Search for stellar BH via other approaches (ellipsoidal mod, RV)

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&
Friends

key questions

10^8 black holes expected in the Milky Way, but only ~60 or so known!

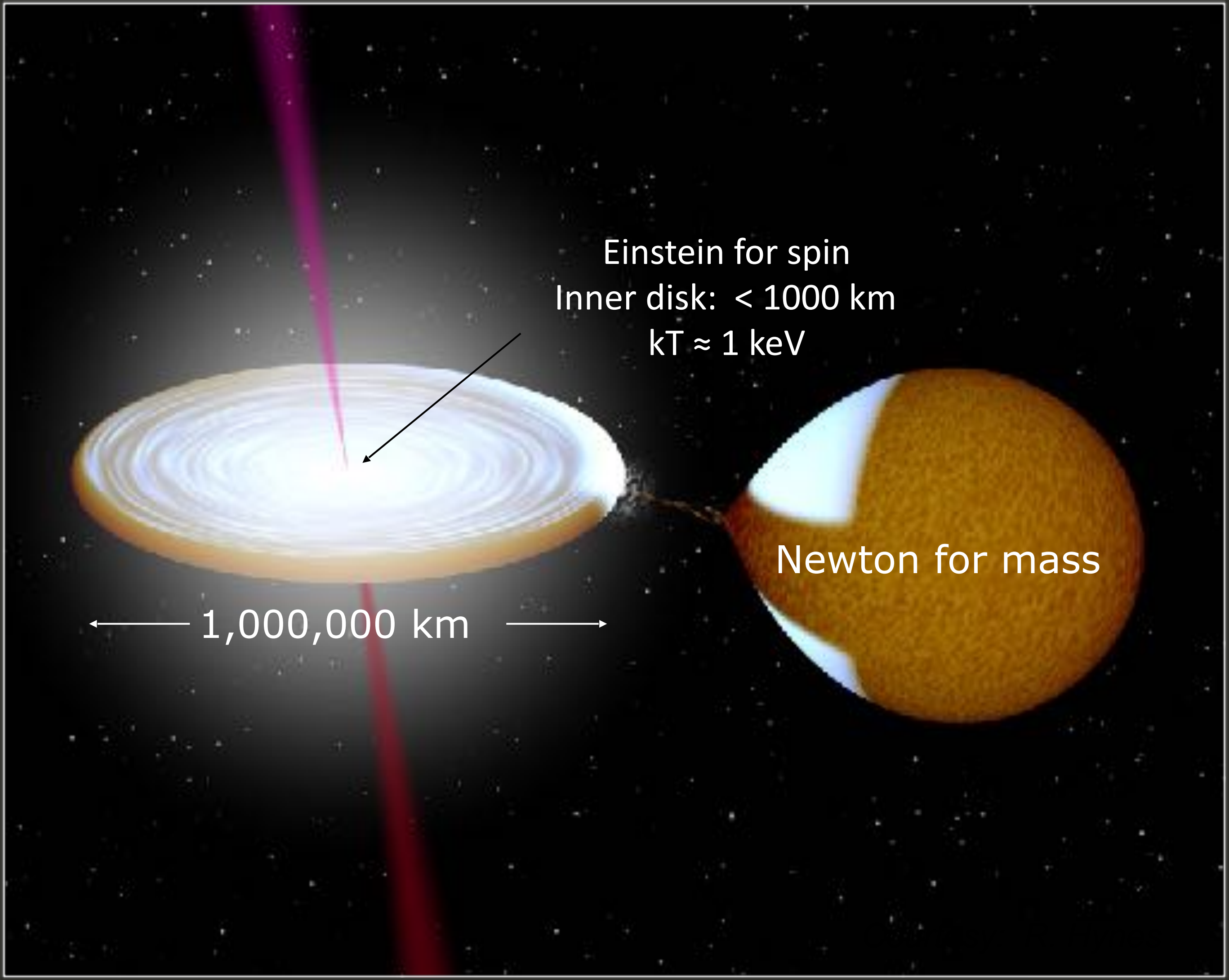
- what's the mass spectrum? spatial distributions? how many in binaries? kinematics (kicks)?
- relationship to gravitational wave binary black holes?

Science goals and methods

- Goal: identify as many black holes as possible in binary systems across different stellar types (B to M types)

