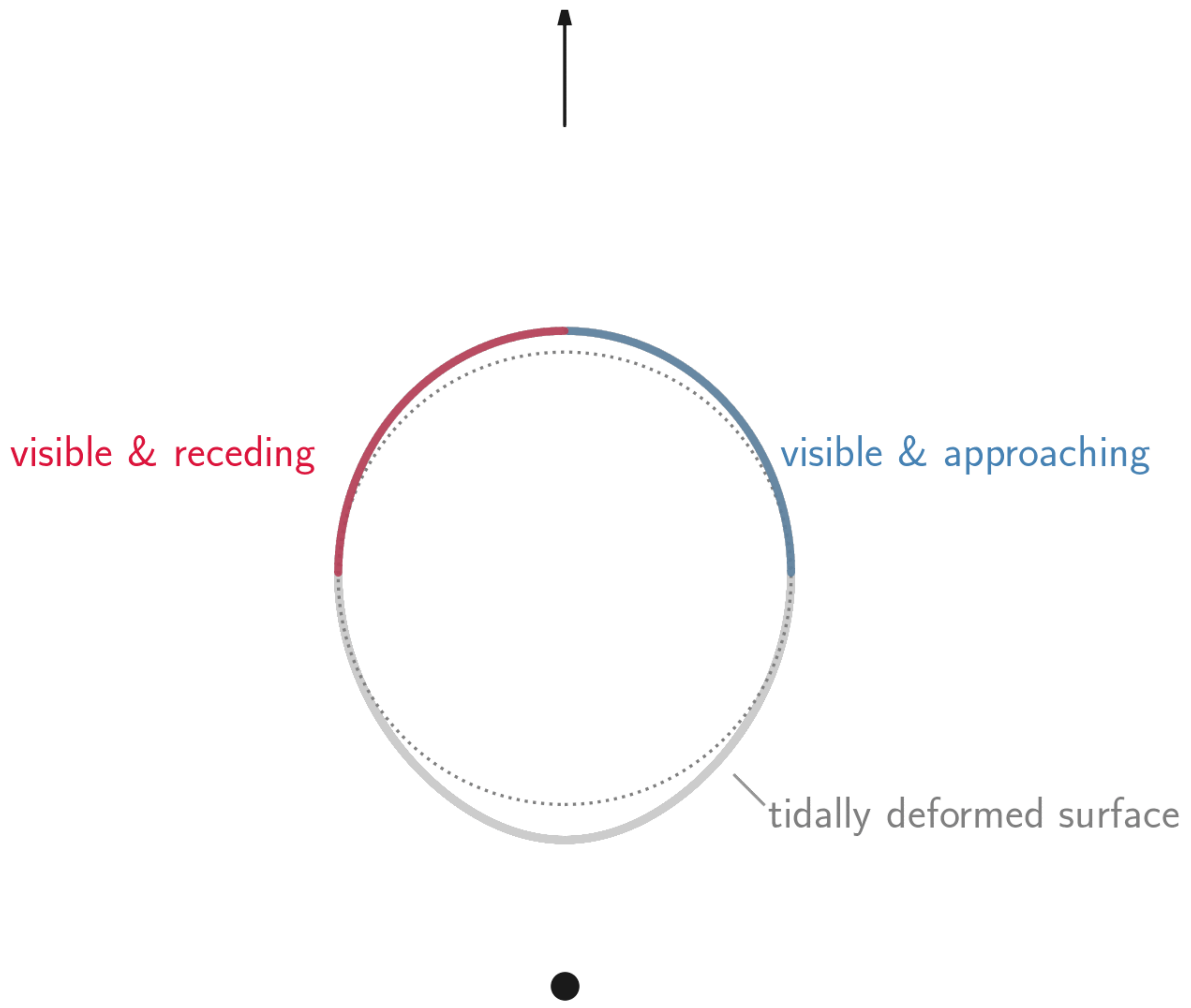
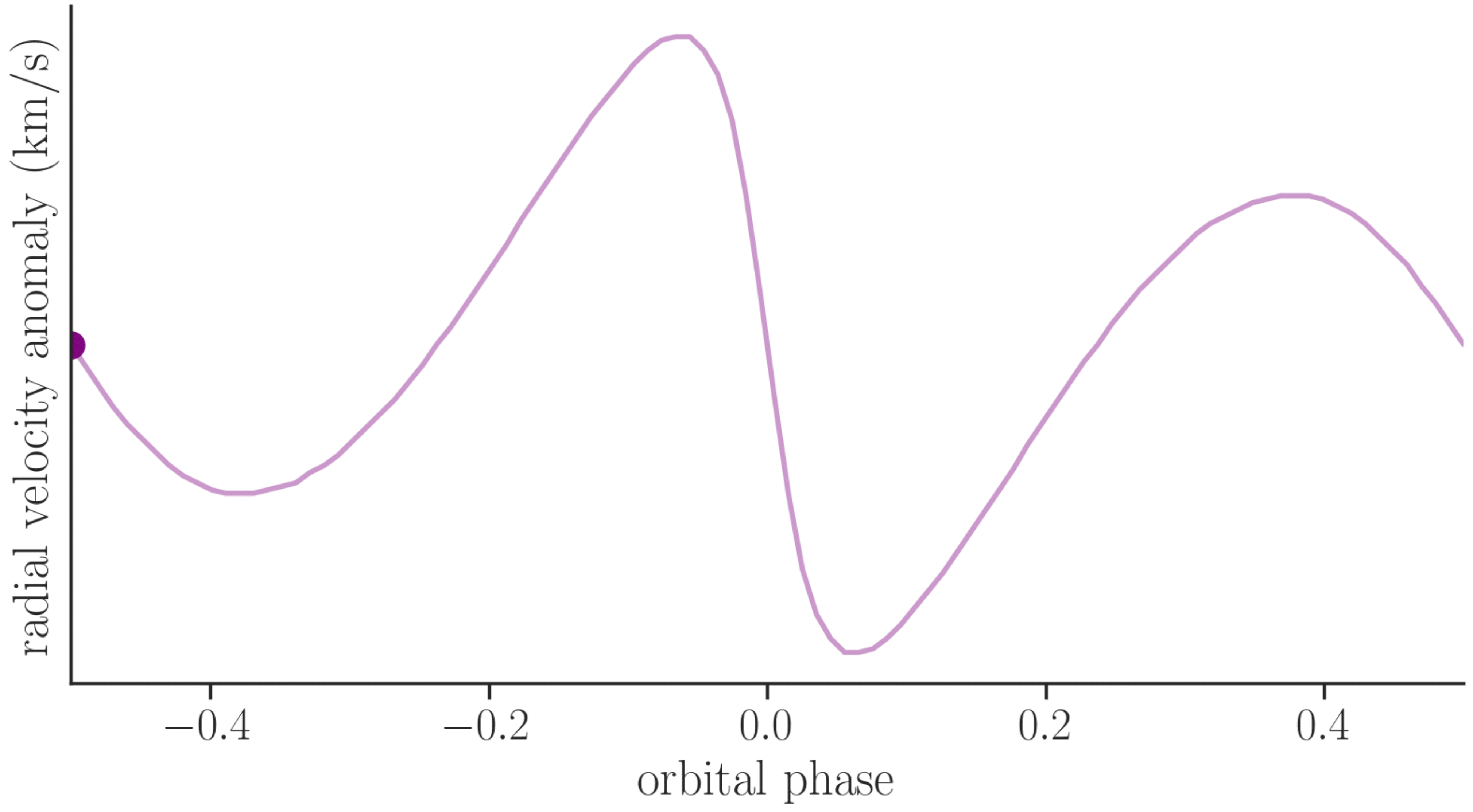
Binary and Multiple Stars in the Era of Big Sky Surveys@Litomysl, Czech
September 12, 2024

Weighing Single-lined Spectroscopic Binaries using Tidal RVs: The Case of V723 Mon

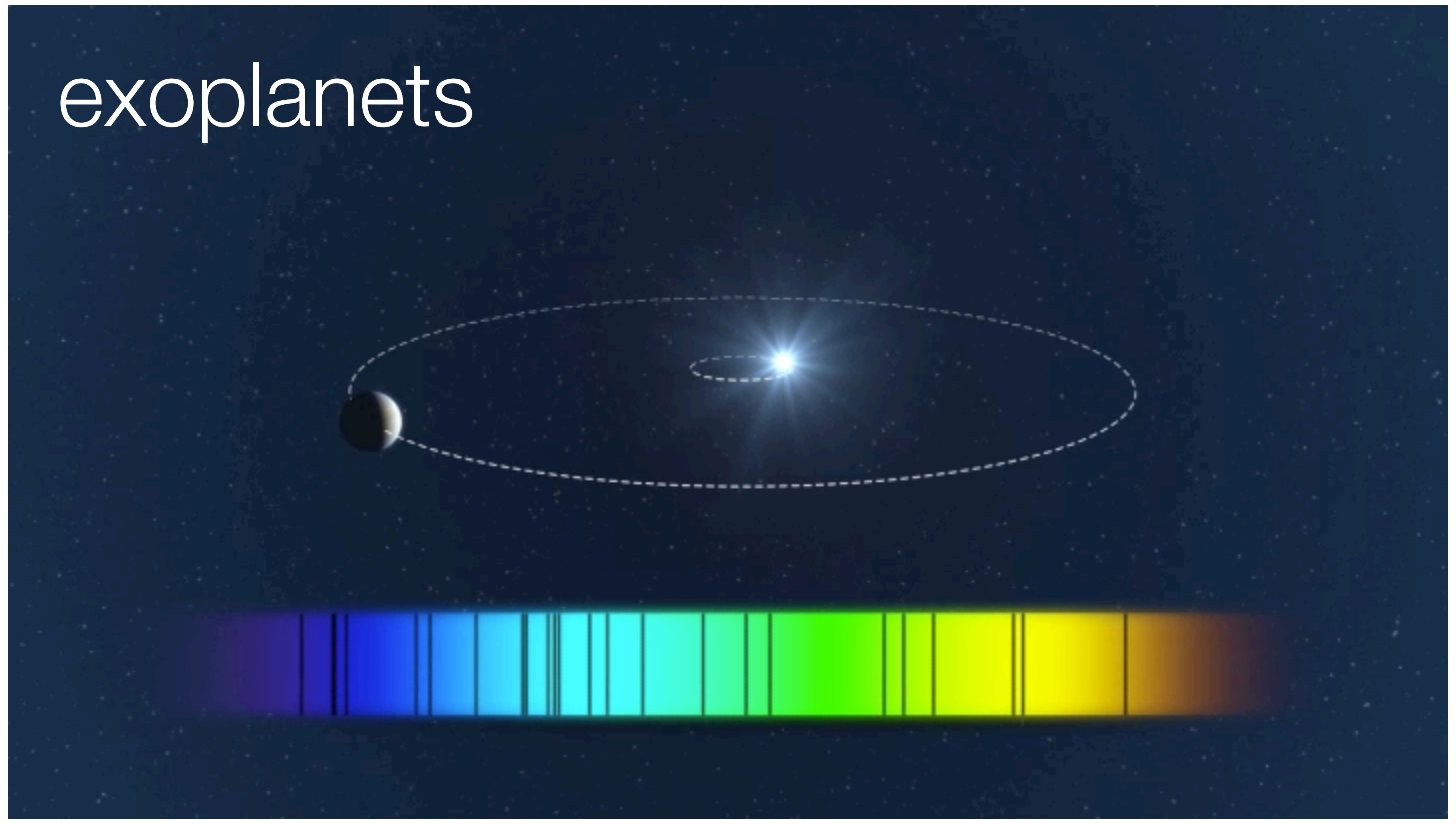
Kento Masuda (Osaka University)

Masuda & Hirano (2021), ApJL 910, L17
Tomoyoshi, Masuda et al. (to be submitted)

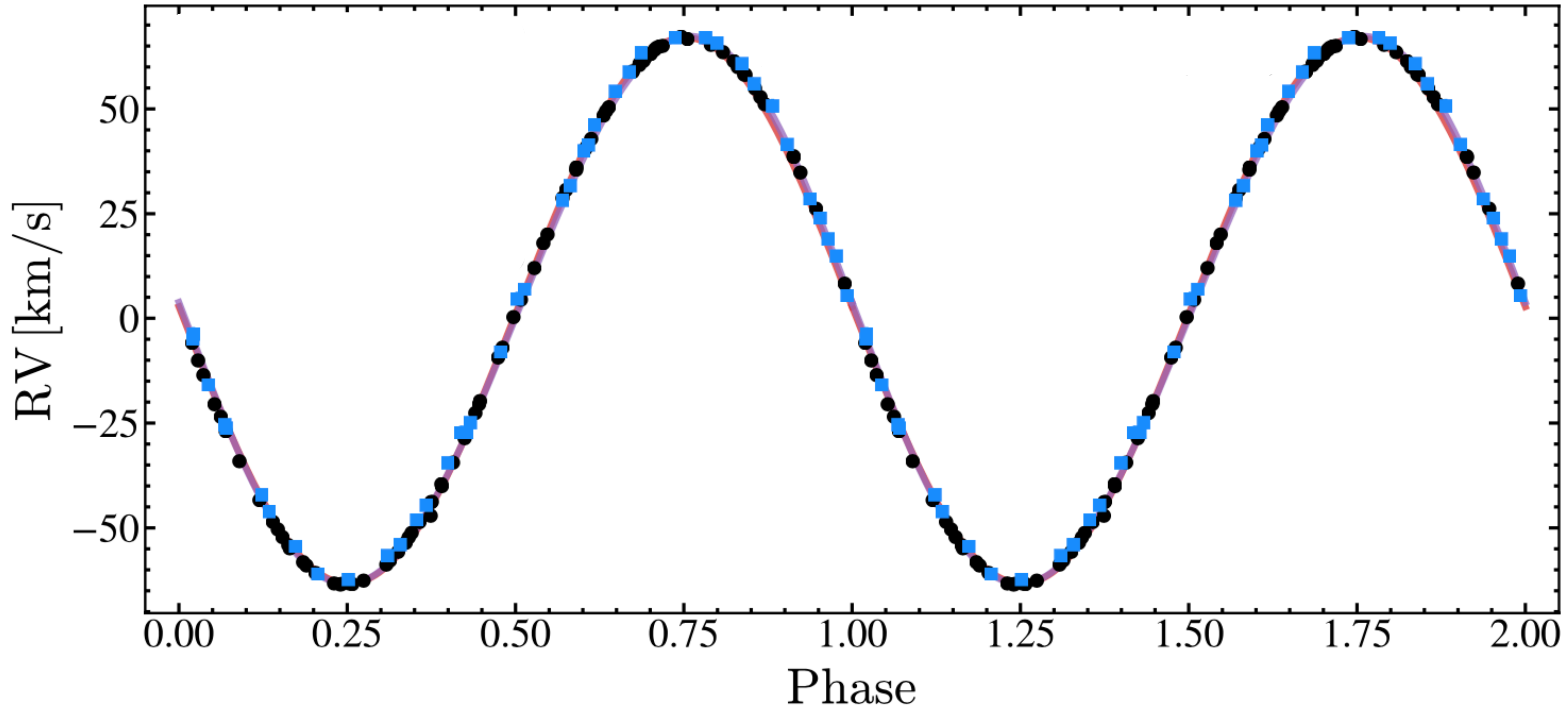


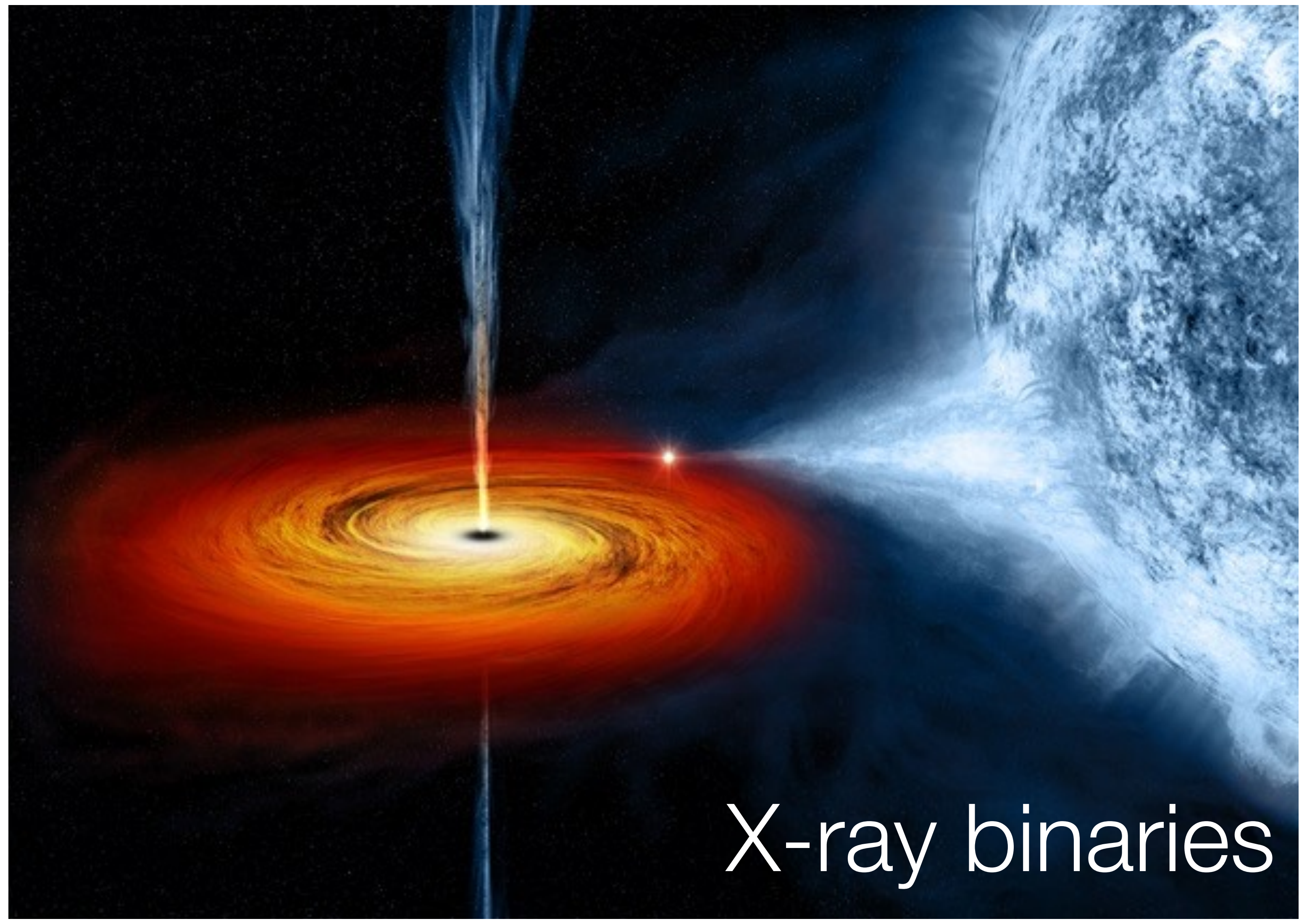


single-lined spectroscopic binaries (SB1s)



