# Properties of Exoplanet Host Stars

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Know Thy Star

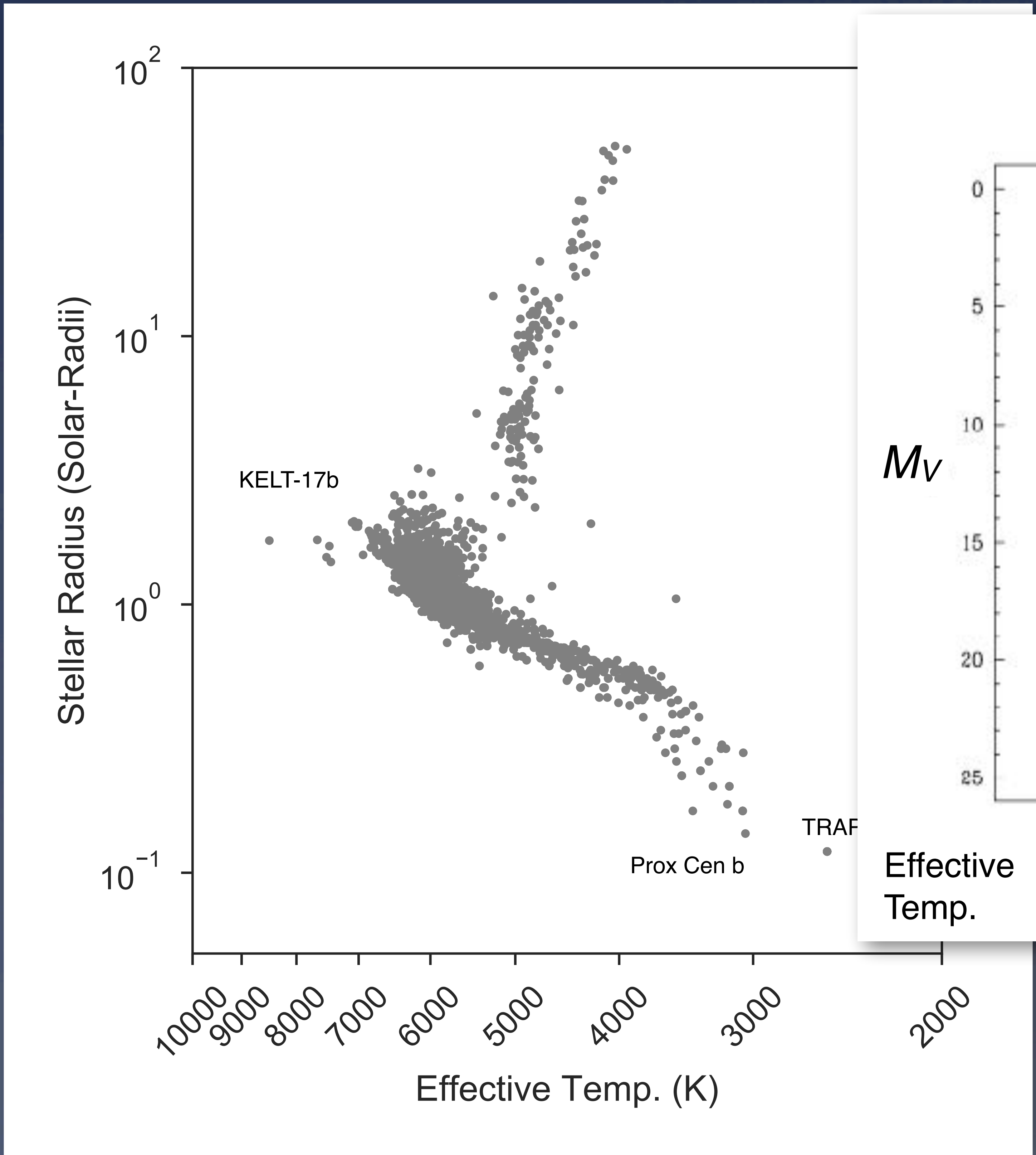
October 9, 2017

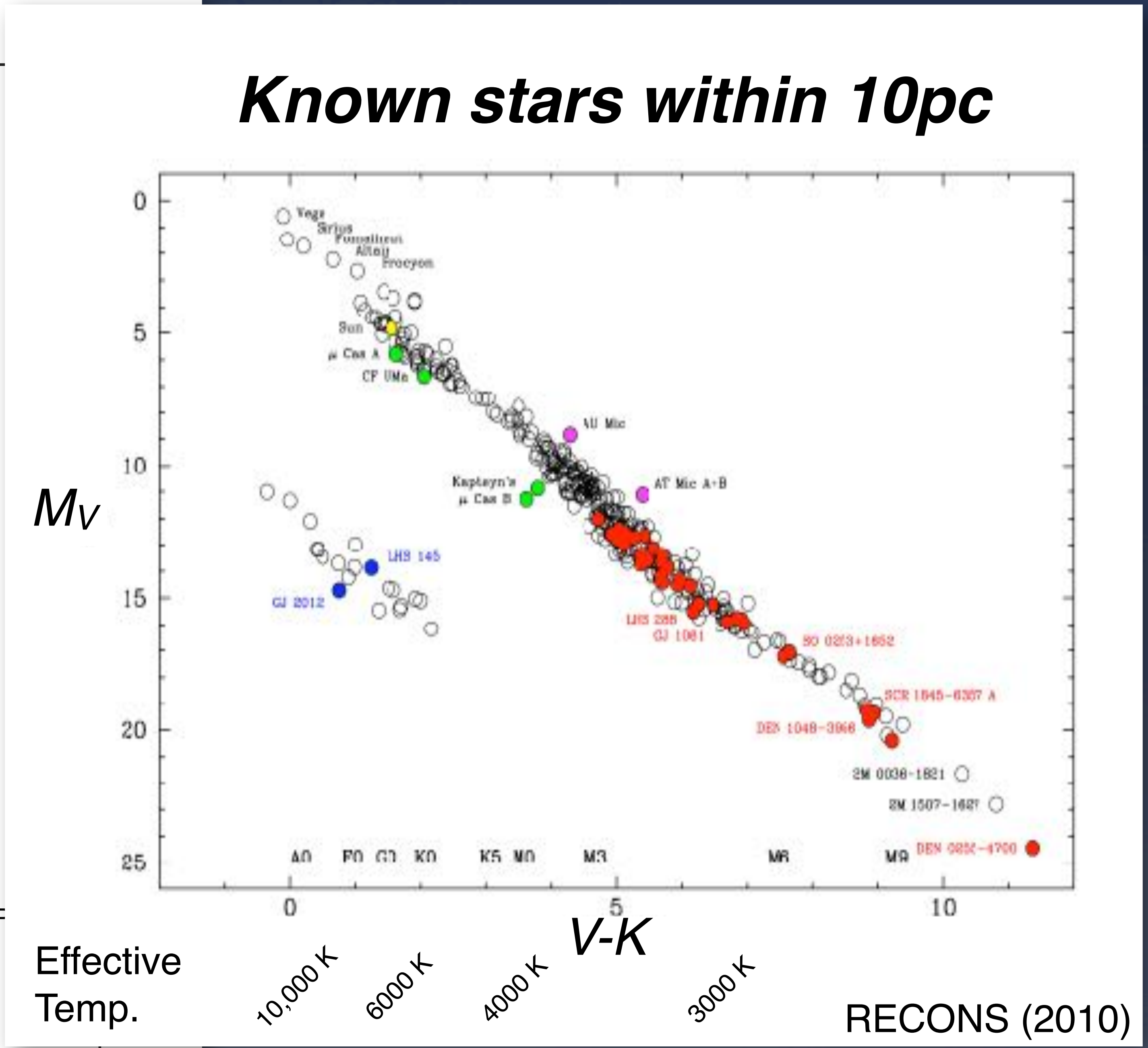
# Properties of Exoplanet Hosts

- Stellar properties influence planet detectability
- Precision measurements of stellar radii
- A frontier: data-driven spectroscopy

# Stellar Properties Influence Planet Detectability

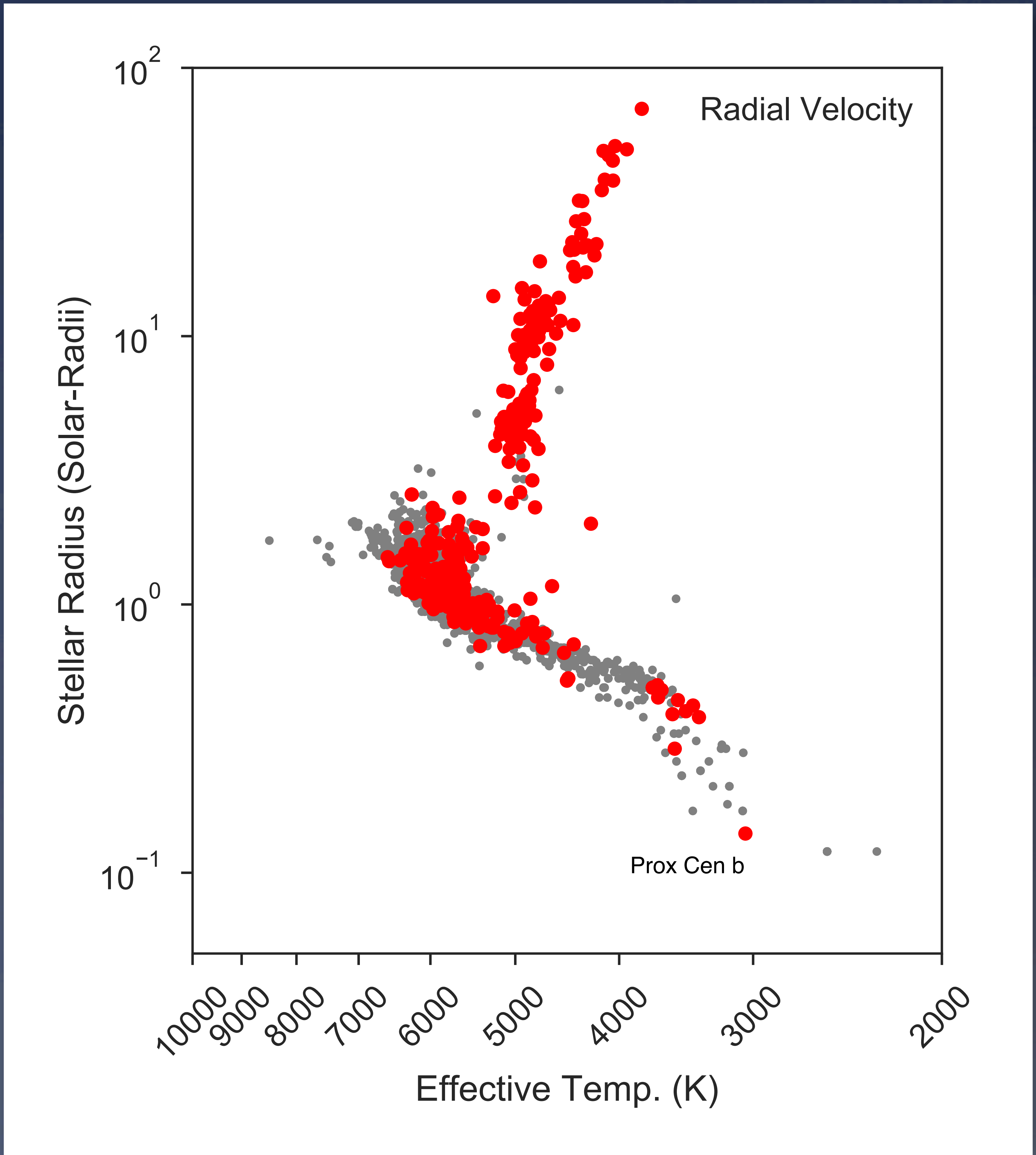
# Planets hosts in the HR diagram




Source: NASA Exoplanet Archive

# Planets hosts in the HR diagram




Source: NASA Exoplanet Archive

***RV technique…***

***…performs best when host stars are…***

- Bright (typically optical)
- Slowly rotating (vsini < 10 m/s)
- Inactive

***…thus favors detection of planets around***

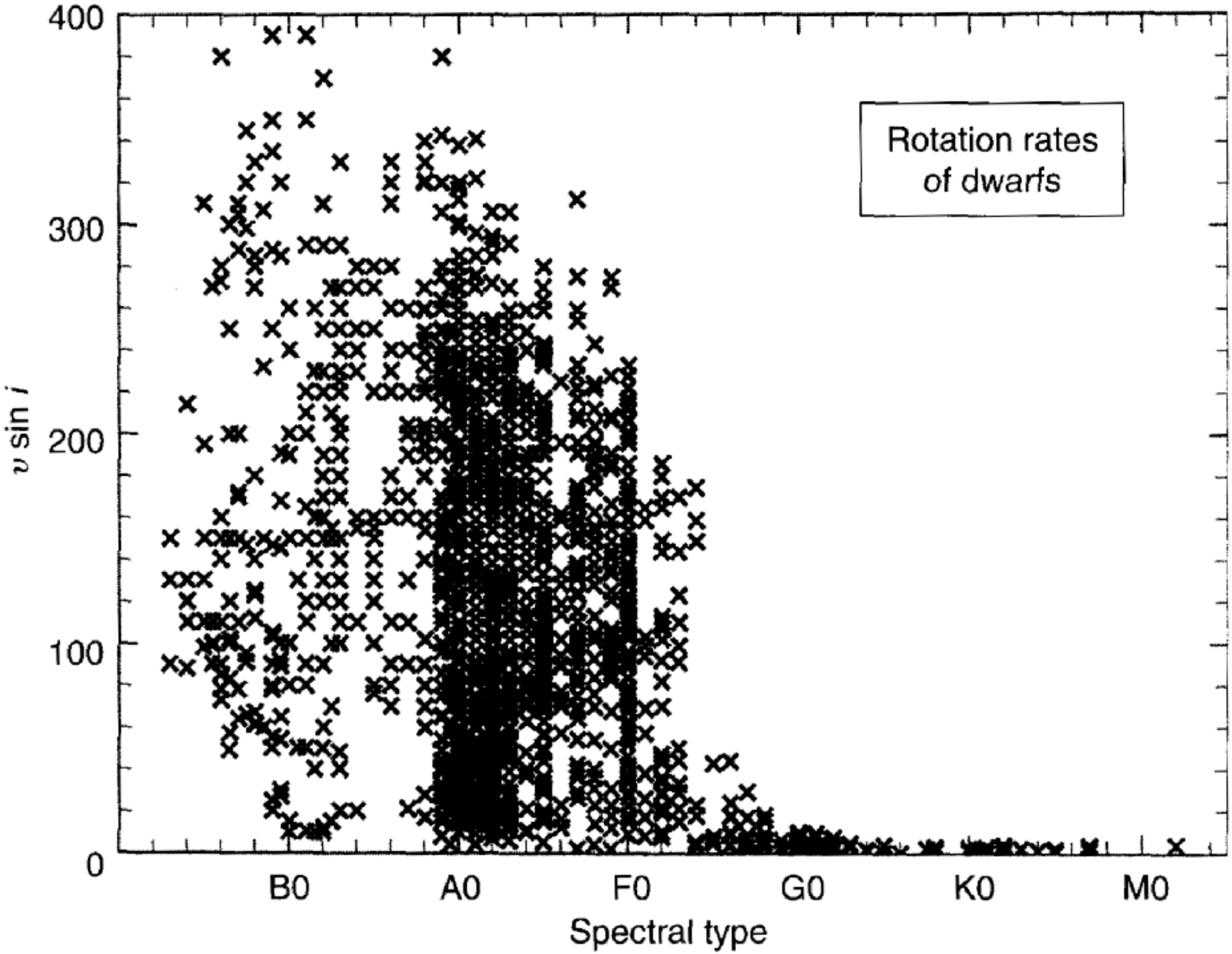
- (single) GK stars
- Main sequence stars (age > 100 Myr)
- Evolved stars (bright, low vsini)

***…and struggles to find planets around***

- F stars and earlier (vsini too high)
- Young stars (too active)

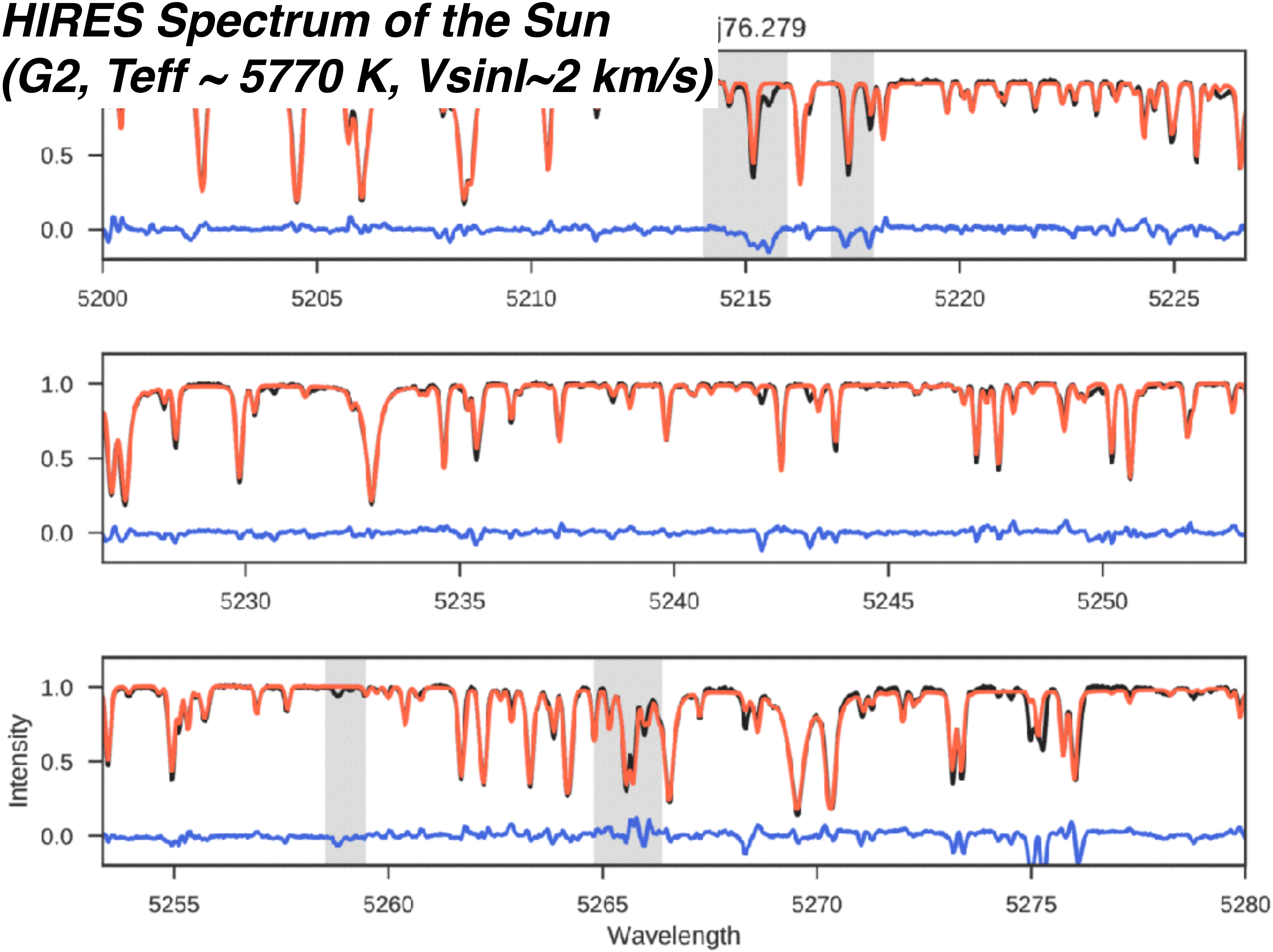
***The future***

- PRV in the NIR: M-stars, young stars.

