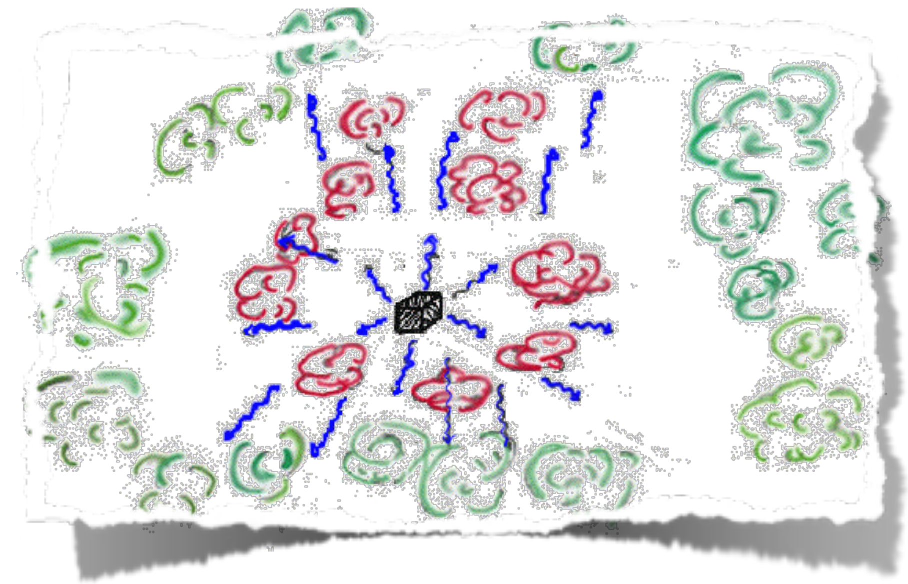
they are invoked to explain a number of other phenomena

- ✦ 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)


Stall?
Loss Cone
Depletion
Dynamical
Friction
Other
Processes
GW
Orbit
Decay
Observational
Normalization
0.3 mas
@ z=0.2
TIME SCALE, |R/Ṙ| [years]
10^{10}
10^{8}
10^{6}
10^{4}
10^{-2}
1
100
1000
RADIUS, R [parsec]

Typical Spectra of Active Galactic Nuclei (AGNs)





Properties of the AGN Central Engine

✦ Size:

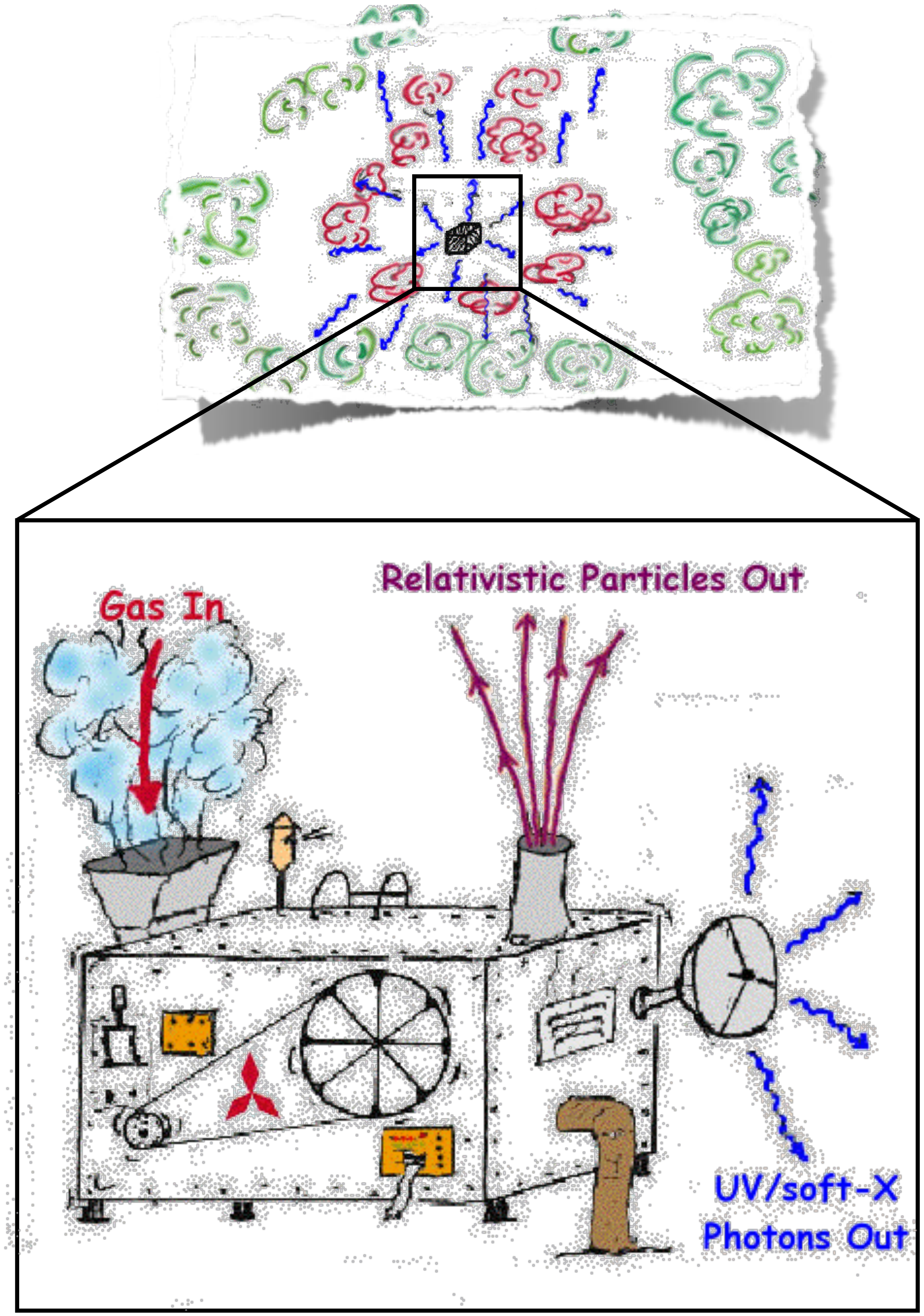
a few light-hours
(10s - 100s of AU)

✦ Luminosity:

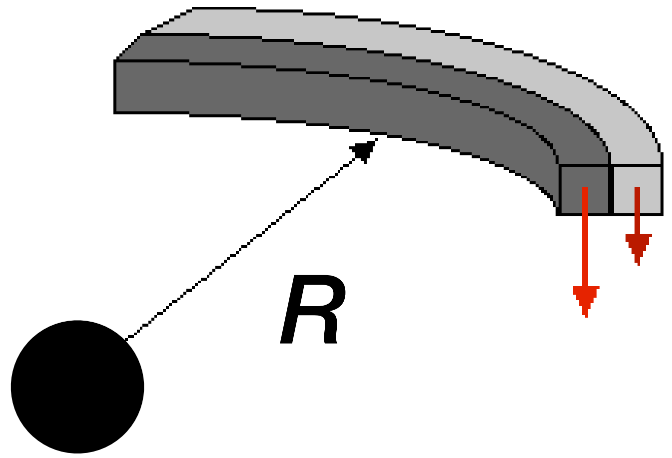
up to 10^{47} erg s^{-1}
(10^{40} W or 10^{14} $L_{\odot}$)

✦ Mass:

10^{6}–10^{9} $M_{\odot}$



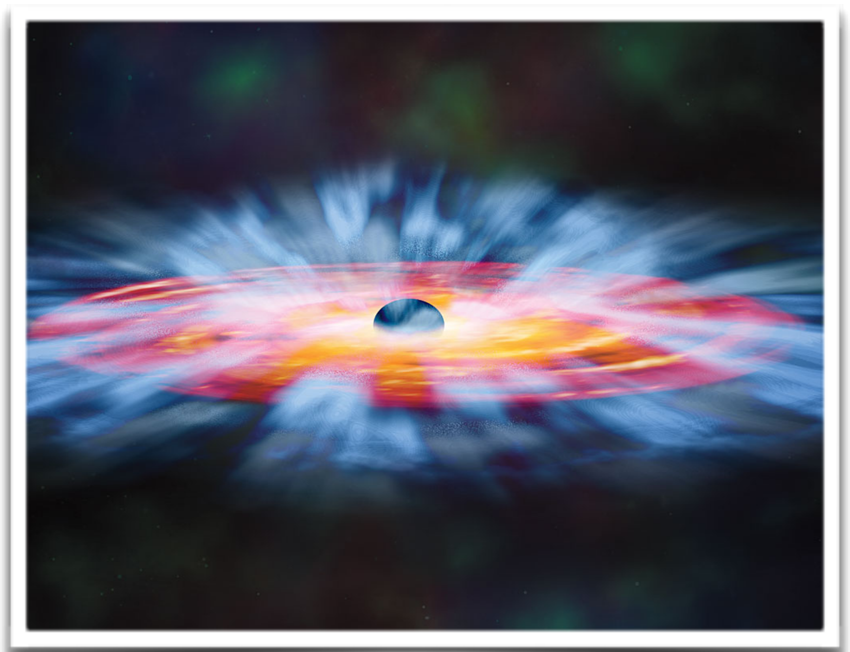
What is the central engine anyway?

