Searching for Massive Black Hole Binaries The Point of View of an Optical Observer

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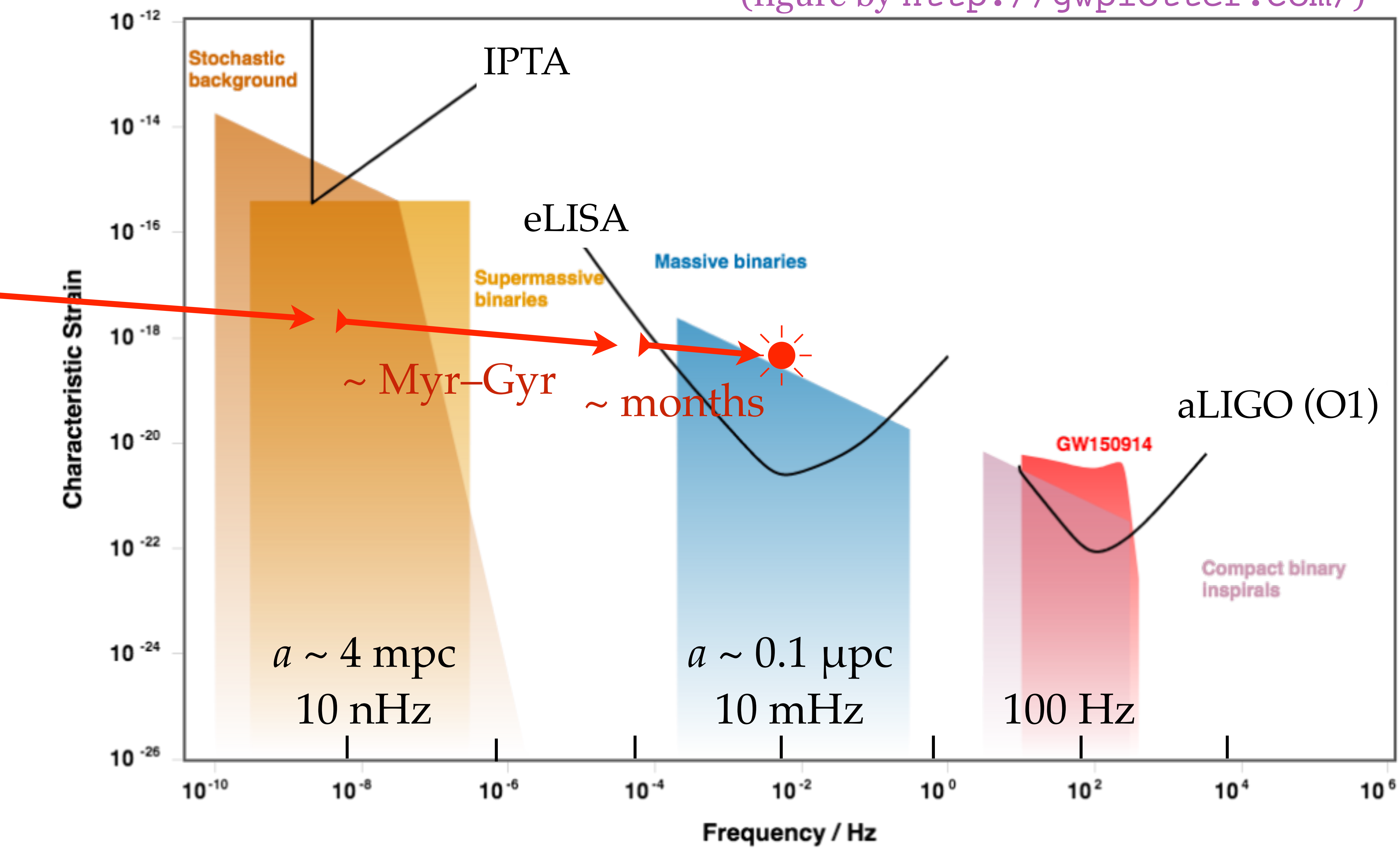
The journey of a 2×(10⁶ M⊙) supermassive binary through the GW frequency spectrum

(figure by http://gwplotter.com/)

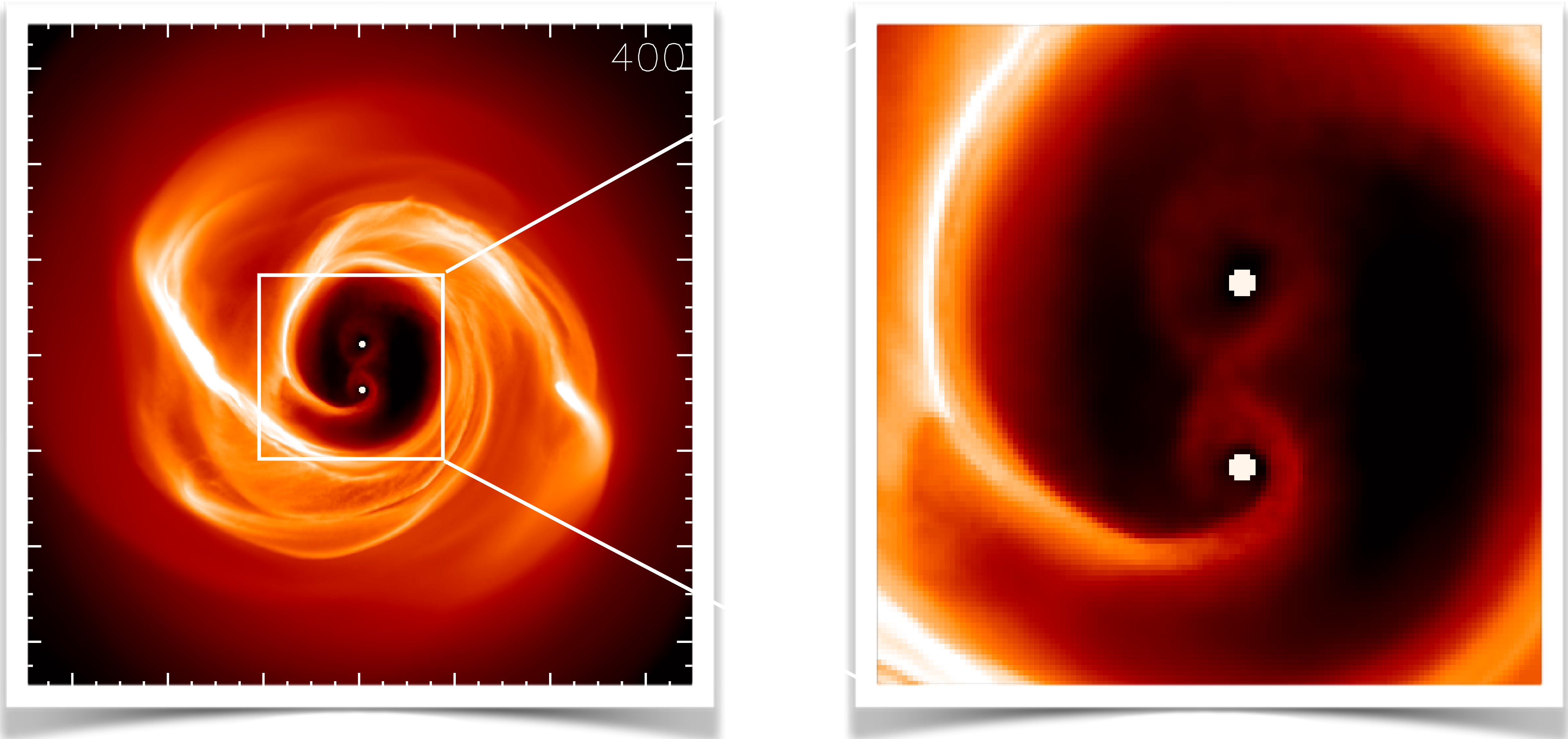


Observing five stages of the journey of a $2\times(10^6\ M_\odot)$ supermassive binary from 1 pc to coalescence.