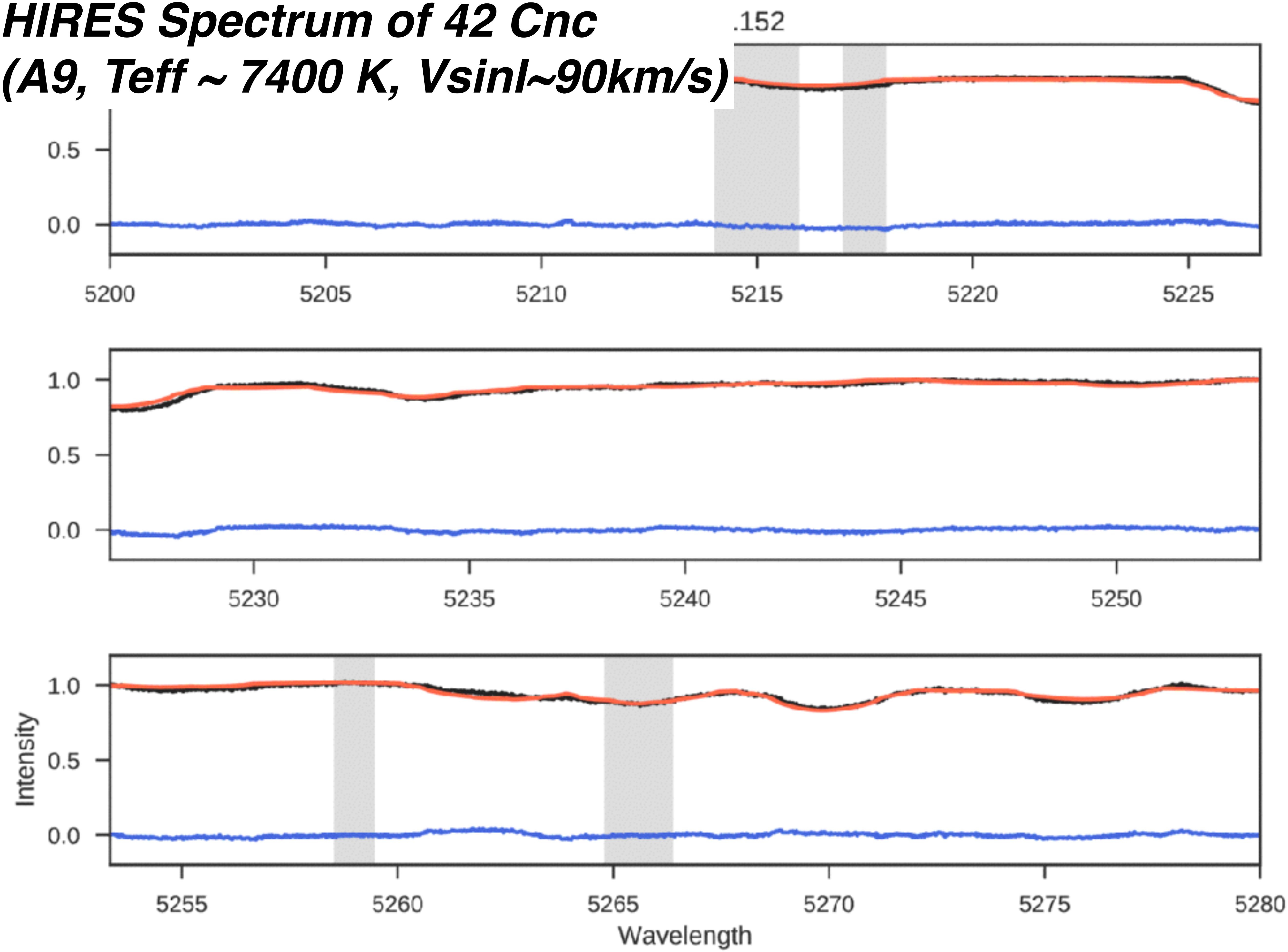

Rotation rates
of dwarfs
v sin i
400
300
200
100
0
B0
A0
F0
G0
K0
M0
Spectral type

David Gray

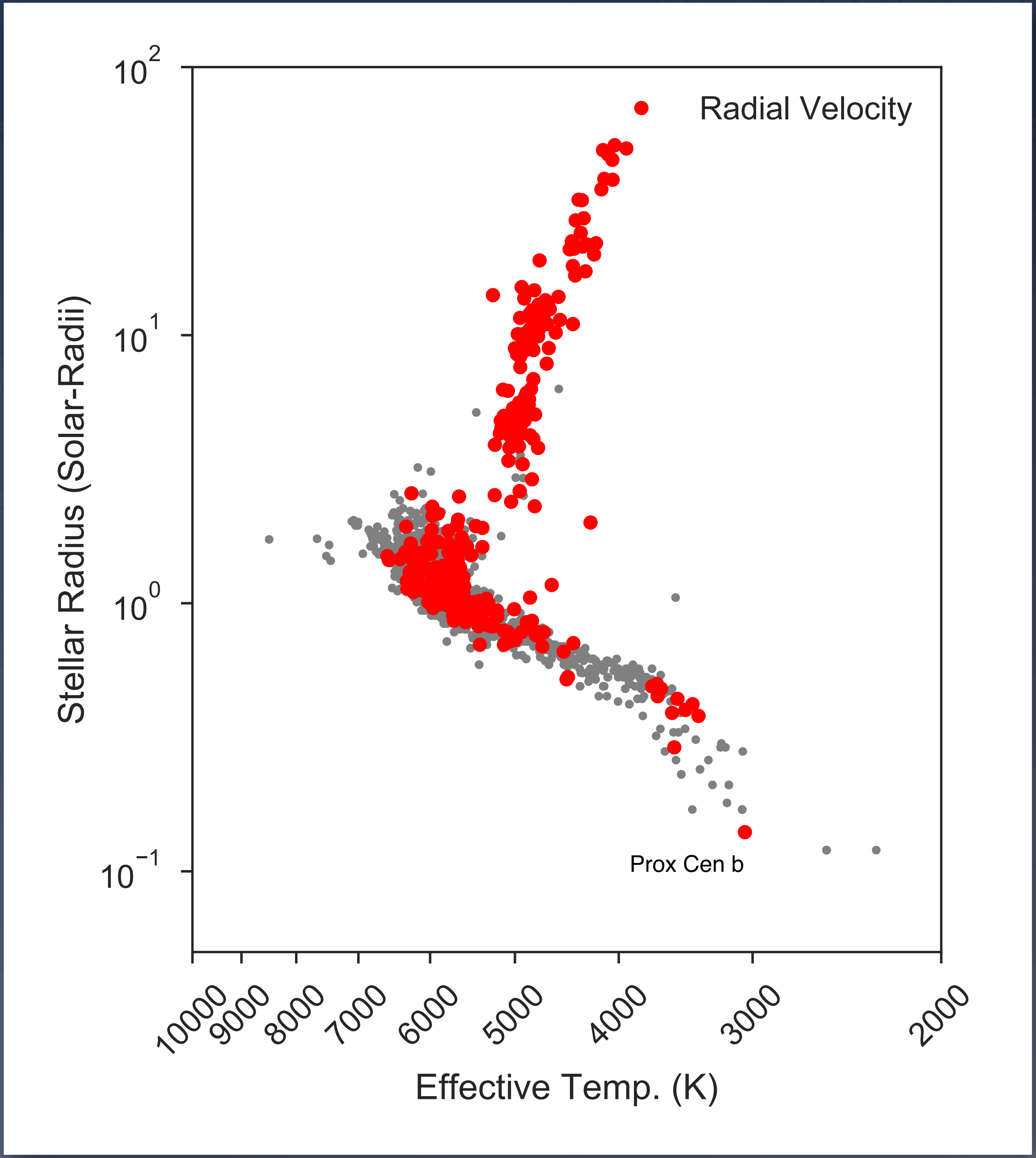
# *HIRES Spectrum of the Sun*
# *(G2, Teff ~ 5770 K, VsinI~2 km/s)*



# HIRES Spectrum of 42 Cnc
# (A9, Teff ~ 7400 K, VsinI~90km/s)



# Planets hosts in the HR diagram

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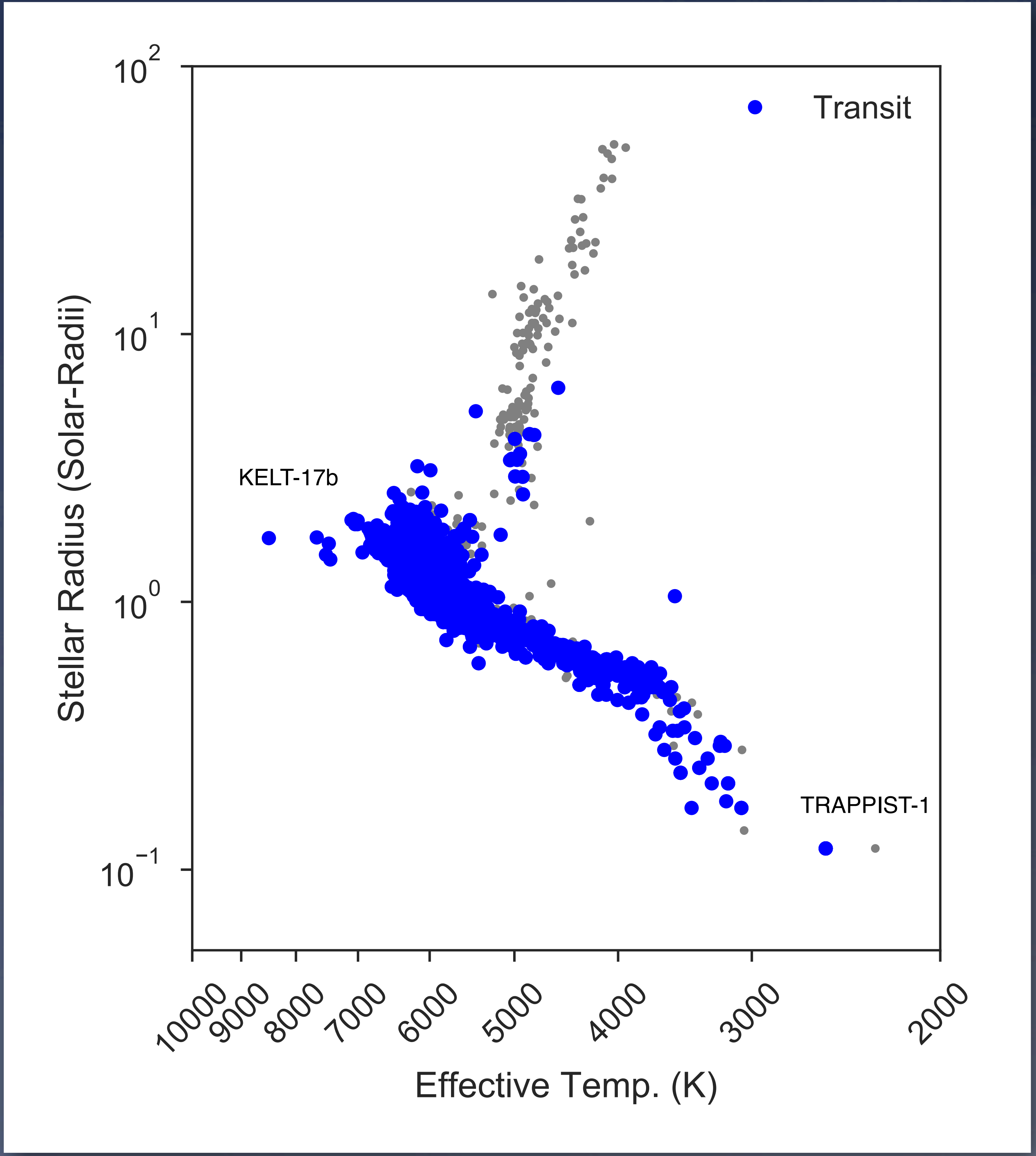
***The future***

- PRV in the NIR: M-stars, young stars.

# Planets hosts in the HR diagram




Source: NASA Exoplanet Archive

***Transit technique…***

***…performs best when host stars are…***

- Bright (typically optical)
- Small (favorable radius ratio)
- Inactive

***…thus favors detection of planets around***

- GK stars
- M stars (if restricted to bright)
- Rapidly rotating stars are fine.

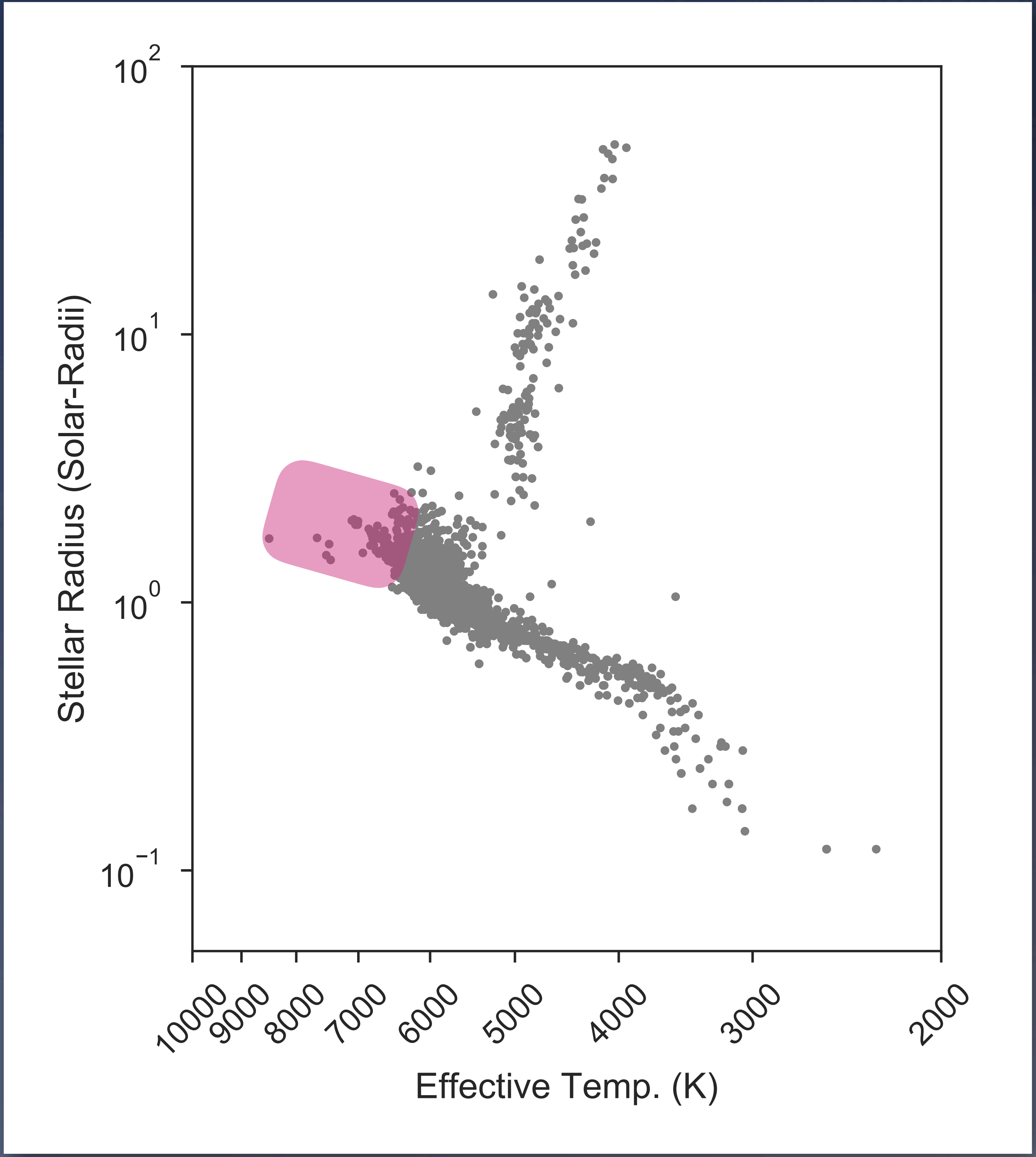
***…and struggles to find planets around***

- Evolved stars (unfavorable radius ratio)
- Young stars (high photometric variability)

***The future***

- K2 and TESS, more M-stars, young stars

# Planets hosts in the HR diagram




Source: NASA Exoplanet Archive

***Direct imaging technique***

***performs best when host stars are…***

- Nearby (inner working angle)
- Young (favorable contrasts)

***…thus favors detection of planets around***

- Young A stars

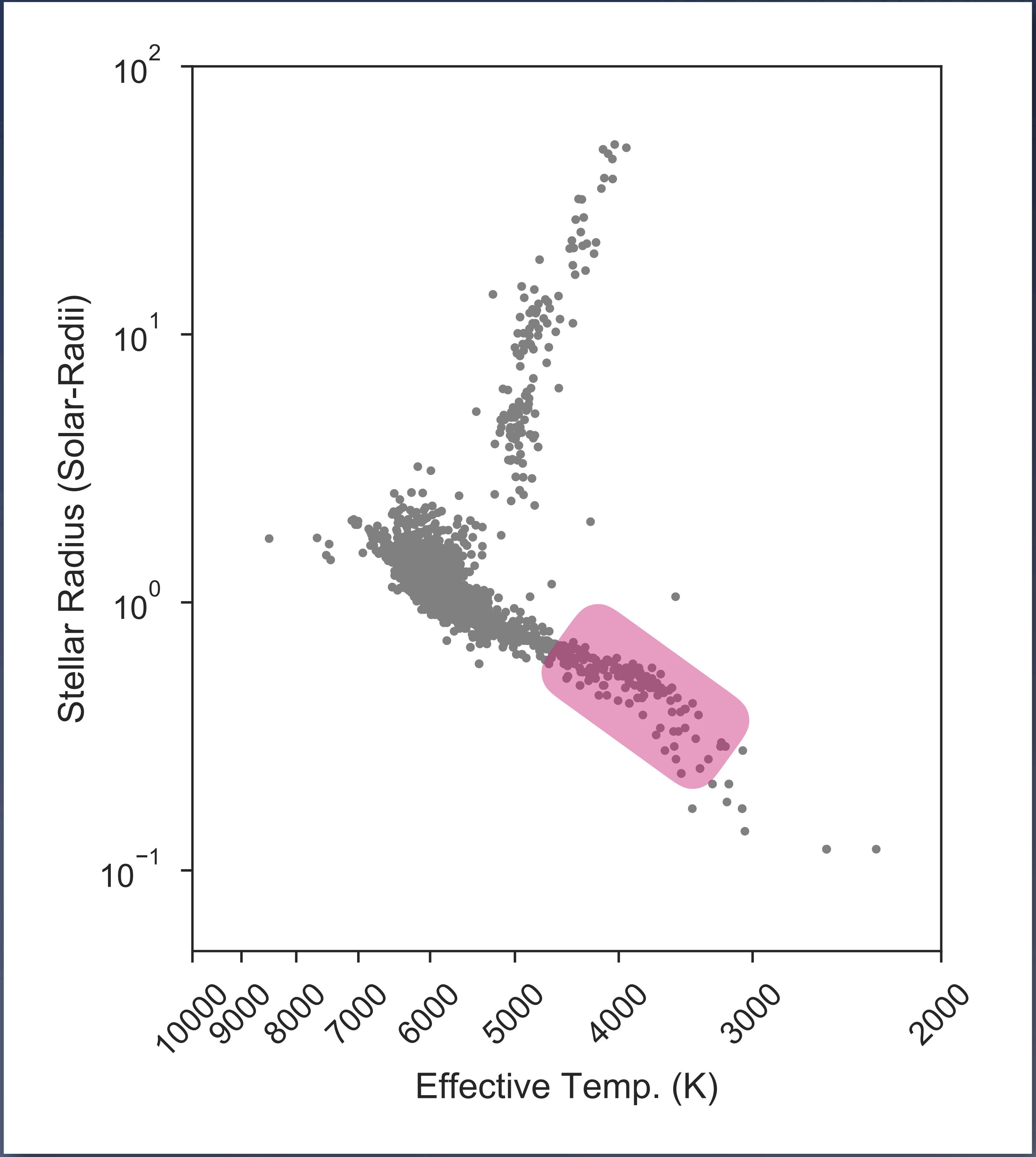
***…and struggles to find planets around***

