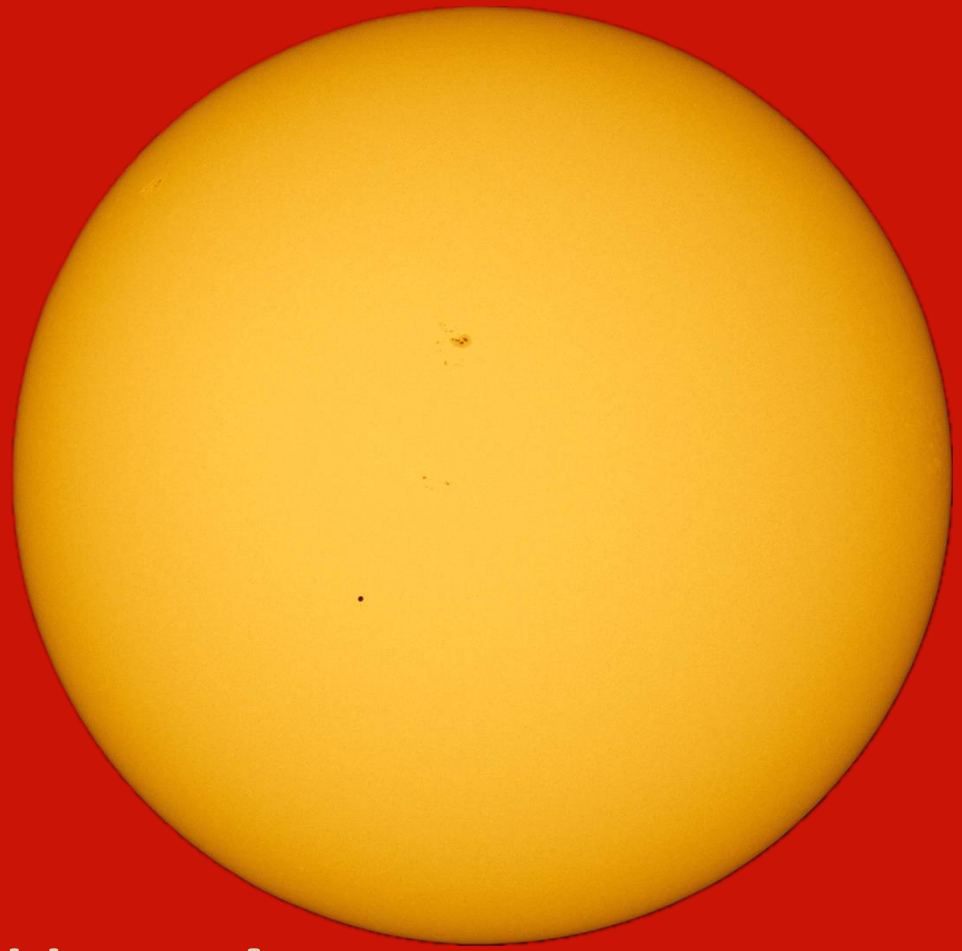
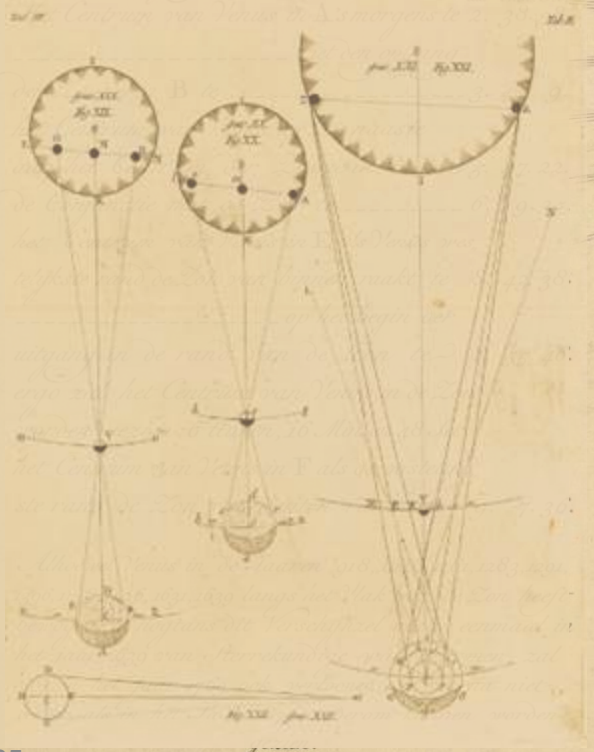


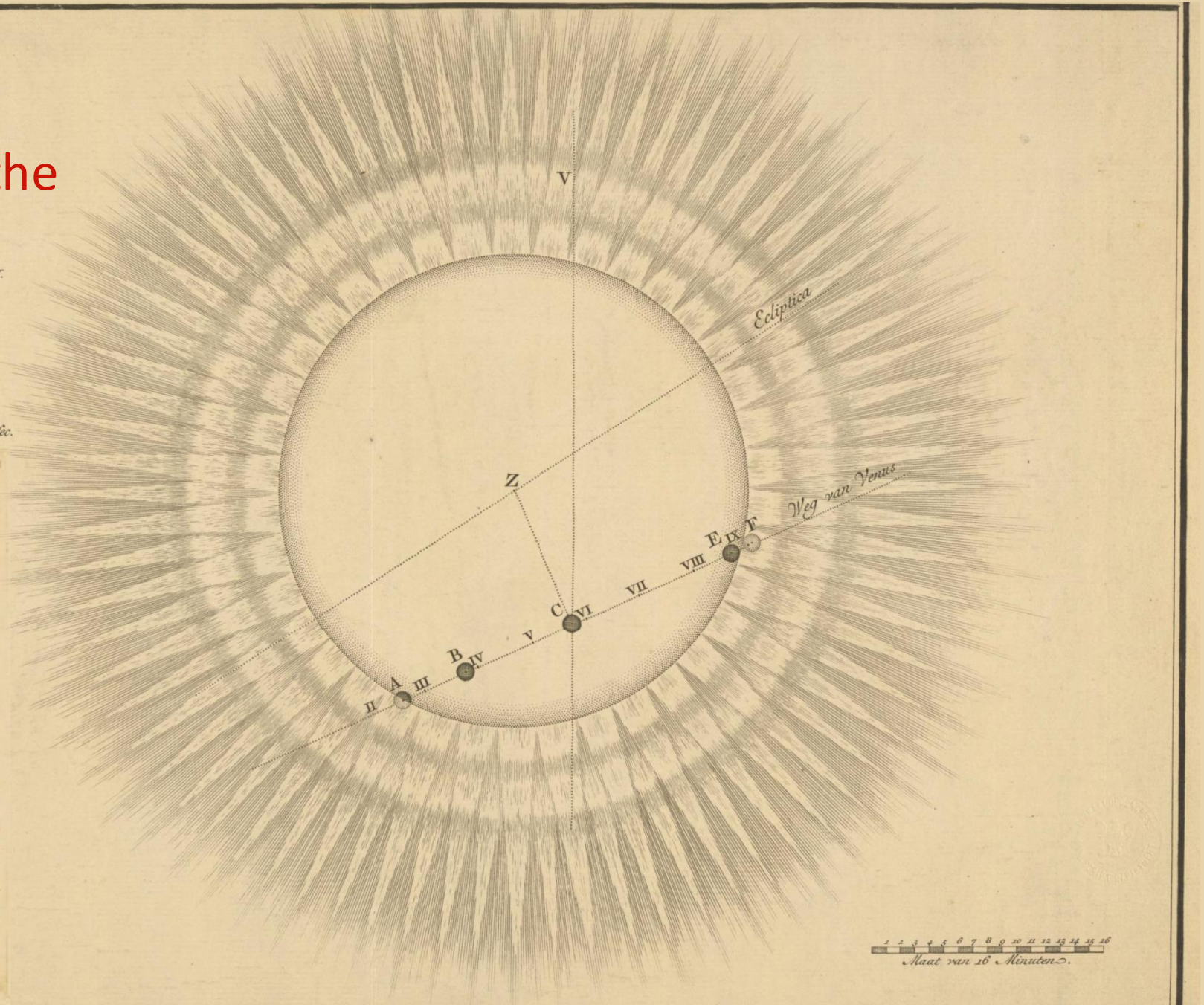
The Transit Age:

Precise Main Sequence Planet Host Ages
in the Era of Gaia and JWST

Zafar Rustamkulov

Venus' transit duration refined the value of the AU, constraining the Sun's mass





Kepler's 3rd law + density of a sphere

$$\frac{P^2}{4\pi^2} \simeq \frac{a^3}{GM_*} \qquad \rho_* = \frac{M_*}{\frac{4}{3}\pi R_*^3}$$

A planet's transit duration is linked to the stellar bulk density

$$\rho_* = \frac{3\pi}{G} \frac{a^3}{P^2 R_*^3} \qquad \frac{a}{R_*} = \frac{1}{\pi} \frac{P}{T}$$

** For circular orbits*

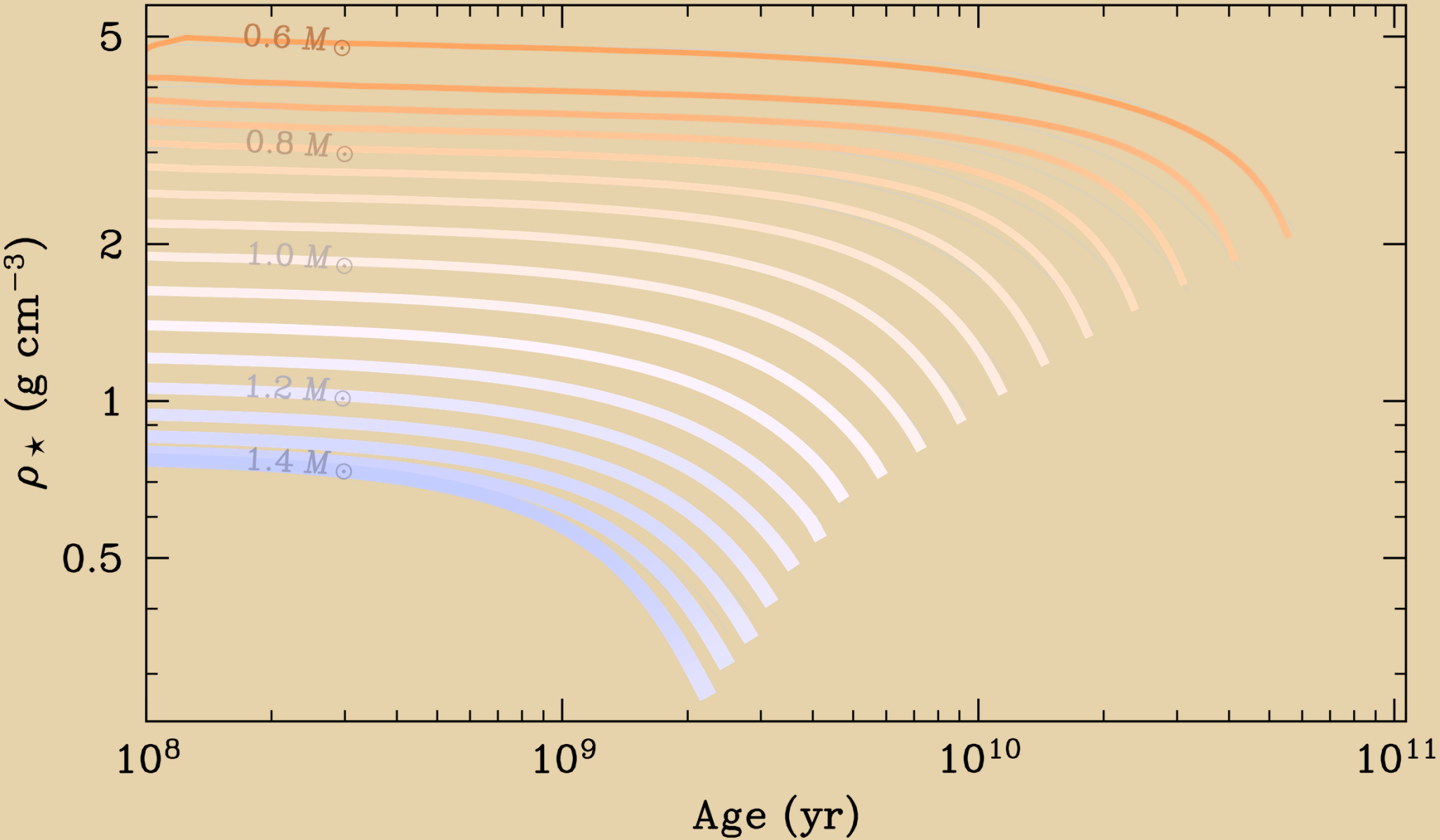
From homology, changes to the stellar core are reflected as changes to the envelope

