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Host Star Properties from Stellar Evolution Models

Willie Torres

Center for Astrophysics | Harvard & Smithsonian

Planet-Star Connections in the Era of TESS and Gaia
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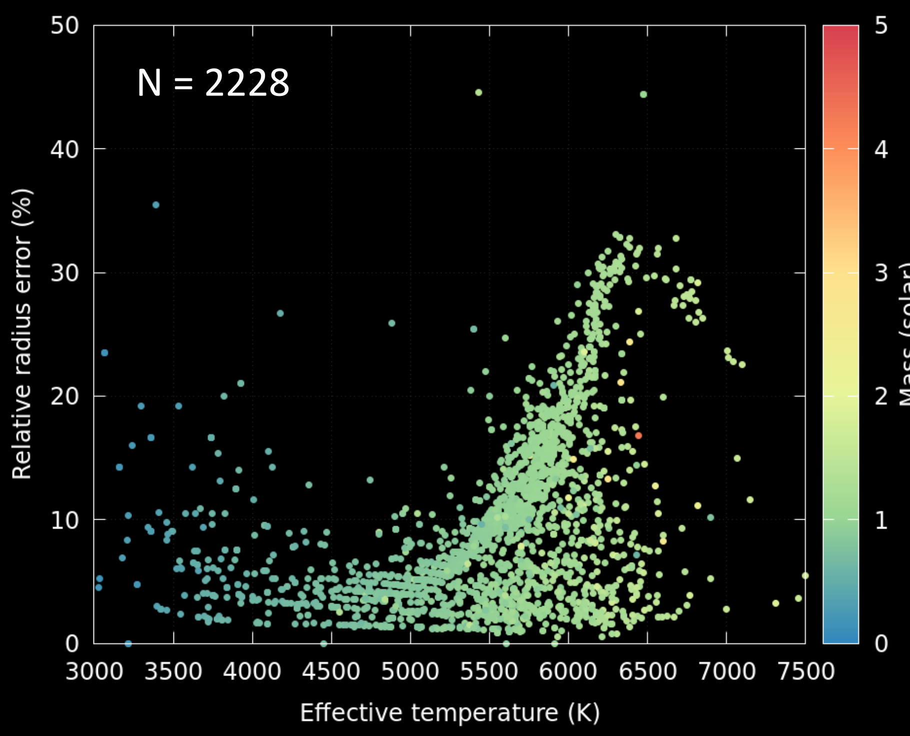
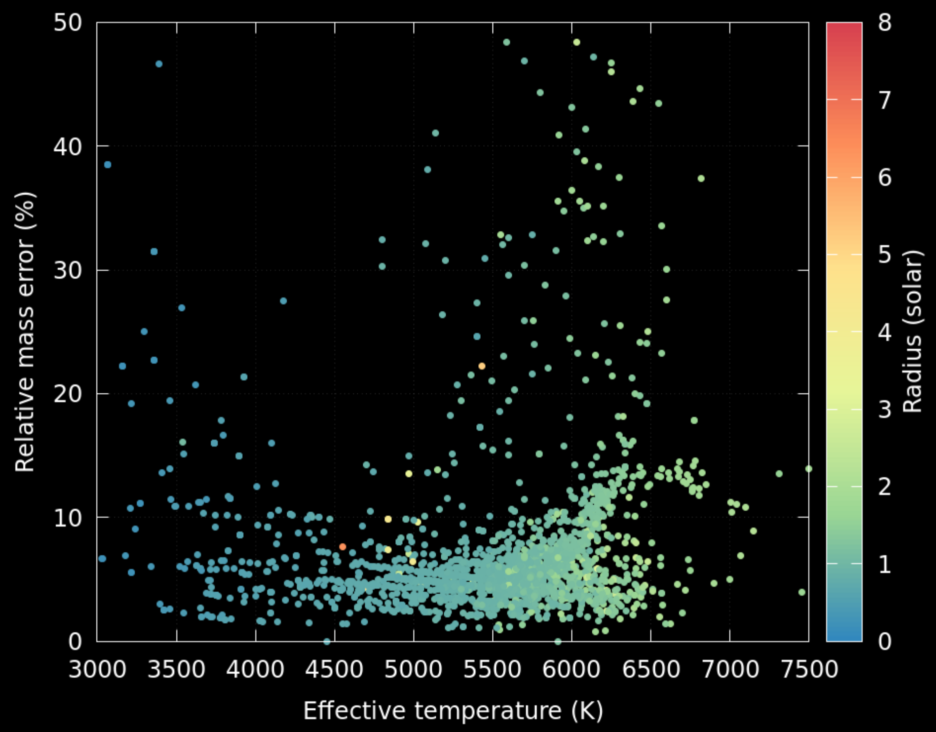
Calculating planetary masses and radii

- Planetary mass from Doppler observations:
  - $M_p \sin i = \text{const} \times K_* P^{1/3} (1\text{-}e^2)^{1/2} (M_* + M_p)^{2/3}$
  - Stellar mass error does not enter in full
- Planetary radius from transit observations:
  - $R_p = (R_p/R_*) R_*$
  - Stellar radius error enters in full
- Planetary density proportional to M_p/R_p^3
  - Precision and accuracy of R_* are more critical

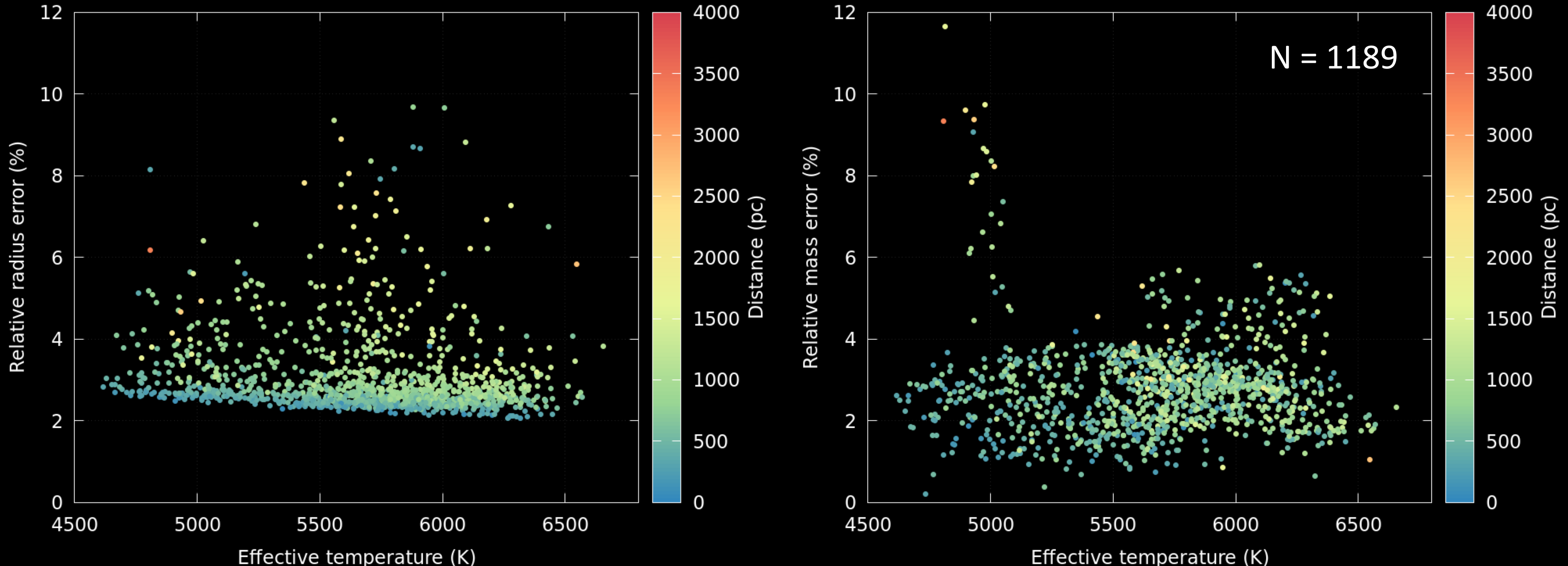
How well are M_* and R_* determined in the literature?

