Astrometry & Exoplanet Host Star Properties

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Stellar Properties: what are they and what can we measure?

What are some examples of fundamental stellar properties?

?

Fundamental

Effective Temperature (T_{eff})

Radius (R)

Mass (M)

Chemical Composition

Surface Gravity (g)

Luminosity (L)

Density (ρ)

Age

Observed

Color

Spectral Type

Luminosity Class

Rotation Period

Activity Level / Cycle

Multiplicity

Fundamental Properties of Stars

Effective Temperature (T_{eff})

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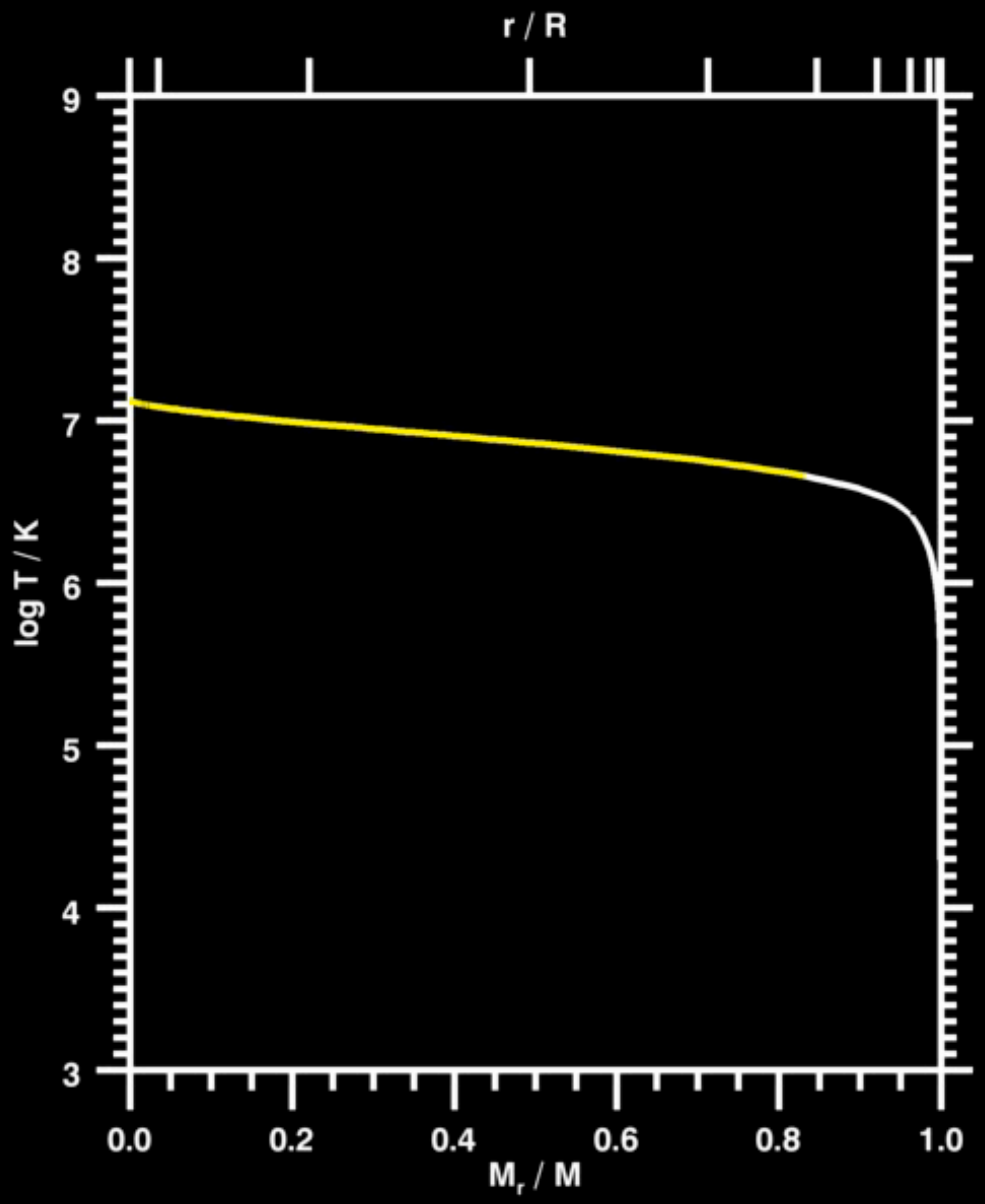
Most fundamental properties are not independent

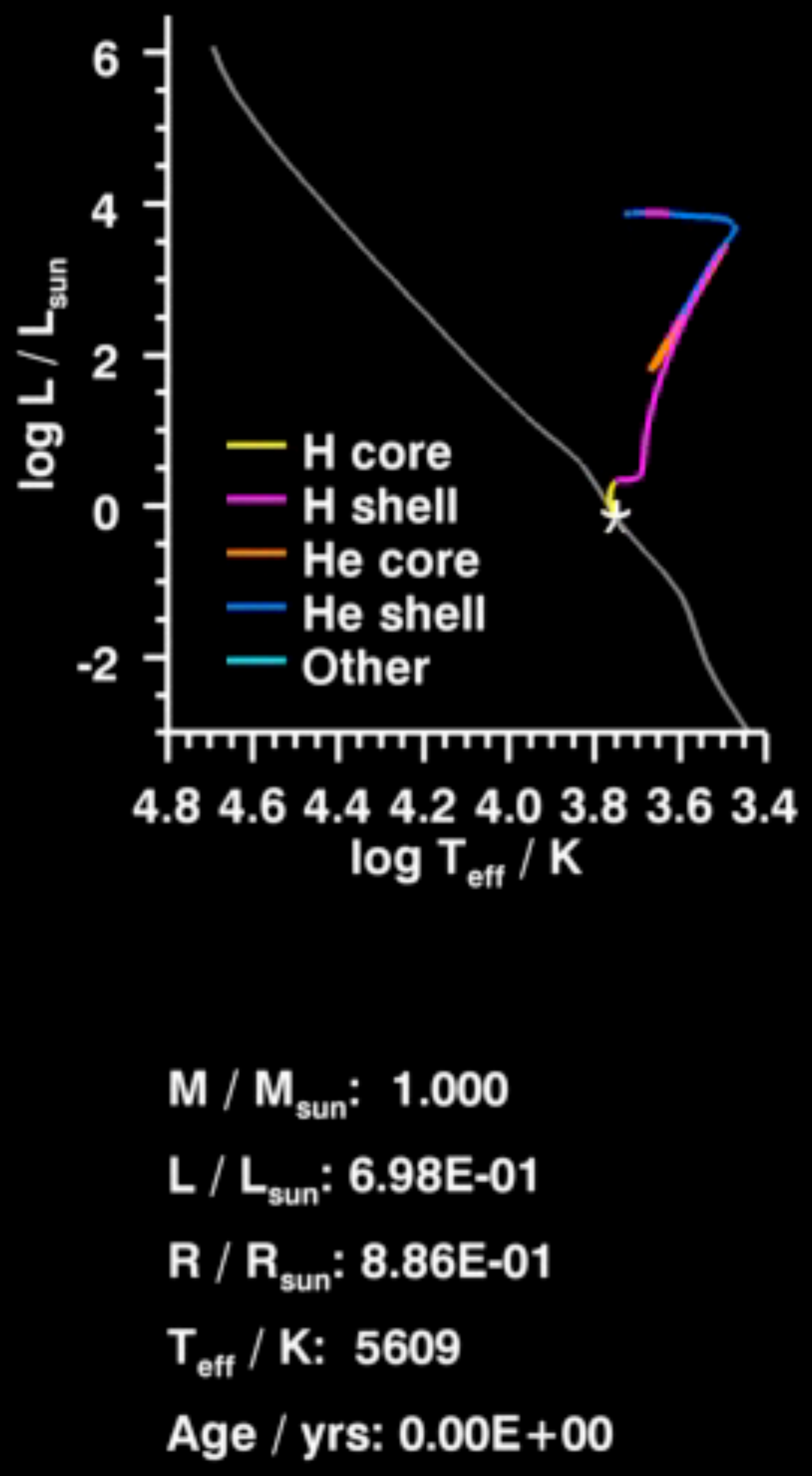
$$\rho \propto M/R^3$$

$$g \propto M/R^2$$

$$L \propto R^2 T_{eff}^4$$

Assumes: atmospheres are thin & stars ~ blackbodies



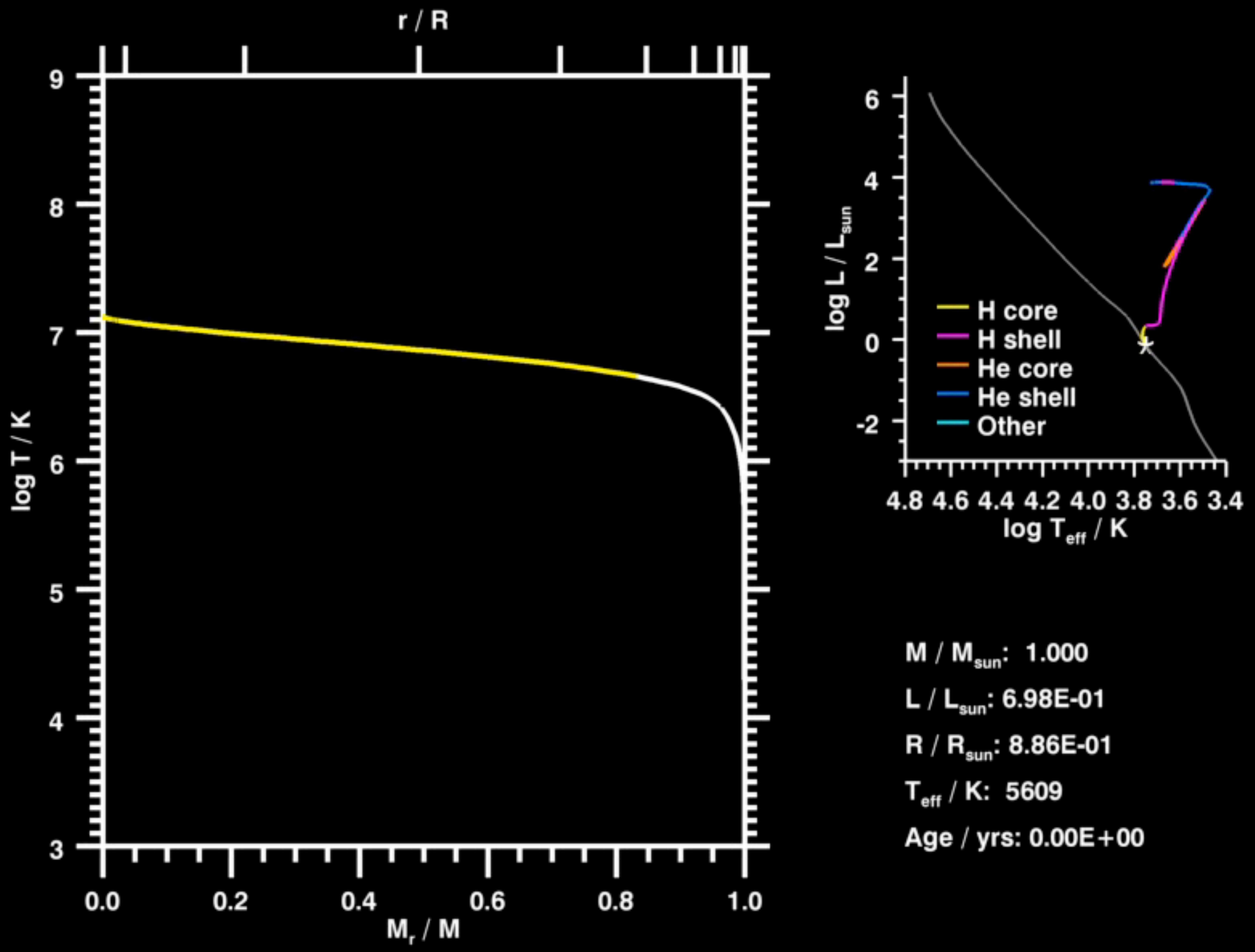


Mass, composition & age uniquely define other fundamental stellar properties

(Vogt-Russell "Theorem")

Rich Townsend

(http://www.astro.wisc.edu/~townsend)



Rich Townsend

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Mass, composition & age uniquely define other fundamental stellar properties

(Vogt-Russell “Theorem”)

Unfortunately, mass & age (+ some elements such as He) are hard to measure!

Fundamental Properties of Stars

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Age

"Easy"

Possible

Hard

Astrometry is critical for inferring ~ all fundamental parameters of stars

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Stellar Luminosity: Distance Modulus

$$m_b - M_b = \quad 5\log_{10}(d) - 5 + A_b$$

observed (apparent) magnitude in band b

d=10pc (absolute) magnitude in band b

distance in pc

interstellar extinction in band b

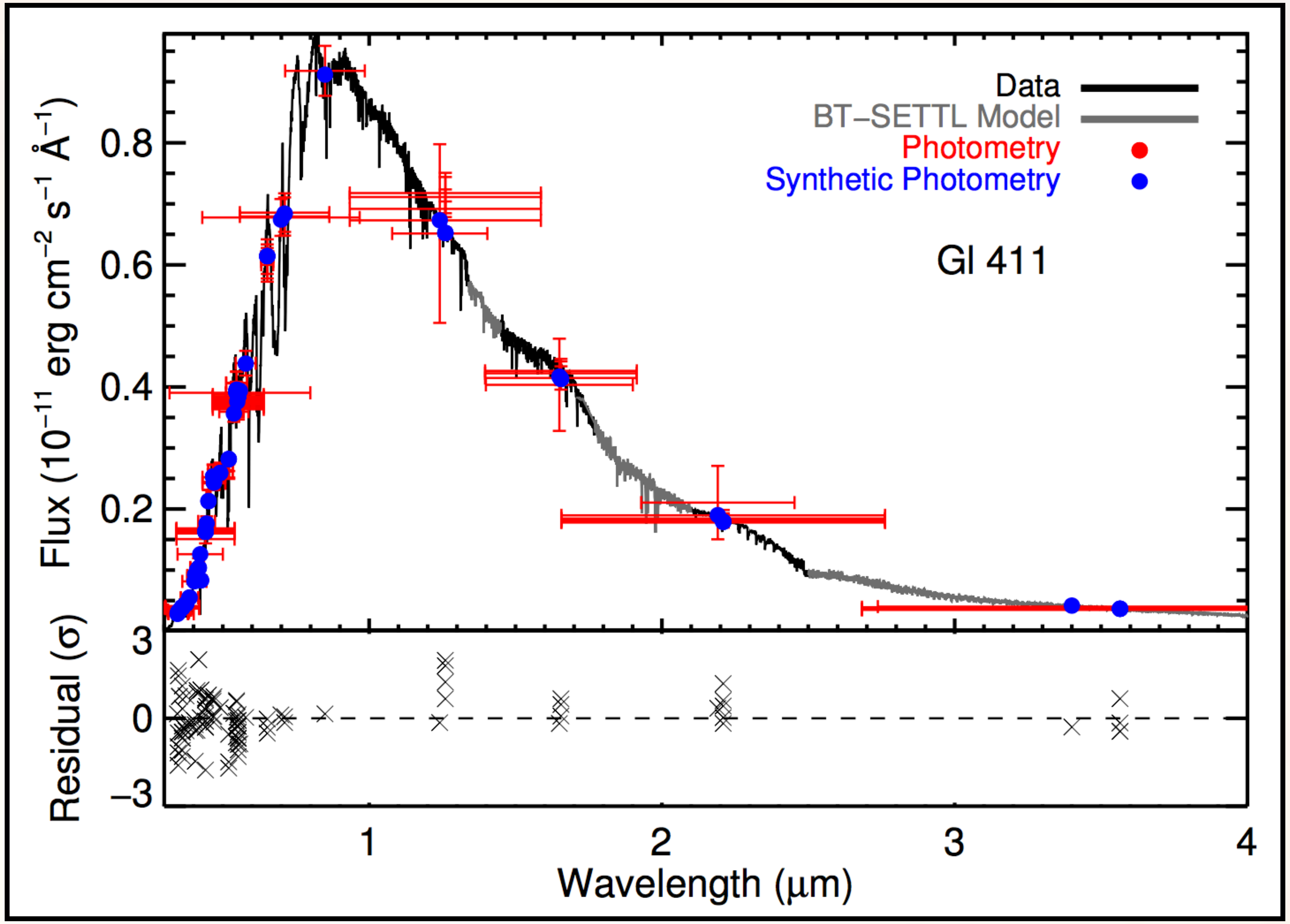
$$M_{\mathrm{bol}} = M_b + BC_b$$

BC = bolometric correction (from model atmospheres)

$$M_{\mathrm{bol}} - M_{\mathrm{bol},\odot} = -2.5\log_{10}(L/L_\odot)$$

Advantage: Observables (m_b & d) are available for lots of stars
Disadvantange: Need to be confident in your BC and extinction model!

Bolometric Fluxes: SED Fitting



Mann+ 2016

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

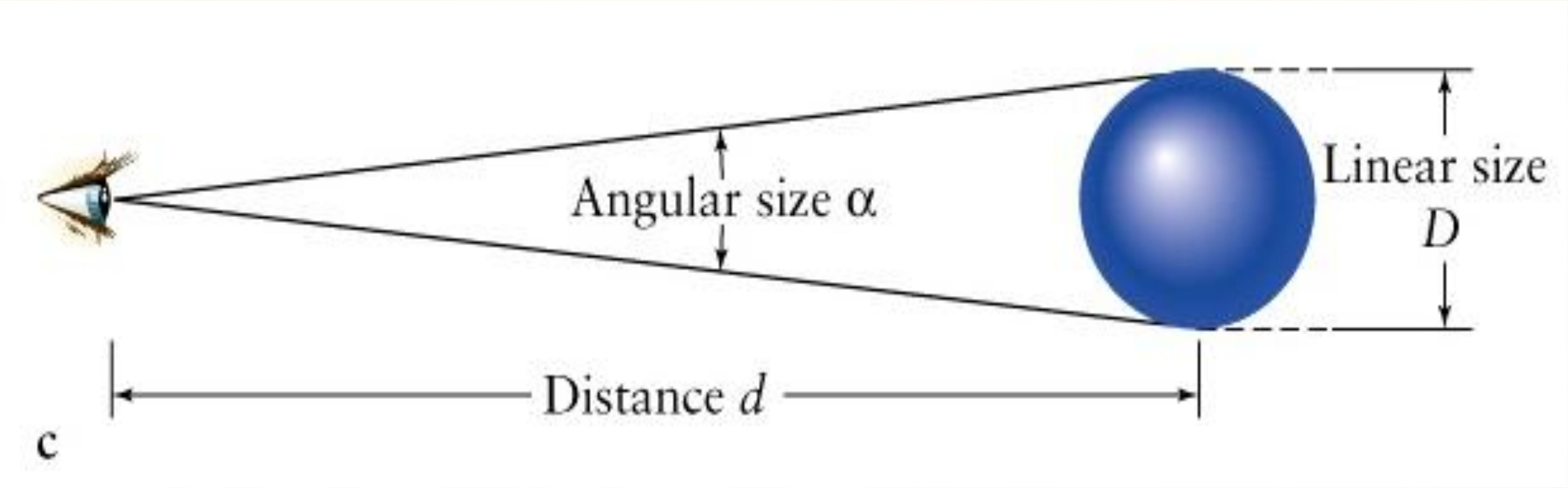
Advantage: Less model dependent than bolometric corrections

Disadvantage: Zeropoint offsets between photometric surveys

Challenge (also true for BCs): Depends on T_{eff} and extinction, which are highly degenerate

Gaia Bp/Rp spectra are critical for this! See Orlagh's talk tomorrow

Stellar Radii from Parallaxes

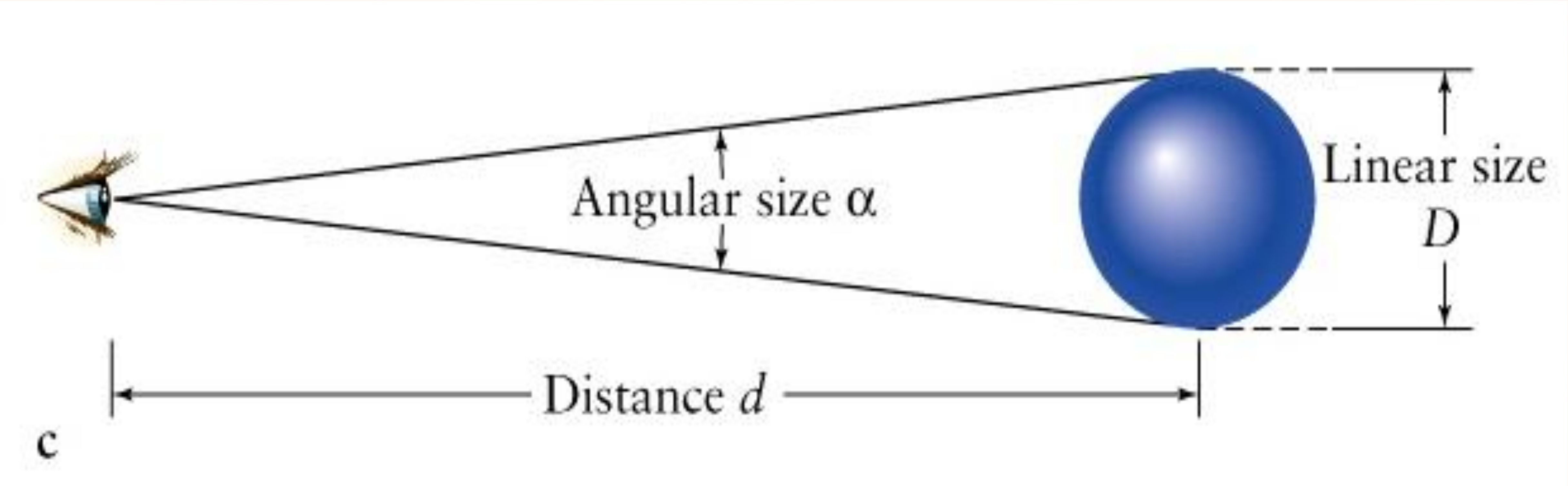


$$R = d\,\alpha/2$$

Angular size + Distance gives a direct measurement of the star's Radius

Problem: stellar diameters are small and require interferometry to be resolved.
More on this by Roxanne tomorrow!

Stellar Radii from Parallaxes



$R = d\,\alpha/2$

Angular size + Distance gives a direct measurement of the star's Radius

Problem: stellar diameters are small and require interferometry to be resolved.
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Alternative: Stefan-Boltzmann Law

$$R_\star = \sqrt{\frac{F_{\rm bol} d^2}{\sigma T_{\rm eff}^4}}$$

But what is T_{eff} and how well do we know it?

Effective Temperatures

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

$T_{\rm eff}$ 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 $T = T_{\rm eff}$.

