# Reanalyzing KELT-15b: An Exploration of Systematic Errors in Transiting Planets and Their Host Stars

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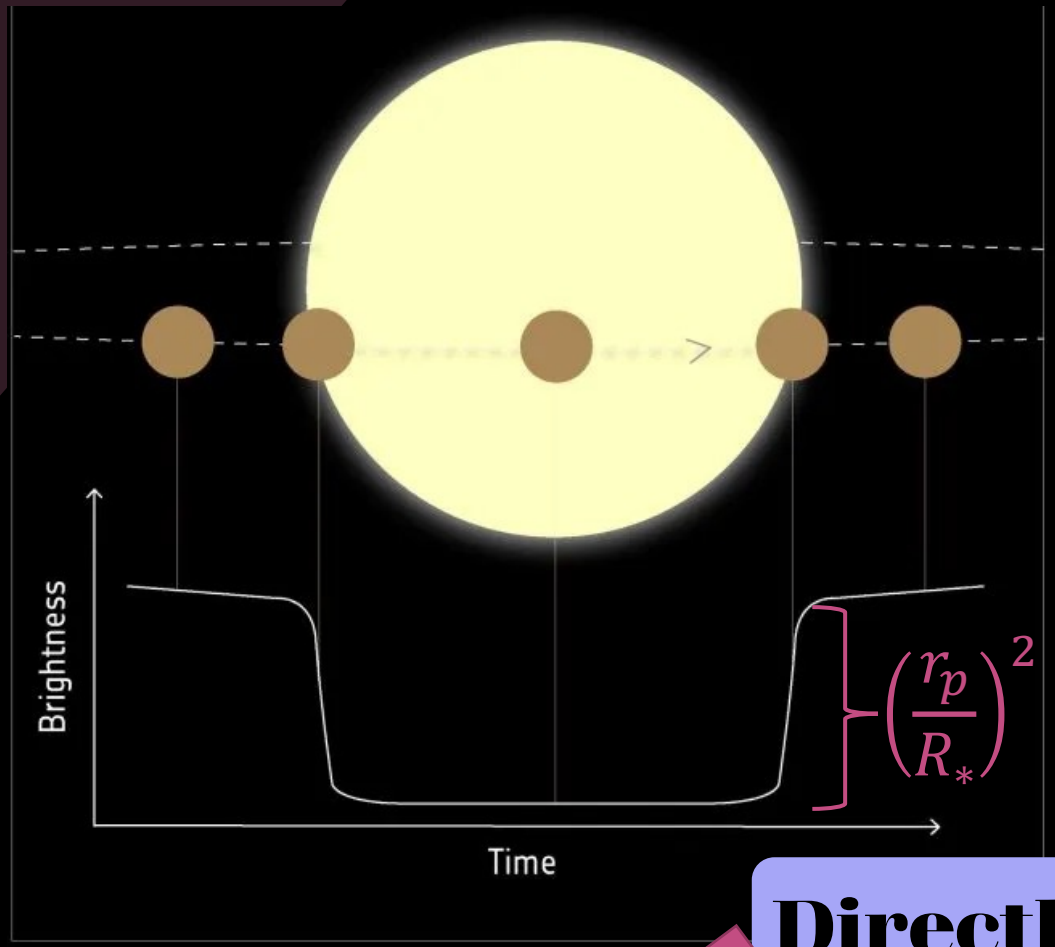
# The Need for Precise & Accurate Fundamental Parameters of Transiting Planets

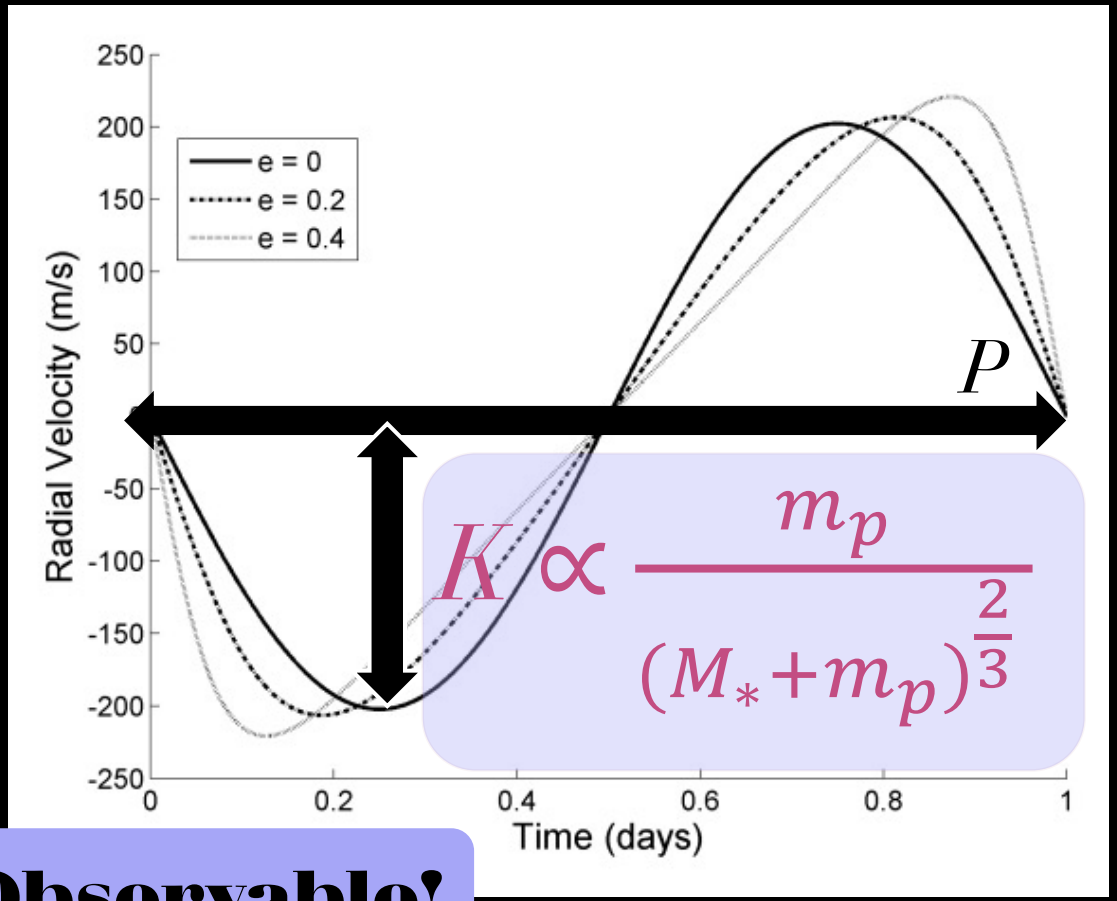
Foundational questions in exoplanet science require precise & accurate parameters of transiting planets


Demographics

Interior Composition

Atmospheric Characterization




**Directly Observable!**

$$\rho_* \approx \frac{3\pi}{GP^2}\left(\frac{R_*}{a} = \frac{\pi}{\delta^{\frac{1}{4}}}\frac{\sqrt{T\tau}}{P}\left(\frac{1 + e\sin\omega}{\sqrt{1-e^2}}\right)\right)$$