- NASA Exoplanet Archive
  - Many different methods, many different authors

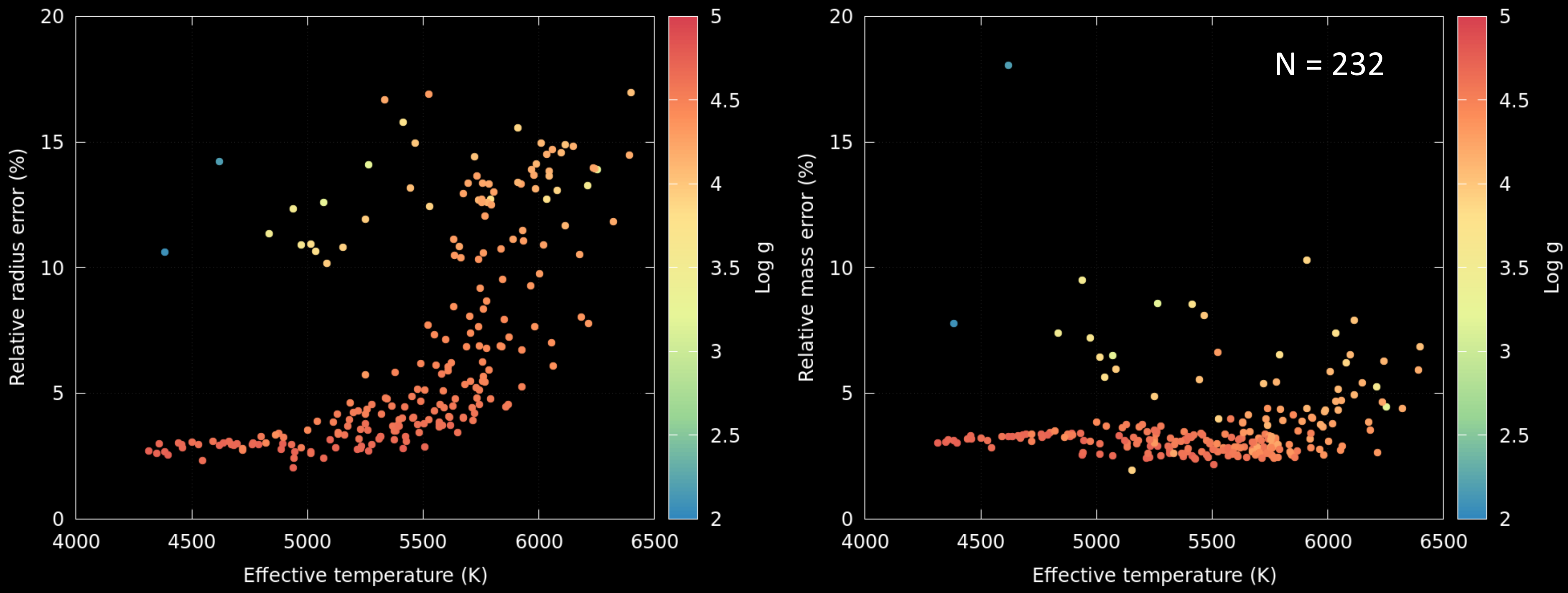




- Fulton et al. (2018)
  - Homogeneous determinations
  - Spectroscopic T_{eff}, Gaia/DR2 parallax, 2MASS K_S, extinction, and bolometric corrections from MIST models
  - Fits performed with the *isoclassify* package (Huber et al. 2017) and MIST isochrones
  - Formal $\sigma_R \approx 2–3\%$, formal $\sigma_M \approx 1–4\%$

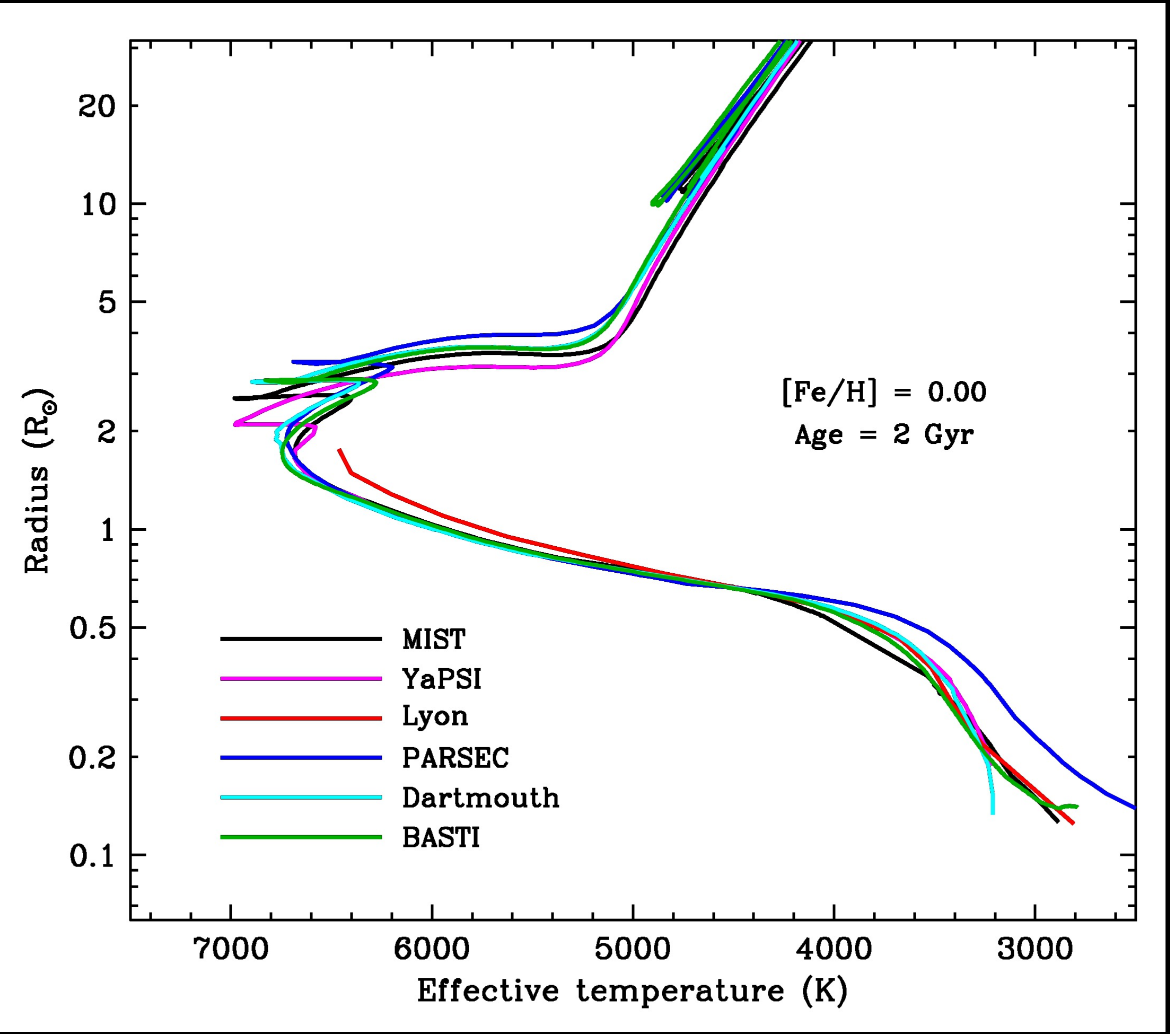


- Mayo et al. (2018)
  - Homogeneous determinations
  - Spectroscopic T_{eff}, metallicity, and log *g* (but no parallaxes)
  - Fits performed with the *isochrones* package (Morton 2015) and unspecified isochrones



