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On the signature of a 70-solar-mass black hole in LB-1

The Nature of LB 1-like Systems

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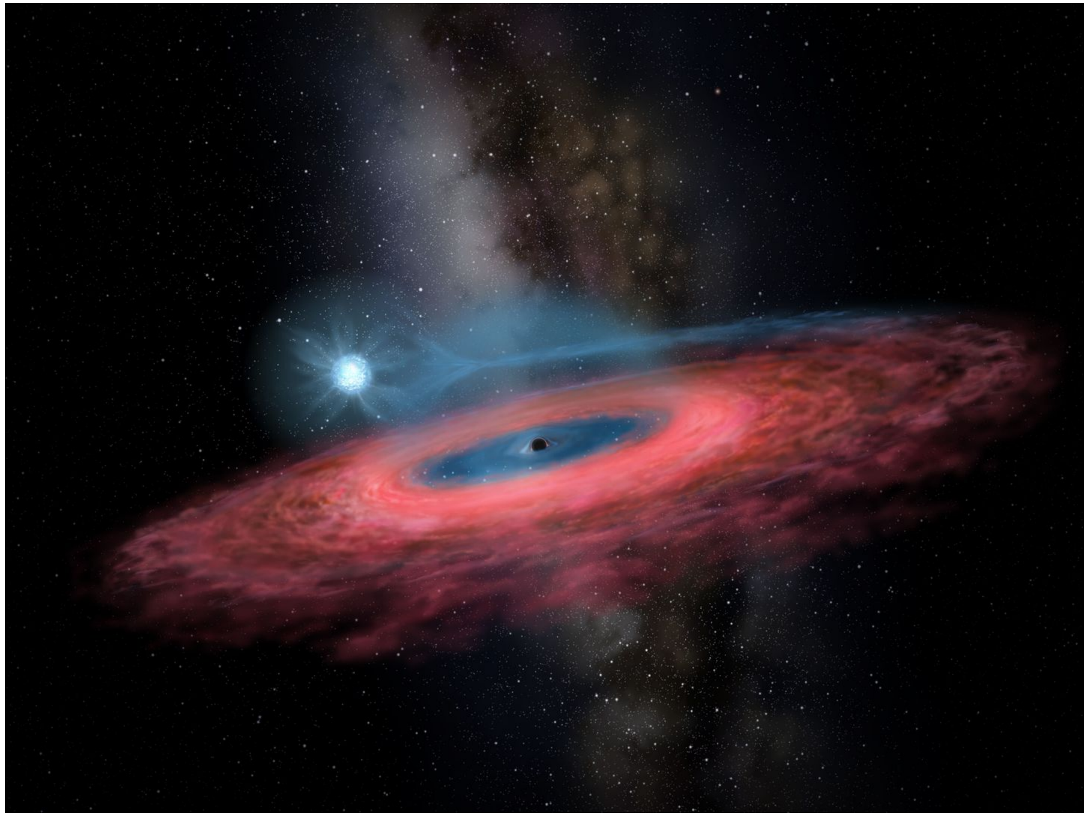
LB-1 system



Yu Jingchuan

Clue: The motion of the B star (radial velocity) + an accompanying Hα emission line

Conclusion: 68 solar mass BH and a companion B-type star

Jifeng Liu et al. 2019

LAMOST

Chandra X-ray Observatory

Spectroscopy

Non-detection of X-ray

GTC/OSIRIS

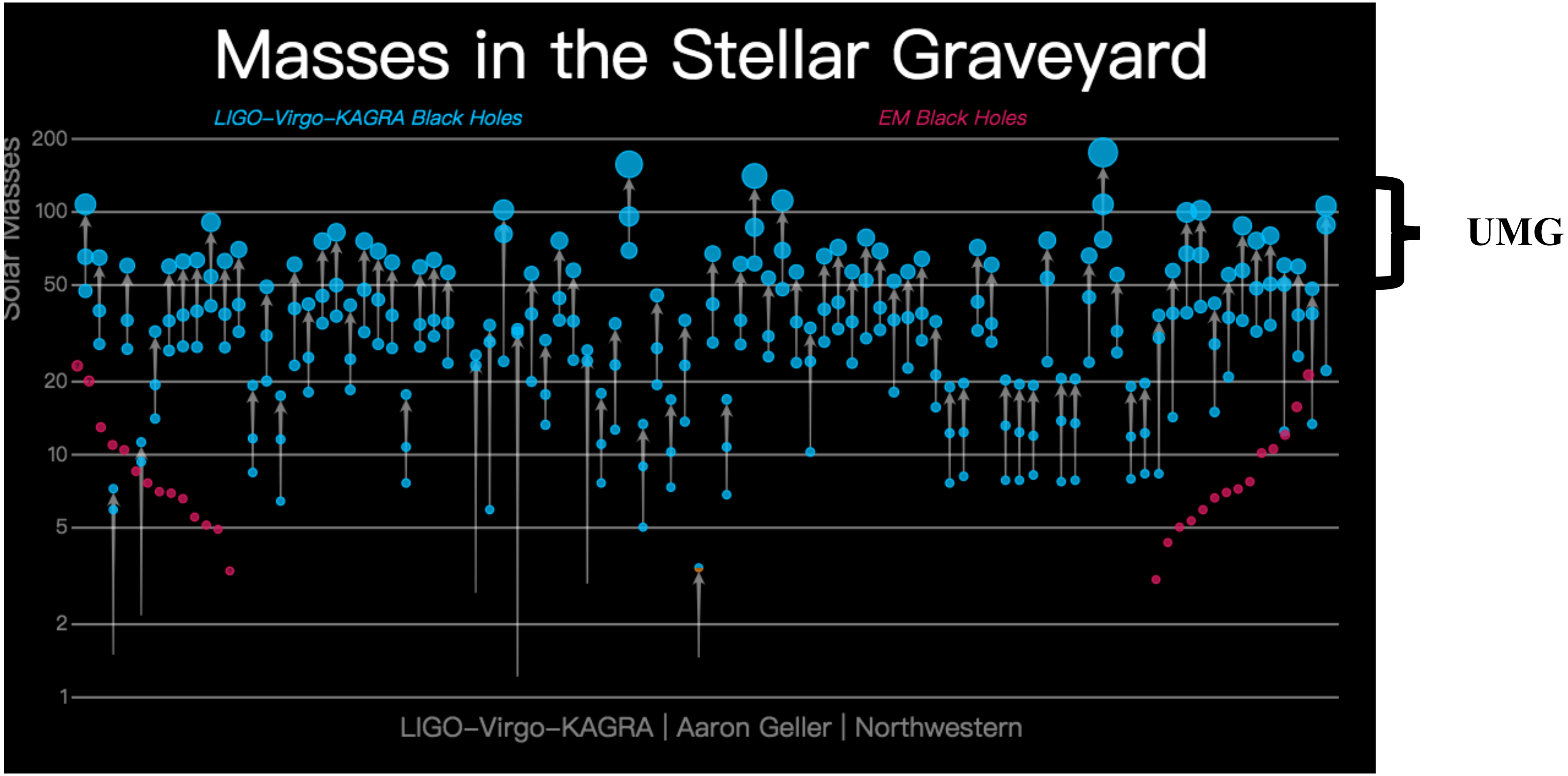
Keck/HIRES

Credit: Caltech

Properties of LB-1 BH

- **High mass**
- **Non-interacting**

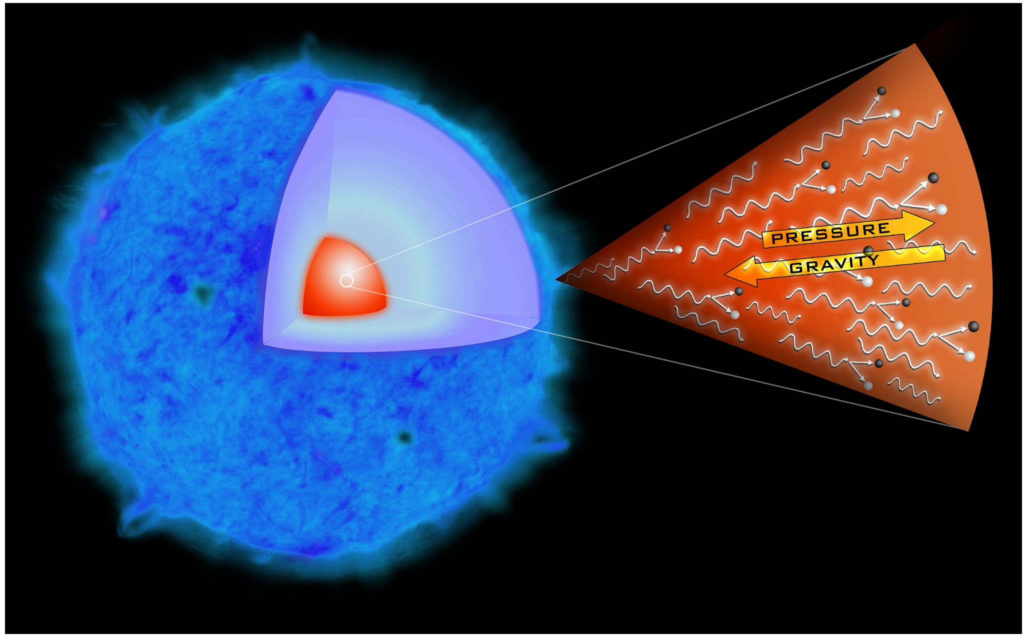
Upper mass gap (UMG)



UMG: 50-150 (52-133) solar mass

Upper mass gap (UMG)

Pair-instability supernova

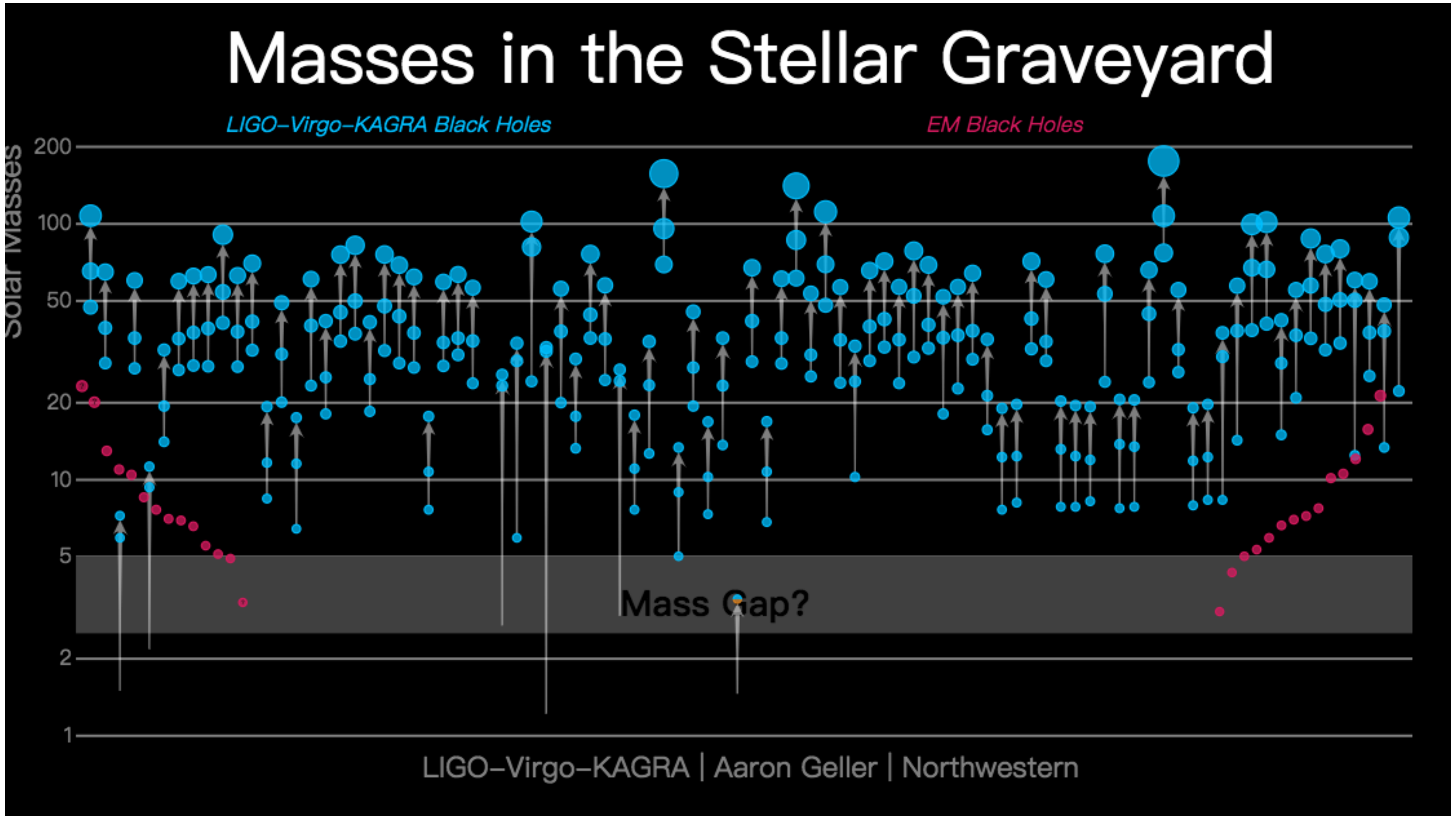


- Collision between atomic nuclei and energetic gamma rays
- Production of free electrons and positrons (consume energy)
- Reduces the internal radiation pressure
- Partially collapse under its own huge gravity
- Runaway thermonuclear explosion

130 to 250 solar masses
low to moderate metallicity (**Population III stars**)

Lower limit: 45 (pair-instability pulsational mass loss) - 60 (nonrotating stars) $M_\odot$

Lower mass gap (LMG)



LMG: 2-5 solar mass

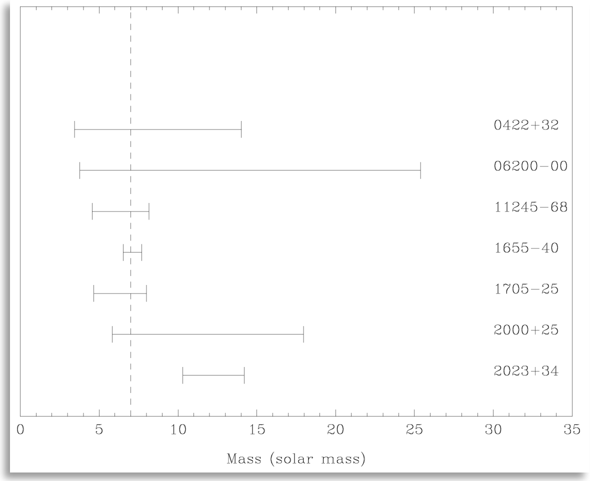
Tolman–Oppenheimer–Volkoff **limit of neutron star**: around 2 solar masses

Lower mass gap (LMG)

Black hole mass distribution in low-mass X-ray binaries

Discovery (Bailyn et al, 1998)

- The supernova explosion itself.
- The binary nature of the observed systems.



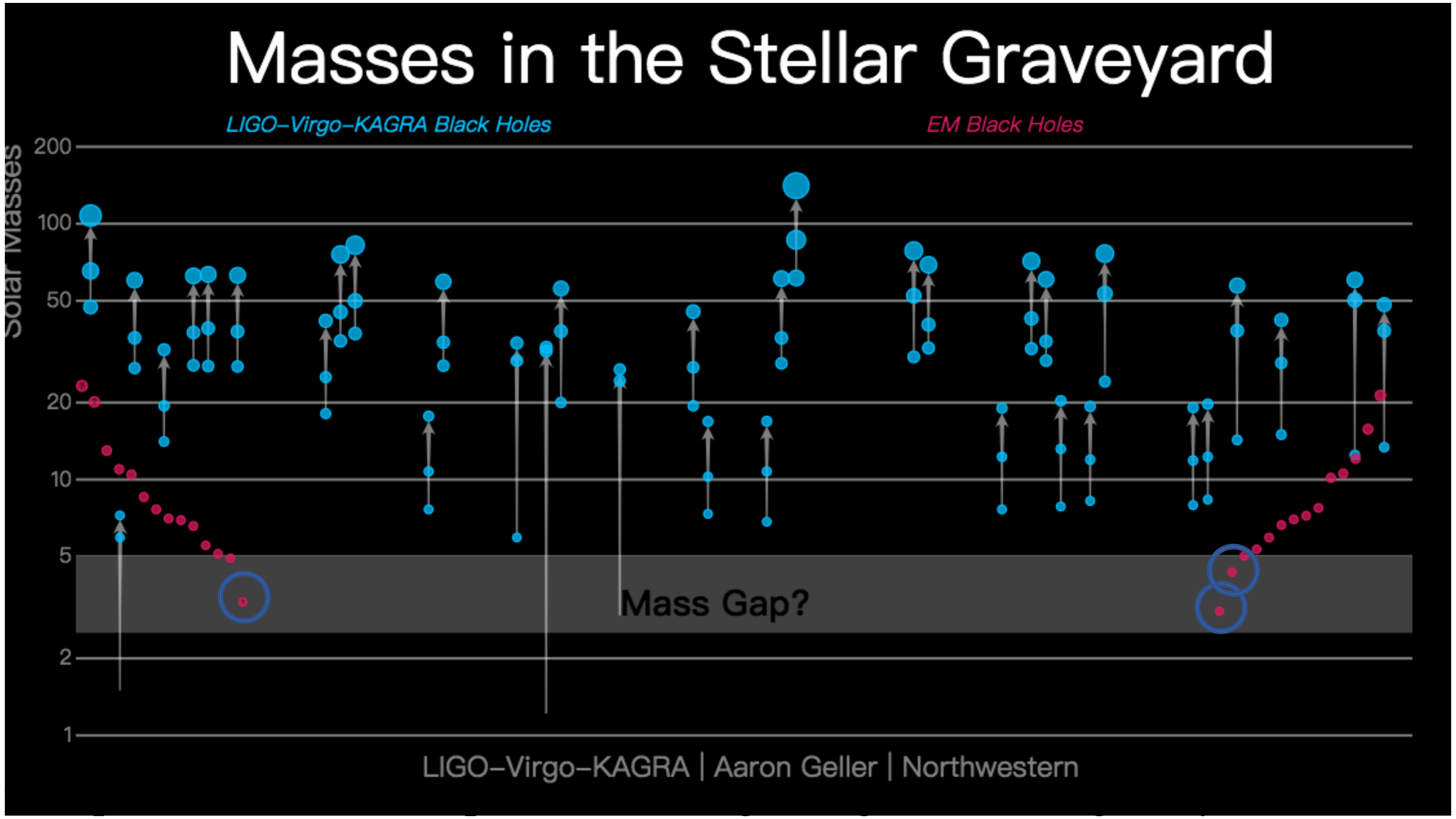
Simulation (Fryer 1999 ; Fryer & Kalogera 2001)

- A step-like dependence of supernova energy on progenitor mass
- Selection biases.