ESO





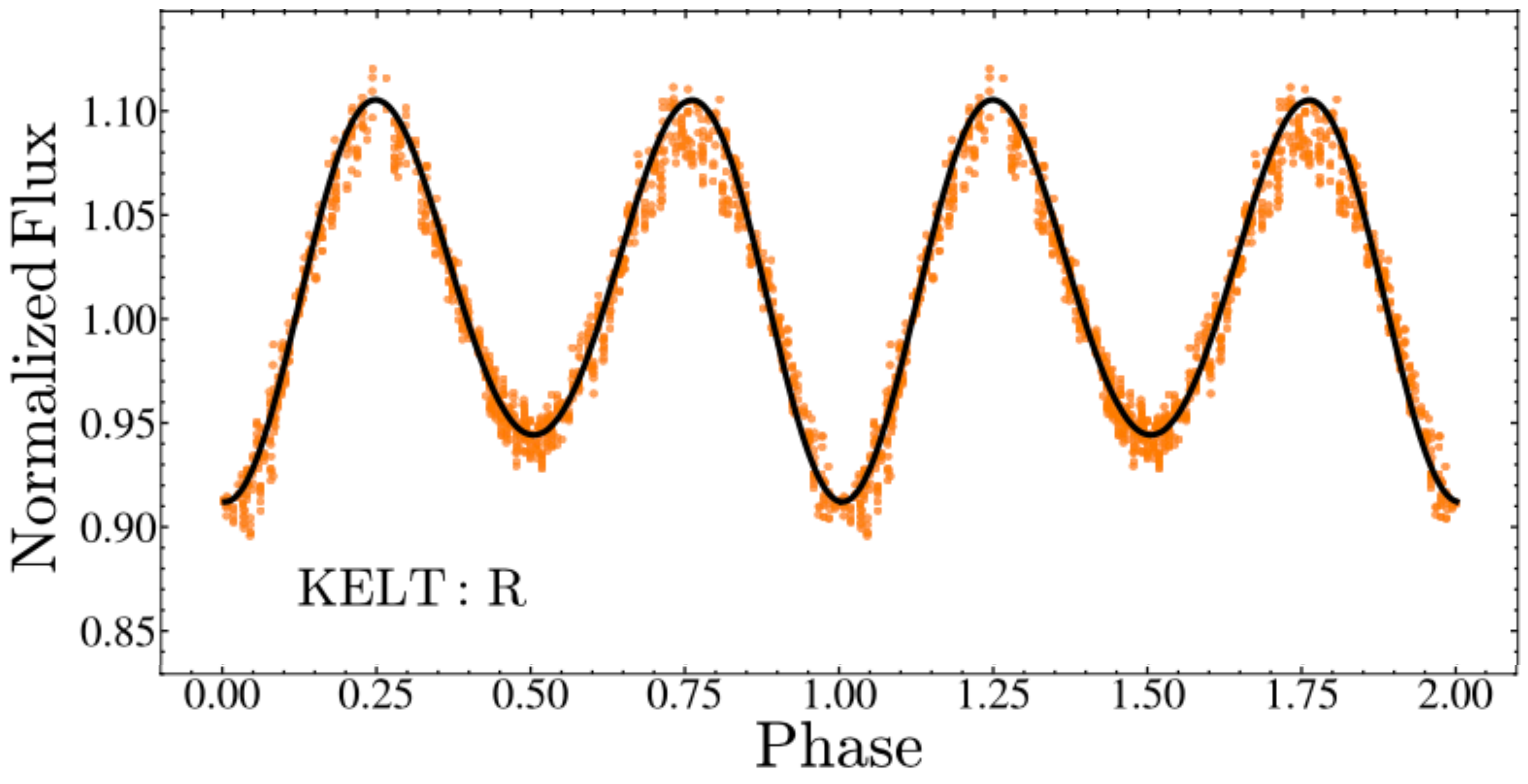
binary mass function

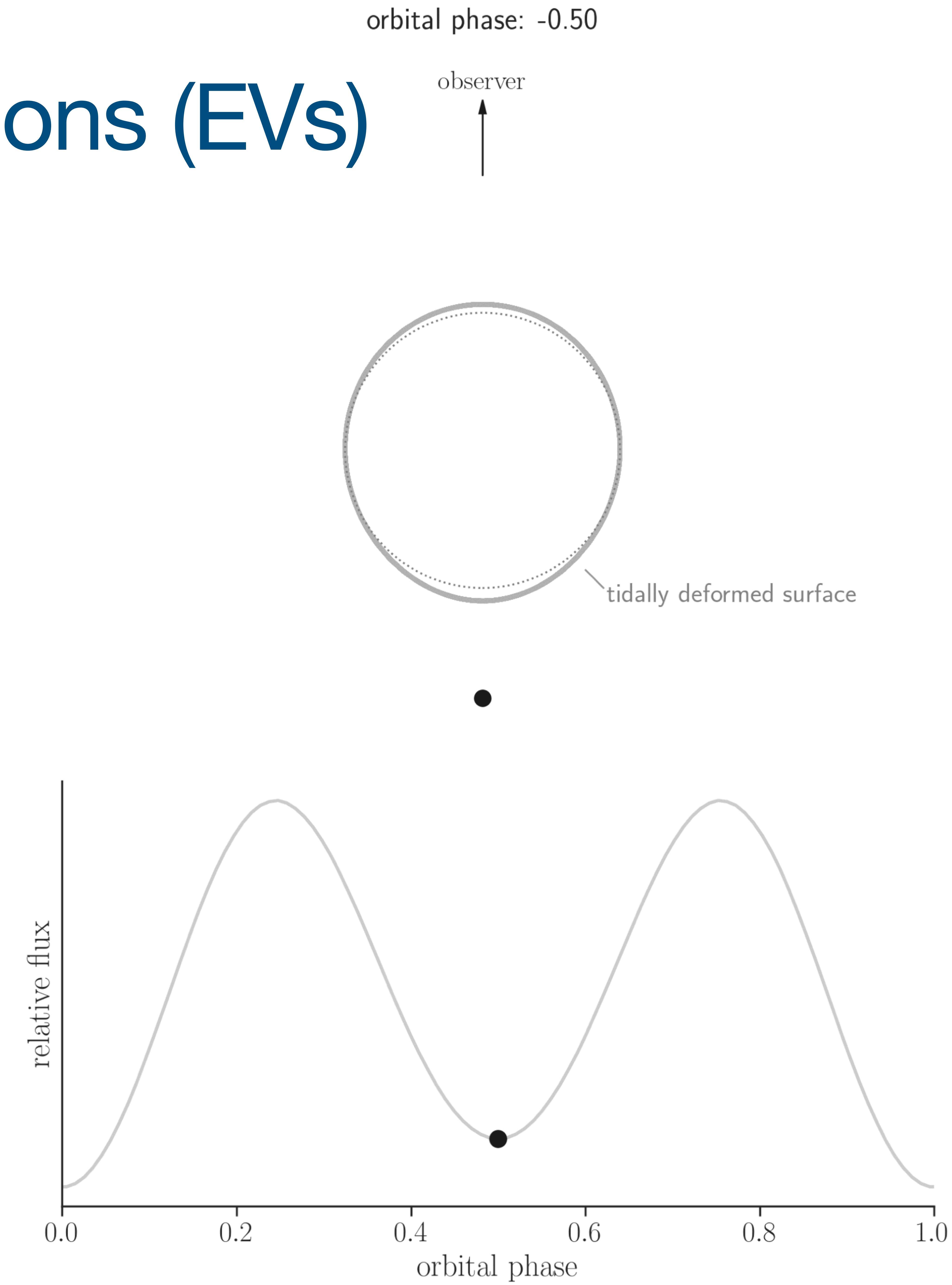
$$\frac{PK_1^3(1-e^2)^{3/2}}{2\pi G} = \frac{M_2^3 \sin^3 i}{(M_1+M_2)^2}$$

1 constraint, **3** unknowns

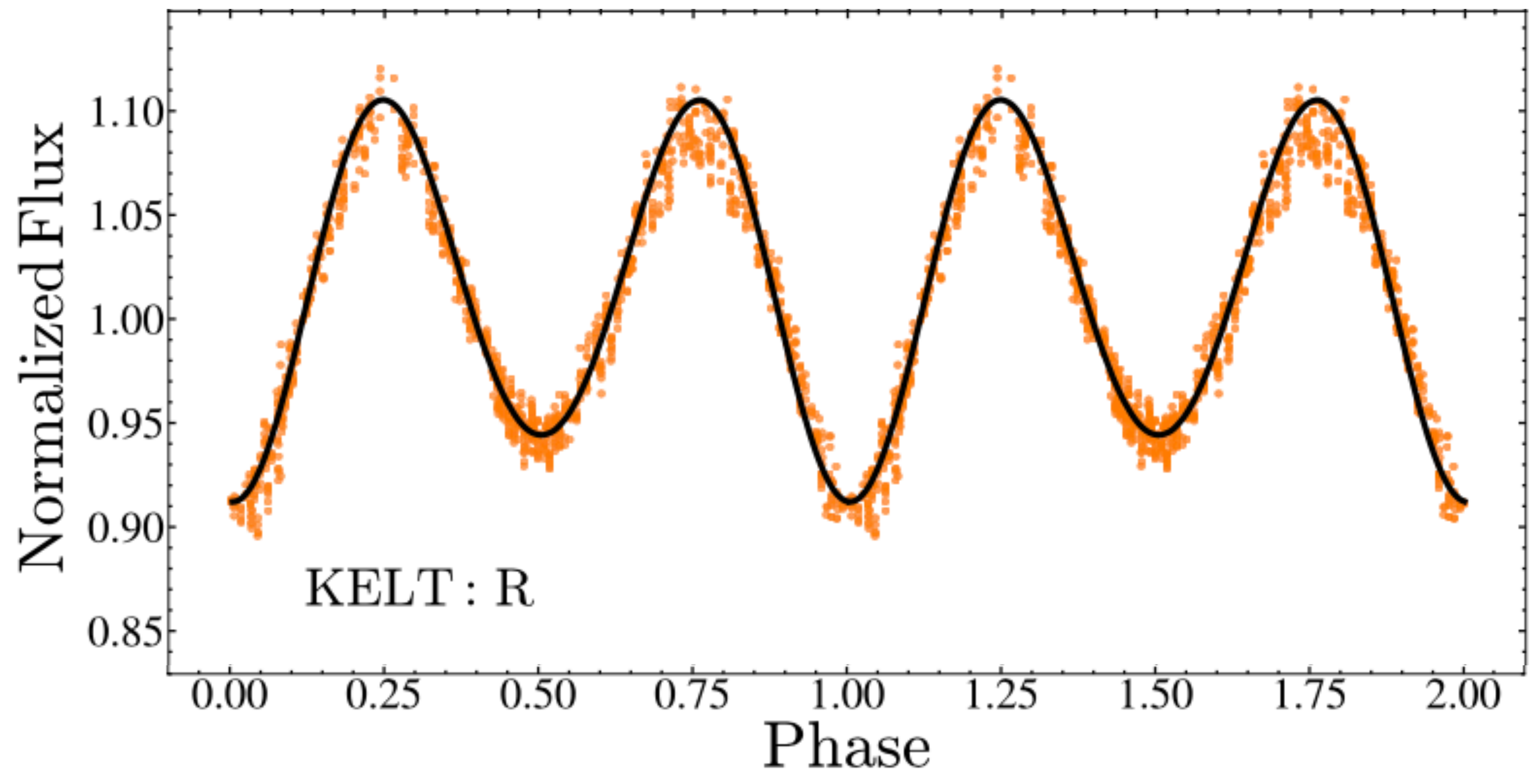
in this talk, "1" is the **brighter object for which RVs are measured**

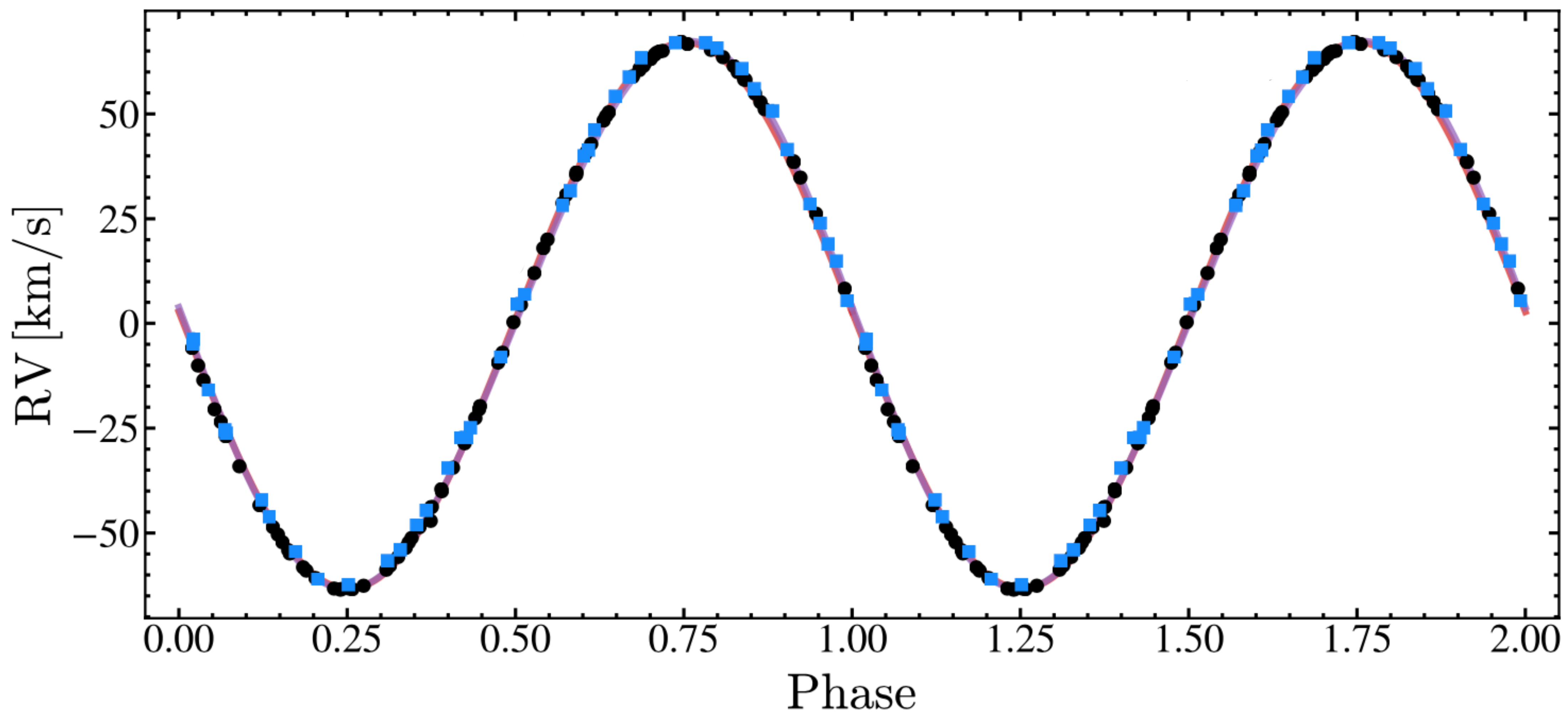
SB1 mass from ellipsoidal variations (EVs)





SB1 mass from ellipsoidal variations (EVs)





amplitude & shape (odd harmonics)

2 constraints on $\frac{M_2}{M_1}, \frac{R_1}{a}, i \quad (a^3 \sim M_1 + M_2)$

1 more unknown: R_1

binary mass function

$$\frac{PK_1^3(1-e^2)^{3/2}}{2\pi G} = \frac{M_2^3 \sin^3 i}{(M_1+M_2)^2}$$

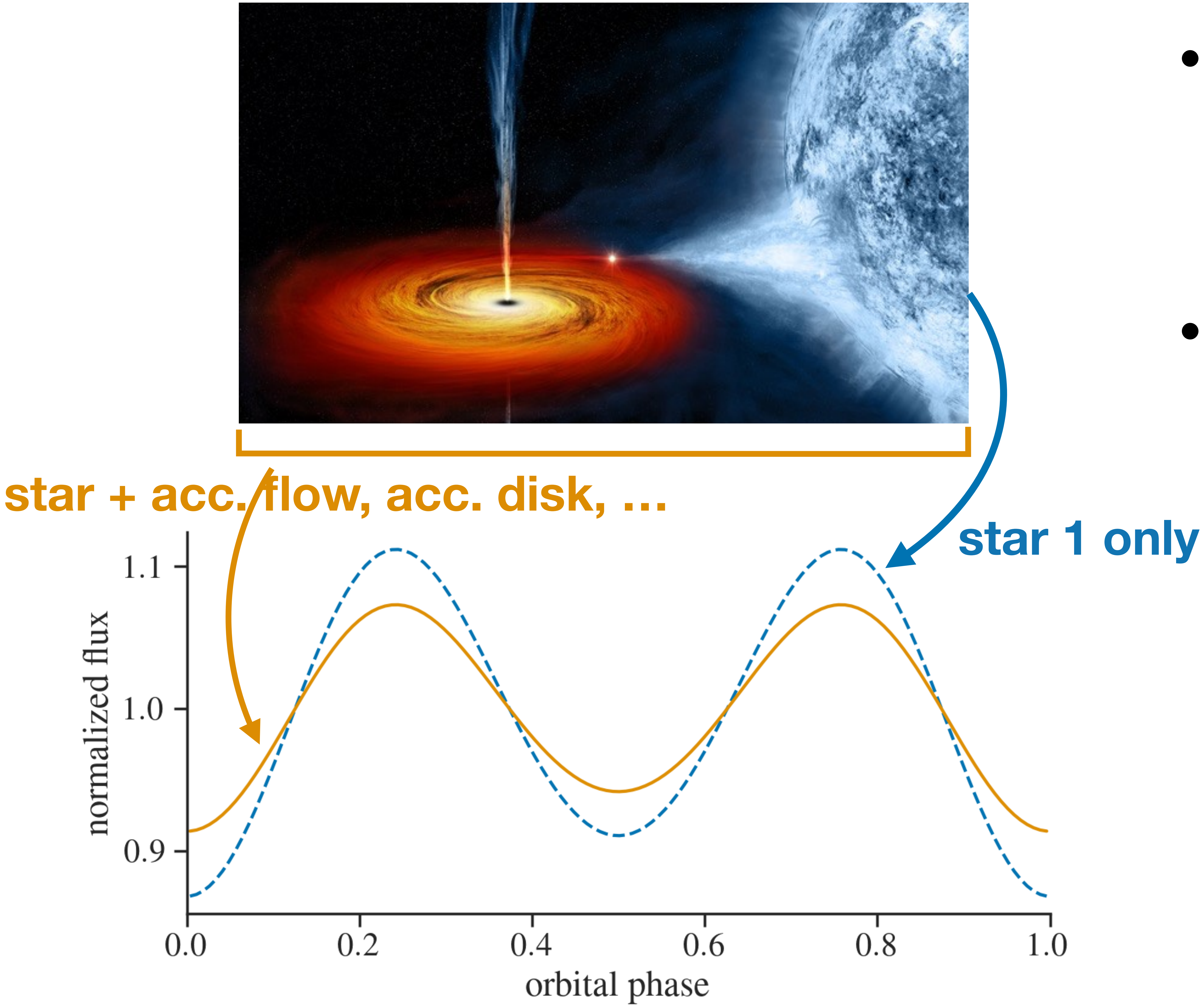
1 constraint, **3** unknowns

3 constraints vs **4** unknowns:

M_1, M_2, R_1, i solved with **1 more constraint** →

- $v_1 \sin i$
- assume “1” fills Roche lobe
- R_1 from flux & distance

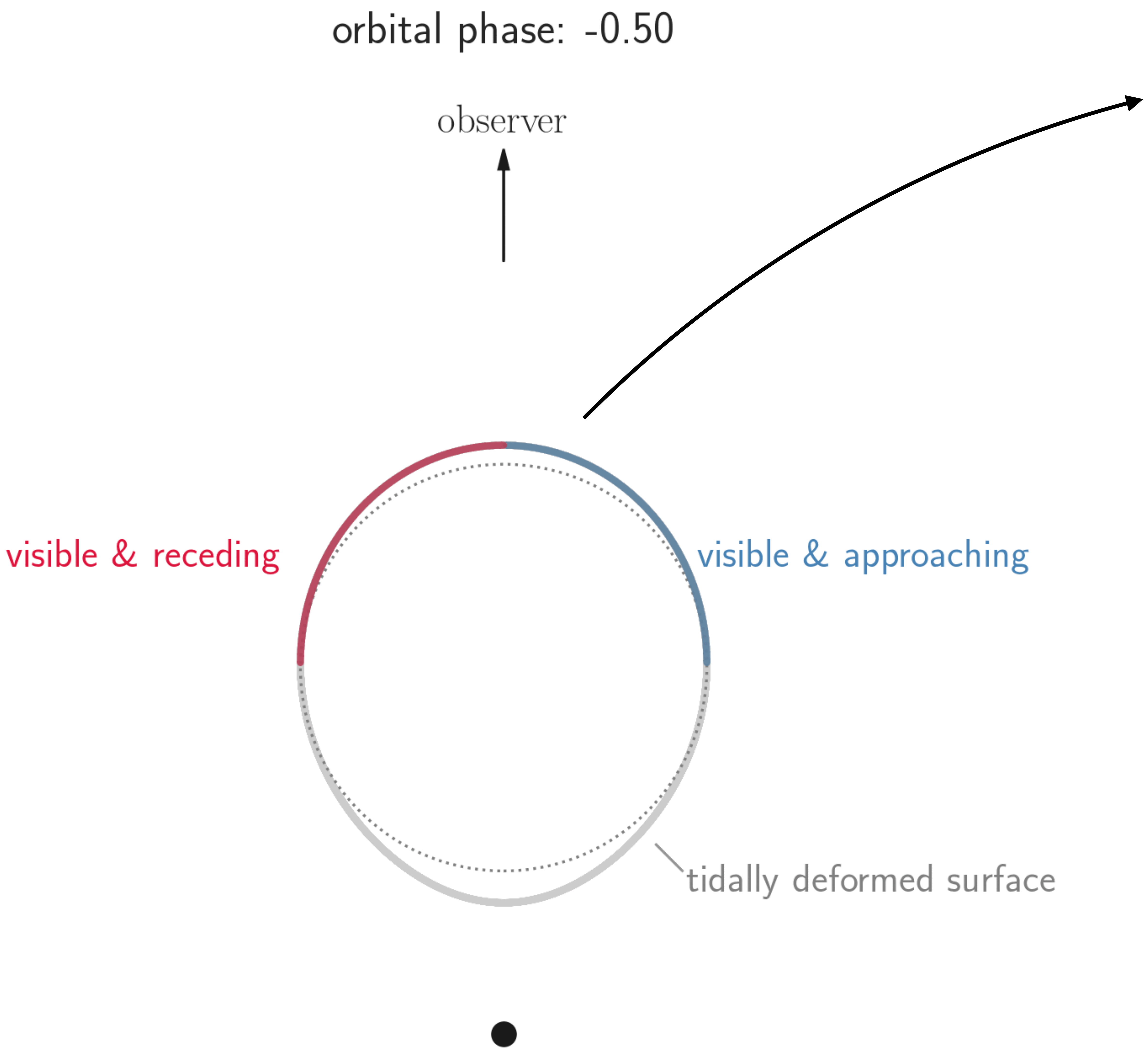
possible source of systematics: flux dilution