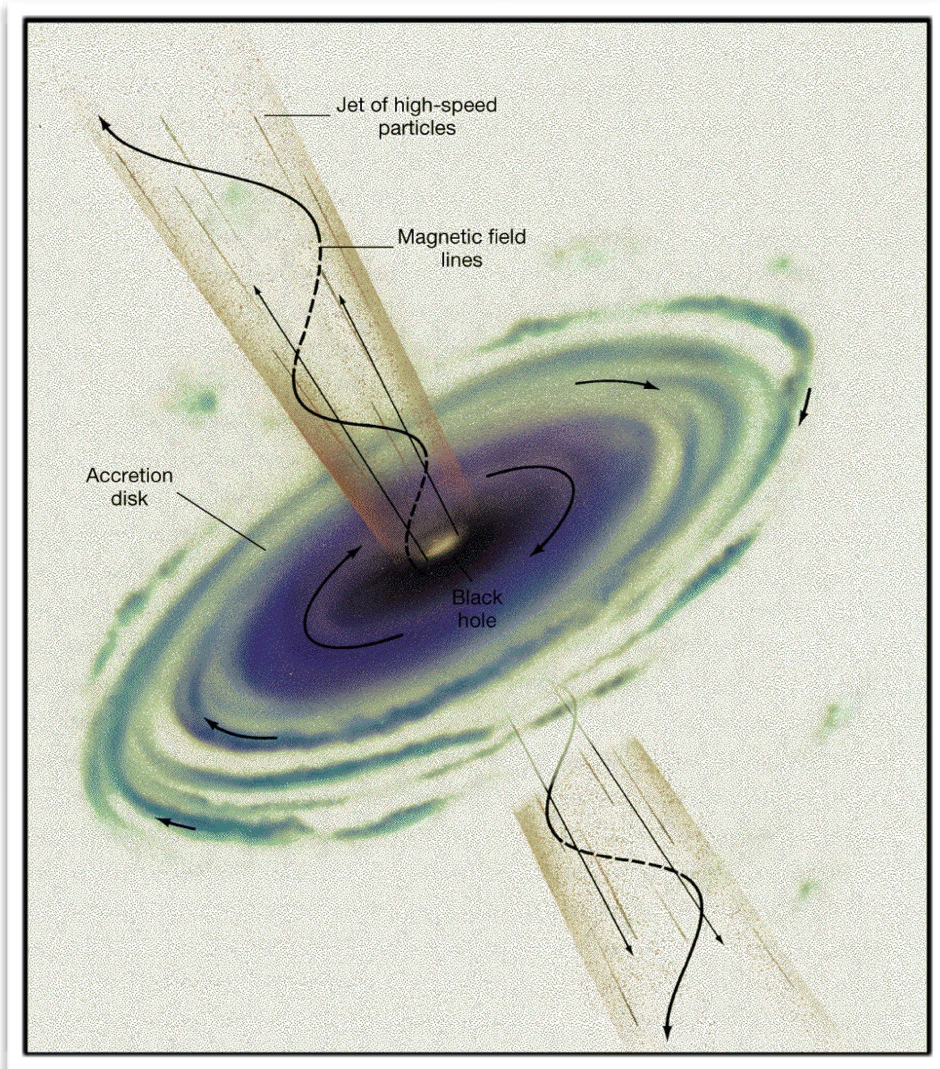


differential rotation
+
magic viscocity

↓

torque
+
energy dissipation





SBHBs @ 0.1–1 pc within circumbinary disk

- Direct imaging via radio interferometry
  e.g., Burke-Spolaor 2011, MNRAS, 410, 2113
- Indirect detection via emission line properties
  - Relative intensities and profiles of broad lines
    Montuori et al. 2011, MNRAS, 412, 26
    and 2012, MNRAS, 425, 1633
  - Radial velocity changes
    details to follow...

At even shorter separations...

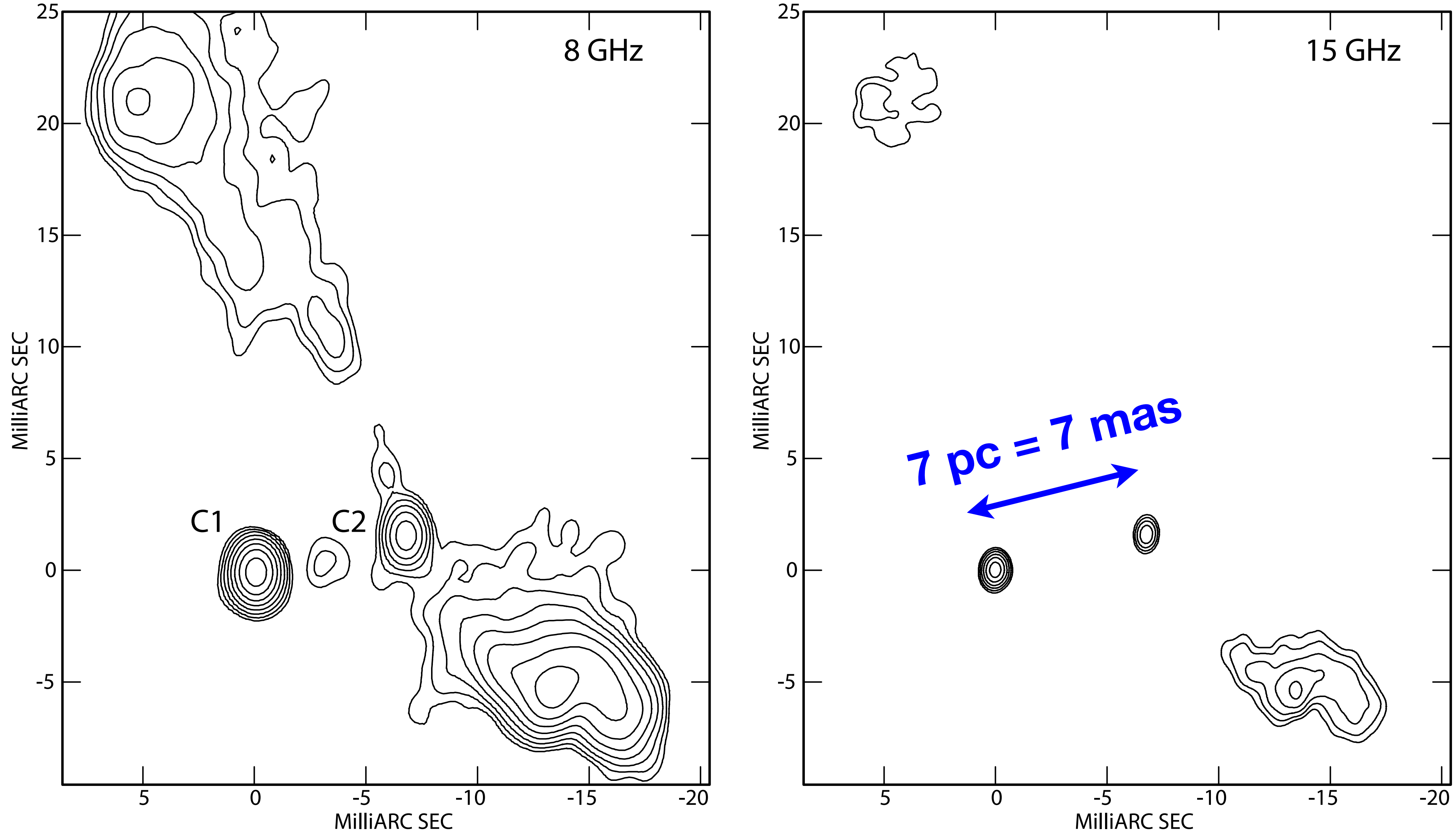
- ✦ Gravitational waves via pulsar timing
  e.g., Lommen & Backer 2001, ApJ, 562, 297; Jenet et al. 2004, ApJ, 606, 799

- ✦ Observational consequences of gaps in accretion disk
  - Fe Kα profile: McKernan et al. 2013, MNRAS, 432, 1468
  - Broad-band SED: Sesana et al. 2012, MNRAS, 420, 860
    Gükltekin & Miller 2012, ApJ, 761, 90

- ✦ Periodic X-ray or optical emission during inspiral
  e.g., Bode et al. 2010, ApJ, 715, 1117 and 2012, ApJ, 744, 45
  Noble et al. 2012, ApJ, 755, 51
  D'Orazio et al. 2013, MNRAS, 436, 2997
  cf. OJ 287, Valtonen et al., many papers

