Overcoming the challenges: Radial Velocity Detection of Circumbinary Exoplanets

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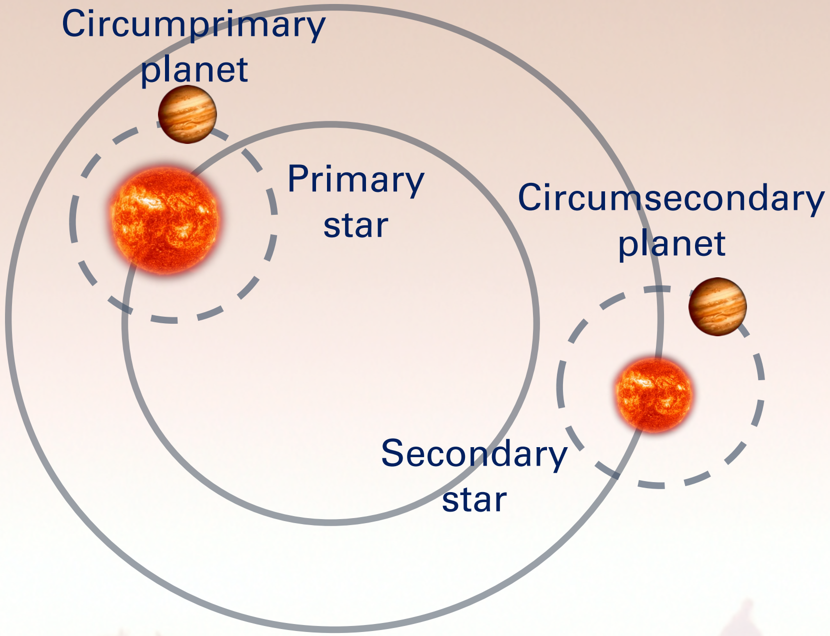
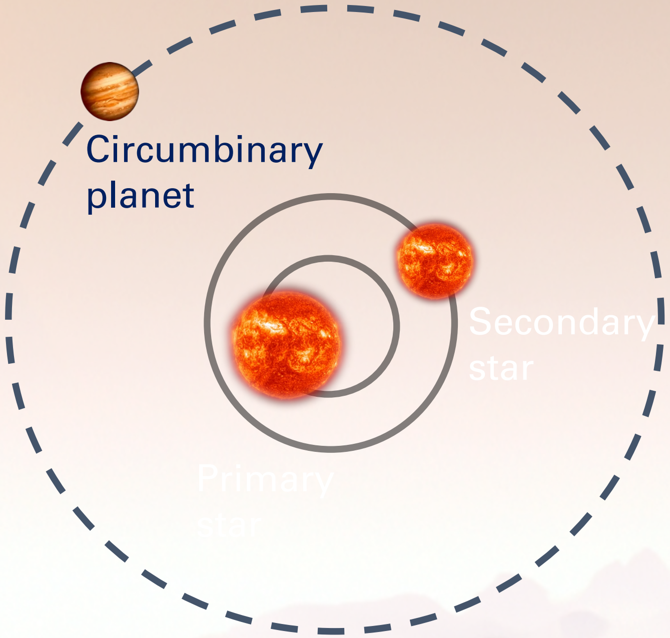
Exoplanets orbiting binary stars

- 220+ planets orbiting around 155+ binary star systems
- Two categories: Satellite-like orbit and Planetary orbit
- Fascinating architecture – planet formation

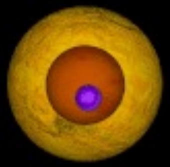


S-type planets



P-type planets

Kepler-16



PLANET TYPE	MASS
Gas Giant	0.333 Jupiters
PLANET RADIUS	**ECCENTRICITY**
0.754 x Jupiter	0.01
ORBITAL RADIUS	**ORBITAL PERIOD**
0.7048 AU	228.8 days
DETECTION METHOD	**DISCOVERY DATE**
Transit	2011

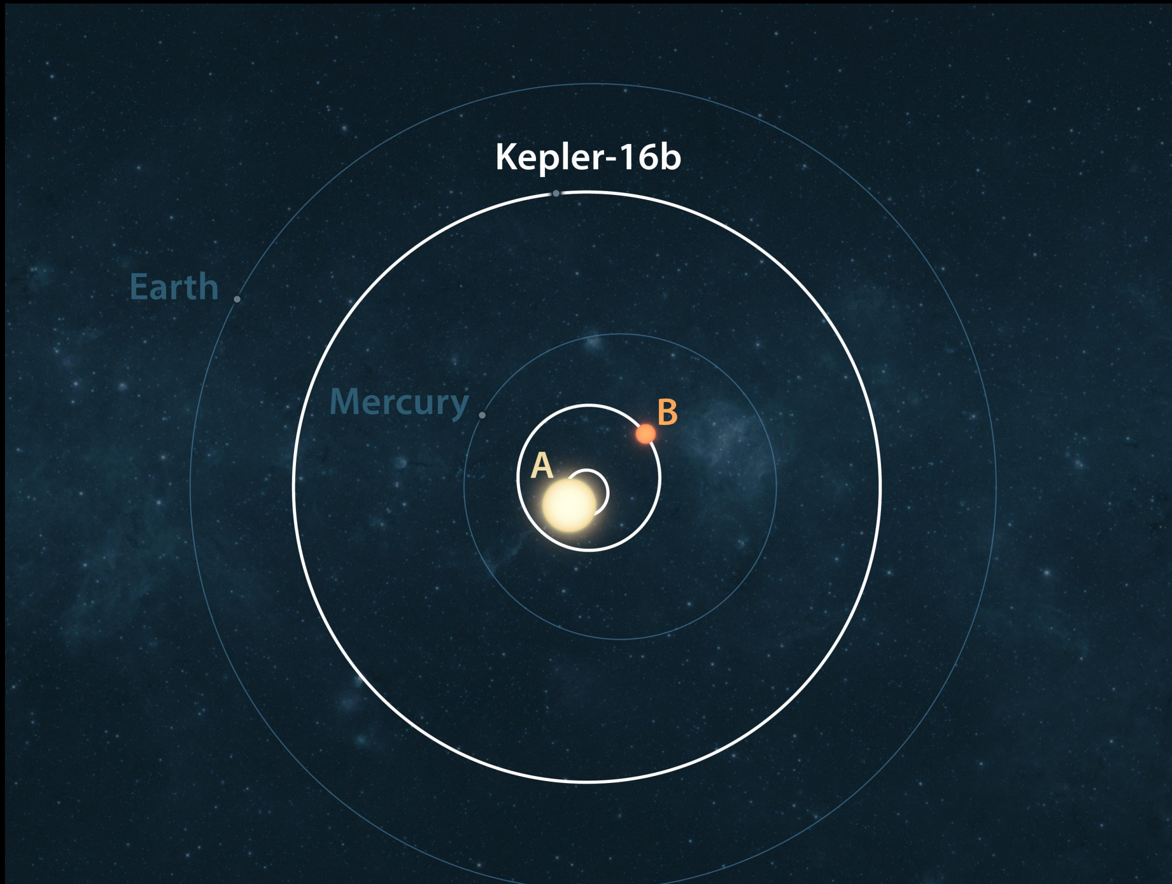
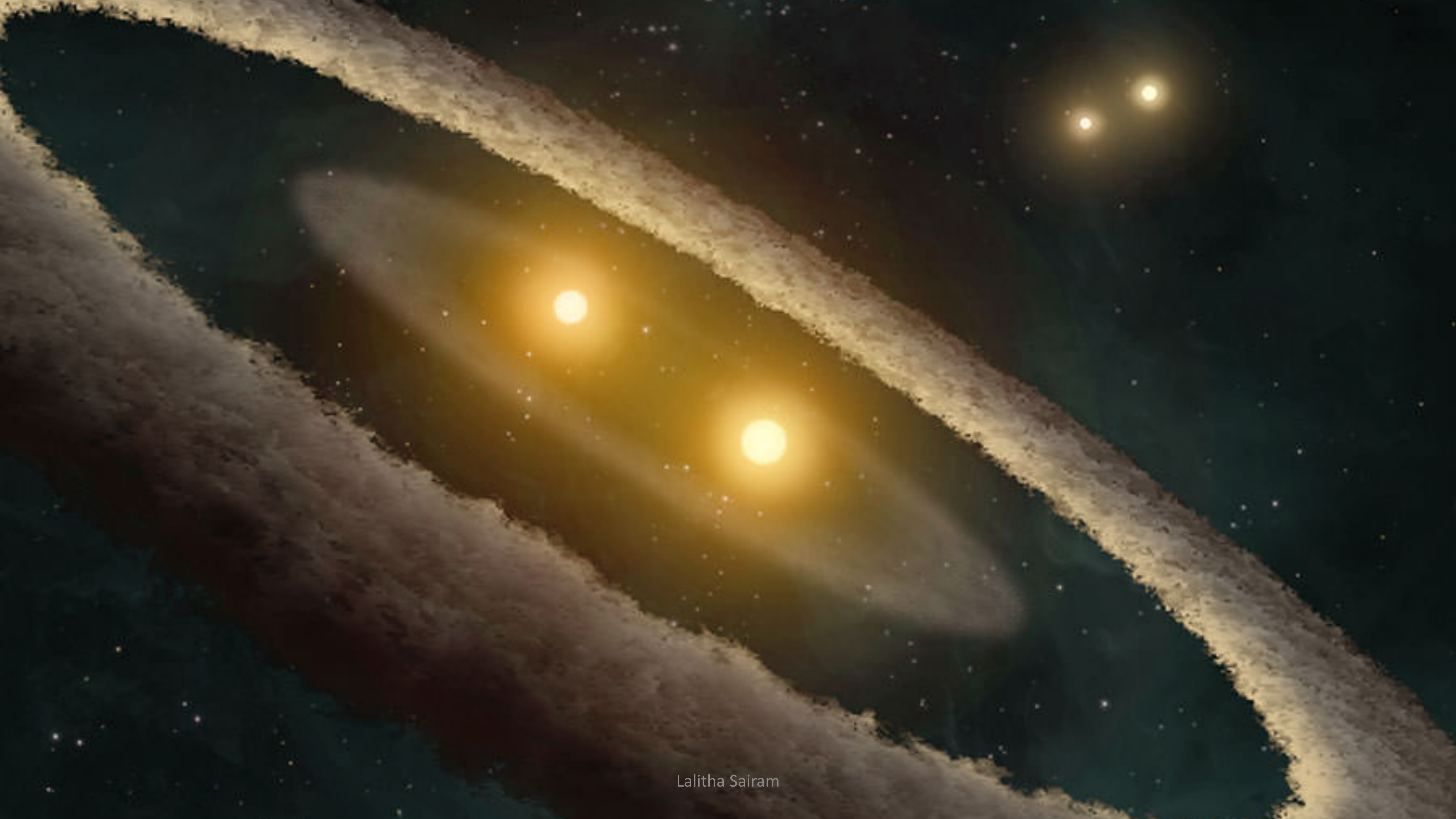


Image: NASA



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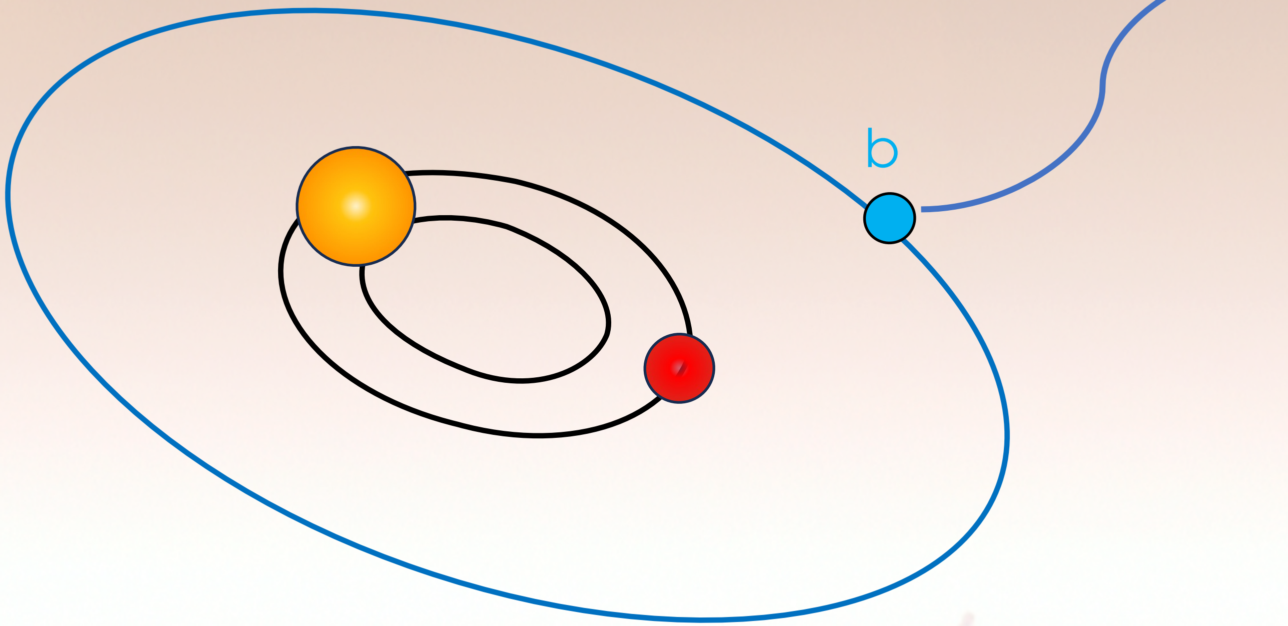
BEBOP