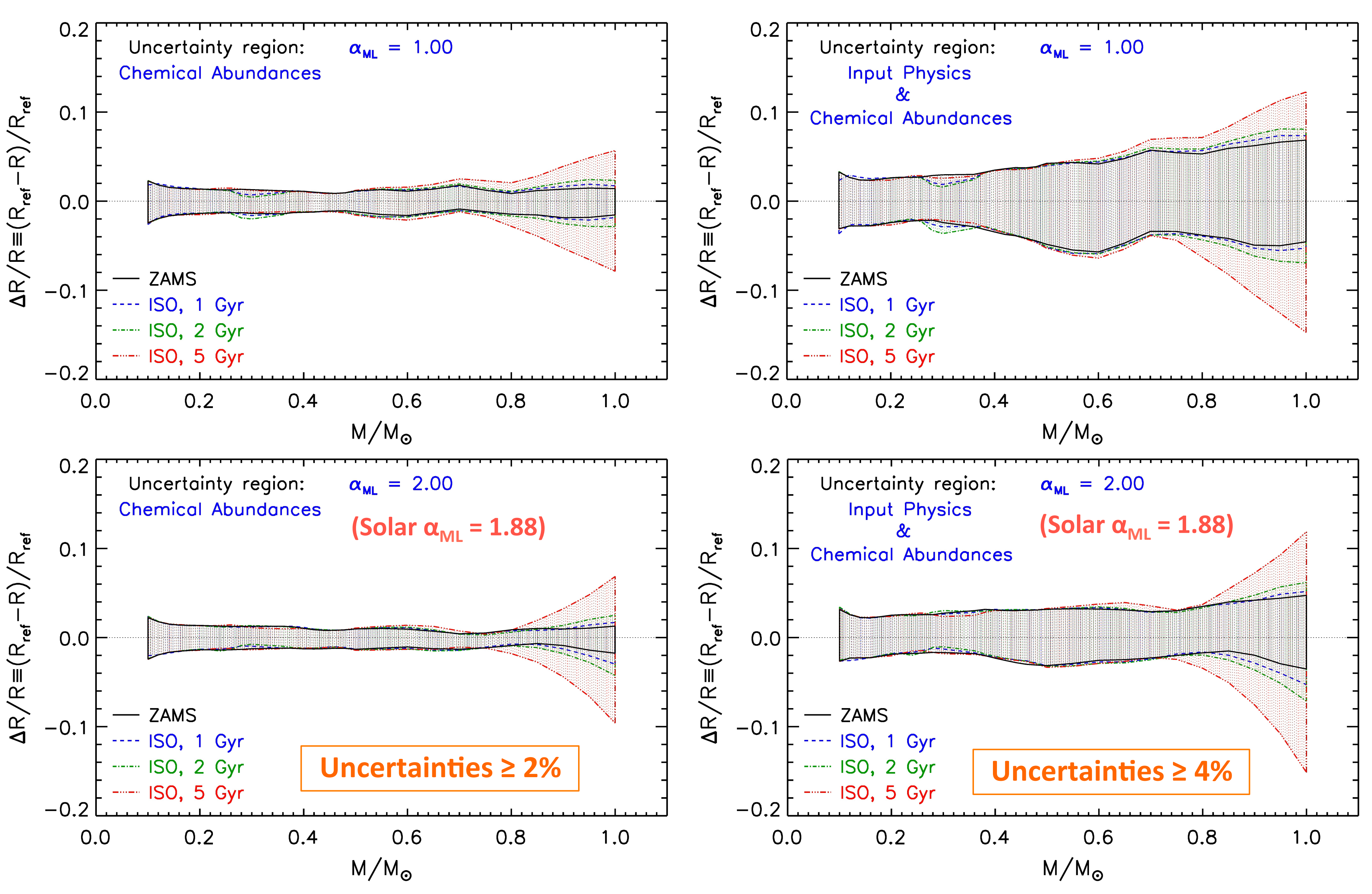
How good are current models, and how well do they agree with each other?

- Main differences
  - Turnoff region and later stages of evolution
  - Cool dwarfs
- Key inputs
  - Boundary conditions (must be non-gray!)
  - Overshooting
  - Element mixture
  - Many others



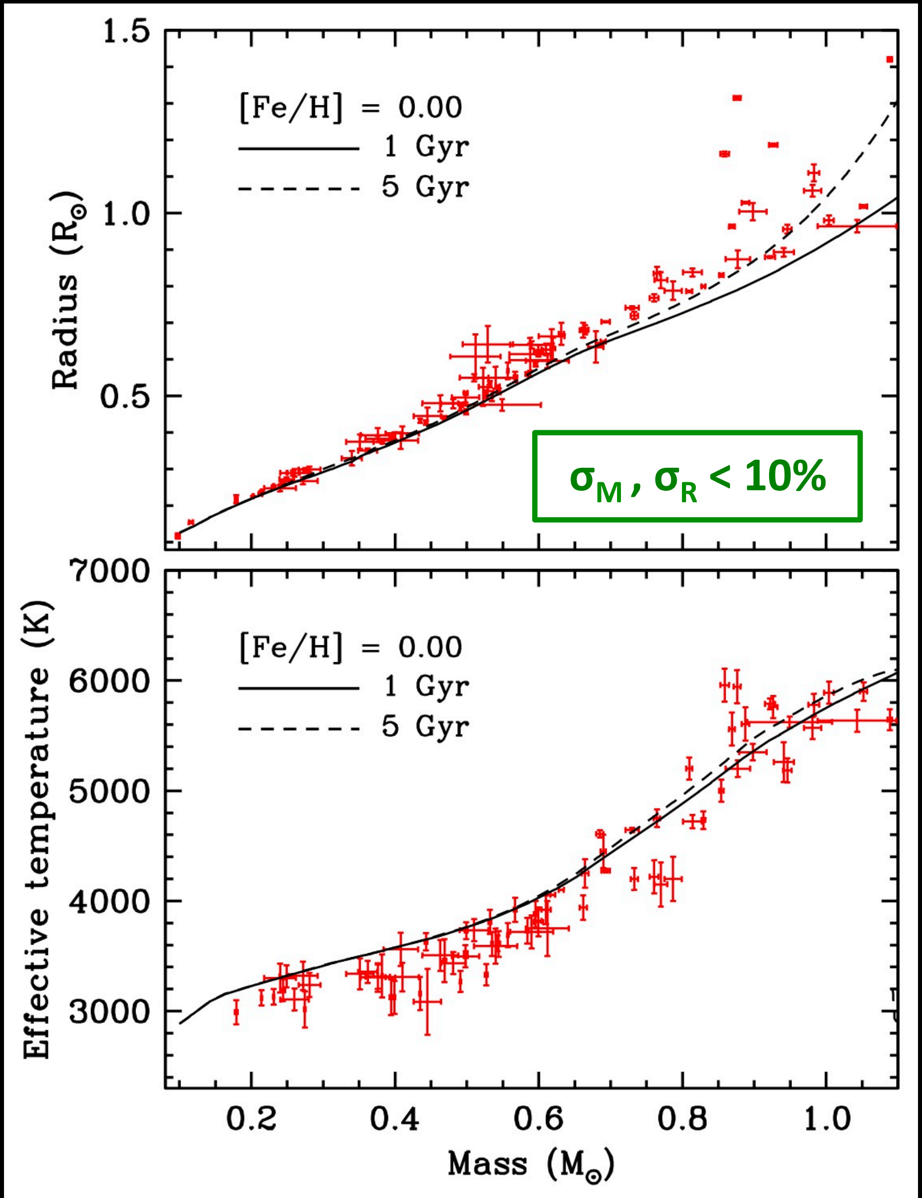
Theoretical uncertainties in the models, and their effects on the radii of low-mass stars

- Differential study by Tognelli et al. (2018)
  - FRANEC code, standard mixing length theory
  - Non-gray boundary conditions
- Quantified effects of changes in input physics
  - Radiative opacities (±5%)
  - Atmosphere models used for boundary conditions (several)
  - Optical depth (*τ)* connecting boundary conditions (τ = 2/3, or 100)
  - Equation of state (two different sources)
- Quantified effects of changes in chemistry
  - [Fe/H] = solar ± 0.1 dex
  - ΔY/ΔZ = 2 ± 1 , slope of helium enrichment law $Y = Y_p + (\Delta Y/\Delta Z)\, Z$
  - Solar metals-to-hydrogen ratio $(Z/X)_\odot$ = 0.0181 ± 15%