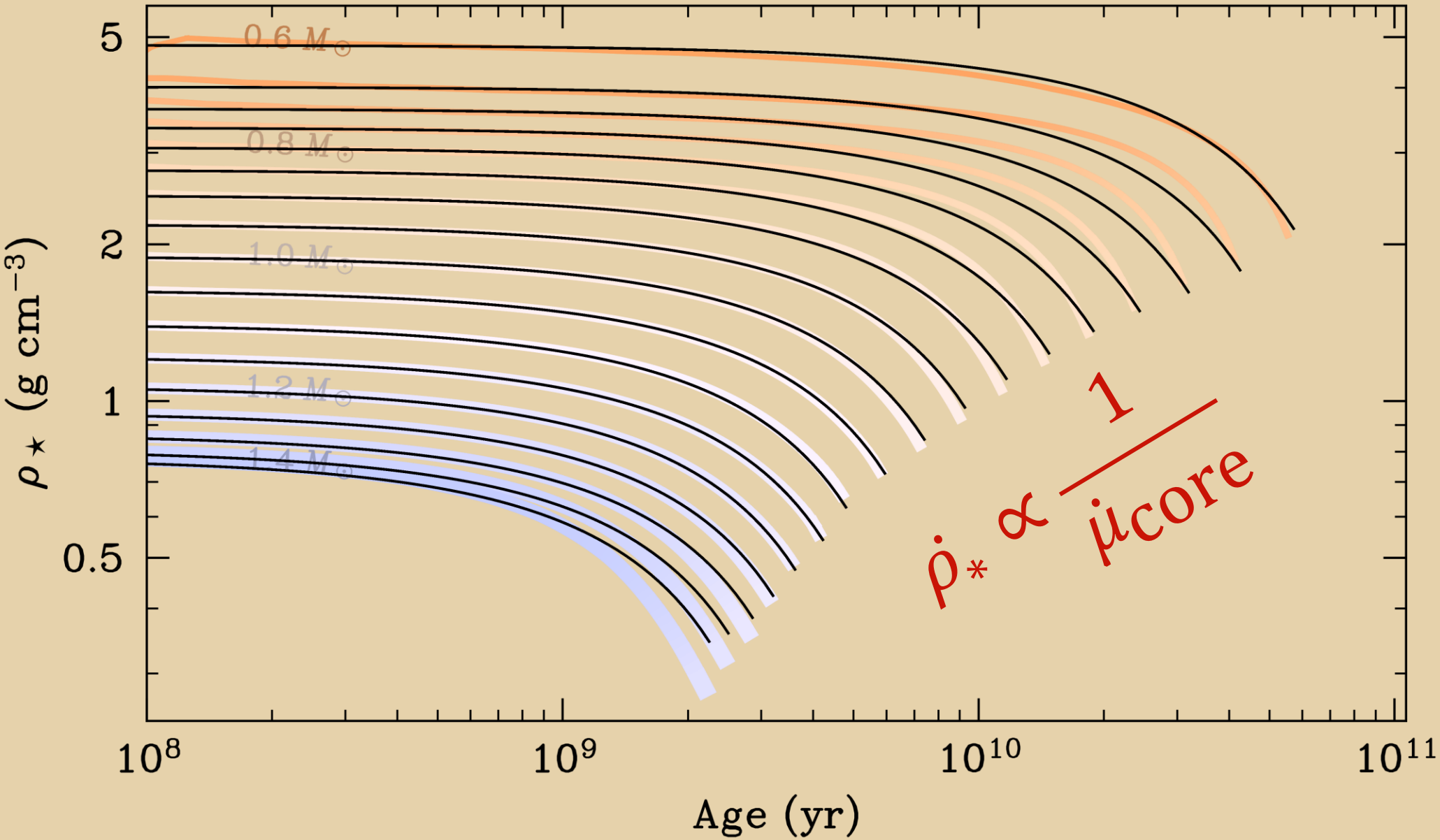
$$\dot{\rho}_* \propto \frac{1}{\dot{\mu}_{\mathrm{core}}}$$

The core helium fraction grows with age

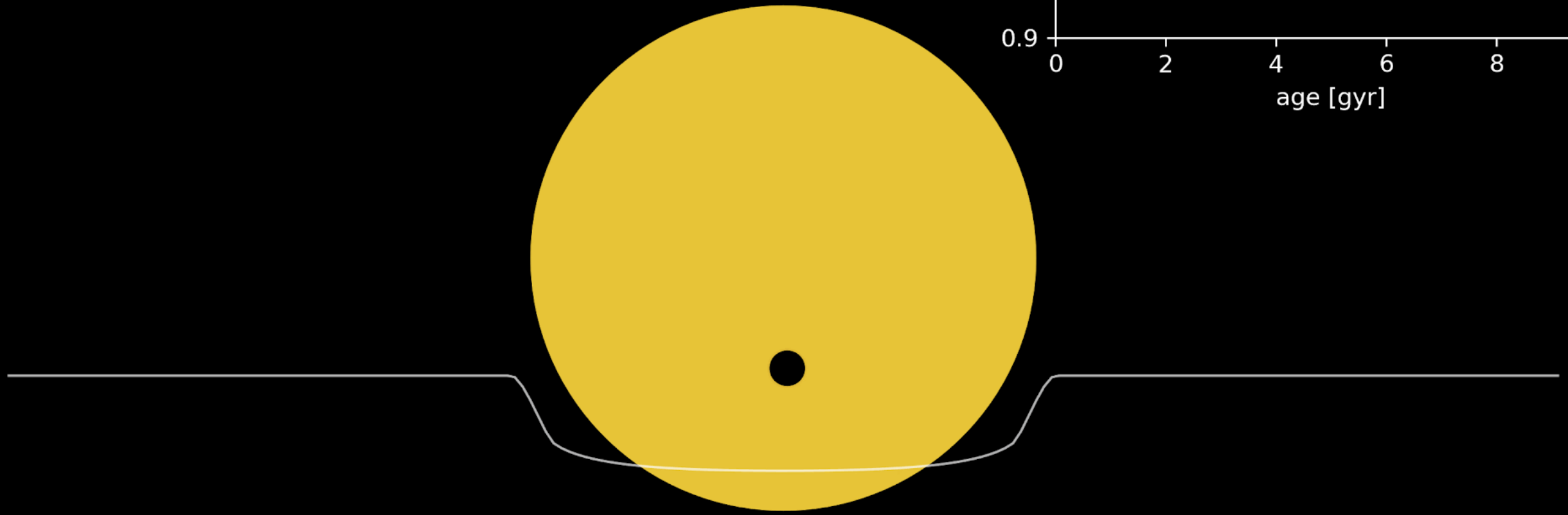
A constraint of the bulk density mirrors the changing helium fraction of the shrinking core