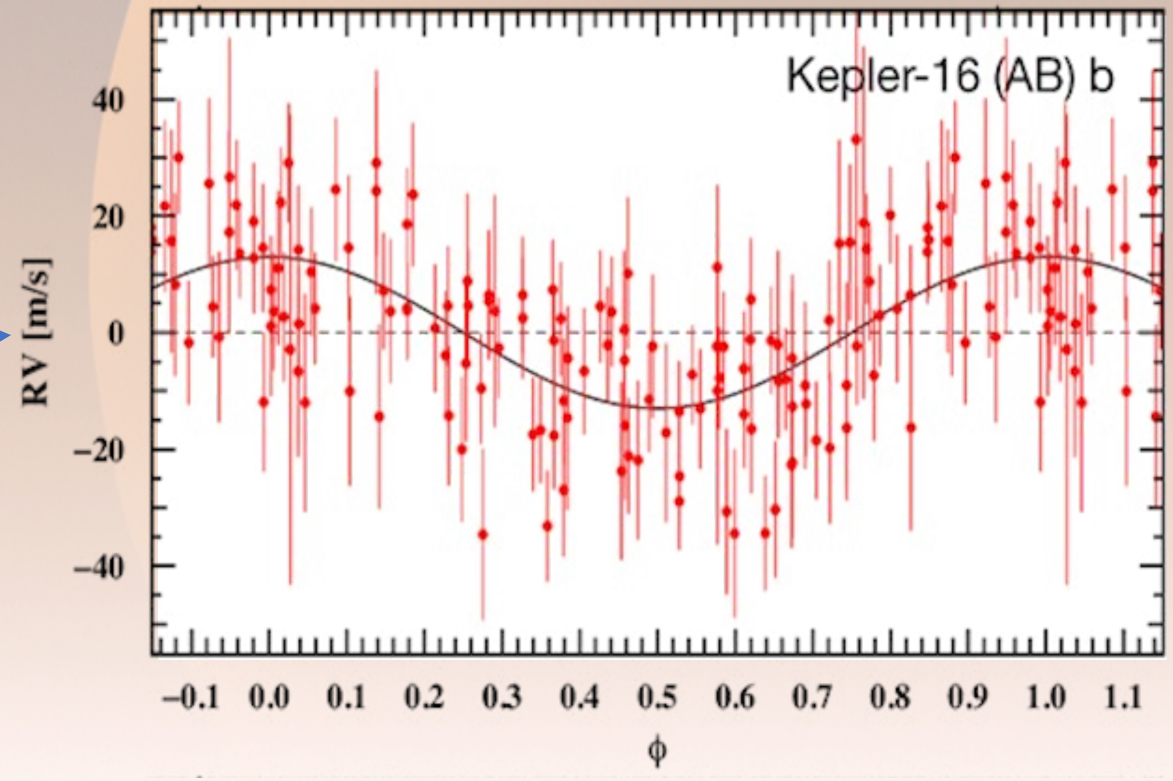
Binaries escorted by Orbiting Planets

Circumbinary state of affair

- Ground based RV survey – efficient and less biased
- BEBOP input targets from Eclipsing Binary Low Mass (EBLM) survey (more details talk by Daniel Sebastian on Thursday)
- Single-line binary – OHP and ESO
- Began in 2013 with CORALIE in La Silla (~ 6 m/s stability)

First RV Detection of circumbinary planet – Kepler 16



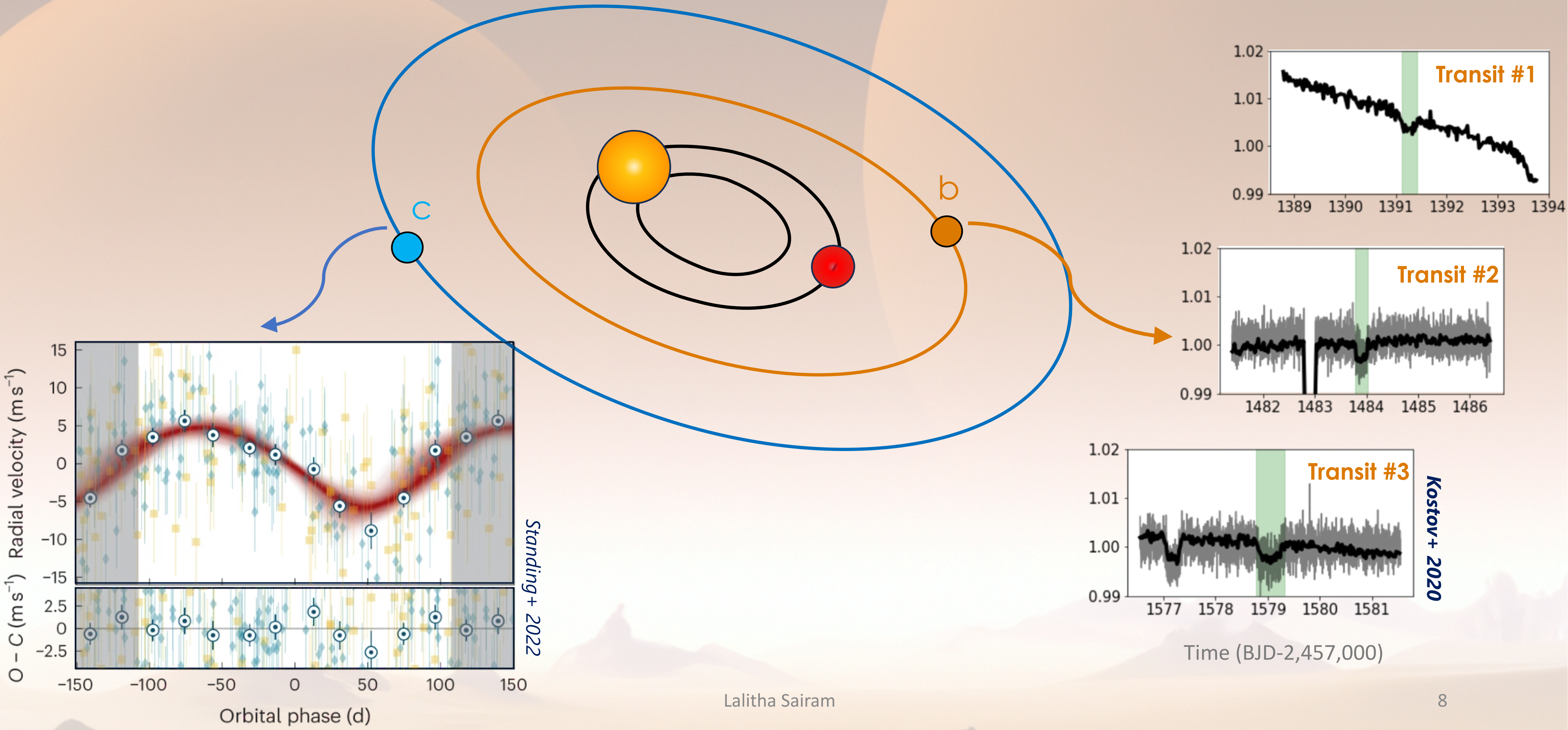


Triaud+ 2022

Mass from ETVs: 0.333 ± 0.016 M_{Jup}

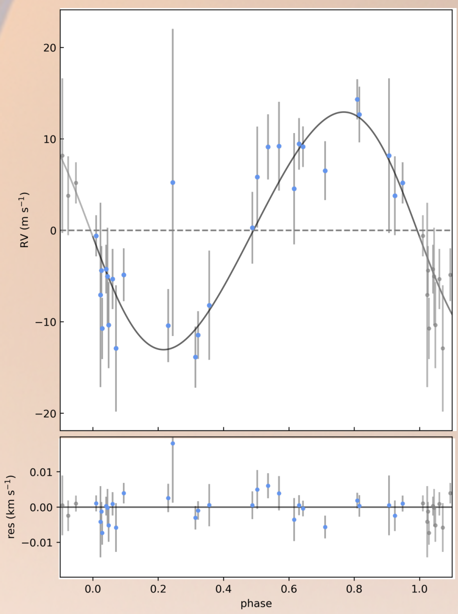
Mass from RVs: 0.345 ± 0.041 M_{Jup}

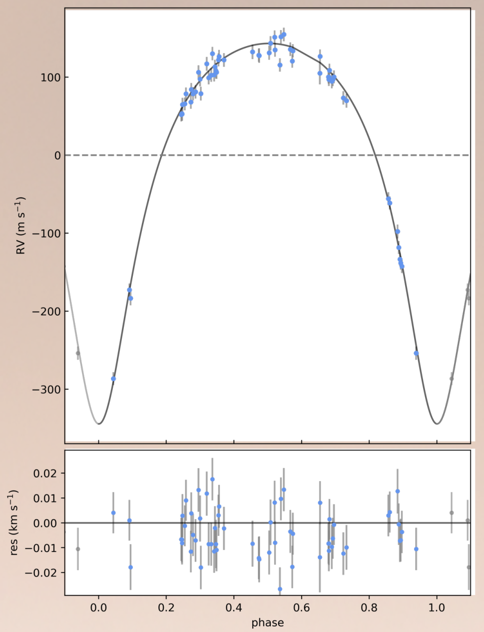
First RV Discovery– BEBOP I / TOI 1338

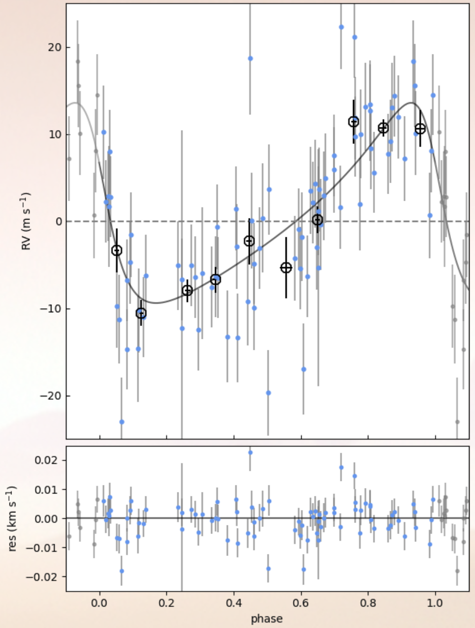


BEBOP so far

- ➢ Northern hemisphere 74+ targets
- ➢ Southern hemisphere 72+ targets
- ➢ Reaching precision of 1-2 m/s – reaching photon noise limit







Baycroft et al. (in preparation)