More explanation (Postnov & Cherepashchuk 2003)

- Black hole evaporation in braneworld gravity models?

LMG?



Third Observing Run (between 1 April 2019 15:00 UTC and 27 March 2020)

Undetectable via the usual x-ray signature?

Properties of LB-1 BH

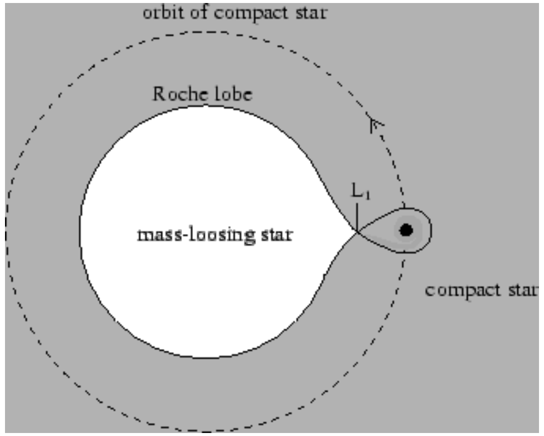
- High mass
- Non-interacting

Non-interacting BH systems

Interacting BH systems

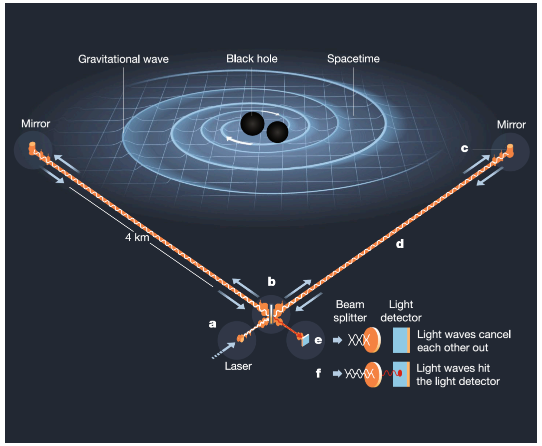
X-ray binaries

- The companion must either fill its Roche lobe
- or have a modest separation and a strong wind.



Gravitational wave observations

- Very small fraction of surviving binaries
- On very short orbits leading to a merger



Non-interacting BH binaries

- Hard to find
- Important & Far larger population

Non-interacting BH systems

Before

Numerous spectroscopic and photometric surveys (since more than 50y ago)

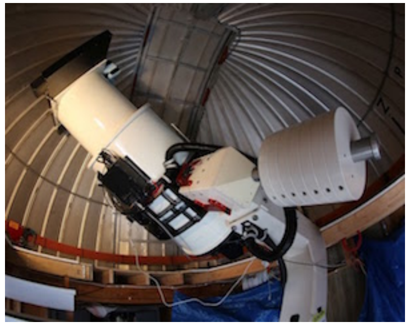
Recently

- Rapidly increasing **wide-field surveys**
- and growing interest in the **progenitors** of **gravitational wave sources**.

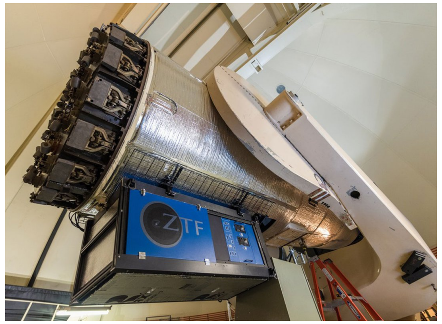
Giraffes in the binary zoo

Light curves

TESS



ATLAS



ZTF

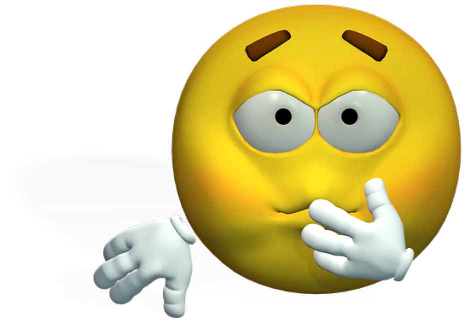
RV signal

LBT

BH or not?

Two typical systems: mass-gap, non-interacting

- LB-1 system (UMG)
- Giraffes (LMG)



Debate on

- Model fitting
- Hα emission line
- …

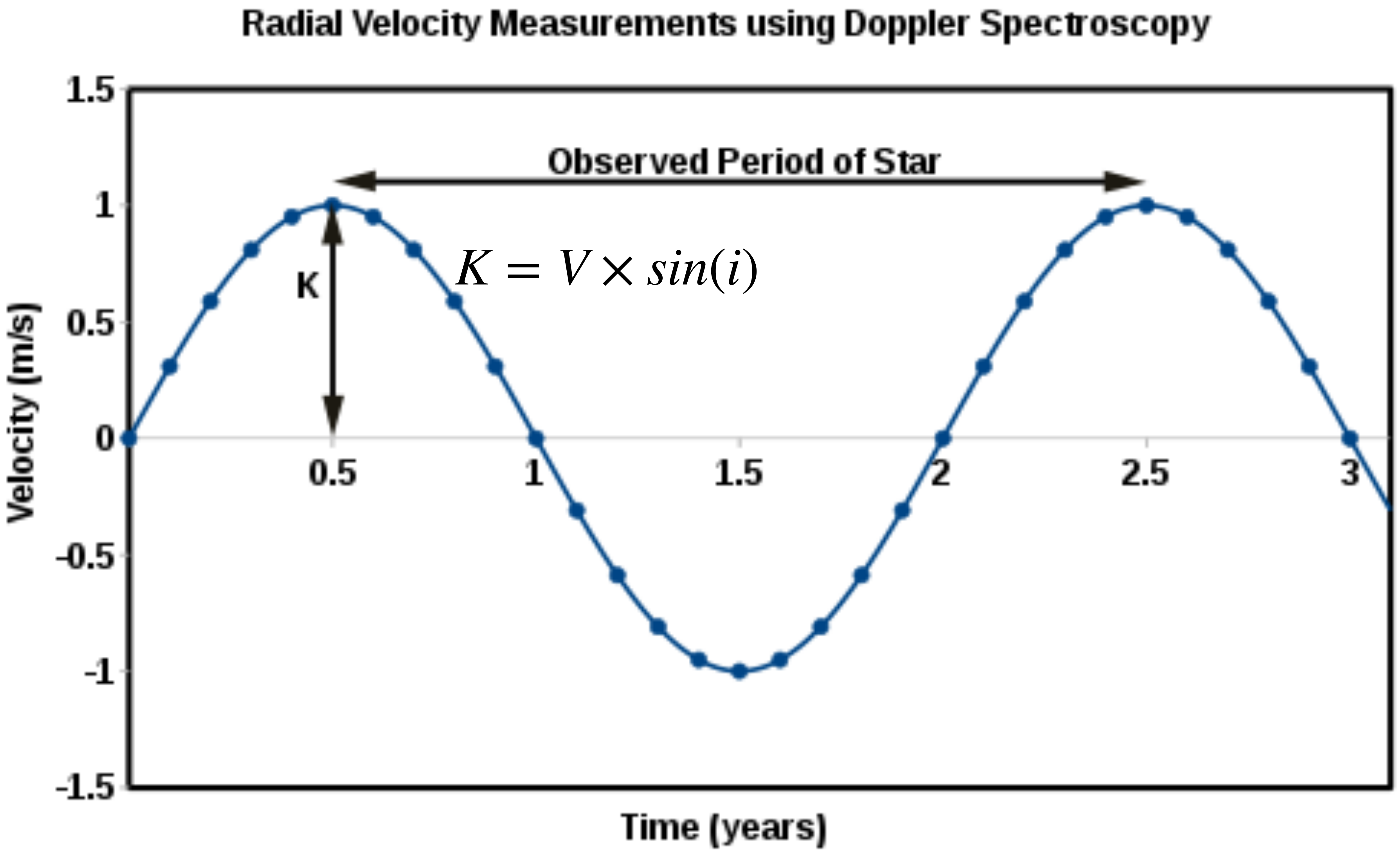
Yes!

No

LB-1

Liu et al. 2019 (Nature, 575, 618)

Radial velocity of a binary system



$$K = V \times sin(i)$$

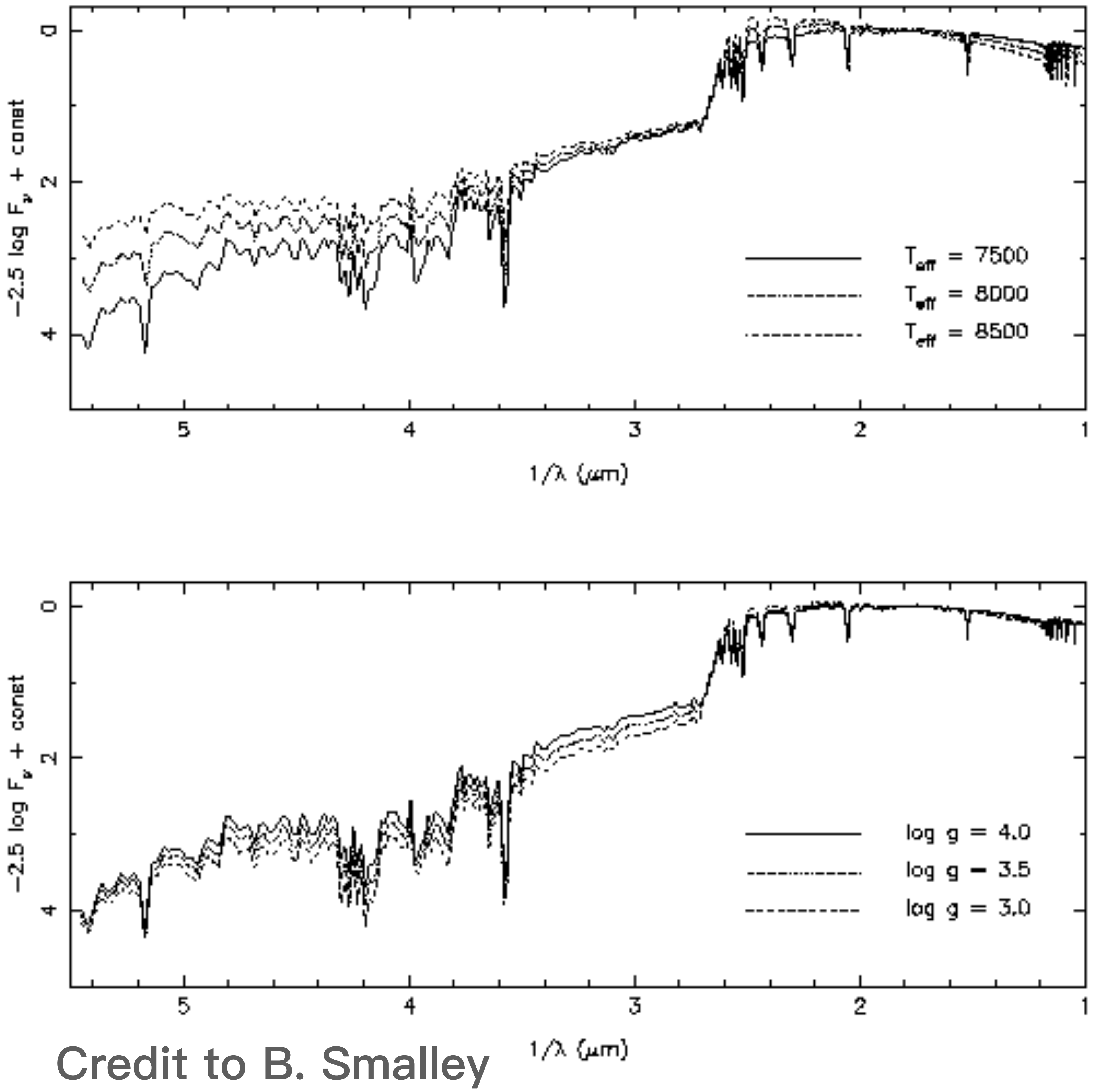
$$M_{comp} = \frac{M_{star} \times K_{star}}{K_{comp}}$$

$$\frac{PK^3(1 - e^2)^{1.5}}{2\pi G} = \frac{M_{unseen}^3 sin^3 i}{(M_{unseen} + M_{seen})^2}$$

$$a^3 = \frac{G(M_{unseen} + M_{seen})P^2}{4\pi^2}$$

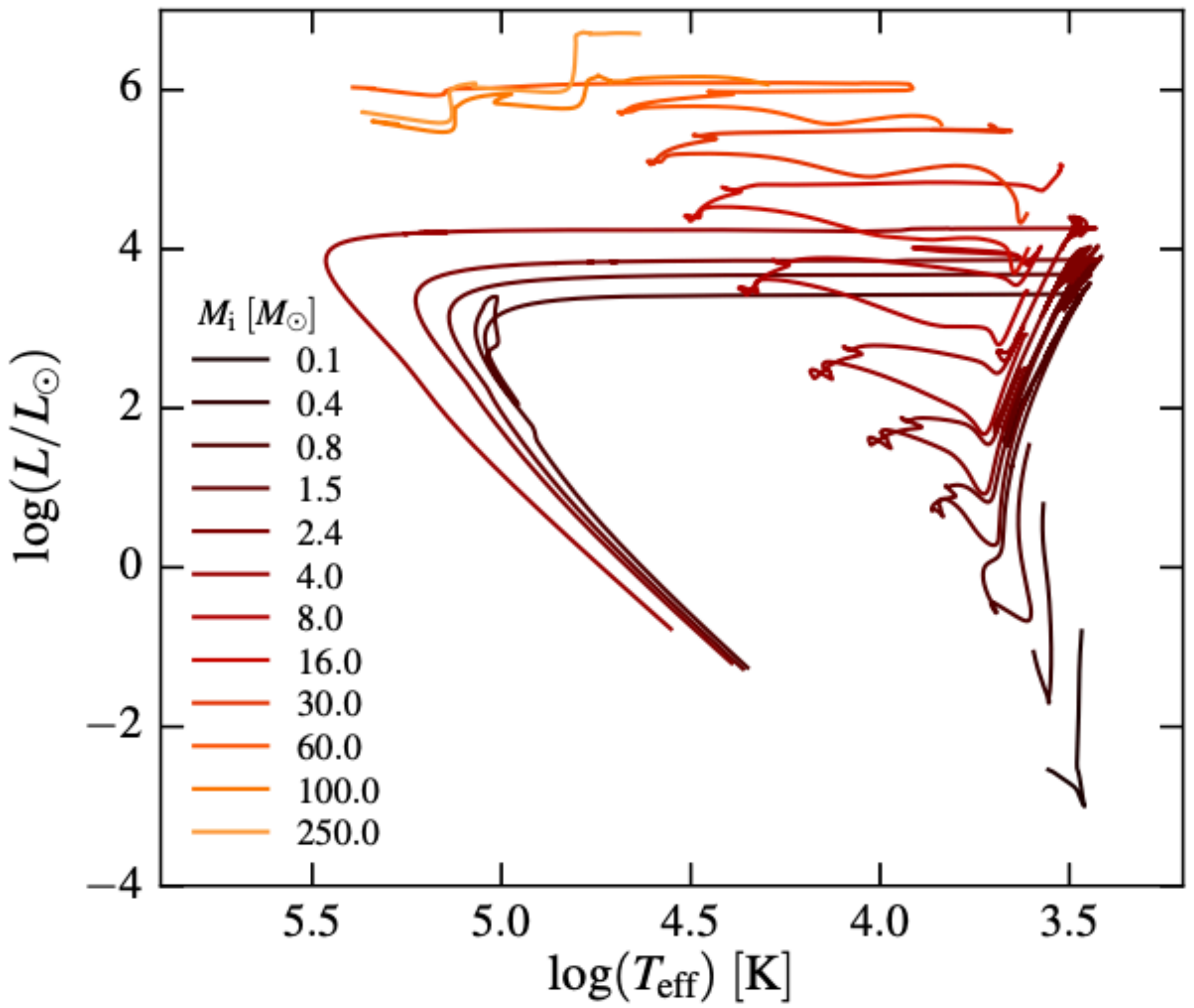
Stellar fitting of spectra, isochrone

The flux distribution to the various atmospheric parameters for an A-type star



Credit to B. Smalley

solar metallicity grid of stellar evolutionary tracks



Jieun Choi et al. 2016

Spectrum fitting + Distance + isochrone fitting —> constrain the properties of stars