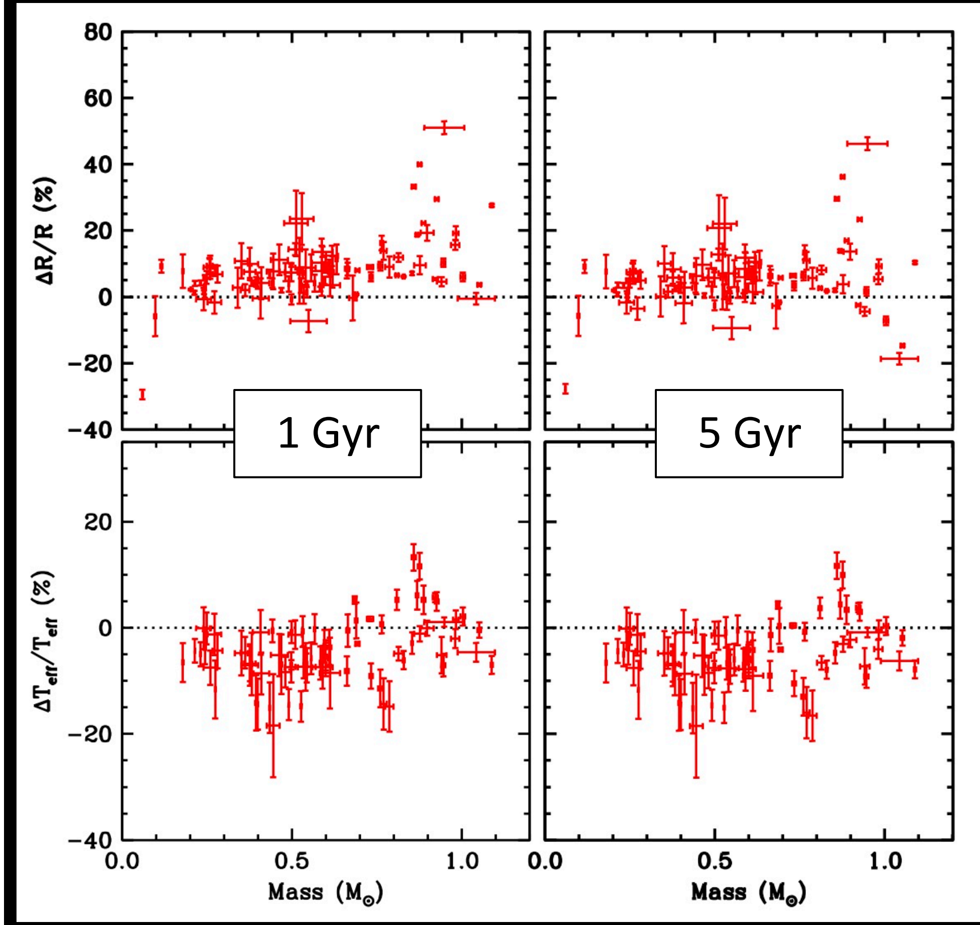

Uncertainty region:
α_{ML} = 1.00
Chemical Abundances
ZAMS
ISO, 1 Gyr
ISO, 2 Gyr
ISO, 5 Gyr
$\Delta R/R \equiv (R_{ref} - R)/R_{ref}$
$M/M_\odot$
Uncertainty region:
α_{ML} = 1.00
Input Physics
&
Chemical Abundances
ZAMS
ISO, 1 Gyr
ISO, 2 Gyr
ISO, 5 Gyr
Uncertainty region:
α_{ML} = 2.00
Chemical Abundances
(Solar α_{ML} = 1.88)
Uncertainties ≥ 2%
Uncertainty region:
α_{ML} = 2.00
Input Physics
&
Chemical Abundances
(Solar α_{ML} = 1.88)
Uncertainties ≥ 4%

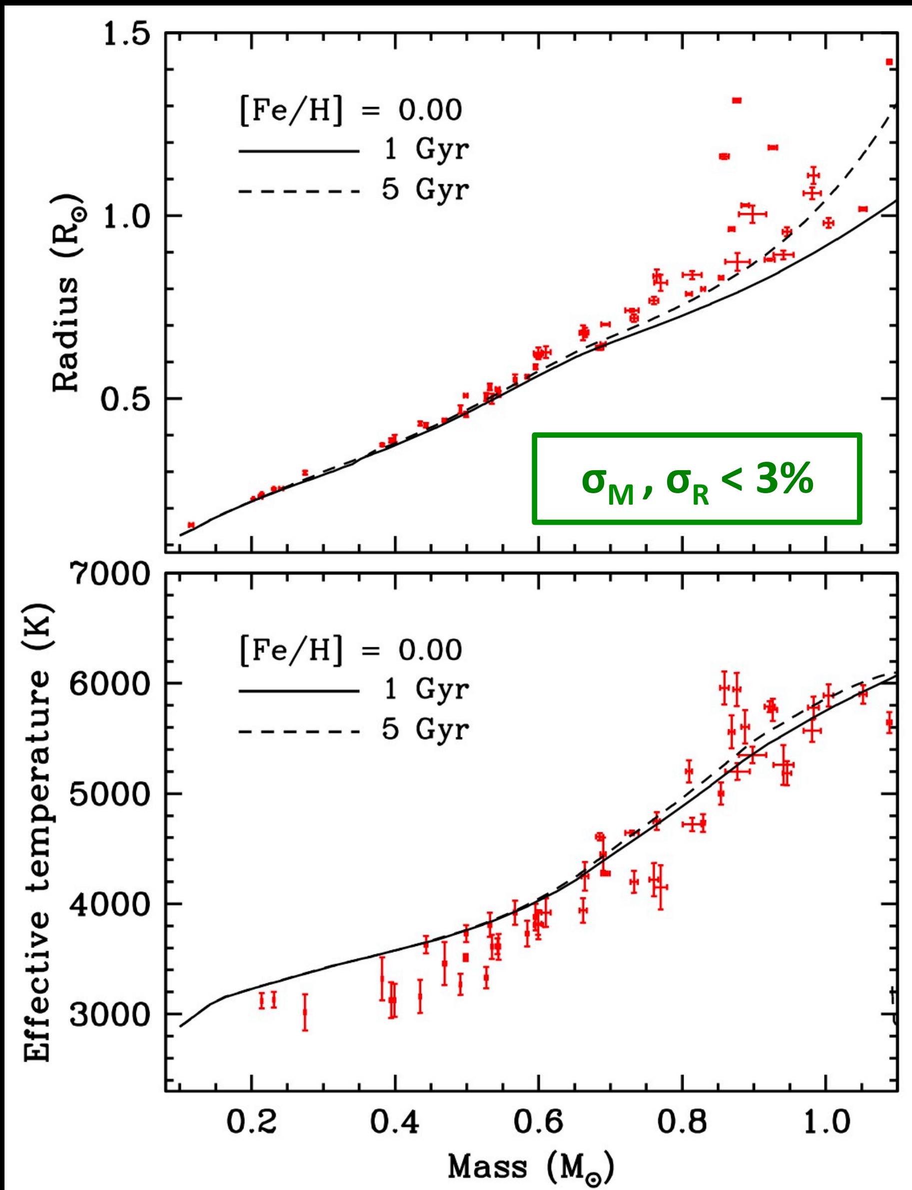
How well do current models agree with observations?

- Low-mass stars are of greatest interest for planet searches
- Current models are known not to match the radii or temperatures of low-mass stars at their measured masses, in many cases
  - *Radius inflation* (real stars are larger than predicted)
  - *Temperature suppression* (real stars are cooler than predicted)
  - Cause believed to be related to stellar activity and/or metallicity (spots and/or magnetic inhibition of convection)
  - The problem can be present in any star with a convective envelope (not just M dwarfs: it extends up to 1 $M_{\odot}$)
- Scatter in mass-radius diagram may be due in part to systematic errors in the measurements

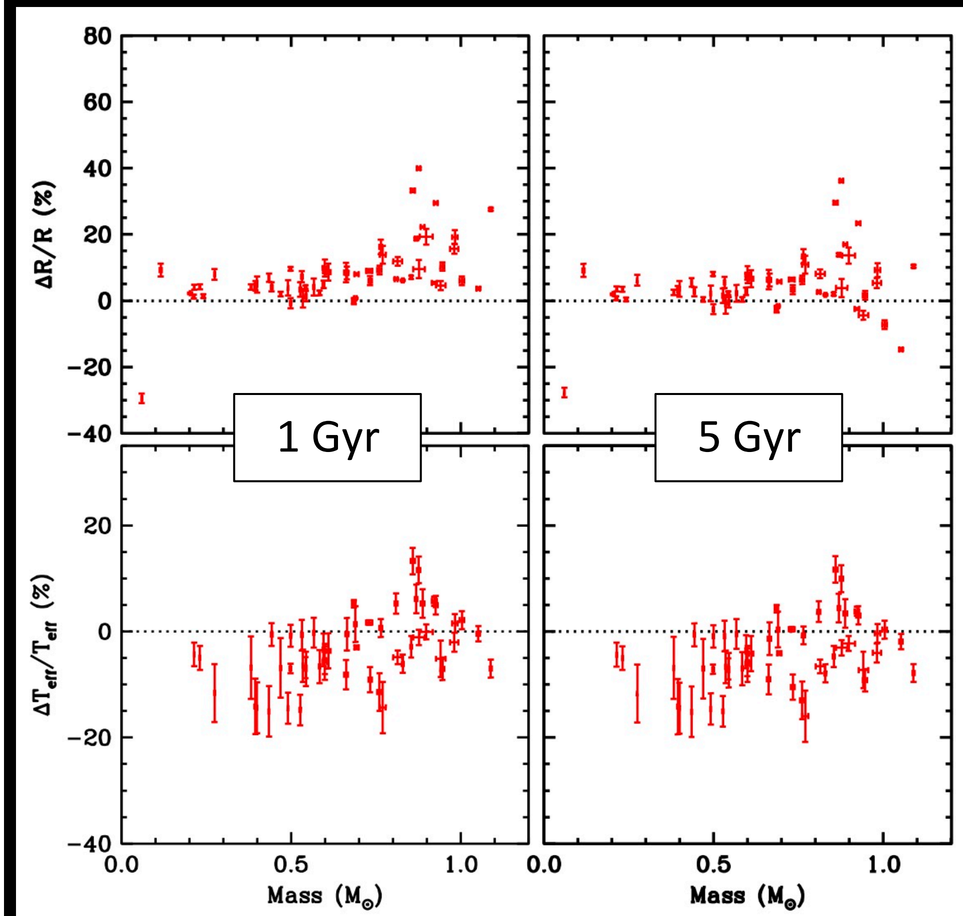


MIST models (Choi et al. 2016)

