How Well Do We Really Know “Our” Stars?

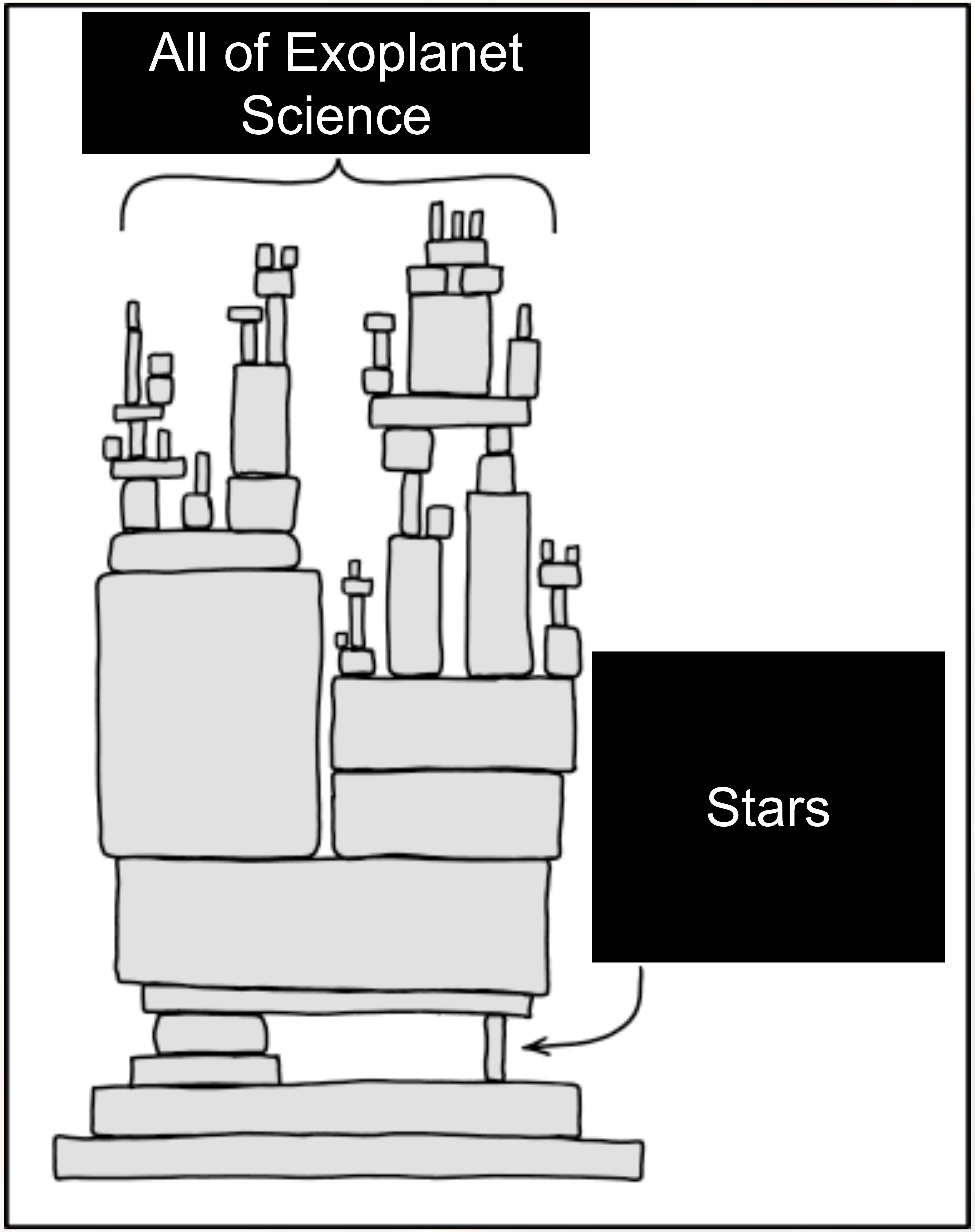
Daniel Huber

Institute for Astronomy,
University of Hawaiʻi

Know Thy Star 2

February 2025

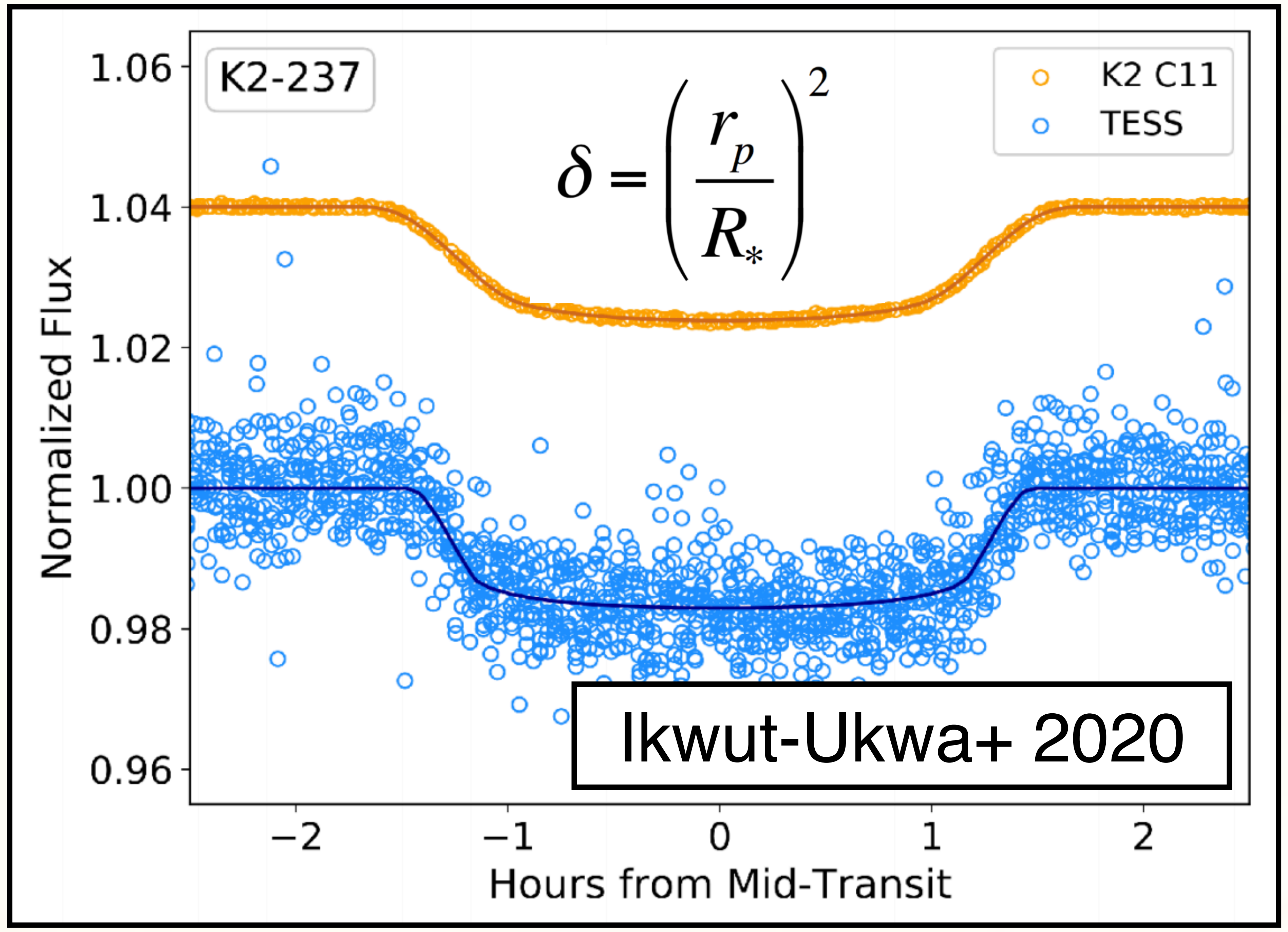
What brings us together at this conference?

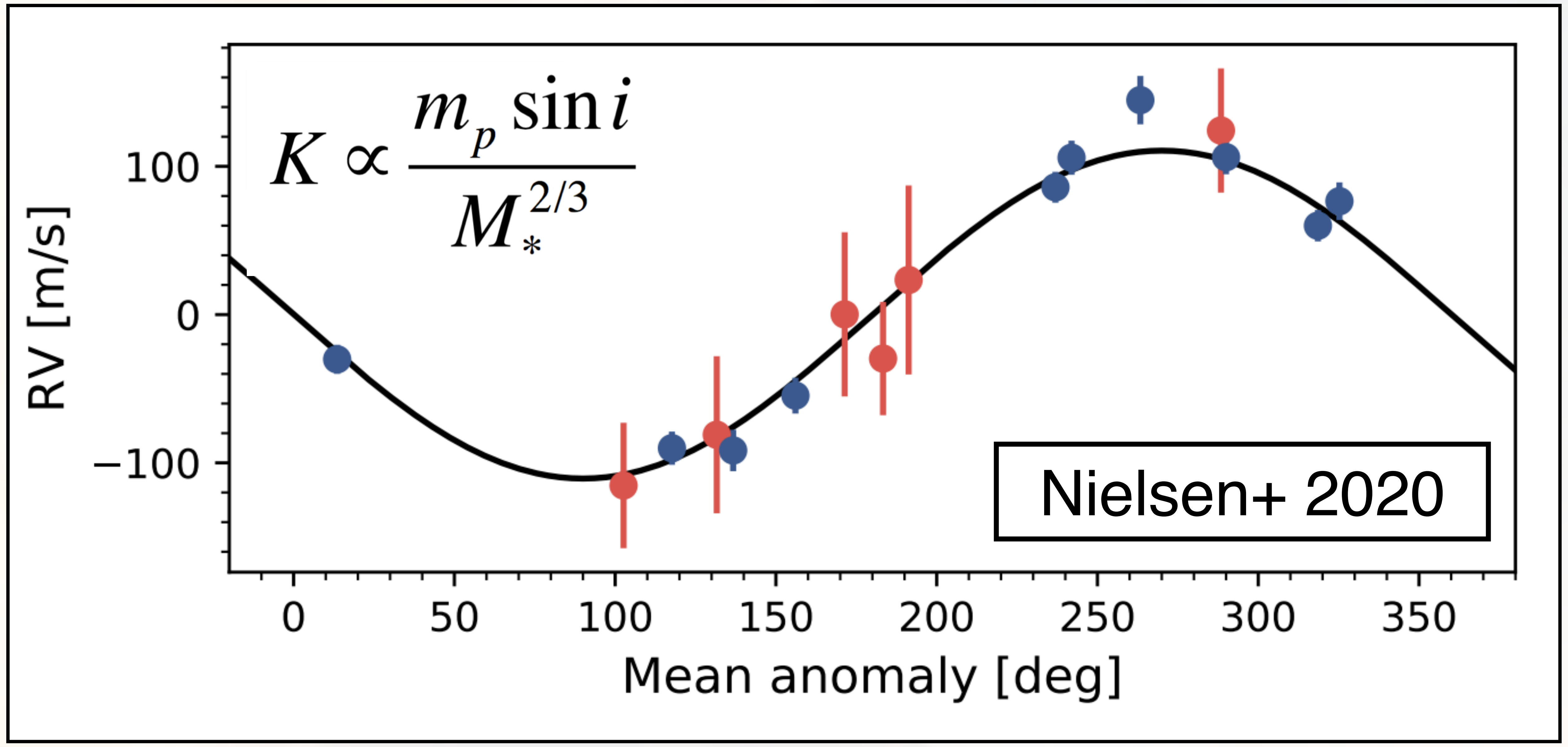


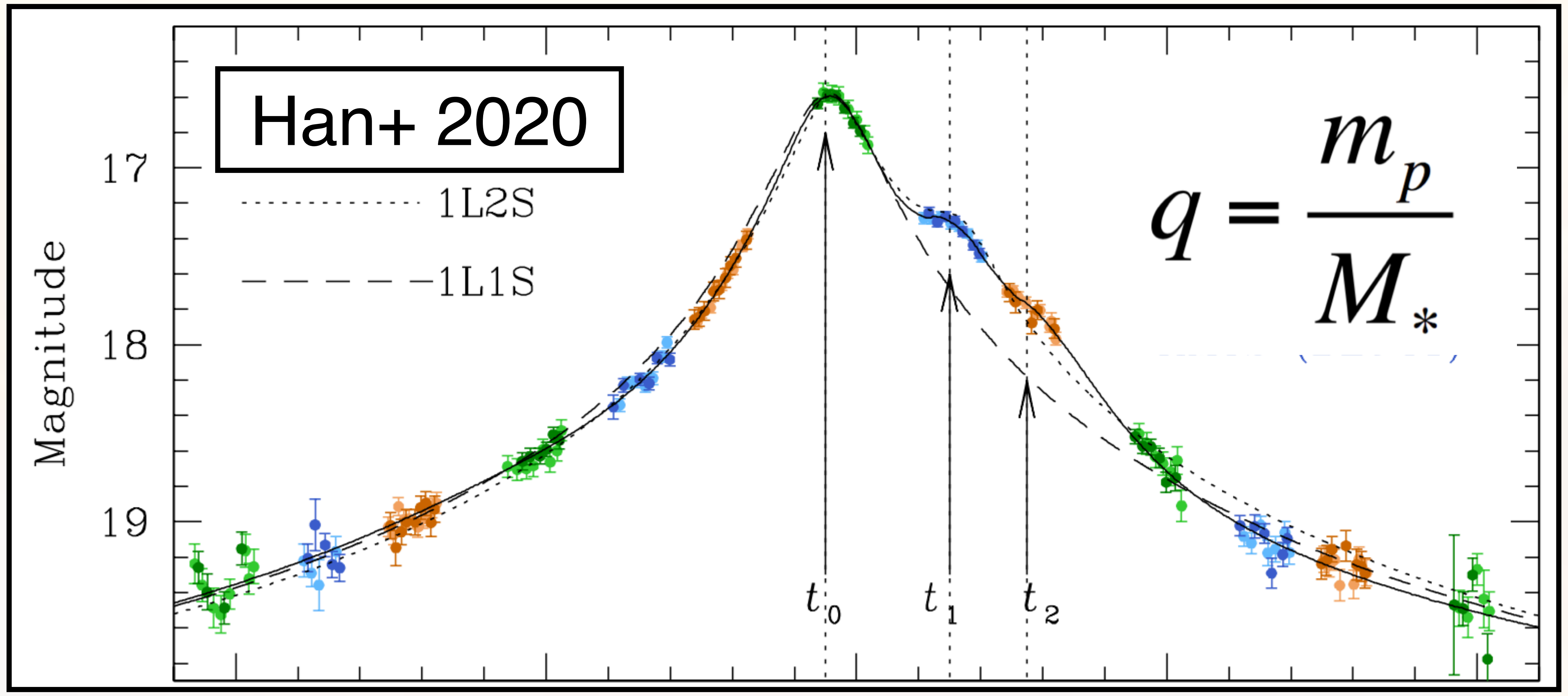
xkcd #2347: Munroe (2020)

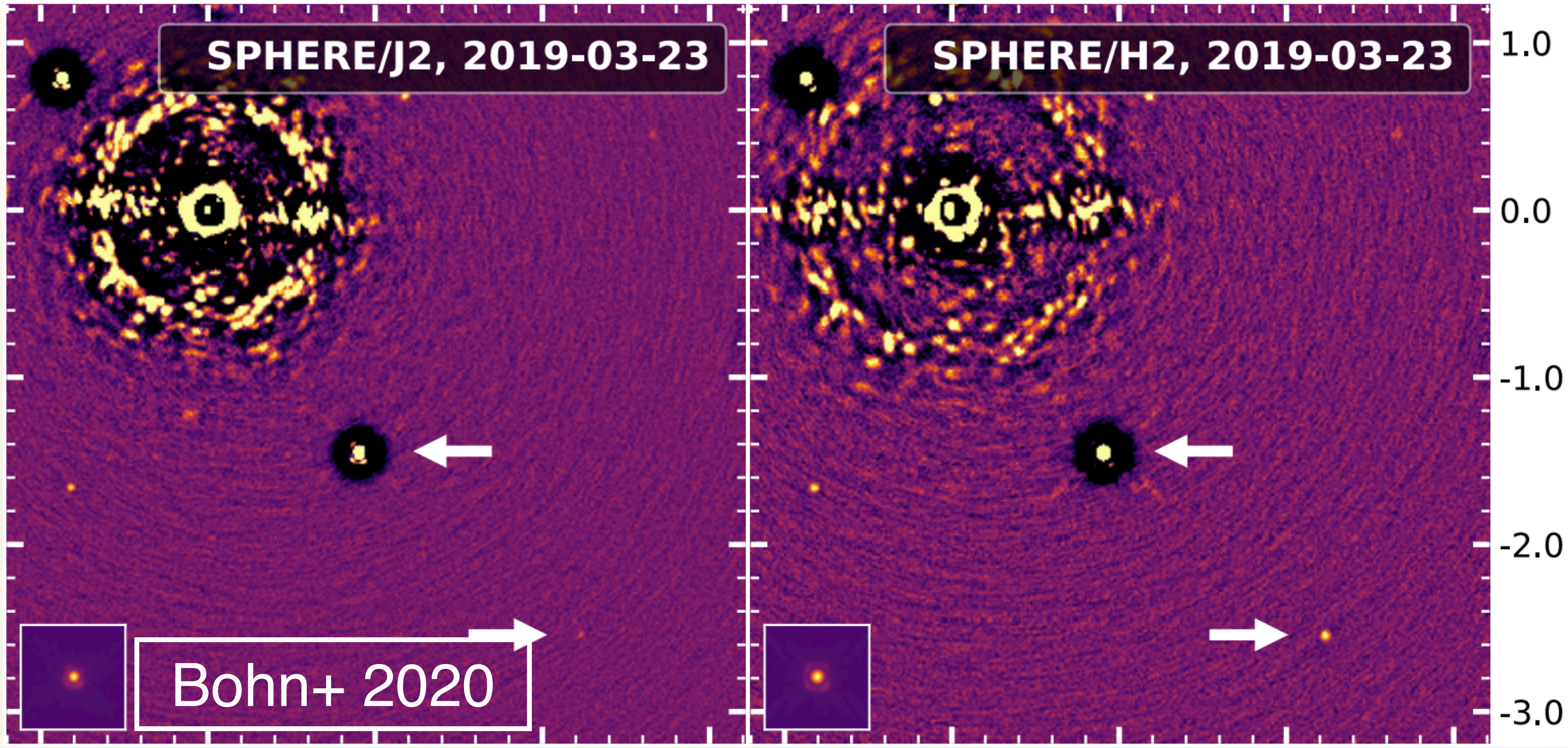
(inspiration by Joel Ong)

Know Thy Star, Know Thy Planet



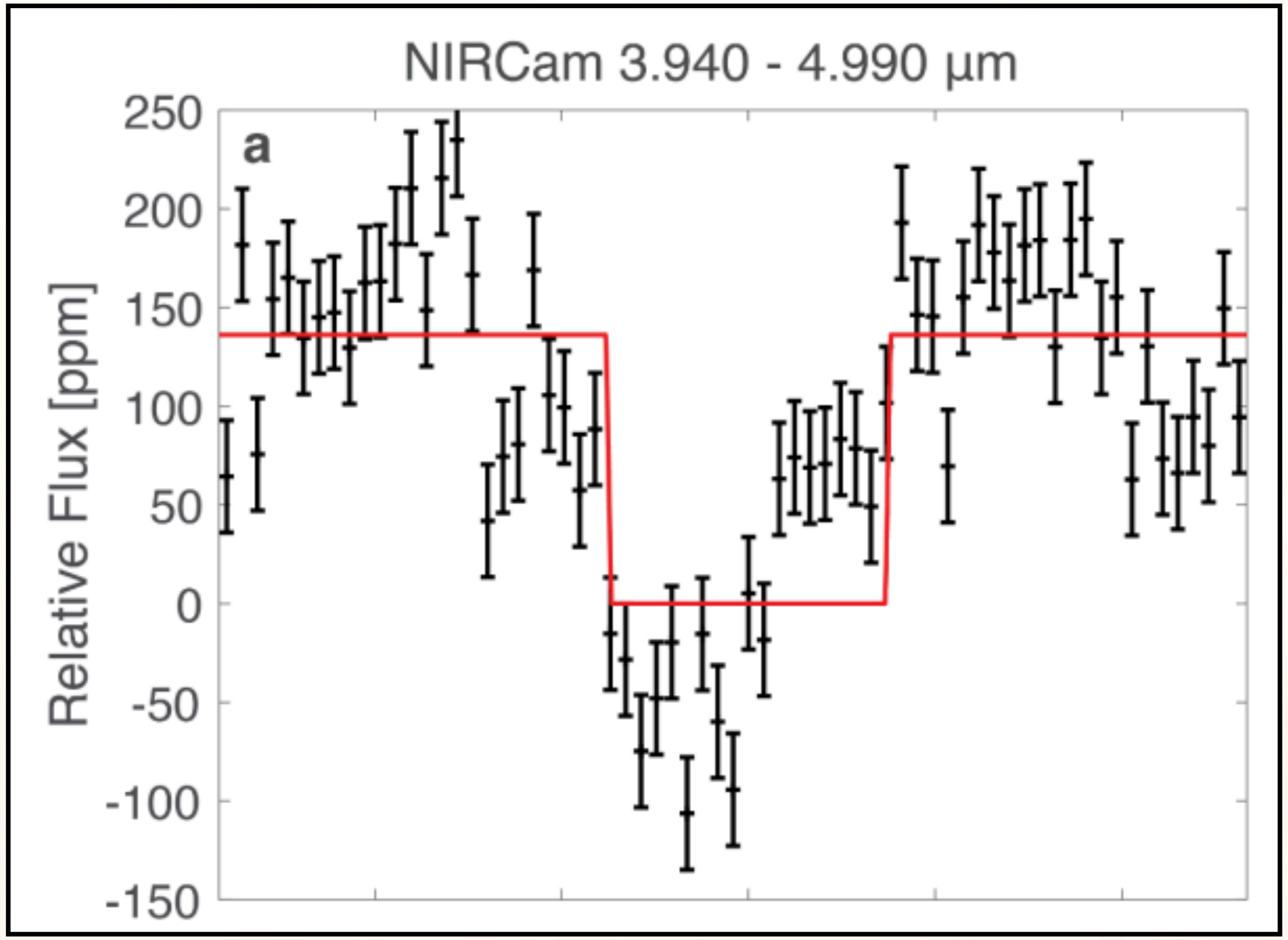






Know Thy Star, Know Thy "Noise"