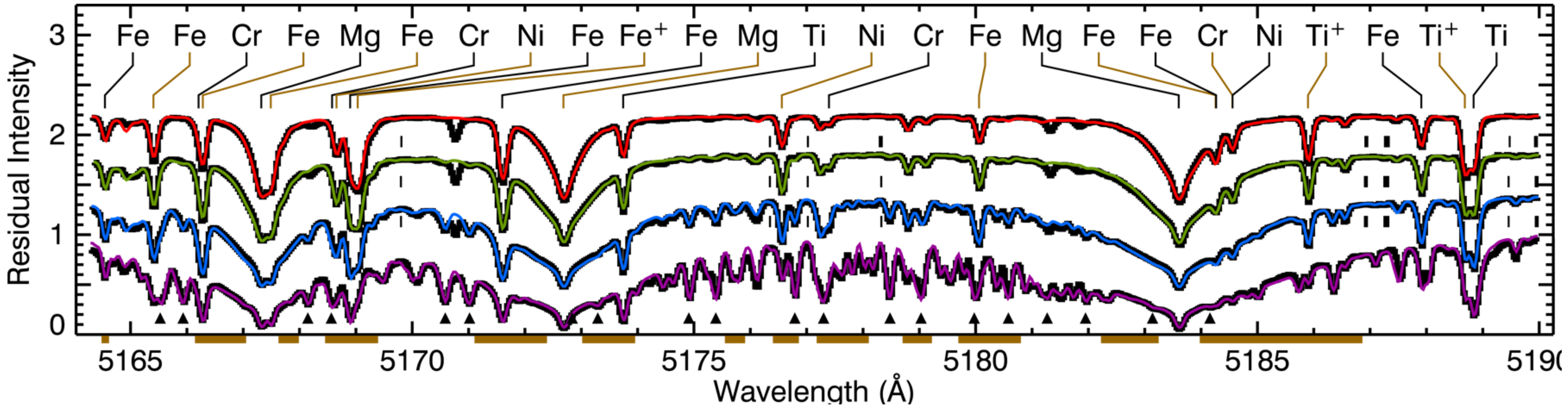
$F = \sigma T_{\rm eff}^4$ ⟶ $F = f_{\rm bol}\, d^2/R^2$, $R = d\, \alpha/2$ ⟶ $T_{\rm eff} = (4\, f_{\rm bol} / \sigma\, \alpha^2)^{1/4}$

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

Effective Temperatures

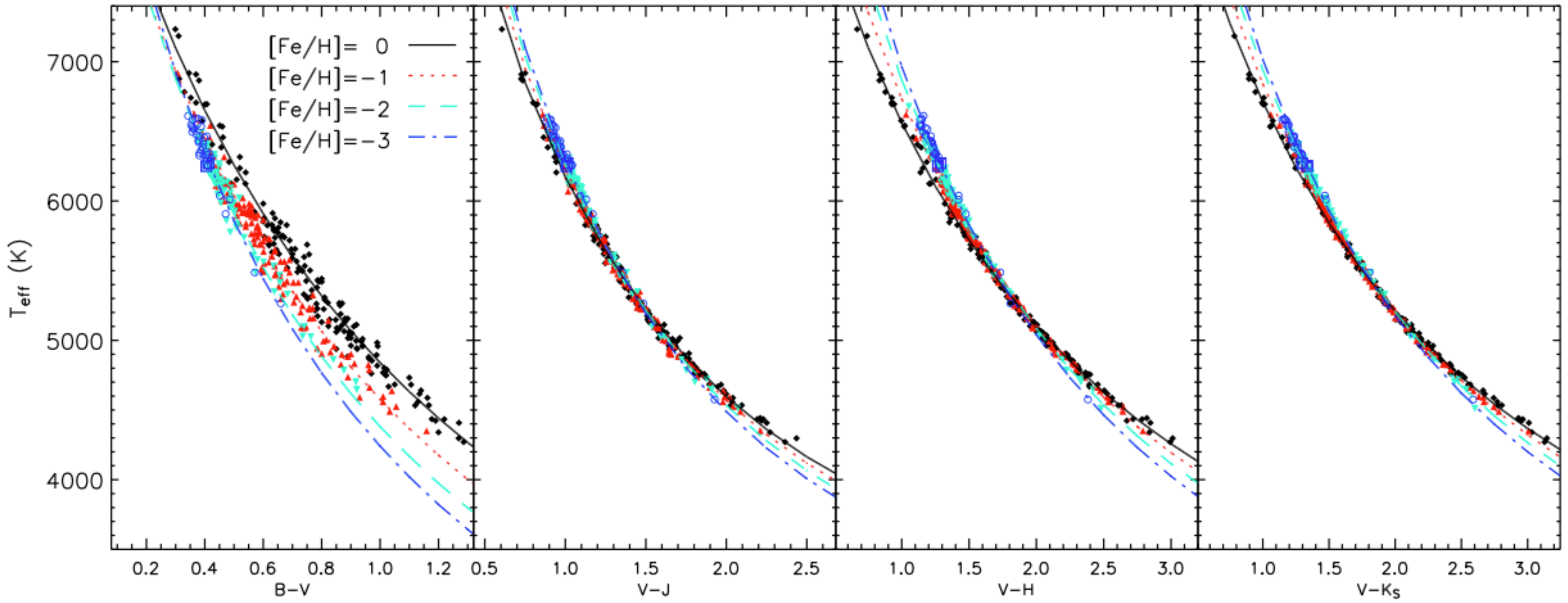
$$R_\star = \sqrt{\frac{F_{\mathrm{bol}} d^2}{\sigma T_{\mathrm{eff}}^4}}$$

High-Resolution Spectroscopy



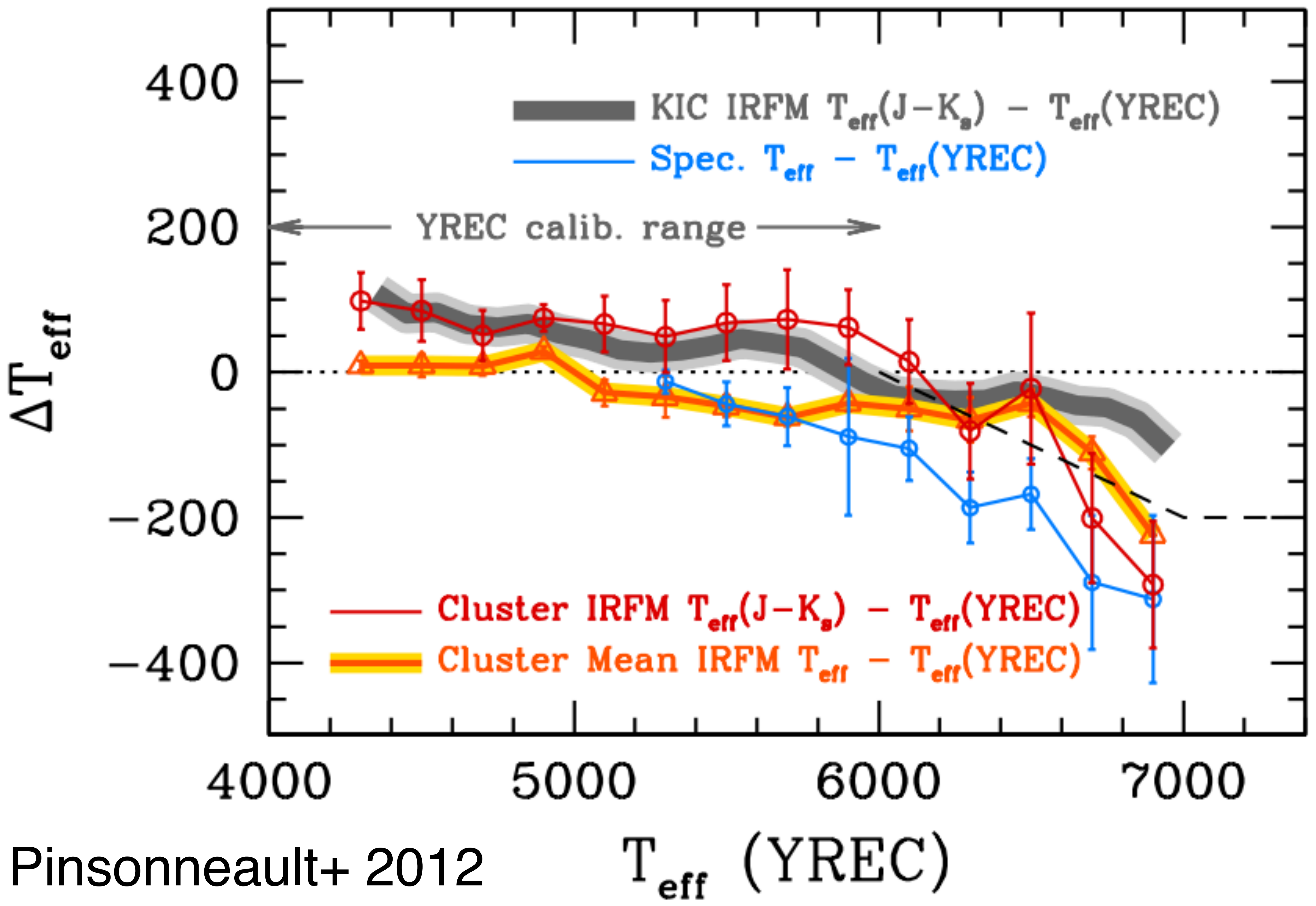
Petigura 2015

Color-T_{eff} Relations, SED, IRFM



Casagrande+ 2010

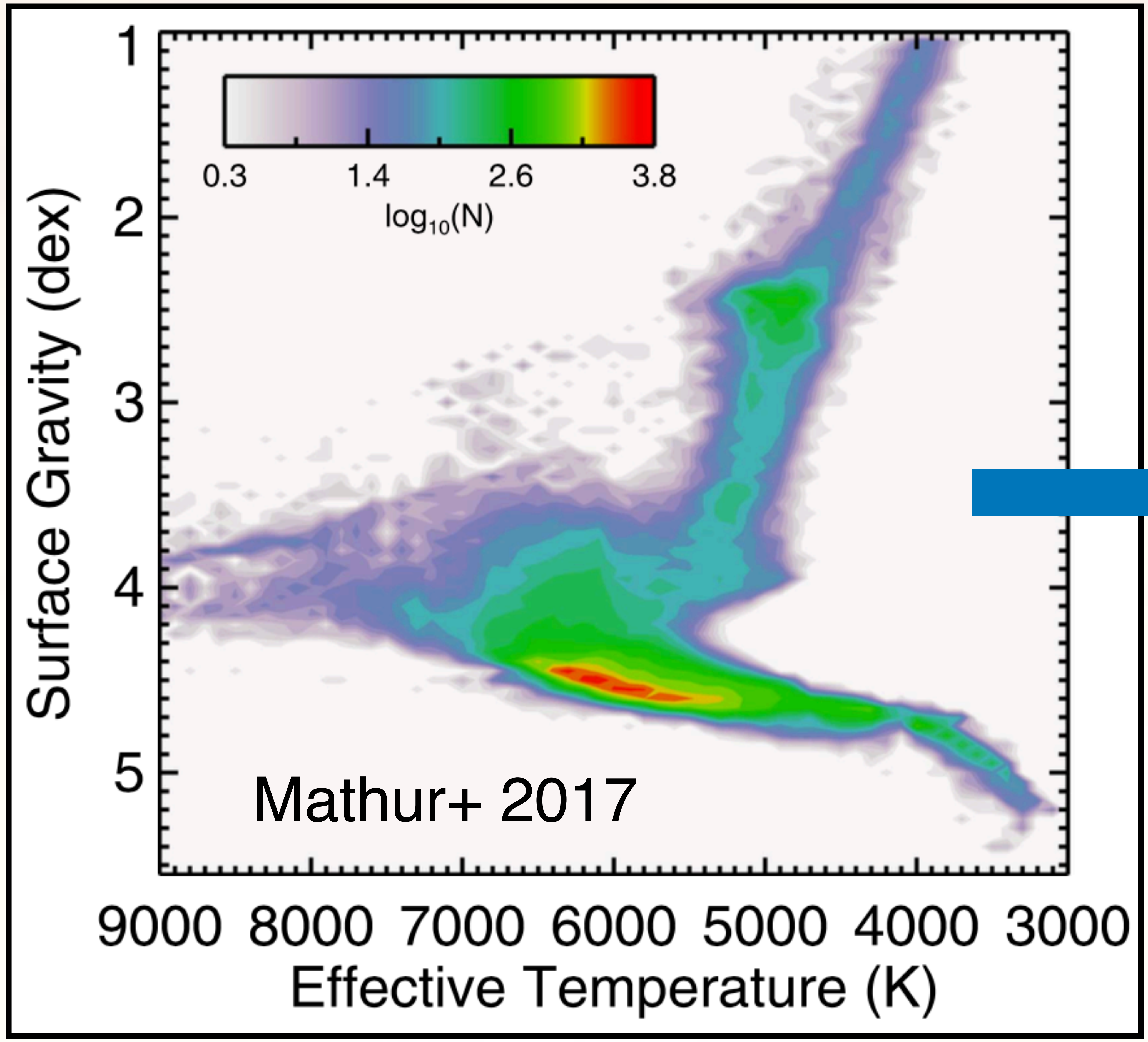
T_{eff} from different methods (and absolute scale) can vary by up to ~2%. Sets a floor of ~4% on stellar radii!

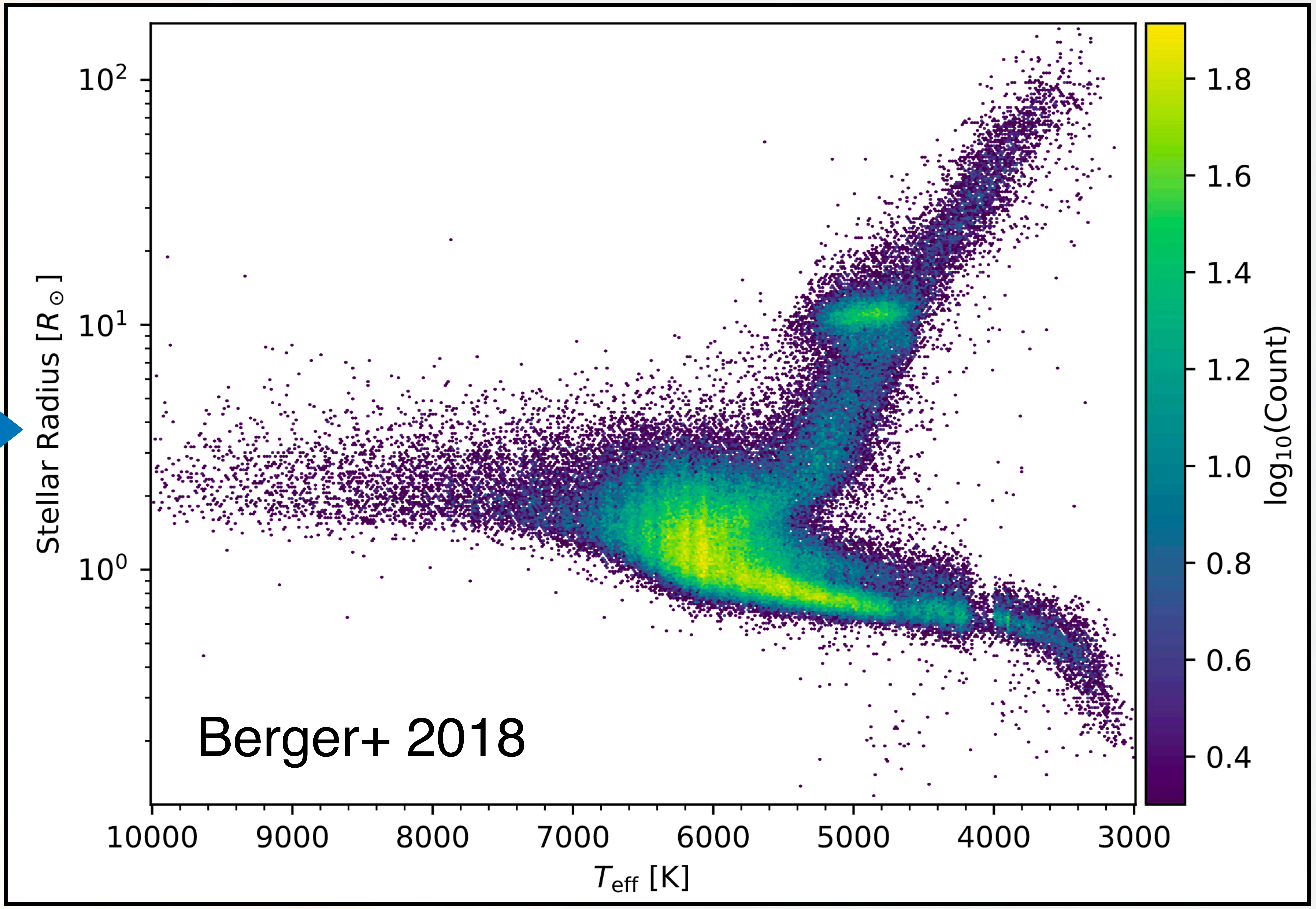


Pinsonneault+ 2012

pre-Gaia

post-Gaia

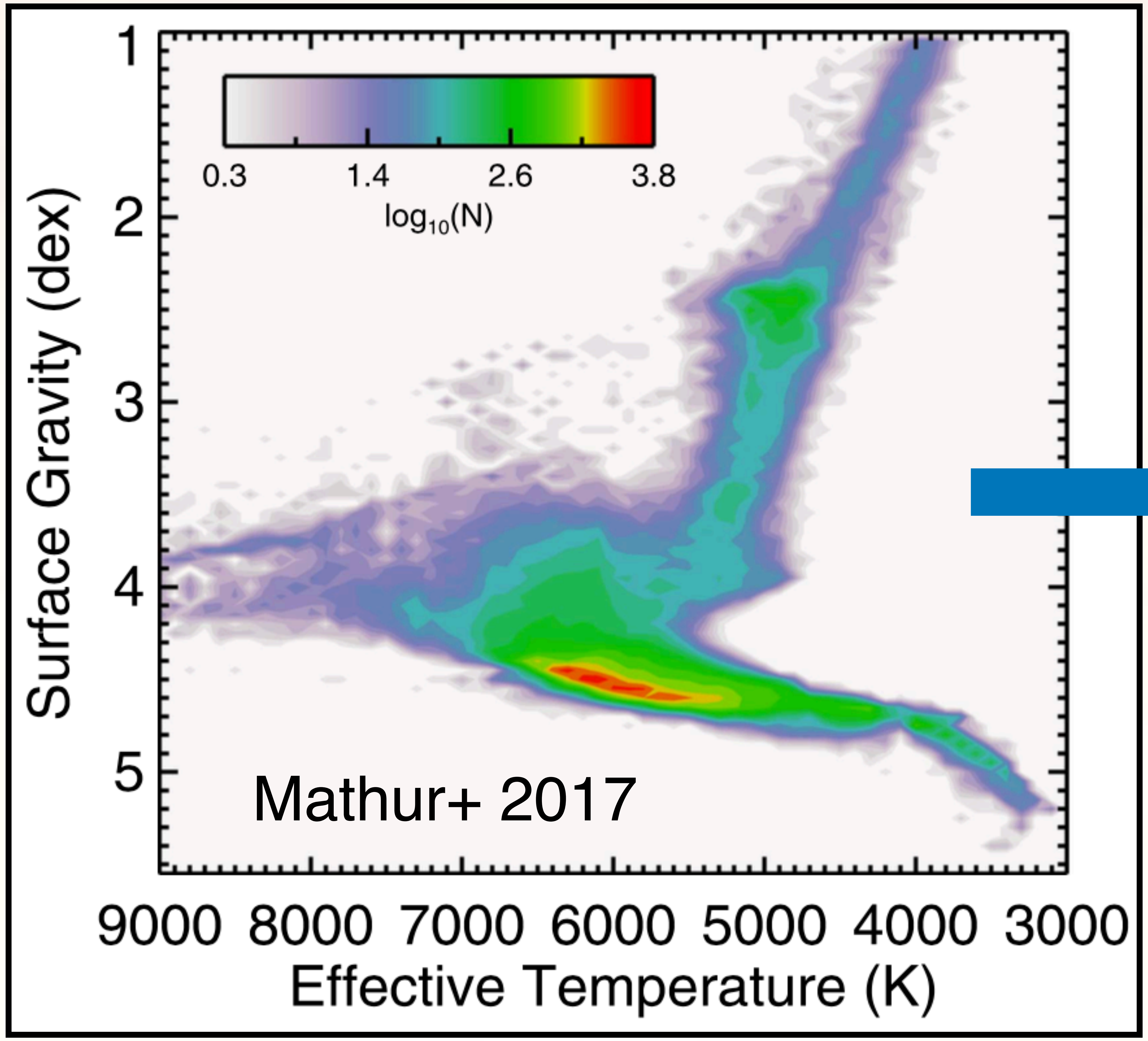


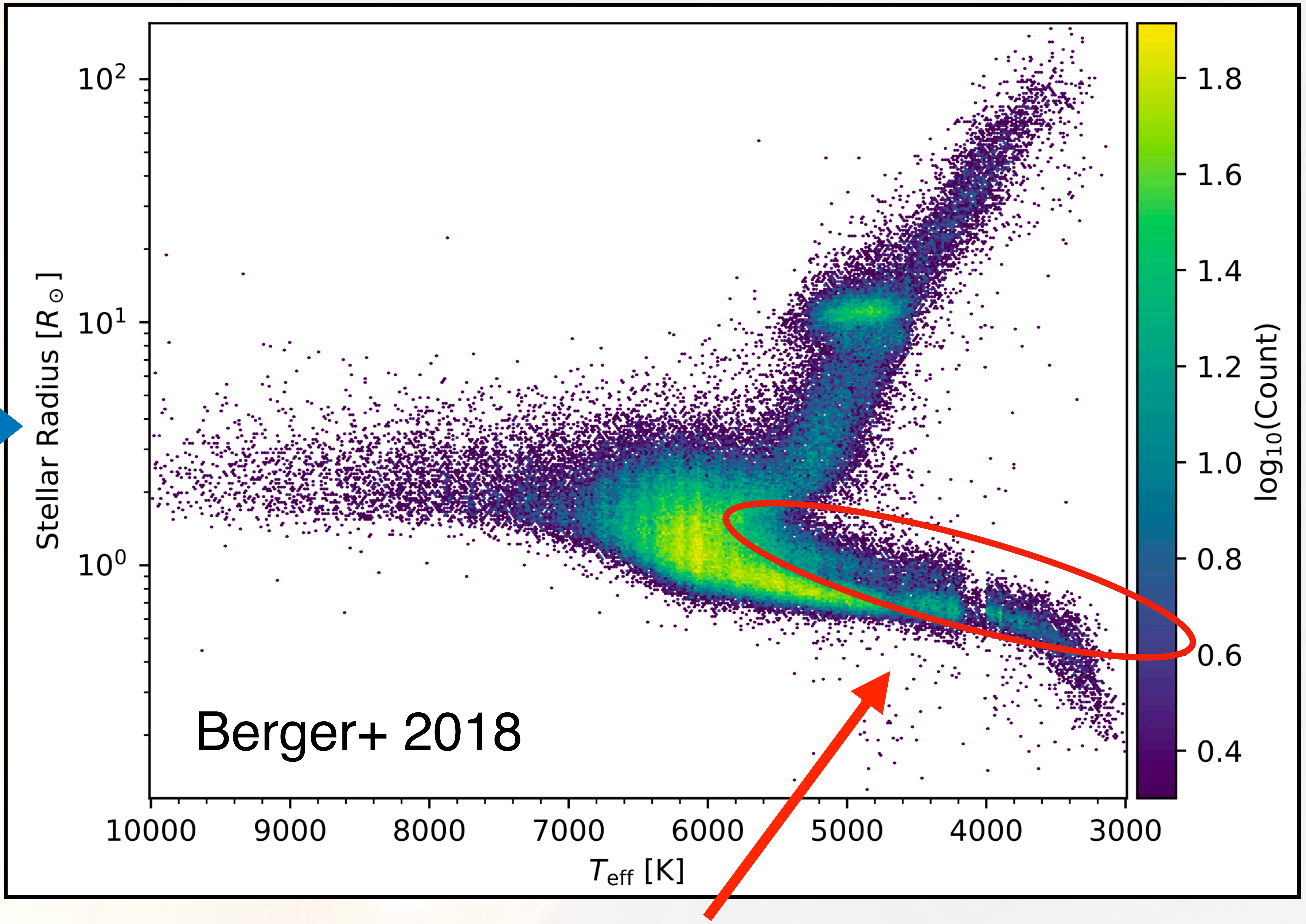


Gaia parallaxes decreased radius uncertainties for Kepler stars by a factor of ~5-6!

pre-Gaia

post-Gaia





Challenge (opportunity?): unresolved binaries. In general, causes overestimation of L and underestimation of T_{eff}

Fundamental Properties of Stars

Effective Temperature (T_{eff})