a	f_{GW}	E.M. Observability
1 pc	0.7 pHz	resolved by radio interferometry (proper motion may be observable)
0.1 pc	20 pHz	optical spectroscopy (displaced emission lines)
2 mpc	5 nHz	(f_{GW} within PTA band) modulation of optical light curves
2 μpc	0.4 mHz	(entering LISA band) fast modulation of X-ray light curves (?)
0.1 μpc	20 mHz	(merger in LISA band, chirp) polychromatic E.M. flare (?)

Geometry of accretion flow and possible signatures

(figure from Cuadra et al. 2009)



- Binary period introduces a characteristic time scale
  ⇒ photometric variations

- Gas bound to individual black holes follows them in their orbits
  ⇒ spectroscopic variations

Potential E.M. signatures of supermassive binaries at separations of 0.1–few pc

- Direct imaging via radio interferometry

  Burke-Spolaor et al. 2011, MNRAS, 410, 2113
  Bansal et al. 2017, ApJ, 843, 14

  observations

- Radial velocity variations of broad emission lines

  Runnoe et al. 2017, ApJS, 201, 23
  Guo et al 2019, MNRAS, 482, 3288
  Decarli et al. 2013, MNRAS, 433, 1492
  Wang et al. 2017, ApJ, 834, 129

  observations

- Modulation of optical light curves

  Graham et al. 2015, MNRAS, 453, 1562
  Charisi et al. 2016, MNRAS, 463, 2145
  Liu et al. 2019, arXiv:1906.08315
  Vaughan et al. 2016, MNRAS, 461, 3145

  observations

E.M. signatures of supermassive binaries (*continued*)

- Combination of photometric and radial velocity modulations

  Bon et al. 2012, ApJ, 759, 118
  Li et al. 2016, ApJ 822, 1

  observations

- Relative intensities and profiles of broad lines

  predictions

  Montuori et al. 2011, MNRAS, 412, 26 and 2012, MNRAS, 425, 1633

- Deficit in the spectral energy distribution because of gaps in the accretion disk.

  Gükltekin & Miller 2012, ApJ, 761, 90
  McKernan et al. 2013, MNRAS, 432, 1468

  predictions

- Modulated extreme-UV/X-ray emission during late stages of inspiral and periodic shifts of X-ray emission lines.

  Bode et al. 2010, ApJ, 715, 1117 and 2012, ApJ, 744, 45
  McKernan et al. 2013, MNRAS, 432, 1468
  d'Ascoli et al. 2018, ApJ, 865, 140

  predictions

The main limitation in all the methods is ambiguity. It comes from incomplete understanding of the underlying physical processes that shape the observational appearance of “typical” quasars.

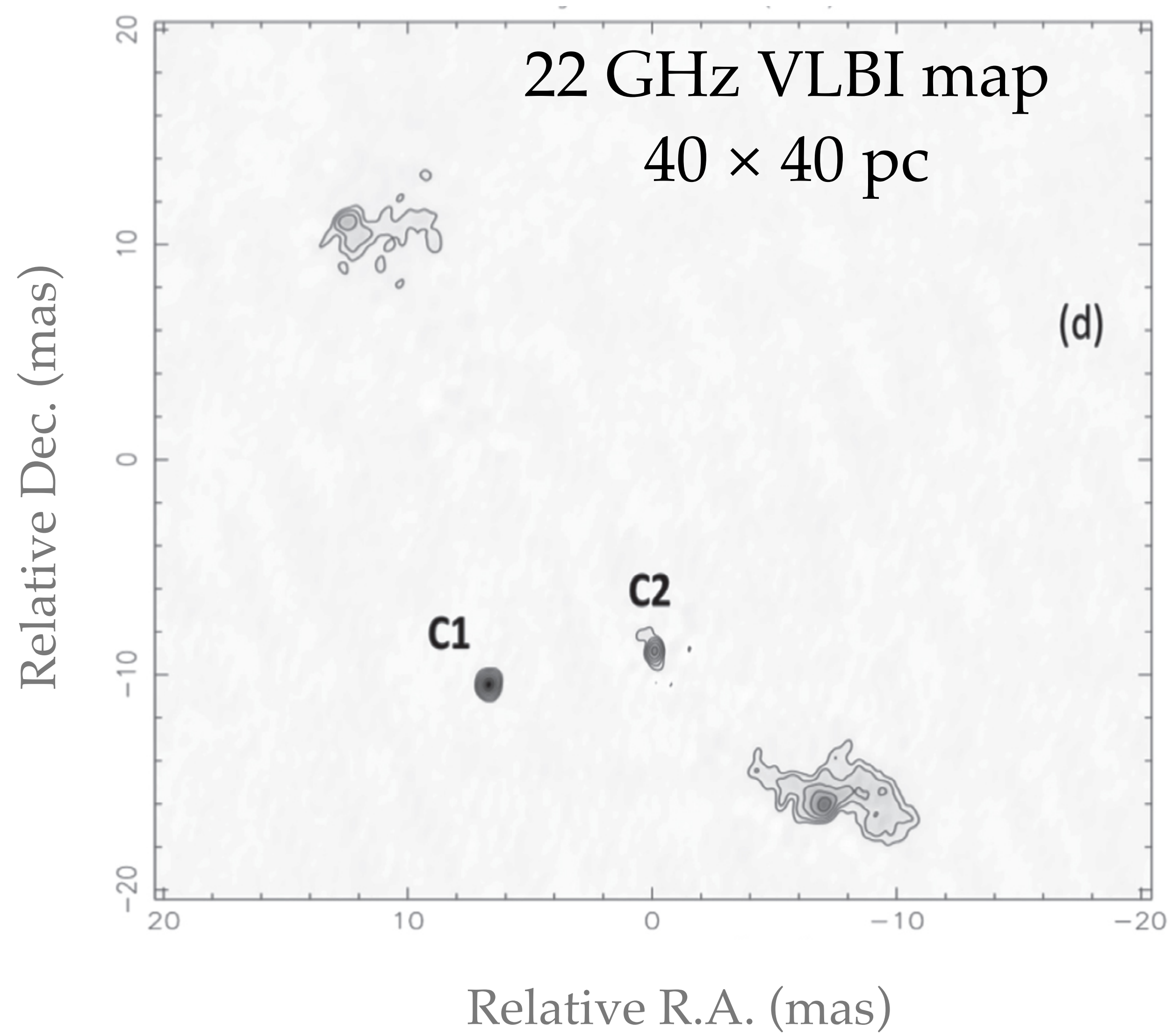
“Quasars do some weird s☠️🚫⚠️!“

– Anonymous theorist, ca. early 21st century

For every theoretical prediction of what a binary black hole will do, we have to be sure that a typical quasar cannot do the same thing, but better.