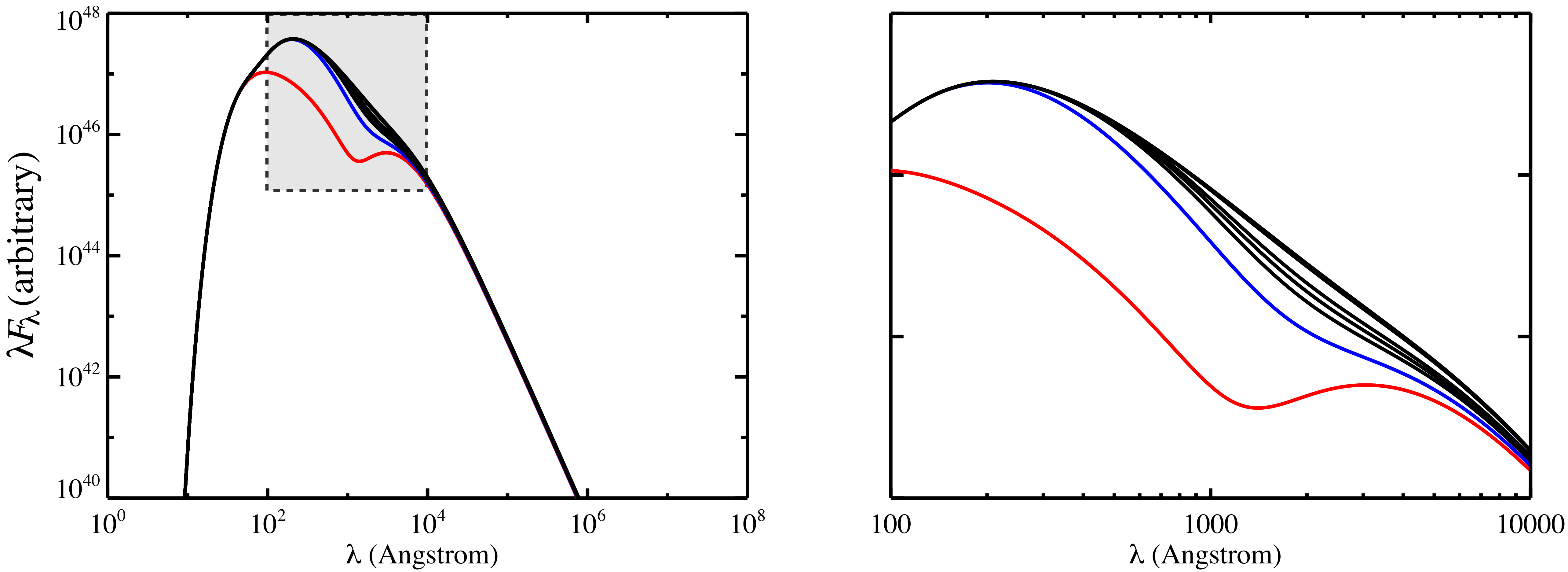
Some Famous Examples

4C+37.11: radio imaging



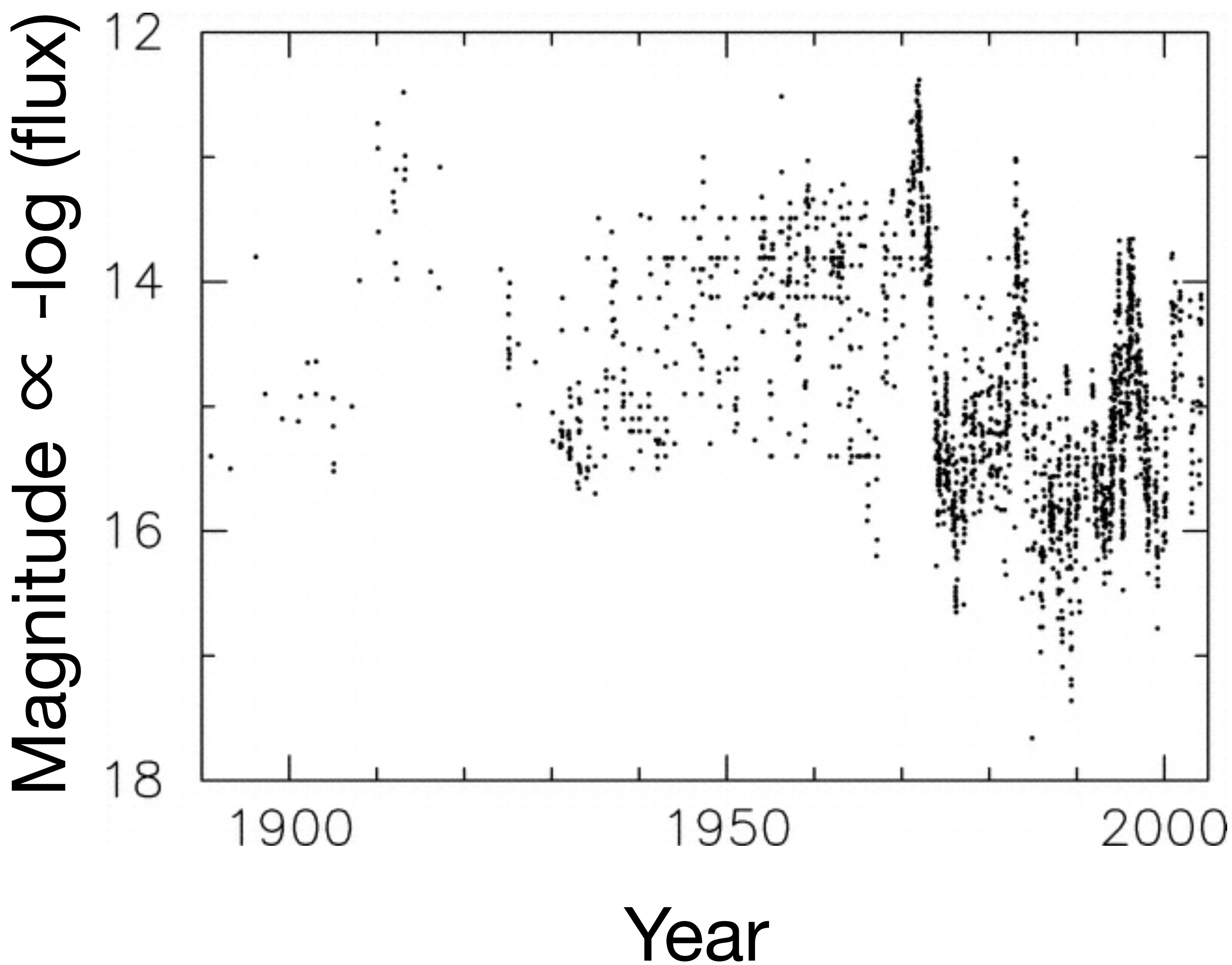
Rodriguez et al. 2006, ApJ, 646, 49

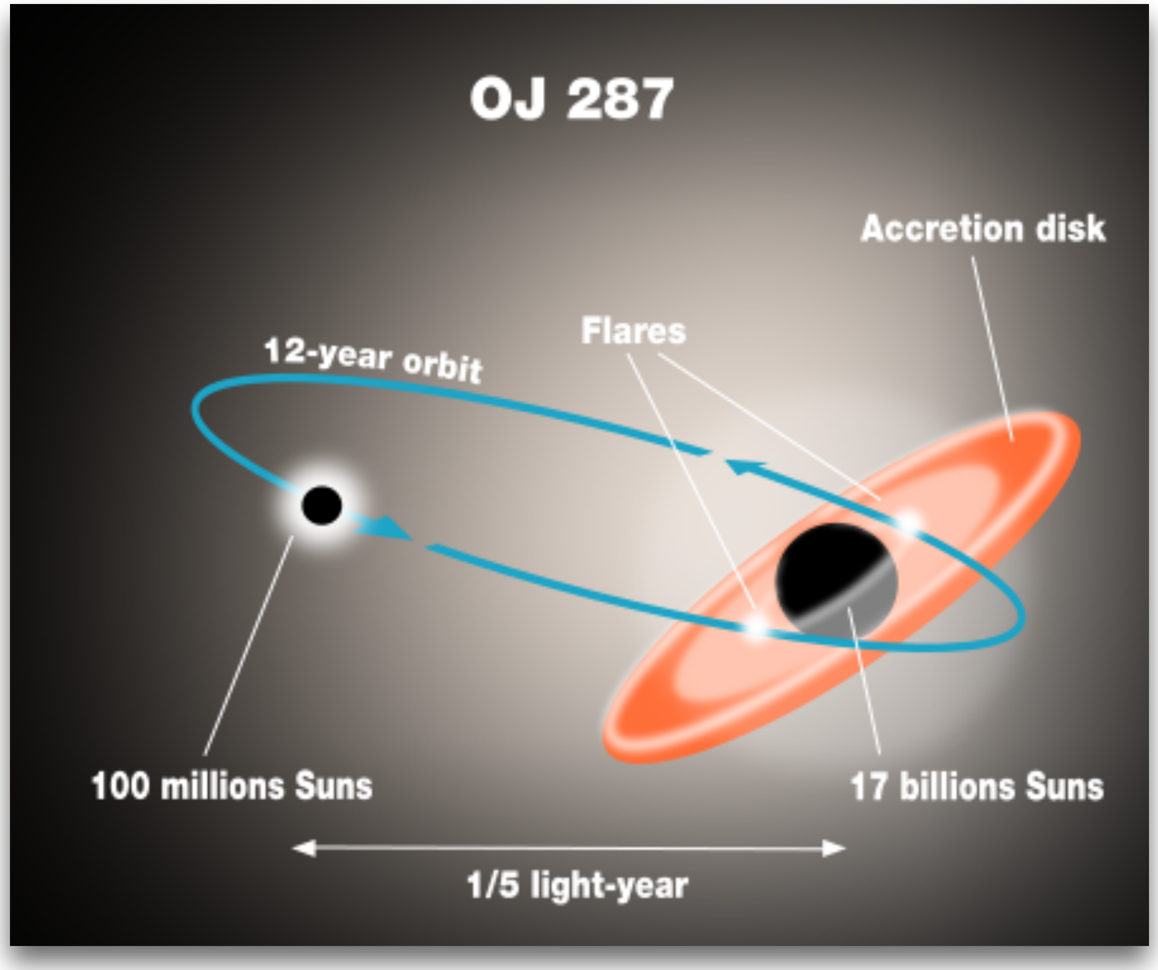
Effect of a gap in the accretion disk



Gültekin & Miller 2012, ApJ, 761, 90

OJ 287: 12-year quasi-periodic signal





Valtonen et al. 2006, ApJ, 646, 36

Searching for close supermassive black hole binaries (SBHBs) via shifted broad lines

The hypothesis: binary in a circumbinary disk.

