One big exoplanet family: A detailed look into the properties of the HD 219134 multiplanet system

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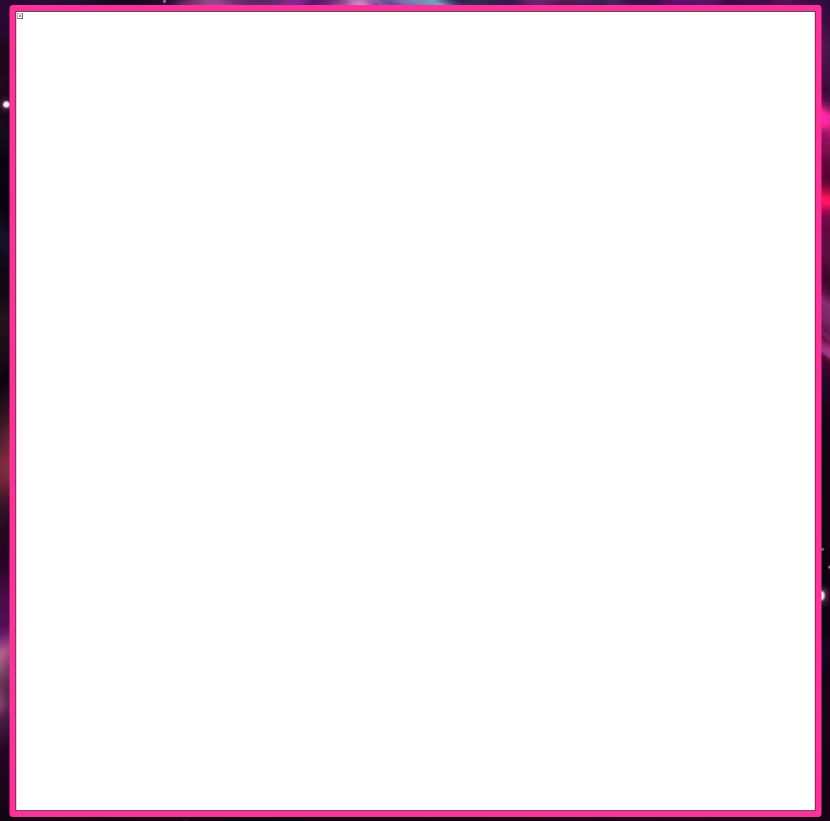


What can we learn about exoplanets by studyin the host star?

- ★ Exoplanets, at some point, have been under the direct influence of their host
- ★ Almost all exoplanet parameters are functions of the host star's parameters.

Stellar Parameters

- ★ Radius
- ★ Mass
- ★ Effective Temperature

Exoplanet Parameters

- ★ Radius
- ★ Density
- ★ Habitable zone

How do we study the host stars?

- ★ Indirect methods:
  - Stellar evolutionary models
  - Stellar atmospheric models

- ★ Direct methods:
  - Parallax
  - Spectral Energy Distributions
  - Asteroseismology
  - Eclipsing Binaries
  - Long-baseline optical/near-IR interferometry

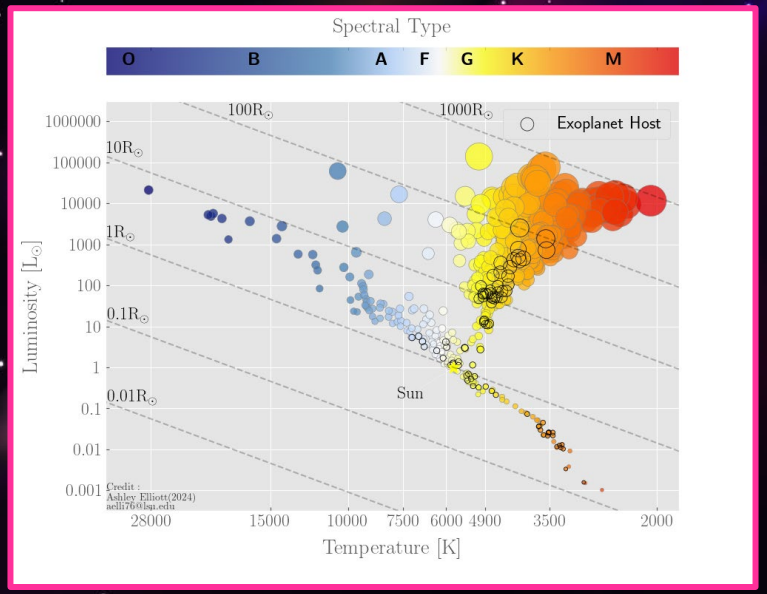
“Know thy star, know thy planet.”