$$\rho_* \propto \frac{M_*}{R_*^3}$$

However, $M_*$ and $R_*^3$ are **Degenerate**

# Breaking the Degeneracy

Stellar Evolutionary Tracks

Empirical Scaling Relations

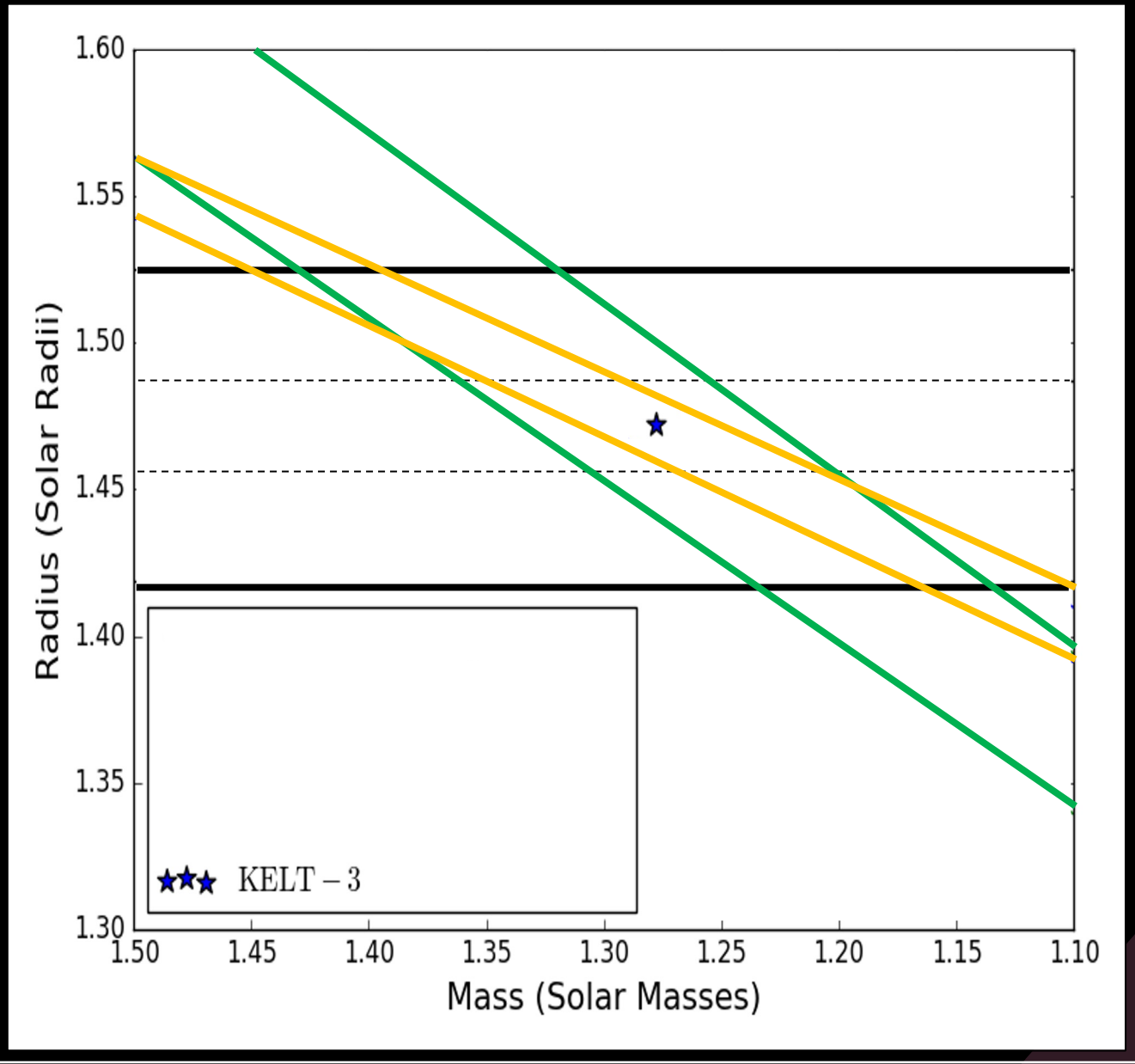



Fig 12. from Doré et al. 2018

# Goals of This Work

1

Analyze one system with four mass-radius degeneracy breaking techniques

2

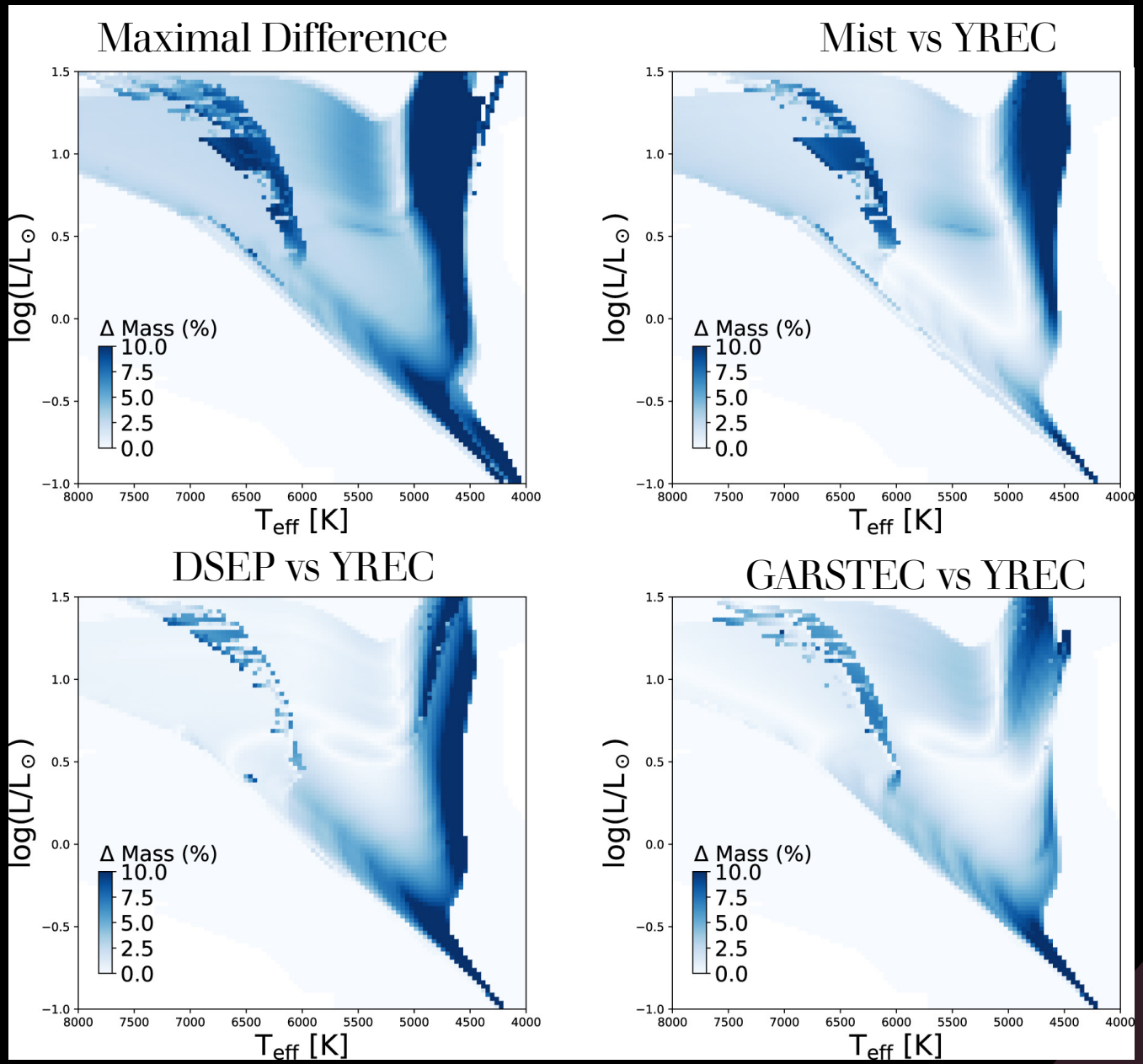
Check agreement between the methods

3

Quantify the systematic error introduced by mass-radius degeneracy breaking method

# Tayar et al. 2022

Discovered systematic differences of ~5% in stellar mass and ~20% in age based on model selection



# Breaking the Mass-Radius Degeneracy

Semi-Empirical Mass-Radius Relationships

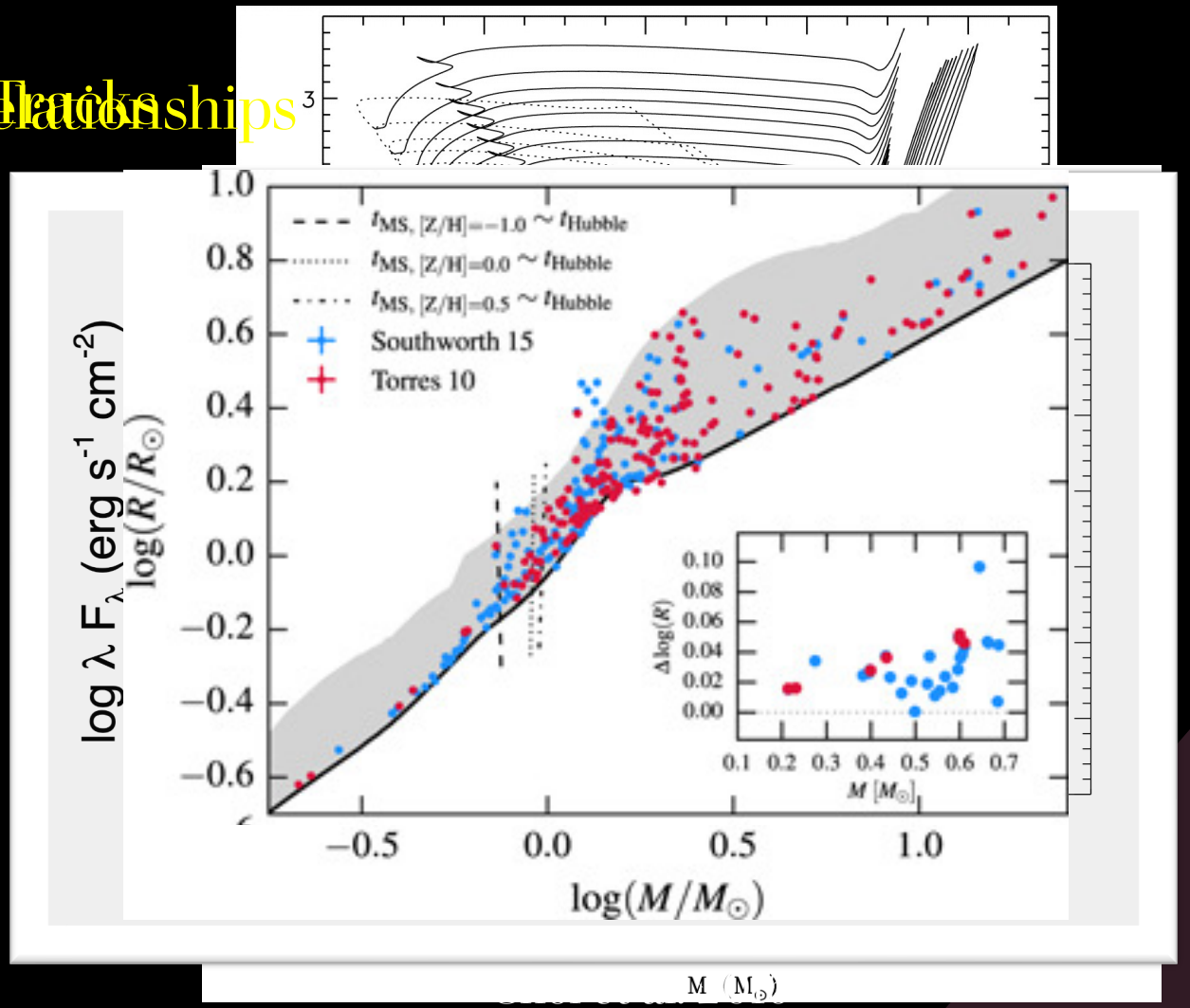
The Empirical Stellar Evolution Tracks

MIST (MESA Isochrones and Stellar Tracks)

YY (Yonsei-Yale)