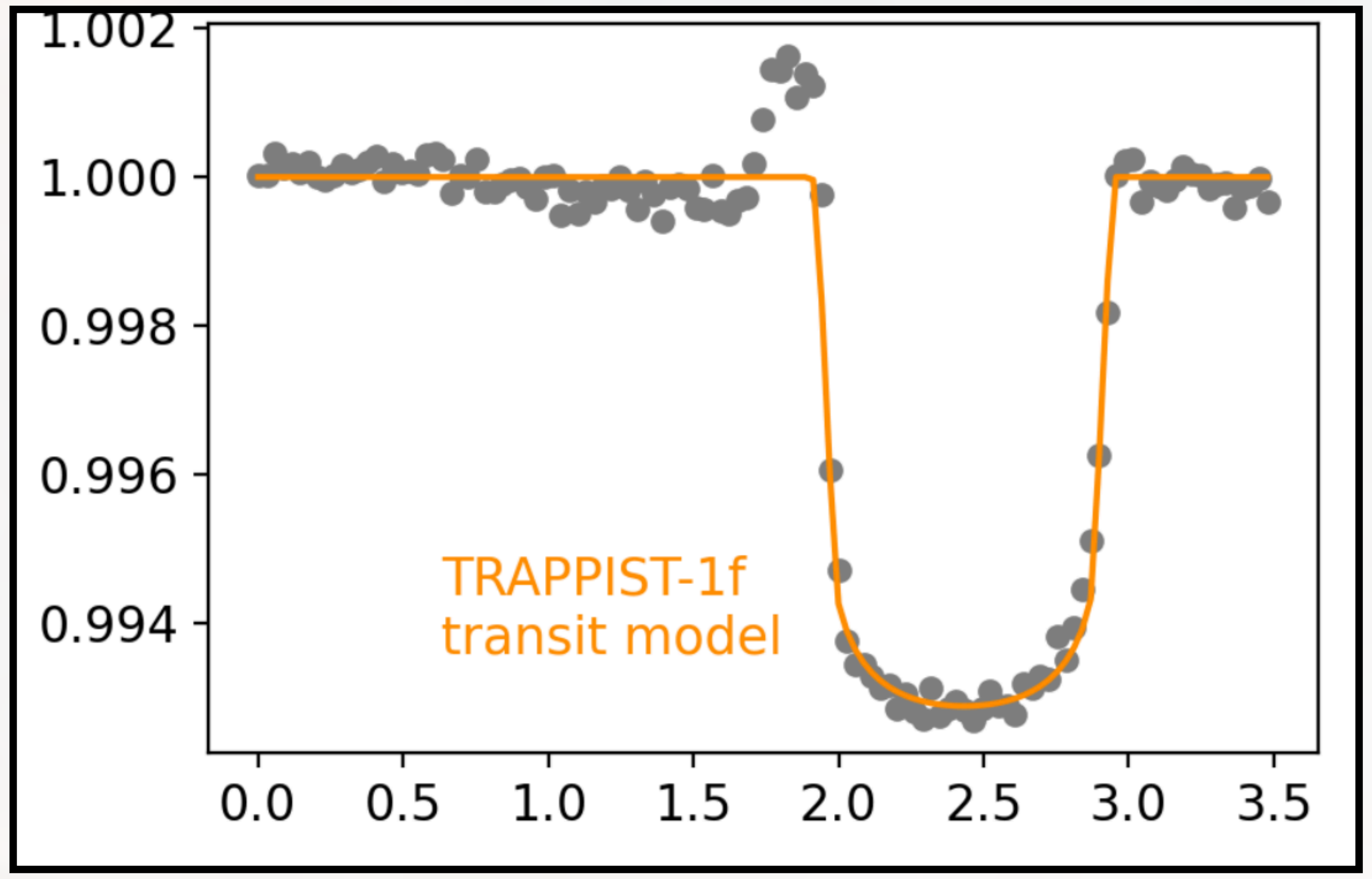
55 Cnc, JWST



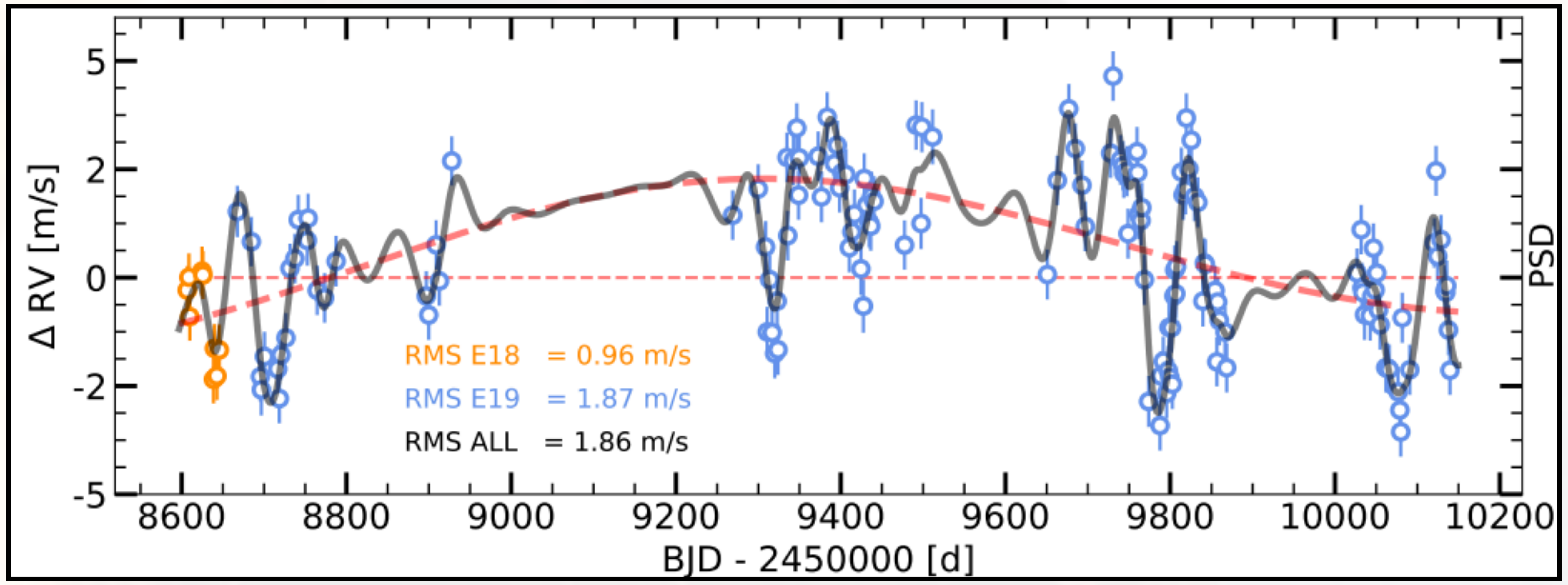
Hu+ 2024

Trappist-1, JWST

Howard+ 2023

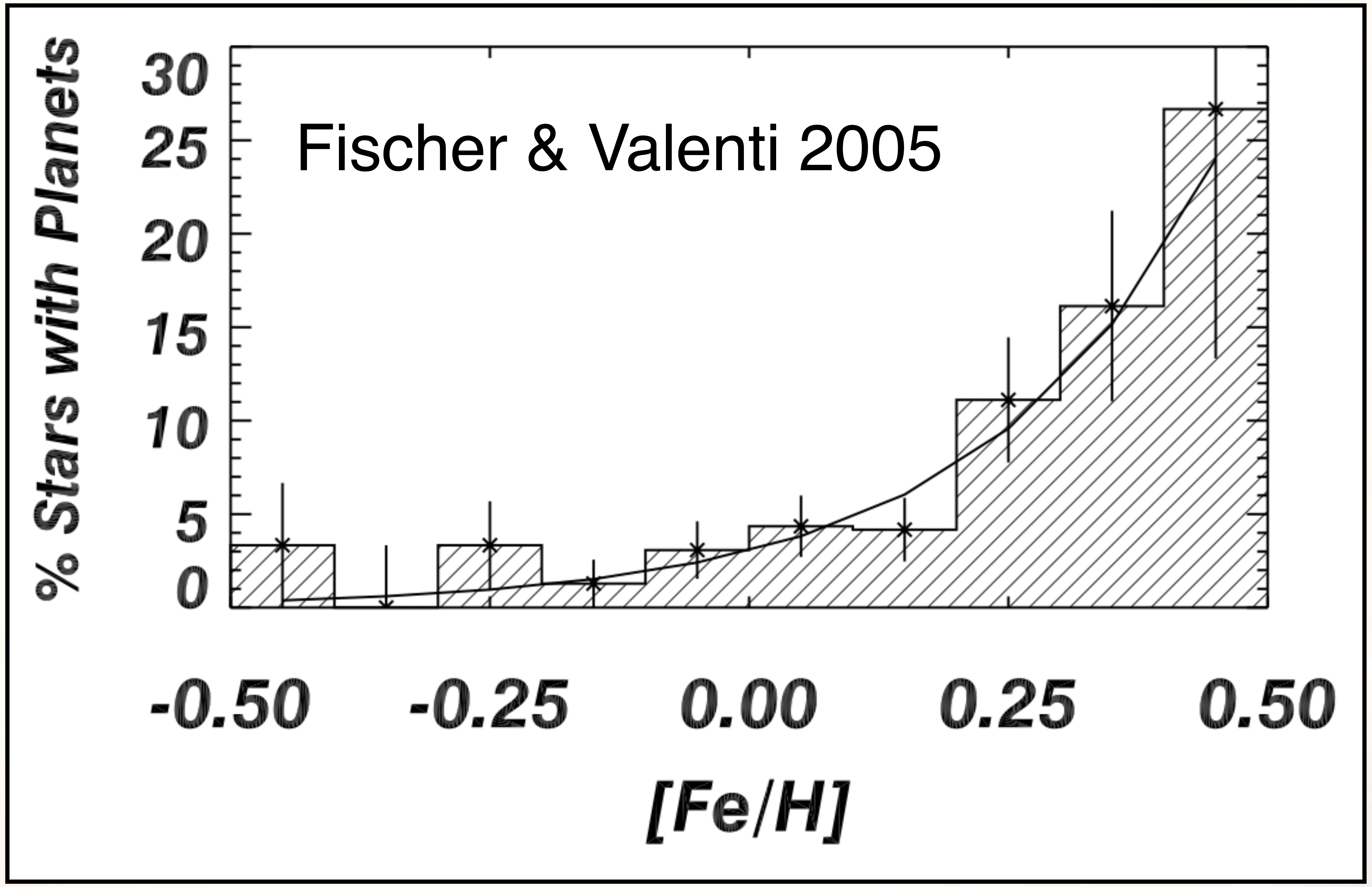


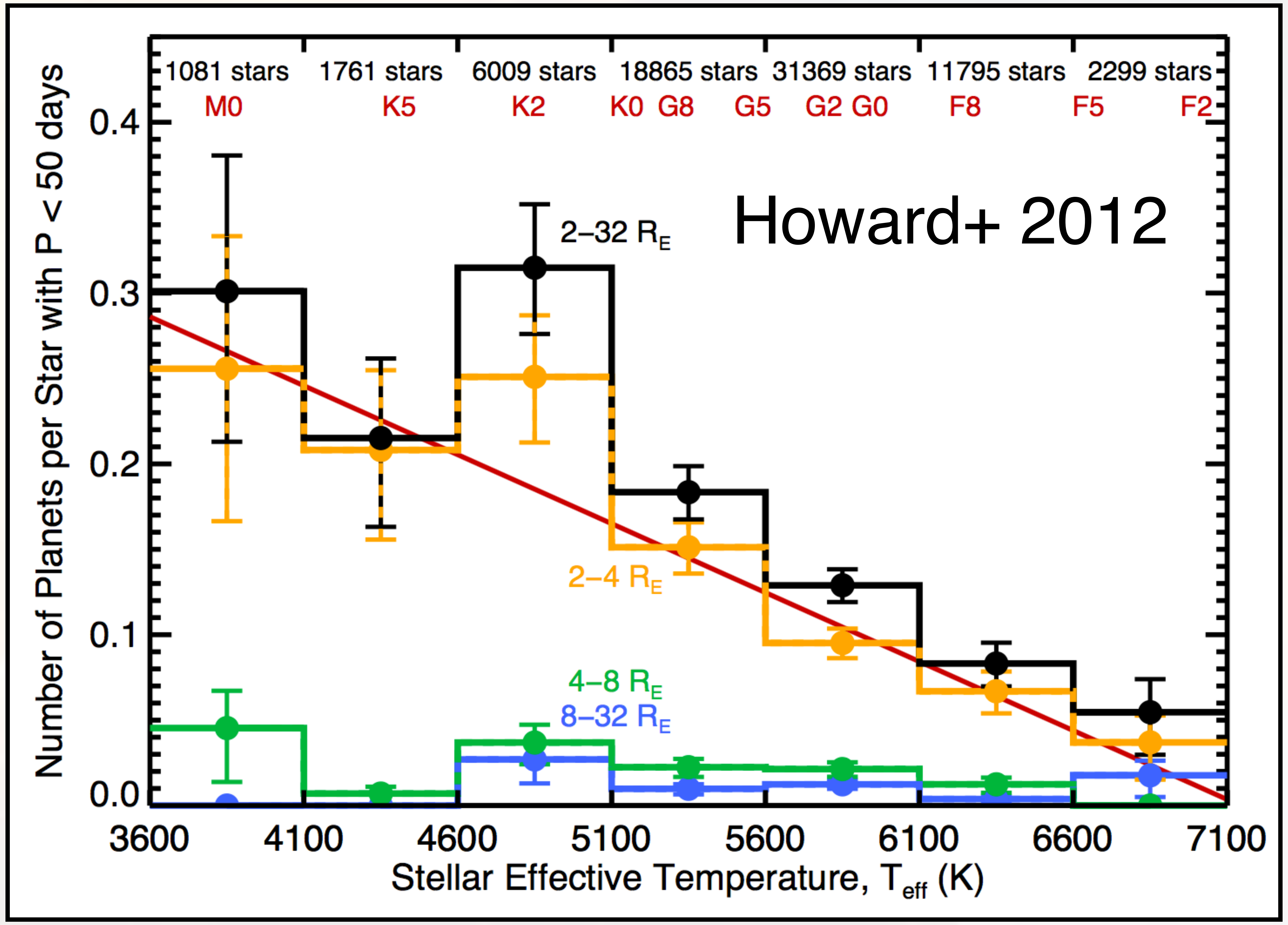
Barnard's Star, VLT/ESPRESSO



González Hernández+ 2024

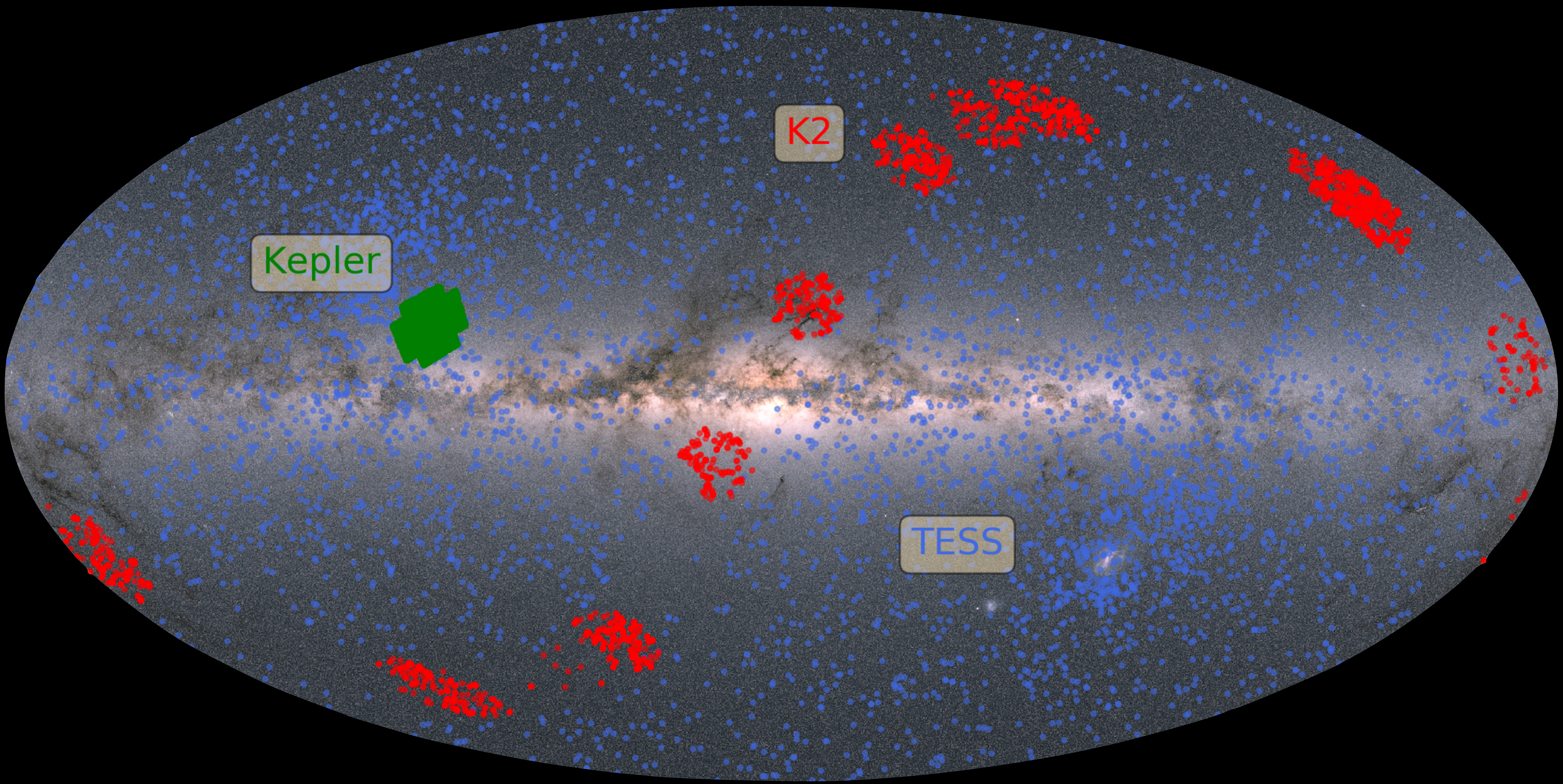
Know Thy Star, Know Thy Formation



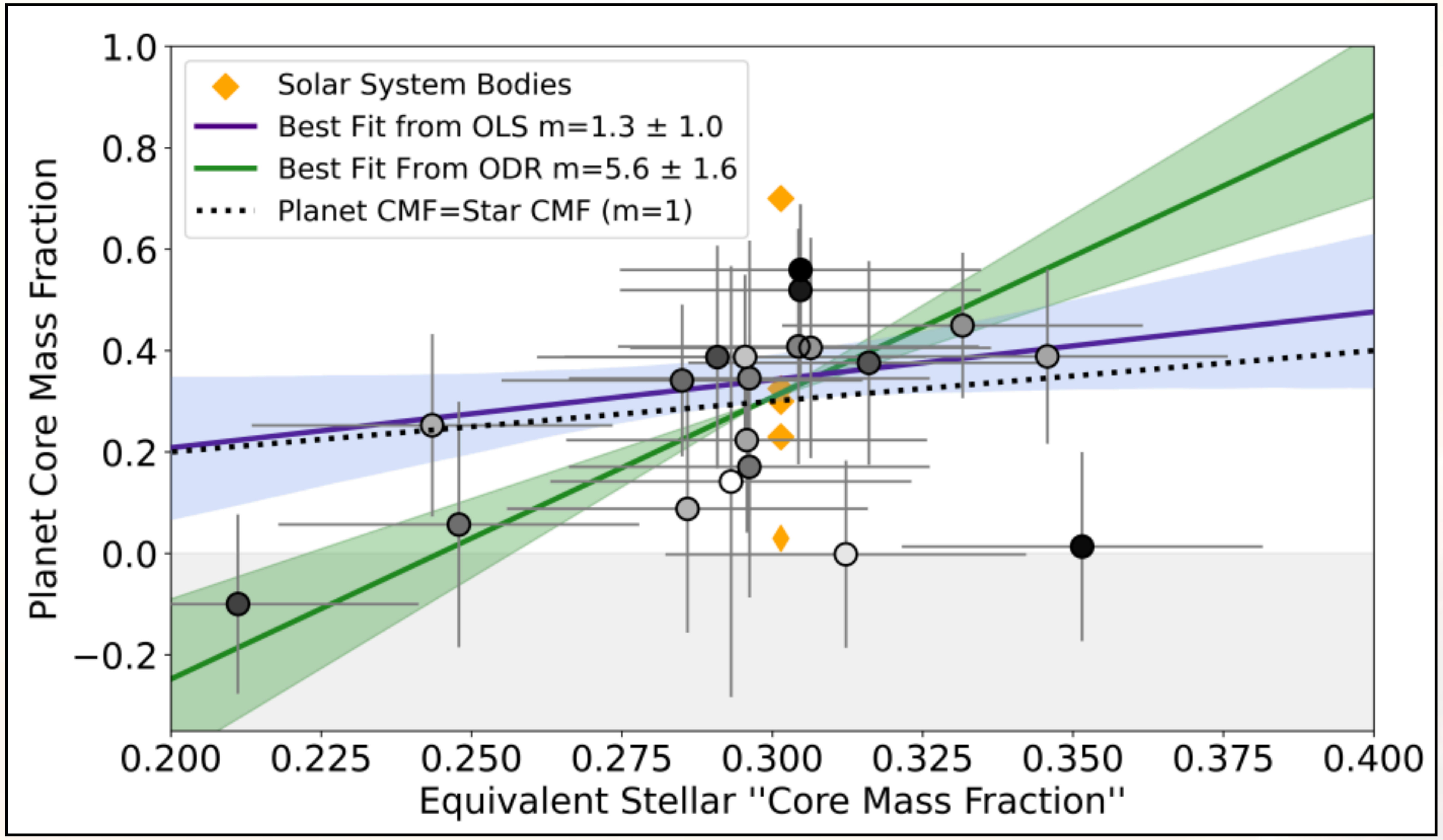


Strong observational links between host star properties (mass, age, metallicity, multiplicity, …) and planet occurrence

Exoplanets on a Galactic Scale

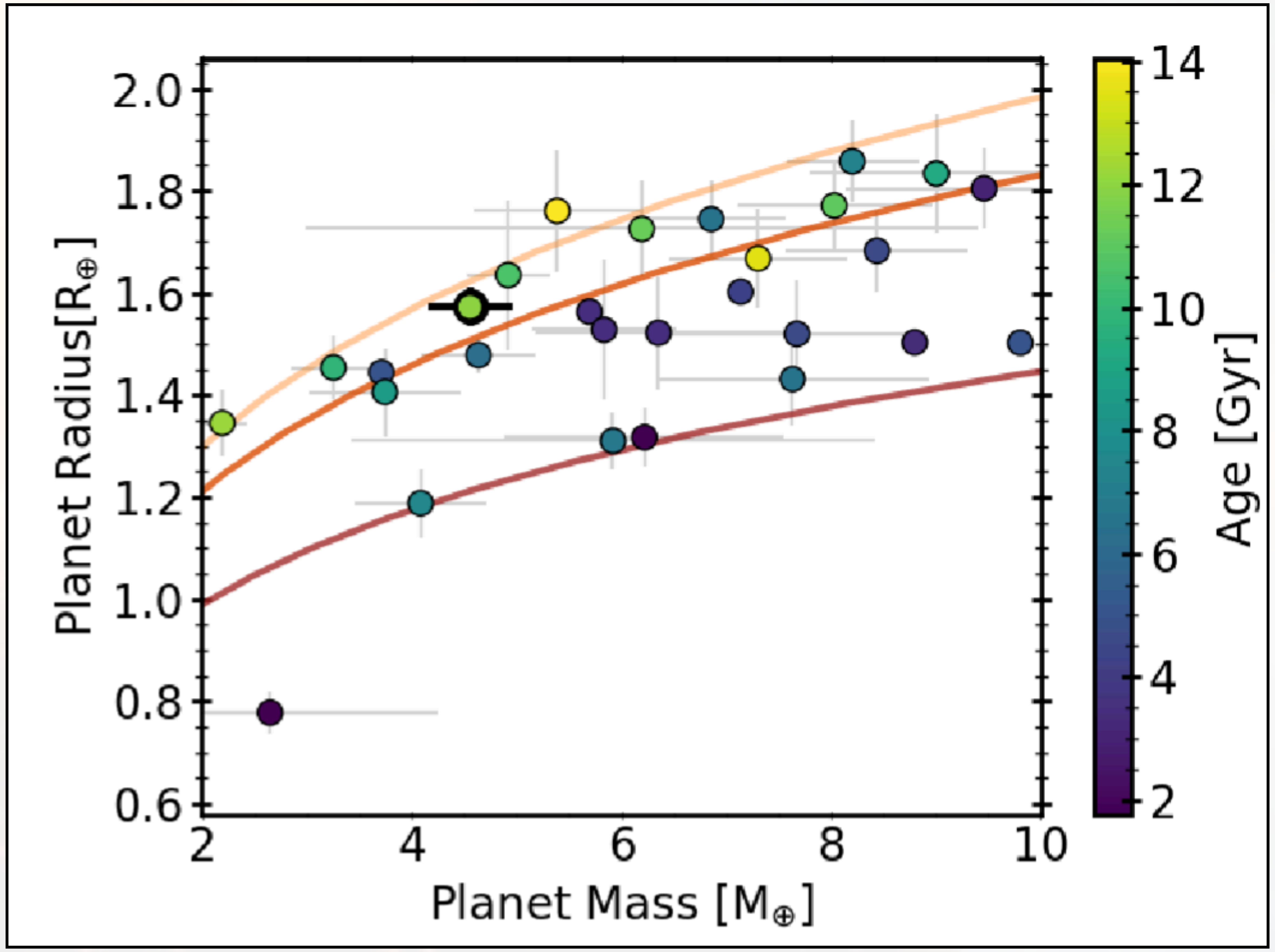


Weak link between rocky planet compositions and stellar abundances …



Brinkman+ 2024

… but a strong link between rocky planet compositions and stellar age?

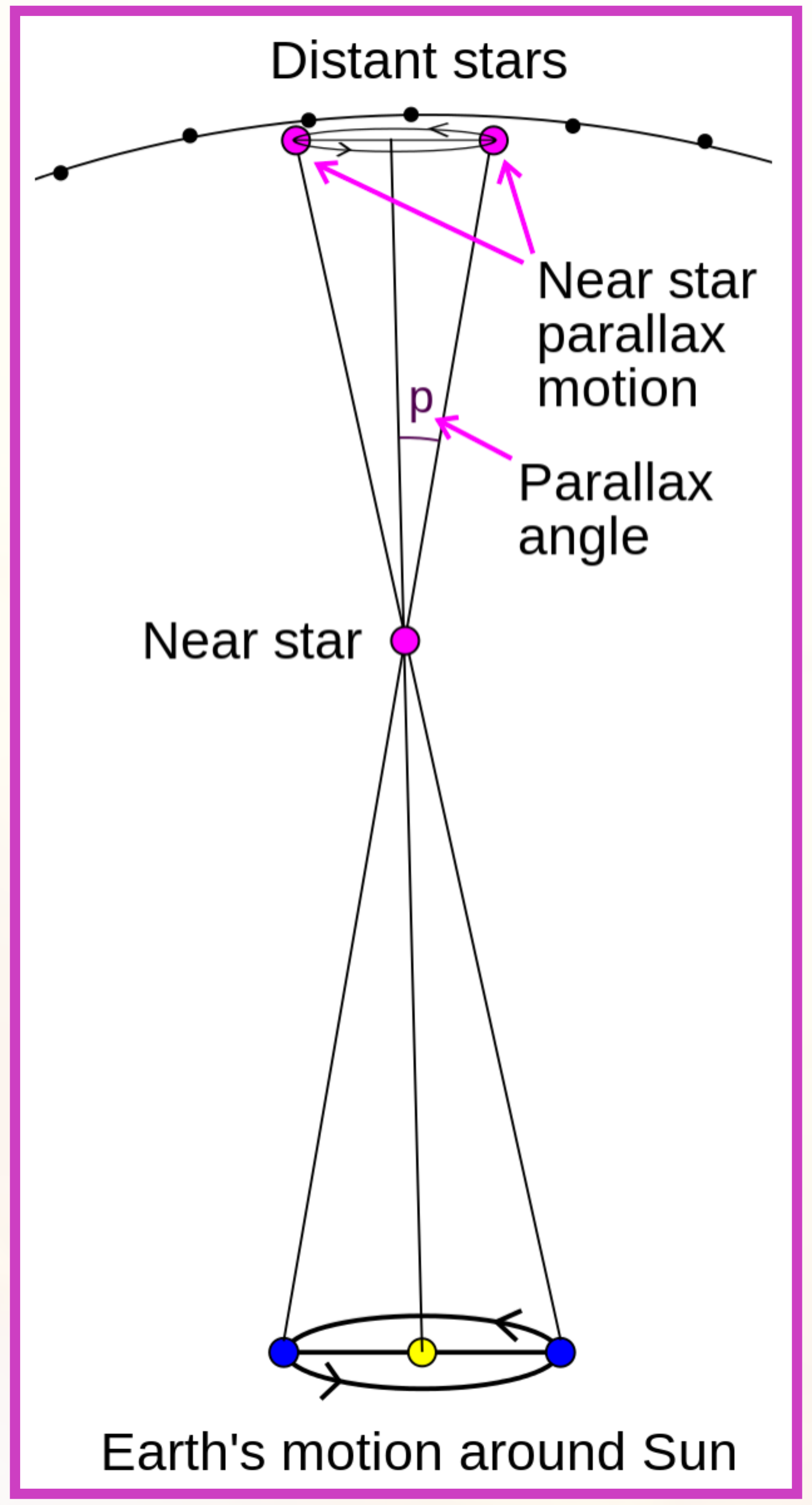


Weeks+ 2024, Weeks+ in prep

How do we measure Host Star Properties?

