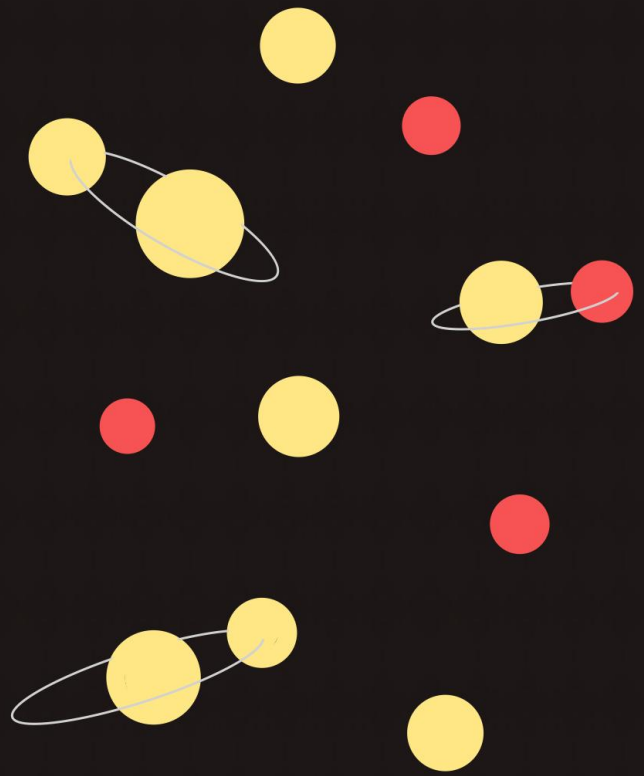
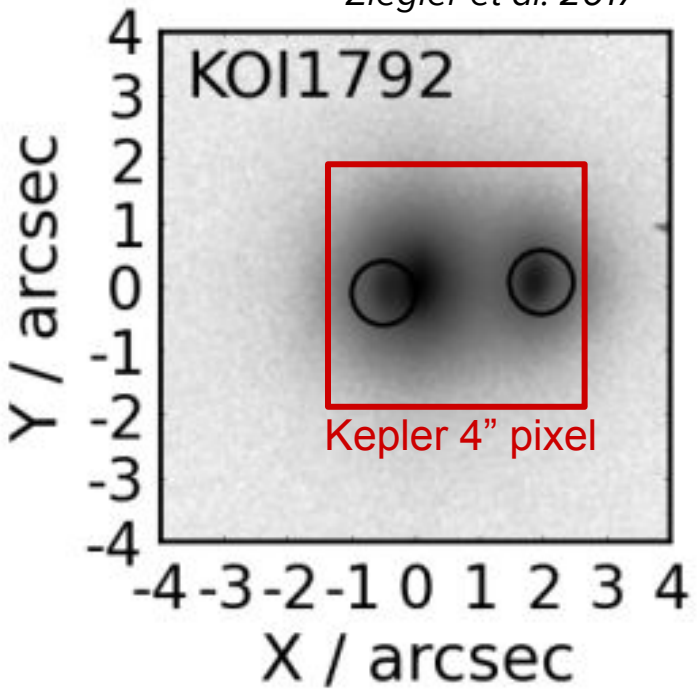
On the Road to Detecting Spectral Binaries with Data-Driven Models



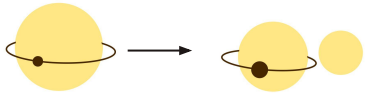
Isabel Angelo
Know Thy Star, Know Thy Planet 2
February 3, 2025

Close binaries in Kepler + TESS are mistaken for single stars

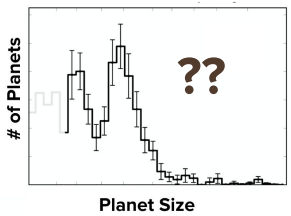
Ziegler et al. 2017



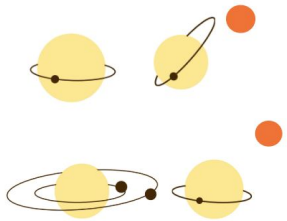
underestimated planet radii



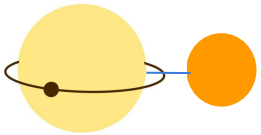
errors in demographic trends like the radius gap



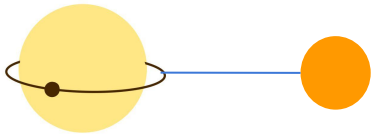
open questions about whether and how planets form in binaries



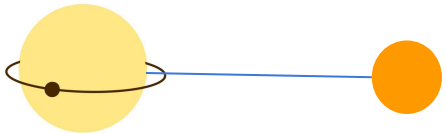
Previous searches for binaries among Kepler planet hosts miss binaries with 10-100au separations



a<10au:
offset spectra
Kolbl et al. 2015

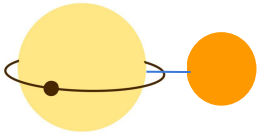


a = 10-100au:
??



a≳50au:
ground-based imaging + AO
Kraus et al 2016, Horch et al 2014

Previous searches for binaries among Kepler planet hosts miss binaries with 10-100au separations



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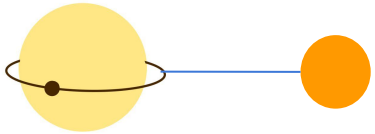

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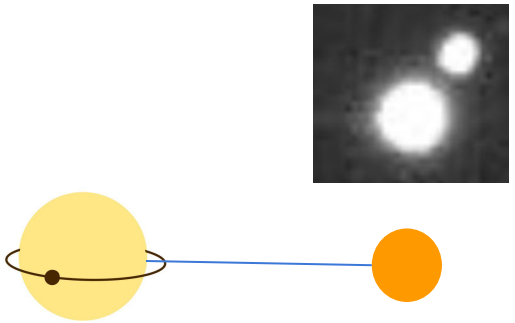
??