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Possible

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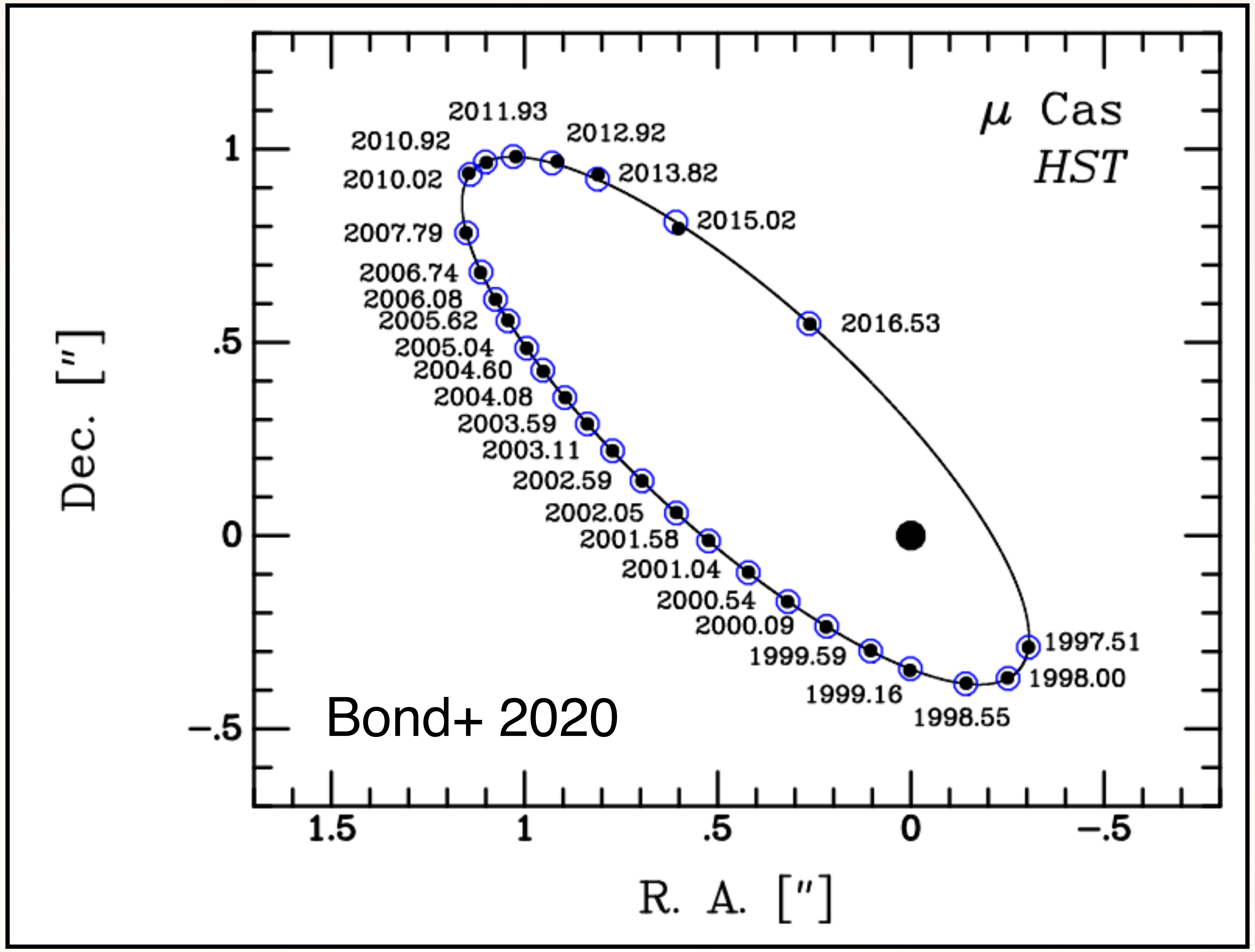
Astrometry is critical for inferring ~ all fundamental parameters of stars

Dynamical Masses from Astrometry

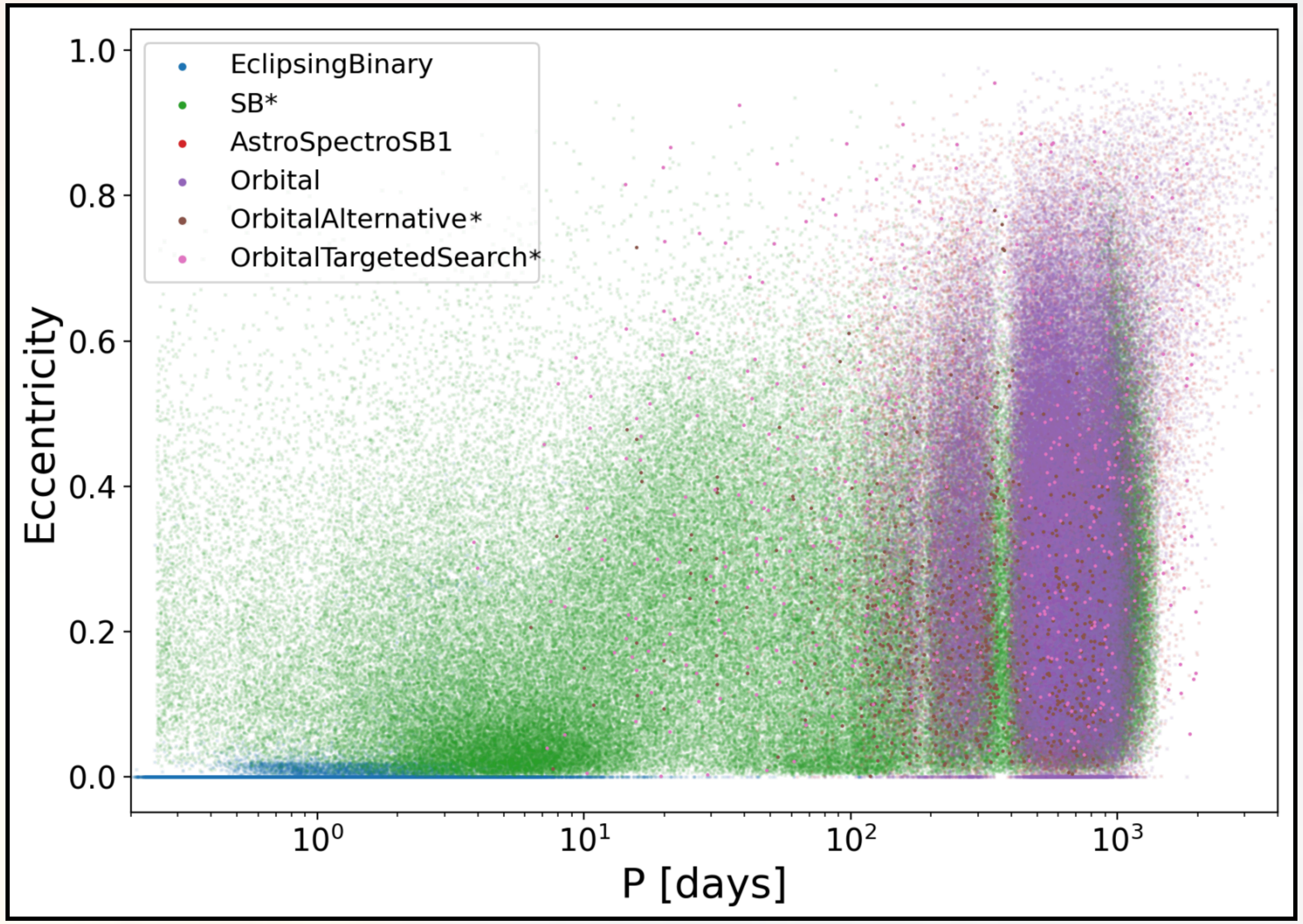


Bond+ 2020

~1-2% Masses!

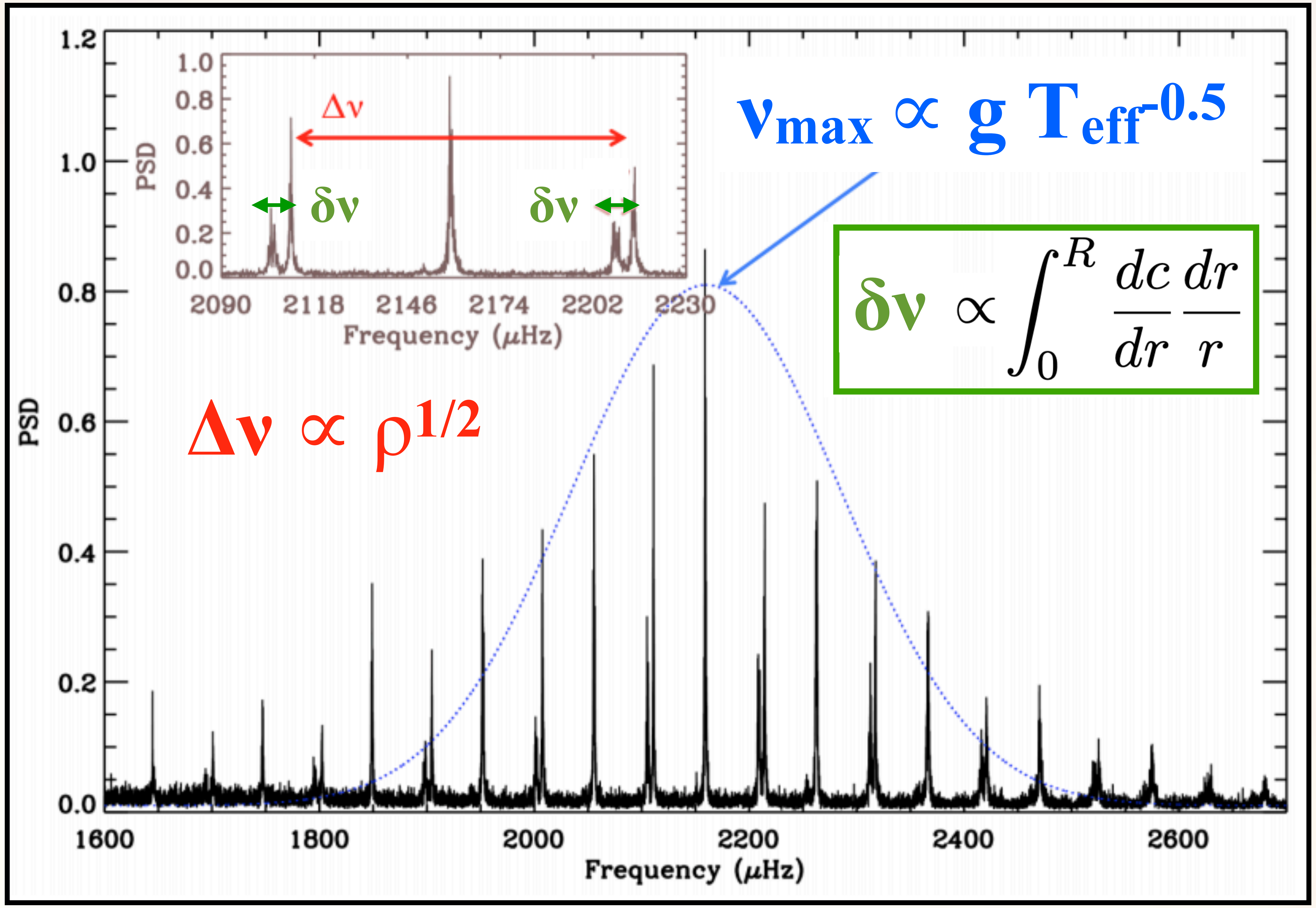
Quantity	This paper
Total mass, $M_A + M_B$	$0.9168 \pm 0.0148 M_\odot$
Mass of μ Cas A, M_A	$0.7440 \pm 0.0122 M_\odot$
Mass of μ Cas B, M_B	$0.1728 \pm 0.0035 M_\odot$

A hidden treasure: ~10^5 astrometric solutions from Gaia



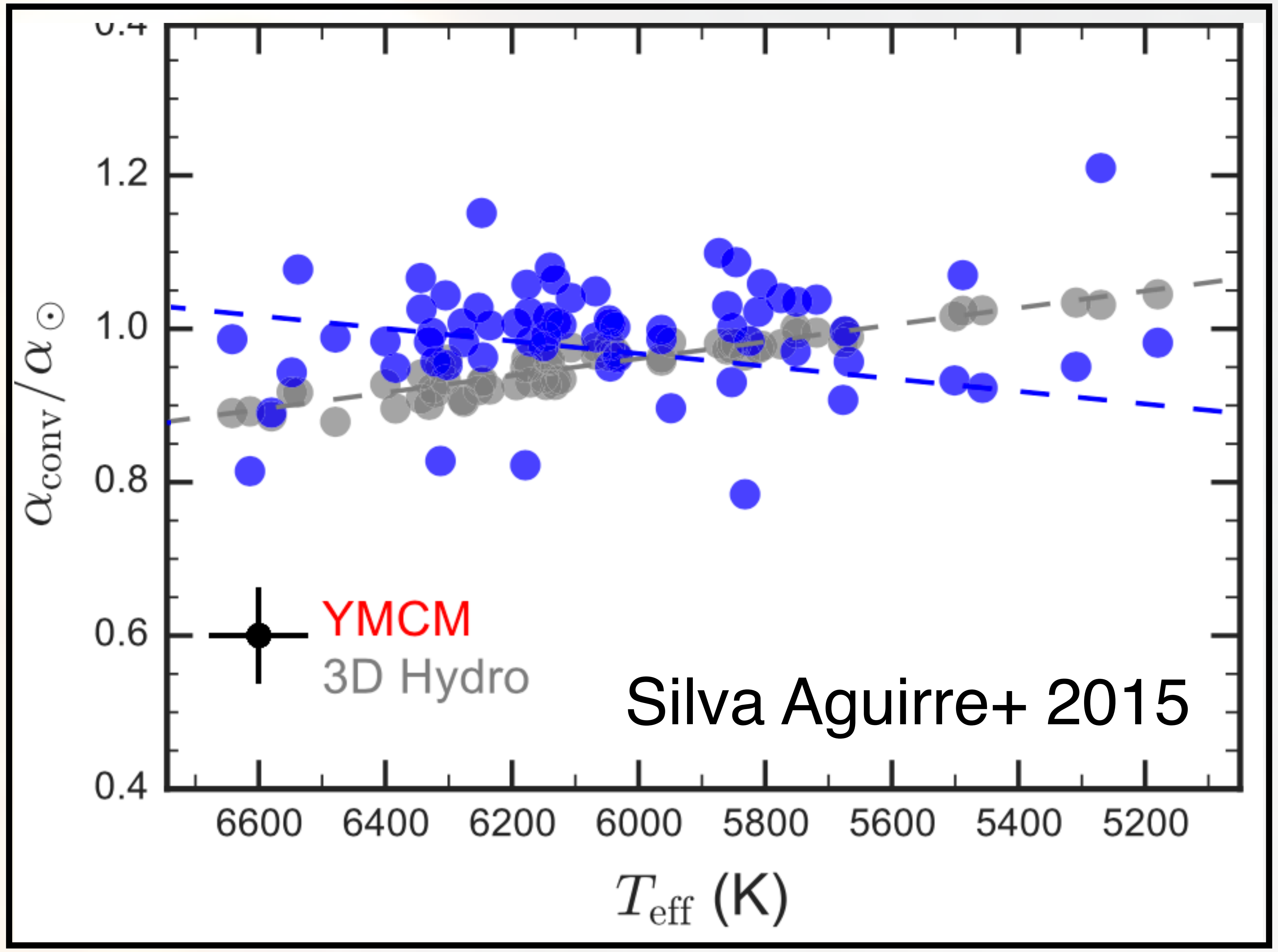
Gaia Collaboration+ 2022

Asteroseismology: Densities, log(g) & Ages

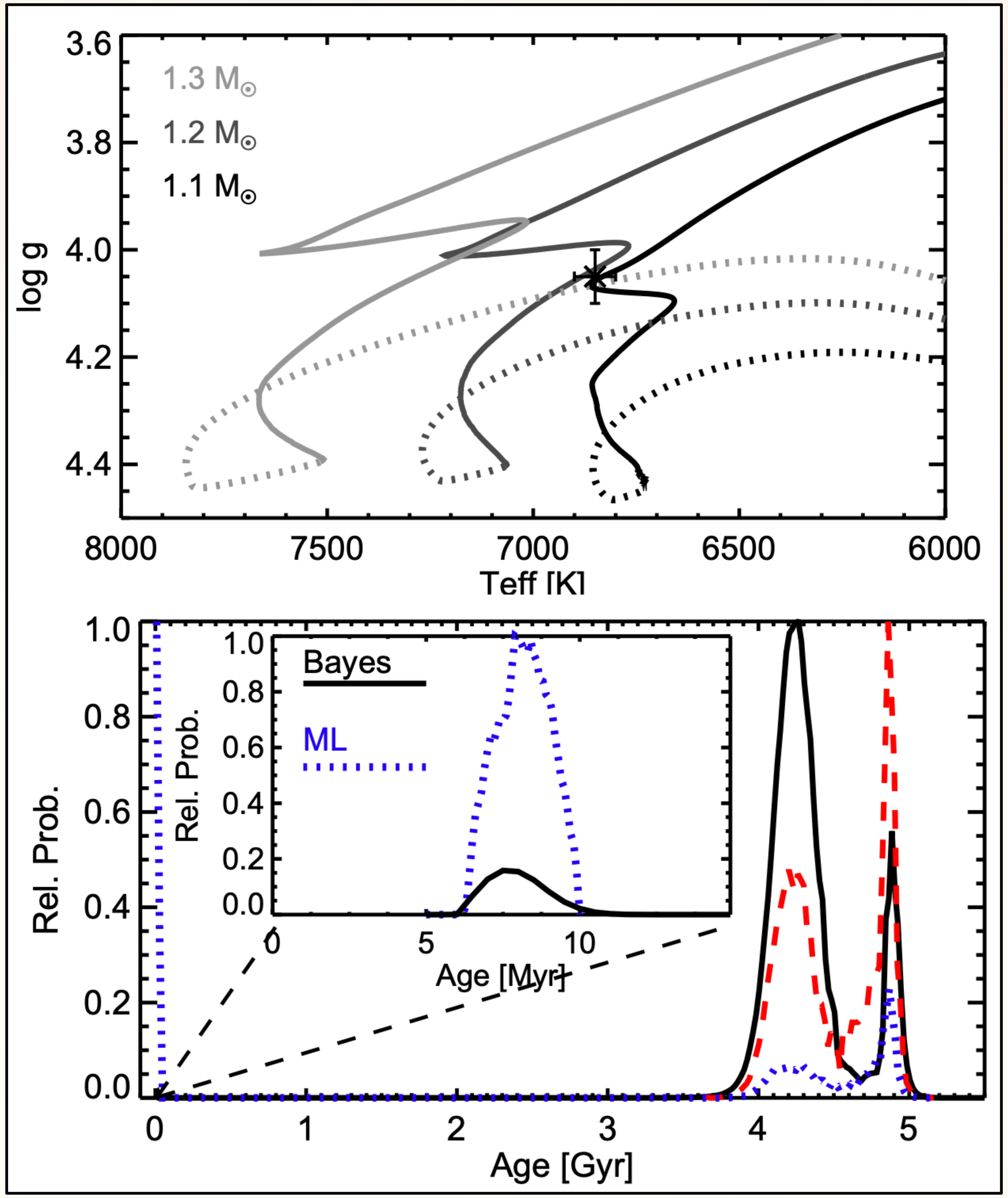


Garcia & Ballot 2019

Gaia luminosity is an important external constraint for testing model physics (e.g. convection)



Masses & Ages of Single Stars: "Isochrone" Fitting



Serenelli+ 2017

Models (Mass, Age, Composition) predict quantities to be compared to observations (T_{eff}, L, [M/H], absolute mag, colors)

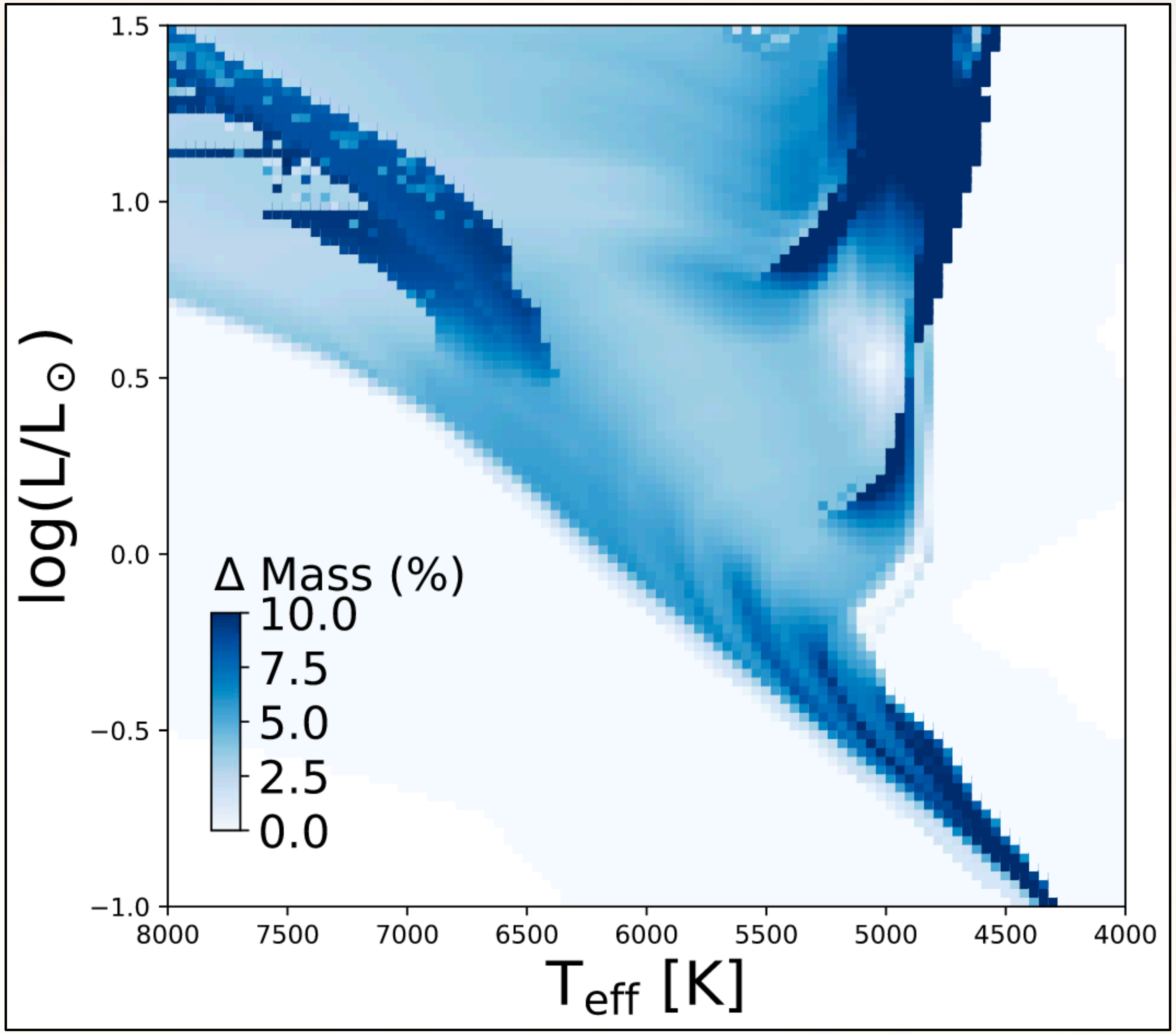
Available software tools (incomplete list!):

isochrones: https://github.com/timothydmorton/isochrones
isoclassify: https://github.com/danxhuber/isoclassify
BASTA: https://github.com/BASTAcode/BASTA
Param: http://stev.oapd.inaf.it/cgi-bin/param

Morton+ 2015, Huber+ 2017, Silva Aguirre+ 2022, da Silva+ 2006

Age diagnostics not discussed here: rotation, chemical abundances, kinematics & clusters (*more on this from Melissa & Marina tomorrow!*)