BEBOP so far

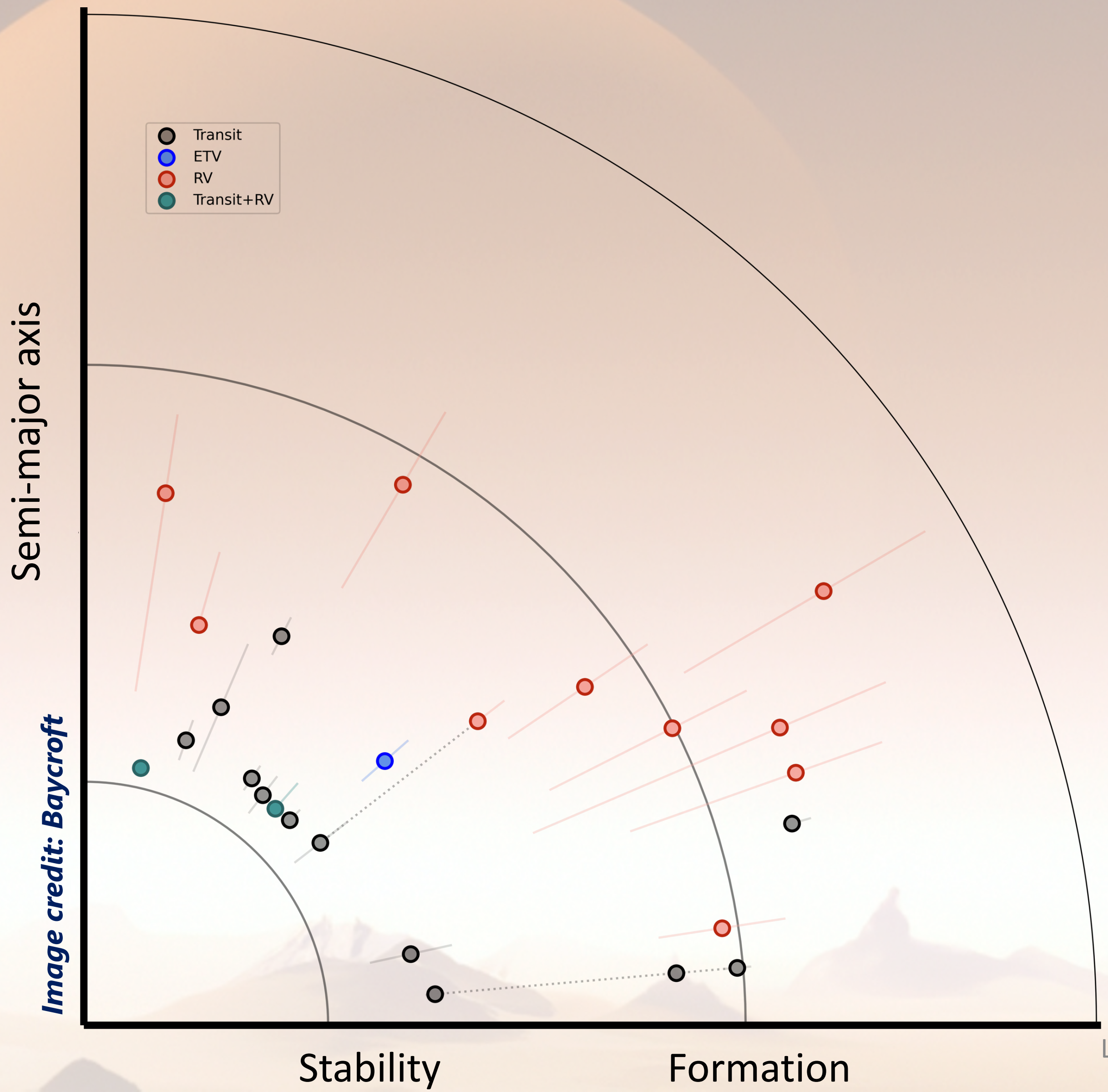
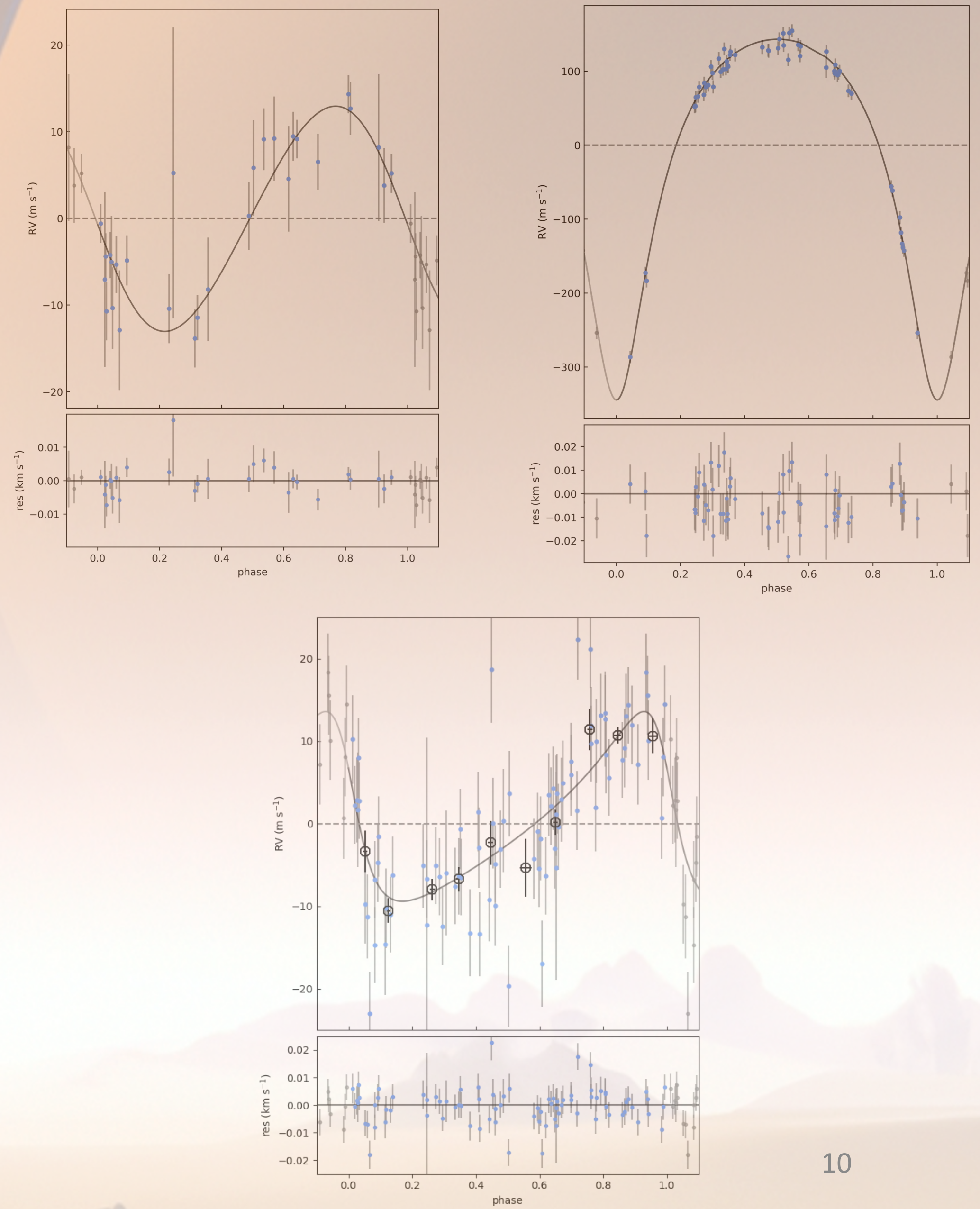
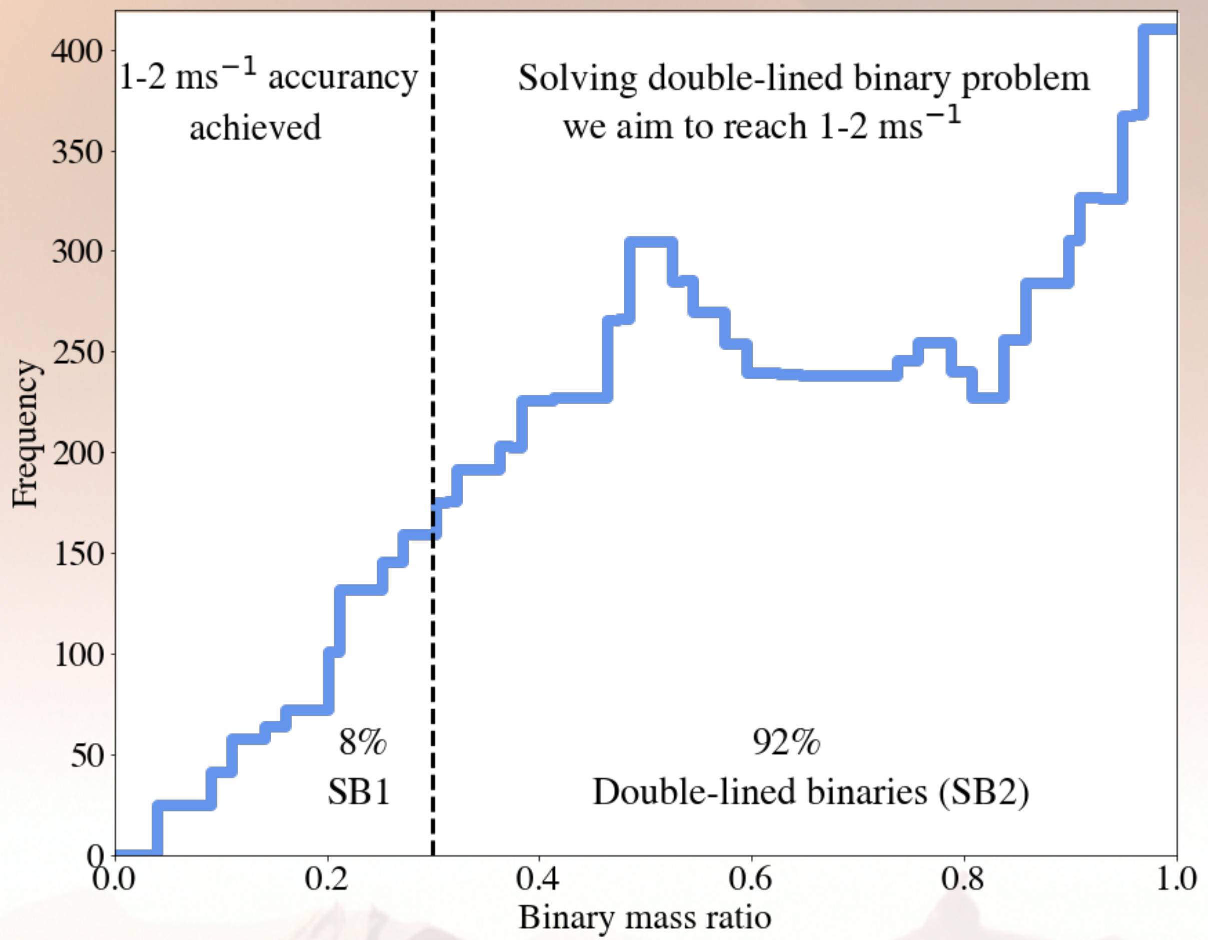


Image credit: Baycroft

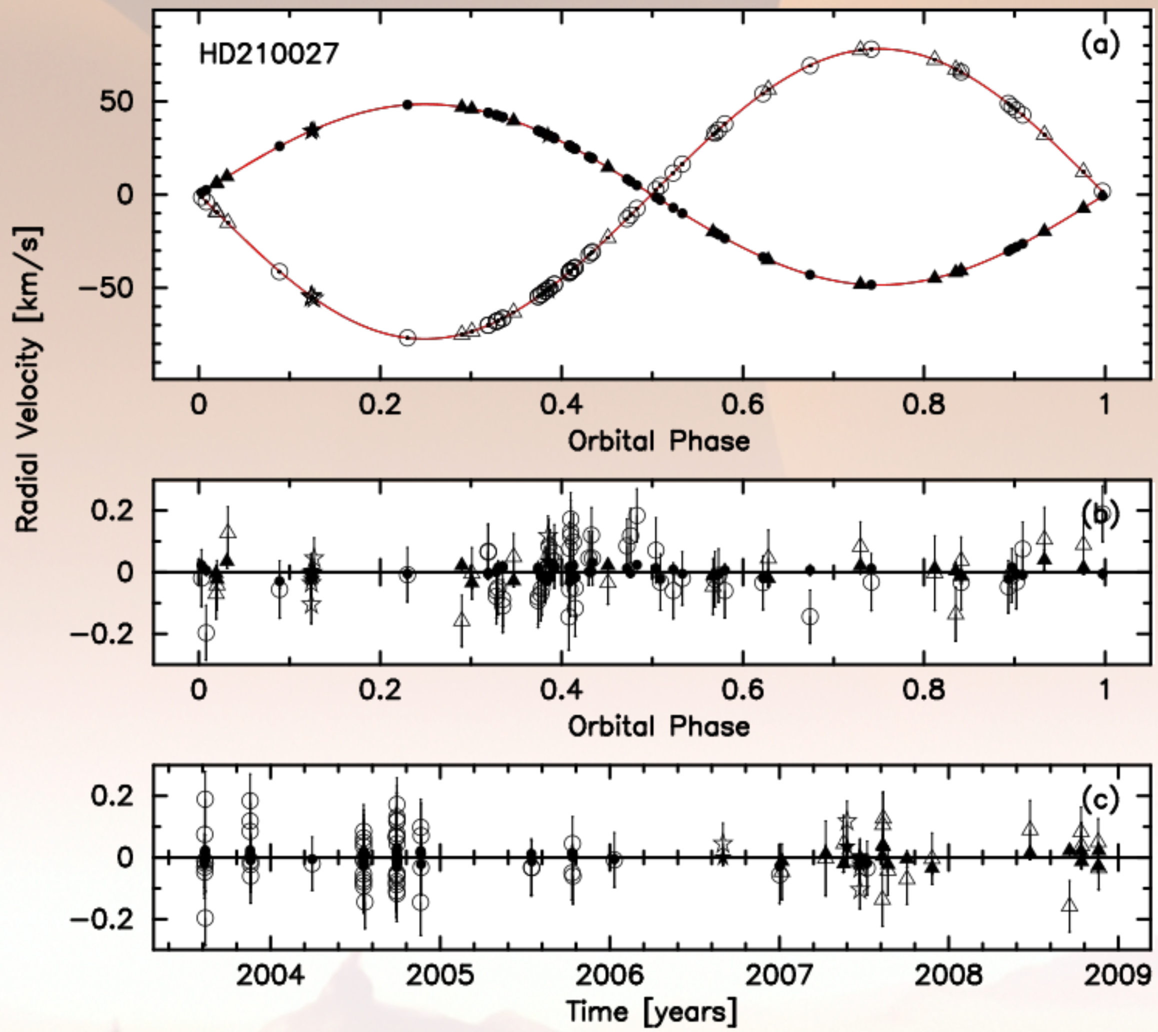


Why double-line binaries?