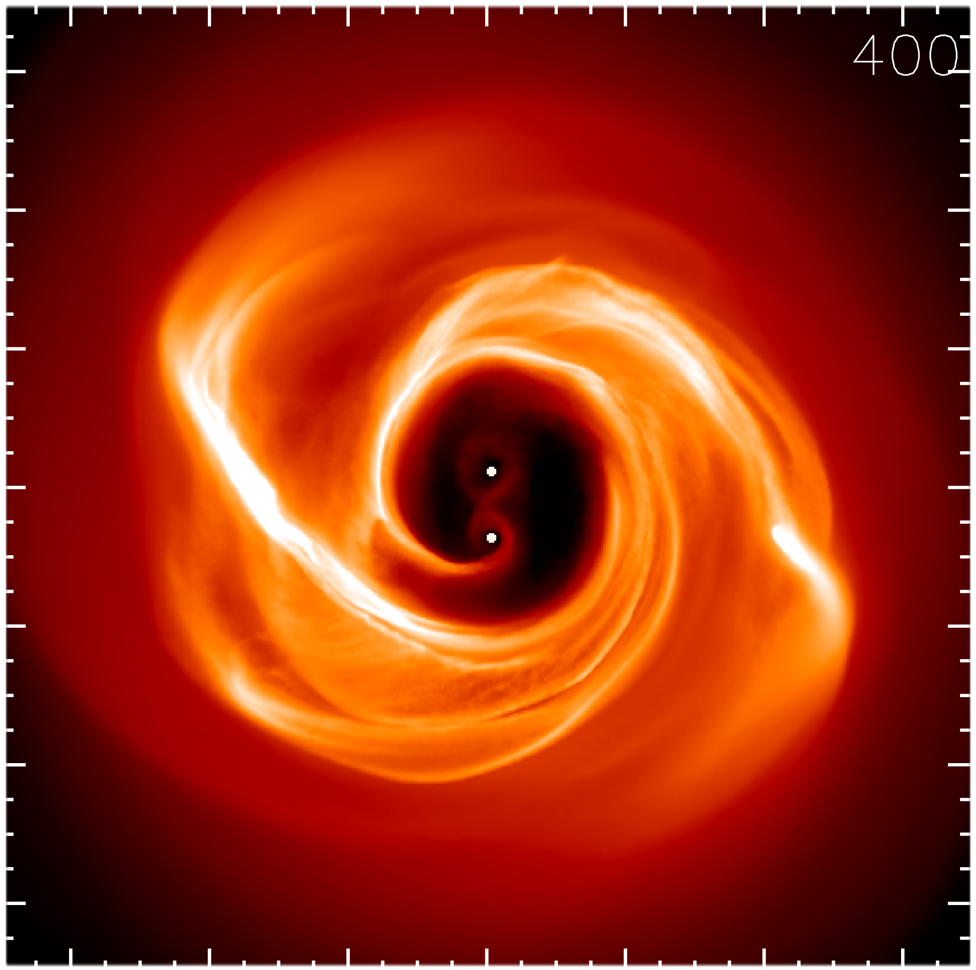


Figure from
Cuadra et al. 2009, MNRAS, 393, 1423
see also
Hayasaki et al. 2007, PASJ, 59, 427

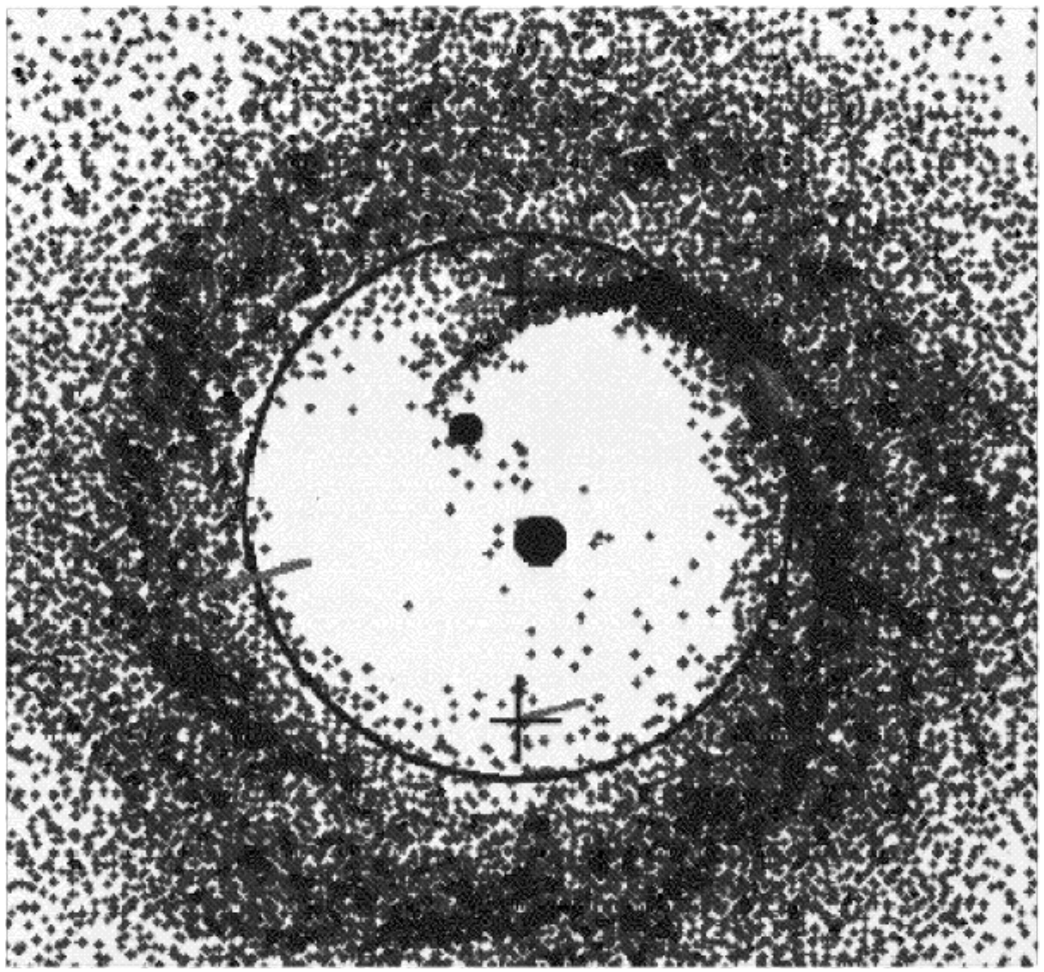


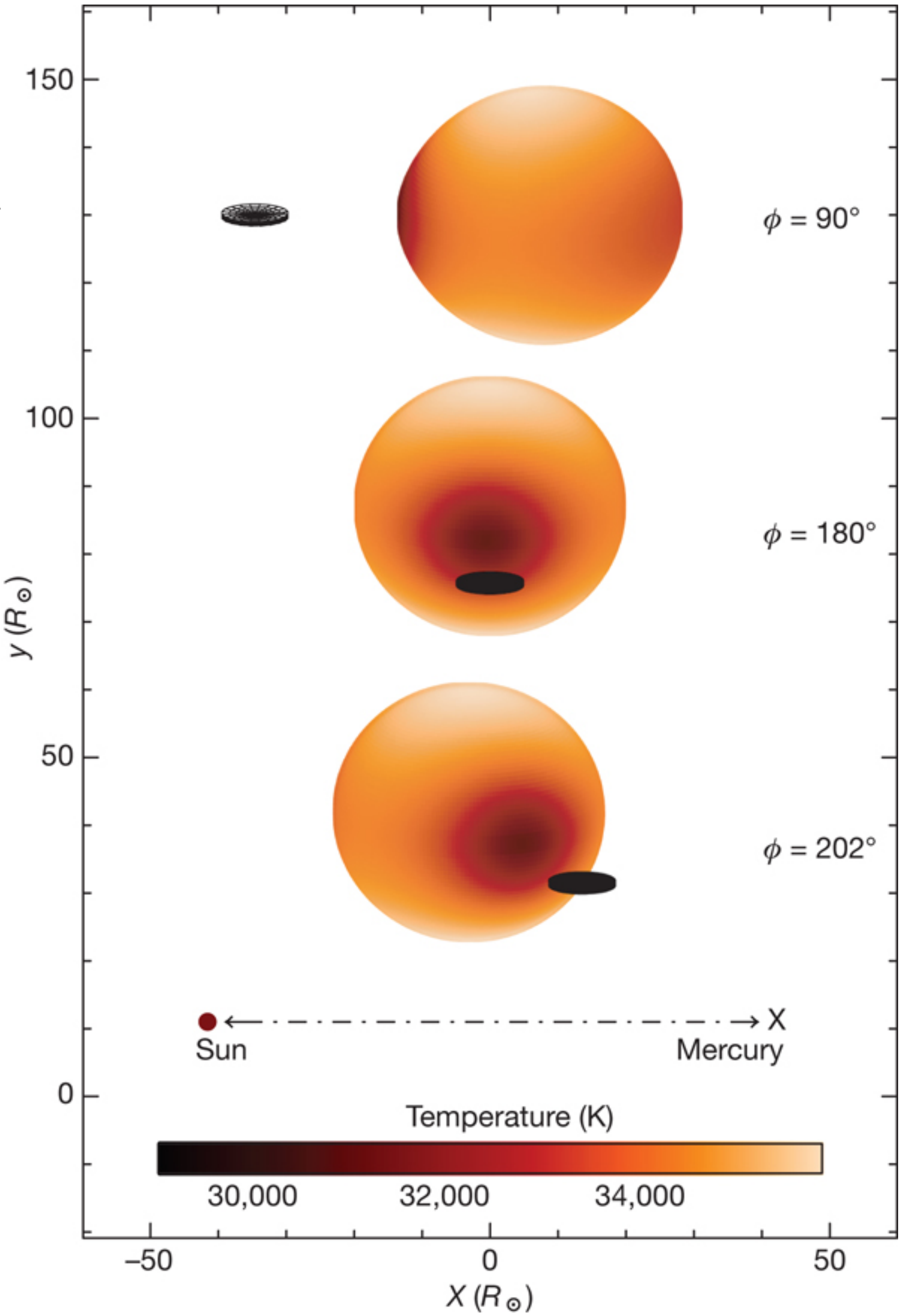
Figure from
Artymowicz & Lubow 1996, ApJ, 467 L77
see also
Gunther & Klay 2002, A&A, 387, 550