Caveat: Stellar models have systematic errors



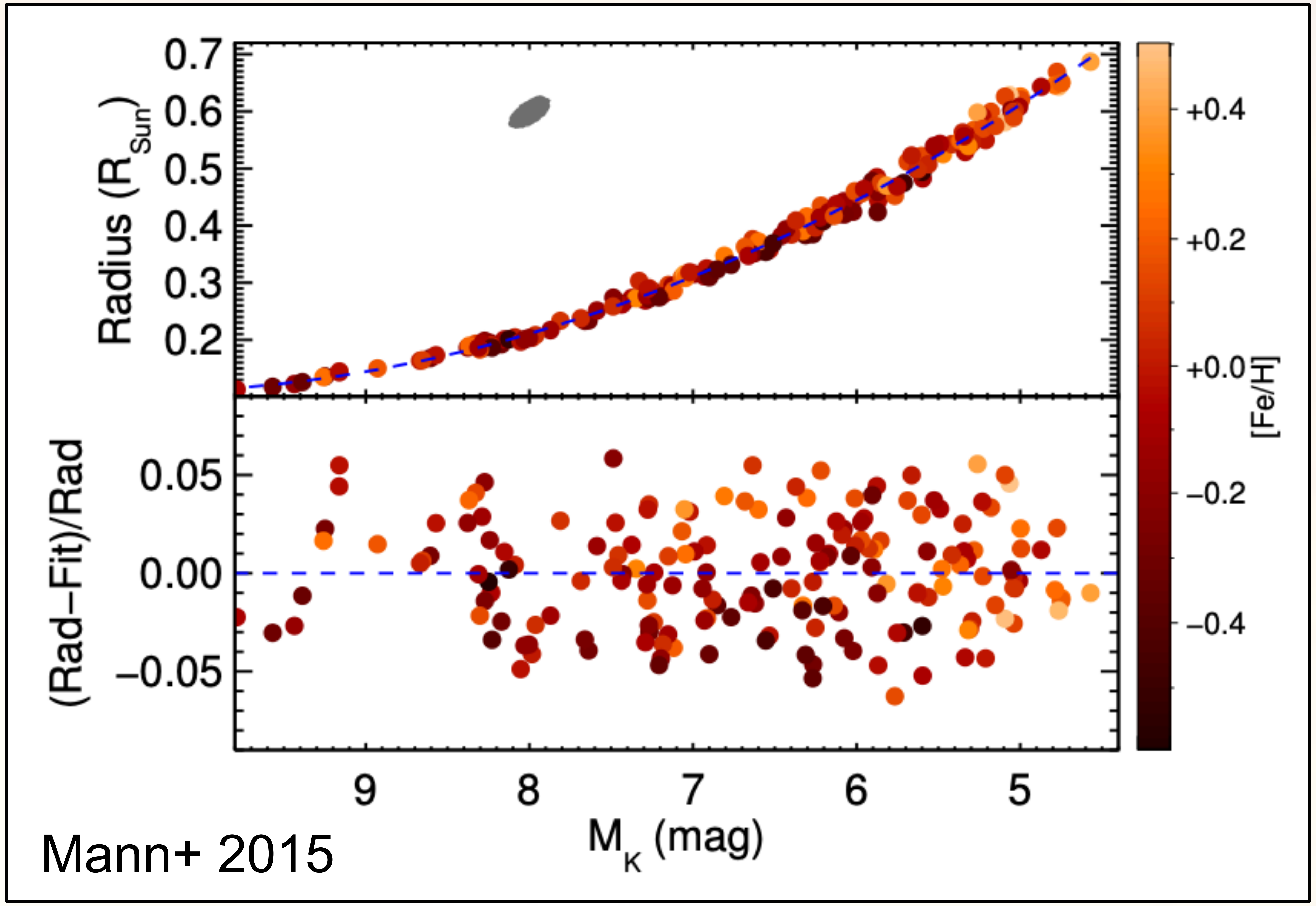
Tayar et al. 2022

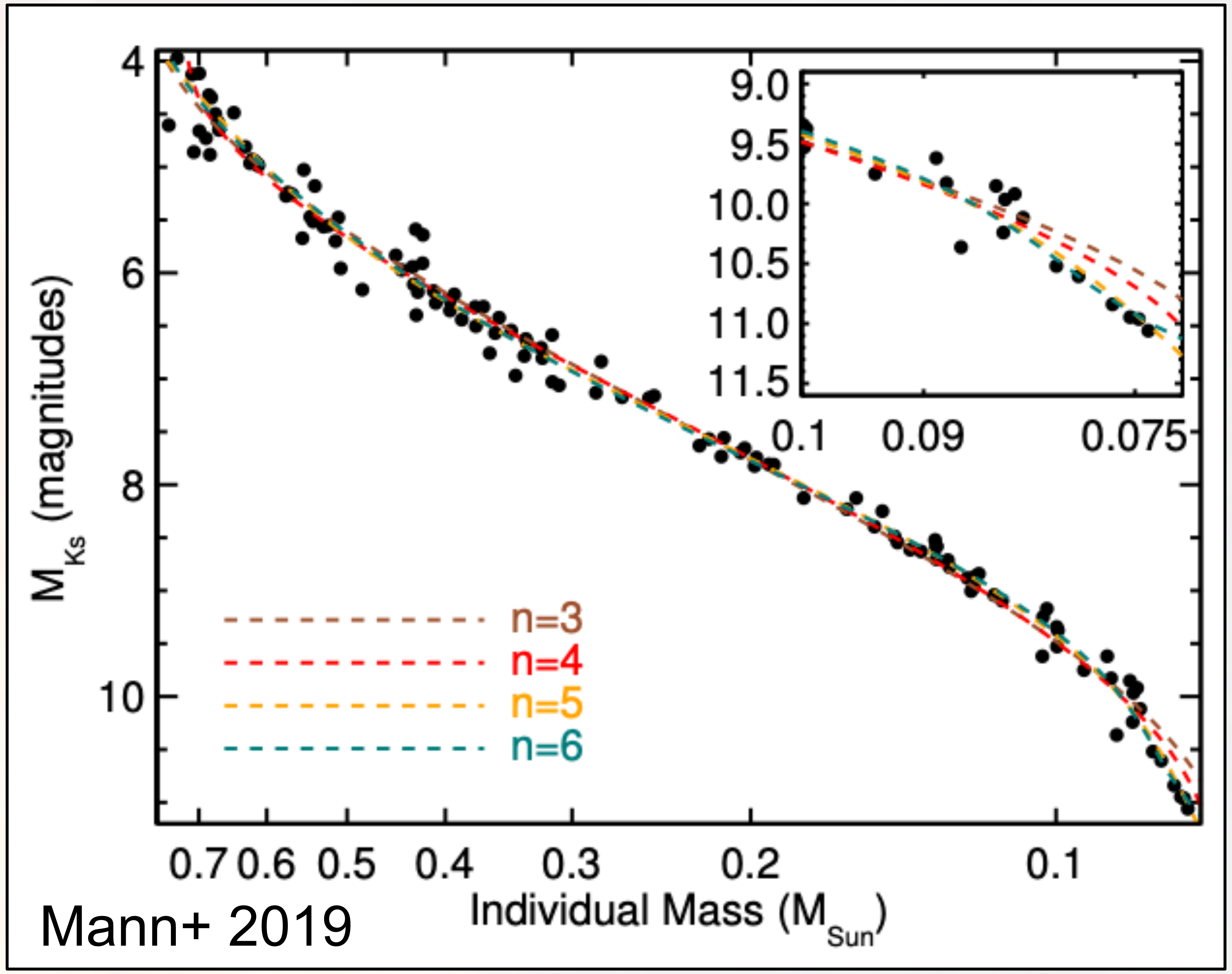
Source of systematics: uncertain input physics such as convection, atmospheric boundary conditions, rotation, opacities and overshoot

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**!

Empirical Relations for M Dwarfs

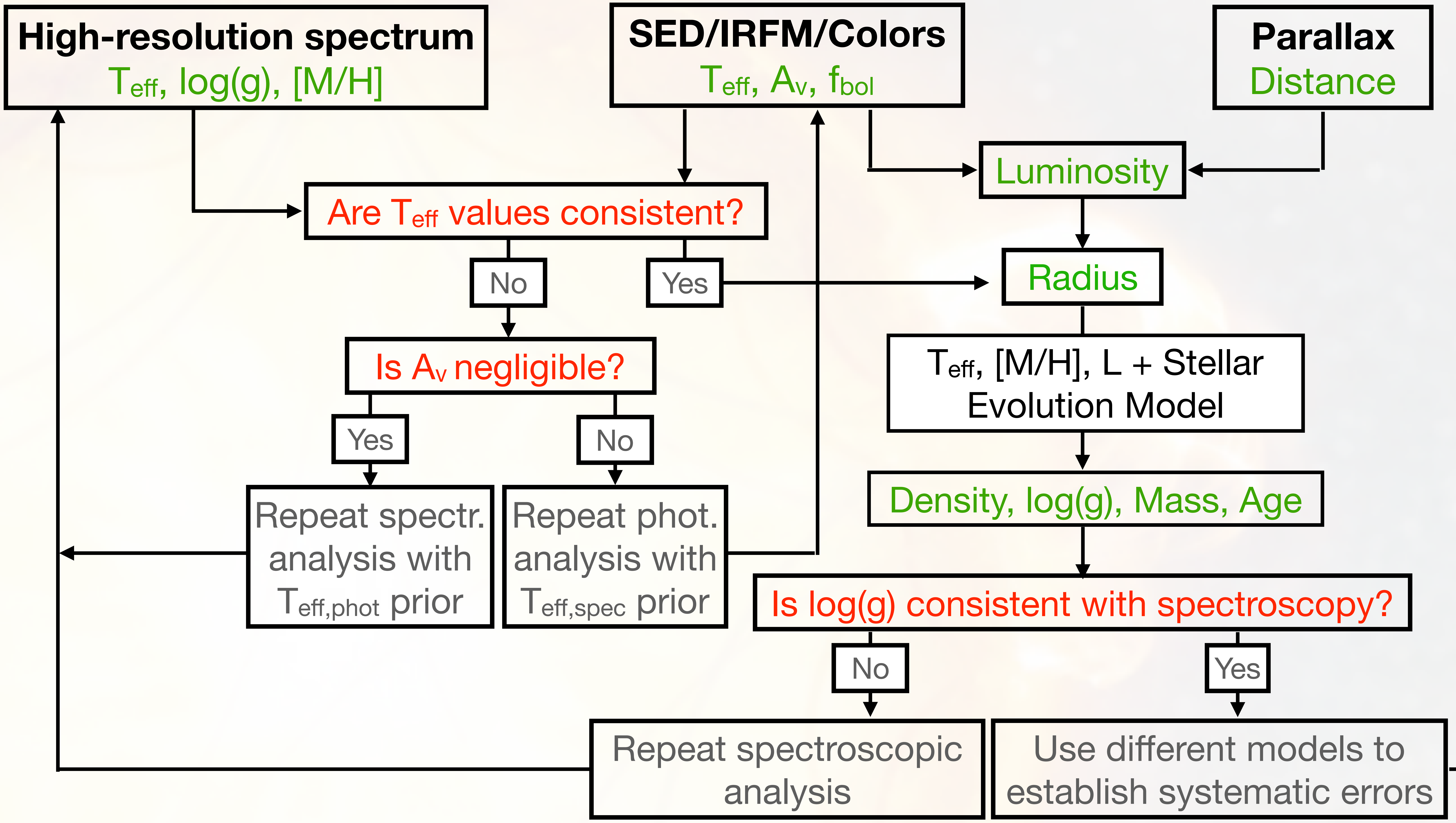




T_{eff}-L-R-M relations calibrated using interferometric angular diameters, bolometric fluxes and dynamical masses. Possible because M dwarfs hardly evolve!

A Stellar Properties "Cook Book"

(for single, solar-type field stars)



How do Stellar Properties Impact Exoplanet Properties?

Fundamental Properties of Stars

Effective Temperature (T_{eff})

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Which stellar parameters are important for understanding exoplanets?

Fundamental Properties of Stars

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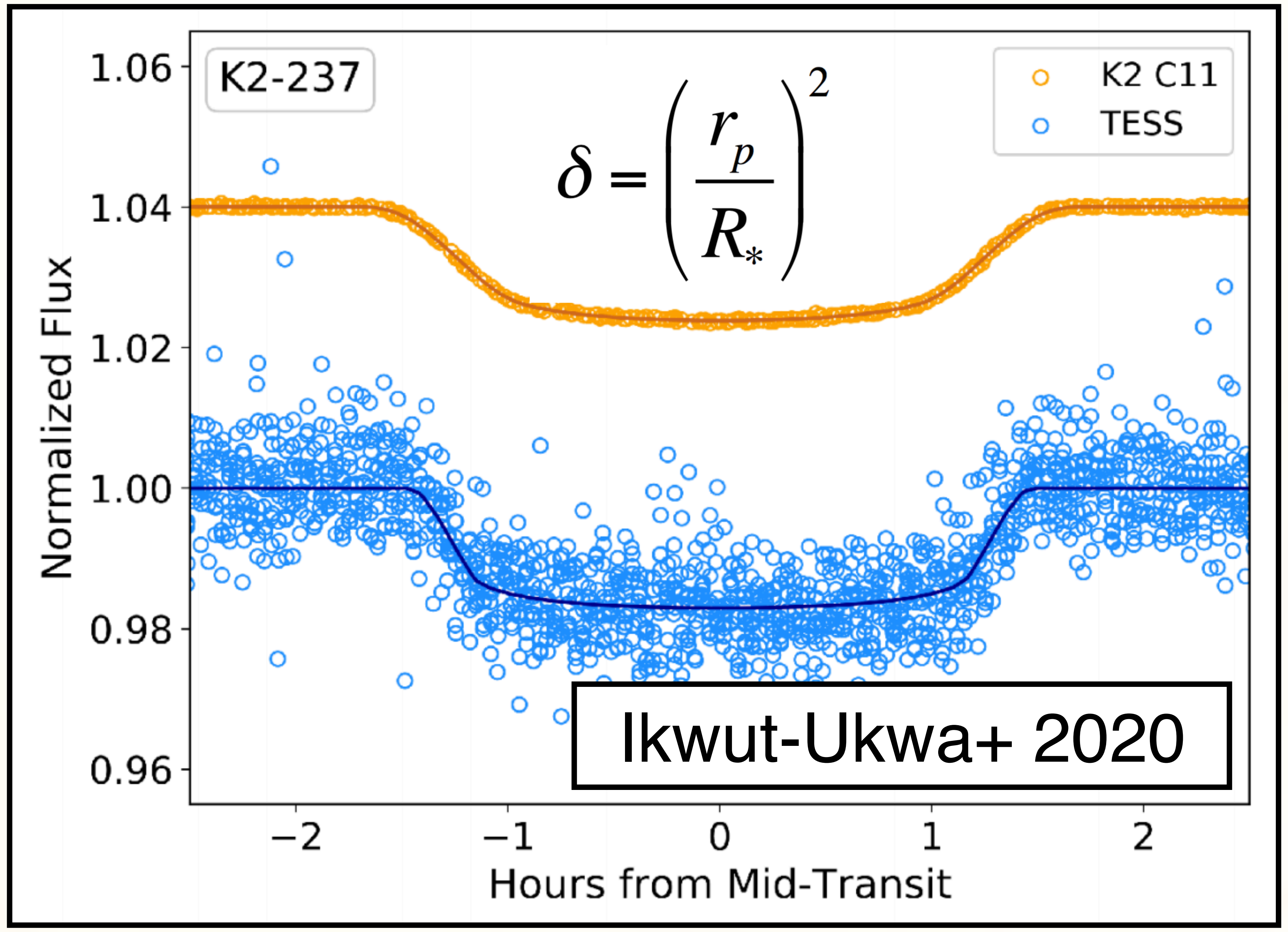
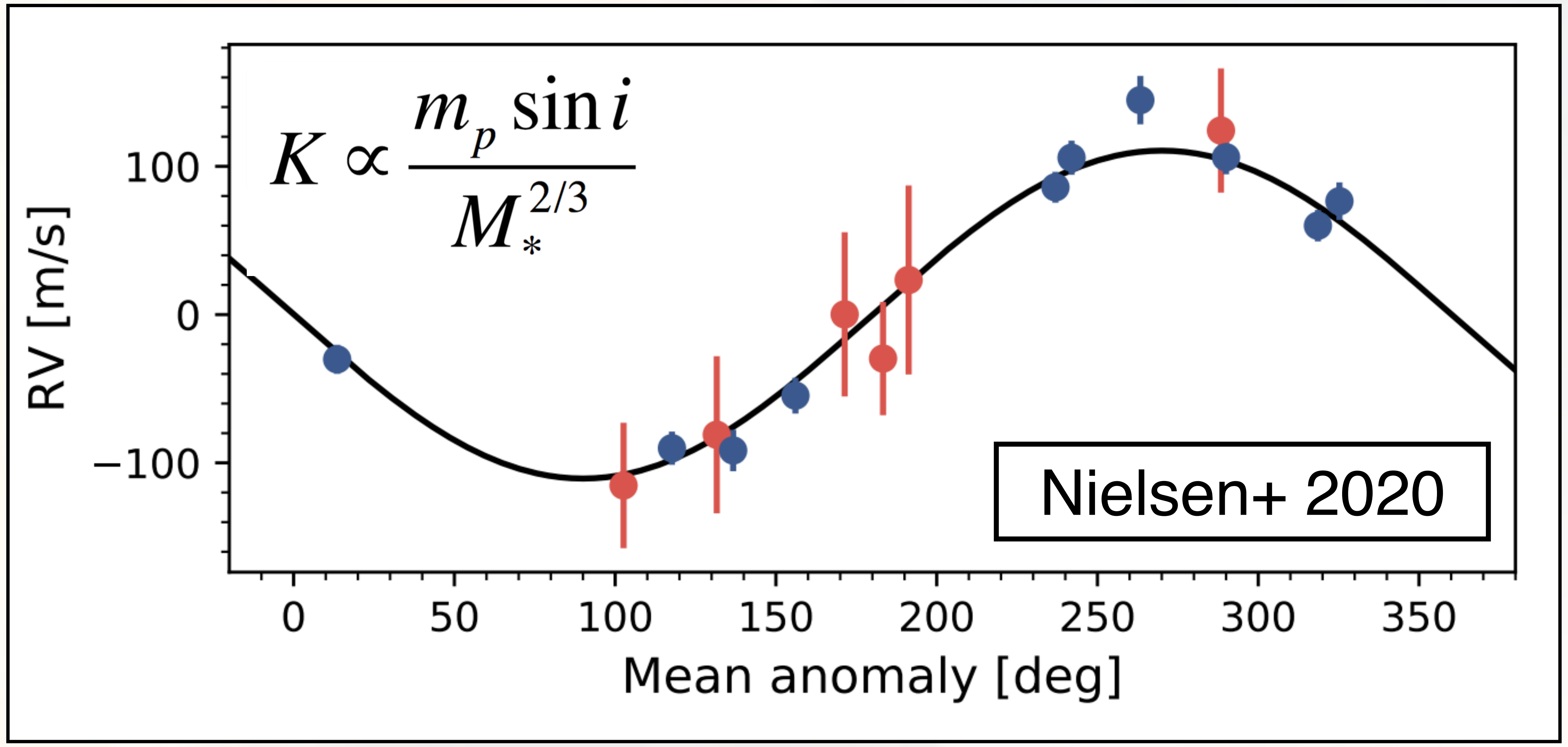
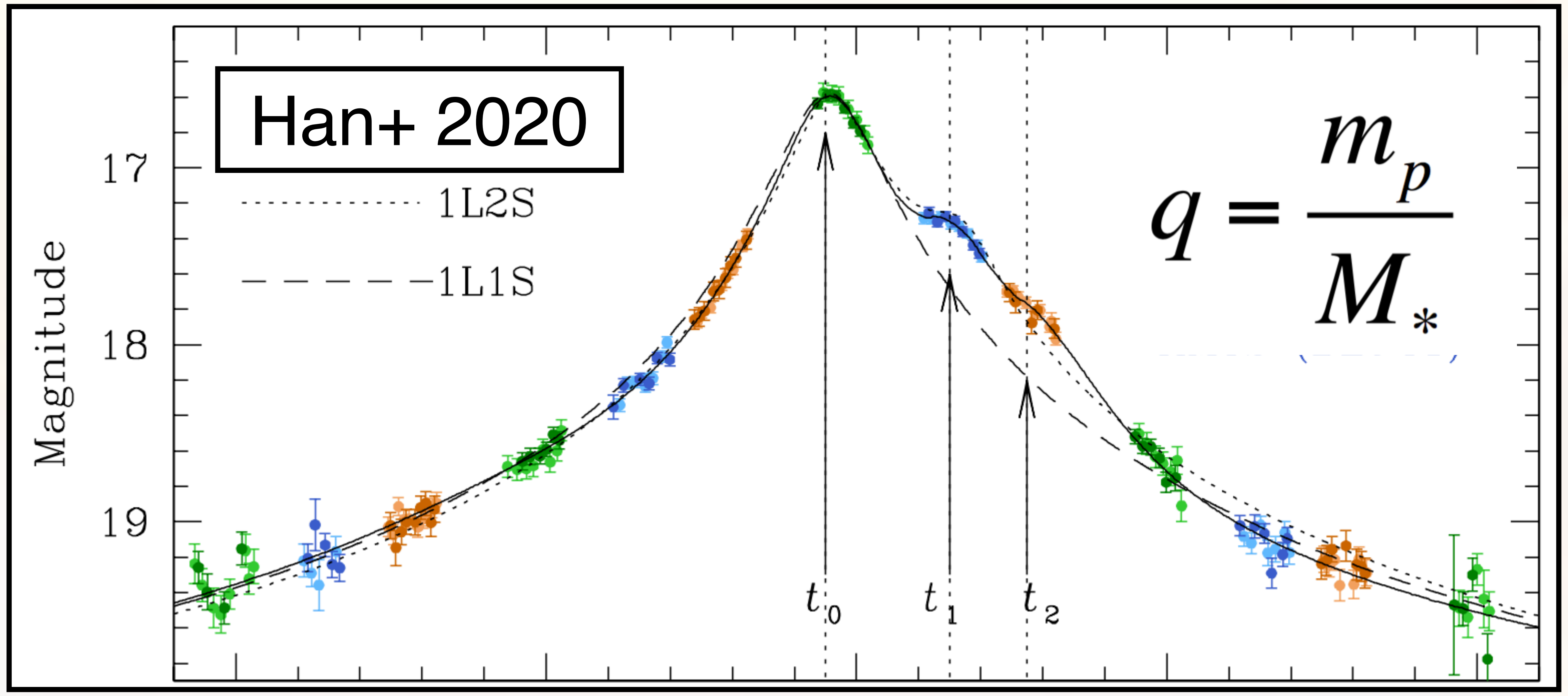
Which stellar parameters are important for understanding exoplanets?

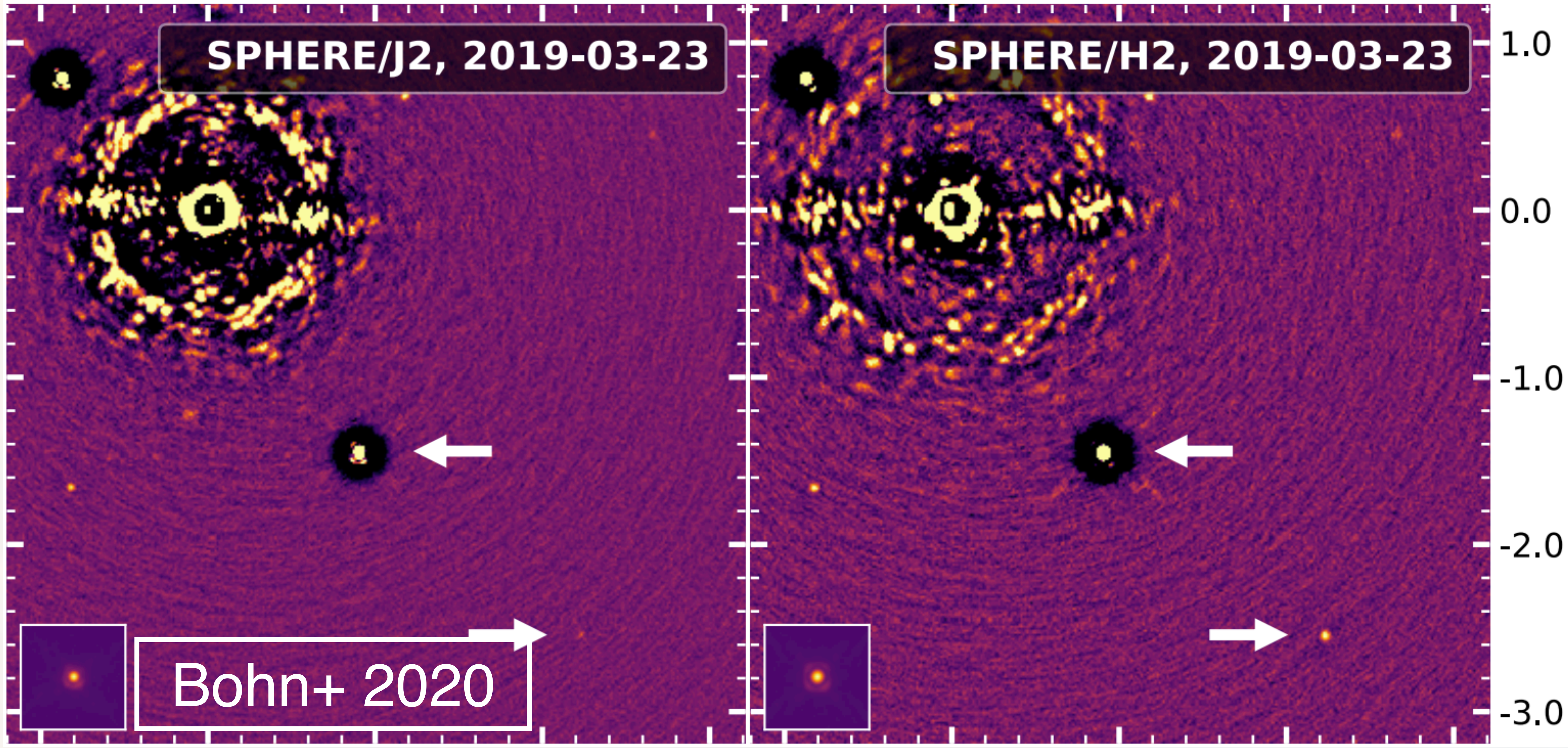
All of them!

