Words of Caution

on the fitting of **metal-poor benchmark stars** and **globular clusters** with stellar tracks and isochrones

...and on fitting anything else

Lund Reference Stars Workshop
31st March 2021

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Using four types of stellar models to understand the physics of stars and design the best possible theoretical descriptions of their behavior:

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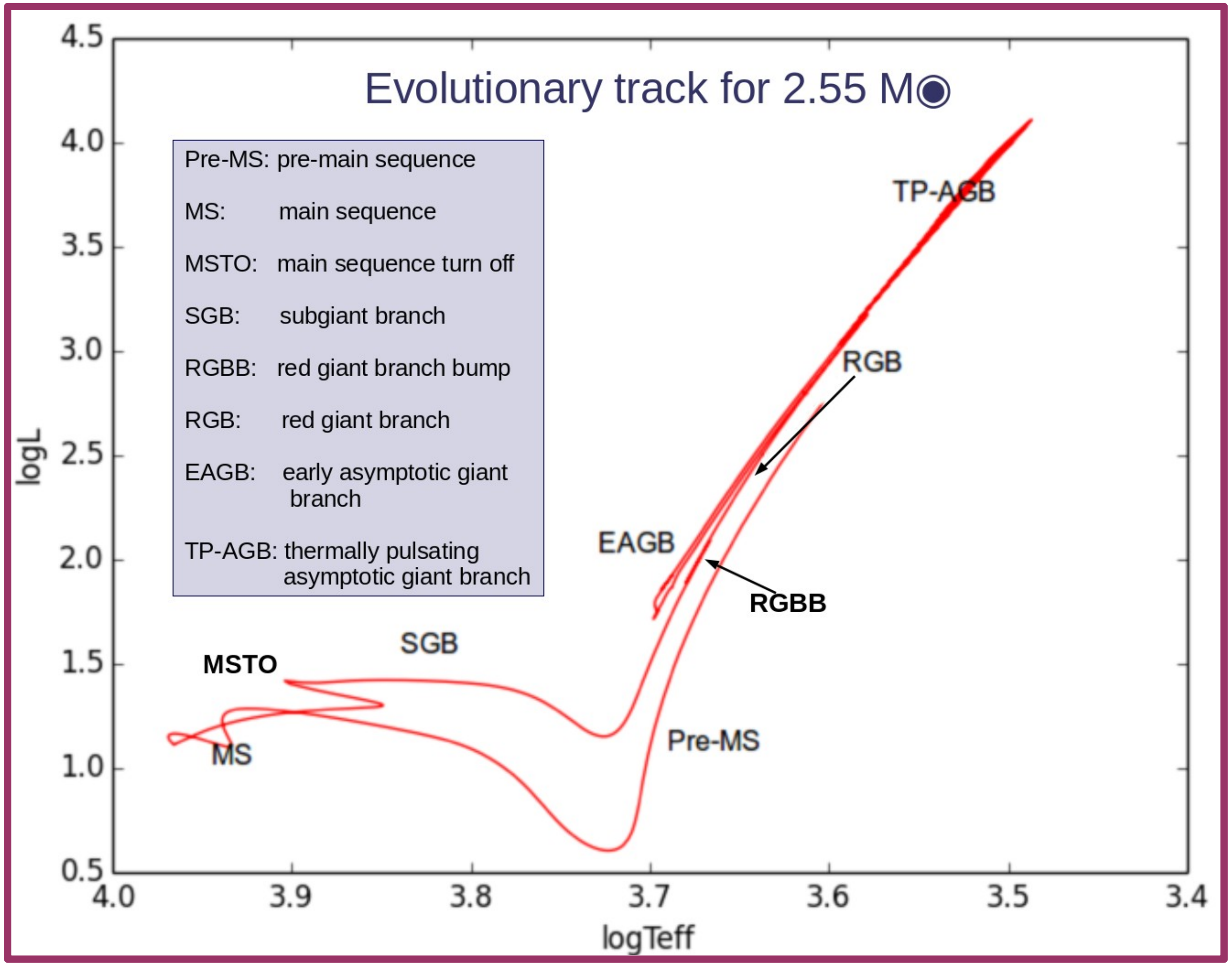

Using four types of stellar models to understand the physics of stars and design the best possible theoretical descriptions of their behavior:

-stellar evolution tracks

-stellar profiles

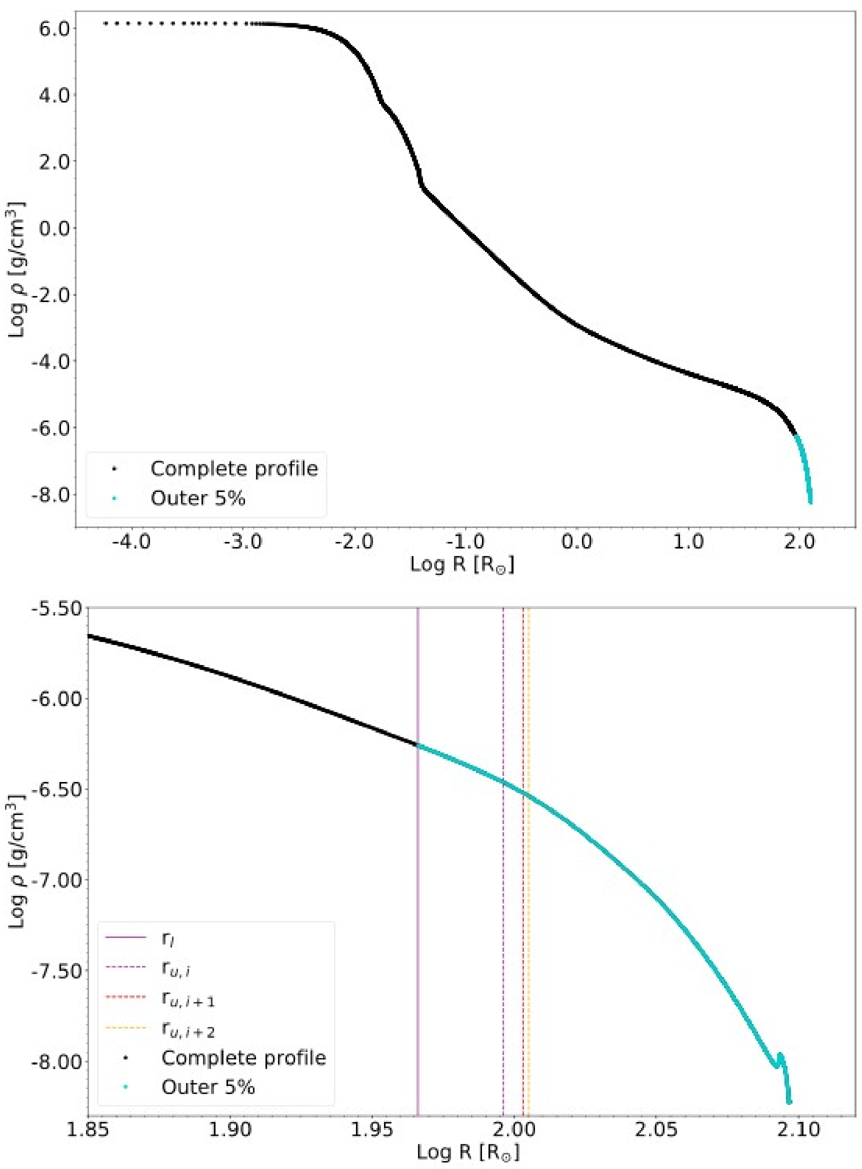

Figure 2. Top: complete MESA density profile, from core to surface,

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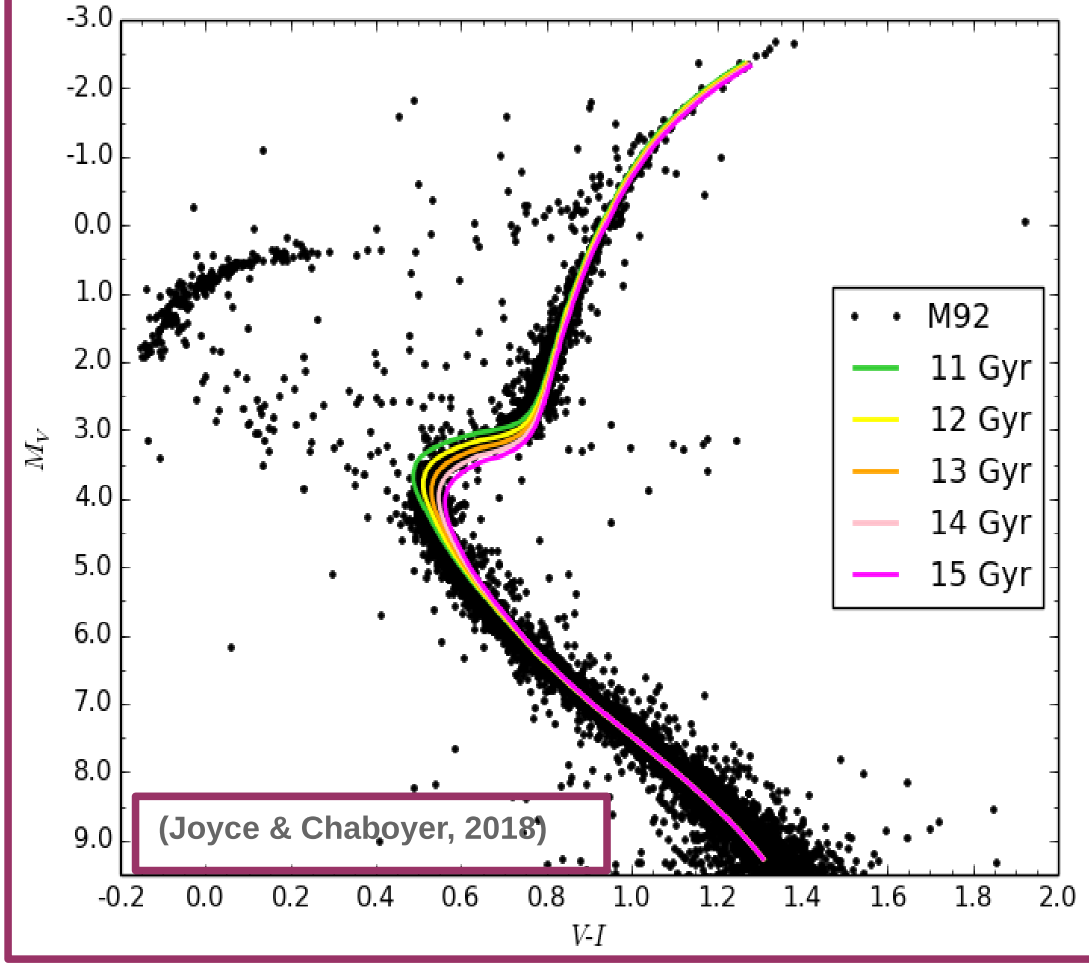
-isochrones



(Joyce & Chaboyer, 2018)