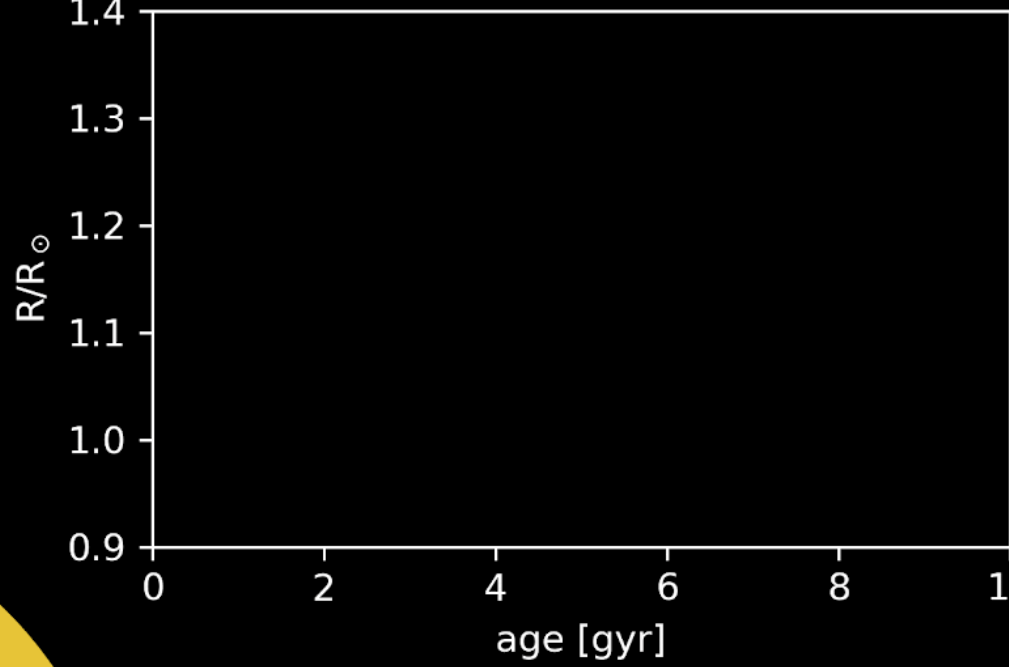
Stars inflate with age

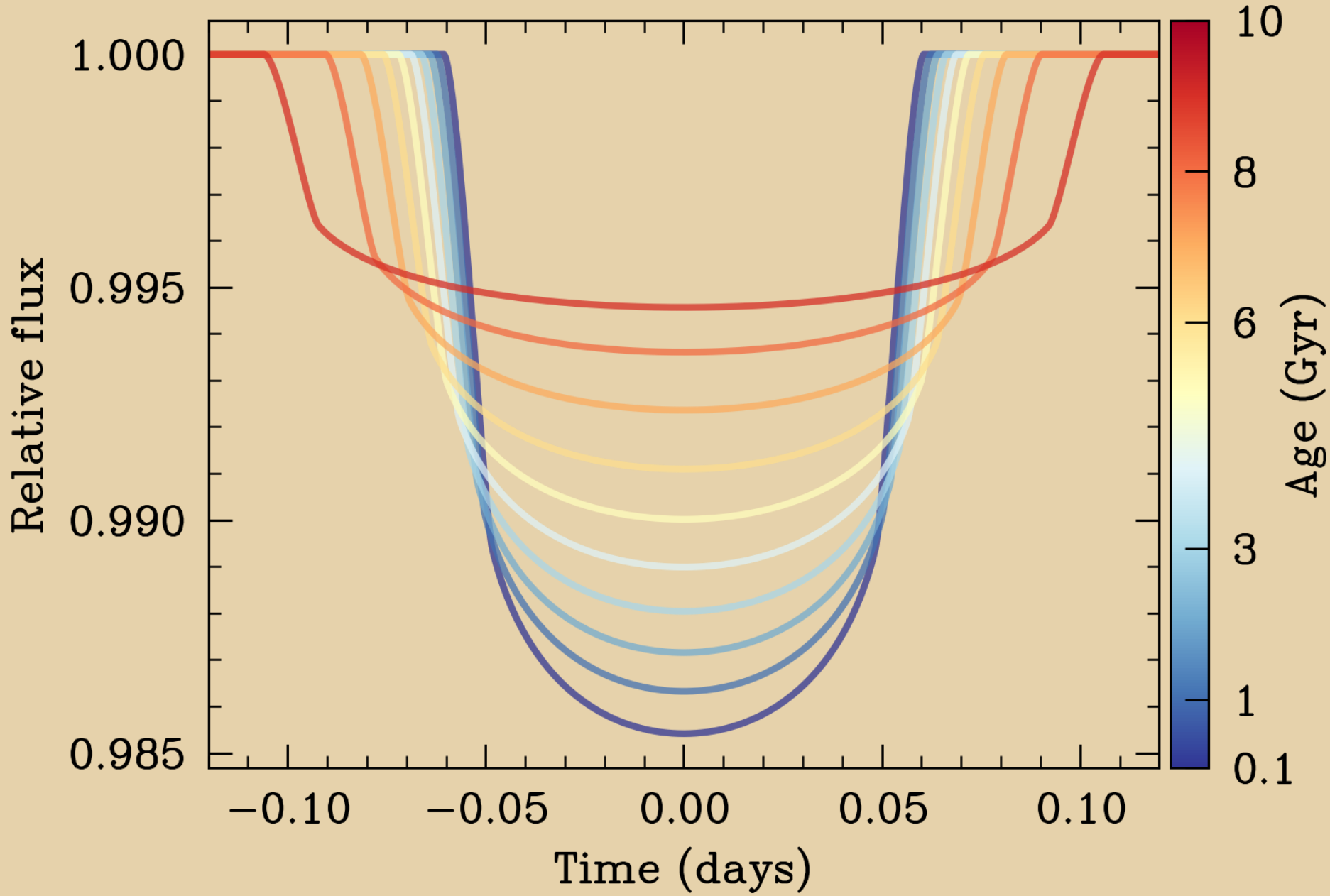


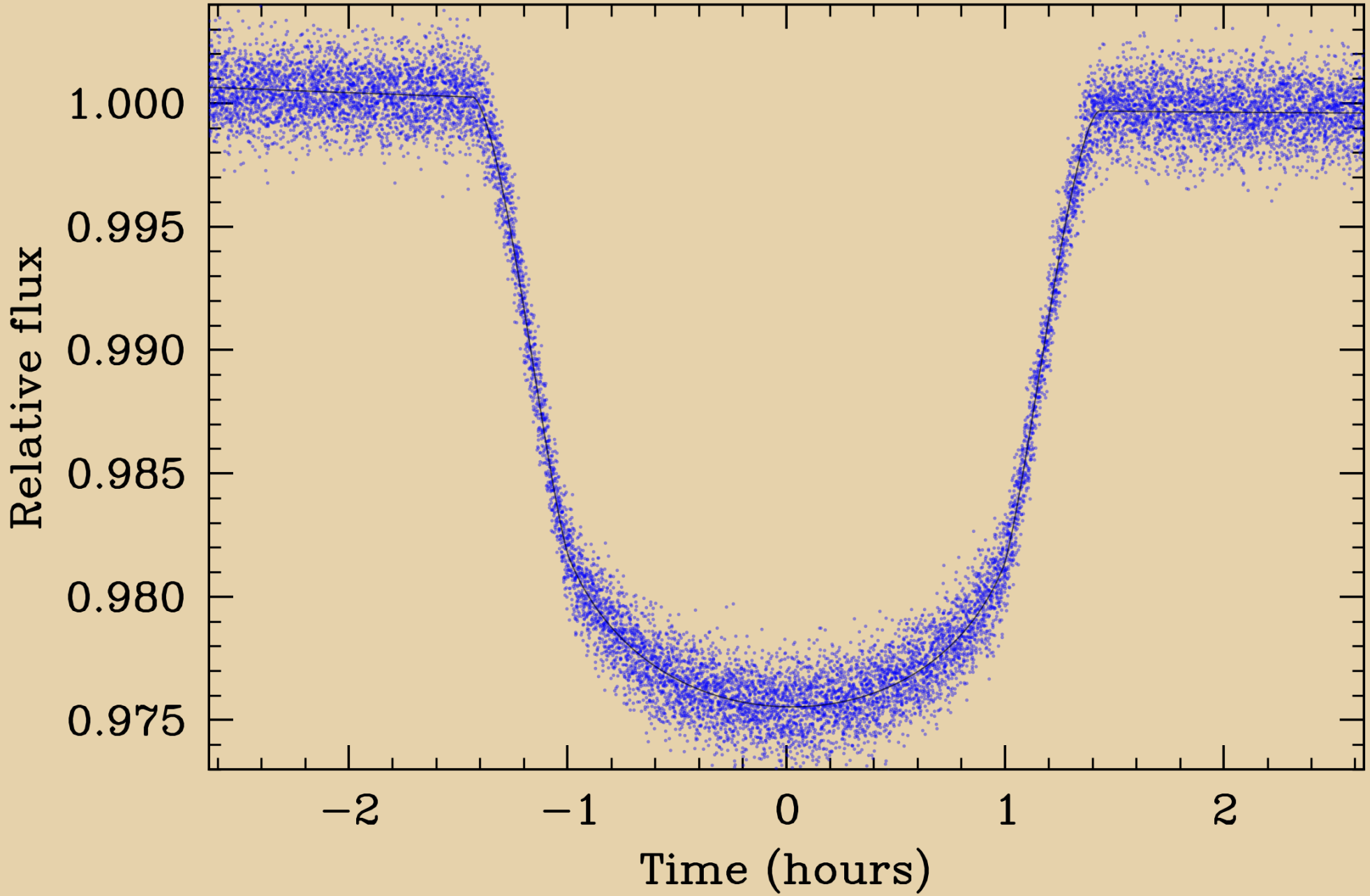

0.6 $M_\odot$
0.8 $M_\odot$
1.0 $M_\odot$
1.2 $M_\odot$
1.4 $M_\odot$
$\rho_\star$ (g cm^{-3})
5
2
1
0.5
10^8
10^9
10^{10}
10^{11}
Age (yr)
$\dot{\rho}_* \propto \frac{1}{\dot{\mu}_{core}}$

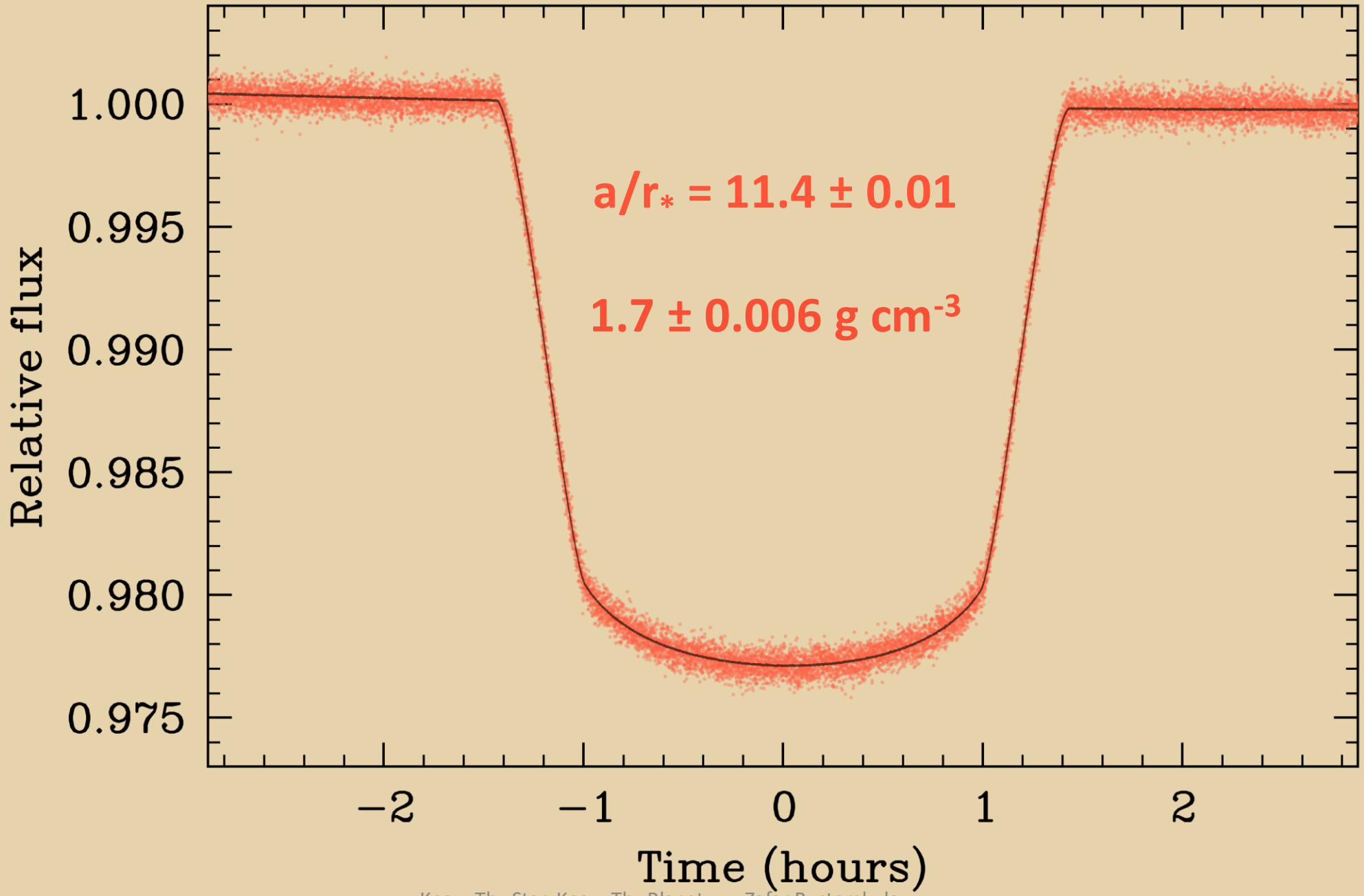
Aging affects a planet's transit light curve






1.000
0.995
0.990
0.985
Relative flux
−0.10
−0.05
0.00
0.05
0.10
Time (days)
10
8
6
3
1
0.1
Age (Gyr)


1.000
0.995
0.990
0.985
0.980
0.975
Relative flux
−2
−1
0
1
2
Time (hours)


1.000
0.995
0.990
0.985
0.980
0.975
Relative flux
−2
−1
0
1
2
Time (hours)
a/r∗ = 11.4 ± 0.01
1.7 ± 0.006 g cm-3

WASP-39 (Faedi+ 2011)

9 + 3/-4 Gyr
230 ± 80 pc
0.93 ± 0.09 $M_\odot$
1.00 ± 0.25 $R_\odot$

Main sequence ages are quite uncertain (approx. 50%)
Also, distances pre-Gaia were uncertain by >>>10%!