"Know Thy Star, Know Thy Planet"









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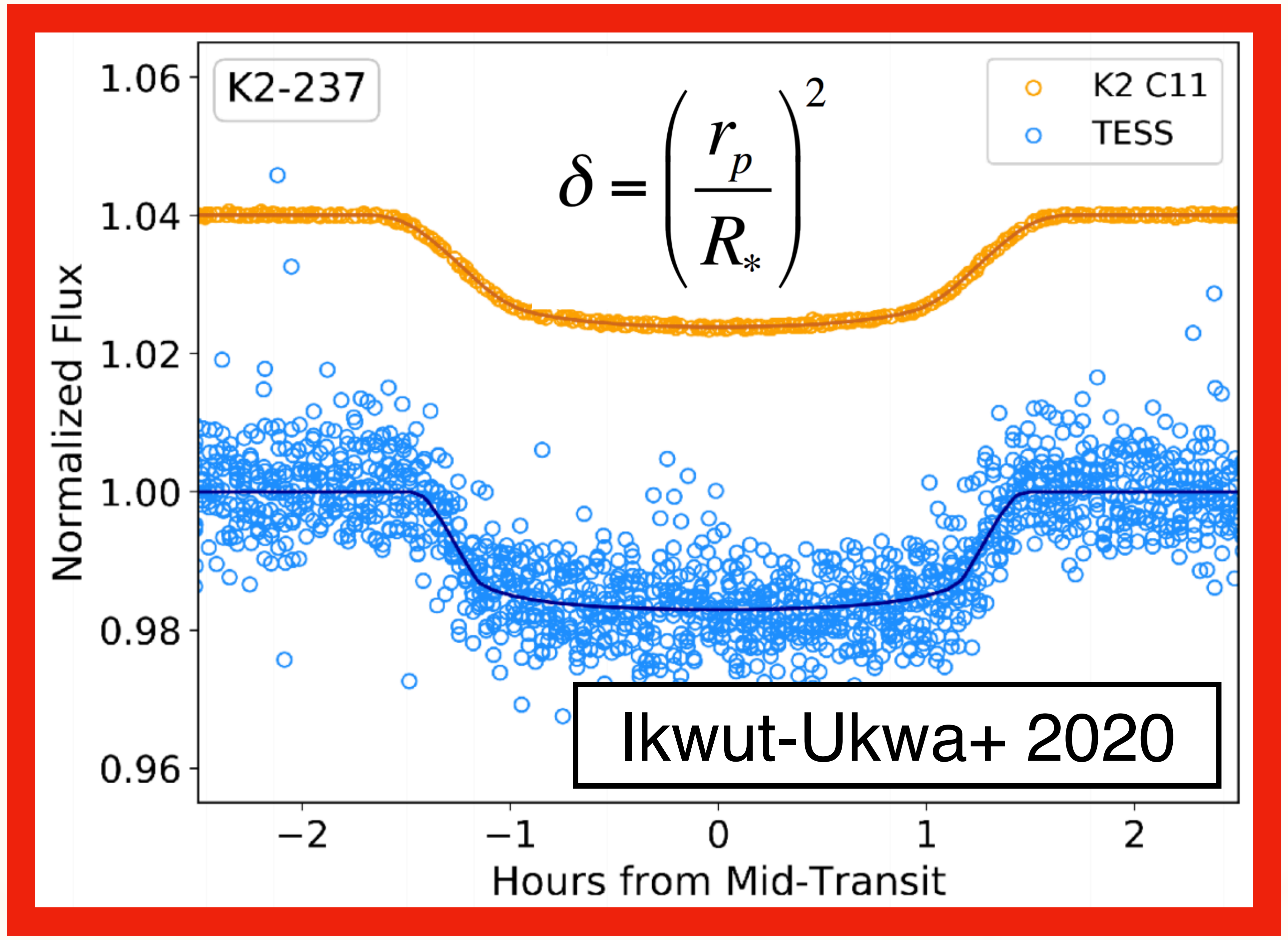
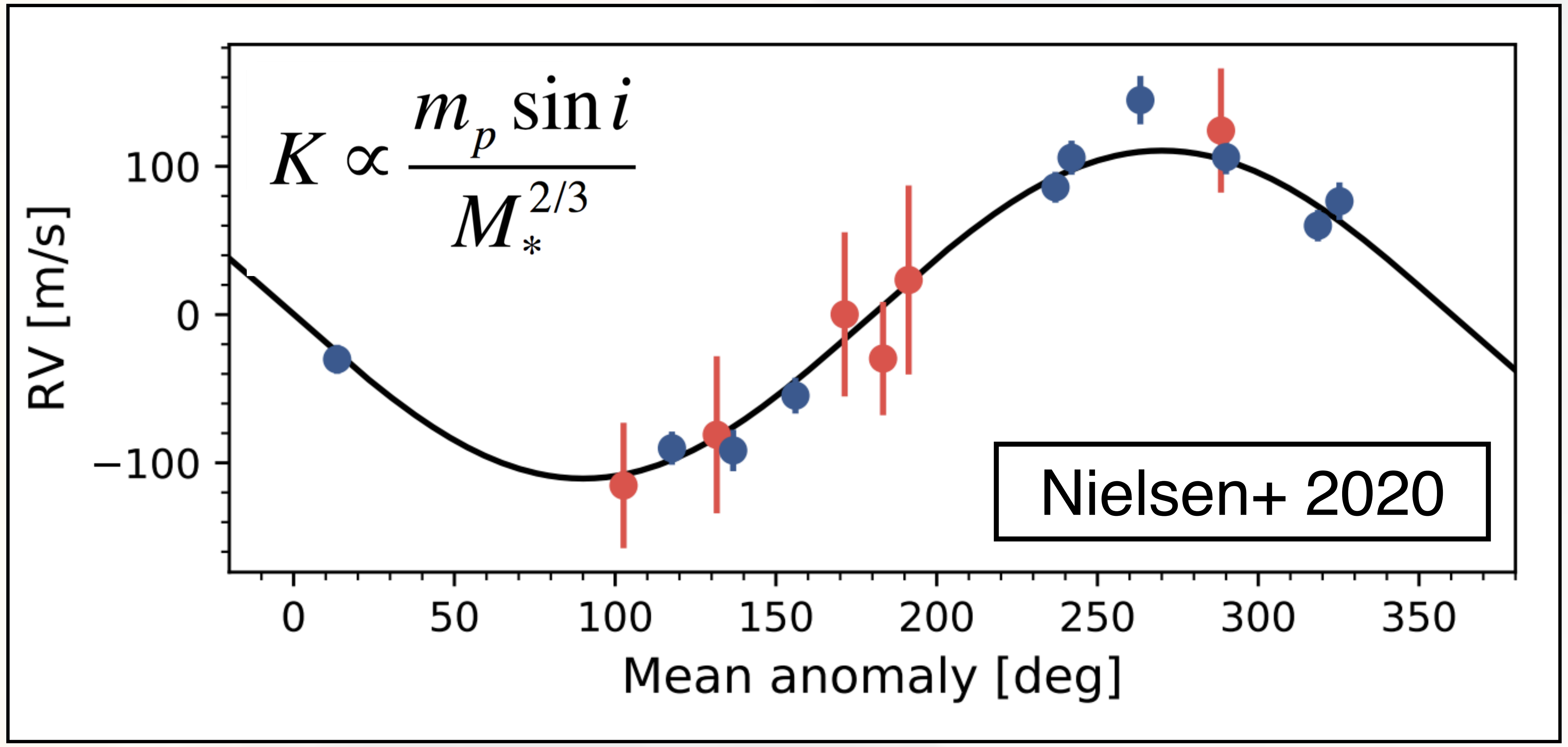
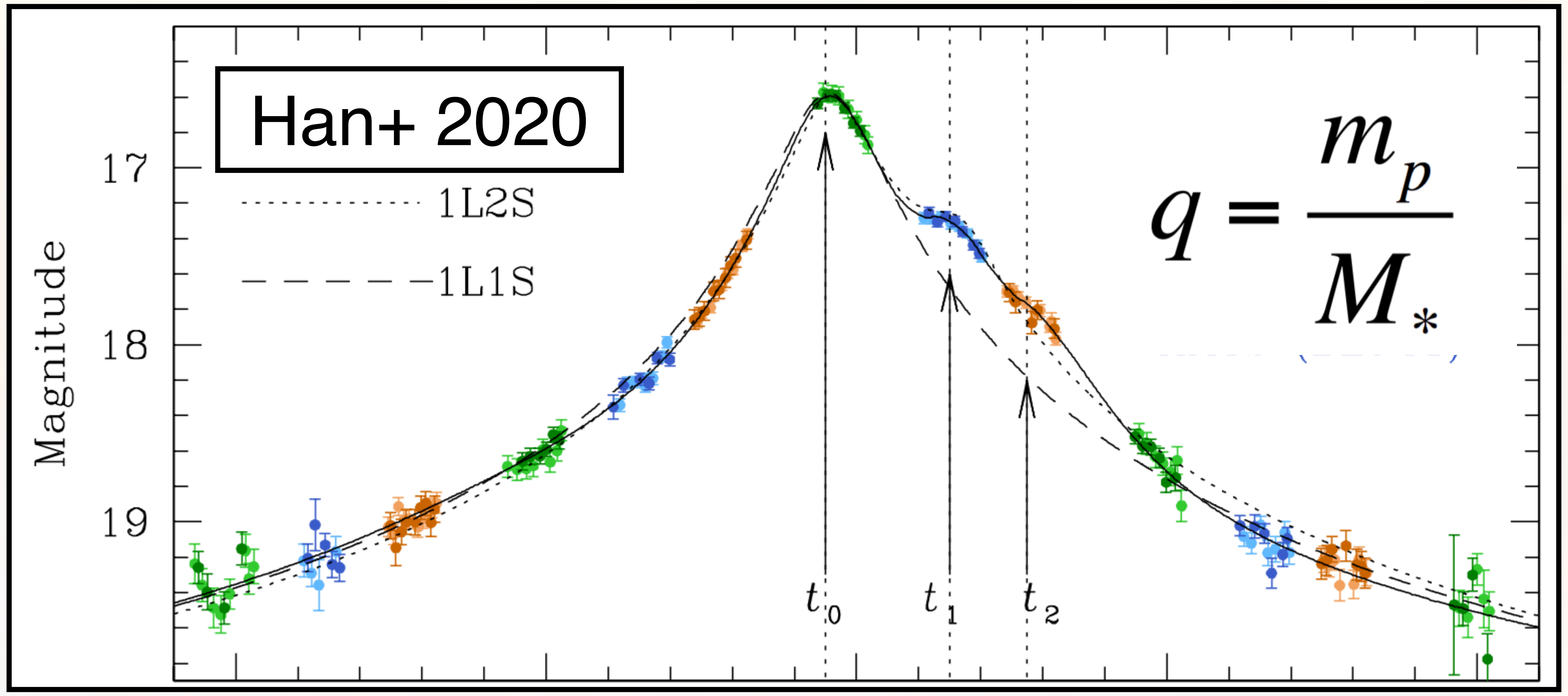
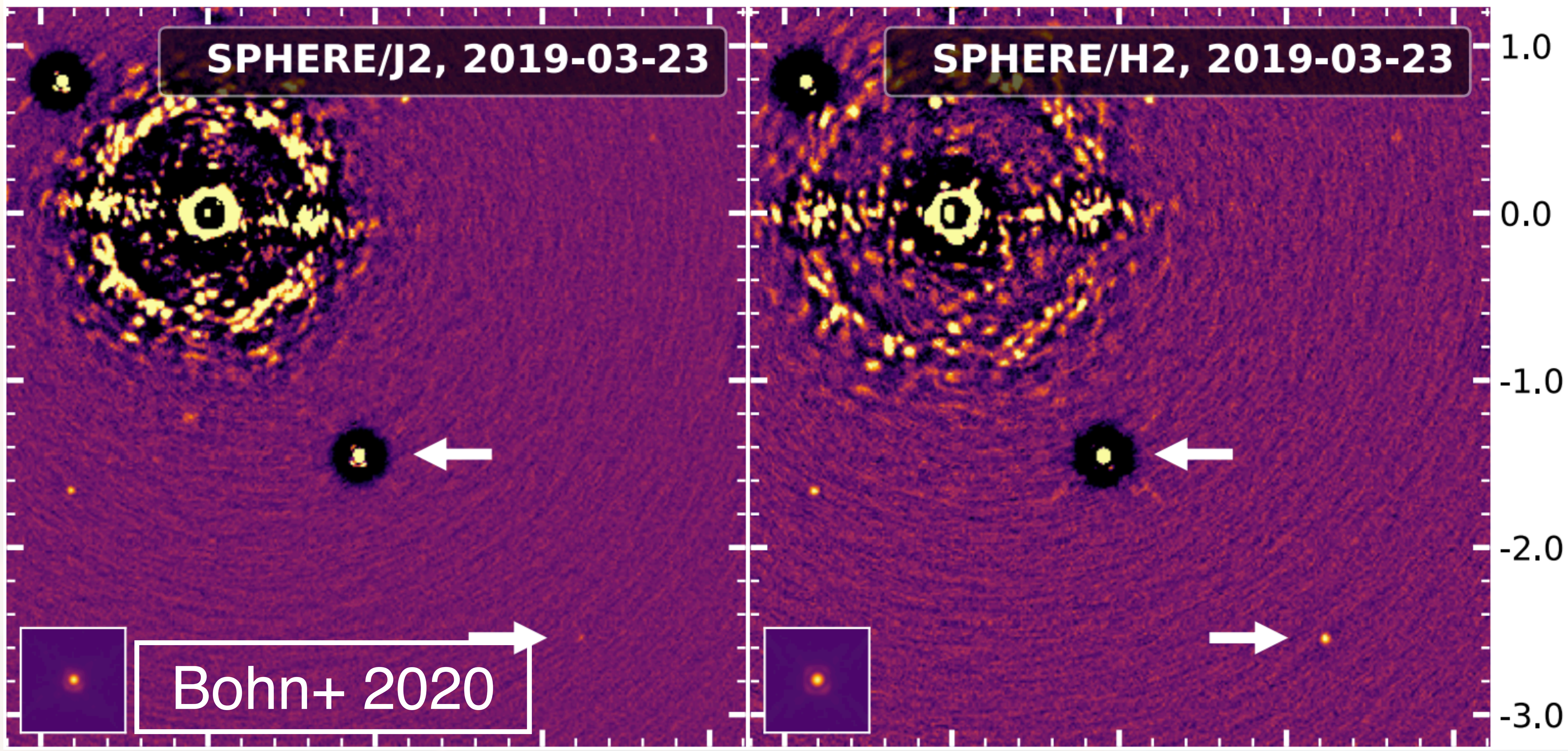
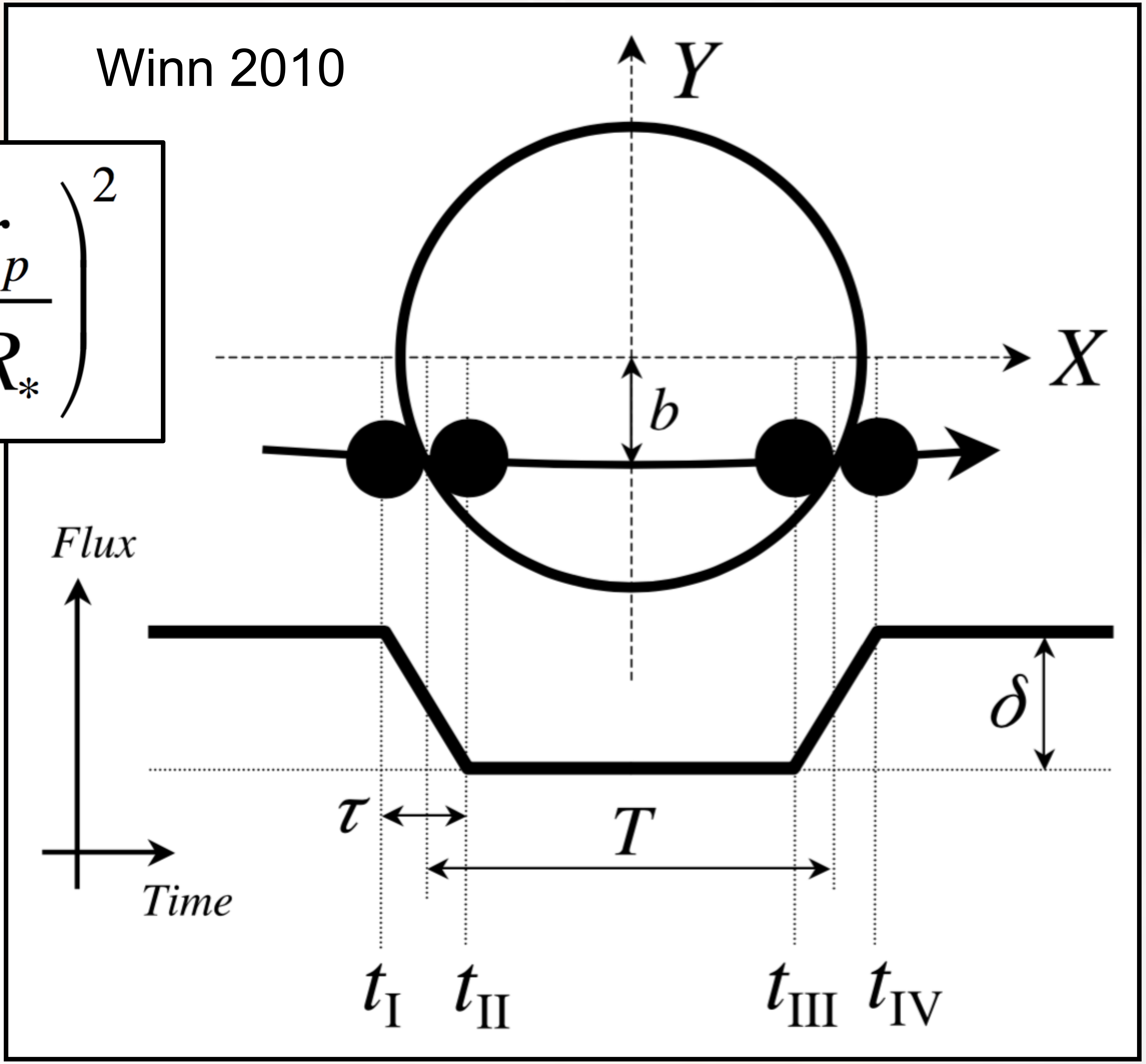




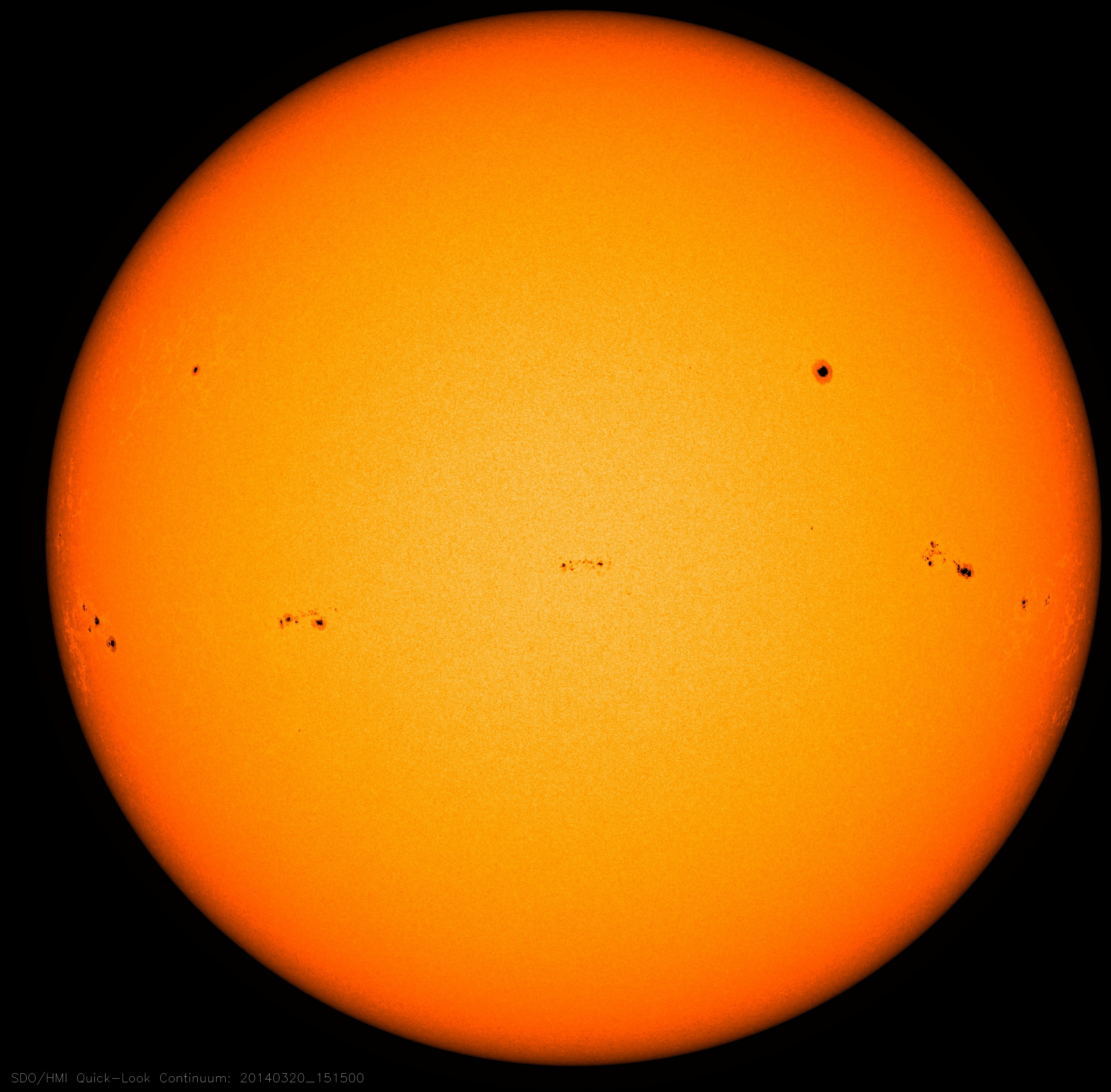




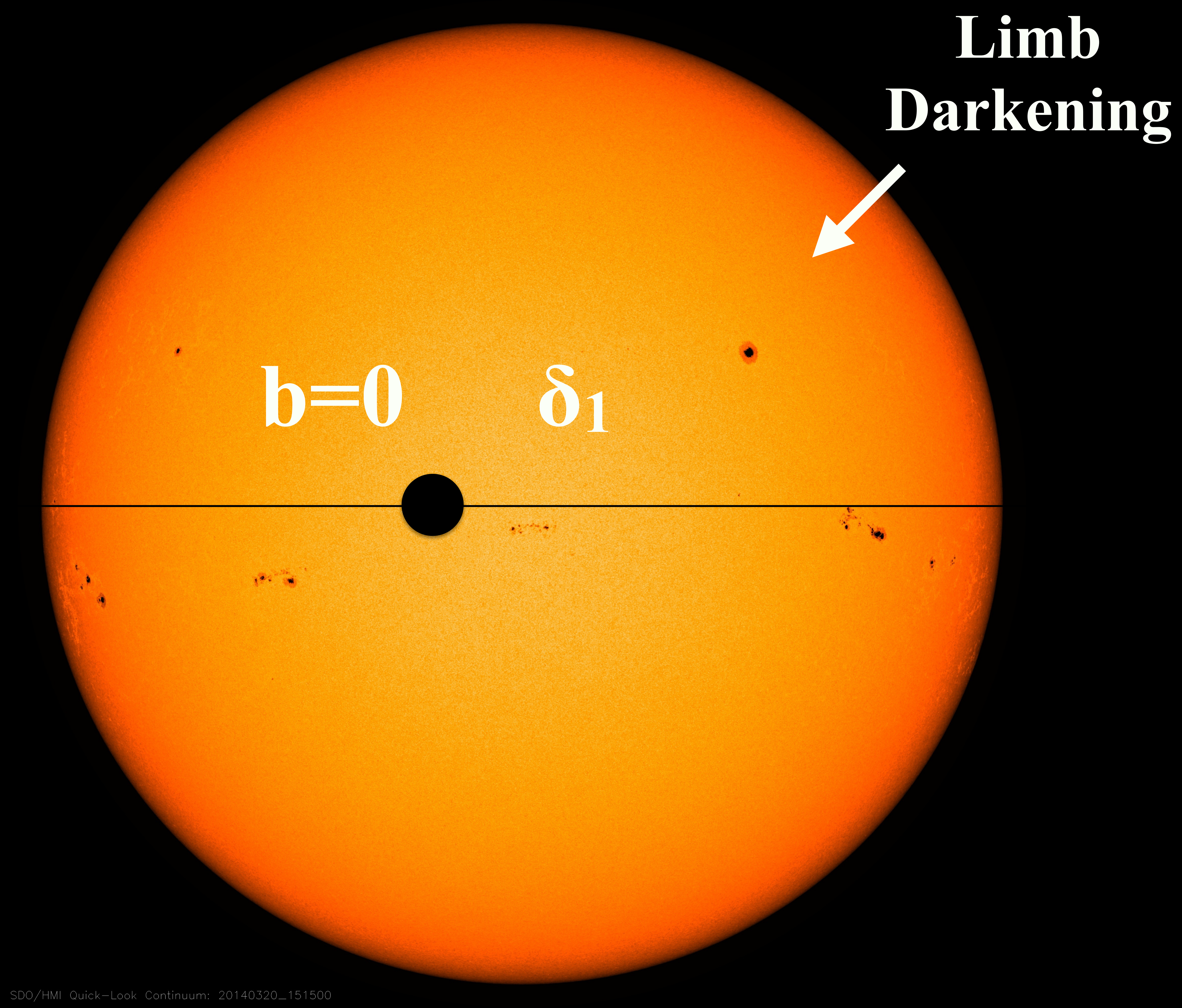
$$\delta = \left(\frac{r_p}{R_*} \right)^2$$