Heuristic Example: M33 X-7

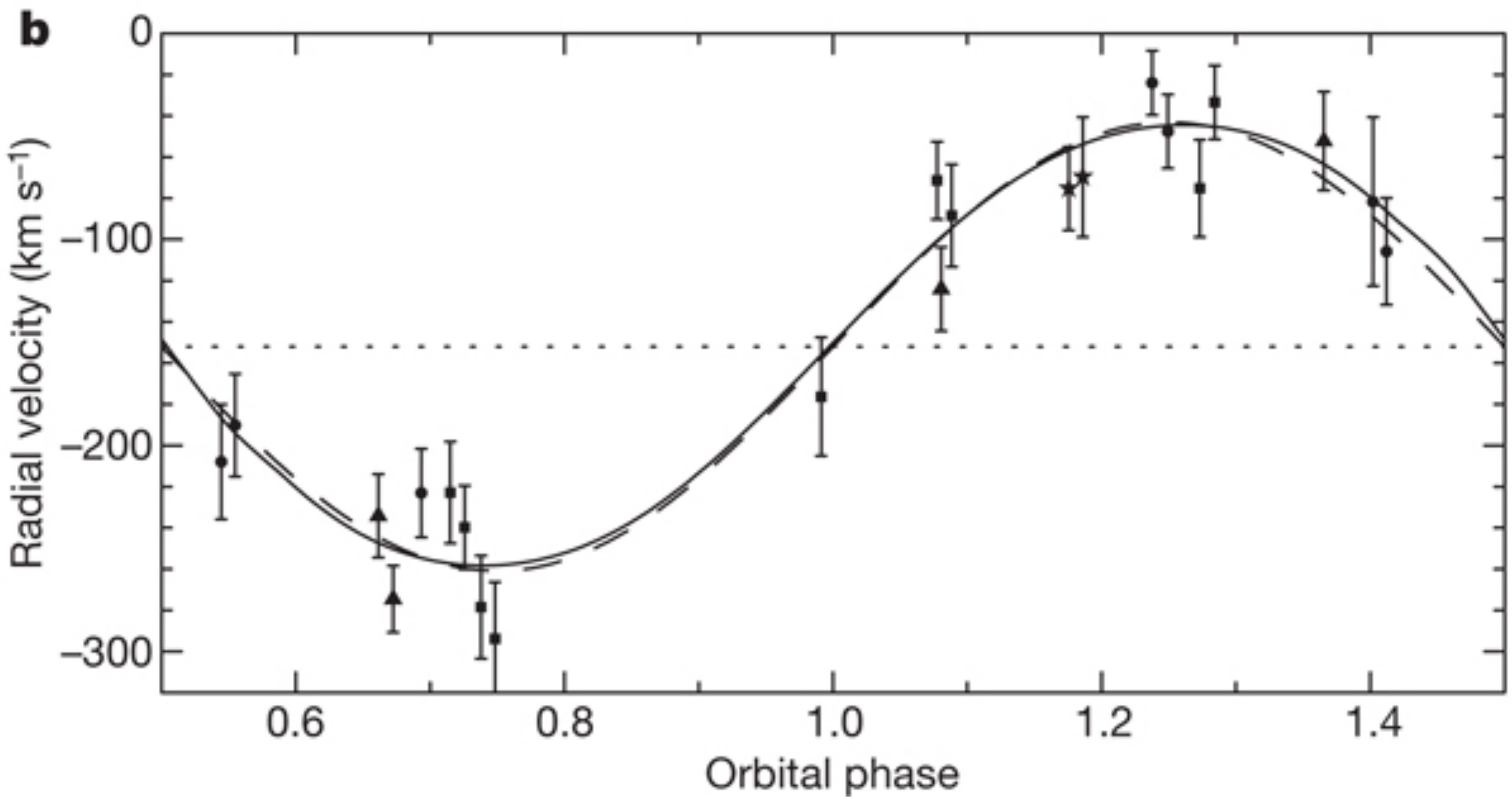
$P = 3.45$ days

$M_\bullet = 16\ M_\odot$

$M_* = 70\ M_\odot$



M33 X-7 radial velocity curve



P = 3.45 days

$M_\bullet = 16\ M_\odot$

$M_* = 70\ M_\odot$

Orosz et al. 2007, Nature, 449, 872

One black hole active:
Single-lined spectroscopic binaries

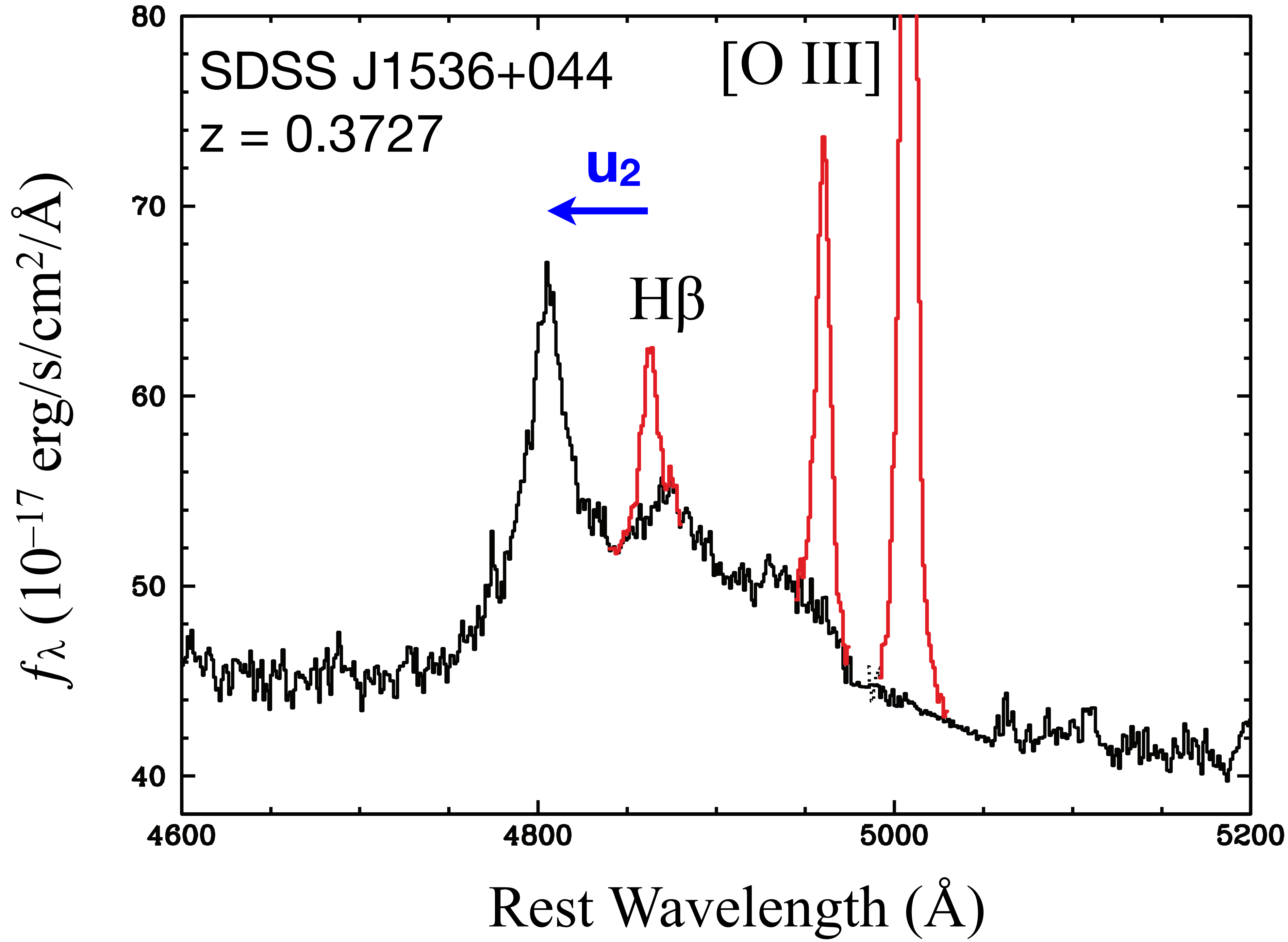
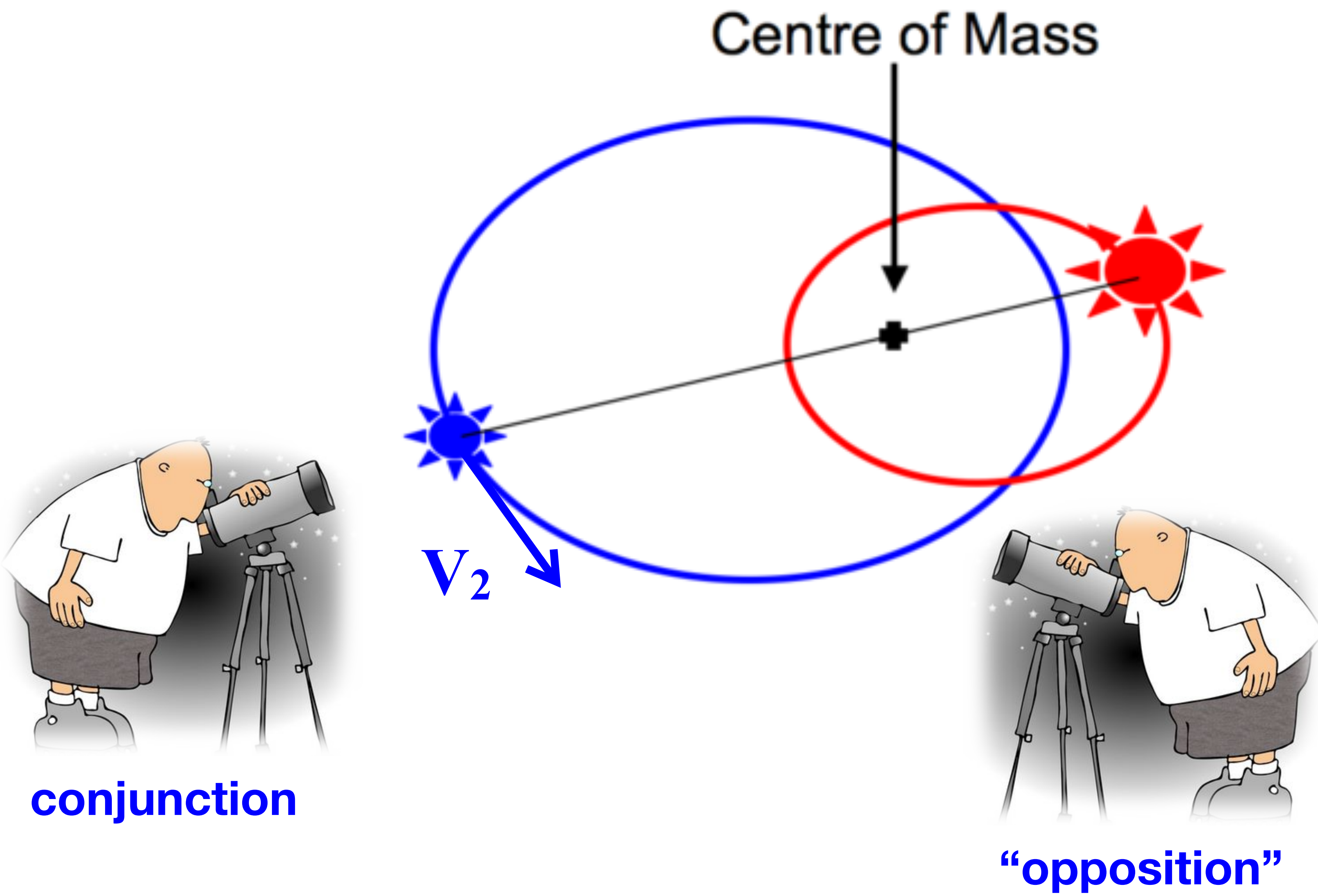


figure from Boroson & Lauer 2009, Nature, 458, 53

Expected binary properties



We observe:

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

$$u_{2,3} = \frac{V_2 \sin i \sin \phi}{10^3 \text{ km s}^{-1}}$$

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

