Young stars in the Galactic bulge?
A mystery explored using modern isochrones, careful statistics, and model uncertainties

Seminar
Uppsala Universitet
13 October, 2022

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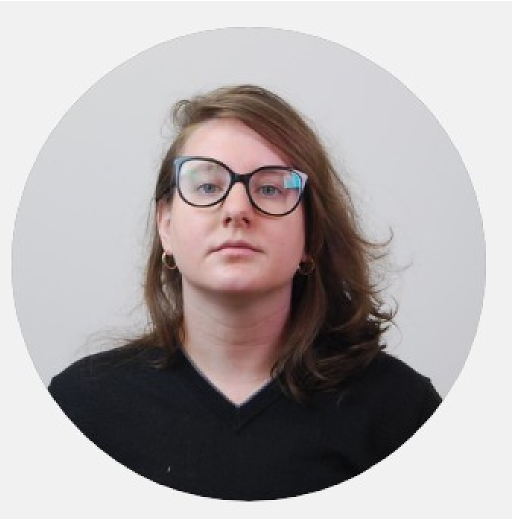
Dr Meridith Joyce*

Marie Curie Widening Fellow: MATISSE
CSFK Konkoly Observatory, Budapest
MESA Developers

About Me:

I have enjoyed work and life all over the world, and now I've joined you in Europe!



MATISSE: Measuring Ages Through Isochrones, Seismology, and Stellar Evolution

Timeline of Project	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
WP1—Asteroseismic dating								
Stage 1: Understanding MESA systematics		M1	WP1.1					
Stage 2: Identification, characterization of seismic targets								
Stage 3: MLT calibrations to seismic binaries, etc.						WP1.2		
Stage 4: Implementation of empirical convective formalism								WP1.3
WP2—Isochrone dating								
Stage 1: Building the MISTiC database	WP2.1							
Stage 2: Applying MISTiC to *Gaia* GCs			M2	WP2.2				
Stage 3: Applying MISTiC to special stars				WP2.3				
WP3: Characterizing high-mass variables								
Secondment: KU Leuven					KUL			
Stage 1: Enrichment timescales from TP-AGB stars							WP3.1	
Stage 2: Evolutionary dating with chemical yields						M3		
Conferences, workshops, press releases	R			Mesa, C	R		PR	Mesa, PR, C

Key: WP work package; WP X.Y science deliverable Y for WP X; M milestone; Q quarter of the annual (3 months)

The MESA developers team

(**M**odules for **E**xperiments in **S**tellar **A**strophysics)


Josiah Schwab


Adam Jermyn


Meridith Joyce

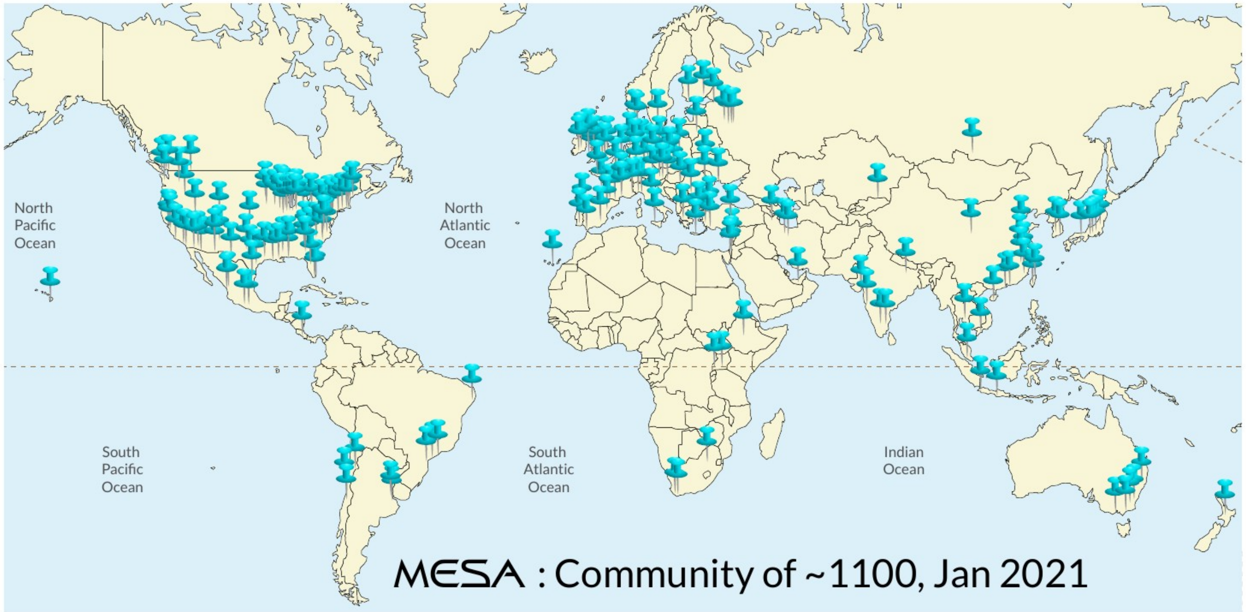

Evan Bauer


Earl Bellinger


Anne Thoul


Radek Smolec


Rob Farmer




Bill Wolf


Pablo Marchant


Warrick Ball


Aaron Dotter


Rich Townsend


Frank Timmes


Bill Paxton


Lars Bildsten


Matteo Cantiello

The project I will discuss today was done in collaboration with

Dr Christian Johnson (STScI)

Dr Tommaso Marchetti (ESO)

and

Prof R Michael Rich (UCLA)

Dr Iulia Simion (Shanghai Key Lab for Astrophysics)

Dr John Bourke (MSP Berkeley)

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Chemical evolution of the Galactic bulge as traced by microlensed dwarf and subgiant stars

VI. Age and abundance structure of the stellar populations in the central sub-kpc of the Milky Way[⋆,⋆⋆]

T. Bensby[1], S. Feltzing[1], A. Gould[2,3,4], J. C. Yee[5], J. A. Johnson[4], M. Asplund[6], J. Meléndez[7], S. Lucatello[8], L. M. Howes[1], A. McWilliam[9], A. Udalski[10,⋆⋆⋆], M. K. Szymański[10,⋆⋆⋆], I. Soszyński[10,⋆⋆⋆], R. Poleski[10,4,⋆⋆⋆], Ł. Wyrzykowski[10,⋆⋆⋆], K. Ulaczyk[10,11,⋆⋆⋆], S. Kozłowski[10,⋆⋆⋆], P. Pietrukowicz[10,⋆⋆⋆], J. Skowron[10,⋆⋆⋆], P. Mróz[10,⋆⋆⋆], M. Pawlak[10,⋆⋆⋆], F. Abe[12,⋆⋆⋆⋆], Y. Asakura[12,⋆⋆⋆⋆], A. Bhattacharya[13,⋆⋆⋆⋆], I. A. Bond[14,⋆⋆⋆⋆], D. P. Bennett[15,⋆⋆⋆⋆], Y. Hirao[16,⋆⋆⋆⋆], M. Nagakane[16,⋆⋆⋆⋆], N. Koshimoto[16,⋆⋆⋆⋆], T. Sumi[16,⋆⋆⋆⋆], D. Suzuki[15,⋆⋆⋆⋆], and P. J. Tristram[17,⋆⋆⋆⋆]

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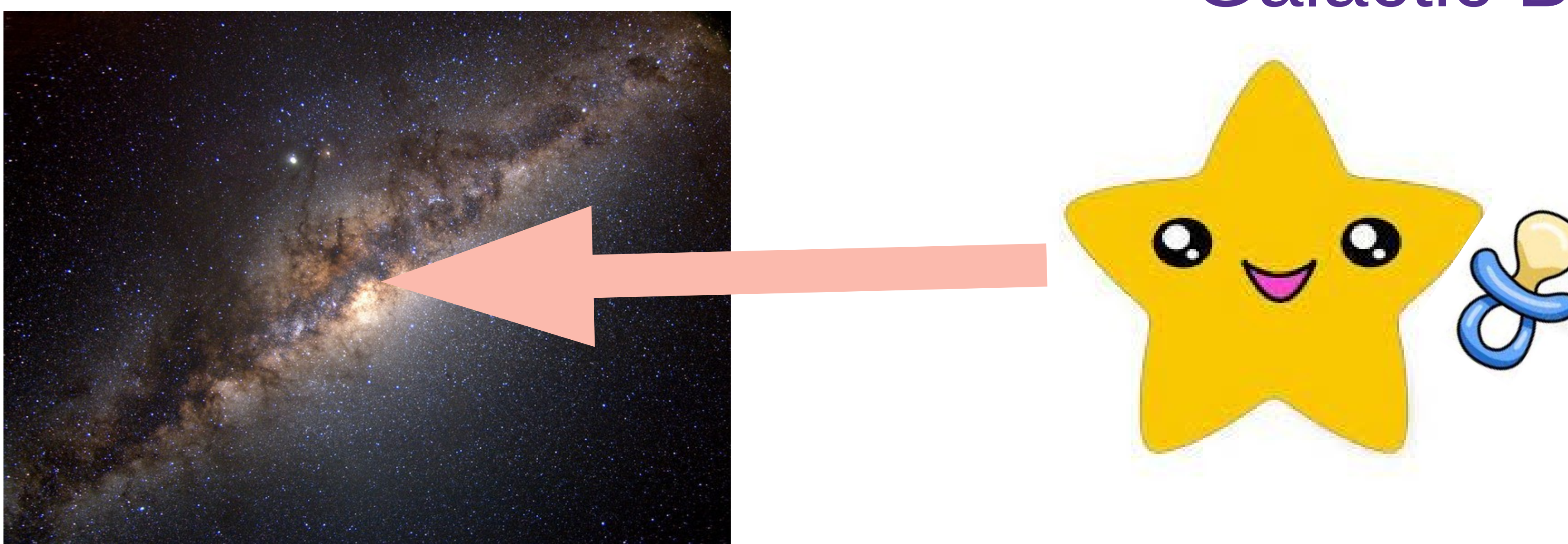

Young stars in the Galactic bulge?

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Basically, prolonged star formation.

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- an overabundance of young stars in this region thus calls into question the formation history of the Galaxy and galaxy evolution mechanisms more generally

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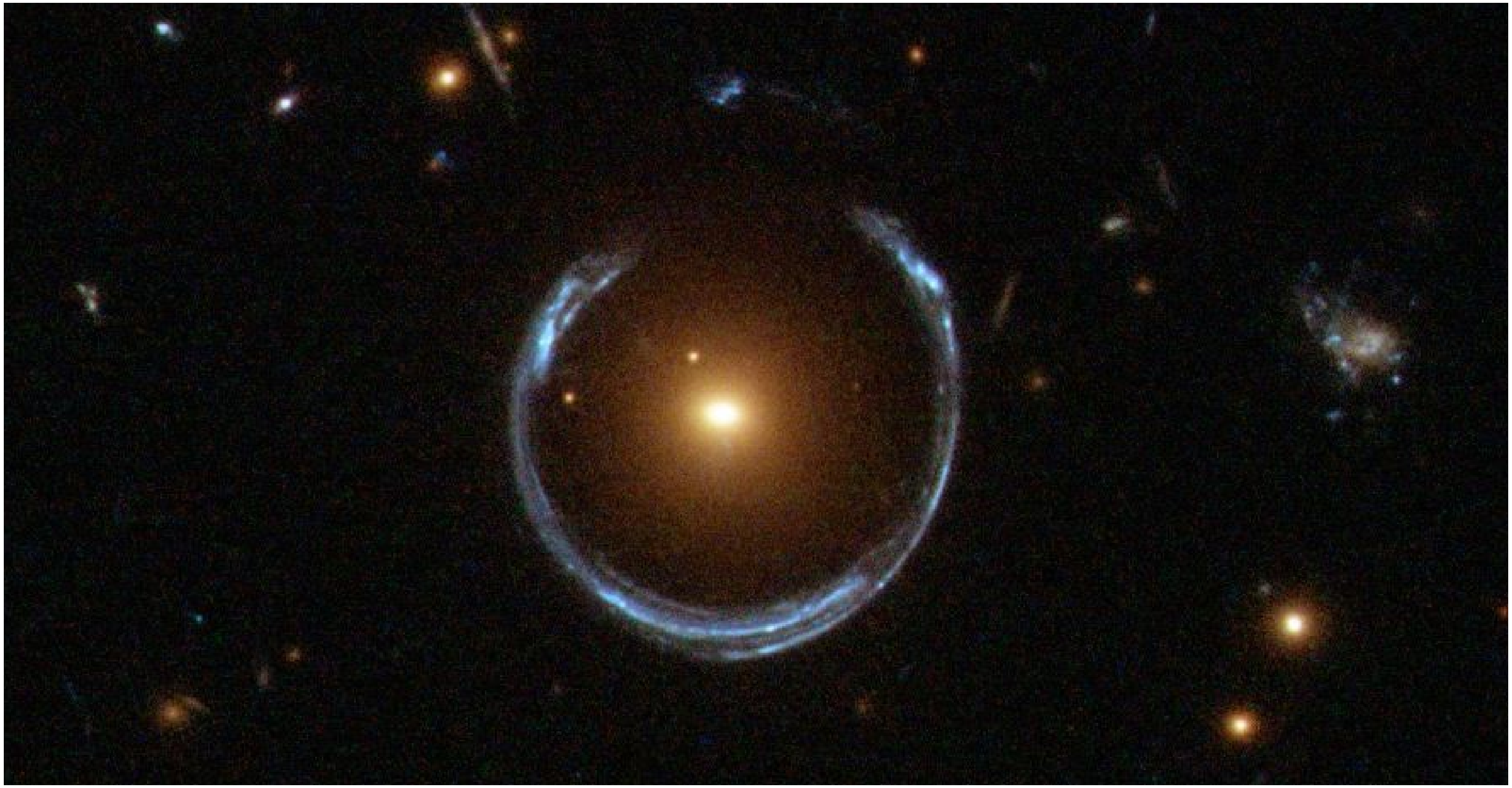
...and ages derived from **microlensing (spectroscopy)**, which claims a **broad age distribution**

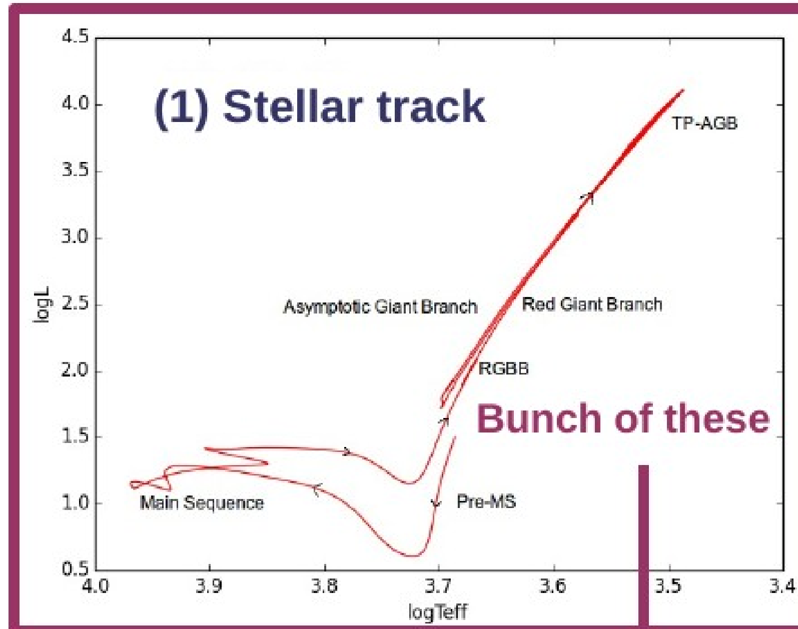
...but in order for something to be true, it must be true regardless of inference method

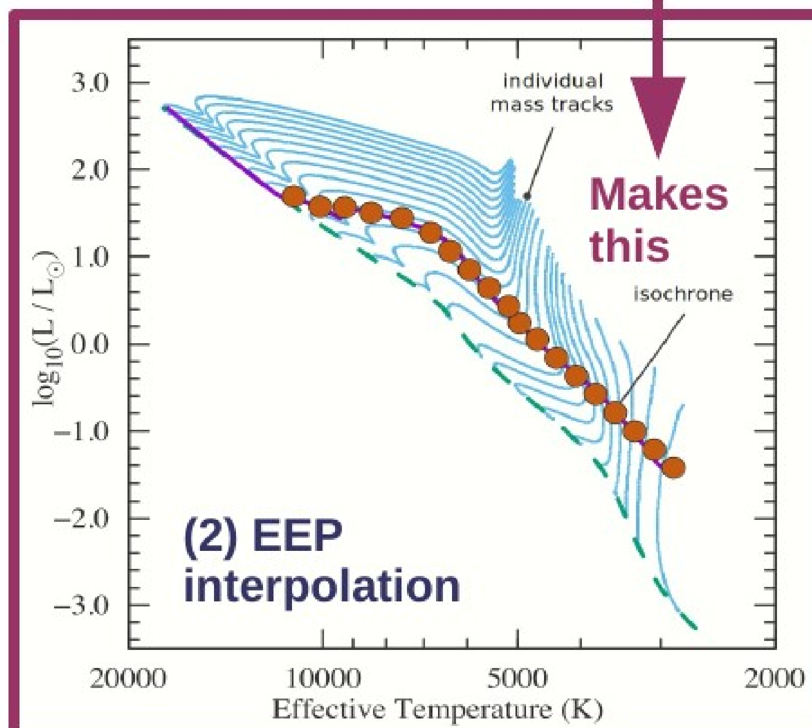
A rare and powerful dataset

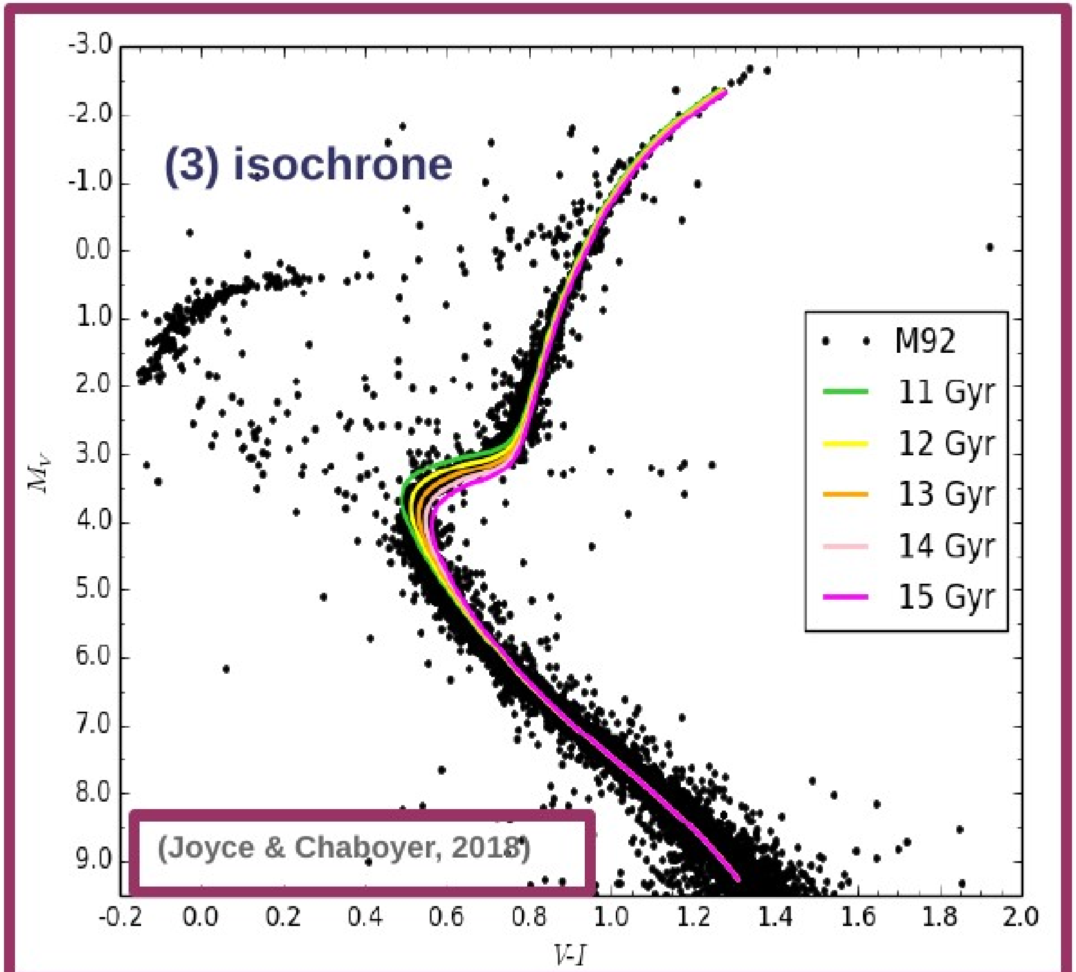
Microlensing permits the direct inference of physical, spectroscopic coordinates (Teff, logg) of faint, cool stars due to the 10-1000x brightness magnification they experience during these events