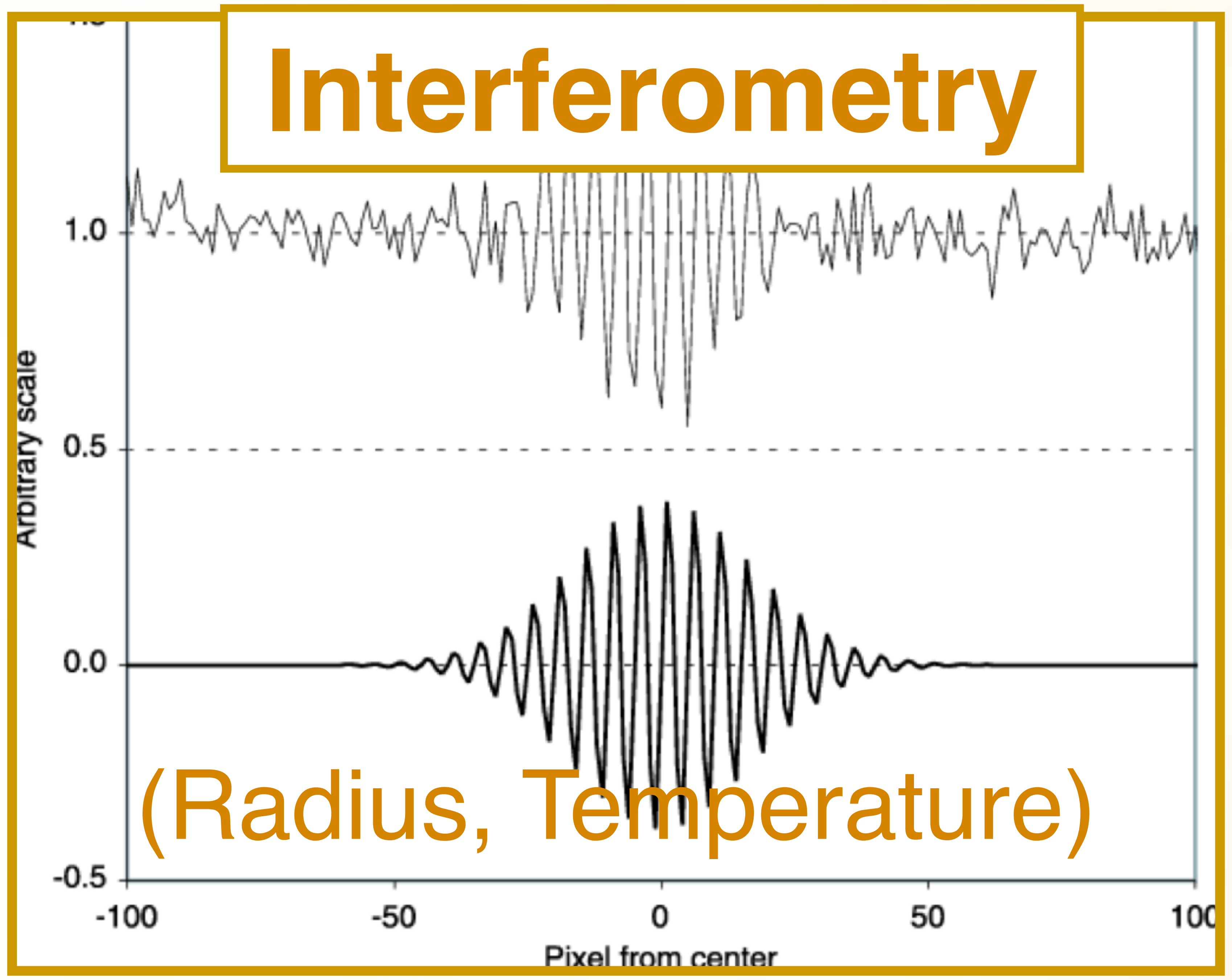
The Classics

Parallax



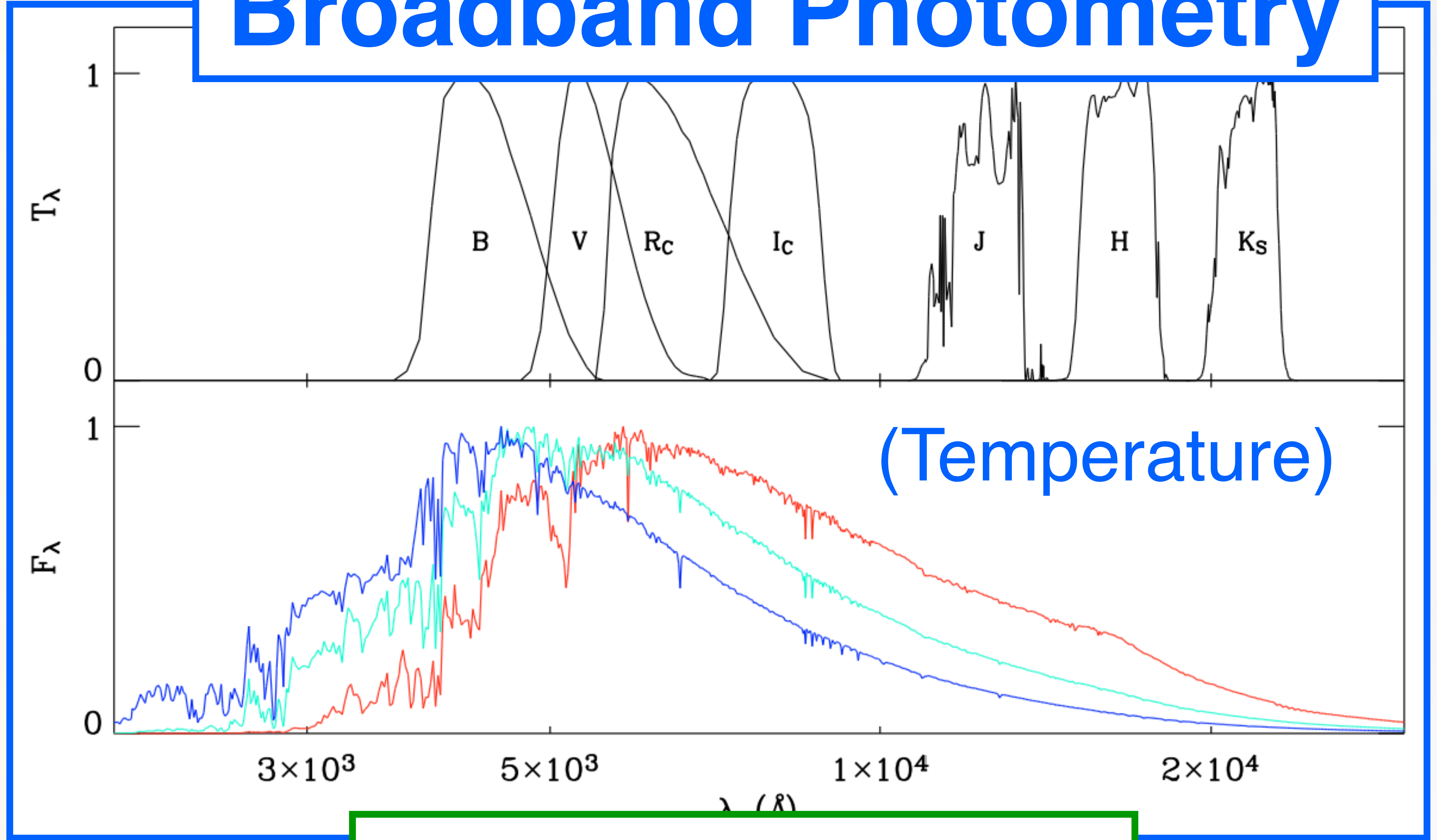
(Luminosity)

Interferometry



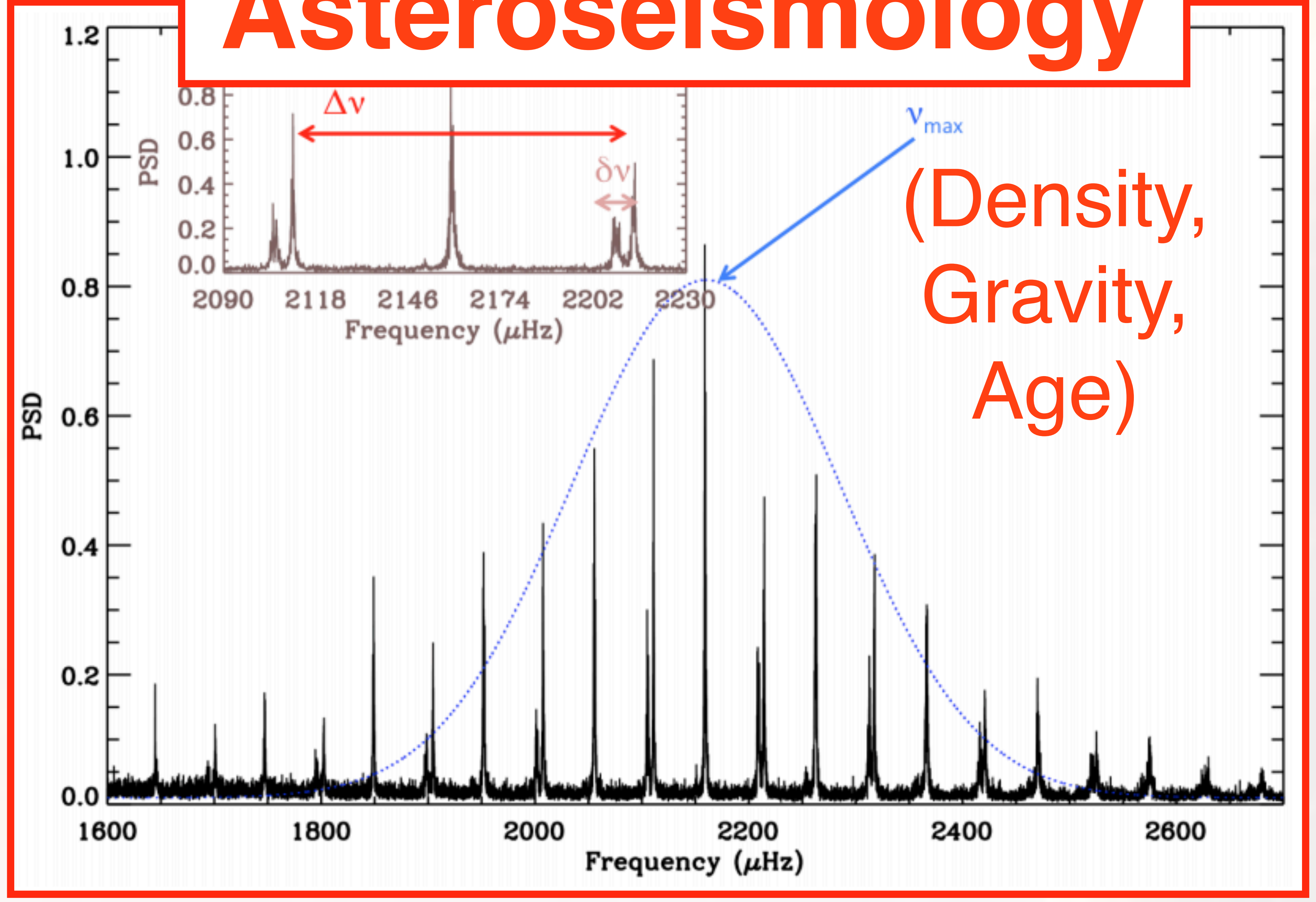
(Radius, Temperature)

Broadband Photometry



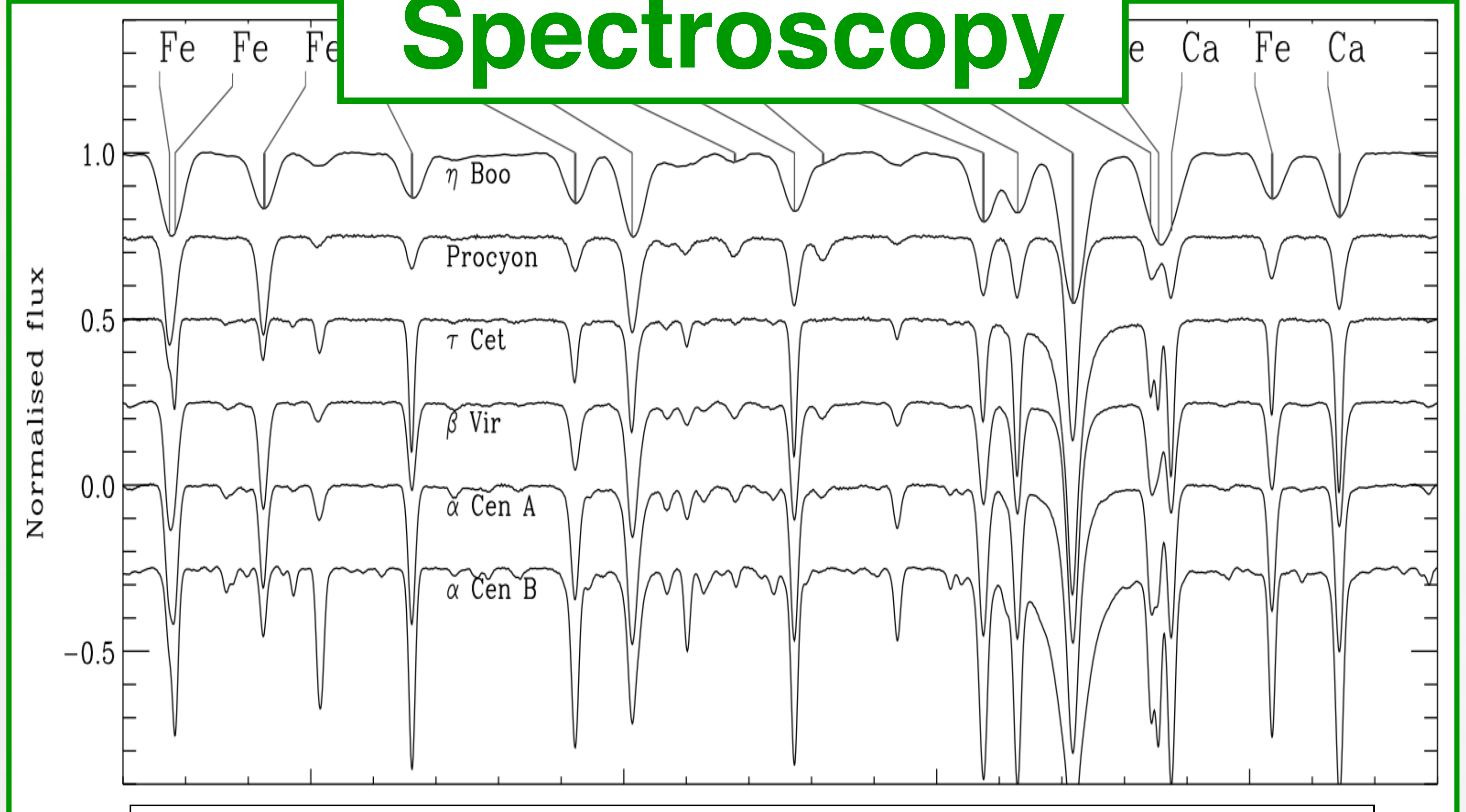
(Temperature)

Asteroseismology



(Density, Gravity, Age)

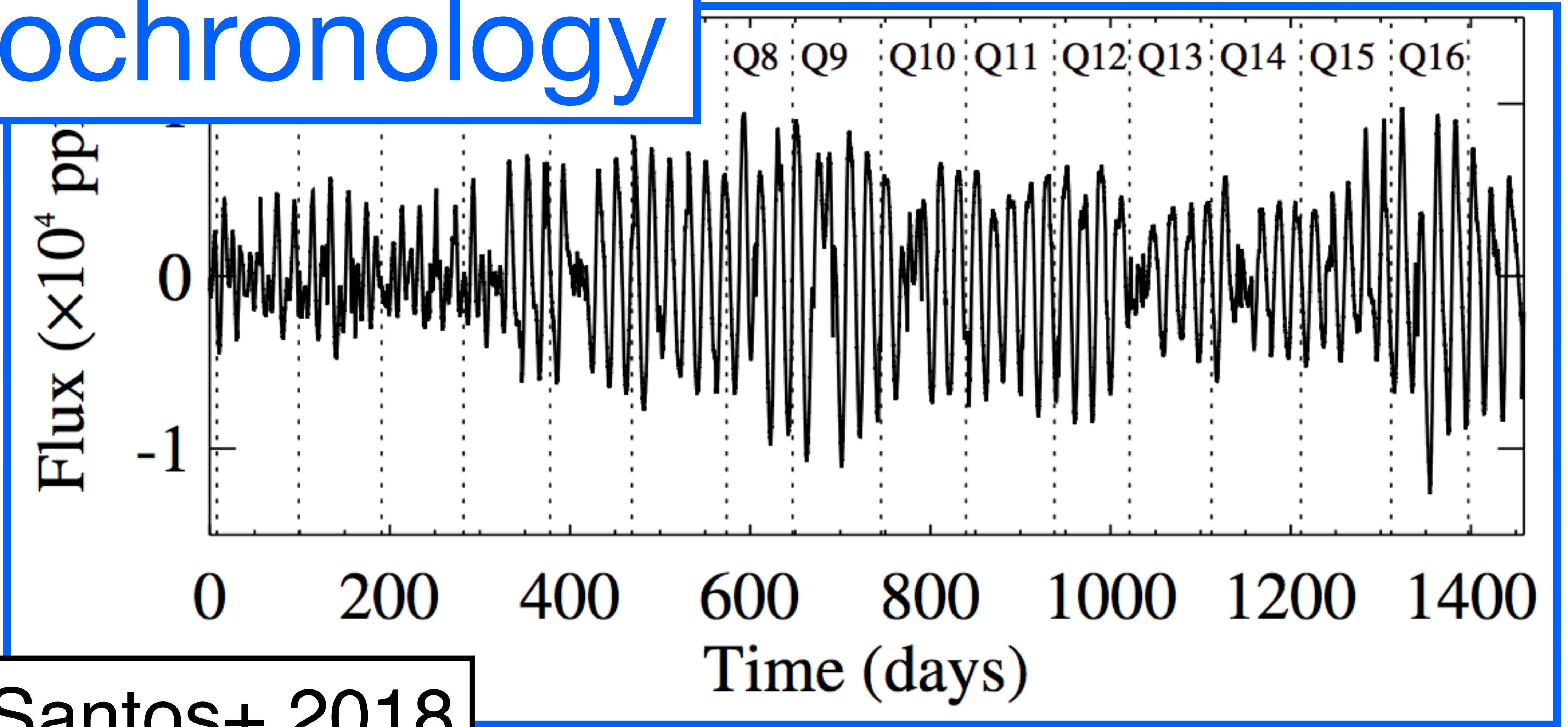
Spectroscopy



(Temperature, Gravity, Composition)

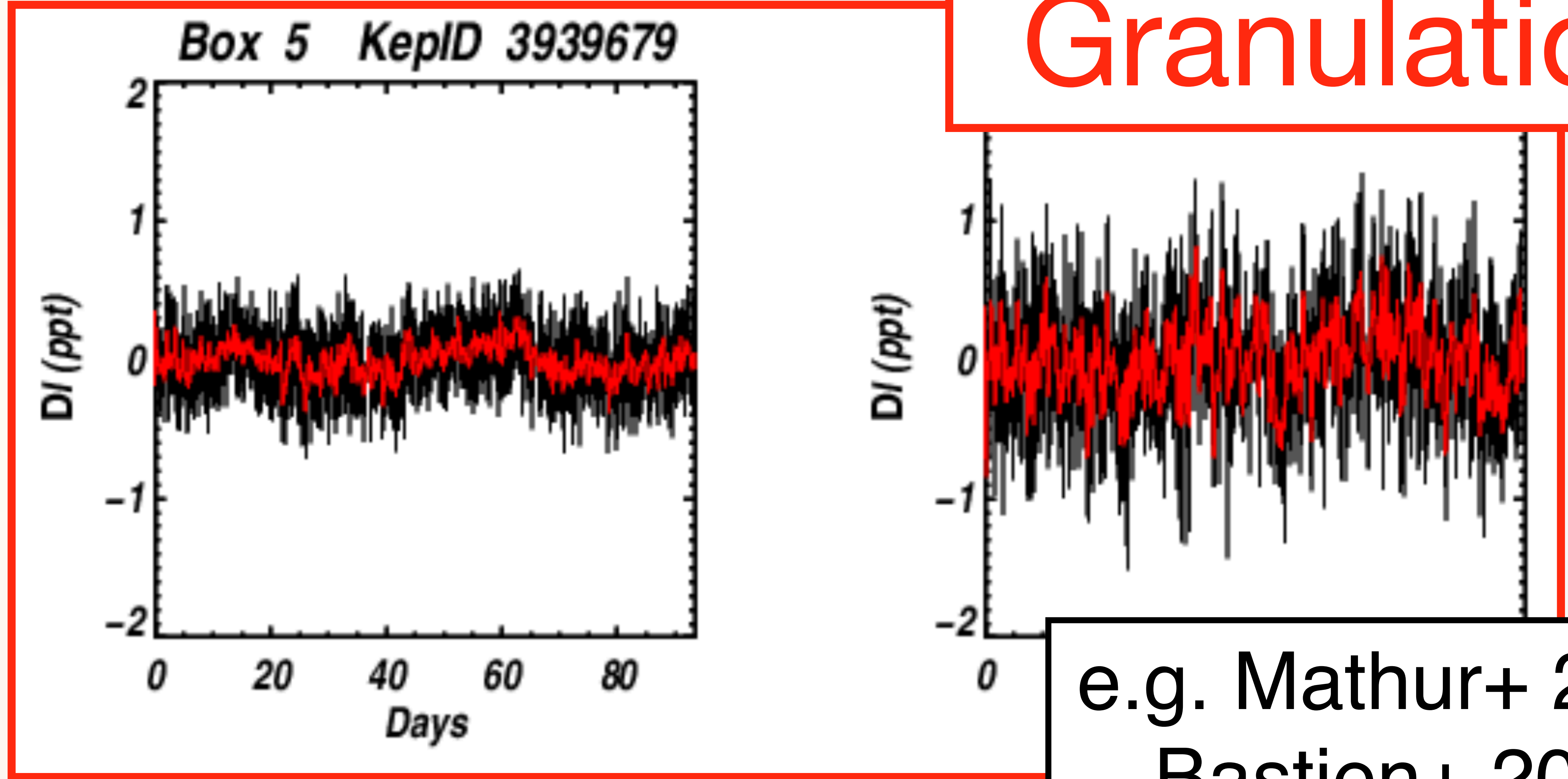
New Methods (more from Jamie later today!)

Gyrochronology



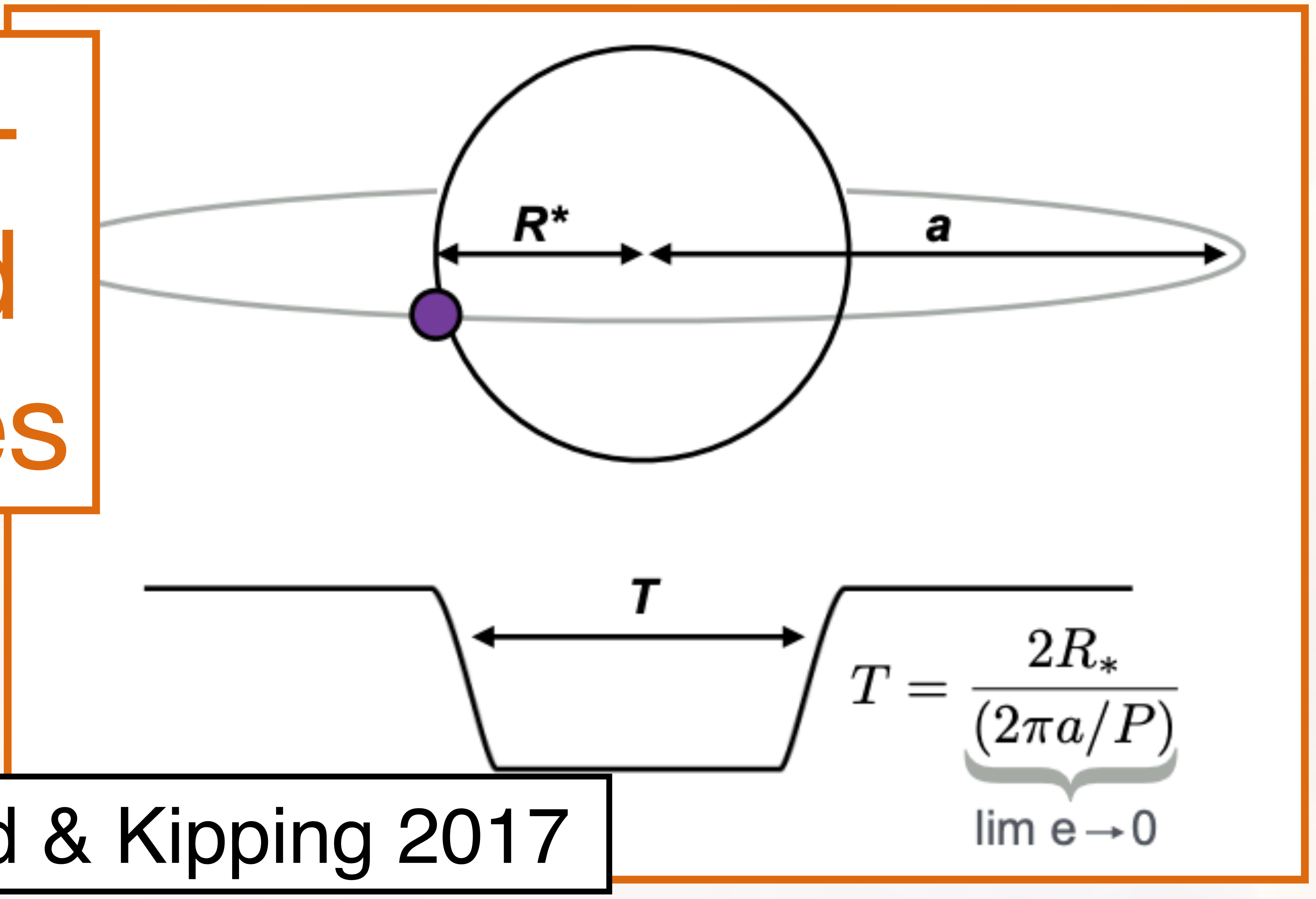
e.g. Santos+ 2018

Granulation

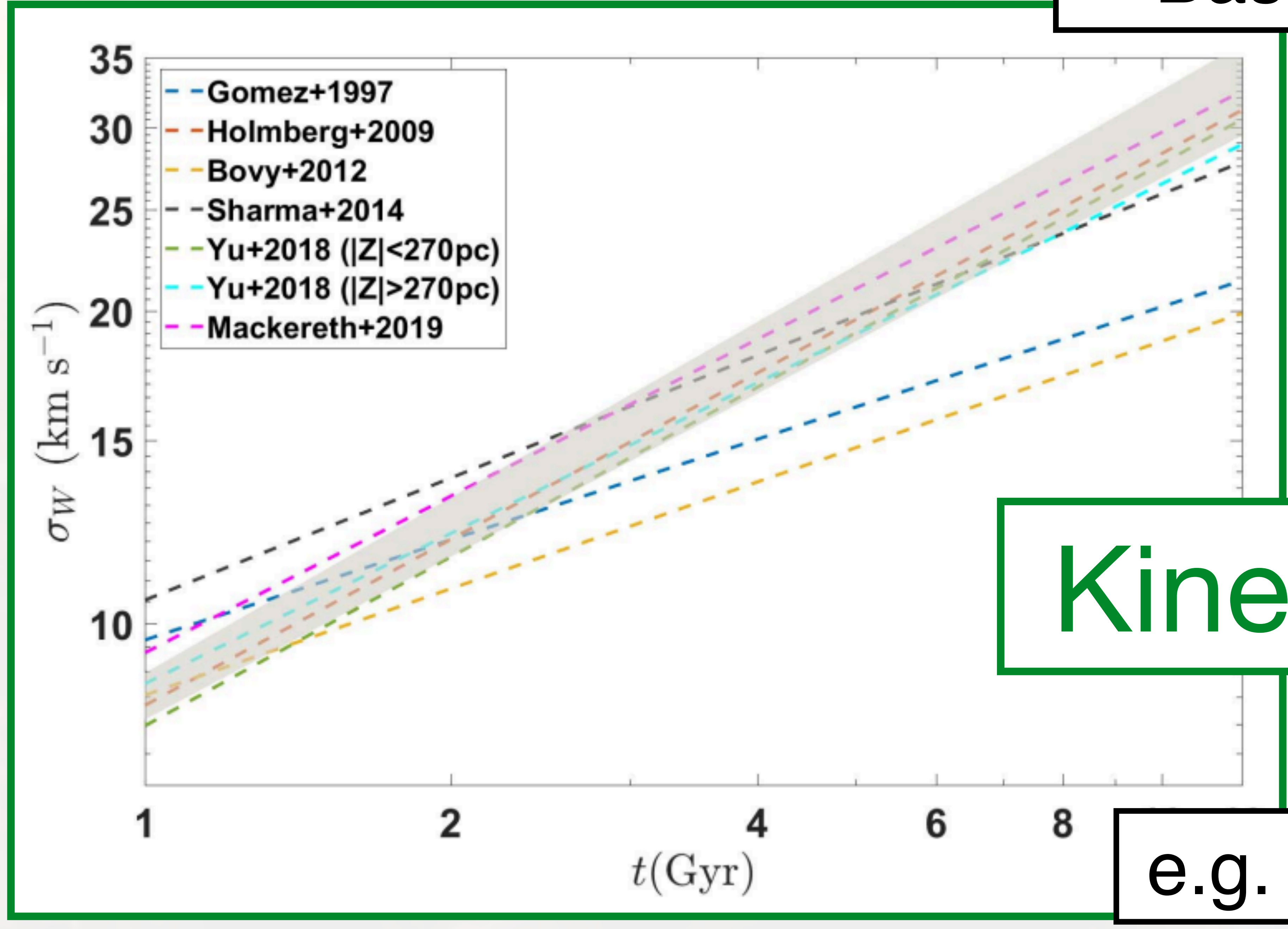


e.g. Mathur+ 2011, Bastien+ 2013

Transit-derived Densities



e.g. Sandford & Kipping 2017



Kinematics

e.g. Chen+ 2021

The Basics: Parallaxes & Fluxes

The Gaia Revolution

$$L = 4\pi f_{\rm bol}\, d^2$$

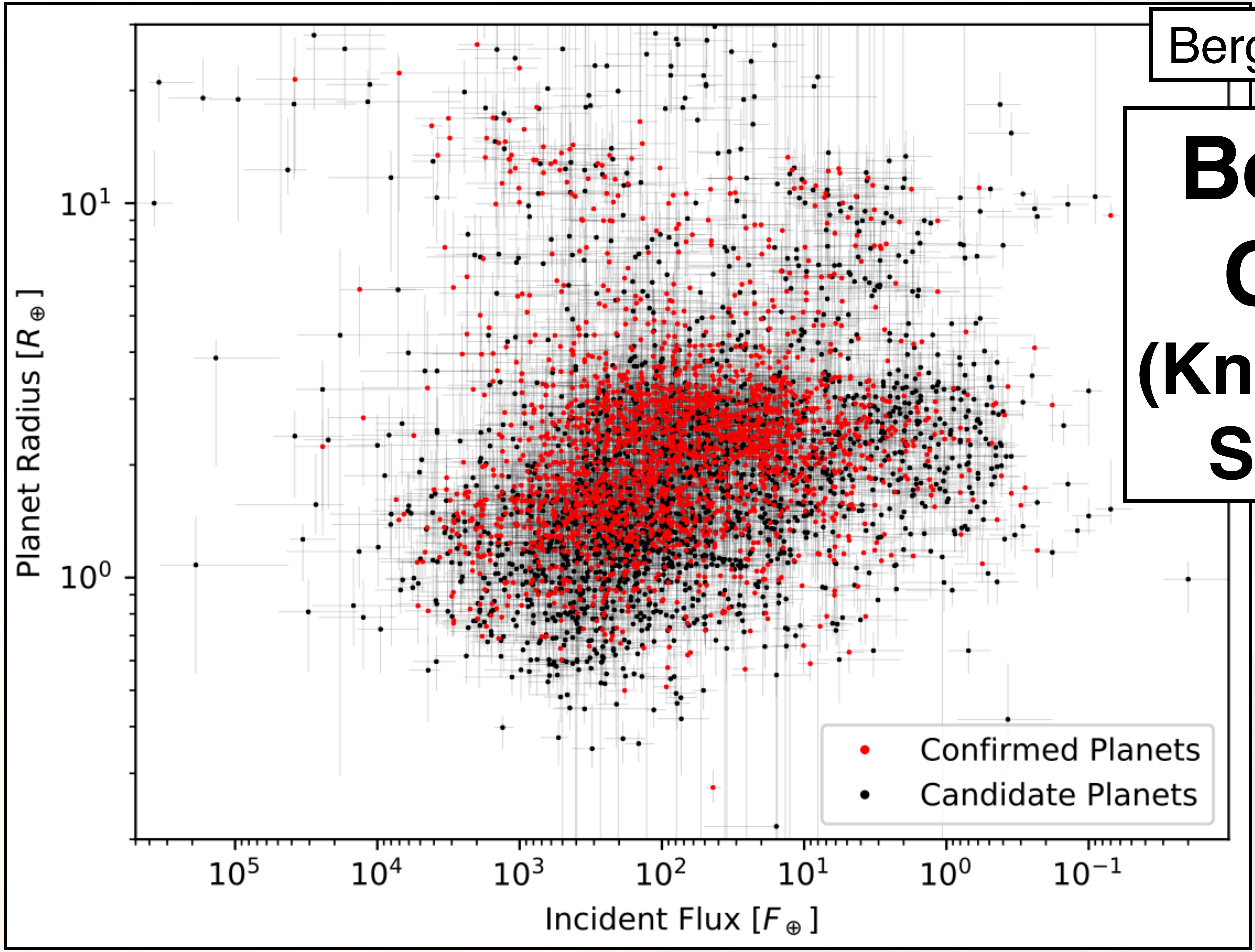
$$R = \sqrt{\frac{f_{\rm bol}\, d^2}{\sigma T_{\rm eff}^4}}$$