★Direct measurements
- Angular diameter
- Parallax
- Bolometric flux

★Derived stellar properties
- Effective Temperature
- Luminosity
- Radius

★Modeled stellar properties
- Age
- Mass

★Exoplanet characterization



For more info on this really cool HR diagram, scan here:

The HD 219134 system

Star:

- ★ K3V dwarf star
- ★ ~6.5 parsecs away

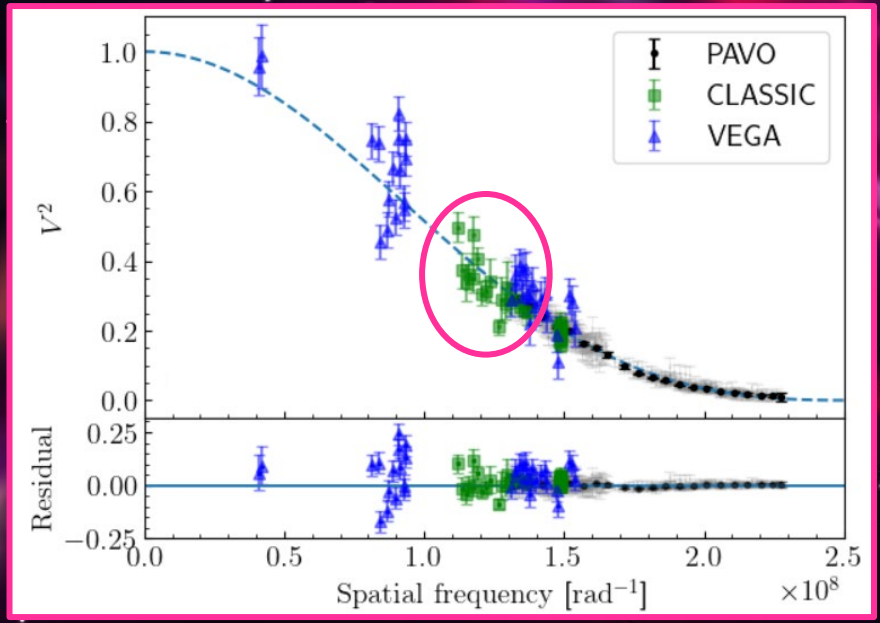
Planets:

- ★ 6* planets
- ★ Discovered by Motalebi et al. 2015 and Vogt et al. 2015
- ★ Planets b and c are transiting exoplanets
- ★ Planets b, c, f, d, g, and h are all RV planets

* Planet f's existence is controversial

Past LBOI Work on the HD 219134 Syste

HD 219134 Angular Diameters		
Author	Value [mas]	Instrument
Boyajian et al. 2012	1.106± 0.007	Classic
Huber et al. 2015	1.093 ± 0.012 1.109± 0.008	Classic/PAVO
Ligi et al. 2019	1.035 ± 0.021	VEGA



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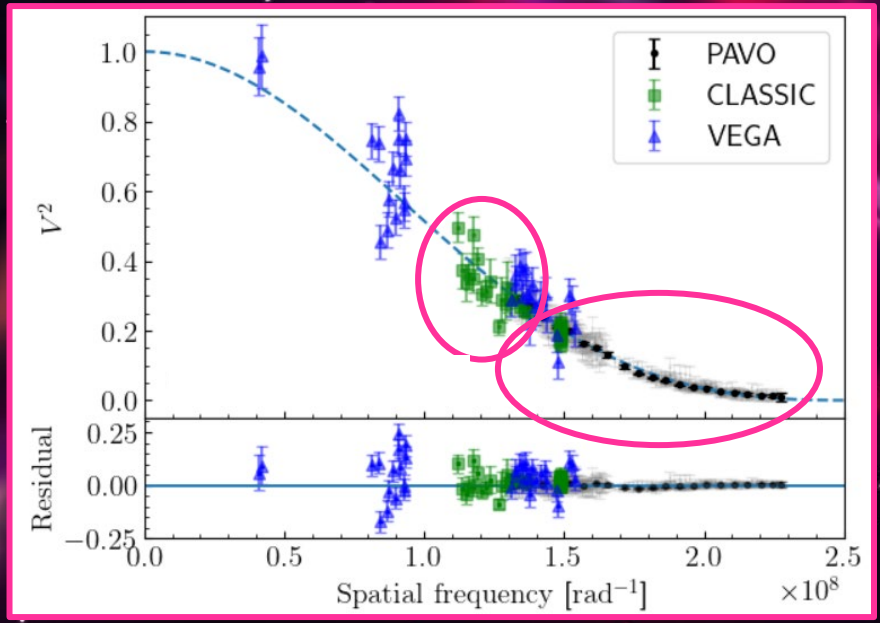