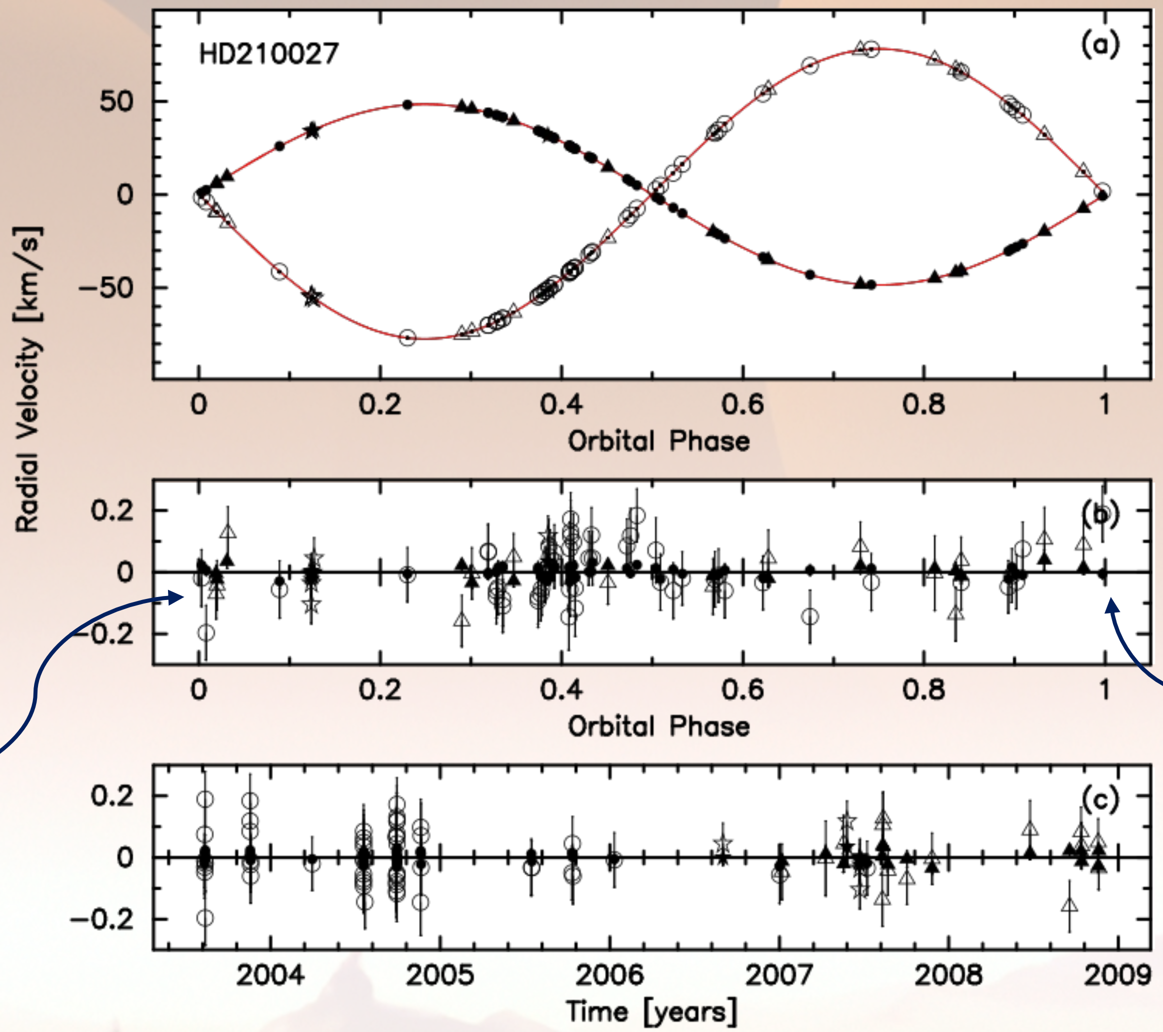
- ✓ Most common potential planet hosting binaries
- ✓ SB2 are brighter
- ✓ Model independent mass – planet RV on both component

TATOOINE (SB2 radial velocity survey)



Konacki et al. 2009

TATOOINE (SB2 radial velocity survey)

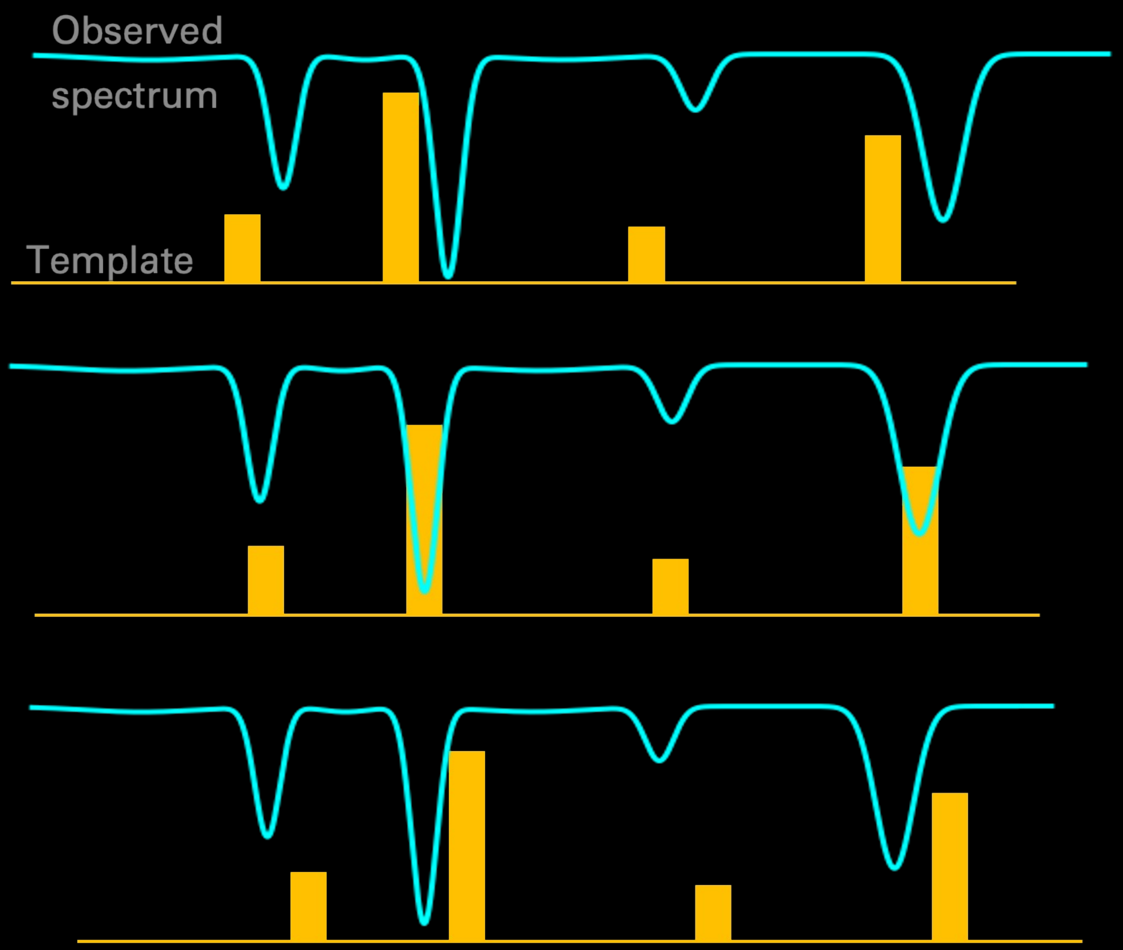


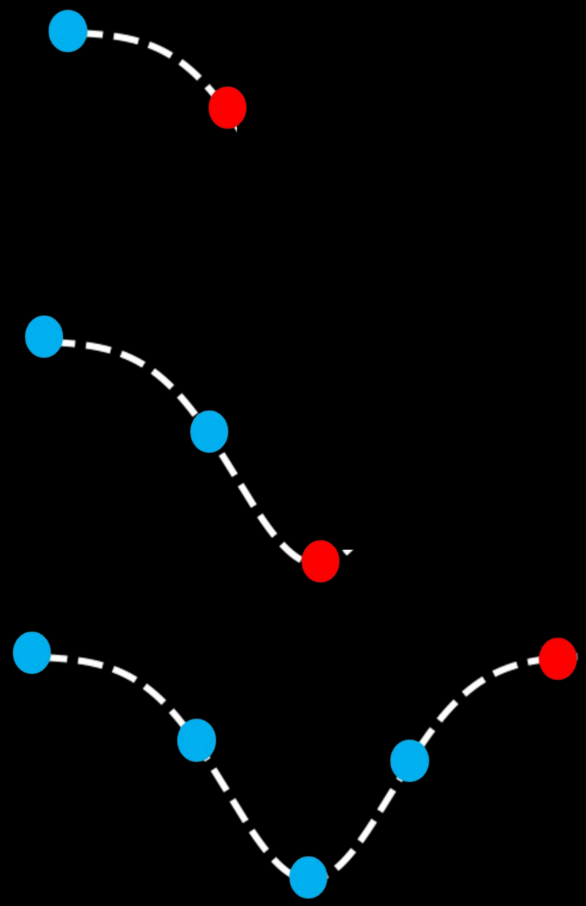
Konacki et al. 2009

Few m/s photon noise

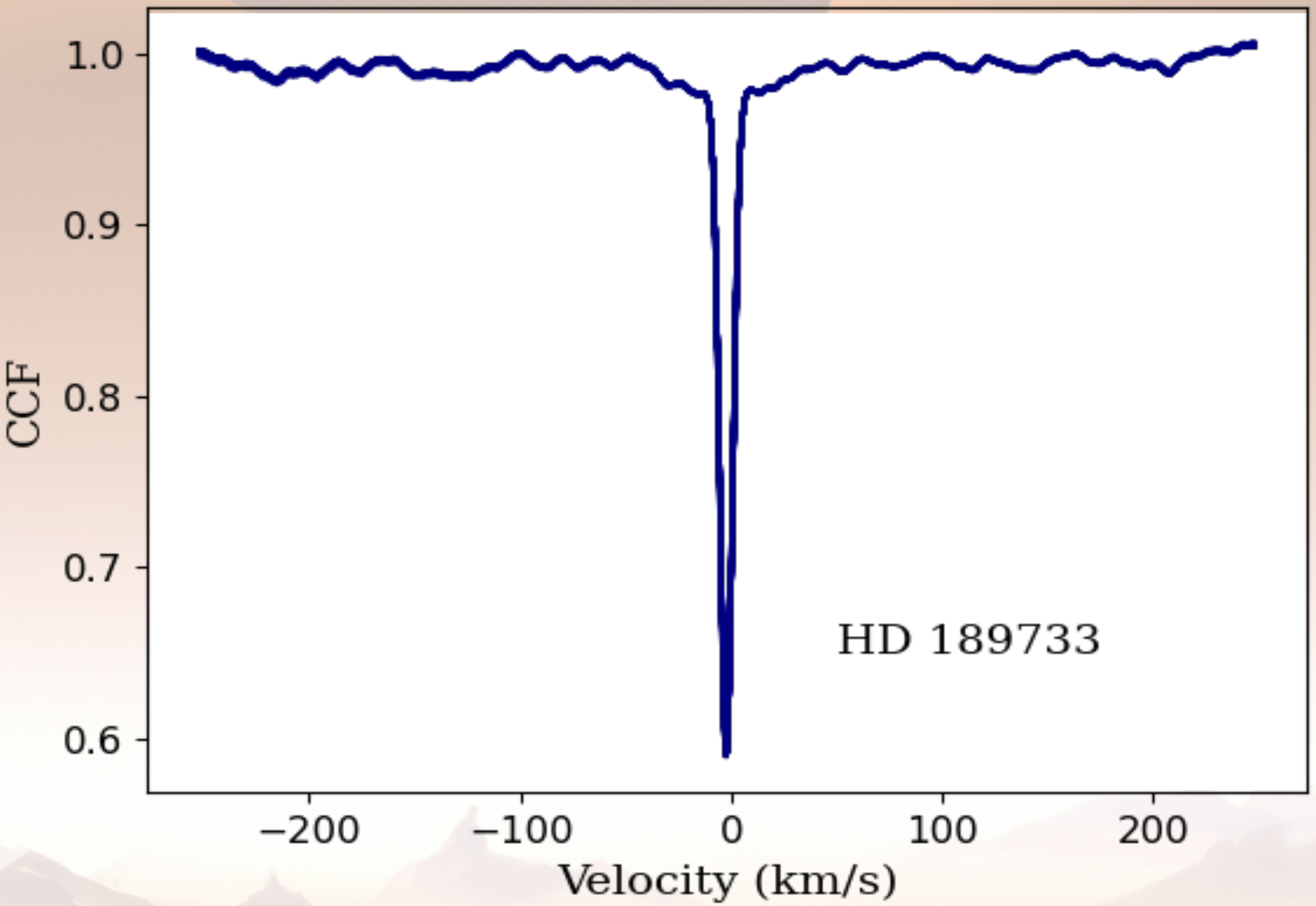
15-20 m/s scatter – prevent – gas giant detection

How do we get our precise radial velocities?