Observables

Distances to most planet hosts of interest are now known to <~ 1%

Large

Small

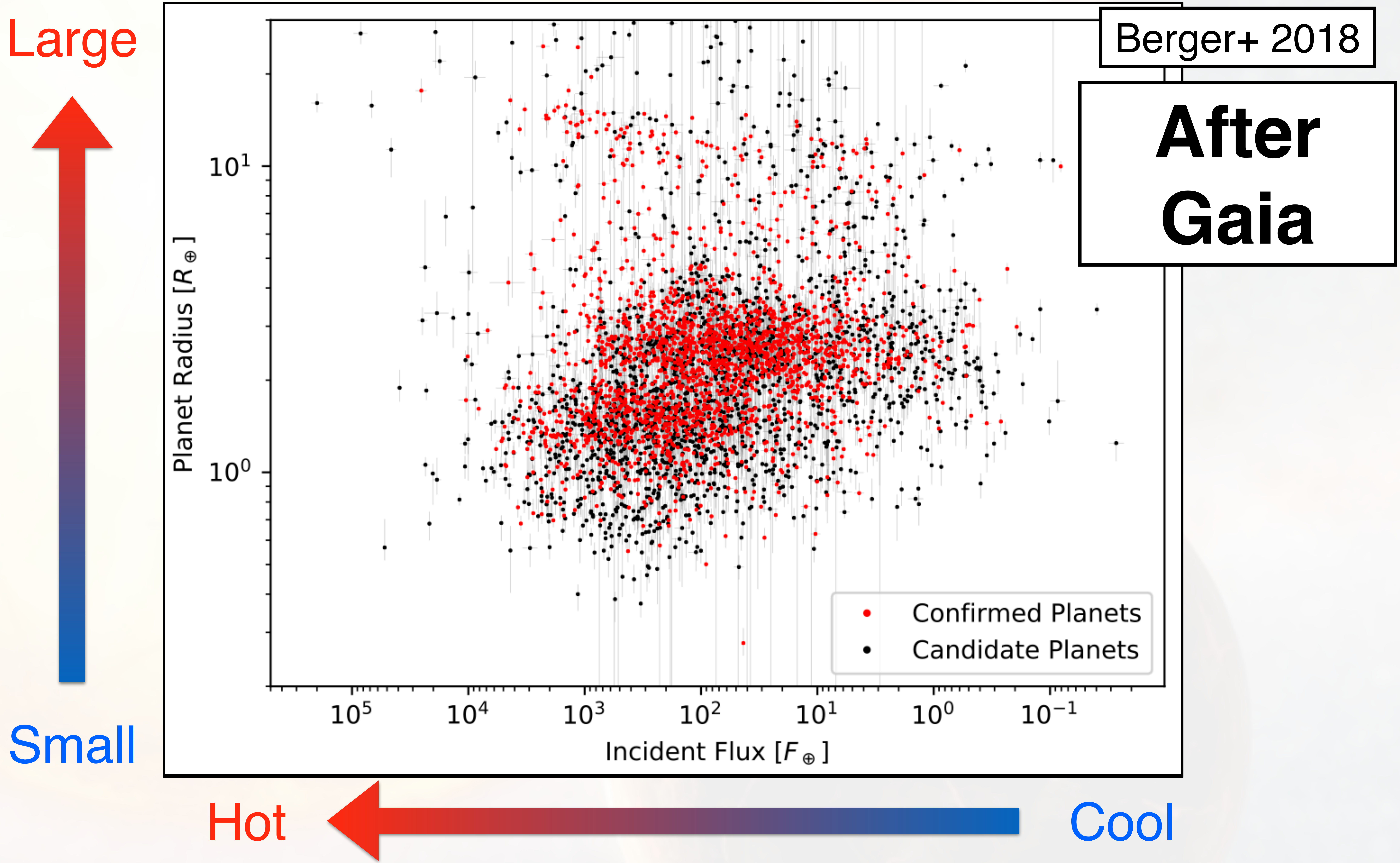


Berger+ 2018

Before Gaia (Know Thy Star 1)

Hot

Cool



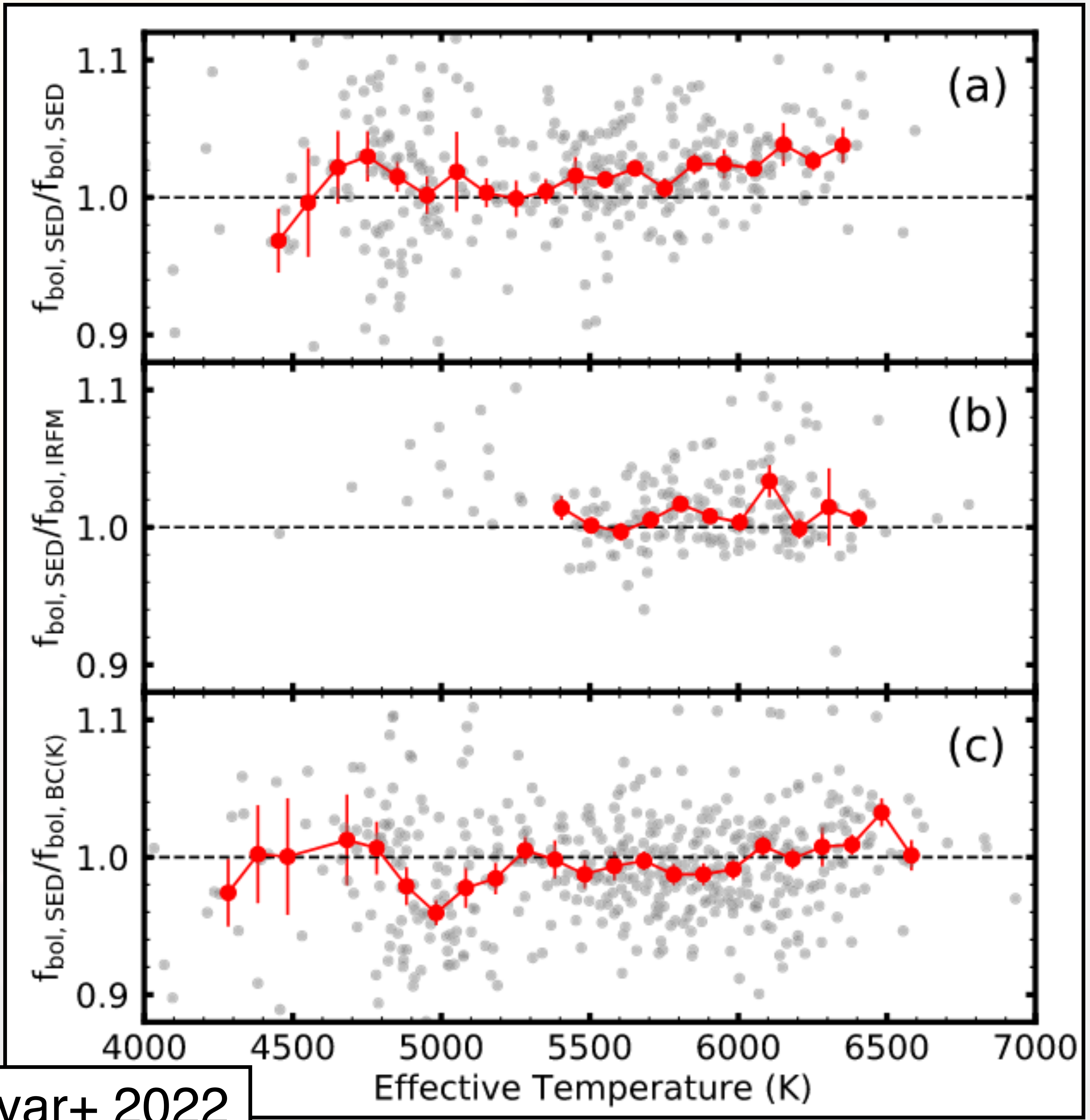
Large
Small
Hot
Cool
Berger+ 2018
After Gaia
Planet Radius [$R_\oplus$]
Incident Flux [$F_\oplus$]
10^1
10^0
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
Confirmed Planets
Candidate Planets

The bolometric flux bottleneck

$$L = 4\pi f_{\mathrm{bol}}\, d^2$$

Different methods (SED fitting, bolometric corrections) show systematics at the ~2% level

Does not include biases from unresolved binaries!



Tayar+ 2022

Accurate absolute flux measurements have become a bottleneck for capitalizing on Gaia distances for exoplanet host star characterization

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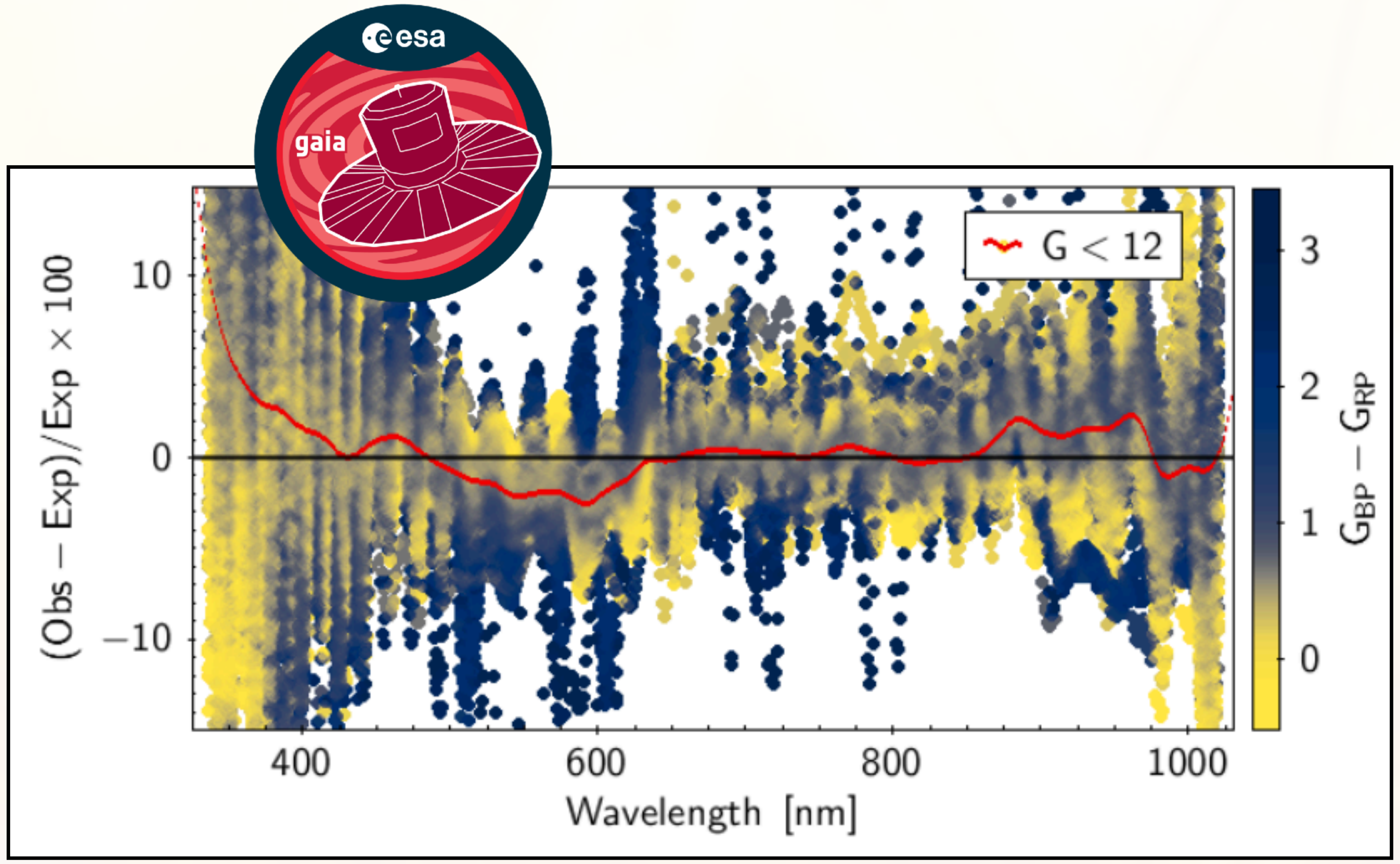


Montegriffo+ 2022

PI Bock (Caltech)
Planned launch this year!

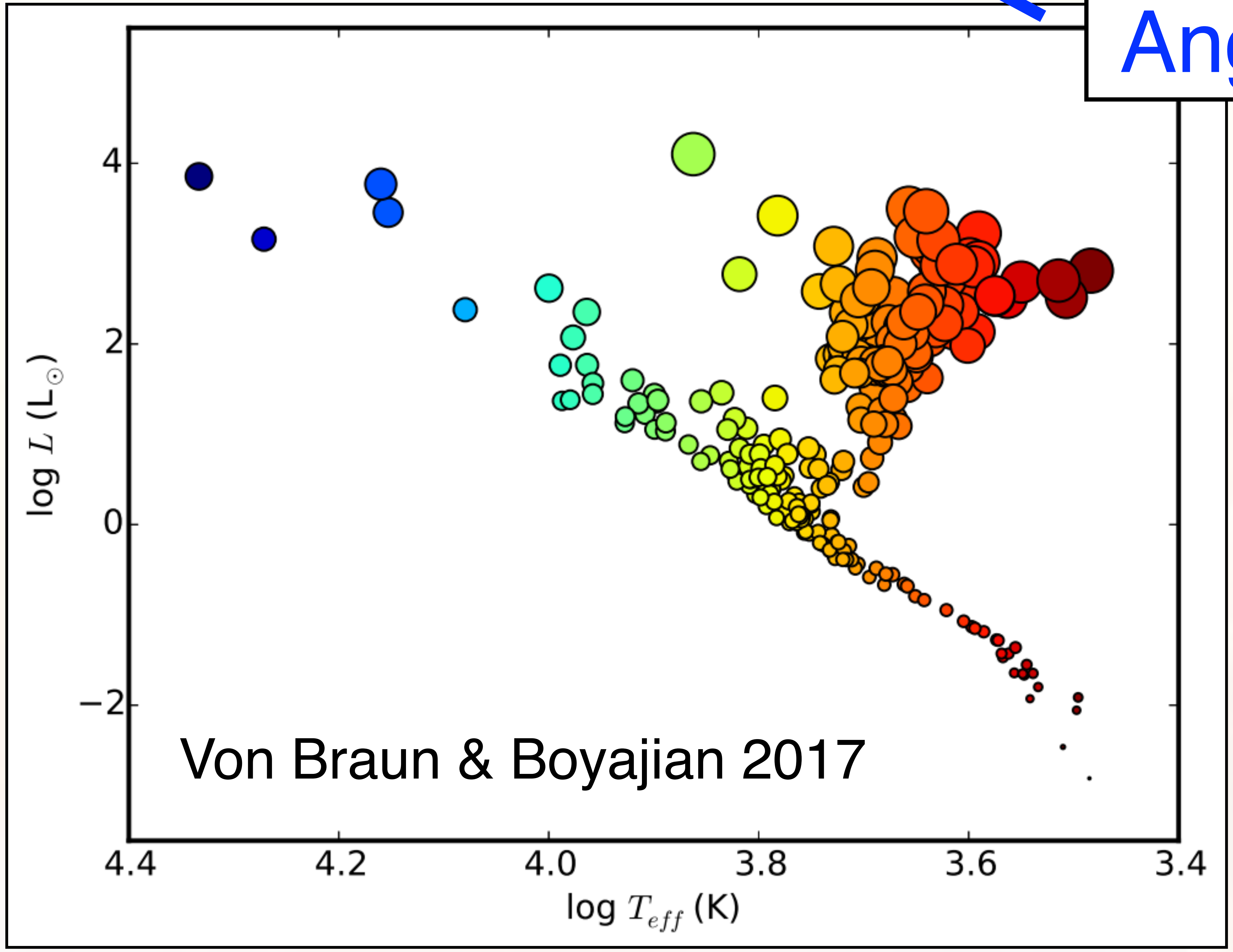
PI Plavchan (GMU)
Launch ~2029

The Truth™: Interferometry & Binaries

Optical Long-Baseline Interferometry

$$R = d\,\theta/2 \qquad T_{\rm eff} = (4 f_{\rm bol} / \sigma \theta^2)^{1/4}$$

Angular Diameter



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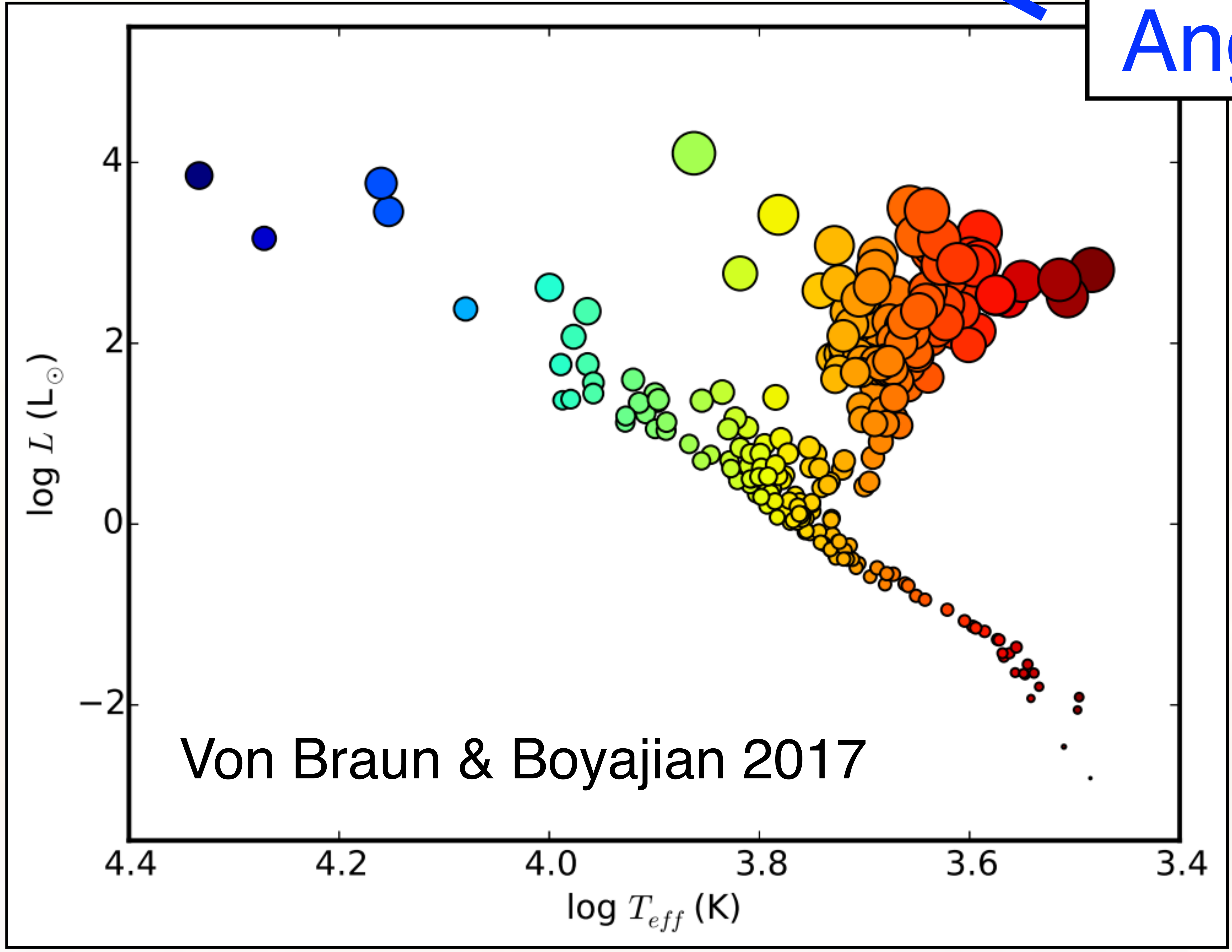
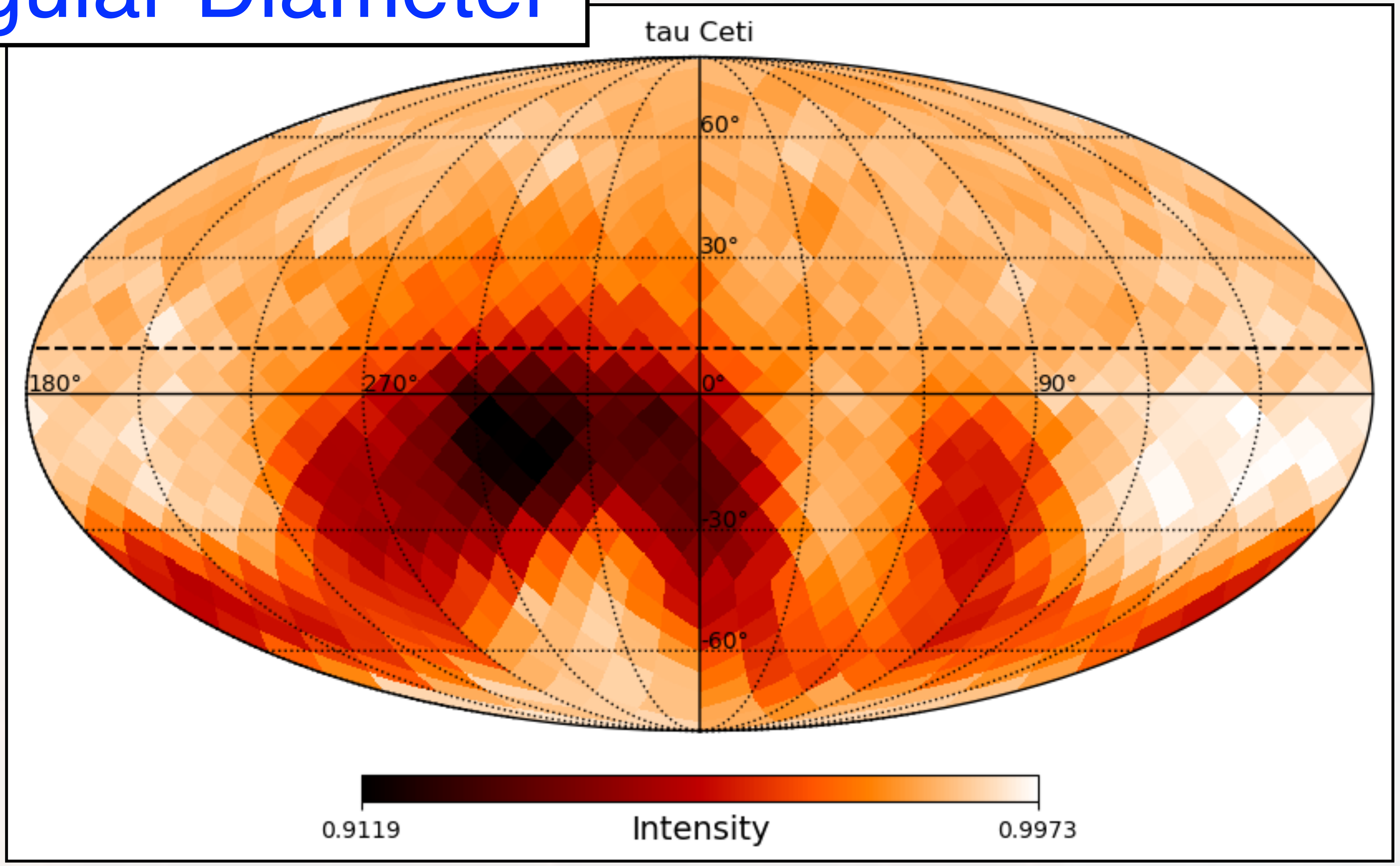
Angular Diameter





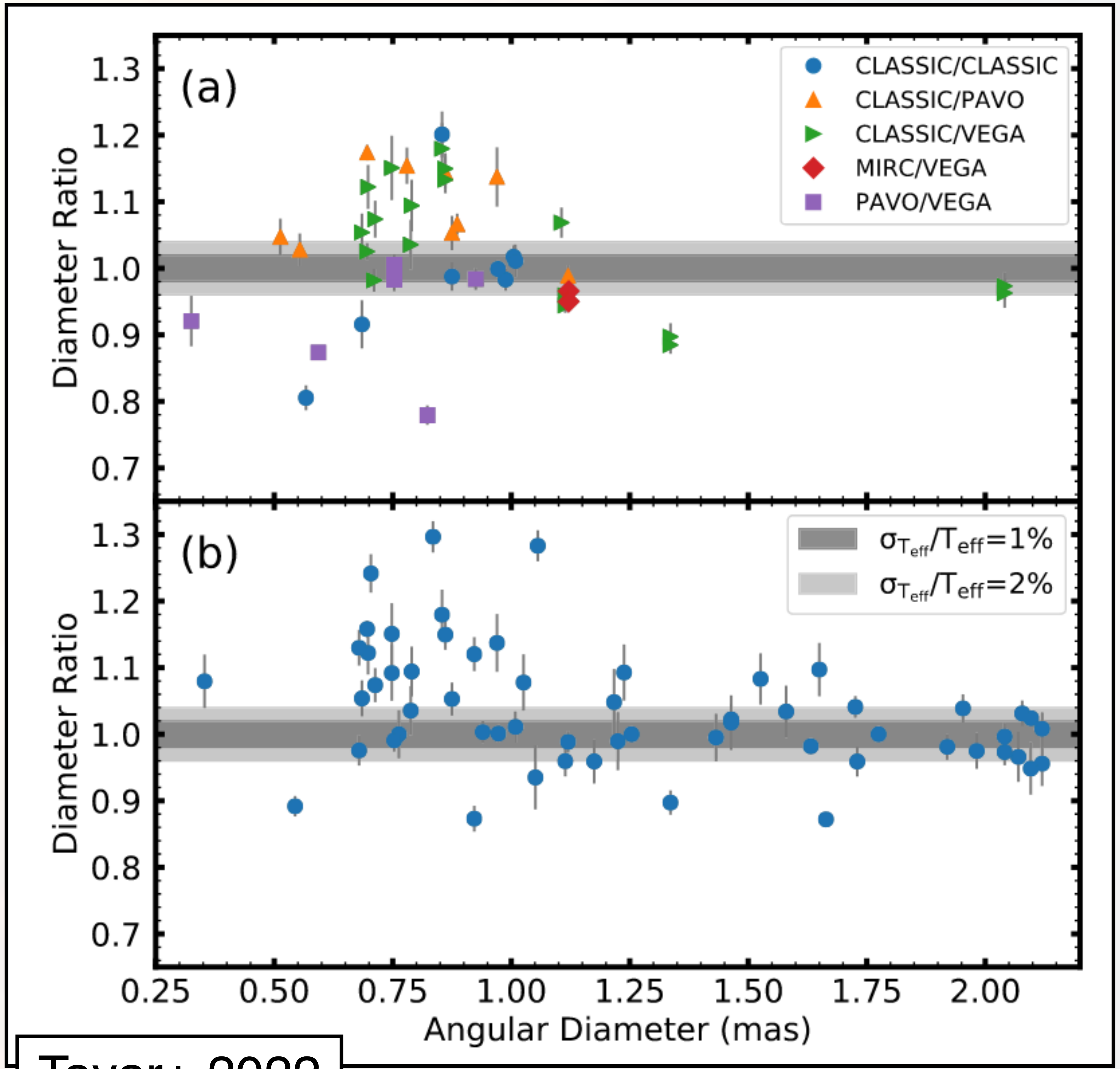
Roettenbacher+ in prep

Calibration, calibration, calibration …

$$R = d\,\theta/2$$

$$T_{\mathrm{eff}} = (4 f_{\mathrm{bol}} / \sigma\,\theta^2)^{1/4}$$

~4% systematics from unresolved diameters lead to ~2% & ~4% floors on T_{eff} and radius