Isochrone review



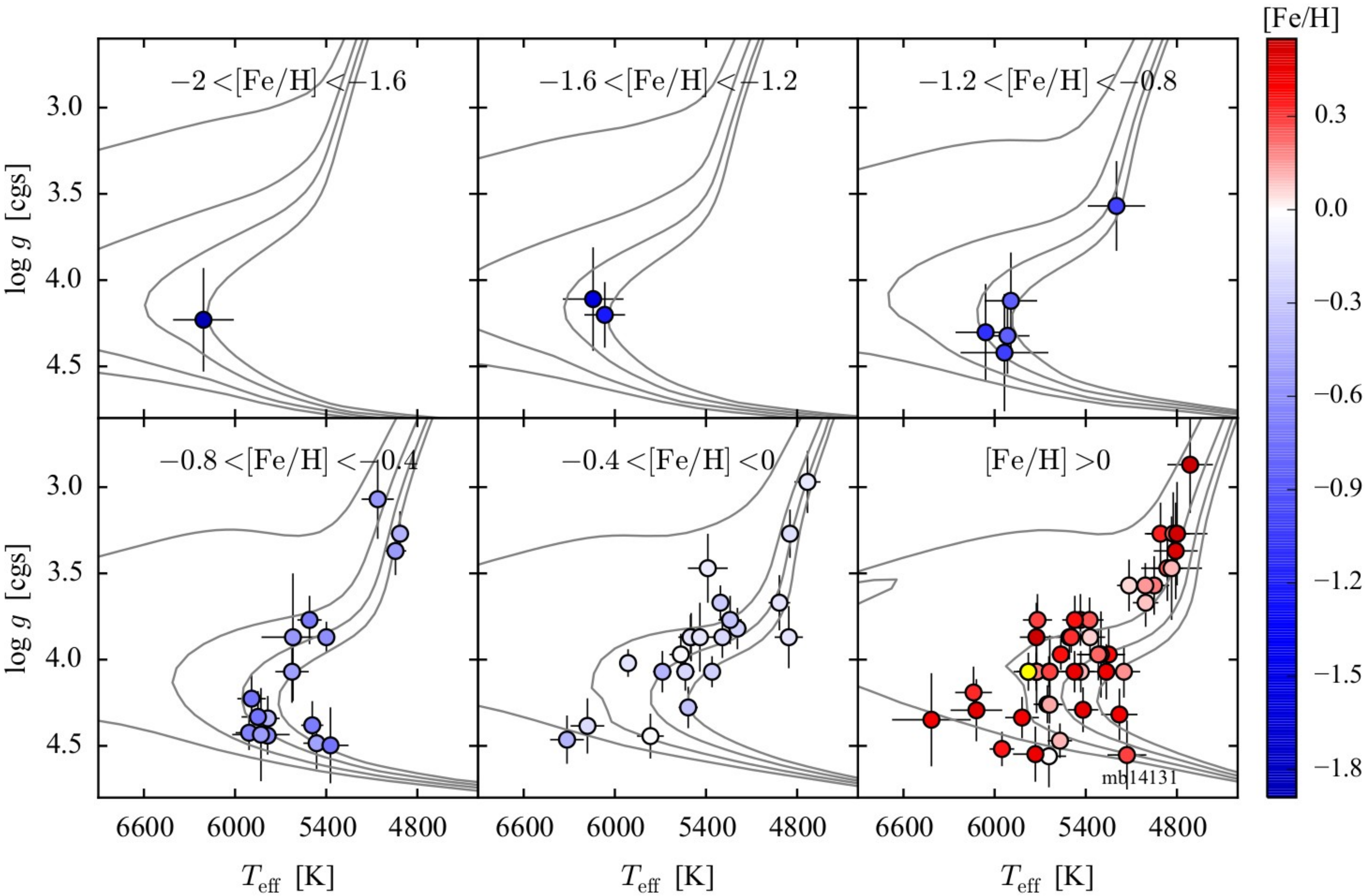




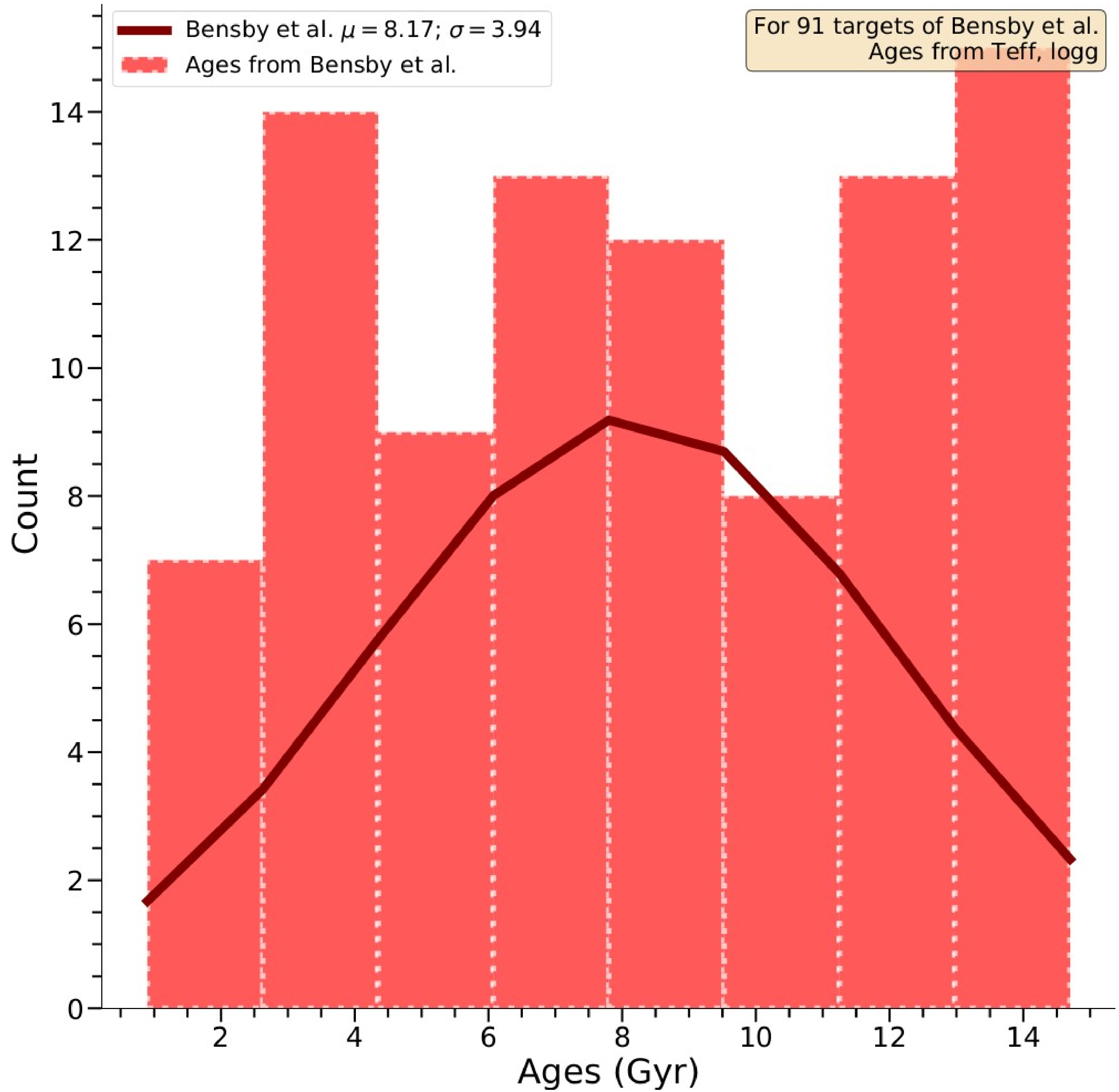
Derive fundamental parameters for both individual stars and stellar populations

Credit :Greg Feiden

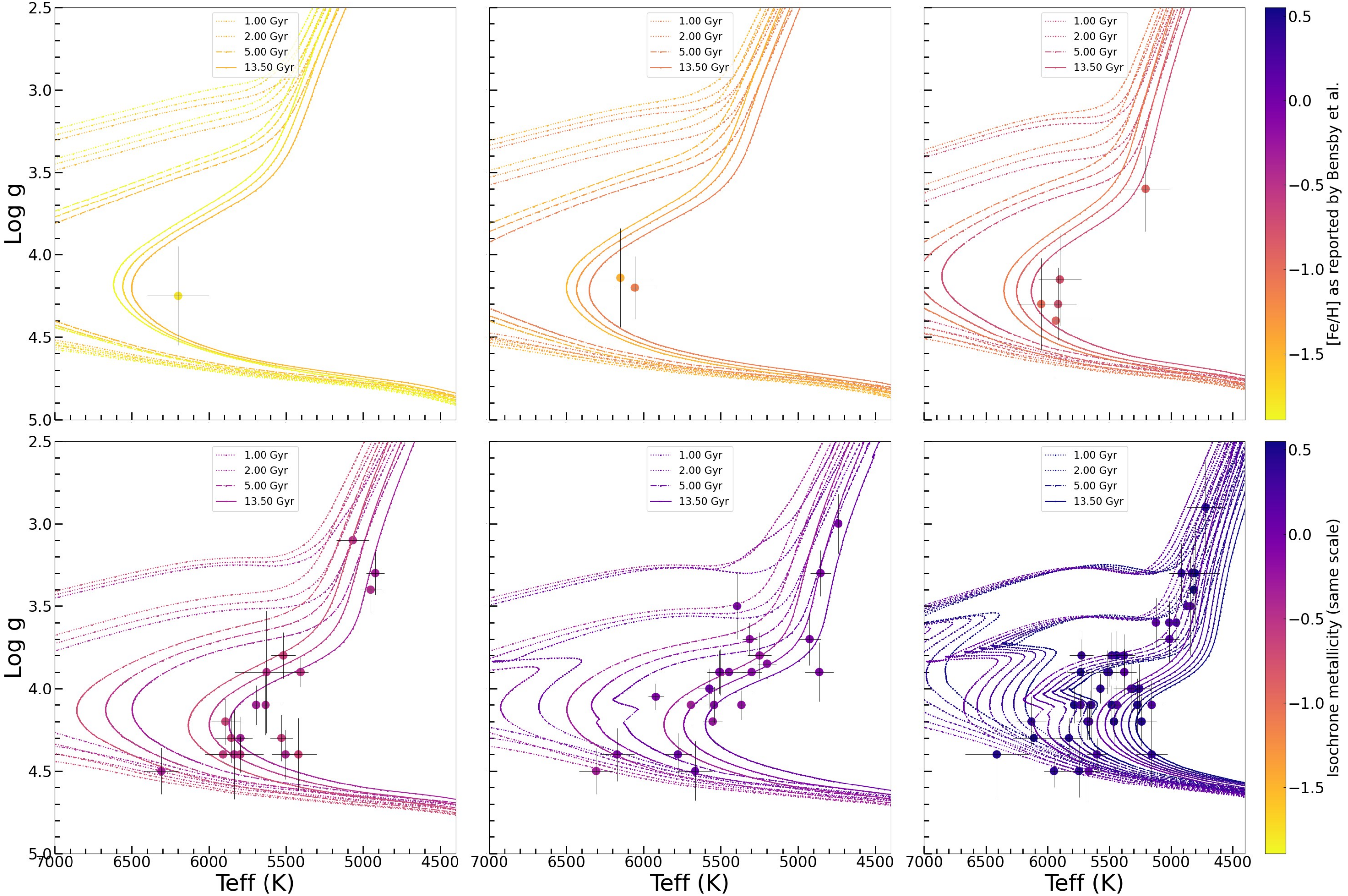
Fig 6, Bensby et al. 2017: 91 stars on Yale isochrones



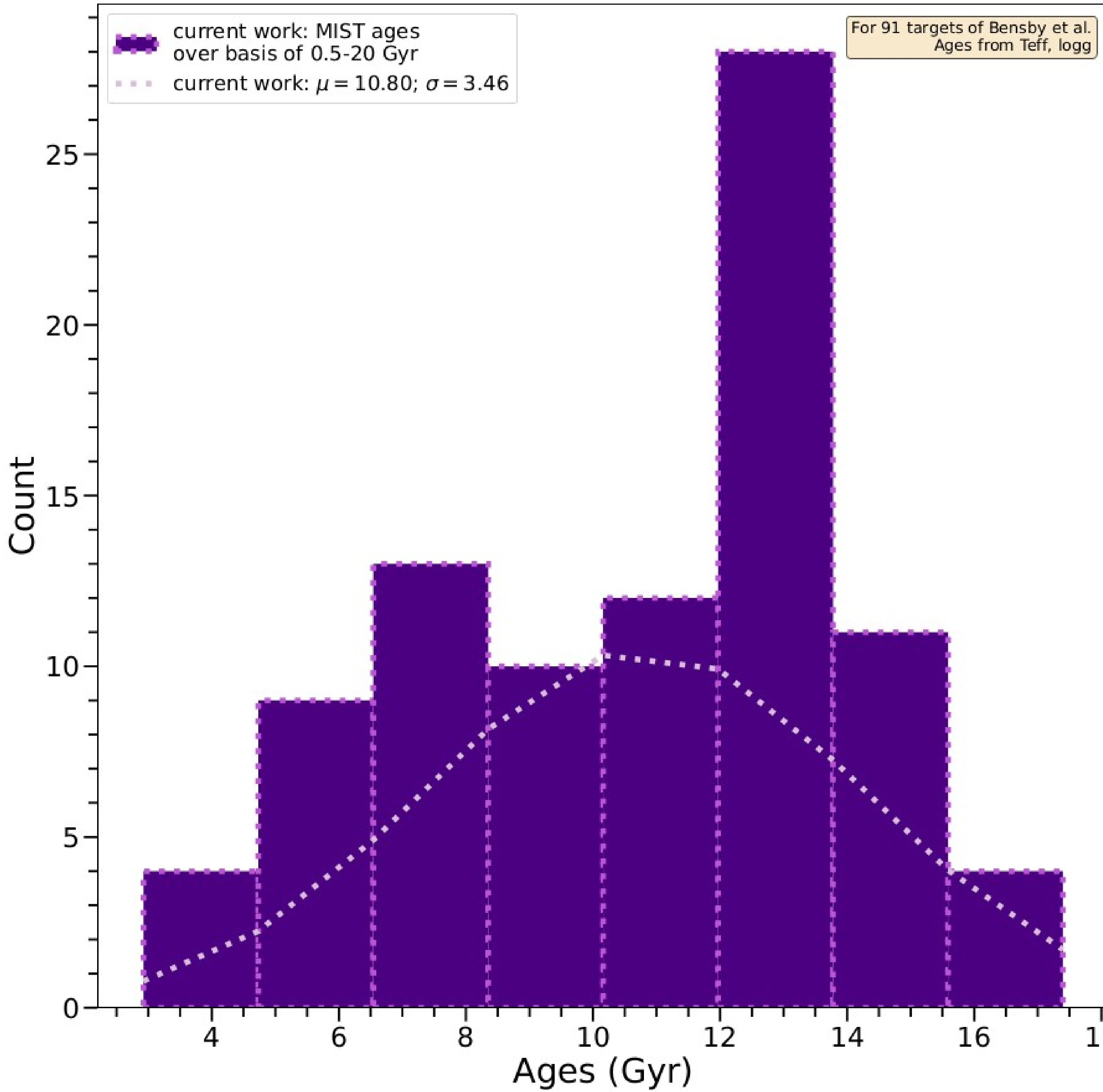
Resulting age distribution (Bensby et al.; Yale)