T = Transit Duration   τ = In/Egress Duration   δ = Transit Depth

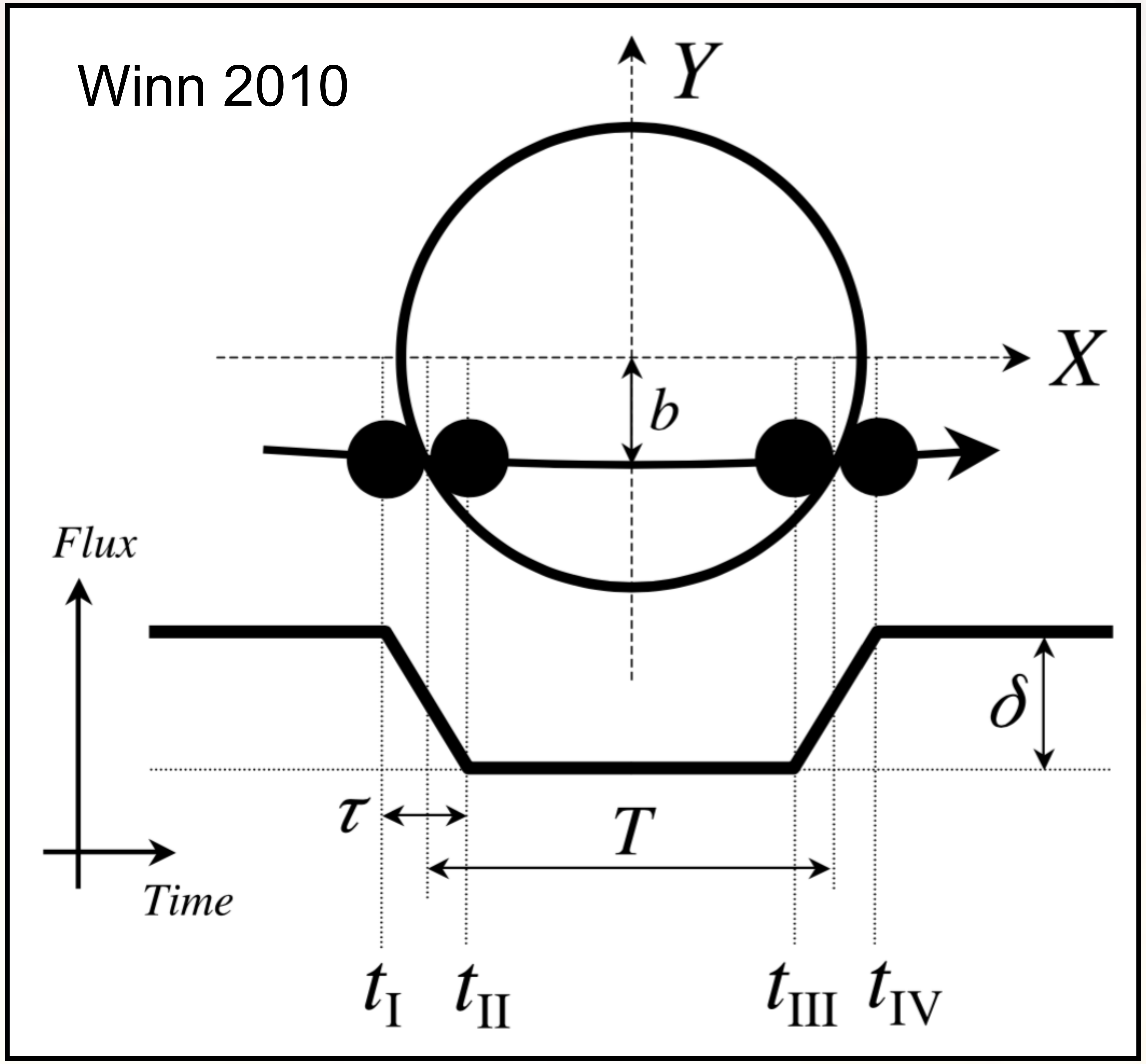

SDO/HMI Quick-Look Continuum: 20140320_151500


Limb
Darkening
SDO/HMI Quick-Look Continuum: 20140320_151500


Limb
Darkening
b=0
δ1
SDO/HMI Quick-Look Continuum: 20140320_151500


Limb
Darkening
fixed
Rp/Rs
b=0
δ1
b=0.8
SDO/HMI Quick-Look Continuum: 20140320_151500


Limb
Darkening
fixed
Rp/Rs
b=0 δ1
b=0.8 δ2 < δ1!
SDO/HMI Quick-Look Continuum: 20140320_151500



for circular orbits and
$R_p << R_\star << a$:

(see Saeger & Mallen-Ornelas 2003 for a rigorous derivation)

$$T \approx T_0 \sqrt{1 - b^2},$$

$$T_0 \equiv \frac{R_\star P}{\pi a}$$

Can rewrite a/R_s using Kepler's 3rd law …

$$T_0 \equiv \frac{R_\star P}{\pi a}$$

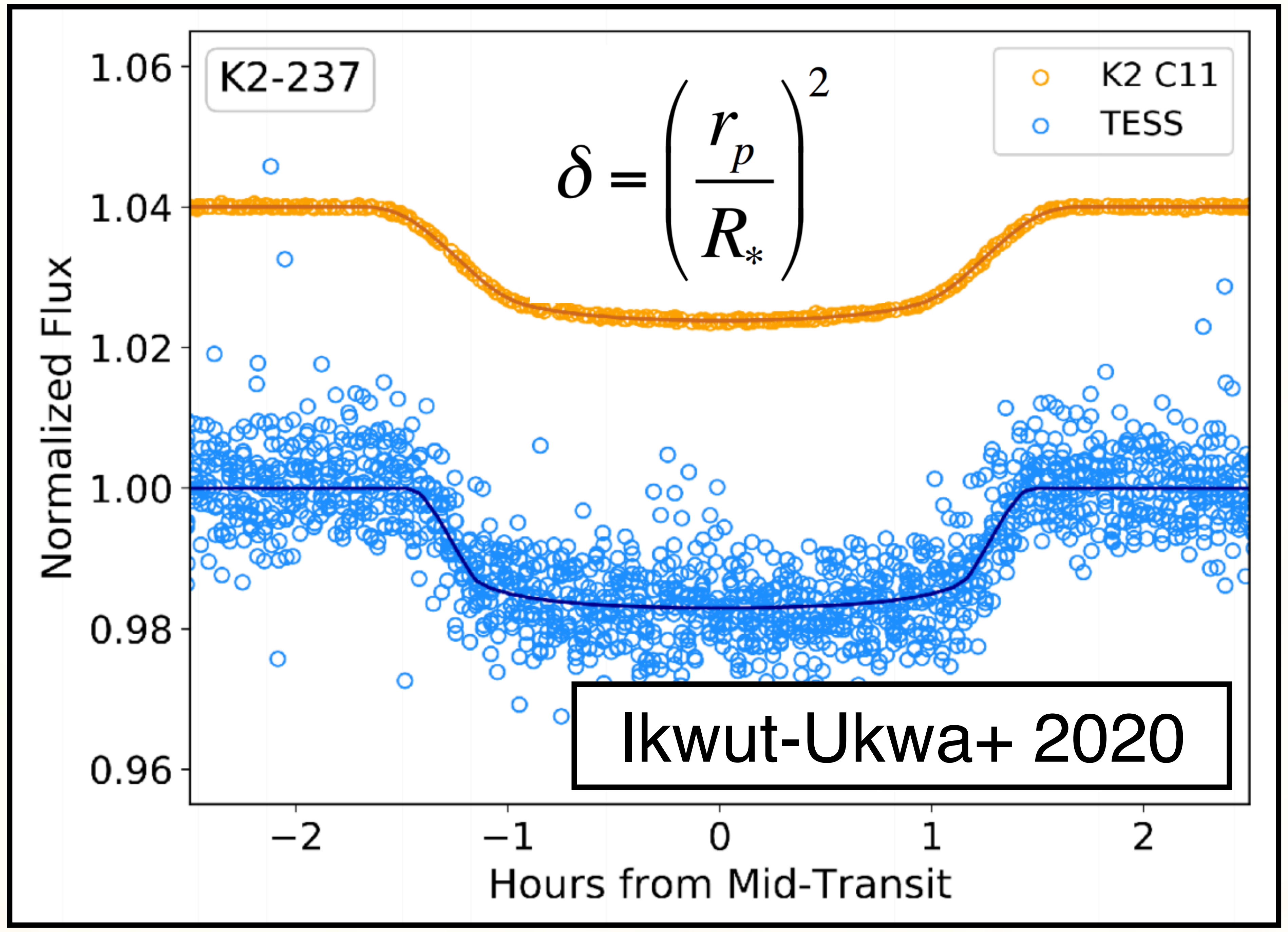
$$\rho_{\star,\mathrm{transit}} = \frac{3\pi}{GP^2}\left(\frac{a}{R_\star}\right)^3$$

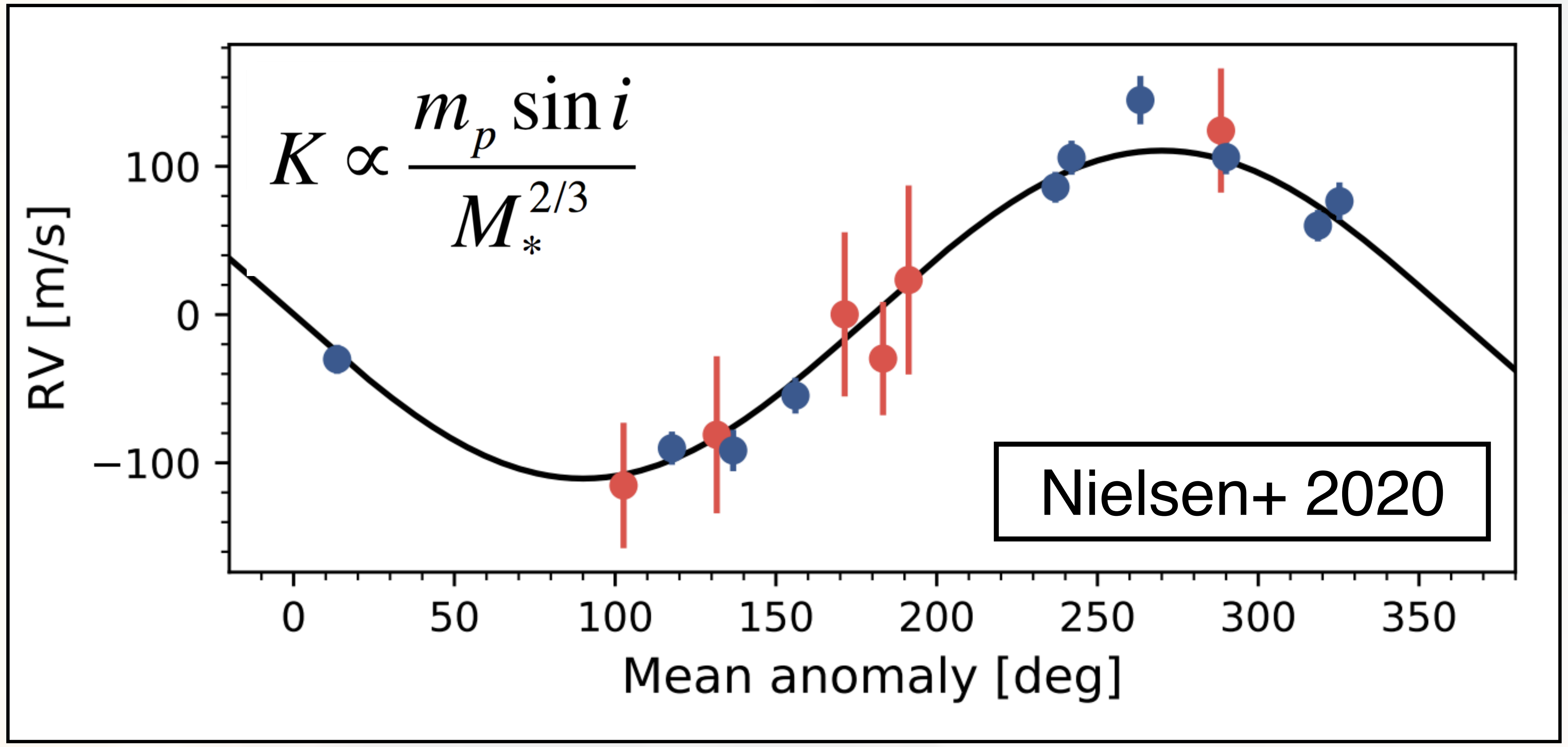
Big Result 1: Independent stellar parameters can be used to improve transit parameters!

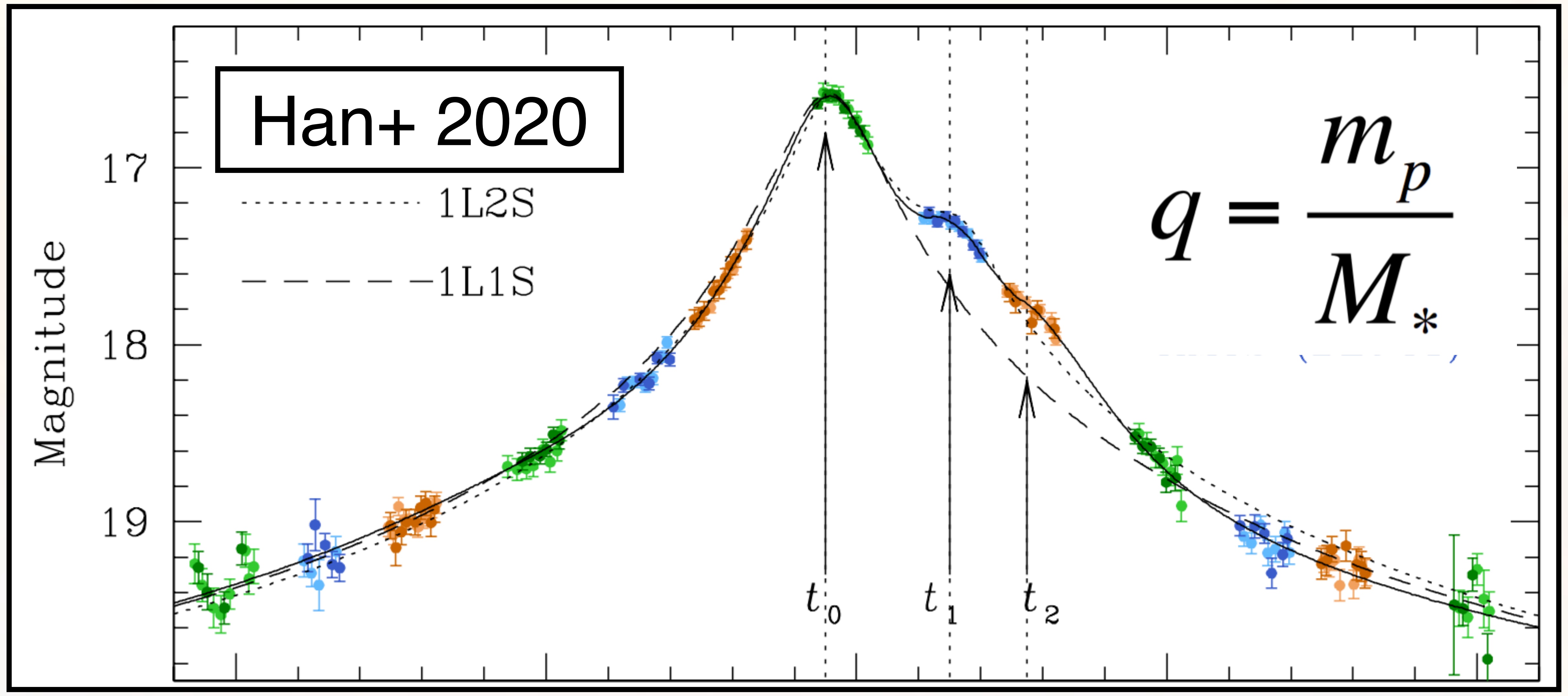
Big Result 2: Transit observables can be used to measure stellar parameters

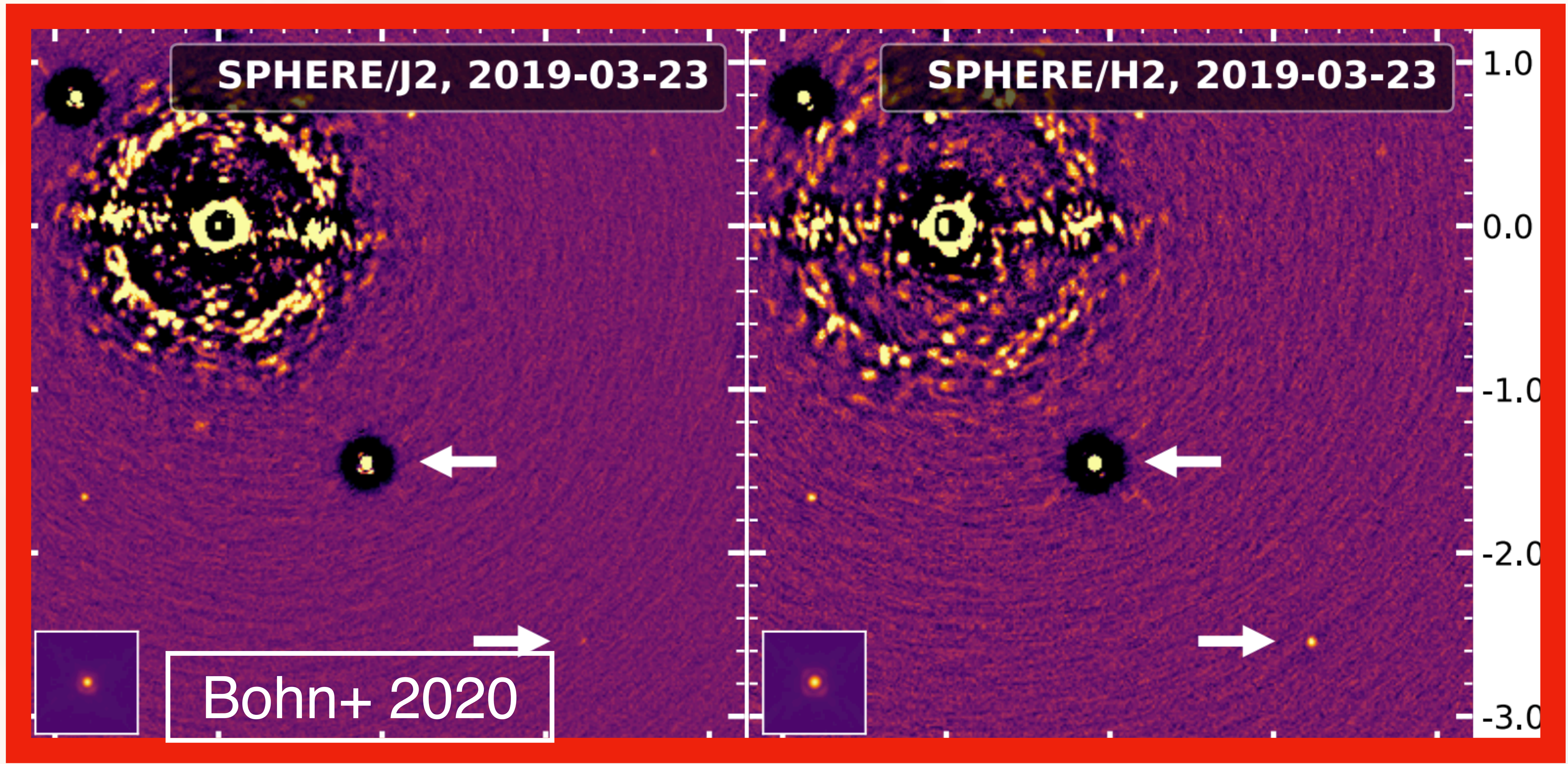
Eccentricities from asteroseismic densities + transit durations. Gaia parallaxes ($\rho \propto M/R^3$!) should now allow this for many more systems

"Know Thy Star, Know Thy Planet"