Tayar+ 2022

More well resolved interferometric angular diameters are needed to lower the floor of fundamental T_{eff} calibrations

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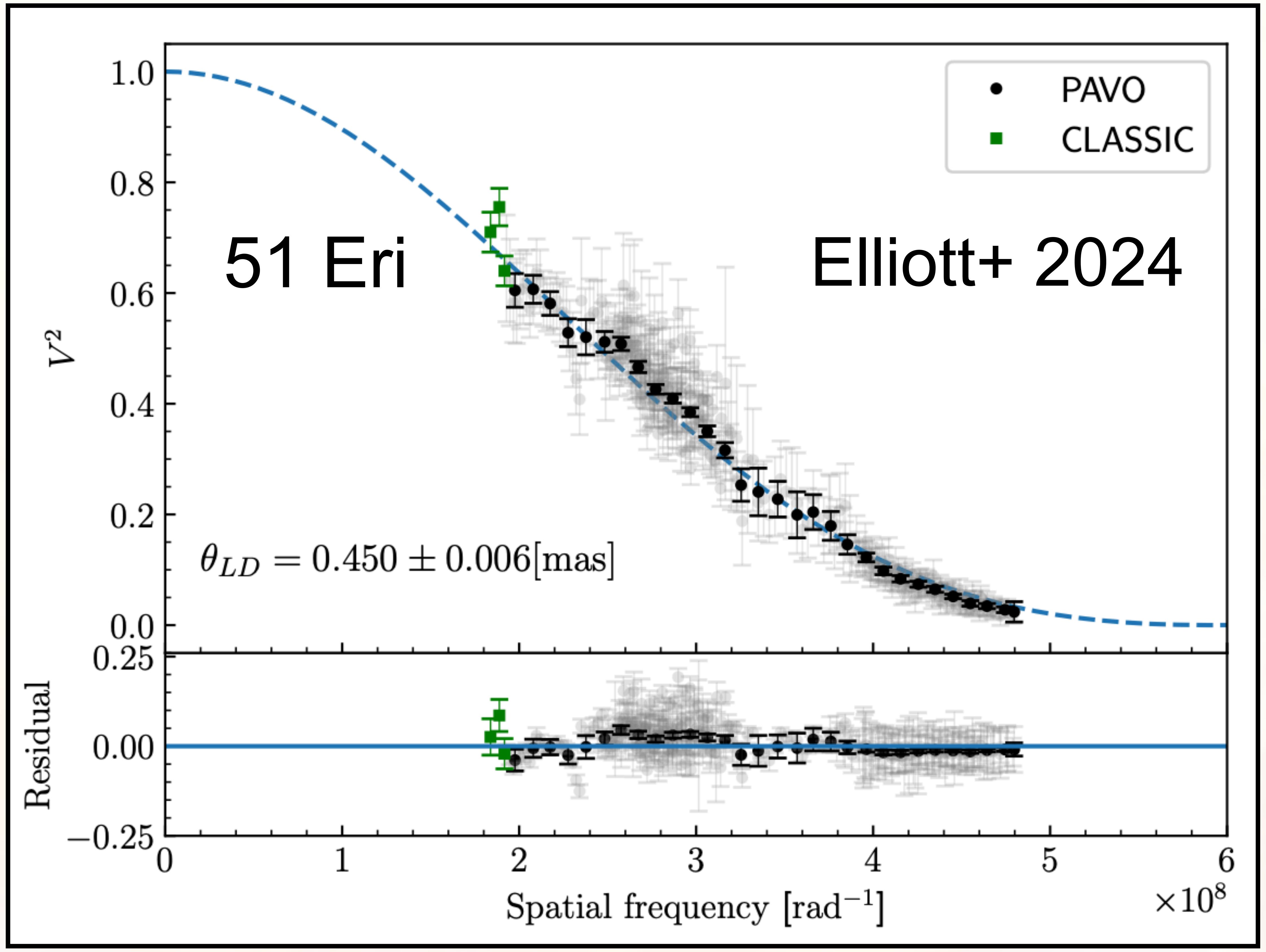

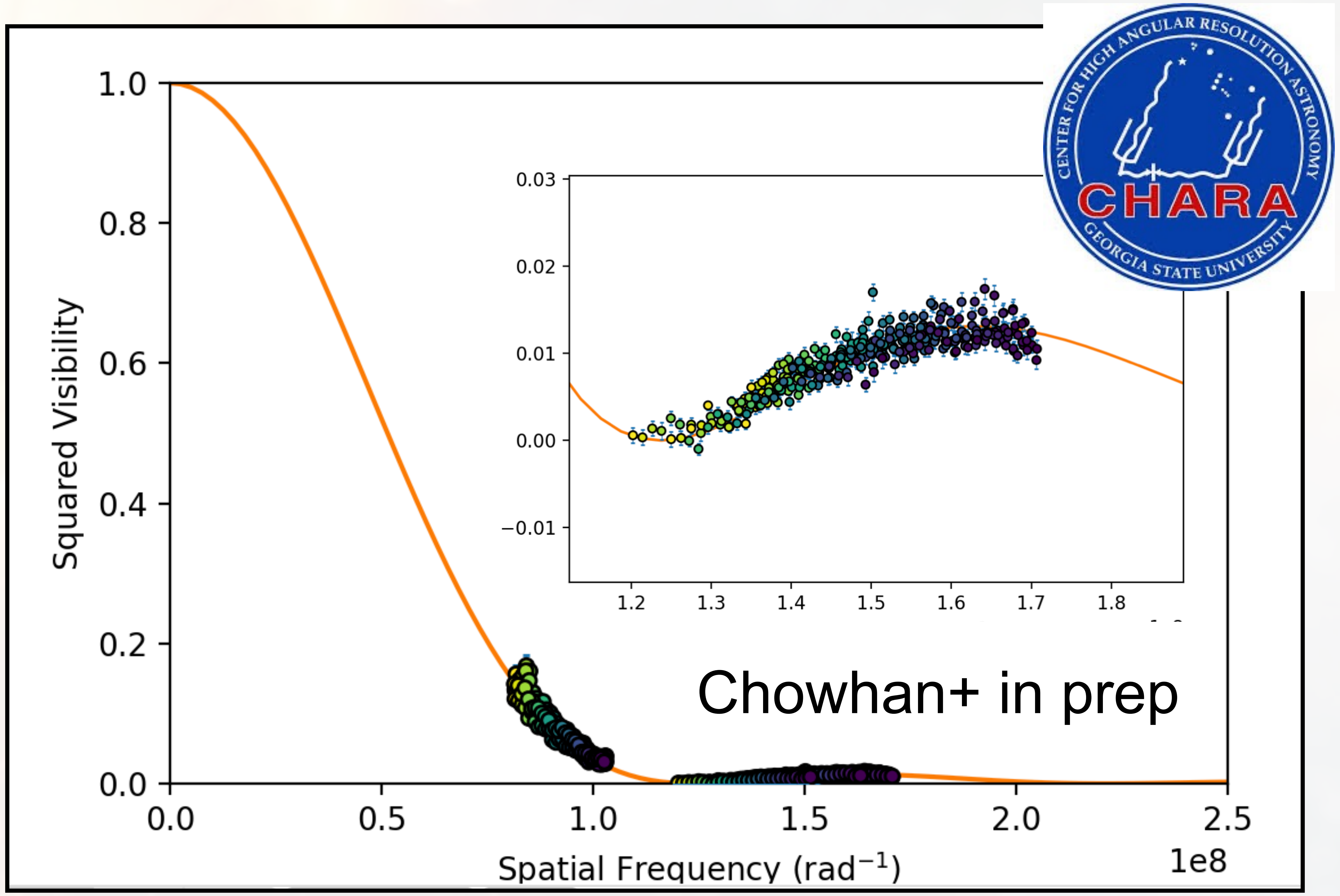

See also poster 1.02 (van Belle)

Current empirical masses & radii from binaries are limited to near solar metallicities and evolutionary stages

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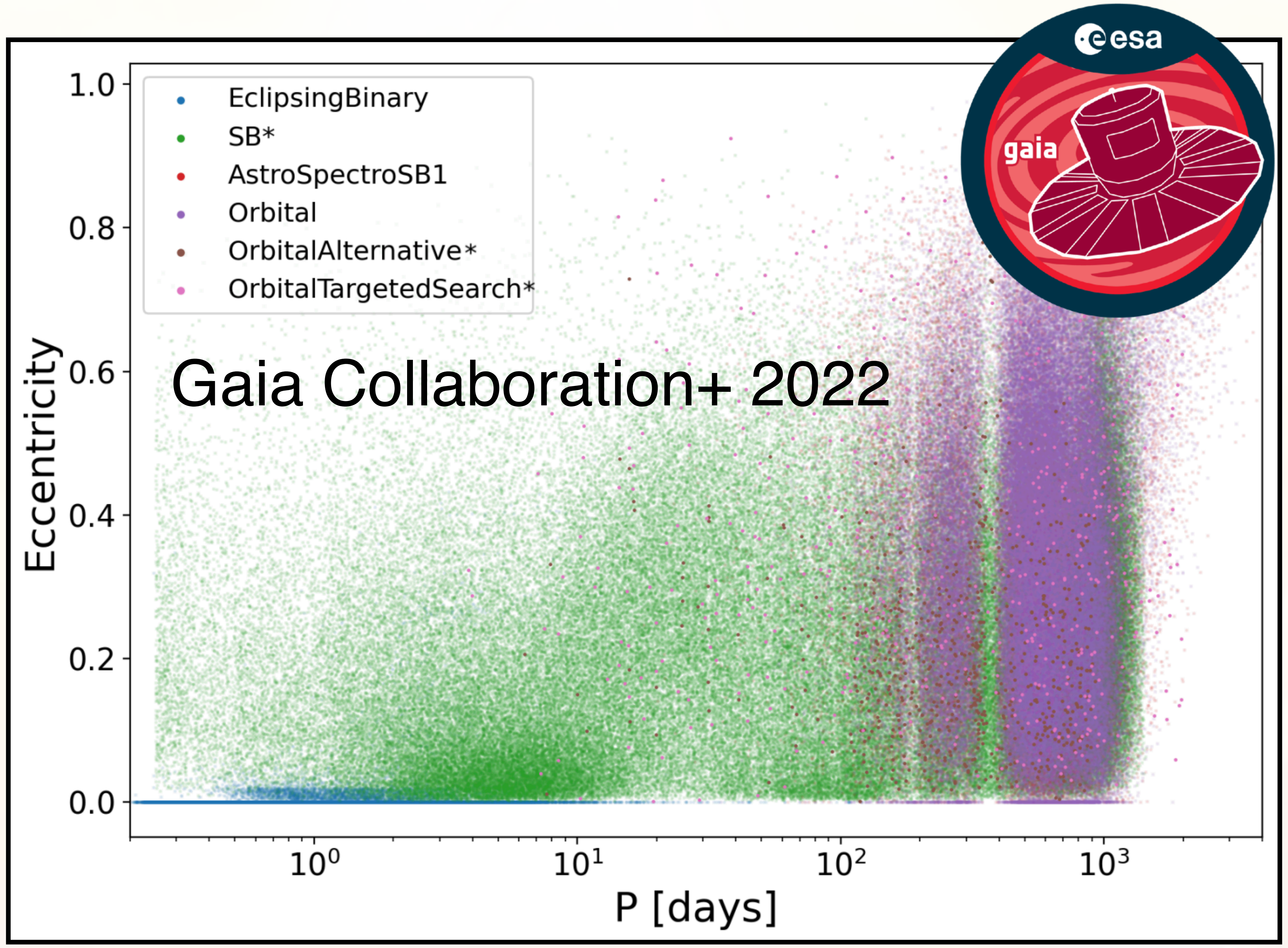
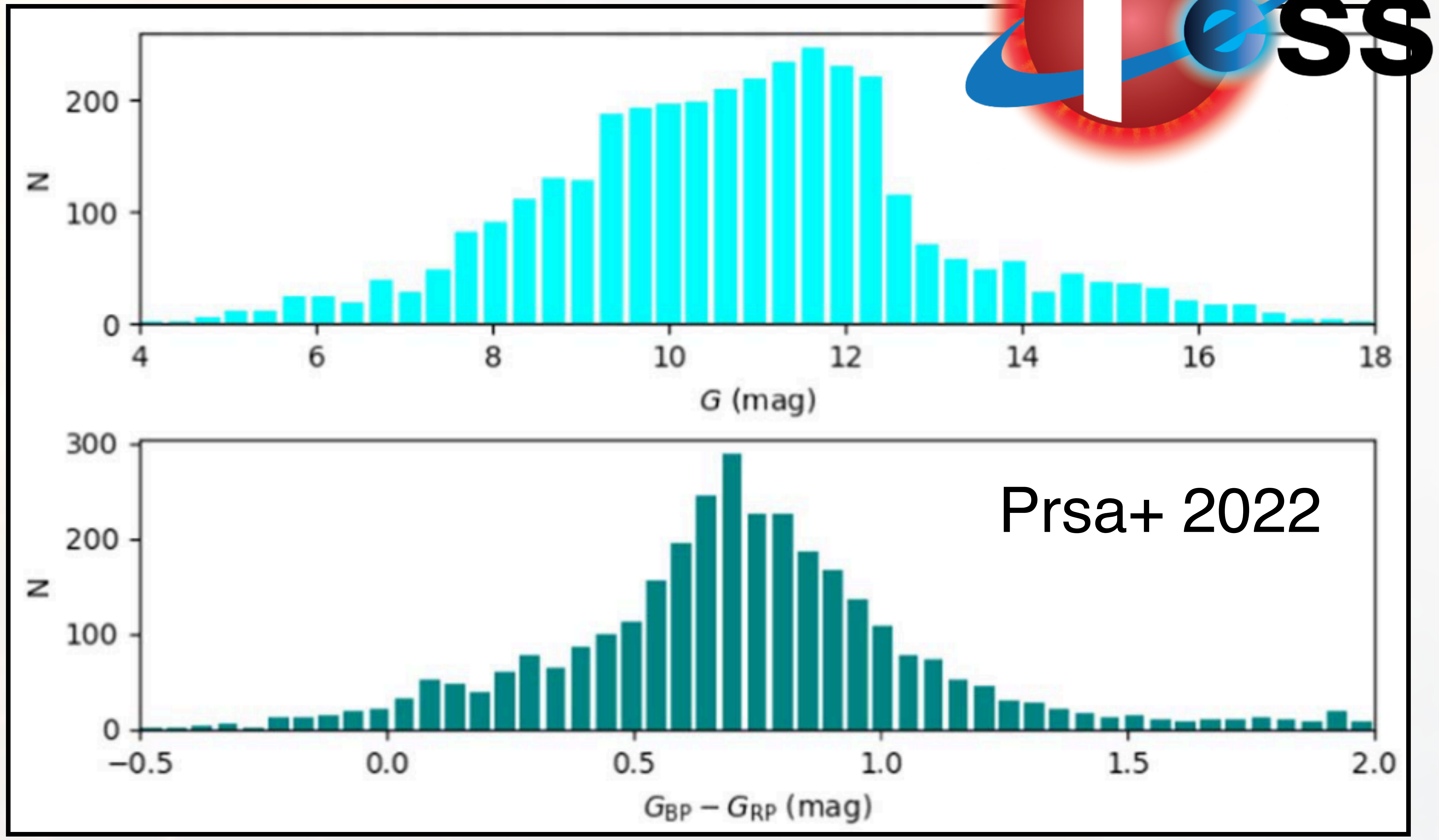
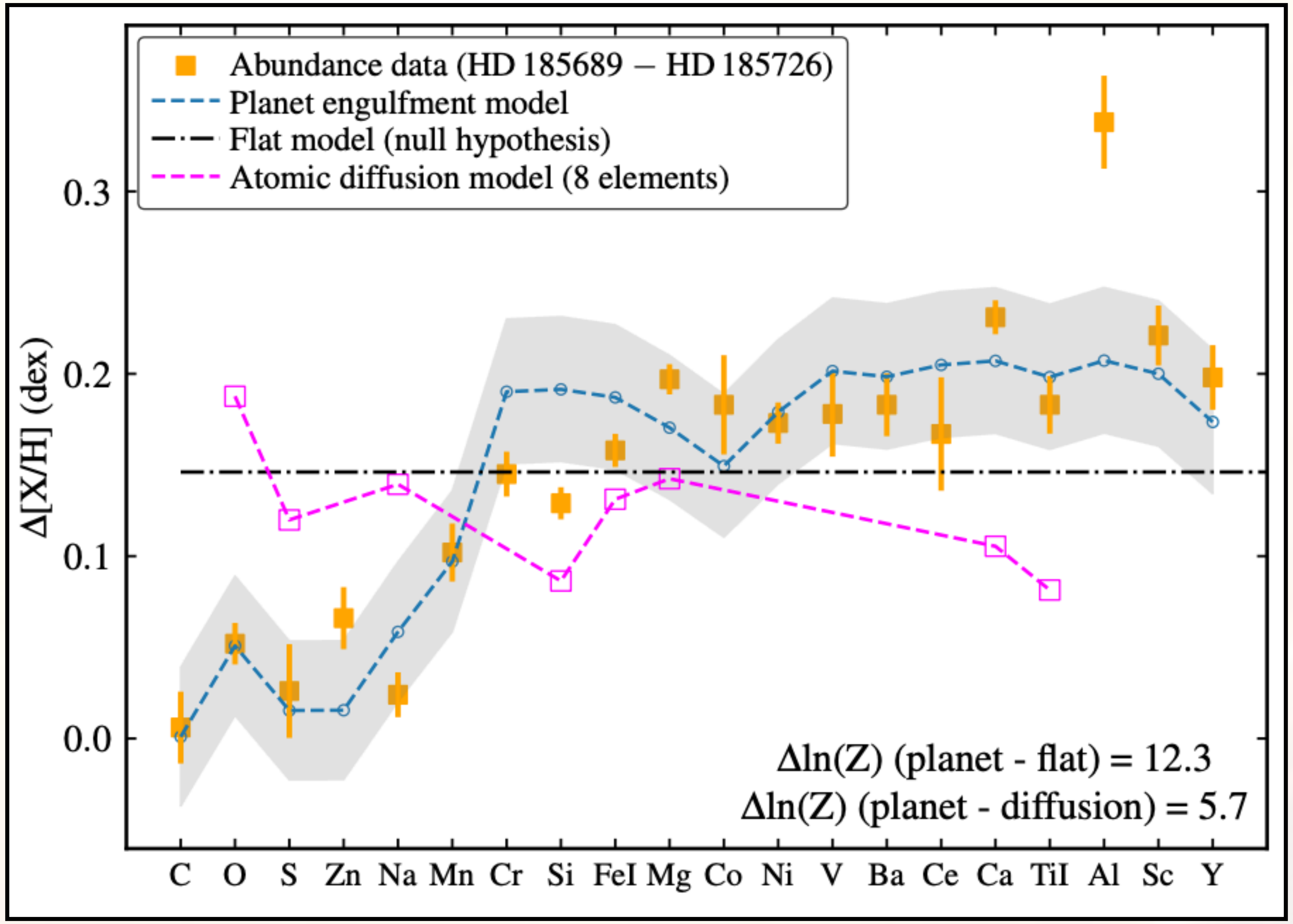




See also posters 1.08 (Salazar), 1.15 (Oddo) & 1.19 (Flores), 1.26 (Uttamchandani)

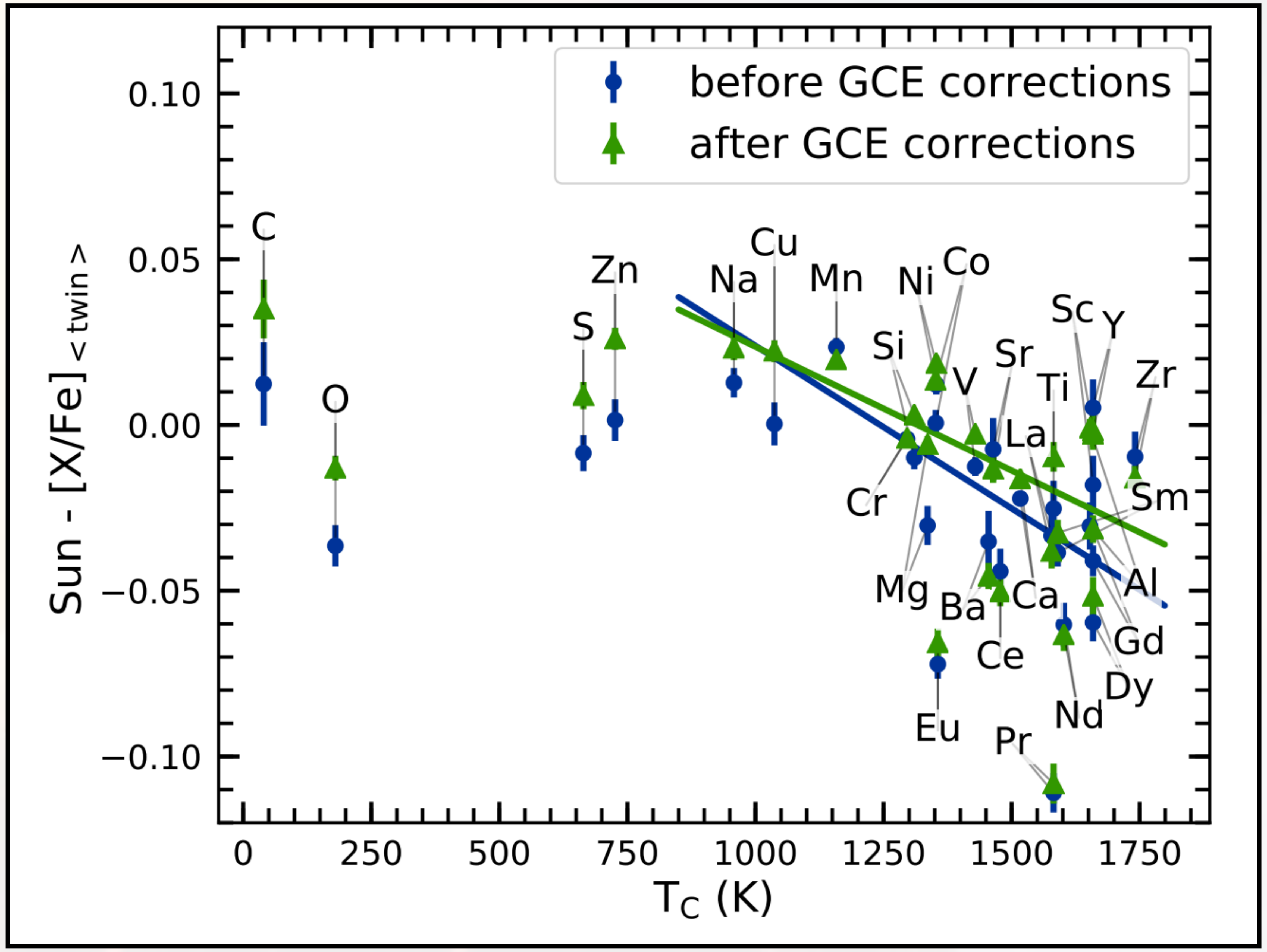
The Classic: Spectroscopy

Chemical Imprints of Planets in Solar ~Twins?