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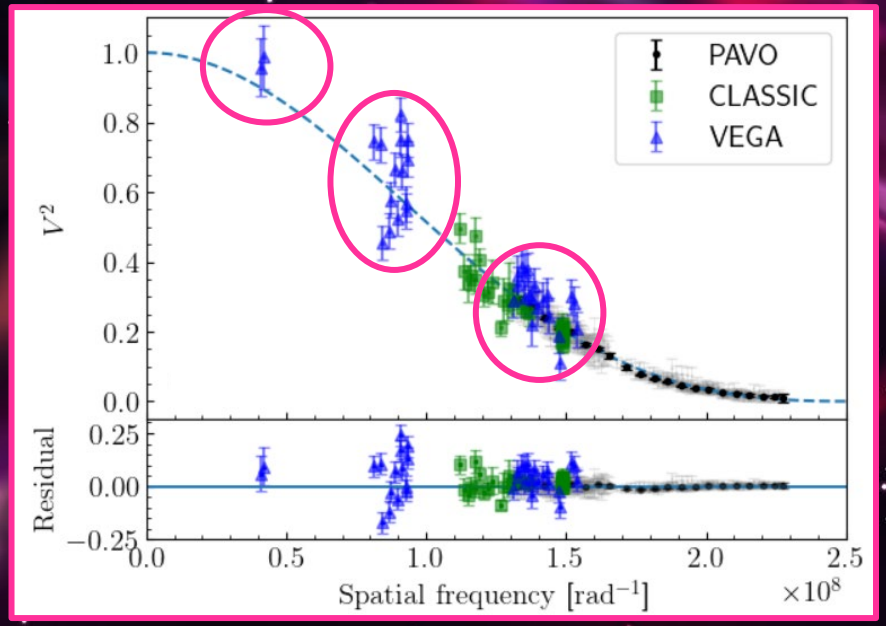


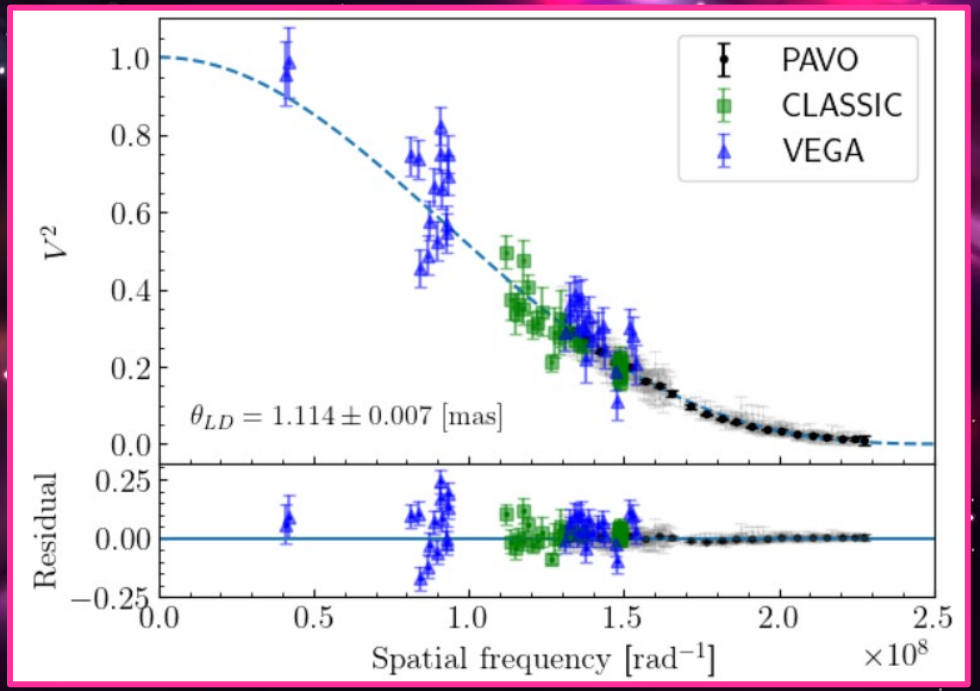
Additional Work on the HD 219134 Syster

HD 219134 Stellar Parameters from Li et al. 20215		
Parameter	**Value**	**Method**
Radius [$R_\odot$]	$0.748 \pm 0.007/0.004$ (stat/sys)	Asteroseismology modeling
Mass [$M_\odot$]	$0.763 \pm 0.020/0.014$ (stat/sys)	Asteroseismology modeling
Age [Gyr]	$10.2 \pm 1.5/1.0$ (stat/sys)	Asteroseismology modeling

★ Used Teff measured by Ligi et al. 2019, spectroscopic [Fe/H] from Rosenthal et al. 2021, and the oscillation frequencies measured by the author