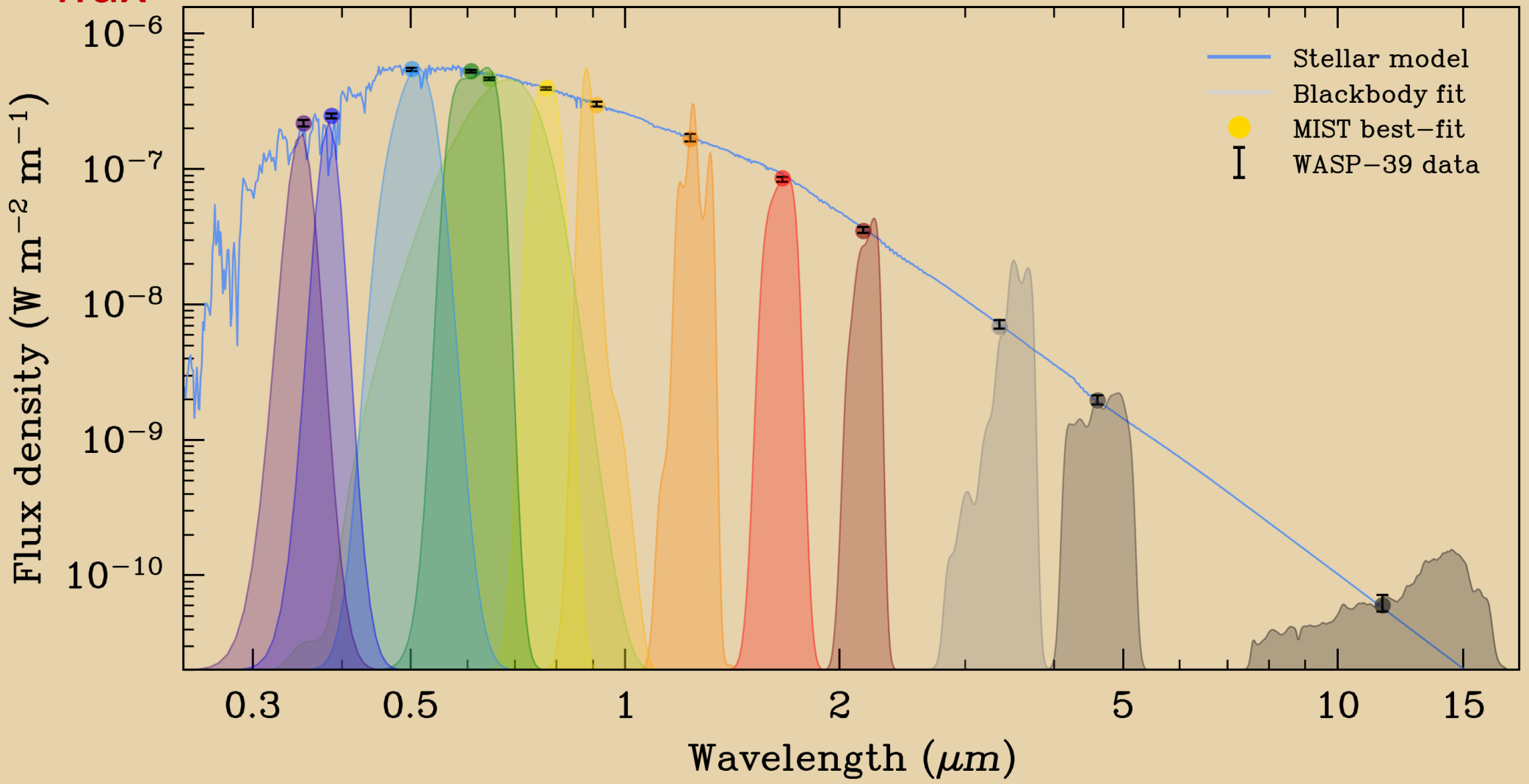
Why are stellar ages hard to measure?

- Stars change slowly
- We need precise constraints of mass, radius, temp., comp.
- Techniques are full of biases/systematic uncertainties

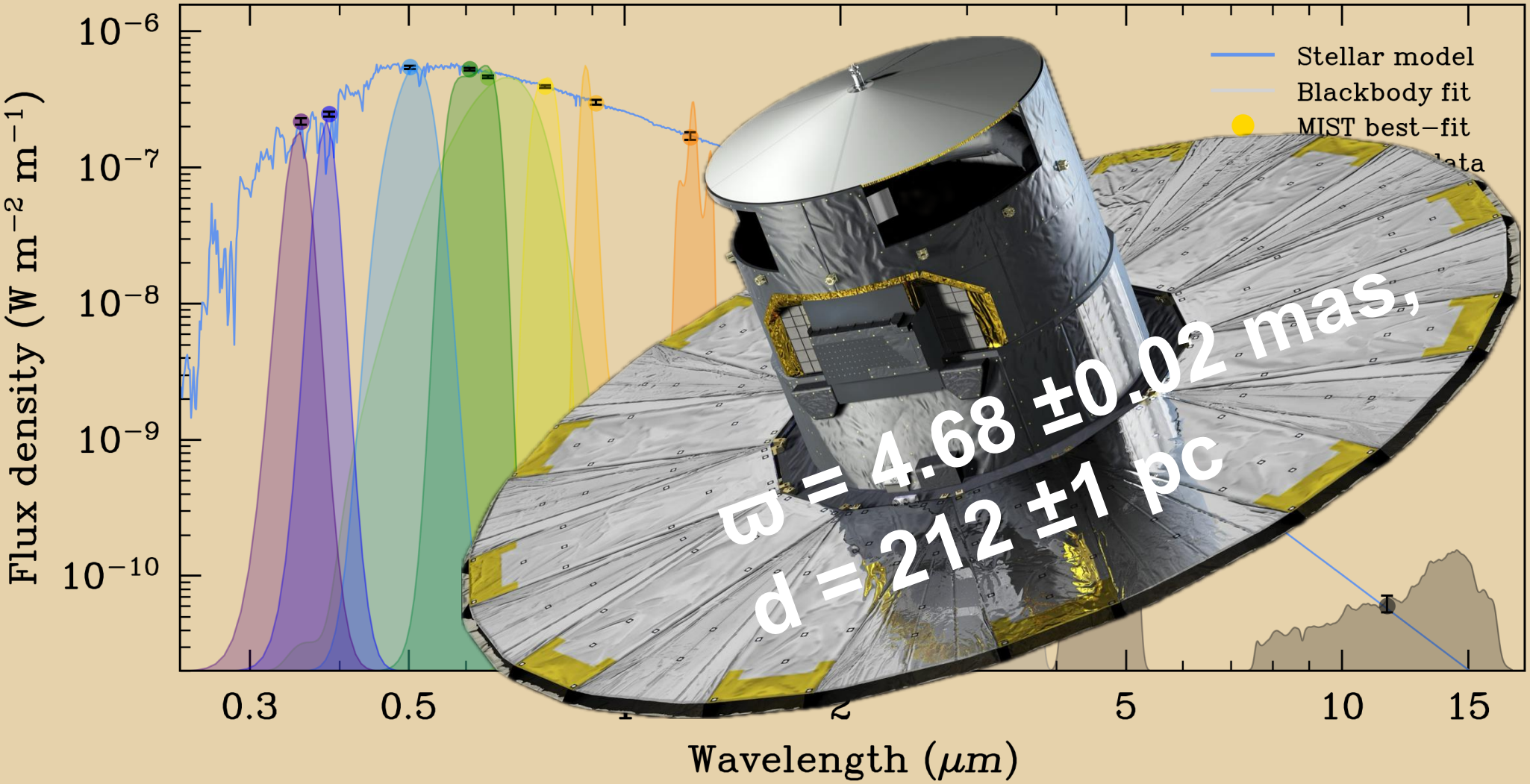
Why do we care about them?

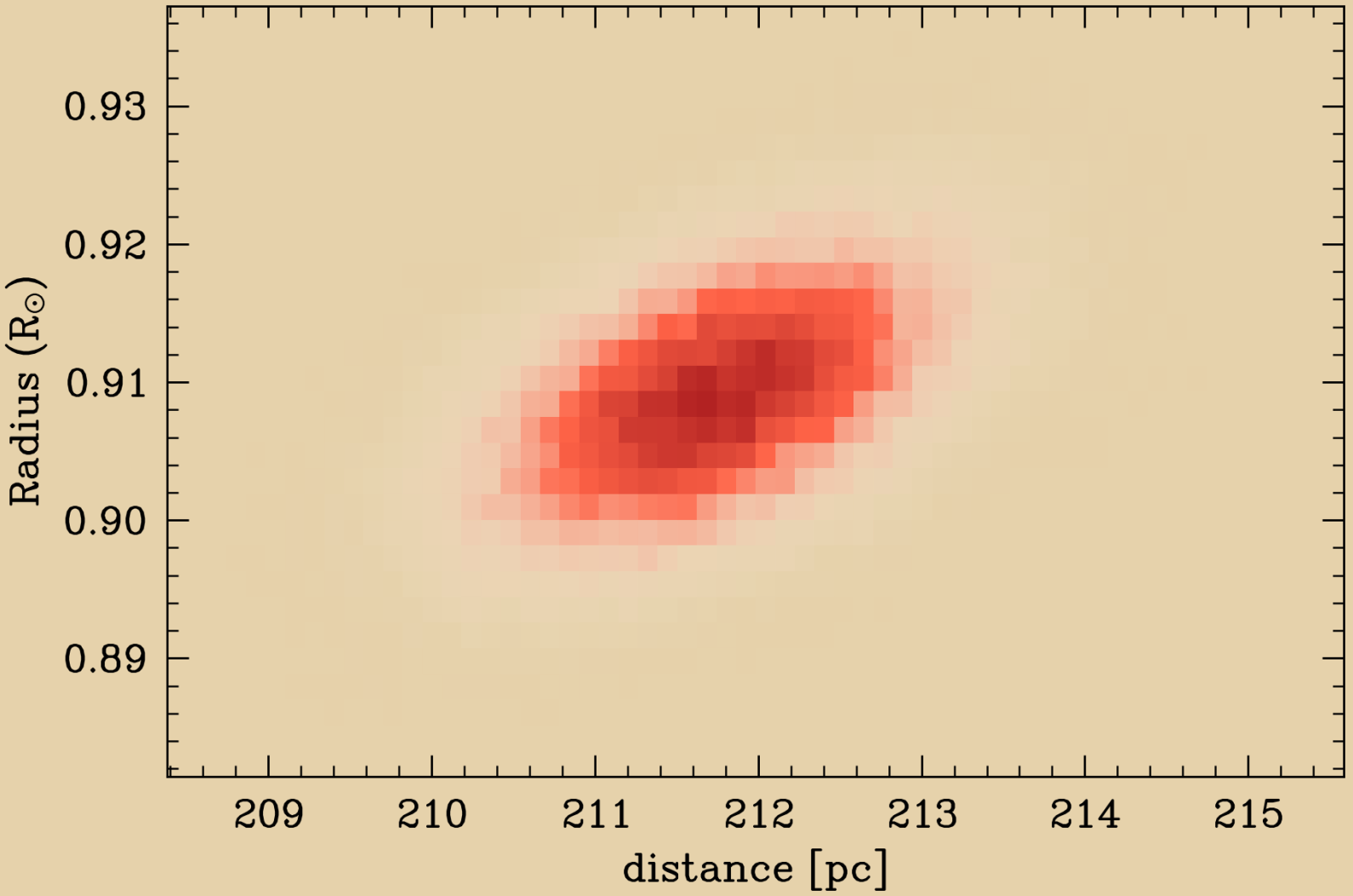
- Might be relevant for getting at the hot Jupiter migration and inflation problems…
- Curious to see how atmospheres and interiors change