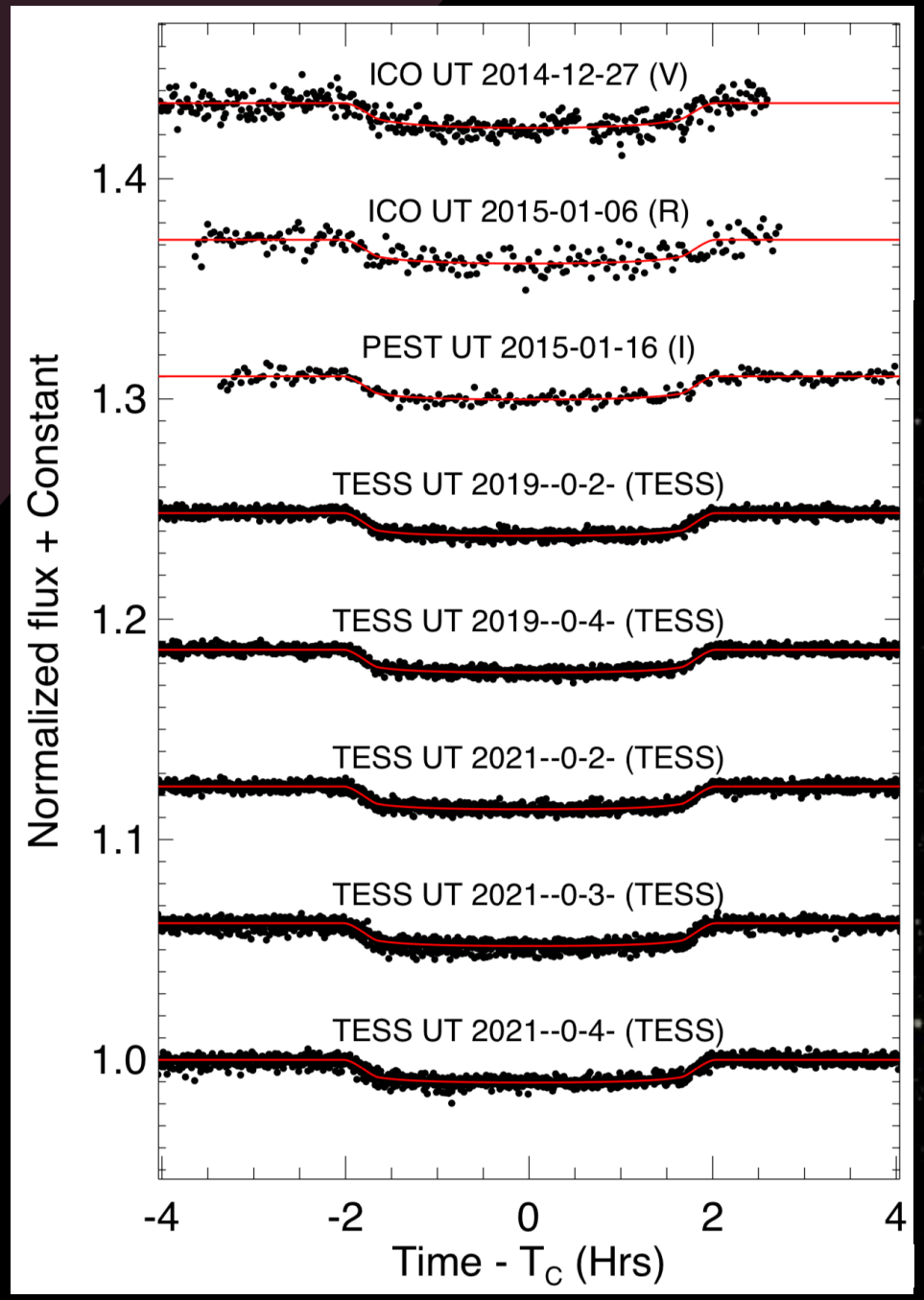
The Torres Relations

Spectral Energy Distribution (SED) Fitting




Yi, Kim & Demarque 2003

Duck, Gaudi et al. (Under Review)




Duck, Gaudi et al. (Under Review)

# KELT-15

Roughly Solar G0 Host Star

Rodriguez et al. 2016

Hot Jupiter

KELT Survey Discovery

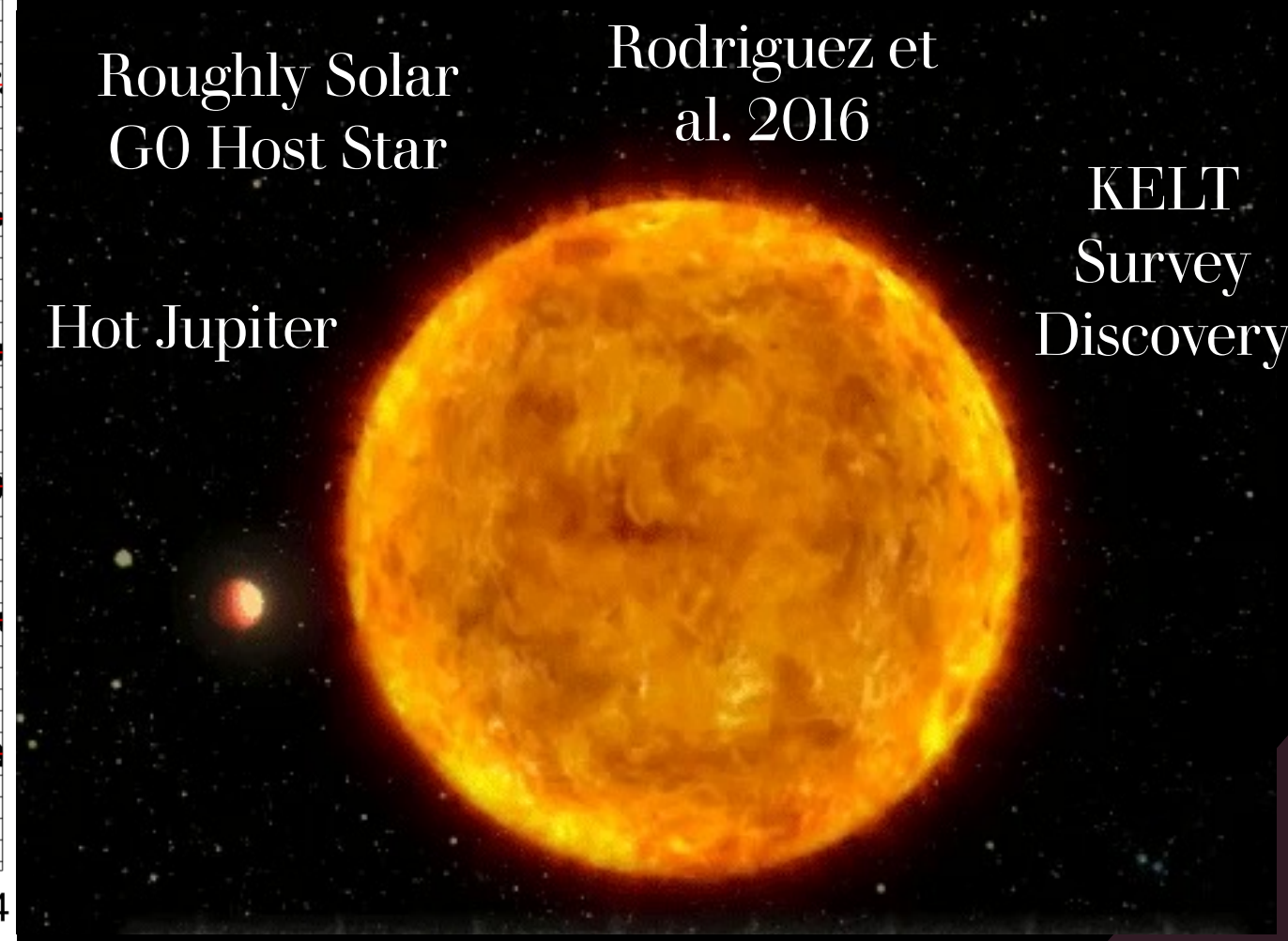


*Image: NASA's Goddard Space Flight Center*

# Replicating discovery with EXOFASTv2

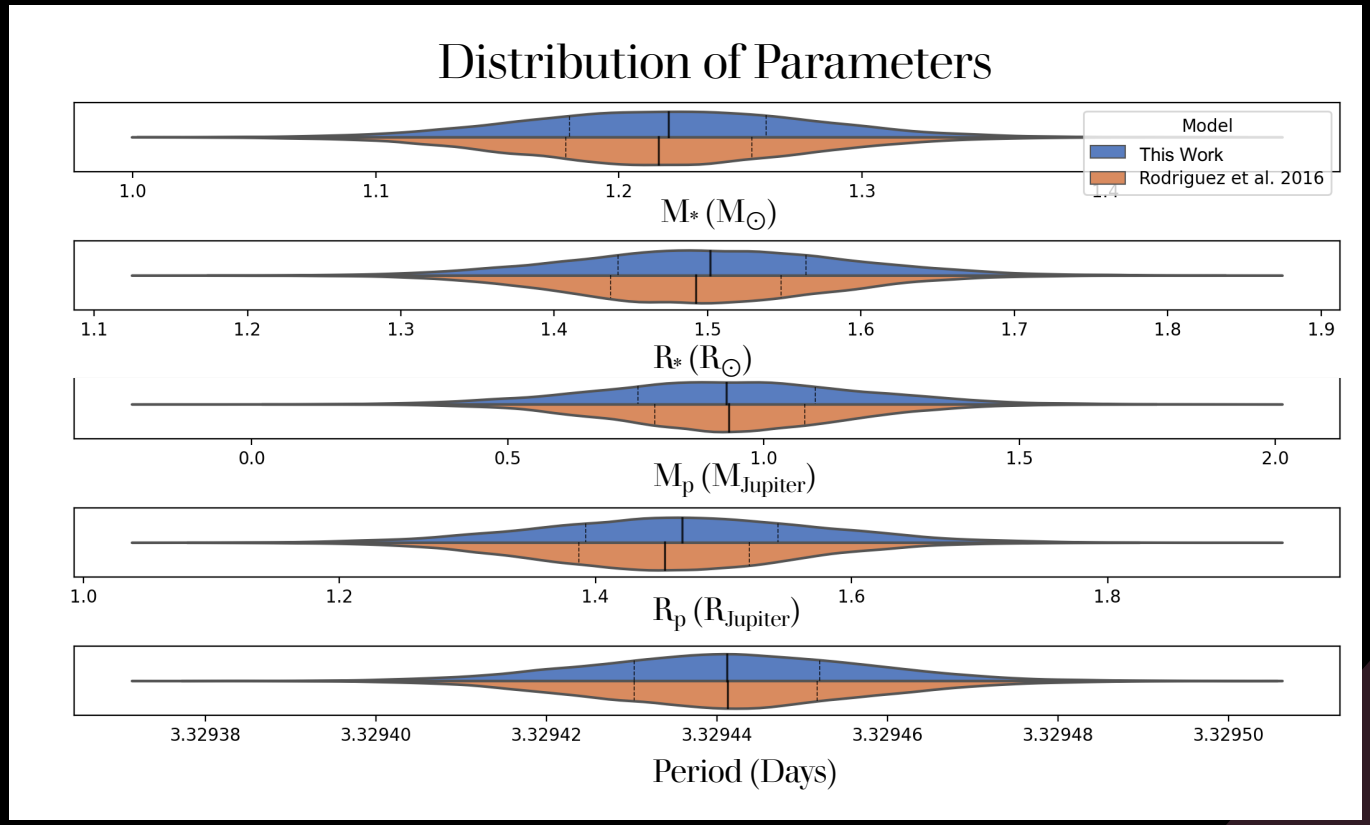
## EXOFASTV2

Simultaneously fits the planet and host star

Jointly fits transit and RV observations

Based on a Markov Chain Monte Carlo approach

Eastman et al. 2012, 2017



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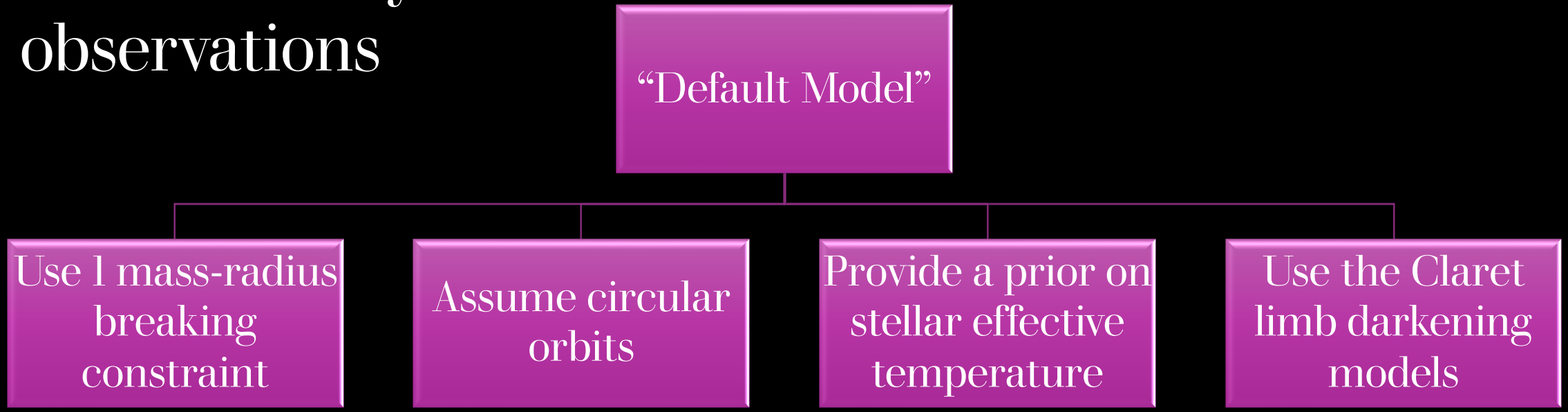
All fits use the **same** transit and radial velocity observations