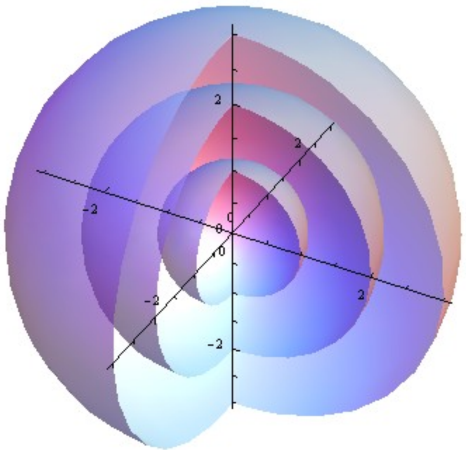
Using four types of stellar models to understand the physics of stars and design the best possible theoretical descriptions of their behavior:

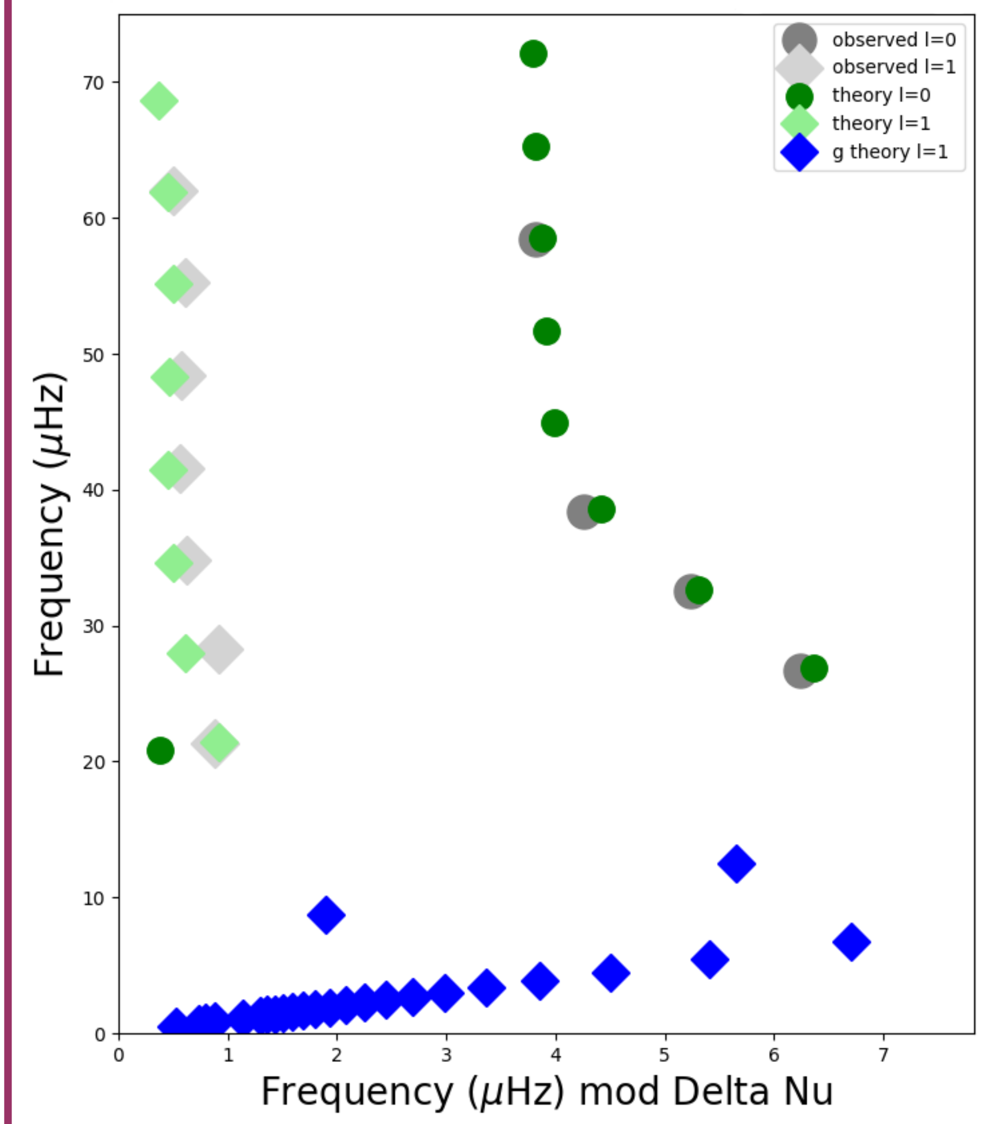
-stellar evolution tracks

-stellar profiles

-isochrones

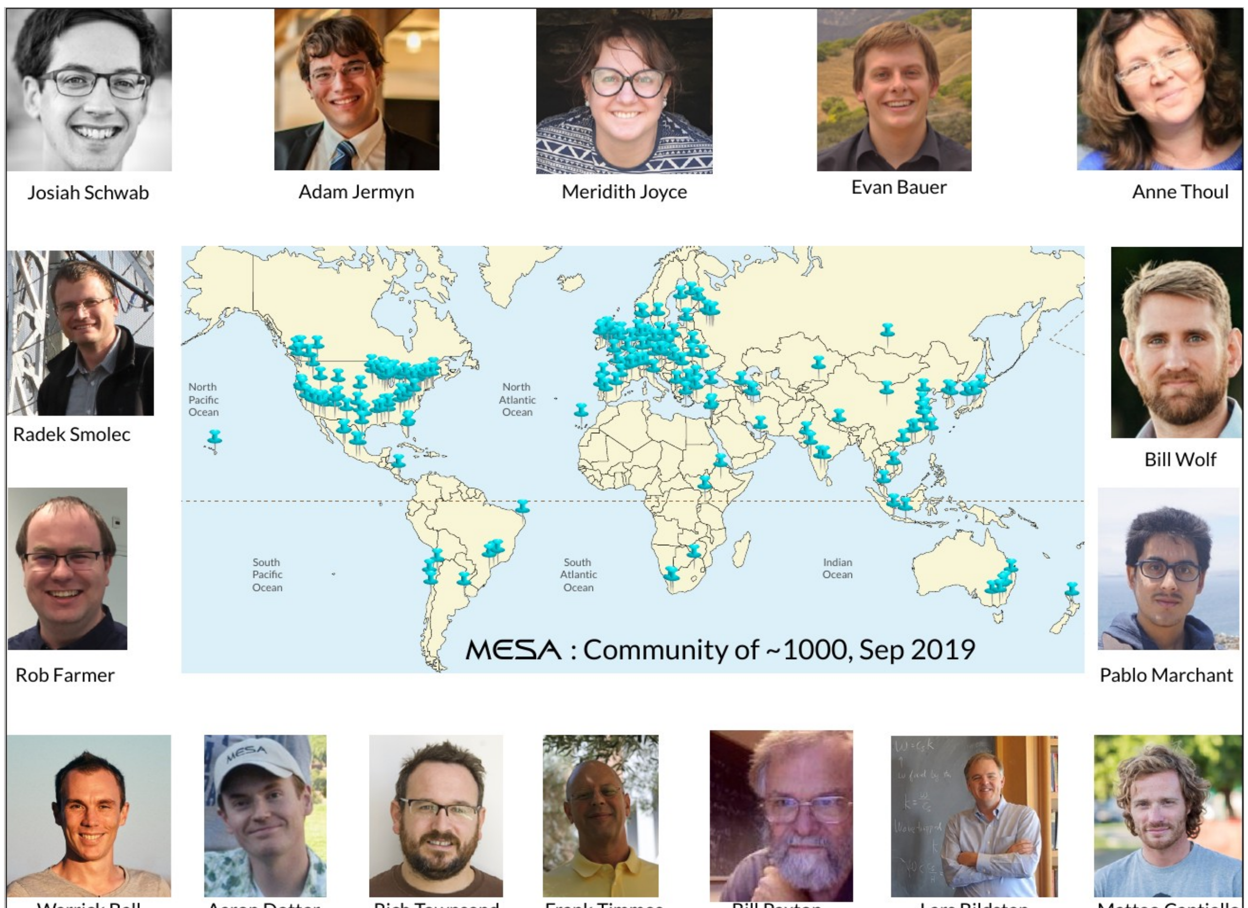
-synthetic seismology





Using four types of stellar models to understand the physics of stars and design the best possible theoretical descriptions of their behavior:

With sophisticated tools and a team of theoreticians and computer scientists



MESA

GYRE

1D 3D
MESA2HYDRO

D S E P
Dartmouth Stellar Evolution Program

Stellar modeling: Why should I care?

Even if you are not a modeller, your work likely relies on results from stellar models

In the era of *Gaia*, TESS, PLATO, GALAH, and any large survey, a goal is to estimate non-observables (mass, age) for huge numbers of stars

→stellar models are how we get those non-observables

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Order-of-magnitude uncertainties imparted from modeling systematics

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Non-observable parameters are often quoted at precisions **an order of magnitude better** than is actually appropriate