The stellar SED constrains the temperature and bolometric flux

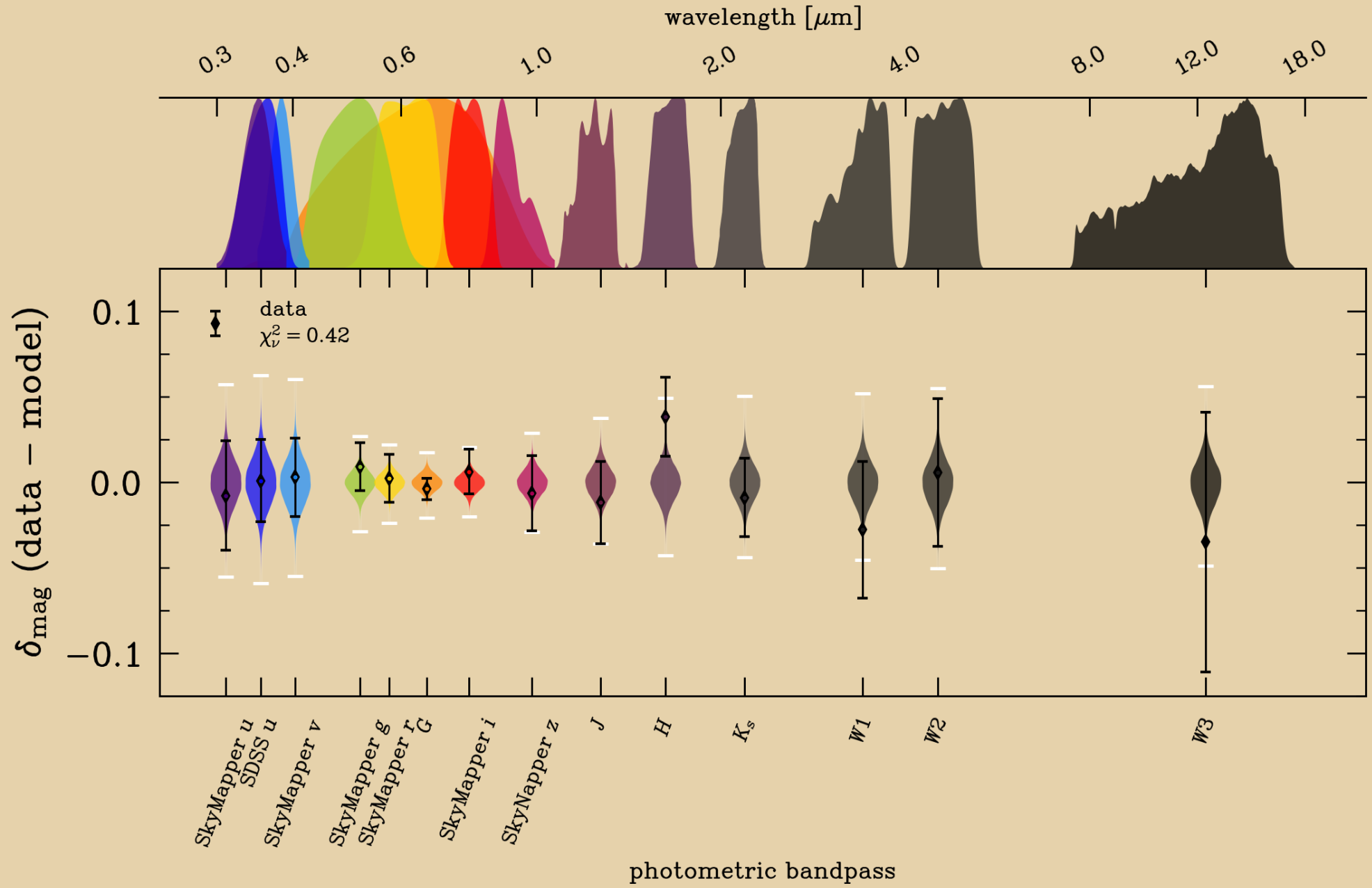


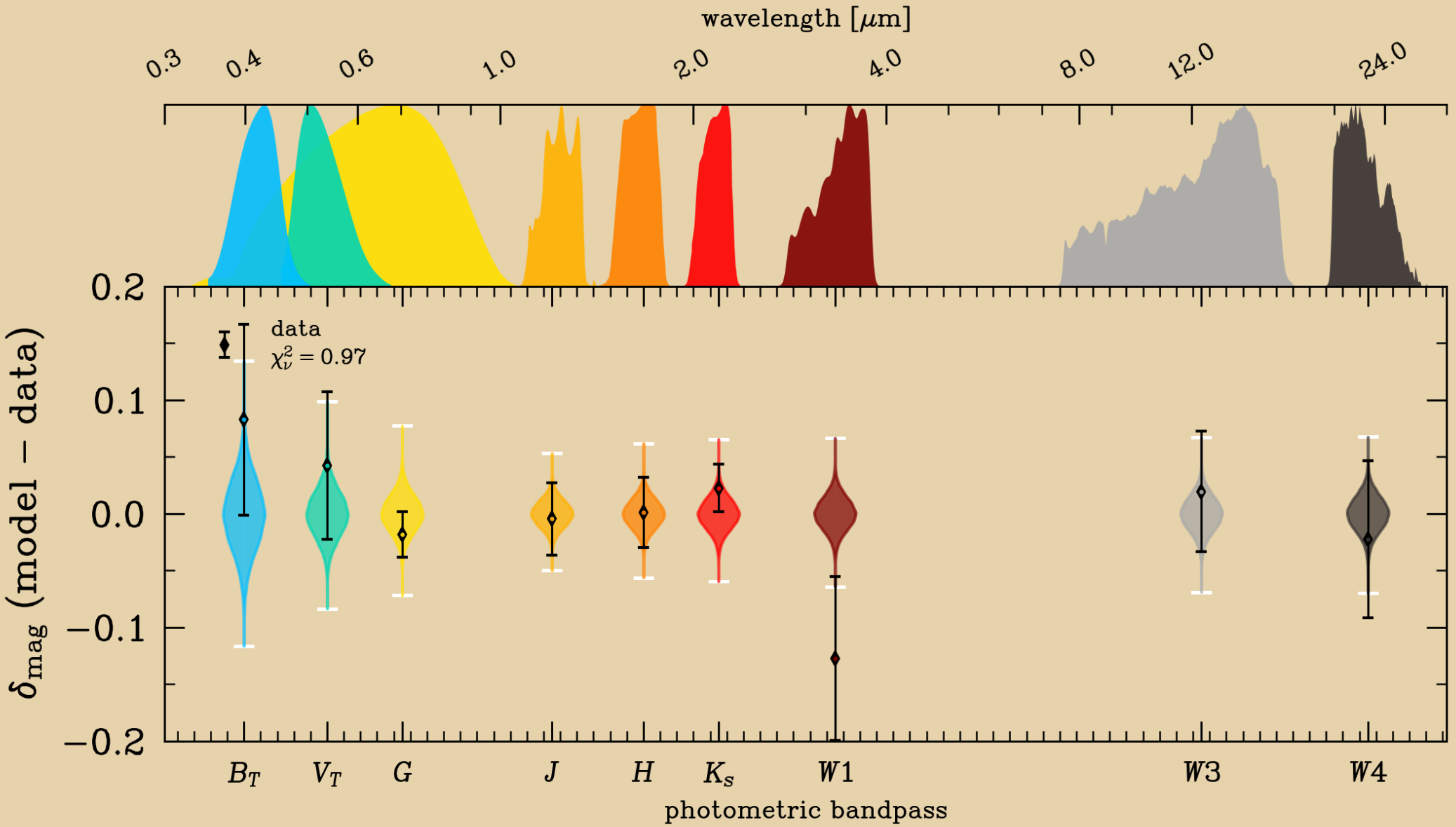
The distance constrains the stellar luminosity and radius



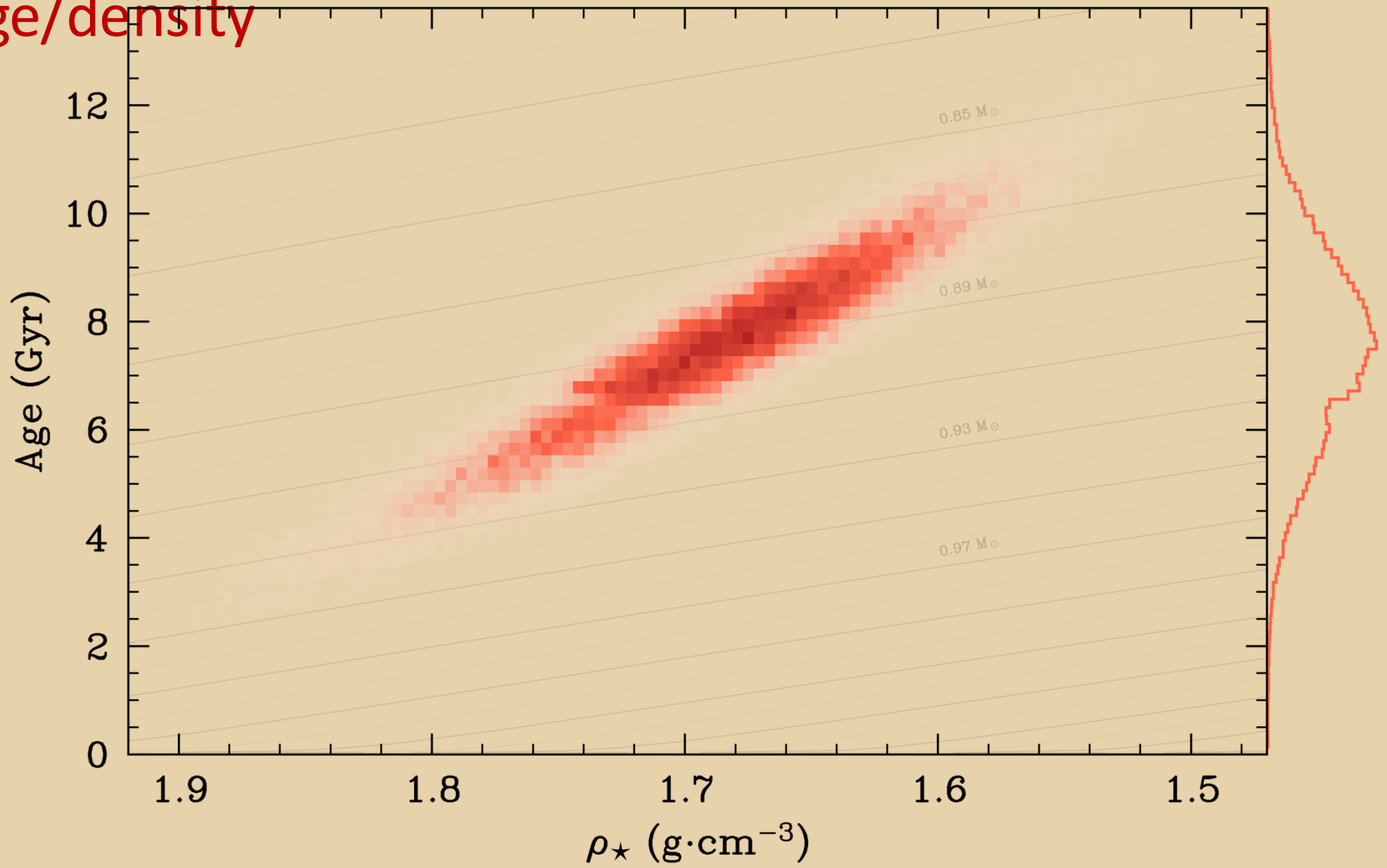


We use the *isochrones* package to fit our input data with the MIST grid of MESA stellar models