4C+37.11, a.k.a. CSO 0402+379 (from Bansal et al 2017, ApJ, 843, 14)

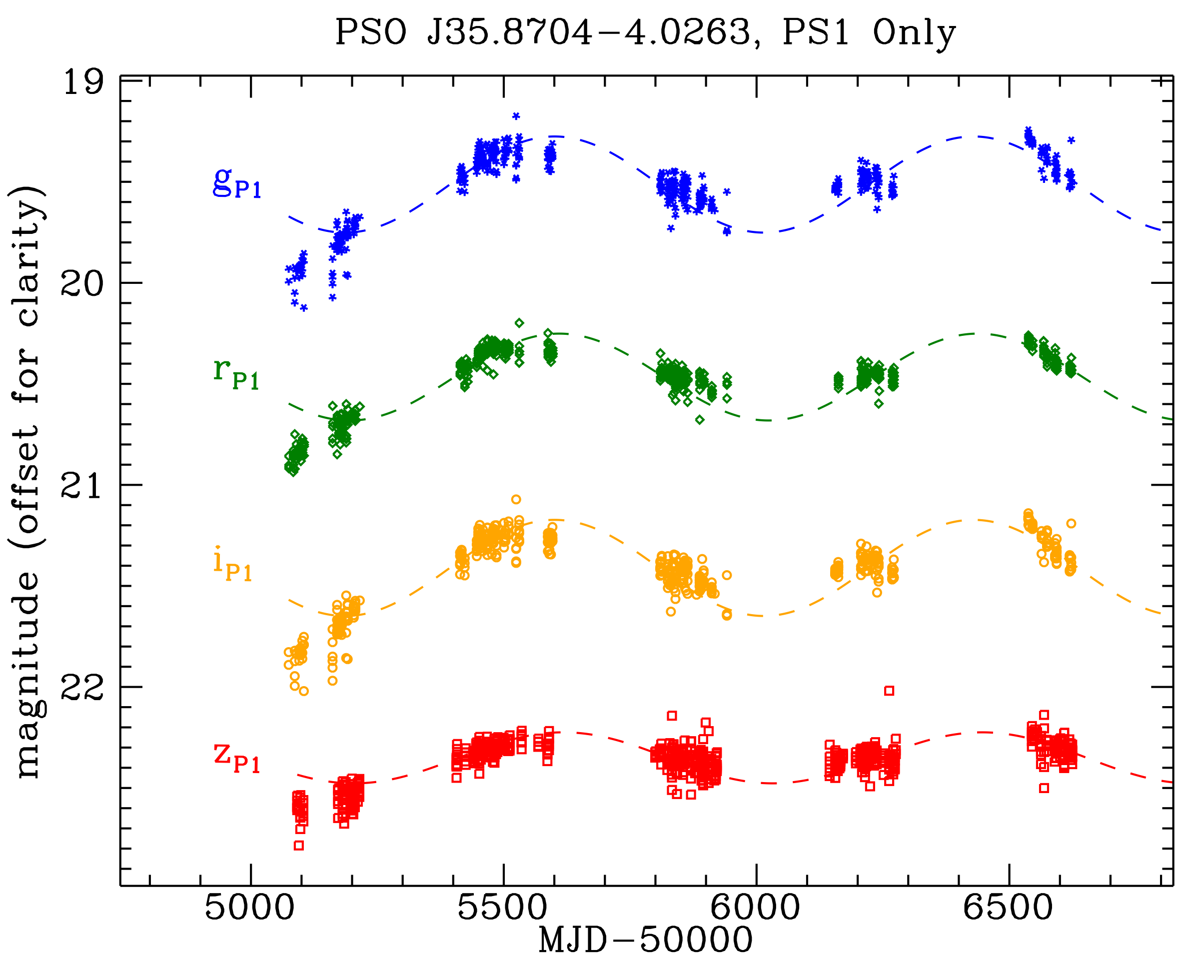
- Separation 7.3 pc @ $z = 0.055$
- Small proper motion detected in 12 years
- Infer (assuming circular orbit):
  - $P = 3\times10^4$ yr
  - $M = 1.5\times10^{10}\ M_\odot$