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

Instantaneous acceleration:

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

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

Recent attempts to find offset broad lines and radial velocity variations:

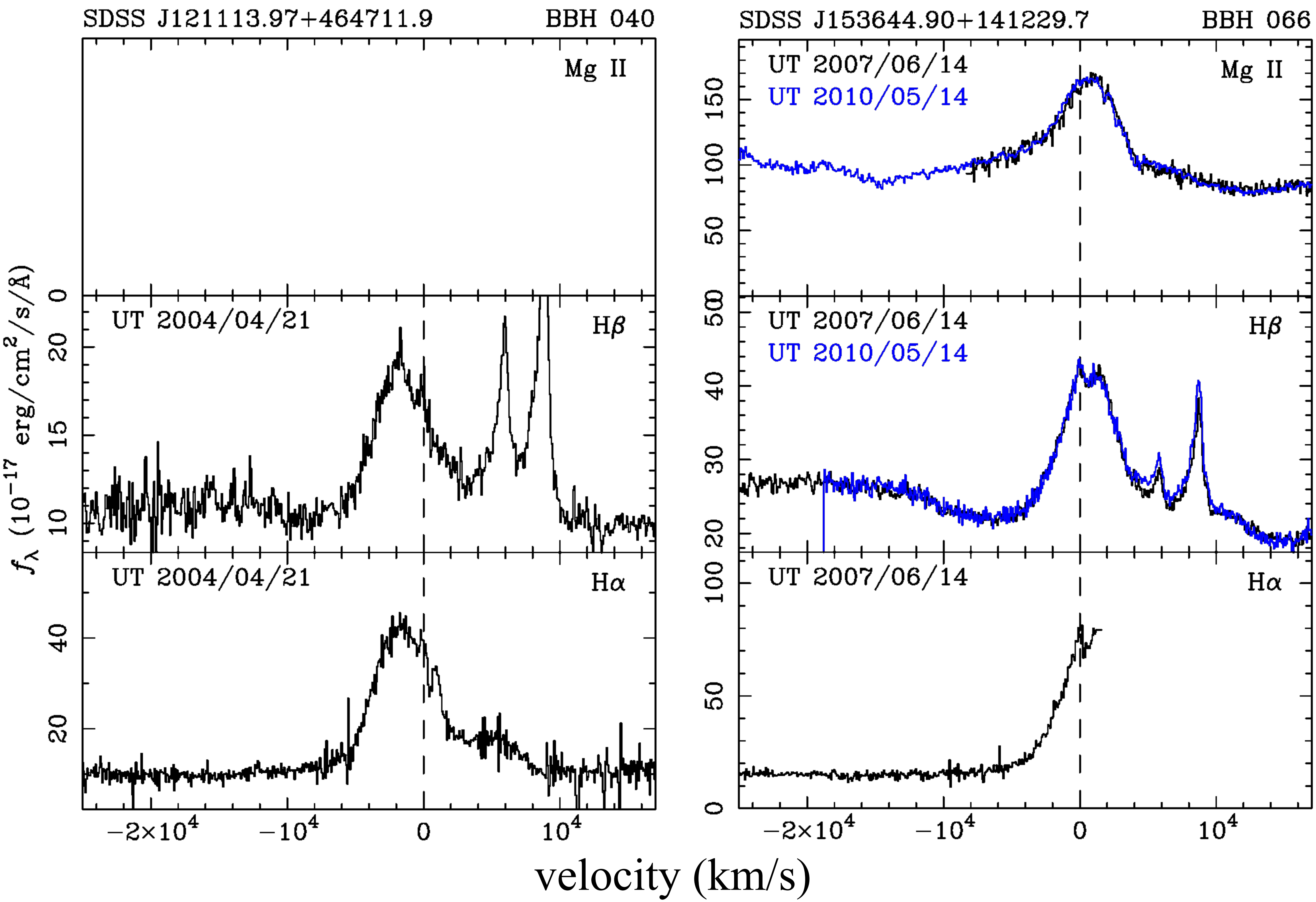
- “Opposition:” $\varphi \neq 0$
  $\Rightarrow u,\ du/dt \neq 0$
  - Bonning et al. 2007, ApJ, 666, L13
  - Tsalmantza et al. 2011, ApJ, 738, 20; Decarli et al. 2013, MNRAS, 433, 1492
  - Eracleous et al. 2012, ApJS, 201, 23
  - Liu et al 2014, ApJ, 789, 140

- Conjunction: $\varphi = 0$
  $\Rightarrow u = 0,\ du/dt = \max$
  - Shen et al. 2013, ApJ, 775, 49
  - Ju et al. 2013, ApJ, 777, 44