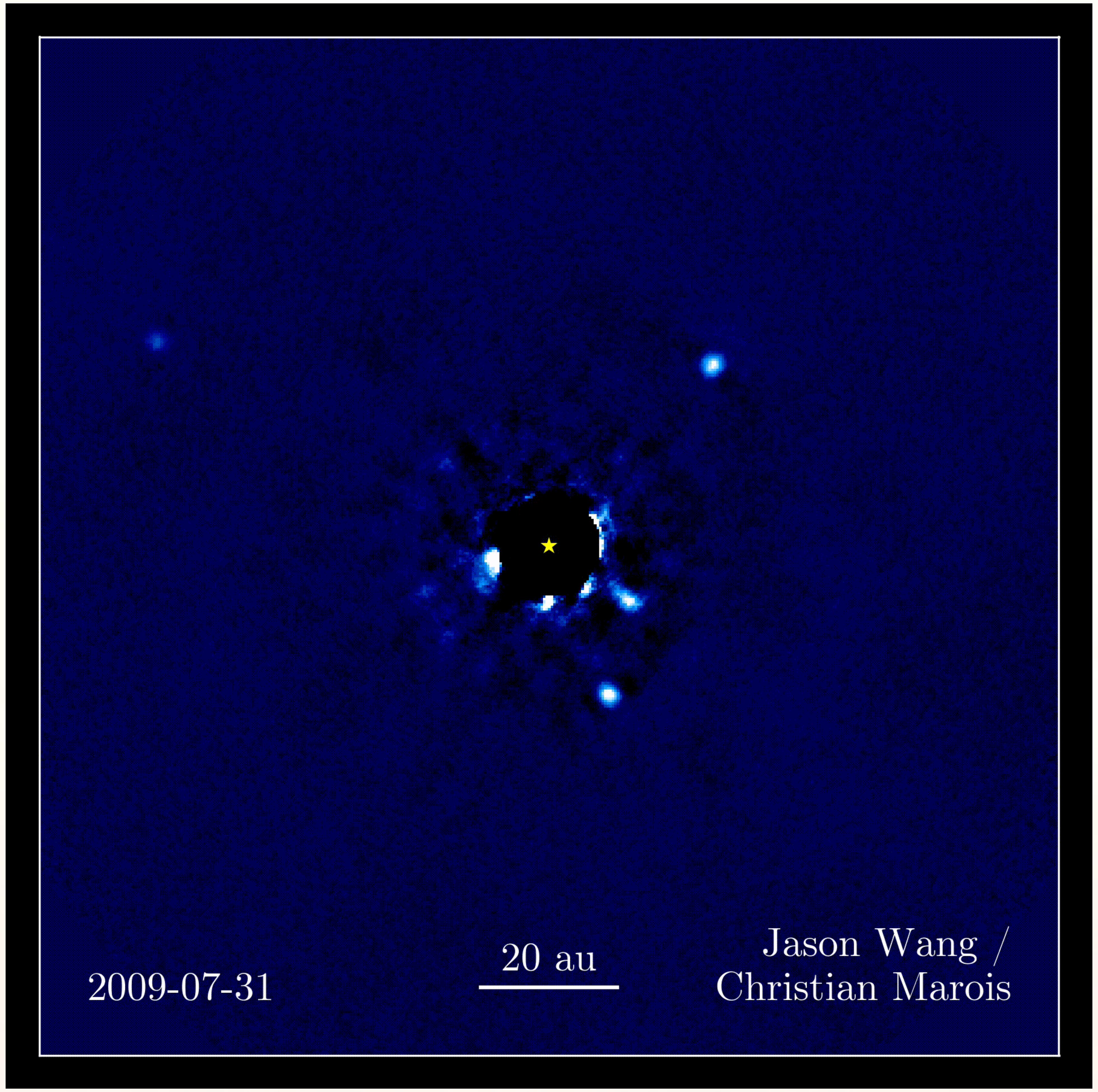


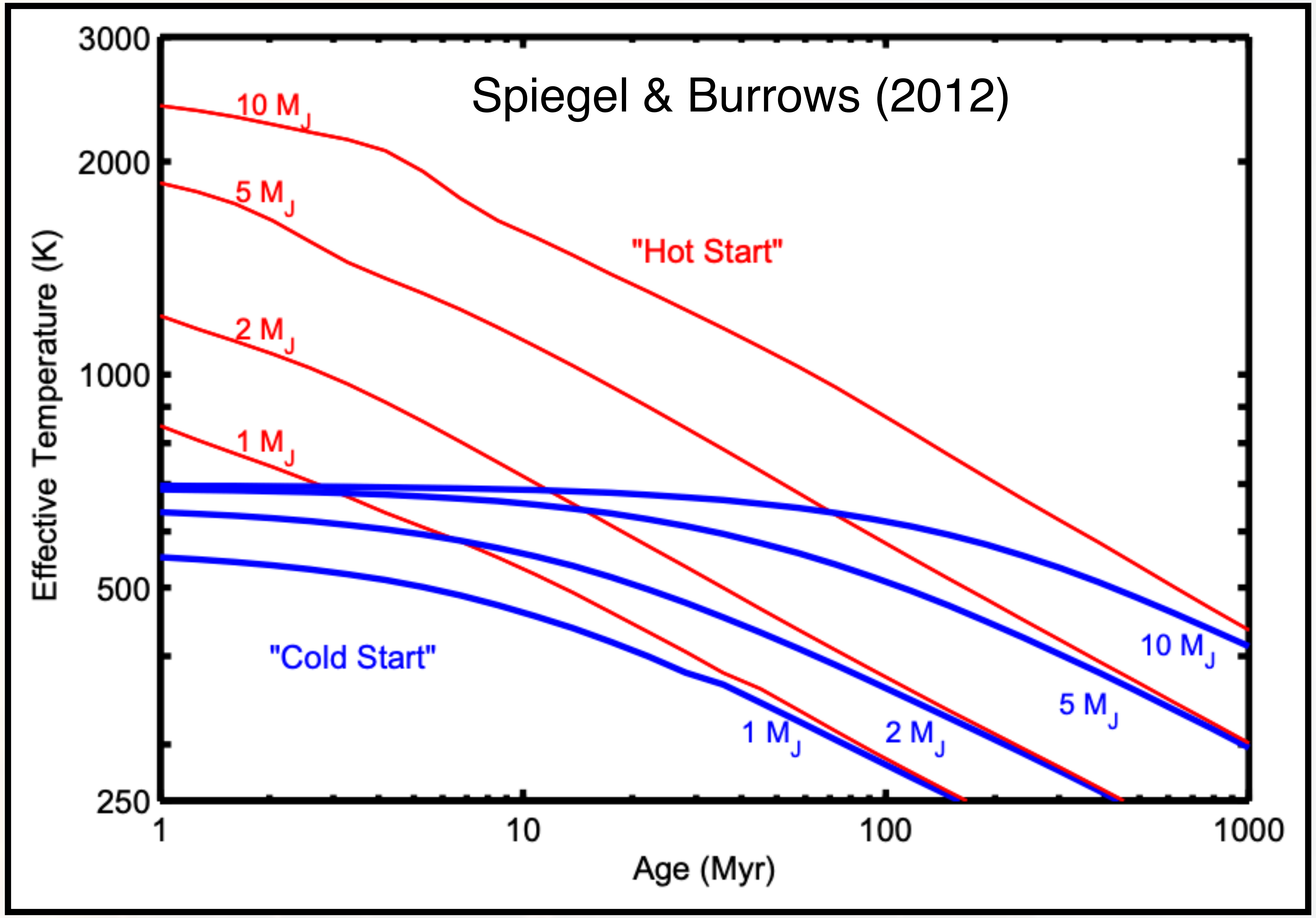






Ages of Directly Imaged Planet Hosts

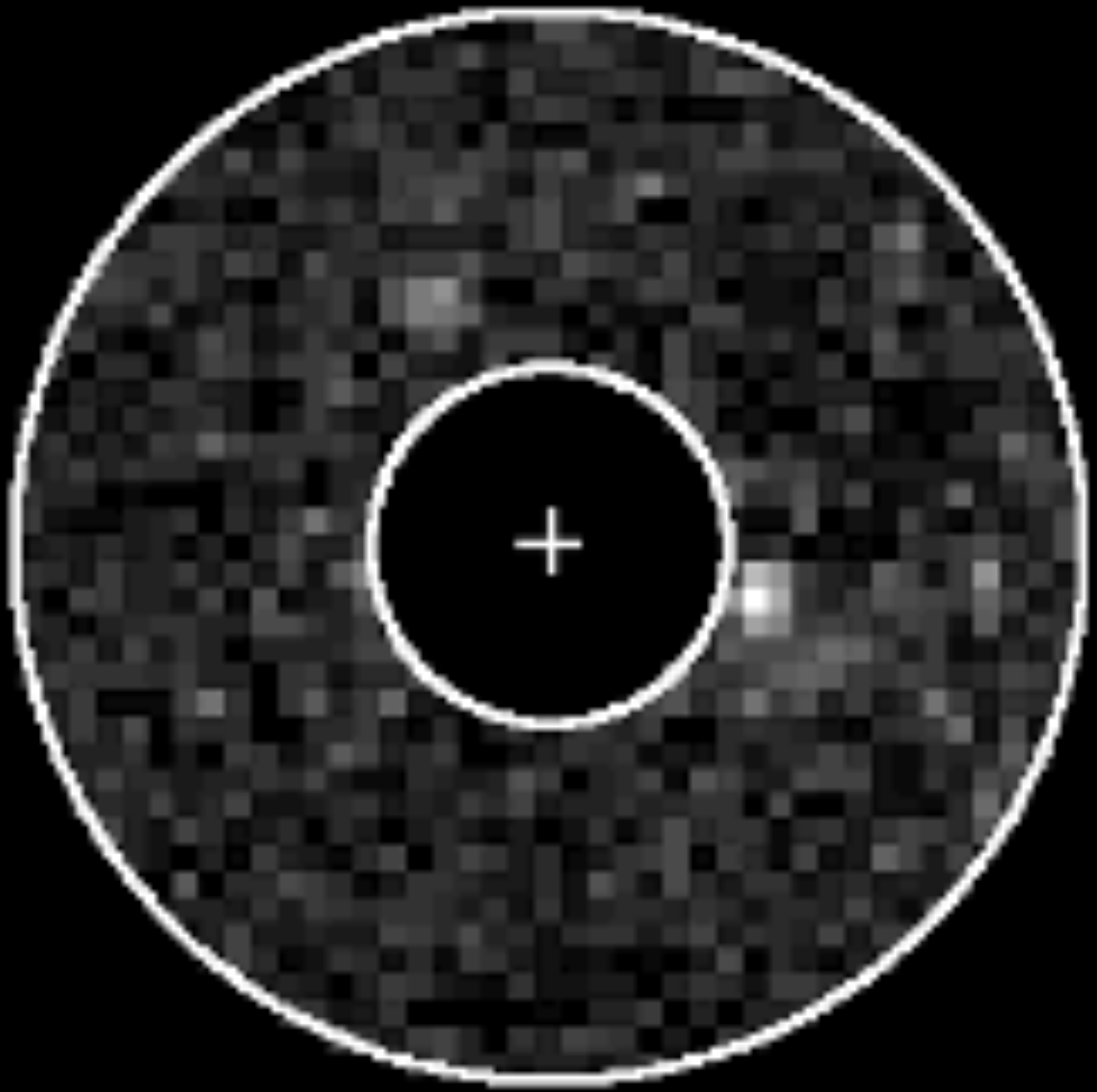




Ages are important for masses of young planets & to test formation models

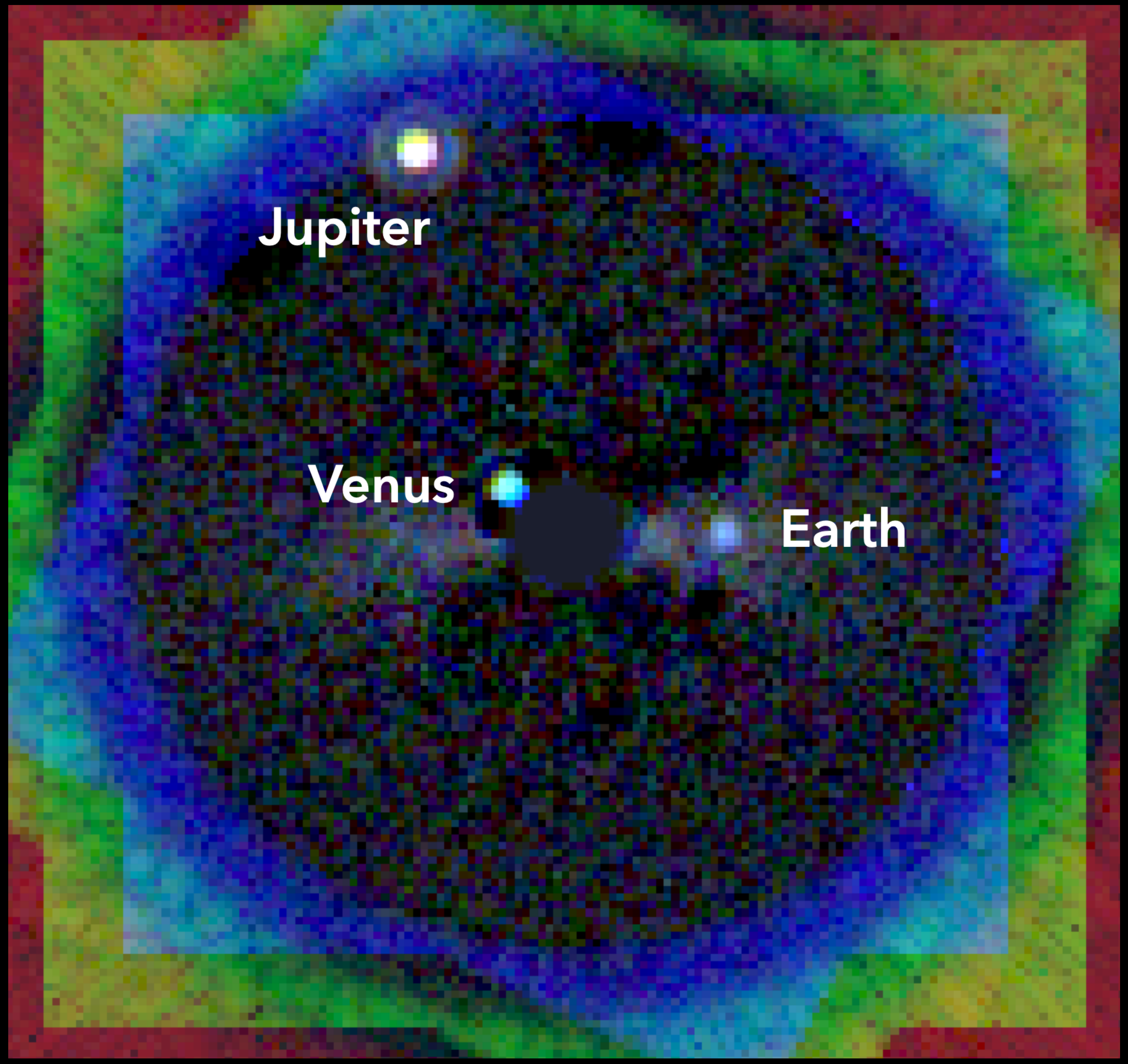
Host Stars of Directly Imaged Earth-like Planets

Roman Coronagraph Instrument

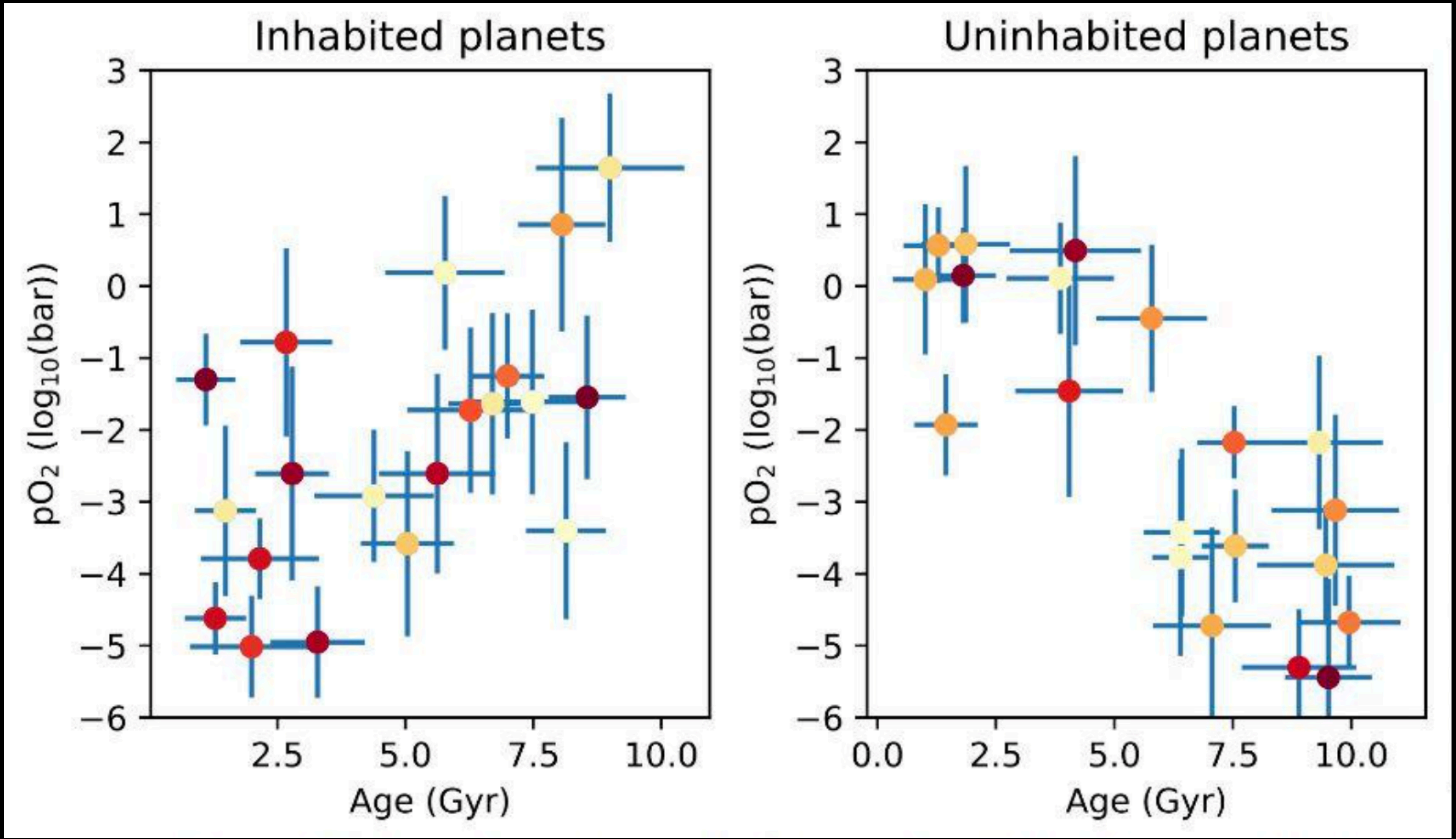


John Krist (NASA JPL)

6-m Class Astro2020 Flagship



Juanola Parramon, Zimmerman, Roberge (NASA GSFC)



Krissansen-Totton, Huber, MacGregor & O'Rourke (see also Bixel & Apai 2021)

Ages of nearby bright stars may be critical for interpreting biosignatures on (future) directly imaged exoplanets

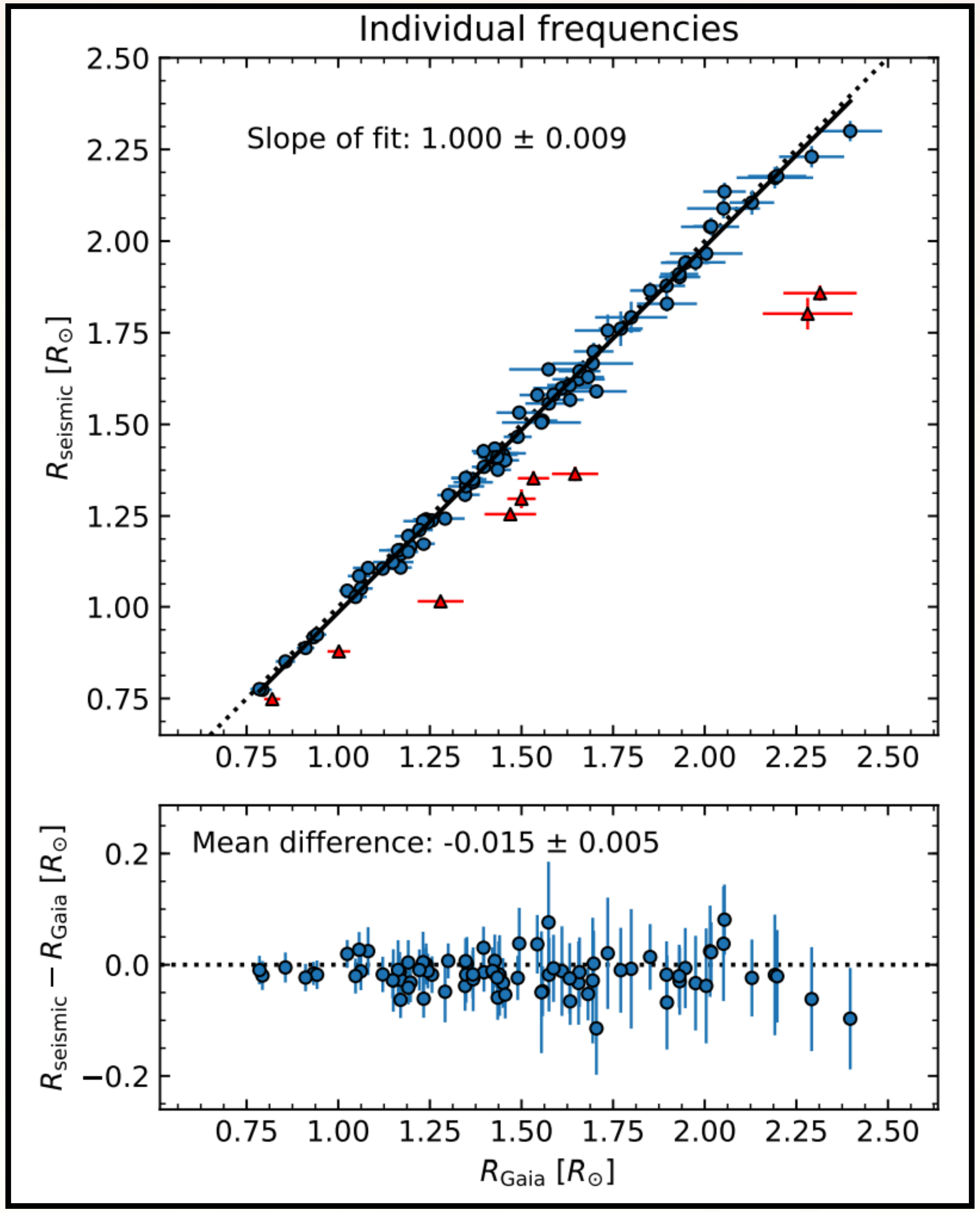
Summary

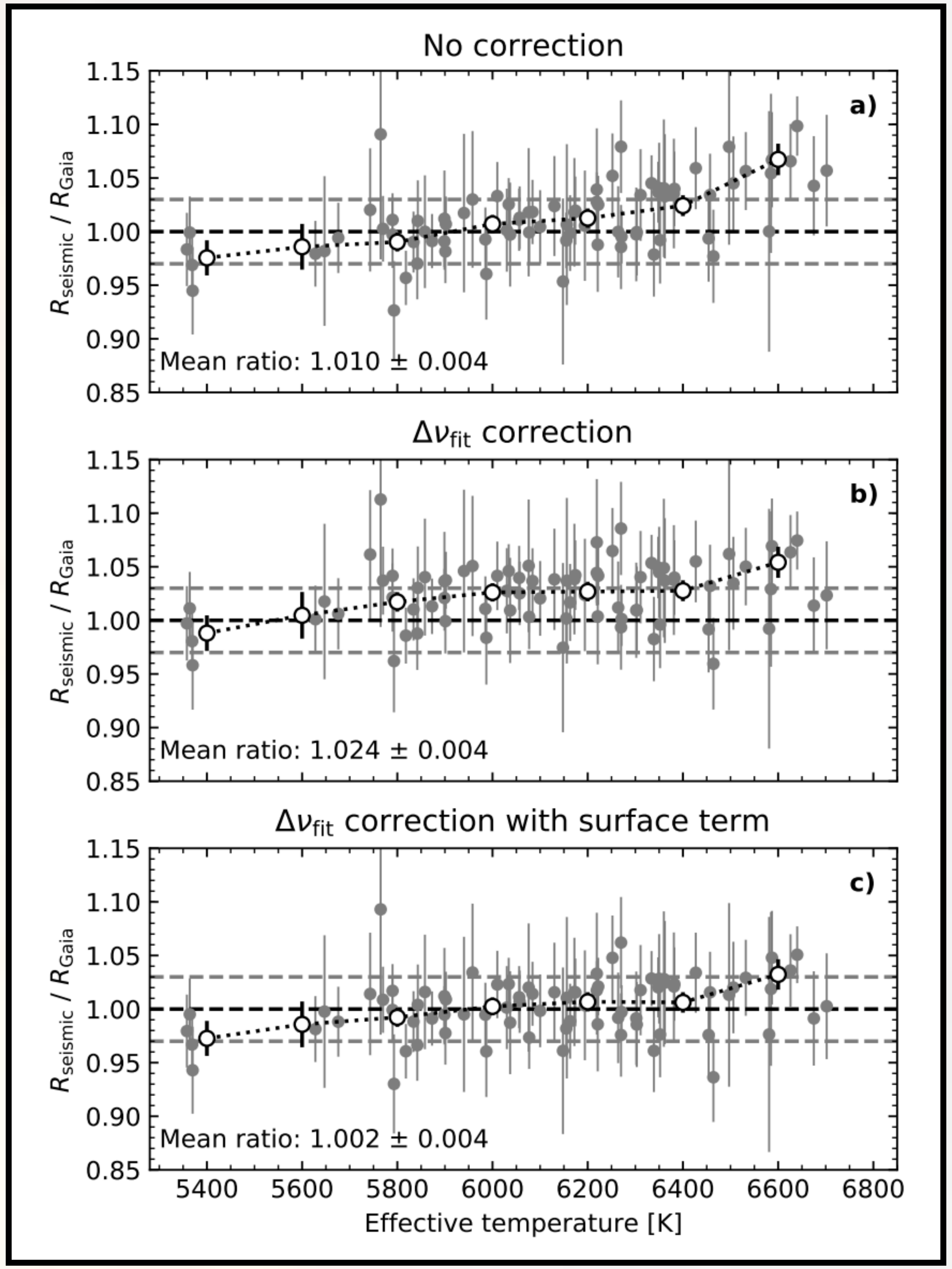
- **Astrometry from Gaia has revolutionized our ability to derive fundamental properties of stars:** Luminosities and radii to <~5%(!) are now routinely possible. F_{bol} and T_{eff} are the new bottlenecks!
- **Masses and ages of stars remain challenging:** Binaries from Gaia will be critical to calibrate models that are required for most field stars
- **Stellar properties are important for virtually all fields of exoplanet science,** ranging from improving transit fits to interpreting biosignatures in (future) directly imaged planets. Much more on this tomorrow!