....but modeling uncertainties are complicated

Common misconceptions

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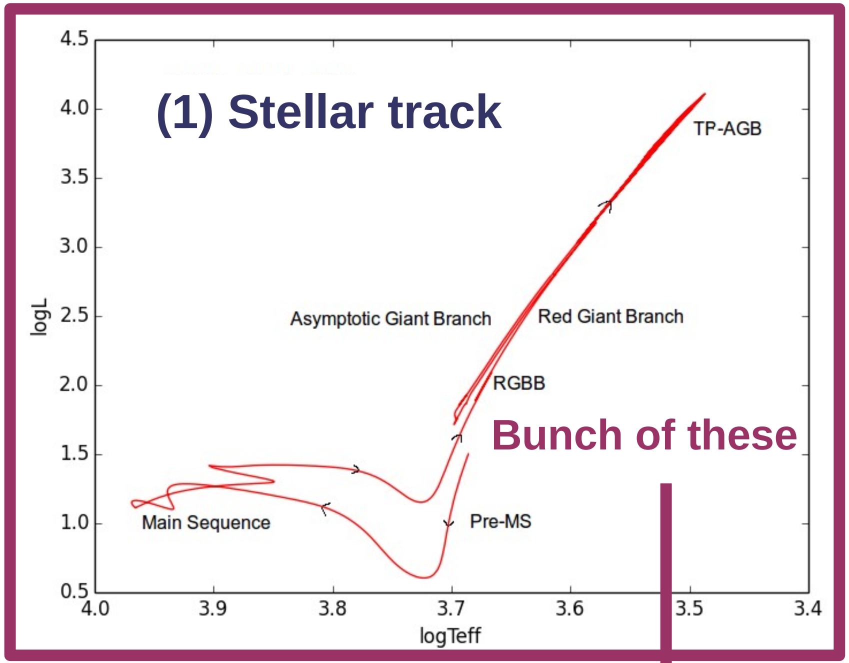
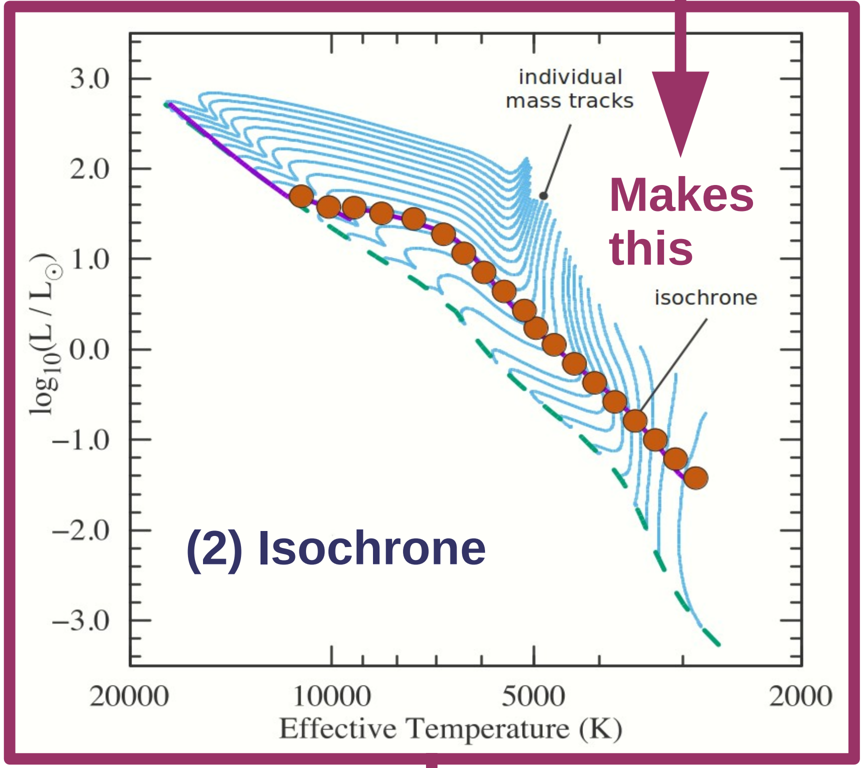
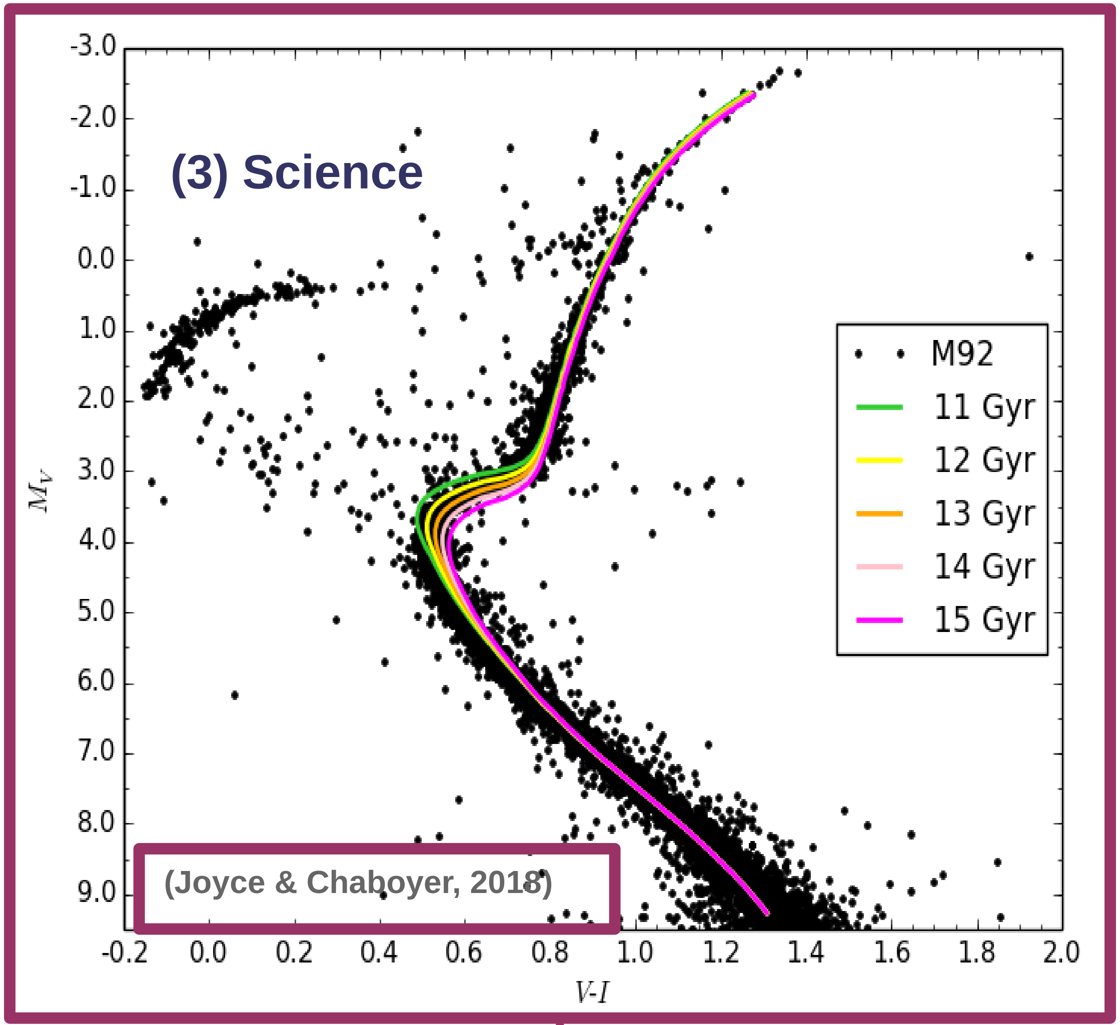
Math to Astronomy







Derive fundamental parameters for both individual stars and stellar populations

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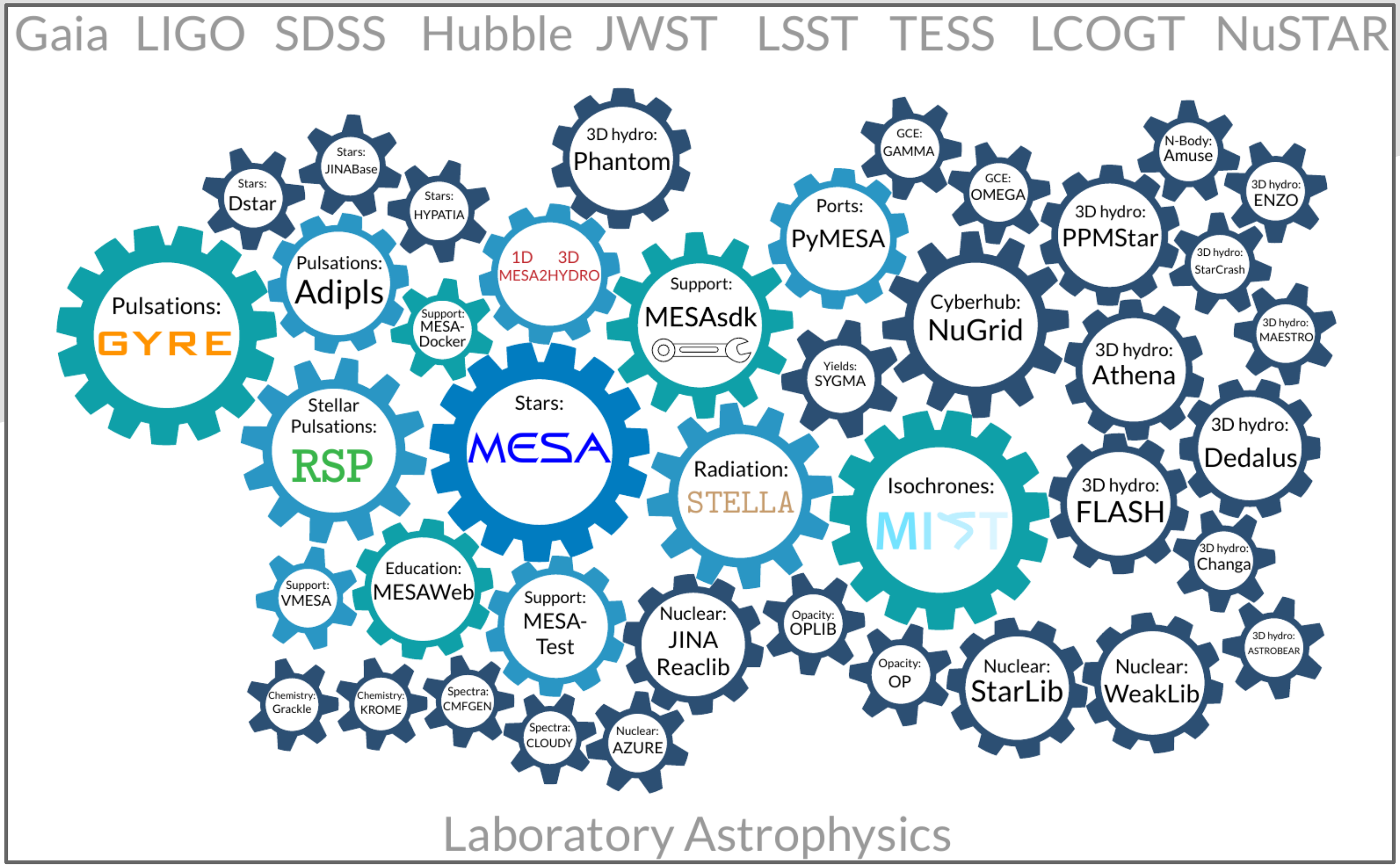

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Contact me to give your star the modeling it deserves

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    > unfortunately, also no.

Physical choices in stellar models that observers should worry about: an incomplete list

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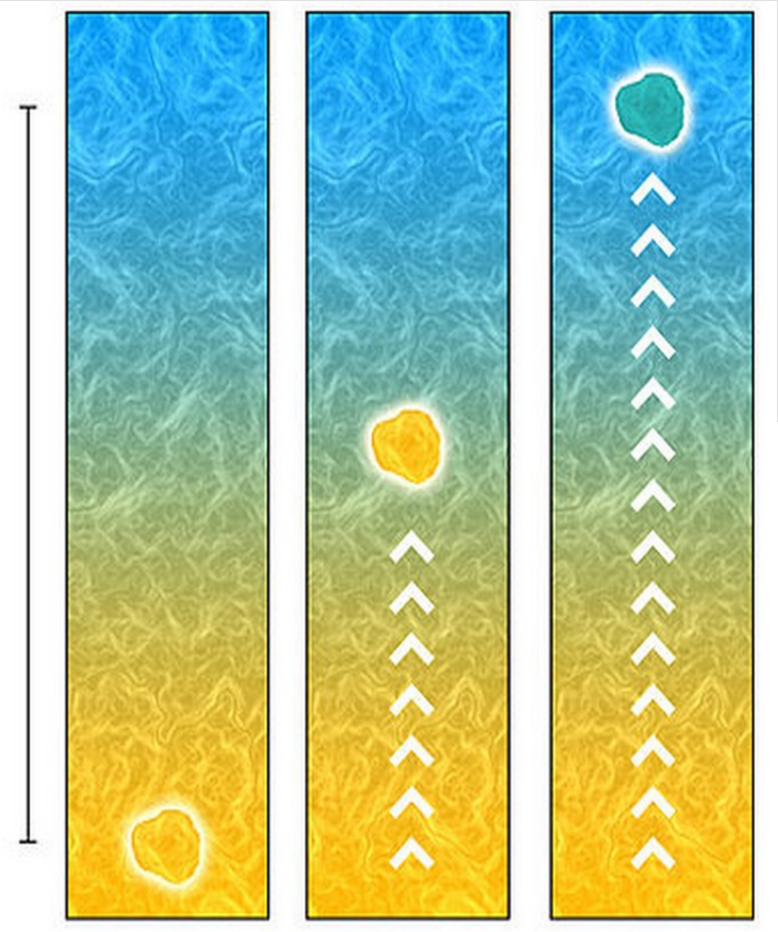
Convective parameters, especially the **mixing length**

$$F_{\text{conv}} = \frac{1}{2}\rho v c_p T \frac{\lambda}{H_P}(\nabla_T - \nabla_{\text{ad}}).$$

$$\alpha_{\text{MLT}} = \frac{\lambda}{H_P}$$

$$\nabla_T = \left(\frac{d\ln T}{d\ln P}\right)$$



- "mixing length:" average vertical distance over which parcels in pressure, but not thermal, equilibrium can travel before denaturing