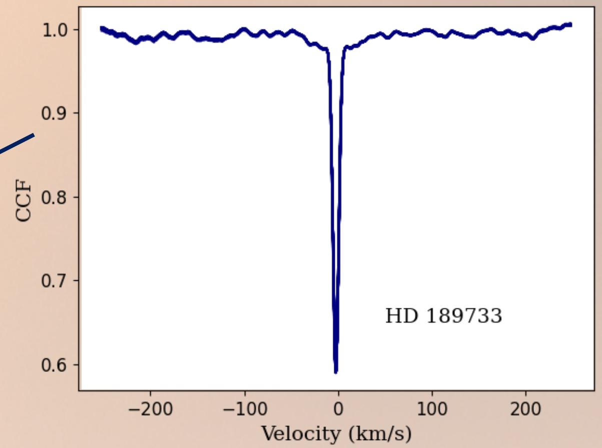


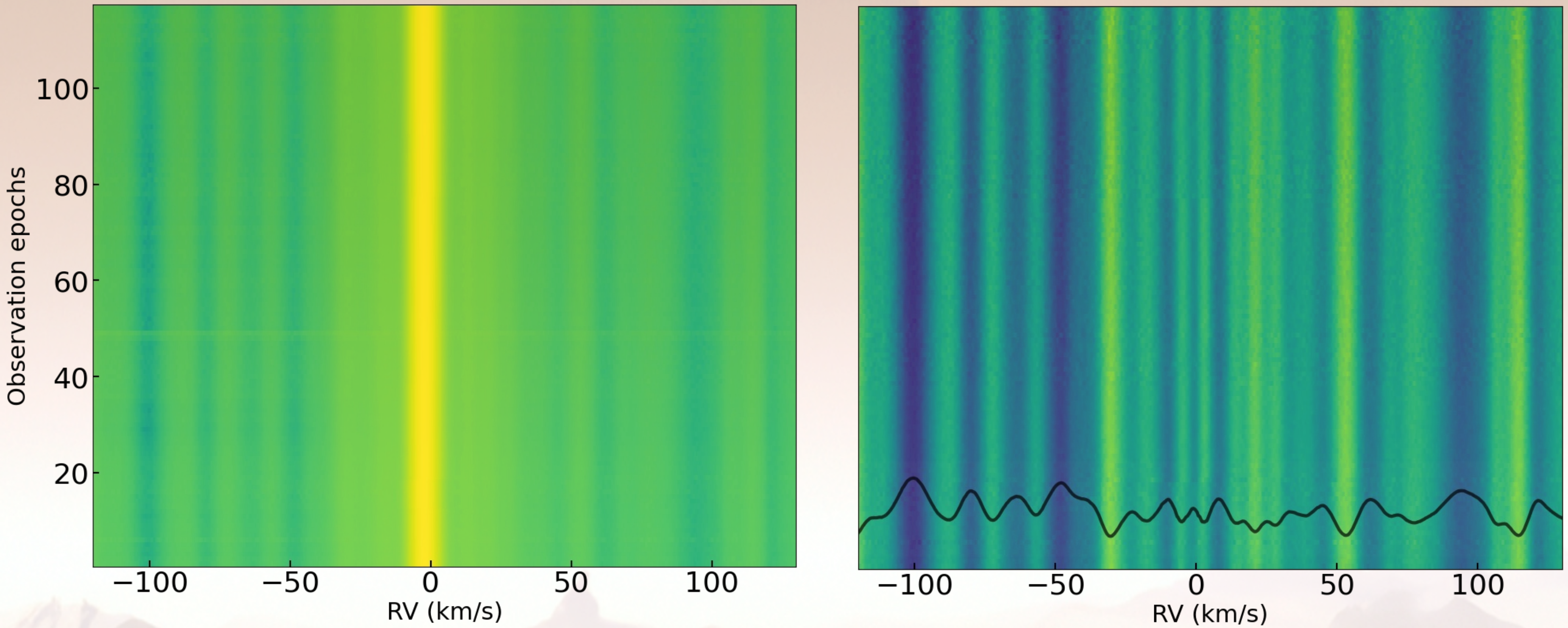
CCFs of single star



Lalitha Sairam et al. 2024

CCFs of single star





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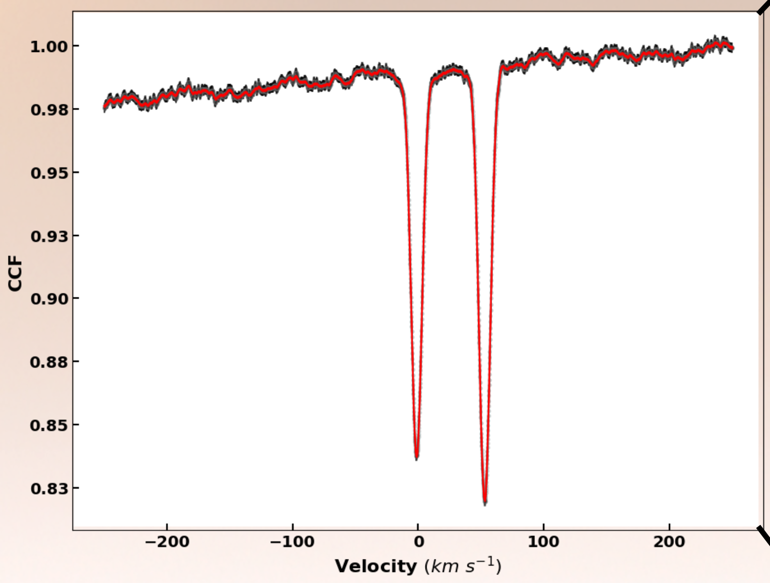
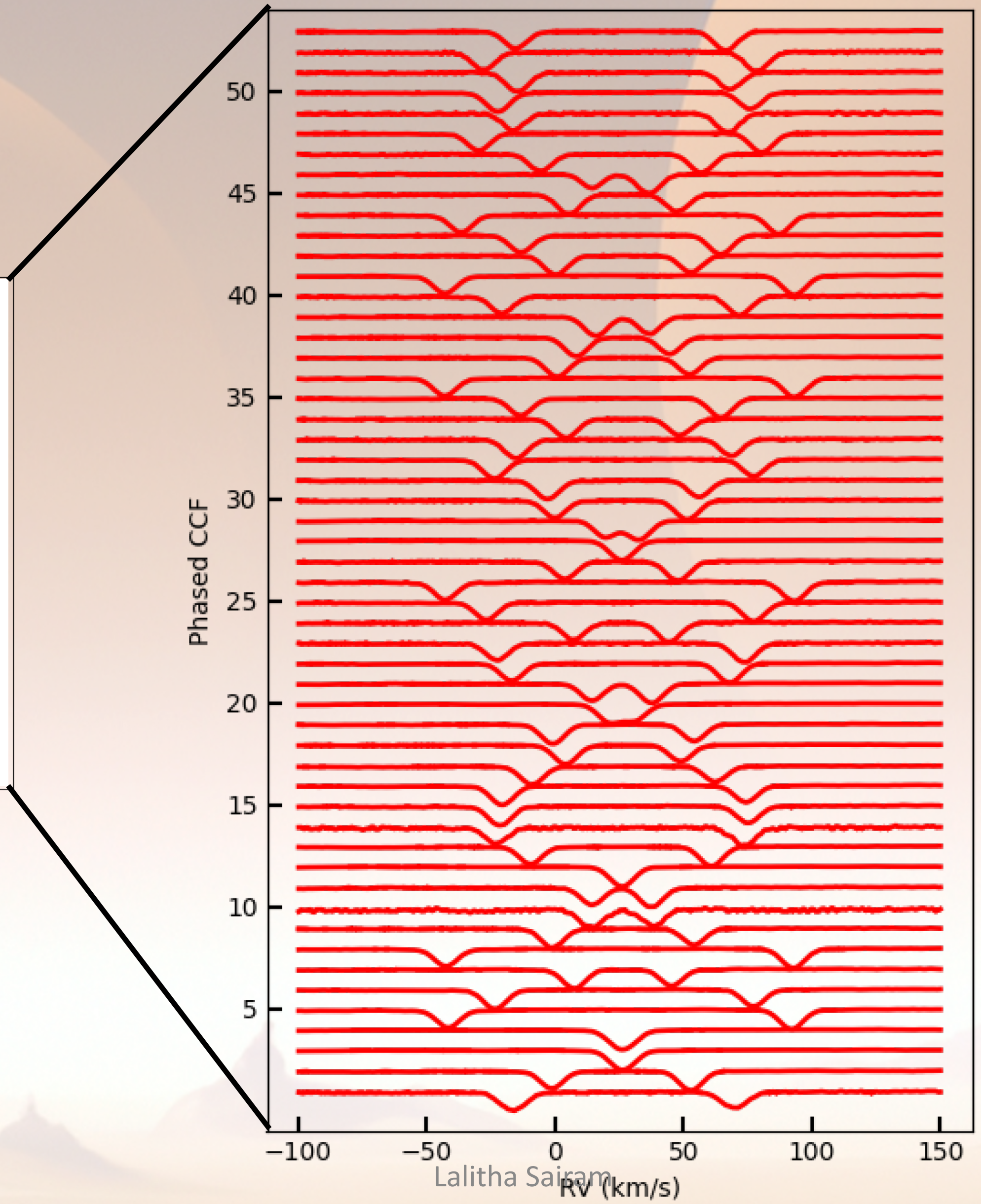
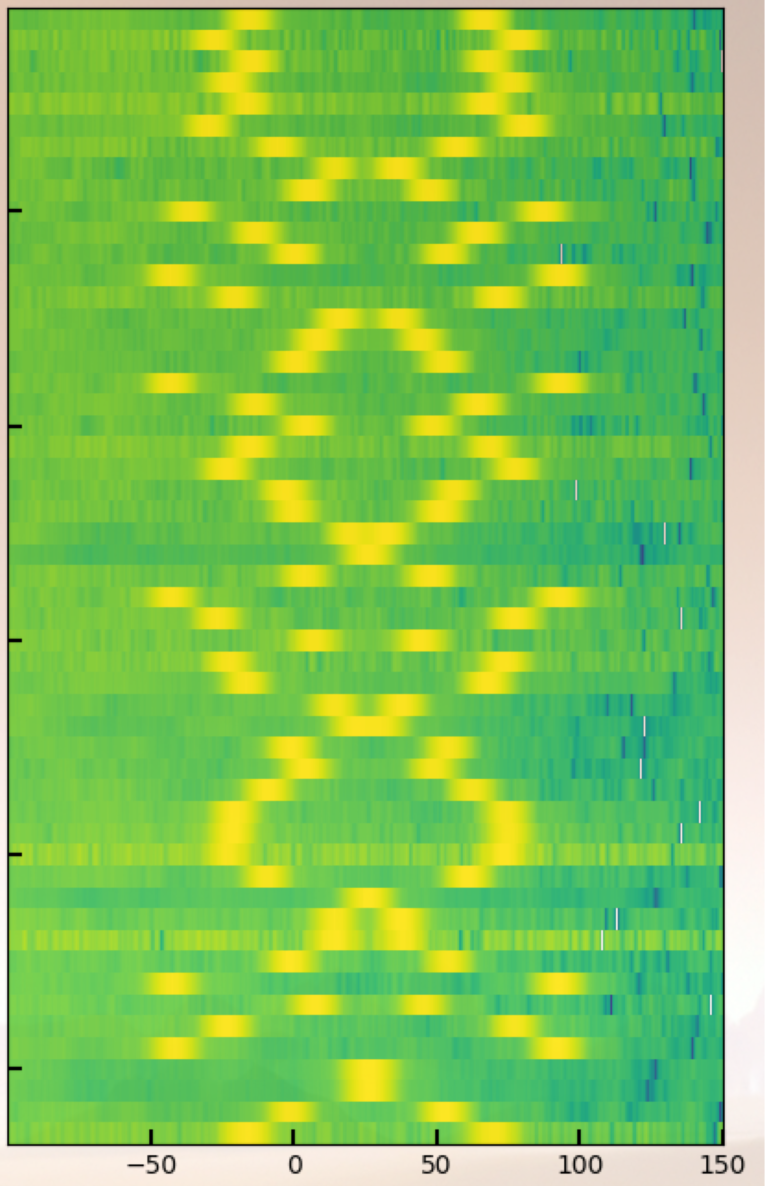
CCFs of double-lined binary star







DOLBY -- data driven modelling of observed binary spectra

Intrinsic spectrum of the star — GP

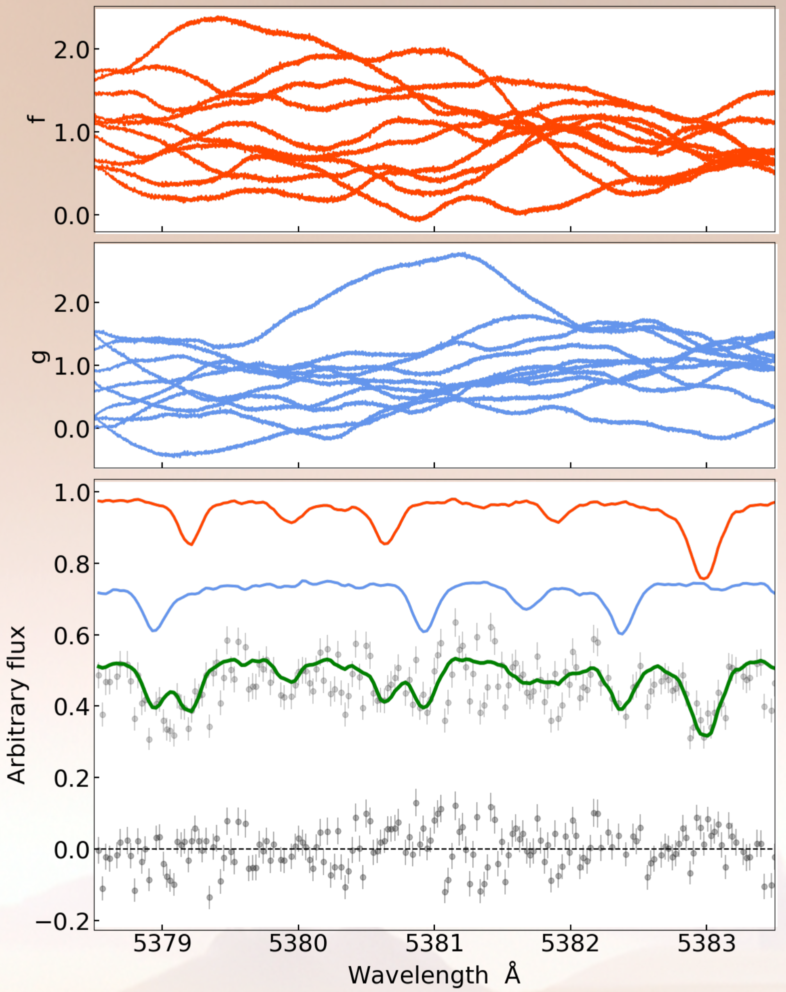
$$f(\lambda) \sim GP(\mu(\lambda)\ k(\lambda, \lambda'))$$