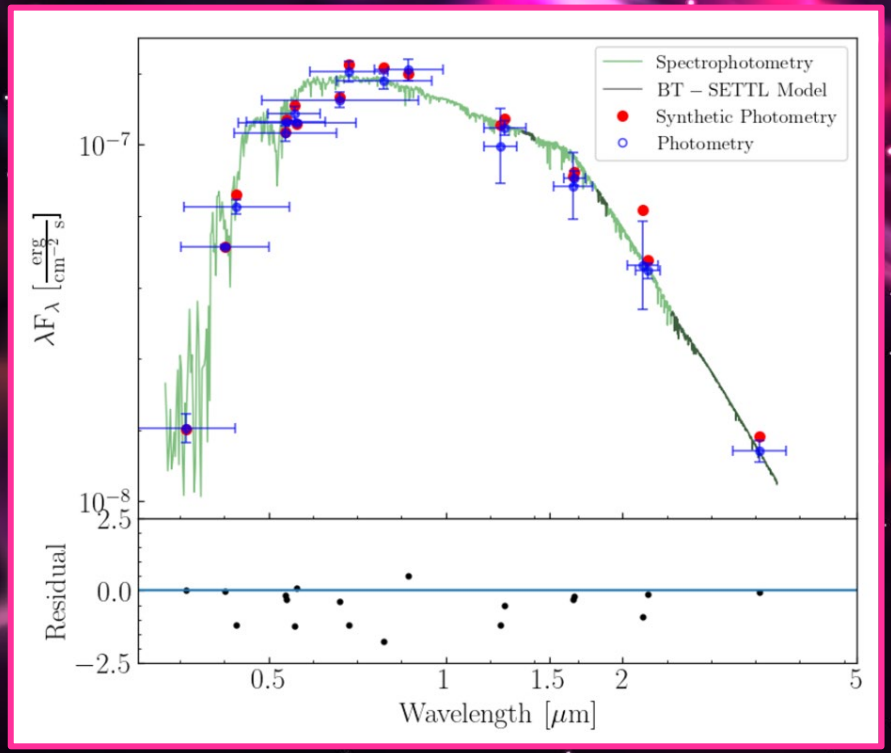
Combined V² Fit with RADPy:

- ★ Used **RADPy** to perform a combined V^2 fit
  - **R**obust **A**ngular **D**iameters in **Py**thon
  - Is able to fit interferometric visibilities from multiple different instruments at CHARA to get a stellar angular diameter
- ★ RADPy will be up on github soon!



Spectral Energy Distribution:

- ★ For the SED fit:
  - Literature photometry
  - SNIFS and SpEX spectro-photometry in the optical red, blue, and near-IR
  - BT-SETTL model to fill in gaps
- ★ Obtained:
  - $F_{BOL} = (22.58 \pm 0.90) \times 10^{-8}$ erg/s^{-1}cm^{2} Å^{-1}



Derived Stellar Parameters:

- From the parallax, angular diameter, and bolometric flux:
  - T_{eff} = 4835 ± 50 K (~1%)
  - $L_{\star}$ = 0.300 ± 0.012 $L_{\odot}$ (4%)
  - $R_{\star}$ = 0.785 ± 0.005 $R_{\odot}$ (<1%)

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→

★Derived stellar properties
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- Radius

→

★Modeled properties
- Age
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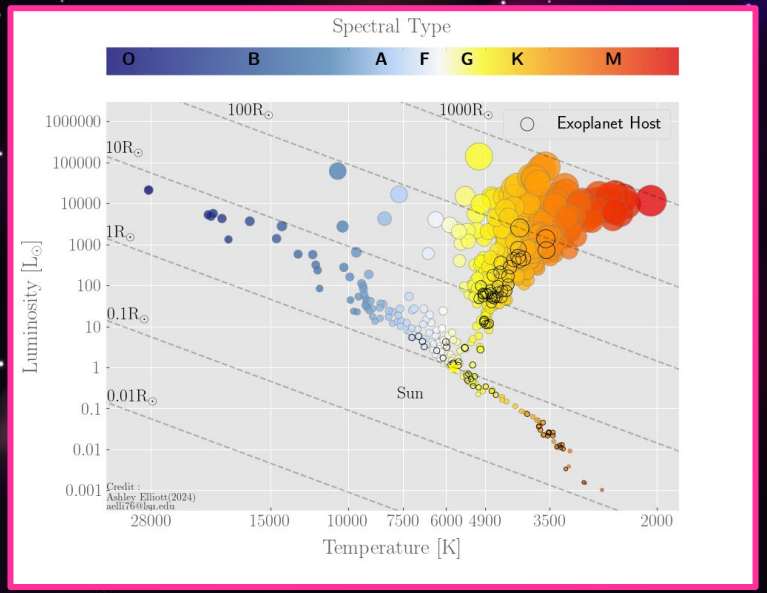
★Exoplanet characterization