... and a big thank you to the Gaia team for these amazing astrometric datasets!

Extra Slides

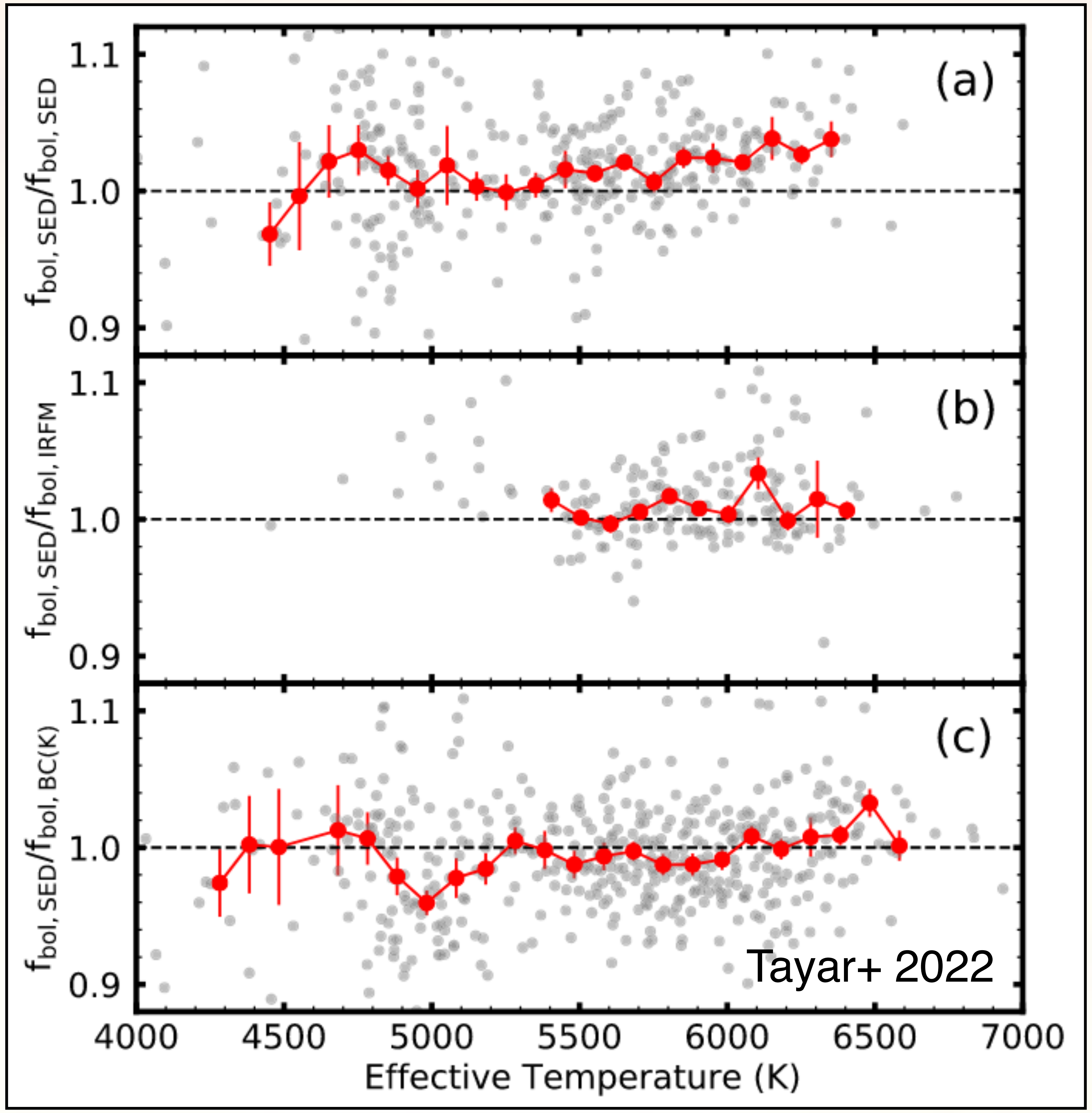
Asteroseismology versus Gaia

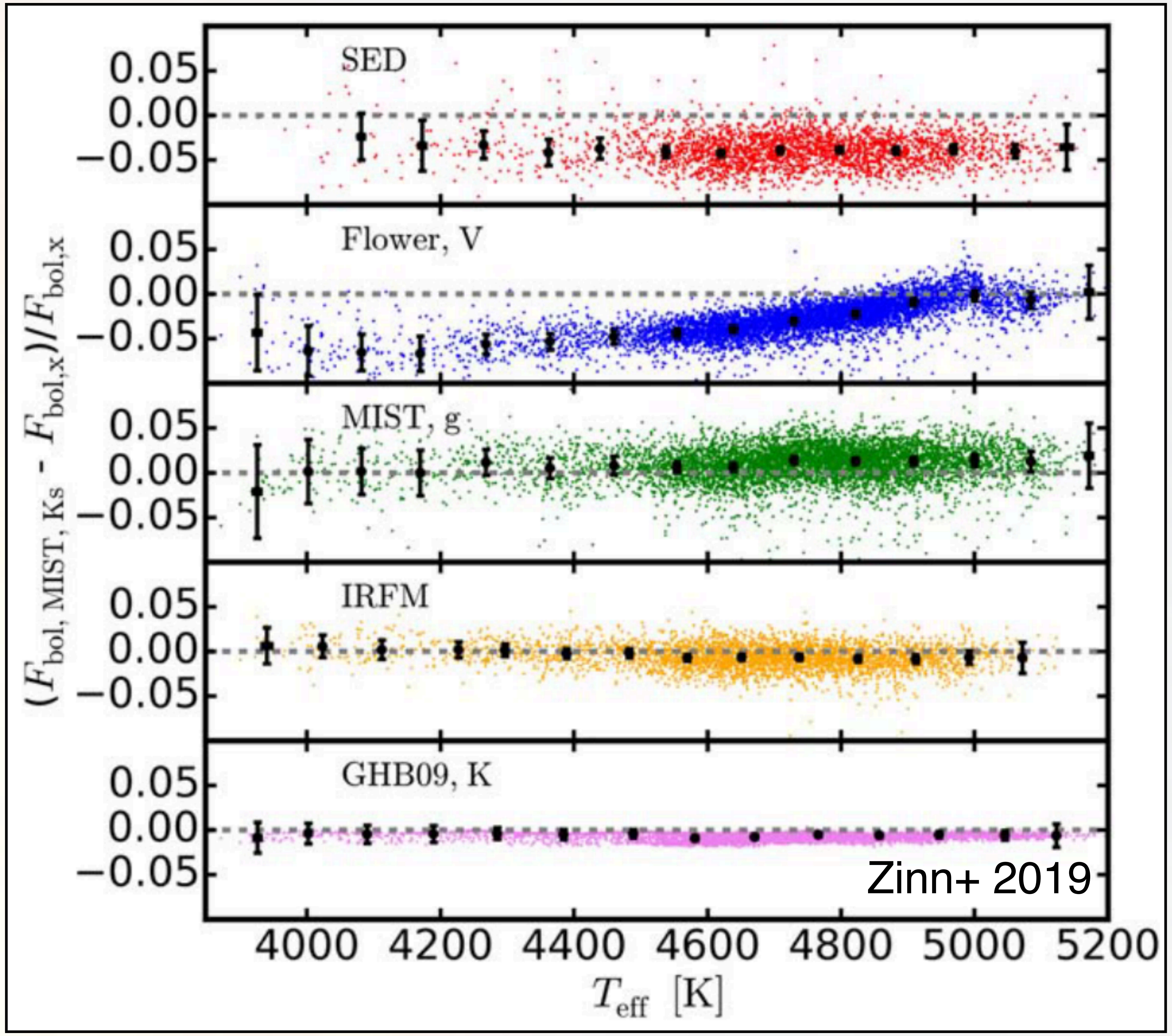




Sahlholdt & Silva Aguirre 2018

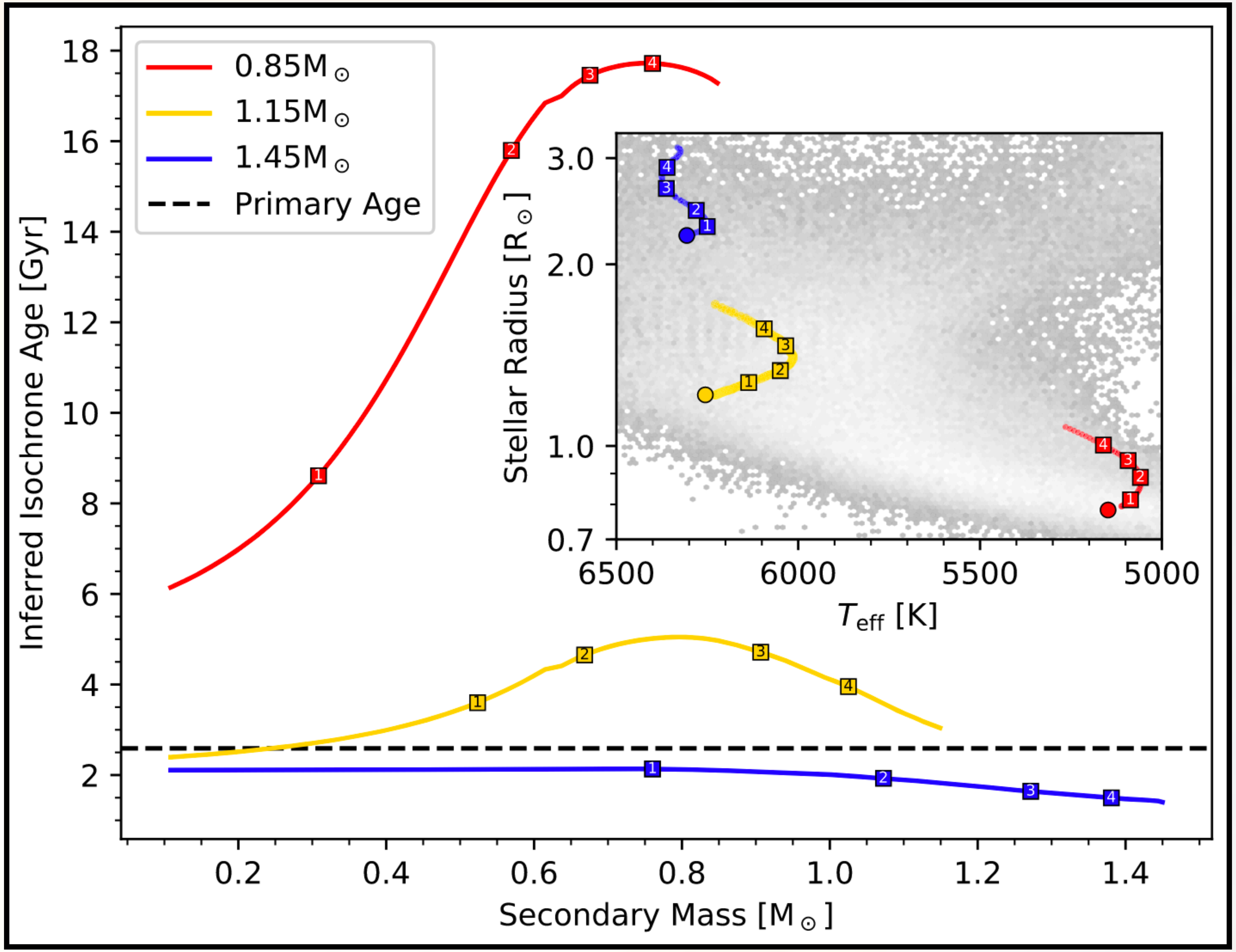
Bolometric Fluxes: Systematic Errors





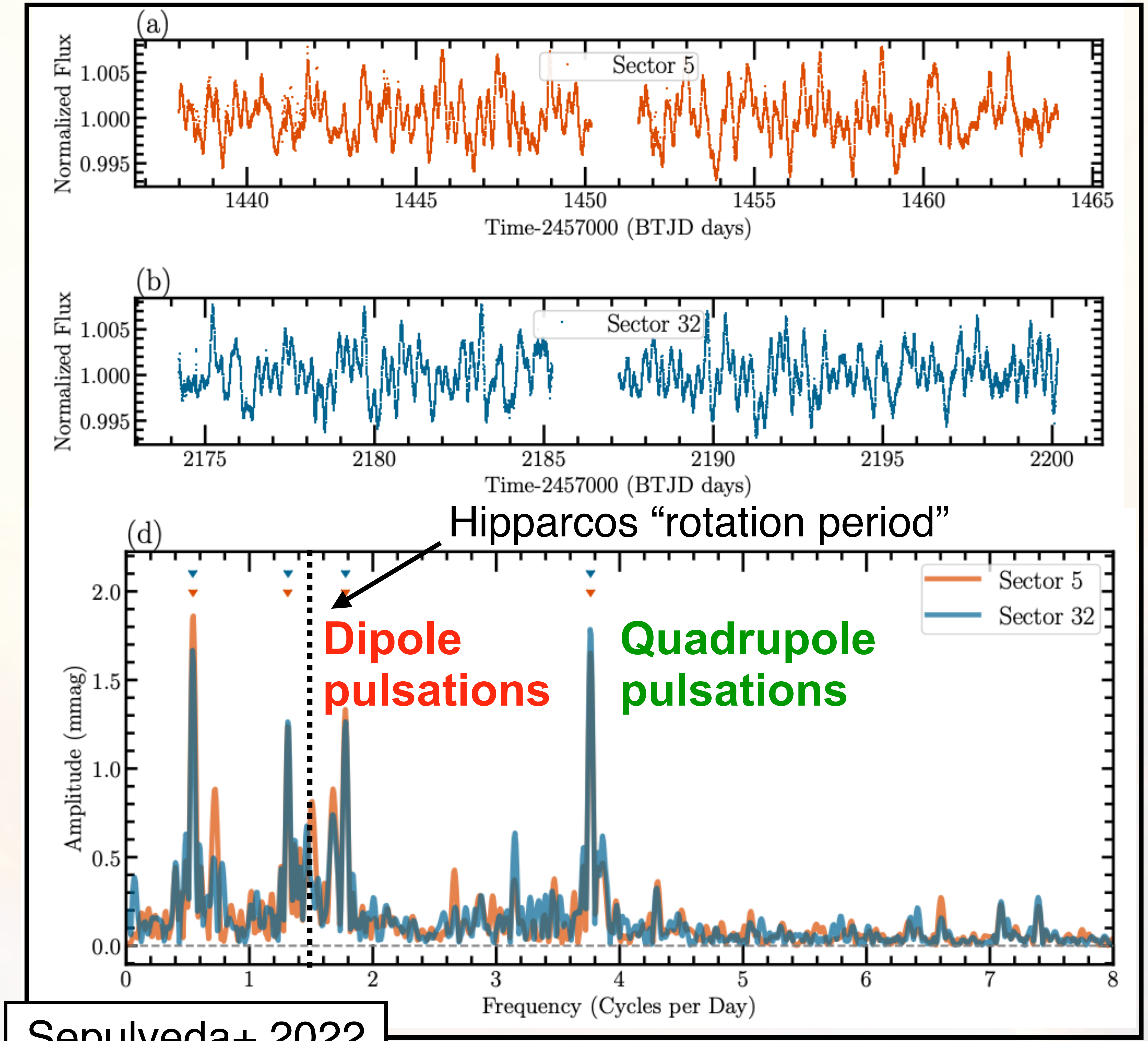
~2-4% offsets not uncommon. Can dominate the error budget on L ∝ f_{bol} d^2!

Effects of Unresolved Binaries

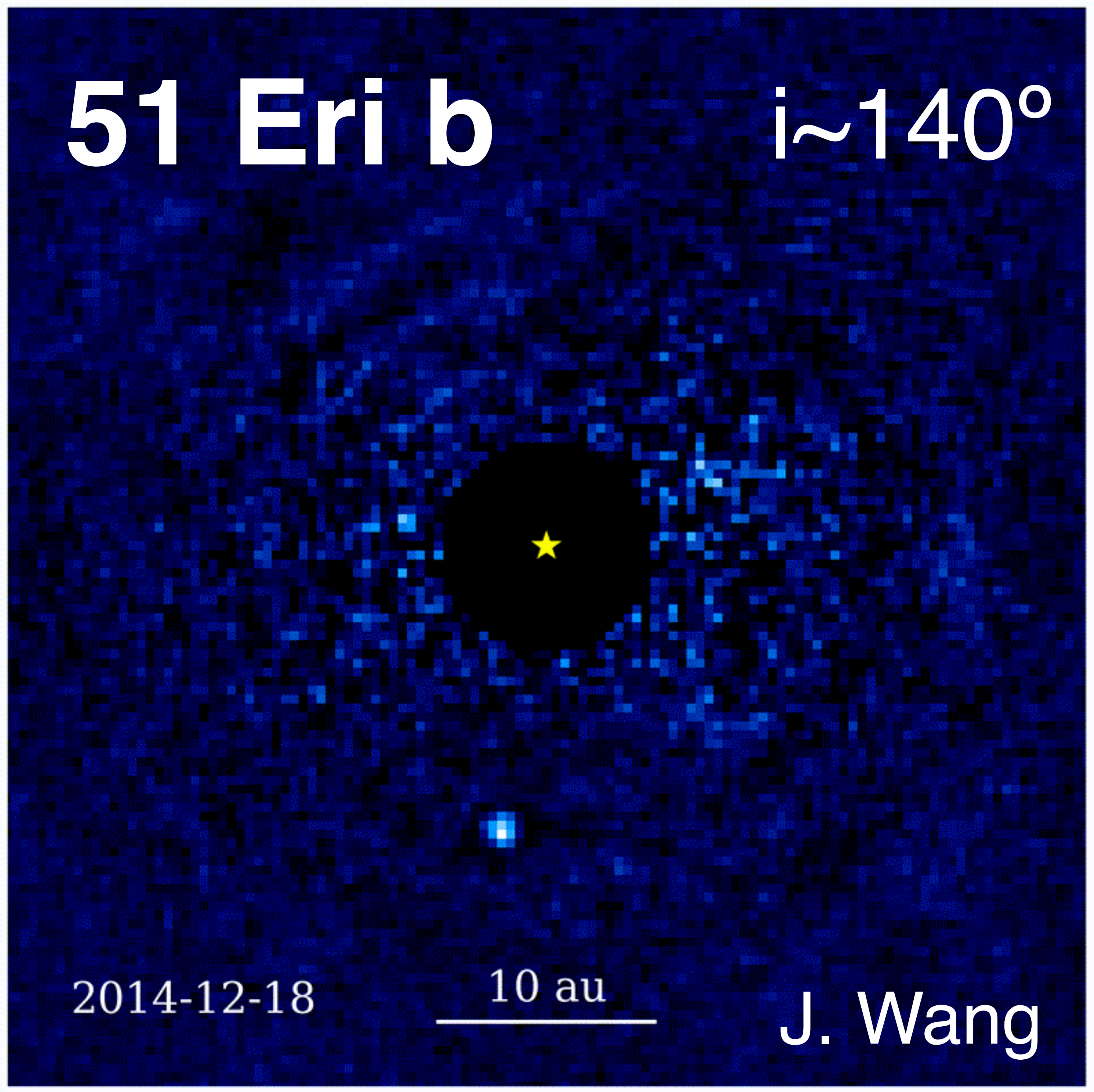


Berger+ 2018

Architectures of Imaged Planets



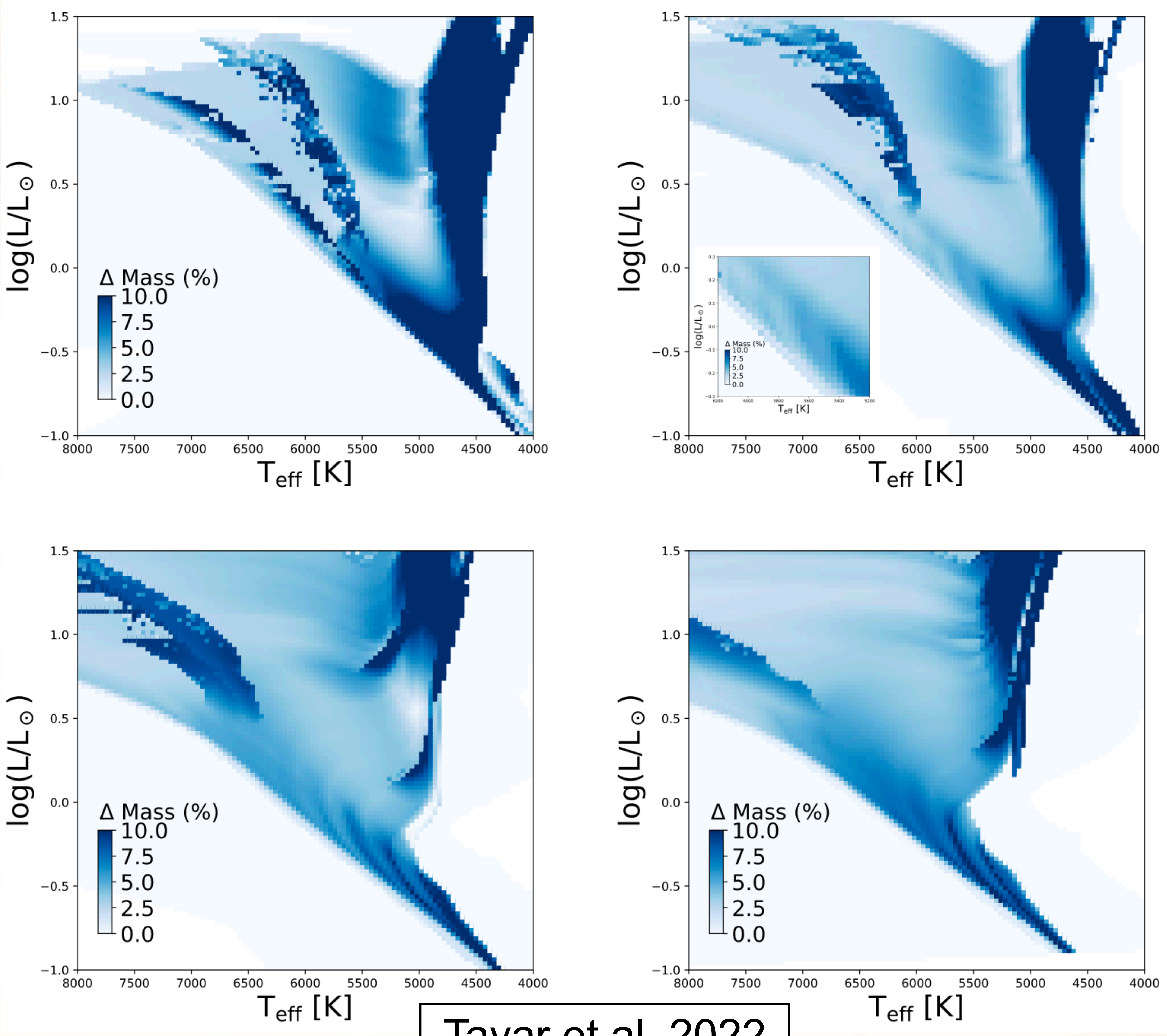
Sepulveda+ 2022



Aldo Sepulveda

Asteroseismic rotation period constrains line-of-sight inclination to i~60° (i~120°). Consistent with planetary orbit alignment?

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**!