-α_{MLT} represents mean free path measured in pressure scale heights, $H_P = d\ ln(P)/dln(T)$

- a measure of "efficiency" of convection

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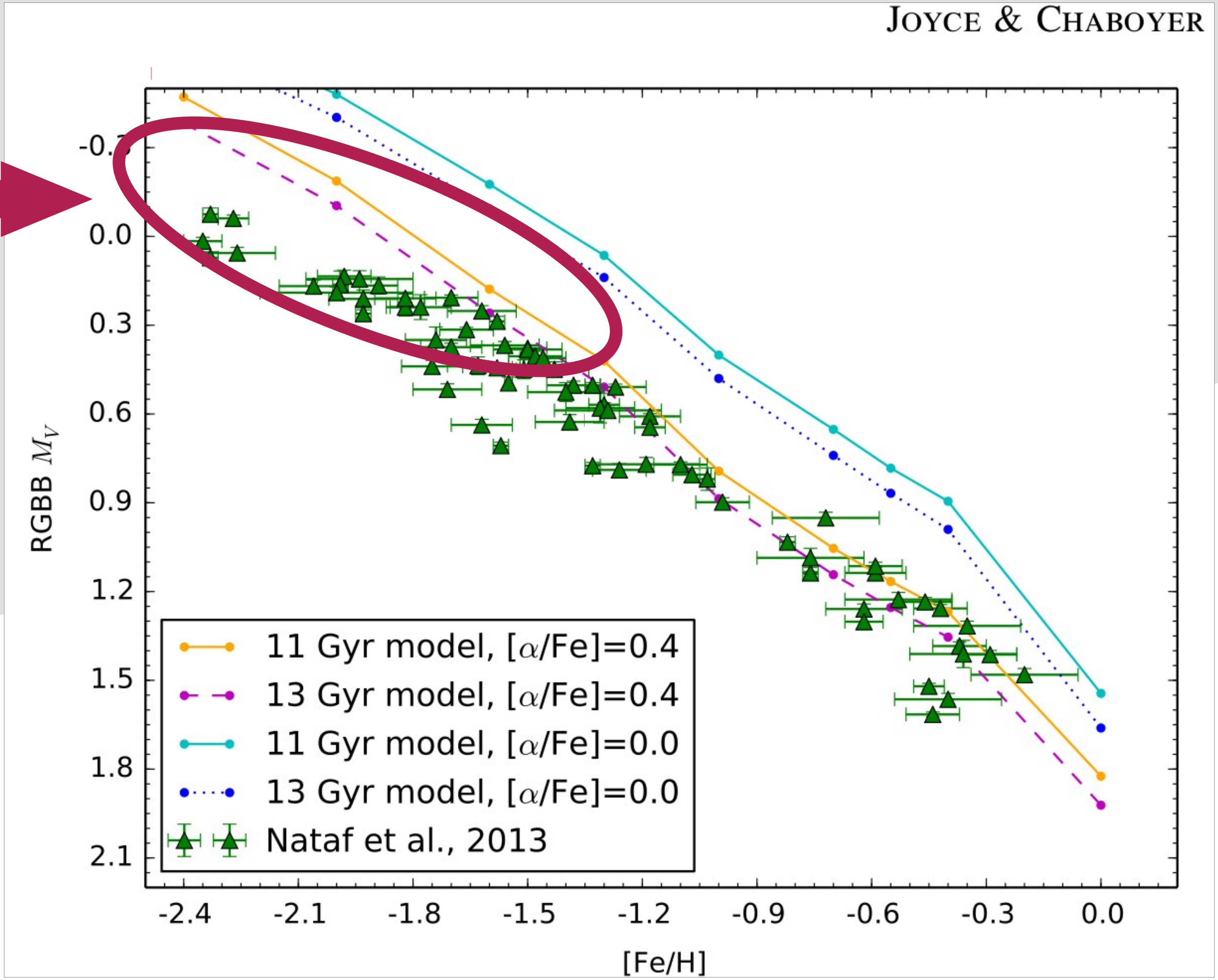
similar metallicity-dependence with **convective overshoot**

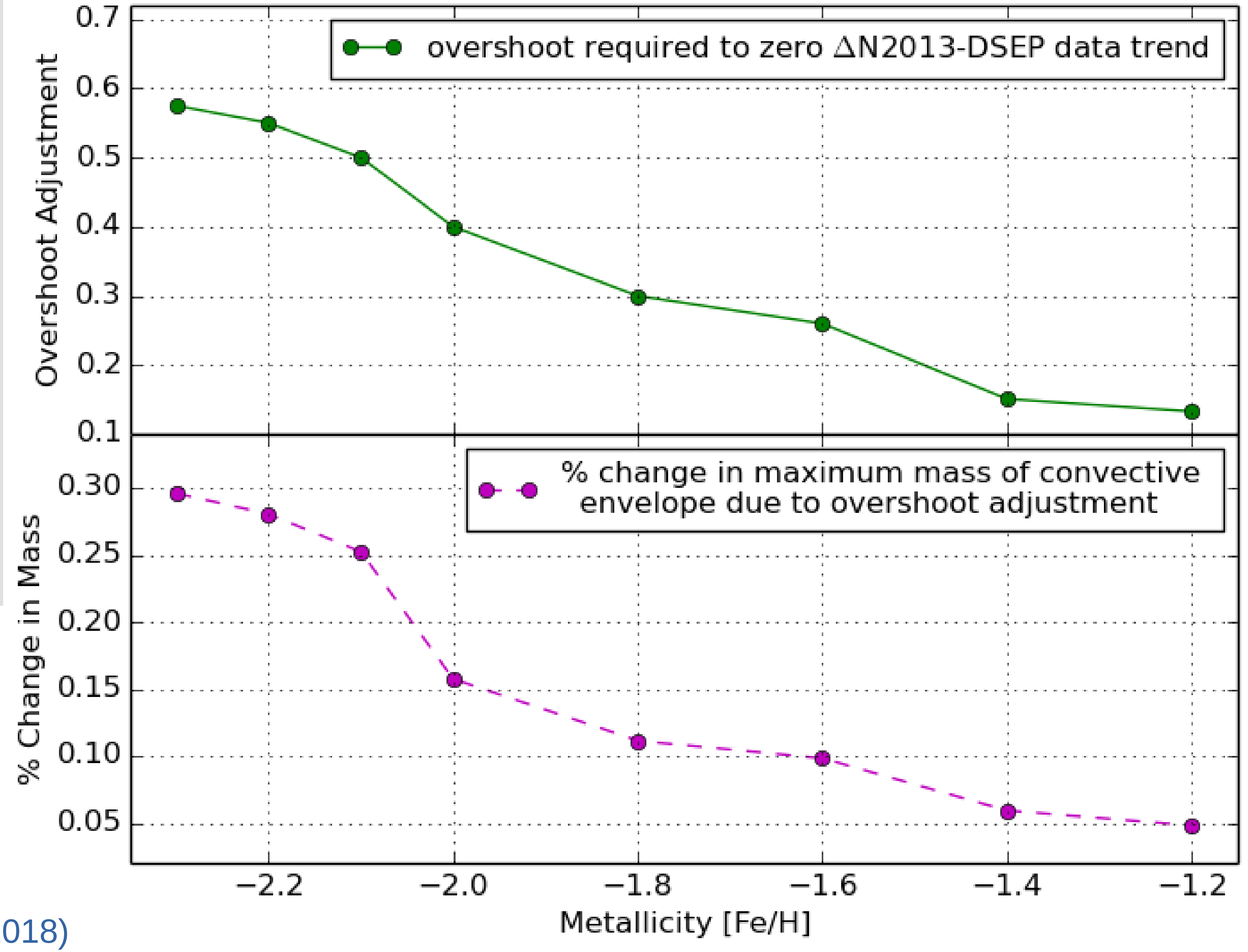
Example: “artificial” adjustments to the size of the convective envelope can erase trends of luminosity overprediction from models of metal-poor globular clusters

Overprediction of magnitudes



(Joyce & Chaboyer, 2015)

Example: “artificial” adjustments to the size of the convective envelope can erase trends of luminosity overprediction from models of metal-poor globular clusters



(Joyce thesis, 2018)

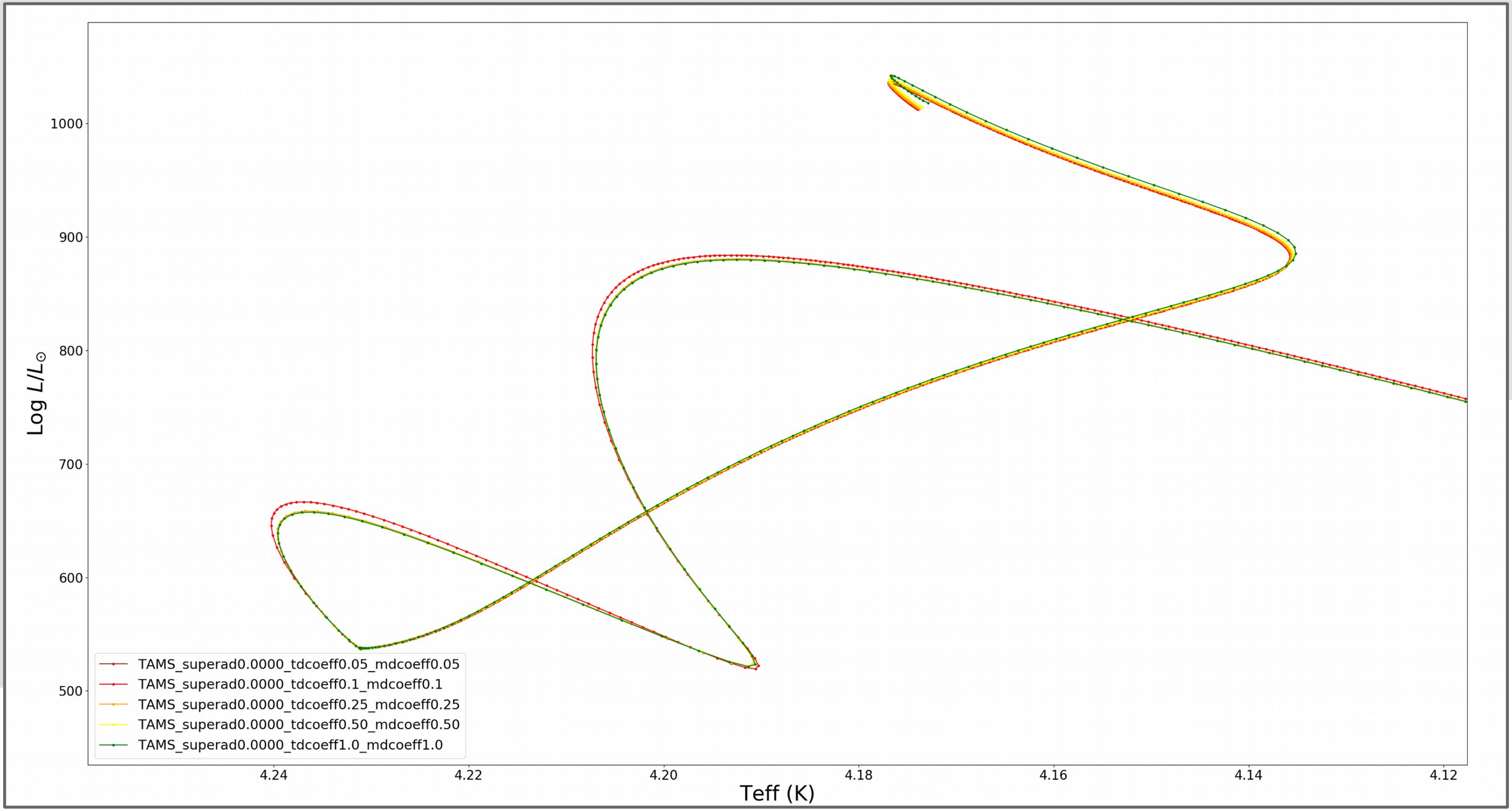
If "empirical trends" can be removed through *ad hoc* adjustments to unconstrained modeling assumptions, how do we know

what is *physical*?