- Method: combining photometric and spectroscopic surveys

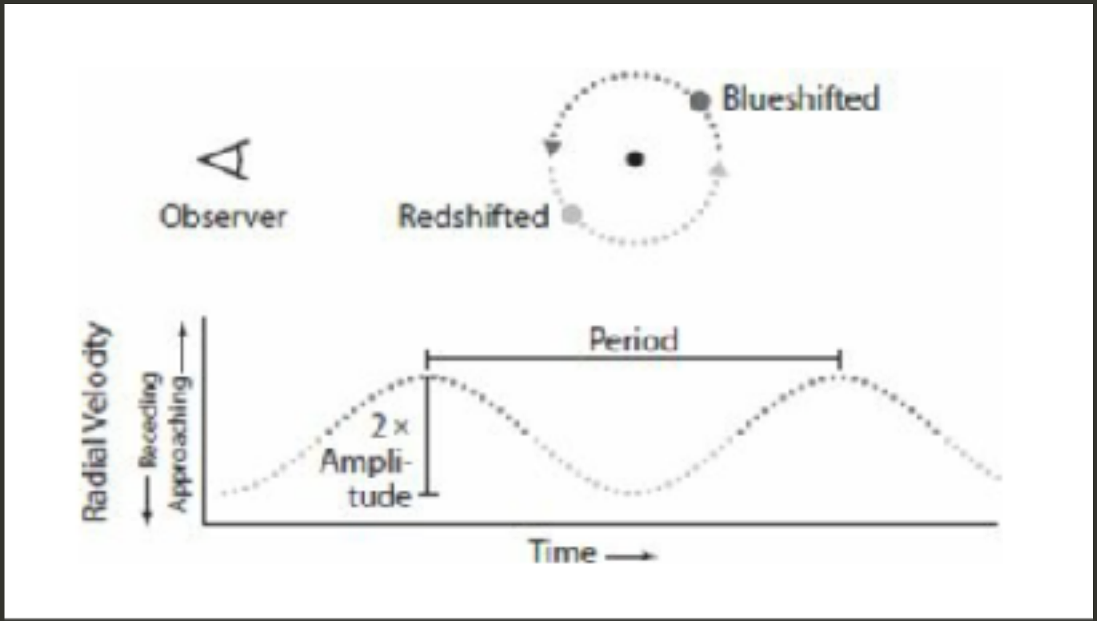
A BH X-ray Binary System

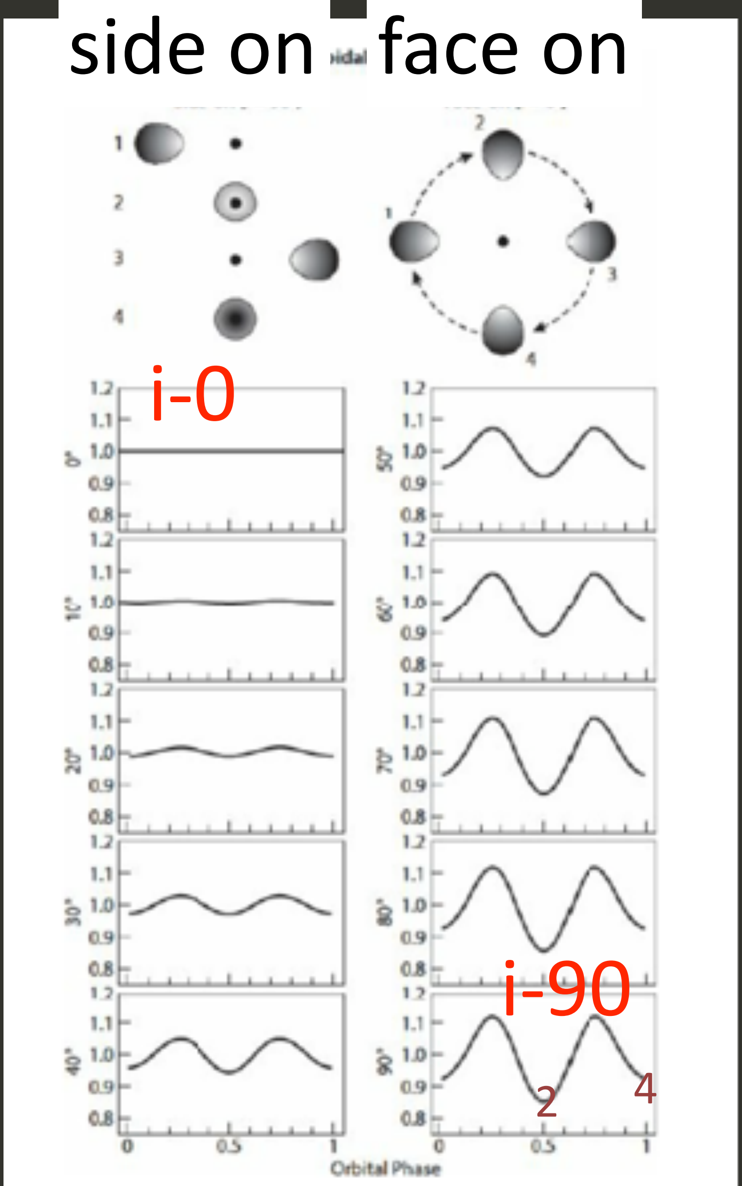


Mass Measurement:Mass function

$$f = PK_*^3/(2\pi G) = M_x \sin^3 i/(1 + M_*/M_x)^2$$

$$f \leq M_x$$

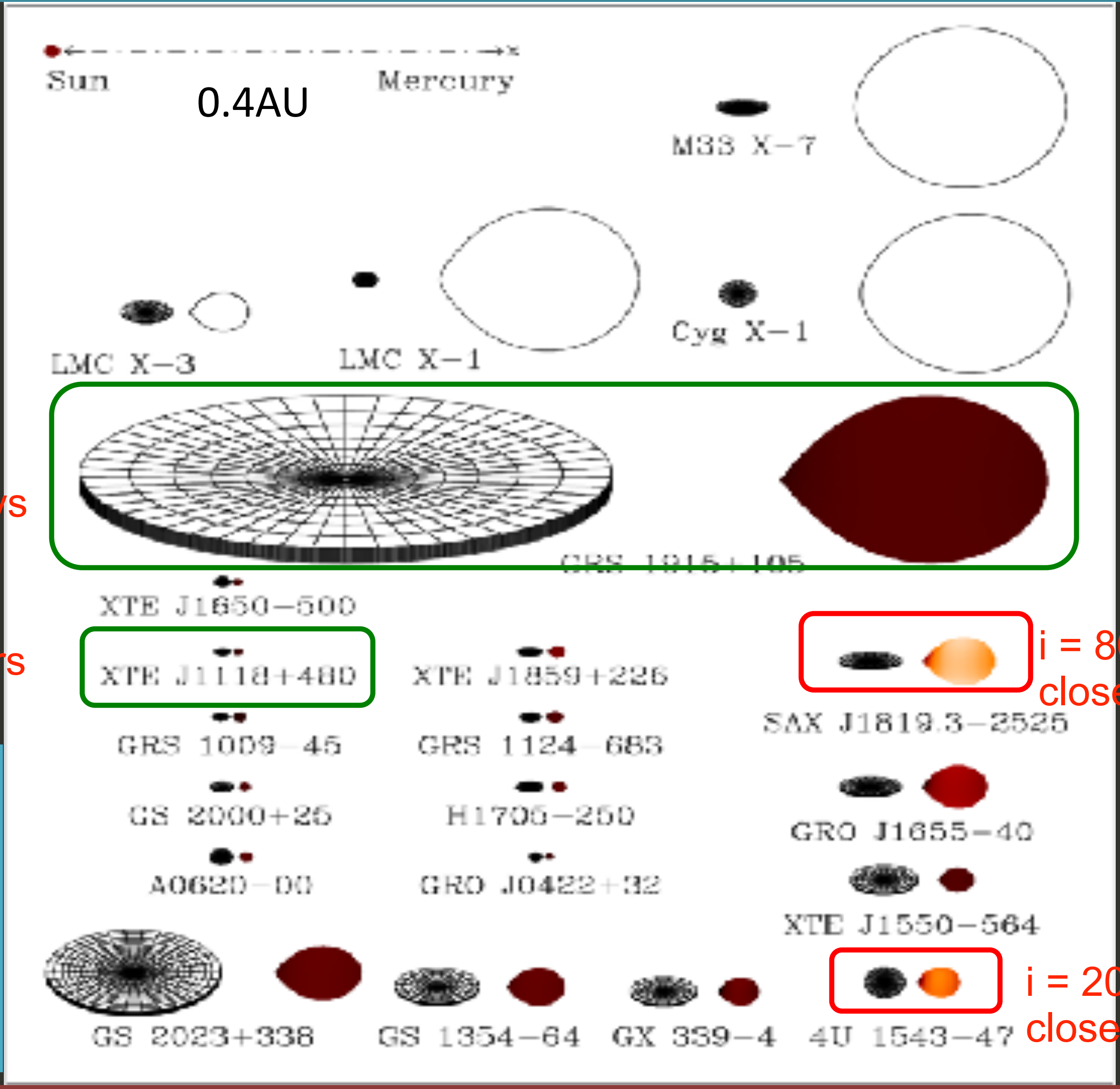




inclination and mass ratio

if mass is larger than 3 solar mass, it will be BH

21 Black Hole Binaries



P = 30 days

P = 4 hours

i = 80 deg
close to side-on

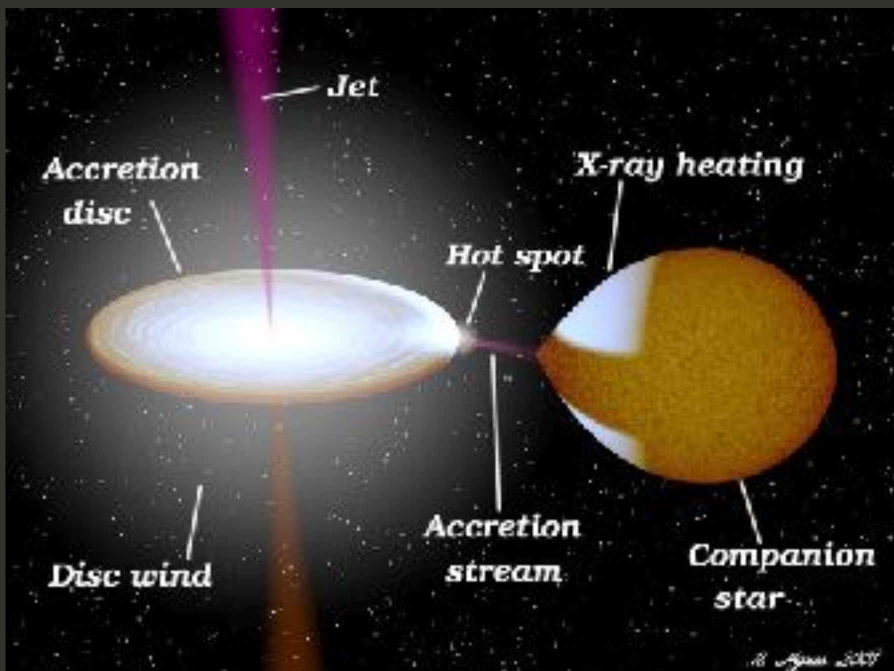
i = 20 deg
close to edge-on

high mass
companion
mass>1 Msun

Courtesy: J. Orosz

More at http://swift.gsfc.nasa.gov/docs/swift/results/transients/BlackHoles.html

Mass Determination



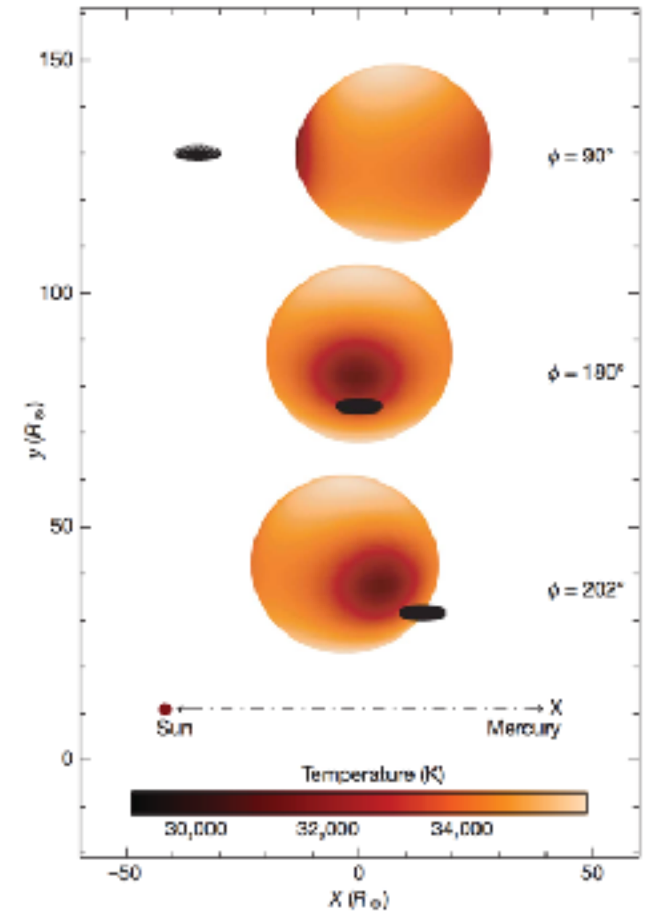


Figure 4 | Schematic diagram of M 33 X-7. The companion star and the accretion disk surrounding the black hole are shown to scale, as seen projected onto the plane of the sky at three orbital phases. The colours on the star represent temperatures (not intensities), with cooler temperatures shown by darker colours, as denoted on the bar. The distance between the Sun and Mercury is indicated, and the figure is scaled in solar radii.