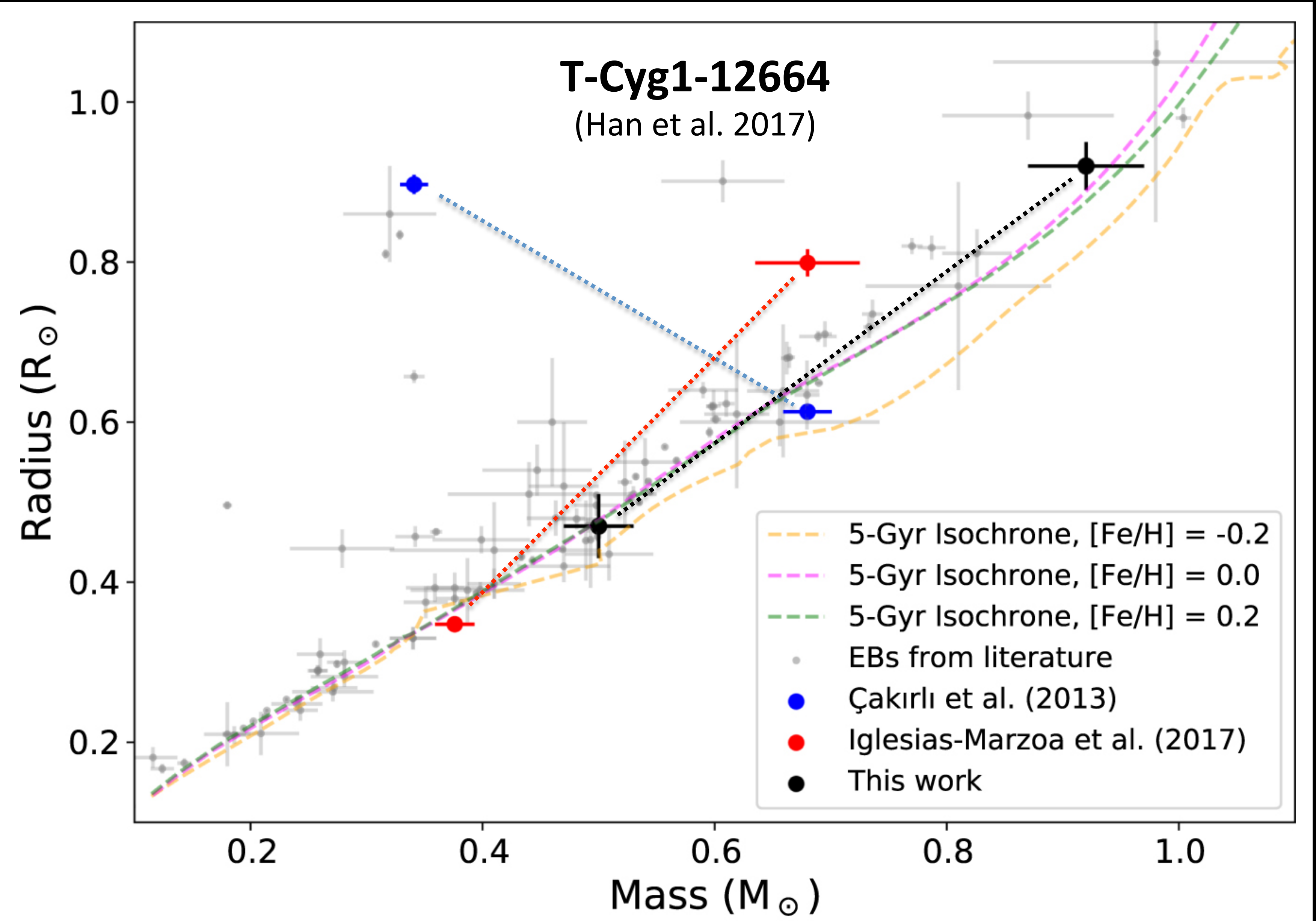




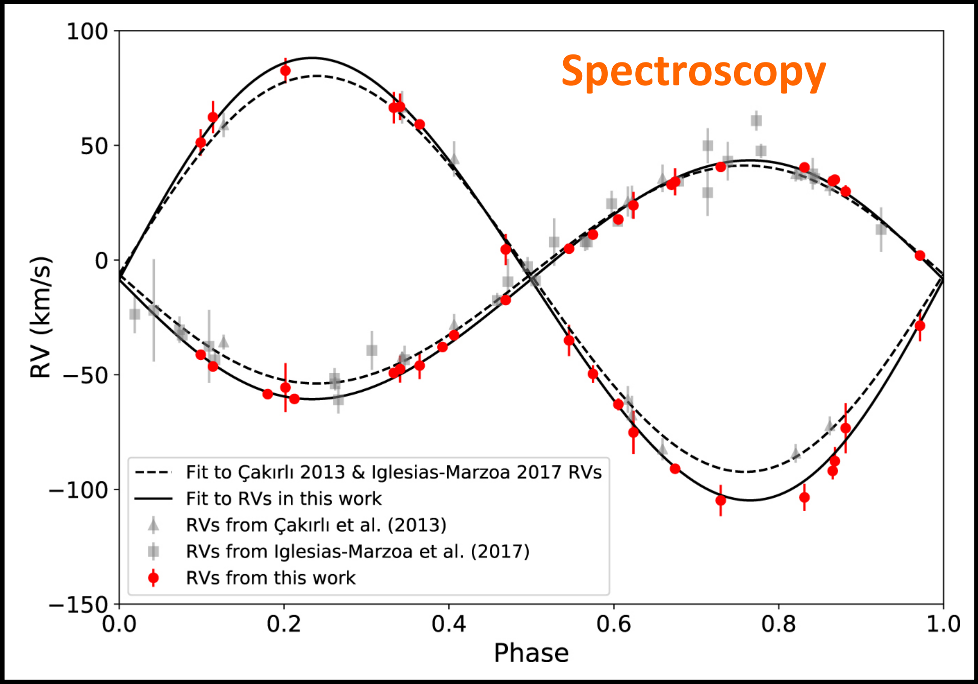
MIST models (Choi et al. 2016)