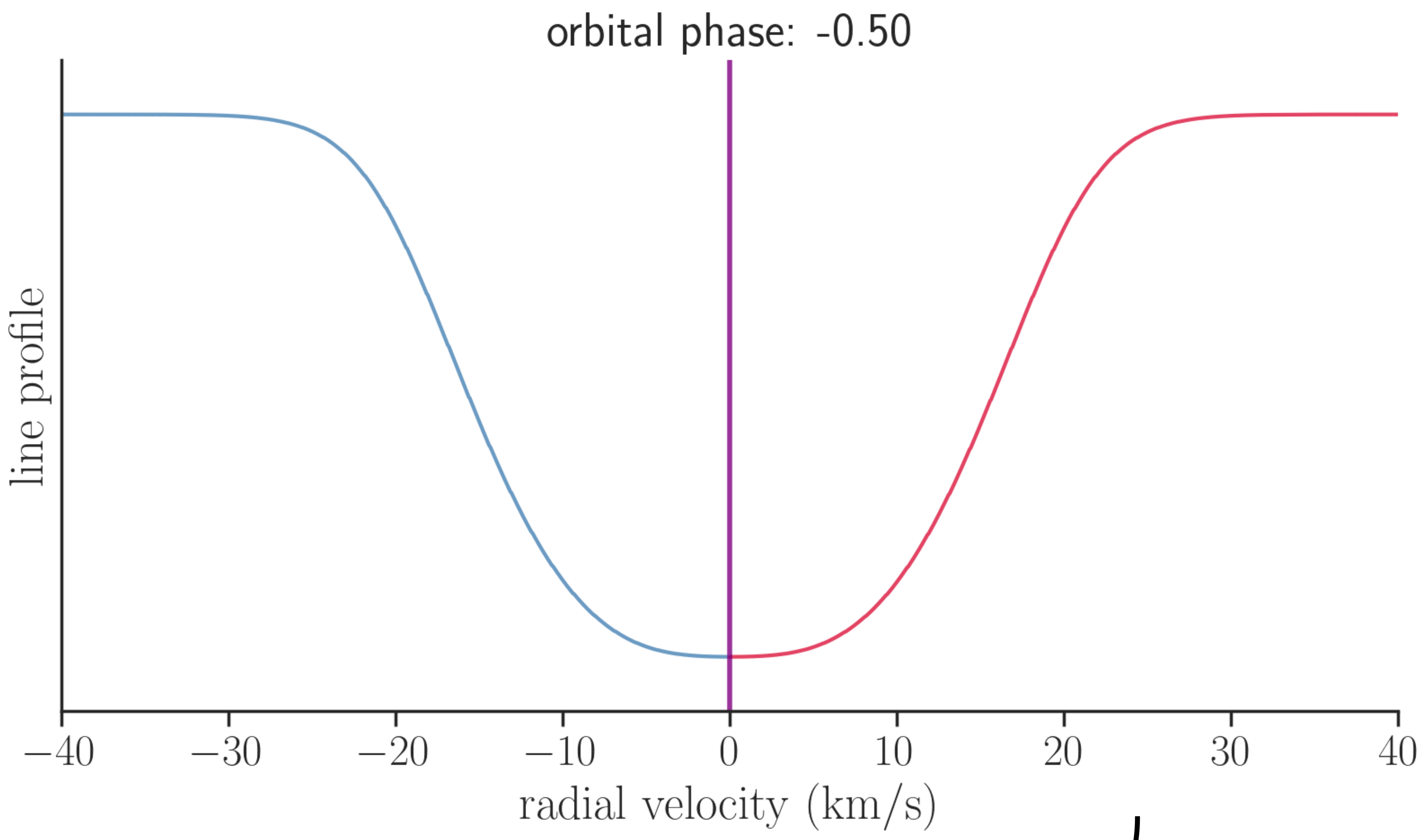


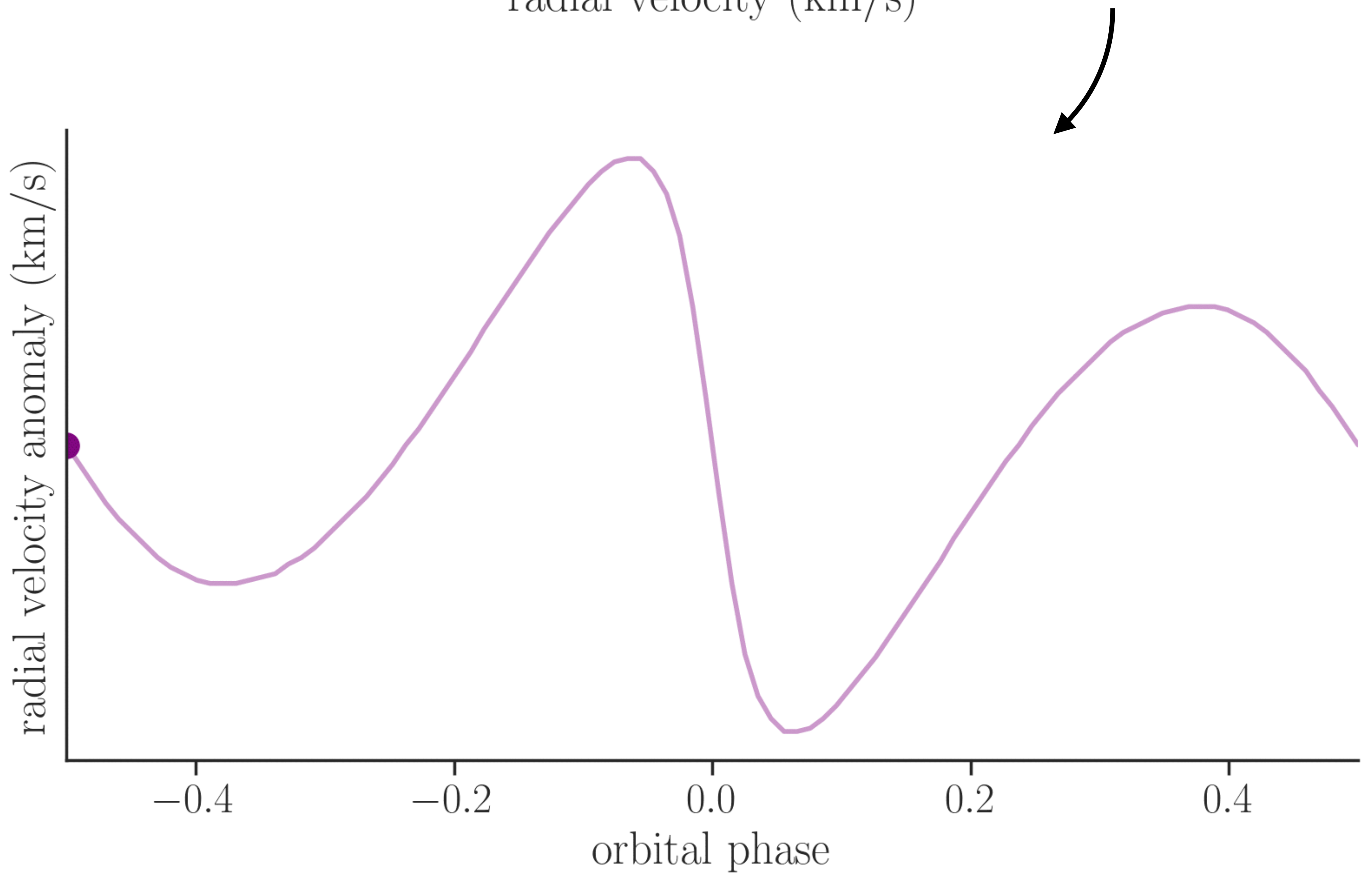
- “non-primary” flux dilutes the amplitude of ellipsoidal variations
  - accretion flow, hotspots, …
- mass/inclination may be biased by $\gtrsim M_\odot / \gtrsim 10^\circ$ in some X-ray binaries

e.g. Kreidberg et al. (2012)

tidal effects on RVs

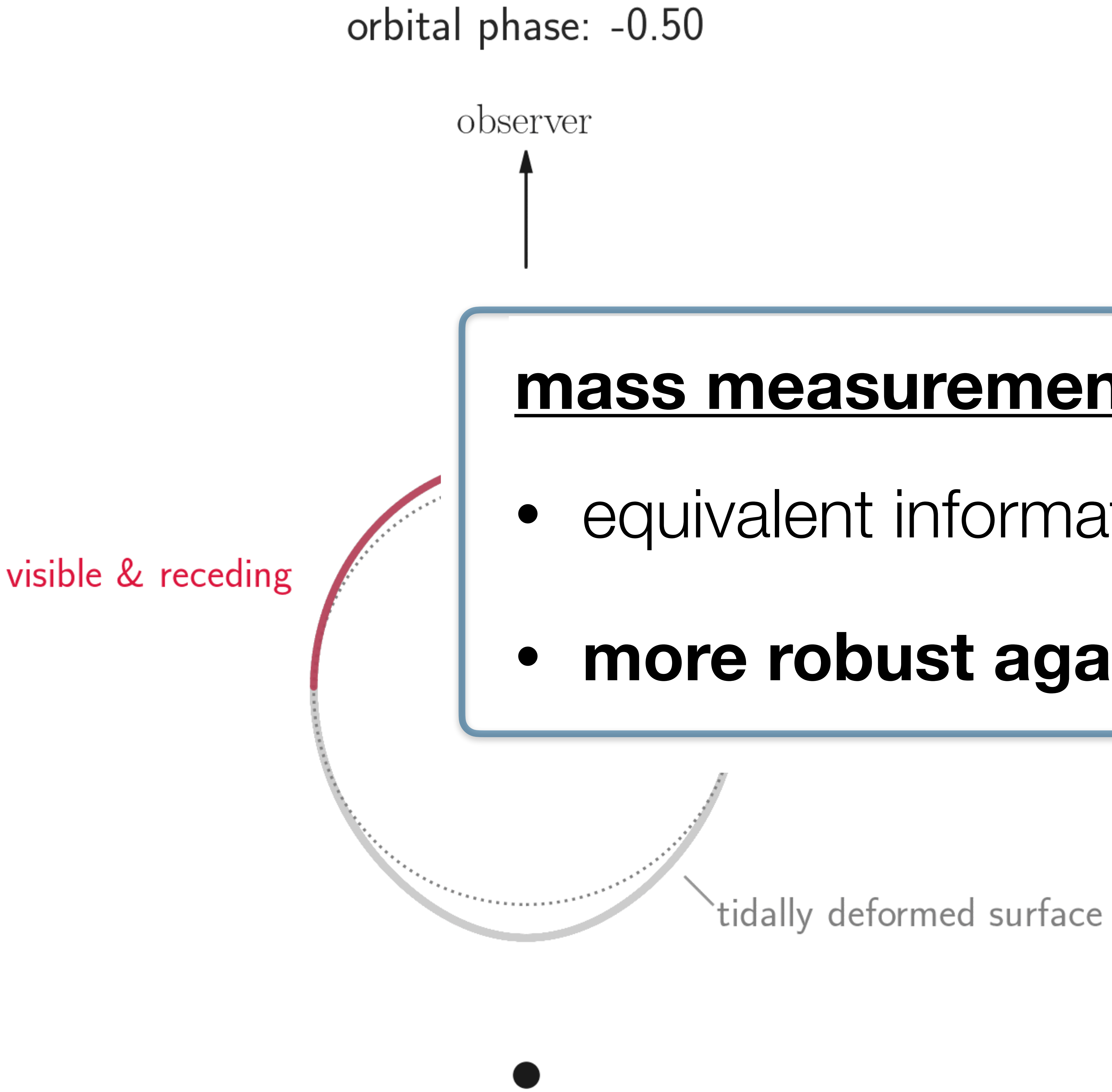


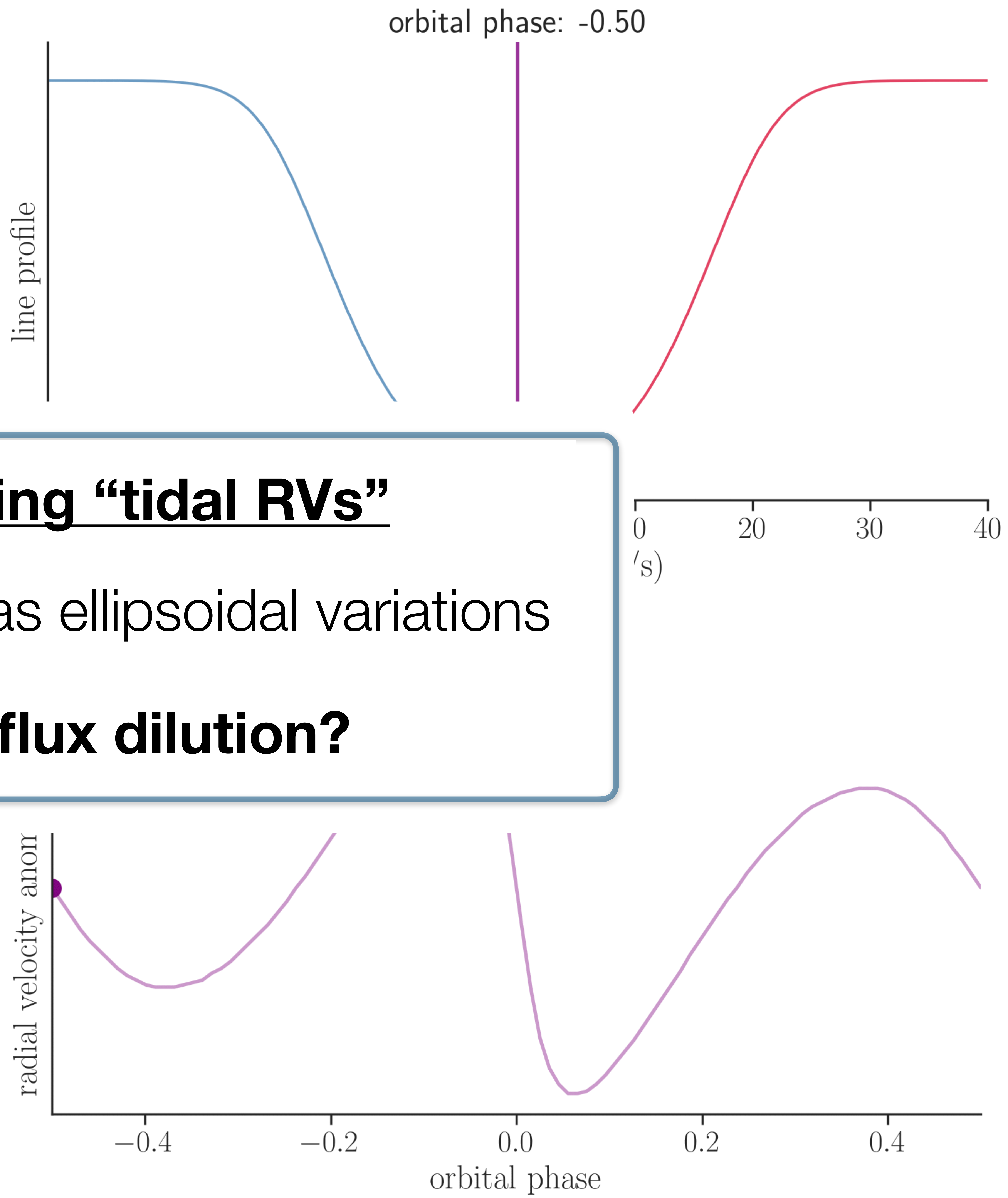




Sterne (1941), Kopal (1959), Wilson & Sofia (1979), Hill (1989), …

tidal effects on RVs





mass measurement using "tidal RVs"

- equivalent information as ellipsoidal variations
- **more robust against flux dilution?**

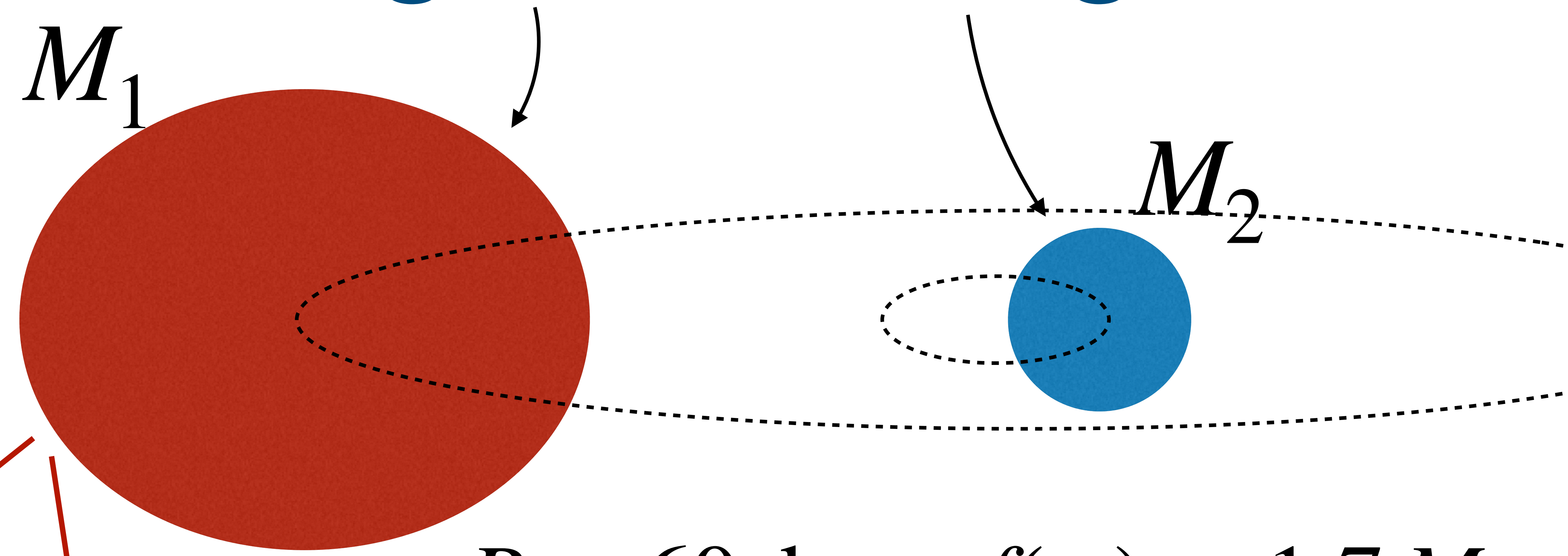
Sterne (1941), Kopal (1959), Wilson & Sofia (1979), Hill (1989), …

V723 Mon: “SB1” system of a red giant + subgiant

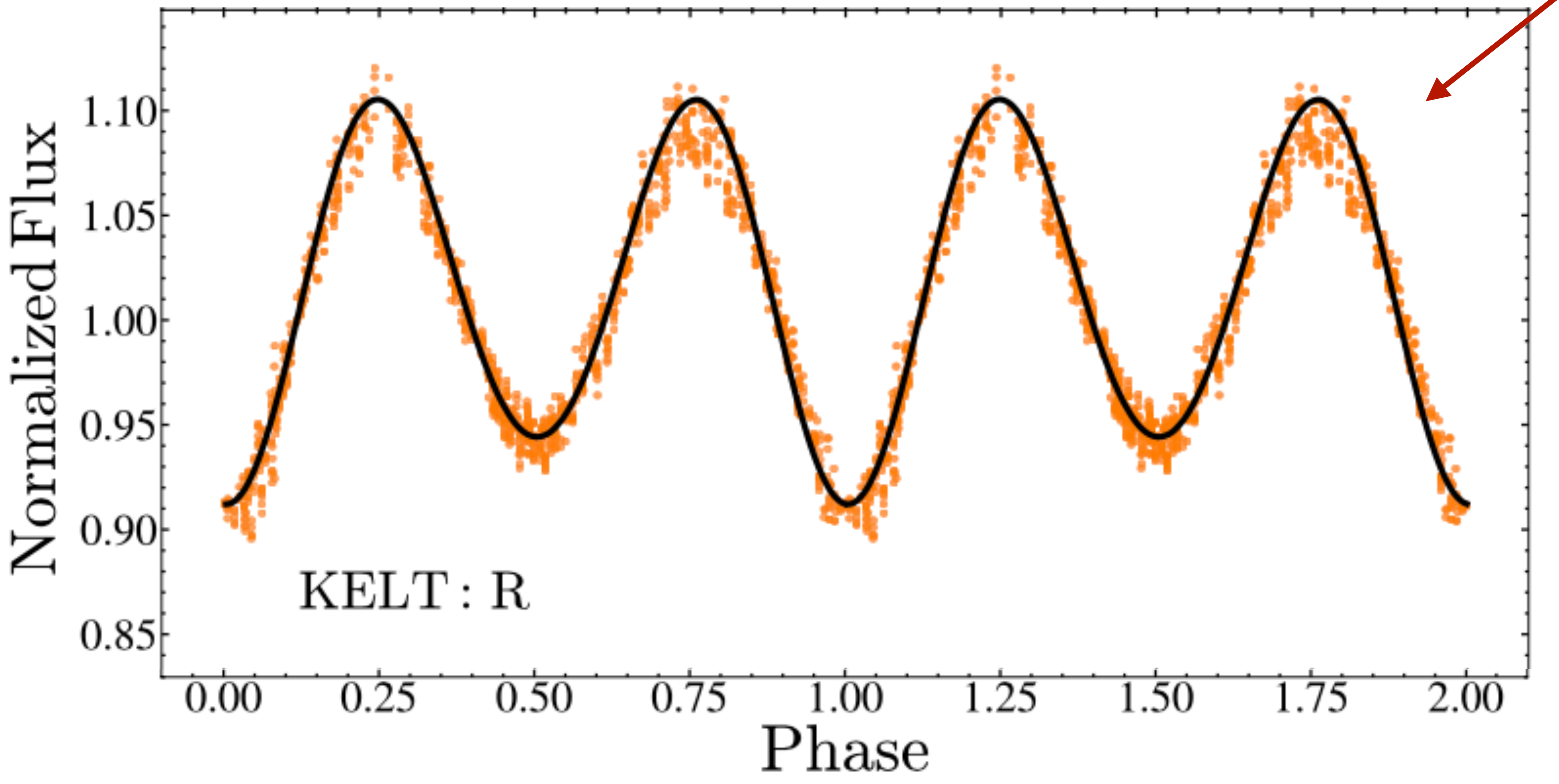
RV + EV + SED-based R_1 (Jayasinghe+2021)

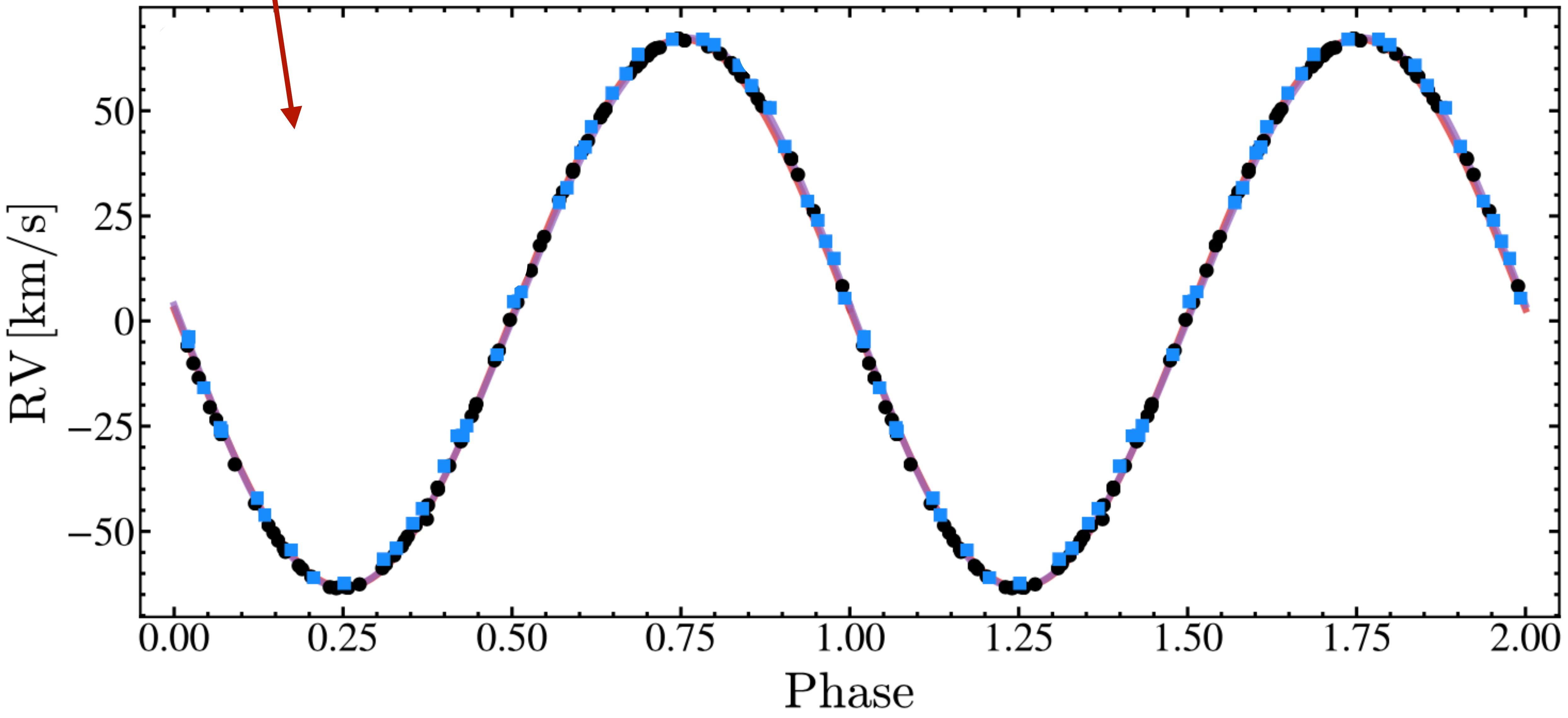
$$M_1 = 1.00 \pm 0.07\, M_\odot,\; M_2 = 3.04 \pm 0.06\, M_\odot$$

black hole??