edge-on eclipsing observed, M33 X-7

Black hole mass determinations

$$f(M) \equiv \frac{PK_2^3}{2\pi G} = \frac{M \sin^3 i}{(1+q)^2},$$

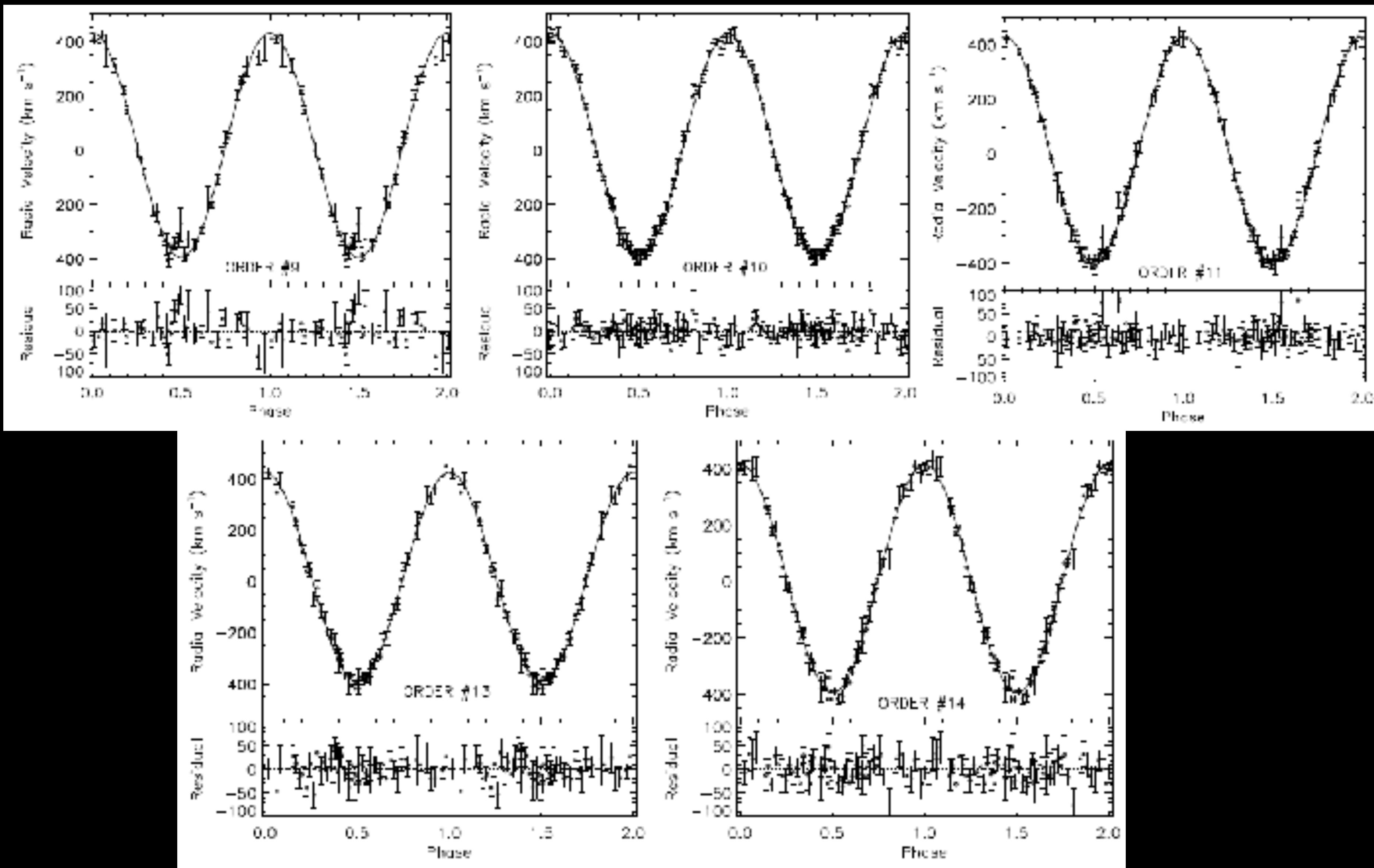
- Mass function $f(M)$: K_2 → spectroscopy
- Mass ratio $q = M_2/M$: $v \sin i$ → spectroscopy
- Systemic inclination i : light curve → photometry

Challenge for short-period BH binaries: disk veiling

- disk light contaminates the emission from the secondary
- fraction could be high and varying

→ difficult to model the light curve and the inclination angle

Radial Velocity Curve
X-ray Nova Muscae 1991 (GS/GRS 1124-683)



Radial Velocity Modeling

$$V(t) = \gamma + K_2 \cos(2\pi \frac{t - T_0}{P})$$

Order #	K_2 (km s^{-1})	γ (km s^{-1})	$T_0 - 2454900$ (d)	No. of Object Spectra	χ^2/ν	λ Coverage (Å)
9[a]	413.6 ± 4.3	17.4 ± 3.1	46.90550 ± 0.00072	39	1.55	6300–7300
10	409.5 ± 2.7	19.4 ± 2.0	46.90351 ± 0.00044	72	0.92	5680–6630
11	413.0 ± 3.1	15.2 ± 2.3	46.90258 ± 0.00051	67	0.74	5170–6000
12	401.2 ± 2.6	9.7 ± 1.9	46.90327 ± 0.00044	72	0.87	4700–5500
13	407.0 ± 4.2	17.0 ± 3.1	46.90211 ± 0.00069	57	0.92	4370–5100
14	403.9 ± 3.9	9.2 ± 2.9	46.90086 ± 0.00068	63	1.02	4060–4730
Average	406.8 ± 2.2	14.2 ± 2.1	46.90278 ± 0.00042			