# Overview of Process

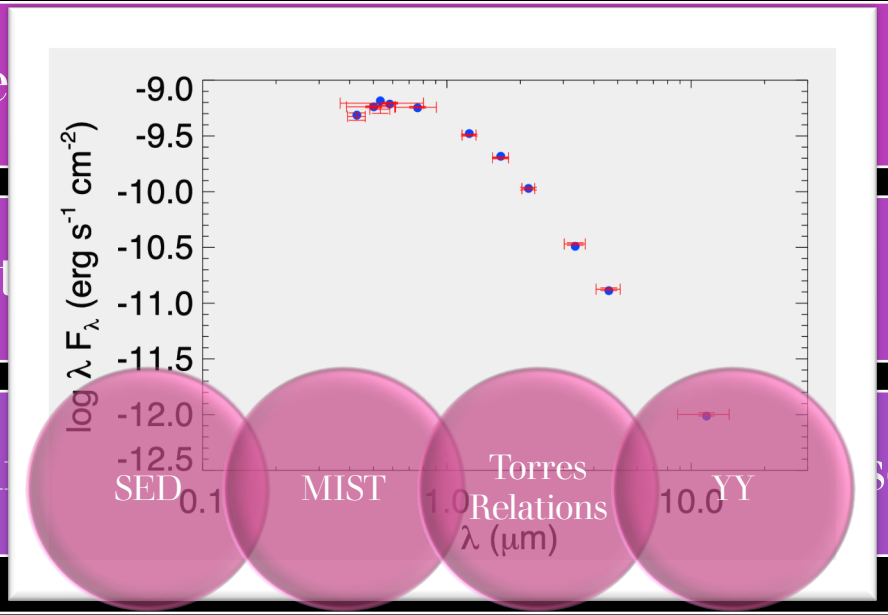
Starting priors are generated from an initial SED fit

Use all ground base

Model is select

Iterate u

score of 1.01



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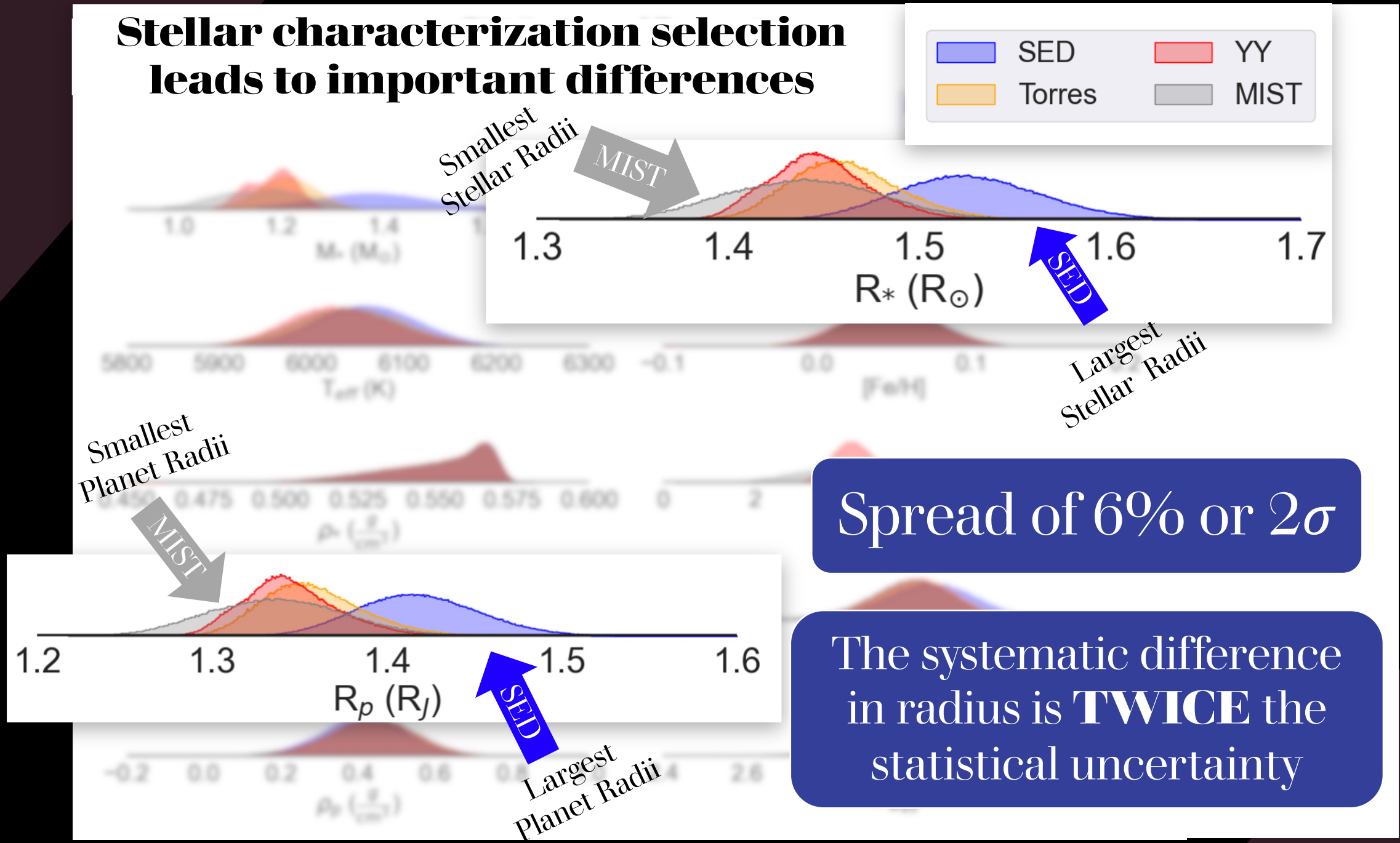
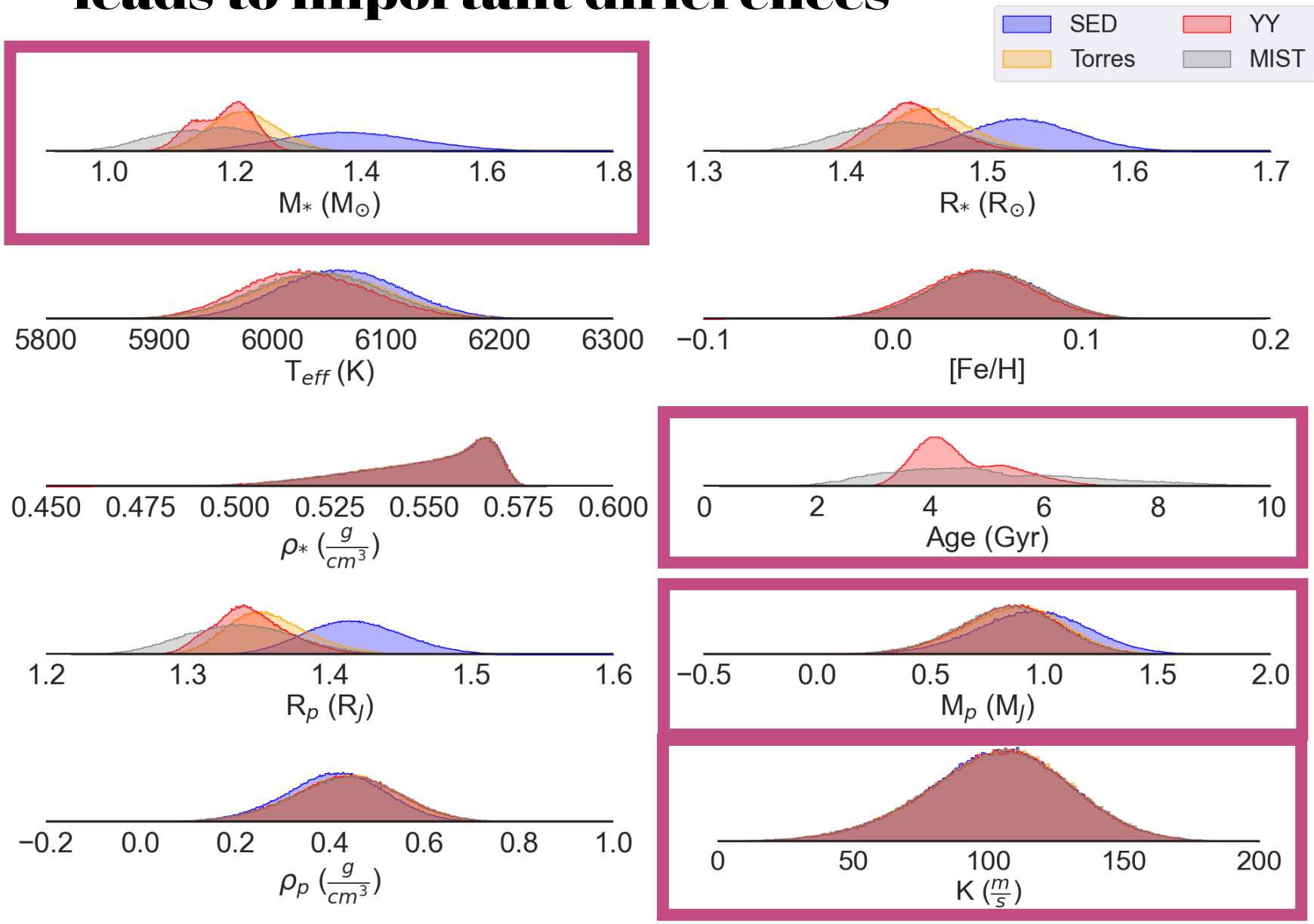
# Stellar characterization selection leads to important differences