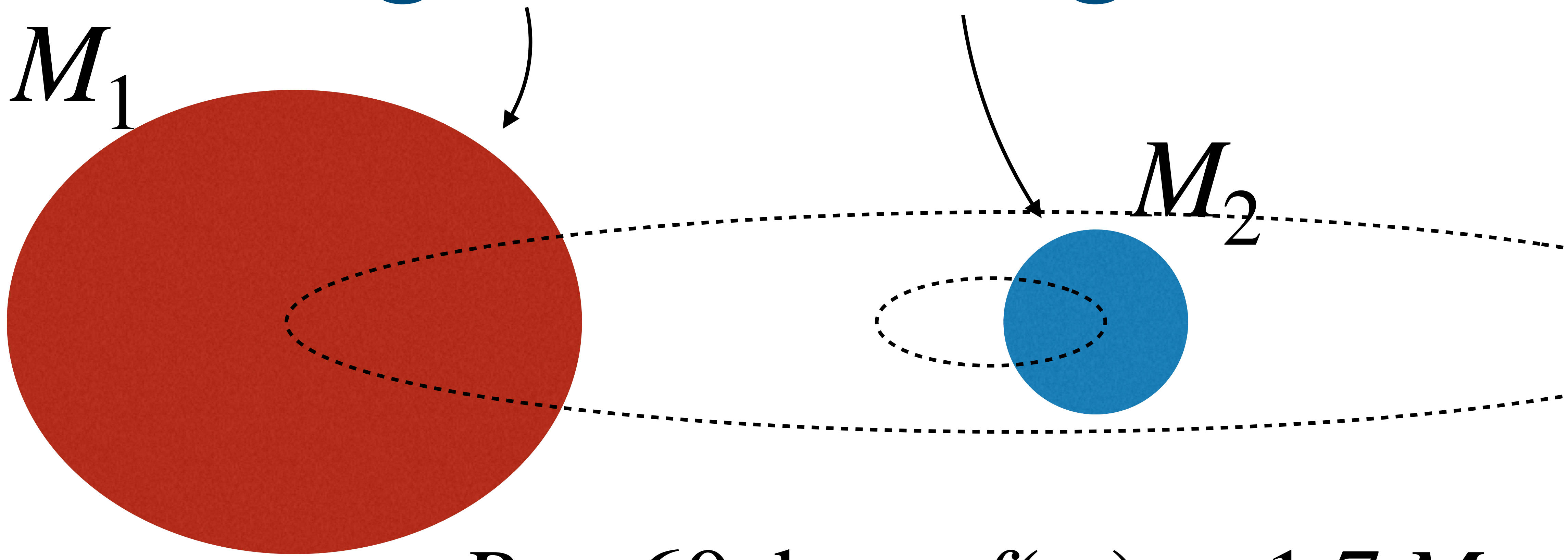
$$P \approx 60\,\text{days},\; f(m) \approx 1.7\, M_\odot$$





Jayasinghe et al. (2021)

V723 Mon: "SB1" system of a red giant + subgiant



RV + EV + SED-based R_1 (Jayasinghe+2021)

$M_1 = 1.00 \pm 0.07\,M_\odot$, $M_2 = 3.04 \pm 0.06\,M_\odot$

black hole??

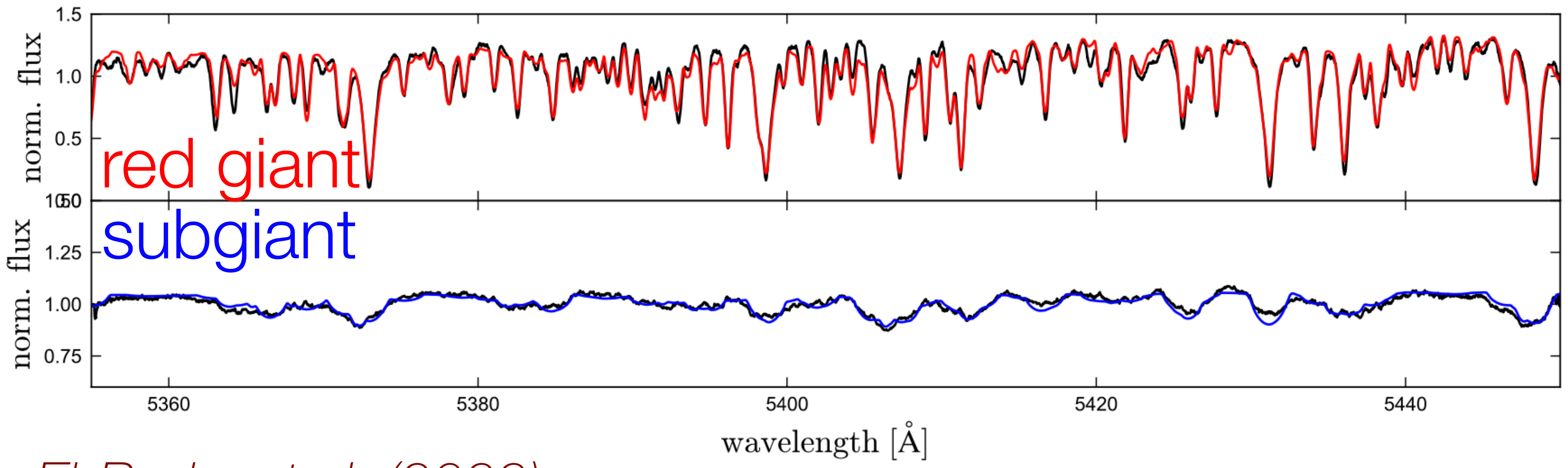
$P \approx 60$ days, $f(m) \approx 1.7\,M_\odot$

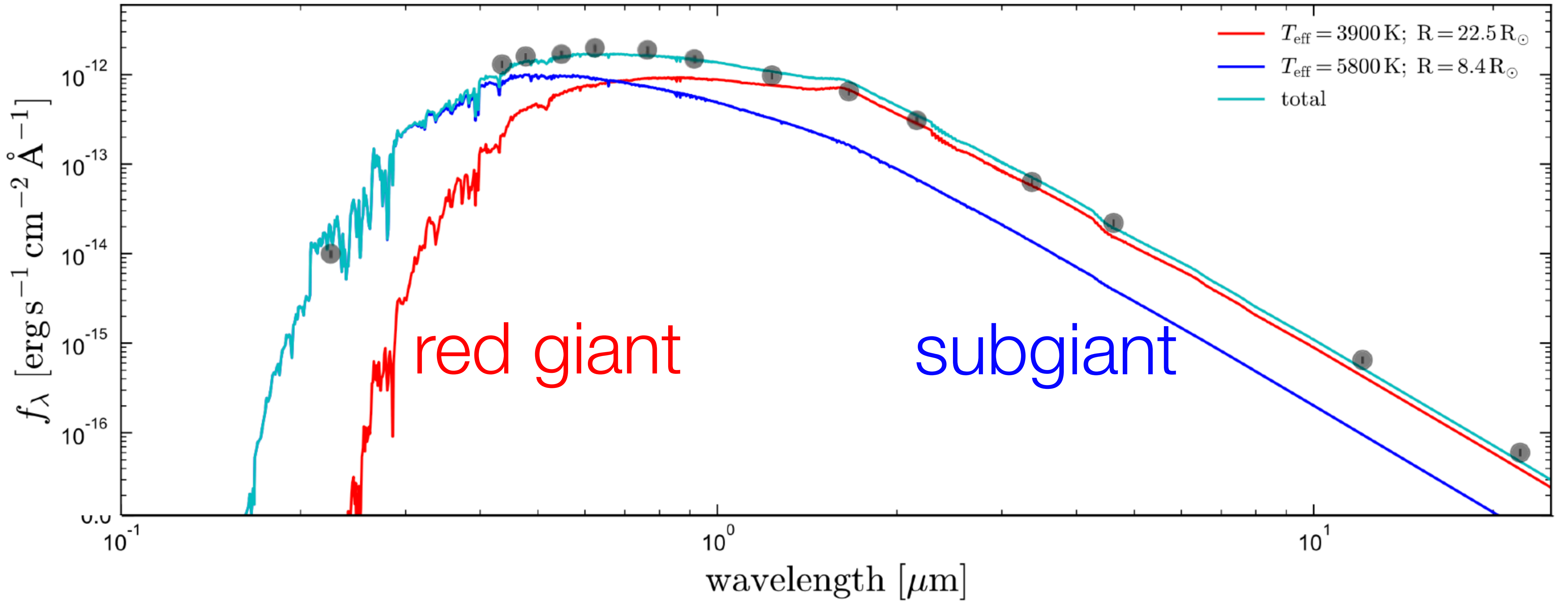
revised analysis taking into account the companion's dilution flux (El-Badry+2022)

$M_1 = 0.44 \pm 0.06\,M_\odot$, $M_2 = 2.8 \pm 0.3\,M_\odot$

$L_2 \approx 0.7\,L_1$: dilution from subgiant is significant

subgiant's lines are broad and shallow





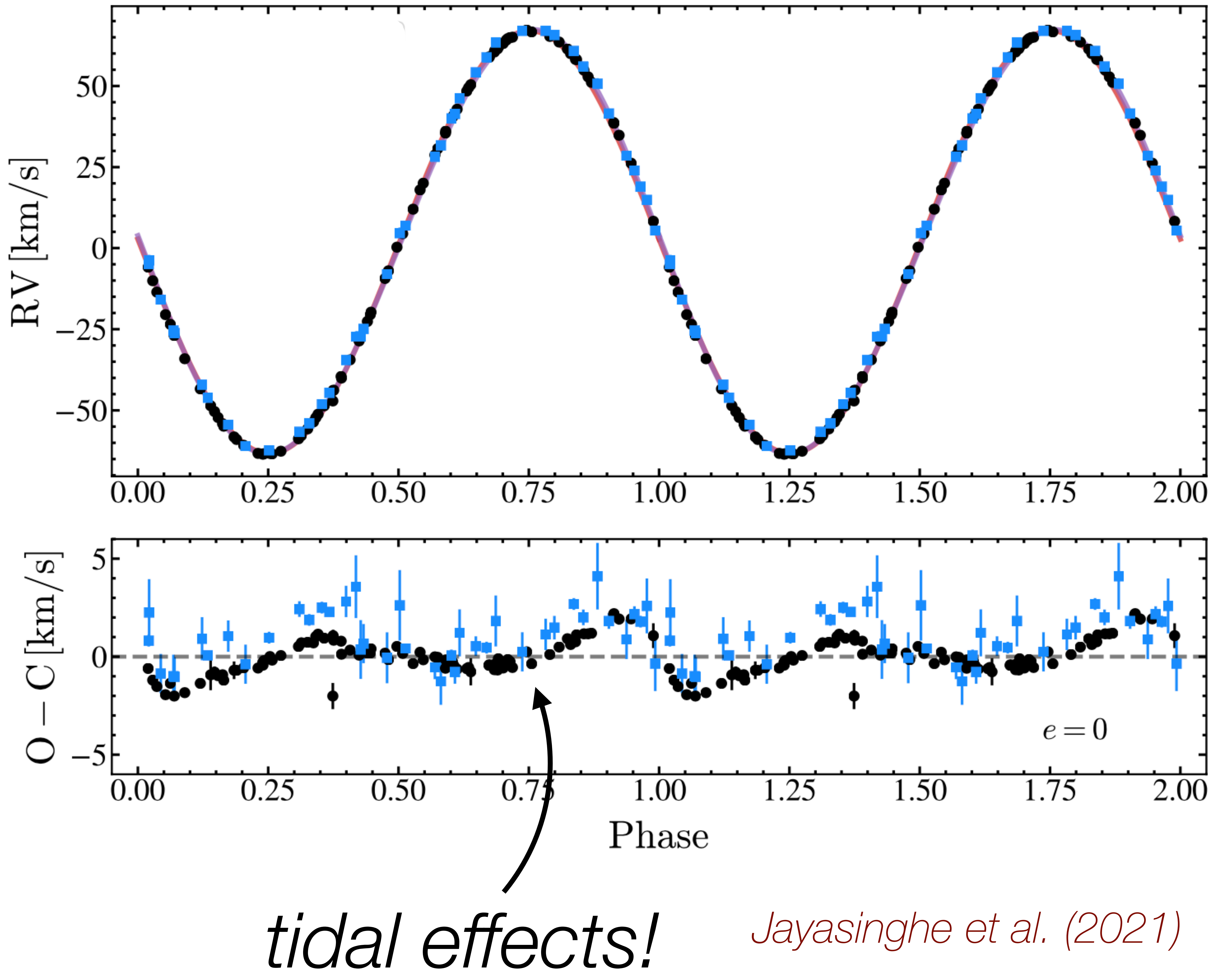
El-Badry et al. (2022)

V723 Mon as a test case of "tidal RV" modeling

- SB1-like system where the **flux dilution** biases the masses based on ellipsoidal variations
- RV residuals show **tidal effects**

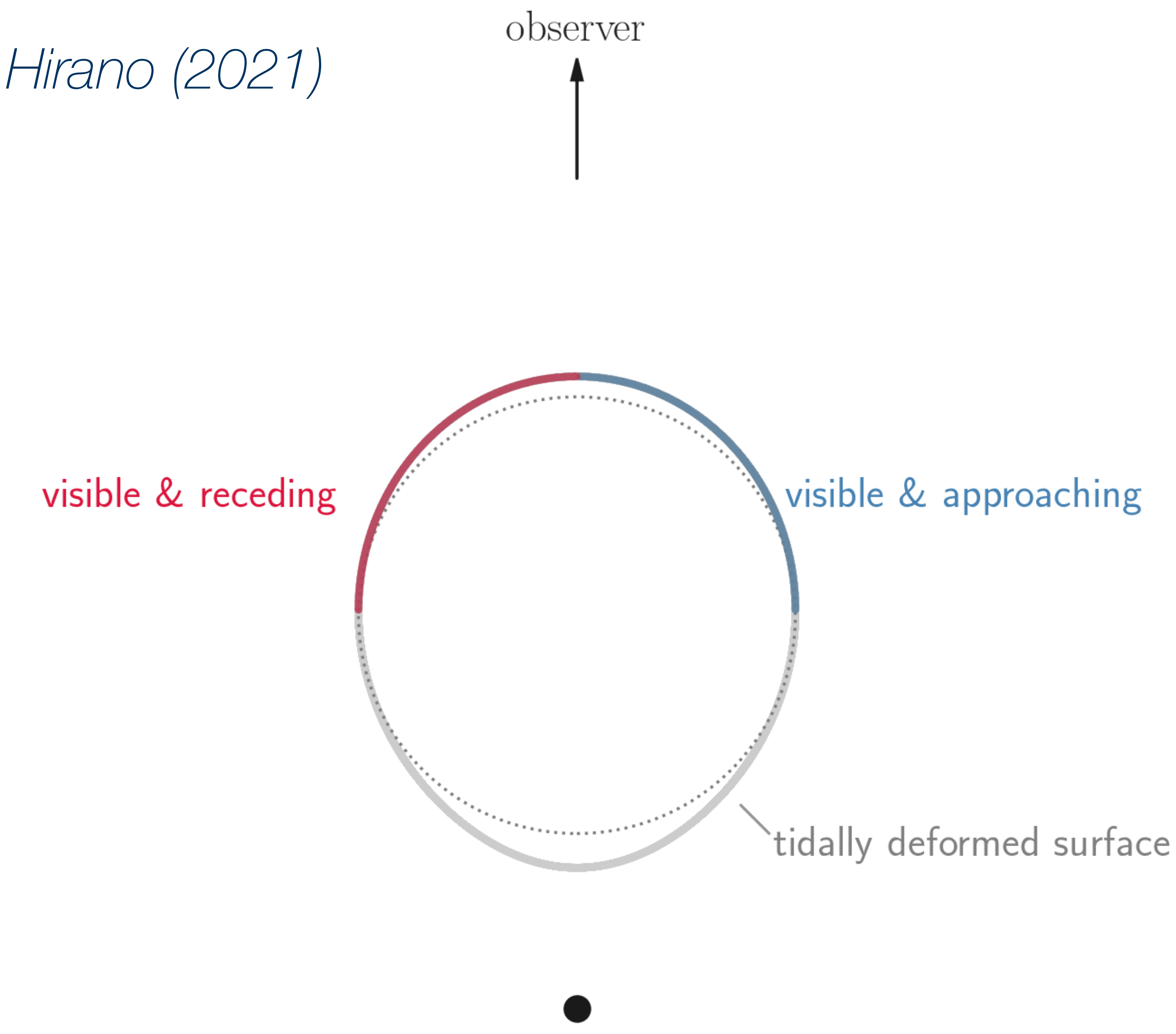
- we **ignore companions' light** and measure the mass using **tidal RVs**
- check how they compare to the **EV-based** mass that **explicitly accounts for flux dilution**

RV data (black) are from STELLA echelle spectrograph (Strassmeier et al. 2012)



Jayasinghe et al. (2021)

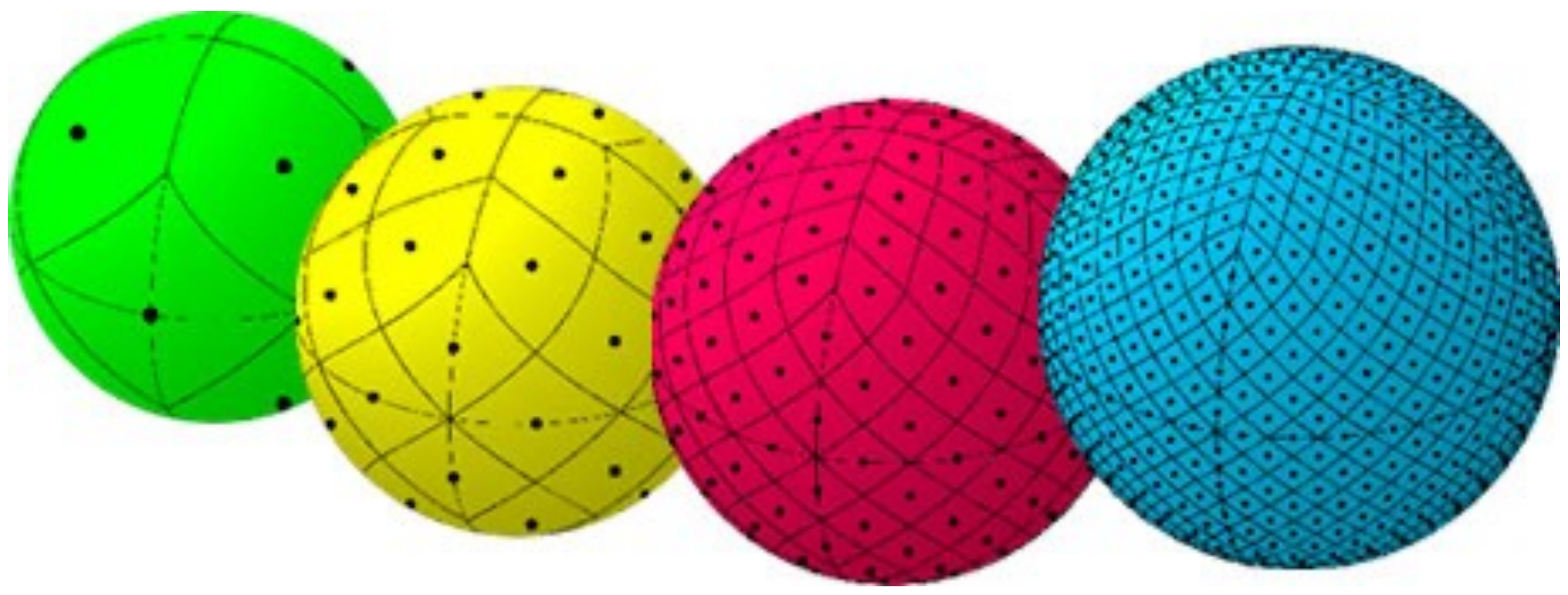
KM & Hirano (2021)



binary system parameters
(incl. masses, orbital inclination)