LB-1

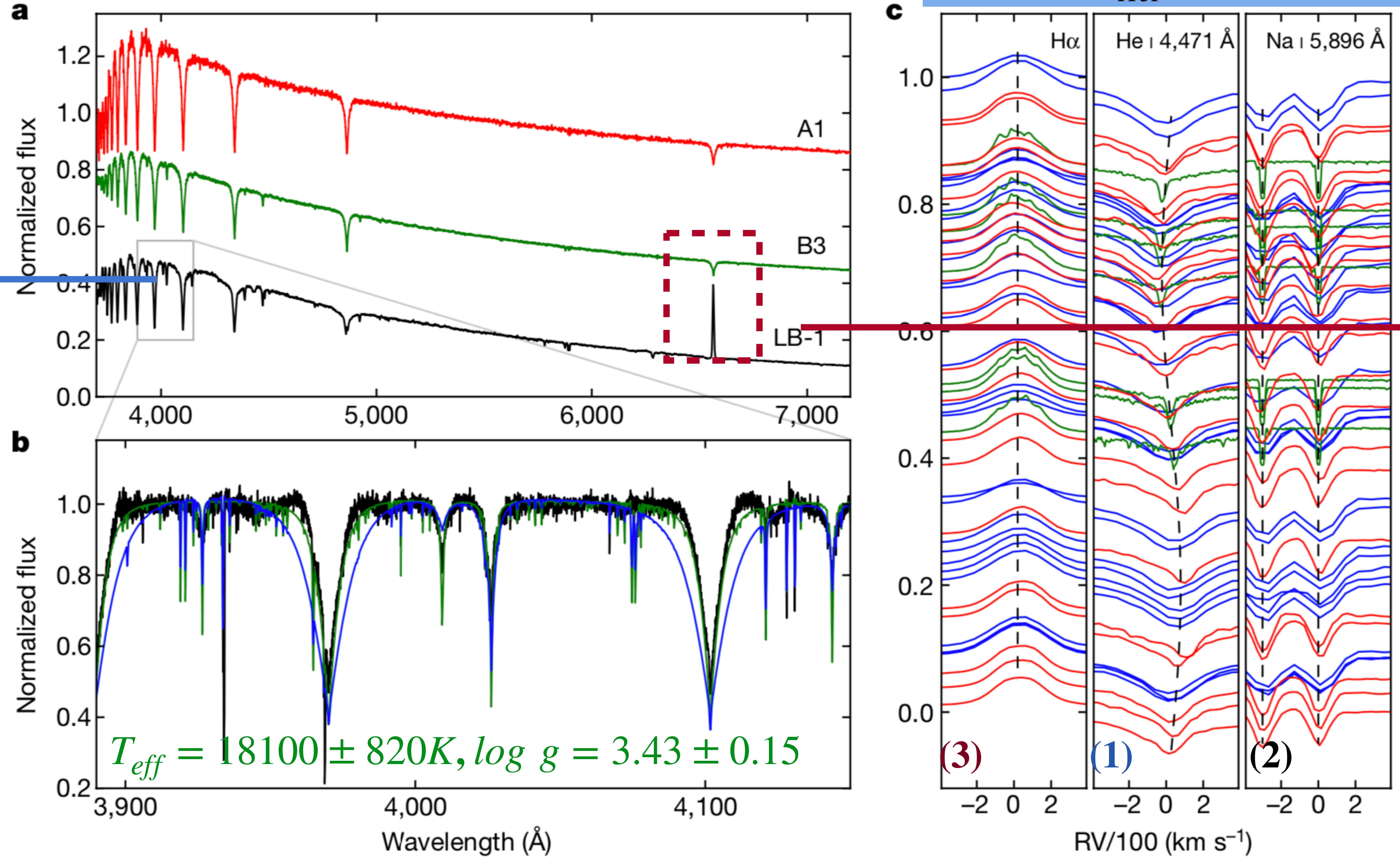
- One of the LAMOST target, shows periodic radial-velocity variation + strong H_α emission line
- Spectra from LAMOST+ higher resolution spectra from Keck & GTC
- Wide band spectral energy distribution (SED) from the UCAC4 catalogue, 2MASS and the AllWISE data release
- Chandra: Non-detection in X-ray

RV + spectra fitting —> $M_{comp} = \dfrac{M_{star} \times K_{star}}{K_{comp}}$

B star + dark companion ~ $68M_\odot$
Non-interacting black hole

Spectra of LB-1 contain 3 components

(1) stellar component (dominant), absorption lines with periodic motion



P=78.9d, K_{HeI}=52.8 $\pm$ 0.7km/s

$$M_{comp} = \frac{M_{star} \times K_{star}}{K_{comp}}$$

$T_{eff} = 18100 \pm 820K$, $log\ g = 3.43 \pm 0.15$

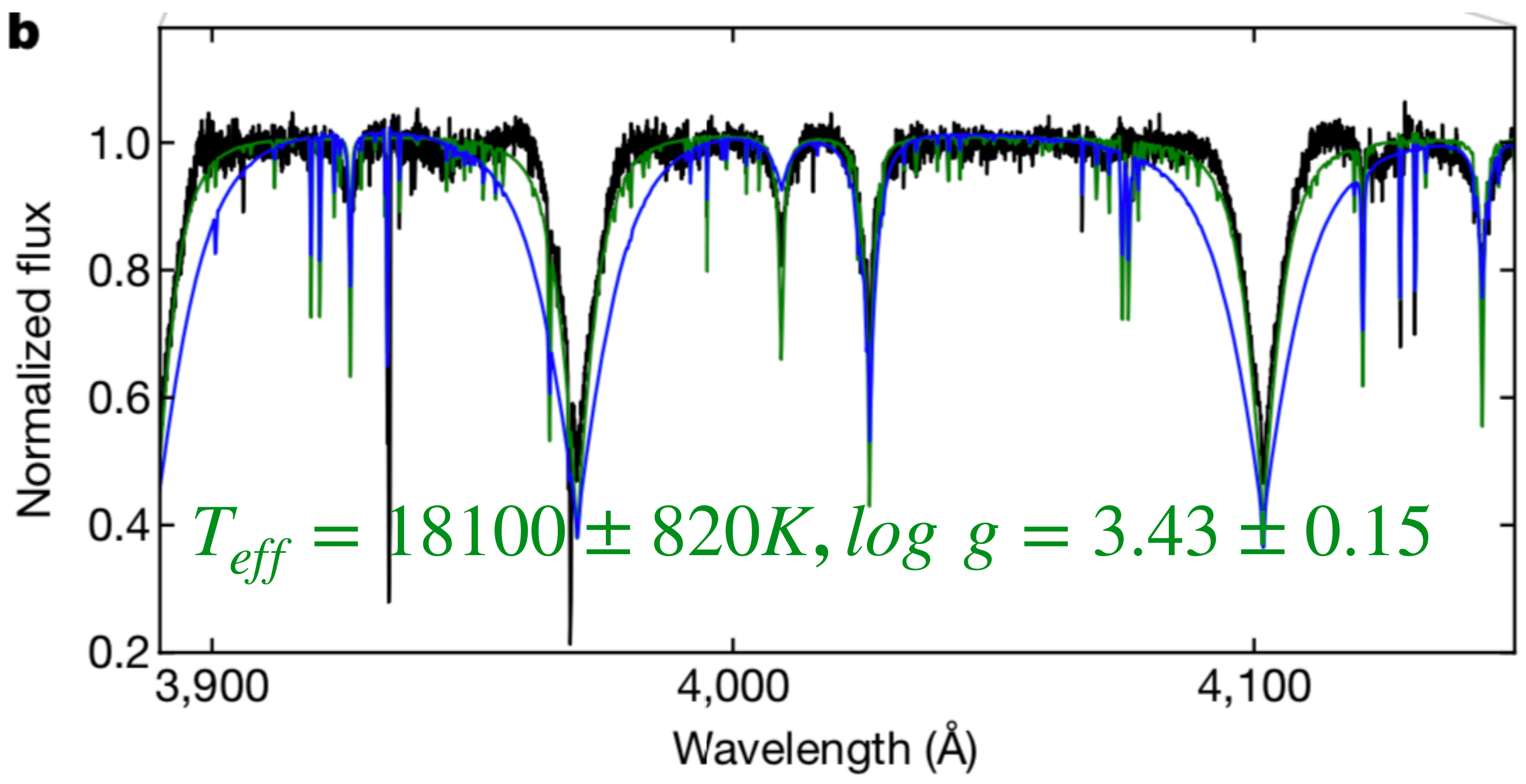
(2) interstellar absorption lines (e.g. NaI), stable

(3) broad H_α emission line, anti-phase periodic motion with star Unknown origin

Spectrum fitting of signal star: **mask** H_α **and** H_β, because they are contaminated by emission lines from other component

Constrain properties of the visible star

From spectrum fitting, get T_{eff} and $log\ g$, likely to be a B-type star or a subdwarf



From spectrum fitting, the Balmer lines is too narrow for a subwarf.

With T_{eff} and $log\ g$, generate theoretical SED models. Compare theoretical models with real SED: Distance (D)=4.23± 0.24kpc, E(B-V)=0.55±0.03mag

—> too far for a subdwarf!

A sub-giant B star, $M_B = 8.2^{+0.9}_{-1.2} M_\odot$, $R_B = 9 \pm 2 R_\odot$, age = 35^{+13}_{-7}Myr, metallicity (1.2±0.2)$Z_\odot$

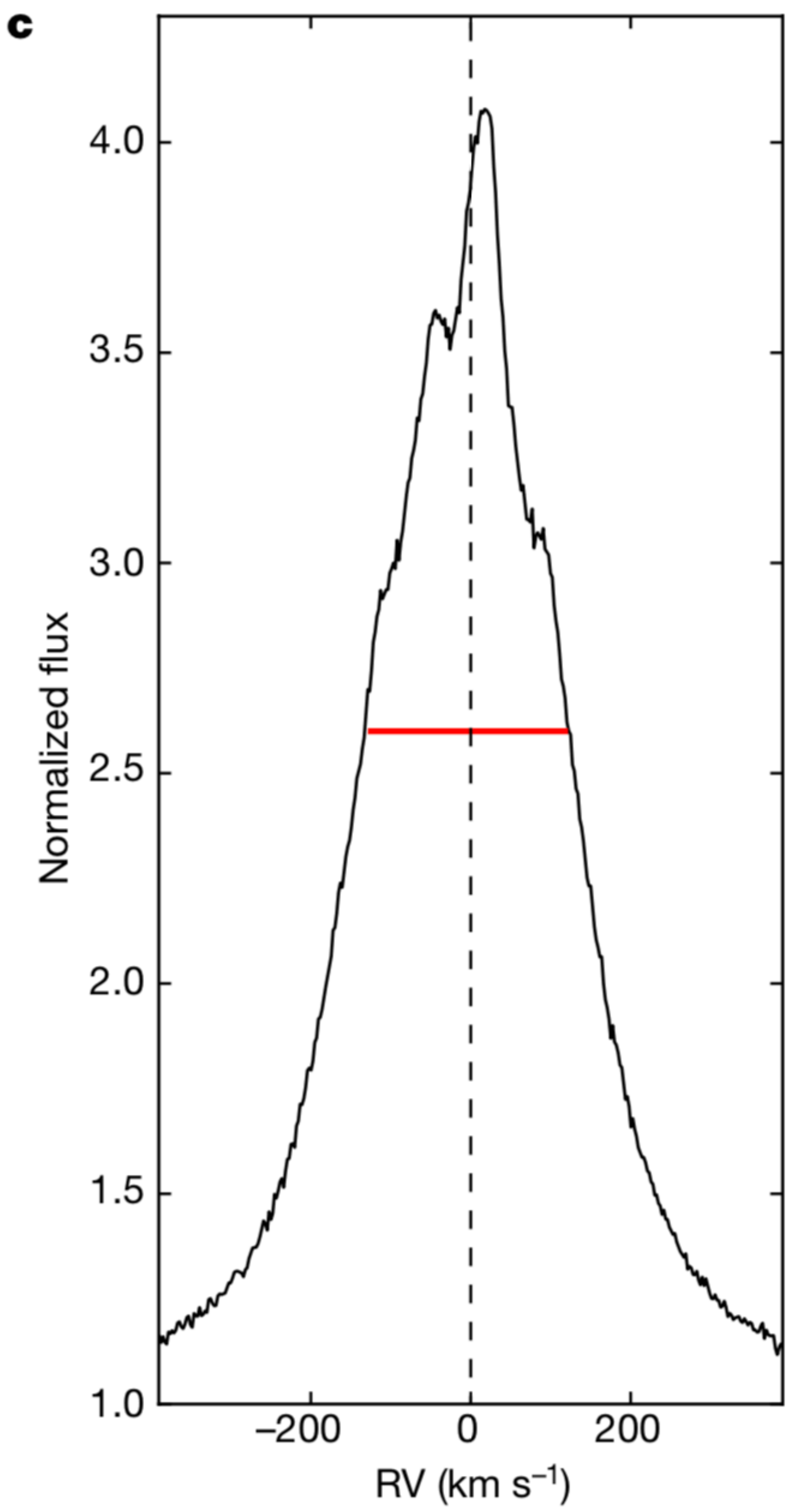
P + M_B —> M_{comp}~(6-250)$M_\odot$, degenerate with inclination

Too faint to be a main sequence star,

a black hole!

$$M_{comp} = \frac{M_B \times K_B}{K_{comp}}$$

The origin of broad H_α emission line



M dwarf or surrounding nebulae ❌ —> the emission line is too broad

A gaseous Keplerian disk of

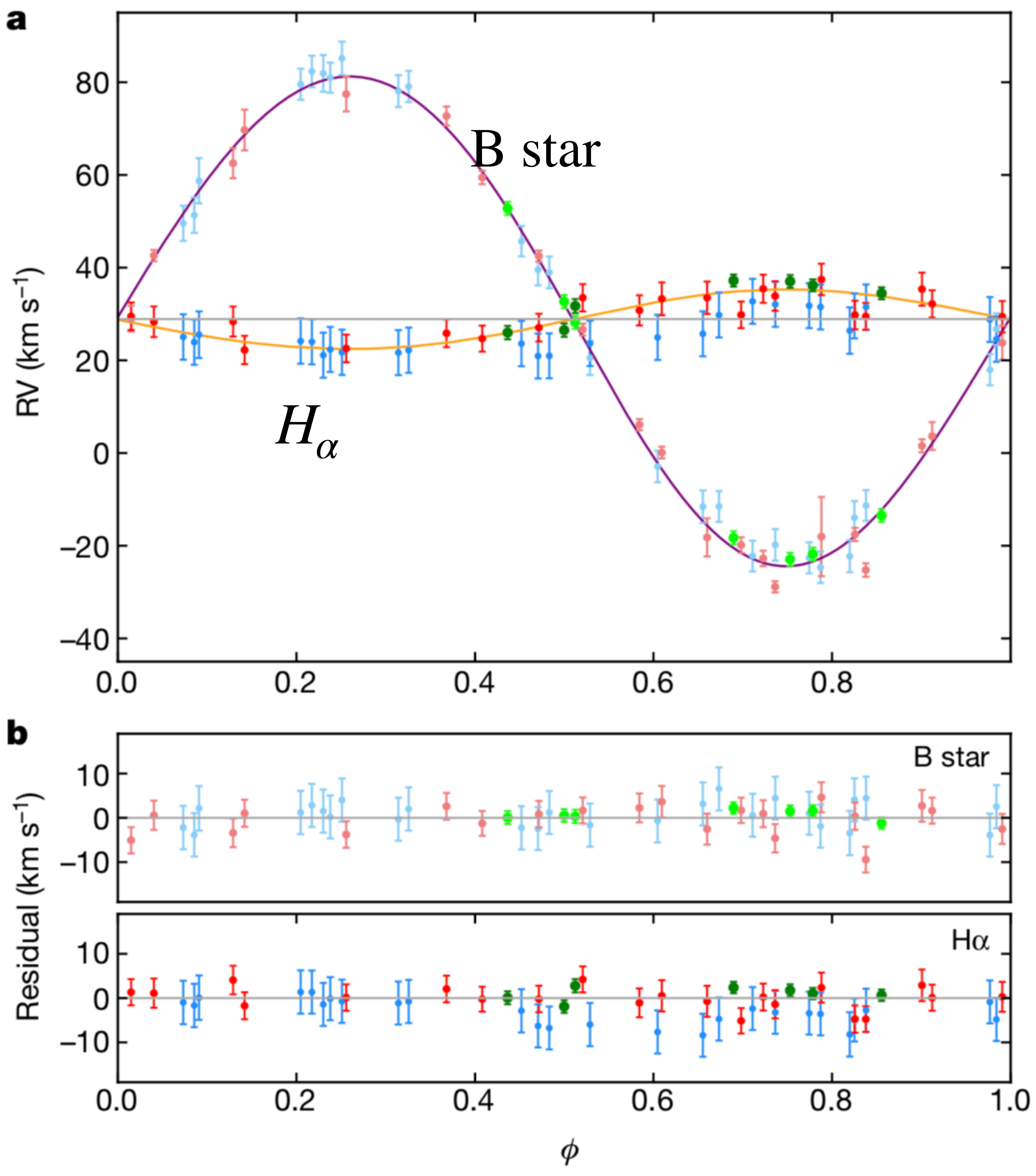
- Around B star ❌ —> not tracing the motion of B star
- Circumbinary disk ❌ —> the FWHM is too large
- Around black hole ✅, but may contaminated by e.g circumbinary materials, accretion spots in line centre

Mask from centre region, measure the RV —> the measurement converge when mask region large than 1/3 height.