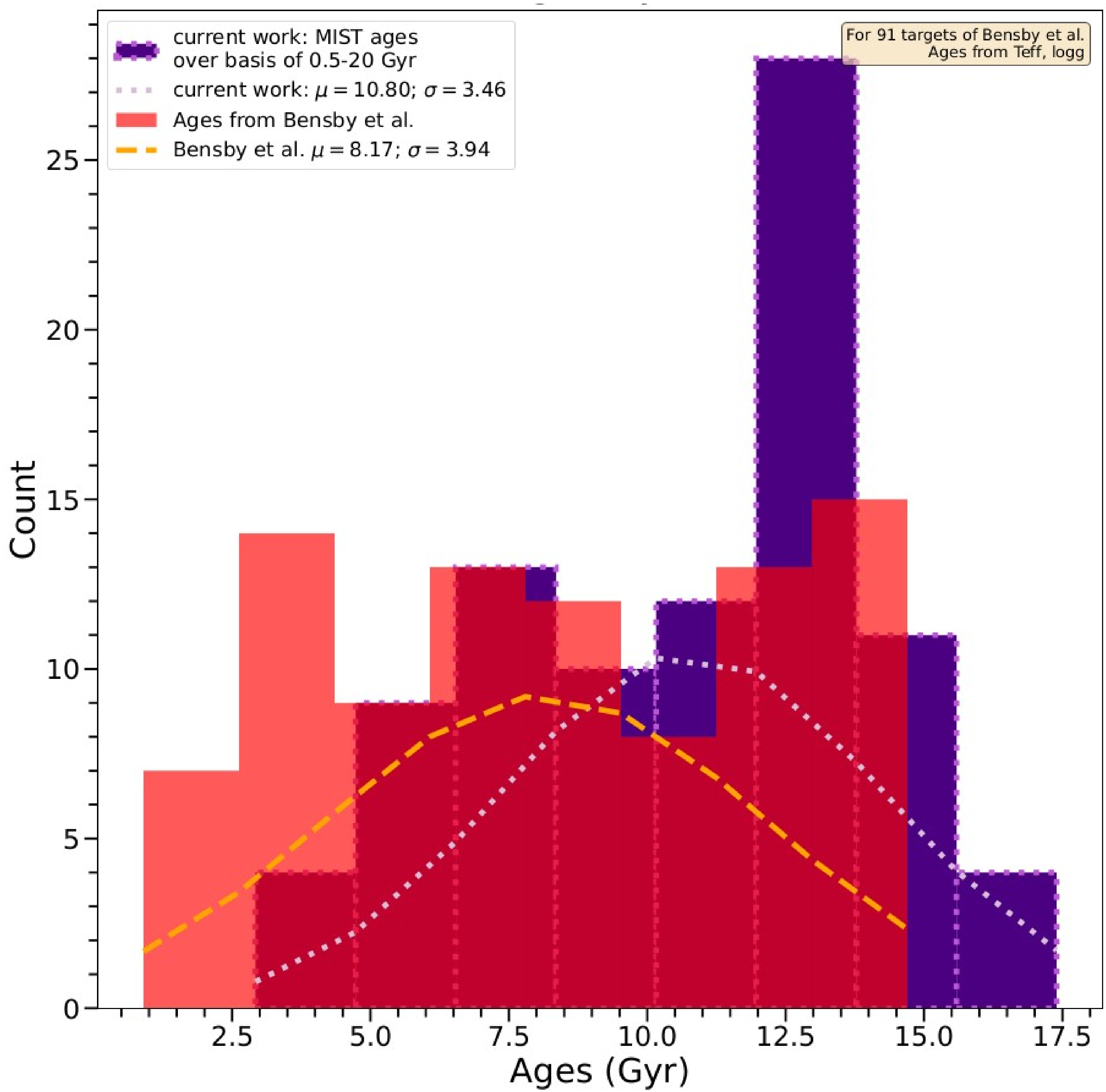
Reproduction with MIST isochrones

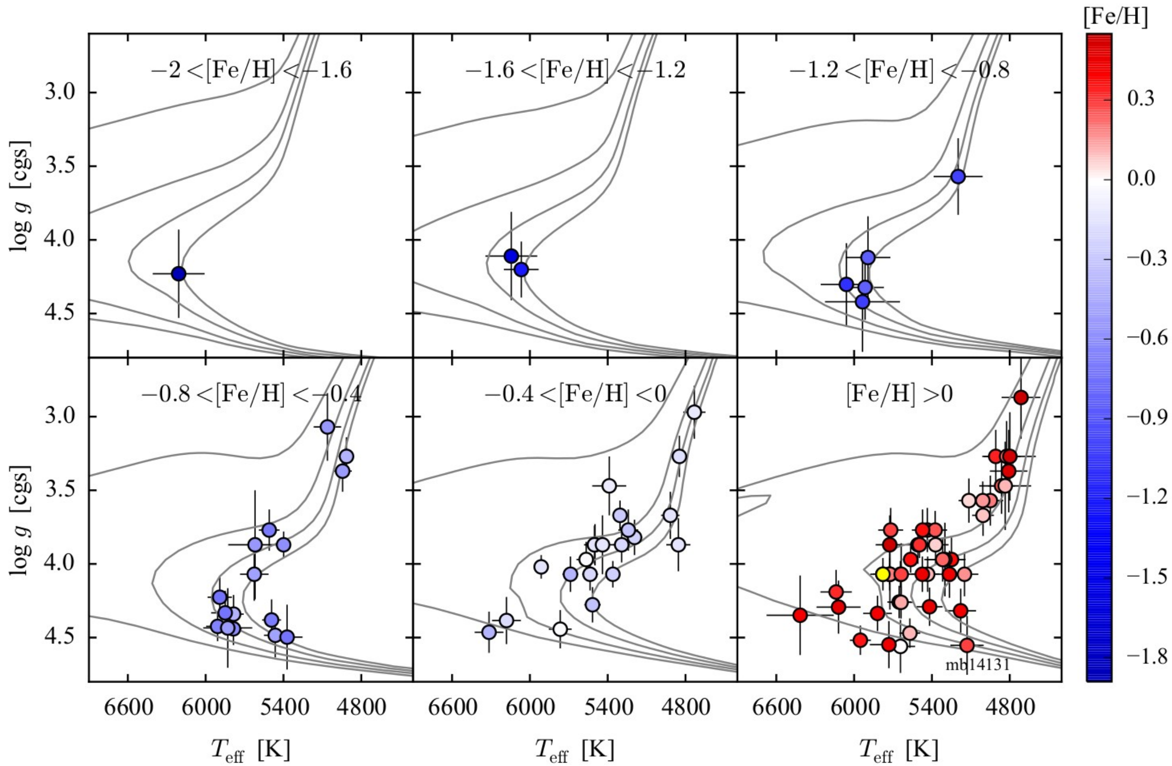


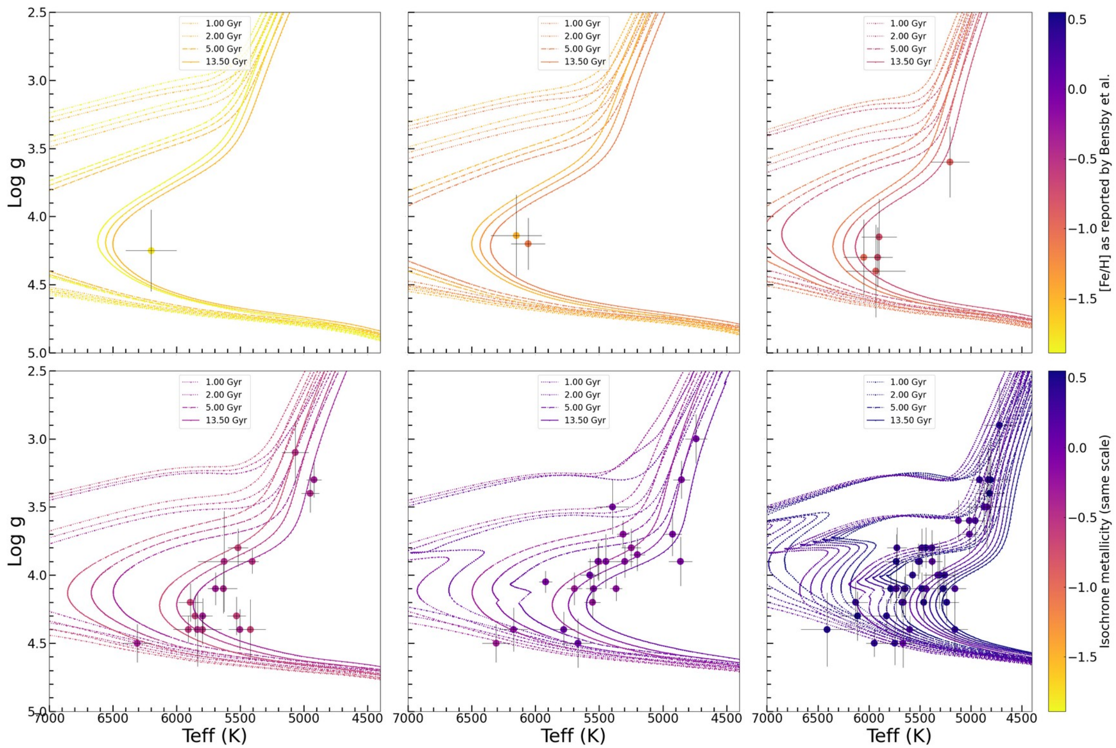
Resulting age distribution
(Joyce et al; MIST)



Distributions overlaid




[Fe/H]
$-2 < [Fe/H] < -1.6$
$-1.6 < [Fe/H] < -1.2$
$-1.2 < [Fe/H] < -0.8$
$-0.8 < [Fe/H] < -0.4$
$-0.4 < [Fe/H] < 0$
$[Fe/H] > 0$
mb14131
log g [cgs]
T_{eff} [K]
0.3
0.0
−0.3
−0.6
−0.9
−1.2
−1.5
−1.8


1.00 Gyr
2.00 Gyr
5.00 Gyr
13.50 Gyr
Log g
Teff (K)
[Fe/H] as reported by Bensby et al.
Isochrone metallicity (same scale)

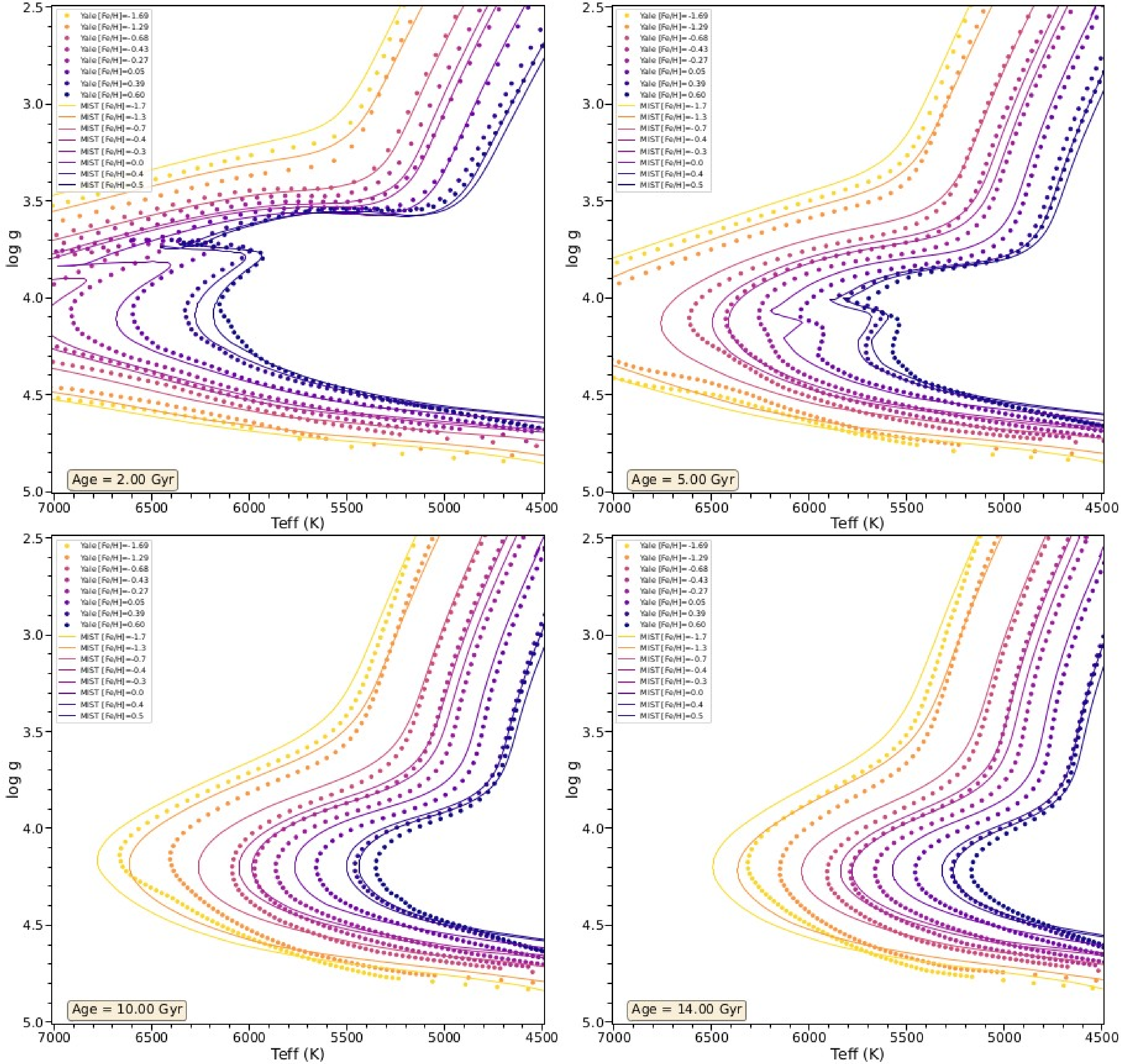

They're the same picture.

??

One could reasonably ask…

Is it because the MIST and Yale models use wildly different physics and therefore yield different ages?

Yale vs MIST



Yale [Fe/H]=-1.69
Yale [Fe/H]=-1.29
Yale [Fe/H]=-0.68
Yale [Fe/H]=-0.43
Yale [Fe/H]=-0.27
Yale [Fe/H]=0.05
Yale [Fe/H]=0.39
Yale [Fe/H]=0.60
MIST [Fe/H]=-1.7
MIST [Fe/H]=-1.3
MIST [Fe/H]=-0.7
MIST [Fe/H]=-0.4
MIST [Fe/H]=-0.3
MIST [Fe/H]=0.0
MIST [Fe/H]=0.4
MIST [Fe/H]=0.5
Age = 2.00 Gyr
Age = 5.00 Gyr
Age = 10.00 Gyr
Age = 14.00 Gyr
log g
Teff (K)
2.5
3.0
3.5
4.0
4.5
5.0
7000
6500
6000
5500
5000
4500

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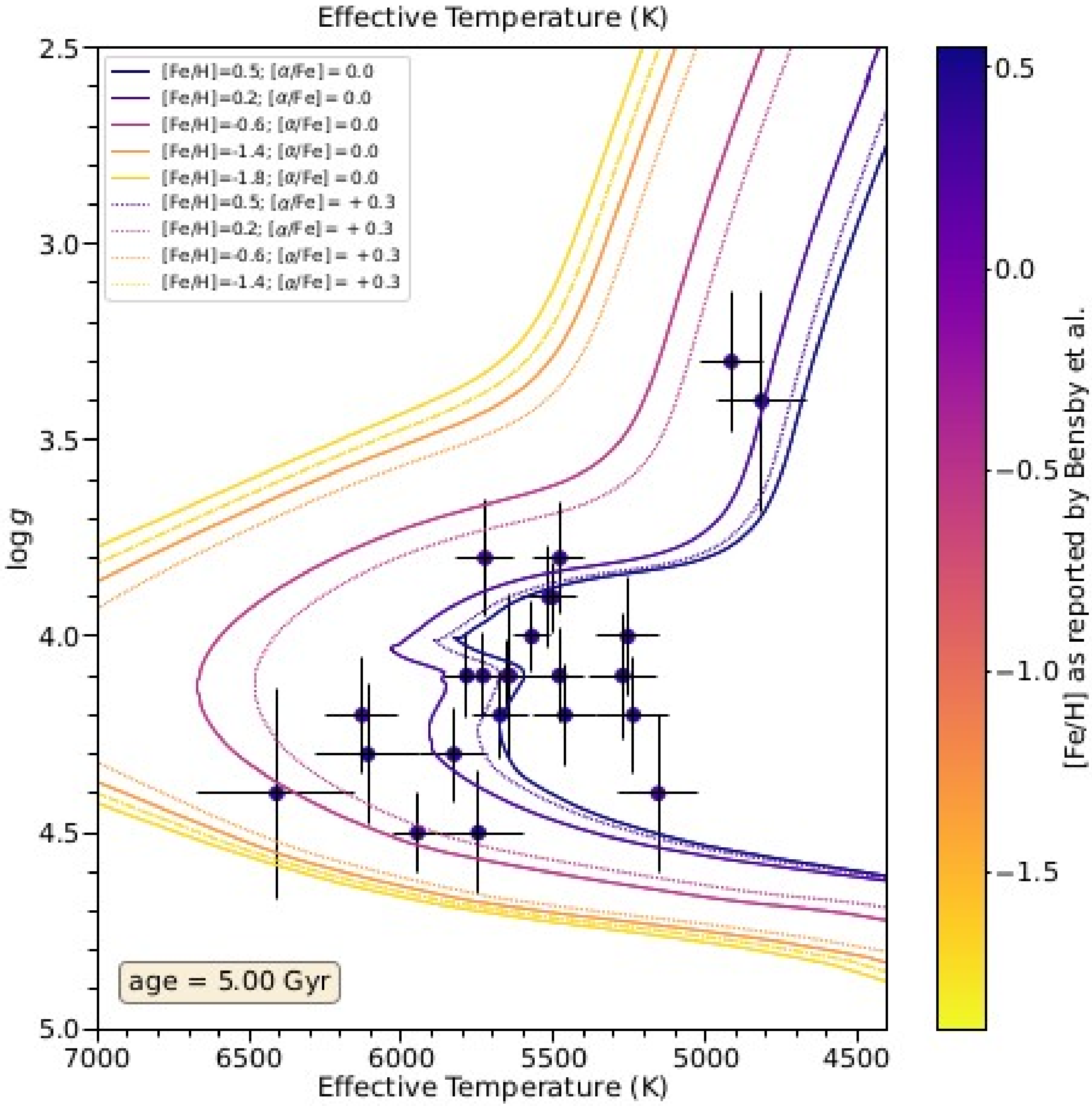
Is it because we consider alpha-element enhancement as a function of metallicity (Christian I. Johnson+, 2022) in the isochrones and the other age determinations do not?