vs

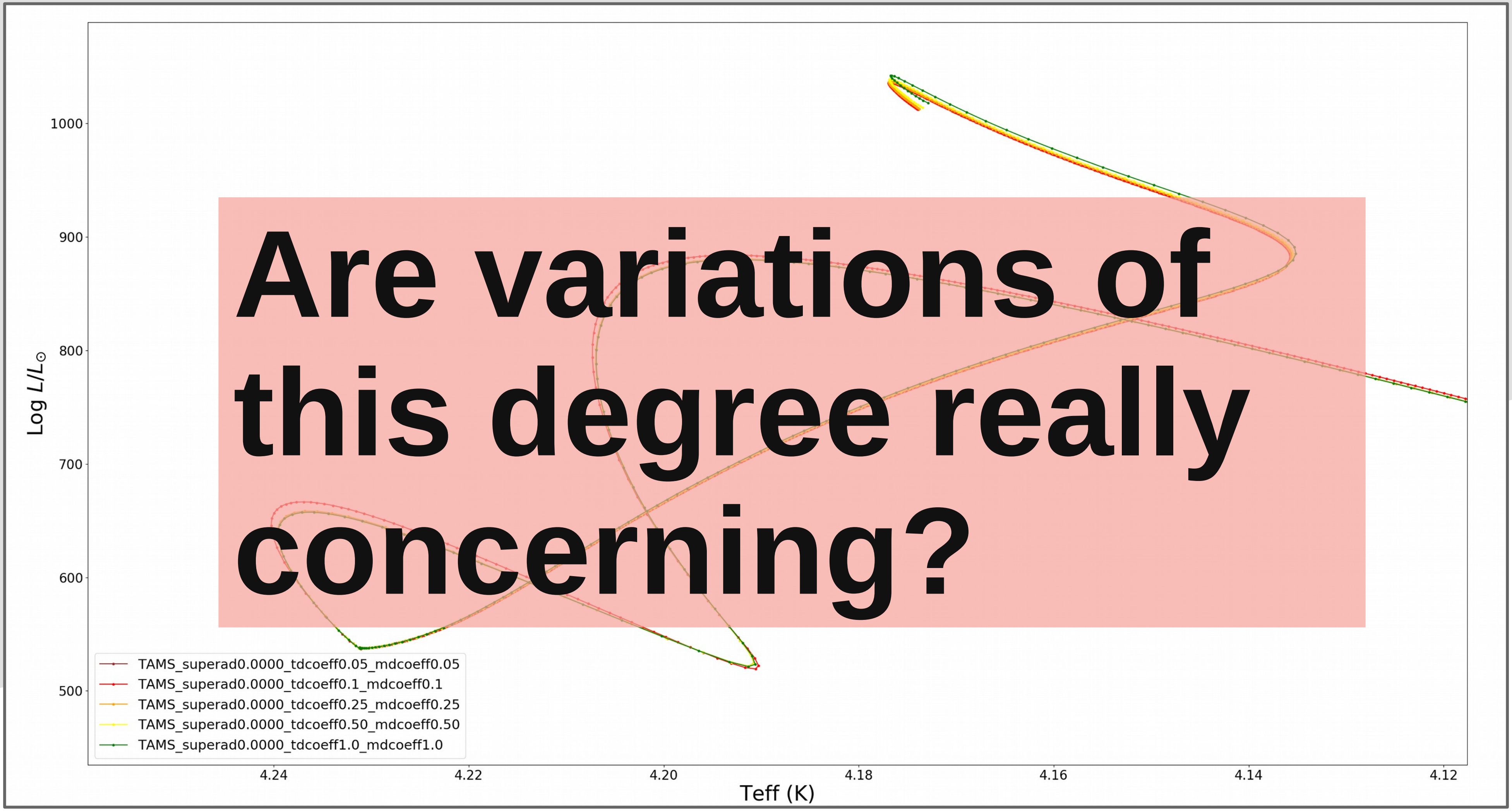
what is *numerical*?

An insidious, overlooked threat: resolution-dependent results



Convergence studies 2021, MESA developers, unpublished

An insidious, overlooked threat: resolution-dependent results



Are variations of this degree really concerning?

Convergence studies 2021, MESA developers, unpublished

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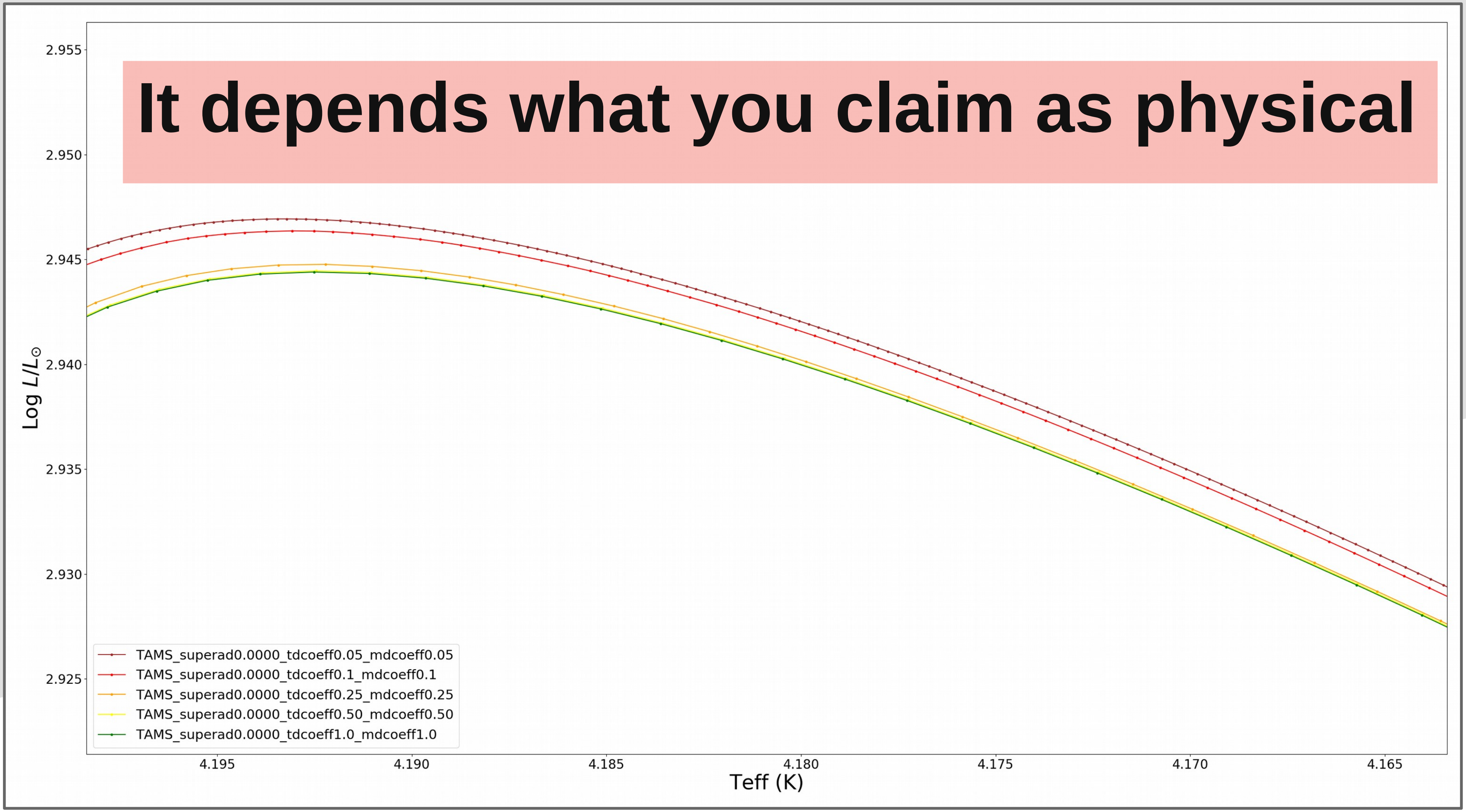

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If the former, which solar abundances are the opacities based on?

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To make matters worse, diffusion, convection, and boundary conditions are interconnected in degenerate ways

Isochrones, *Gaia* benchmarks, globular clusters & the mixing length

HD 140283 & M92

Not All Stars are the Sun: Empirical Calibration of the Mixing Length for Metal-Poor stars using 1D Stellar Evolution Models

Meridith Joyce & Brian Chaboyer
ApJ, *Feb* 2018

MLT calibrations: the typical approach

Steps:

(1) Find the optimal mixing length value α_{MLT} for a model of the Sun under the desired physcal prescription by trial-and-error until the Sun's observables have been reproduced to high precision

Reason: the Sun is the best constrained of any star!

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Obvious Problem: Not all stars are the Sun*!