- Main sequence and evolved stars

***The future***

- WFIRST image planets around main-sequence dwarfs (reflected light)

# Planets hosts in the HR diagram




Source: NASA Exoplanet Archive

***Microlensing technique***

***performs best when host stars are…***

- In front of dense star fields (e.g. Galactic bulge)

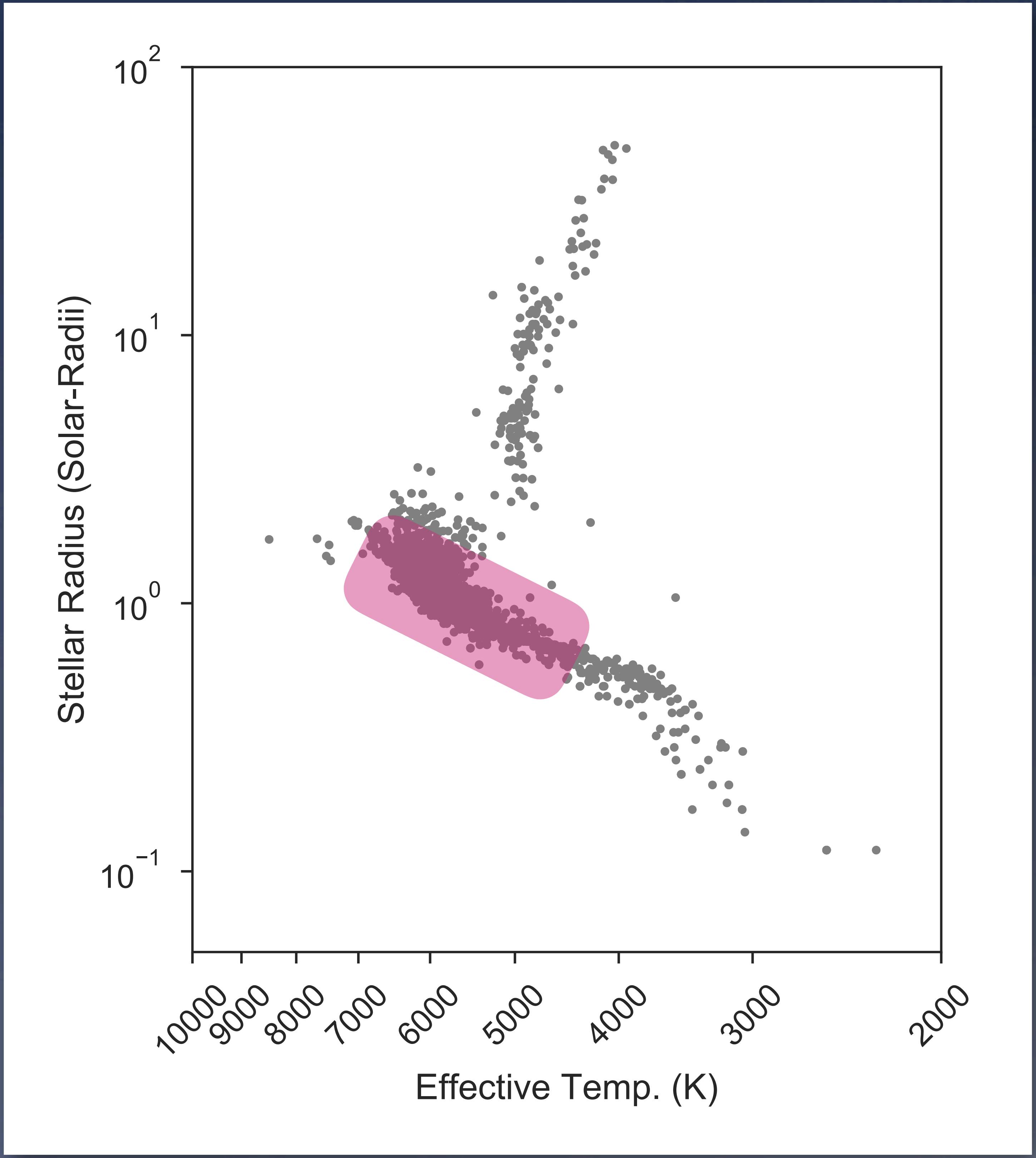
***…thus favors detection of planets around***

- Early-M stars (~0.5 $M_{sun}$—common)

***…and struggles to find planets around***

- Nearby stars (low event rate)

# Planets hosts in the HR diagram




Source: NASA Exoplanet Archive

***Astrometry technique***

***performs best when host stars are…***

- Nearby
- Bright (in Gaia bandpass)

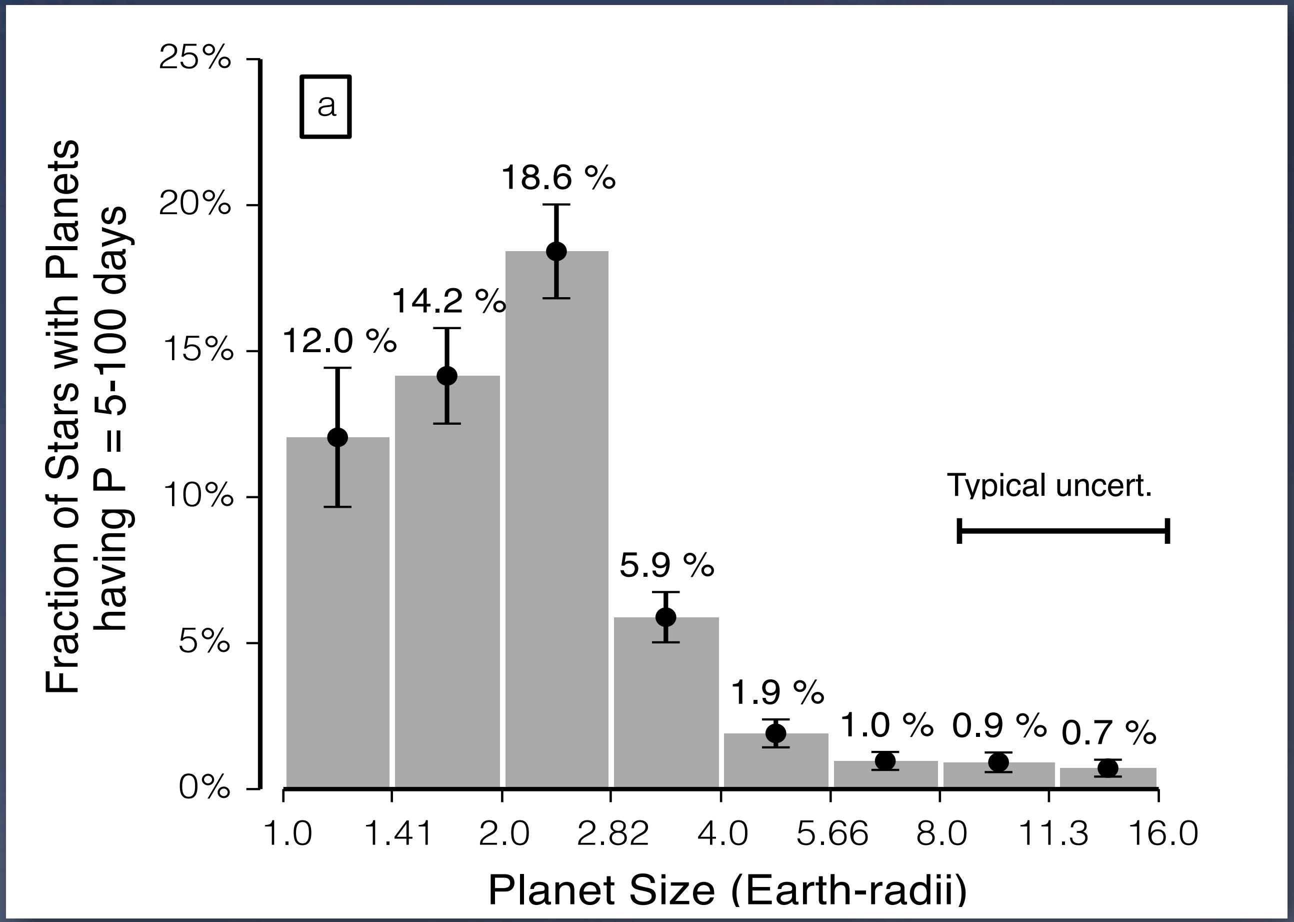
***…thus favors detection of planets around***

- Nearby FGK stars
- Rapid rotators are fine
- Young stars are fine

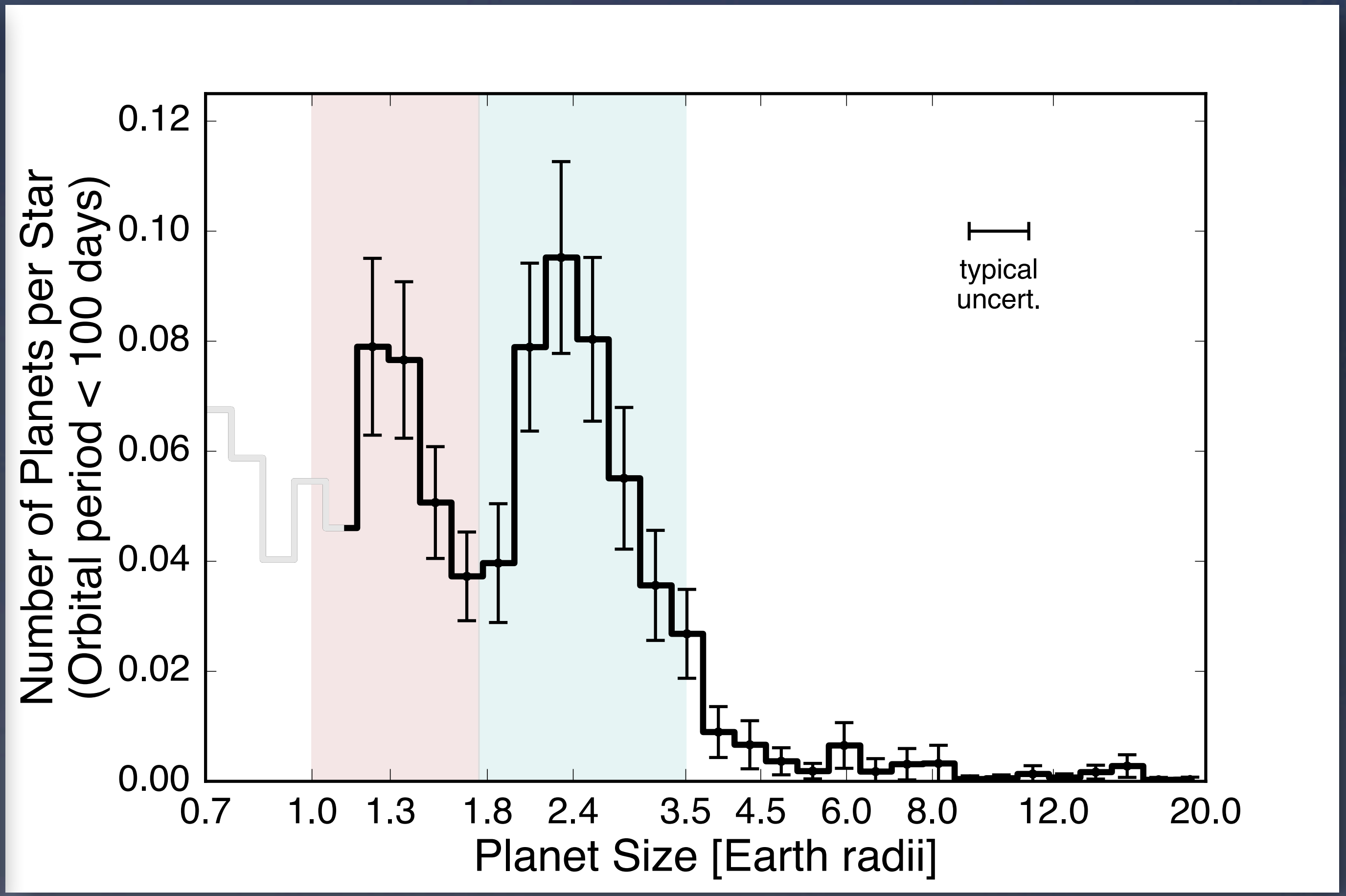
***…and struggles to find planets around***

- Distant stars
- Faint stars (M-dwarfs)

# Precision Stellar Radii

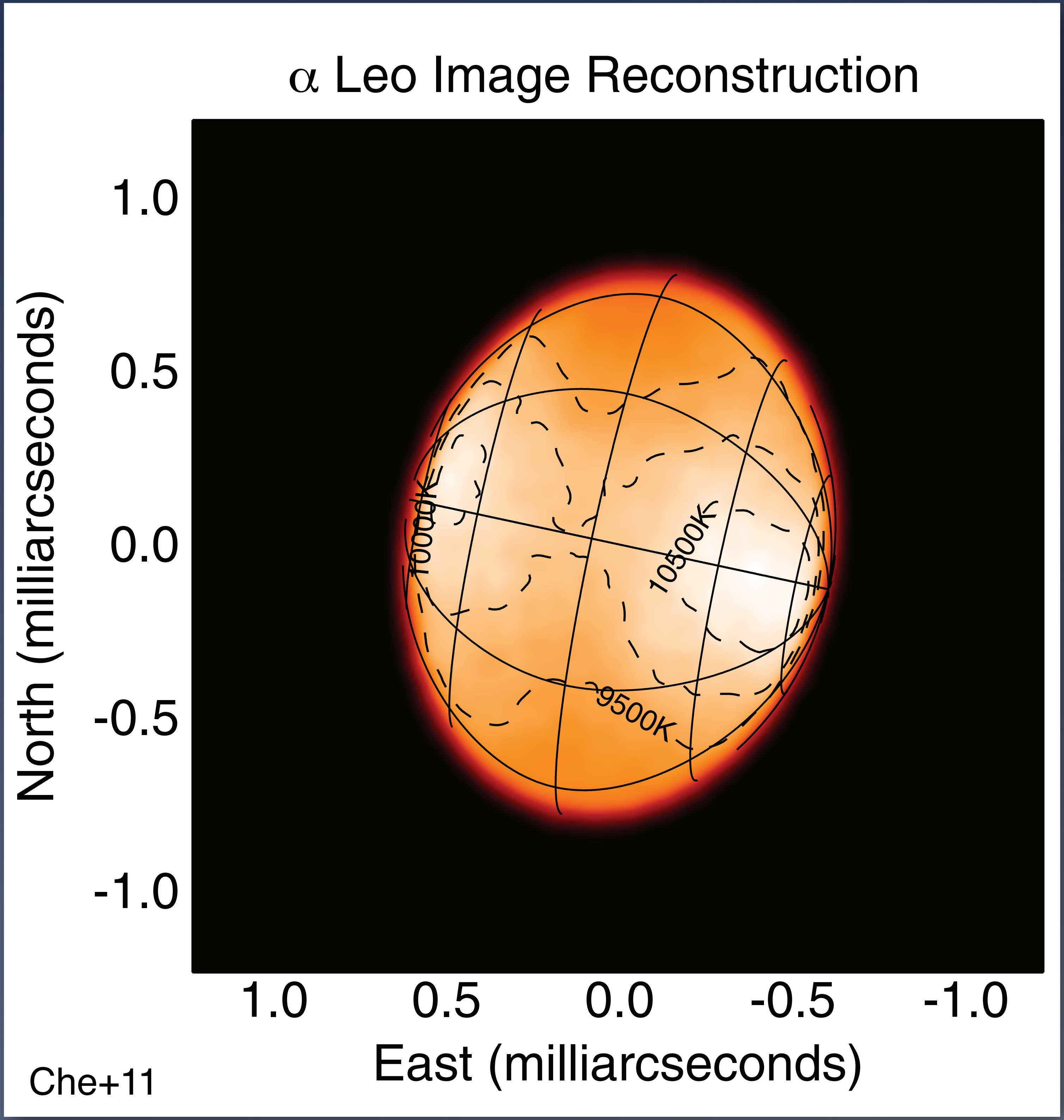



Petigura, Howard, Marcy 2013




Fulton, Petigura, Howard et al. 2017

# Interferometry




***Method***

- Directly measure stellar angular size
- sub-mas resolution with CHARA
- Combine with parallax to derive $R_\star$

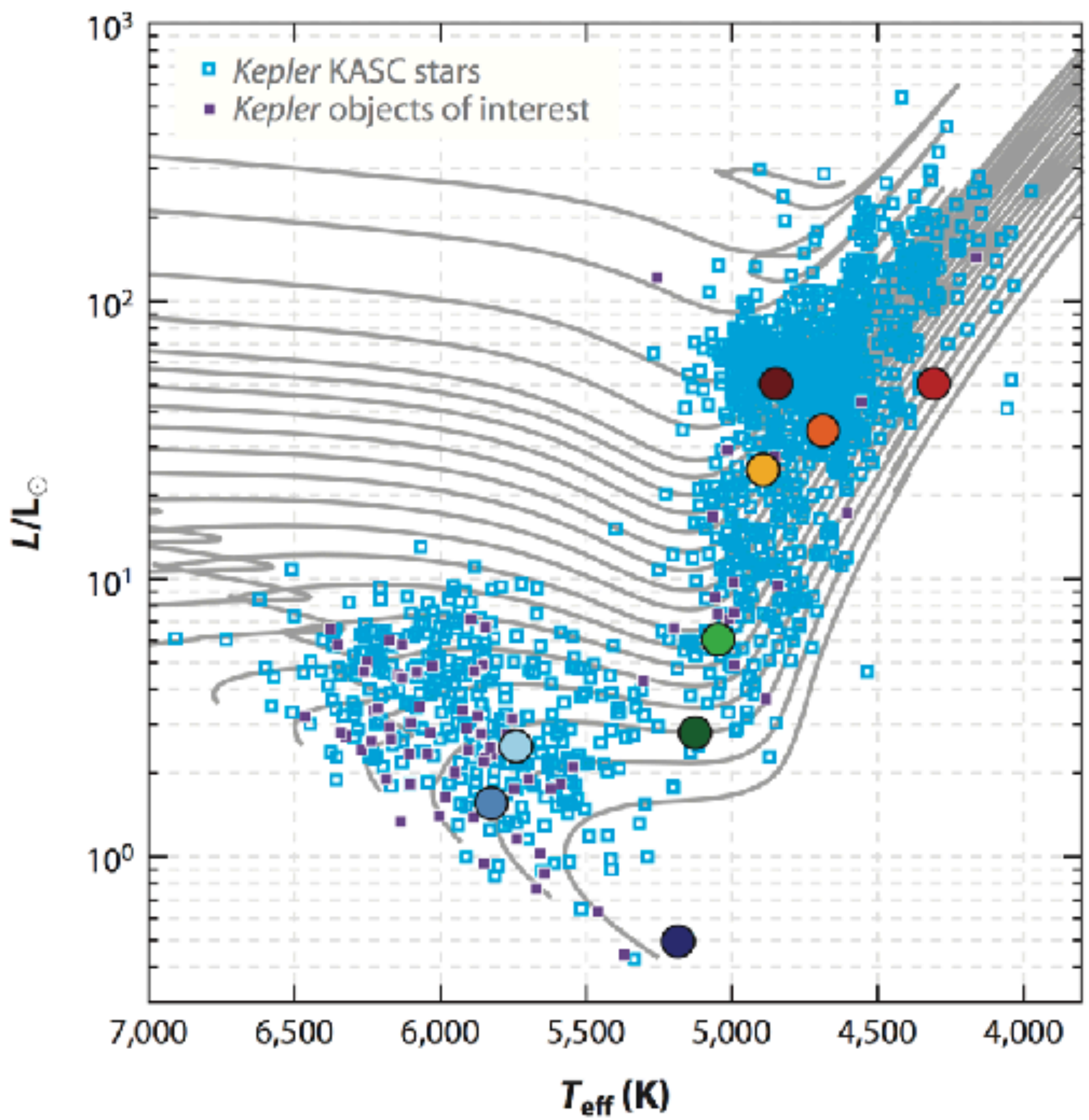
***Strengths***

- $R_\star$ as good as ~1%
- (almost) model-independent
- Establish “touchstone” stars