Effects of alpha-element enhancement

Example: MIST neutral vs MIST alpha-scaled



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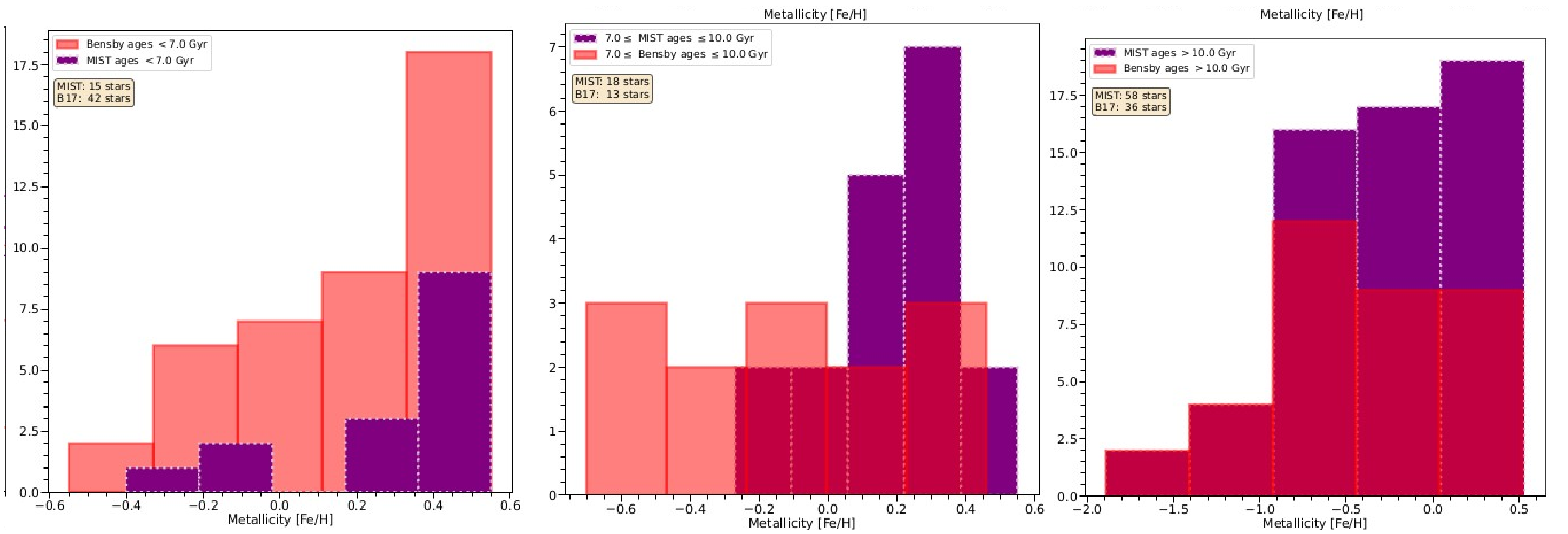
→ No

Is it because we consider alpha-element enhancement as a function of metallicity (Christian I. Johnson et al. 2022) in the isochrones and the other age determinations do not?

→ Also no

*see full paper (arXiv: 2205.07964) for rigorous demonstration of this using actual math & histograms

Punchline: we (Joyce + MIST) **do not** find an abundance of young stars at high metallicities



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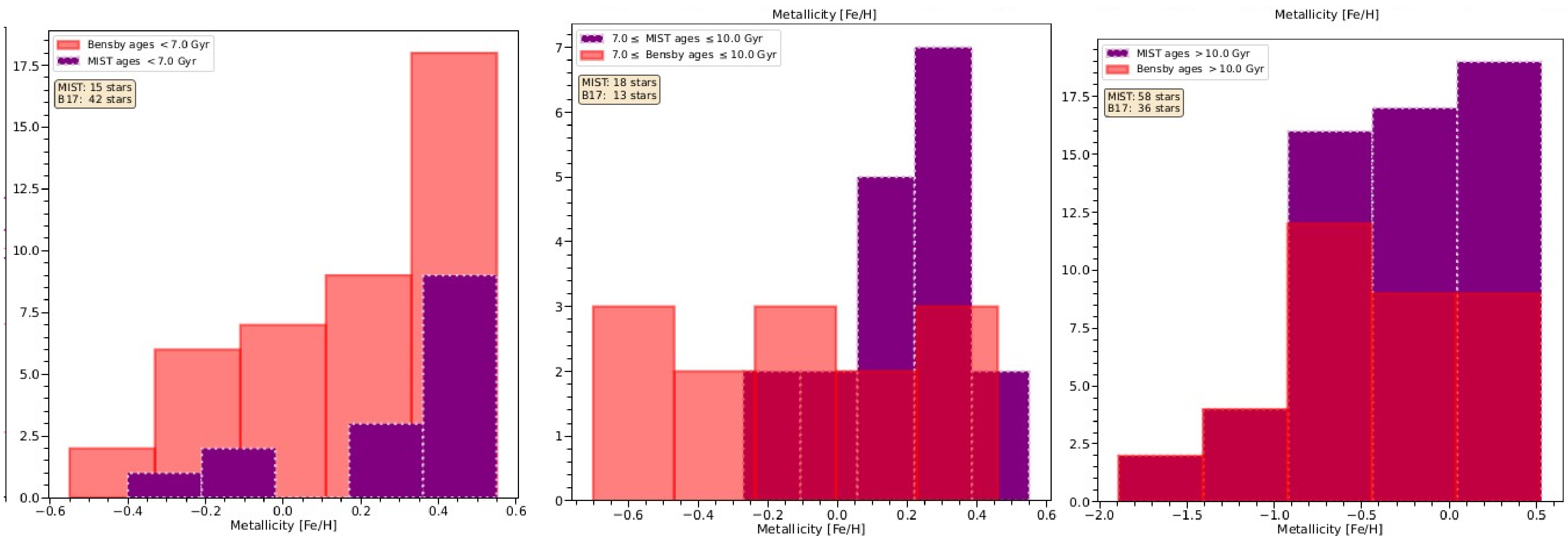

Bensby+ :

42 stars <7 Gyr, all [Fe/H]>-0.6
13 stars >7, <10 Gyr
36 stars >10 Gyr

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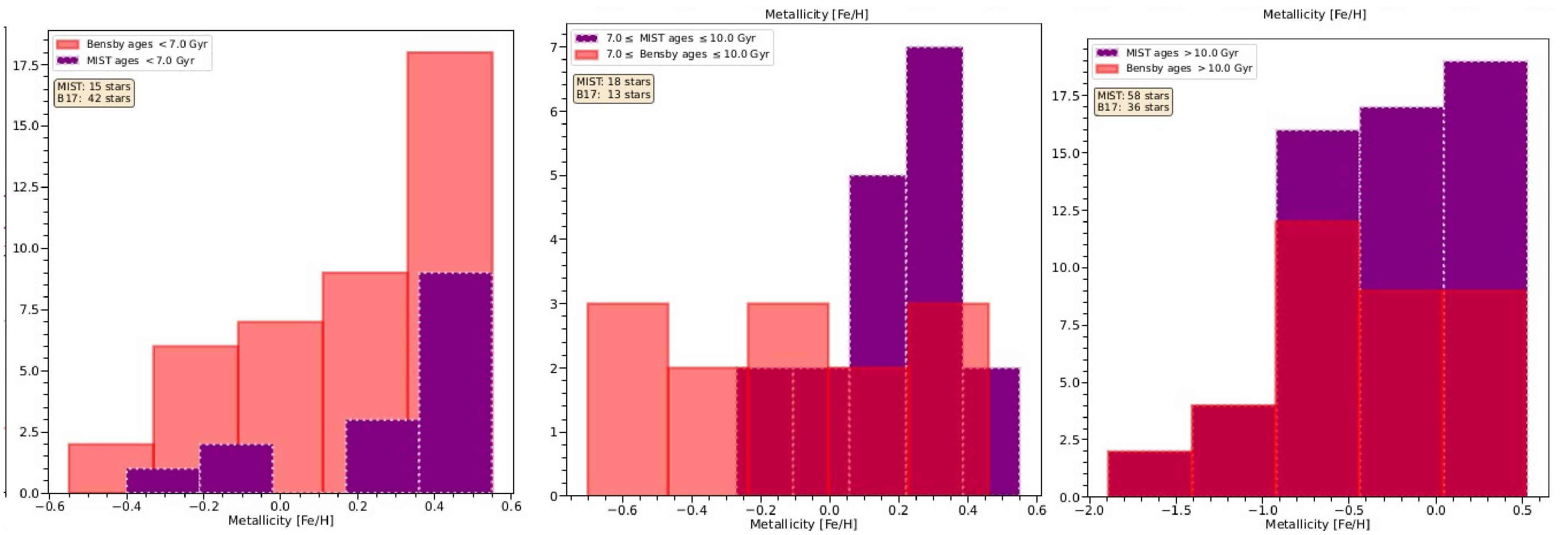


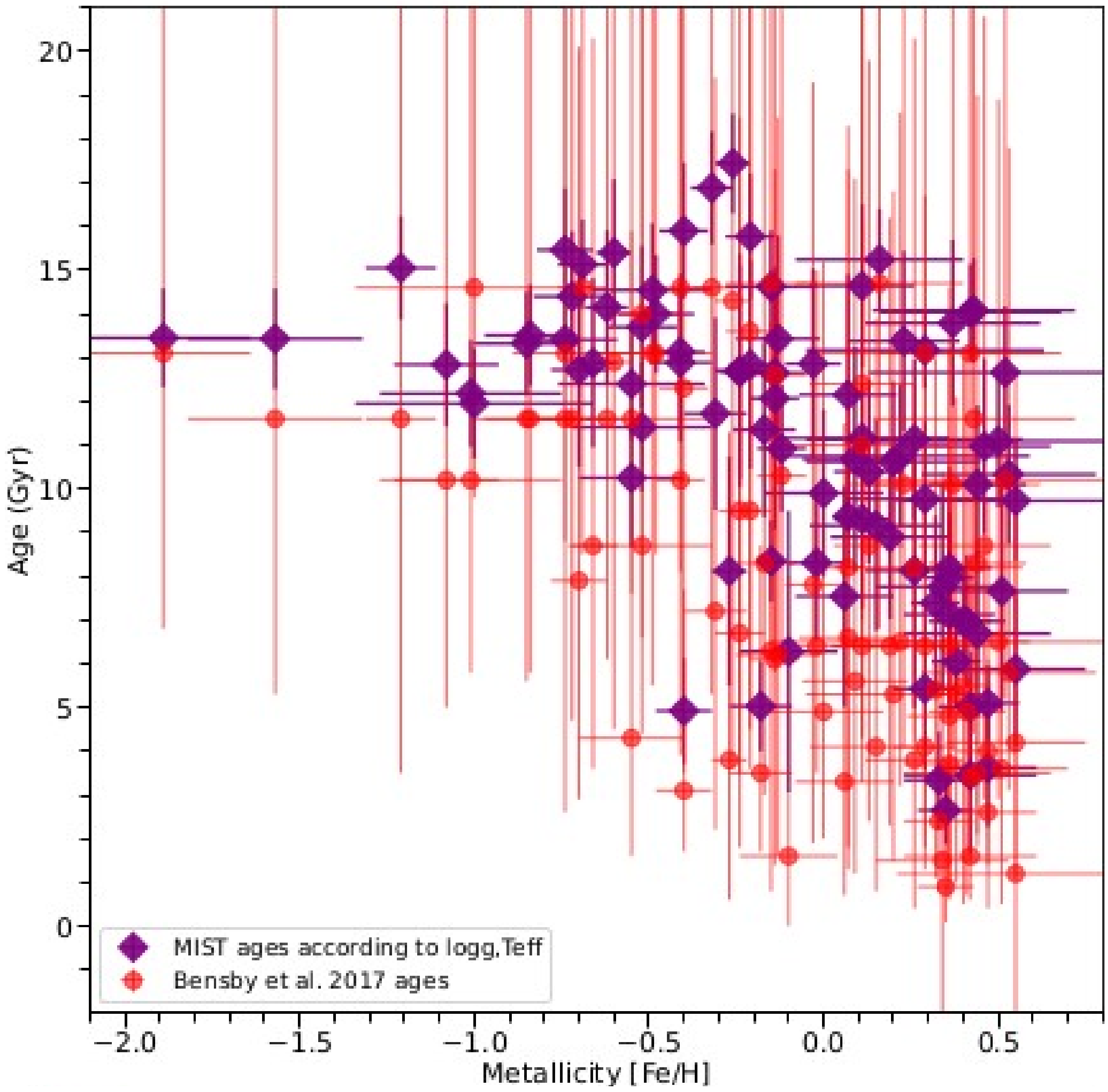
Bensby+ :

42 stars <7 Gyr, all [Fe/H]>-0.6
13 stars >7, <10 Gyr
36 stars >10 Gyr

Joyce+ :

15 stars <7 Gyr, all [Fe/H]>-0.3
18 stars >7, <10 Gyr
58 stars >10 Gyr

Punchline: we (Joyce + MIST) **do not** find an abundance of young stars at high metallicities...**nor** do we find young or intermediate-age stars at metallicities below ~solar [Fe/H]



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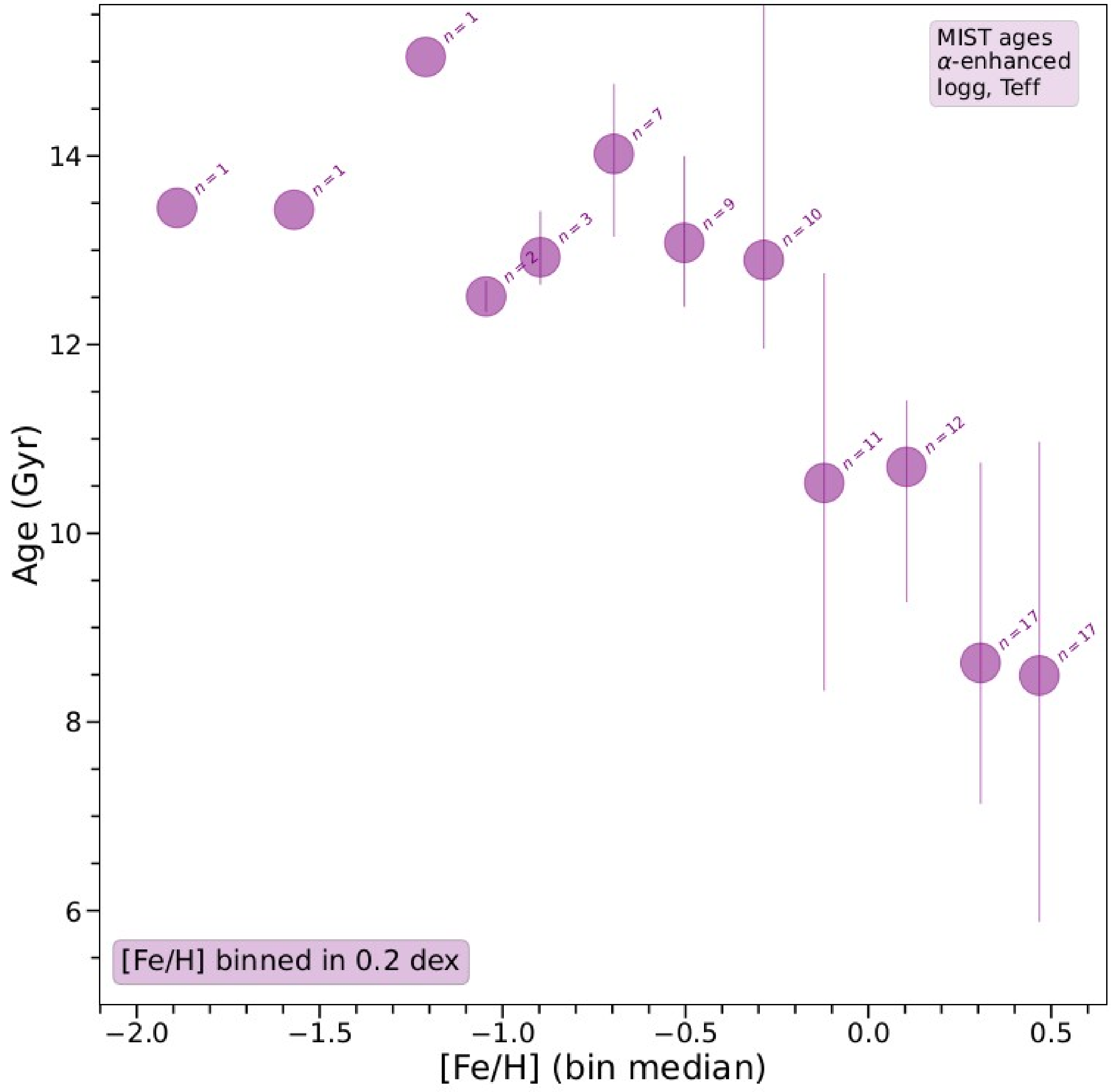

Why should you believe Joyce+MIST over the previous result?

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Carefully considered hybrid statistical techniques

Age determination algorithm

Challenges:

Though it is straightforward to fit an isochrone to an observation "by eye," it is much more difficult to construct a mathematically rigorous definition of a best-fitting model. This is especially true in a situation where:

1. many observations are plausibly consistent with a large number of isochrones (i.e., the isochrone falls within the star's 1σ uncertainties);
2. the isochrones are discretely spaced in age and metallicity and thus limited in resolution; and
3. the models contain their own intrinsic uncertainties that are both difficult to quantify and highly variant over different parameter regimes—a point to which we will return in later discussion.