Liu+ 2024

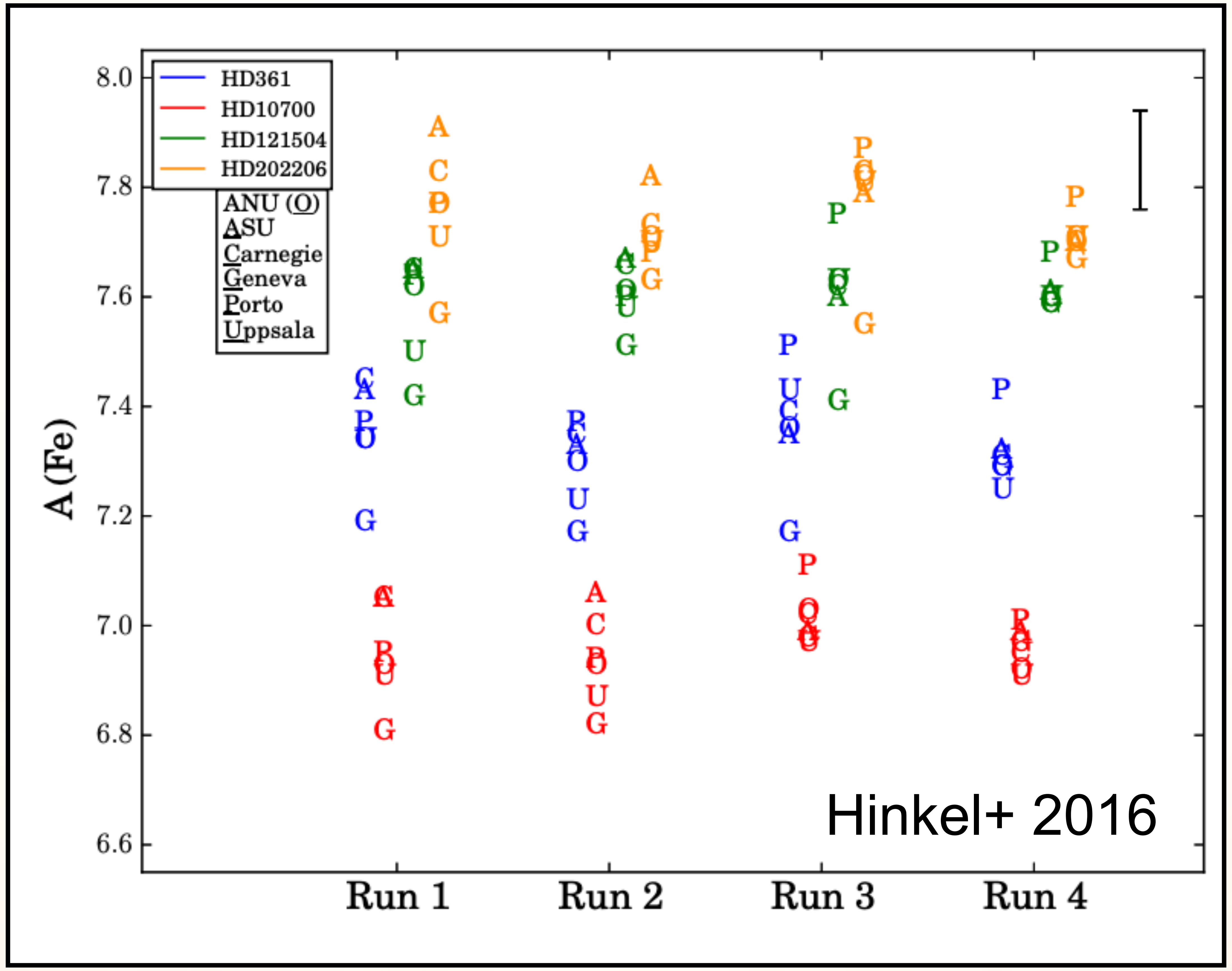
see also Soares-Furtado+ 2021, Ong+ 2024



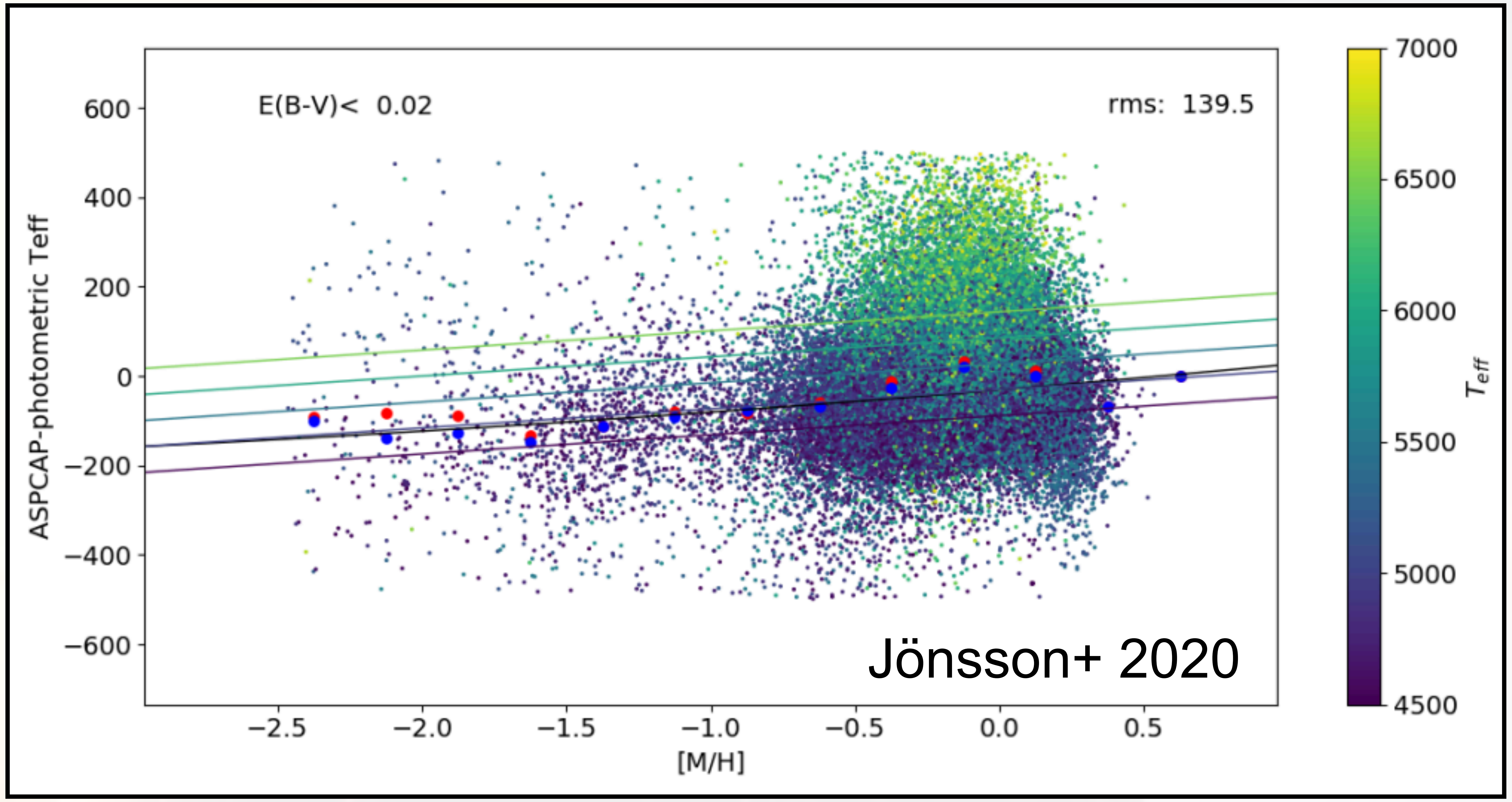
Bedell+ 2018

see also Melendez+ 2009, Ramirez+ 2010, Gonzalez Hernandez+ 2013, Adibekyan+ 2014

Accuracy vs Precision: Spectroscopy Challenges



Typical abundance differences between methods of ~0.1 dex (using the same spectrum!)



Temperatures derived from spectra have to be calibrated to the fundamental (interferometric!) scale

Uncertainties in the analysis of stellar spectra likely limit our ability to probe important planet formation signatures (except for solar twins)

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APOGEE

SDSS III

GALAH

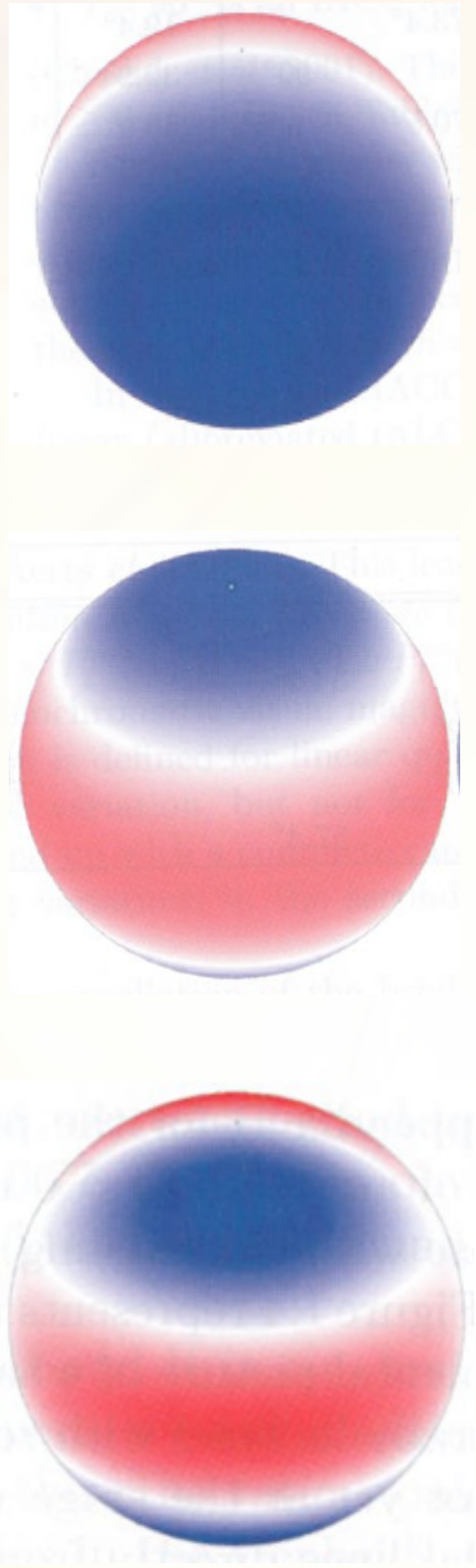
GALactic Archaeology with HERMES

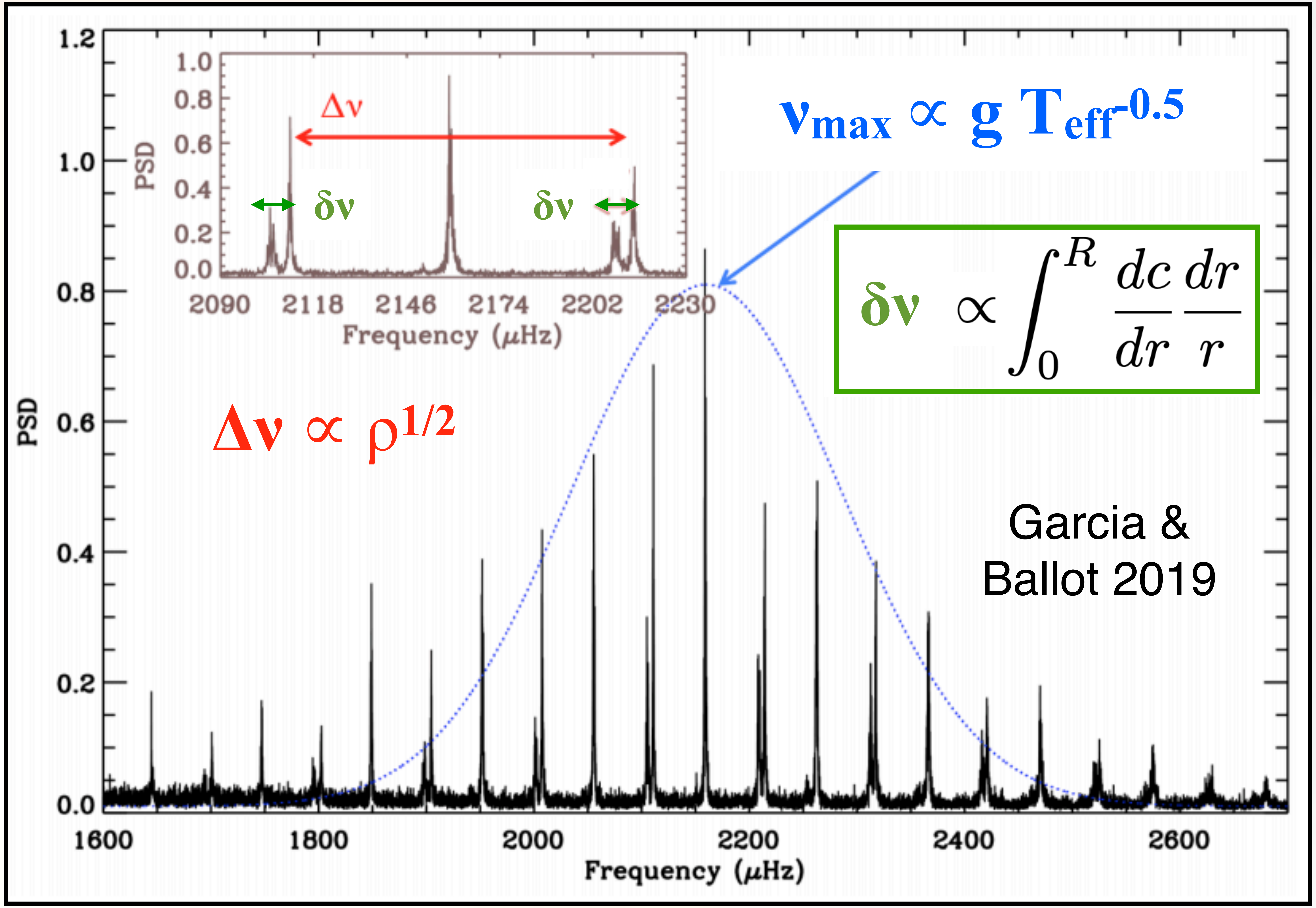
4MOST

See also posters 1.03 (McCreery), 1.17 (Gromek),1.20 (Rodriguez), 1.23 (Nascimento), 1.24 (Polanski), 4.09 (Galarza)

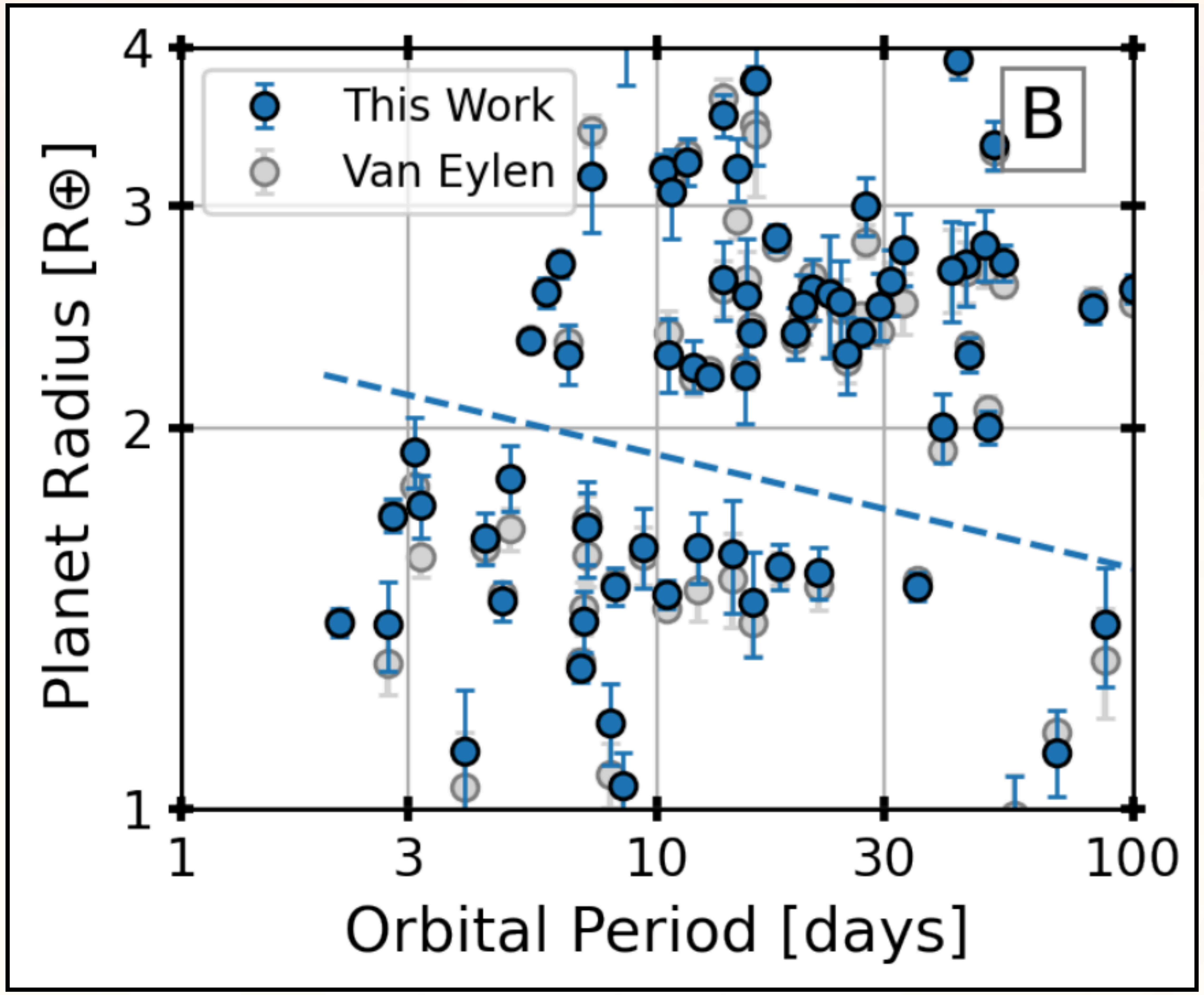
Peering inside: Asteroseismology

Asteroseismology: Densities, Ages & More





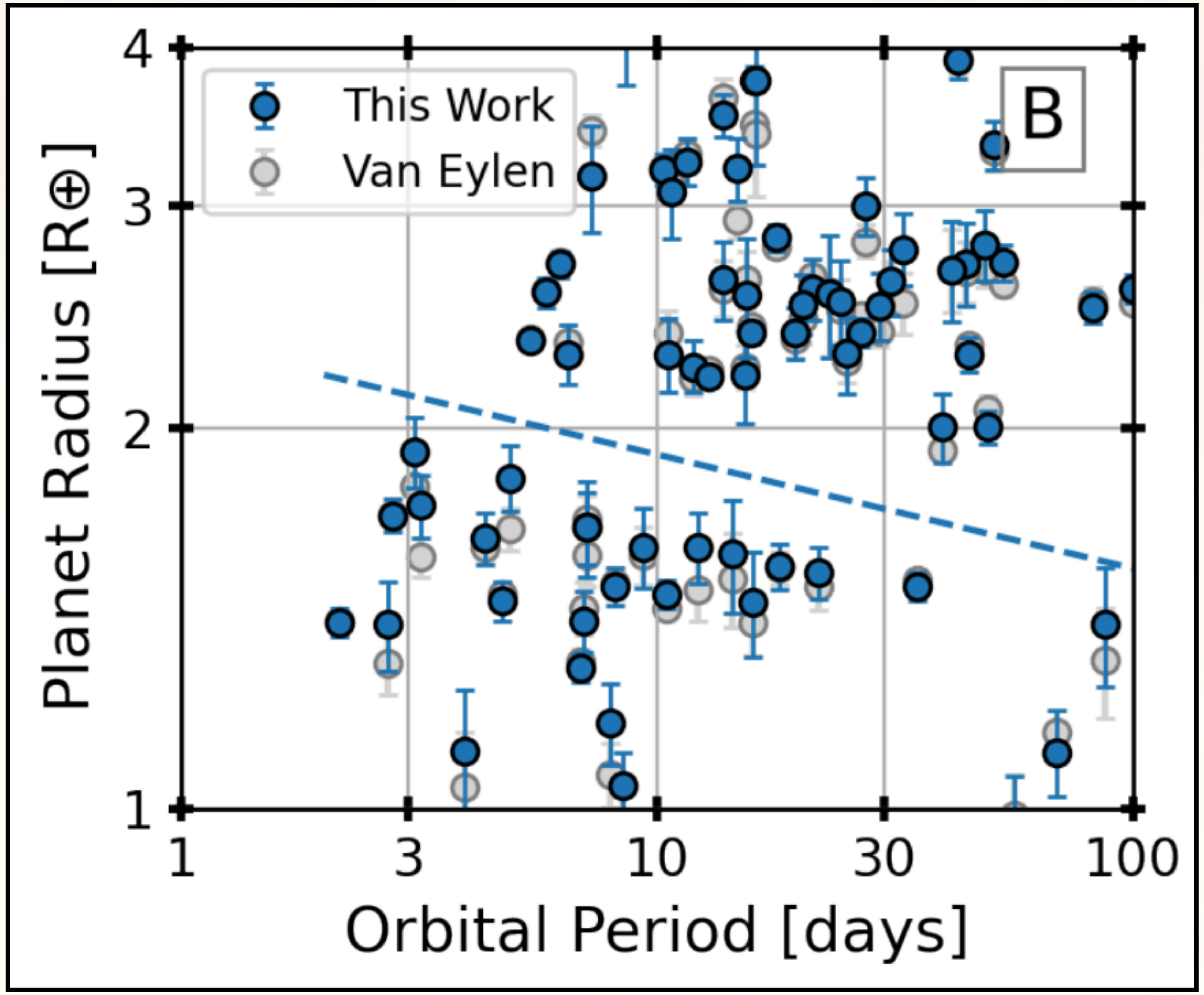
Asteroseismology & Exoplanets



Huber+ 2013

Sayeed+ in prep
(see also Van Eylen+ 2017,
Petigura 2020)

Asteroseismology & Exoplanets



Sayeed+ in prep
(see also Van Eylen+ 2017,
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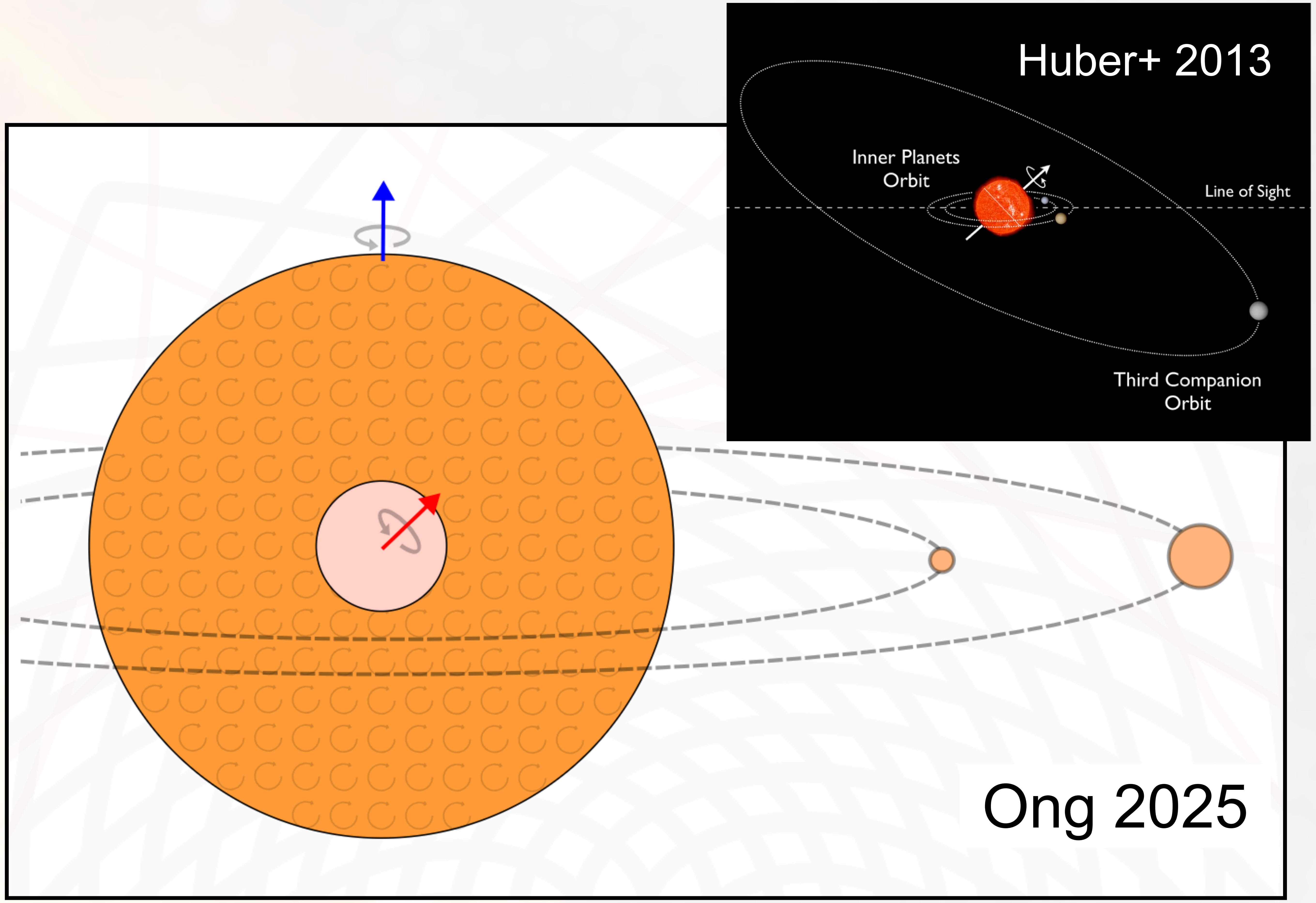


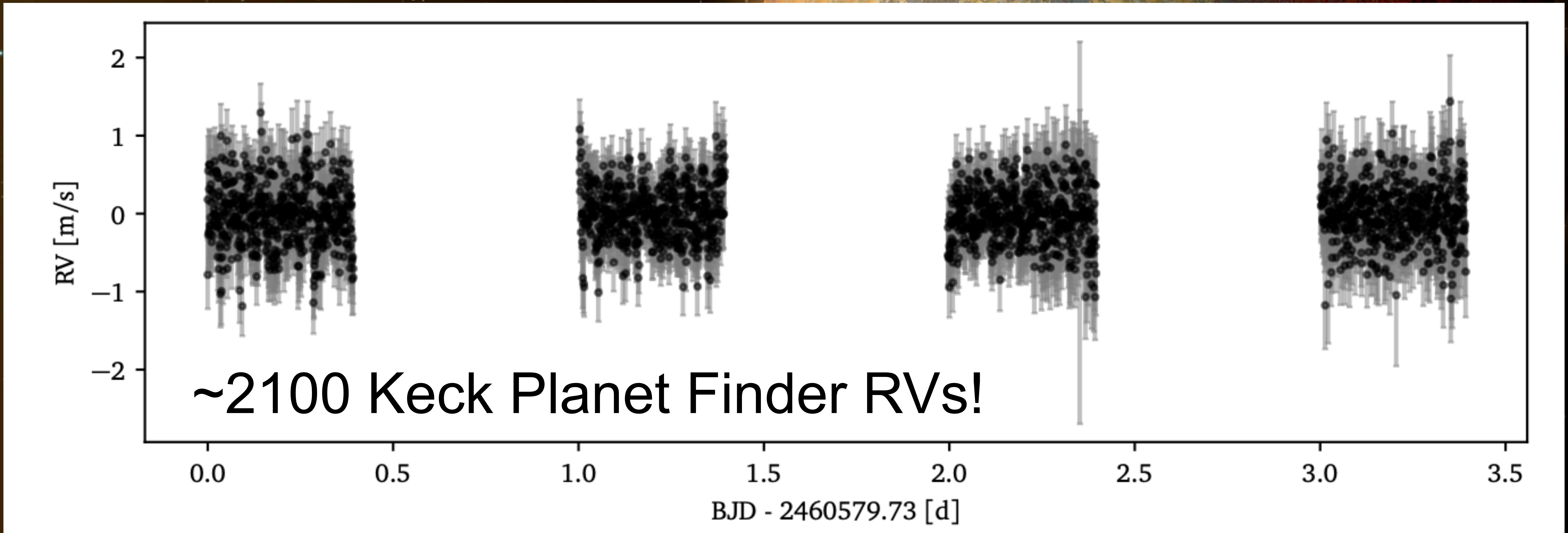
Kepler-56 planets are misaligned
“only” with the stellar core!