$f(M) = 3.02 \pm 0.06\ M_\odot$

entirely consistent with previous work with three times better precision

Rotational Broadening

Measuring Rotational Velocity $v \sin i$

- mass ratio $q = M_2/M$ *(tidally locked)*

$$\frac{v \sin i}{K_2} = 0.462 q^{1/3} (1+q)^{2/3}$$

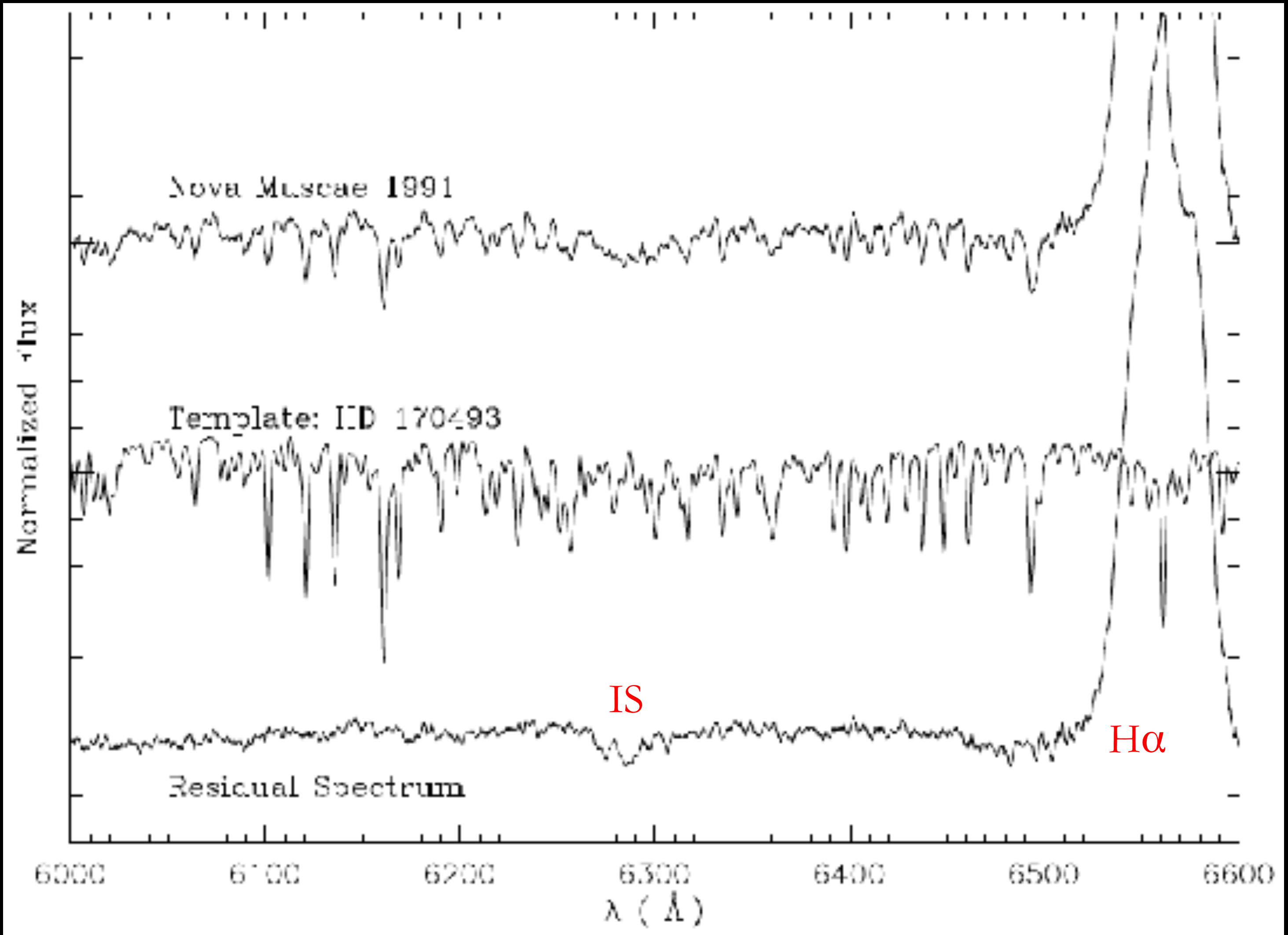
(Wade & Horne 1988)

- disk veiling factor $1 - f$

$$F_d = F_s - F_t * f$$

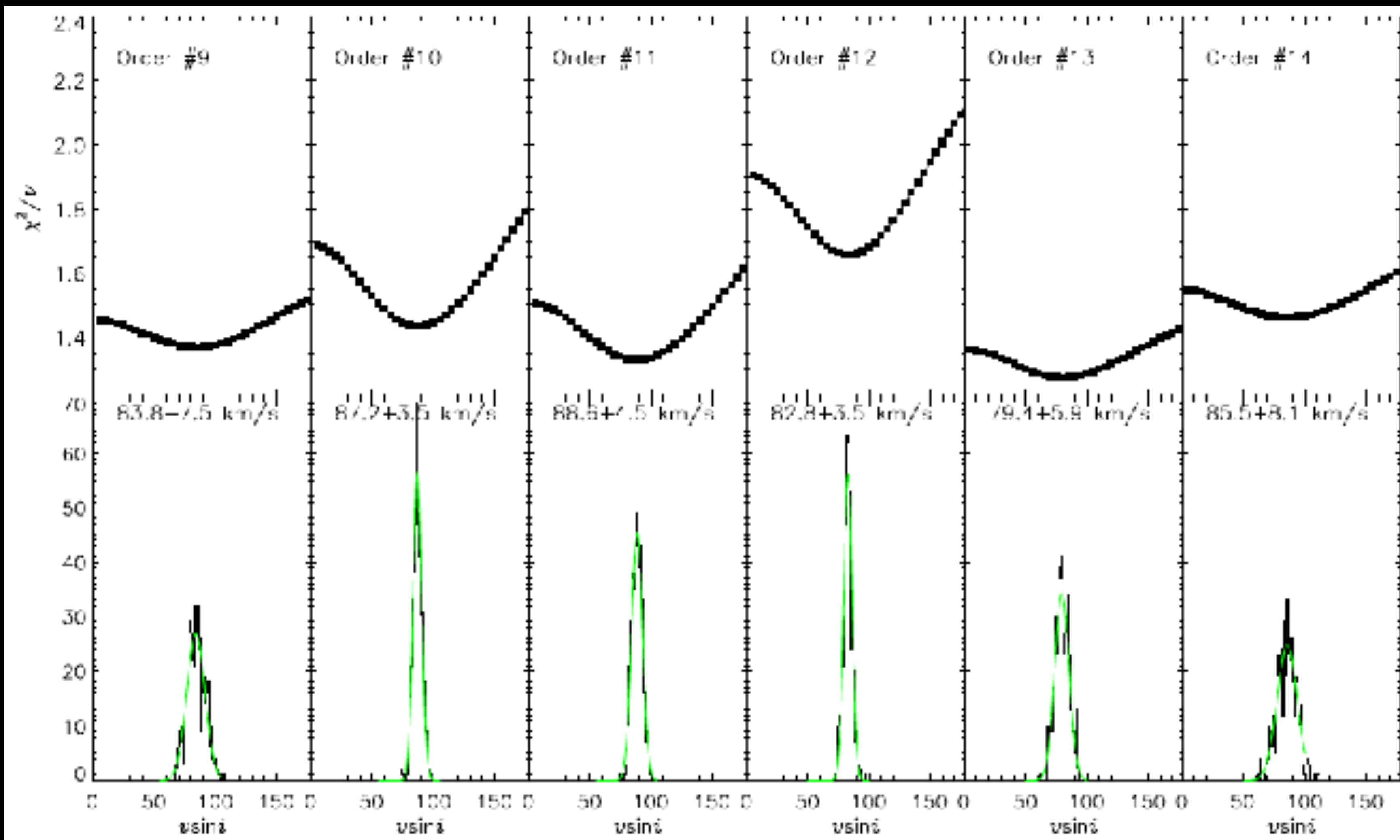
Rotational Broadening & Disk Veiling Measurements