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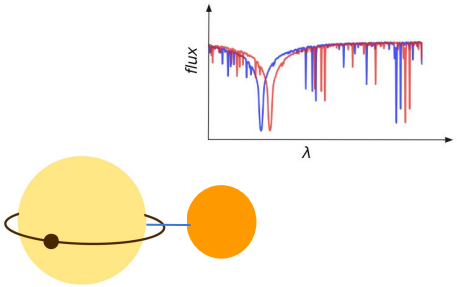
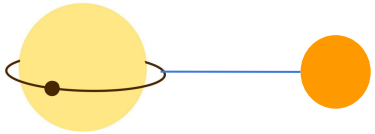


a<10au:
offset spectra
Kolbl et al. 2015



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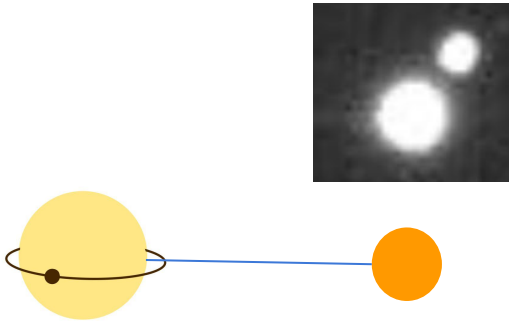

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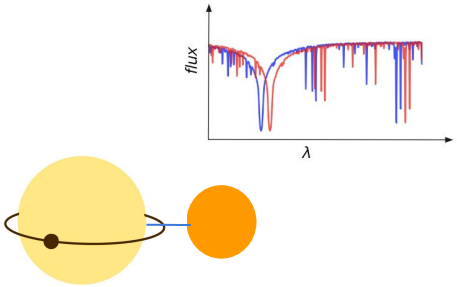
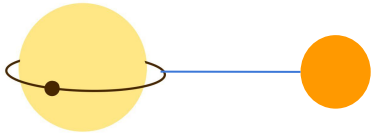
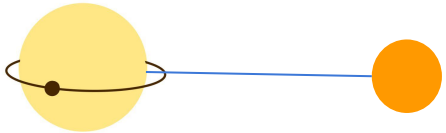


a<10au:
offset spectra
Kolbl et al. 2015

“spectral binaries”



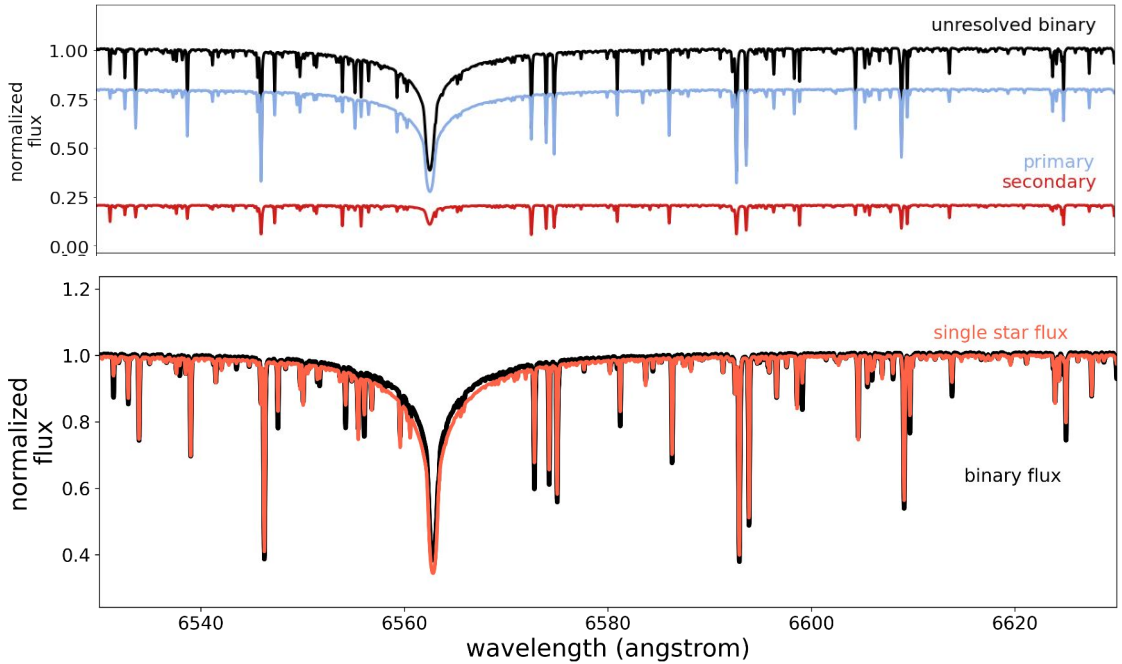
a = 10-100au:
??



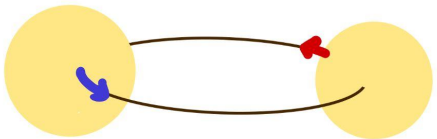
a≳50au:
ground-based imaging + AO
Kraus et al 2016, Horch et al 2014

“Spectral binaries” with overlapping features show **subtle deviations** from single star spectra, which we can detect with **accurate models**

(e.g., Burgasser et al. 2010, El-Badry et al. 2018)

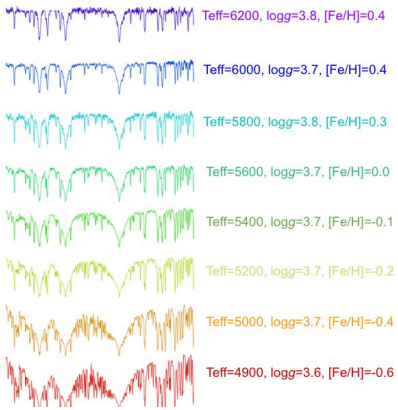


sensitive to binaries with a=1-200au!