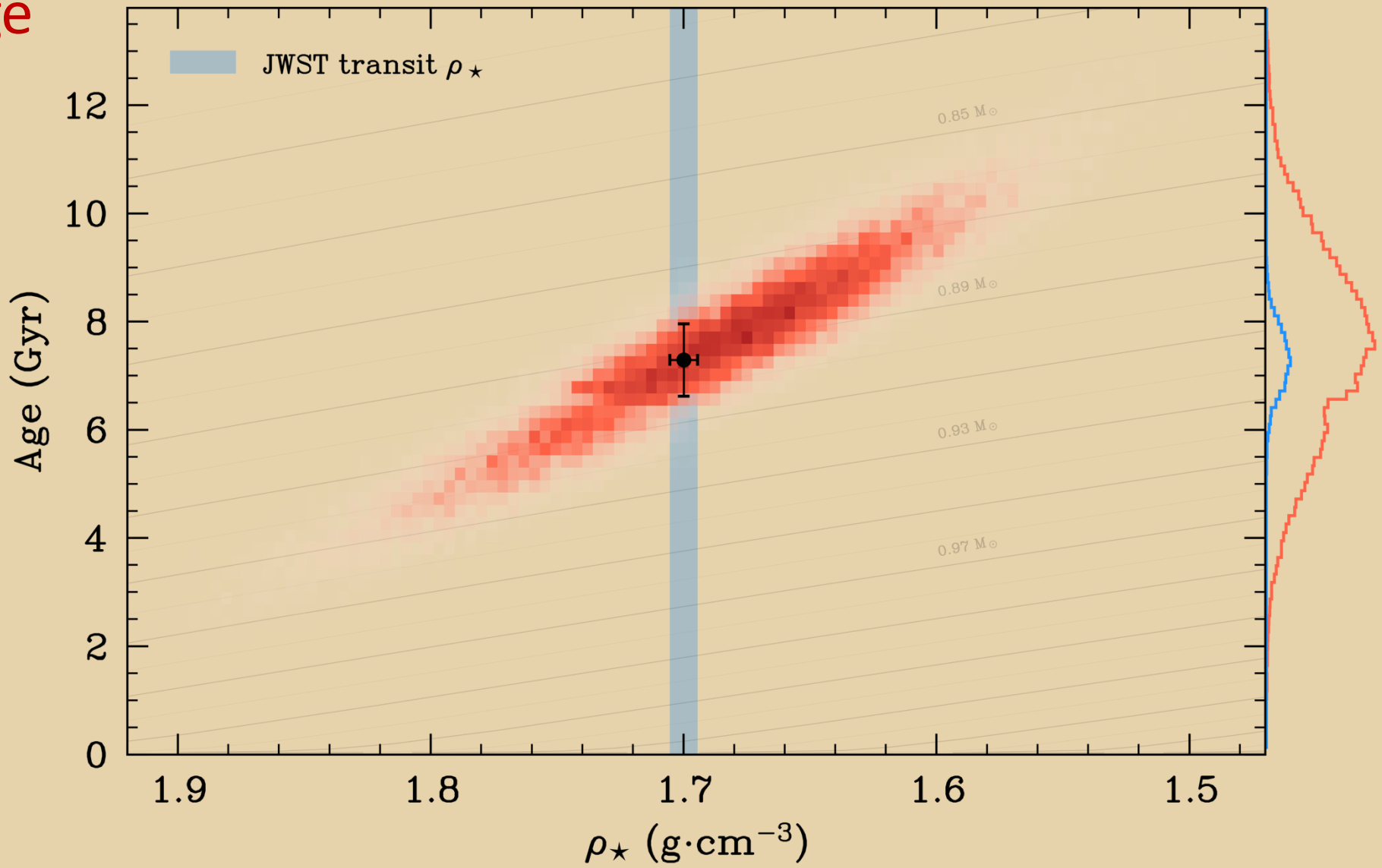

wavelength [μm]
0.3
0.4
0.6
1.0
2.0
4.0
8.0
12.0
18.0
data
$\chi^2_\nu = 0.42$
$\delta_{\rm mag}$ (data − model)
0.1
0.0
−0.1
SkyMapper u
SDSS u
SkyMapper v
SkyMapper g
SkyMapper r
G
SkyMapper i
SkyNapper z
J
H
K_s
W1
W2
W3
photometric bandpass


wavelength [μm]
0.3
0.4
0.6
1.0
2.0
4.0
8.0
12.0
24.0
0.2
0.1
0.0
−0.1
−0.2
δmag (model − data)
data
χ²ν = 0.97
BT
VT
G
J
H
Ks
W1
W3
W4
photometric bandpass

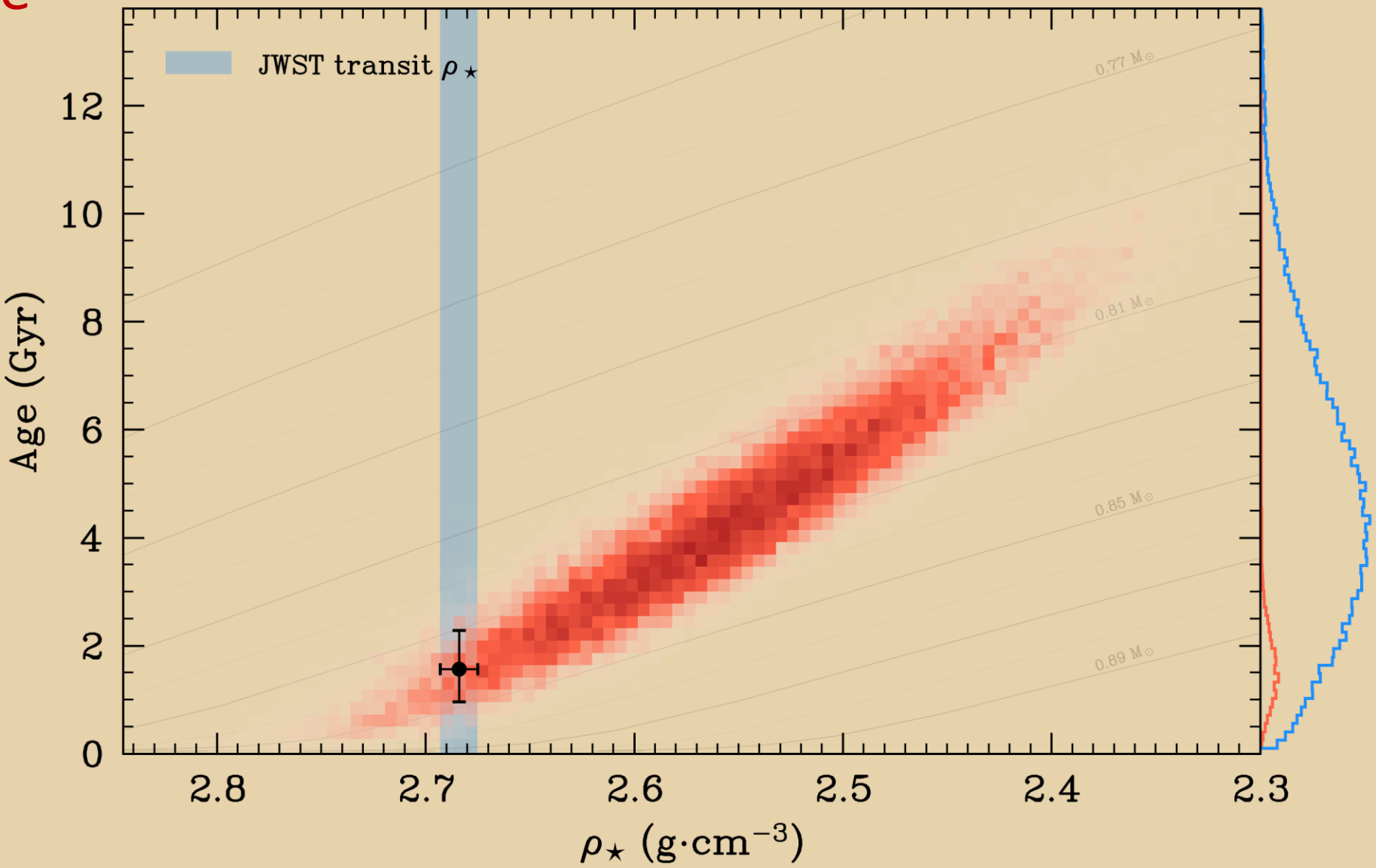
Isochrone fitting gives us an initial estimate of the age/density



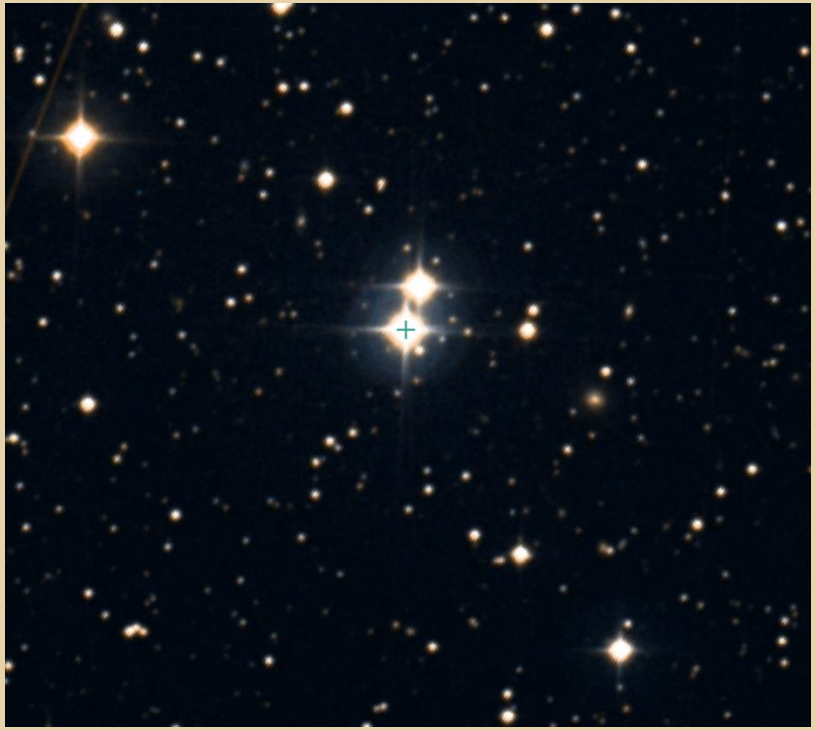
Applying the JWST density cut to the posterior constrains age