$$g(\lambda) \sim GP(\mu(\lambda)\ k(\lambda, \lambda'))$$

Sum of realisations for components

$$d = \mathcal{N}(\mu_f, \mu_g, \sum_f + \sum_g + \sum_N)$$

GPs independent -- Doppler shifts → disentangle spectra



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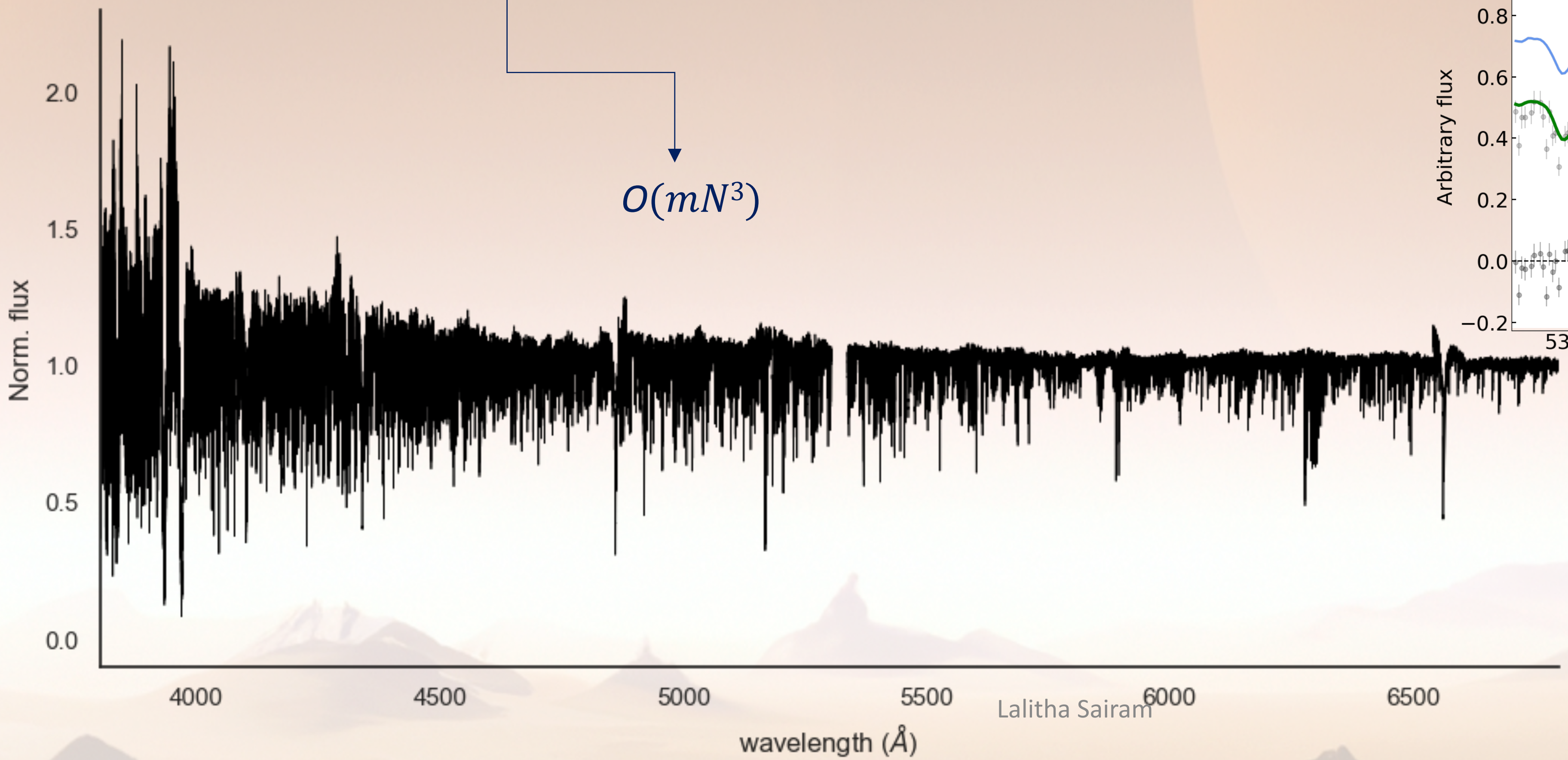
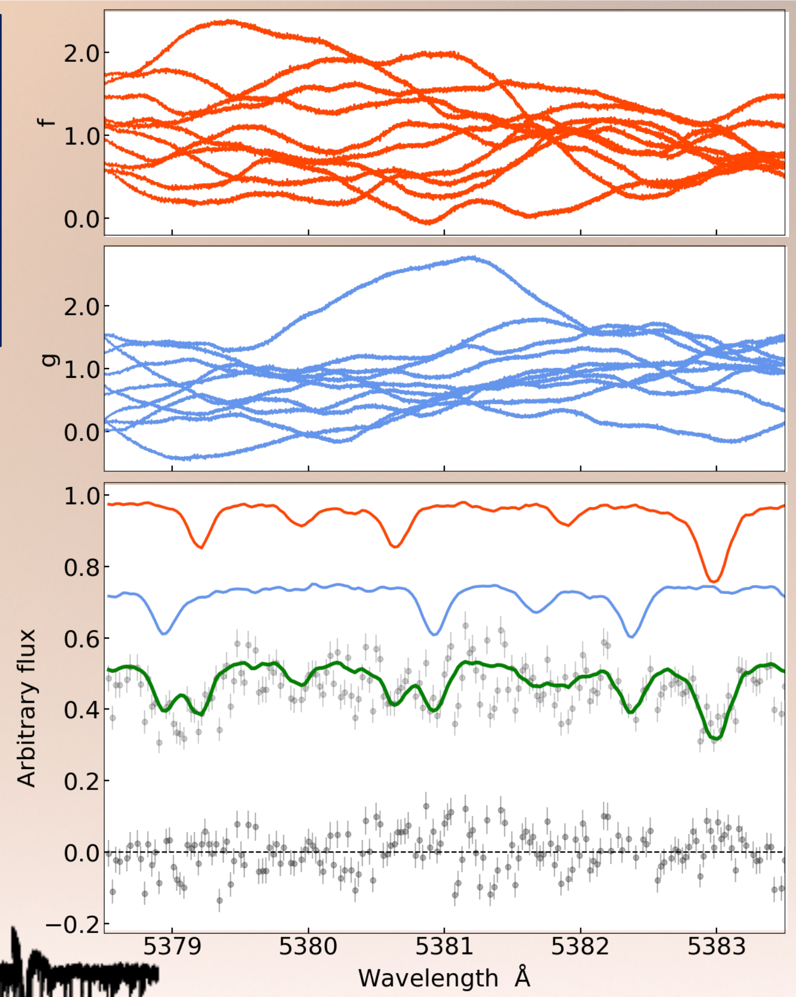
Approach 1 - Efficient Spectral Decomposition using Gaussian Processes (SD-GP)

Computationally expensive → $O(N^3)$

→ $O(mN^3)$





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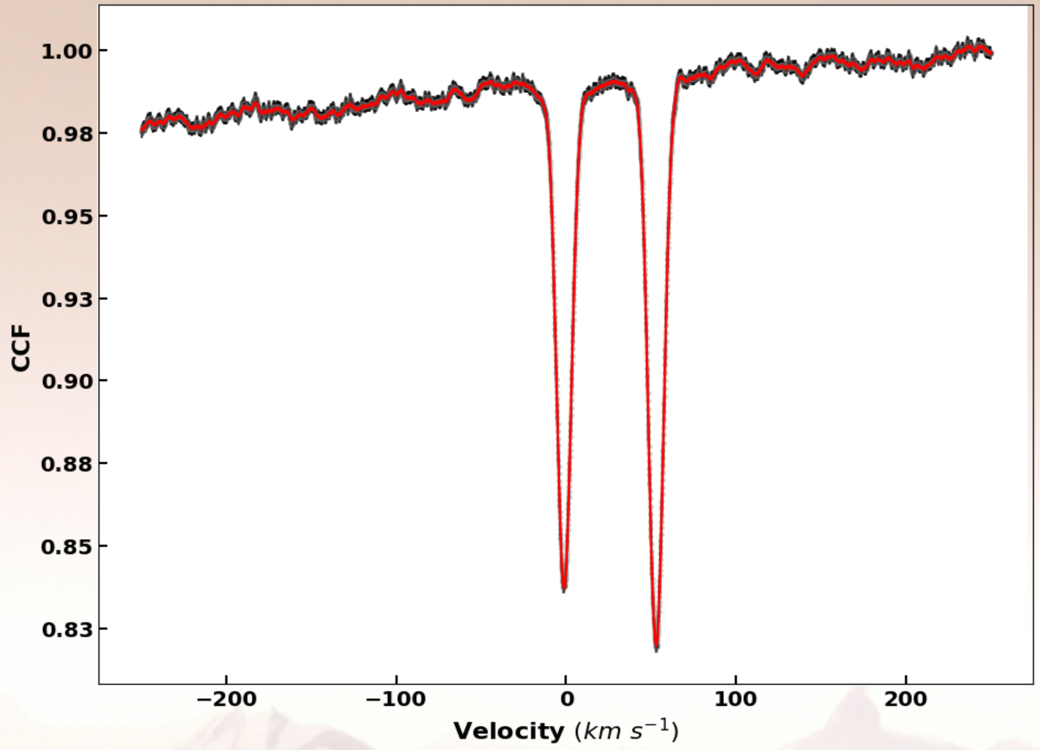
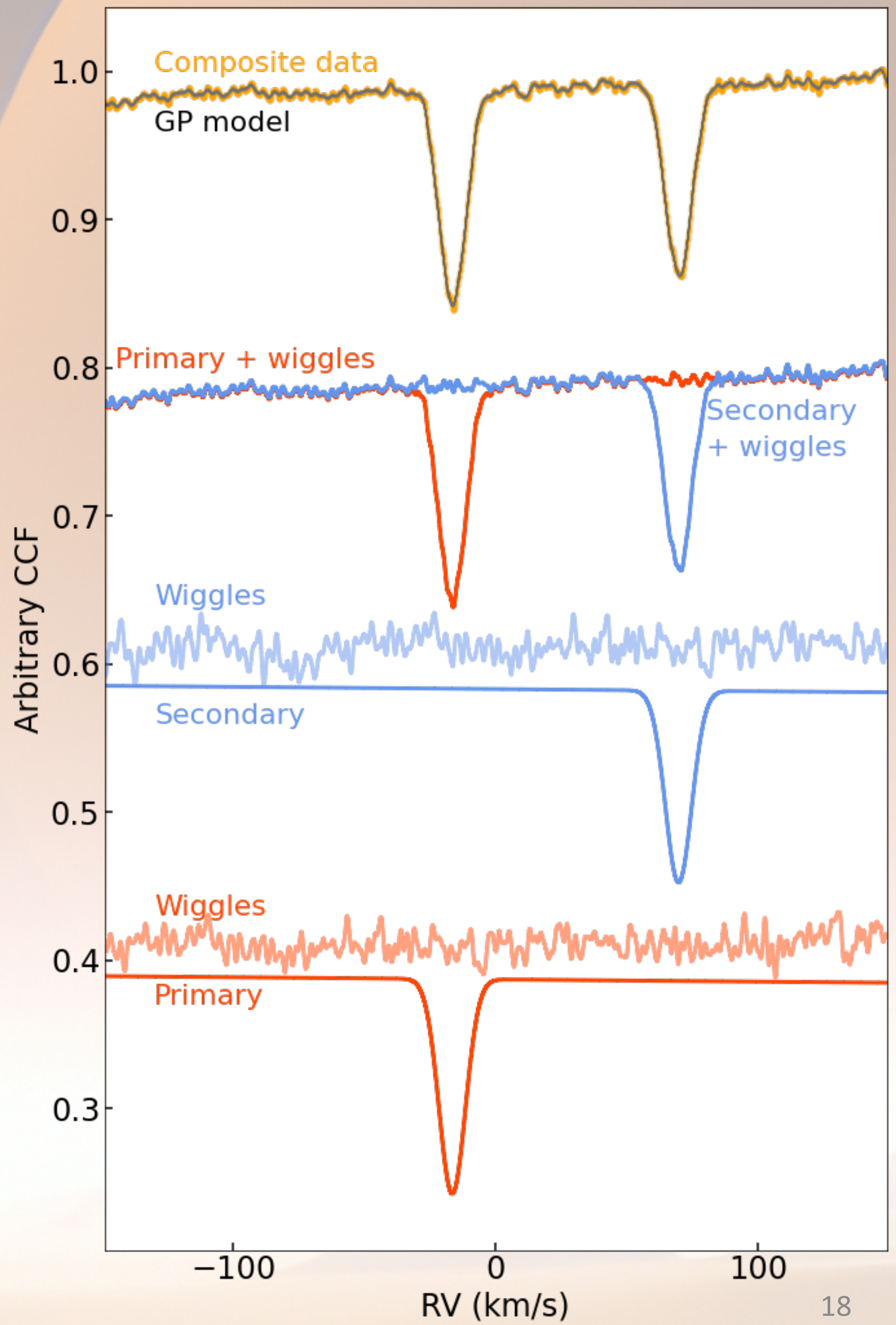
Approach 2 – Cross-correlation functions modelled using Gaussian process (CCF-GP)