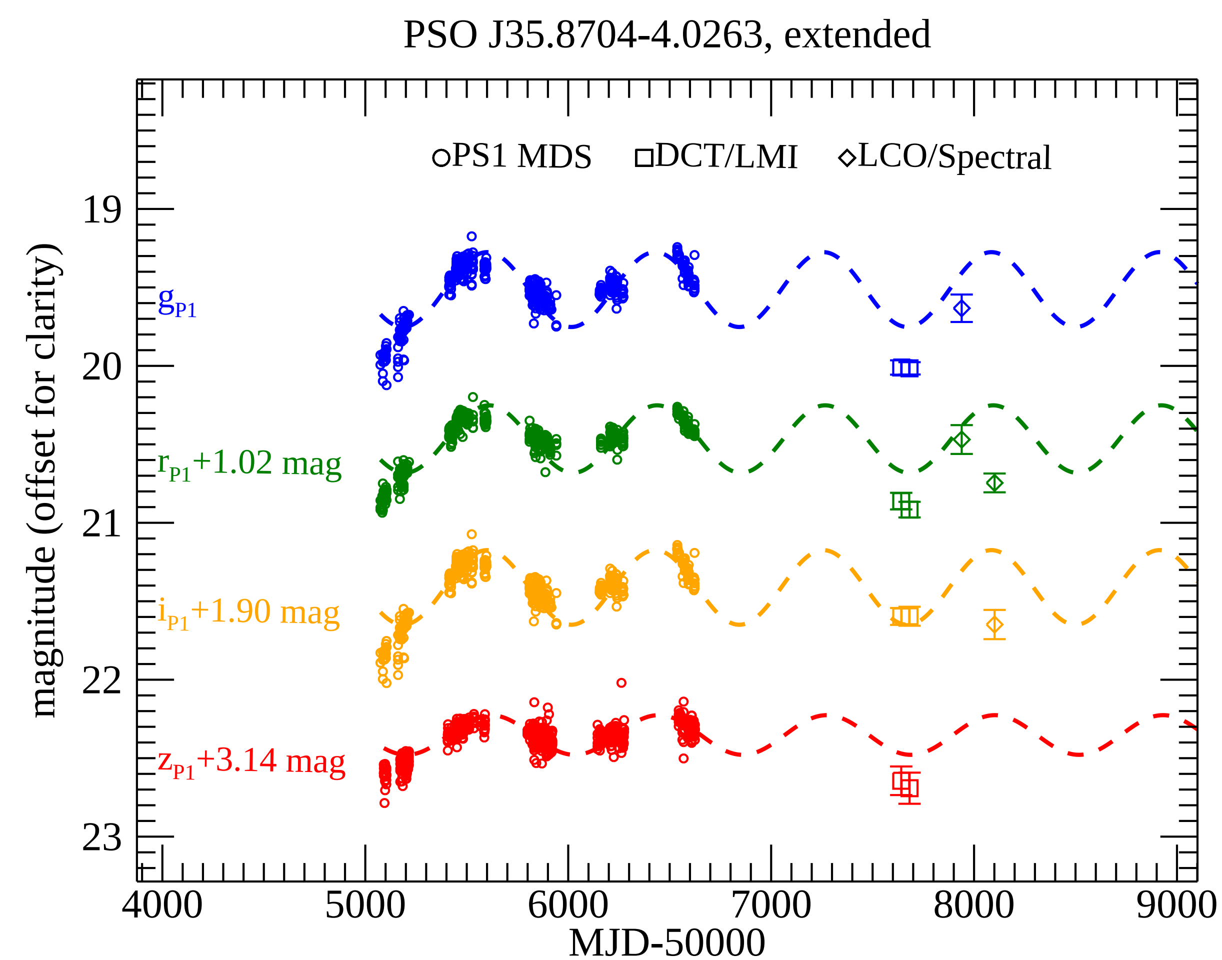


Angular resolution limited since 1 pc → 0.3 mas @ $z = 0.2$

Examples of modulated light curves

from Liu, T. et al.
arXiv:1906.08315



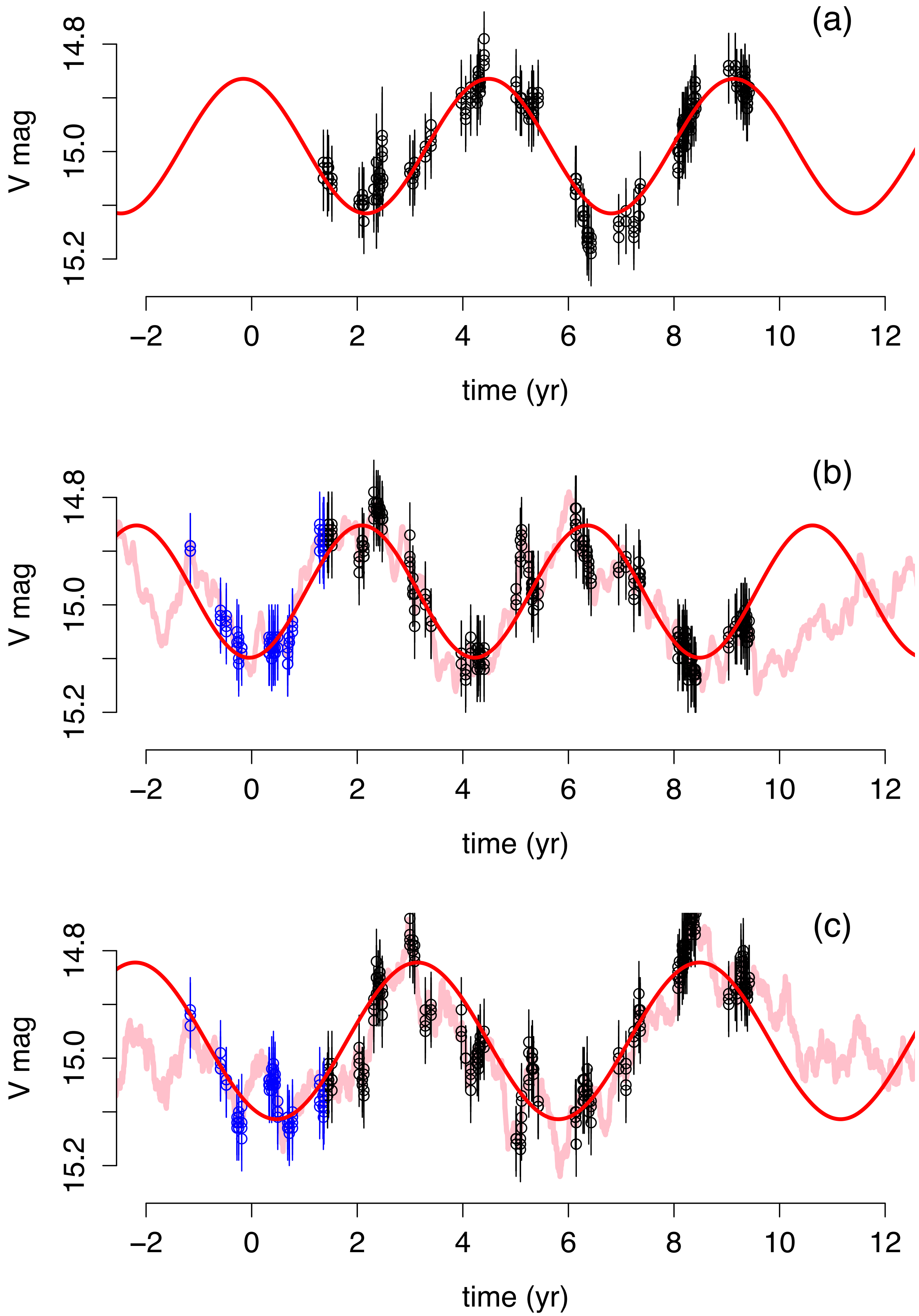


← 4 years →

← 8 years →

Original data set from PS1 MDS