Angelo et al., in prep

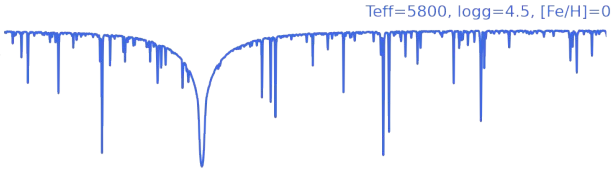
We used data-driven algorithms to develop accurate models of Keck-HIRES spectra



training set: continuum normalized HIRES spectra + corresponding labels (T_{eff}, logg, [Fe/H], vsini) of single stars

training step determines the relationship between flux and stellar labels*

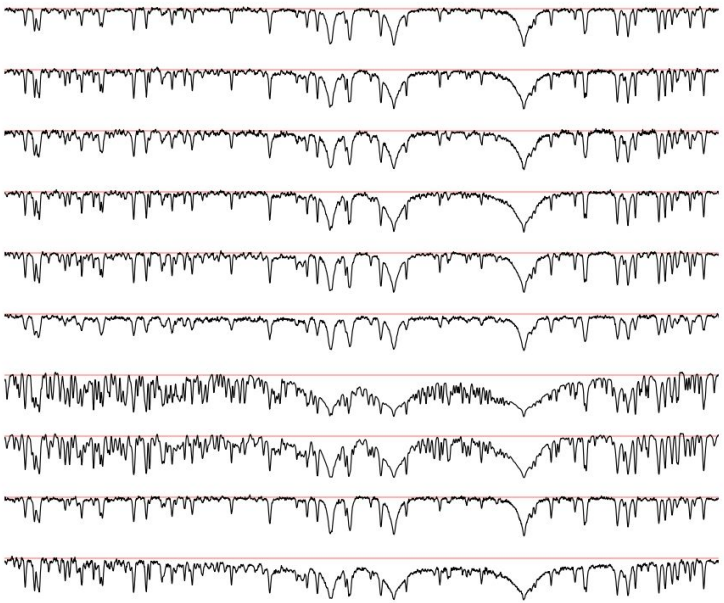
**we use two data-driven algorithms, The Cannon and The Payne, to train multiple models*



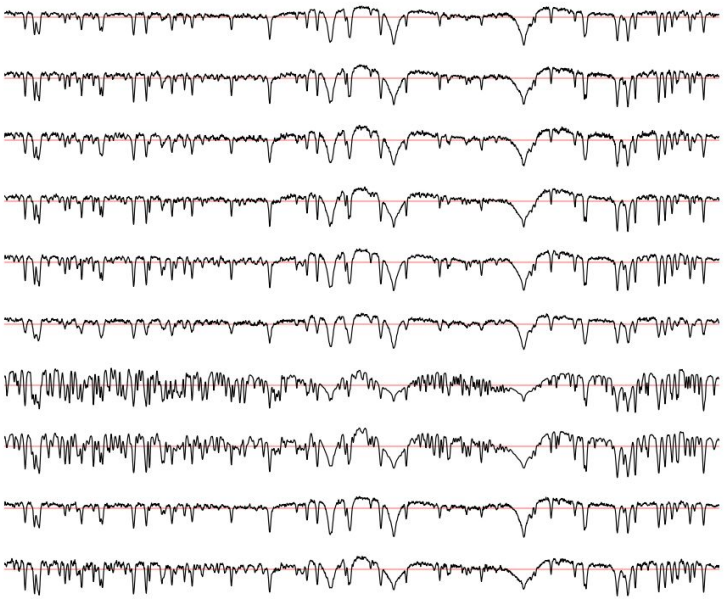
single star model = f(λ)

see: Ness at al. 2015, Ting et al. 2019, Rice & Brewer 2020

Our (new!) **wavelet-based continuum treatment** is an effective alternative to more advanced continuum normalization



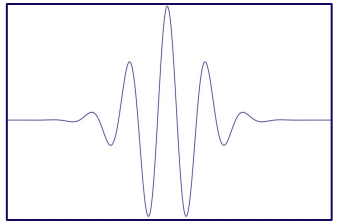
standard de-blazed spectra: continuum-level flux variations present, model temperature precision is limited to ~100K