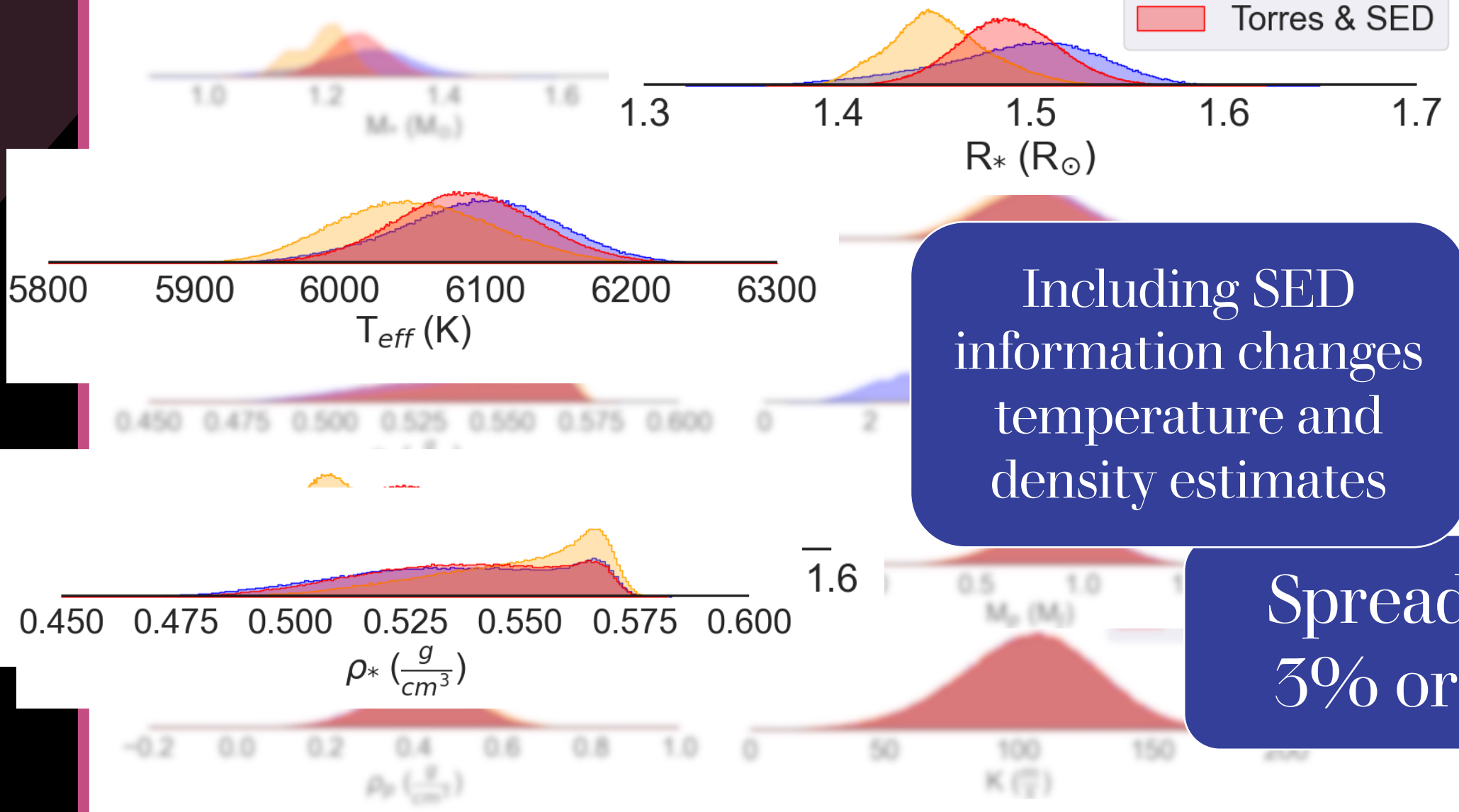

Spread of 6% or $2\sigma$

The systematic difference in radius is **TWICE** the statistical uncertainty

# Stellar characterization selection leads to important differences



# Combining characterization methods




Including SED information changes temperature and density estimates

Spread of 3% or 1$\sigma$

1

Analyze one system with four mass-radius degeneracy breaking techniques

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Check agreement between the methods

3

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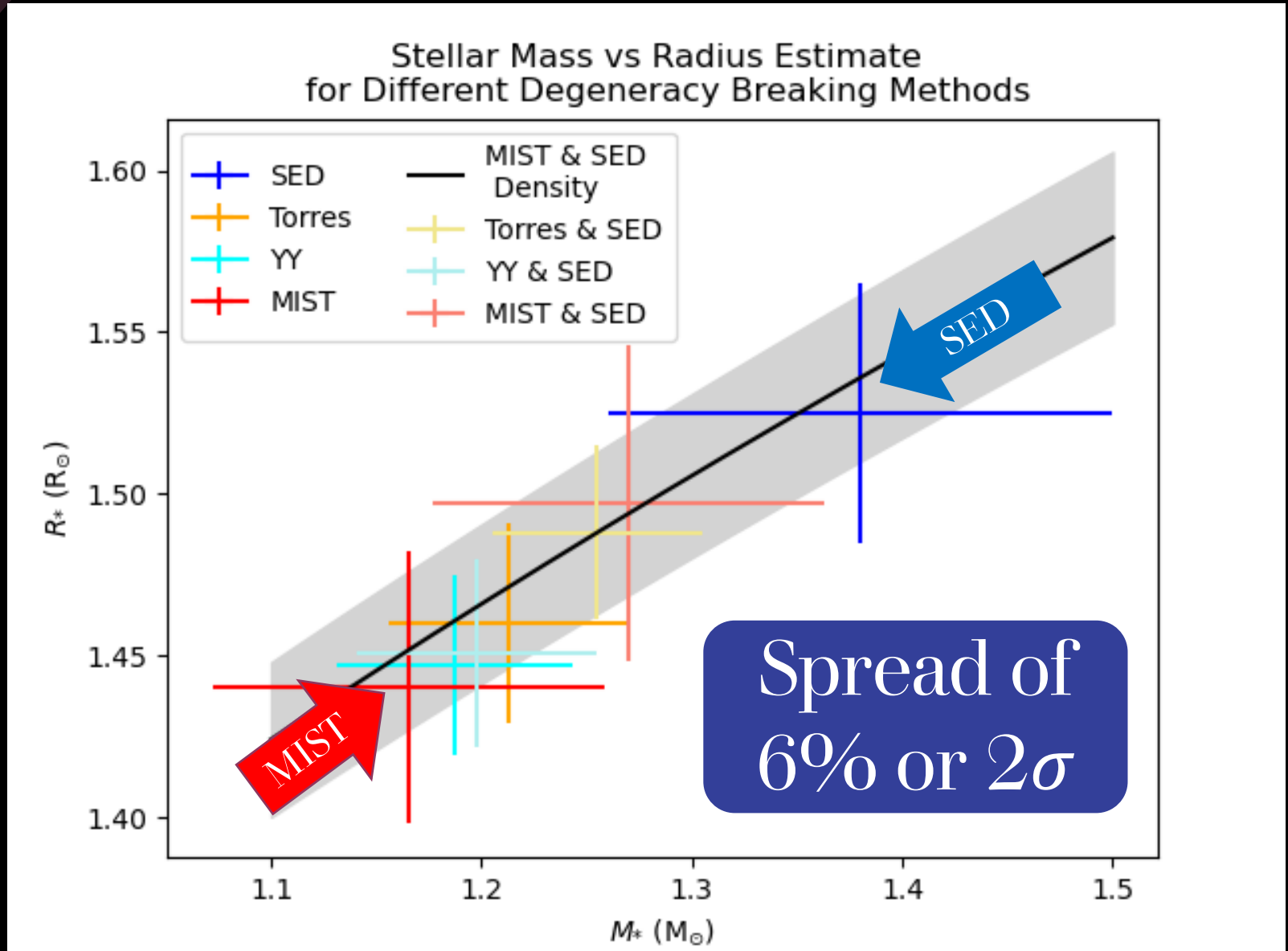

Stellar Mass vs Radius Estimate
for Different Degeneracy Breaking Methods
SED
Torres
YY
MIST
MIST & SED Density
Torres & SED
YY & SED
MIST & SED
SED
MIST
Spread of 6% or 2σ
1.60
1.55
1.50
1.45
1.40
R* (R⊙)
1.1
1.2
1.3
1.4
1.5
M* (M⊙)