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(1) For a given star, compute the (3 DoF) chisq score for the fit of that star's observational parameters to ***every*** point along a candidate model (e.g. isochrone)

$$\chi^2_{\text{for } i \text{ DoF}} = \sum_i \frac{(o_i - t_i)^2}{\sigma_i^2}$$

$$\chi^2_{\text{B17}} = \frac{(\log g_o - \log g_t)^2}{\sigma^2_{\log g,o}} + \frac{(T_{\text{eff},o} - T_{\text{eff},t})^2}{\sigma^2_{T_{\text{eff}},o}} + \frac{(Z_o - Z_t)^2}{\sigma^2_{Z,o}},$$

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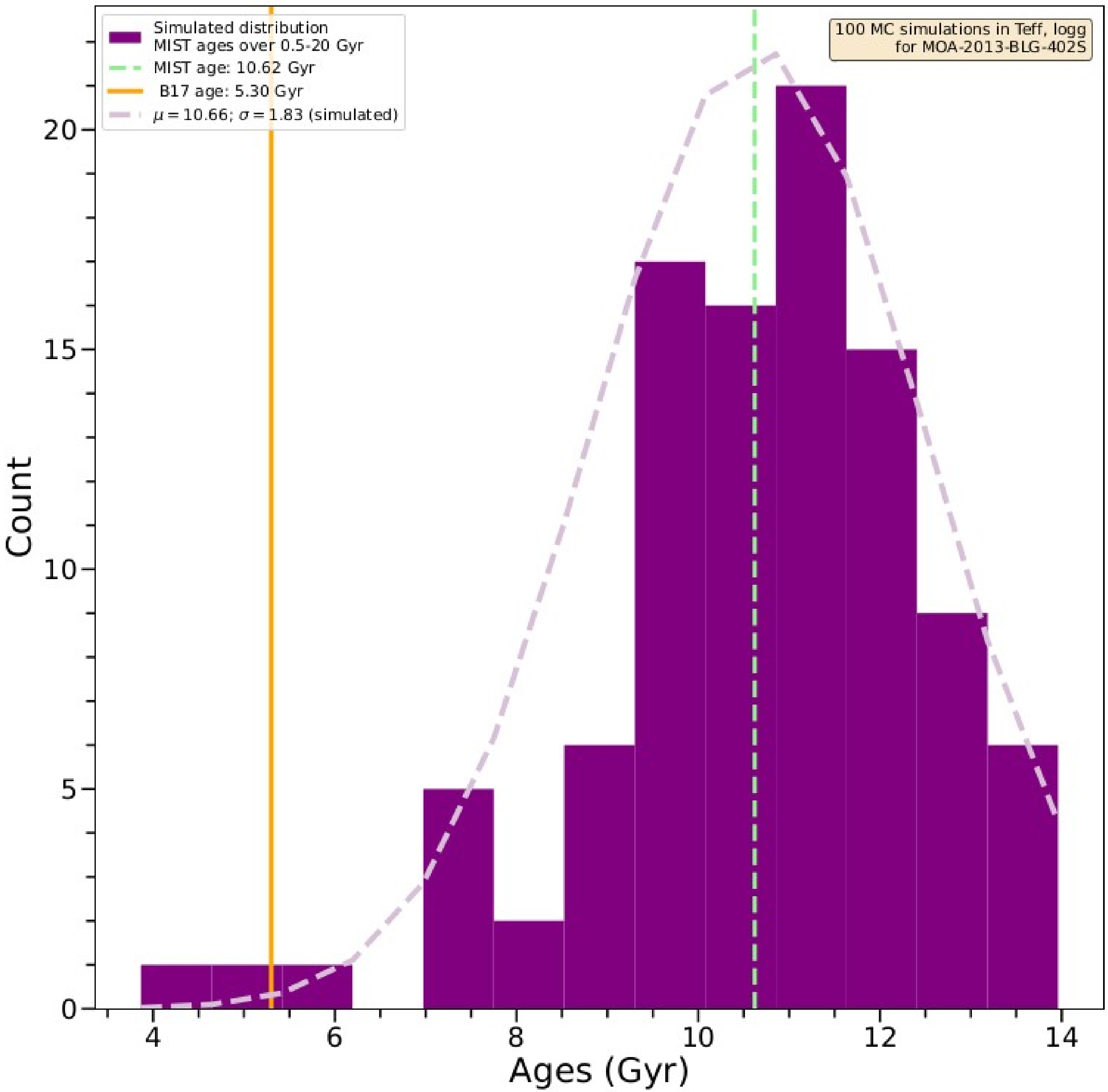
(3) - Compute a weighted average over all candidate hypotheses (each point on each isochrone)
- A point with age t_n is weighted by its likelihood, p_n, of being an appropriate fit to the star
- The final weighted average, t_S, is our estimate for the age of the star

$$t_S = \frac{\sum_n t_n p_n}{\sum_n p_n},$$

Error bars: Monte Carlo resampling



Construct three independent normal distributions with densities

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2}$$

defined by

$$\mu = T_{\mathrm{eff},S}, \quad \sigma = \sigma_{T_{\mathrm{eff},S}},$$
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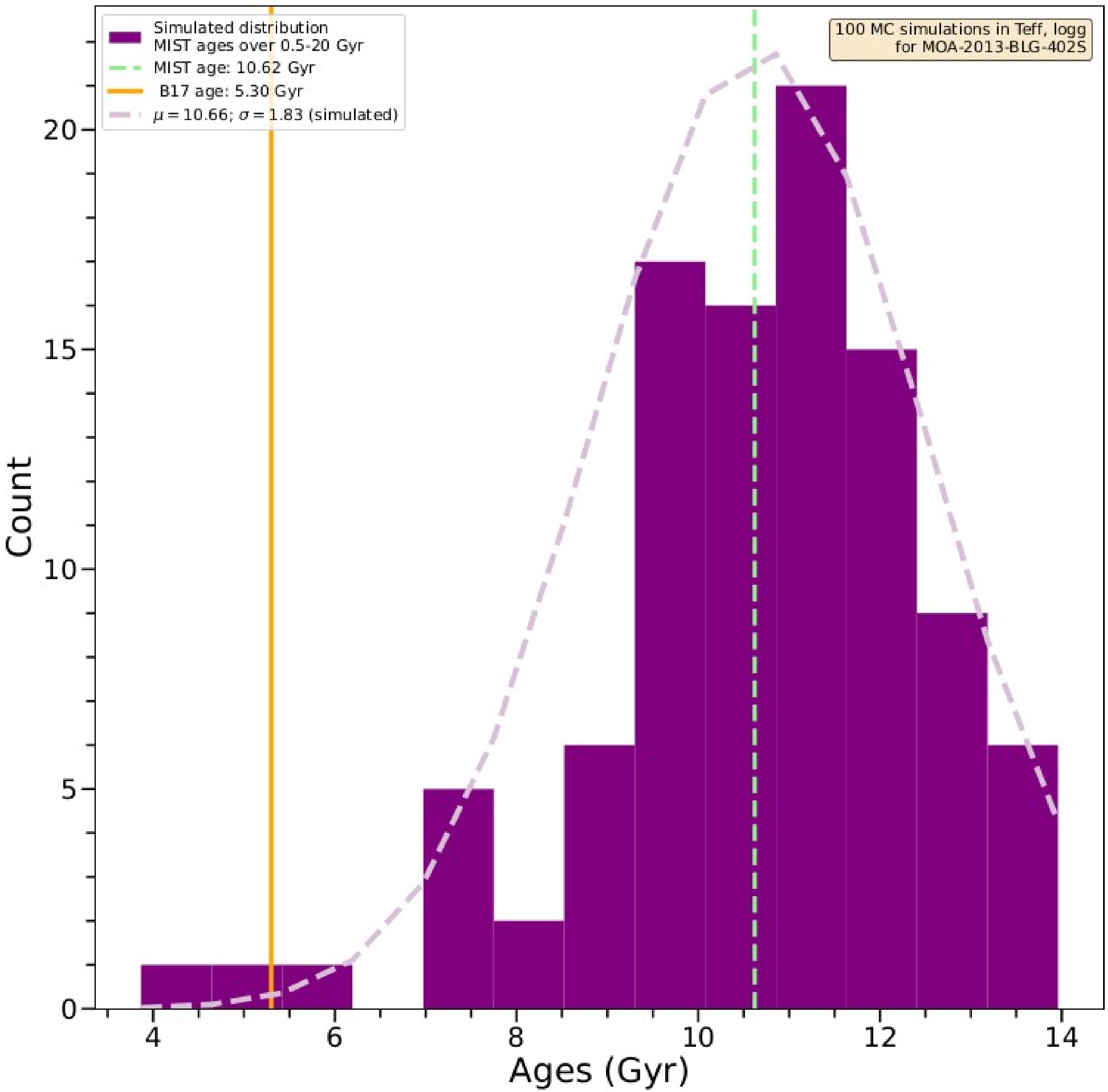

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$$\mu = Z_S, \quad \sigma = \sigma_{Z_S}$$

→ the fact that our MC simulations build a distribution **approaching a *normal distribution*** as number of trials increases suggests that **the assumption of normally distributed variables is reasonable**

Observational vs global uncertainties

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- how is it implemented?
- gravitational settling?
- are all isotopes treated the same?

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- are all isotopes treated the same?

Atmospheric boundary conditions:

- Is it a T-tau relation, & what kind of integration? Eddington vs Krishna-Swamy
- if instead using a table-based treatment from external simulations (e.g. PHOENIX, Kurucz), what solar scale and other physics were used in those simulations? Are they self-consistent with the assumptions in the stellar models?

Point of demonstration: the convective mixing length, α_{MLT}

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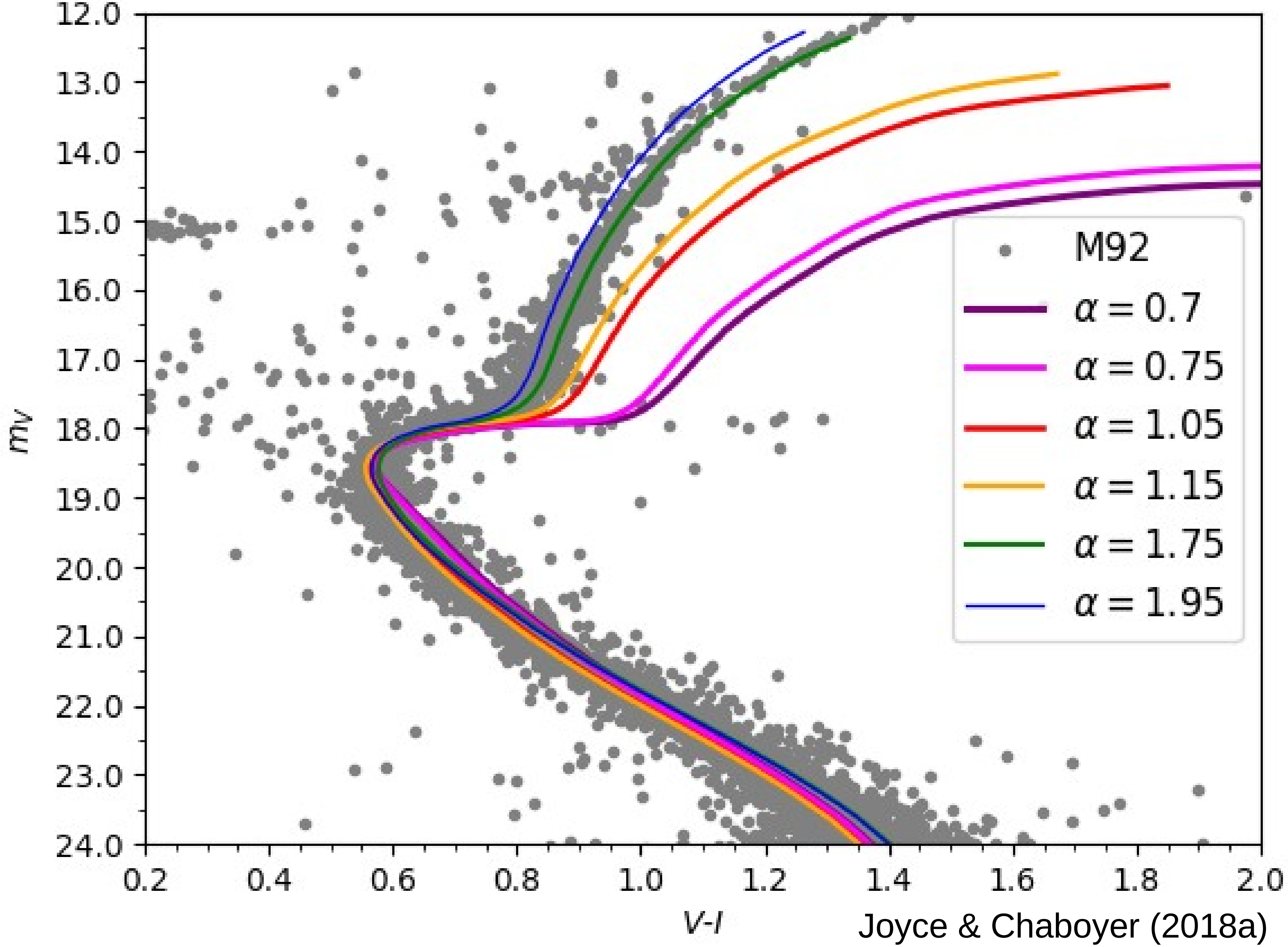
- even modest changes to α_{MLT} dramatically affect the morphology of isochrones between the MSTO and tip of the red giant branch

Look at those RGBs!



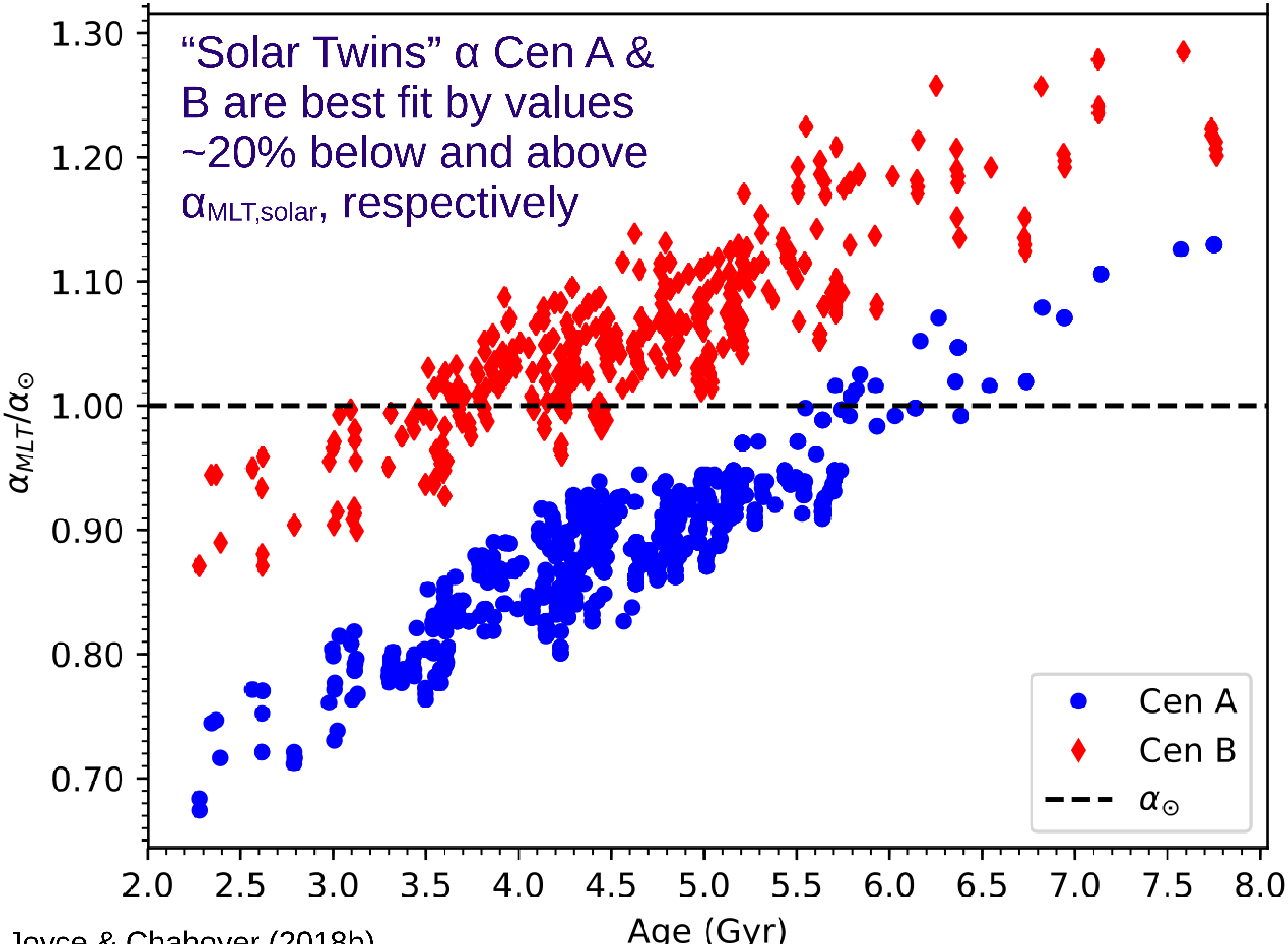
Joyce & Chaboyer (2018a)

Point of demonstration: the convective mixing length, α_{MLT}

Why this parameter?

- even modest changes to α_{MLT} dramatically affect the morphology of isochrones between the MSTO and tip of the red giant branch

- previous work has shown that even stars very similar to the Sun are better fit by mixing length values 10-20% different than the solar-calibrated value



Joyce & Chaboyer (2018b)

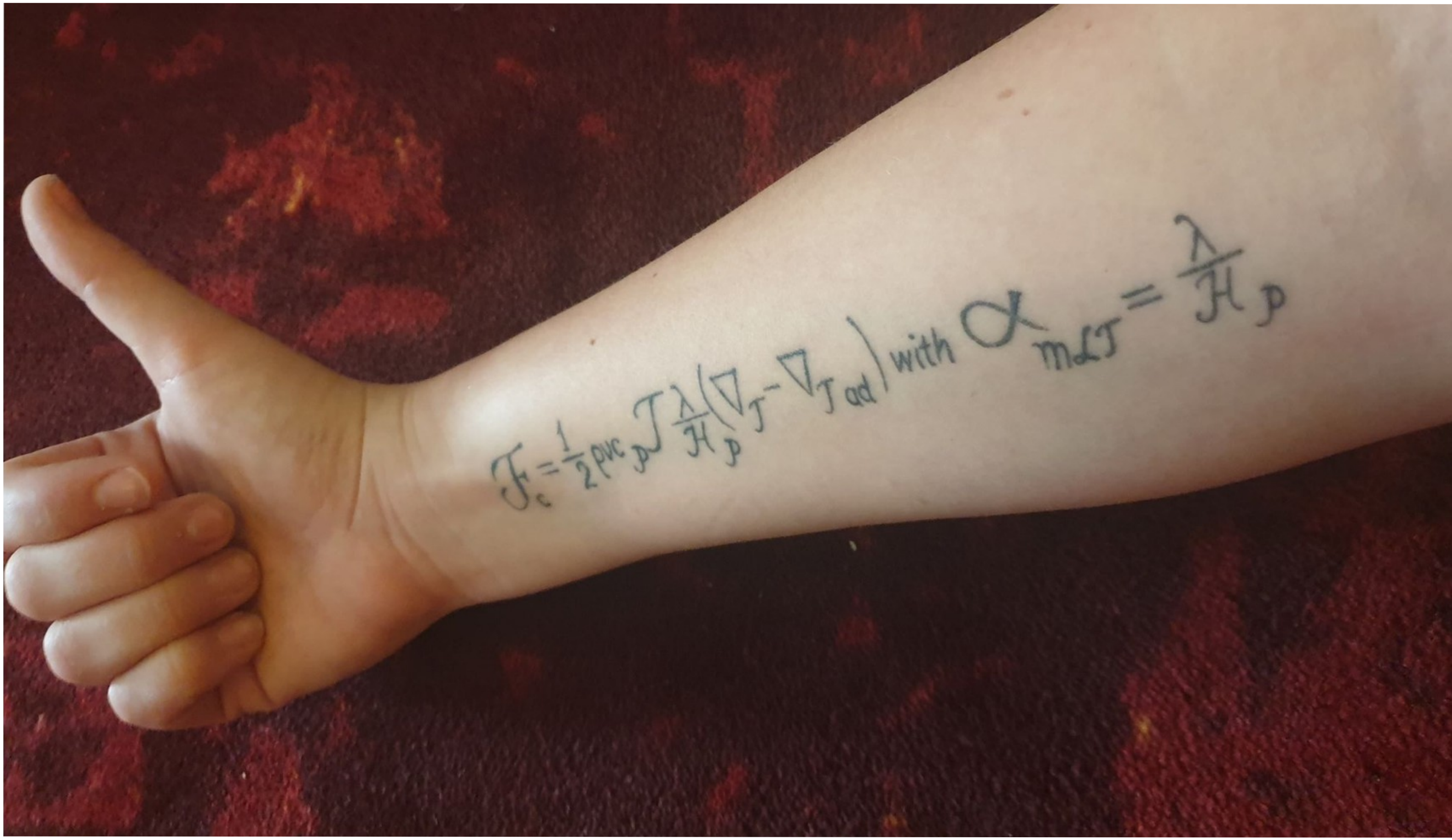
Point of demonstration: the convective mixing length, α_{MLT}

Why this parameter?