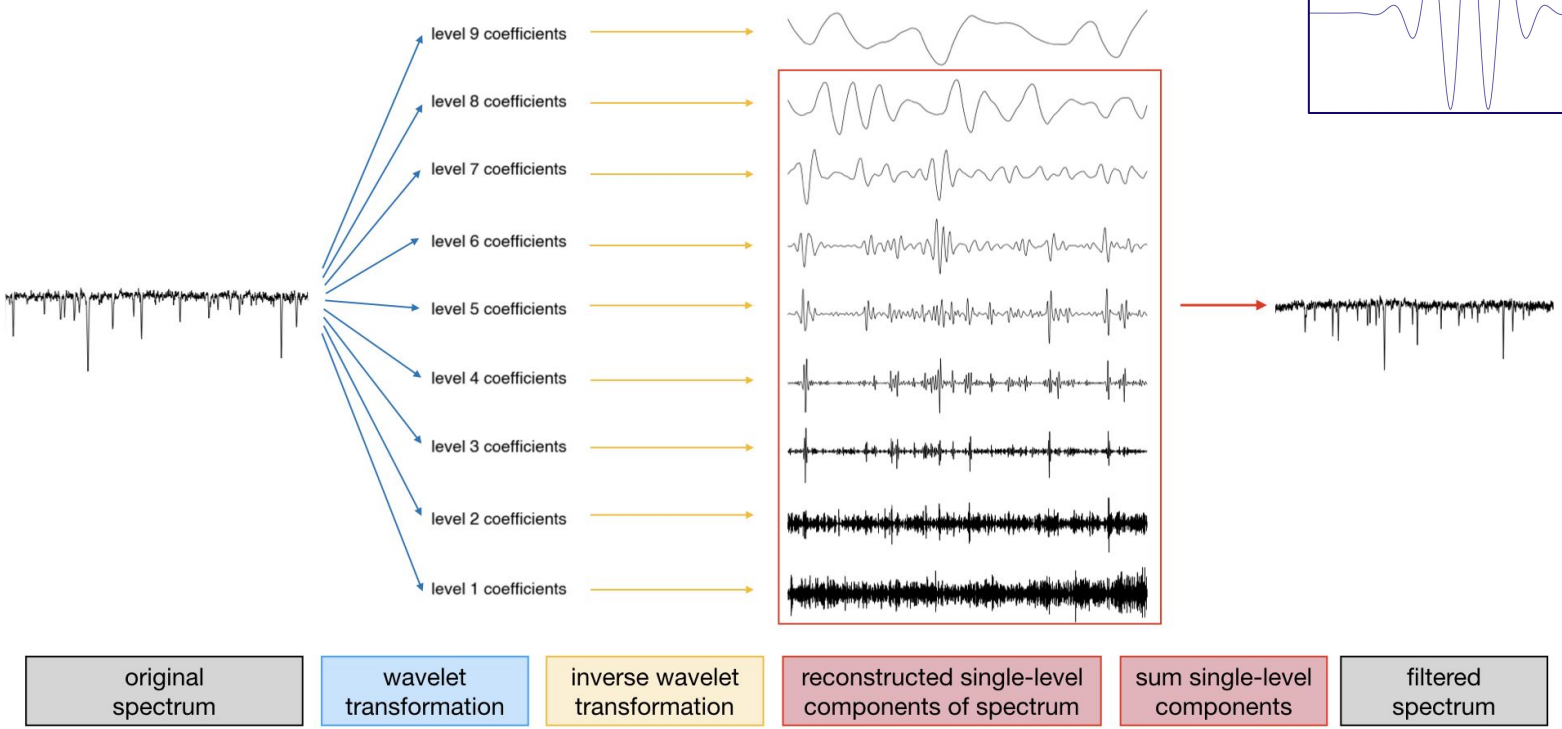


wavelet-filtered spectra: non-uniform low-frequency flux variations are removed, achieves model temperature precision of 60K

Angelo et al., in prep

Wavelet-based continuum treatment of stellar spectra



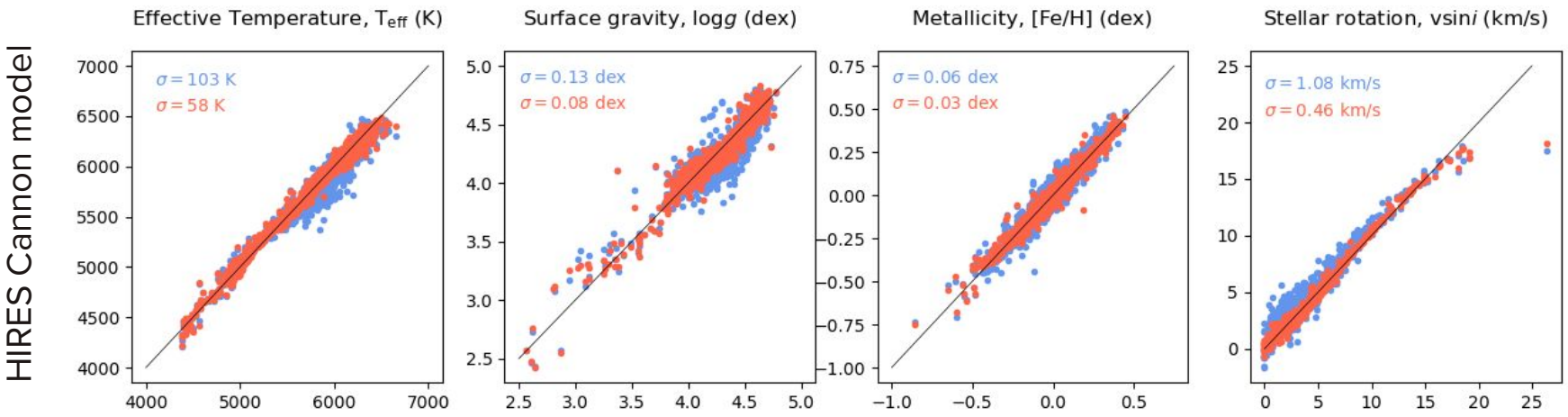


we deconstruct the spectrum into wavelet components and **remove the lowest-frequency component associated with continuum behavior** before reconstructing the signal

Angelo et al., in prep

Using wavelet-filtered spectra in our analysis significantly improves our model performance