# Stellar characterization is not the only source of systematic uncertainties

# Changin umptions

Previous Assumptions

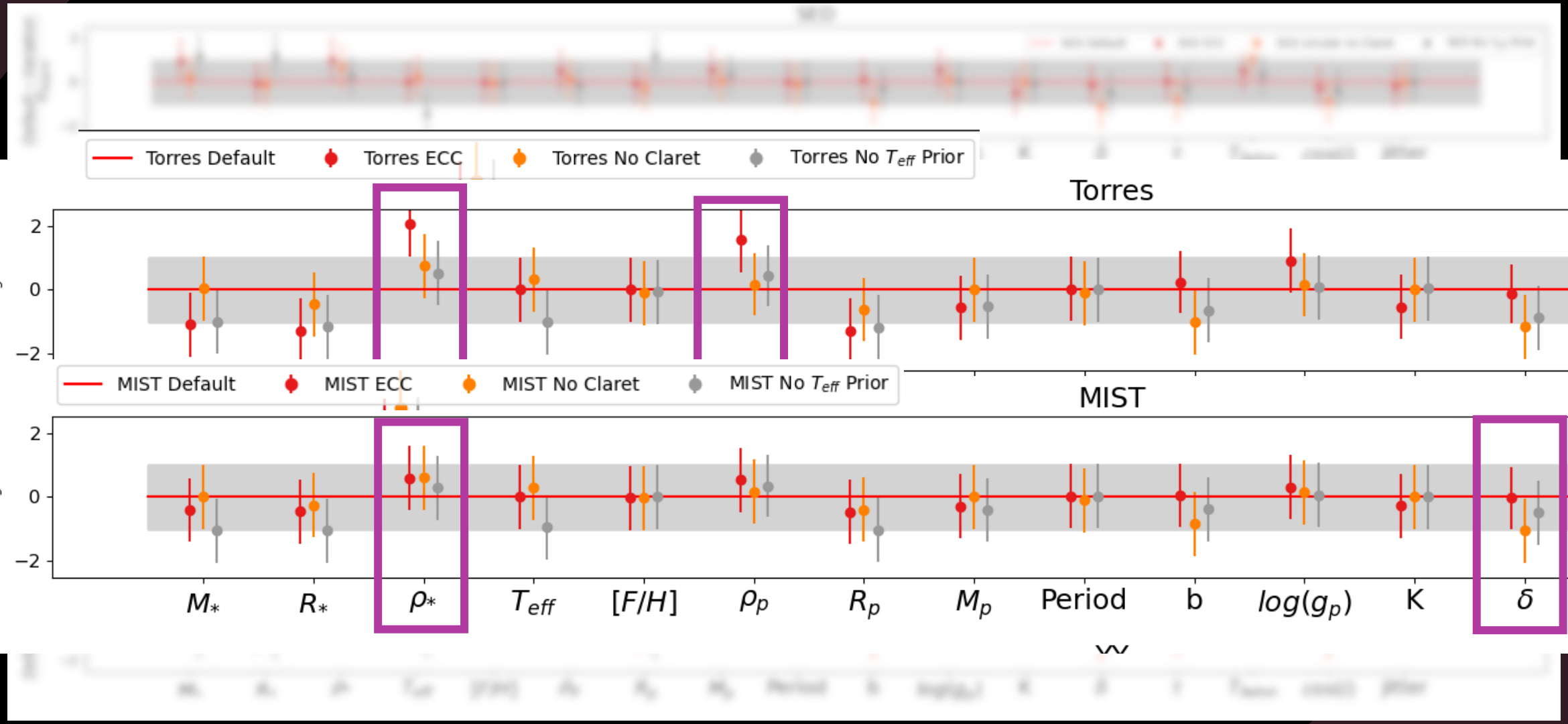
| Name | Teff P | | Claret? |
|---|---|---|---|
| No Teff Prior | Starting value for Teff | Circular Orbit | Claret Limb Darkening |
| | Prior o | bit | |
| | Prior o | t | |

Assume circular orbits

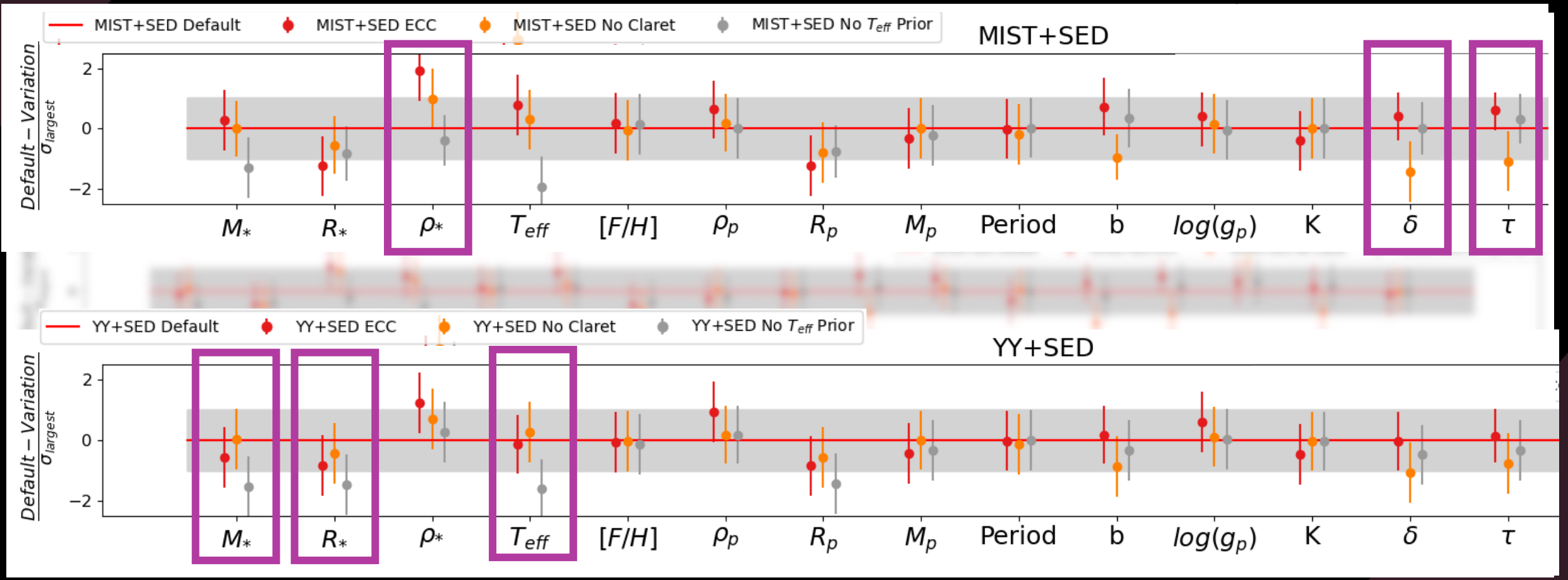
A prior on stellar effective temperature

Use the Claret limb darkening models

# Initial Assumptions Contribute to Systematic Uncertainties

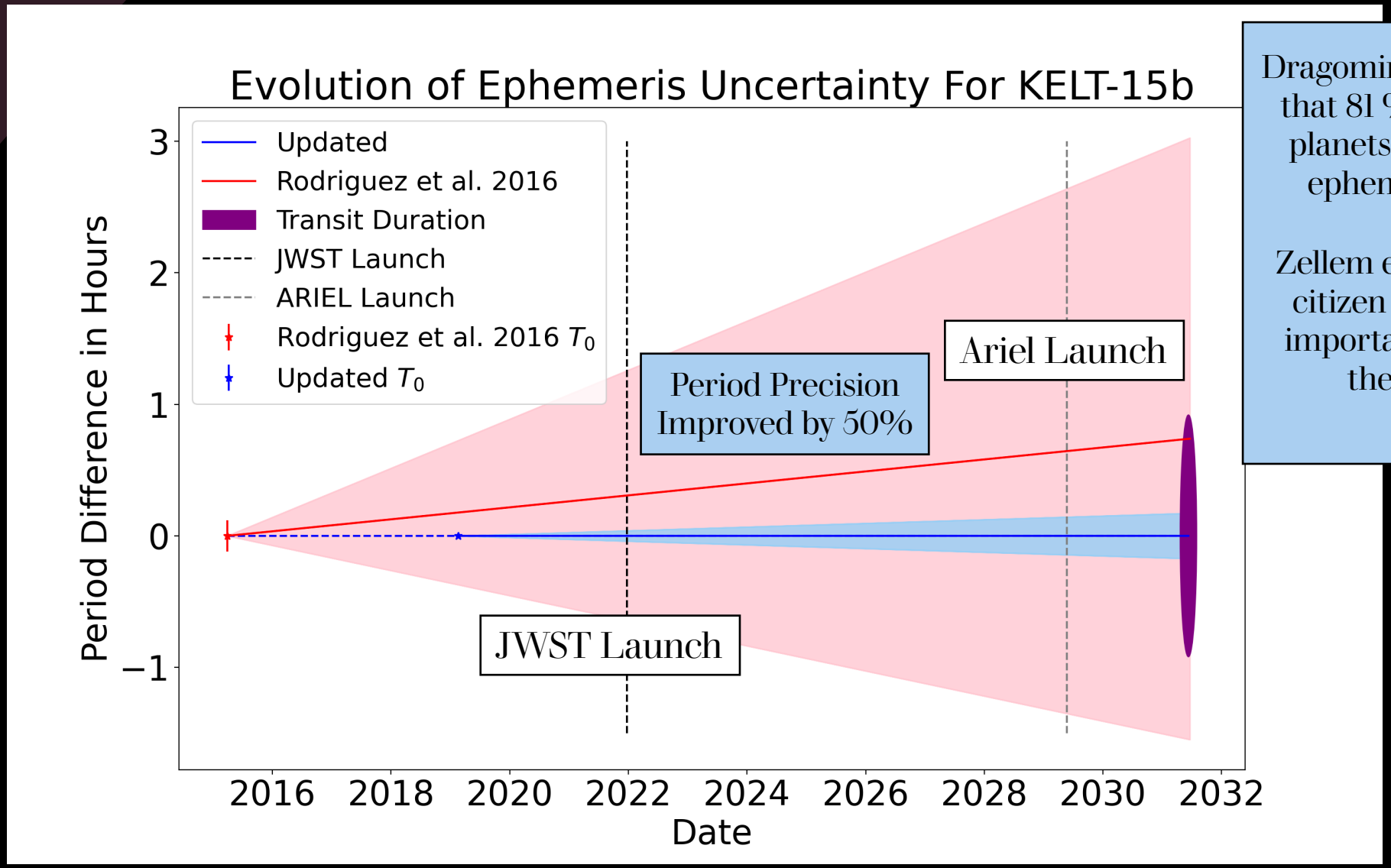


# Combination Constraints



# Need for Consistent Modeling Practices

- There is a significant contribution of systematic error from model choice alone
- Systematic Uncertainties can be TWICE statistical uncertainties
- Detailed choices of priors introduce additional systematic uncertainties at the same magnitude as statistical uncertainties