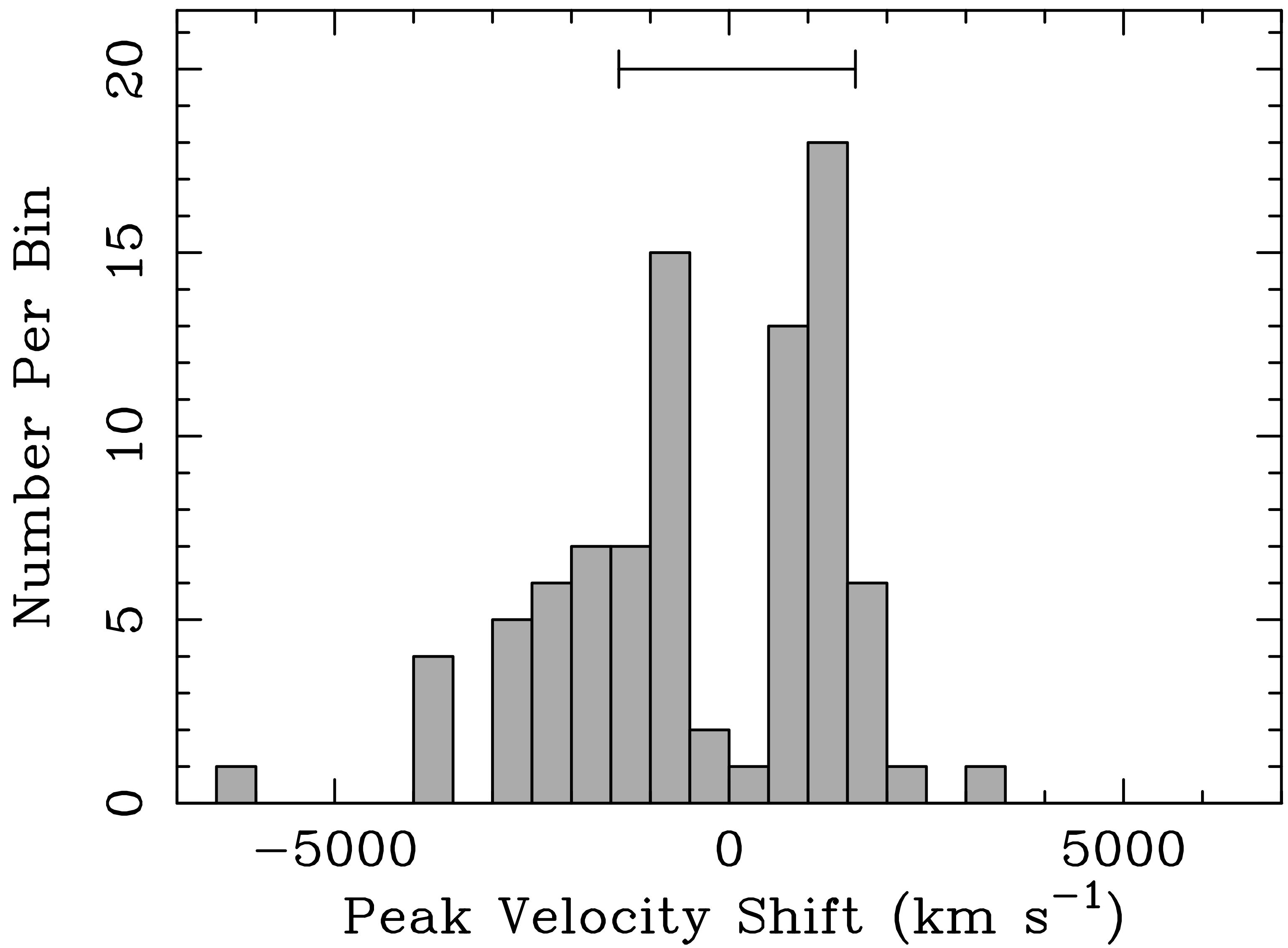
  Acceleration is easier to detect but there are many more interlopers

Examples of line profiles

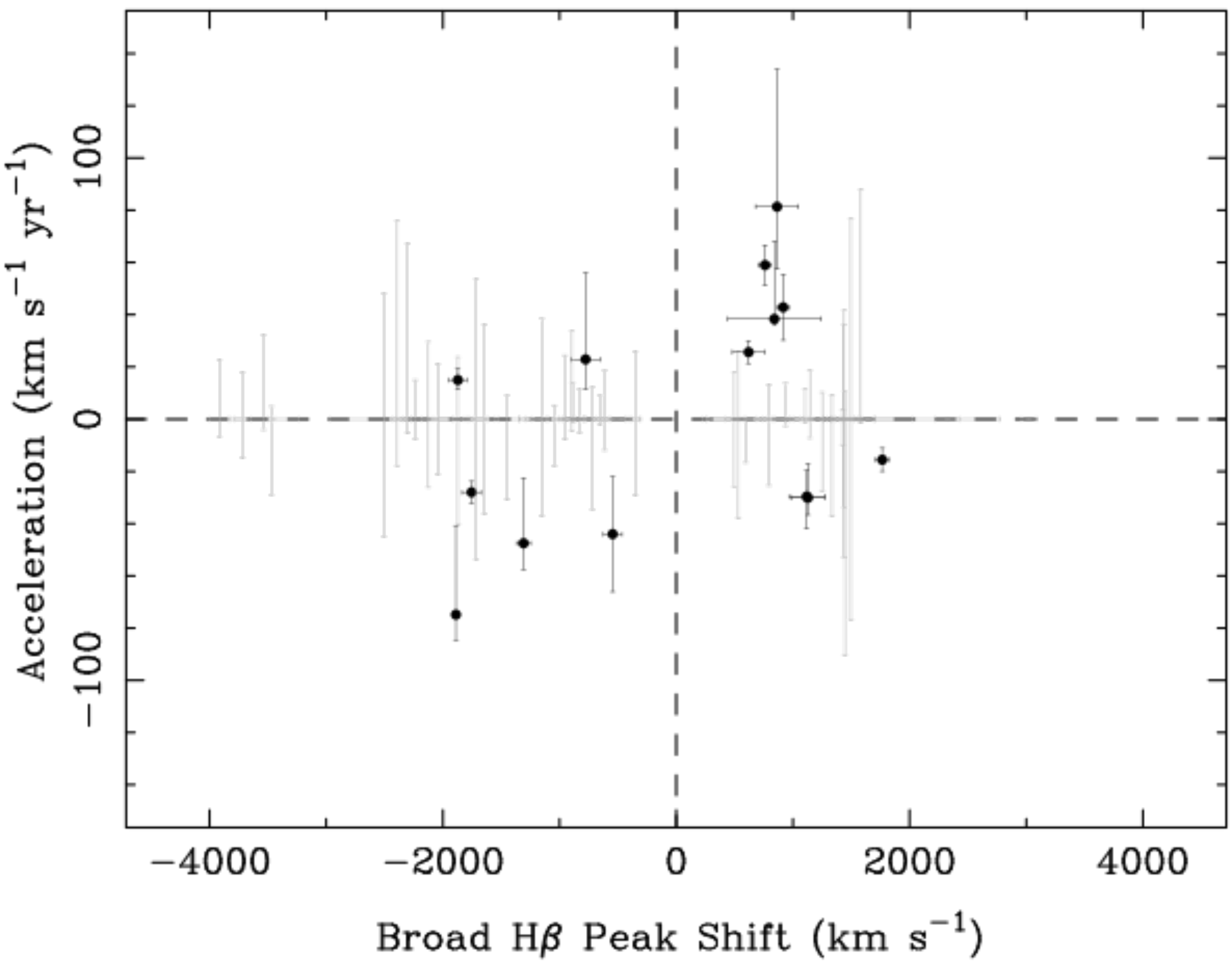
from Eracleous, Boroson, Halpern, & Liu 2012, ApJS, 201, 23



Distribution of initial velocity offsets



from Eracleous, Boroson, Halpern, & Liu 2012, ApJS, 201, 23



from Eracleous, Boroson, Halpern, & Liu 2008, ApJ, 686, 138

Summary of observational results by other groups

Shen et al. (Hβ @ϕ=0)

- 28 vel. variables / 521
- disfavor $M \gtrsim 10^9\ M_\odot$ at $a/R < 5$

Decarli et al. (Hβ @ϕ ≠ 0)