(*title of Joyce & Chaboyer 2018a)

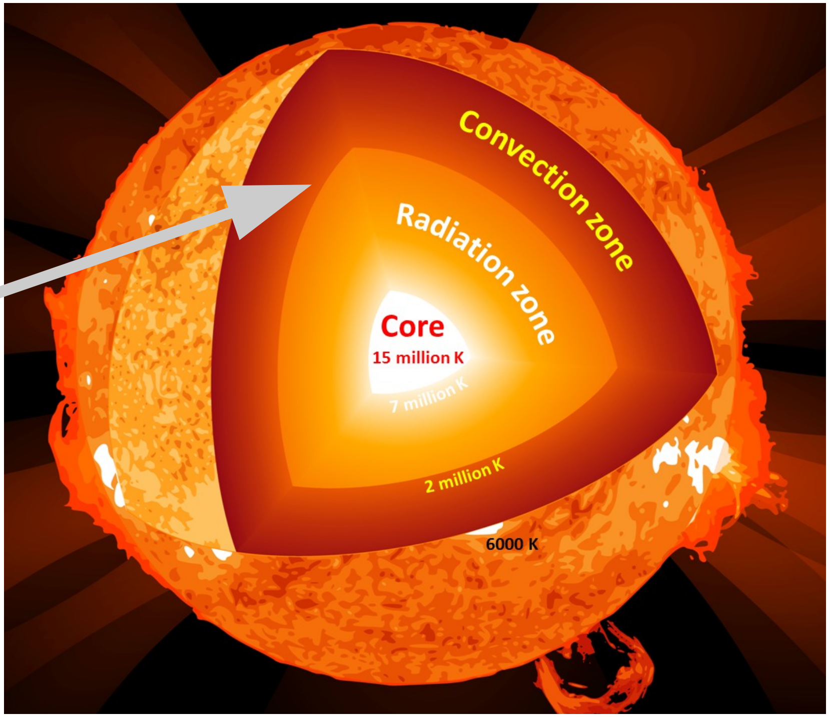
MLT calibrations

a pathway for mitigating modeling issues for **ideal** systems

Solution: Calibrate α_{MLT} to other stars, quantify the differences

Calibrate here:

- low mass stars (0.5 – 1.4 Ms)
- sub-surface convective envelope
- main sequence, subgiant, or early RGB

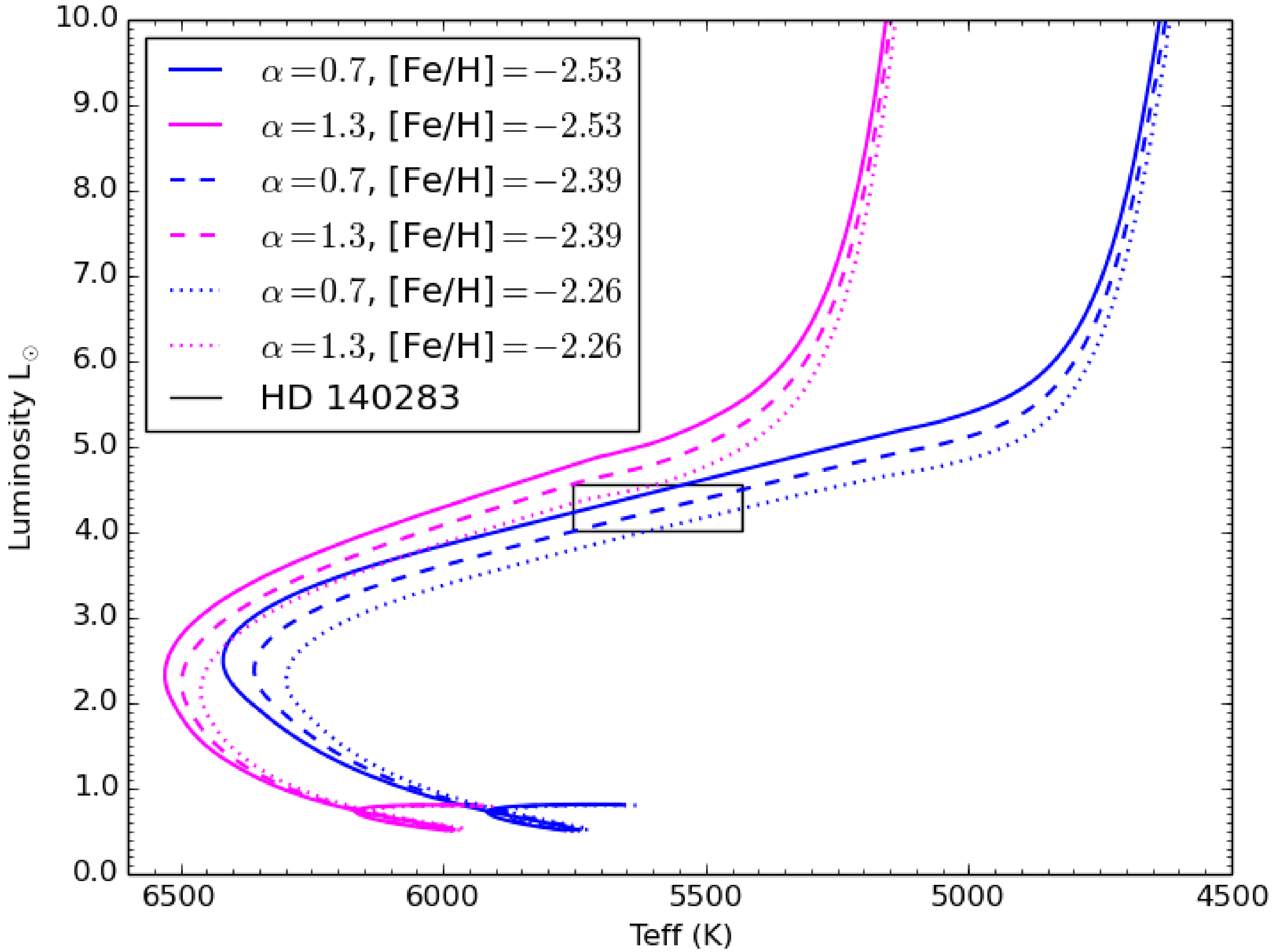


Two separate science questions:

(1) How does α_{MLT} vary among stars with different global properties?

(2) How does α_{MLT} change within a single star's evolution?

HD 140283: the notorious **mass—mixing length—metallicity degeneracy** can be disentangled if a star is sufficiently well constrained and in the right part of the HR diagram



(Joyce & Chaboyer, 2018a)

Fitting the metal-poor globular cluster M92:

Changing the mixing length in constituent tracks deeply affects the structure of an isochrone model

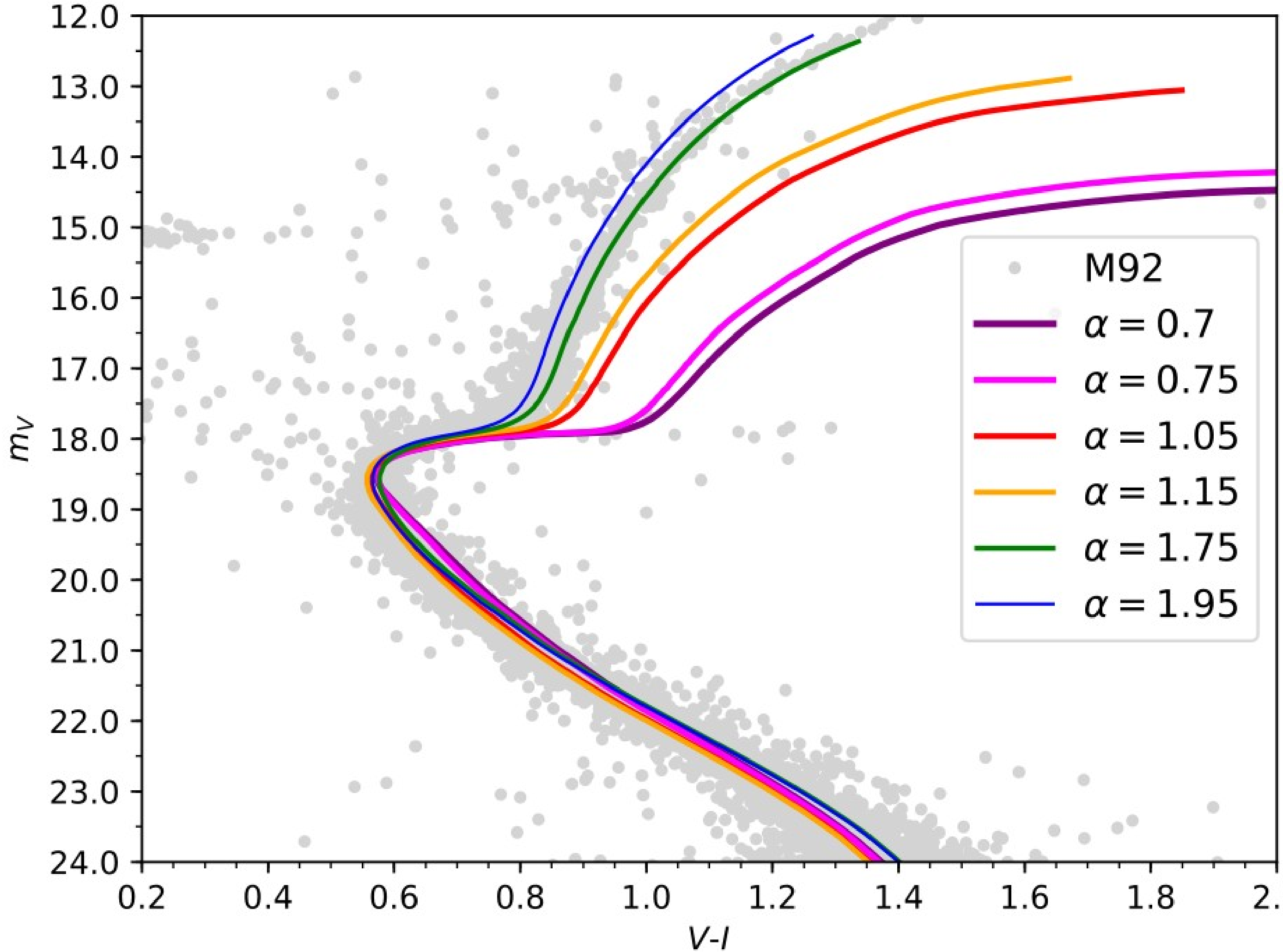


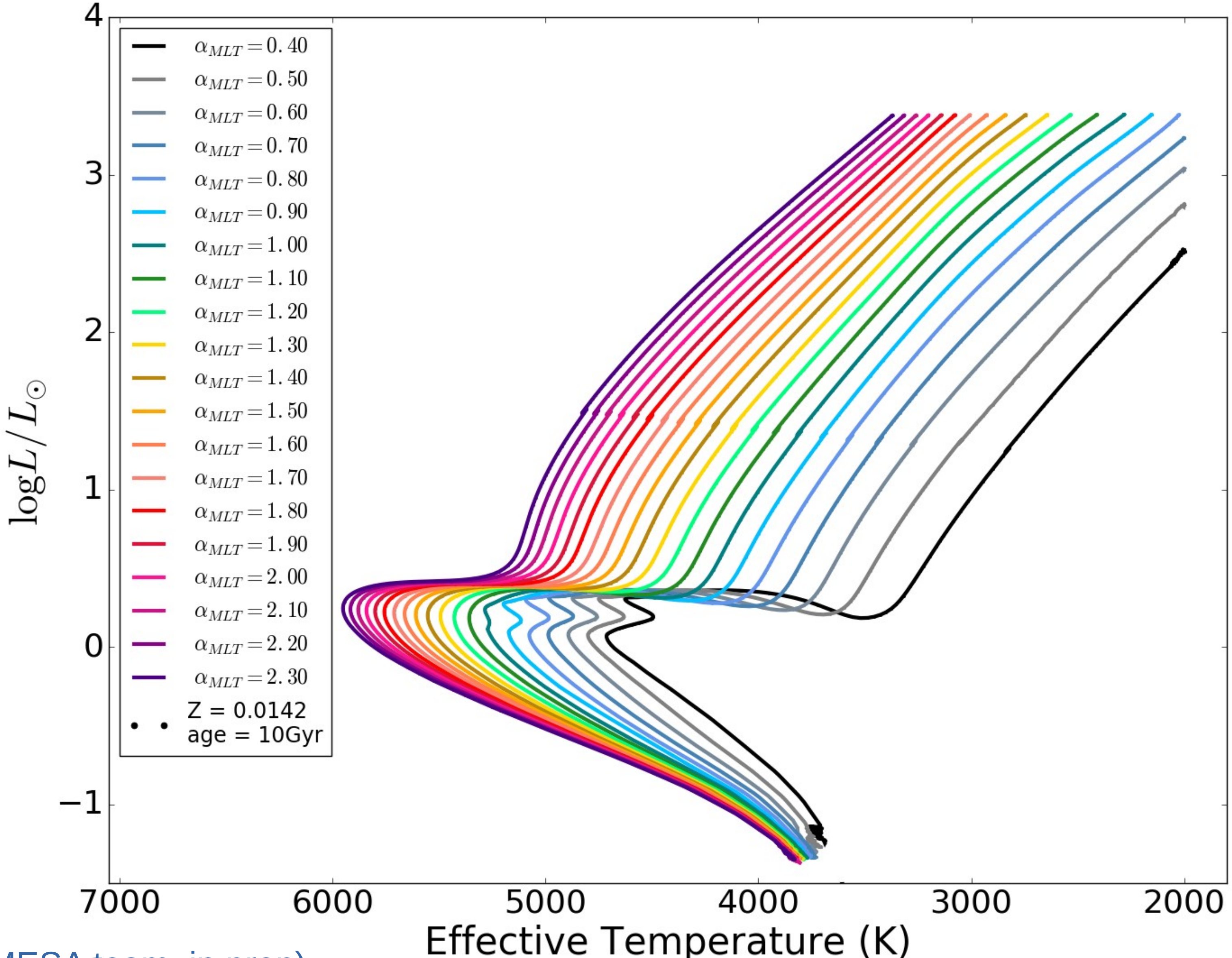
Figure 5. Six isochrones, each of age 13 Gyr, generated with different mixing lengths and shown against M92 for reference. Each isochrone in the figure