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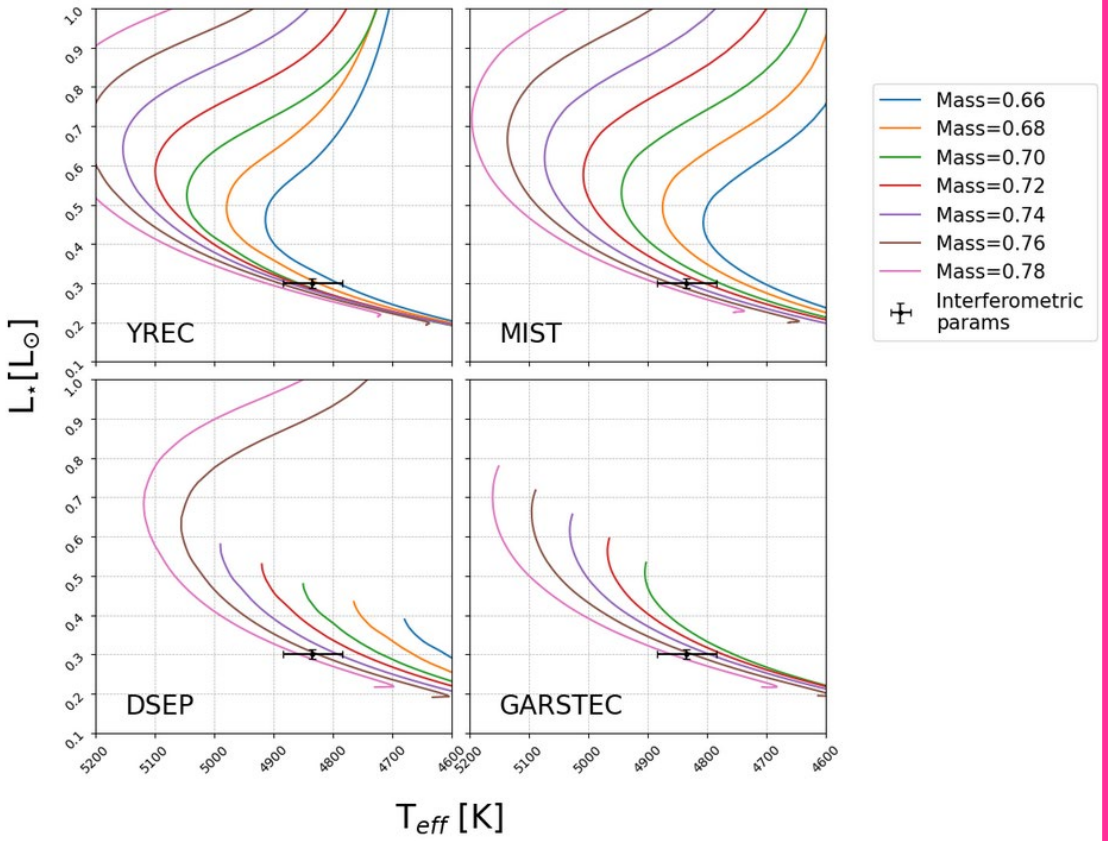
Stellar Modeling

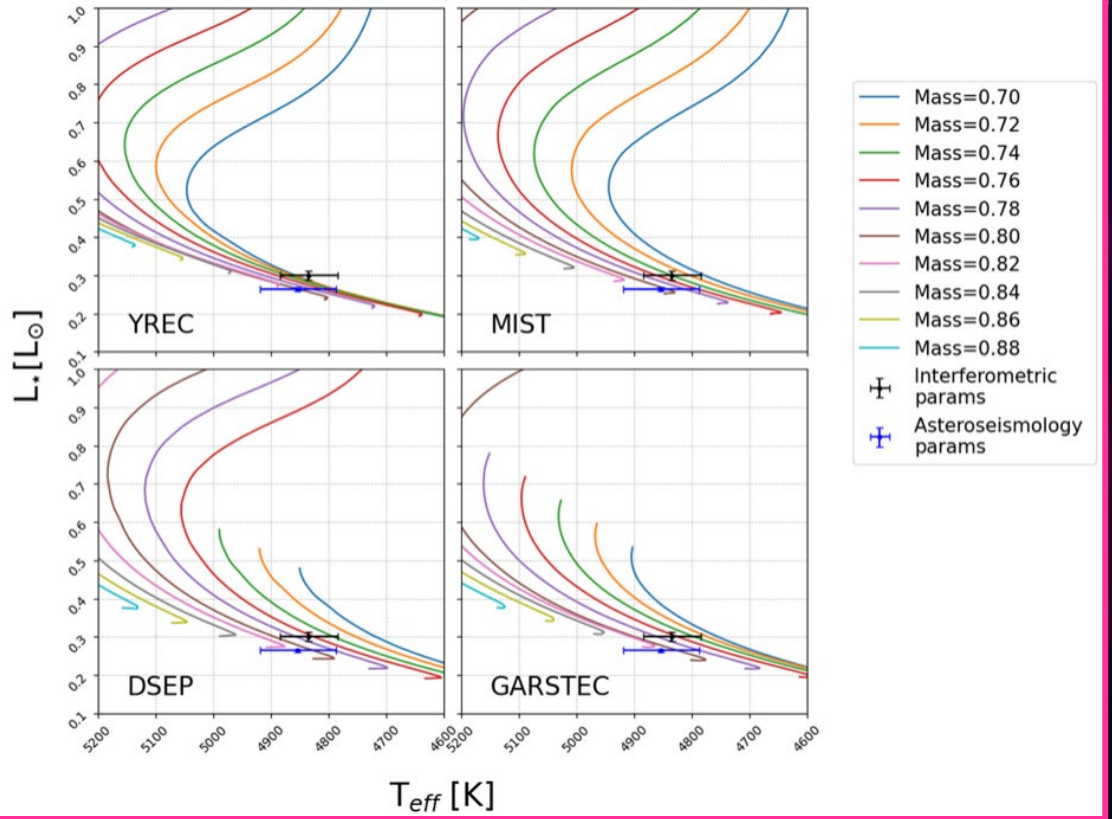
- ★ Age is difficult to constrain given star's low mass
- ★ `kiauhoku` (Claytor et al. 2020) is used to explore the results of 4 different stellar evolutionary codes
  - YREC: Yale Rotating Evolution Code
  - MIST: MESA Isochrones and Stellar Tracks
  - DSEP: Dartmouth Stellar Evolution Program
  - GARSTEC: Garching Stellar Evolution Code