Find $K_{H_\alpha} = 6.4 \pm 0.8$km/s.

$$M_{comp} = \frac{M_B \times K_B}{K_{comp}}$$

Fit RV, constrain the mass of black hole



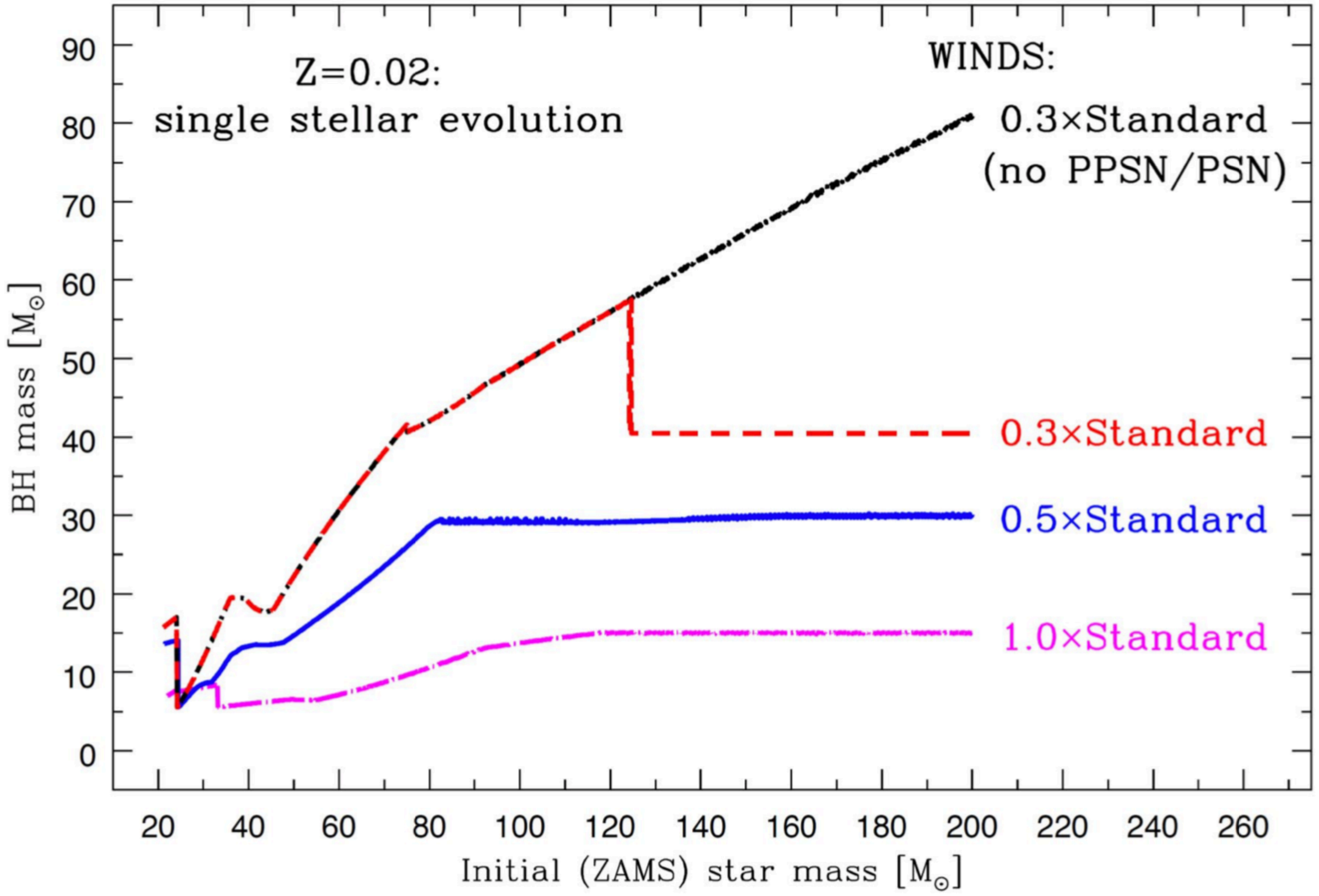
Fit RV, find $K_{H_\alpha} = 6.4 \pm 0.8$km/s.

$$M_{comp} = \frac{M_B \times K_B}{K_{comp}} = \frac{M_B \times K_B}{K_{H_\alpha}} = 68^{+11}_{-13} M_\odot$$, inclination angle i~15°-18°

How to form this kind of black hole?

$M_{comp} = 68^{+11}_{-13} M_{\odot}$, reach the upper mass gap of black hole.

Also, the metallicity of B star is about $1.2 Z_{\odot}$, much higher to form massive black hole (need $<0.2 Z_{\odot}$)



Even with low metallicity, this system still challenge the current stellar formation theories

Two possible models:
(1) actually, two black holes

(2) Initially, it is a triple system. Later on, the inner two form a massive black hole, the outer one evolve to a B star.

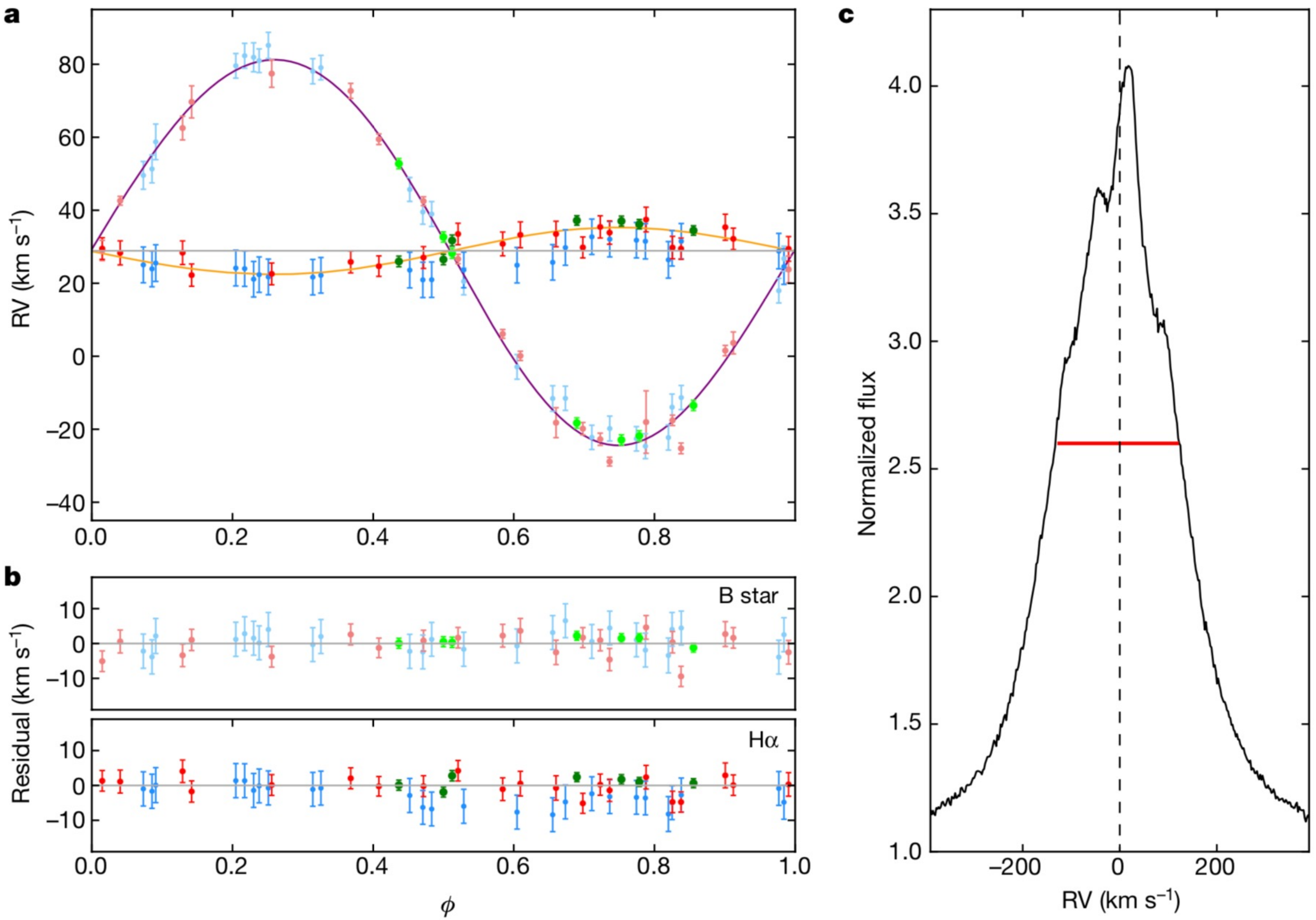
Summary of LB-1

From spectrum fitting, they constrain the properties of LB-1 system:

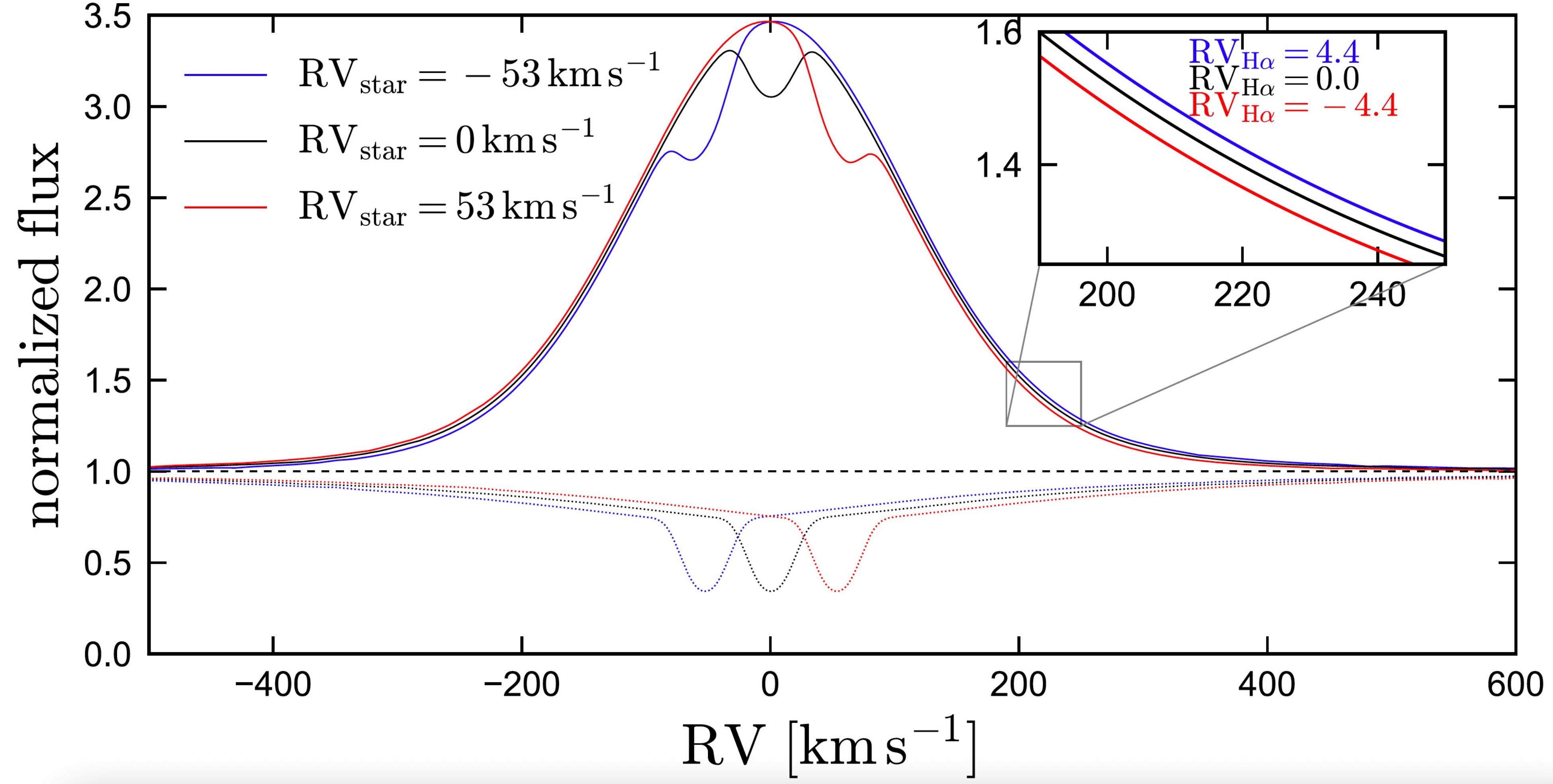
B star + dark companion ~ $68M_\odot$
Non-interacting black hole that reaches upper mass gap

In their analysis, the assumption of H_α emission is important for determining the BH mass.

❖ The LB-1 system

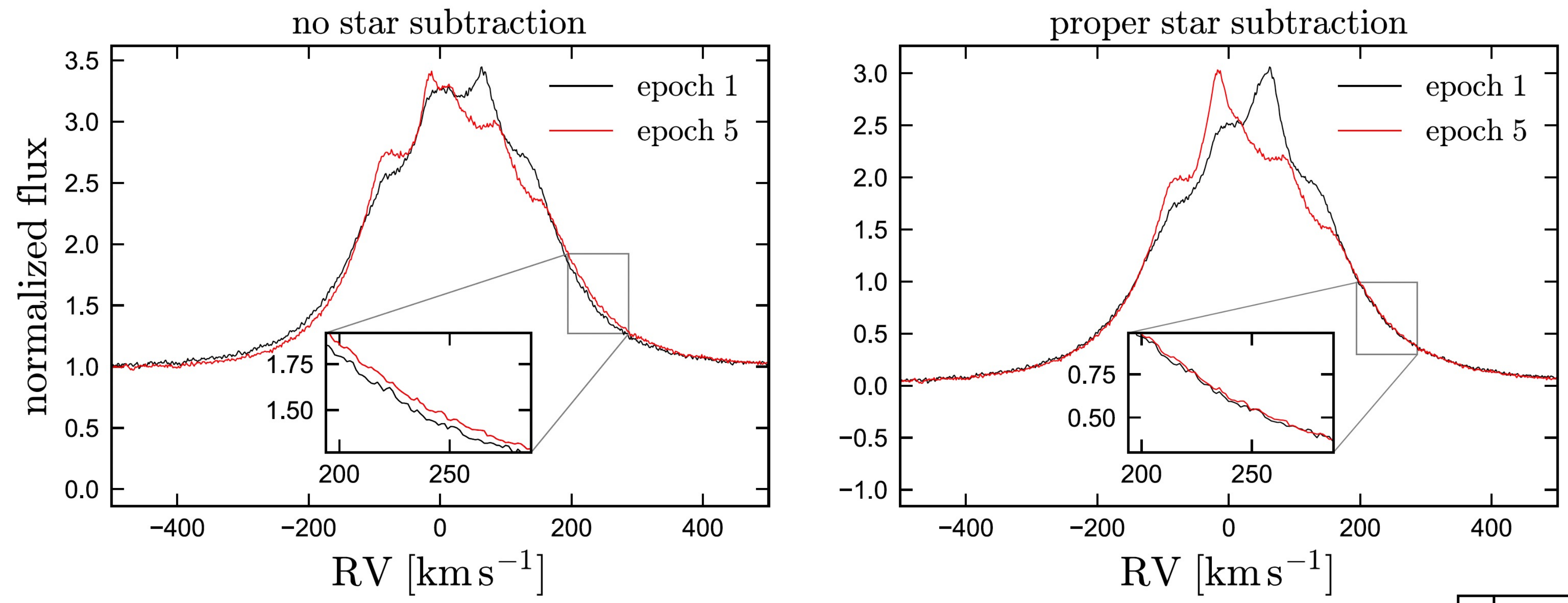


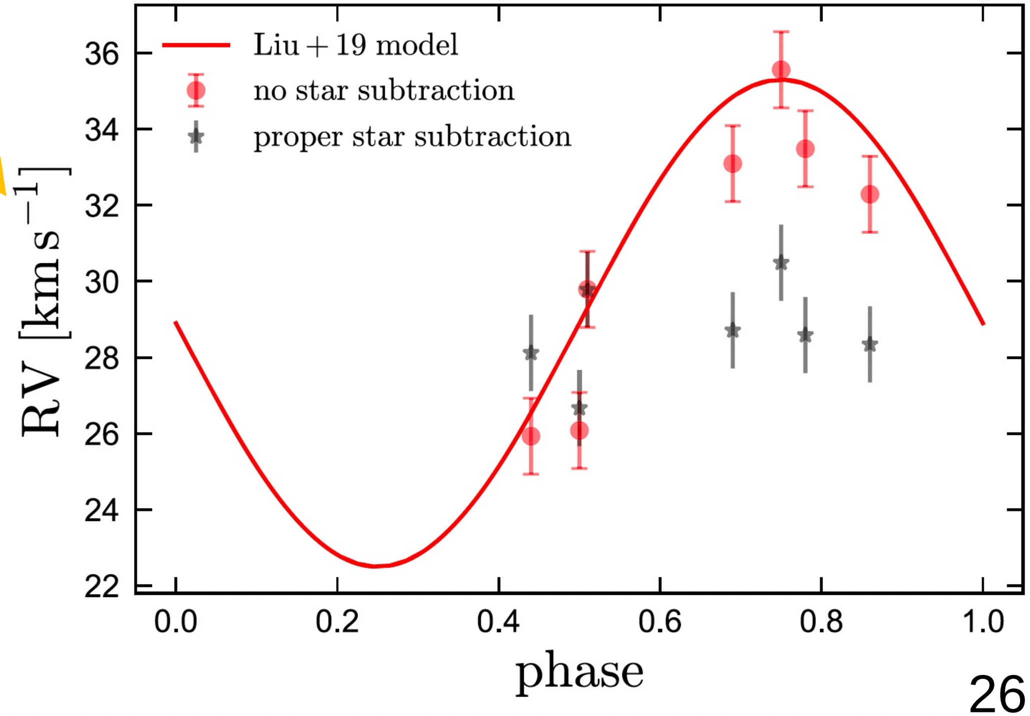
(Liu et al., 2019)



- ➢ The RV-variable absorption line will shift the Hα emission line and result in an apparent velocity offset.
- ➢ The RV signal is not real.