- de-blazed spectra
- de-blazed, wavelet-filtered spectra

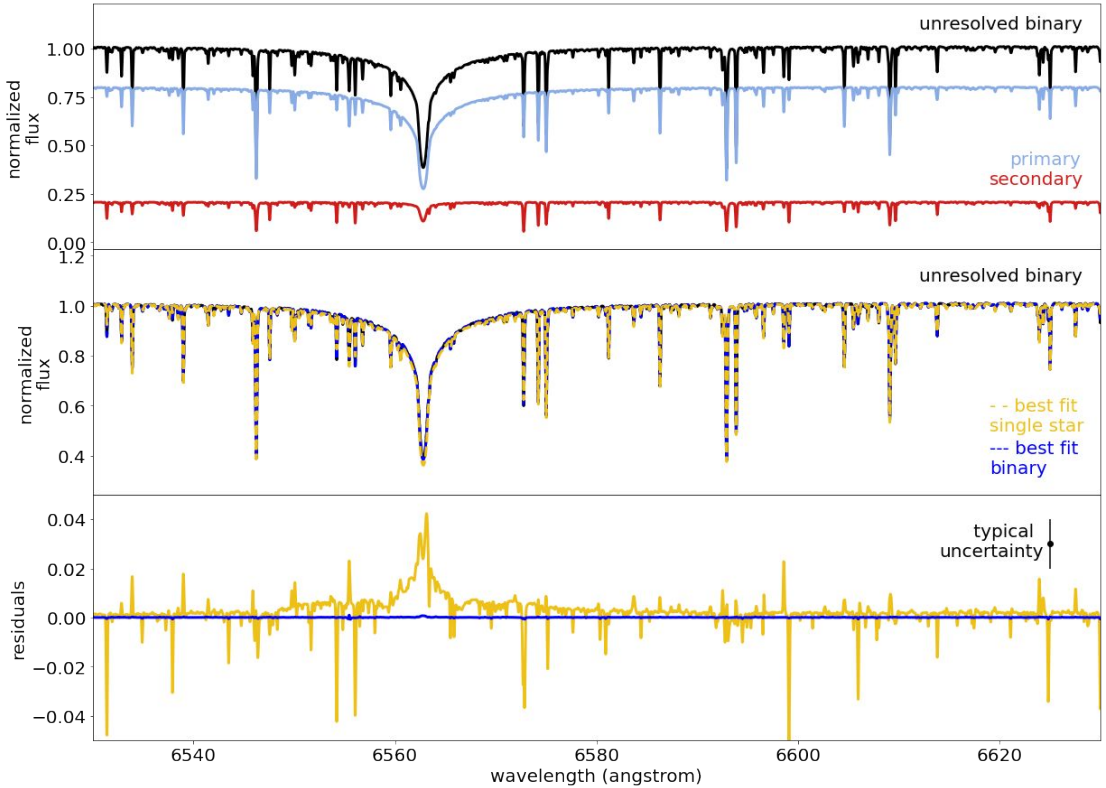


Angelo et al., in prep

Relative to a sample of single stars, we'd expect binaries to be:

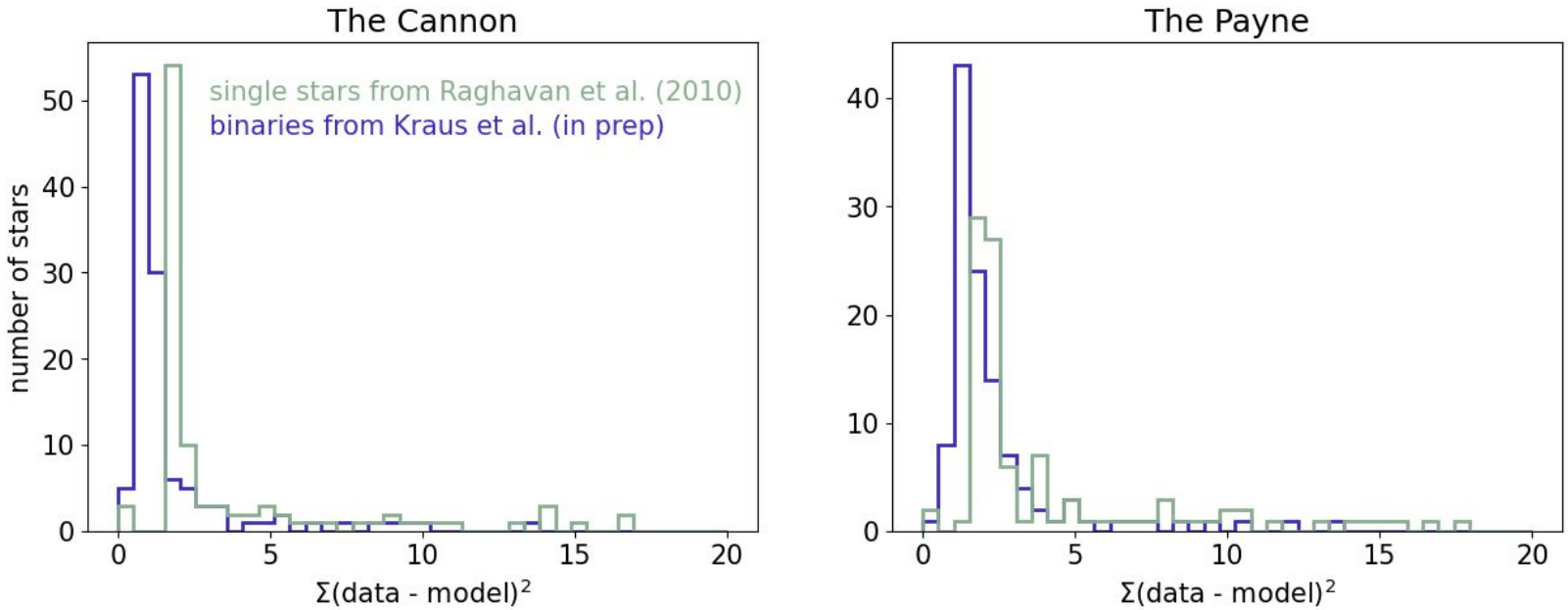
- poorly fit by our data-driven single star model
- significantly better fit by a spectral binary model than a single star model
- binary spectrum differs from single star spectrum by ~3%