HD219134b

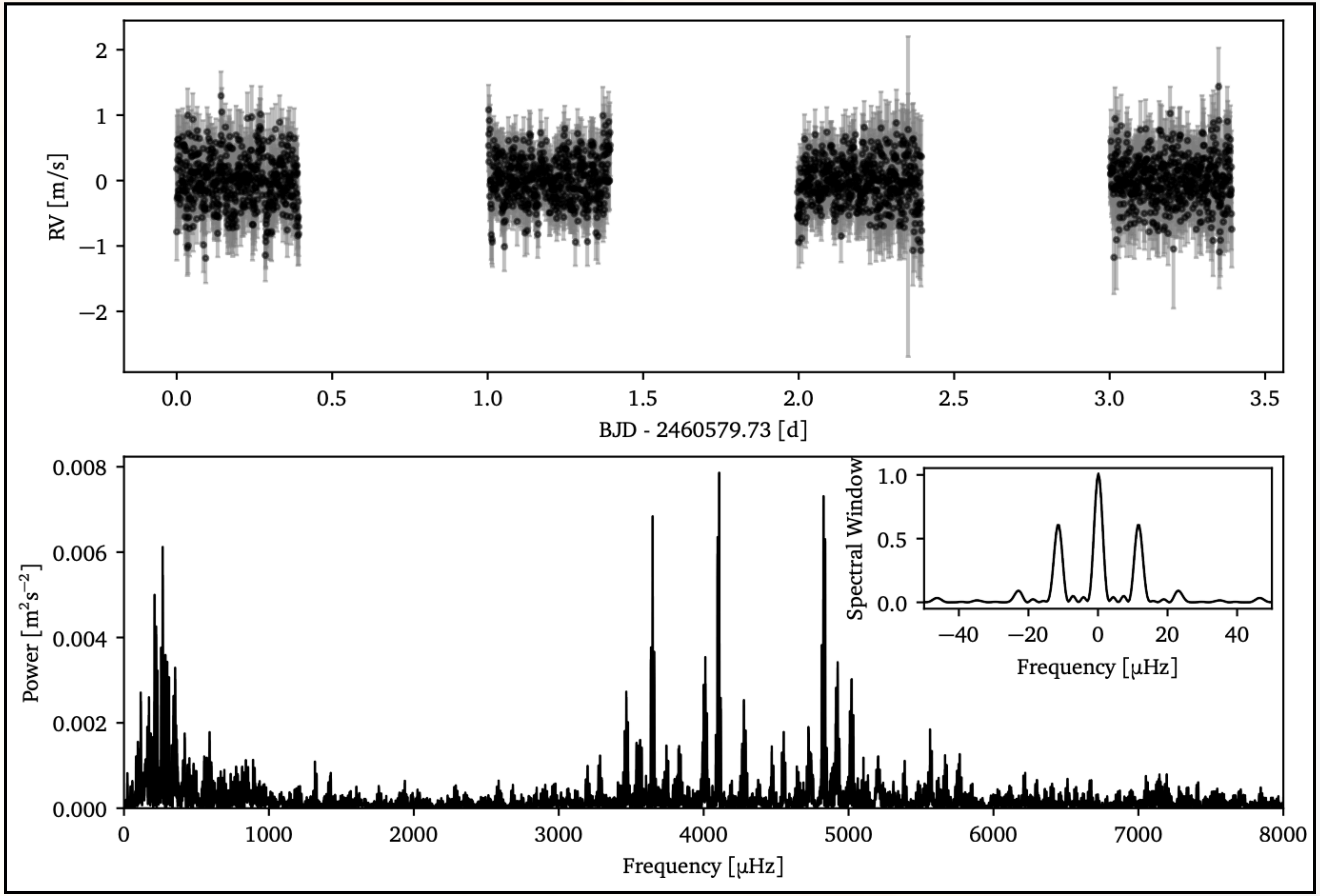
NASA/JPL

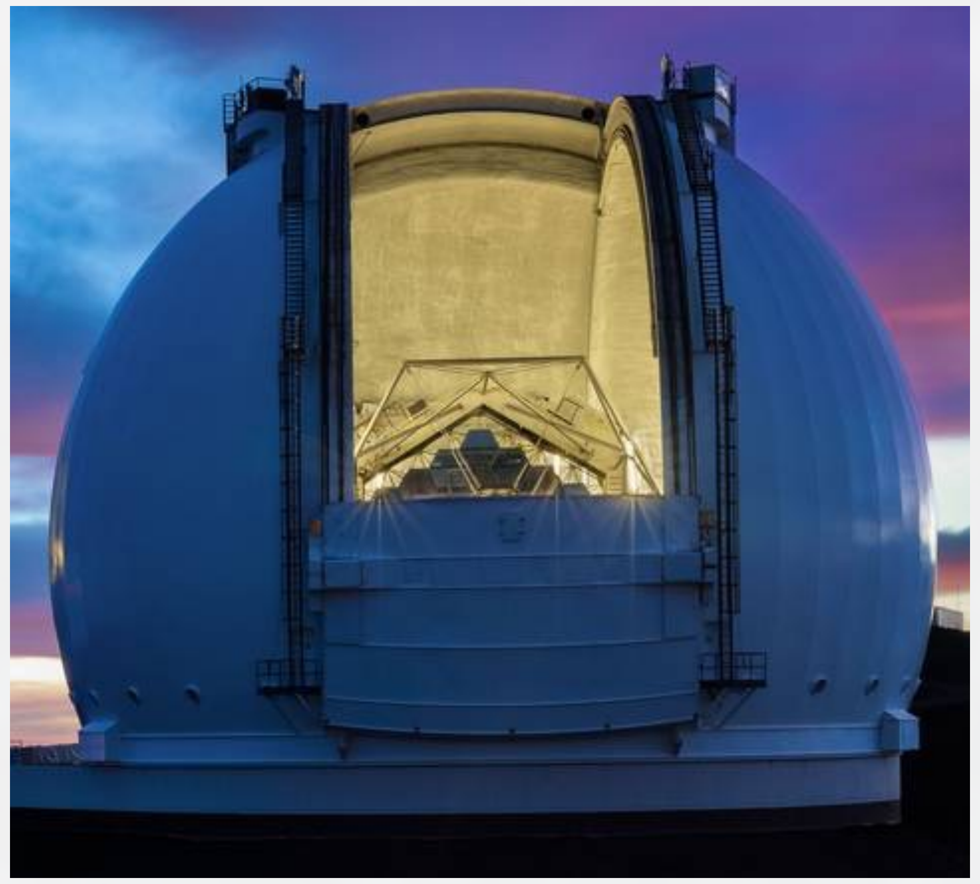
K-dwarf Radius Inflation and a 10-Gyr Spin-down Clock Unveiled through Asteroseismology of HD 219134 from the Keck Planet Finder

Yaguang Li (李亚光)[1], Daniel Huber[1], J. M. Joel Ong (王加冕)[1], Jennifer van Saders[1], R.R. Costa[2,3], Jens Reersted Larsen[4], Sarbani Basu[5], Timothy R. Bedding[6], Fei Dai (戴飞)[1], Ashely Chontos[7], Theron W. Carmichael[1], Daniel Hey[1], Hans Kjeldsen,[4] Marc Hon[8], Tiago L. Campante[2,3], Mário J. P. F. G. Monteiro[2,3], Mia Sloth Lundkvist[4], Nick Saunders[1], Howard Isaacson[9], Andrew W. Howard[10], Steven R. Gibson,[11] Samuel Halverson[12], Kodi Rider,[13] Arpita Roy[14], Ashley D. Baker[11], Jerry Edelstein[13], Chris Smith,[13] Benjamin J. Fulton[15], and Josh Walawender[16]



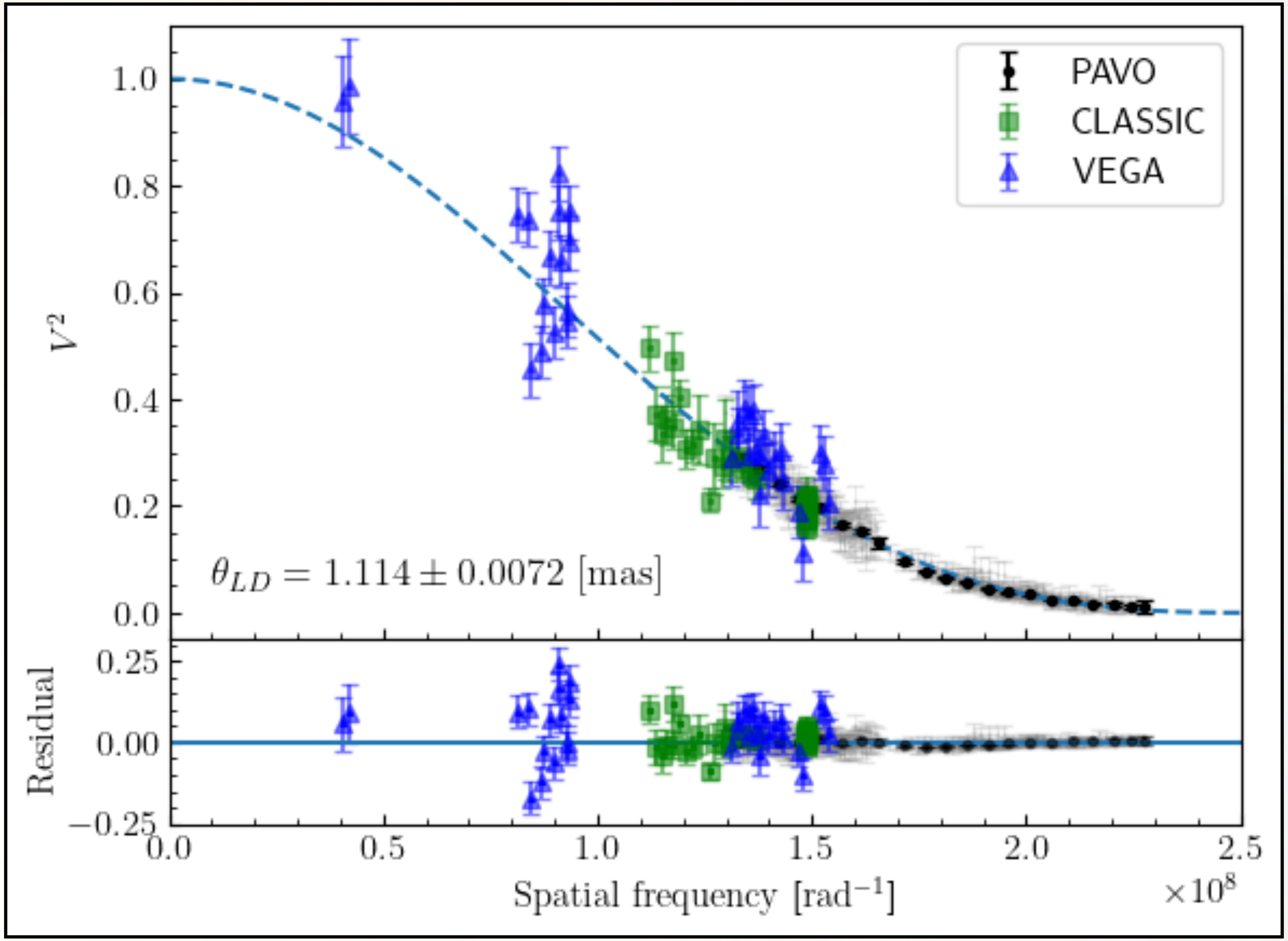
Probing Fundamental Limits: HD219134





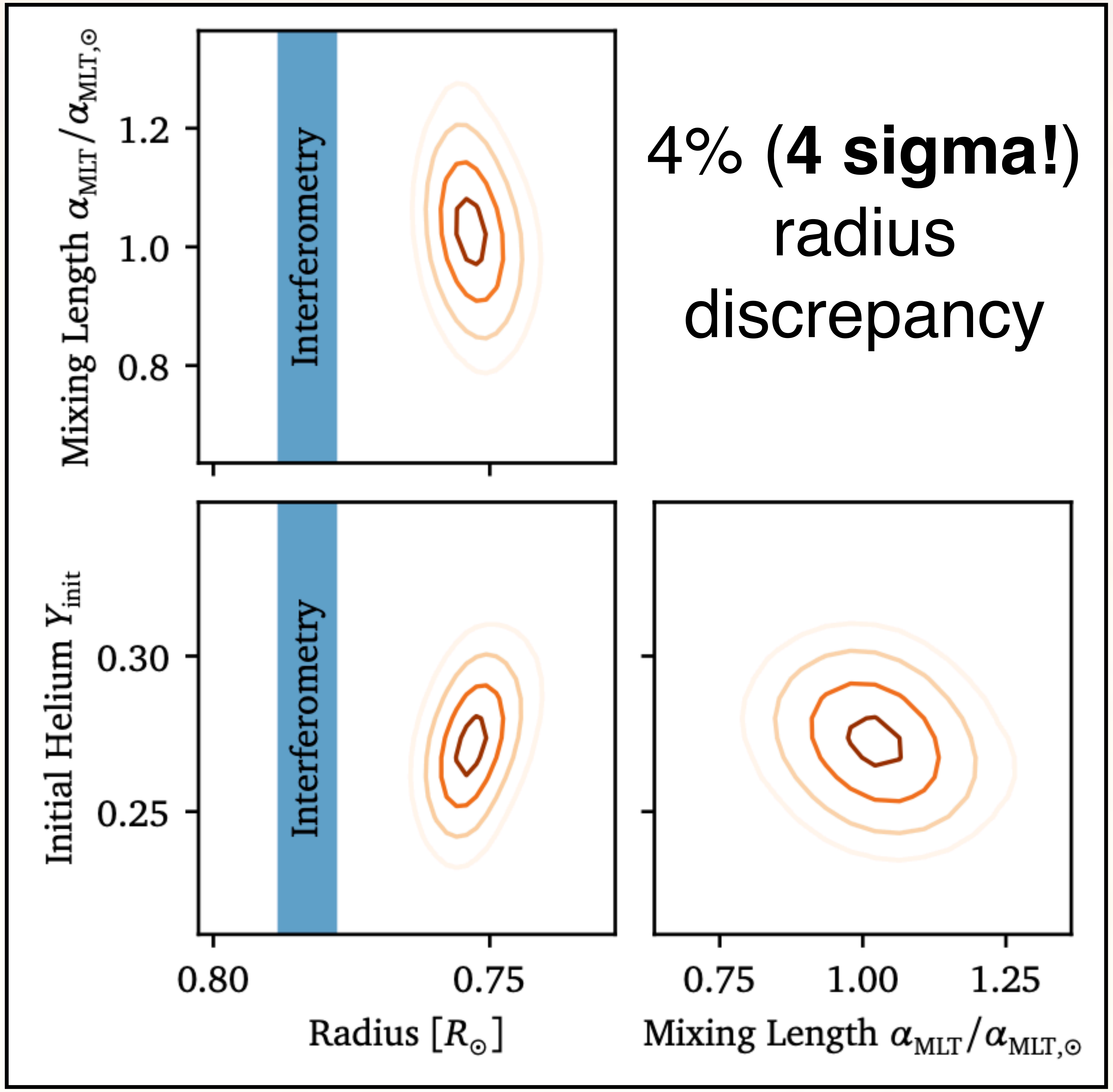
Yaguang Li+
submitted

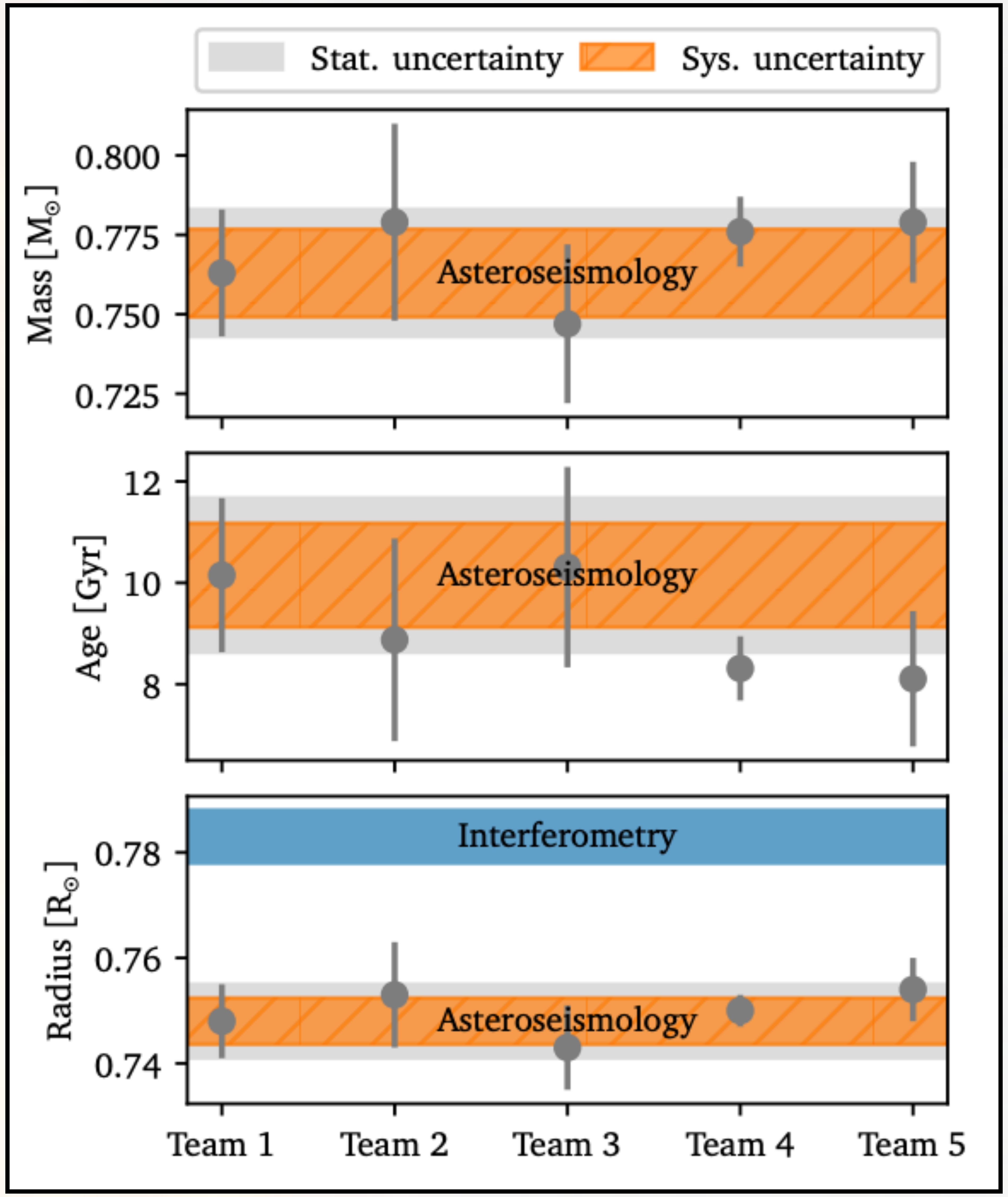
Probing Fundamental Limits: HD219134



Ashley Elliott+
in prep

Probing Fundamental Limits: HD219134





Yaguang Li+ submitted

Uncertainties in stellar model physics remain a major bottleneck for fundamental properties of exoplanet host stars

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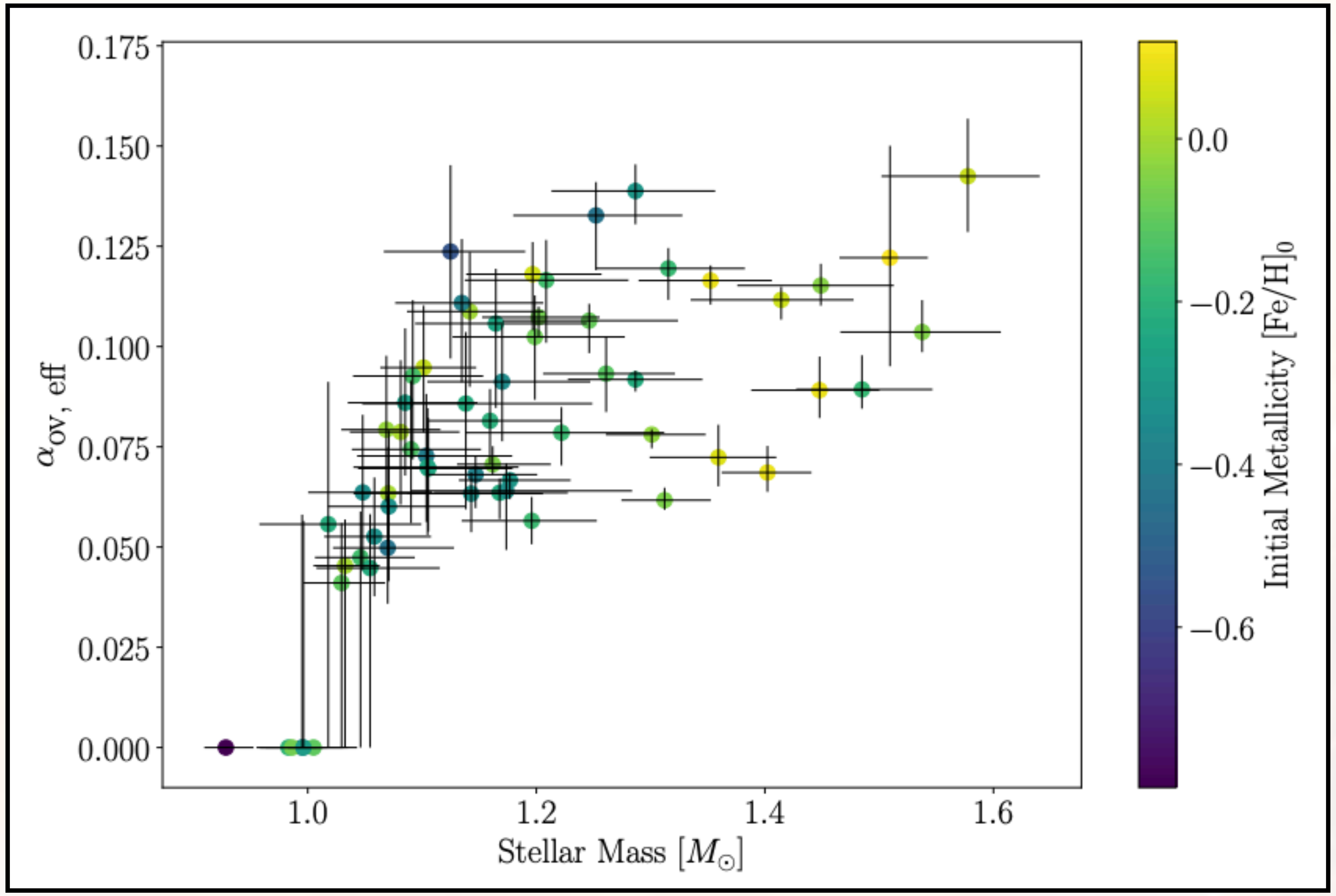
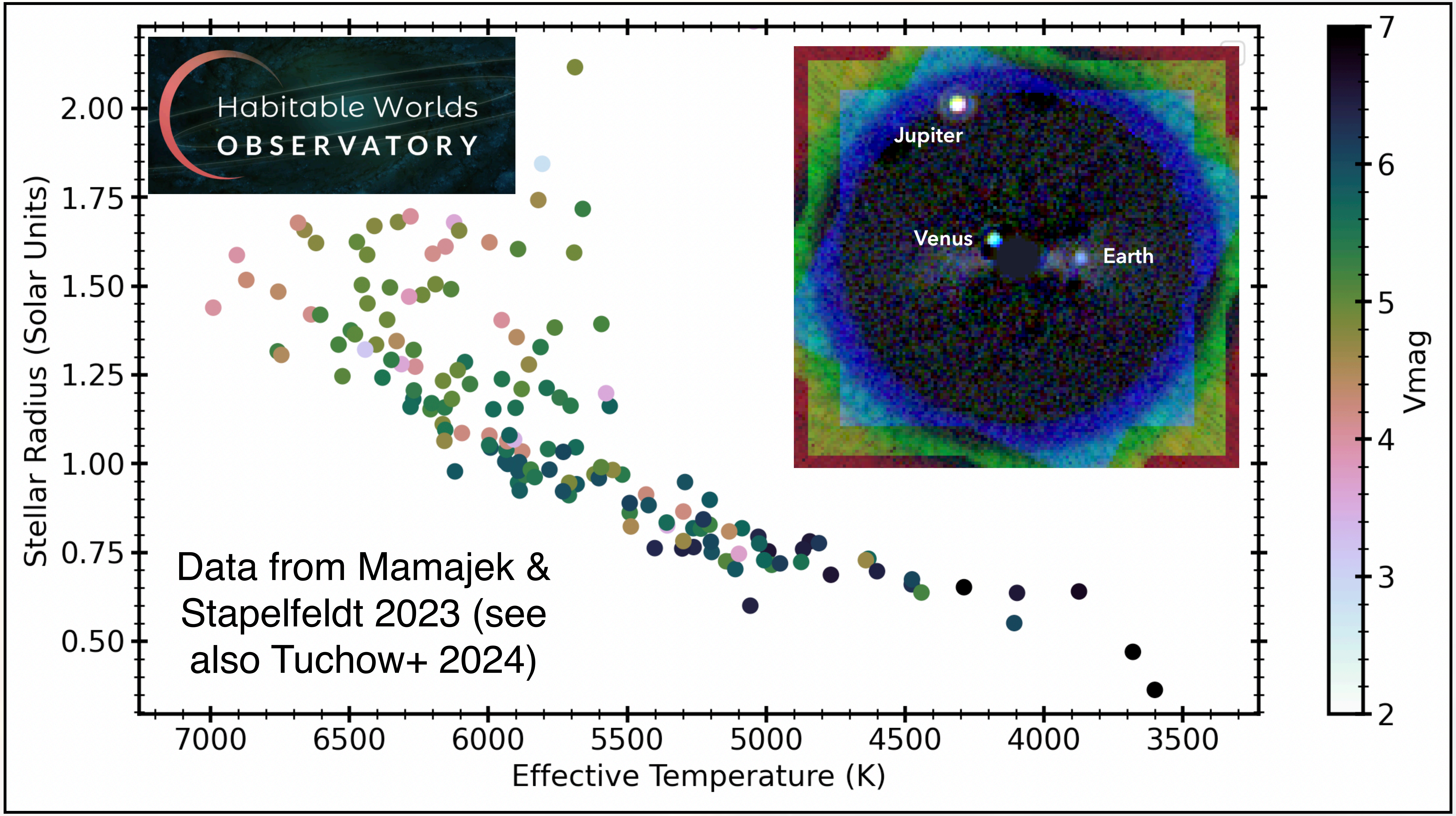


Lindsay+ 2024

TESS

Kepler

The Stars around which we will search for life are the best targets for stellar astrophysics