(El-Badry & Quataert, 2020)

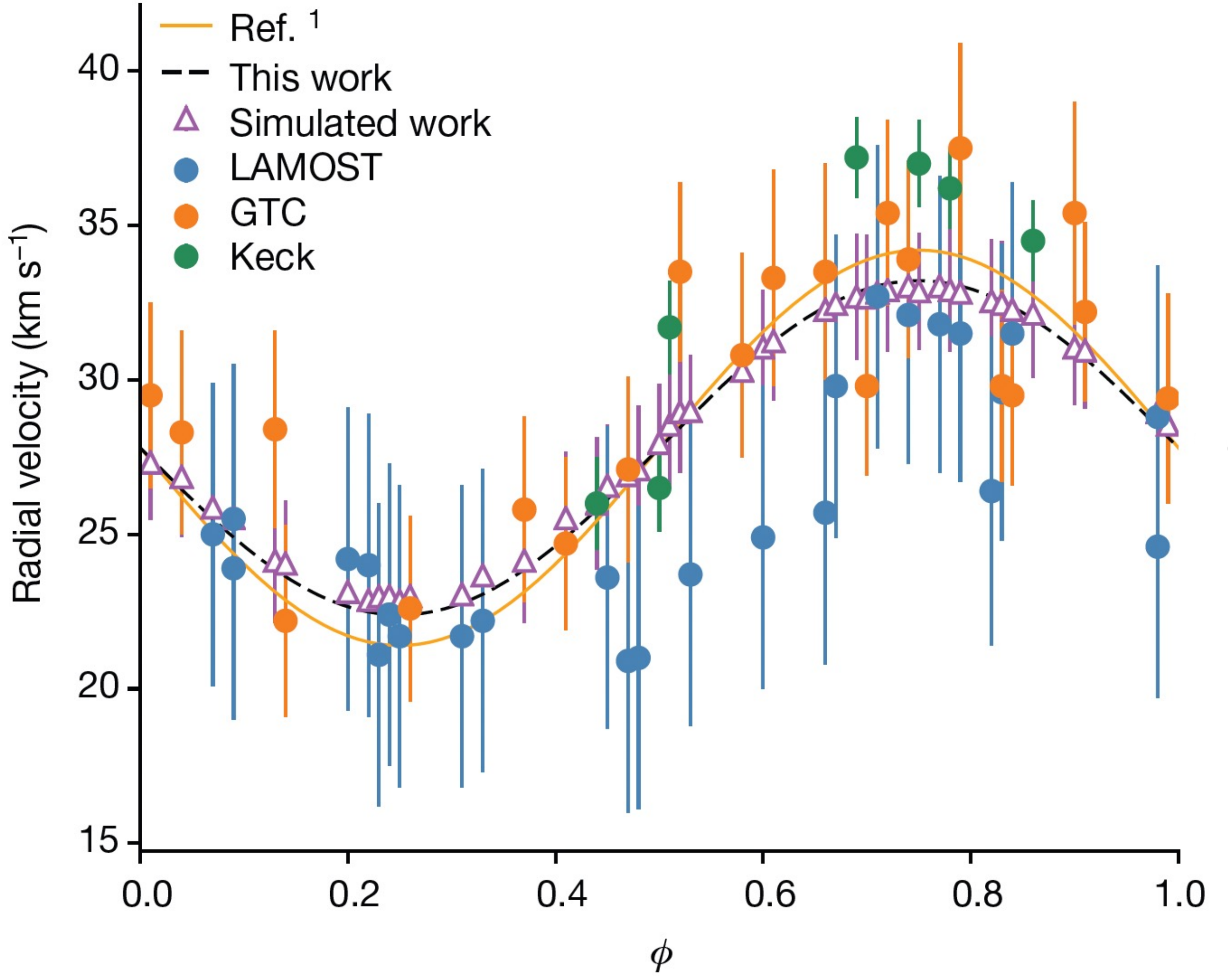




- ➢ Rule out any > 1.3 km/s

$$K_{\mathrm{H}\alpha} = 0.25^{+0.7}_{-0.3}\,\mathrm{km\,s^{-1}}$$

(El-Badry & Quataert, 2020)



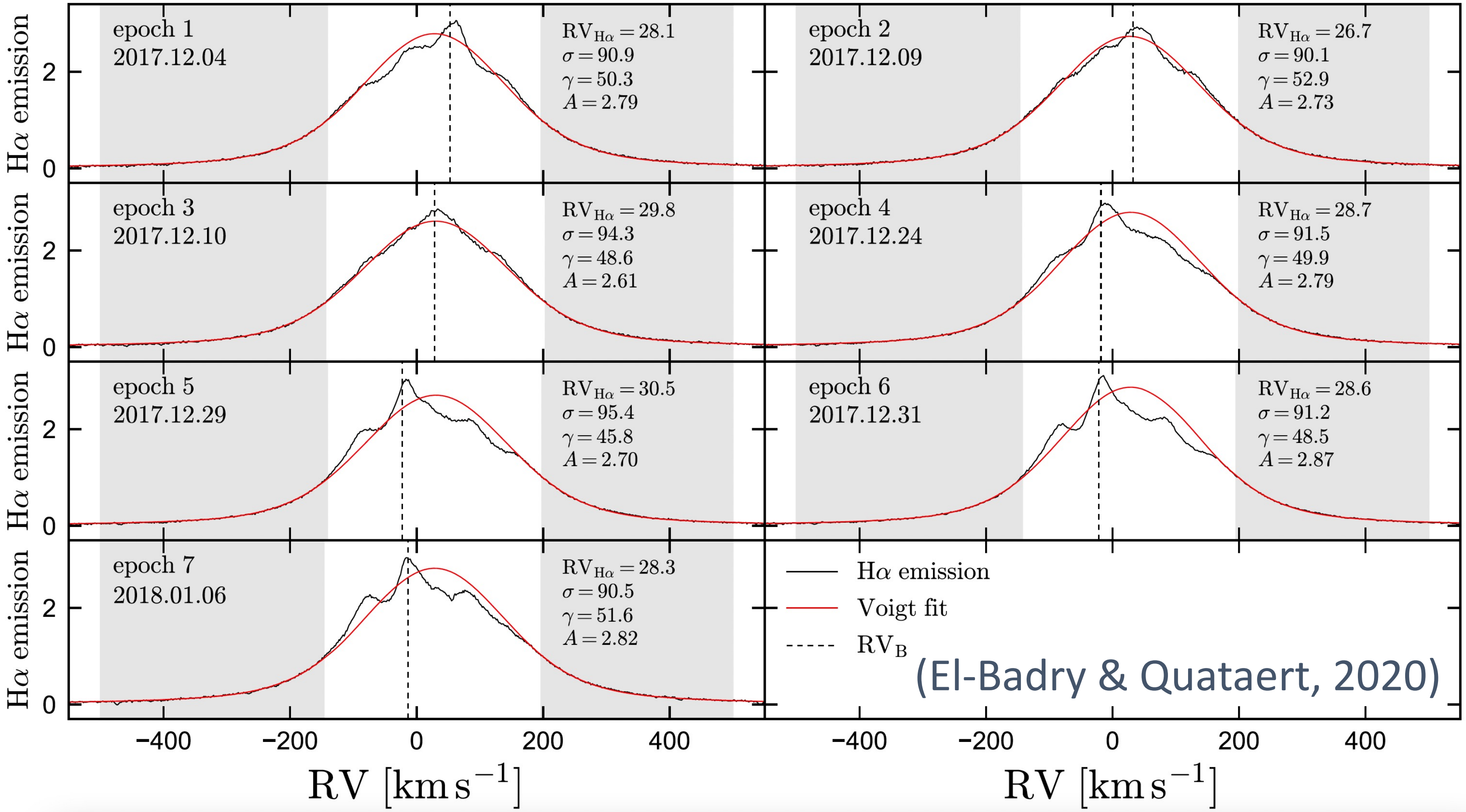
(Abdul-Masih et al. 2020)

- Simulation: a static Hα emission + a Doppler-shifting stellar absorption

- Same results as in Liu et al.

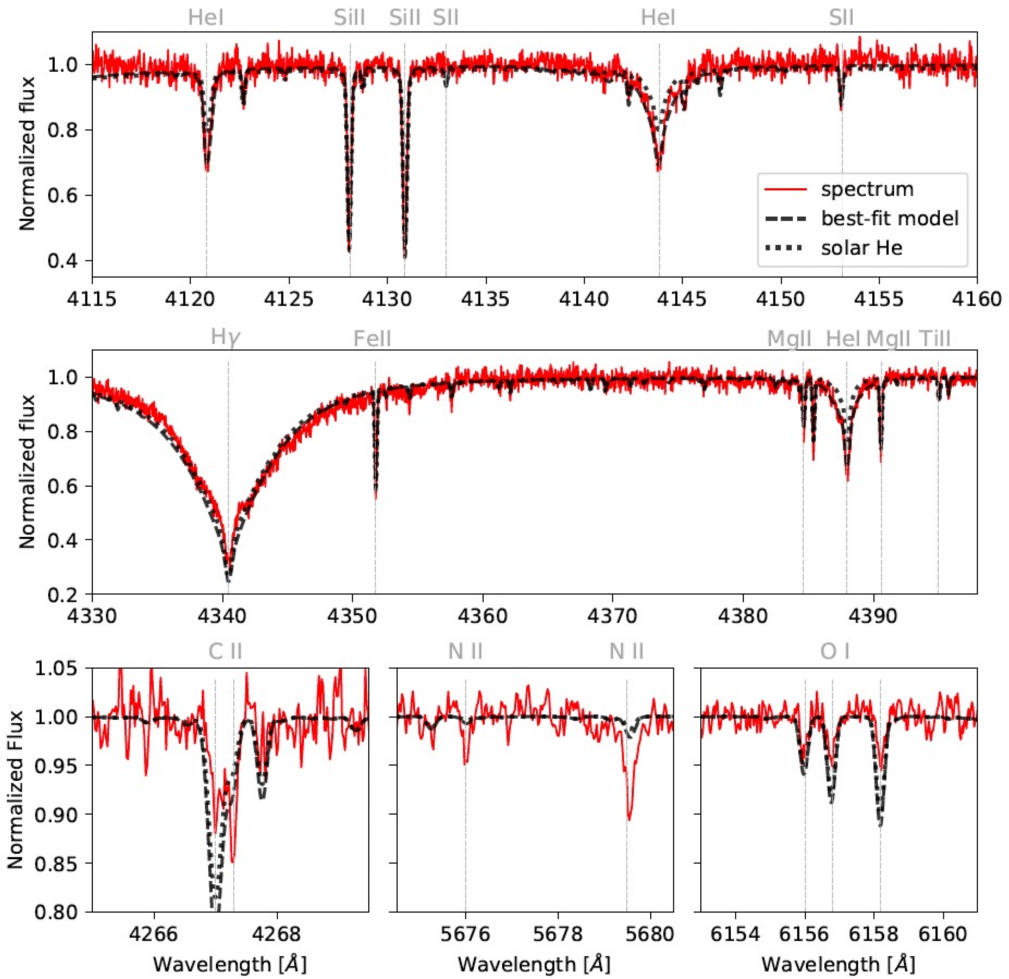
❖ Source of the Hα emission?

- The centre peak of the Hα line profile seems to track the velocity of the B star.
- Accretion of the stellar wind?

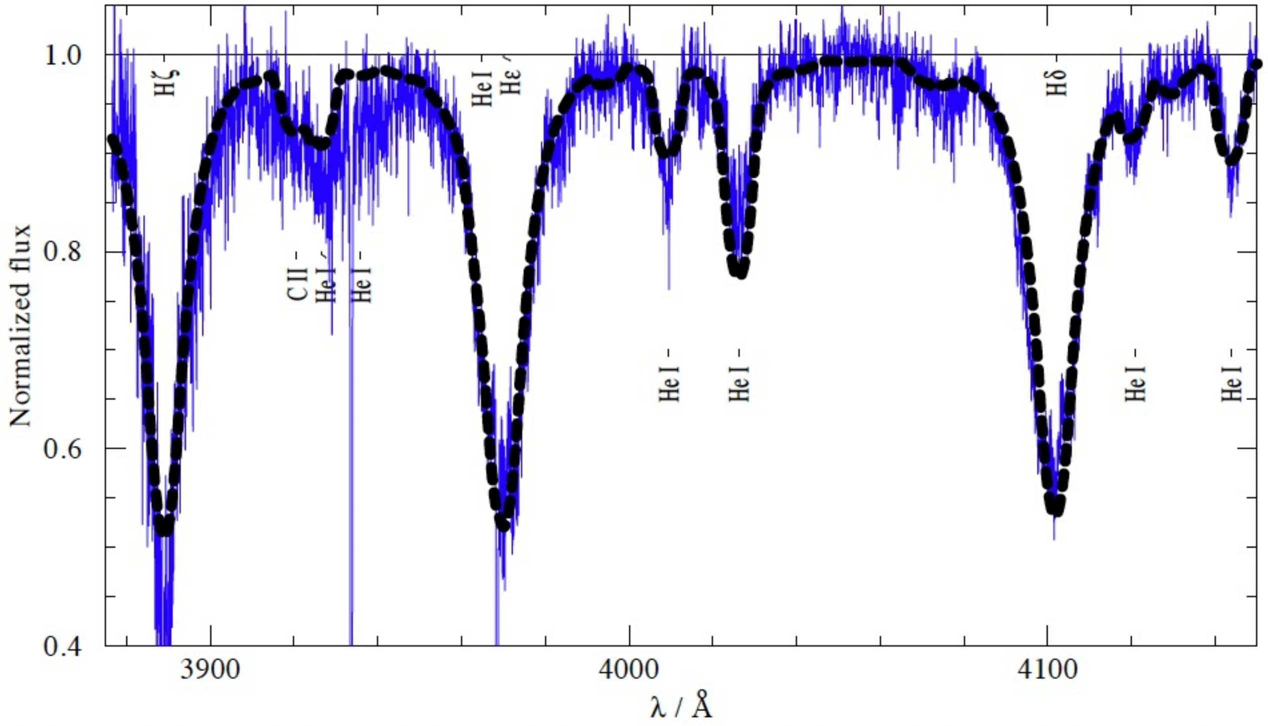


❖ Two stellar components with comparable brightness in optical flux

➢ Primary: a stripped star, B type, 1.5 $M_\odot$



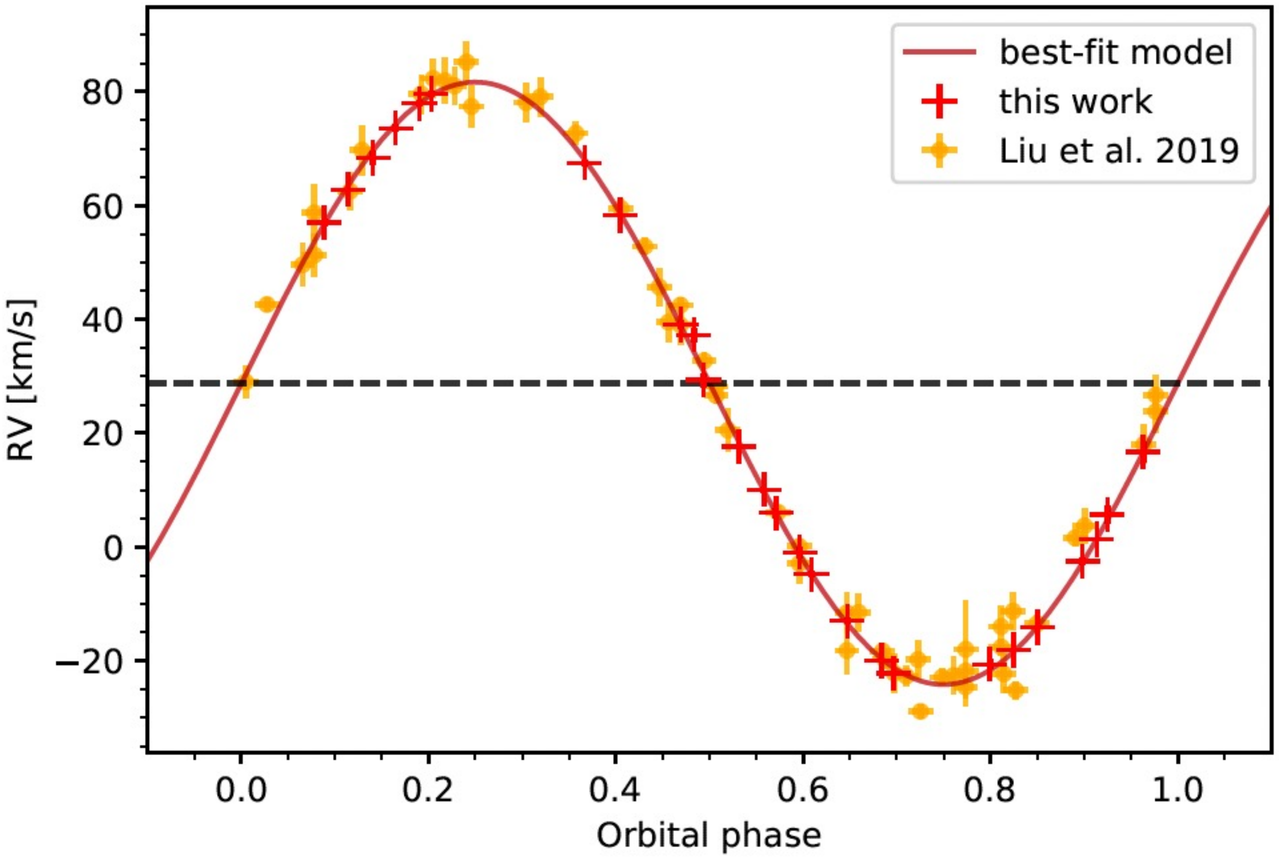
➢ The unseen secondary: a Be star (rapidly rotating B3 V star with a decretion disk), 7 $M_\odot$