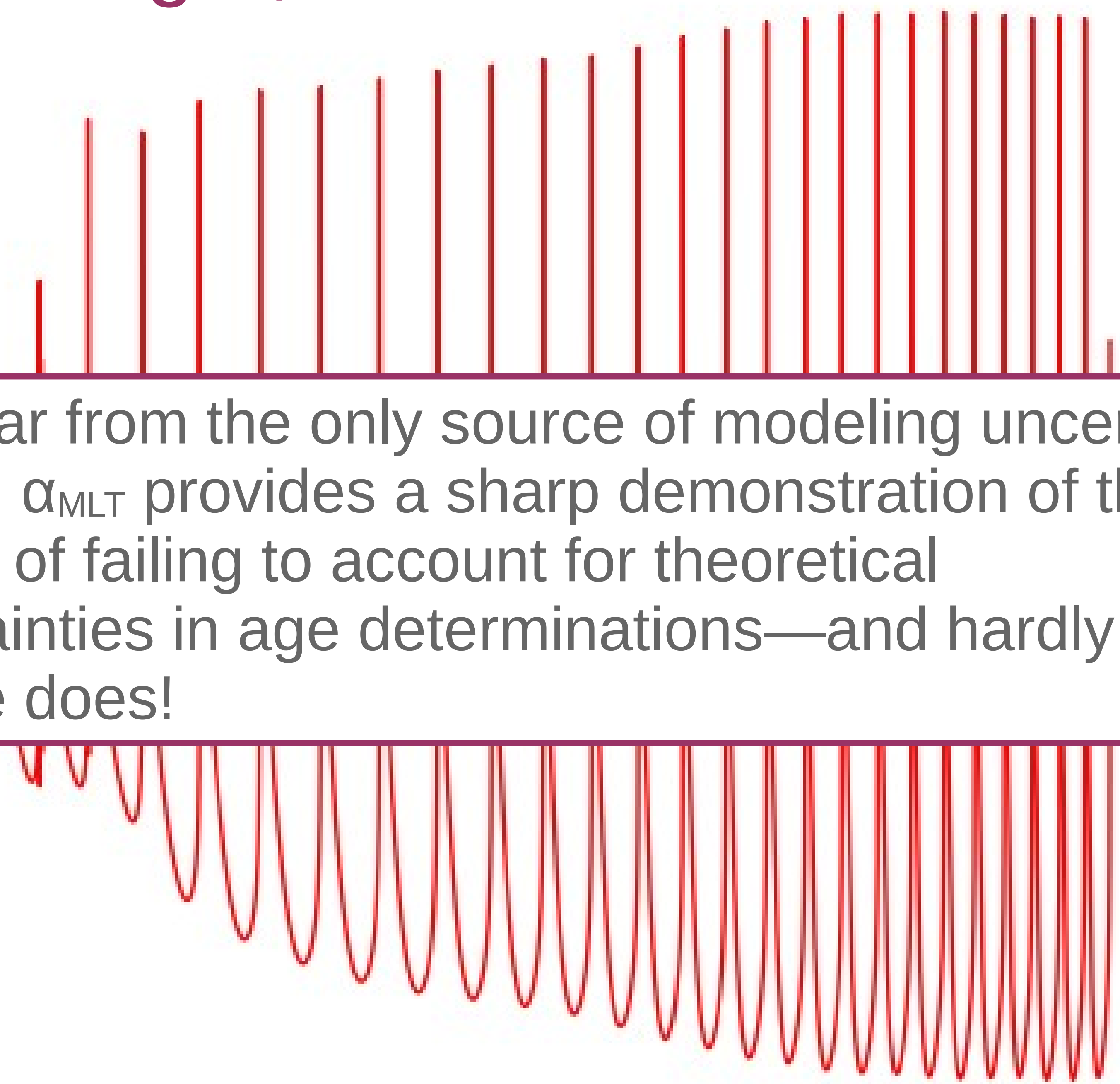
- even modest changes to α_{MLT} dramatically affect the morphology of isochrones between the MSTO and tip of the red giant branch

- previous work has shown that even stars very similar to the Sun are better fit by mixing length values 10-20% different than the solar-calibrated value

- because it's my favorite parameter/because I can

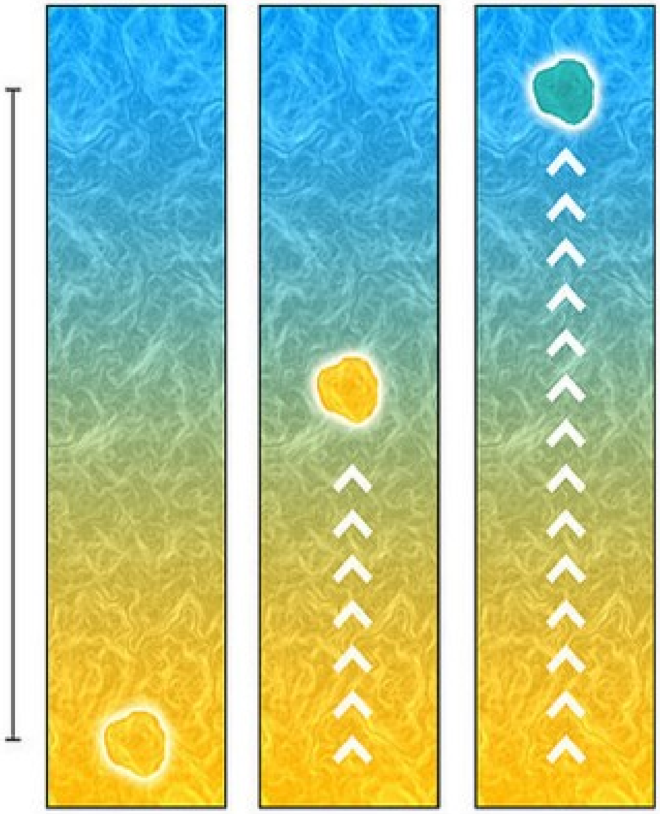

$F_c = \frac{1}{2} \rho v c_p T \frac{\lambda}{H_p} (\nabla_T - \nabla_{T\,ad})$ with $\alpha_{mLT} = \frac{\lambda}{H_p}$

Point of demonstration: the convective mixing length, α_{MLT}



While far from the only source of modeling uncertainty, varying α_{MLT} provides a sharp demonstration of the danger of failing to account for theoretical uncertainties in age determinations—and hardly anyone does!

The convective mixing length: The most important neglected parameter in stellar modeling!



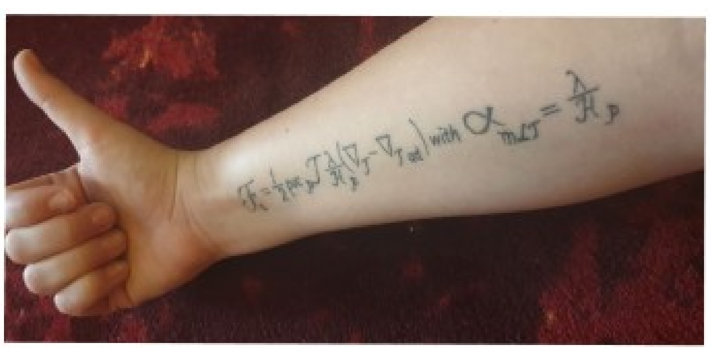
$$F_{\rm conv} = \frac{1}{2}\rho v c_p T \frac{\lambda}{\rm H_P}(\nabla_T - \nabla_{\rm ad}).$$

$$\alpha_{\rm MLT} = \frac{\lambda}{\rm H_P} \qquad \nabla_T = \left(\frac{d\ln T}{d\ln P}\right)$$

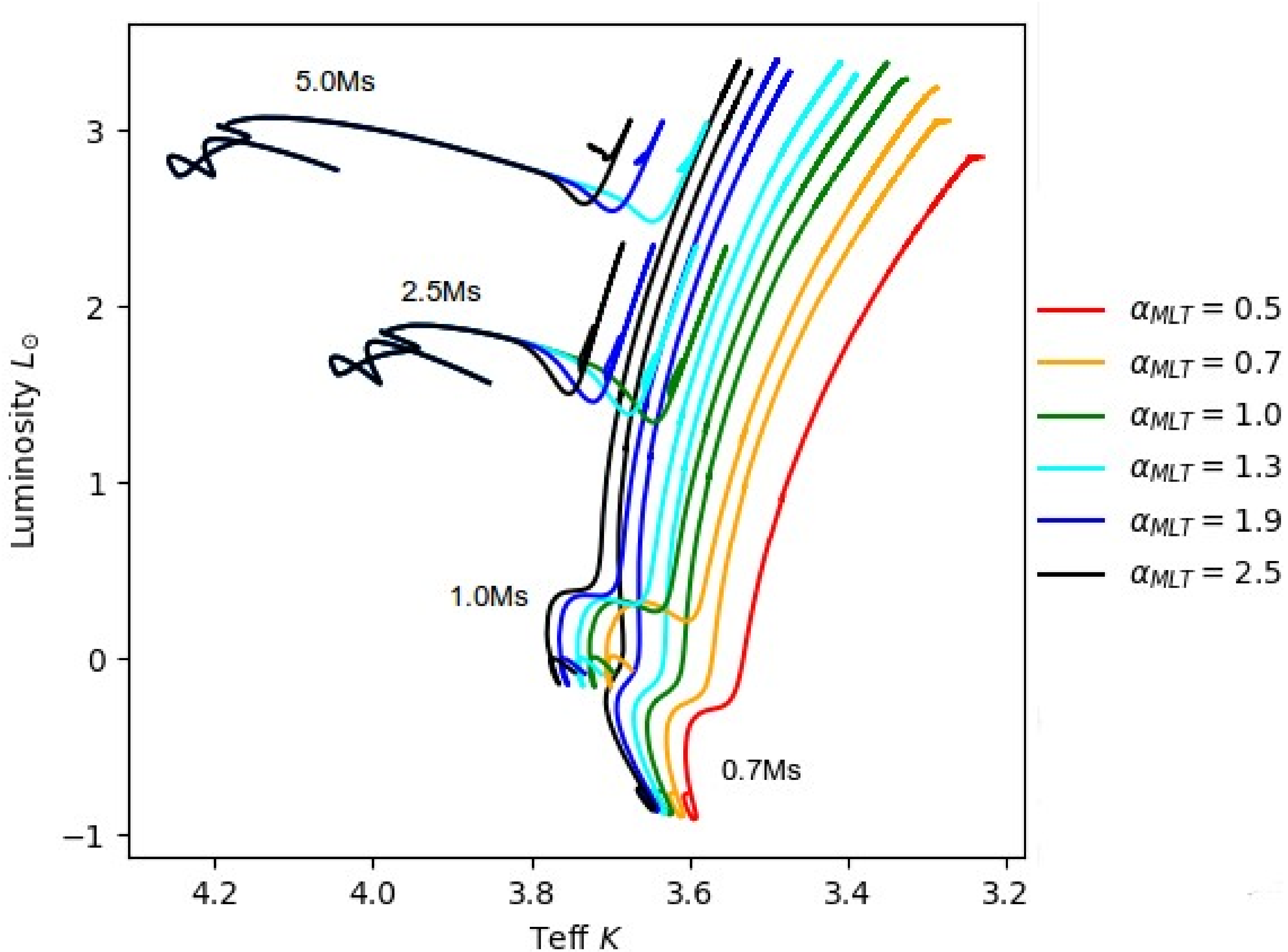
- "mixing length:" average vertical distance over which parcels in pressure, but not thermal, equilibrium can travel before denaturing

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

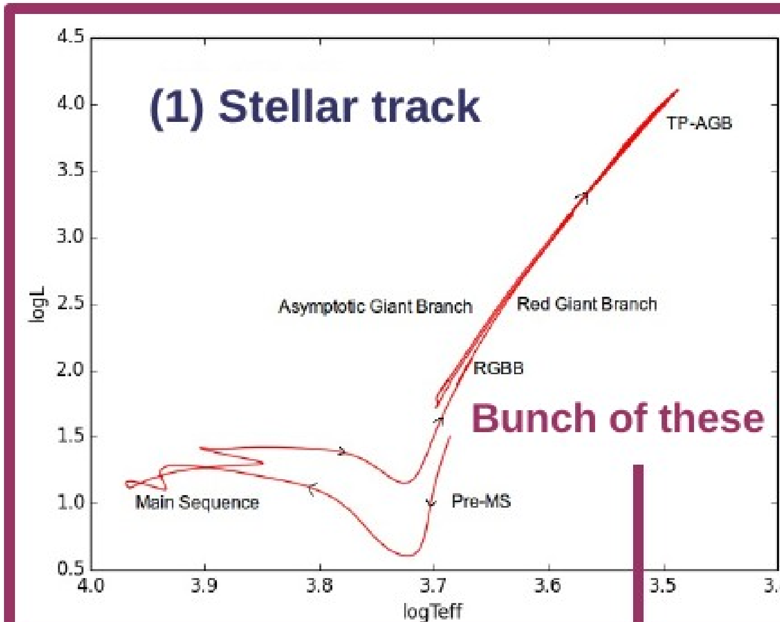
- a measure of "efficiency" of convection