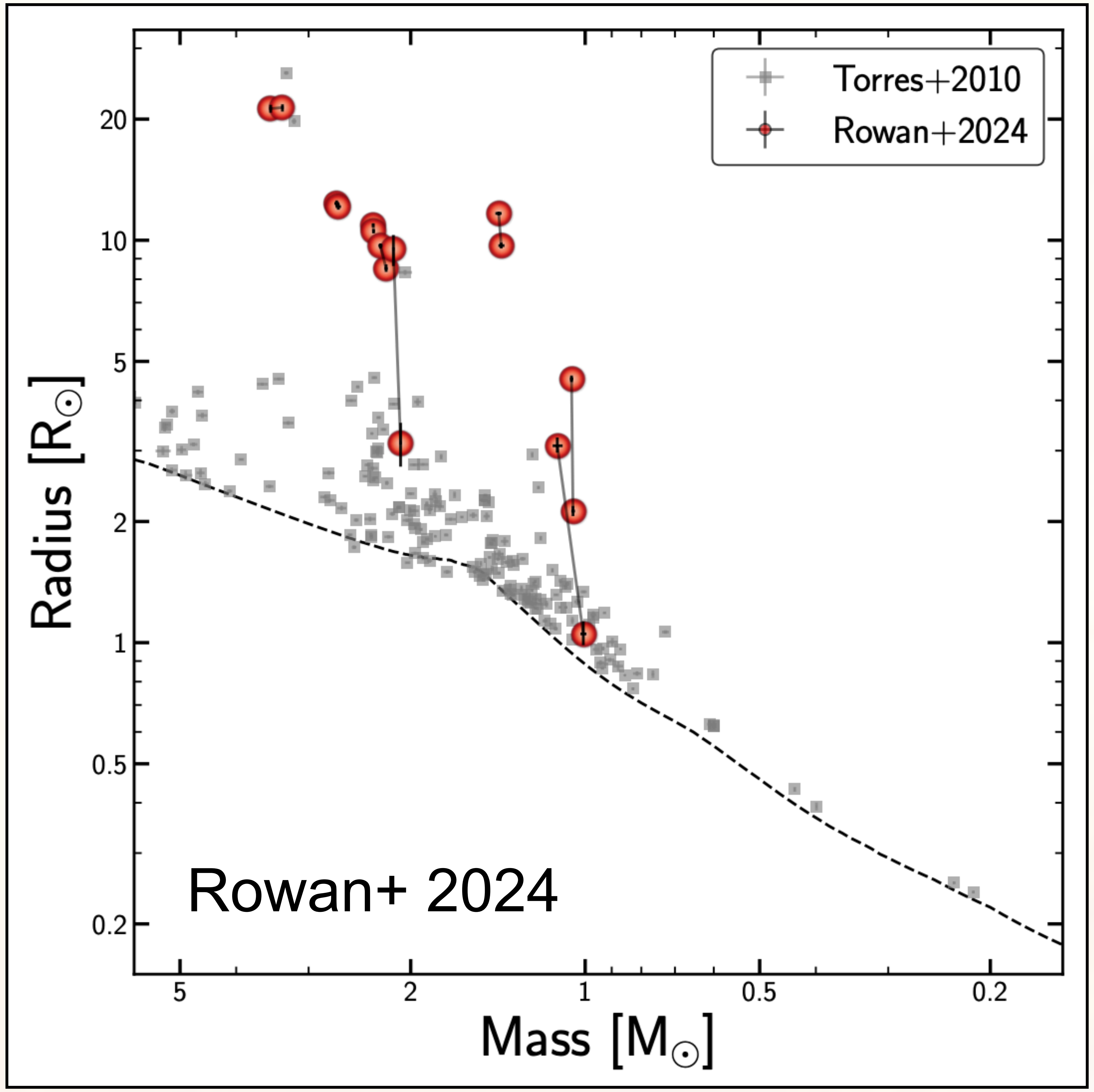
Conclusions

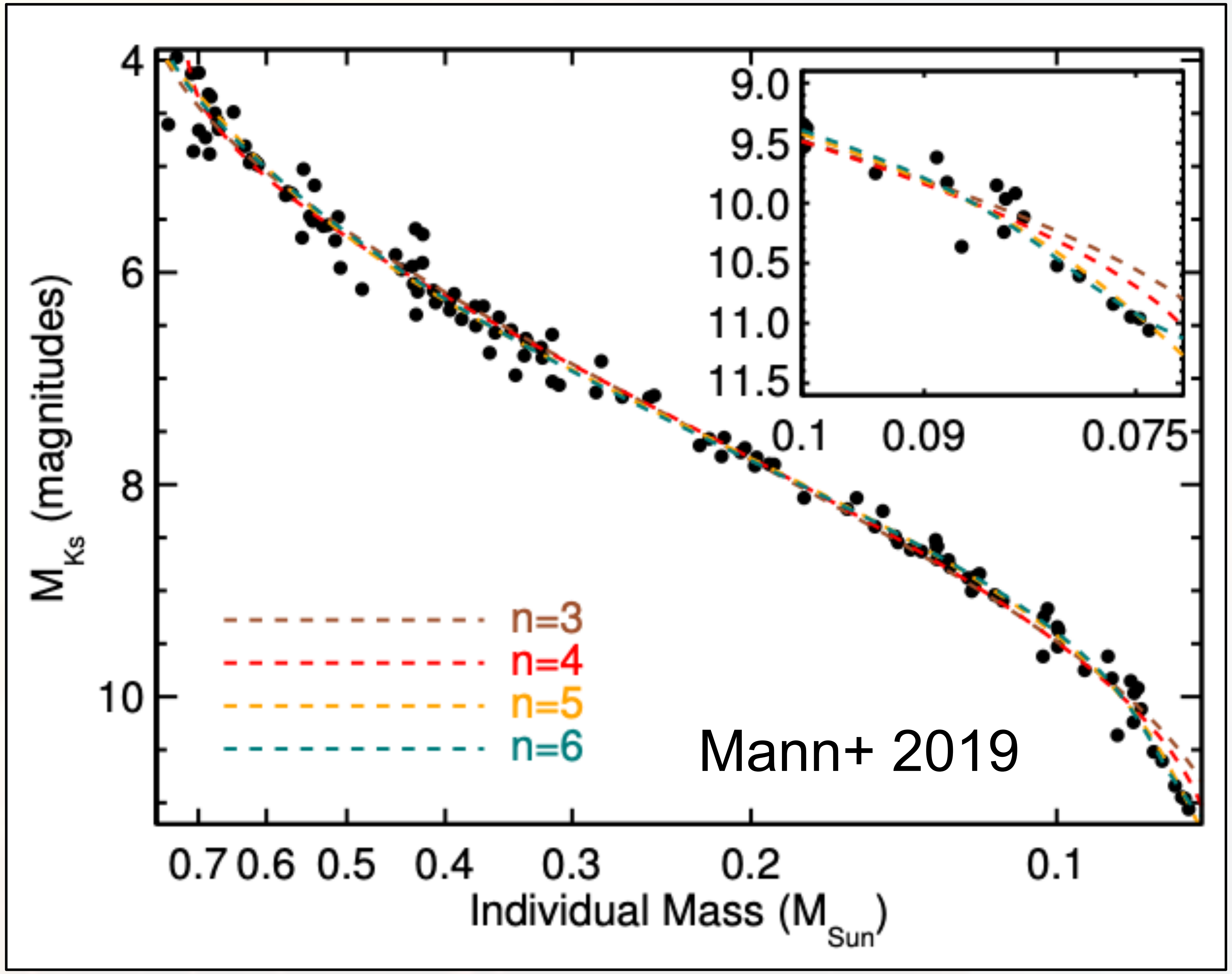
- **Absolute flux measurements have become a bottleneck** for capitalizing on Gaia distances for exoplanet host star characterization
- **More well resolved interferometric angular diameters are needed** to lower the floor of fundamental T_{eff} calibrations
- **Current empirical masses & radii from binaries are limited** to near solar metallicities and evolutionary stages
- **Uncertainties in the analysis of stellar spectra** likely limit our ability to probe important planet formation signatures
- **Uncertainties in stellar model physics remain a major bottleneck** for fundamental properties of exoplanet host stars

We have/will soon have data to tackle these challenges!

Extra Slides

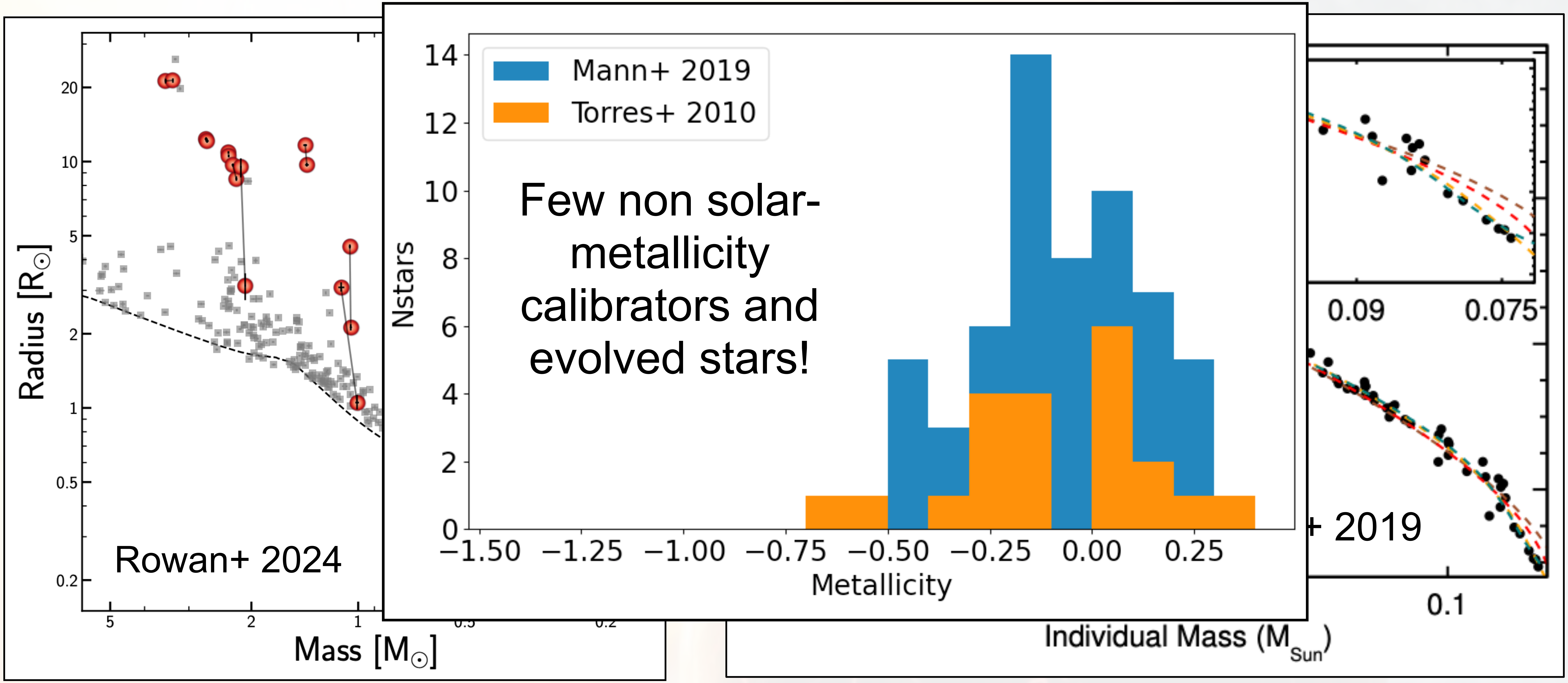
Astrometric & Eclipsing Binaries





See also Torres+ 2010 (1300+ citations!) & Southworth *"The Observatory"* paper series

Astrometric & Eclipsing Binaries



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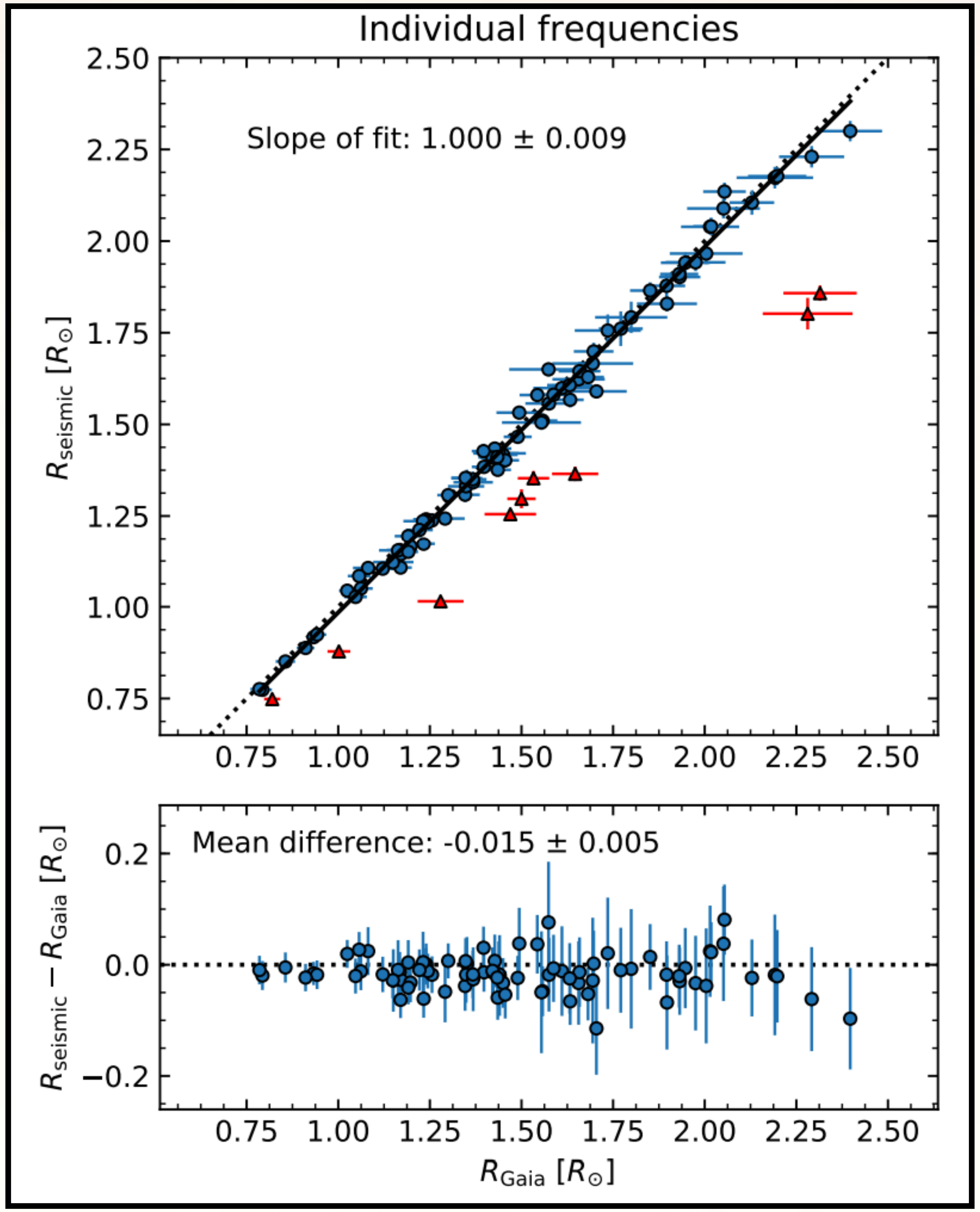
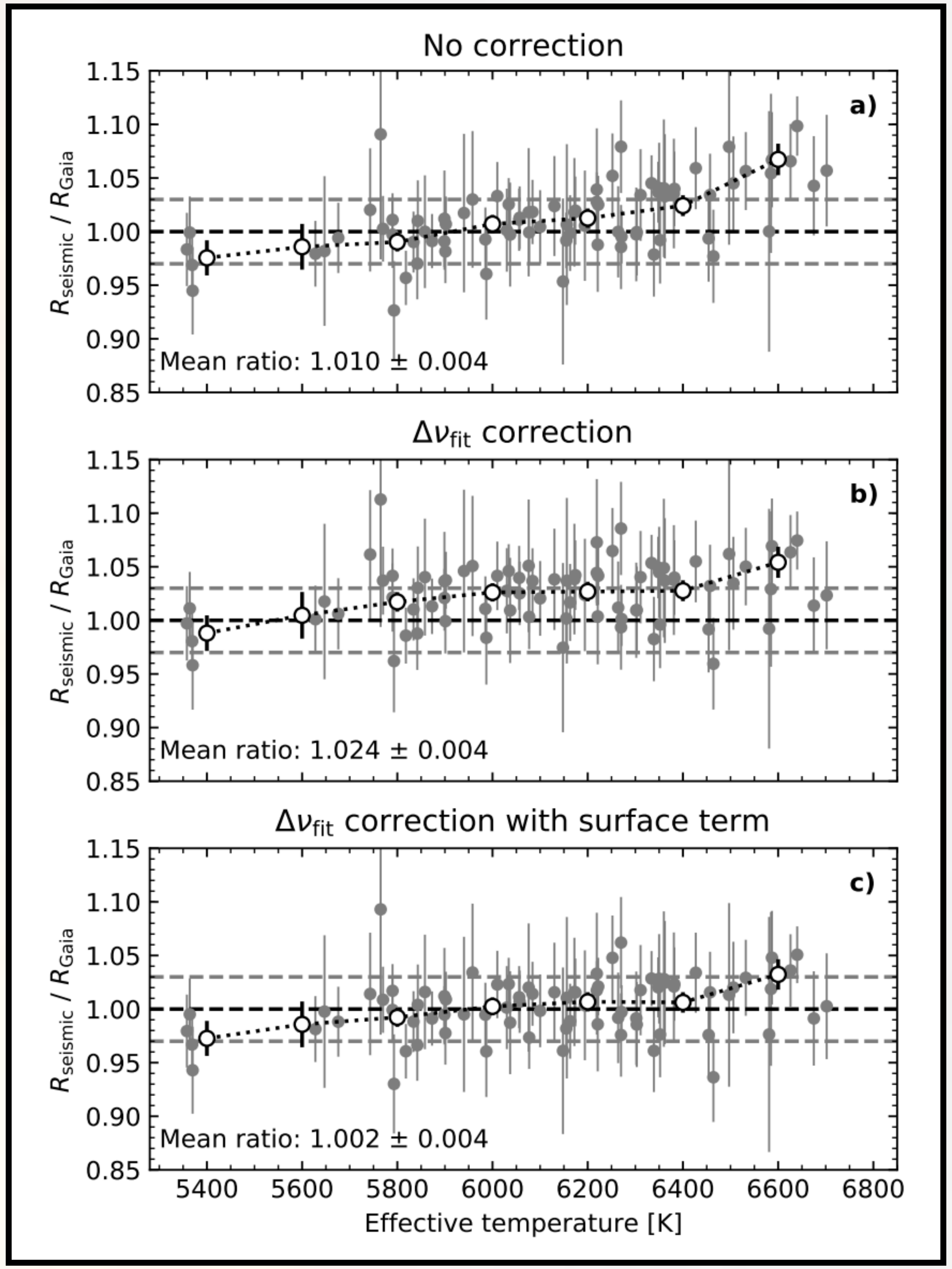
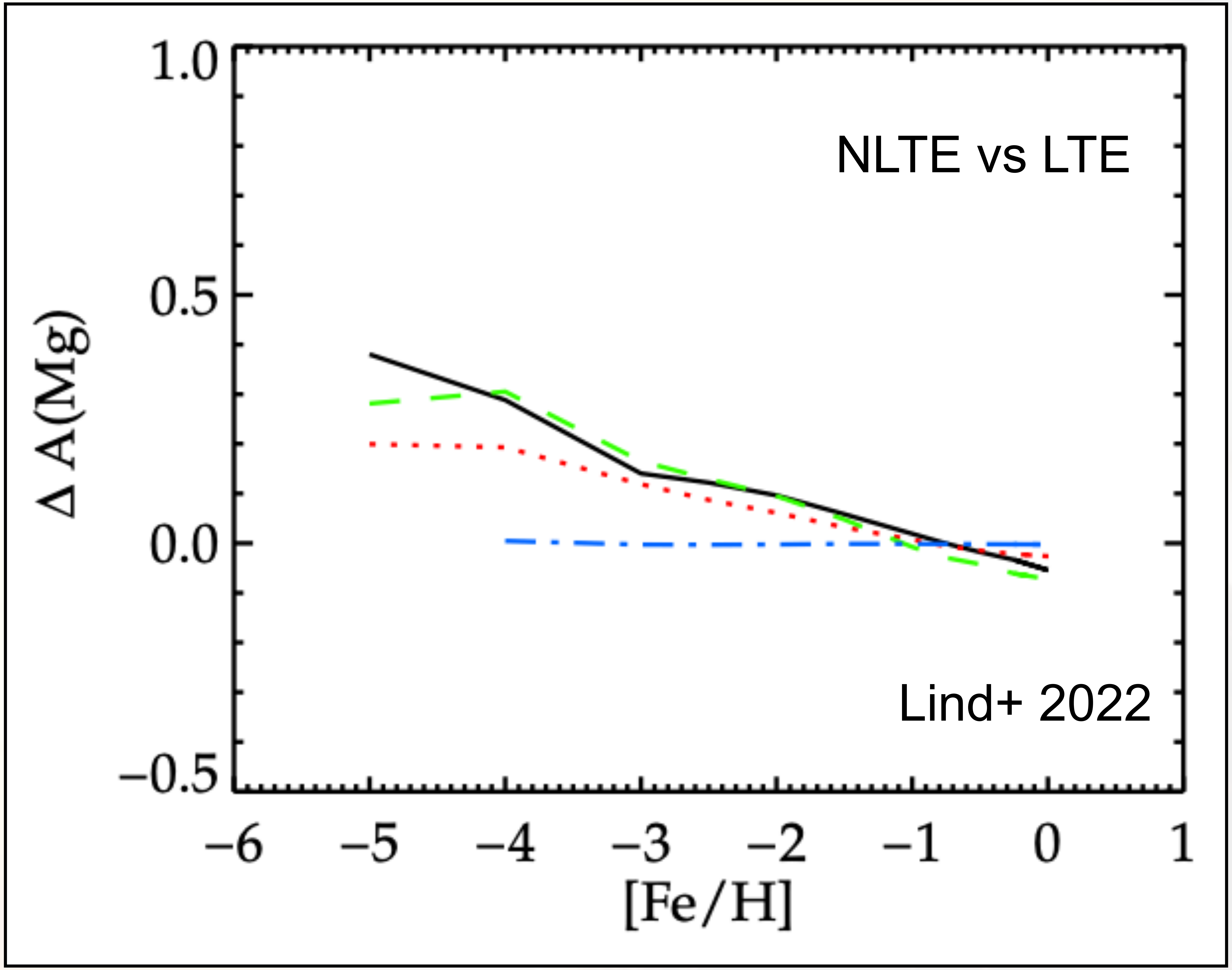
Asteroseismology versus Gaia



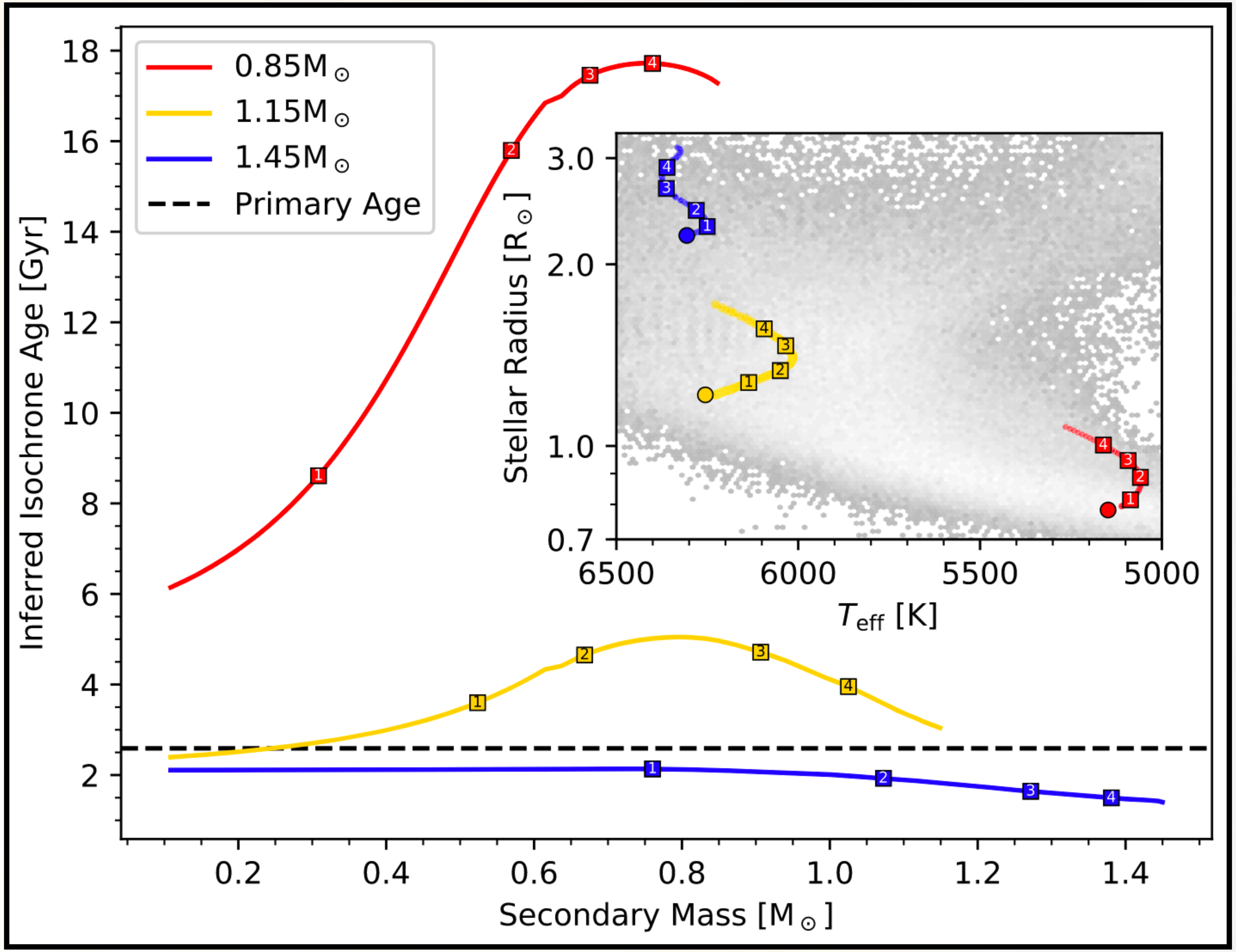


Sahlholdt & Silva Aguirre 2018



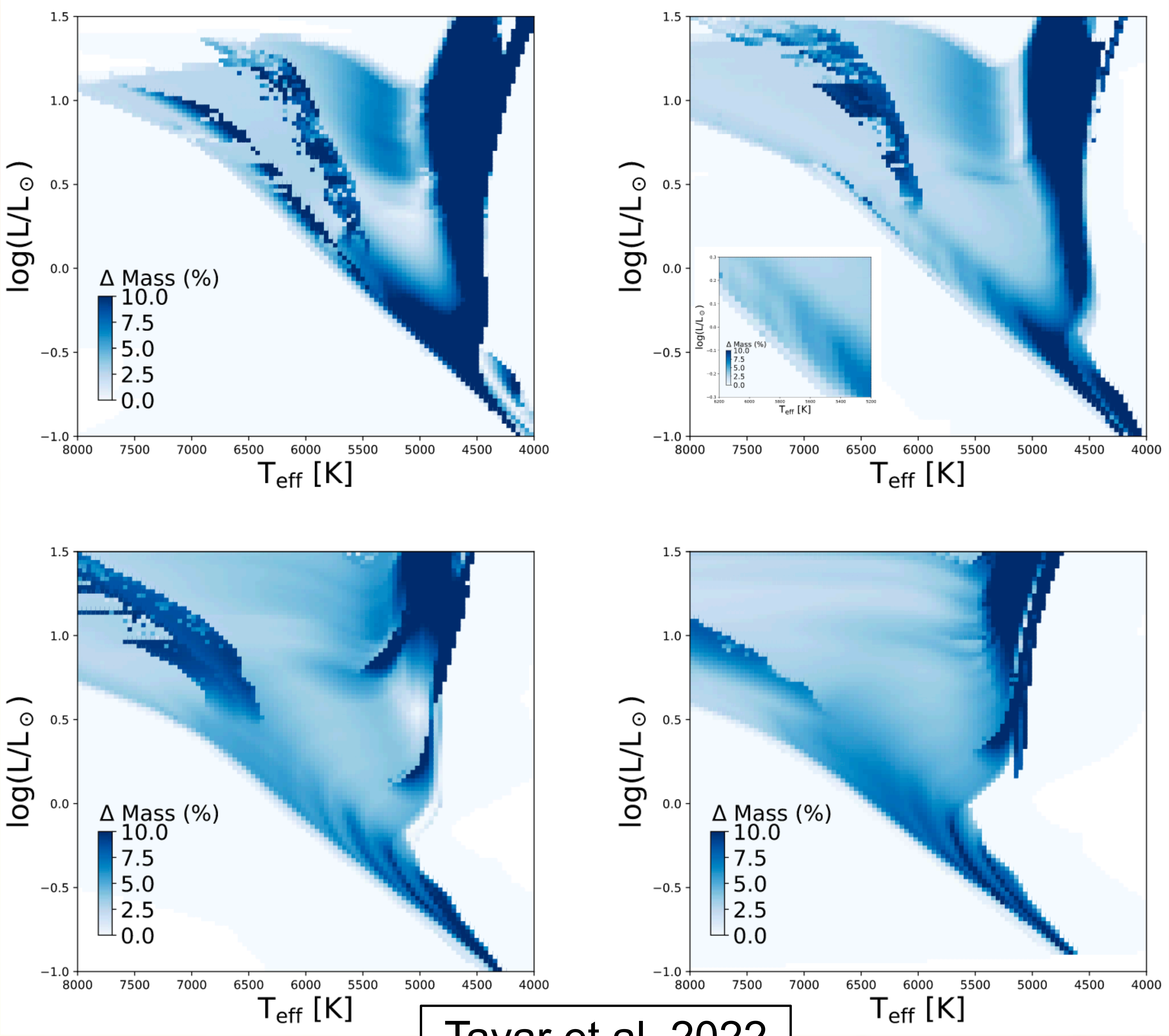
NLTE vs LTE
Lind+ 2022
1.0
0.5
0.0
−0.5
Δ A(Mg)
−6
−5
−4
−3
−2
−1
0
1
[Fe/H]

Effects of Unresolved Binaries



Berger+ 2018

Caveat: Stellar models have systematic errors



Tayar et al. 2022

Source of systematics: uncertain input physics such as convection, atmospheric boundary conditions, rotation, opacities and overshoot

Sets **error floor of ~5% in mass and ~20% in age** for solar-type stars, with variation across HRD

Always a good idea to establish systematic errors by using **different model grids**!

Effective Temperatures

$$4\pi \int_0^\infty H_\nu \, d\nu = \sigma T_{\text{eff}}^4$$

T_{eff} characterizes the total radiative flux transported through the atmosphere.

It can be regarded as an average of the temperature over depth in the atmosphere.

A blackbody radiating the same amount of total energy would have a temperature $T = T_{\text{eff}}$.

$$F = \sigma T_{\text{eff}}^4 \longrightarrow \begin{matrix} F = f_{\text{bol}}\, d^2/R^2 \\ R = d\, \alpha/2 \end{matrix} \longrightarrow T_{\text{eff}} = (4\, f_{\text{bol}} / \sigma\, \alpha^2)^{1/4}$$

Effective Temperature is *defined* through angular diameter & bolometric flux