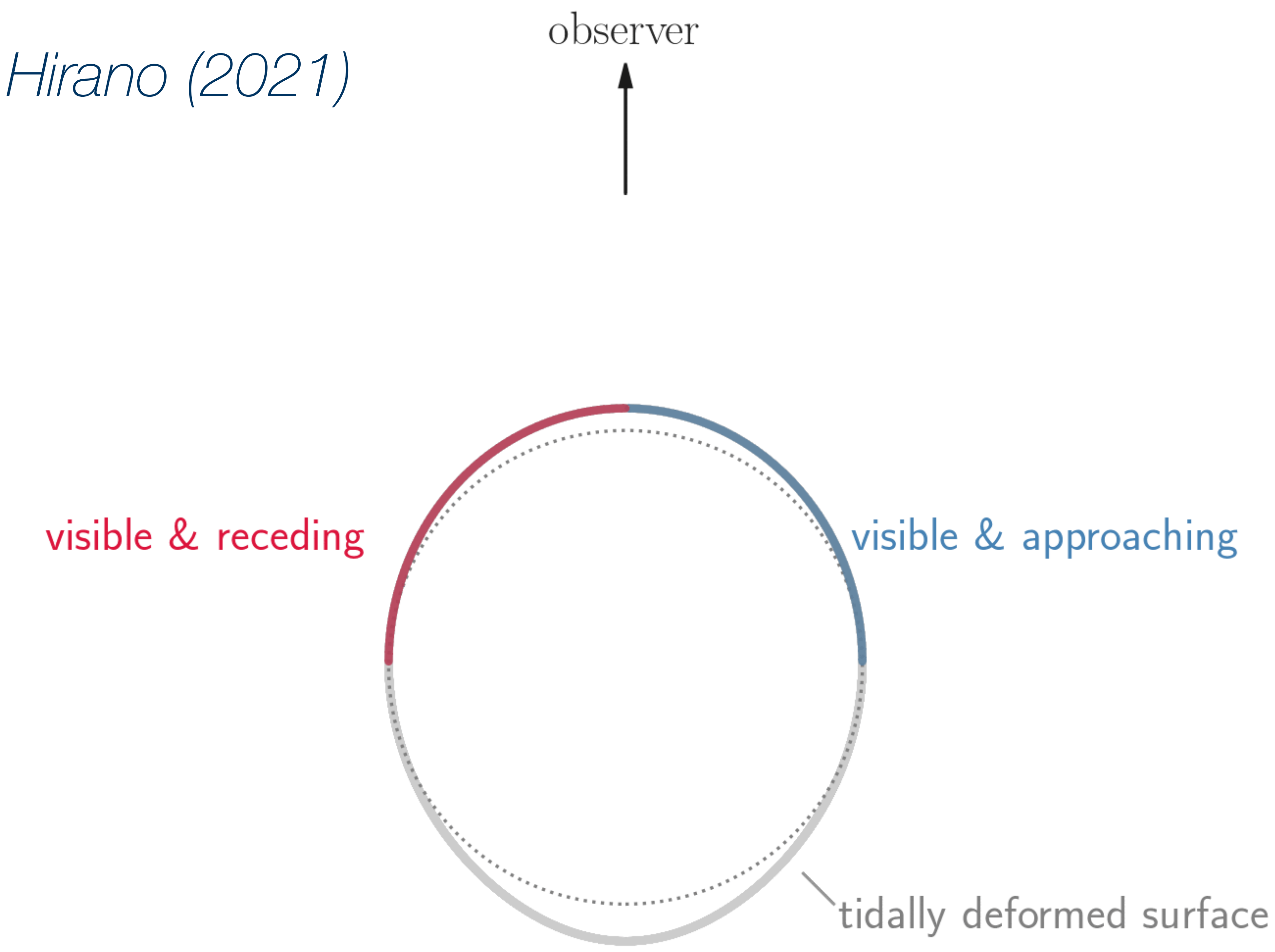
1. tidal deformation & flux distribution

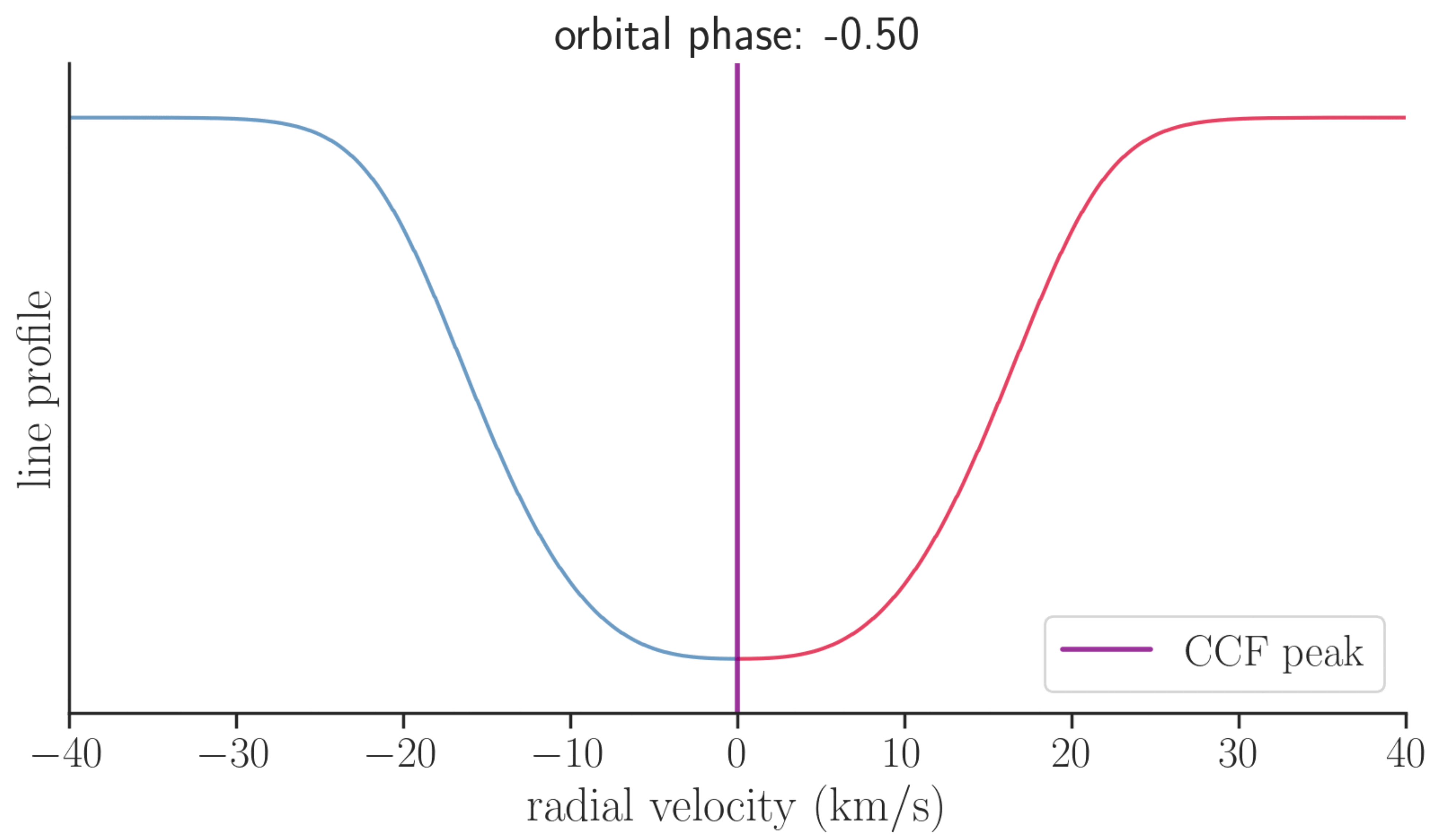
- Roche model for surface shape (assume tidal synchronization)
- limb & gravity darkening for flux



pixelization using healpix/healpy
(Górski et al. 2005, Zonca et al. 2019)

KM & Hirano (2021)





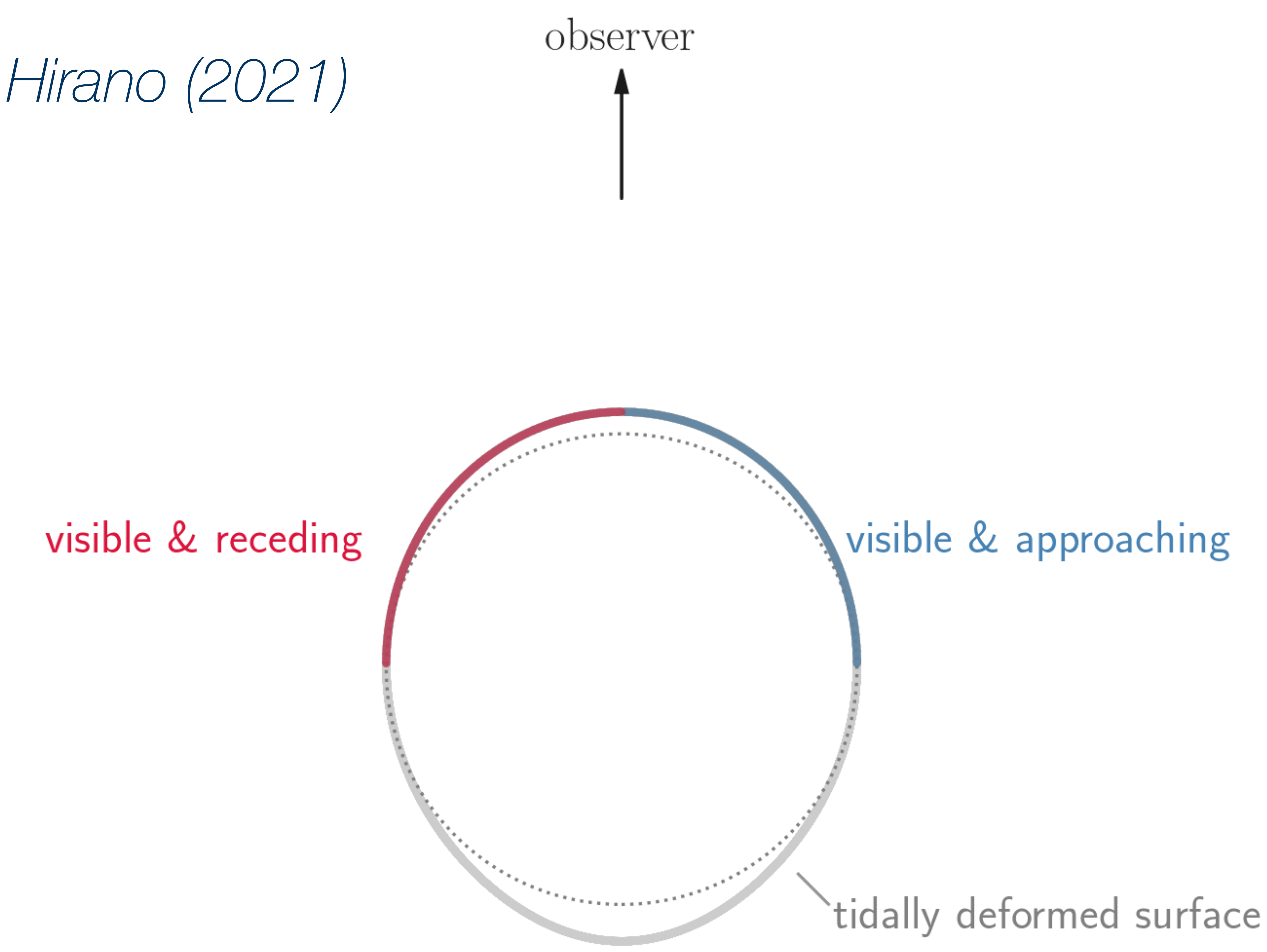
binary system parameters
(incl. masses, orbital inclination)

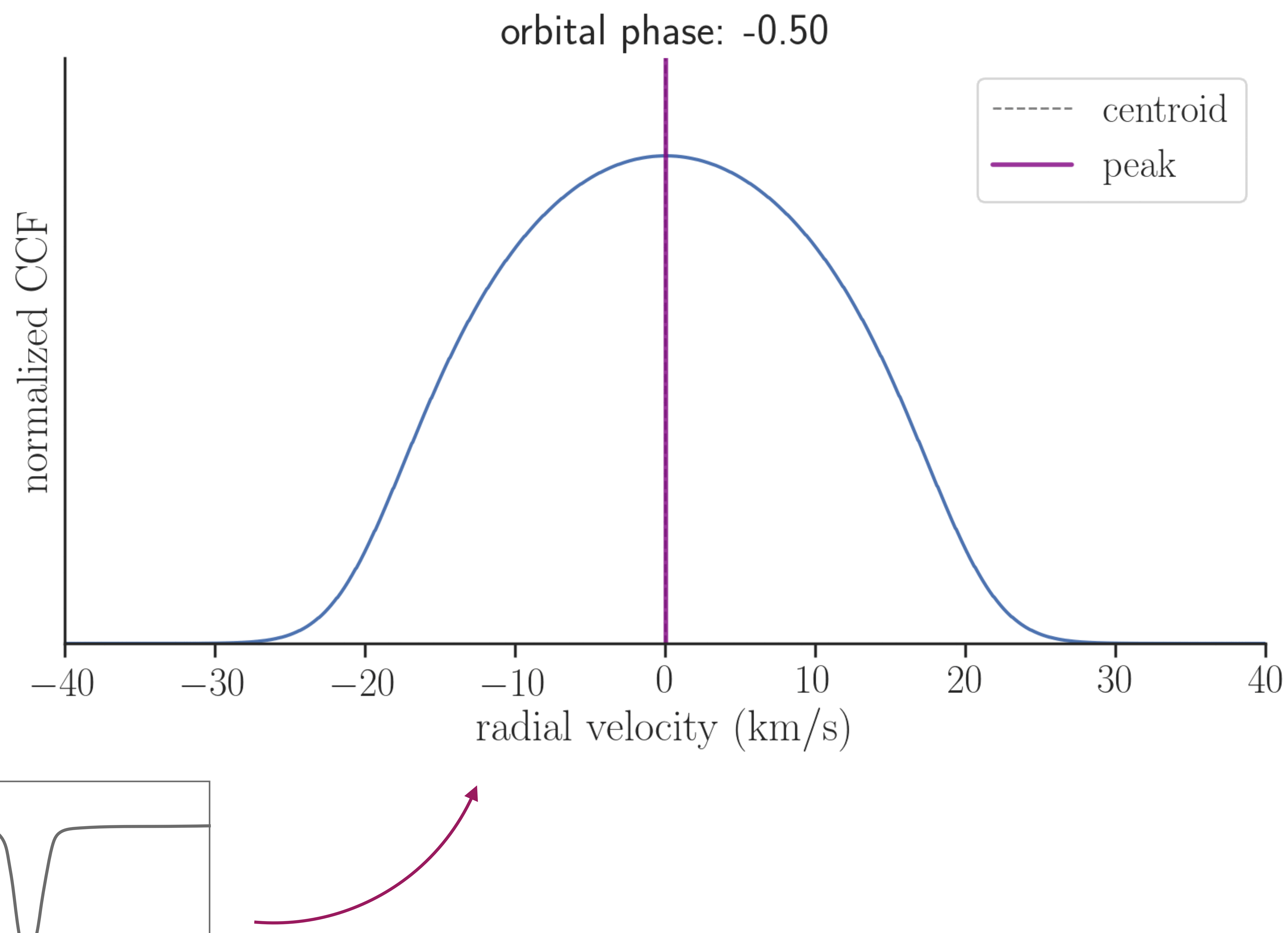
1. tidal deformation & flux distribution

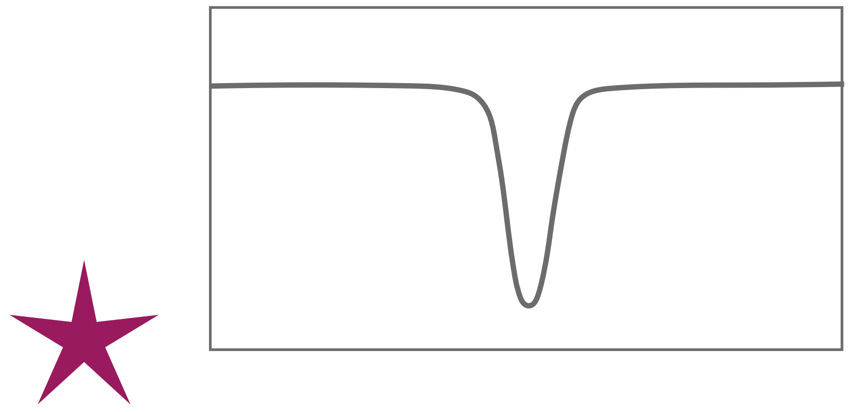
- Roche model for surface shape (assume tidal synchronization)
- limb & gravity darkening for flux

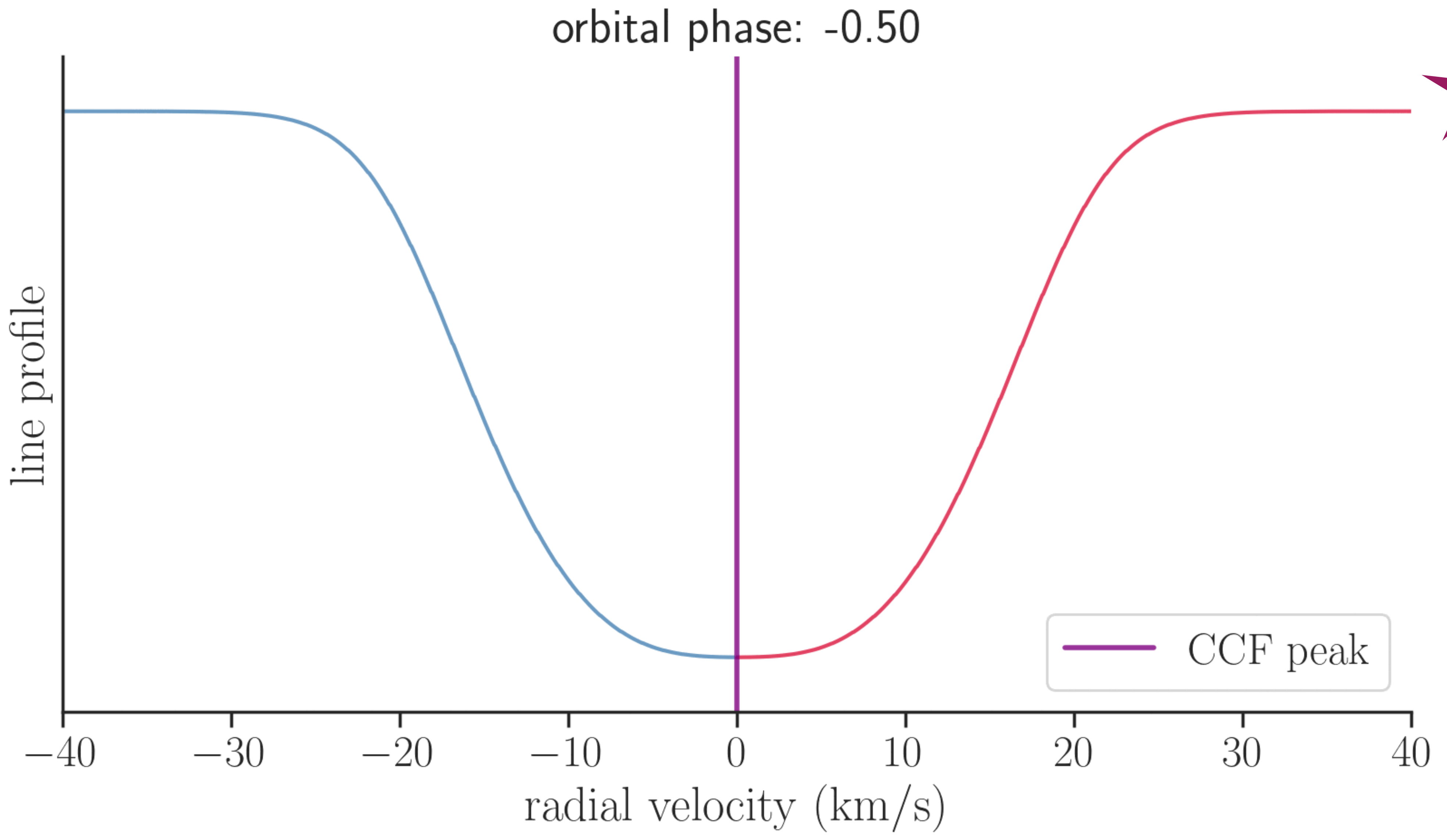
2. absorption line profile

- rotation & macro-turbulence broadening
- intrinsic line width (thermal broadening, instrumental profile, micro-turbulence)