***Weaknesses***

- Requires very bright stars
    - Very nearby dwarfs
    - Only a few KM
    - A few distant giants
- Not feasible for majority of exoplanet hosts

# Asteroseismology




Chaplin & Miglio 2013

***Method***

- Measure stellar acoustic modes from high precision (space-based) photometry
- Apply simple scaling relations tied to Sun

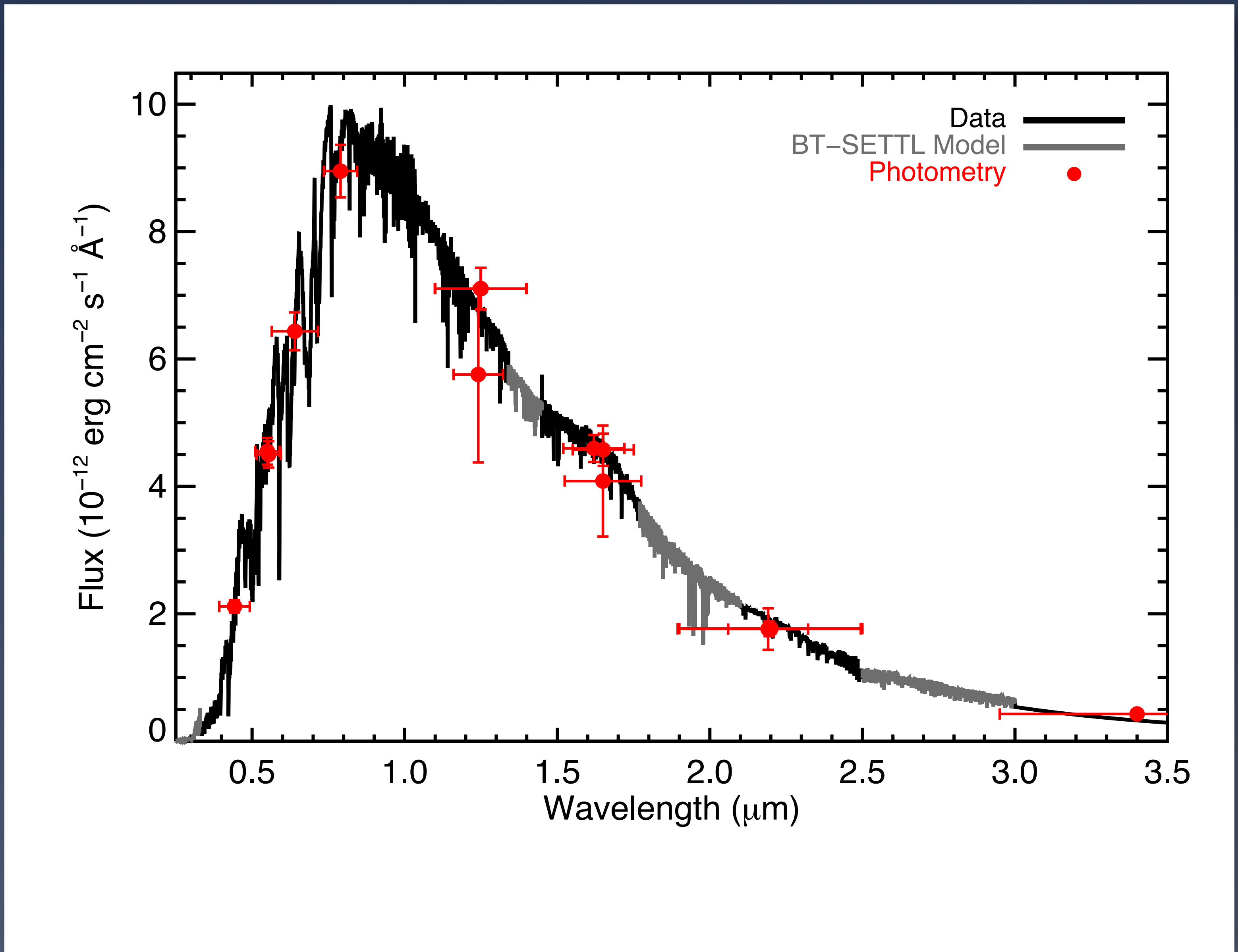
***Strengths***

- $R_*$ as good as a few %
- Weakly dependent on models and prior assumptions
- Extinction-independent

***Weaknesses***

- Typically detectable only in ~Sun-like and earlier or in evolved stars
- Roughly ~100 out of ~4000 Kepler planet hosts have AS radii

# SED-fitting+Parallax




SED fitting from Mann+15, which established ~200 touchstone M stars.

***Method***

- Exploit Stefan-Boltzmann equation

$$R_\star \propto d\, F_{bol}^{0.5} \;/\; T_{eff}^2$$

Parallax  Spec  
Phot.+SED model

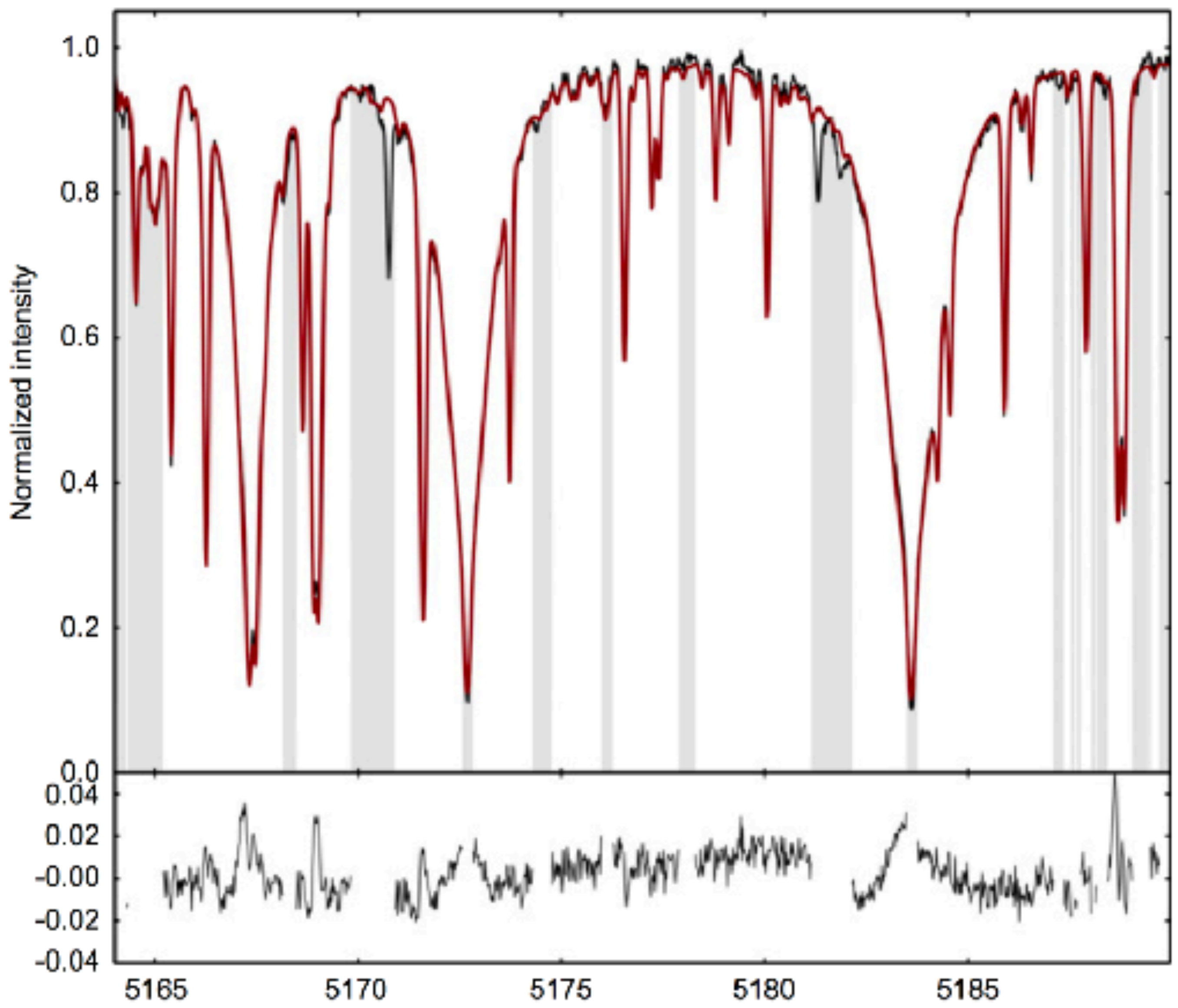
***Strengths***

- $R_\star$ as good as a few %
- Applicable across HR diagram
- Weak dependence on models
- *Gaia* will soon provide 1% distances to typical *Kepler* stars

***Weaknesses***

- Photometric precision requirements of 0.01 mag pushes the limits of flux-calibrated photometry
    - Zero point offsets
    - Errors in filter profiles
- Extinction must be corrected at the 0.01 mag level.

# Spectroscopy+Isochrones




Fit of Mg b triplet from Brewer+15, which achieve logg accuracies of 0.05 dex

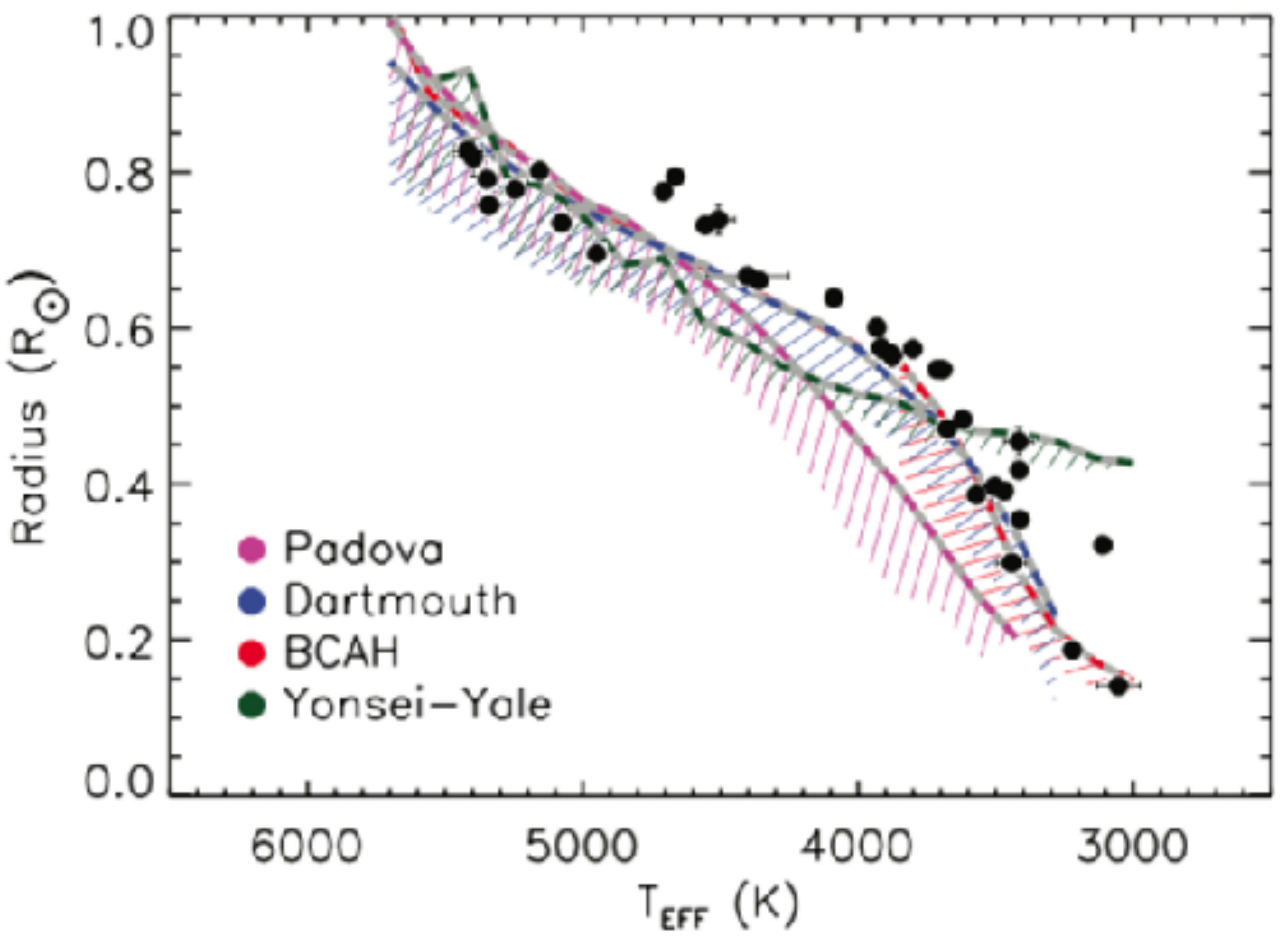
***Method***

- Derive $T_{eff}$, logg, [Fe/H] from spectra
- Consult isochrone to derive $M_\star$, $R_\star$, and age
- Isochrones derived from stellar structure/ evolution models

***Strengths***

- Works over a fraction of HR diagram (F and later)
- Not sensitive to extinction
- No additional observations needed
- $R_\star$ as good as ~10%
- High precision (repeatable)

# Spectroscopy+Isochrones




Boyajian+12 comparison of measured Teff and Rstar. Some models differ by ~50%

***Weaknesses***

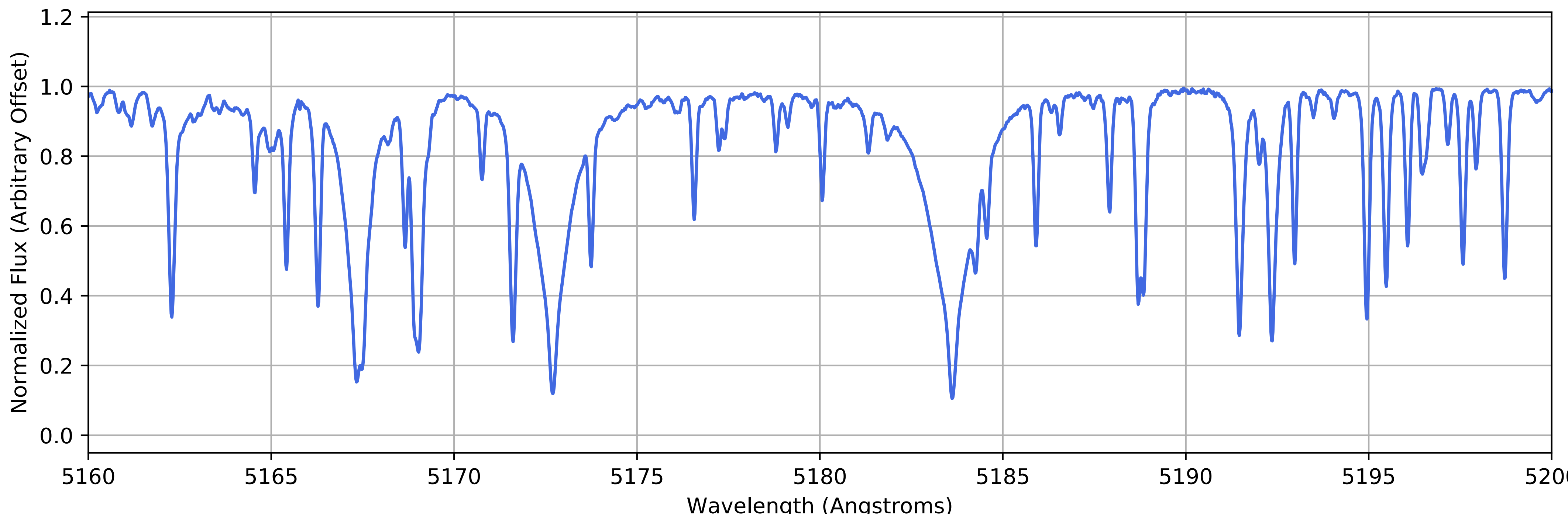
- Strong model-dependance
    - Model atmospheres
    - Isochrones
- Struggles for cool stars
    - Largest model uncertainties
    - Challenging to fit complex spectra.
- Dominated by systematics
- Beware combining results that
    - use different spectral resolution
    - use different regions of spectrum
    - use different spectral codes
    - use different isochrones

***Major challenges for CKS project***

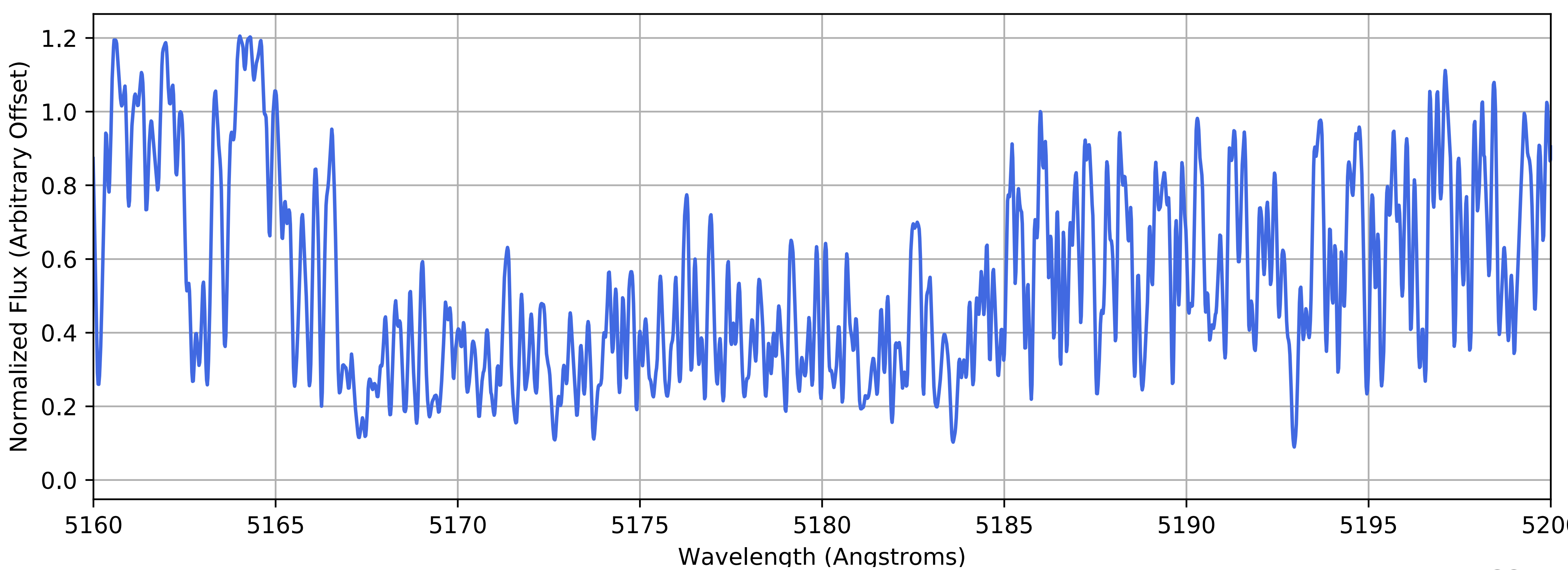
- Uniform resolution
- Uniform SNR
- Uniform analysis
- Characterize model dependent offsets