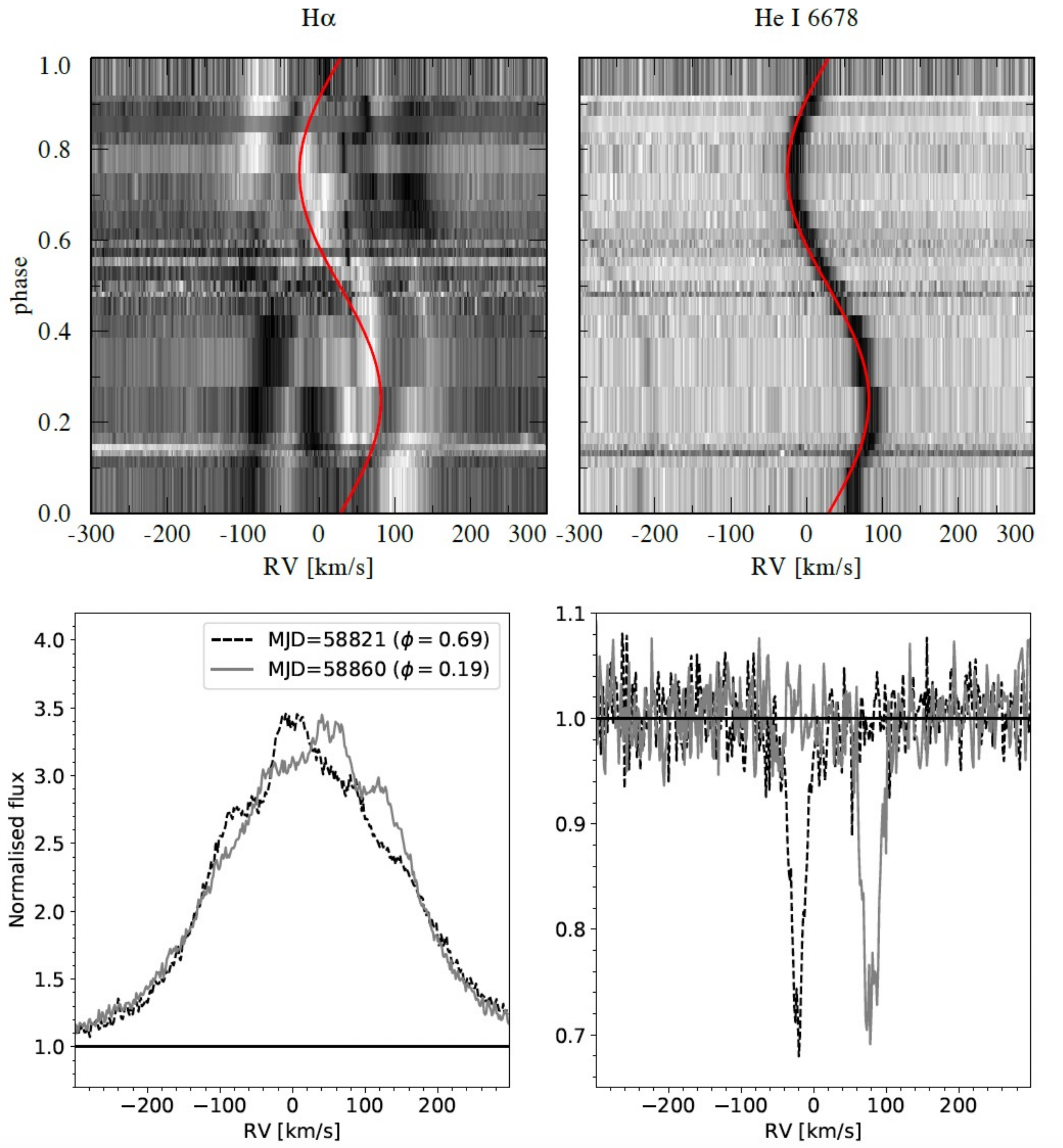
(T. Shenar et al., 2020)

➢ RVs from HERMES and FEROS

- Period: 78.7999 ± 0.0097 days
- K_1: 52.94 ± 0.13 km/s
- Mass: 1.5 $M_{\odot}$

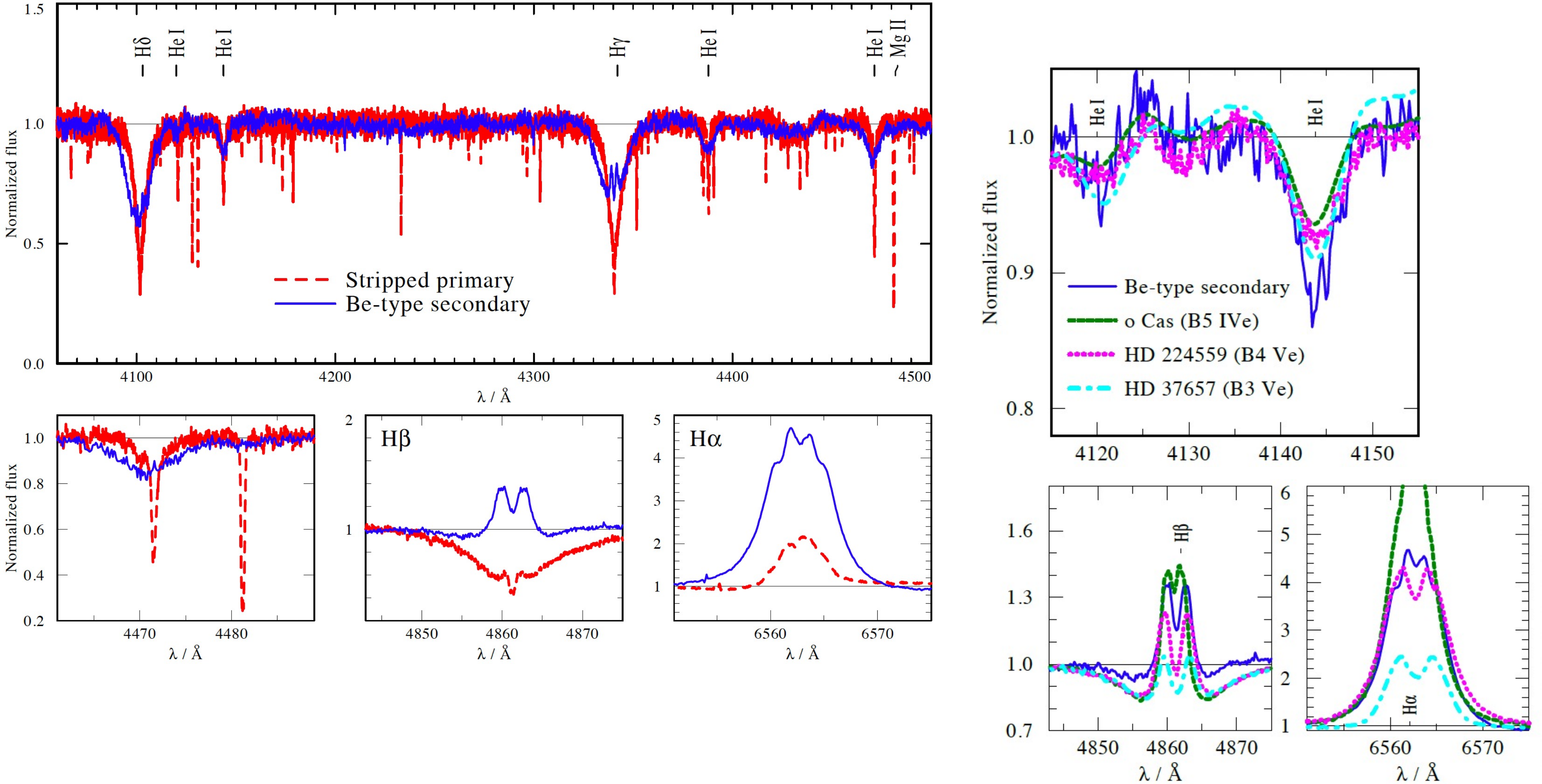


(T. Shenar et al., 2020)

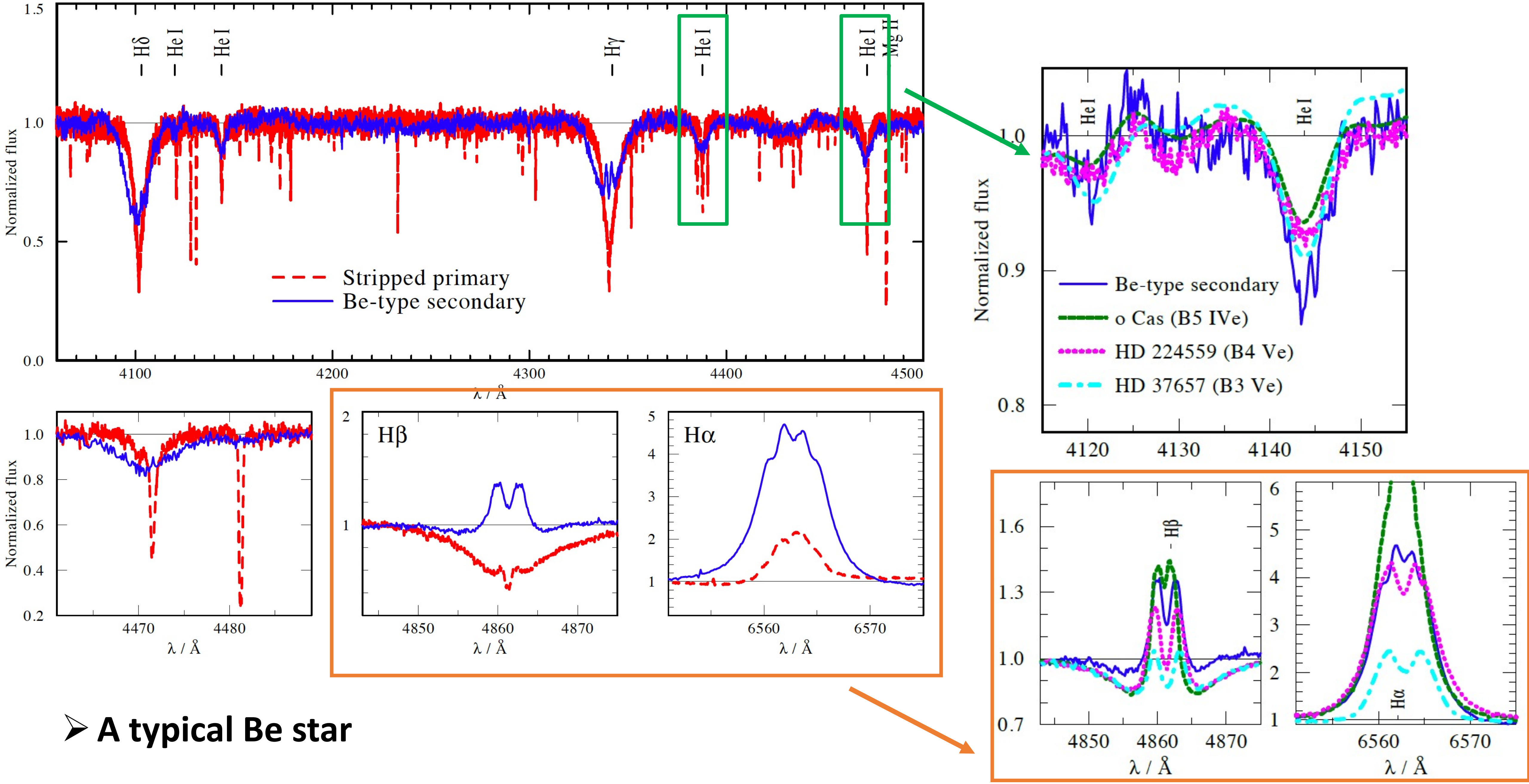


- Hα line moves the same as He I 6678, which has been used to extract RV.
- The primary star has Hα emission

(T. Shenar et al., 2020)



(T. Shenar et al., 2020)



- **A typical Be star**

(T. Shenar et al., 2020)

❖ The possible scenarios of LB-1

- From K_2 < 1.3 km/s → M_2 > 330 $M_\odot$ (El-Badry & Quataert, 2020)
- A stellar remnant (mentioned in El-Badry & Quataert, 2020)
- A stellar-mass BH (mentioned in El-Badry & Quataert, 2020)
- A solar mass pre-subdwarf + a less massive companion (e.g. NS) (Eldridge et al., 2019 and Irrgang et al., 2019)
- A B star + a Be star (T. Shenar, et al., 2020)

2M0412 or the “Giraffe”
Jayasinghe et al. 2022

Why Giraffe? Differences with LB-1

Why people study Giraffe & the data

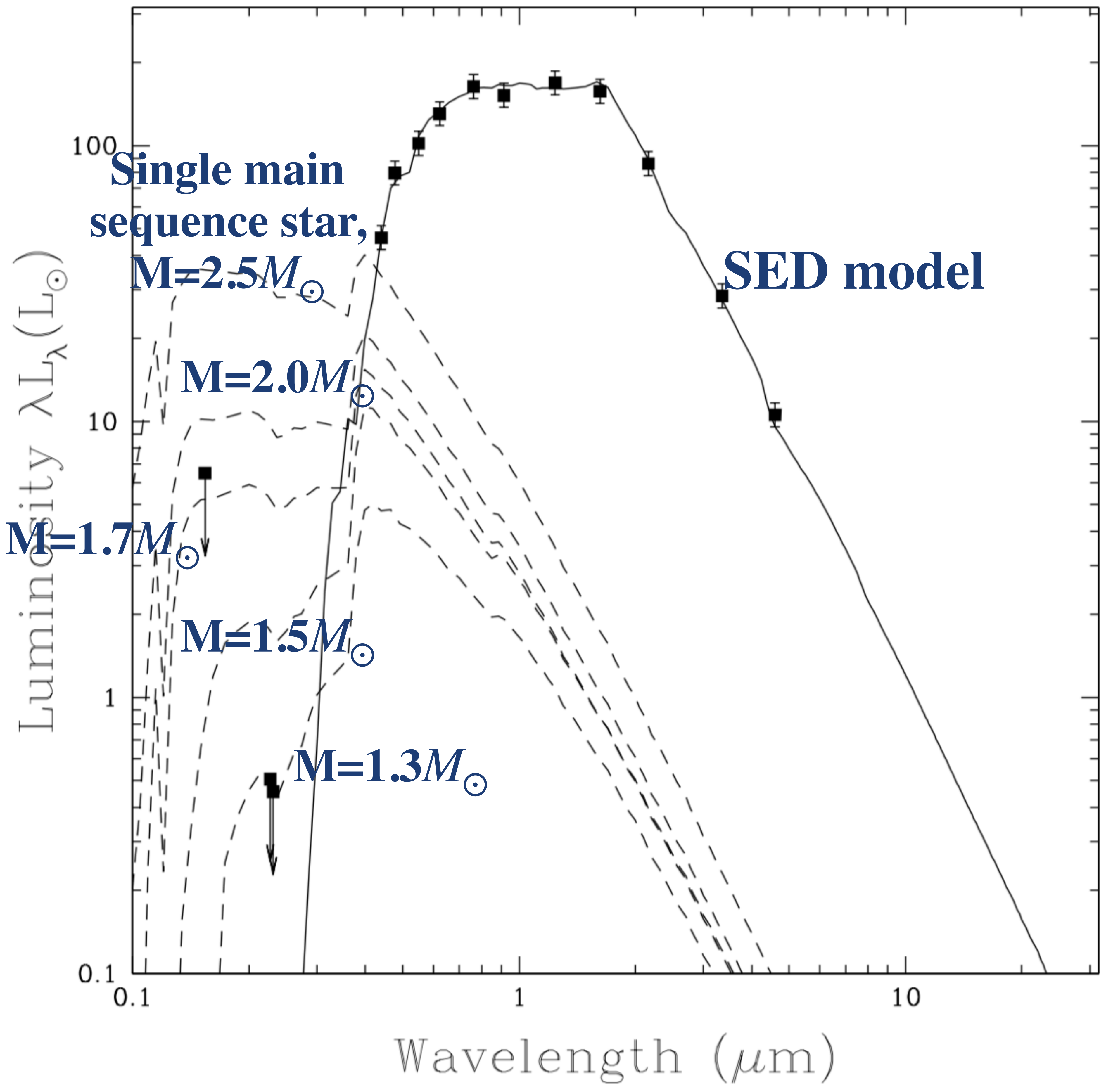
- First classified as a **variable star (P~80.36d)** in the Asteroid Terrestrial-impact Last Alert System (ATLAS) catalog. Then classified as a **semi-regular variable (P~41d)** by the All-Sky Automated Survey for SuperNovae (ASAS-SN), and the Zwicky Transient Facility (ZTF). Light curves from ATLAS, ASAS, ZTF and TESS.
- Spectra from APOGEE, HIRES on Keck and PEPSI.
- Distance and extinction from Gaia. D~3.7-4.3kpc due to the different zero-point correction.
- UV from Swift UVOT & X-ray from *Swift* X-Ray Telescope

Compare with LB-1

- Light curve (LC), which means the tidal deformation happens. Direct constrain from LC.
- In spectra, Giraffe has a larger contribution (both absorption lines and H_α emission) from the companion.
- Support red giant - black hole model, with BH mass ~2-3$M_\odot$—> lower mass gap!