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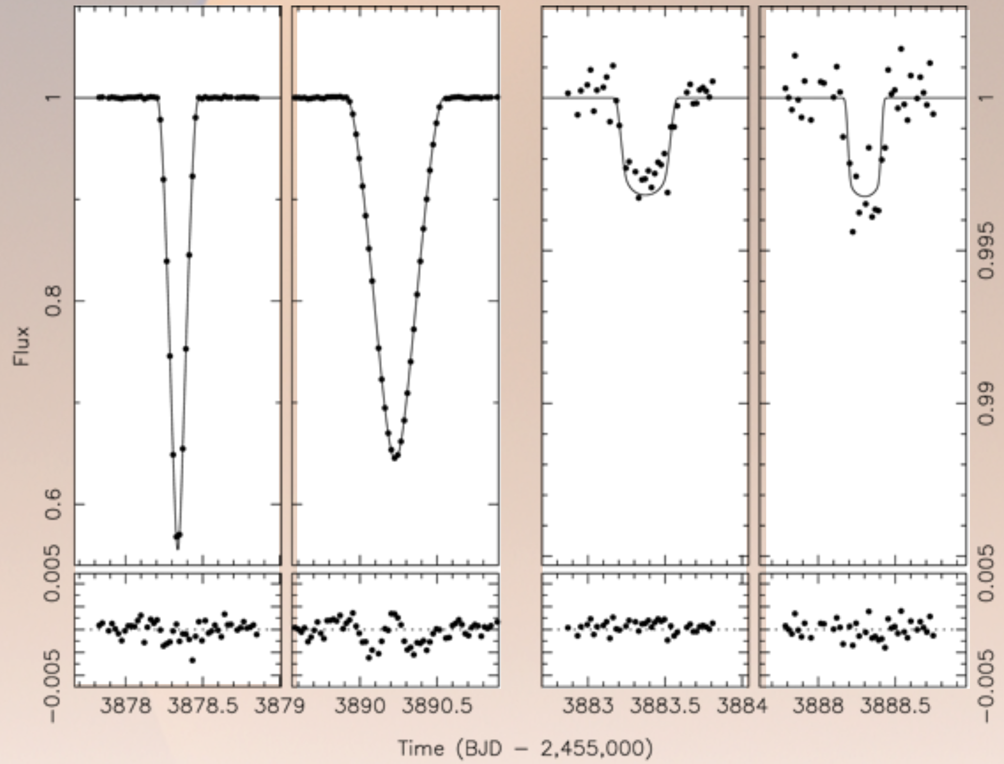
TIC172900988

Kostov et al. 2021

- P_{binary} ~ 19.7 d
- P_{pl} : $188 < P_{pl}$ (d)< 204
- M_{pl} : $823 < M_{pl}$ $(M_{\oplus})$ < 981



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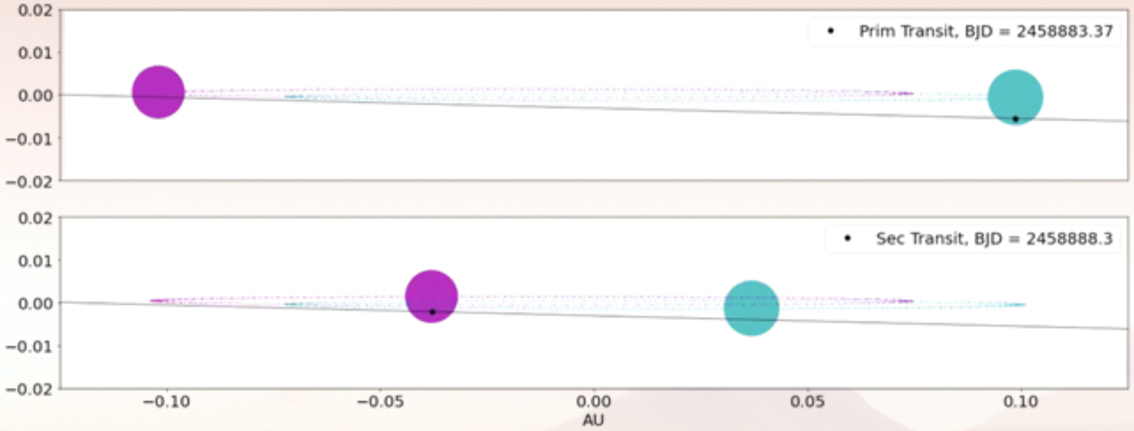
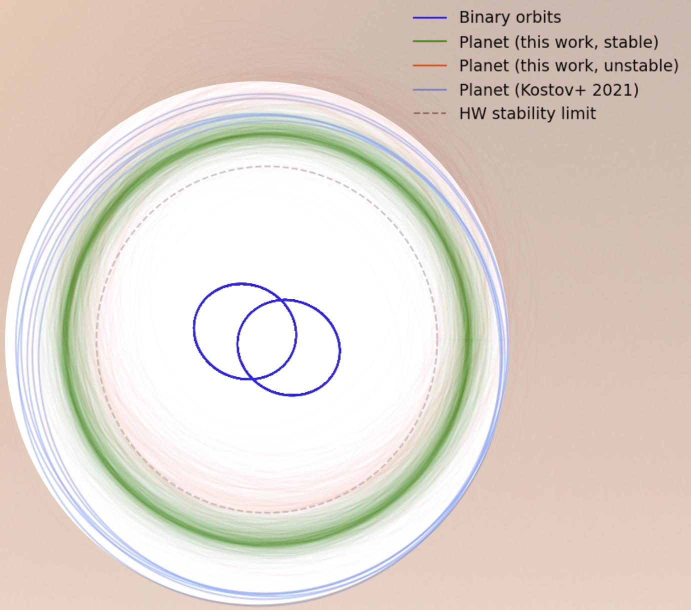
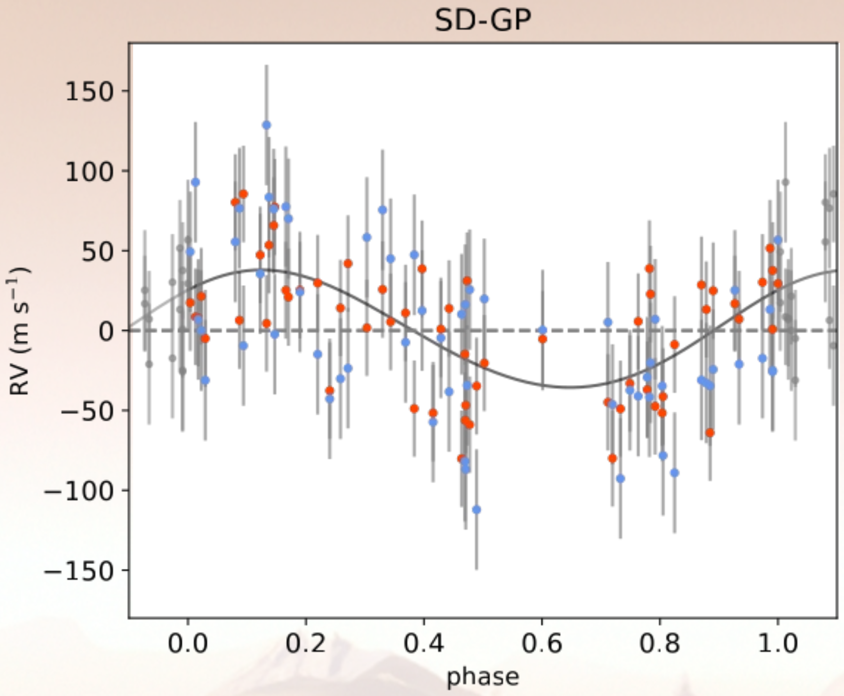
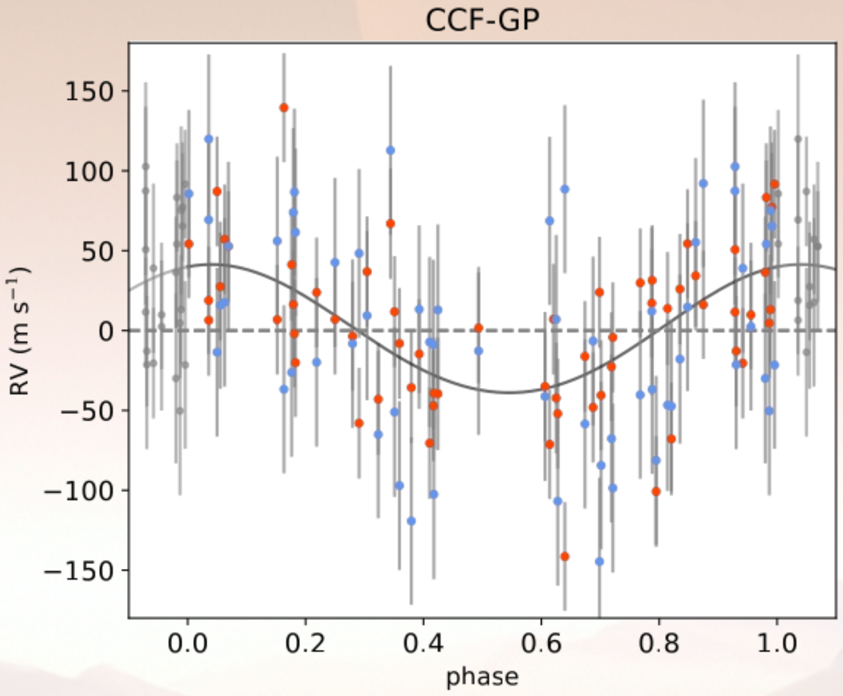


TIC172900988 - First radial velocity circumbinary planet detected orbiting double-lined binary







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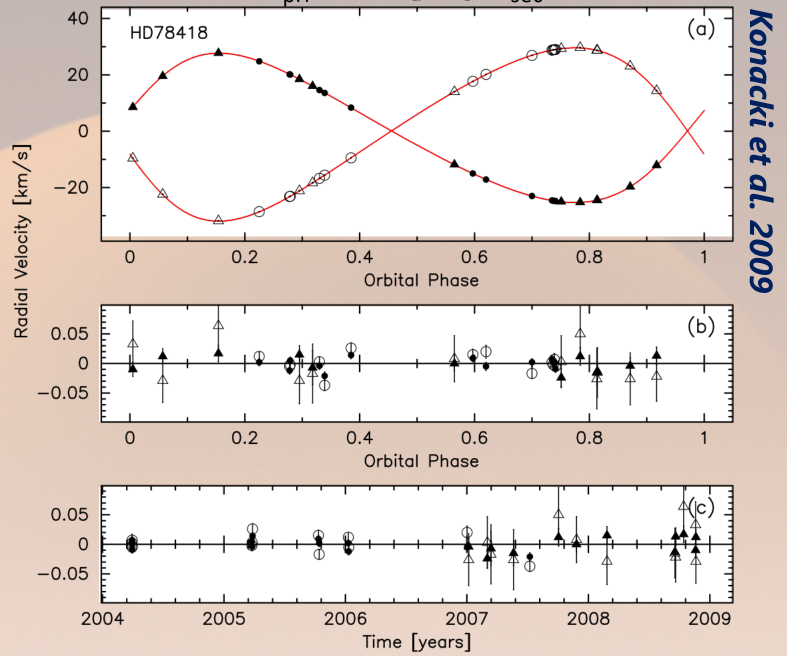
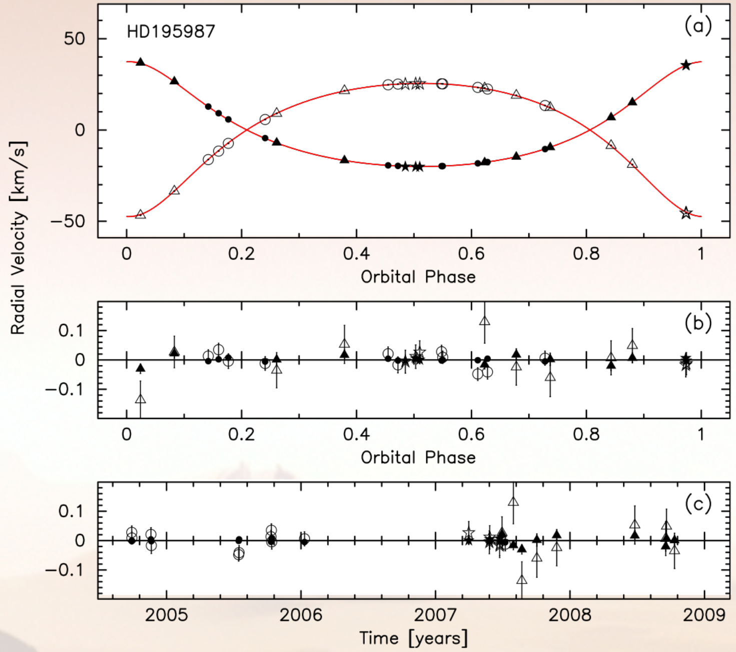
TATOOINE targets