# Spectroscopic Methods

HD190406
SpT: G0V



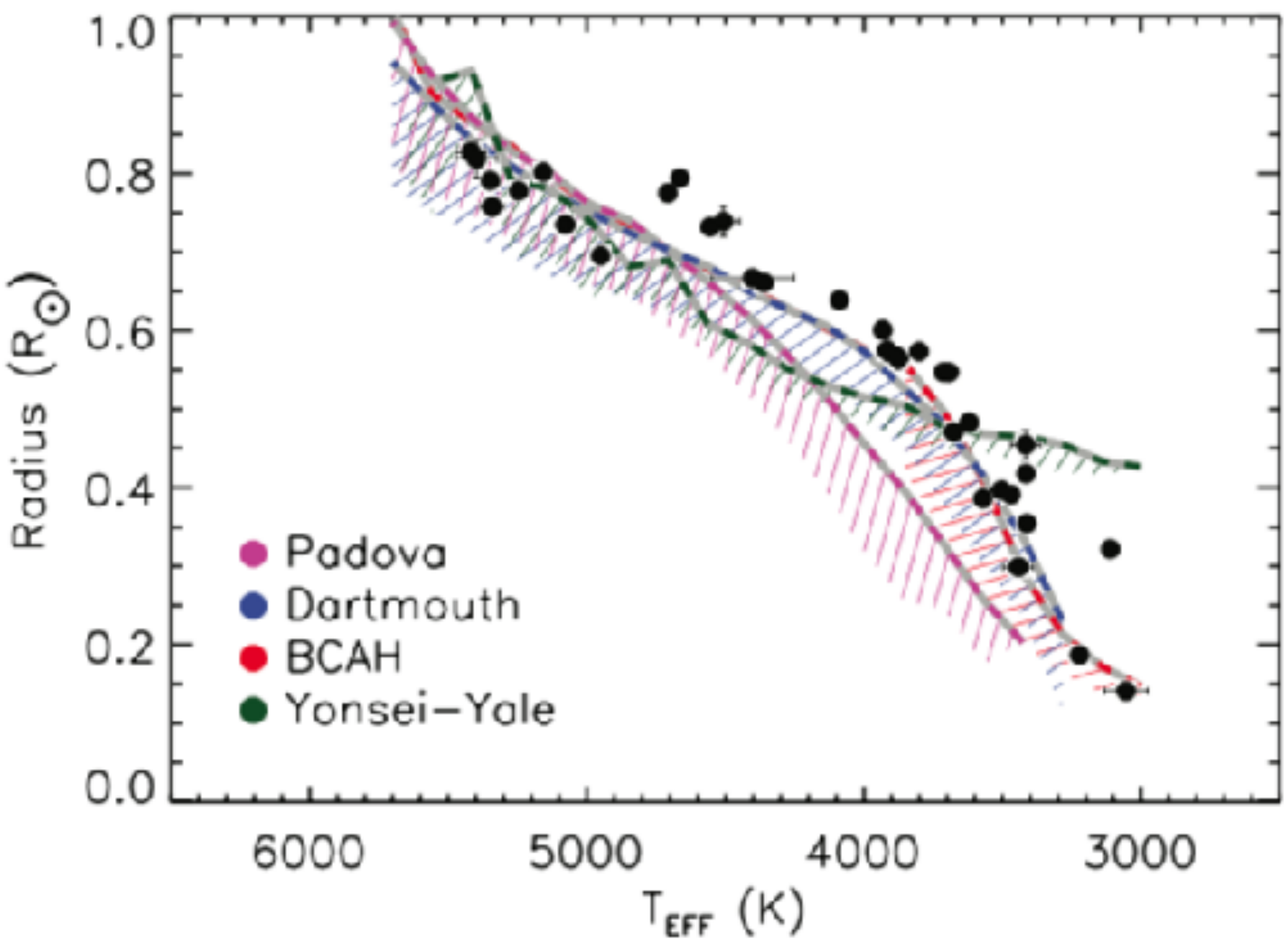

Barnard's Star
SpT: M4V






Yee, Petigura, & von Braun 2016

# Spectroscopy+Isochrones




Boyajian+12 comparison of measured Teff and Rstar. Some models differ by ~50%

***Weaknesses***

- Strong model-dependance
    - Model atmospheres
    - Isochrones
- Struggles for cool stars
    - Largest model uncertainties
    - Challenging to fit complex spectra.
- Hard-to-characterize systematic errors
    - Photon-limited errors are small
    - MCMC of limited use
- Beware combining results that use different
    - spectral resolution
    - regions of spectrum
    - spectral codes
    - isochrones

***Major challenges for CKS project***

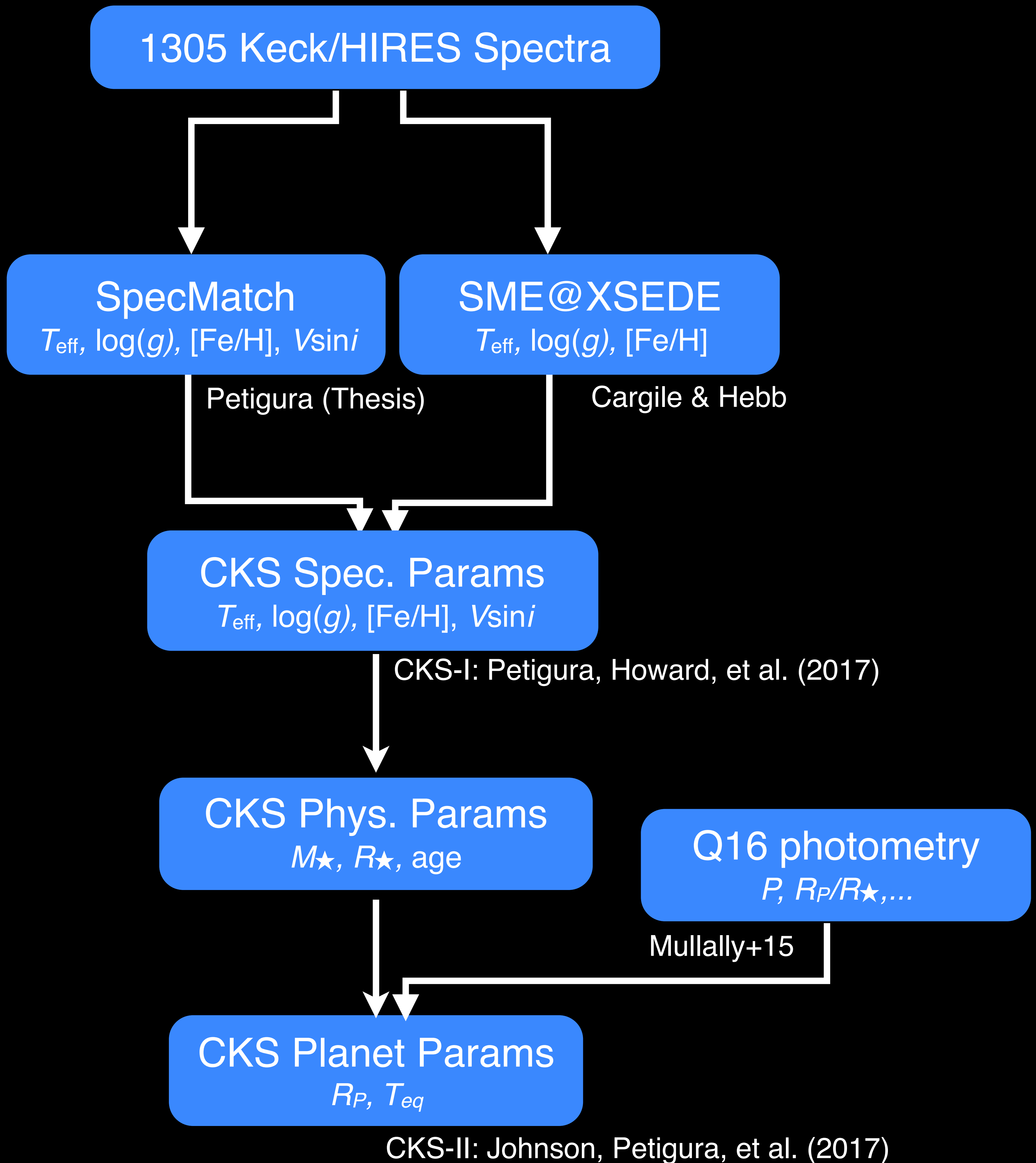
- Uniform resolution
- Uniform SNR
- Uniform analysis
- Characterize model-dependent offsets

# California-Kepler Survey
# Keck/HIRES Spectra of 1305 KOIs

Petigura, Howard, Marcy, et al. 2017
CKS I: Spectroscopic Properties of 1305 Planet-Host Stars From Kepler

Johnson, Petigura, Fulton, et al. 2017
CKS II: Precise Physical Properties of 2025 Kepler Planets and Their Host Stars

Fulton, Petigura, Howard, et al. 2017
CKS III: A Gap in the Radius Distribution of Small Planets



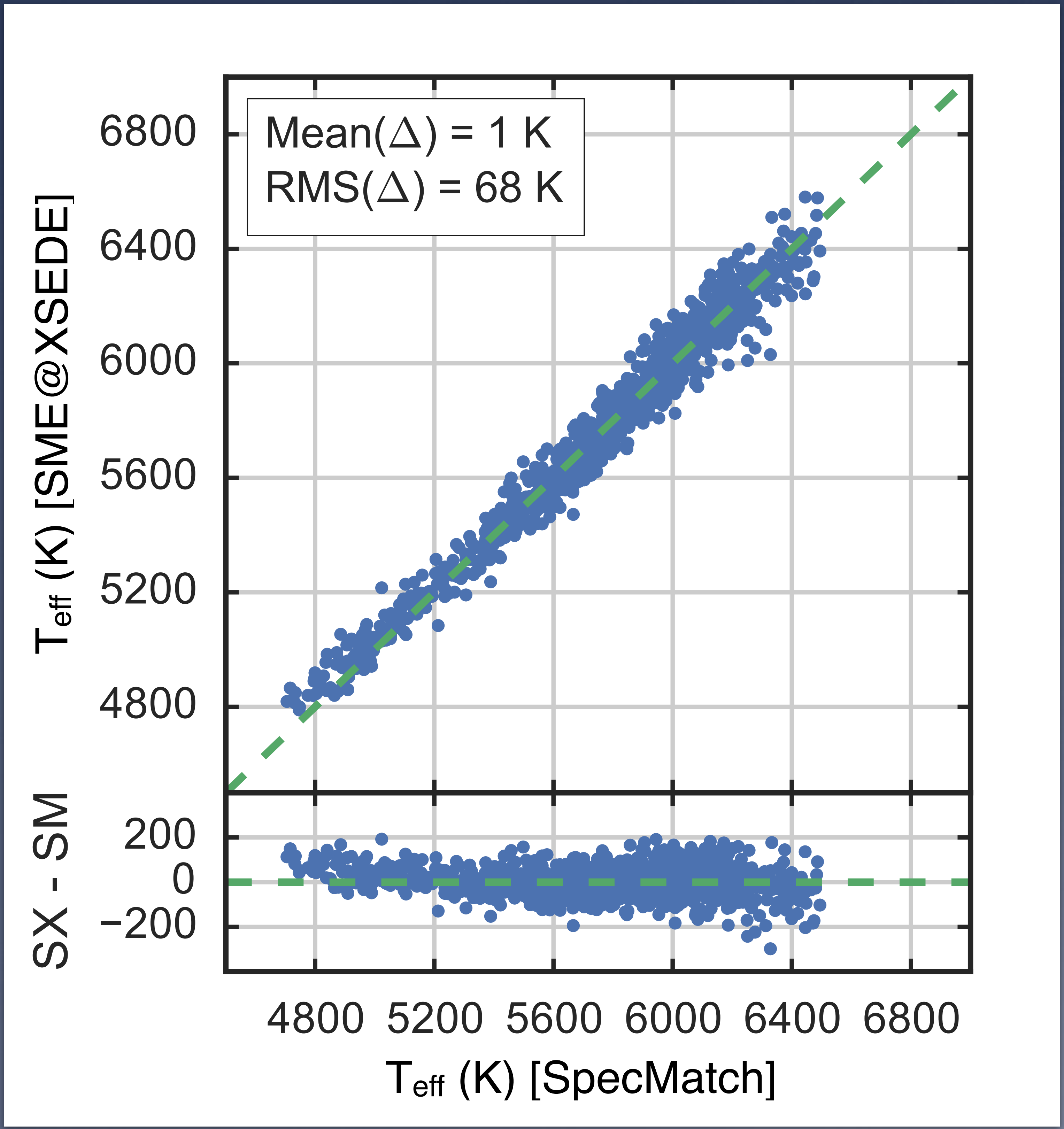

Independently analyze spectra with two spectral codes.

Combine parameters, identify outliers

Isochrone modeling
Morton 2015

Re-derive planet properties

# CKS Precision: Effective Temp.

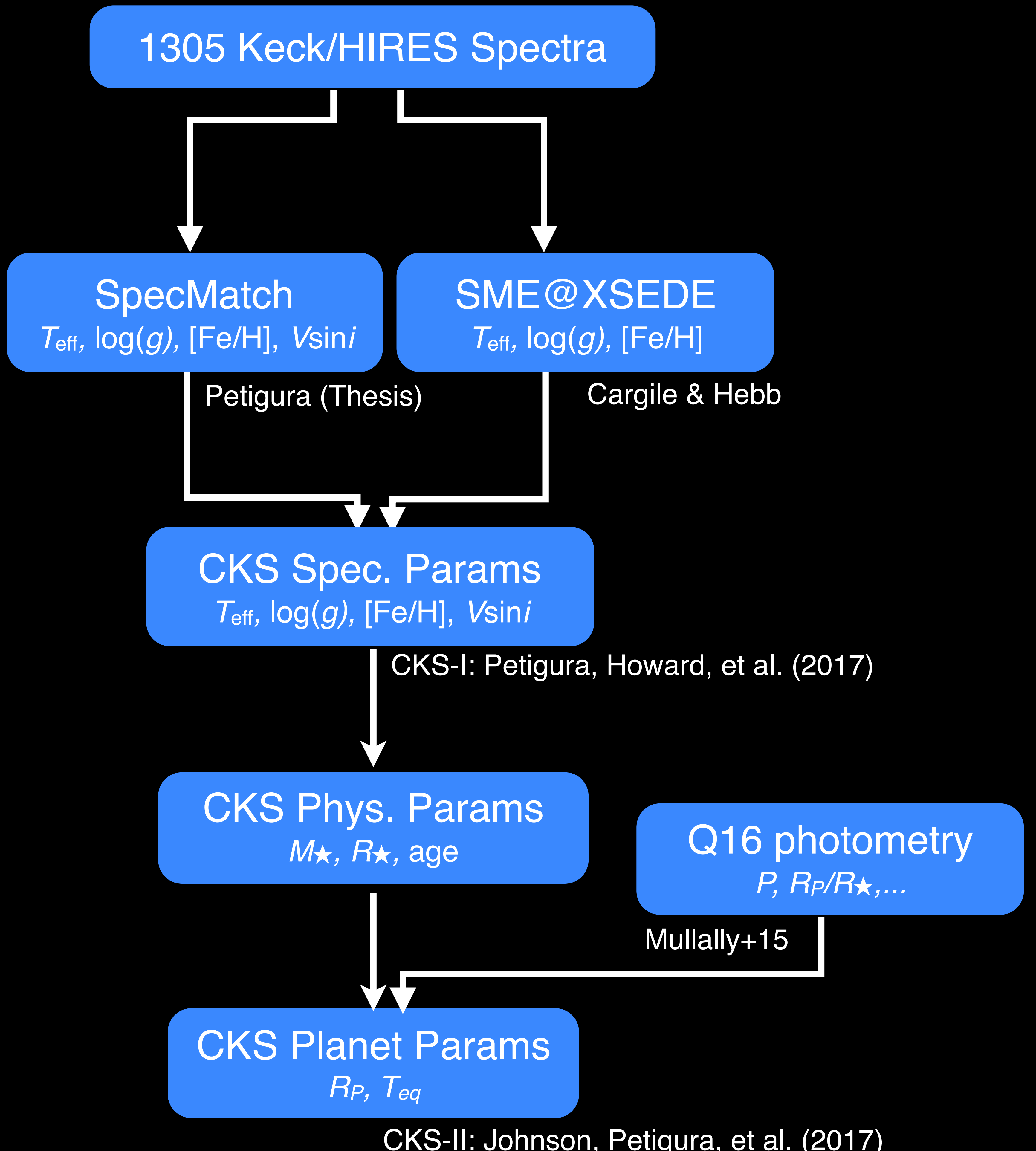



***Spectroscopic***

- $T_{eff}$ ~ 60 K (vs ~200 K phot.)
- log*g* ~ 0.10 dex
- [Fe/H] ~ 0.04 dex
- vsini ~ 1 km/s

***Derived***

- $R_\star$ ~ 10% (vs ~40% phot.)
- $M_\star$ ~ 5%
- ages ~ 30%
- distances ~ 10%