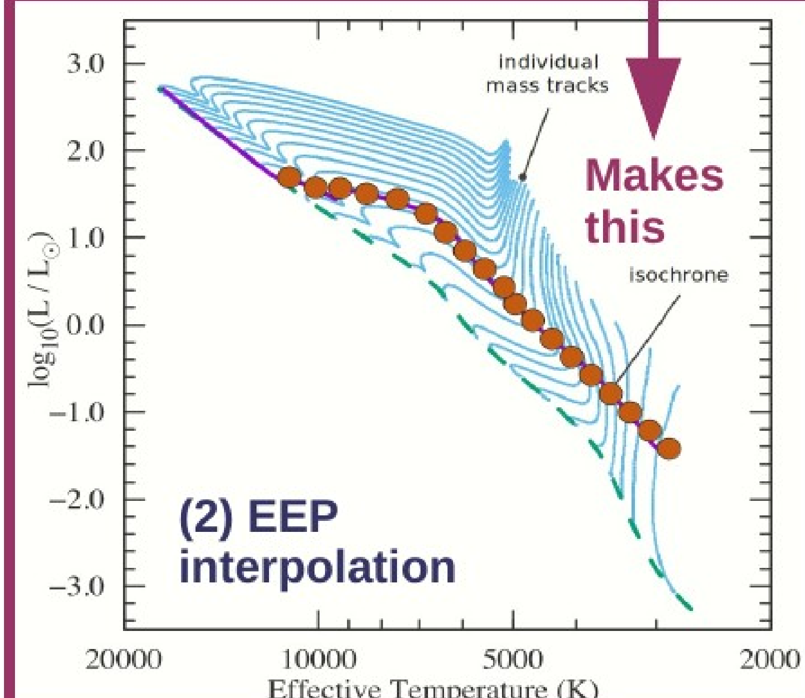


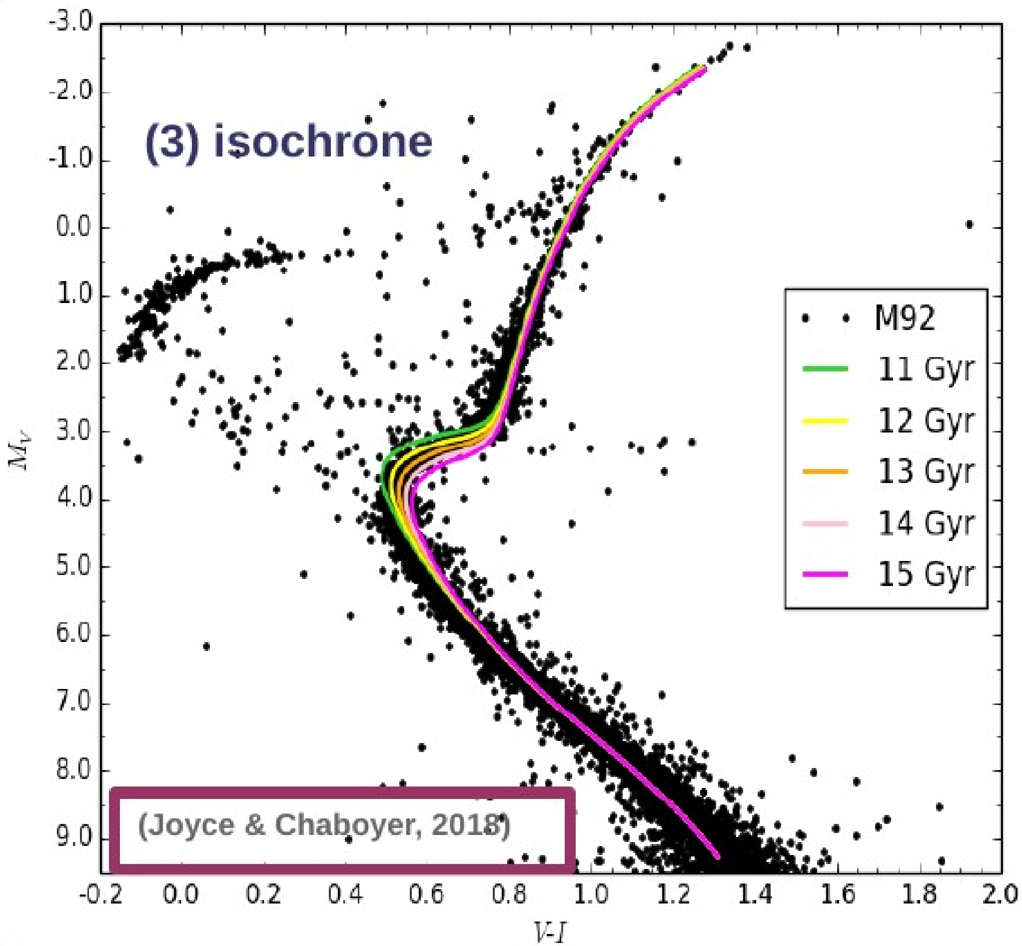
Effect of alpha_MLT on a stellar track



Isochrone review

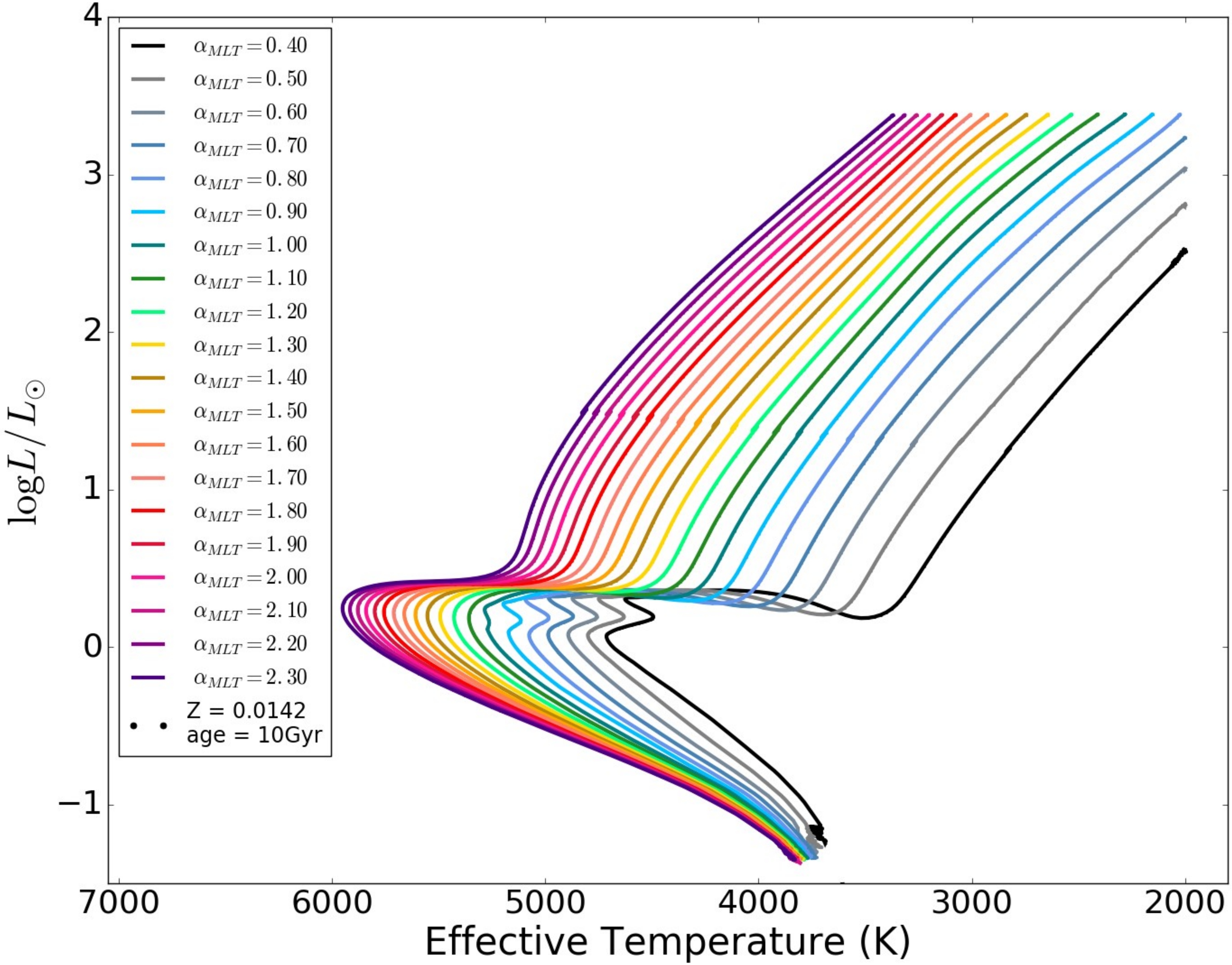




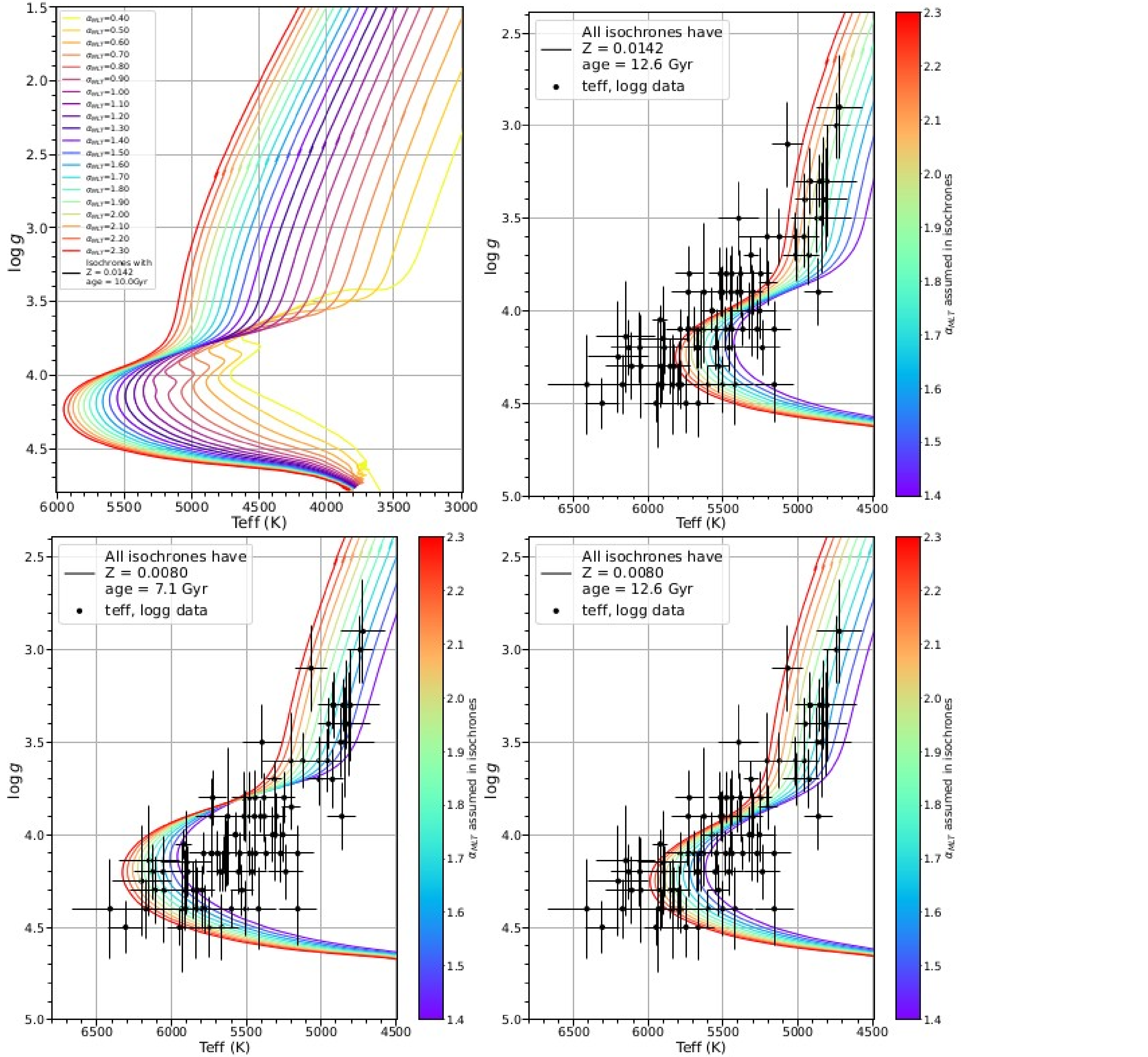


Derive fundamental parameters for both individual stars and stellar populations

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.



The impact of αMLT



How do we incorporate the isochrones' "shift" in our error simulations?

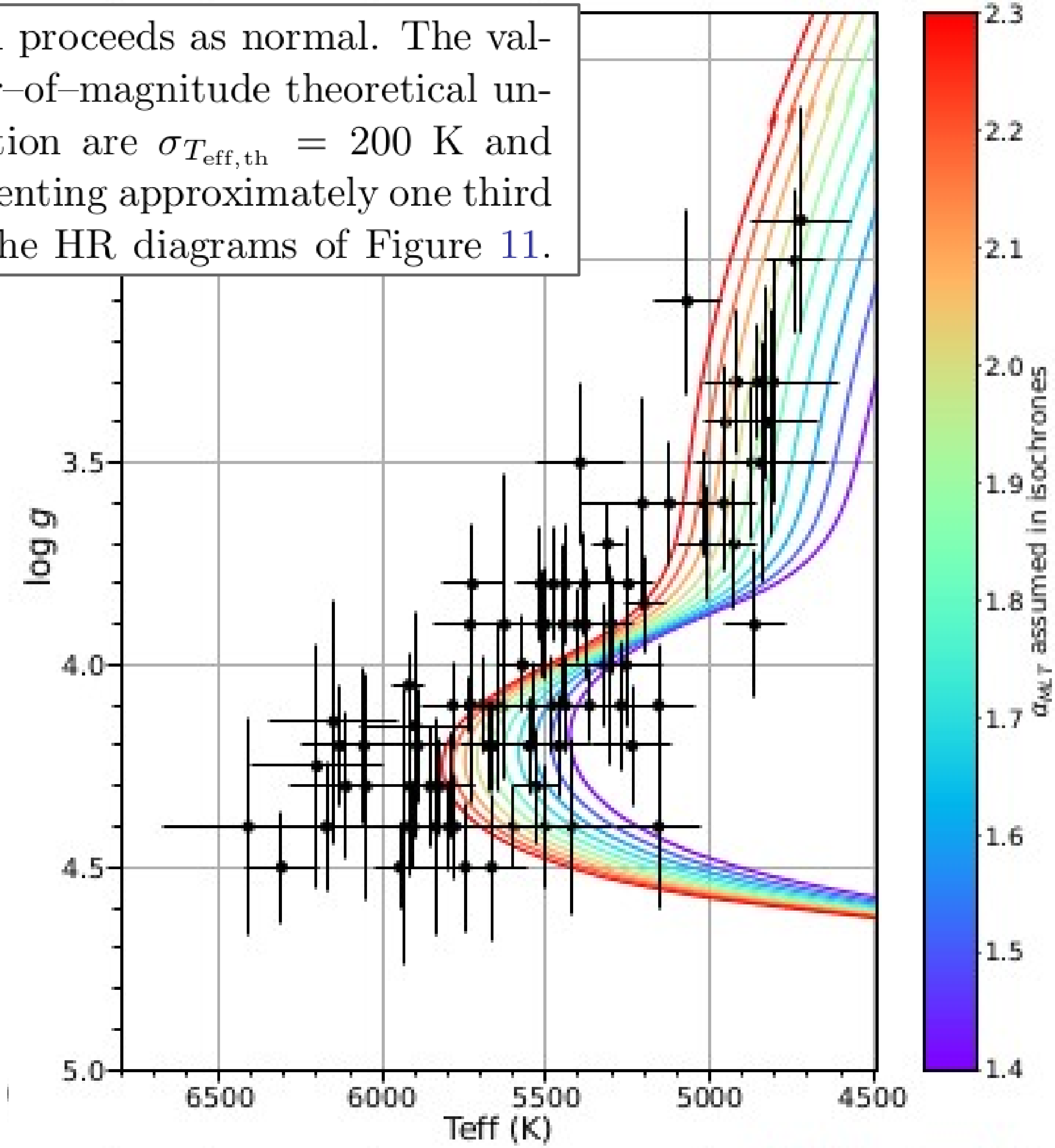
Figure 11. In a new set of Monte Carlo simulations, we adopt the same definitions for χ^2 and t_S given in Equations 2 and 3 and sample from the same distributions in observational parameters given in Equation 4, but we introduce an additional term accounting for variation in the isochrones. In each Monte Carlo simulation, we sample normal distributions given by

$$\mu = 0, \quad \sigma = \sigma_{T_{\mathrm{eff,th}}} \tag{5a}$$

$$\mu = 0, \quad \sigma = \sigma_{\log g_{\mathrm{th}}}, \tag{5b}$$

uniformly shifting the entire basis of isochrones horizontally by a random sample **of Equation 5a and vertically by a random sample from Equation 5b**.

The rest of the algorithm proceeds as normal. The values adopted for the order–of–magnitude theoretical uncertainties in each direction are $\sigma_{T_{\mathrm{eff,th}}} = 200$ K and $\sigma_{\log g_{\mathrm{th}}} = 0.17$ dex, representing approximately one third of the spans[6] shown in the HR diagrams of Figure 11.



What happens when we incorporate variation in the isochrones' position in logg-Teff in the MC simulations?

	Name	.. α-enhanced	...model err
1	MOA-2009-BLG-174S	9.3 ± 2.0	9.3 ± 4.0
2	MOA-2009-BLG-259S	7.8 ± 2.4	7.8 ± 3.8
3	MOA-2010-BLG-167S ★	15.4 ± 1.7	15.4 ± 3.8
4	MOA-2010-BLG-311S	7.7 ± 2.7	7.7 ± 3.3
5	MOA-2010-BLG-446S	4.9 ± 1.2	4.9 ± 2.0
6	MOA-2010-BLG-523S ★	7.5 ± 2.5	7.5 ± 3.8
7	OGLE-2011-BLG-0950S ★ †	3.3 ± 1.1	3.3 ± 1.6
8	OGLE-2011-BLG-0969S ★	13.4 ± 1.1	13.4 ± 1.5
9	MOA-2011-BLG-034S	14.6 ± 1.9	14.6 ± 2.8
10	MOA-2011-BLG-058S	13.8 ± 1.9	13.8 ± 2.8
11	OGLE-2011-BLG-1072S	8.2 ± 2.3	8.2 ± 3.4
12	MOA-2011-BLG-090S	17.4 ± 1.1	17.4 ± 2.7
13	MOA-2011-BLG-104S	13.3 ± 1.2	13.3 ± 1.8
14	OGLE-2011-BLG-1105S	9.9 ± 1.9	9.9 ± 2.9
15	MOA-2011-BLG-174S	5.0 ± 1.0	5.0 ± 2.5
16	MOA-2011-BLG-191S	8.1 ± 3.1	8.1 ± 4.1
17	MOA-2011-BLG-234S †	8.3 ± 1.8	8.3 ± 3.0
18	MOA-2011-BLG-278S	12.7 ± 1.5	12.7 ± 1.8
19	OGLE-2011-BLG-1410S	10.8 ± 1.6	10.8 ± 2.4
20	MOA-2011-BLG-445S	11.1 ± 1.8	11.1 ± 2.8
21	MOA-2012-BLG-022S	5.0 ± 1.3	5.0 ± 2.2
22	OGLE-2012-BLG-0026S	11.1 ± 1.5	11.1 ± 2.5

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8	OGLE-2011-BL[illegible]	[illegible]	[illegible]
9	MO[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible] ± 2.8
[illegible]	[illegible]	[illegible]	8.2 ± 3.4
[illegible]	[illegible]	17.4 ± 1.1	17.4 ± 2.7
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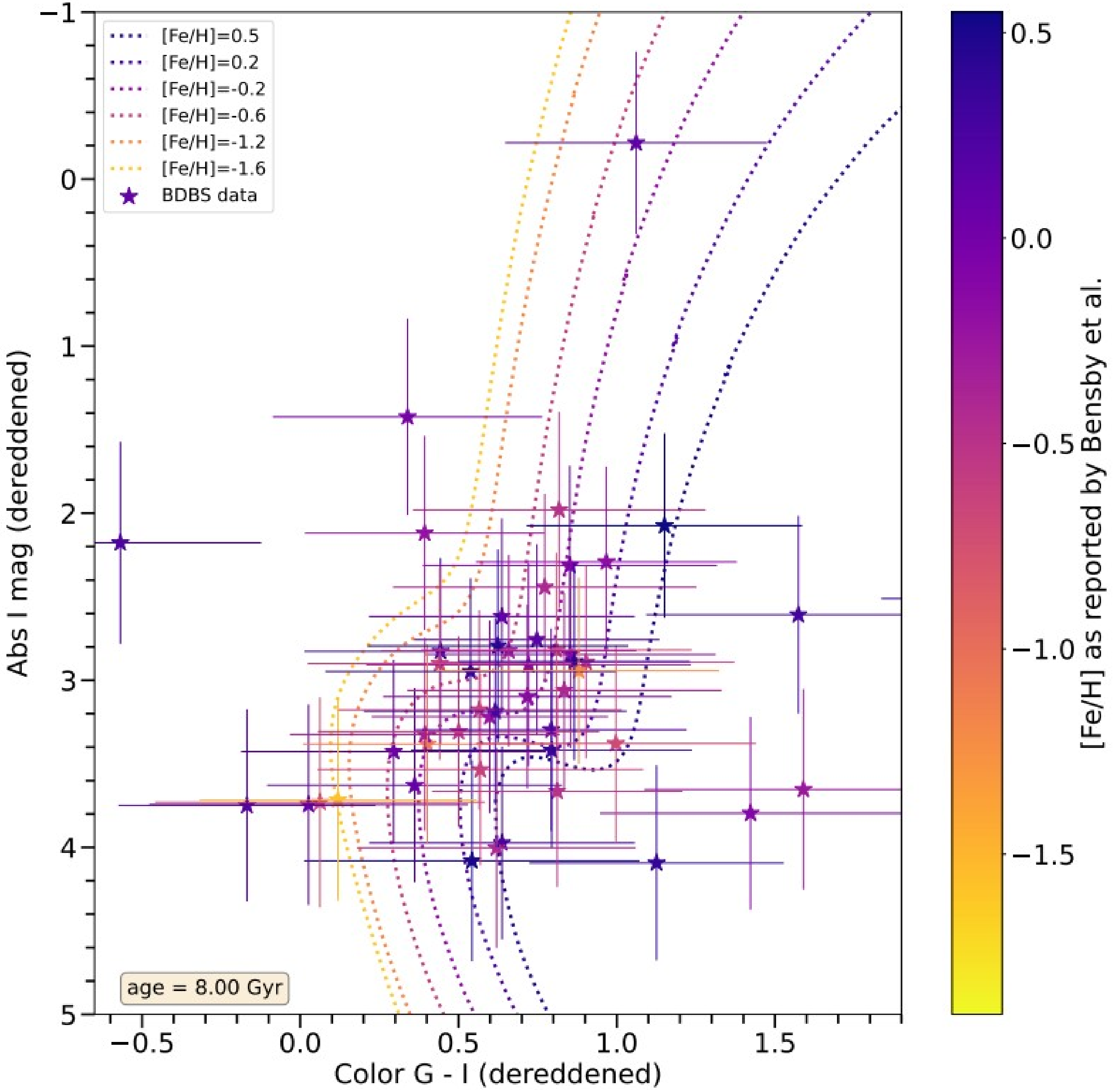
uncertainties increase by a factor of 1.5 - 2x

Tension between inference methods?