kiauhoku Results



- ★ Masses:
  - YREC: 0.67 $M_\odot$
  - MIST: 0.74 $M_\odot$
  - DSEP: 0.77 $M_\odot$
  - GARSTEC: 0.77 $M_\odot$
- ★ Ages:
  - Ranged larger than 12.8 Gyr

kiauhoku Results: Asteroseismology



- ★ Masses:
  - YREC: 0.76 $M_\odot$
  - MIST: 0.76 $M_\odot$
  - DSEP: 0.76 $M_\odot$
  - GARSTEC: 0.76 $M_\odot$
- ★ Ages:
  - YREC: 14.3 Gyr
  - MIST: 9.24 Gyr
  - DSEP: 9.24 Gyr
  - GARSTEC: 10.4 Gyr

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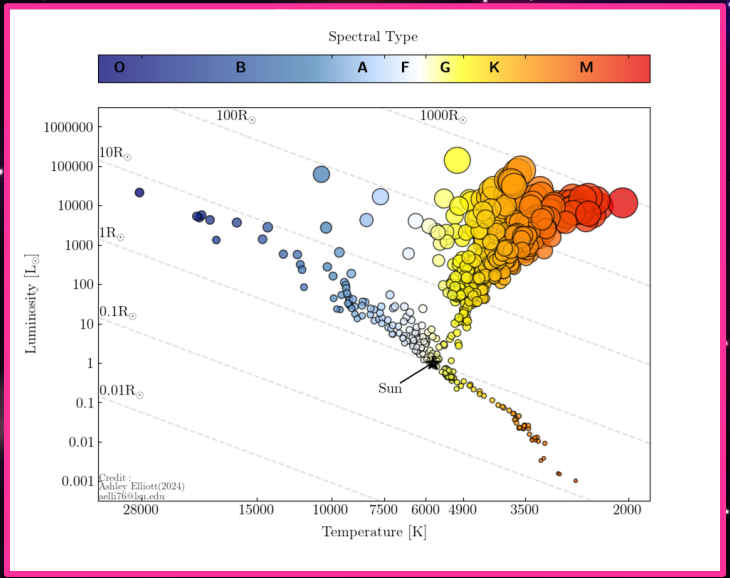

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Modeling with ExoFASTv2

- ★ ExoFASTv2 (Eastman et al. 2019) is a publicly available exoplanet modeling code written in IDL
- ★ Capable of modeling:
  - arbitrary number of planets,
  - radial velocity data sets,
  - astrometric data sets,
  - and/or transits observed in any combinations of wavelengths

Data Available on the HD 219134 system

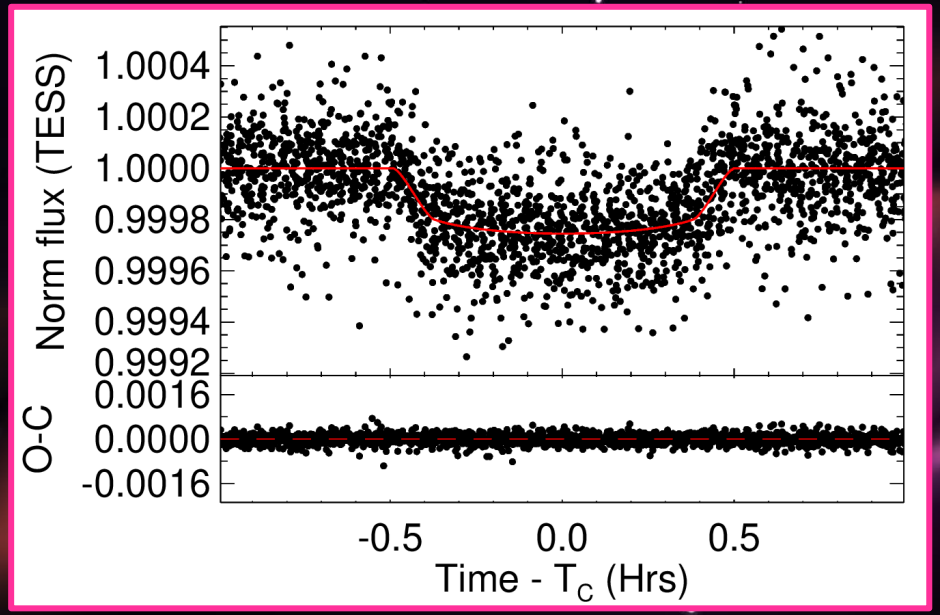
Data Type	# of Data Points	Instrument	Observatory
Radial Velocities	176	Hamilton	Lick
	761	HARPS-N	Roque de los Muchachos
	295	coudé	McDonald
	1517	HIRES	Keck
	583	APF-Levy	Lick
	2155	KPF	Keck
Transit Photometry	5 Sectors	-	TESS