Optimal Subtraction

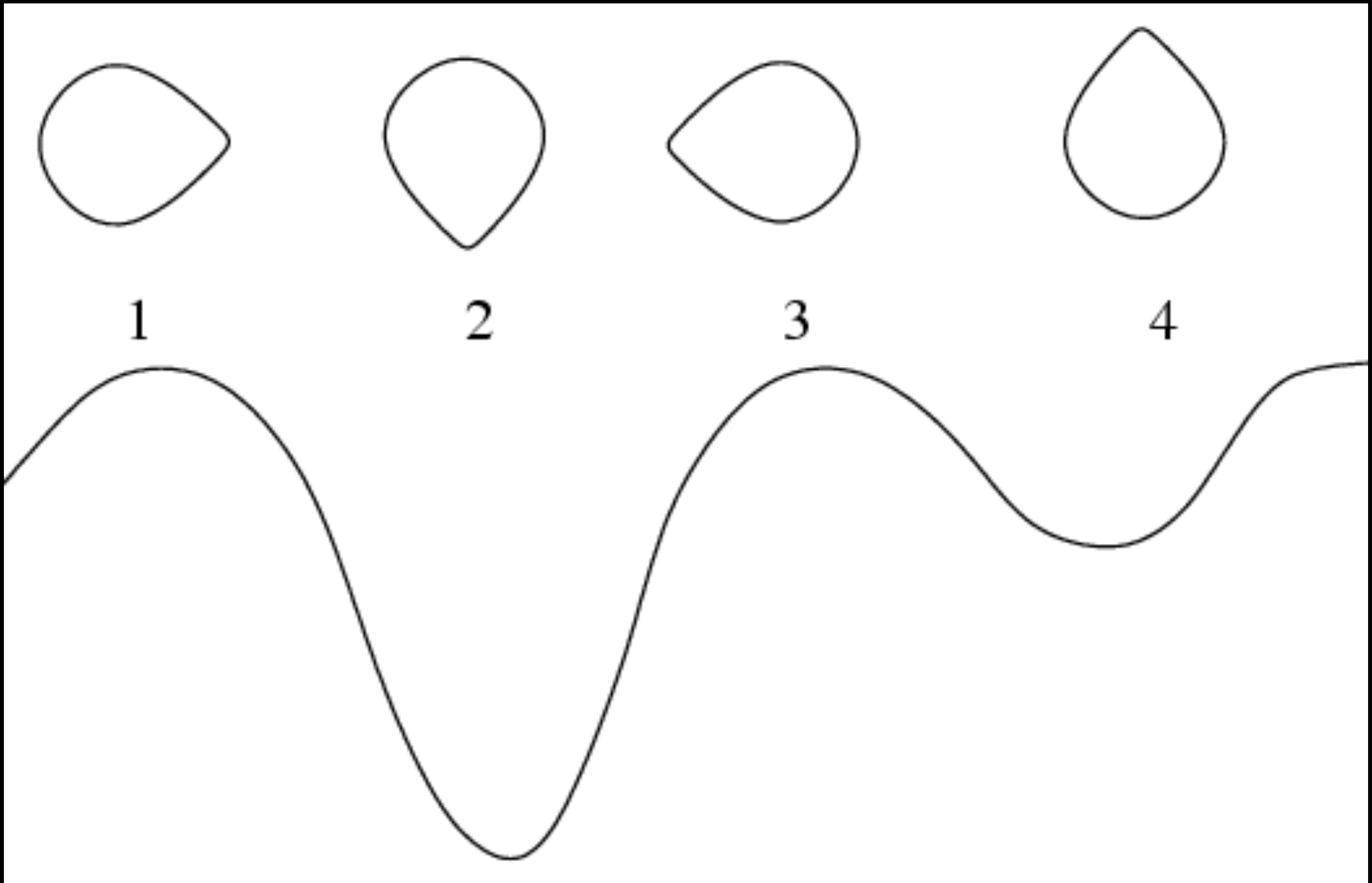


Rotational Broadening & Disk Veiling Measurement

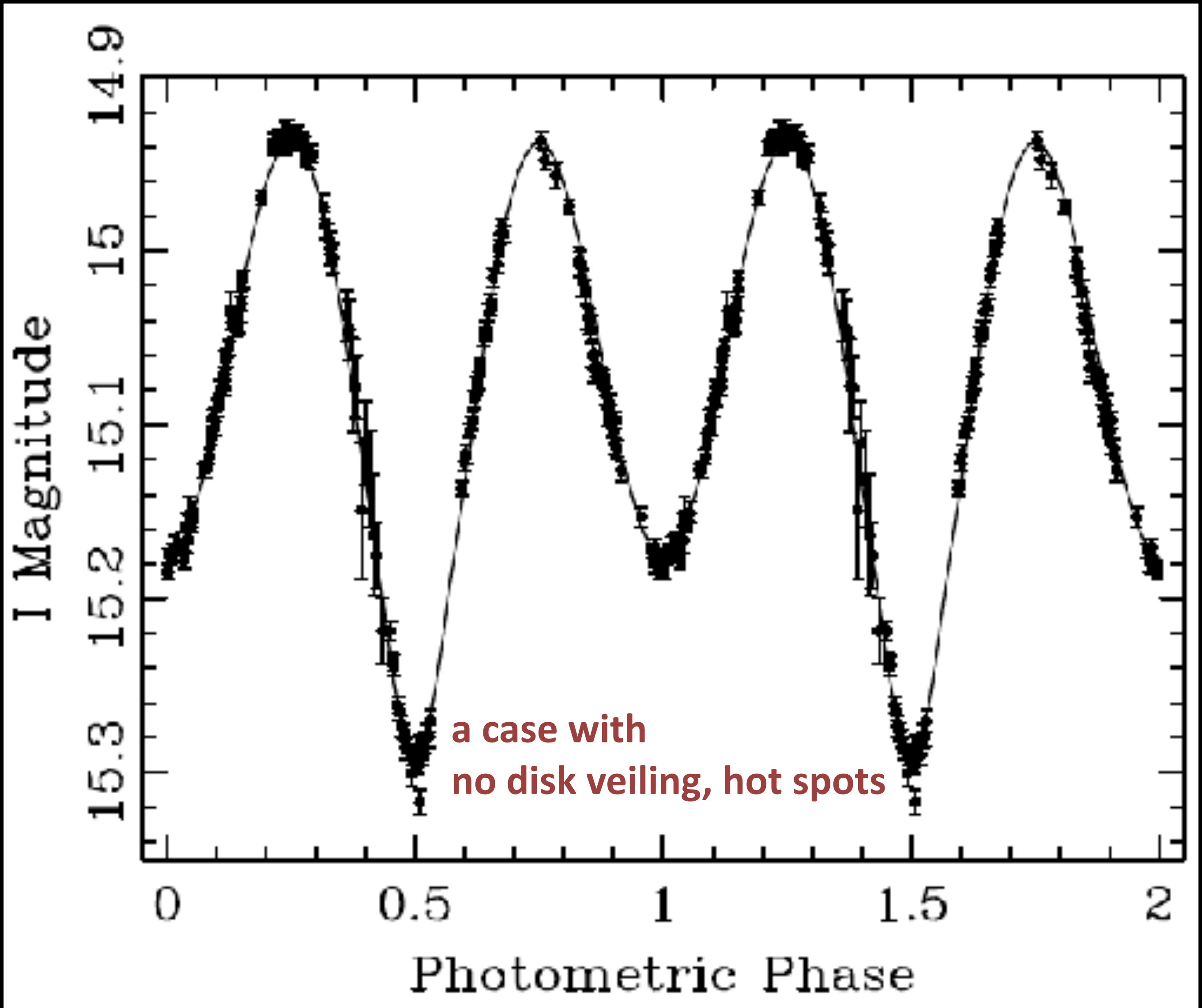
$v \sin i = 85.0 \pm 2.6$ km s^{-1} $\quad q = M_{\rm d}/M_{\rm BH} = 0.079 \pm 0.007$