- 0 vel. variables / 9
- eliminate recoiling BH hypothesis via SEDs

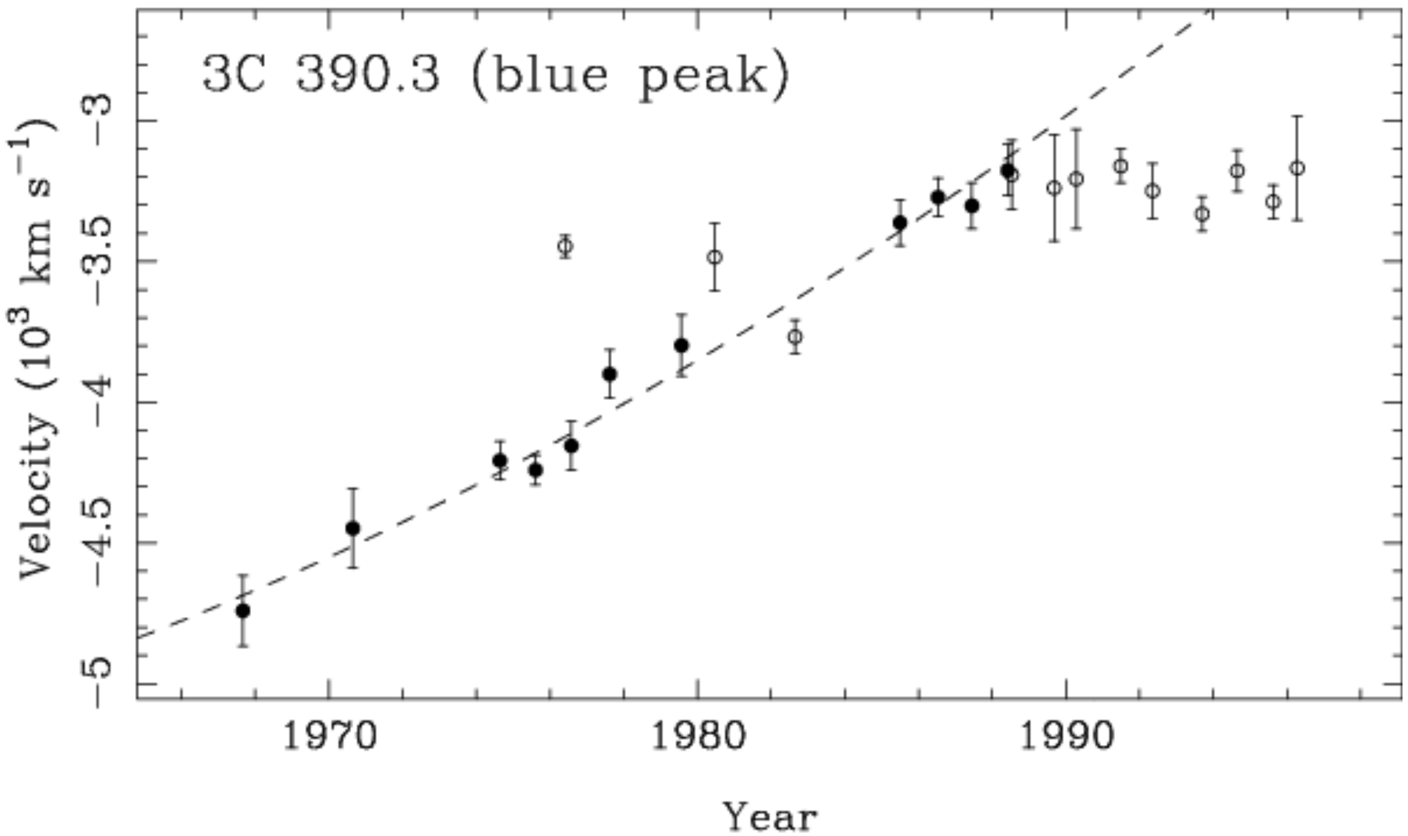
Ju et al. (Mg II @ϕ=0)

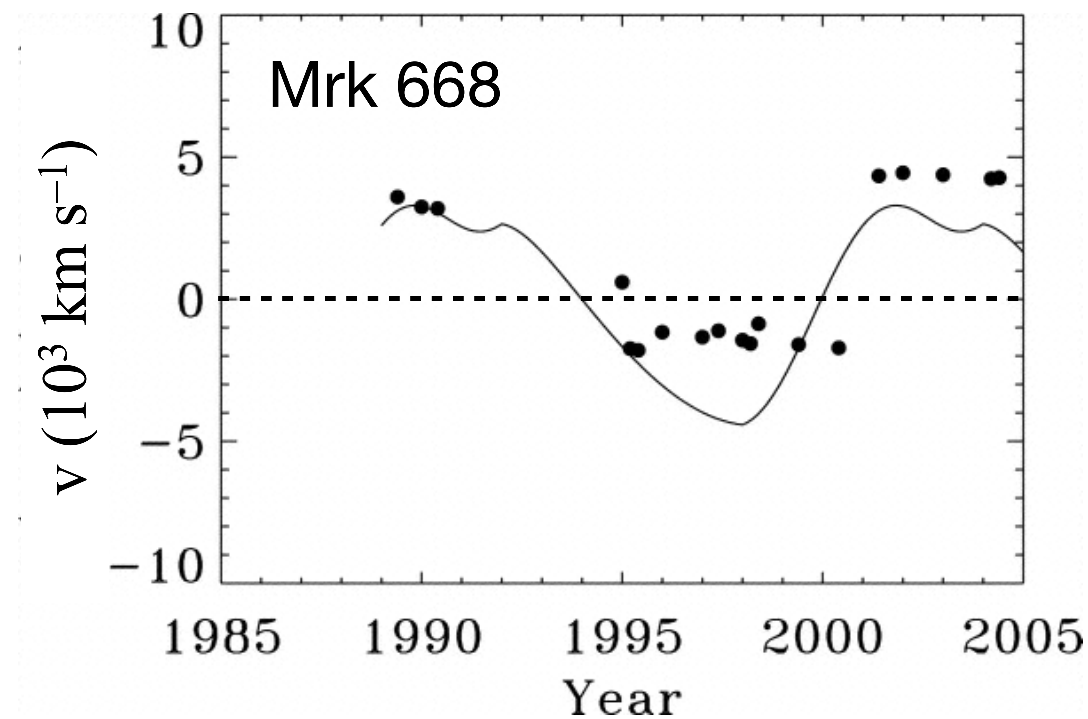
- 7 vel. variables / 1523
- disfavor $M \gtrsim 10^9\ M_\odot$ at a=0.03–0.2 pc

Liu et al. (Hβ @ϕ ≠ 0)

- 24 vel. variables / 50
- 9/24 good candidates

Danger of false positive signals





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

Gezari, Halpern &
Eracleous (2007)
see also
Marziani et al. (1996)

So far, so good, so what...

Systematic followup campaign

Continue monitoring observations

- verify velocity variations, check for monotonic velocity changes:
  3 epochs can constrain a sinusoid ⇒ lower bound on the mass

- eliminate possibility of origin from perturbed disk

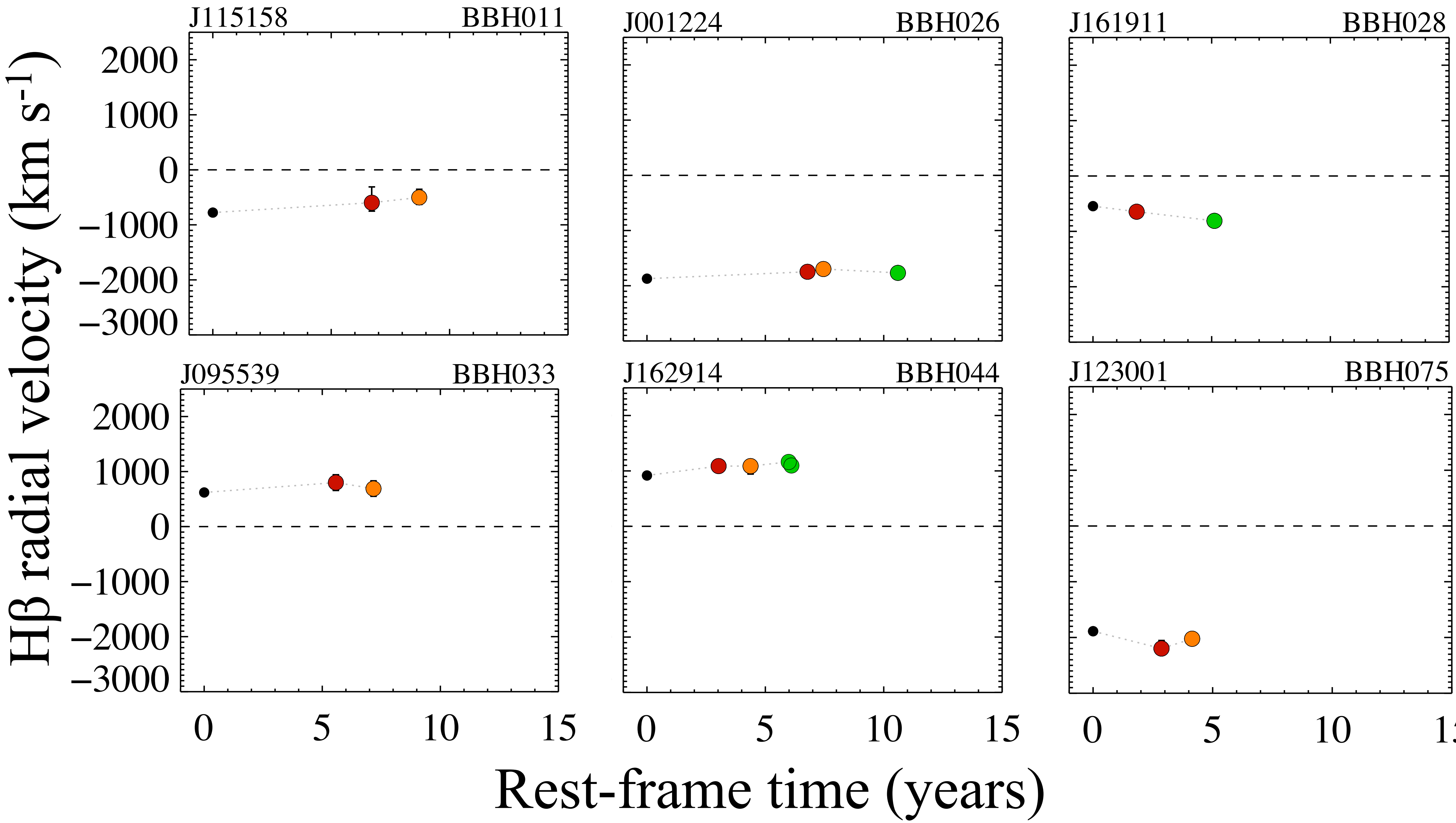
Optical and radio imaging:

- investigate if jets are pushing the gas around

- resolve the nearest binaries with VLBI/VLBA

Simulations of the population properties and assessment of impostors.

Honest radial velocity curves



The End!