Constrain properties of visible star from SED and spectra

P = 80.2 d



- Spectra indicate the visible star is a rotating red giant, with $v_{rot} sini$~13km/s. Assume tidal lock, $P_{rot} = P_{orb}$,

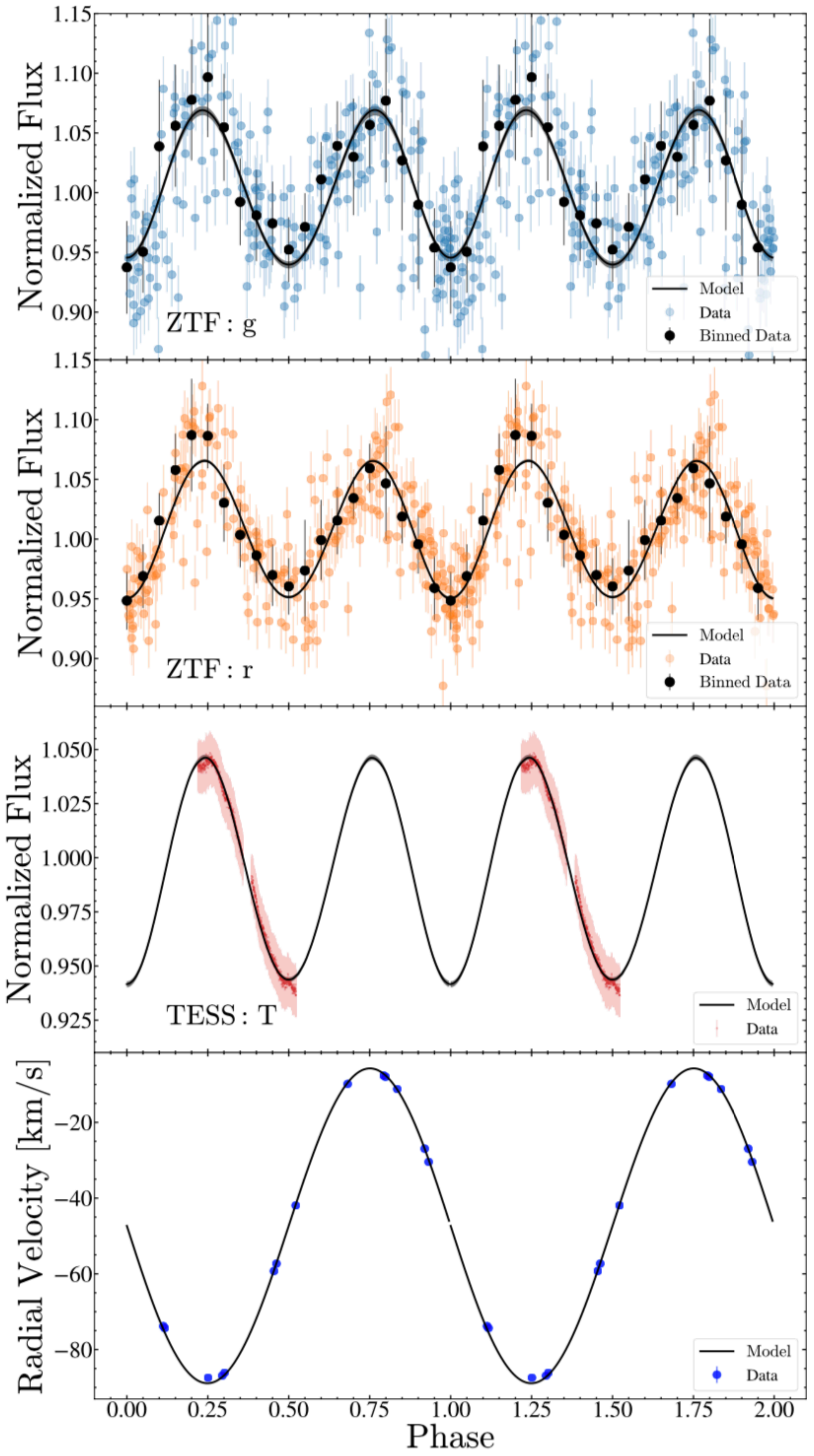
$$v_{rot} = \frac{2\pi R_{giant}}{P_{rot}} = 18.7 \pm 0.4 \text{km/s} \left(\frac{R_{giant}}{30_{R_\odot}}\right) \longrightarrow i\sim 42^\circ.$$

- Joint fitting of SED, spectra and D from Gaia, under the assumption of single star tract without mass stripping —> $M_{giant} = 1.1^{+0.24}_{0.22} M_\odot$, $R_{giant} = 29.9^{+2.2}_{-2.0} R_\odot$,

$T_{eff} = 4306 \pm 39K$, $d_{giant} = 4301^{+318}_{-289} kpc$

- Upper mass of companion: if main sequence star, <1.4$M_\odot$; if sub giant, <1.7$M_\odot$

Combine light curve and RV



- **Keplerian orbit models** (using RV): for $M_{giant} = 1M_{\odot}$, $i = 42°$ —>$M_{comp} = 3.3M_{\odot}$, $a_{orb} = 128R_{\odot}$ and the size of Roche lobe $R_{L,giant} = 36M_{\odot}$.

LC (fitting by *PHOEBE*)+RV:

(1)the giant fills Roche lobe, has mass transfer: too luminous for current distance (at least need D=4.7kpc)

(2)the giant does not fill Roche lobe: i~$39.5 - 47.8°$, $M_{giant} = 0.35 - 0.81M_{\odot}$, $R_{giant} = 23 - 33R_{\odot}$ and $M_{comp} = 2.1 - 3.6M_{\odot}$

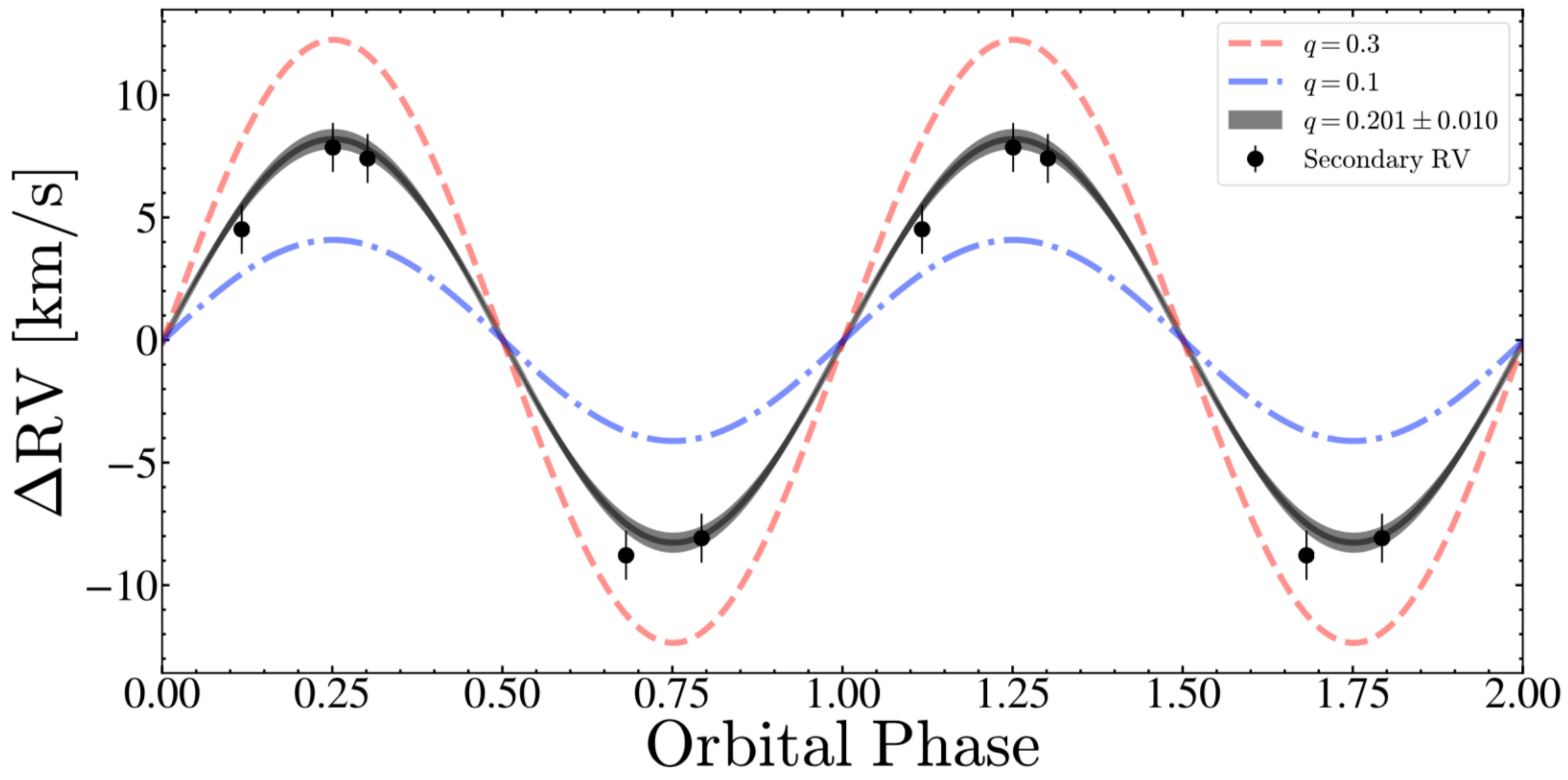
- Mass of giant star is much lower than single star tract

 —> a red giant that has been heavily stripped by binary interactions.

- Mass of companion is much larger than the constrain of SED

 —> non stellar component

From the residuals of RV & spectra to further constrain properties of the companion

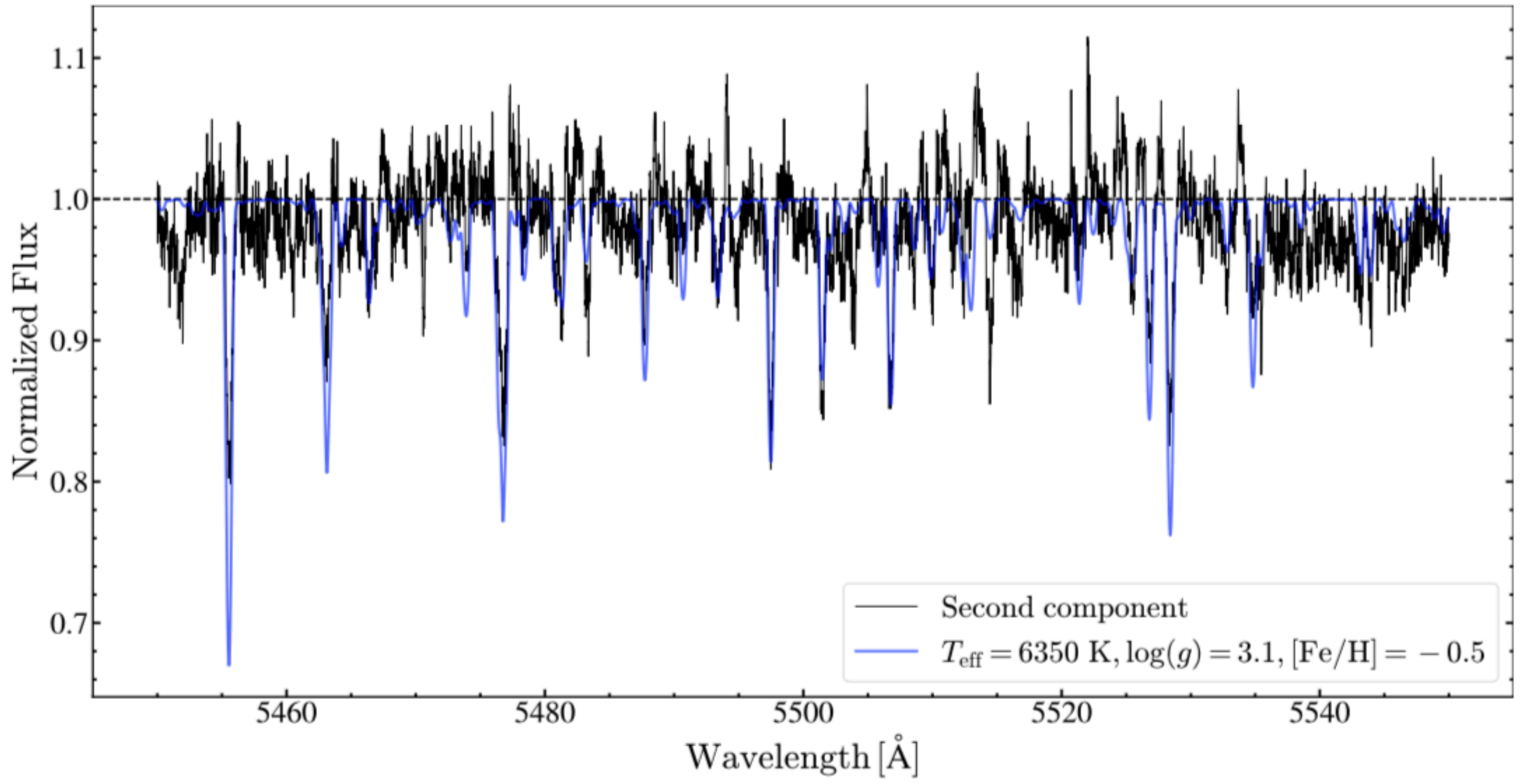


Mass ratio q~0.2

The RV has 2 components —> detect the RV of companion by cross-correlate the spectra with a synthetic spectrum that mimic the spectrum of the companion.

From the residuals of RV & spectra to further constrain properties of the companion

Subtract the spectrum of the red giant, then the residual is the companion. Fit the **residual** spectrum (with model of star) —> $T_{eff} = 6350K,\ log\ g = 3.1$



A main sequence star with 6400K ~$M = 1.3M_{\odot}$

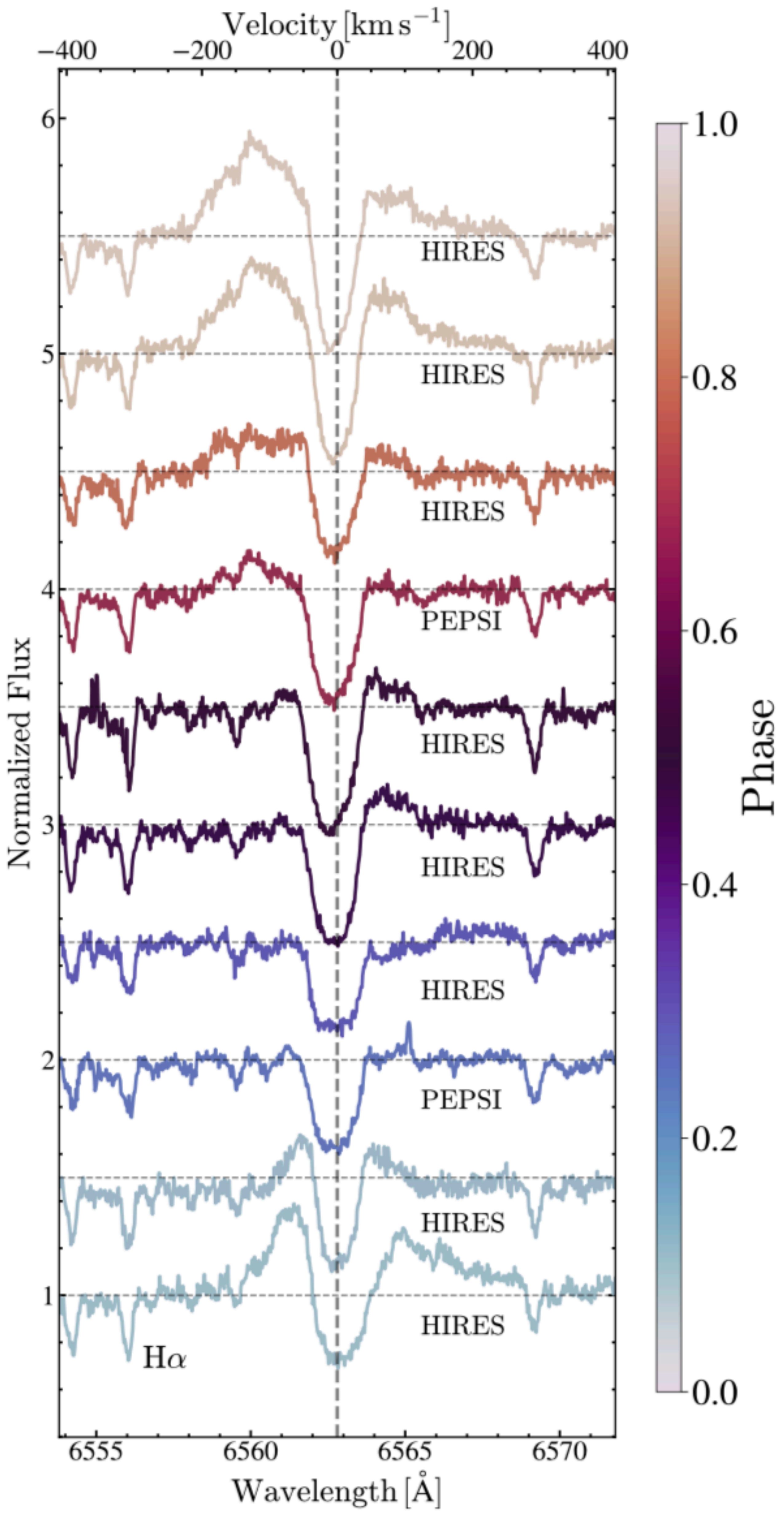
❌

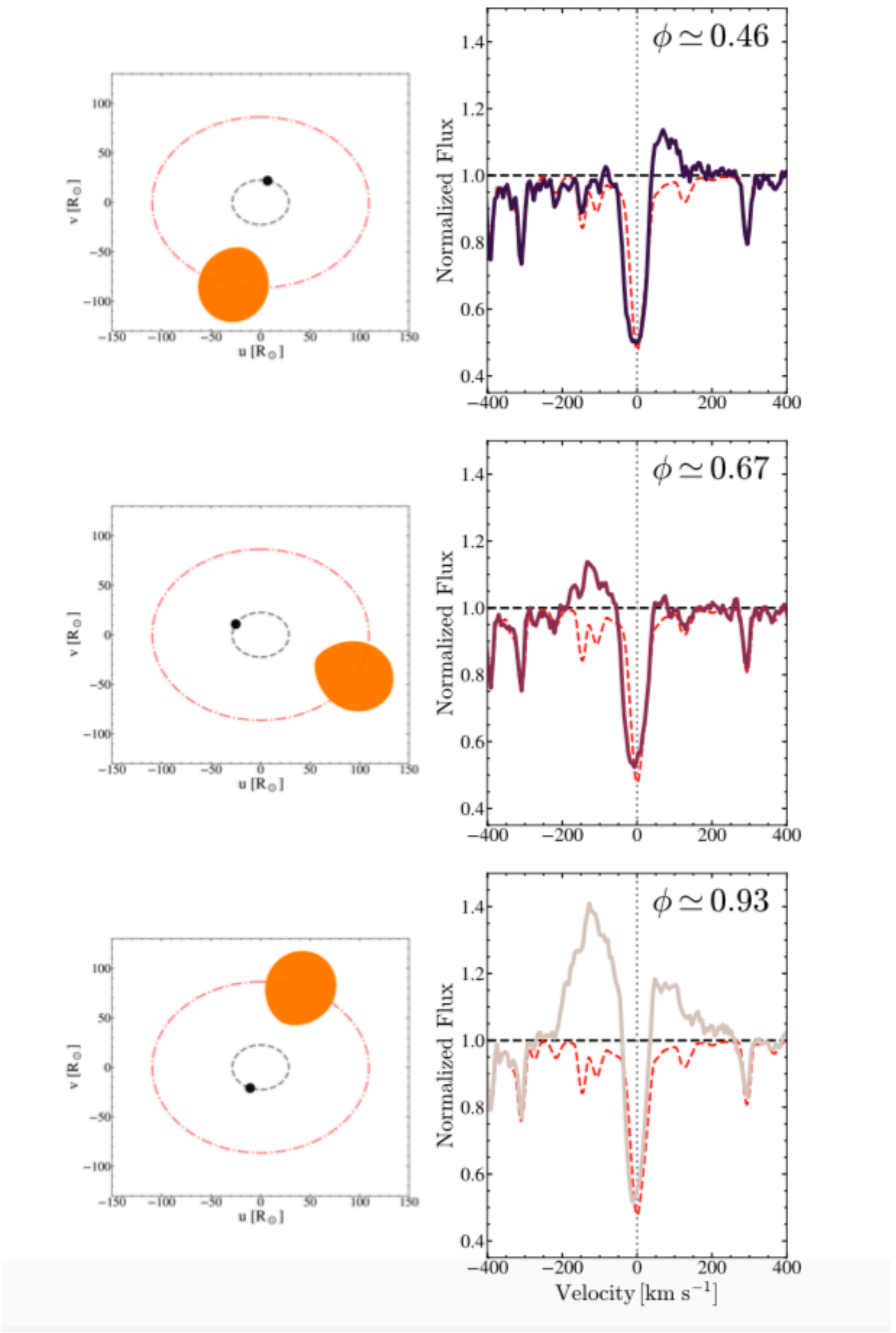
q=0.2, $M_{comp} > 1.6M_{\odot}$

The companion also can not be a binary system —> velocity dispersion is not large enough