Ellipsoidal Modulation of the Secondary Light Curve



Ellipsoidal Modulation: ideal case



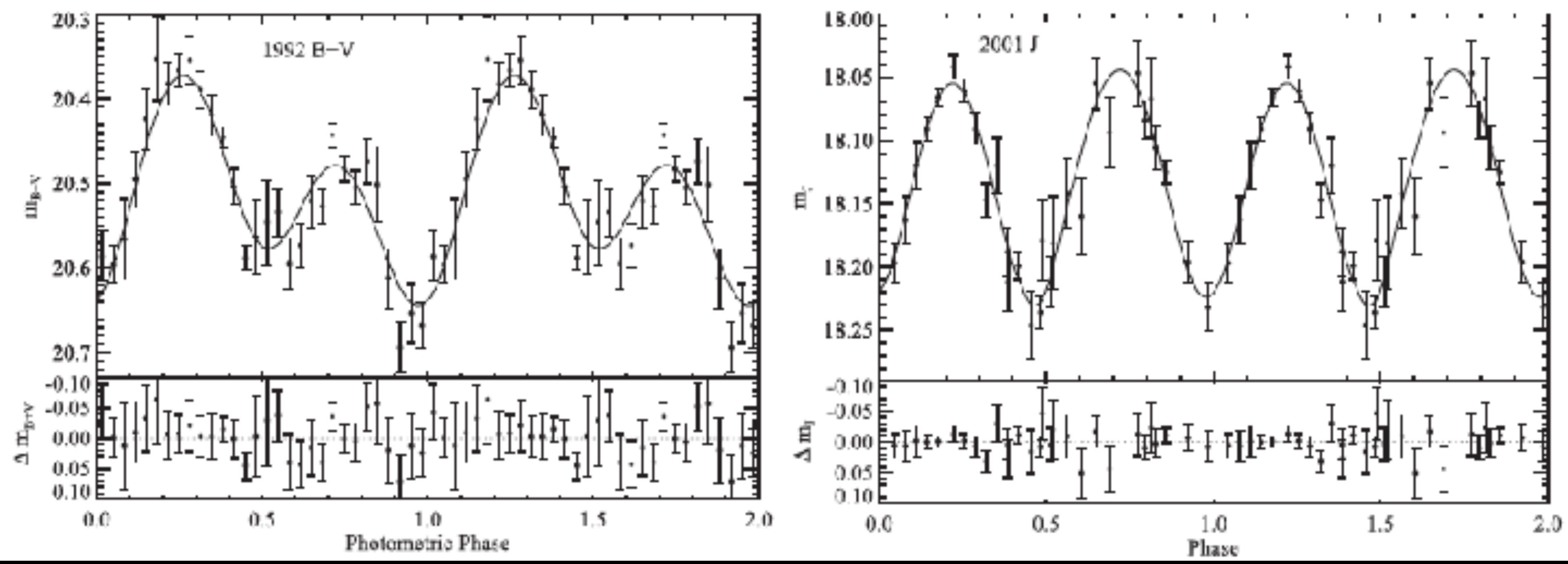
GRO J1655-40

(Beer & Podsiadlowsky 2002)

Light Curve Modeling

- Eclipsing Light Curve (ELC) code (Orosz & Hauschildt 2000)
  -- Stellar emission from the secondary
  -- steady pedestal disk emission
  -- variable disk emission from a hotspot

different bands



Best-fit System Dynamical Parameters

TABLE 4
KEY PARAMETERS FOR NOVA MUS

Parameter	Value
Mass function $f(M/M_\odot)$	3.02 ± 0.06
Mass ratio q	0.079 ± 0.007
Inclination i (deg)	$43.2^{+2.1}_{-2.7}$
Black hole mass M ($M_\odot$)	$11.0^{+2.1}_{-1.4}$
Secondary mass M_2 ($M_\odot$)	$0.89^{+0.18}_{-0.11}$
Secondary radius R_2 ($R_\odot$)	$1.06^{+0.07}_{-0.04}$
Separation a ($R_\odot$)	$5.49^{+0.32}_{-0.24}$
Distance D (kpc)	$4.95^{+0.69}_{-0.65}$

NOTE. — The quoted uncertainties are at the 1σ level of confidence.

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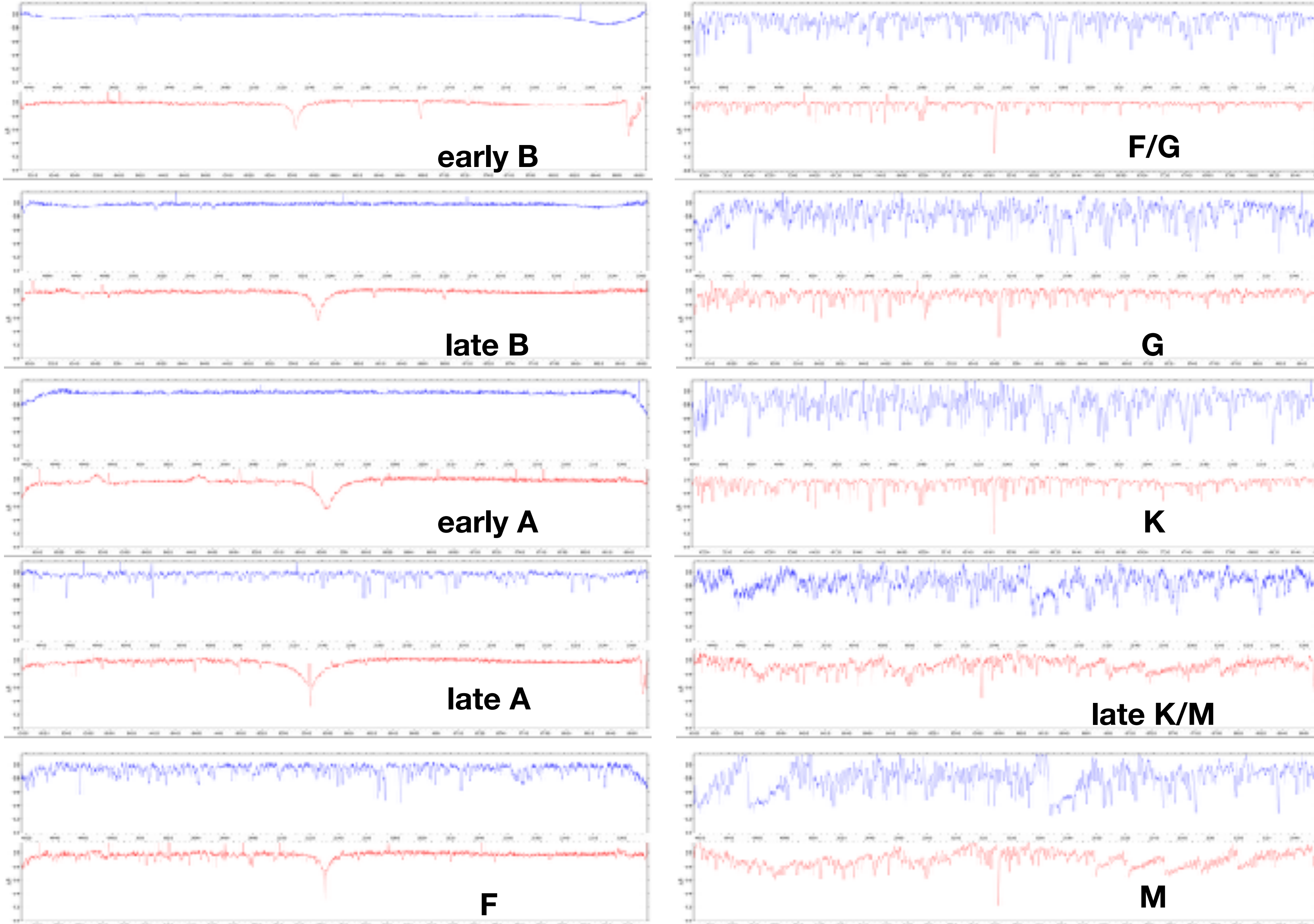

early B
late B
early A
late A
F
F/G
G
K
late K/M
M

Project 1: photometry —> spectroscopy

- Project 1: identify black hole candidates photometrically and then confirm them spectroscopically using LAMOST/DESI etc.
  1. select sources with ellipsoidal variations from ZTF (~10^6) and other photometric surveys
  2. Get rid of equal-brightness pairs using GAIA magnitude and color: select cases with one with little brightness
  3. do spectroscopy for short period candidates (P<1day) and magnitude cutoff G<14
  4. plates already assigned, may need new plates and fiber reassignment