RMS_{pri} ~15m/s RMS_{sec} ~67m/s



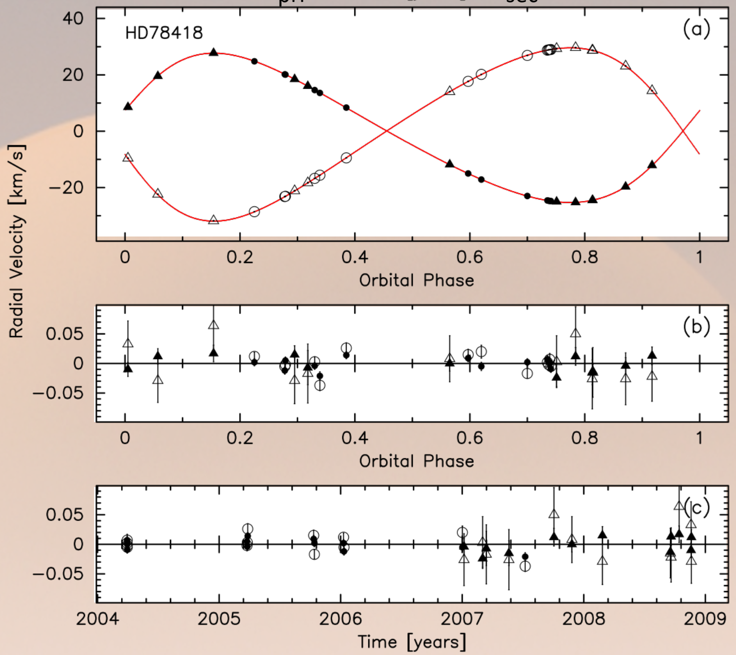
Konacki et al. 2009

RMS_{pri} ~11m/s RMS_{sec} ~48 m/s



TATOOINE targets

RMS$_{pri}$ ~15m/s RMS$_{sec}$ ~67m/s



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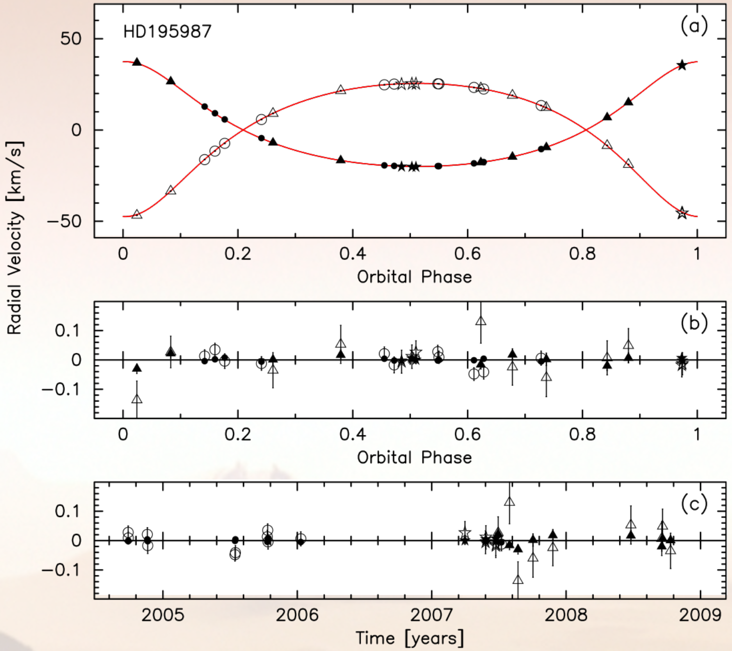
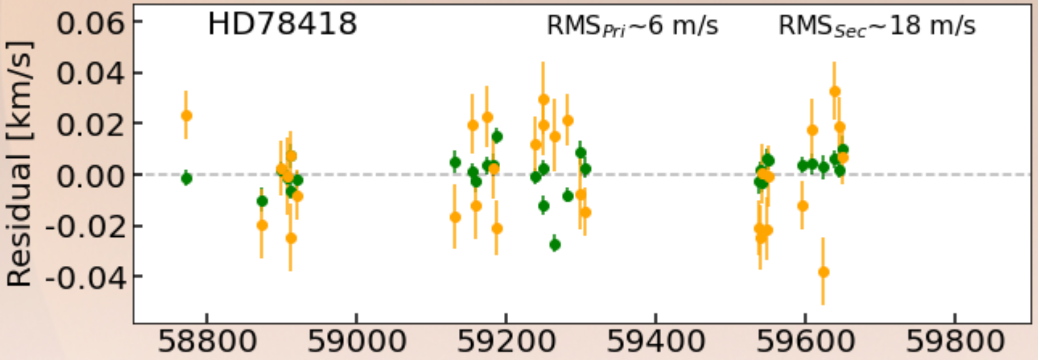
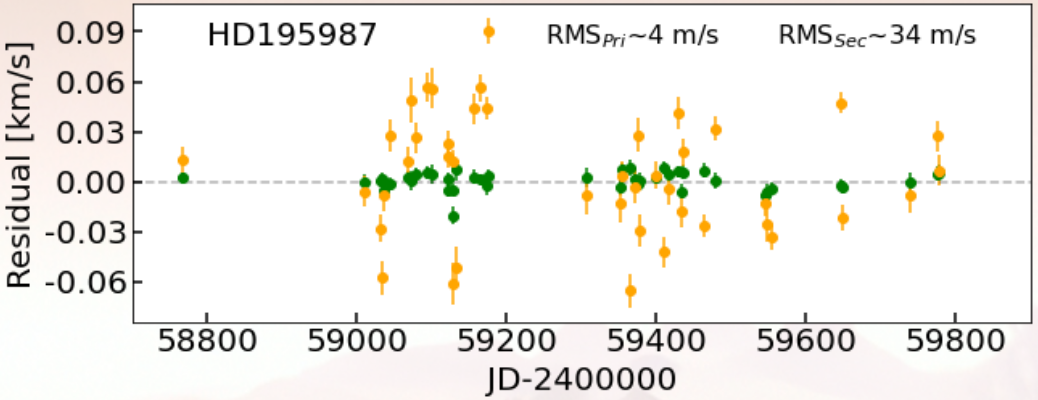
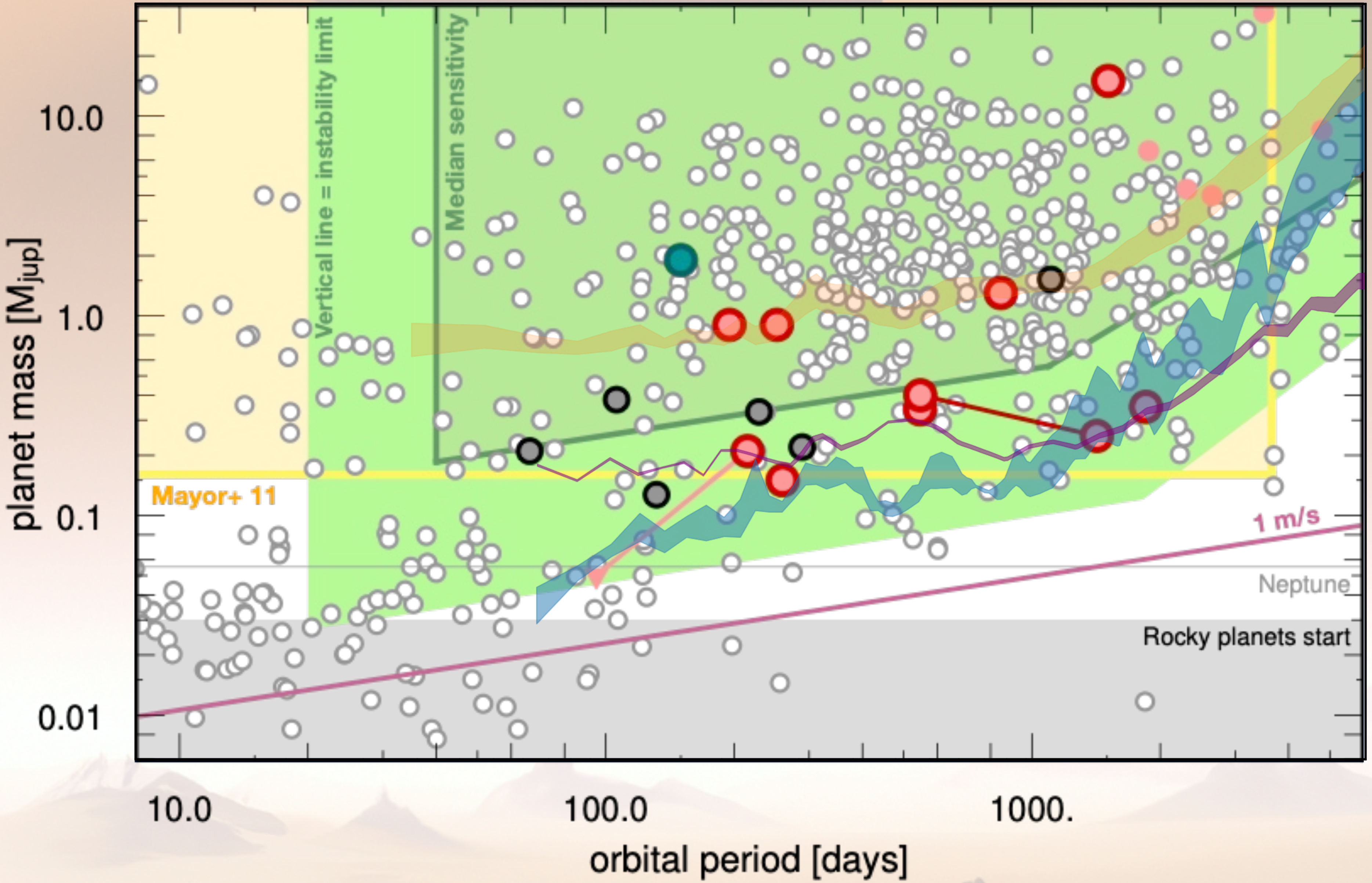






Lalitha Sairam et al. (in press)

Occurrence rates of circumbinaries



Summary

- Circumbinary planets provide unique insights into planet formation.
- BEBOP -- expanded our understanding, focusing on single-line binaries.
- Double-line binaries - DOLBY -- spectra and CCF decomposition are overcoming these barriers.
- Future progress depends on improved methods, larger surveys, and the next generation of instruments.
- We're only scratching the surface—much more to explore in the circumbinary planet population.

Collaborators

Amaury Triaud, Daniel Sebastian, Matthew Standing, Thomas Baycroft,, David Martin, Alexandre Santerne, Isabelle Boisse, Neda Heidari, Gavin A.L. Coleman, Guillaume Hebrard, Richard Nelson, Pierre Maxted, Yasmin Davis, Georgina Dransfield, Vedad Kunovac-Hodžić, Owen J. Scutt, Don Pollacco, Coel Hellier, Magali Deleuil, Andrew Collier Cameron, Stéphane Udry, Rosemary Mardling, Alexandre Correia, Michaël Gillon, Tristan Guillot, James McCormac, Sam Gill, Isabelle Boisse, João Faria

BEBOP BINARY ESCORTED BY ORBITING PLANETS

- ✓ show circumbinary planets can be found using RVs
- ✓ measure an upper bound on the occurrence rate
- ✓ derive a mean mutual inclination
- ✓ verify the metallicity, period and mass distributions
- ✓ 95% of the planets will transit, find them study changing and temperate atmospheres

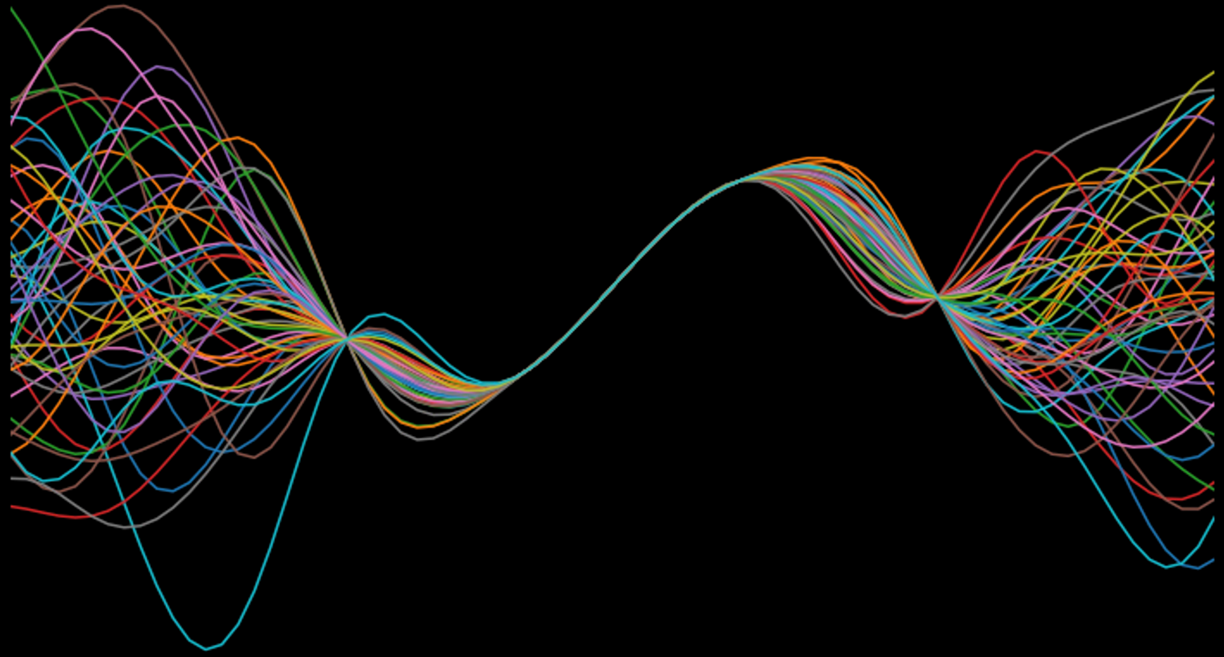
Non-parametric modelling

→ Flexible probabilistic frame work – data driven– Gaussian process

→ Multivariate Gaussian distribution

$$X = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ \vdots \\ X_N \end{bmatrix} \sim N(\mu, \Sigma)$$

Mean vector   Covariance matrix



Lalitha et al. 2022

Data-driven model of observed binary spectra

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→ Sum of realisations for components

$$d = \mathcal{N}(\mu_f, \mu_g, \sum_f + \sum_g + \sum_N)$$

→ GPs independent -- Doppler shifts → disentangle spectra

Non-parametric modelling of the observed binary spectra

→ Orbital motion → Doppler shift – rest frame

$$\lambda(v) = \sqrt{\frac{c+v}{c-v}}\lambda_0$$

→ Radial velocity as function of time

$$\theta = \{q, K_{primary}, e, \omega, P, T_0, \gamma\}$$

→ Velocity of primary and secondary

$$V_A = K_A(\cos(\omega + f(t)) + e\cos\omega) + \gamma$$

$$V_B = -\frac{K_A}{q}(\cos(\omega + f(t)) + e\cos\omega) + \gamma$$