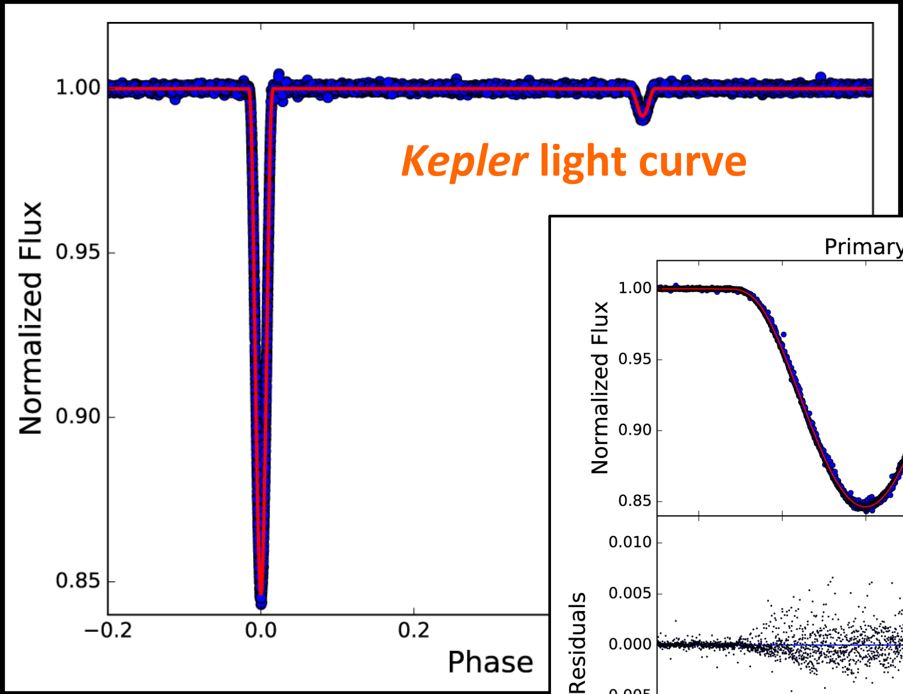


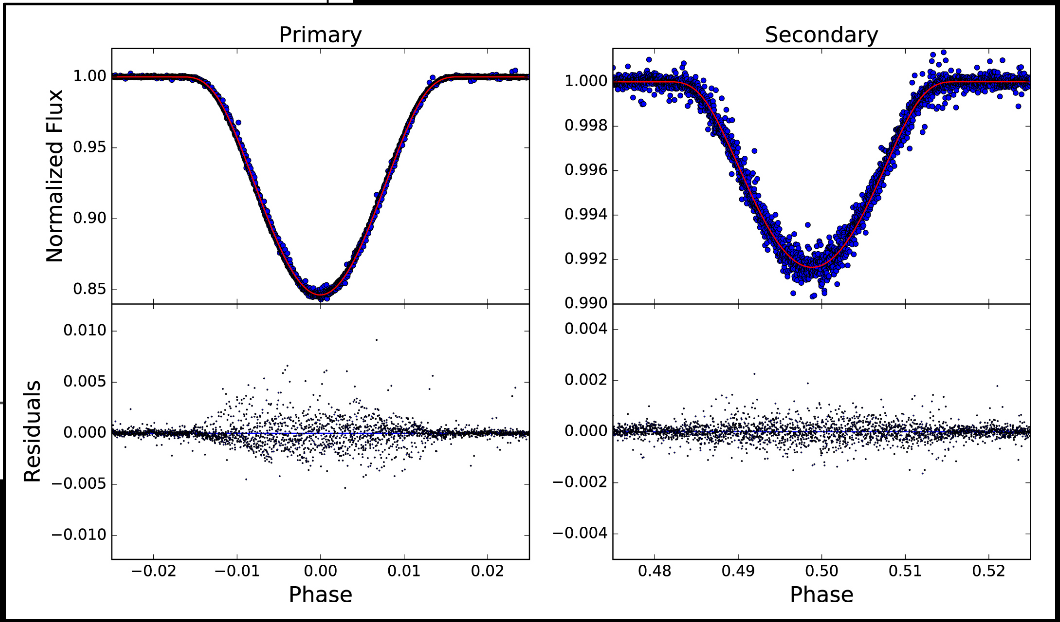
Example of systematic errors in mass-radius measurements



Observations of T-Cyg1-12664
(Han et al. 2017)







Key points so far, and questions

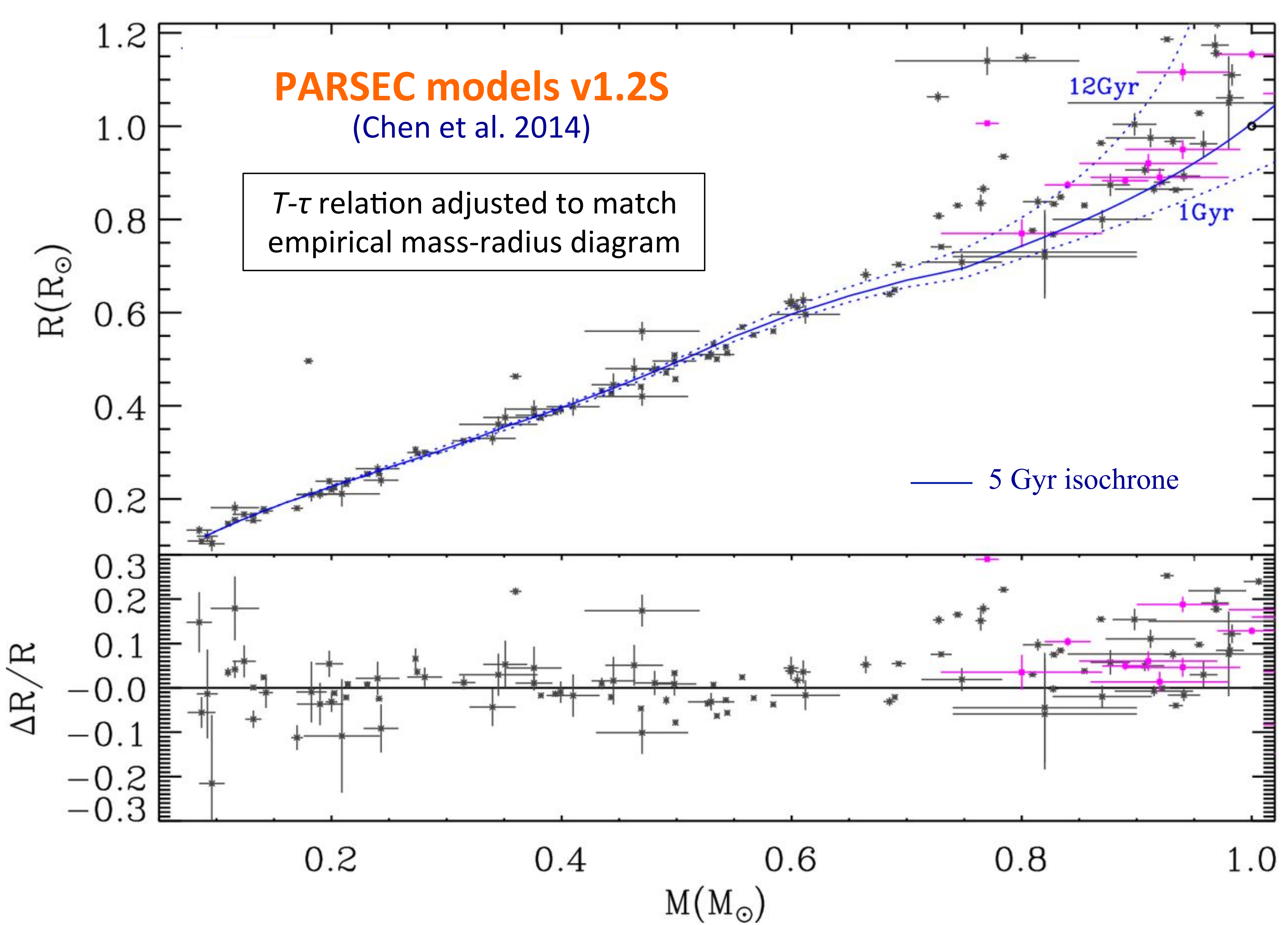
- Some published errors for M_* and R_* derived from stellar evolution models are probably optimistic, in view of the differences between models and the intrinsic theoretical uncertainties
- This is especially true for late-type stars, which models are not even able to fit very well (radius, temperature)
- Can anything be done about radius inflation, to improve the accuracy of the inferred radii of late-type host stars?
  - Use "better" models to get R_*?
  - Avoid models altogether?
- What about the stellar masses?

Better models for low-mass stars?