Project 2: photometry —> spectroscopy

- identify black hole candidates spectroscopically (e.g. from LAMOST), and then cross check light curves from ZTF, Catolina, ASSASN

  - cadence sufficient?
  - on average 50 points over 5 years: same night 6-8 points, may be good for short-period (P<1day) black hole candidates
  - magnitude cutoff r<17.8 for low-res, and G<14 for medium-res

Project 2: spectroscopy—> photometry

preliminary search (Gu et al. 2019) used more than 3 epochs, and dv>80km/s, and identified 7 systems

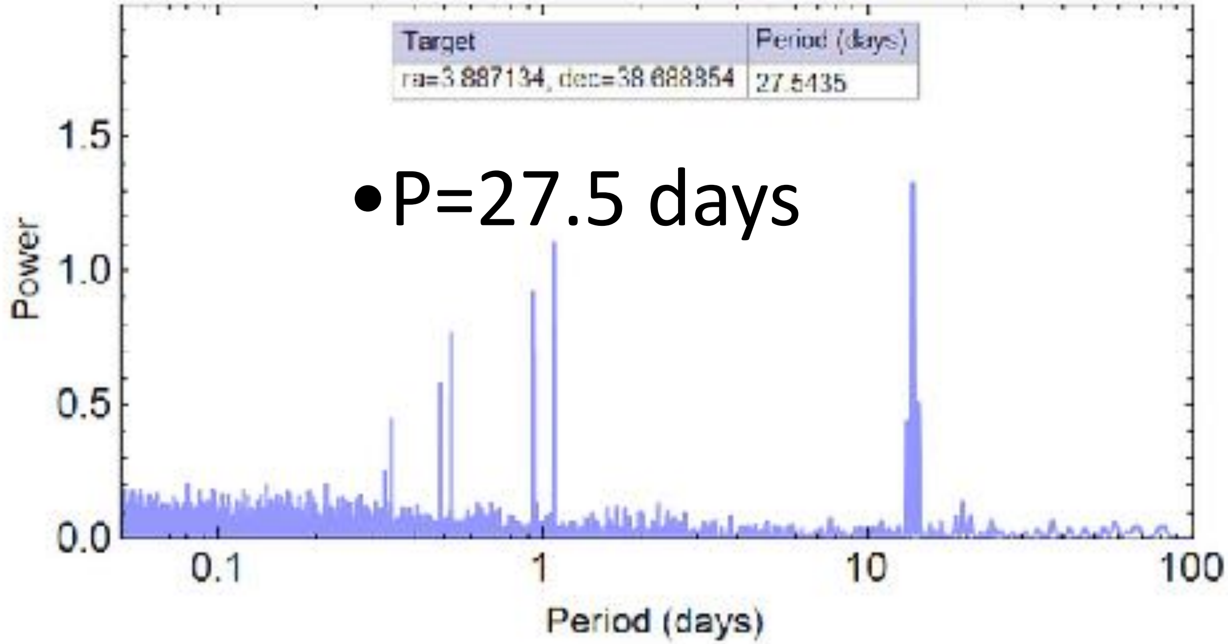
- currently limited to red giant candidates
- 3 show variabilities in ASSASN and Catolina.
- period about 30 days

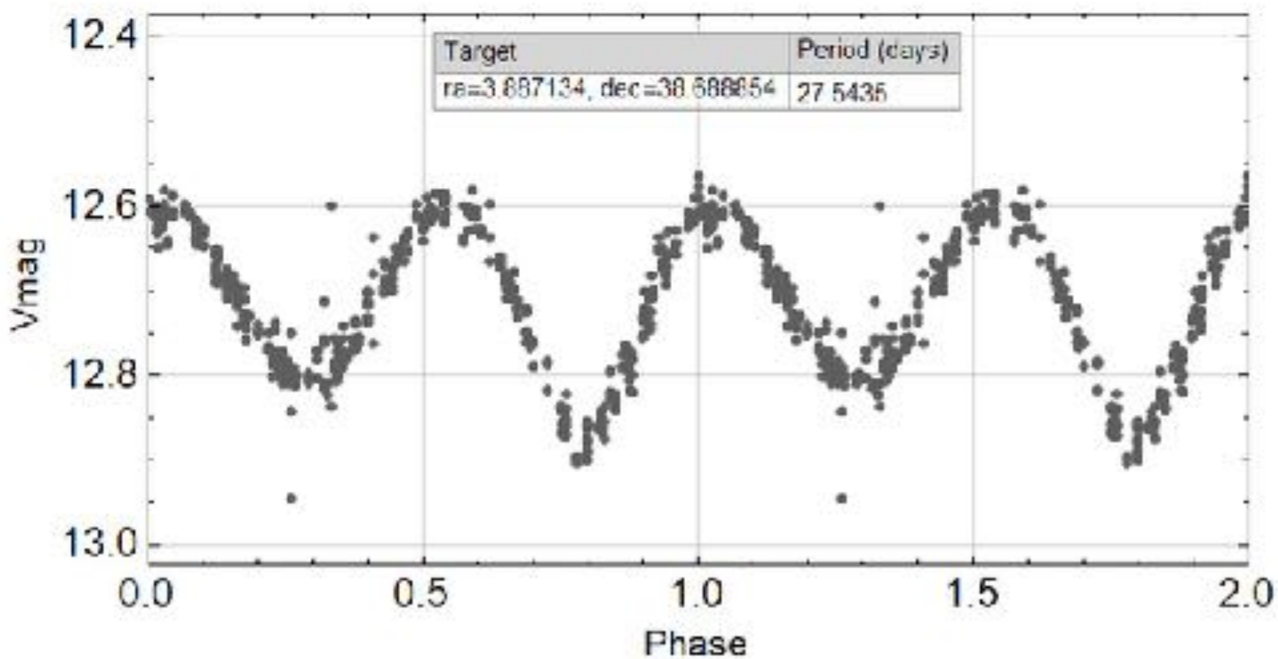
Vmag	$T_{\rm eff}$	$\log g$	[Fe/H]	$N_{\rm obs}$	ΔV_R	ϖ	$R_1^{\rm G}$	$R_1^{\rm LT}$
(mag)	(K)	(dex)	(dex)		(km s^{-1})	(mas)	($R_\odot$)	($R_\odot$)
(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
12.736 ± 0.05	4696 ± 36	2.65 ± 0.06	-0.25 ± 0.03	3	93.5 ± 5.6	0.505 ± 0.043	9.15	10.8 ± 0.2
12.665 ± 0.09	4301 ± 22	1.95 ± 0.04	-0.47 ± 0.02	4	83.7 ± 6.2	0.379 ± 0.032	15.82	19.7 ± 0.3
15.054 ± 0.03	4943 ± 108	2.48 ± 0.17	-0.65 ± 0.10	3	81.9 ± 9.0	0.148 ± 0.034	–	14.7 ± 0.7
12.784 ± 0.11	4823 ± 53	2.74 ± 0.08	-0.29 ± 0.05	4	107.5 ± 7.4	1.068 ± 0.034	6.34	7.0 ± 0.2
14.51 ± 0.02	4655 ± 21	2.53 ± 0.03	-0.31 ± 0.02	3	87.5 ± 5.3	0.122 ± 0.030	–	18.4 ± 0.2
14.698 ± 0.07	4832 ± 83	2.73 ± 0.13	-0.23 ± 0.08	6	85.1 ± 7.6	0.152 ± 0.032	–	11.9 ± 0.4
10.638 ± 0.17	4191 ± 80	1.82 ± 0.12	-0.75 ± 0.07	3	97.8 ± 5.8	1.086 ± 0.031	13.14	17.9 ± 0.7