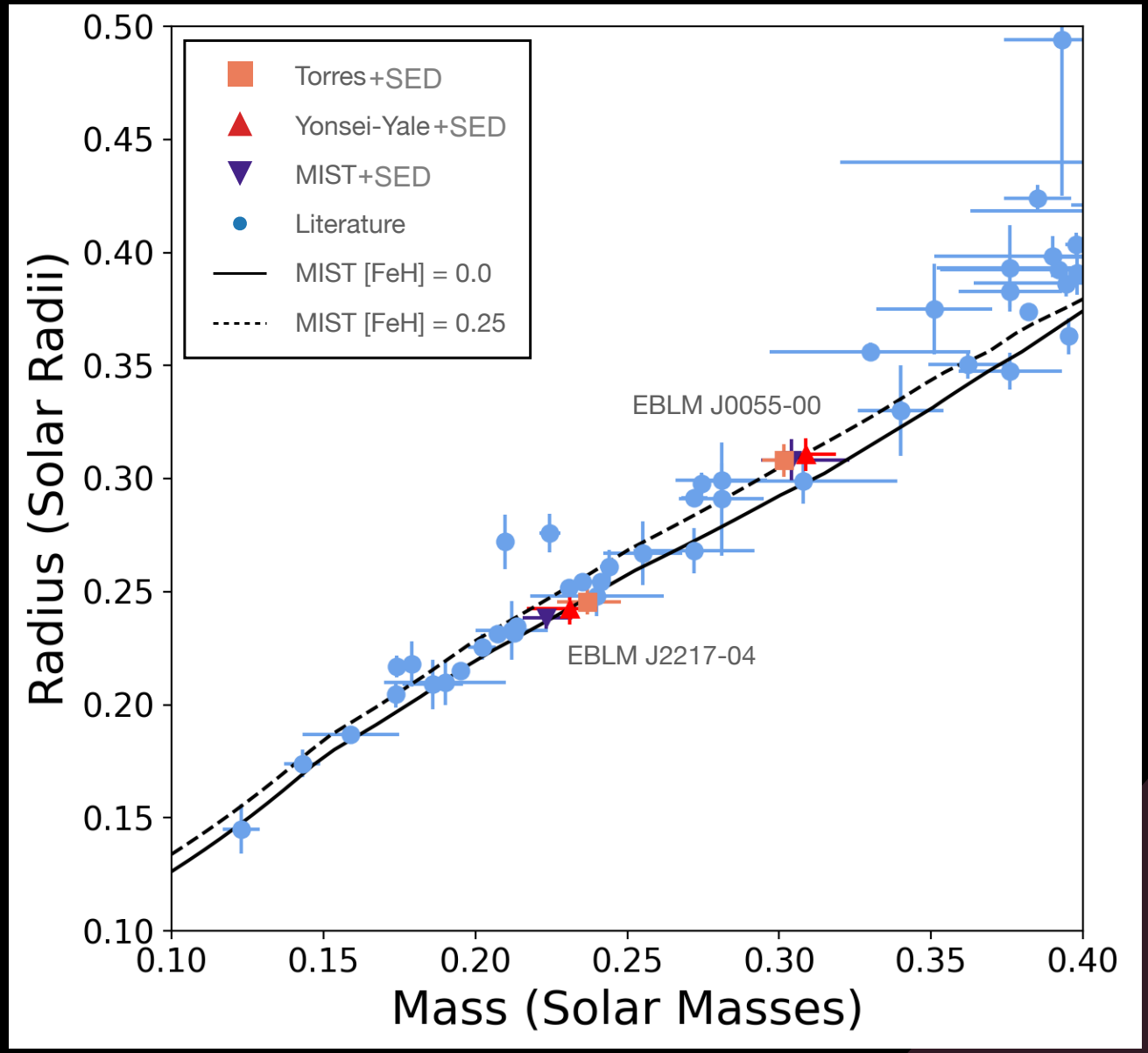

Dragomir et al 2020 highlights that 81 % of simulated TESS planets would have expired ephemerides after 1 year

Zellem et al 2020 shows that citizen observations are an important tool in refreshing these ephemerides

# TESS Observations provided update ephemerides

# Application to Eclipsing binaries

Modeling FGK stars with eclipsing M-dwarf companions leads to a ~3% spread in M-dwarf radius




Duck, Martin et al. (Under Review)

# Future Work Outline

- Reanalyze a sample of exoplanet hosts with interferometrically derived radii
  - Explore the MR degeneracy breaking techniques for circular and eccentric orbits
  - Quantify systematics compared to a fiducial dataset

- Re-analyze a sample of Hot Jupiters with consistent methods
  - Would have similar systematic errors
  - Updated ephemerides from recent TESS observations
  - Could be more directly compared for demographic studies

# Conclusions

- In order to make meaningful comparisons between planets we need full understanding of their error budgets
- There is a significant contribution of systematic error from model choice
- In $R_*$ and $R_p$ we find a difference of 6% or twice the statistical uncertainty
- We encourage exoplanet researchers to consistently report the mass-radius degeneracy breaking method used to characterize their host stars
- Future Work: larger sample & benchmark models

The Paper!