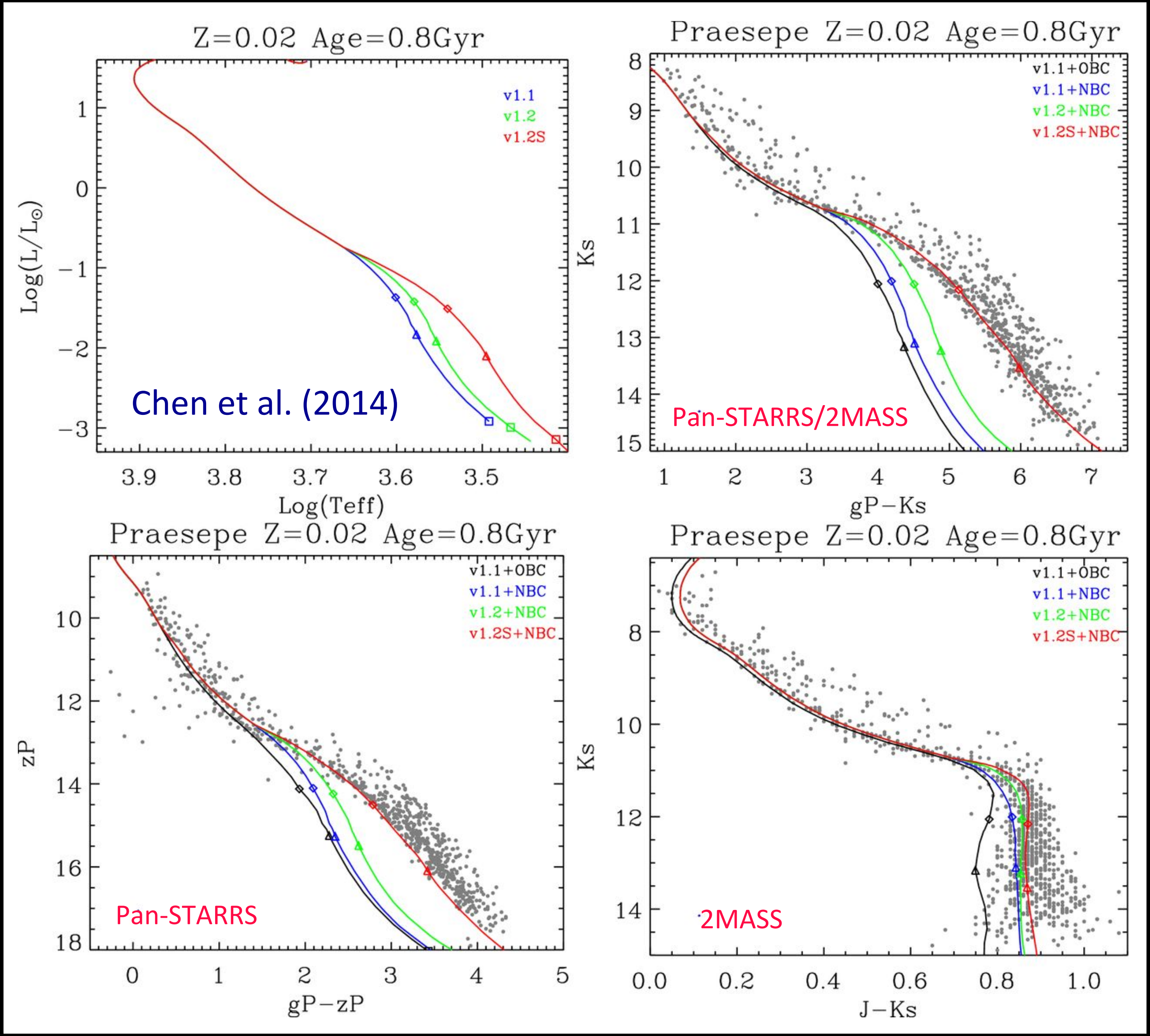
- Attempt to address physical causes of the discrepancies with the observations
  - Magnetic models (e.g., Mullan & MacDonald 2001; Chabrier et al. 2007; Feiden & Chaboyer 2012, 2013, 2014)
  - Models with spots (e.g., Chabrier et al. 2007, Somers & Pinsonneault 2015)
  - Not yet practical for typical exoplanet applications
    - Large grids of models not publicly available
    - More free parameters (magnetic field strength, spot filling factor, spot temperature contrast)
- Give up on trying to understand the physics
  - Recalibrate models to match the observations, and improve predictive power

Recalibrating models for low-mass stars

- Experiments by Chen et al. (2014) (PARSEC models) suggest that the discrepancies in the *M-R* diagram cannot be completely eliminated by
  - Altering the equation of state within reason
  - Changing the mixing length parameter
  - Changing the metallicity or helium content
- Practical solution by Chen et al. (2014): adjust the boundary conditions to match *M-R* observations
  - Change *T-τ* relation, increasing the temperatures starting at 3160 K, by up to 14% at 4730 K ($M_* \approx 0.7\ M_\odot$), or a spectral type range of M4.5V–K4V ⟶ **PARSEC models V1.2S**
  - How does this affect the predicted colors (CMD fits)?

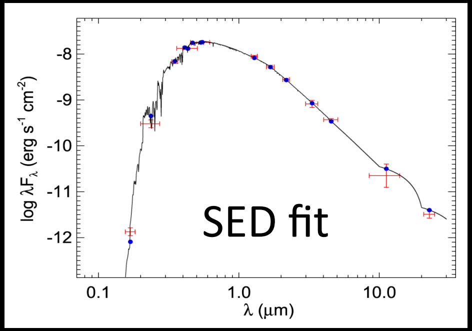


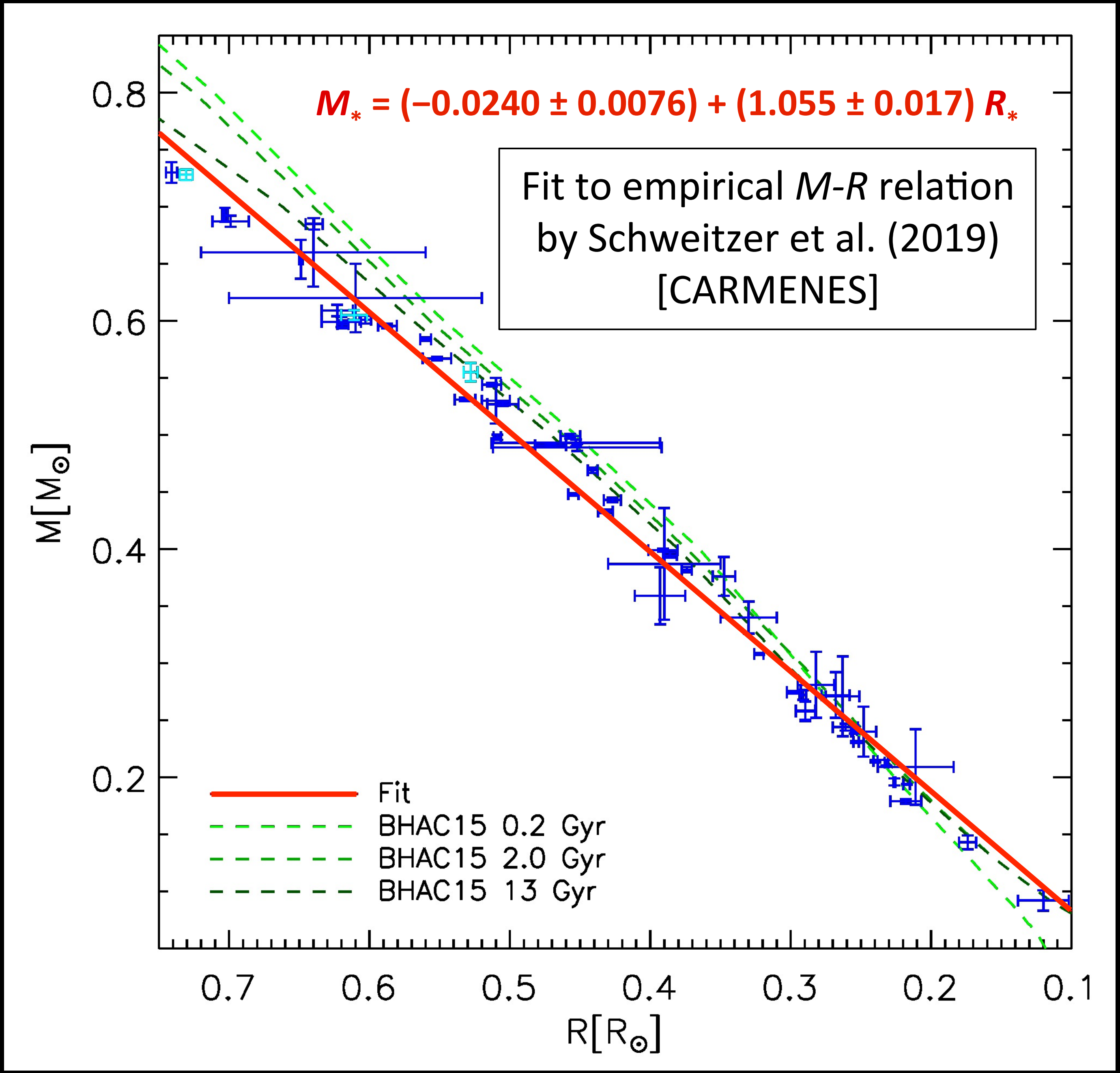
PARSEC models v1.2S
(Chen et al. 2014)
T-τ relation adjusted to match empirical mass-radius diagram
12Gyr
1Gyr
5 Gyr isochrone
R(R⊙)
ΔR/R
M(M⊙)
1.2
1.0
0.8
0.6
0.4
0.2
0.3
0.2
0.1
−0.0
−0.1
−0.2
−0.3
0.2
0.4
0.6
0.8
1.0