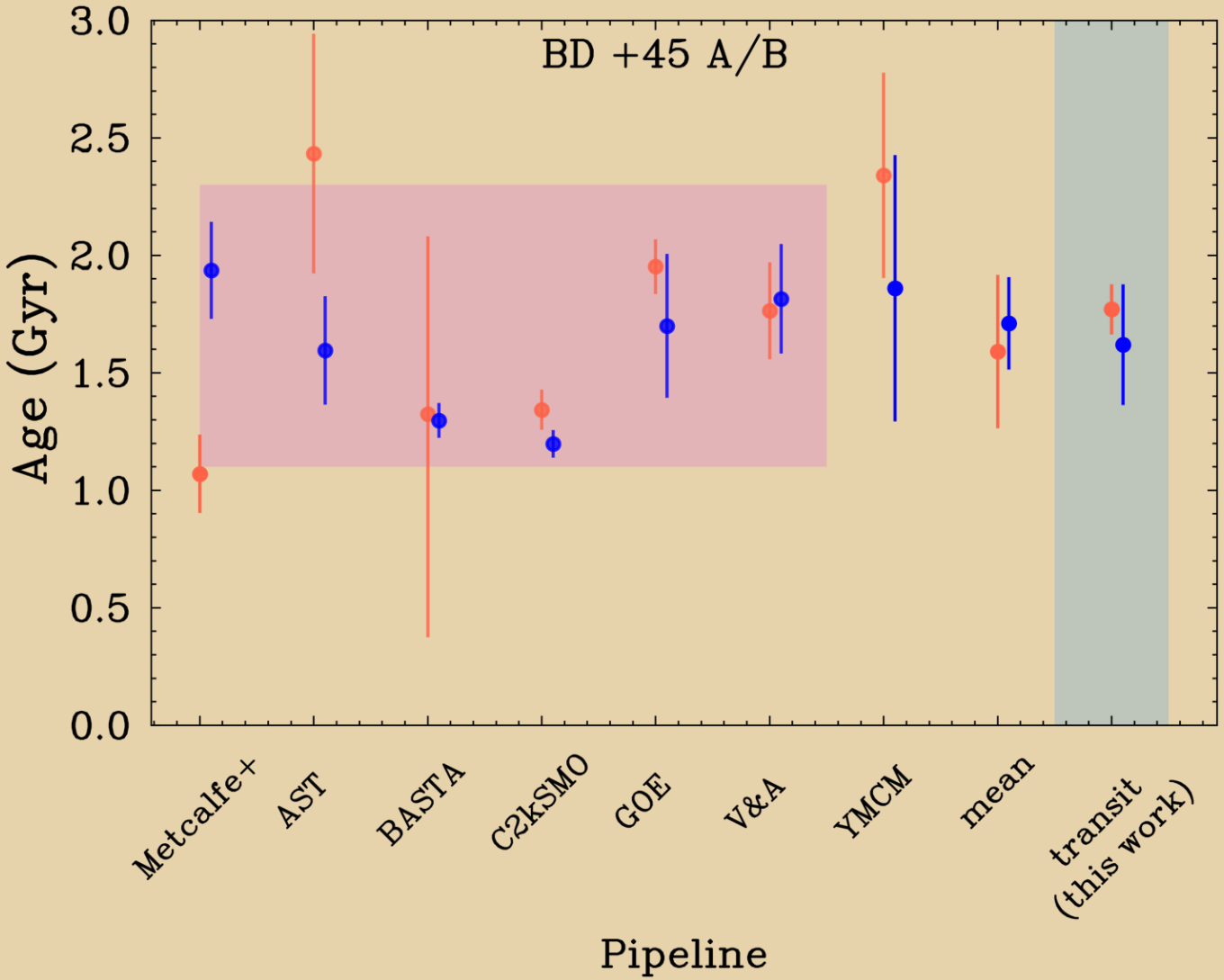


Applying the JWST density cut to the posterior constrains age

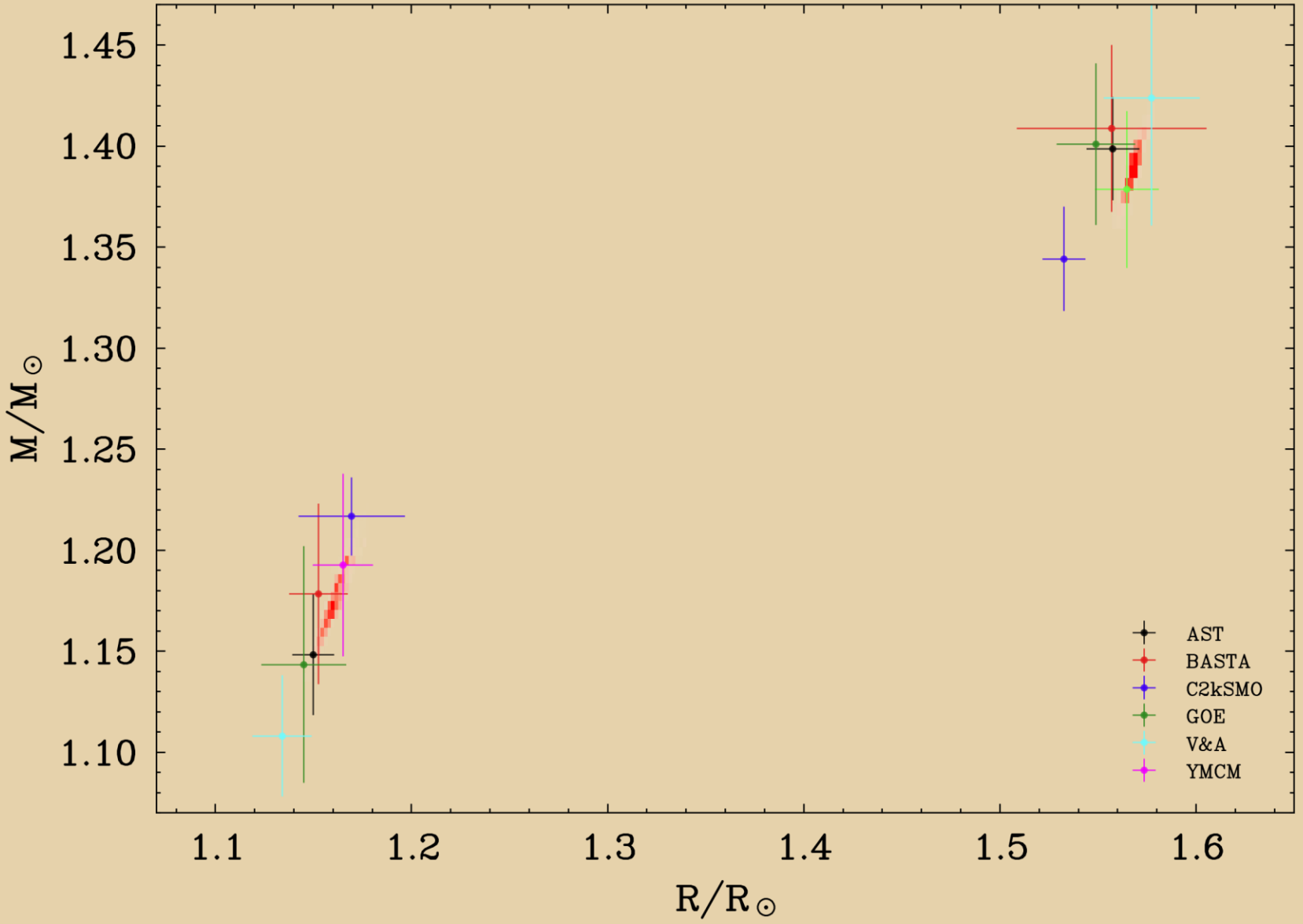


We did the same thing with a well-studied seismic Kepler LEGACY binary and got concordant ages