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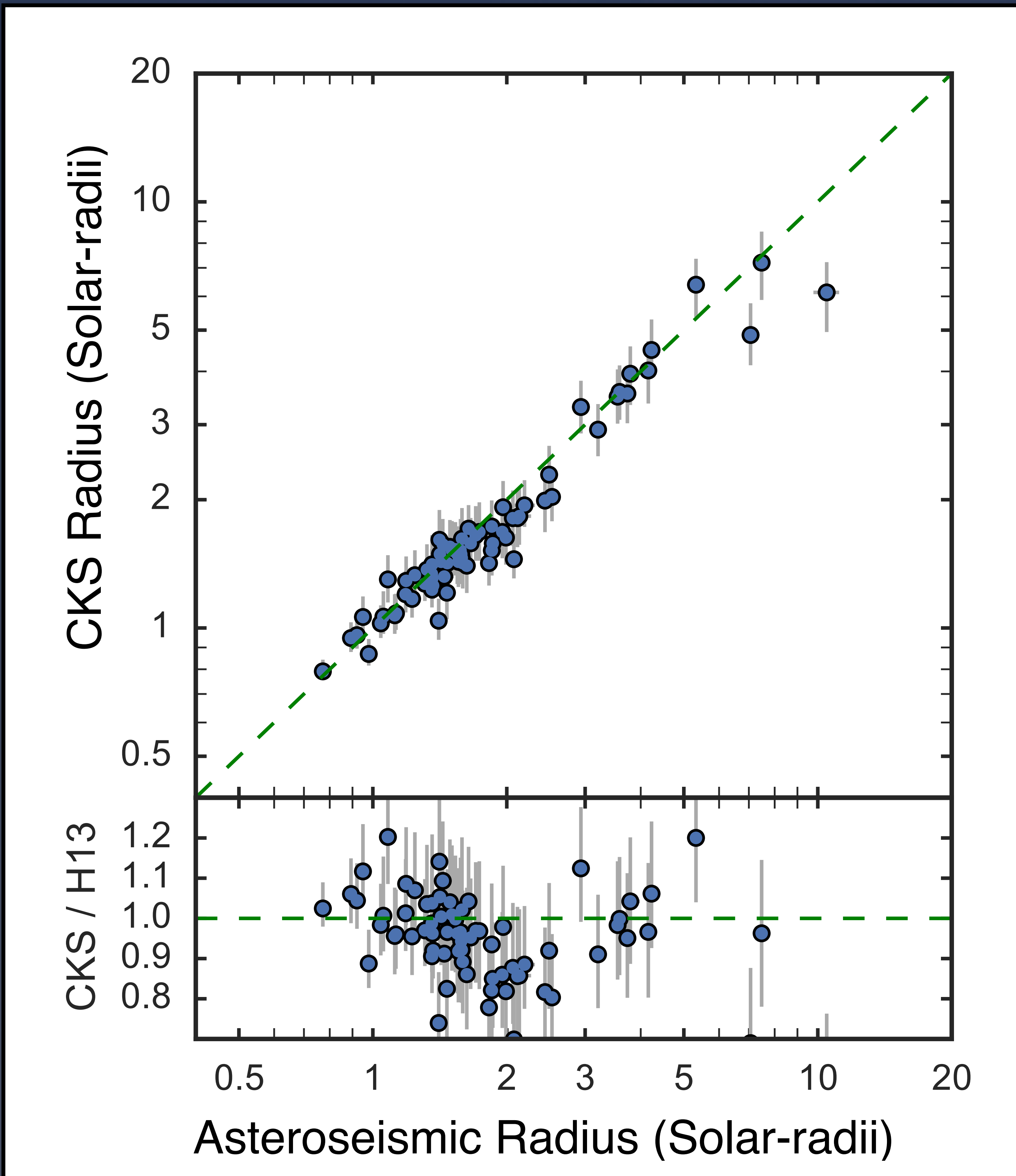
# CKS Precision: Stellar Radii




CKS-II: Johnson, Petigura, et al. (2017)

***Spectroscopic***

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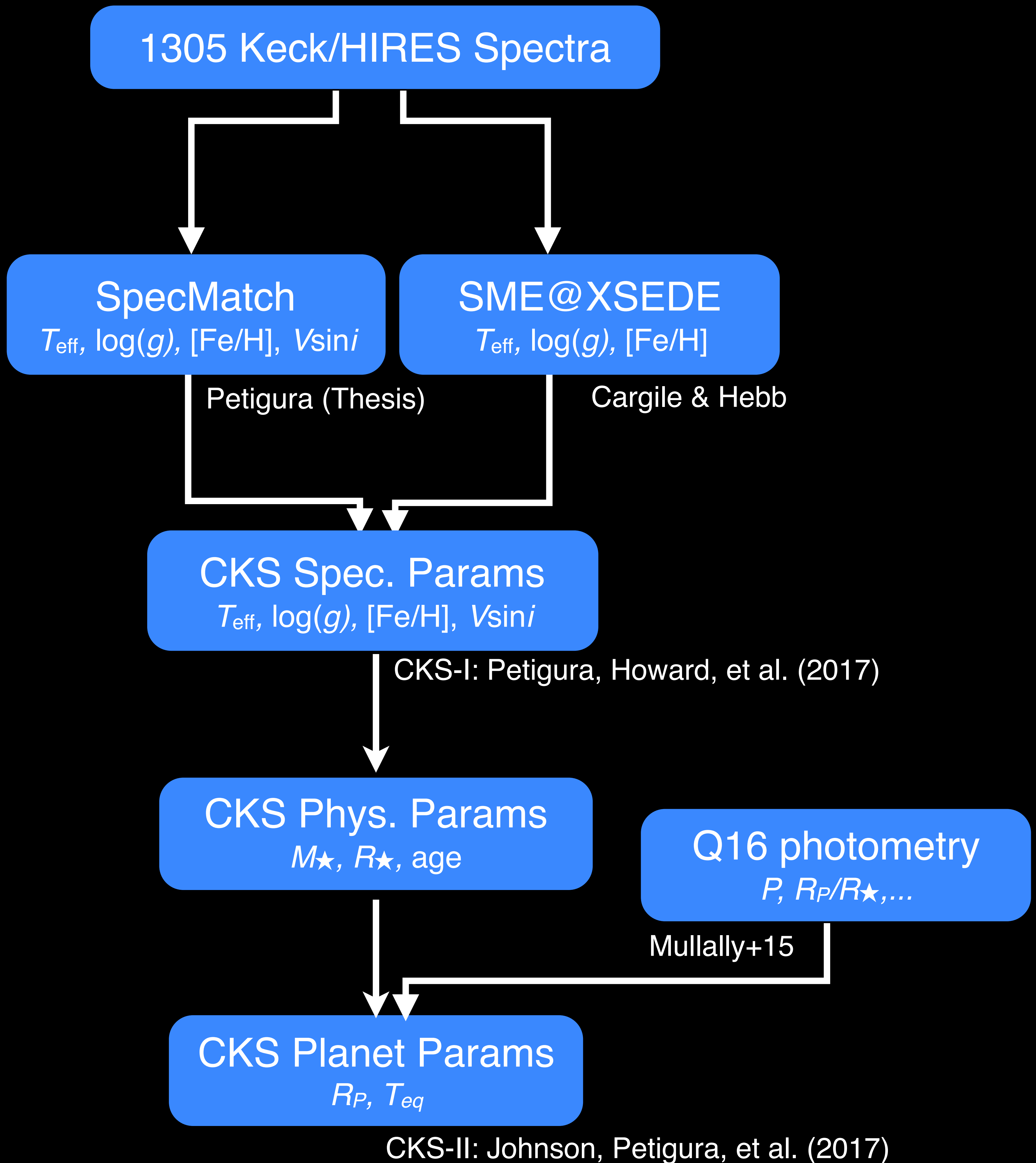


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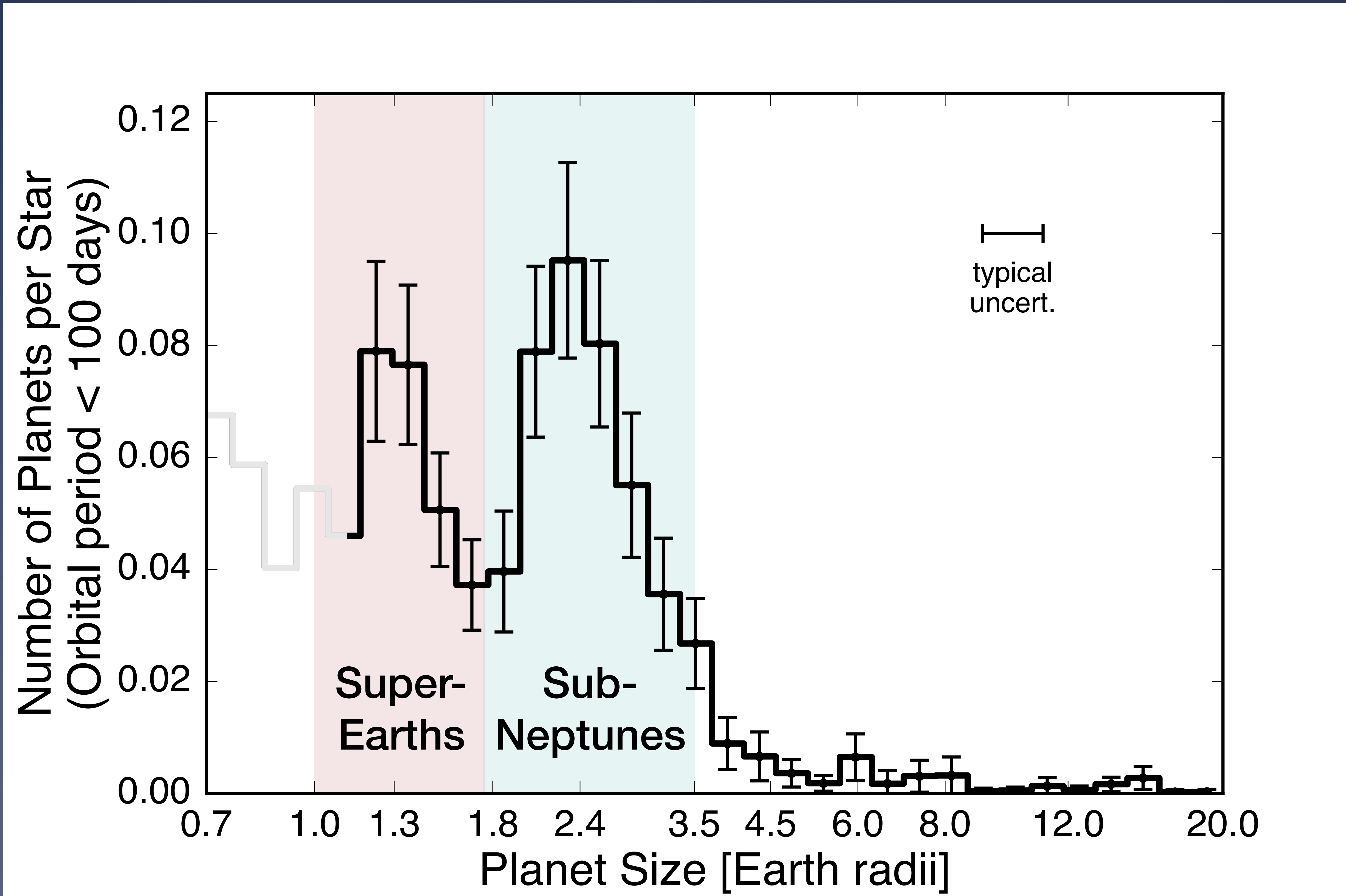
# Gap in Planet Radii

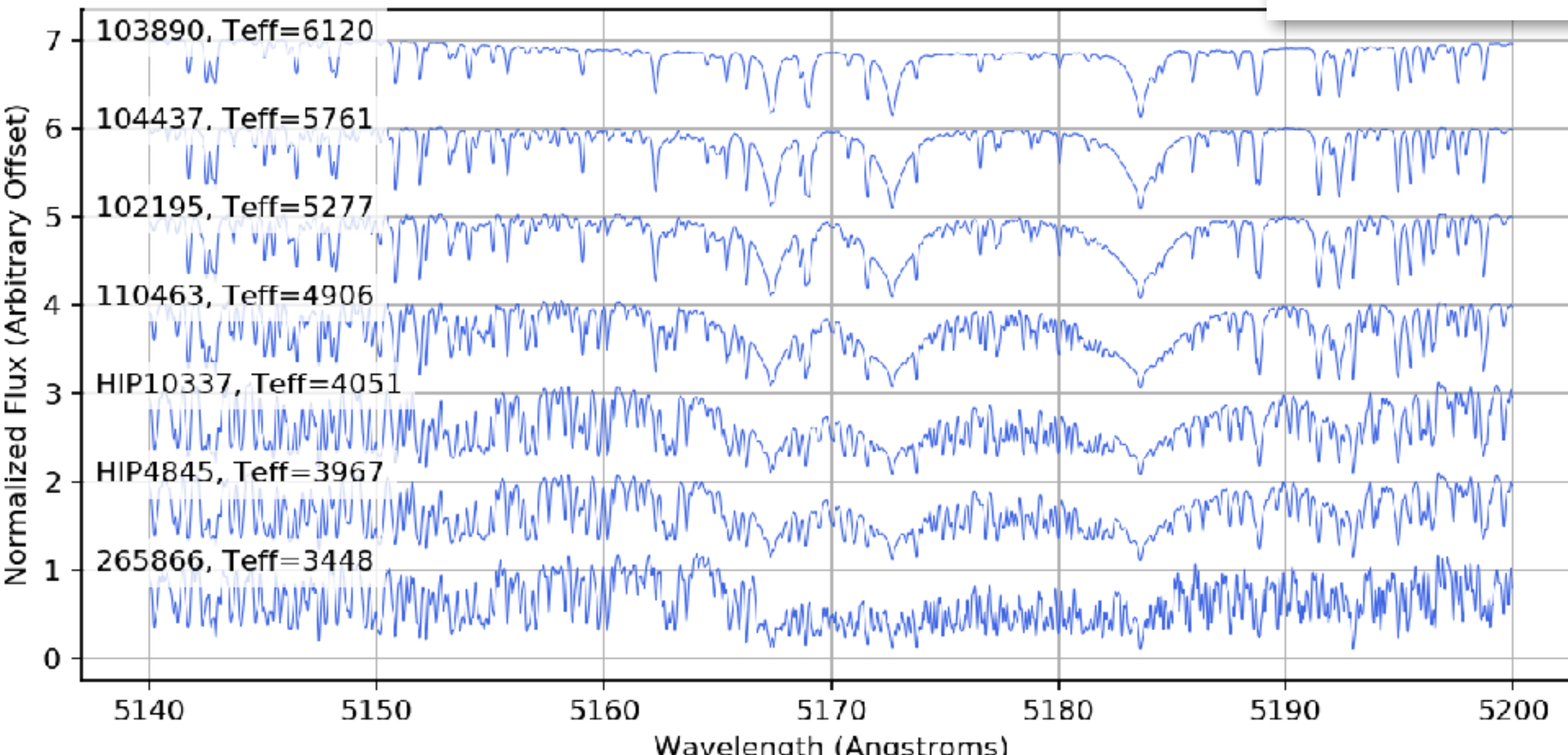


# Data-Driven Spectroscopy

- The challenge
  - Planet surveys will target increasing numbers of stars
  - Spectroscopic datasets growing
    - LAMOST ~$10^7$
    - Gaia ~$10^8$
  - “Bespoke” spectroscopy not scalable
  - Systematic uncertainties in model atmospheres and stellar structure (esp. for cool stars)
- The opportunity
  - Growing samples of “touchstone” stars
  - Use spectra of touchstone stars to constrain unknown stars (no physics!)
  - Advances in computation and machine-learning make data-driven spectroscopy tractable

# SpecMatch-Empical:
## Precision Spectroscopy with Empirical Spectra

See poster by Samuel Yee
Caltech Undergraduate

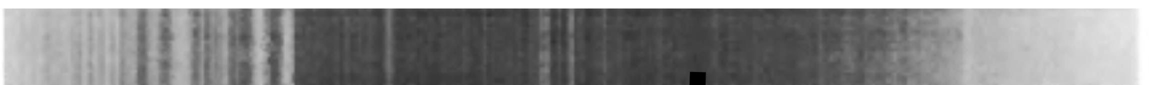





Yee, Petigura, & von Braun 2016

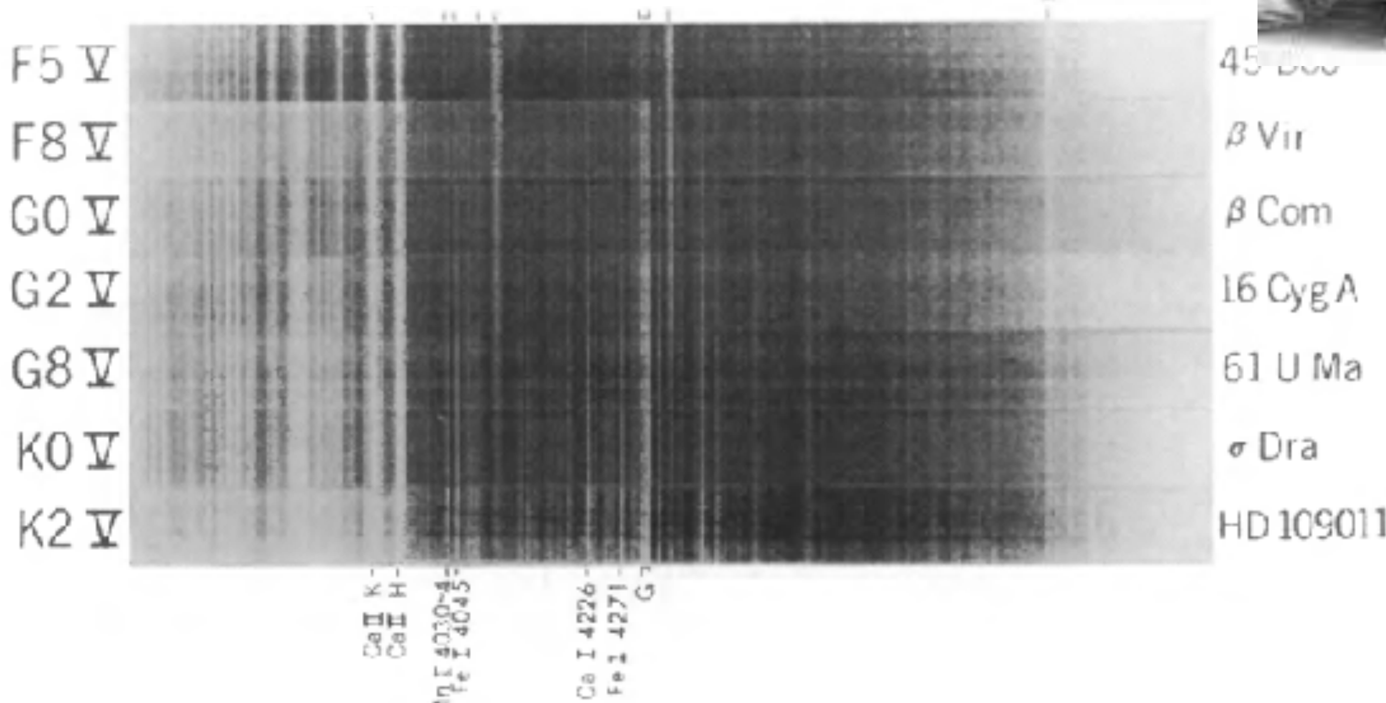
# Data-Driven Spectroscopy (c. 1900)