Additional data from LCO 2m



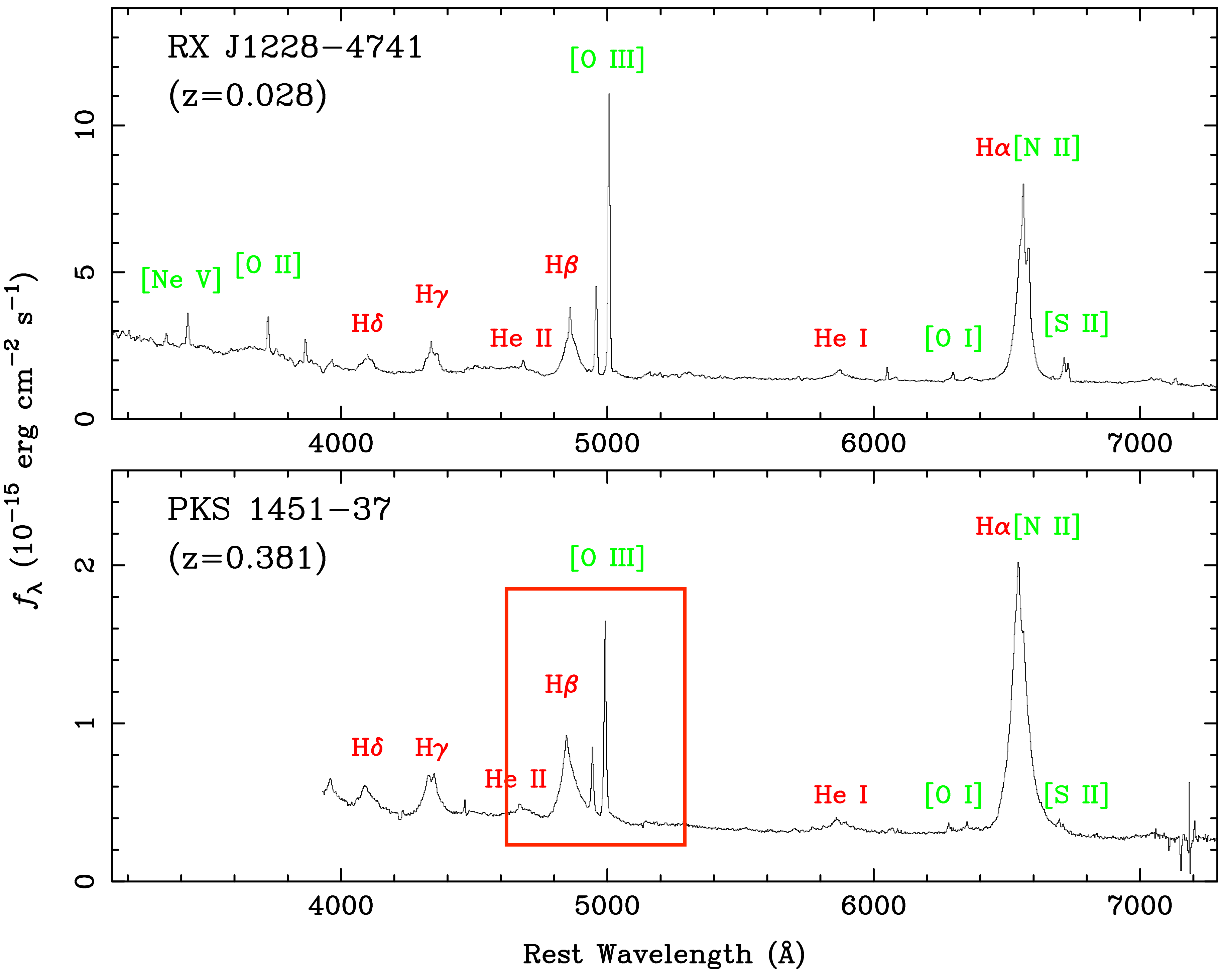
PG 1302–102 Observed (CRTS data only)

(data from Graham et al. 2015, Nature, 518, 74)

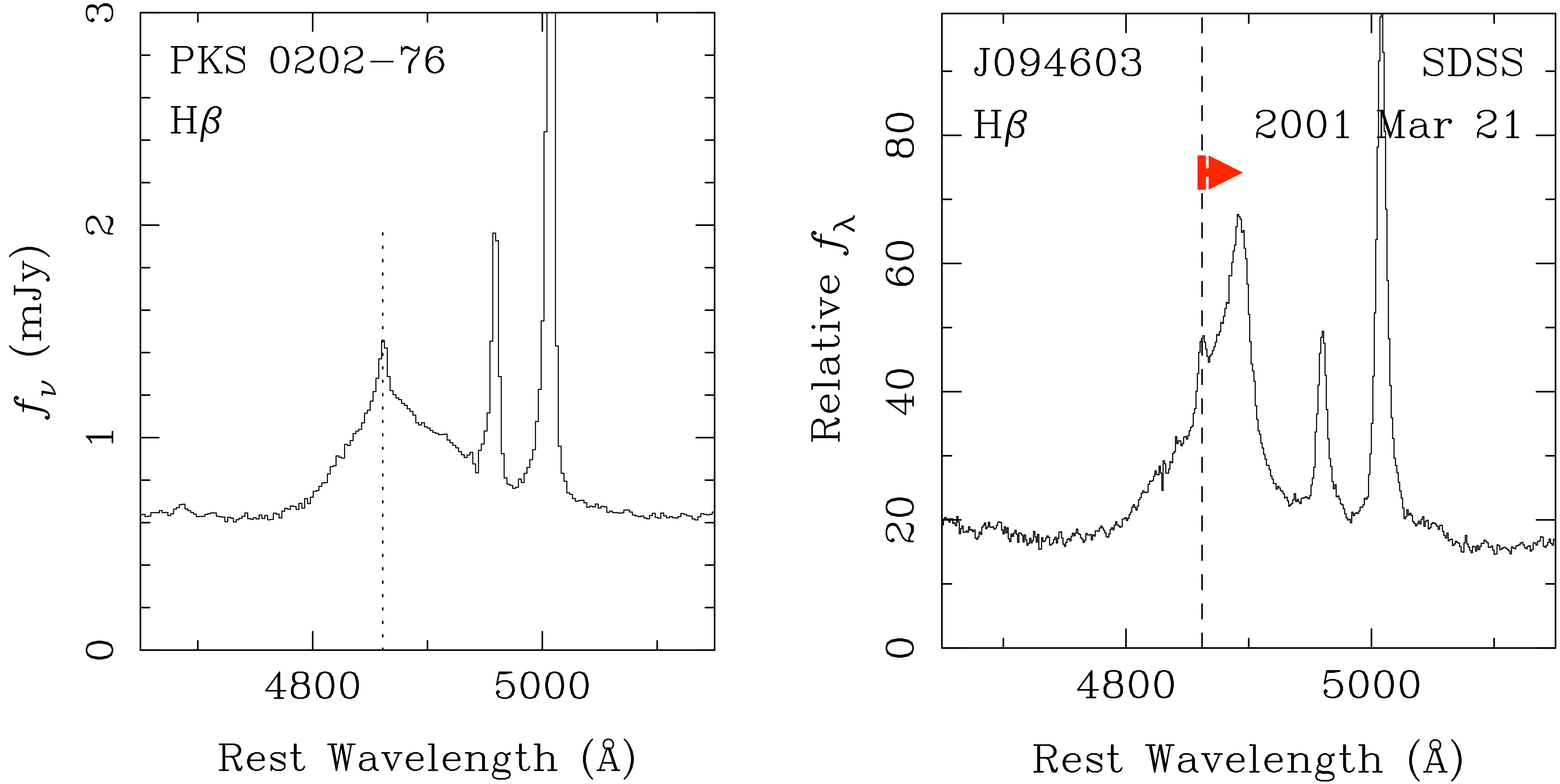
Simulated (LINEAR + CRTS data)

(Vaughan et al. 2016, MNRAS, 461, 3145)