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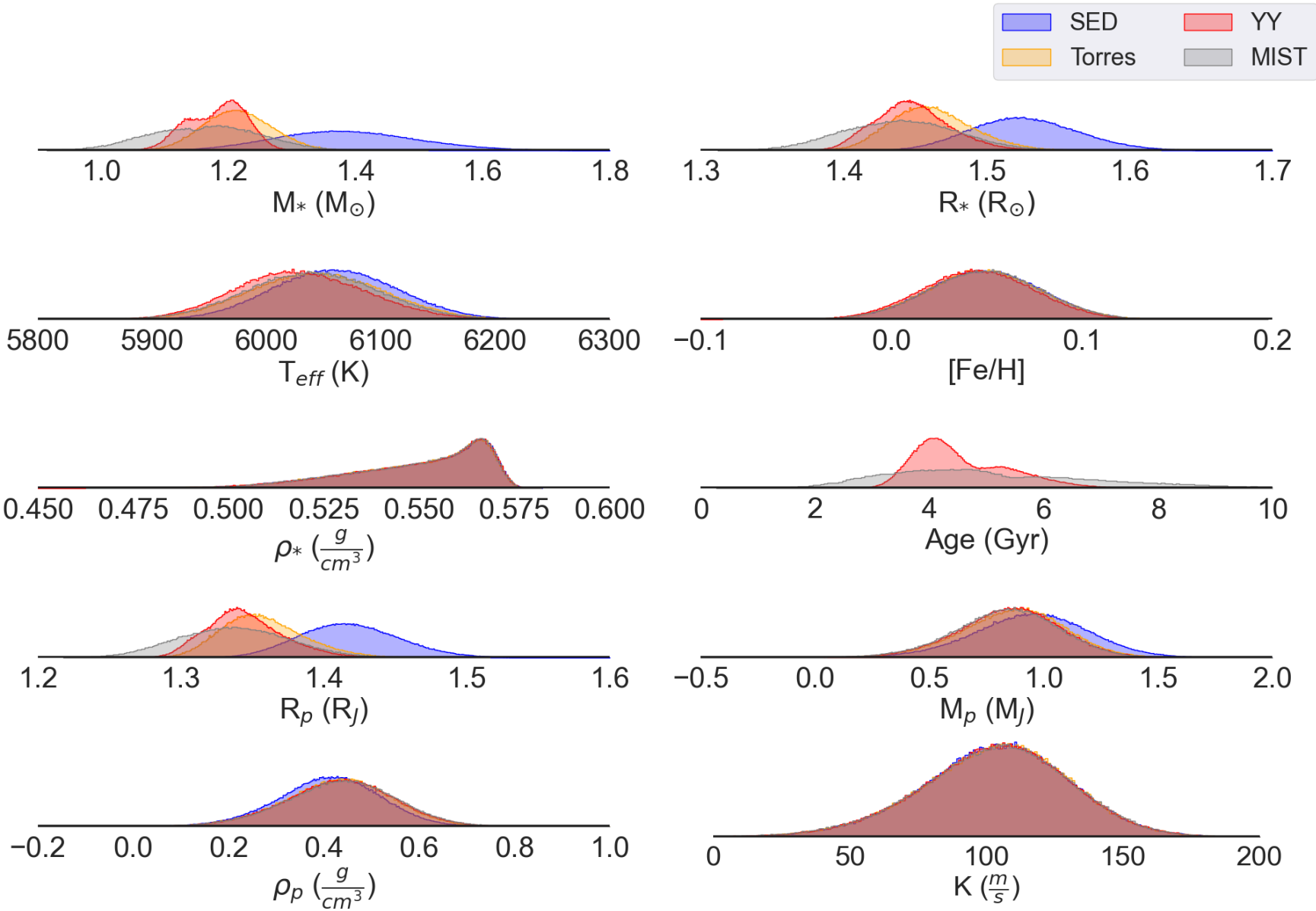
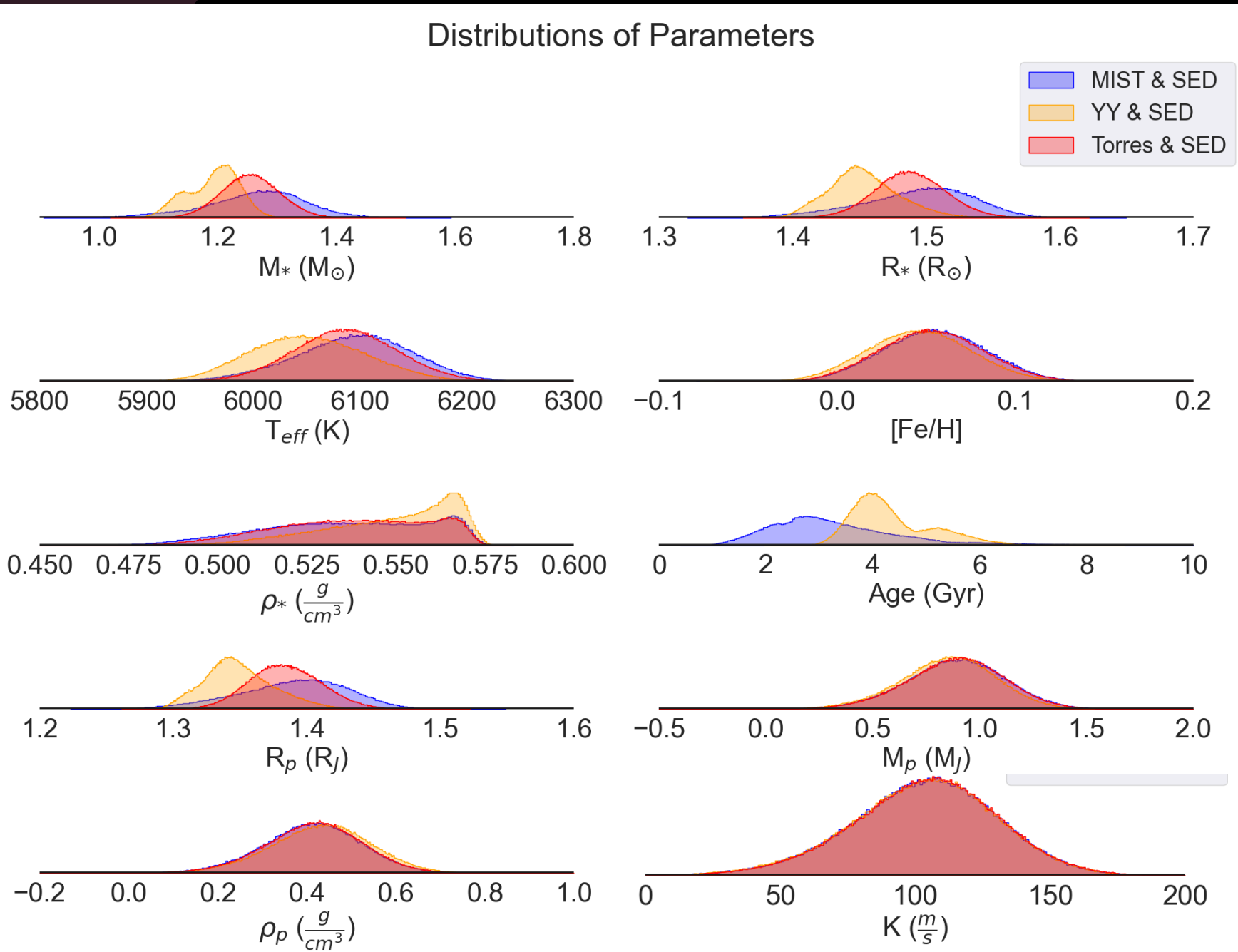
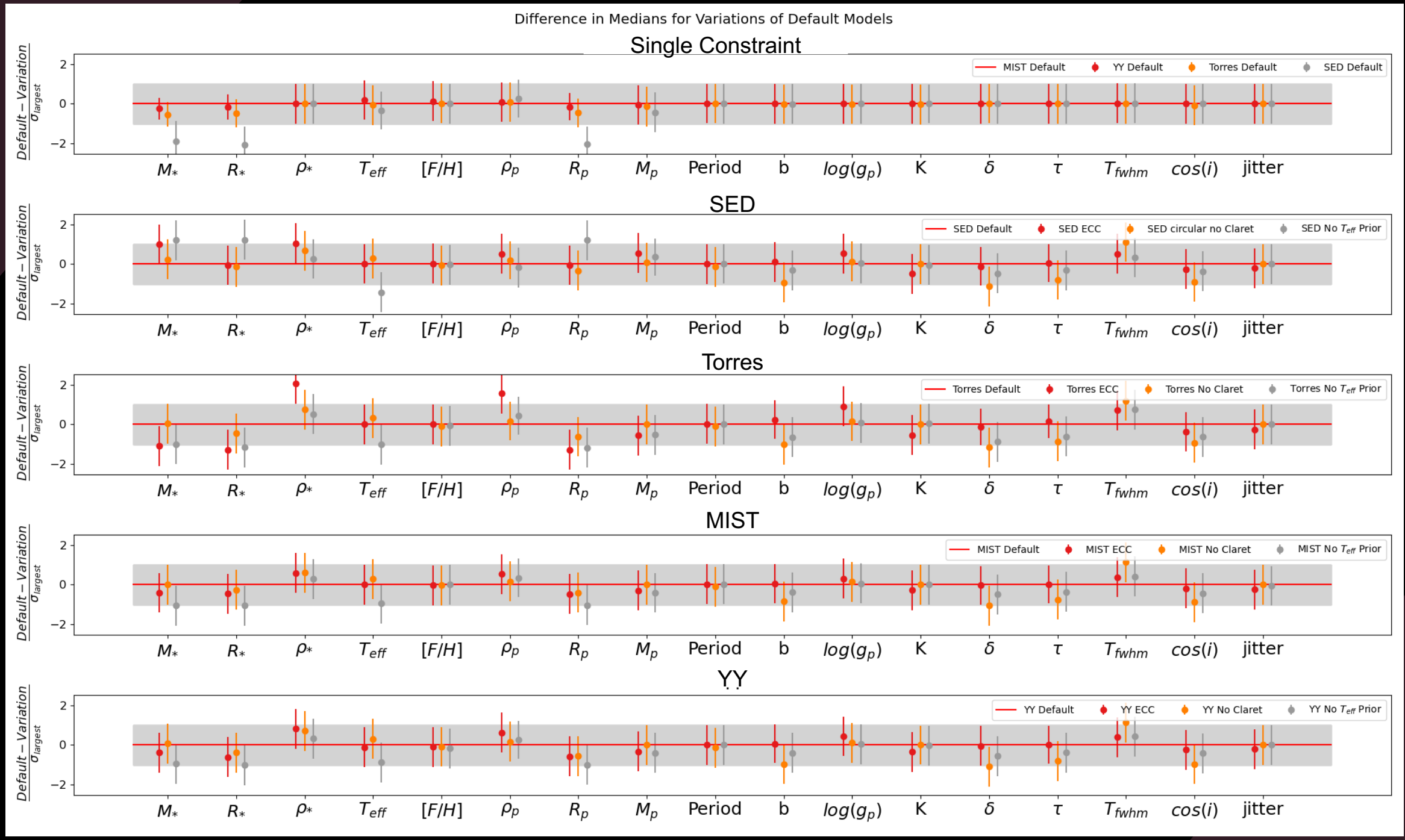
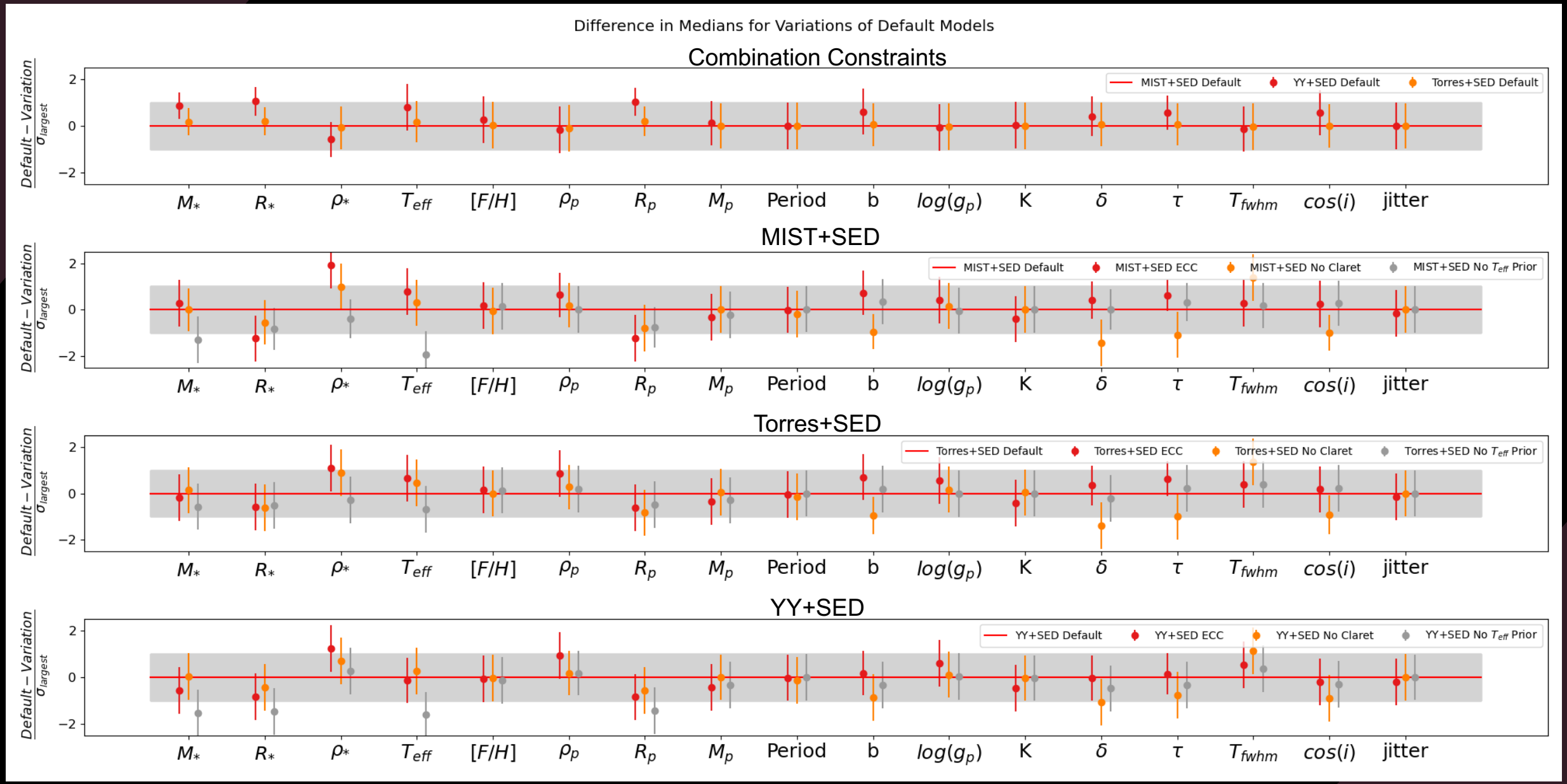
# Distributions of Parameters




Distributions of Parameters
MIST & SED
YY & SED
Torres & SED
1.0 1.2 1.4 1.6 1.8
M∗ (M⊙)
1.3 1.4 1.5 1.6 1.7
R∗ (R⊙)
5800 5900 6000 6100 6200 6300
Teff (K)
−0.1 0.0 0.1 0.2
[Fe/H]
0.450 0.475 0.500 0.525 0.550 0.575 0.600
ρ∗ (g/cm³)
0 2 4 6 8 10
Age (Gyr)
1.2 1.3 1.4 1.5 1.6
Rp (RJ)
−0.5 0.0 0.5 1.0 1.5 2.0
Mp (MJ)
−0.2 0.0 0.2 0.4 0.6 0.8 1.0
ρp (g/cm³)
0 50 100 150 200
K (m/s)


Difference in Medians for Variations of Default Models
Single Constraint
MIST Default
YY Default
Torres Default
SED Default
SED
SED Default
SED ECC
SED circular no Claret
SED No $T_{eff}$ Prior
Torres
Torres Default
Torres ECC
Torres No Claret
Torres No $T_{eff}$ Prior
MIST
MIST Default
MIST ECC
MIST No Claret
MIST No $T_{eff}$ Prior
YY
YY Default
YY ECC
YY No Claret
YY No $T_{eff}$ Prior
$\frac{Default - Variation}{\sigma_{largest}}$
2
0
−2
$M_*$
$R_*$
$\rho_*$
$T_{eff}$
[F/H]
$\rho_p$
$R_p$
$M_p$
Period
b
$log(g_p)$
K
$\delta$
$\tau$
$T_{fwhm}$
$cos(i)$
jitter


Difference in Medians for Variations of Default Models
Combination Constraints
MIST+SED
Torres+SED
YY+SED
Default − Variation / σ_largest
MIST+SED Default
YY+SED Default
Torres+SED Default
MIST+SED ECC
MIST+SED No Claret
MIST+SED No T_eff Prior
Torres+SED ECC
Torres+SED No Claret
Torres+SED No T_eff Prior
YY+SED ECC
YY+SED No Claret
YY+SED No T_eff Prior
M* R* ρ* T_eff [F/H] ρ_p R_p M_p Period b log(g_p) K δ τ T_fwhm cos(i) jitter


30