example simulated binary



Angelo et al., in prep

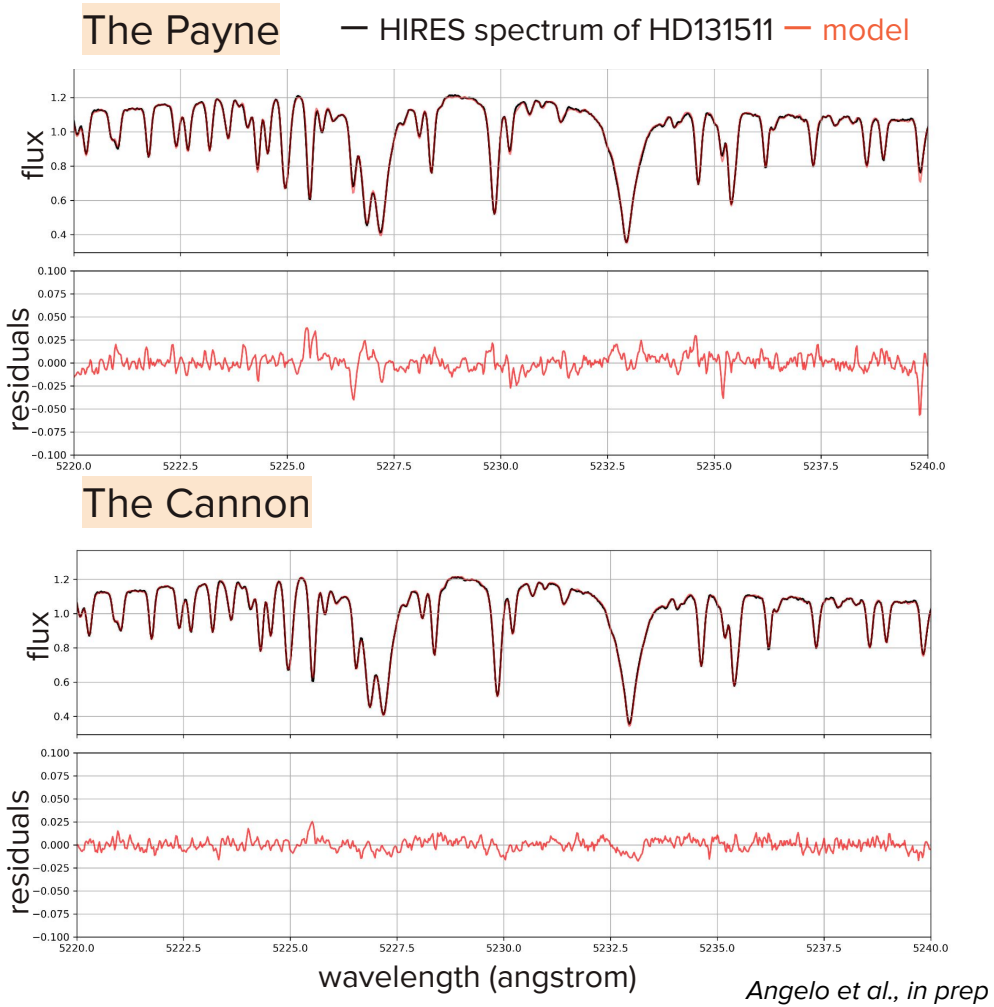
So far, neither of our data-driven models are able to distinguish between single stars and binaries...



Angelo et al., in prep

Binary detection is likely limited by our model's inability to accurately model stellar flux

- simulations show that true binary spectra differ from their best-fit single star spectra by ≤3%
- for single stars, our model flux is only accurate to within ~3%



Angelo et al., in prep

Possible downfalls of our data-driven HIRES models:

- insufficient + inhomogeneous training data
- blaze function instability of HIRES
- PSF instability of HIRES
- something else? come talk to me!

Future Possibilities

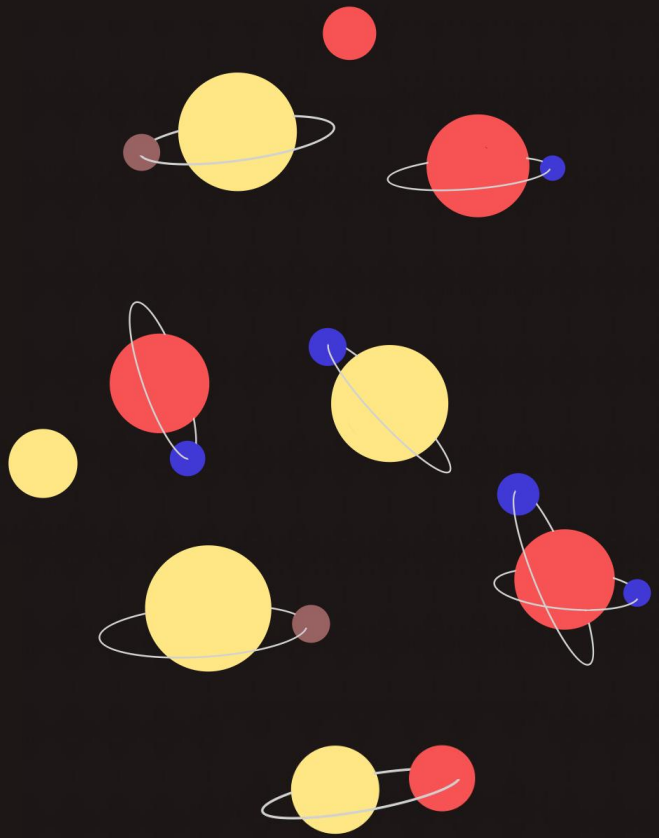
- large spectroscopic surveys like Gaia (Angelo et al. 2024), GALAH, 4MOST
- fiber-fed spectrometers like KPF will address PSF instability

Summary

• we used the Cannon (Ness 2015) and the Payne (Ting 2019) to develop **data-driven spectral models of HIRES spectra**