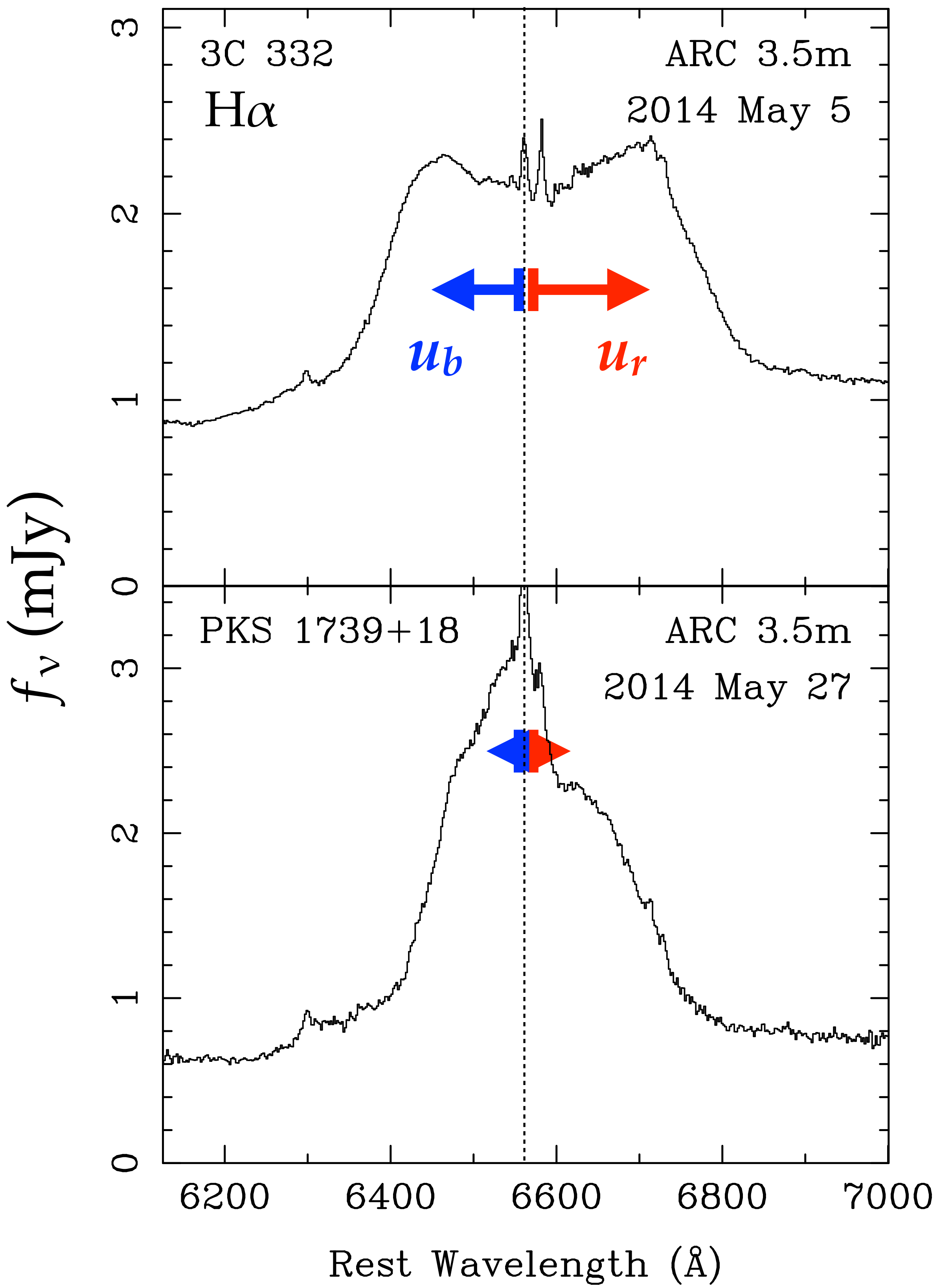
Examples of quasar optical spectra

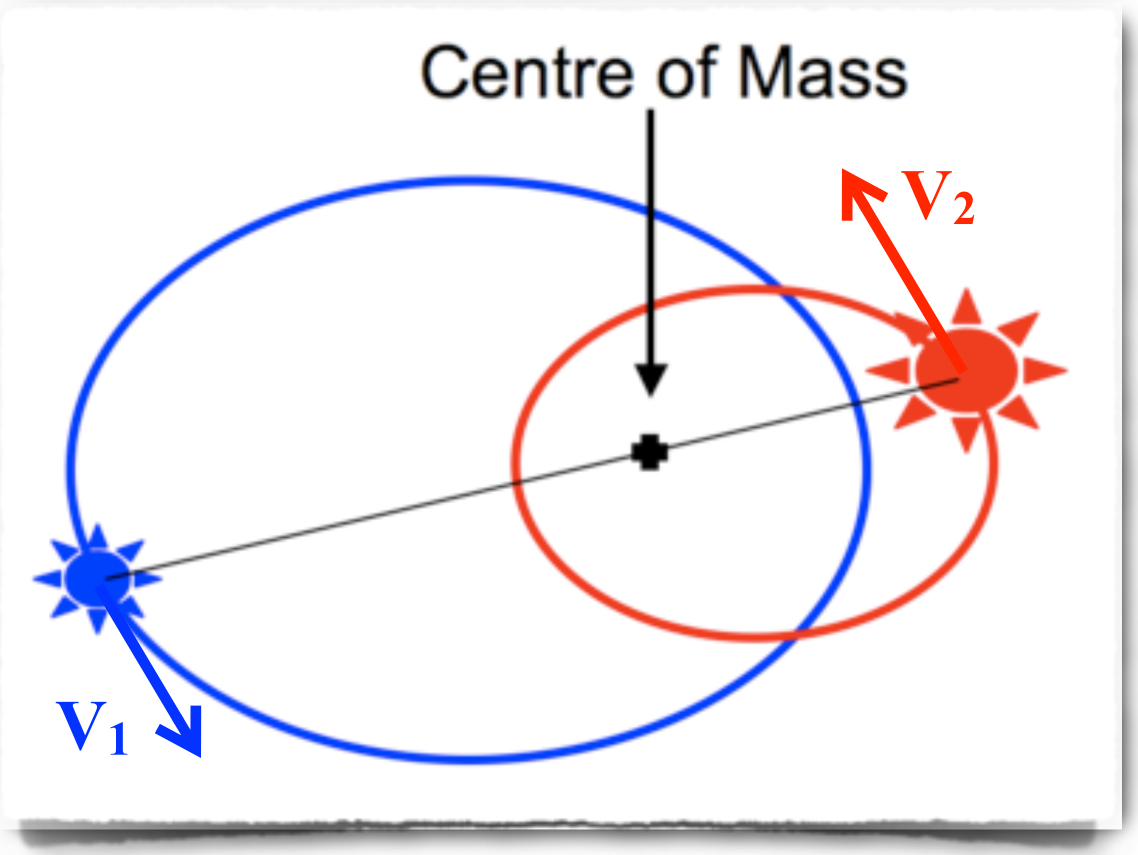


The Hβ emission line: up close and personal



More examples of emission line profiles