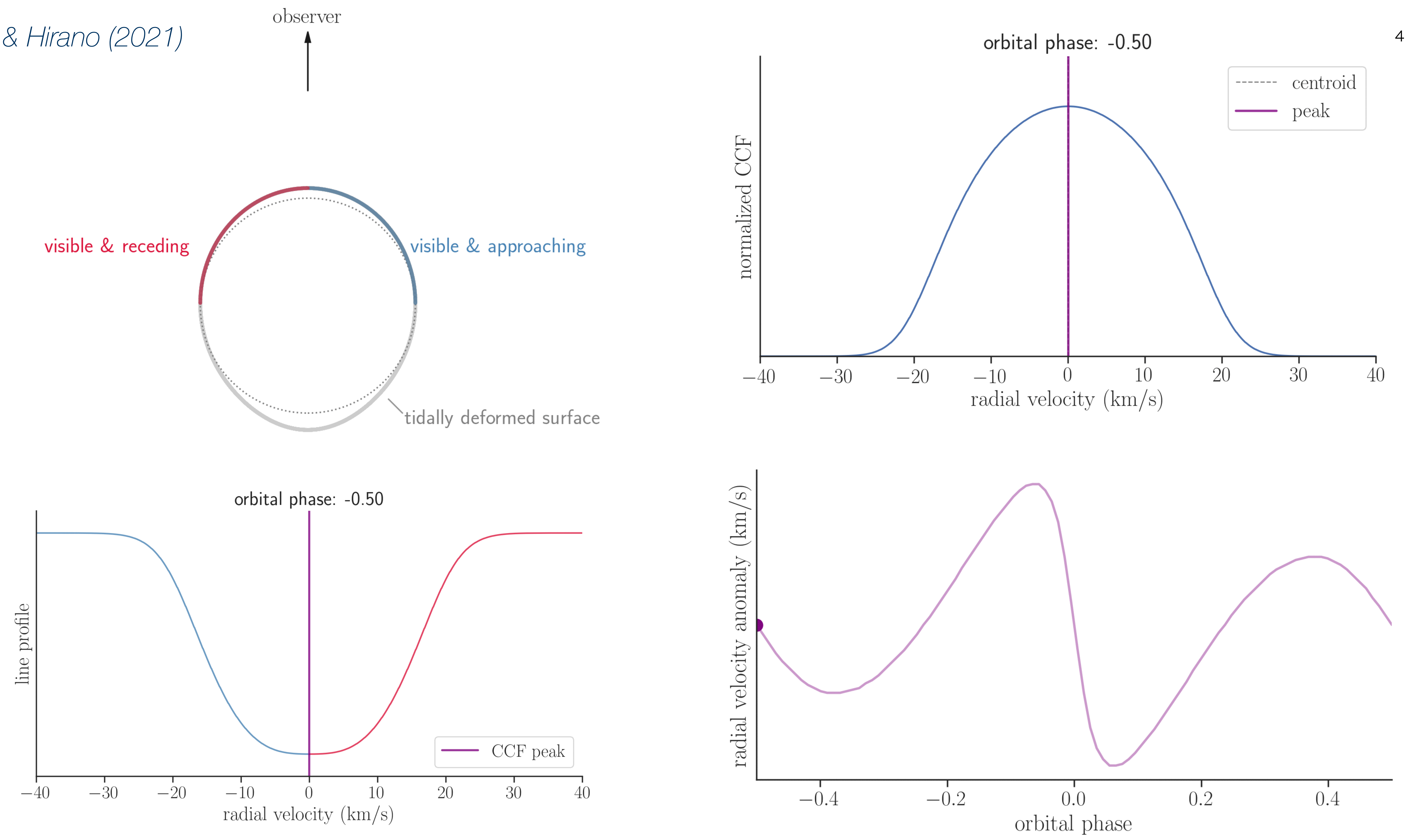






3. cross correlation function (CCF)

- compute CCF with a **theoretical template**
- derive velocity shift as the **CCF peak**


observer
visible & receding
visible & approaching
tidally deformed surface
orbital phase: -0.50
centroid
peak
normalized CCF
radial velocity (km/s)
orbital phase: -0.50
line profile
CCF peak
radial velocity (km/s)
radial velocity anomaly (km/s)
orbital phase

an existing scheme

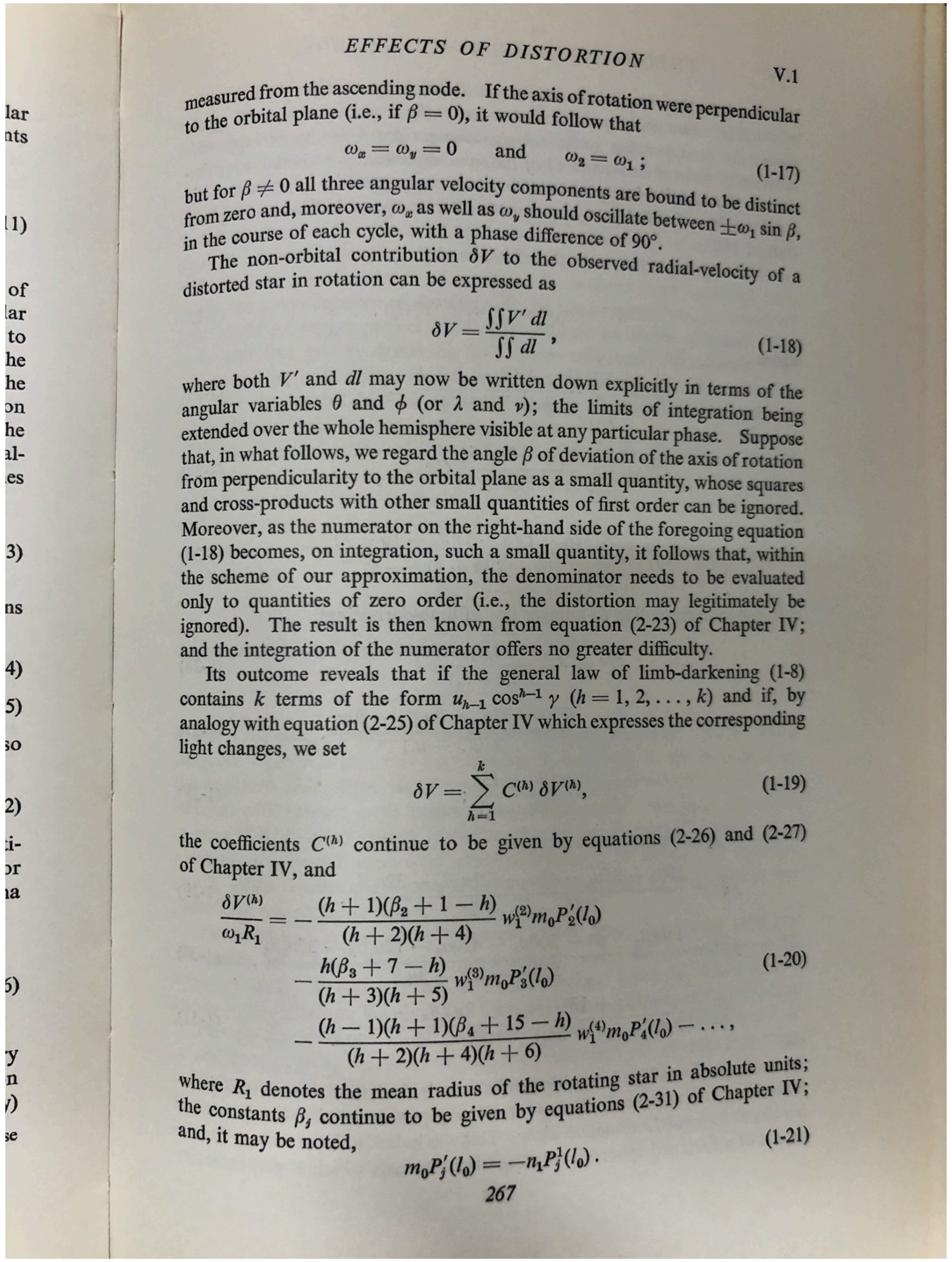
- Sterne (1941): tidal anomaly may mimic a non-zero orbital eccentricity

- compute **flux-weighted mean velocity** (e.g., Kopal 1959, Wilson & Sofia 1967, Orosz & Hauschildt 2000)

velocity

flux

$$v_{\mathrm{tidal}} = \frac{\int_{\mathrm{visible}} v\, F\, \mathrm{d}S}{\int_{\mathrm{visible}} F\, \mathrm{d}S}$$



EFFECTS OF DISTORTION V.1

measured from the ascending node. If the axis of rotation were perpendicular to the orbital plane (i.e., if $\beta = 0$), it would follow that

$$\omega_x = \omega_y = 0 \quad \text{and} \quad \omega_z = \omega_1 ; \tag{1-17}$$

but for $\beta \neq 0$ all three angular velocity components are bound to be distinct from zero and, moreover, ω_x as well as ω_y should oscillate between $\pm\omega_1 \sin\beta$, in the course of each cycle, with a phase difference of 90°.

The non-orbital contribution δV to the observed radial-velocity of a distorted star in rotation can be expressed as

$$\delta V = \frac{\iint V'\, dl}{\iint dl}, \tag{1-18}$$

where both V' and dl may now be written down explicitly in terms of the angular variables θ and ϕ (or λ and ν); the limits of integration being extended over the whole hemisphere visible at any particular phase. Suppose that, in what follows, we regard the angle β of deviation of the axis of rotation from perpendicularity to the orbital plane as a small quantity, whose squares and cross-products with other small quantities of first order can be ignored. Moreover, as the numerator on the right-hand side of the foregoing equation (1-18) becomes, on integration, such a small quantity, it follows that, within the scheme of our approximation, the denominator needs to be evaluated only to quantities of zero order (i.e., the distortion may legitimately be ignored). The result is then known from equation (2-23) of Chapter IV; and the integration of the numerator offers no greater difficulty.

Its outcome reveals that if the general law of limb-darkening (1-8) contains k terms of the form $u_{h-1} \cos^{h-1}\gamma$ ($h = 1, 2, \ldots, k$) and if, by analogy with equation (2-25) of Chapter IV which expresses the corresponding light changes, we set

$$\delta V = \sum_{h=1}^{k} C^{(h)}\, \delta V^{(h)}, \tag{1-19}$$

the coefficients $C^{(h)}$ continue to be given by equations (2-26) and (2-27) of Chapter IV, and

$$\frac{\delta V^{(h)}}{\omega_1 R_1} = -\frac{(h+1)(\beta_2+1-h)}{(h+2)(h+4)} w_1^{(2)} m_0 P_2'(l_0) - \frac{h(\beta_3+7-h)}{(h+3)(h+5)} w_1^{(3)} m_0 P_3'(l_0) - \frac{(h-1)(h+1)(\beta_4+15-h)}{(h+2)(h+4)(h+6)} w_1^{(4)} m_0 P_4'(l_0) - \ldots, \tag{1-20}$$

where R_1 denotes the mean radius of the rotating star in absolute units; the constants β_j continue to be given by equations (2-31) of Chapter IV; and, it may be noted,

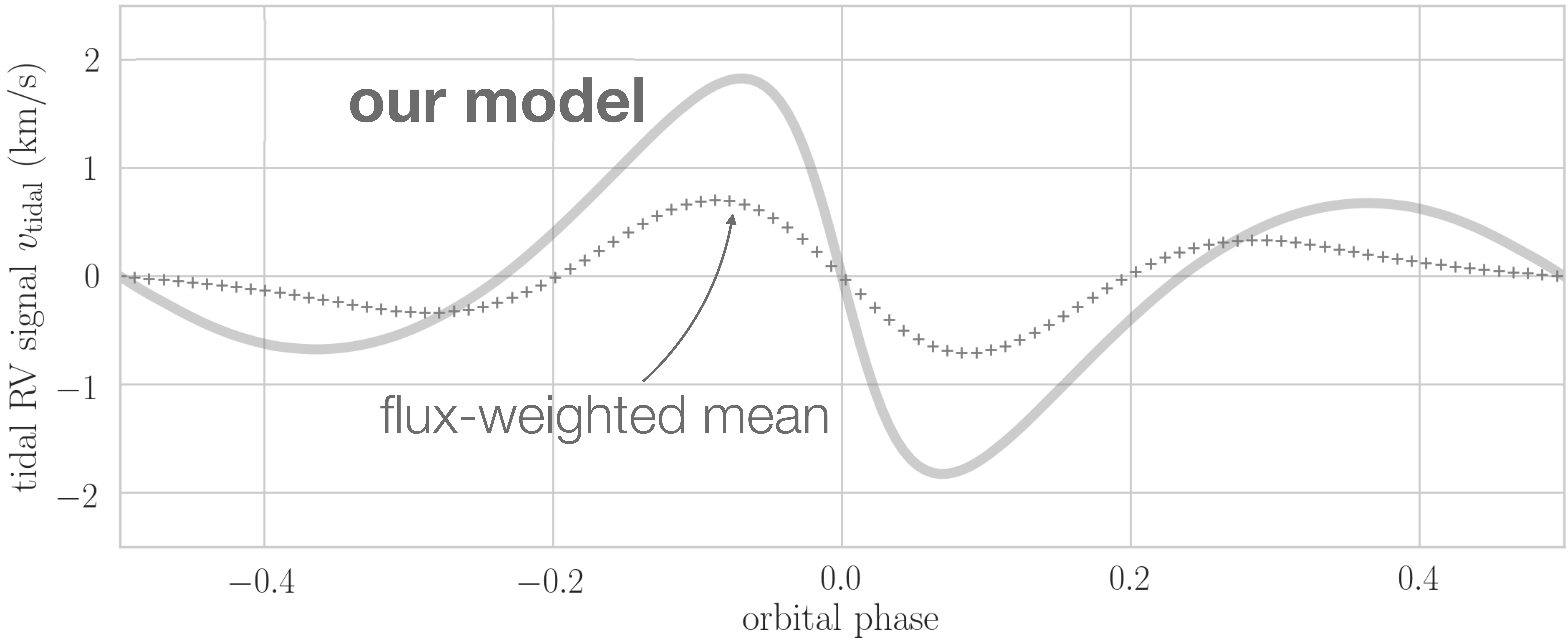
$$m_0 P_j'(l_0) = -n_1 P_j^1(l_0). \tag{1-21}$$

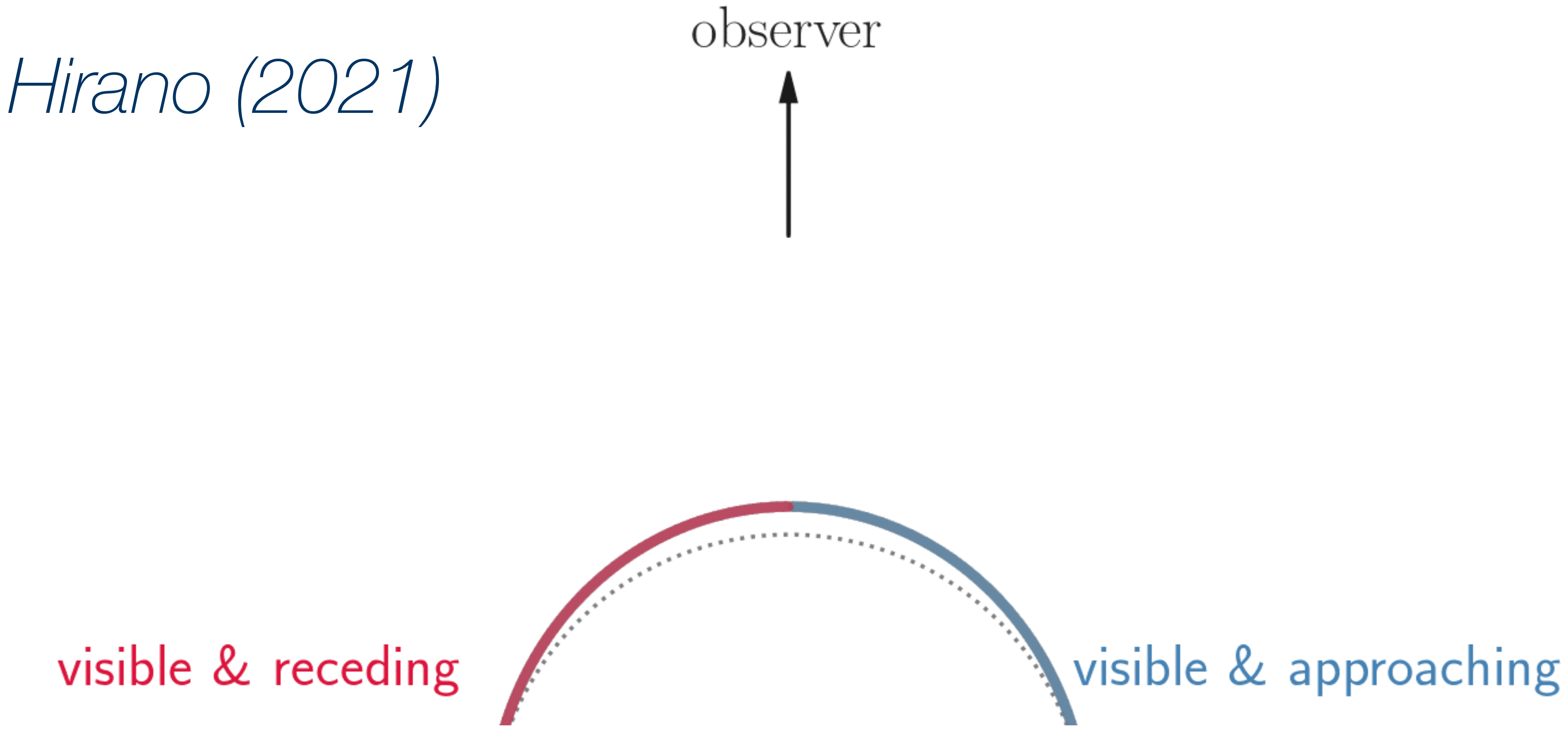
267

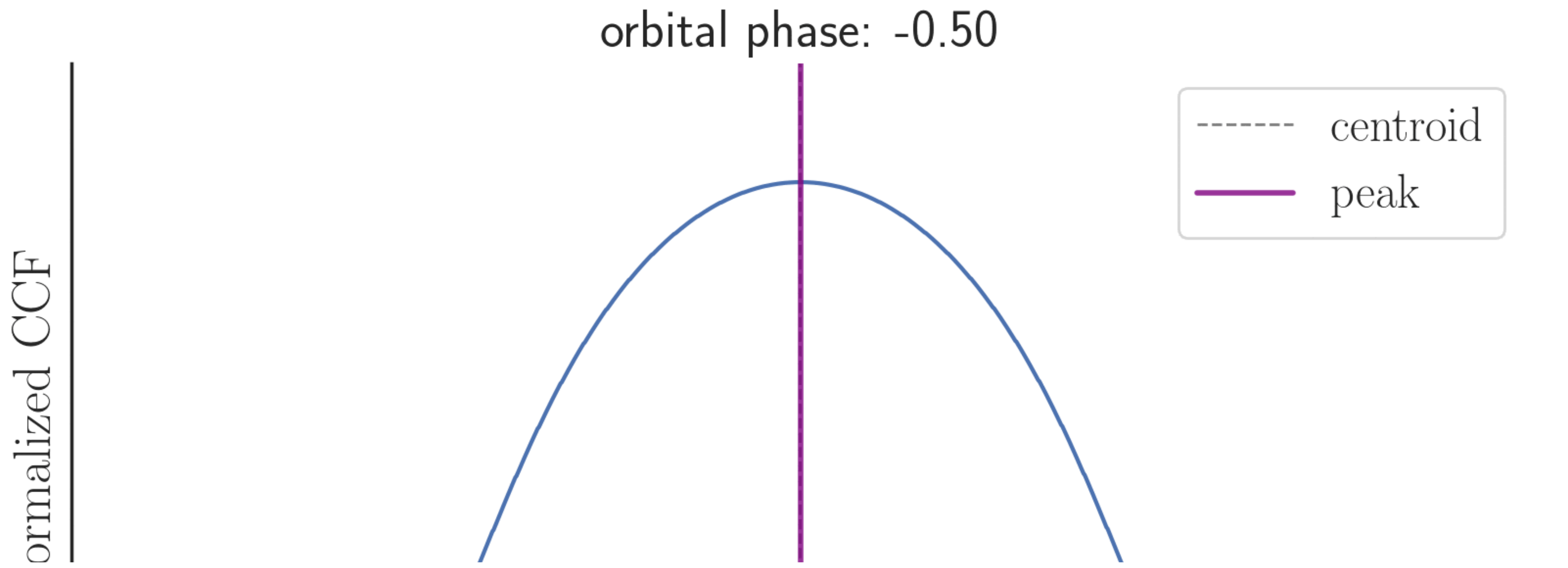
Close Binary Systems (Kopal, 1959)

comparison with flux-weighed mean scheme

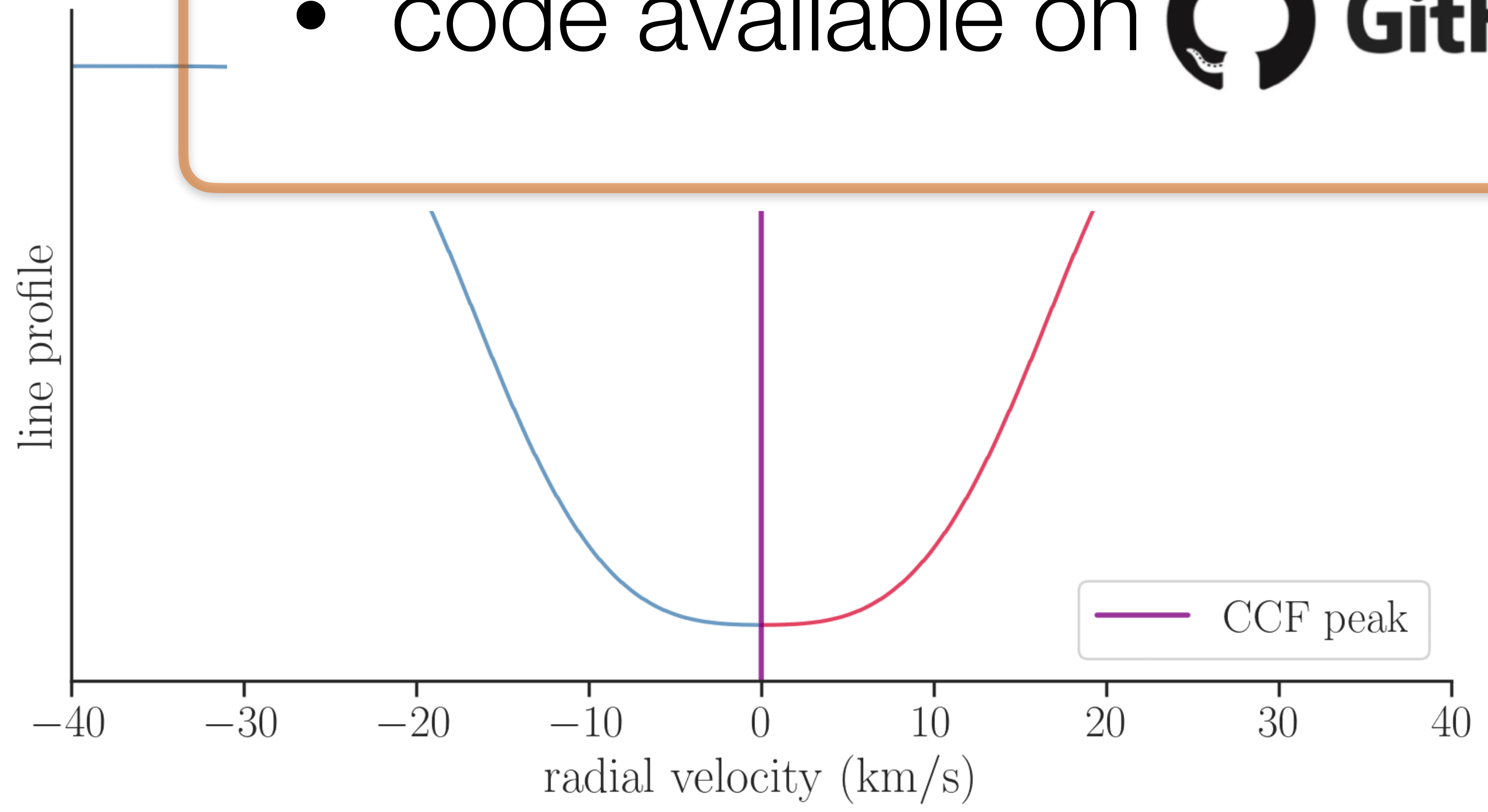
KM & Hirano (2021)