BD+45 A/B

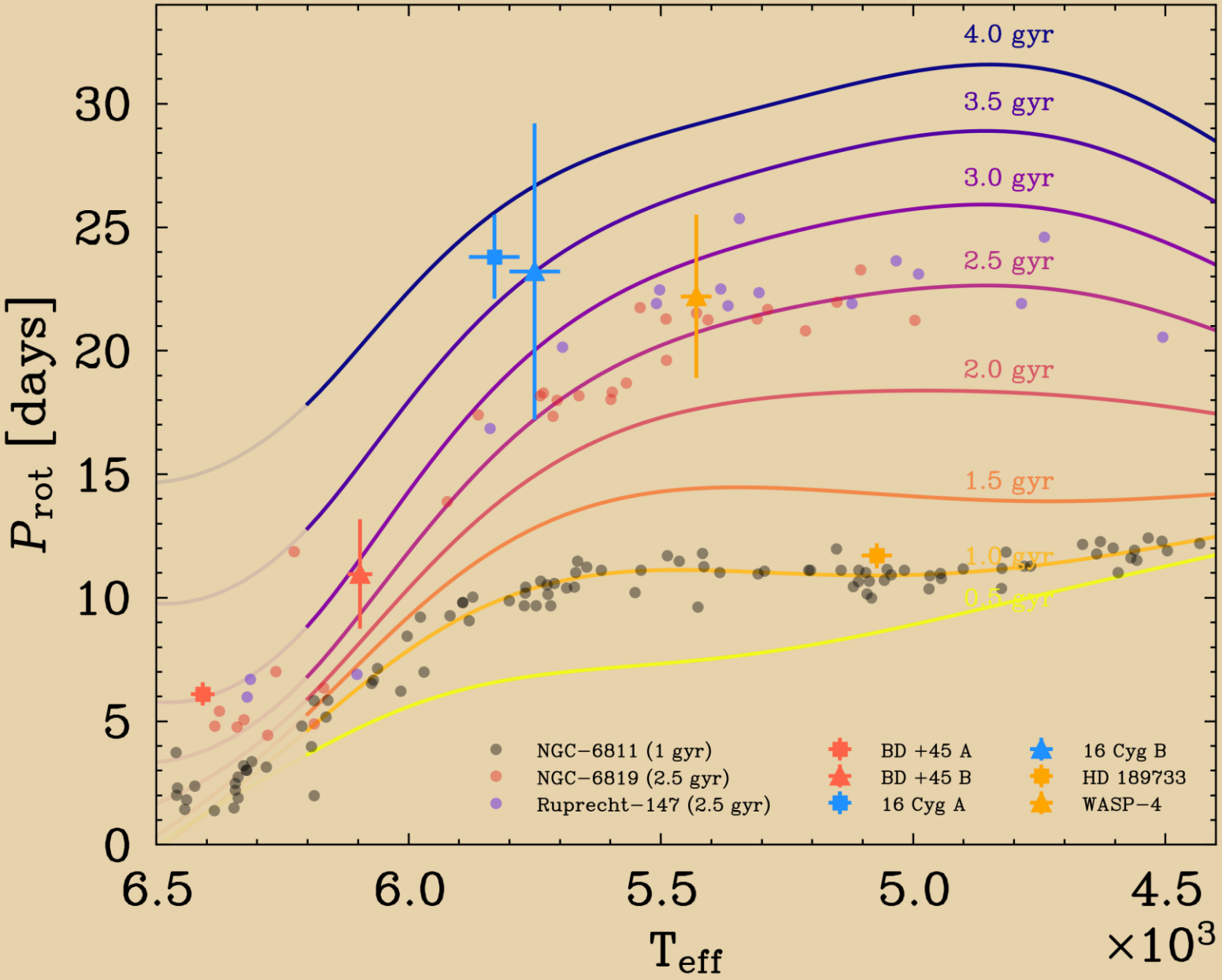

1.45
1.40
1.35
1.30
1.25
1.20
1.15
1.10
M/M⊙
1.1
1.2
1.3
1.4
1.5
1.6
R/R⊙
AST
BASTA
C2kSMO
GOE
V&A
YMCM

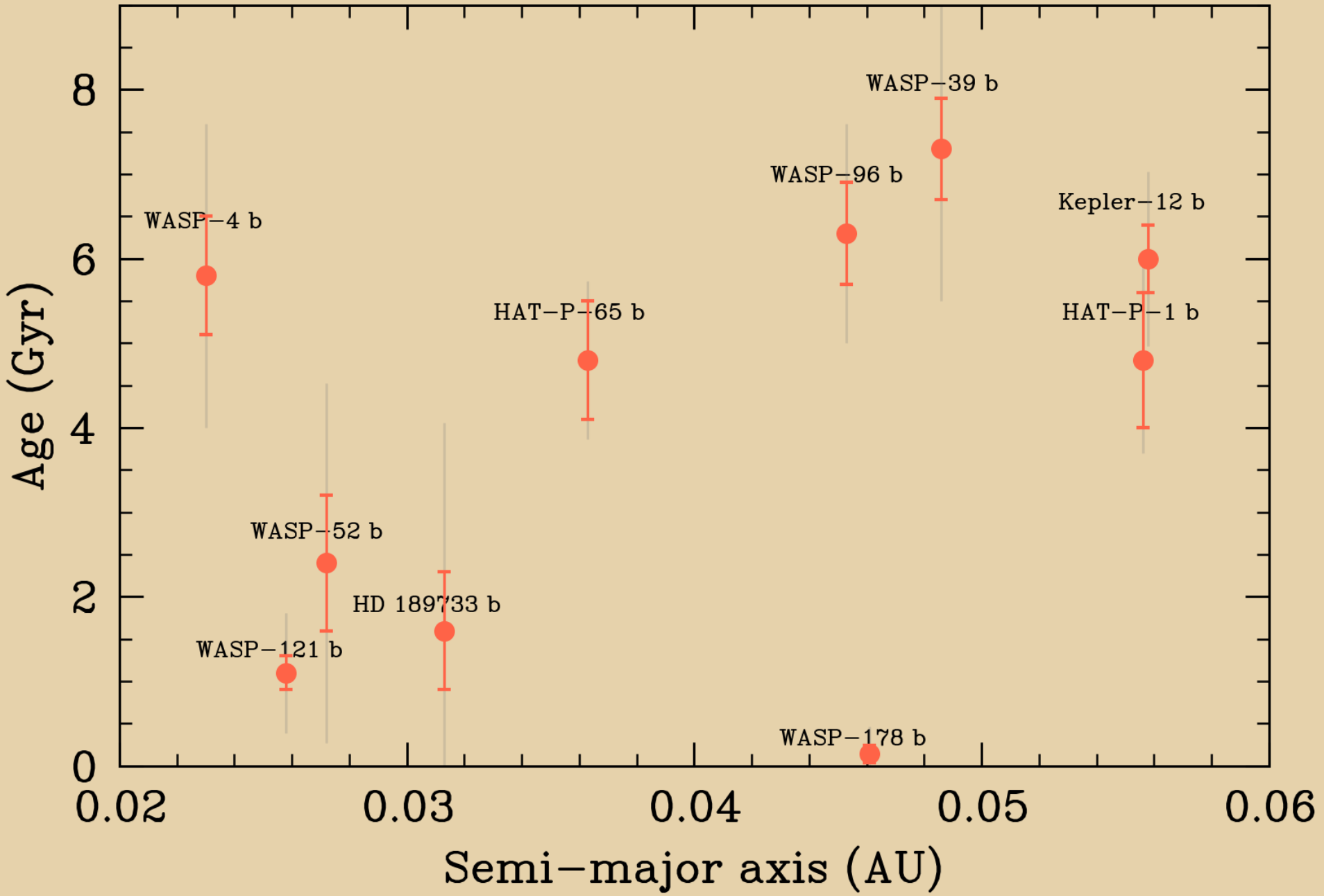
What are the relevant systematic uncertainties?

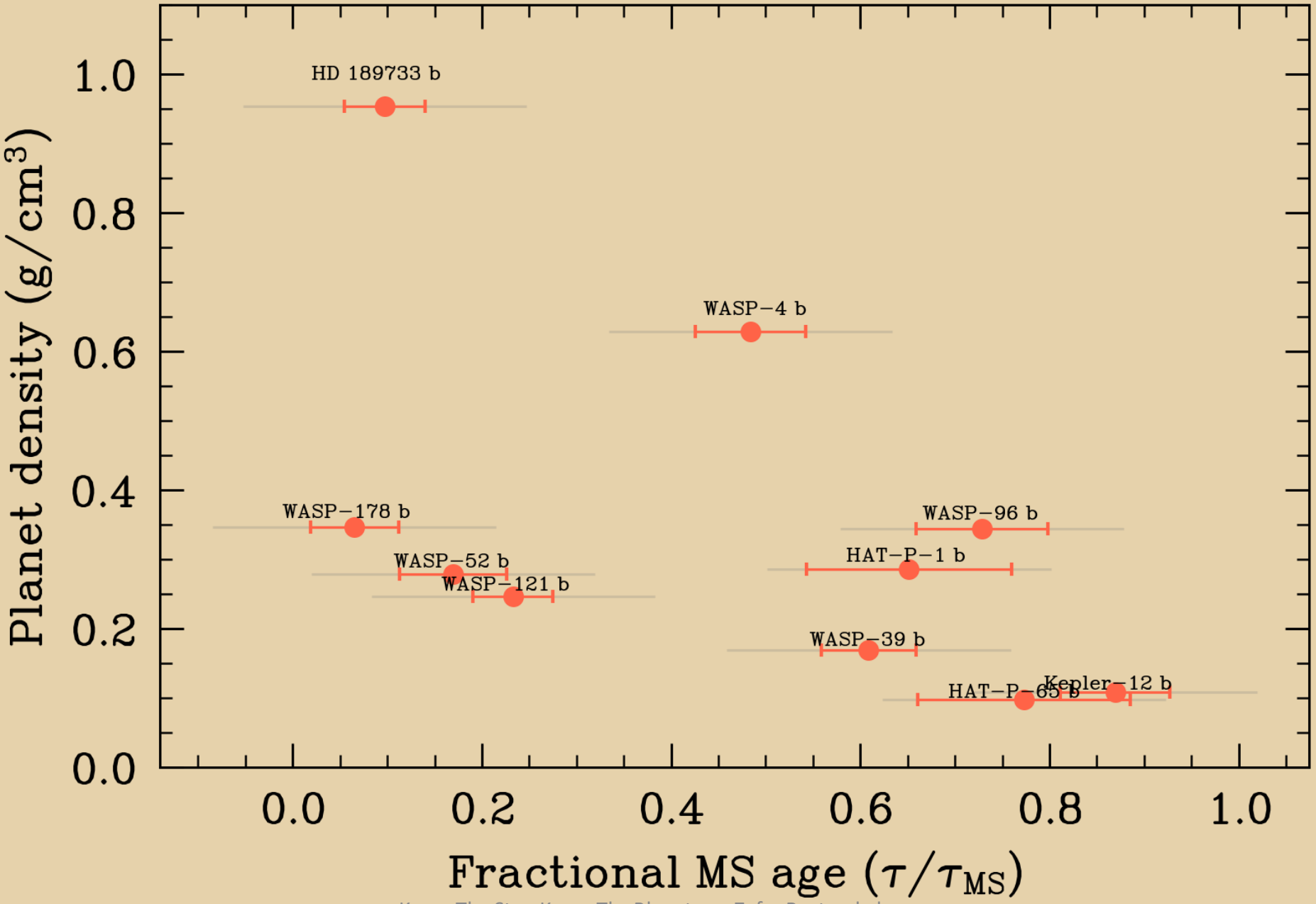
- Photometric/astrometric zero-point offsets
- Differences between stellar models
- Model calibration uncertainties
- Uncertainties in stellar physics (core overshoot, mixing length)
- Unknown initial helium fraction

We find an absolute fractional age uncertainty floor of **15%**

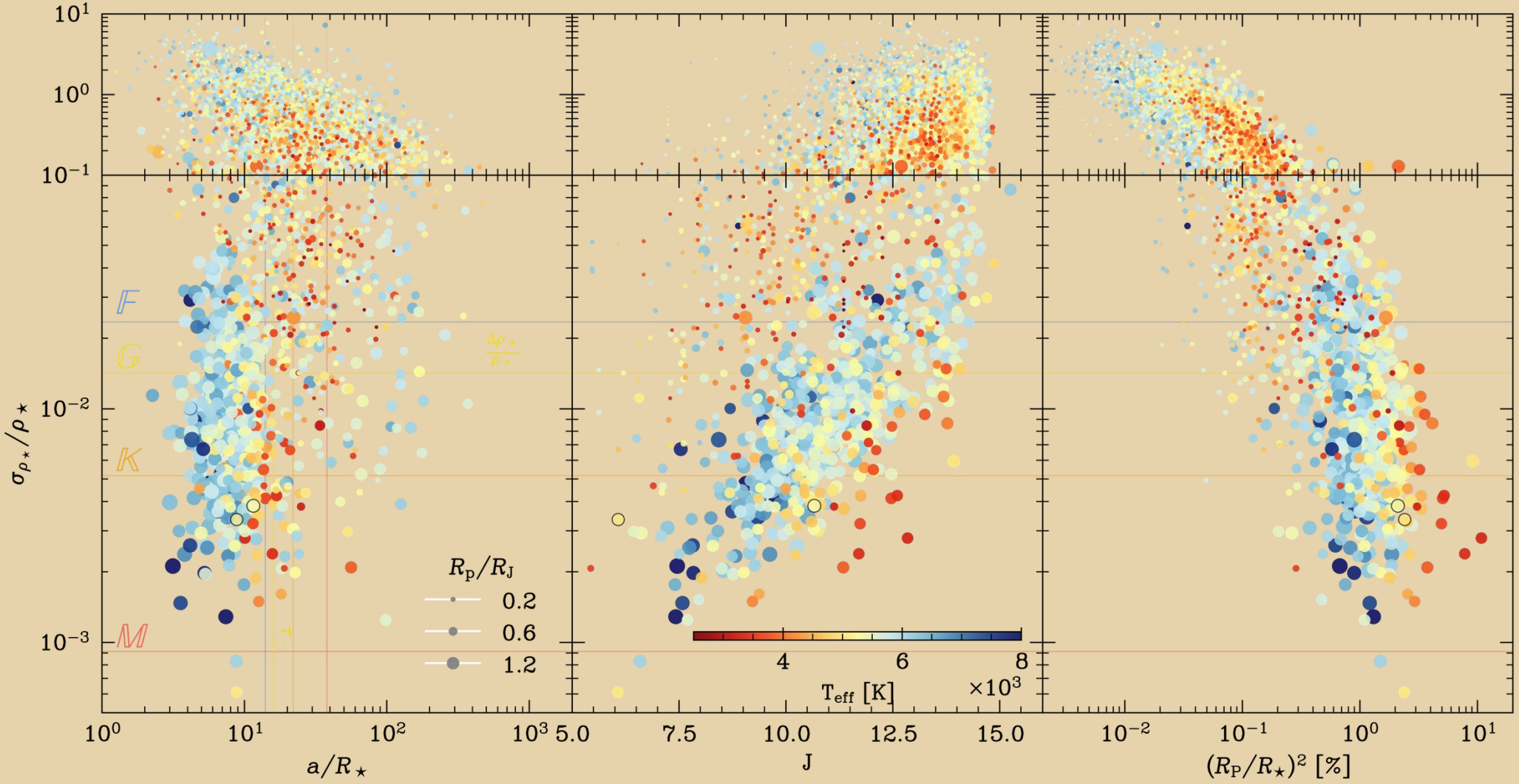
Gyrochronology is in tension with some of our ages




WASP−39 b
WASP−96 b
Kepler−12 b
WASP−4 b
HAT−P−65 b
HAT−P−1 b
WASP−52 b
HD 189733 b
WASP−121 b
WASP−178 b
Age (Gyr)
Semi−major axis (AU)
0
2
4
6
8
0.02
0.03
0.04
0.05
0.06


HD 189733 b
WASP−4 b
WASP−178 b
WASP−52 b
WASP−121 b
WASP−96 b
HAT−P−1 b
WASP−39 b
HAT−P−65 b
Kepler−12 b
Planet density (g/cm^3)
Fractional MS age (τ/τ_{MS})
0.0
0.2
0.4
0.6
0.8
1.0

We can get hundreds of planet ages with single JWST transits



Conclusion

- HD 189733 shows excess angular momentum for its age, indicating 0.03 AU of inward migration

- WASP-39 b is not inflated due to youth

- There may be a preliminary trend in planet density vs. fractional age

- We can get the ages of hundreds of planets with JWST

- The upcoming SPHEREx mission will revolutionize stellar characterization (1% radii!!!)

Thank you:

David Sing
Kevin Schlaufman
Daniel Thorngren
Stephen Schmidt
Alejandro Ross
Jacob Hamer
Guangwei Fu
Chris Wang

Conference Organizers
SOC
Firefighters

Isochrones preserves the multicovariate posterior network