No. 2

https://asas-sn.osu.edu/database/light_curves/61158

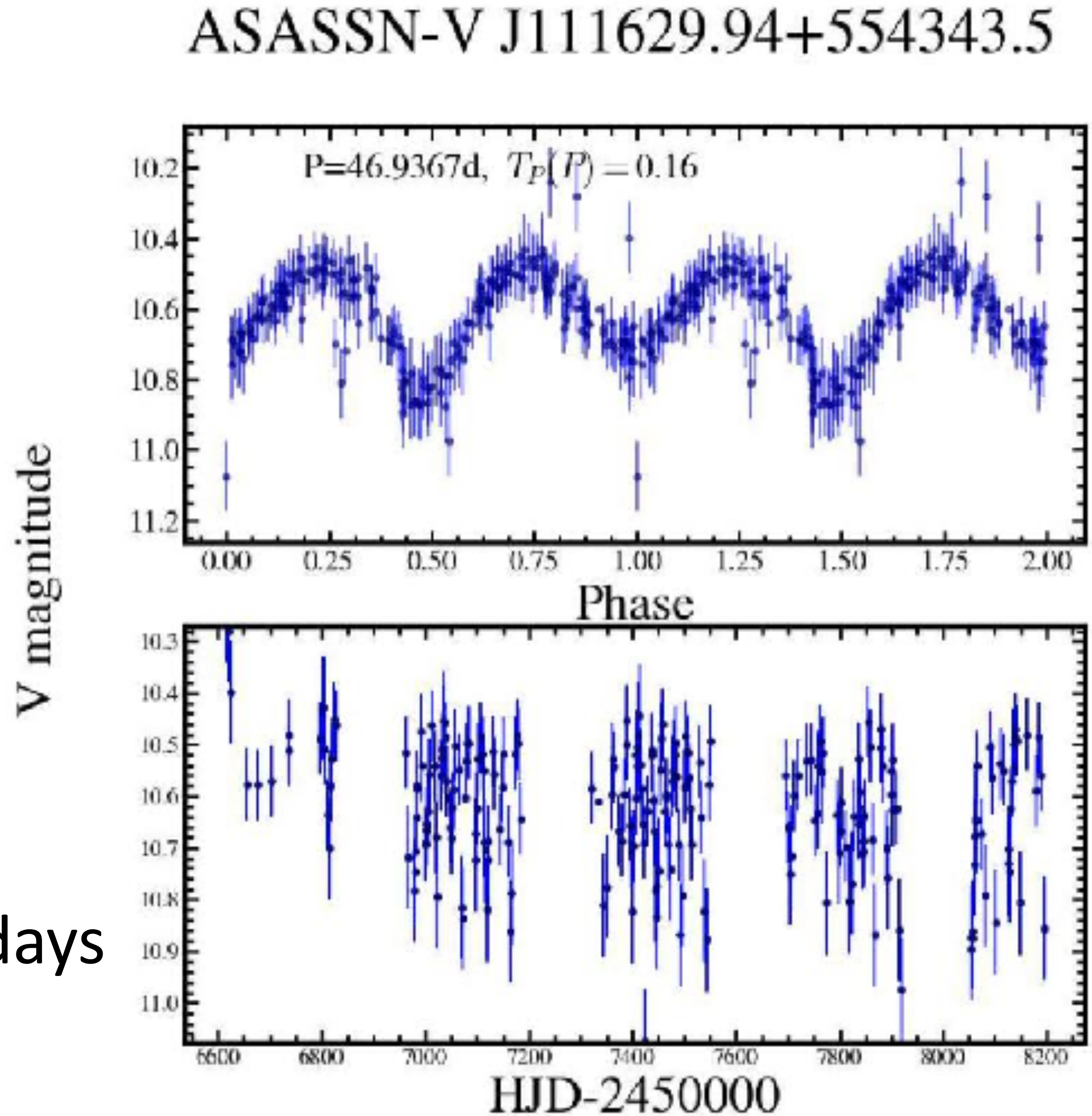
• P=27.5 days



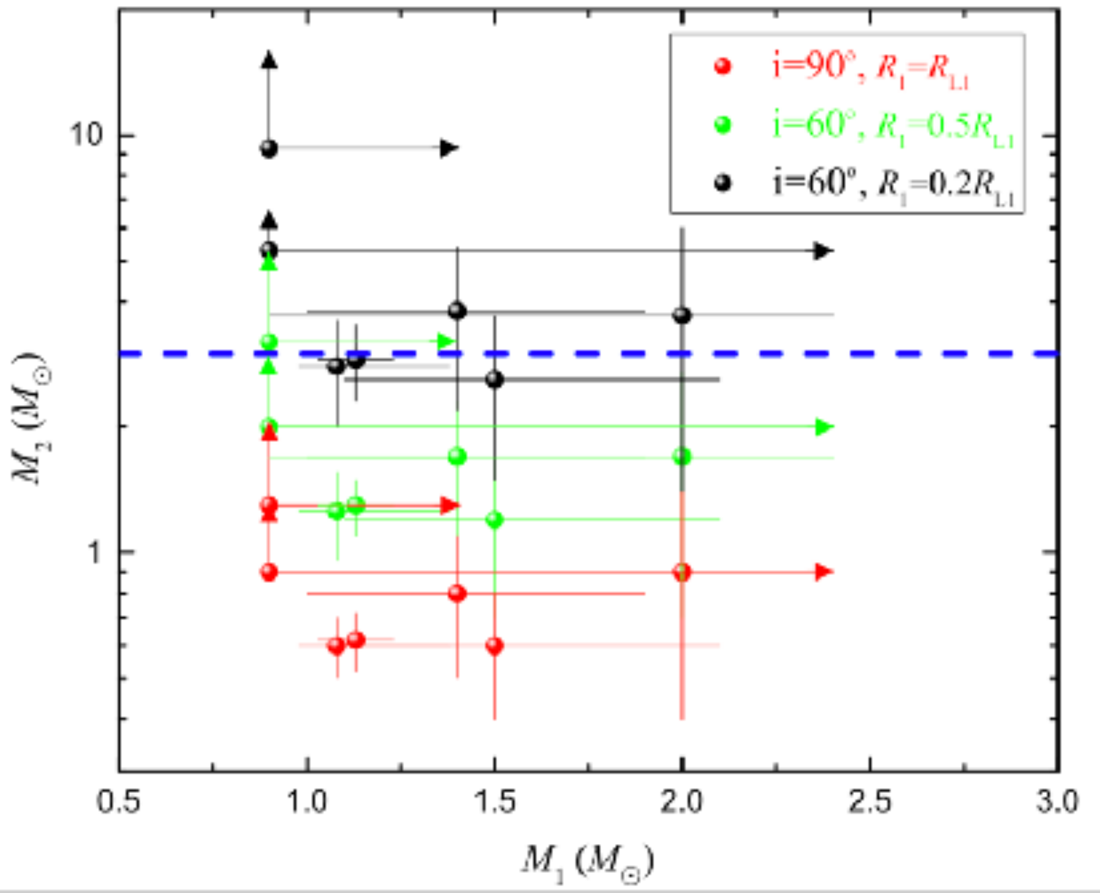


No. 7

https://asas-sn.osu.edu/database/light_curves/74247



- P=46.9 days



intraday variations of radial velocities are being checked.