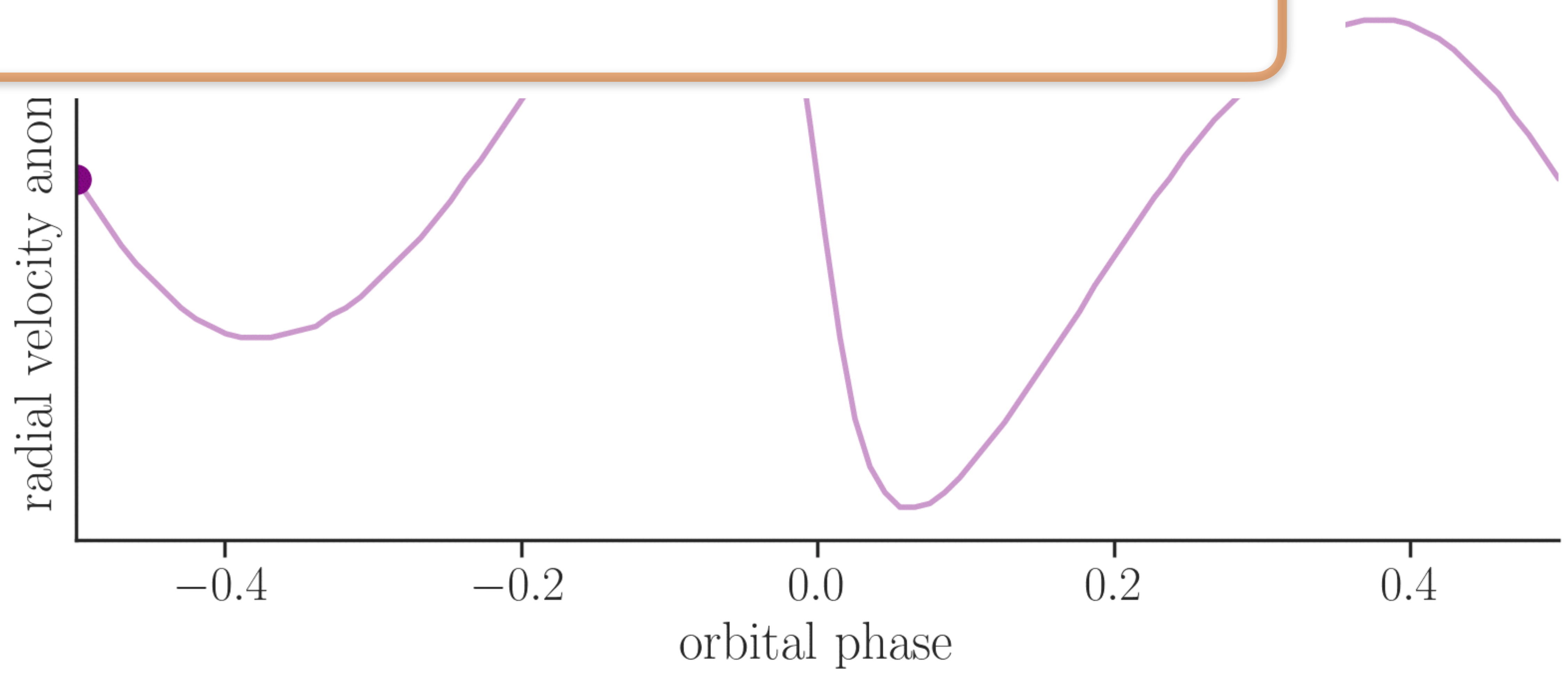






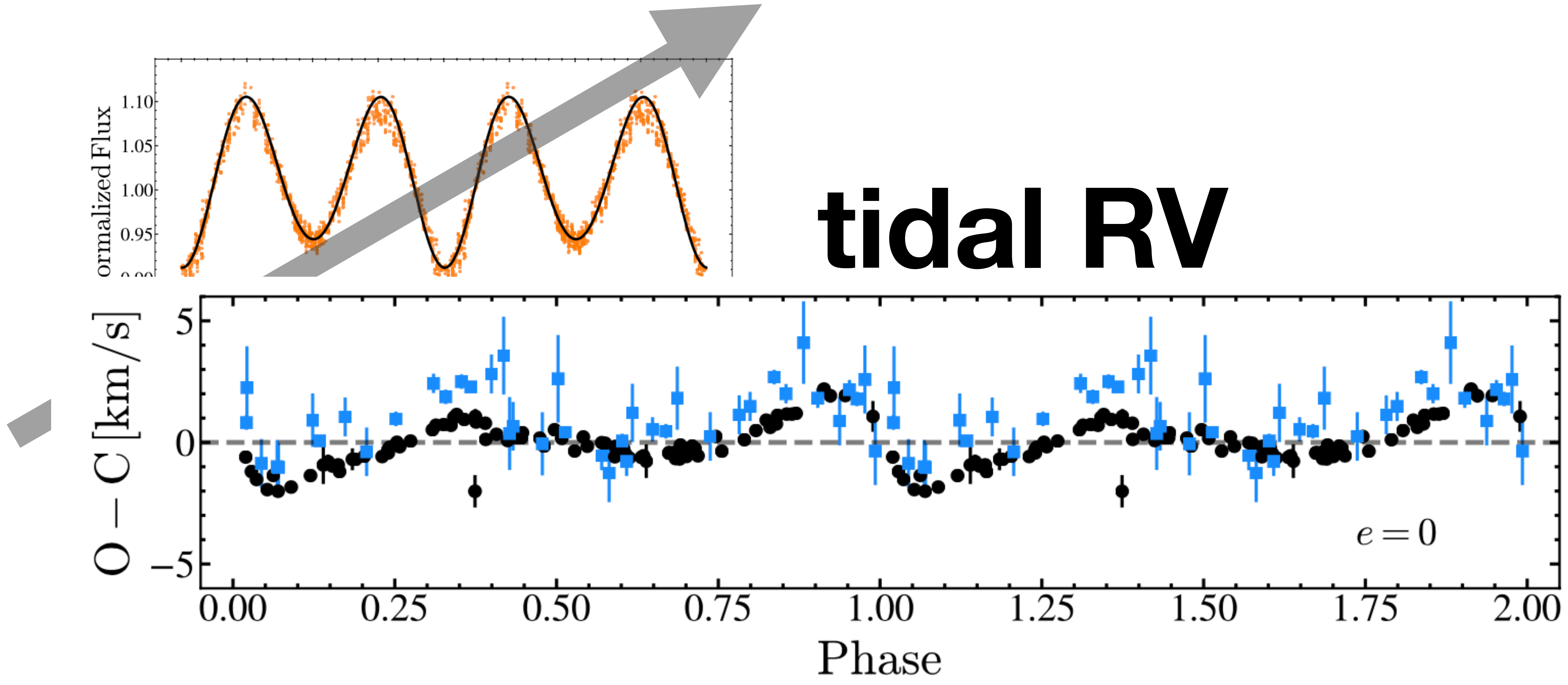
- implemented in **JAX**; RV model is **differentiable**
- **gradient-based** MCMC (Hamiltonian Monte Carlo) can be used
- code available on GitHub https://github.com/kemasuda/rochev

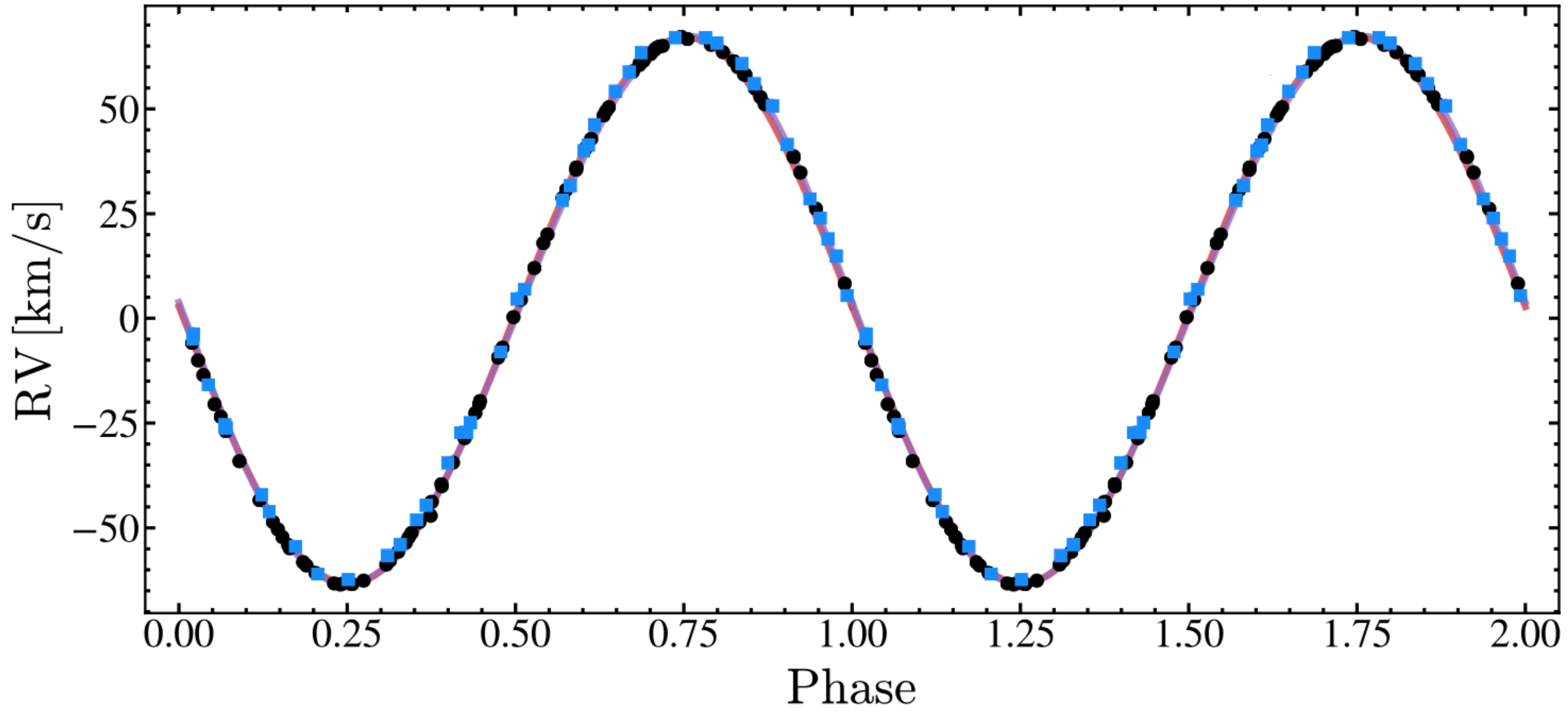




SB1 mass from ~~ellipsoidal variations~~ tidal RV signal

tidal RV





amplitude & shape (odd harmonics)

2 constraints on $\frac{M_2}{M_1}, \frac{R_1}{a}, i \quad (a^3 \sim M_1 + M_2)$

1 more unknown: R_1

binary mass function

$$\frac{PK_1^3(1-e^2)^{3/2}}{2\pi G} = \frac{M_2^3 \sin^3 i}{(M_1+M_2)^2}$$

1 constraint, **3** unknowns

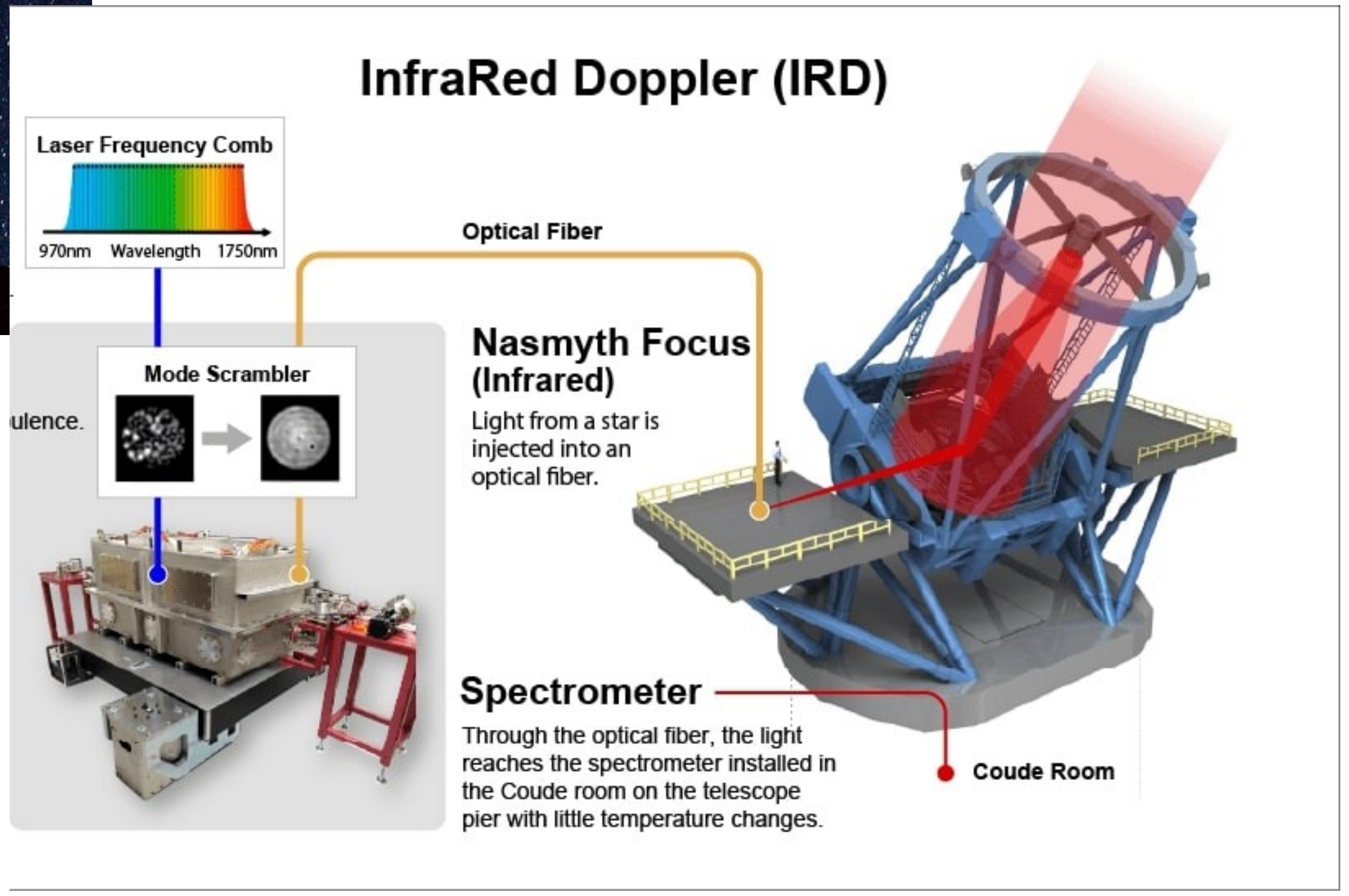
3 constraints vs **4** unknowns:

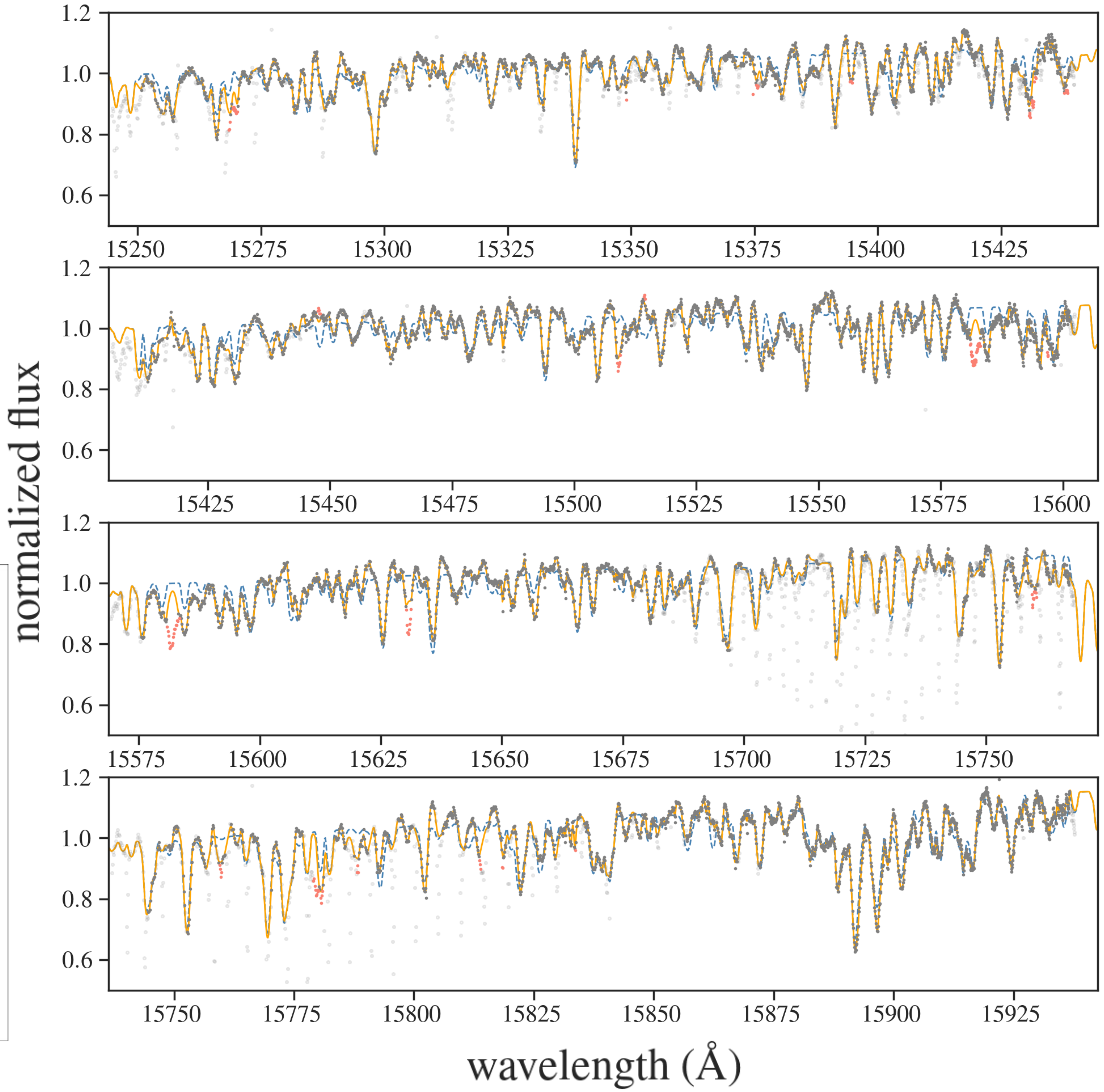
M_1, M_2, R_1, i solved with **1 more constraint** → $v \sin i$

"purely spectroscopic" mass measurement

$v \sin i$ from Subaru/IRD near-IR spectrum *Tomoyoshi, KM et al. (2024)*

- InfraRed Doppler instrument (IRD) on Subaru telescope
  - $R \sim 70{,}000$, YJH band spectrum