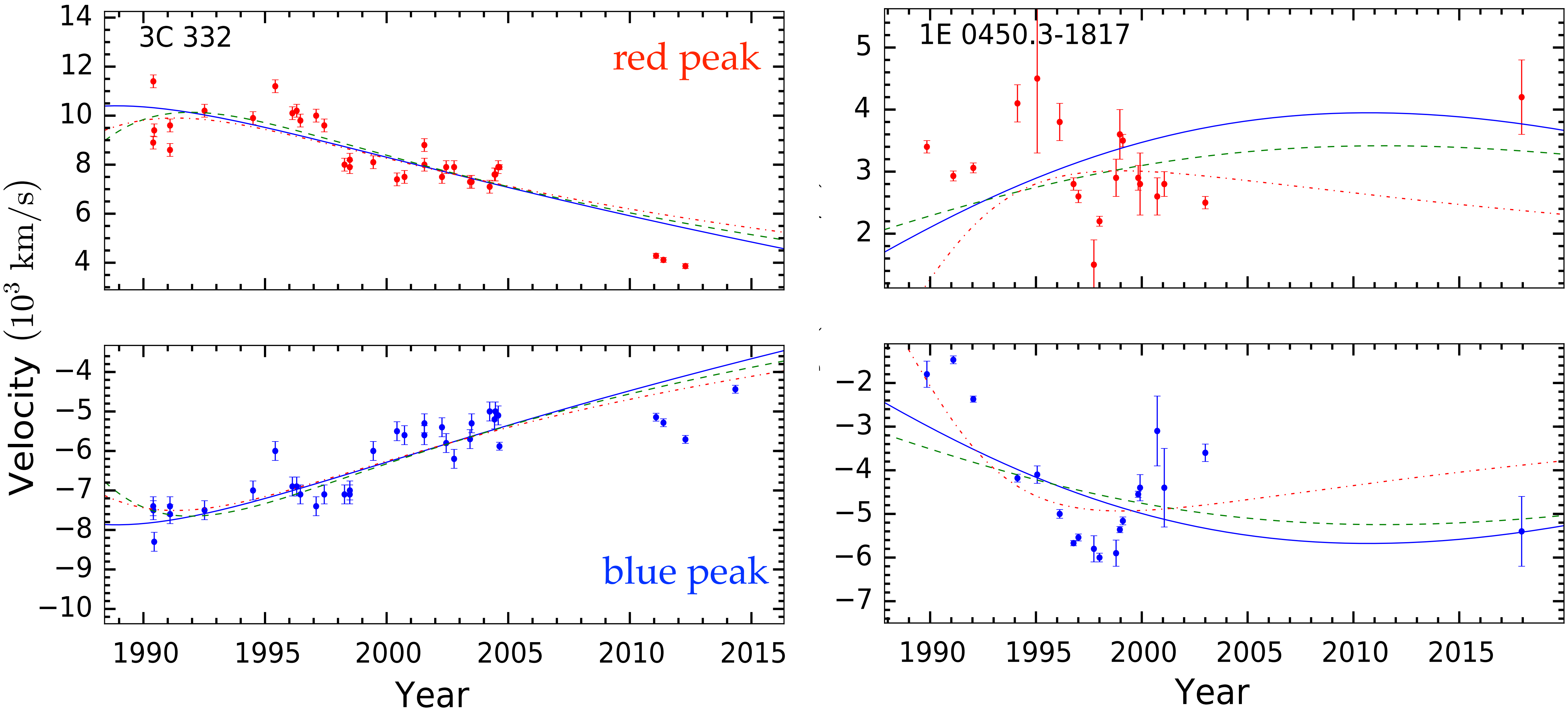




(spectra from Doan et al. 2019, in preparation)

Fits to radial velocity curves: 14 cases of double-peaked lines

(figures from Doan et al. 2019, in preparation)