(Joyce & Chaboyer, 2018a)

MLT-adapted isochrones: the 2021 update

The **precision of model-derived ages** is often **drastically overstated;** not enough effort is put toward quantifying the effects of parameter assumptions

Figure 1: a set of isochrones, each having the same assumption for metallicity but computed with different mixing length values, as indicated on the legend.



(Joyce + MESA team, in prep)

Using seismic parameters to calibrate the convective mixing length in highly constrained systems

α Centauri A & B

Classically and Asteroseismically Constrained 1D Stellar Evolution Models of Alpha Centauri A and B Using Empirical Mixing Length Calibrations

Meridith Joyce & Brian Chaboyer
ApJ, Sept 2018

What makes alpha Cen the perfect lab for stellar modeling?

> The number of independent measurements

Independent measurements remove degrees of freedom and isolate the mixing length parameter

Mass – kinematics

Radius – interferometry

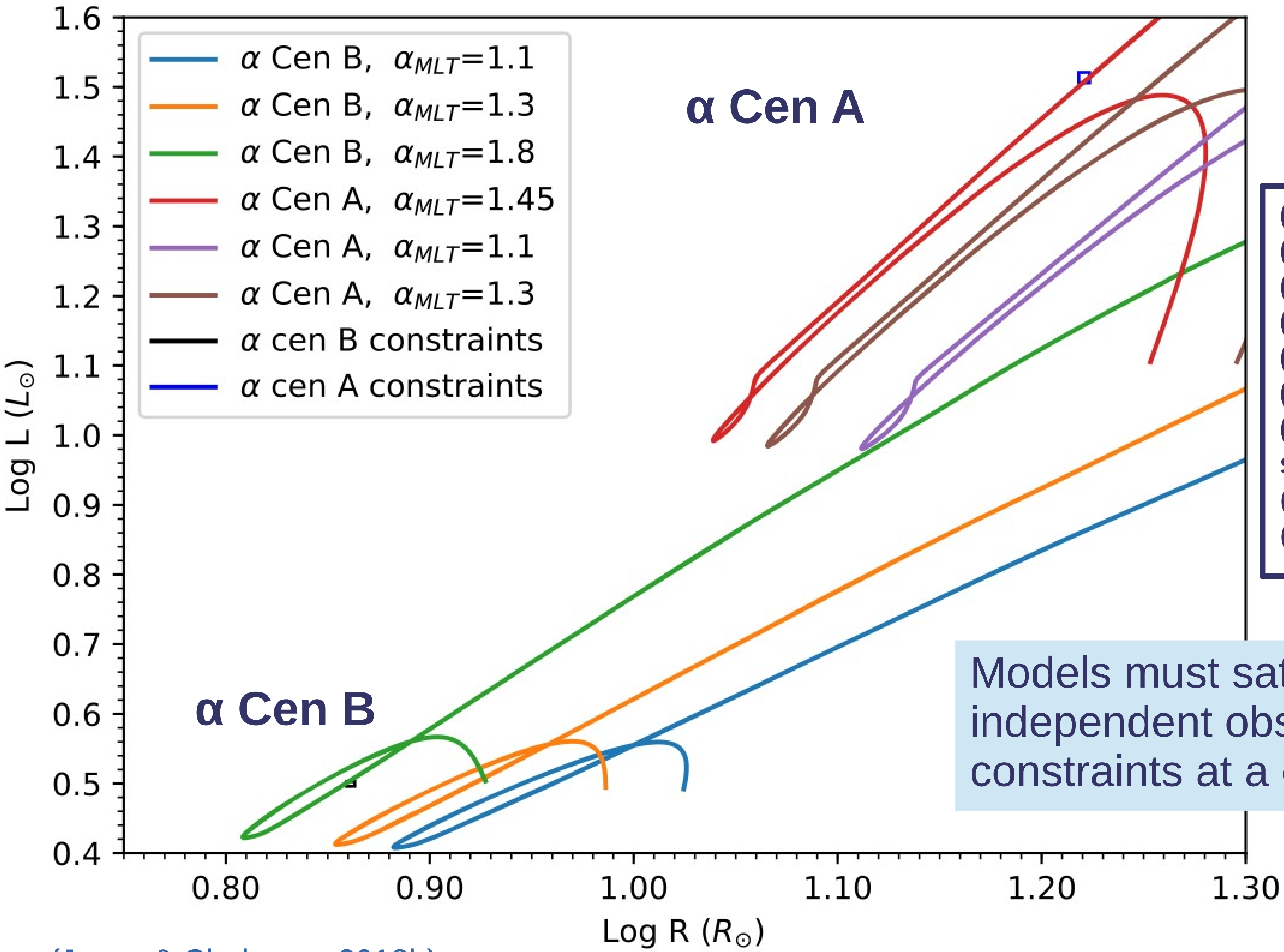
Luminosity – photometry

Surface abundance – high resolution spectroscopy

Stellar interior constraints from seismology

IF the candidate is a binary with all classical measurements satisfied in both components --> free, prior-independent age constraint!

Classical optimization to α Centauri



(1) Mass A
(2) Mass B
(3) Radius A
(4) Radius B
(5) Luminosity A
(6) Luminosity B
(7) Common surface Z/X
(8) r02 A
(9) r02 B

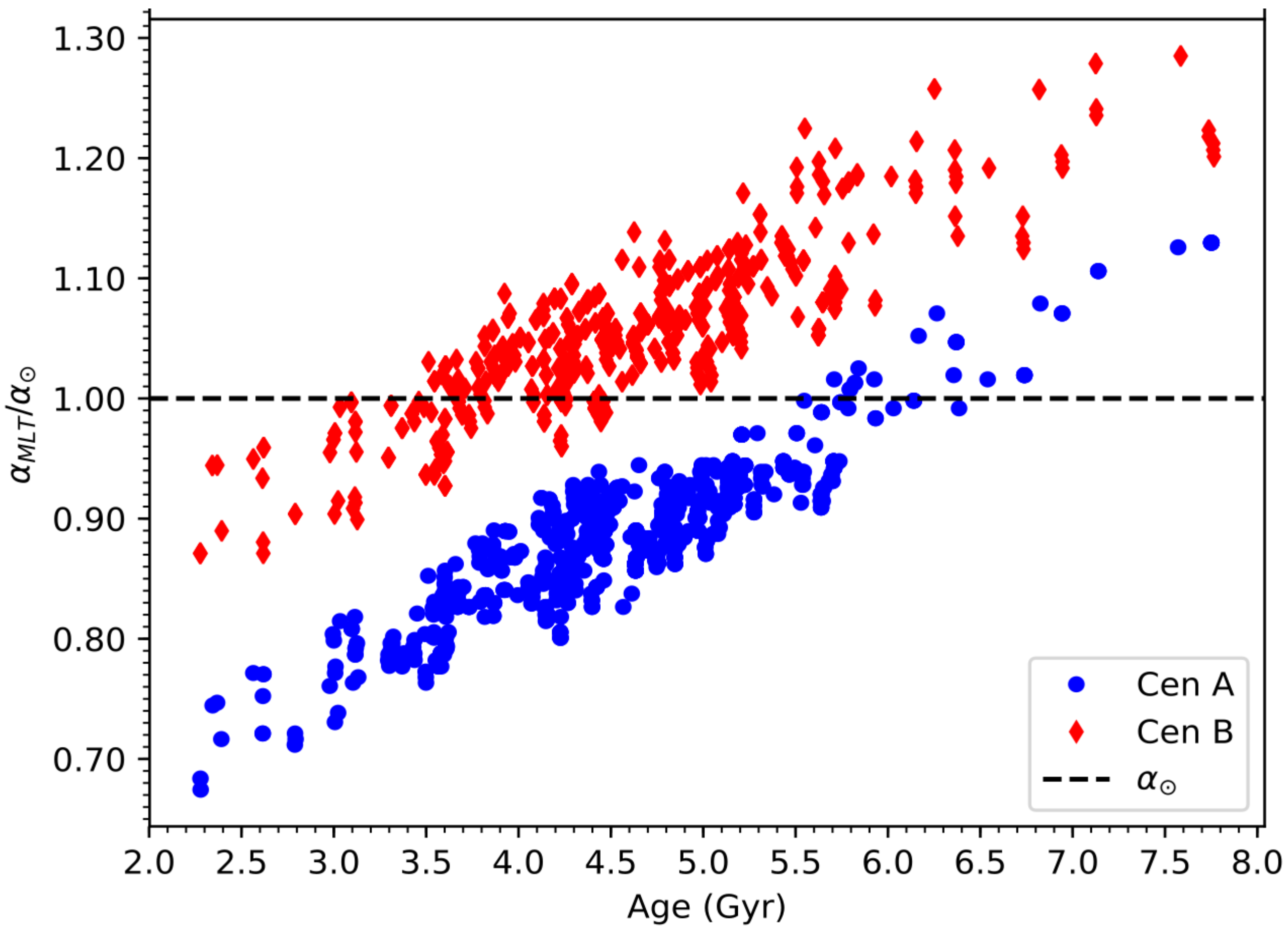
Models must satisfy 7 of 9 independent observational constraints at a common age