Z=0.02 Age=0.8Gyr
v1.1
v1.2
v1.2S
Log(L/L⊙)
Log(Teff)
Chen et al. (2014)
Praesepe Z=0.02 Age=0.8Gyr
v1.1+OBC
v1.1+NBC
v1.2+NBC
v1.2S+NBC
Ks
gP−Ks
Pan-STARRS/2MASS
Praesepe Z=0.02 Age=0.8Gyr
zP
gP−zP
Pan-STARRS
Praesepe Z=0.02 Age=0.8Gyr
Ks
J−Ks
2MASS

Stellar properties for late-type dwarfs independent of stellar evolution models

- Rely on brightness measurements, the Gaia/DR2 parallaxes (π_{DR2}), spectroscopic T_{eff} estimates, and an empirical *M*-*R* relation
  - π_{DR2} + SED fit + extinction ⟶ L_*
  - Spectroscopic T_{eff} + Stefan-Boltzmann law ⟶ R_*
  - Empirical *M*-*R* relation ⟶ M_*





$M_* = (-0.0240 \pm 0.0076) + (1.055 \pm 0.017)\ R_*$
Fit to empirical *M-R* relation
by Schweitzer et al. (2019)
[CARMENES]
0.8
0.6
0.4
0.2
$M[M_\odot]$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
$R[R_\odot]$
Fit
BHAC15 0.2 Gyr
BHAC15 2.0 Gyr
BHAC15 13 Gyr

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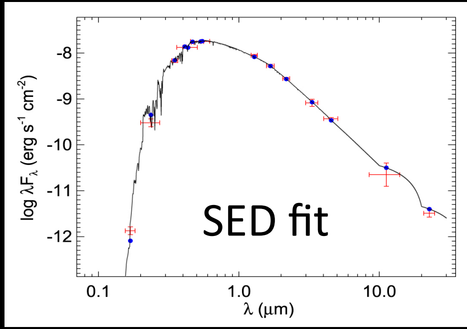

Stellar properties for late-type dwarfs independent of stellar evolution models

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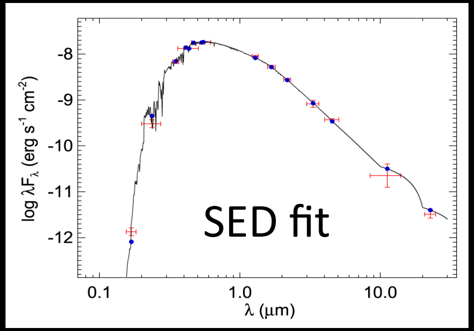
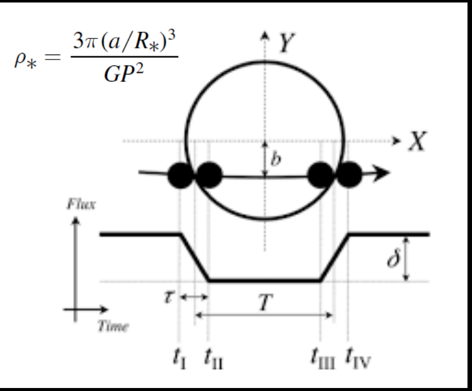
  - Empirical *M-R* relation ⟶ M_*

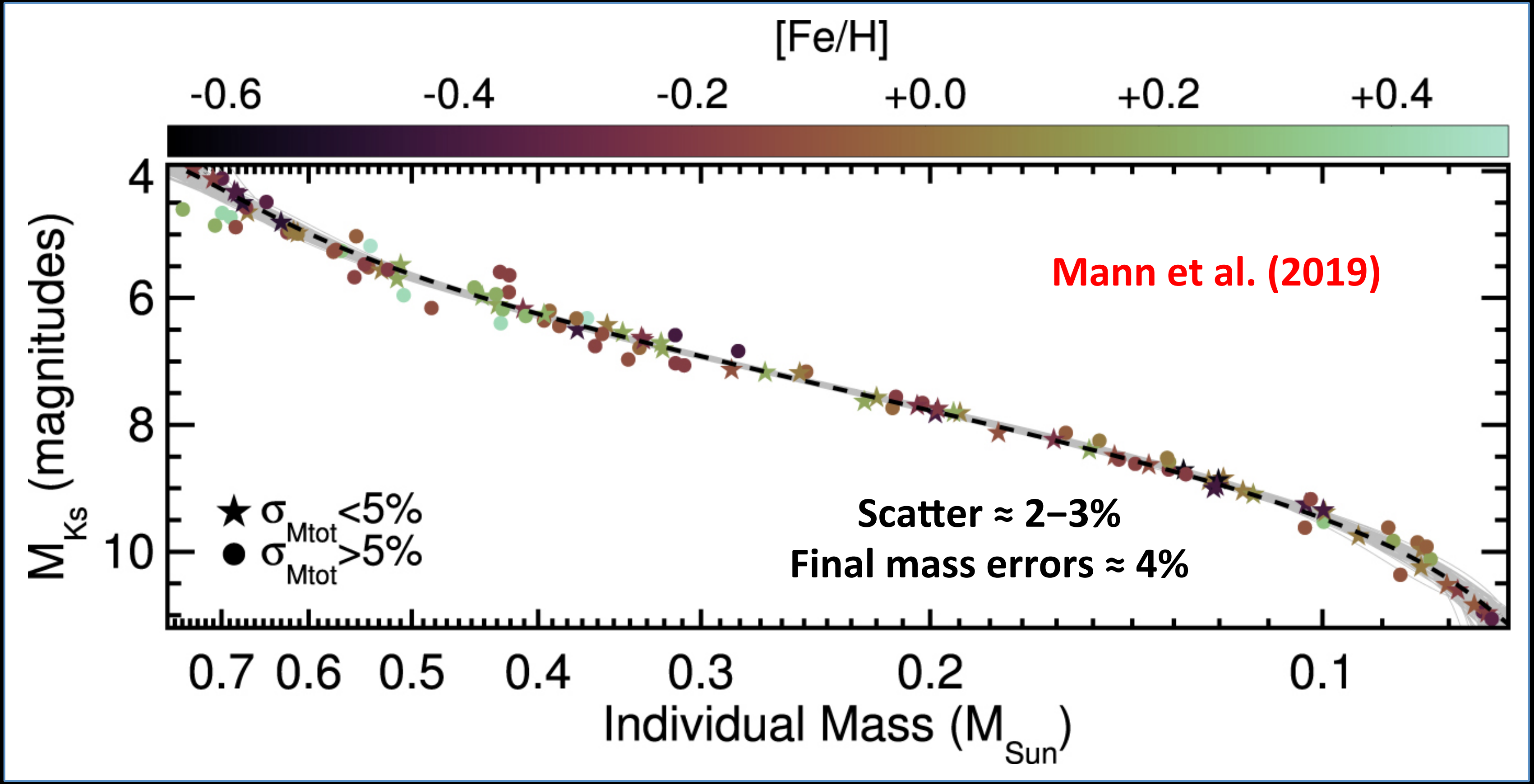


- Variant for transiting planets
  - π_{DR2} + SED fit + extinction ⟶ L_*
  - Spectroscopic T_{eff} + Stefan-Boltzmann law ⟶ R_*
  - Mean stellar density ρ_* (if eccentricity known) ⟶ M_*
  - Not restricted to M dwarfs; no *M-R* relation needed



- Rely on NIR brightness measurements, the Gaia/DR2 parallaxes (π_{DR2}), and empirical *M-L* and *M-R* relations
  - π_{DR2} + 2MASS K_S magnitudes + extinction ⟶ M_{K_S} (absolute magnitude)
  - Empirical *M-L* relation ⟶ M_*
  - Empirical *M-R* relation ⟶ R_*

Avoids use of T_{eff}



Summary

- Theoretical uncertainties in current stellar evolution models can add errors of up to 4% to the stellar radii
- Some previously reported uncertainties for M_* and R_* derived from models are probably optimistic
- Errors for convective stars may be worse due to "radius inflation" and "temperature suppression"
- Some recent models (PARSEC, Chen et al. 2014) have attempted to calibrate out this problem for late-type stars, and probably have better predictive power than standard stellar evolution models
- In some cases it may be better to rely on purely empirical ways of deriving M_* and R_* for M dwarfs