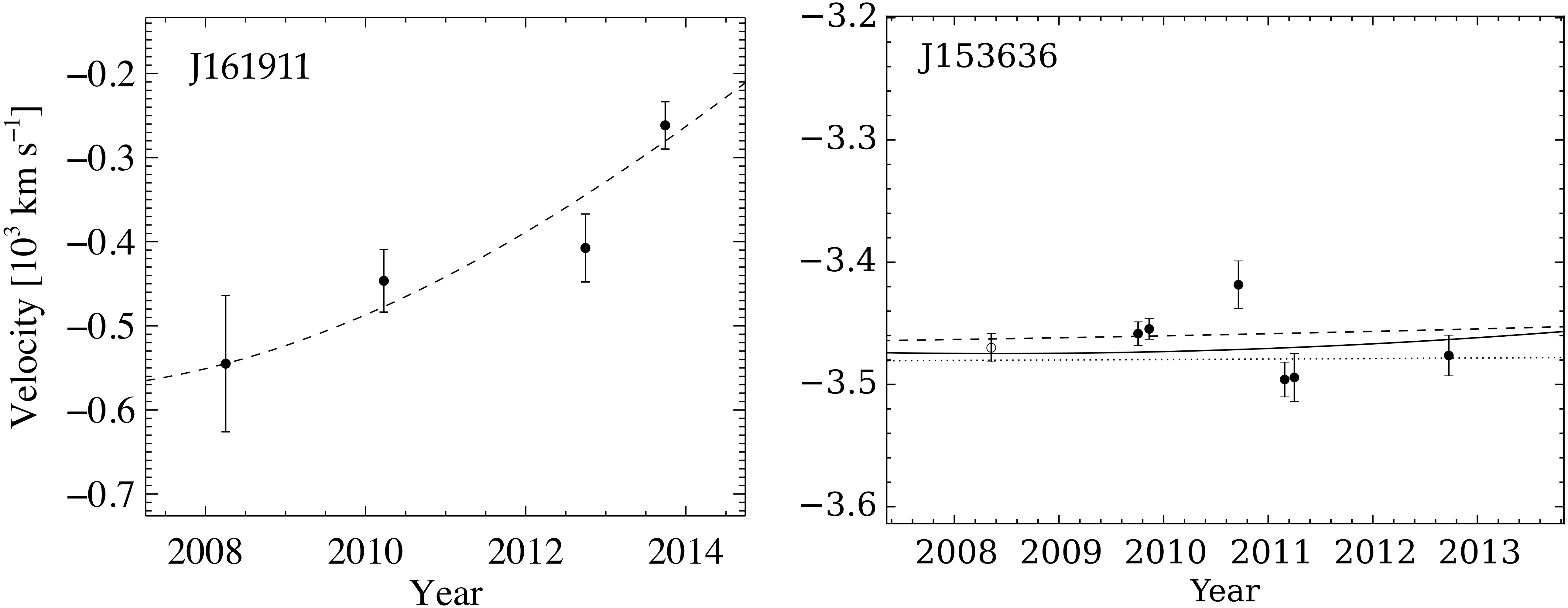


2/14 of cases
good fits with $M > 10^{10}$ M$_\odot$

1/3 of cases
very poor fits

Fits to radial velocity curves: 29/88 cases of single-peaked lines

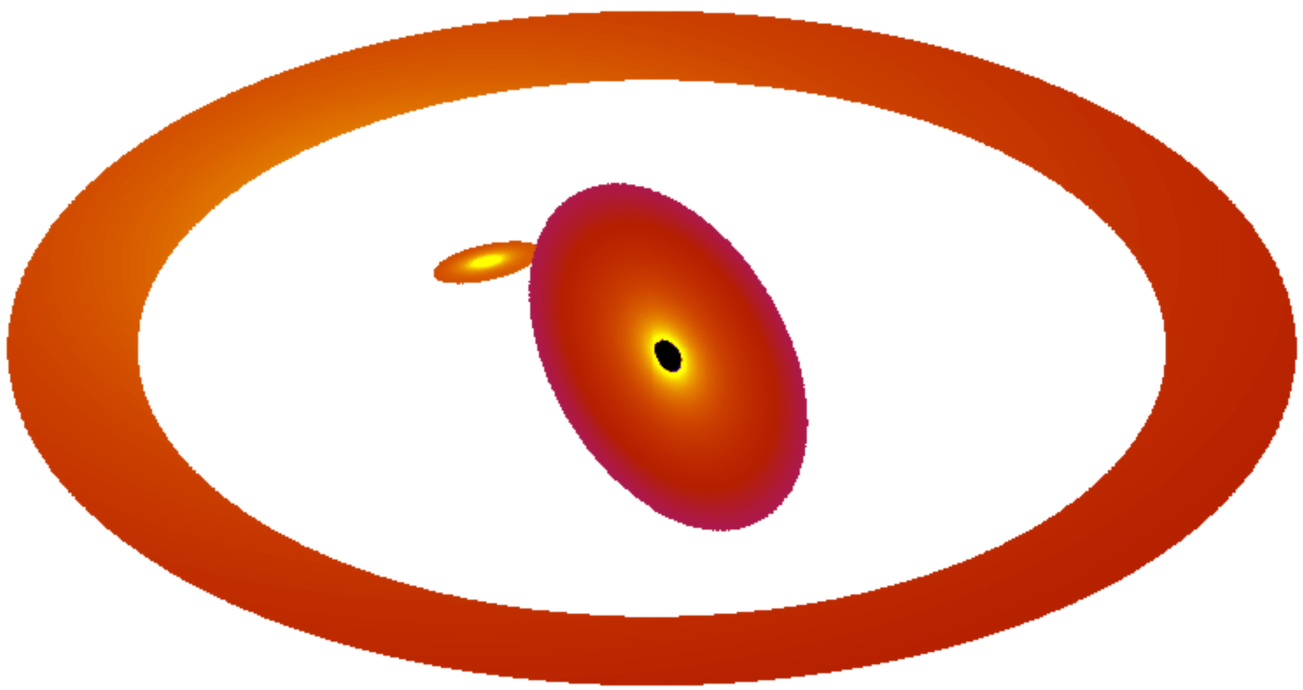
(see Runnoe et al. 2017, ApJS, 201, 23)



10/88 cases of significant radial velocity variations

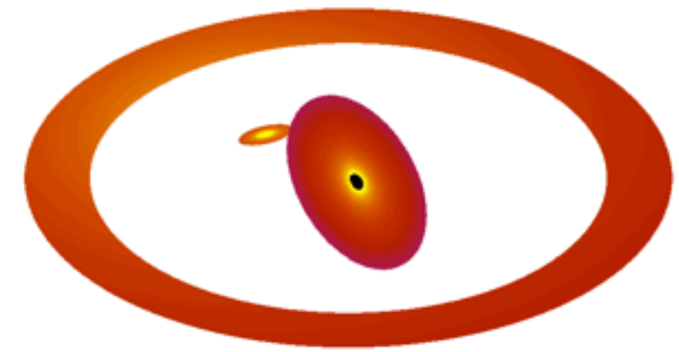
19/88 cases of radial velocity variations consistent with zero

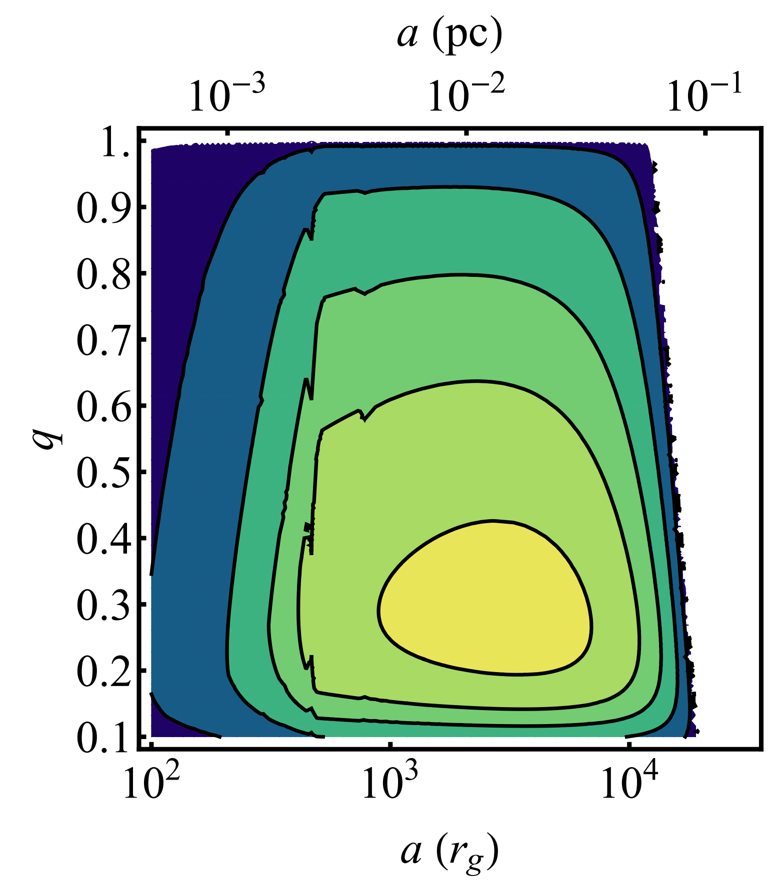
Obligatory cool movie:
two misaligned disks orbiting each other.



Inferences from simple models of line profiles and populations (taking observations at face value)

- ✦ Line profiles:
  - ❖ Calculation of large library of synthetic line profiles.
  - ❖ Develop method to find location of an observed spectrum in the parameter space of the library
  - ➡ Can infer basic properties of system but *cannot prove* that system is a SBHB
- ✦ Population properties:
  - ❖ speed of evolution of SBHB separation
  - ❖ observed speeds andluminosities
  - ❖ dimple prescription for accretion rates
  - ➡ Infer likely mass ratio and separation for an assumed mass





Nguyen & Bogdanovic 2016, ApJ, 828, 68
Plugger et al. 2018, ApJ, 861, 69
Nguyen et al. 2019 ApJ, 870, 16

Limitations and next steps

- **We now only have one signature per evolutionary phase.**
- Continued monitoring (remedy for many problems)
  - record more cycles of photometric modulation
  - establish longer (monotonic?) trend of radial velocity curves
- Better empirical characterization of the time variability of "typical" quasars so that we know what quasars can really do.
- Better theoretical understanding of the continuum sources and broad-line regions of single quasars
  - Modern accretion disk models
  - Radiation-hydro models of winds → broad-line region
  - Radiative transfer → light curves and line profiles
- Get ready to use LISA to figure out the E.M. signature *ex post facto*.

The End (of this talk)