Target Spectrum

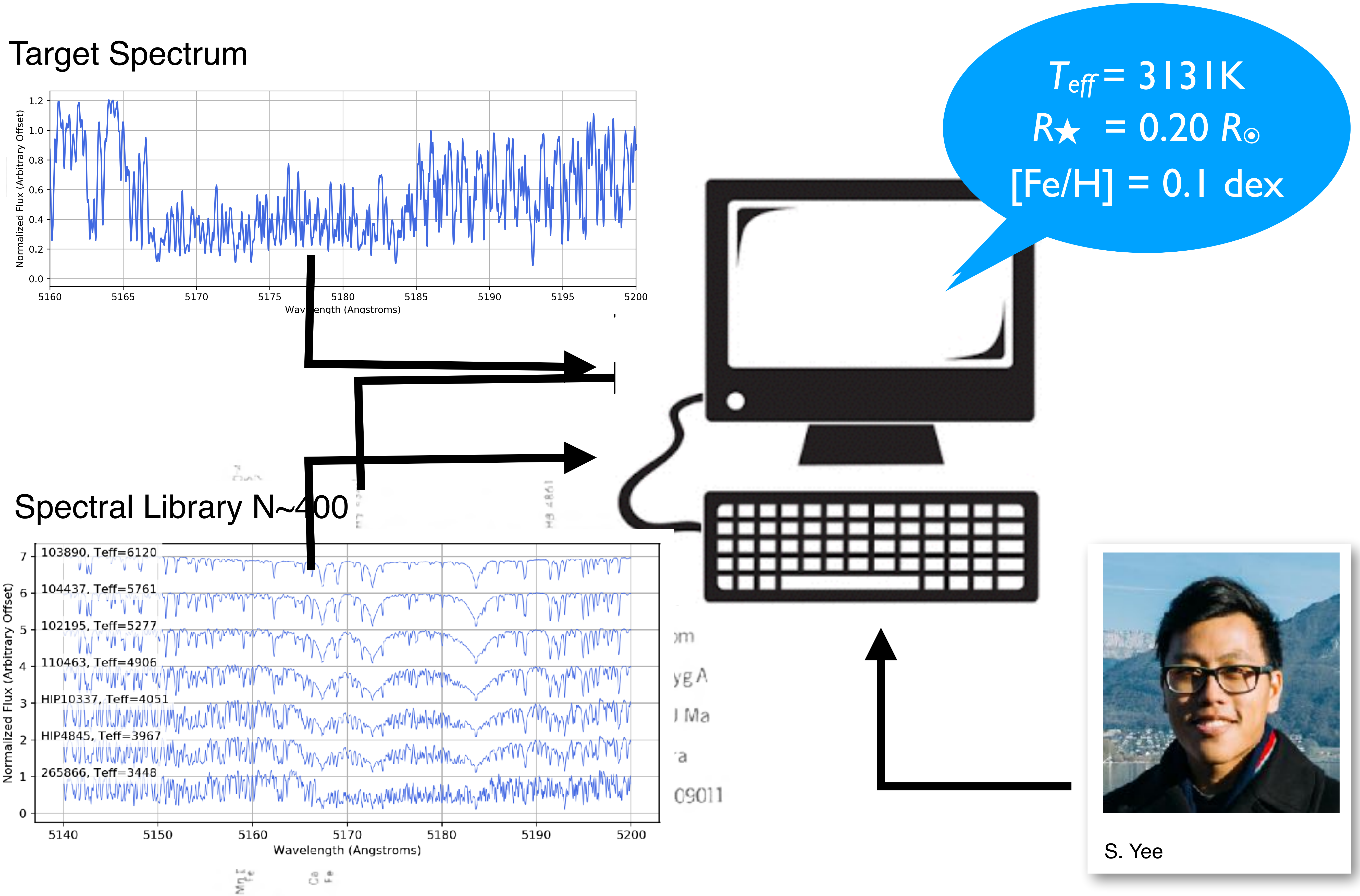



A.J. Cannon

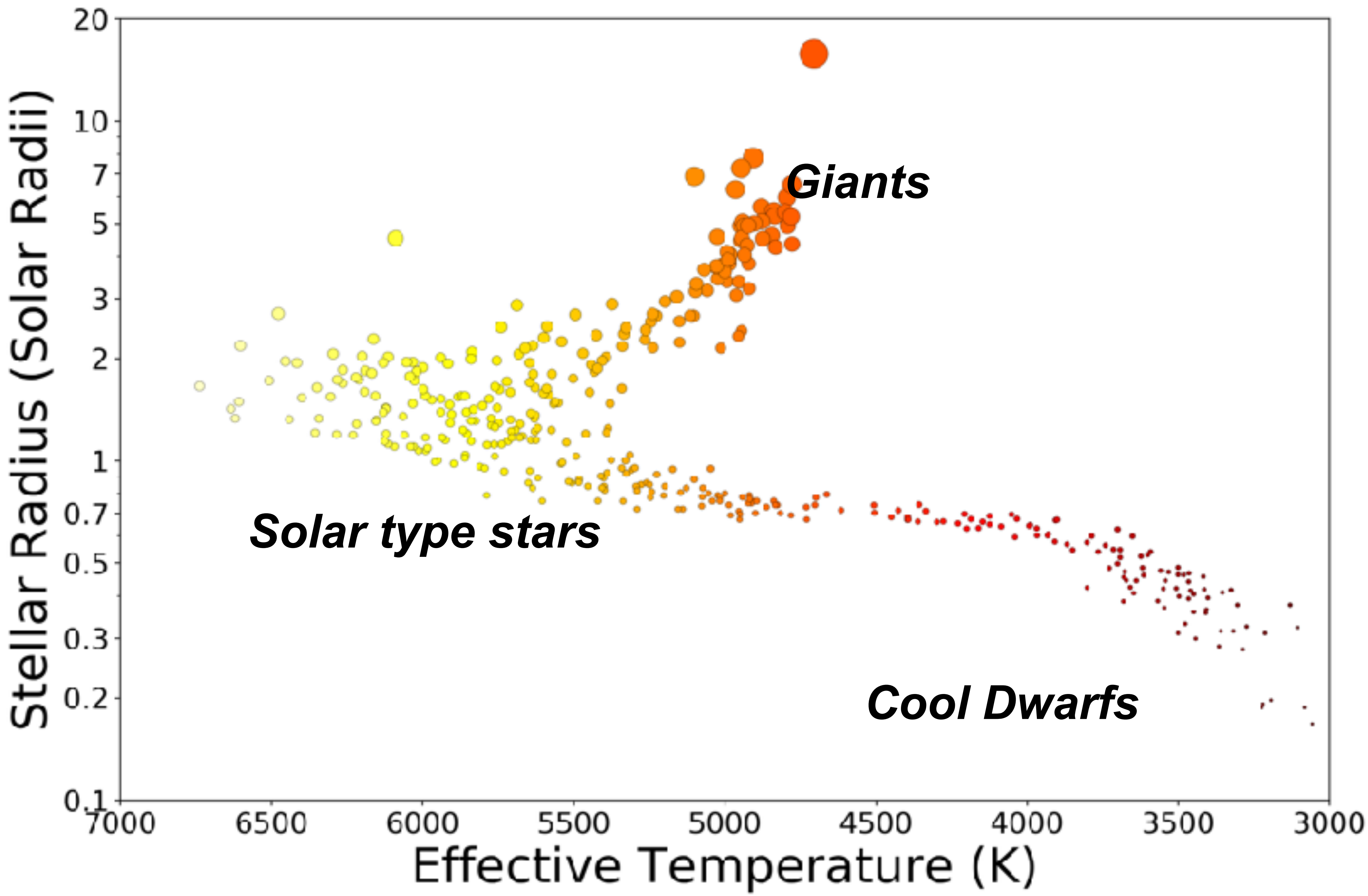
Spectral Library N ~ dozens



# Data-Driven Spectroscopy (c. 2017)

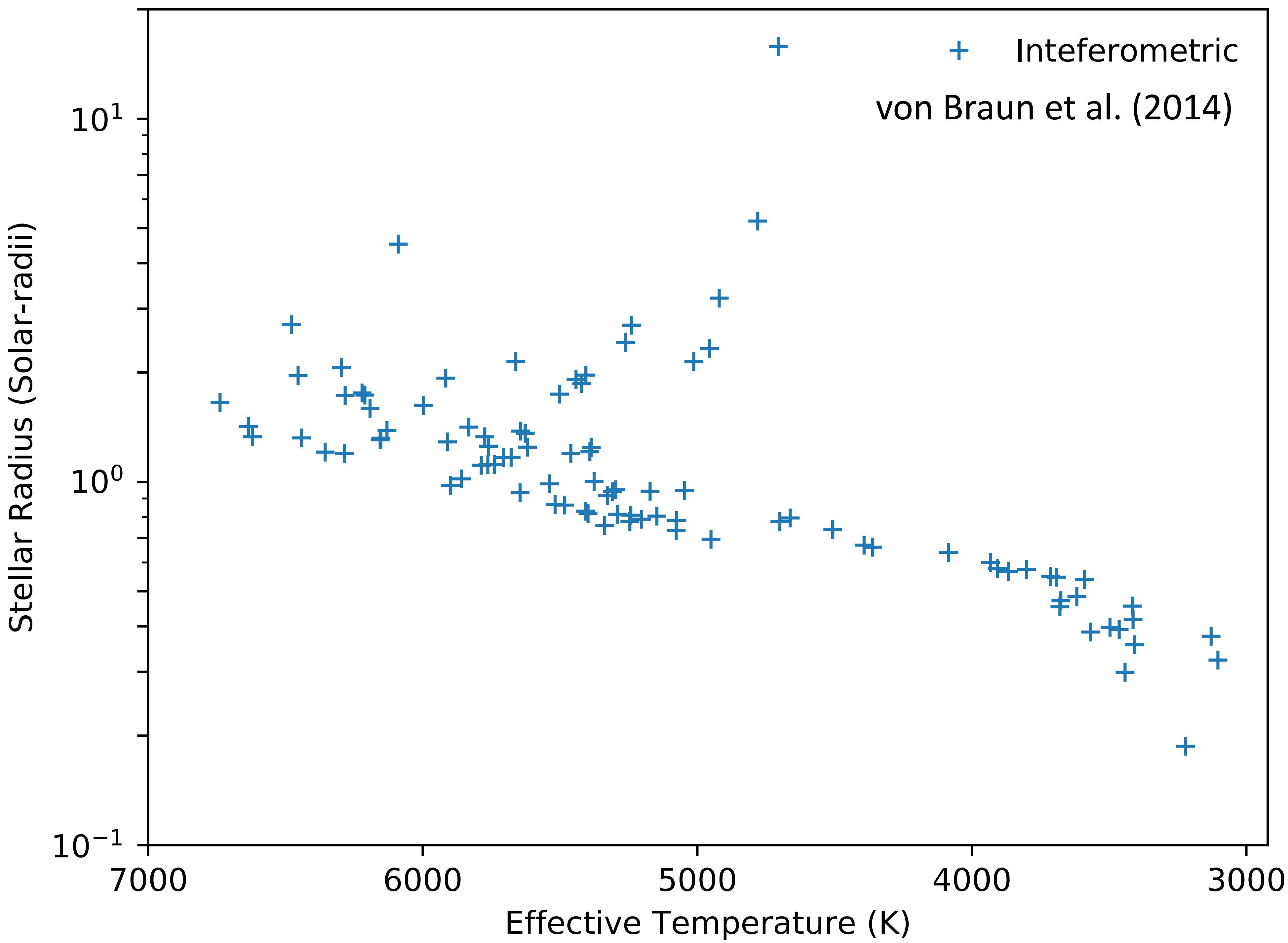


# Library - Parameters



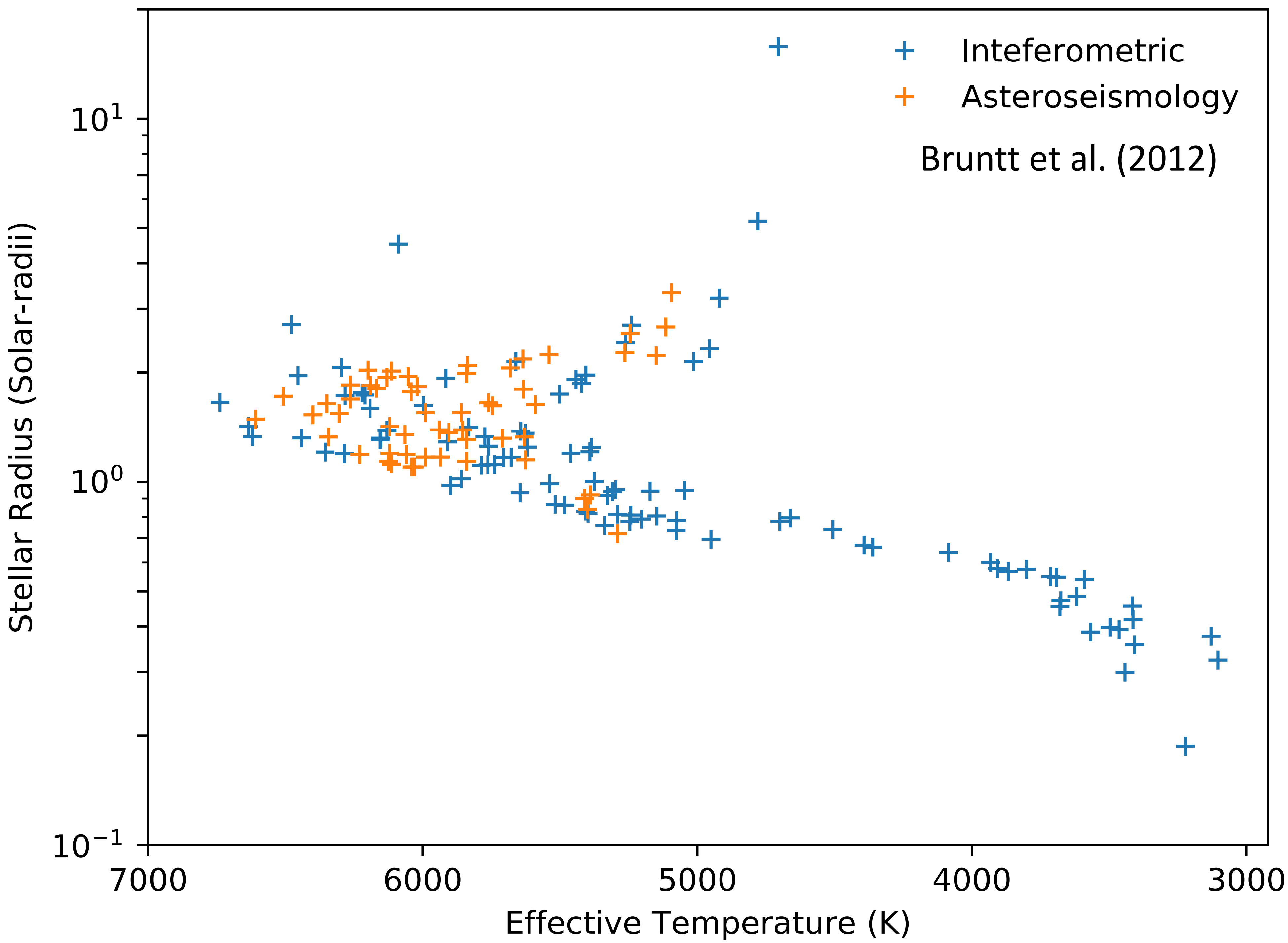

Yee, Petigura, & von Braun 2016

# Library – Interferometric Sample




Yee, Petigura, & von Braun 2016

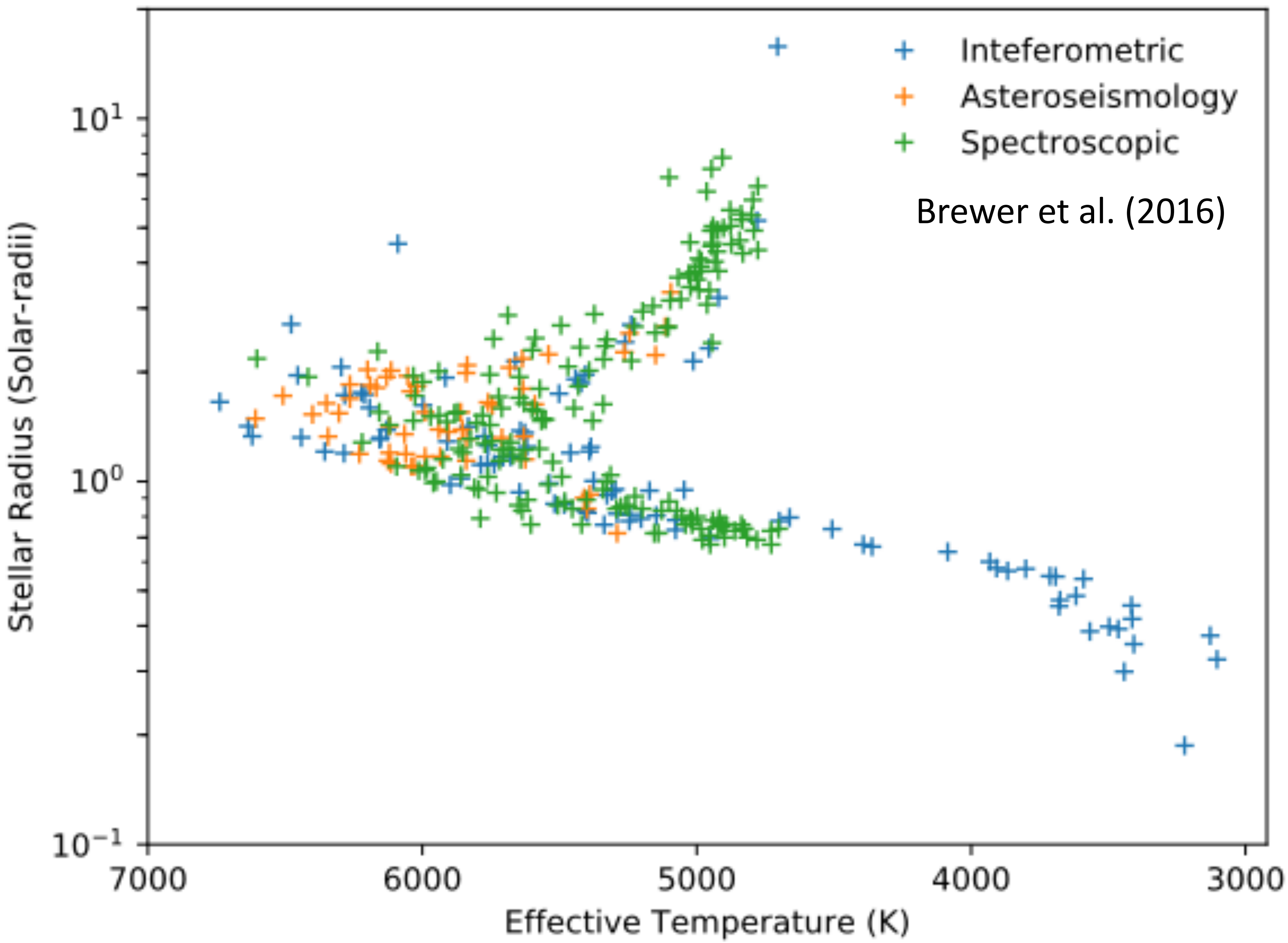
# Library – Asteroseismology Sample





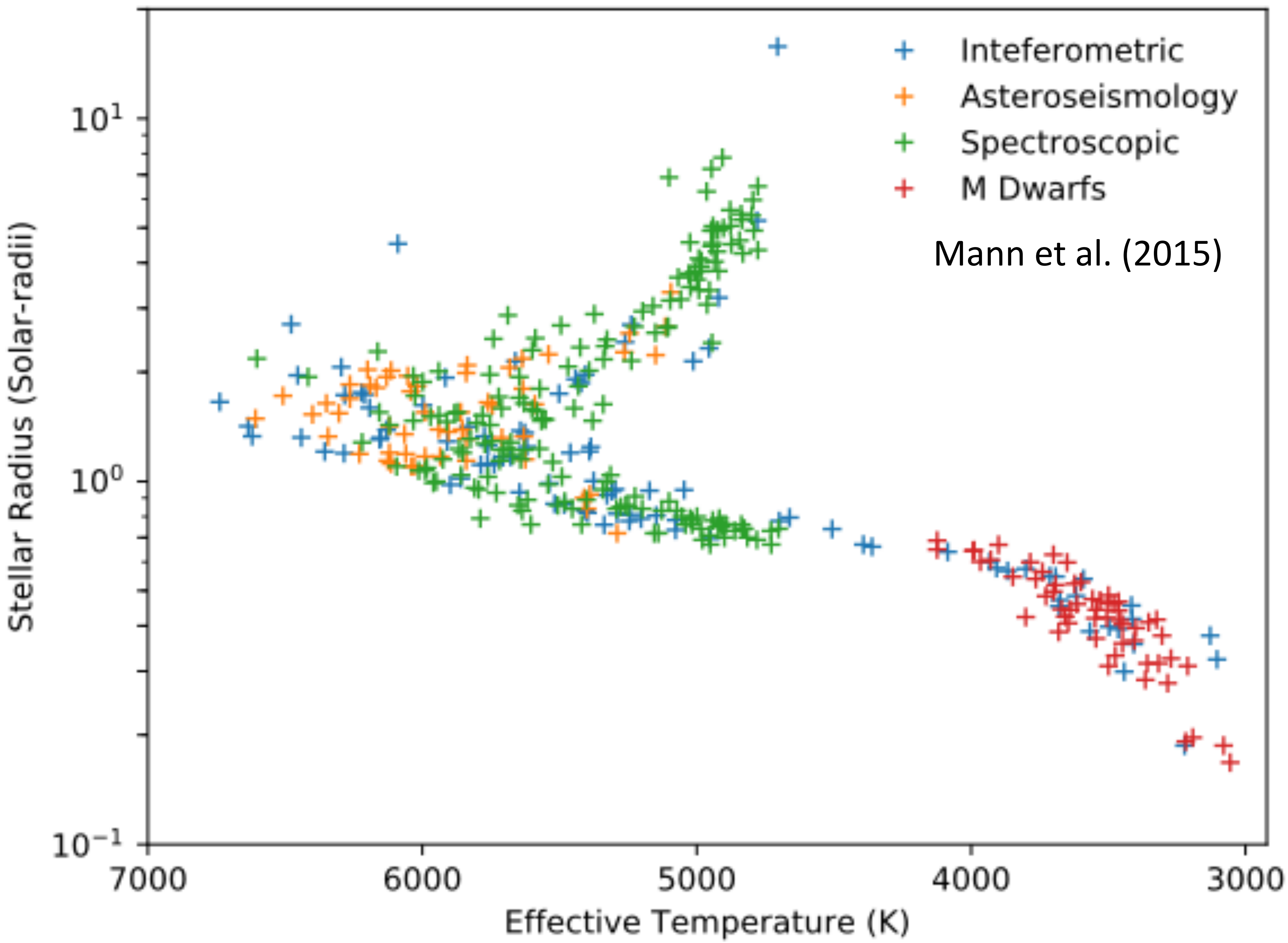

Yee, Petigura, & von Braun 2016

# Library – Spectroscopic Sample



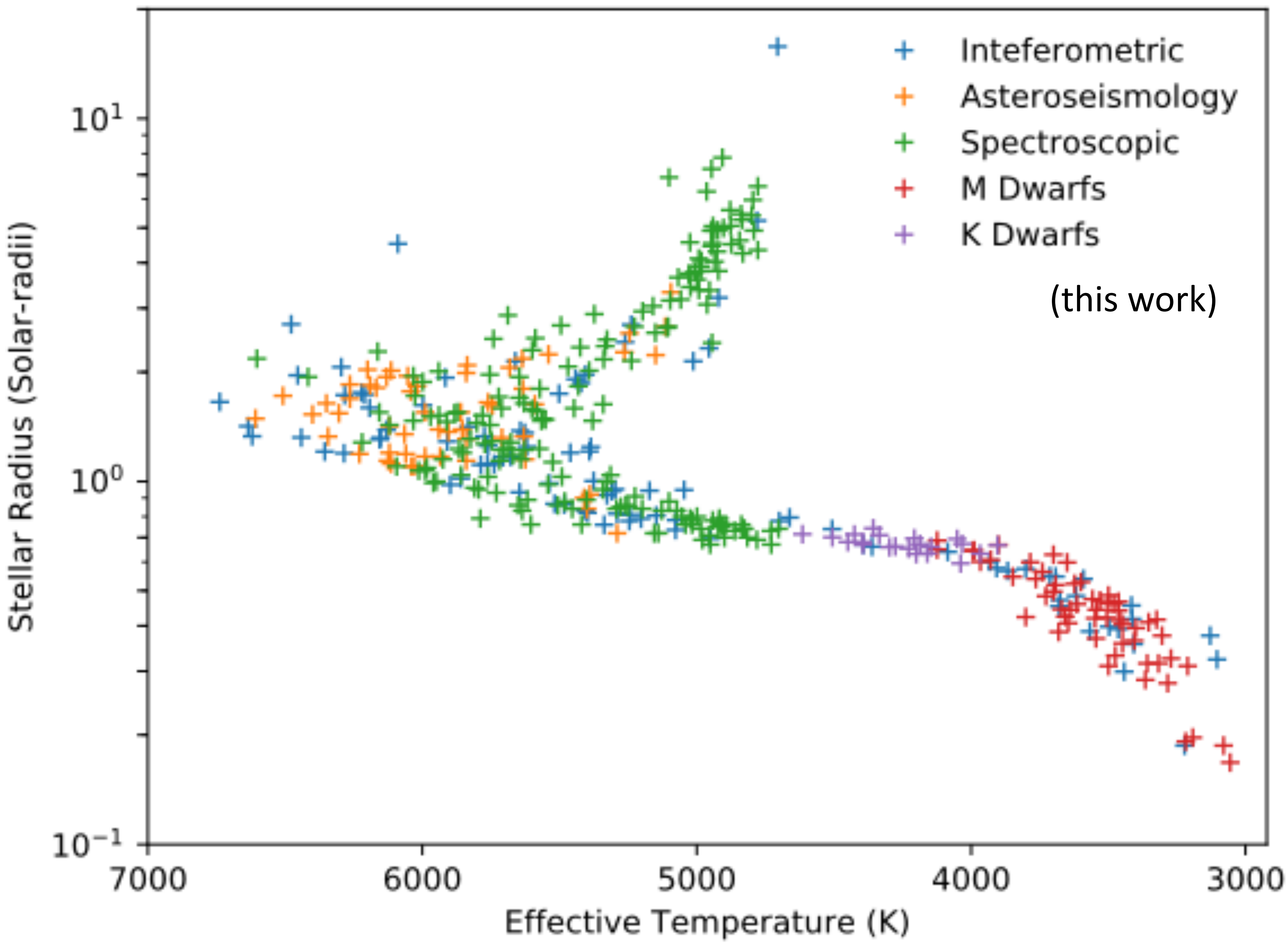

Yee, Petigura, & von Braun 2016

# Library – M Dwarfs



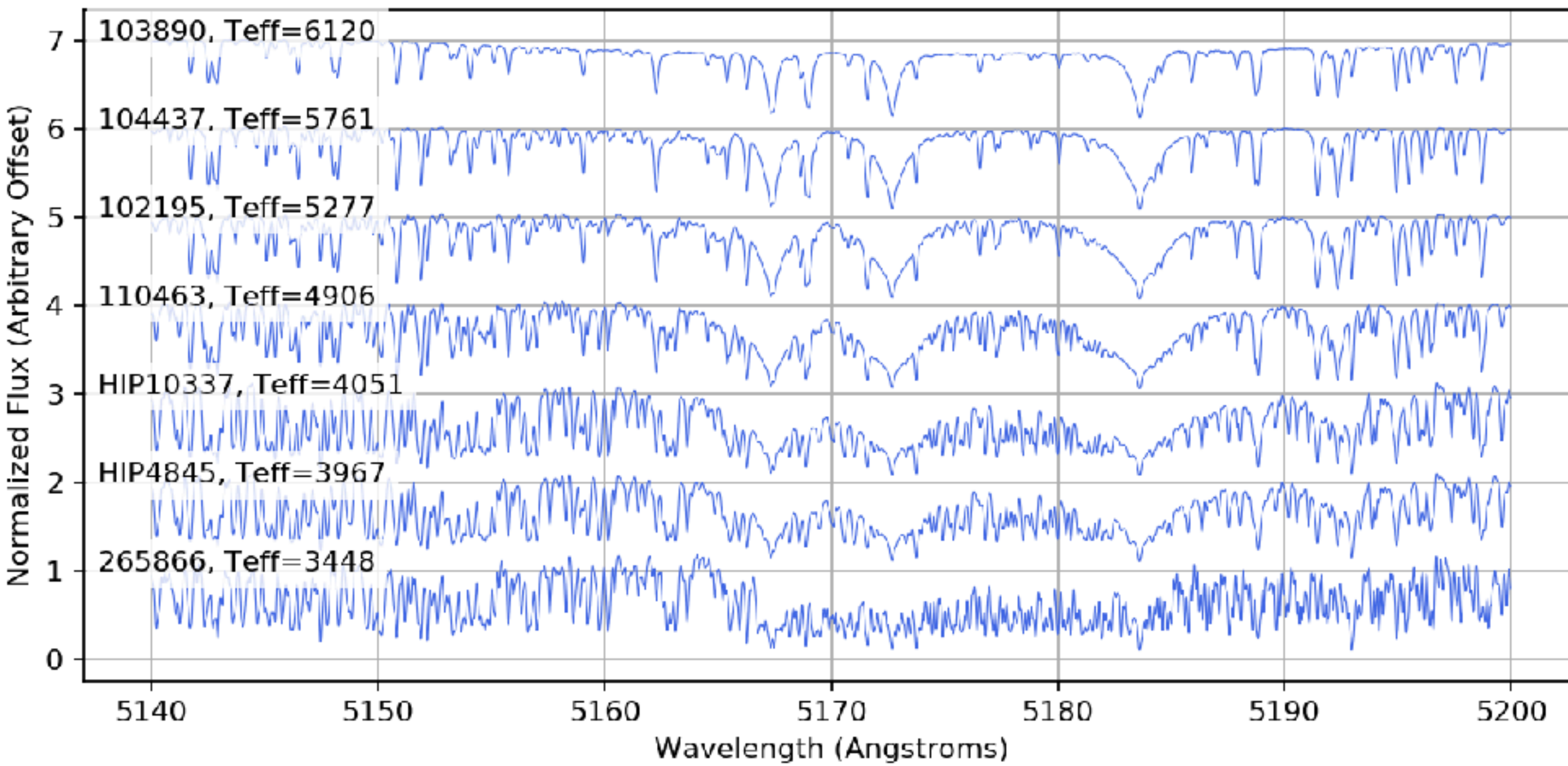

Yee, Petigura, & von Braun 2016

# Library – K Dwarfs




Yee, Petigura, & von Braun 2016

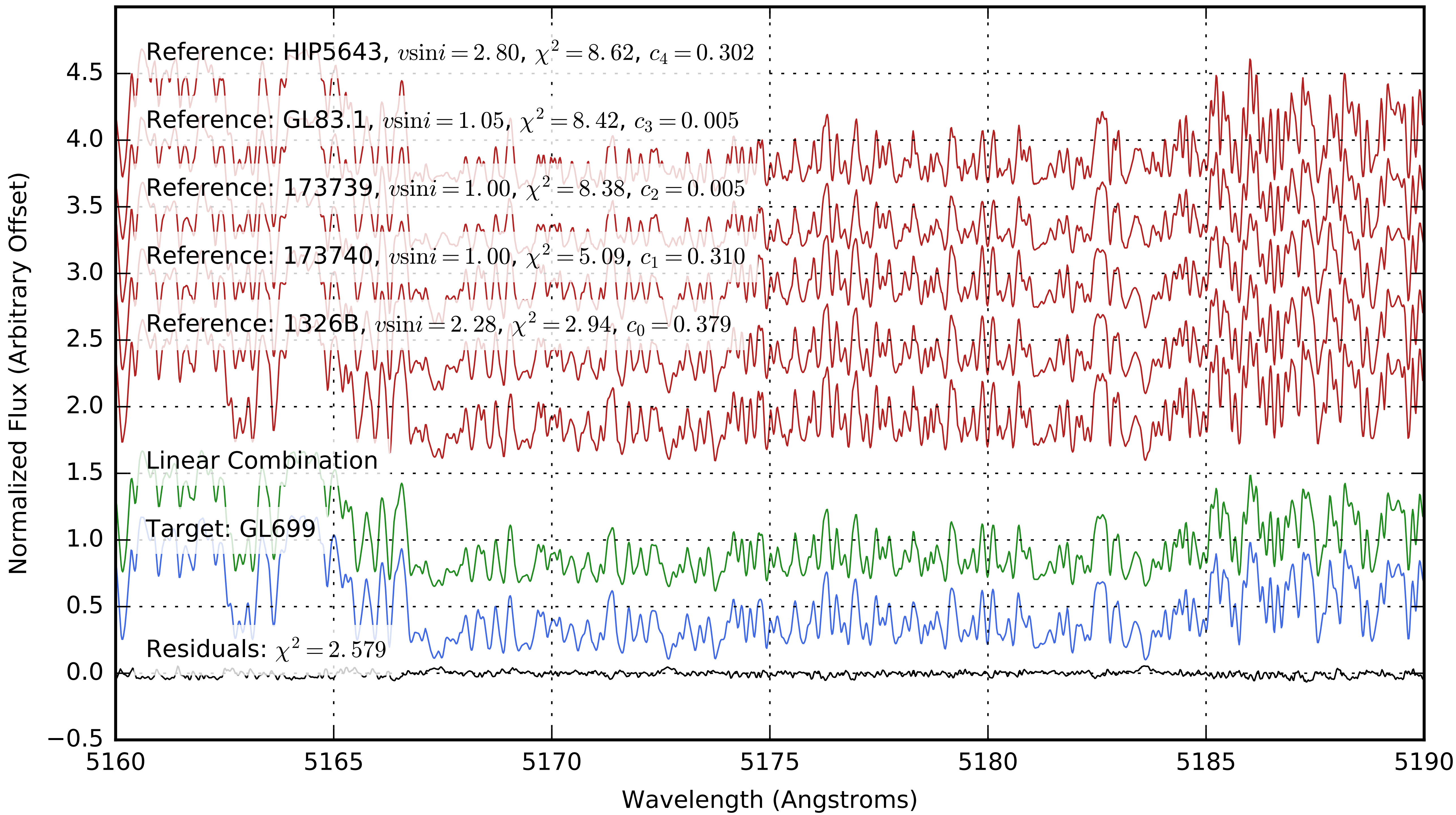
# SpecMatch-Emp Library
# ~400 HIRES spectra of touchstone stars





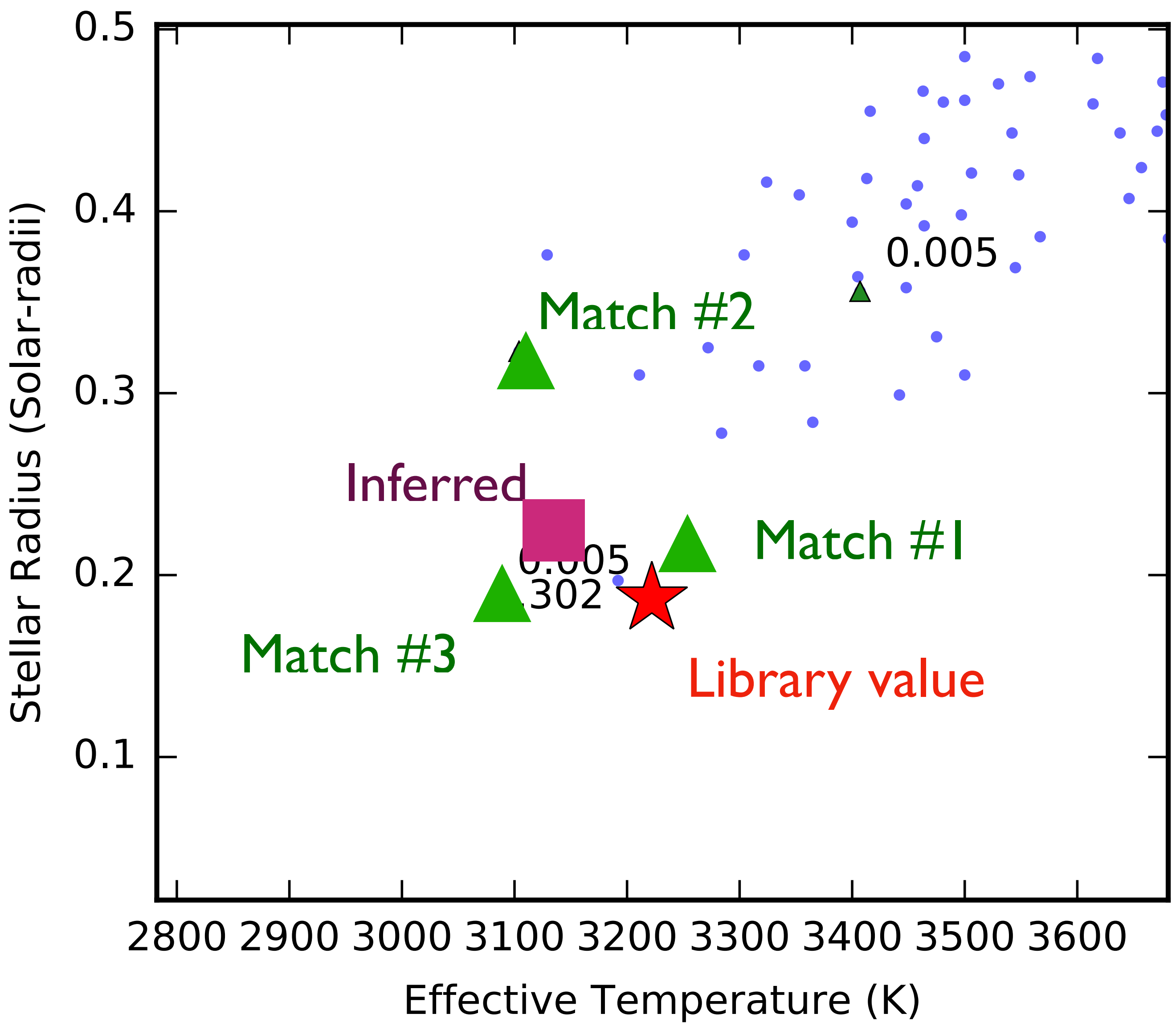

Yee, Petigura, & von Braun 2016