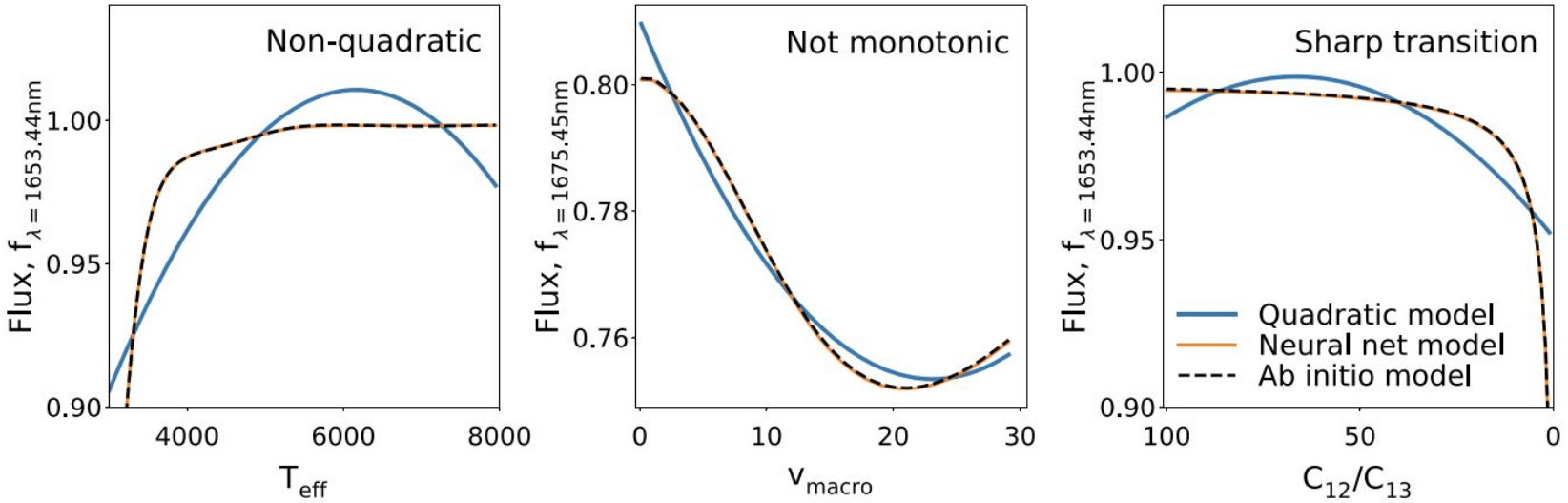
• we develop a **novel wavelet-based continuum treatment** that enables our models to accurately infer star properties (Teff, logg, Fe/H, vsini)

• pushing the limits of data-driven models towards **accurate flux predictions is challenging** and limits our ability to detect spectral binaries



model improvement: interpolate training spectra with neural networks

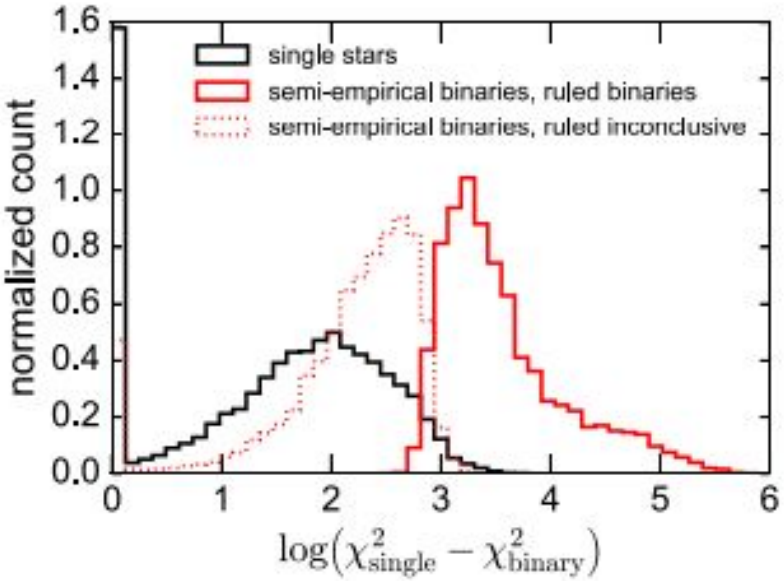
$$f = w_j \cdot \sigma(\tilde{w}_j^i \, \sigma(w_{ji}^k \ell_n + b_{ji}) + \tilde{b}) + \bar{f}_j$$



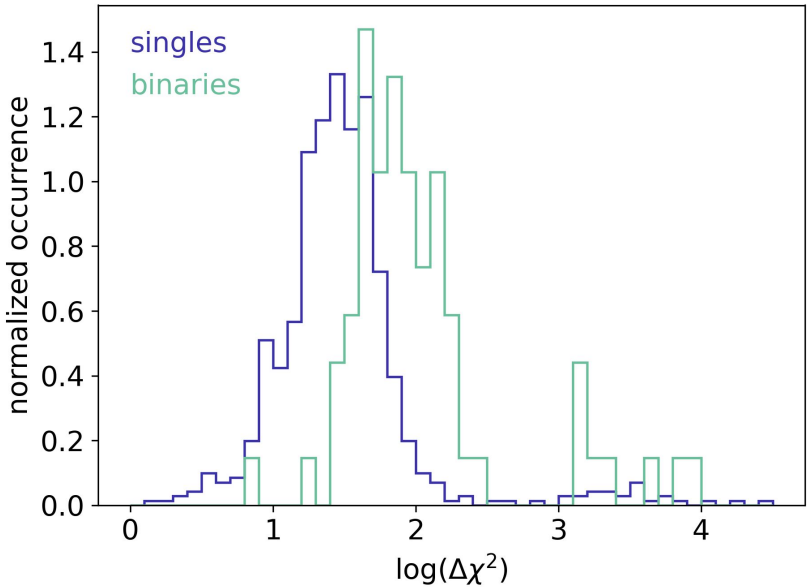
Ting et al. 2019

Binary detection with Gaia

El-Badry et al. 2018



Angelo et al. 2024



`gaiaspec`:
an open-source tool
to identify stellar
companions + activity
for stars in Gaia DR3

https://github.com/isabelangelo/gaiaspec

Create a `Spectrum` object specific to the object of interest:

```
from spectrum import *

# example spectrum for Kepler-93 (KOI-1925, KIC 9955598)
# replace this with the path to the downloaded spectrum
spectrum_path = './data/Kepler-93.csv'
spec = Spectrum(spectrum_path)
```