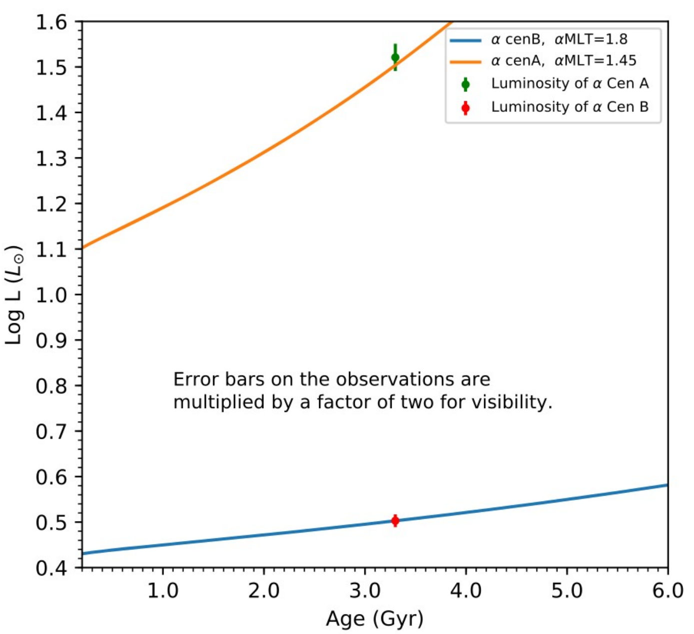
(Joyce & Chaboyer, 2018b)

Classical optimization to α Centauri

$$s^2_{\text{classic}} = \left[\frac{R_{\text{A,obs}} - R_{\text{A,mod}}}{\sigma_{R_{\text{A,obs}}}}\right]^2 + \left[\frac{R_{\text{B,obs}} - R_{\text{B,mod}}}{\sigma_{R_{\text{B,obs}}}}\right]^2 + \left[\frac{L_{\text{A,obs}} - L_{\text{A,mod}}}{\sigma_{L_{\text{A,obs}}}}\right]^2 + \left[\frac{L_{\text{B,obs}} - L_{\text{B,mod}}}{\sigma_{L_{\text{B,obs}}}}\right]^2 + \left[\frac{Z/X_{\text{obs}} - Z/X_{\text{mod}}}{\sigma_{Z/X_{\text{obs}}}}\right]^2$$

Using an agreement statistic comprising 7 classical conditions and a common age, we see a clear bifurcation in α_{MLT}: it is always larger for α Cen B than for α Cen A



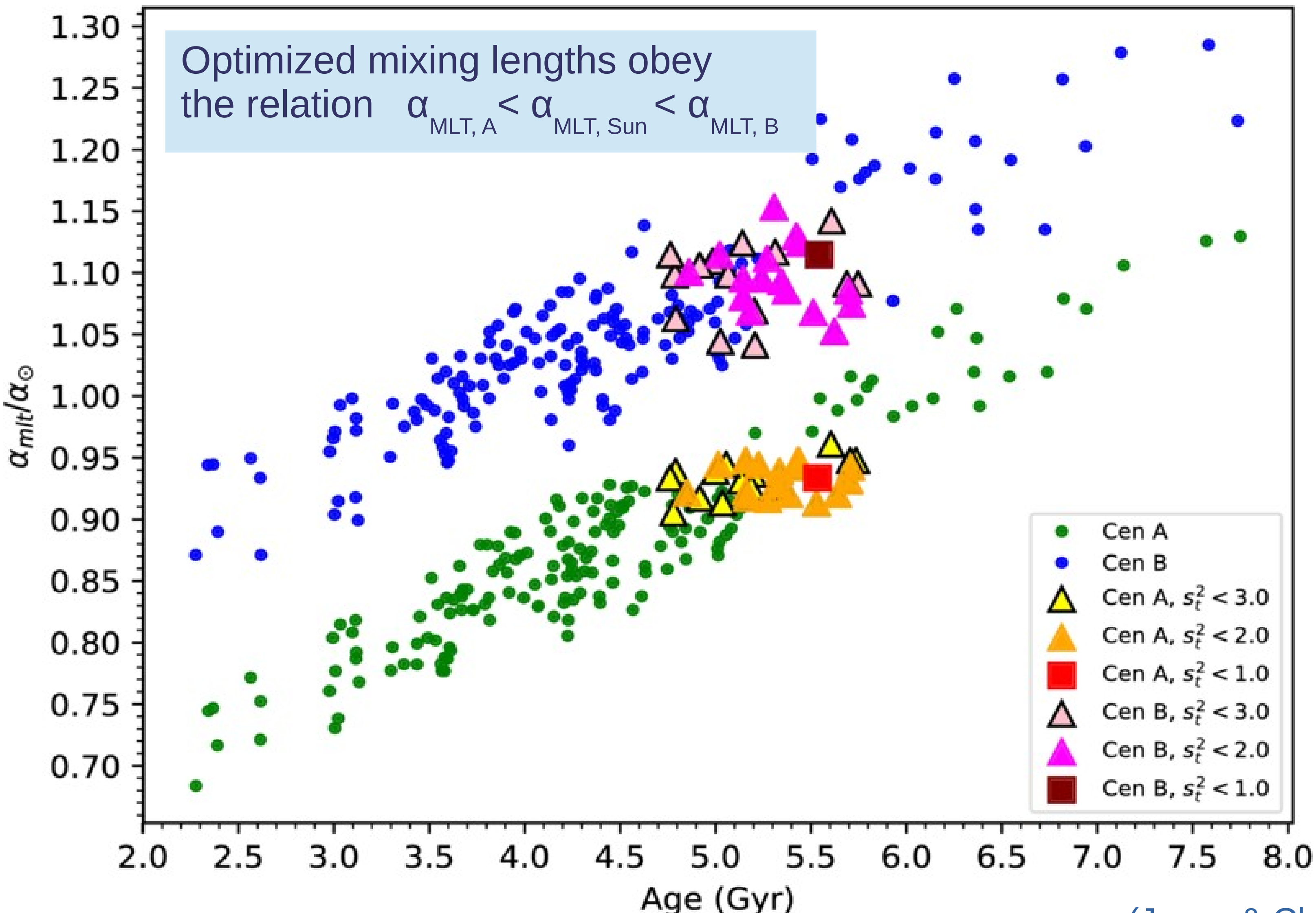


$$s^2_{\text{binary}} = \left[\frac{\tau_A - \tau_B}{5\,\text{Myr}}\right]^2 + \left[\frac{Y_A - Y_B}{0.005}\right]^2 + \left[\frac{Z_A - Z_B}{0.0005}\right]^2$$

(Joyce & Chaboyer, 2018b)

With the addition of asteroseismology...

-refined fundamental parameters of α Centauri A & B
- independent age estimation
-empirical calibration of the mixing length for two non-solar stars



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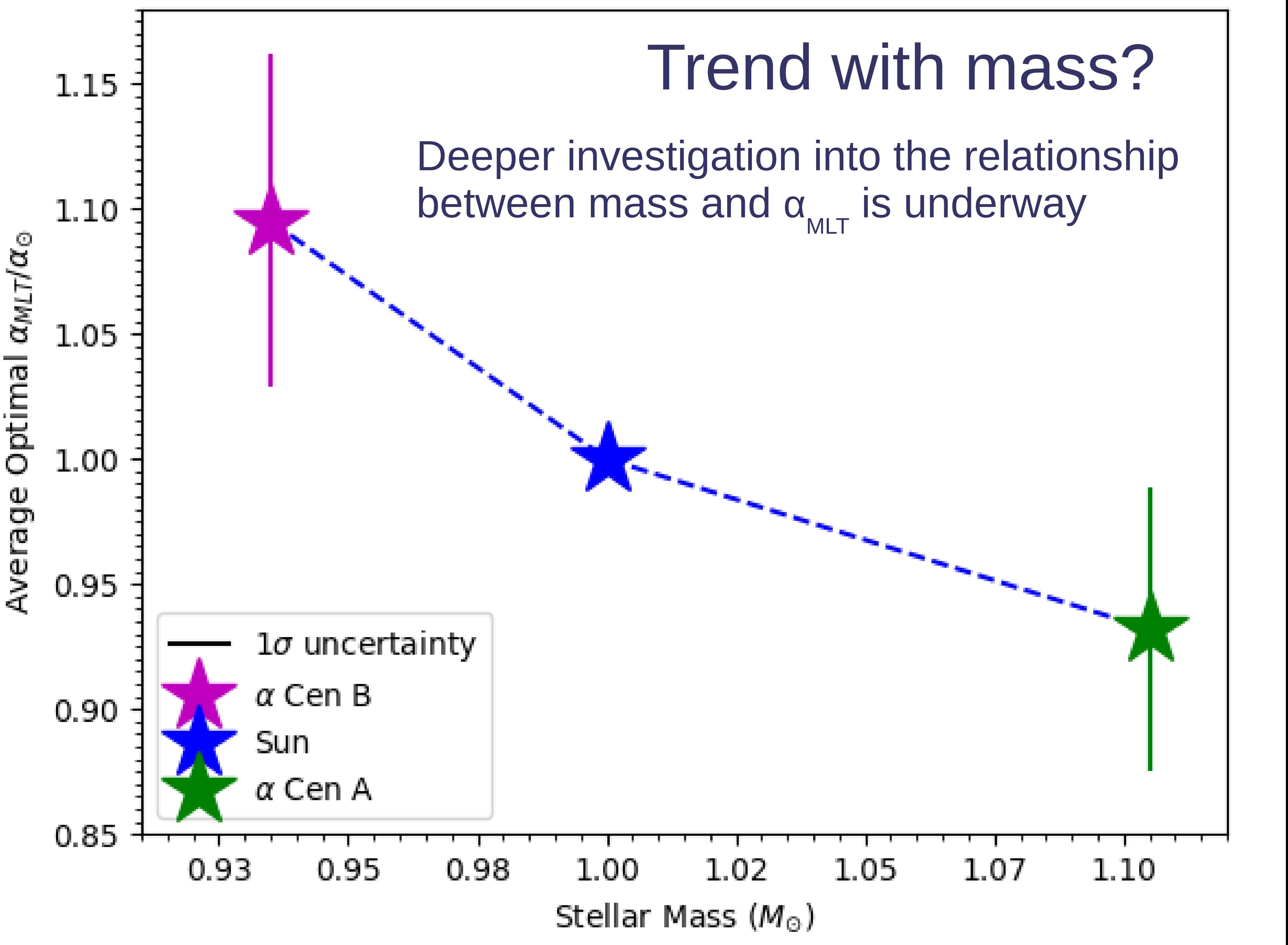

Trend with mass?
Deeper investigation into the relationship between mass and α_{MLT} is underway
Average Optimal $\alpha_{MLT}/\alpha_{\odot}$
Stellar Mass ($M_{\odot}$)
1σ uncertainty
α Cen B
Sun
α Cen A
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.93
0.95
0.98
1.00
1.02
1.05
1.07
1.10

What else can we do?

My repertoire of techniques for parameter determination and stellar chronology is applicable to a broad array of objects...

Betelgeuse

Alpha Centauri A & B

The TP-AGB star T Ursae Minoris

Gaia benchmark star HD 140283

M92 & other metal-poor globular clusters

Pre-main sequence, protoplanetary disc-host HD 139614

Subjects of my other case studies

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Why it matters:

In some way, your science likely relies on the **ages** and **distances** of stars

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- Alpha Centauri A & B
- The TP-AGB star T Ursae Minoris
- *Gaia* benchmark star HD 140283
- M92 & other metal-poor globular clusters
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