# Fit target with linear combinations of library spectra




Yee, Petigura, & von Braun 2016

# Assess accuracy with cross-validation




| | GJ699 | All Cool Stars | Libray Uncert. |
|---|---|---|---|
| $\Delta T_{eff}$ | **80 K** | **70 K** | **60 K** |
| ΔR/R | **15%** | **10%** | **4%** |
| Δ[Fe/H] (dex) | **0.03** | **0.12** | **0.08** |

Yee, Petigura, & von Braun 2016

# Data-Driven Spectroscopy

- SpecMatch-Empircial
  - Yee+16
  - Precision spectroscopy with empirical library
  - Spectral library and code freely available on GitHub
- The Cannon
  - Ness+15, Casey+16, Ho+16,
  - $T_{eff}$, log$g$, [Fe/H] (ver. 1) and 14 other elements (ver. 2)
  - Used to characterize 230,000 LAMOST spectra (Ho+16)
- The Payne
  - Ting+17
  - $T_{eff}$, log$g$, [Fe/H], and other 13 other elements
  - Priors based on model spectra

See poster by Samuel Yee
Caltech Undergraduate

# Properties of Exoplanet Hosts

- Stellar properties influence planet detectability
- Precision measurements of stellar radii
- A frontier: data-driven spectroscopy