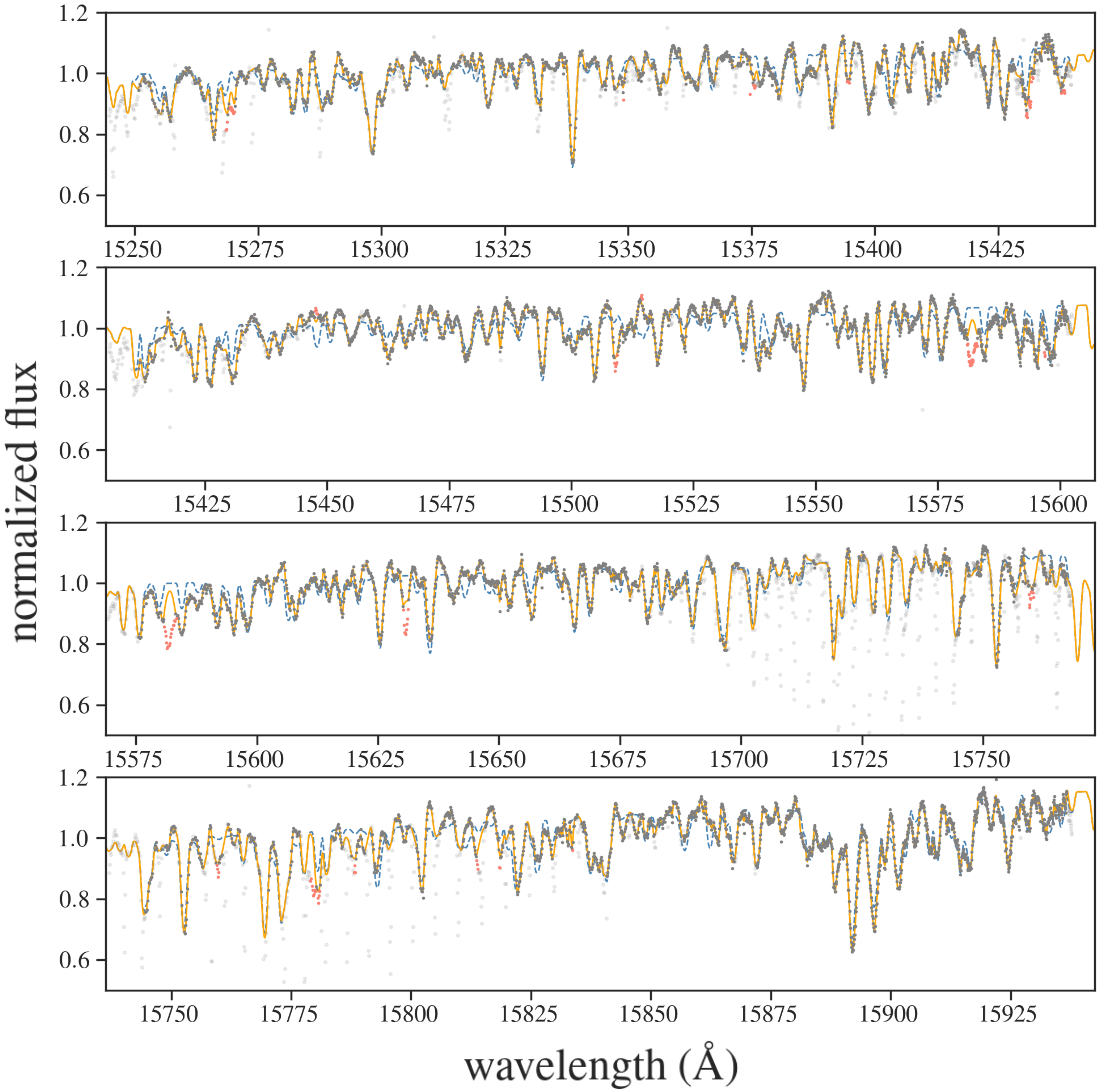
Tamura et al. (2012), Kotani et al. (2018)

$v \sin i$ from Subaru/IRD near-IR spectrum *Tomoyoshi, KM et al. (2024)*

- InfraRed Doppler instrument (IRD) on Subaru telescope
  - $R \sim 70{,}000$, YJH band spectrum

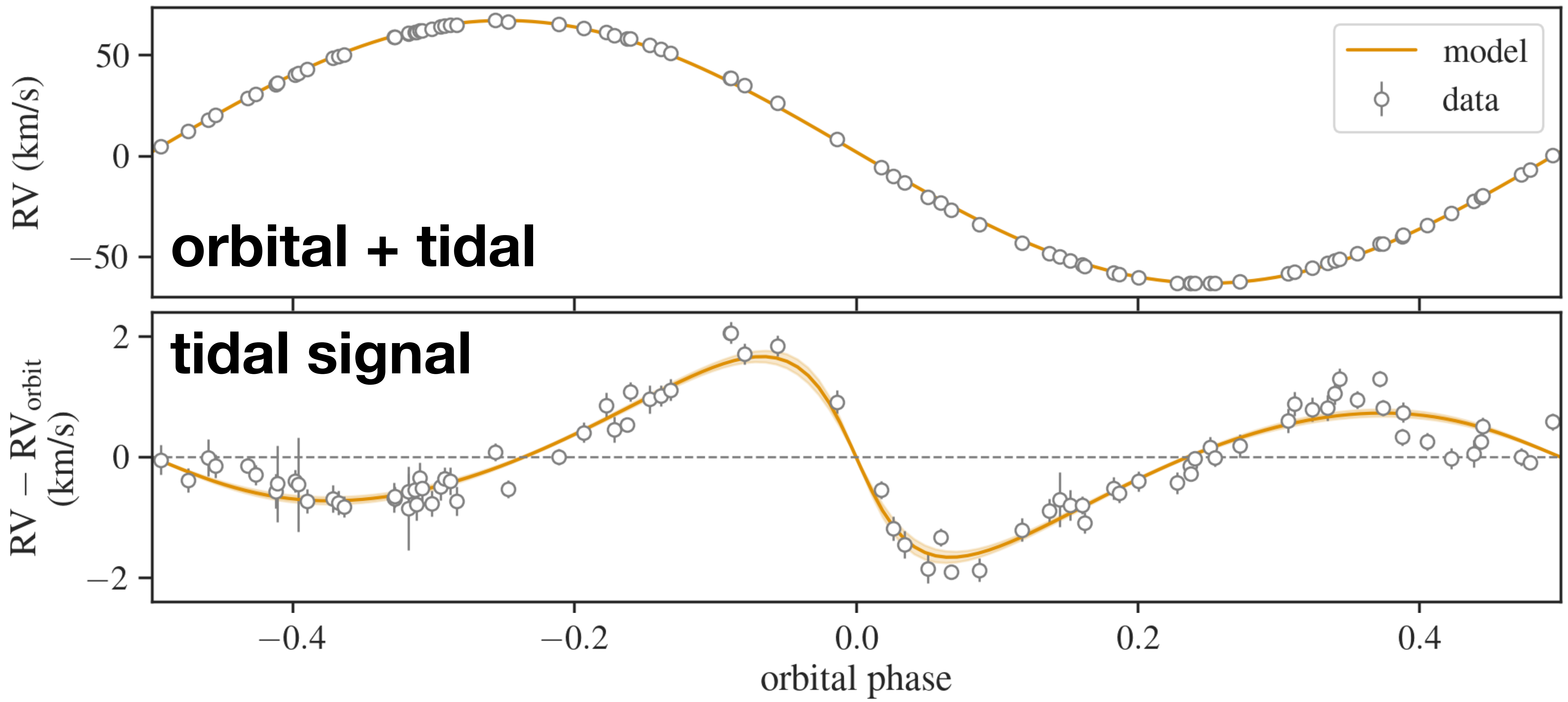
- synthetic model fitting w/ broadening due to $v \sin i$, macro-turbulence, and limb-darkening

- $v_1 \sin i = 15.8 \pm 1.0\,\mathrm{km/s}$



masses from tidal RV modeling

Tomoyoshi, KM et al. (2024)



- reasonable agreement with EV-based masses accounting for flux dilution
- tidal RV seems robust against this systematics

Our results based on RV & $v \sin i$

$$M_1 = 0.46^{+0.12}_{-0.09}\,M_\odot$$

$$M_2 = 2.5 \pm 0.2\,M_\odot$$

RV & EV & SED radius

$$M_1 = 1.00 \pm 0.07\,M_\odot$$

$$M_2 = 3.04 \pm 0.06\,M_\odot$$

Jayasinghe et al. (2021)

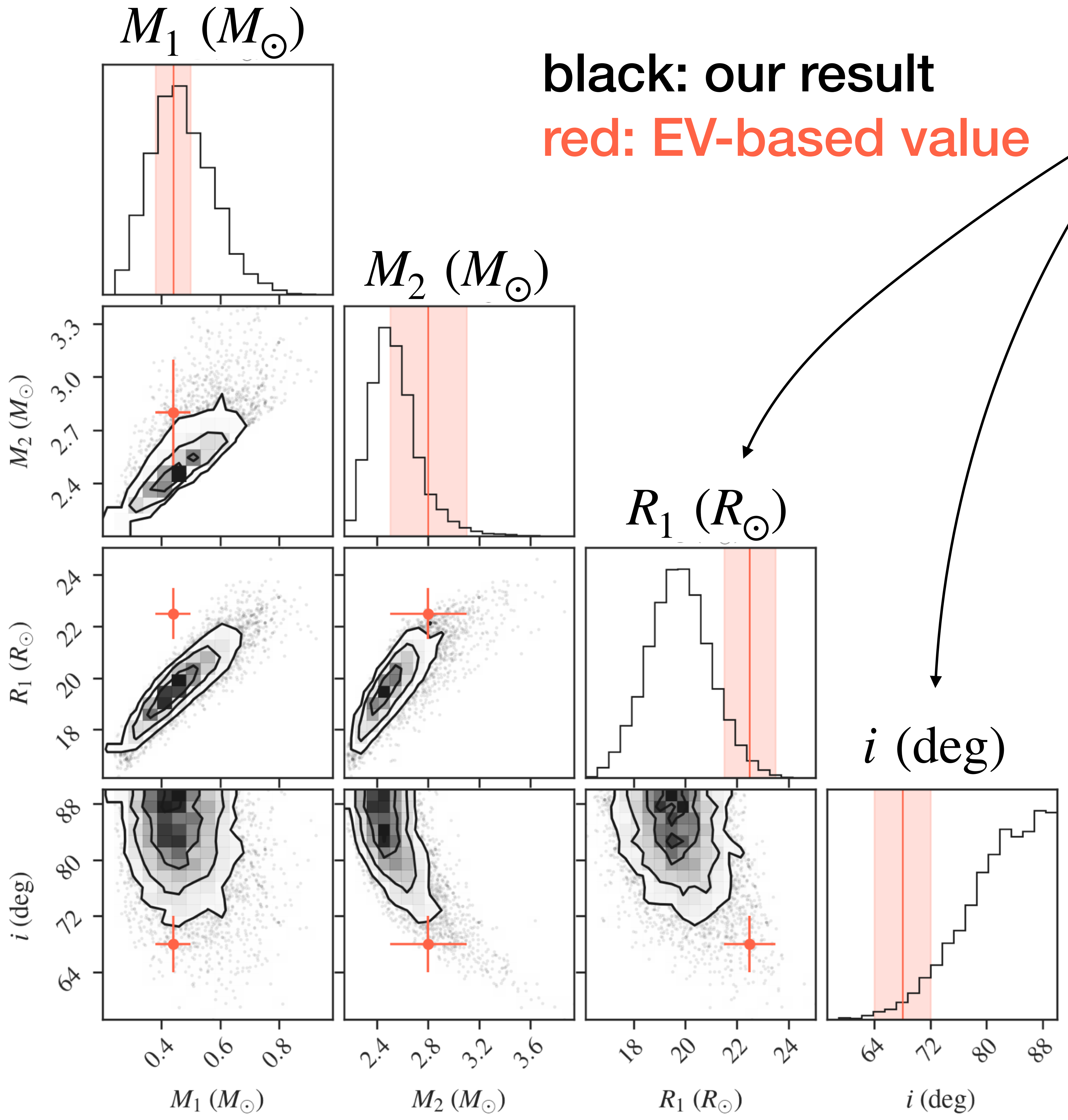
accounting for flux dilution

$$M_1 = 0.44 \pm 0.06\,M_\odot$$

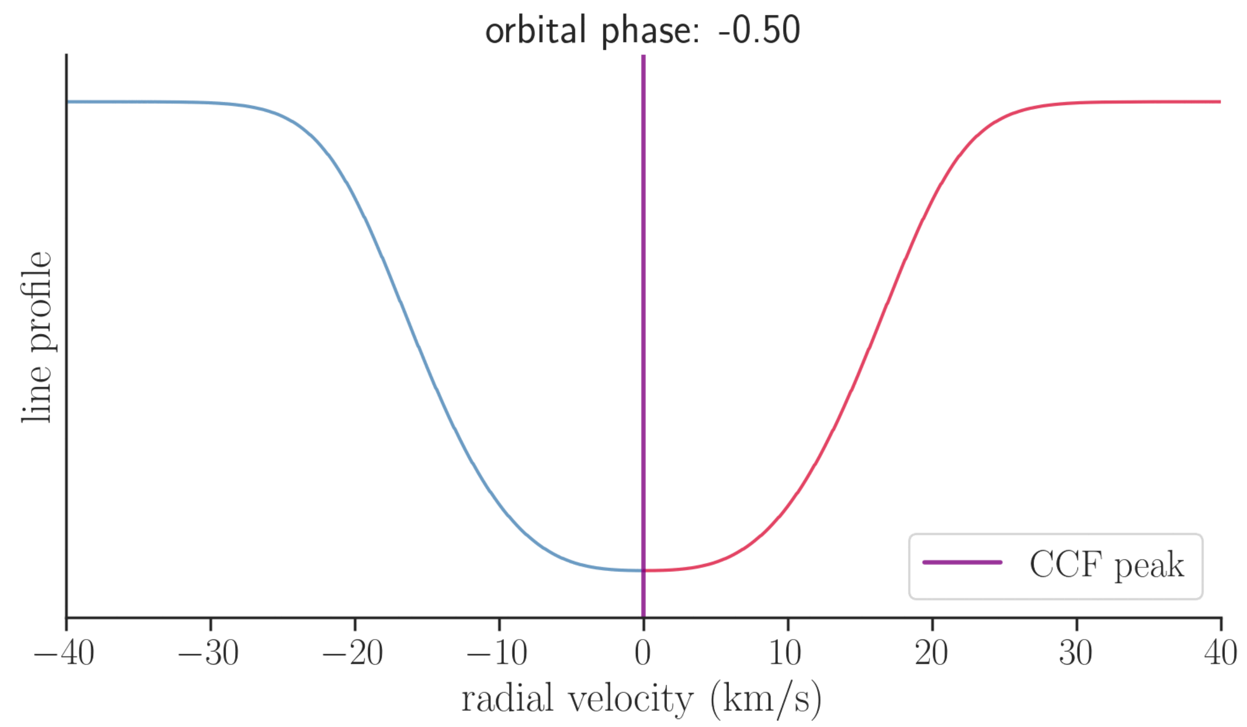
$$M_2 = 2.8 \pm 0.3\,M_\odot$$

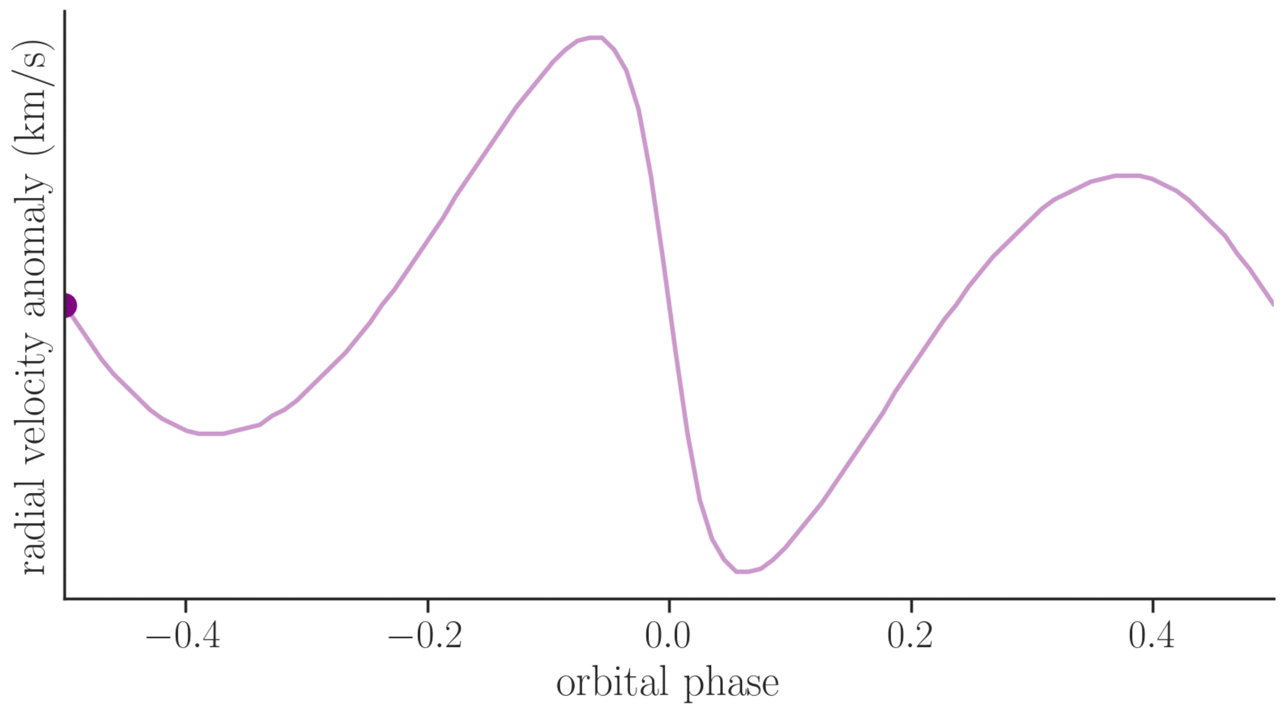
El-Badry et al. (2022)

systematic errors in radius & inclination? *Tomoyoshi, KM et al. (2024)*

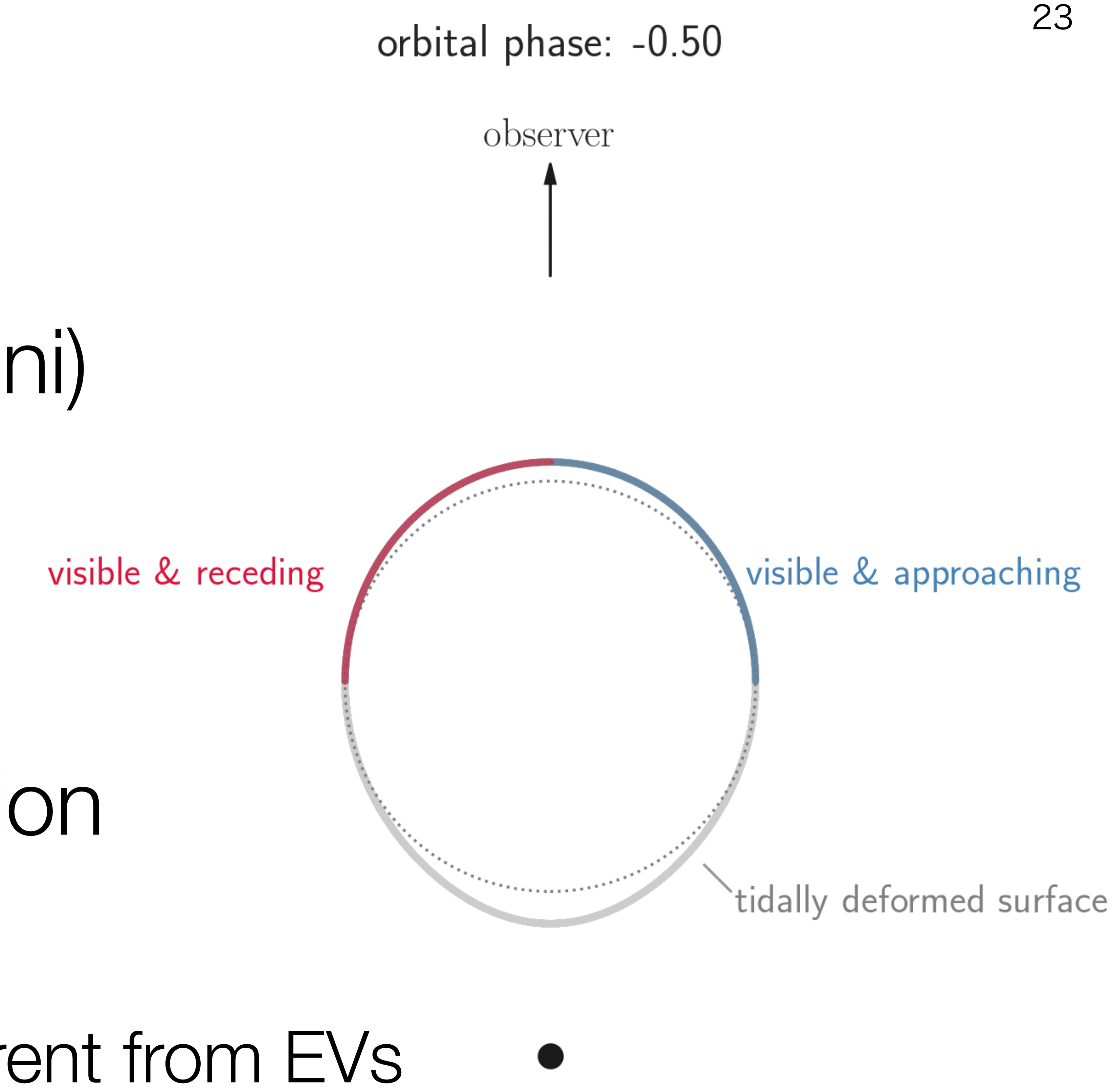


- $\sim 2\sigma$ tension in the estimated radius/inclination; systematic errors?
- direct modeling of line profiles may help clarify/reduce systematics





conclusions



- SB1 mass can be measured using tidal RVs (and vsini)
  - i.e., only positions & shapes of absorption lines
  - no absolute flux measurements, no evolutionary models
- the resulting masses are not so sensitive to flux dilution
  - can be a useful alternative to ellipsoidal variations
  - this method may (also) suffer from systematics, but those different from EVs
- potentially useful for secure mass measurements in tidally-deformed SB1s, including
  - known X-ray systems
  - *X-ray faint* compact object binaries that are being uncovered from ongoing large astrometric/spectroscopic/photometric surveys