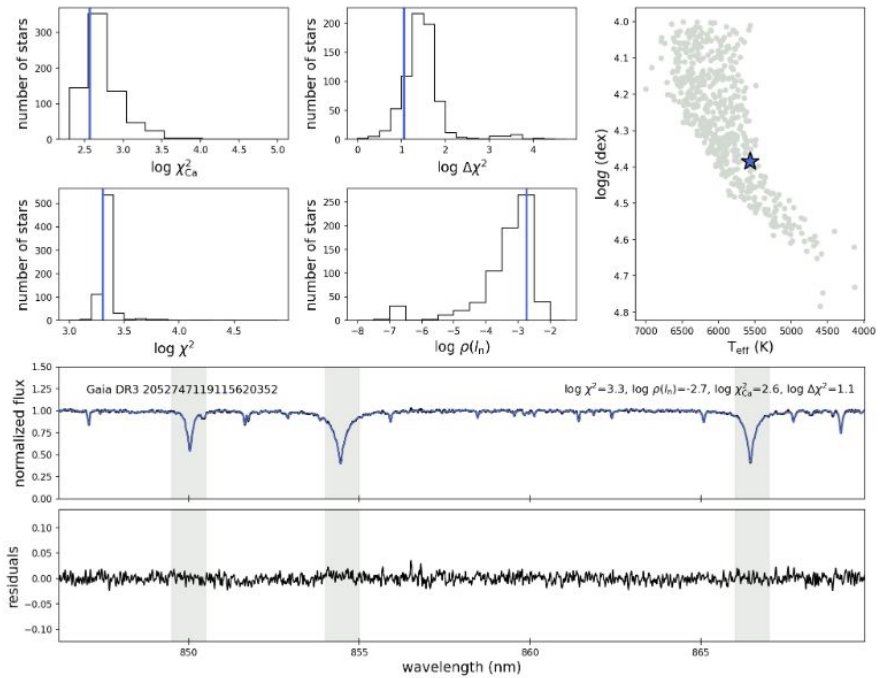
Display the Cannon output stellar labels and metrics:

```
spec.data_table()
```

QTable length=1

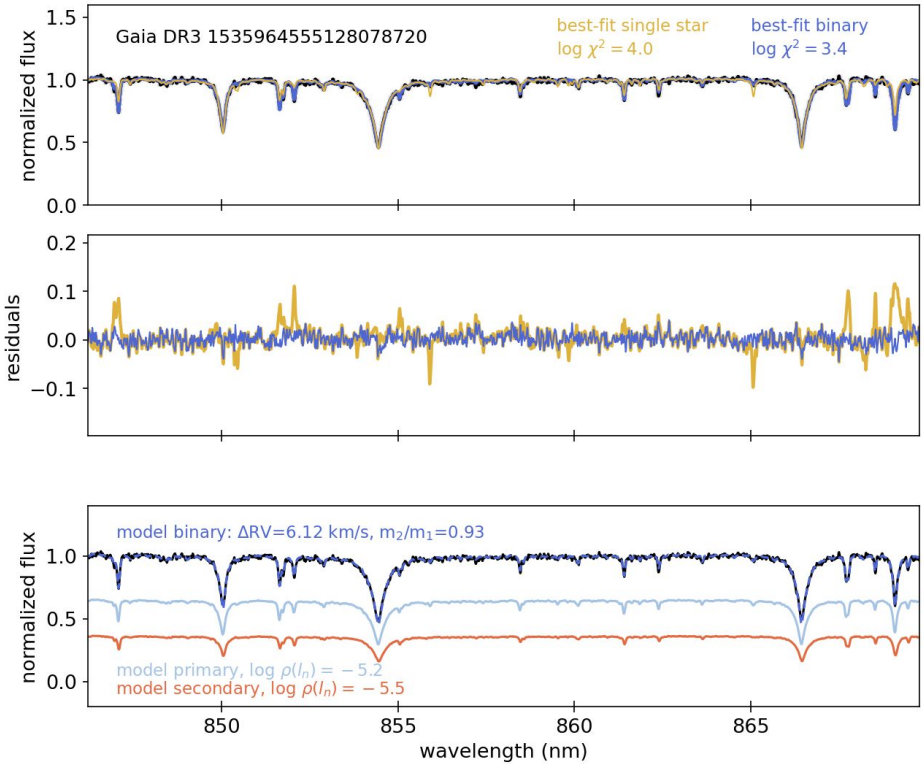
Teff (K)	logg (dex)	[Fe/H] (dex)	[alpha/Fe] (dex)	Vbroad (km/s)	logχ^2	log$\rho(l_n)$	log$\chi_{\rm Ca}^2$
float64	float64	float64	float64	float64	float64	float64	float64
5566.16	4.39	-0.12	0.03	5.73	3.30	-2.73	2.56

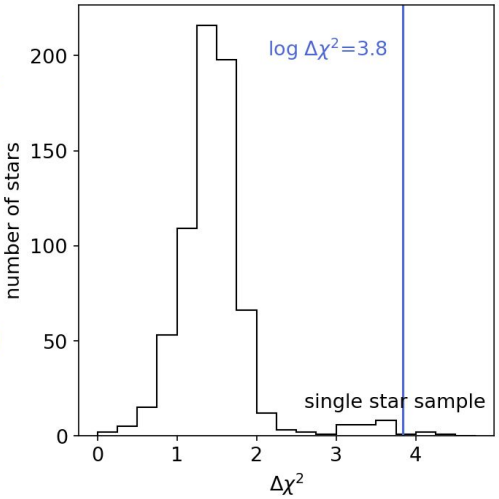
```
spec.spectrum_plot()
```



Angelo et al. (2024)

Example of a binary detection with **gaiaspec**





(binary detection metric)

Angelo et al. (2024)