A black hole/neutron star with an accretion disk

H_α emission — the structure varies with the orbital phase





(1)in phase with companion

(2)If it is related to giant, the structure should be even broader

Emission from accretion disk

Summary of Giraffe

Dark Companion	Possibility	Comment
Single Star	?	Hot, main sequence companions ruled out by SED limit ($M_* \lesssim 1.4\ M_\odot$).
Single WD	✗	WD will exceed Chandrasekhar limit ($M_{\rm WD} > 1.4\ M_\odot$).
Single NS	✗	NS will exceed maximum mass ($M_{\rm NS} > 2.3\ M_\odot$).
Single BH	✓✓	Simplest explanation.
†Star + Star	✗	Ruled out by SED limit ($M_{\rm binary} \lesssim 2.6\ M_\odot$).
†Star + WD	✗	For $M_* \lesssim 1.4\ M_\odot$, the WD mass exceeds Chandrasekhar limit.
†Star + NS	✗	For $M_* < 1.4\ M_\odot$, the NS mass exceeds $2.2 M_\odot$.
†Star + BH	✗	For $M_* < 1.4\ M_\odot$, the BH mass should be $M_{\rm BH} > 2.8\ M_\odot$.
†WD + WD	✗	Both WD components exceed Chandrasekhar limit.
†NS + WD	✗	NS mass is in the observed range if $M_{\rm WD} > 0.8\ M_\odot$
†BH + WD	✗	BH mass is even lower than with no WD.
†NS + BH	✗	The BH must have a NS-like mass.
†NS + NS	✗	Both NS components should have $M_{\rm NS} \gtrsim 1.2\ M_\odot$, so $q_{\rm inner} \gtrsim 0.67$.
†BH + BH	✗	The BHs have NS masses.

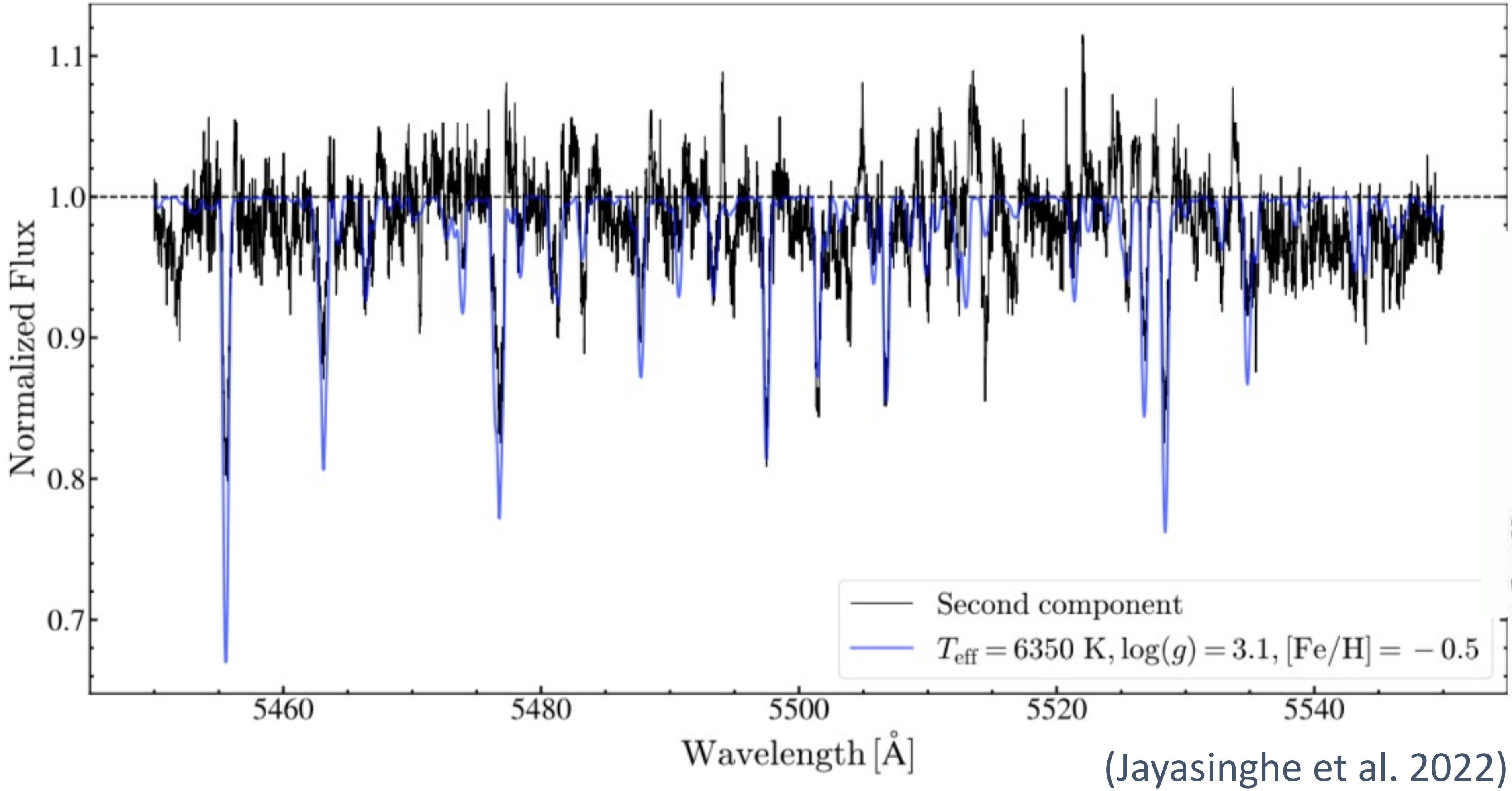
† Disfavored because the orbital motion of an inner binary will dominate over the reflex motion of the giant's orbit observed in our spectra.

Through fitting the **residual spectra** to constrain properties of the companion, they think the companion is a black hole/ neutron star with an accretion disk.

$M_{comp}\ 2 - 3M_\odot$, in the lower mass gap of black hole.

❖ The "Giraffe" system

- A single star model + residuals



(Jayasinghe et al. 2022)

❖ Model fittings

Near-infrared spectra from APOGEE survey

Optical spectra from Keck/HIRES

Gaia eDR3 parallax and SED fitting

Light curve the from ZTF

A binary spectral model

100% filled Roche lobe

Fix mass ratio to 0.2

- A giant with T_{eff}~4050 K
  +
  a sub-giant with T_{eff}~5200 K
- H-band contribution: 80% and 20%
- M_1/M_2 ~ 0.2
- vsini 12 and 16 km/s

- d about 3.7 kpc
- SED: $R_1 \sim 25 R_\odot$, $R_2 \sim 9 R_\odot$

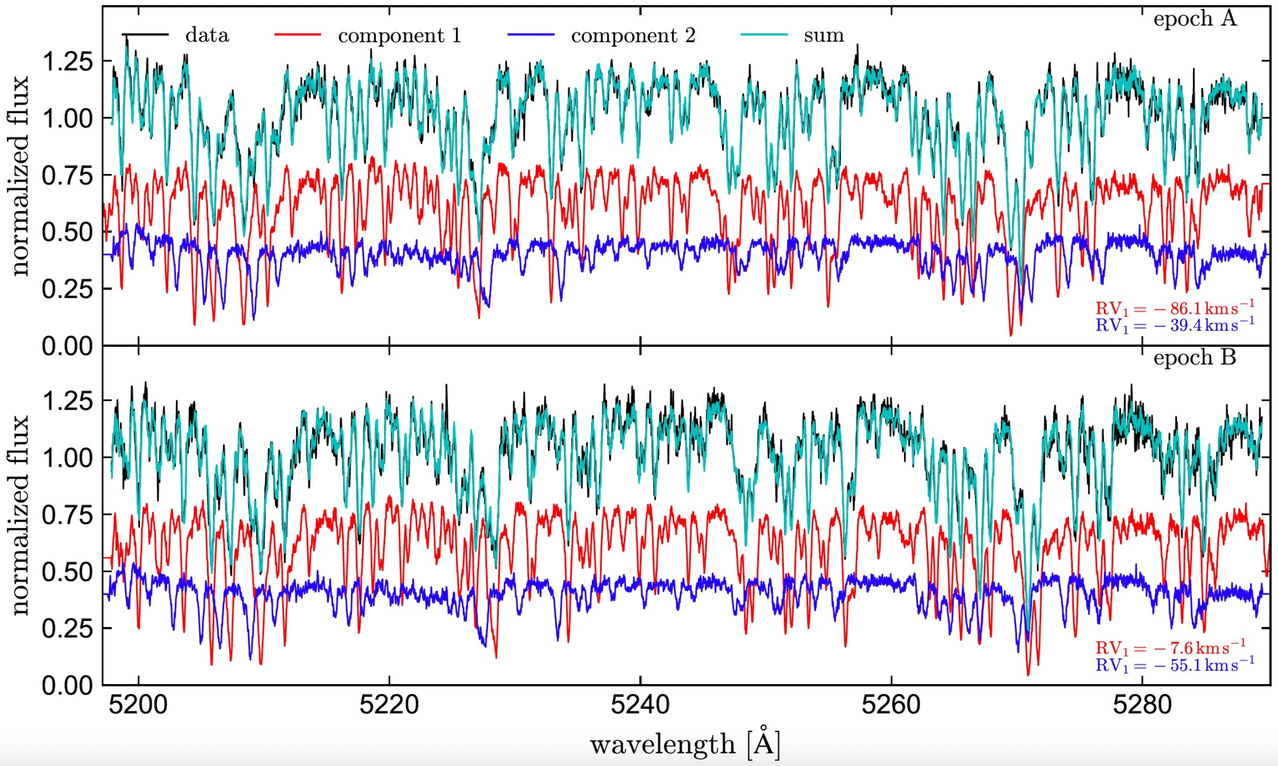
- M_1 = 0.35 $M_\odot$
- Inclination of 50 degrees
- M_2 = 1.83 $M_\odot$

(El-Badry et al., 2022)

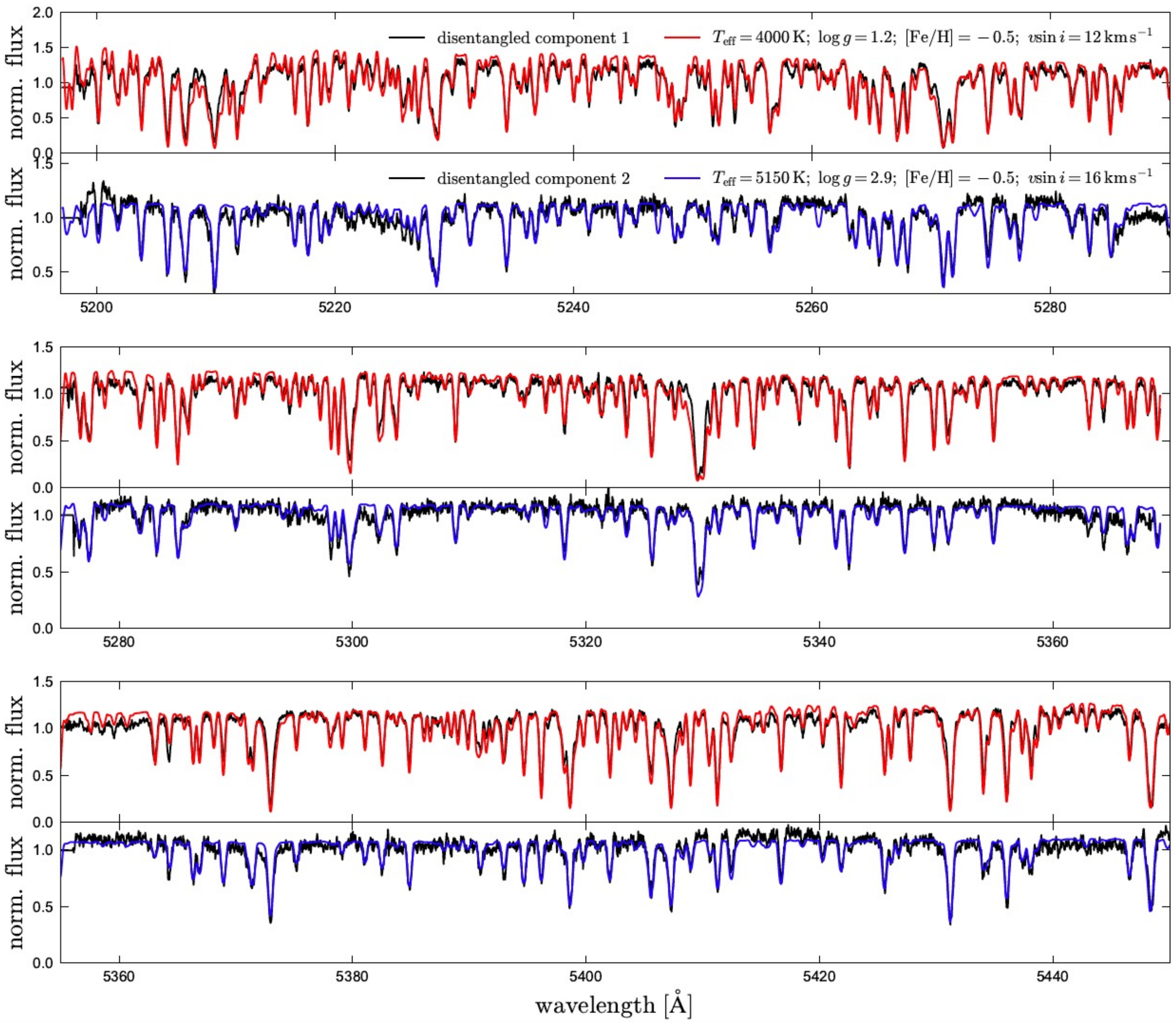
❖ The “Giraffe” system

(El-Badry et al., 2022)

➢ Spectral disentangling of the Giraffe system.



➢ Comparison with the Kurucz model



❖ Why not a BH and Why a subgiant?

- More absorption but less emission
- vsini < 20 km/s + a 3 solar-mass BH
  → materials on AU scales, which is larger than the binary sepration
  → can not trace the secondary's centre of mass?
- X-ray upper limits imply $L_x \lesssim 10^{-5} L_{opt}$

- Selection effect:
  A non-subgiant → blue/UV → detectable → BH candidate (X)
- Evolution scenarios?
  (El-Badry et al., 2022)

Current status of non-interacting BH systems

BH type	Name	Mass ($M_\odot$)	Time	Status
Globular-cluster	NGC 3201 BH1	4.36 ± 0.41	2018	Yes
	NGC 3201 BHC1	$M_{BH}\sin(i) = 7.68 \pm 0.50$	2019	Yes
	NGC 3201 BHC2	$M_{BH}\sin(i) = 4.4 \pm 2.8$	2019	Yes
	NGC 1850 BH1	$11.1^{+2.1}_{-2.4}$	2021	No
	NGC 2004 #115	~ 25	2021	No
Field BH binaries	**LB-1**	$\sim 68^{+11}_{-3}$	2019	**No**
	Giraffes	2.97 ± 0.02	2021	**No**
	Unicorn	3.04 ± 0.06	2021	**No**
	HR 6819	6.3 ± 0.07	2020	**No**
	J05215658	$\sim \mathbf{3.3^{+2.8}_{-0.7}}$	2019	**Yes?**

LMG & non-interacting

Current status of non-interacting BH systems

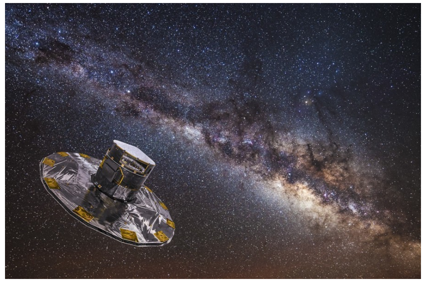
BH type	Name	Ma
Globular-cluster	NGC 3201 BH1	
	NGC 3201 BHC1	M_{B}
	NGC 3201 BHC2	M
	NGC 1850 BH1	
	NGC 2004 #115	
Field BH binaries	**LB-1**	
	Giraffes	
	Unicorn	
	HR 6819	
	J05215658	

LMG & non-interacting

Prospect of Galactic BH

Binary population synthesis models:

- 30-300 non-interacting BHs detectable in binaries with **astrometry from Gaia**



2014-2024 (Gaia DR5)
DR3 (2020) for now.

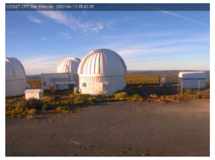
- 10^3 detached non-interacting BHs in the MW,
- 10^2 having luminous companions brighter than $G \sim 20$ mag

In addition…

- Targeted searches combining high-cadence **photometry** and sparsely sampled **radial velocities** from wide-field time-domain surveys

LAMOST

All-Sky Automated Survey for Supernovae (**ASAS-SN**)

South Africa  Chile  Texas  Hawaii