Current EXOFASTv2 Work:

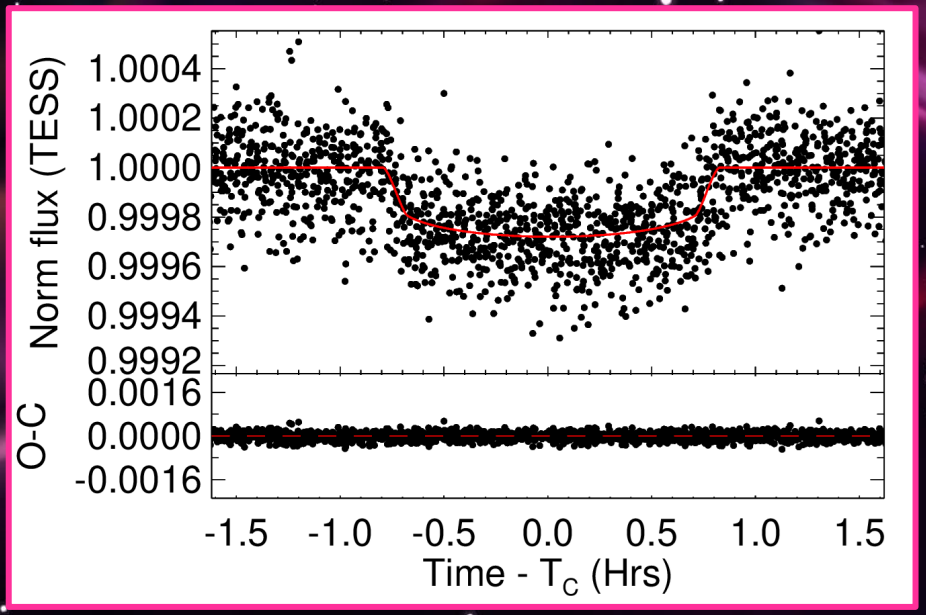
- ★ Interferometric radius and temperature are strict priors
- ★ Working on a 5 planet solution:
  - ○ Only includes planets b, c, d, g, and h
  - ○ Using all radial velocity and transit data

Transit Plots:

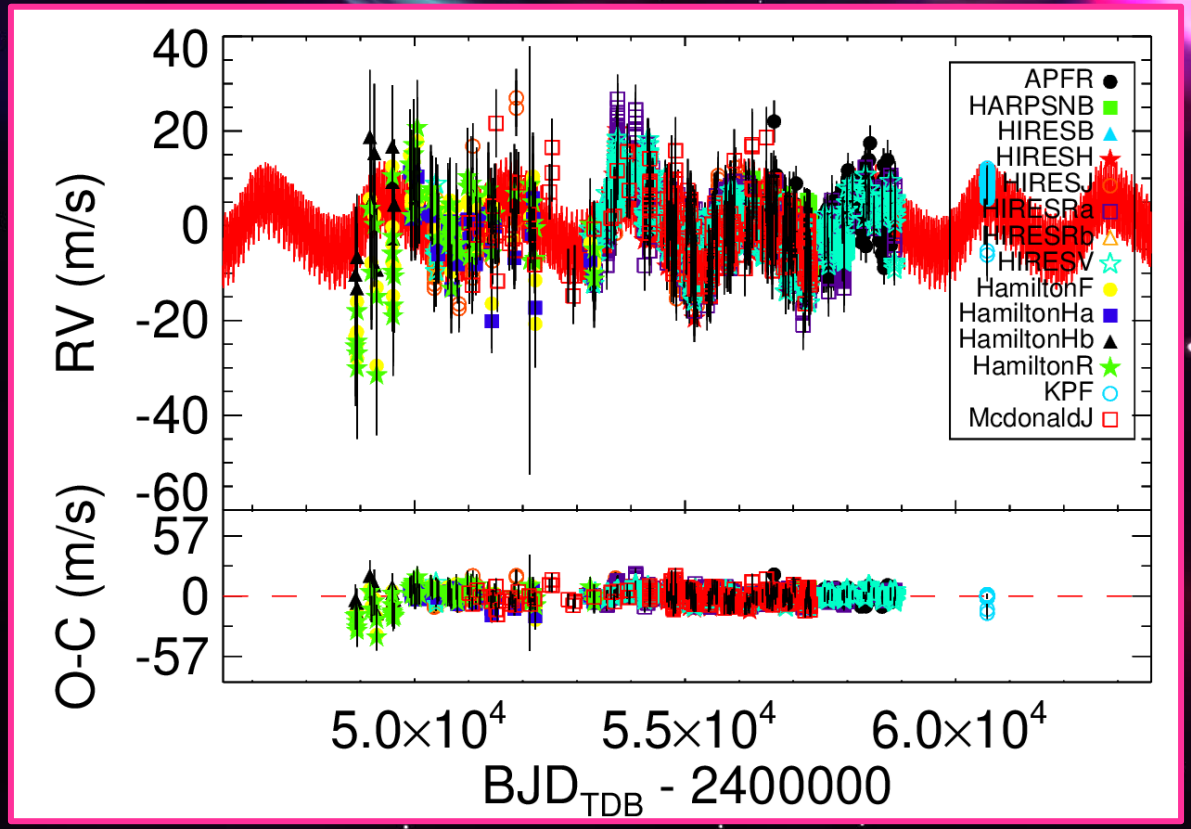
Planet b:



Planet c:



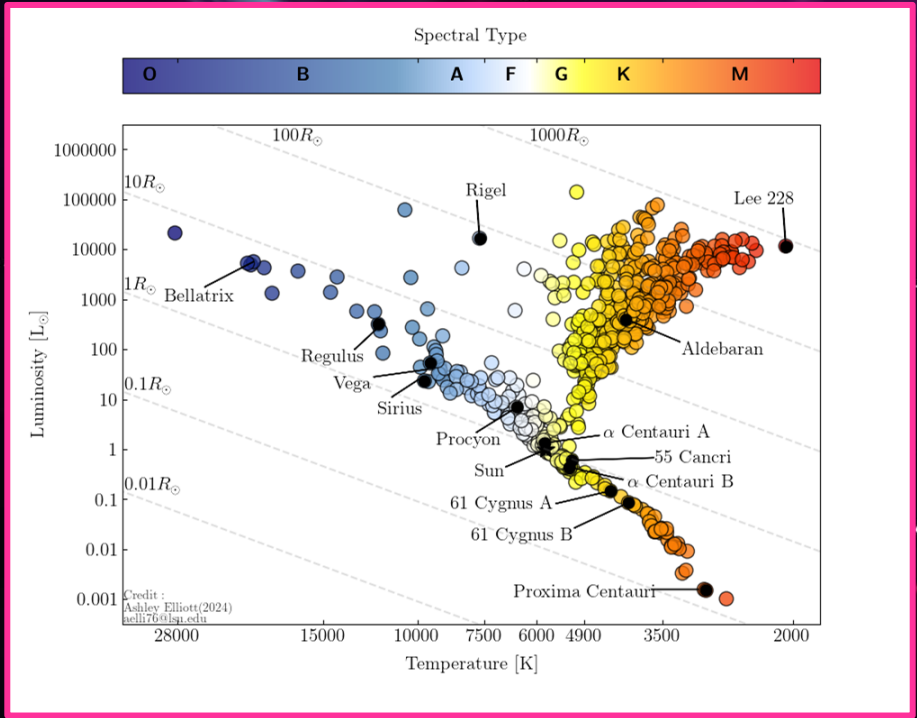
RV Plots:


RV (m/s)
O-C (m/s)
40
20
0
-20
-40
-60
57
0
-57
5.0×10^4
5.5×10^4
6.0×10^4
BJD_TDB - 2400000
APFR
HARPSNB
HIRESB
HIRESH
HIRESJ
HIRESRa
HIRESRb
HIRESV
HamiltonF
HamiltonHa
HamiltonHb
HamiltonR
KPF
McdonaldJ

Future Work

★Finish up 5 planet solution
★Solve for a 6 planet solution without priors on planet f
★Compare two solutions to determine which solution works best
  - Result will be used to provide more evidence to either prove or disprove planet f's existence

Thank you! Any questions?



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RADPy:

- ★ Motivation: needed to fit multi - wavelength visibility data from several instruments at CHARA that requires separate limb - darkening coefficients
- ★ Brief description:
  - Starts with a first initial calculation of a uniform angular diameter and Teff.
  - Generates an LDC for each respective wavelength
  - Enters a MC simulation where the wavelength of observation and the LDCs are sampled on a normal distribution
    - Within the MC, a bootstrapping function is called to bootstrap either the brackets of data to generate "noise" on the V2 data or just the data on its own to generate "noise" (this is dependent on instrument)
    - From the "new" V2 data, lmfit is called and a V2 fit is performed
  - Rinse and repeat
  - Final output is the weighted average of the limb-darkened angular diameter and the median absolute deviation for the error on the angular diameter

RADPy:

- ★ To test reliability, I used the fitting routine on the individual instruments' data and compared the results to the published diameters
  - Successfully reproduced the Classic diameter from Boyajian et al. 2012
  - Successfully reproduced the VEGA diameter from Ligi et al. 2019
  - Successfully reproduced the PAVO diameter generated from the PAVO data reduction and calibration software
- ★ Routine is currently only able to handle Classic, VEGA, and PAVO data
- ★ Working on adding in the capability to handle MIRCX/MYSTIC data and SPICA data
- ★ Will be made publicly available soon on github!