Attempt to fit BDBS photometry



Insufficient data resolution?

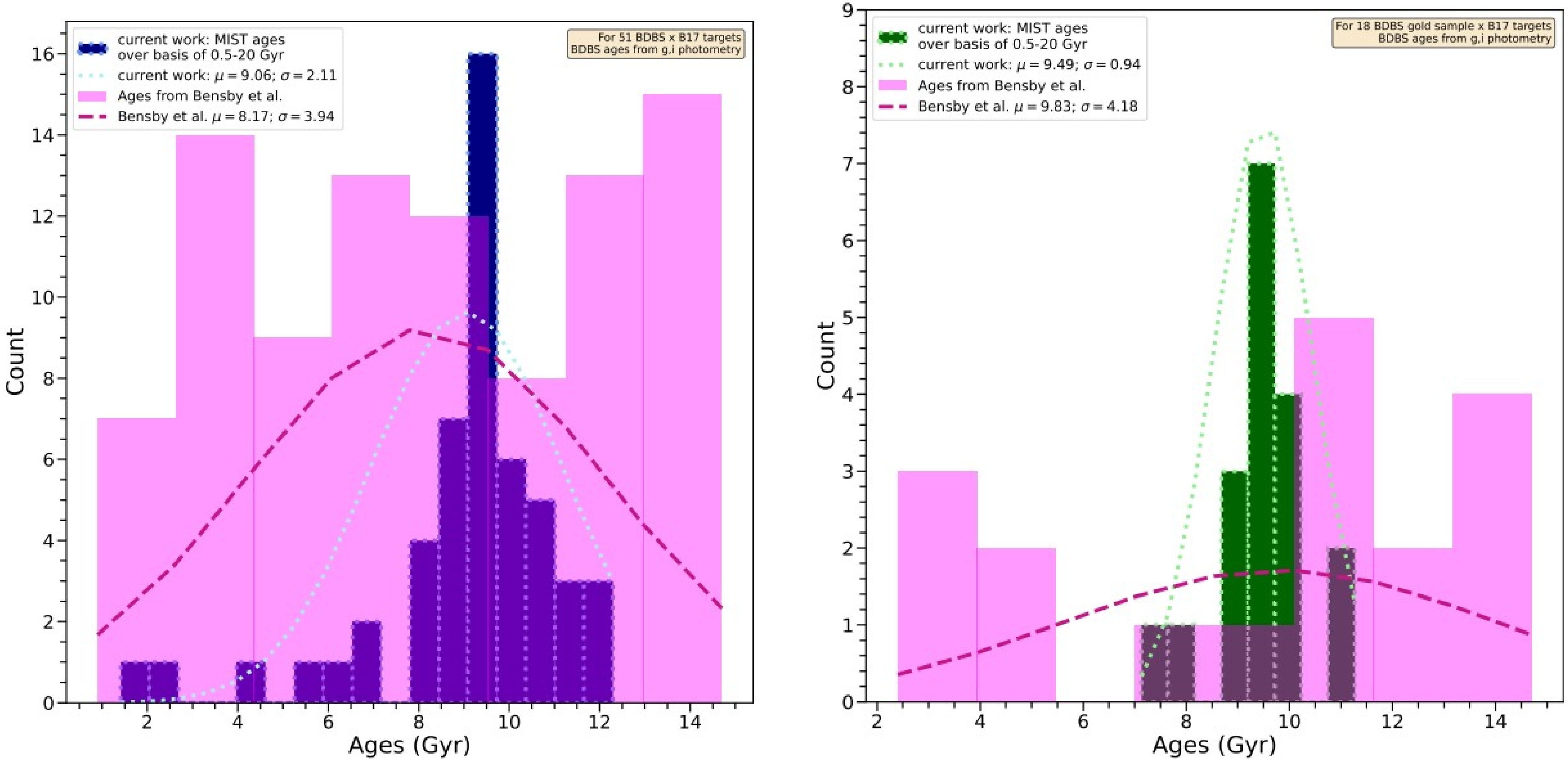
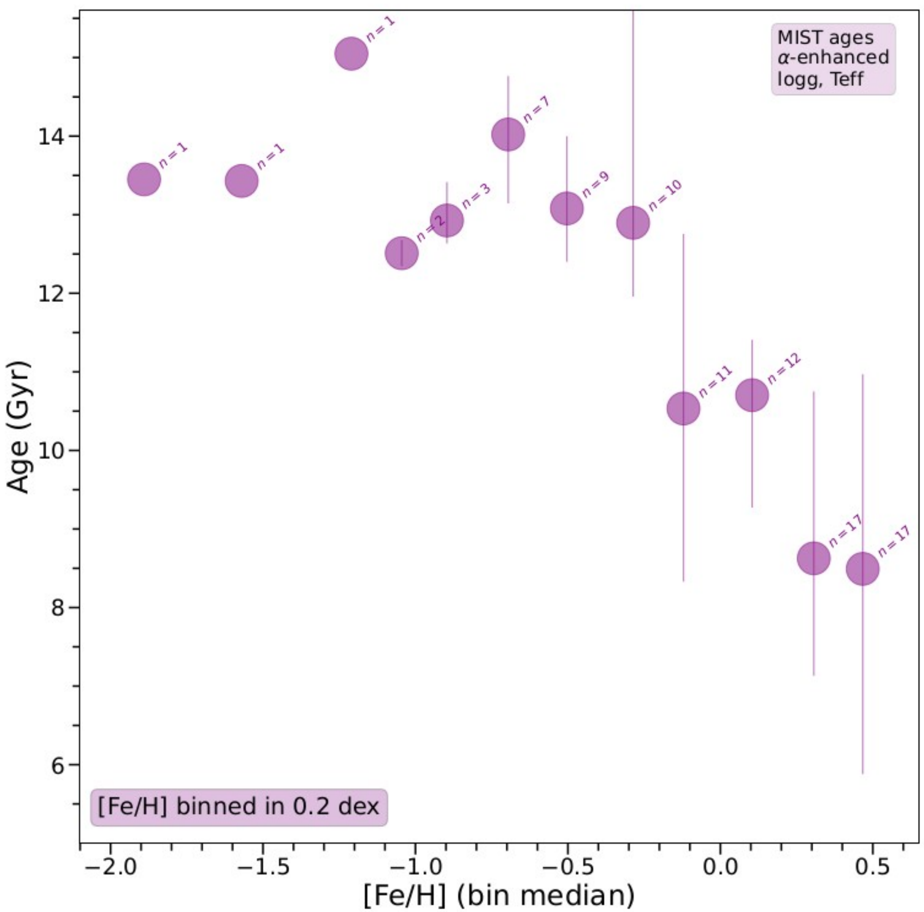
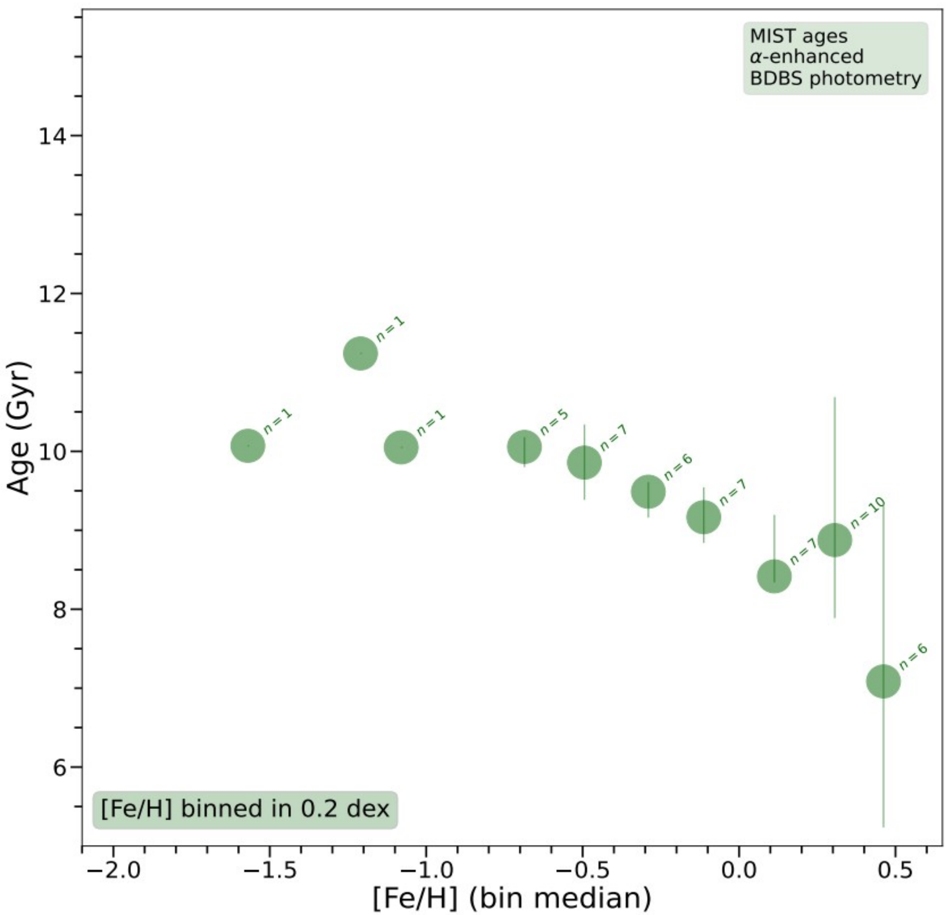


Figure 14. Age histograms in the style of Figures 5 and 7 but with ages derived from BDBS photometry. **LEFT:** The full intersection of the B17 and BDBS target lists for which complete photometric and distance information was available, totalling 51. The age distribution according to Bensby et al. (2017) for the same subset of stars is overlaid in pink. **RIGHT:** Same as left panel, but for the gold sample containing 18 members. The ages for the same 18 stars according to B17 is overlaid in pink.

Spectroscopic vs (poor) photometric



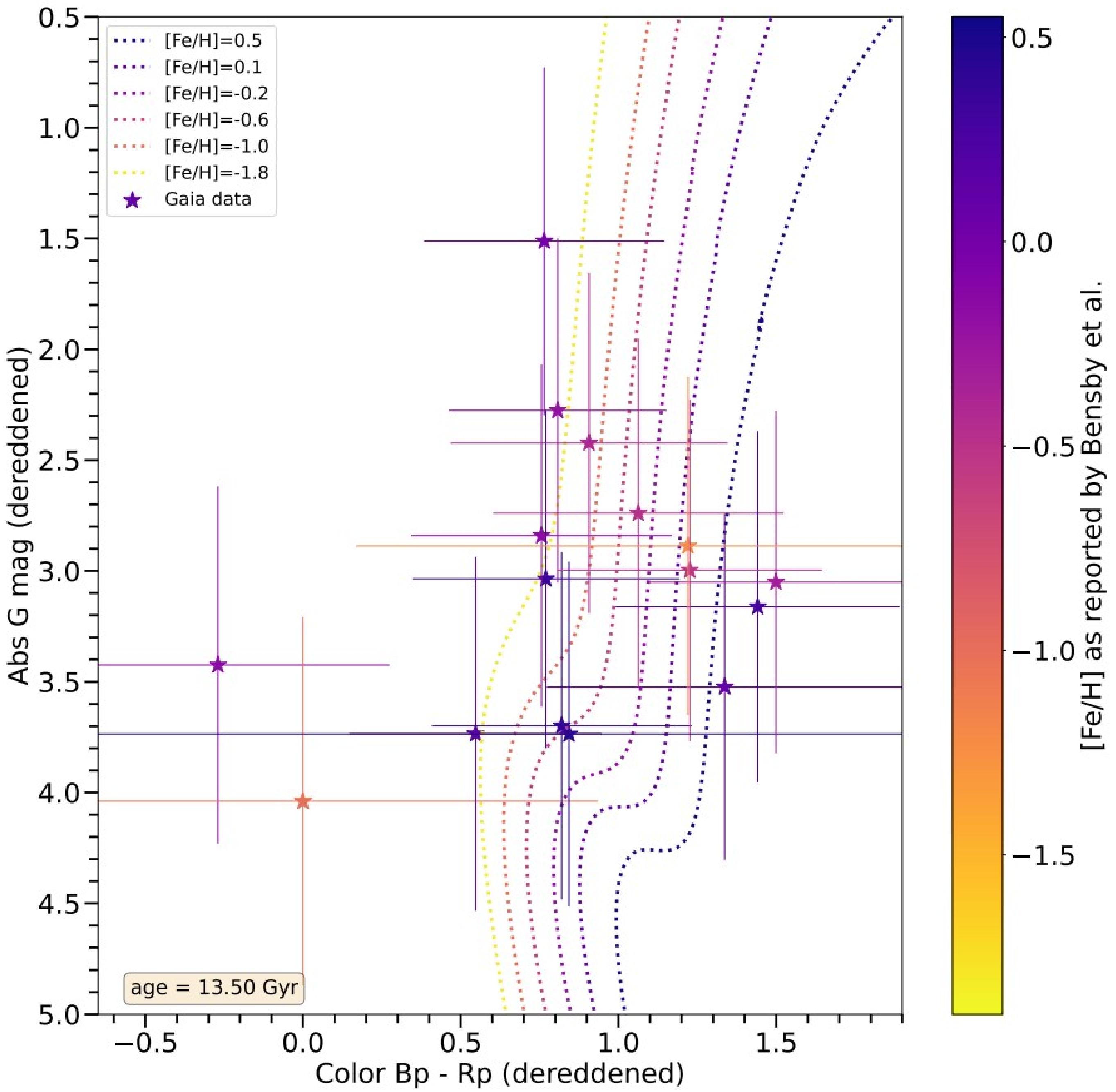
Age-metallicity relation based on re-fitting Bensby et al. spectroscopic data



Age-metallicity relation based on subsample with BDBS photometry, using same algorithm

*Note that BDBS measurements are not precise enough to avoid sensitivity to the set of hypotheses

Attempt to fit *Gaia* photometry



Clear case of insufficient data resolution

30 JOYCE ET AL.

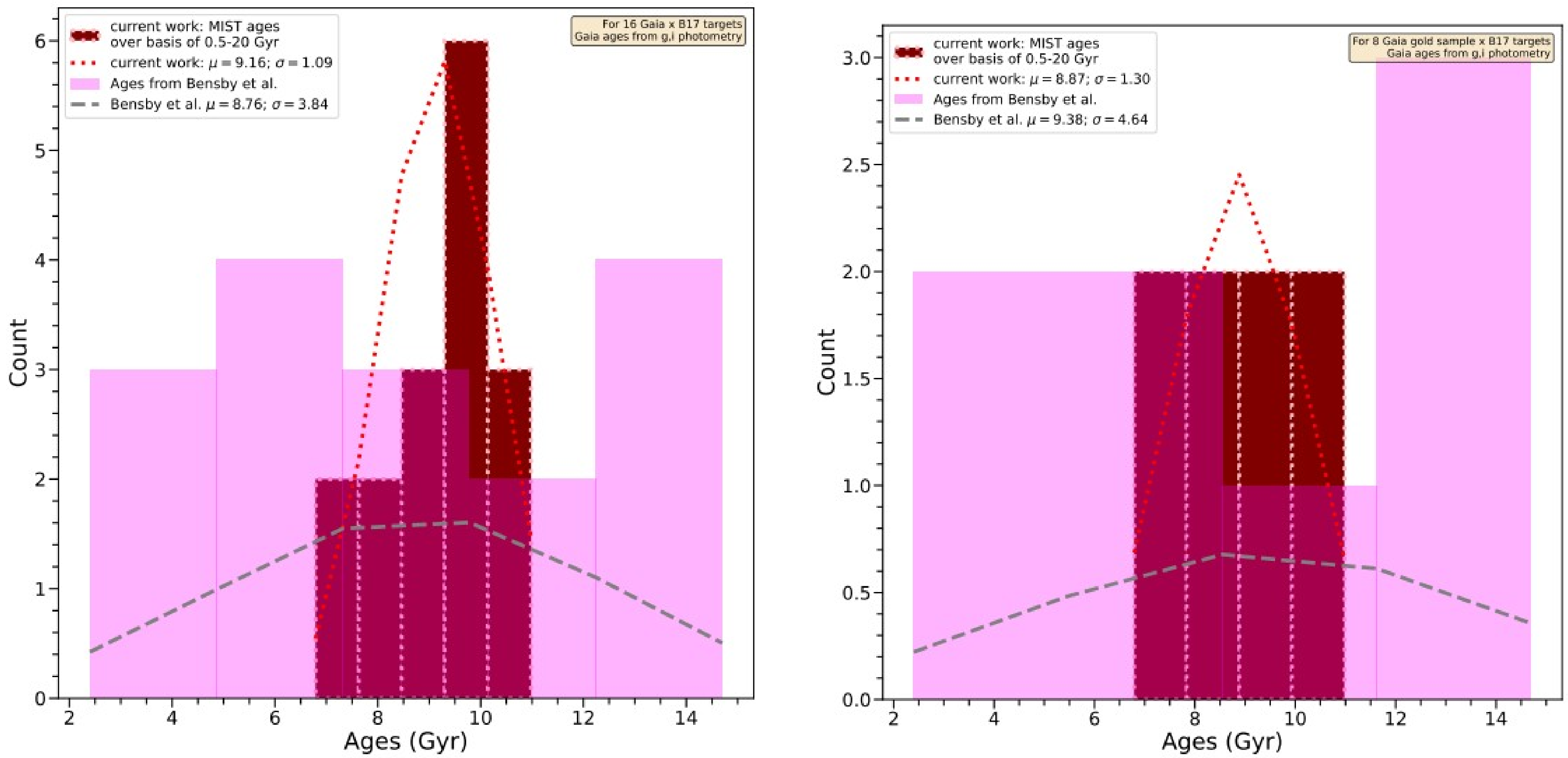


Figure 17. **LEFT:** Same as Figure 14, but for the intersection of the B17 and *Gaia* target lists examining only those stars selected according to the description in Section A.2. This is the "*Gaia* gold sample." **RIGHT:** Same as left panel, but for the entire intersection of the B17 and *Gaia* target lists. This totals 16 stars after the removal of *Gaia* stars with either (1) bad photometry or (2) for which two independent distance determinations with uncertainties were not available.

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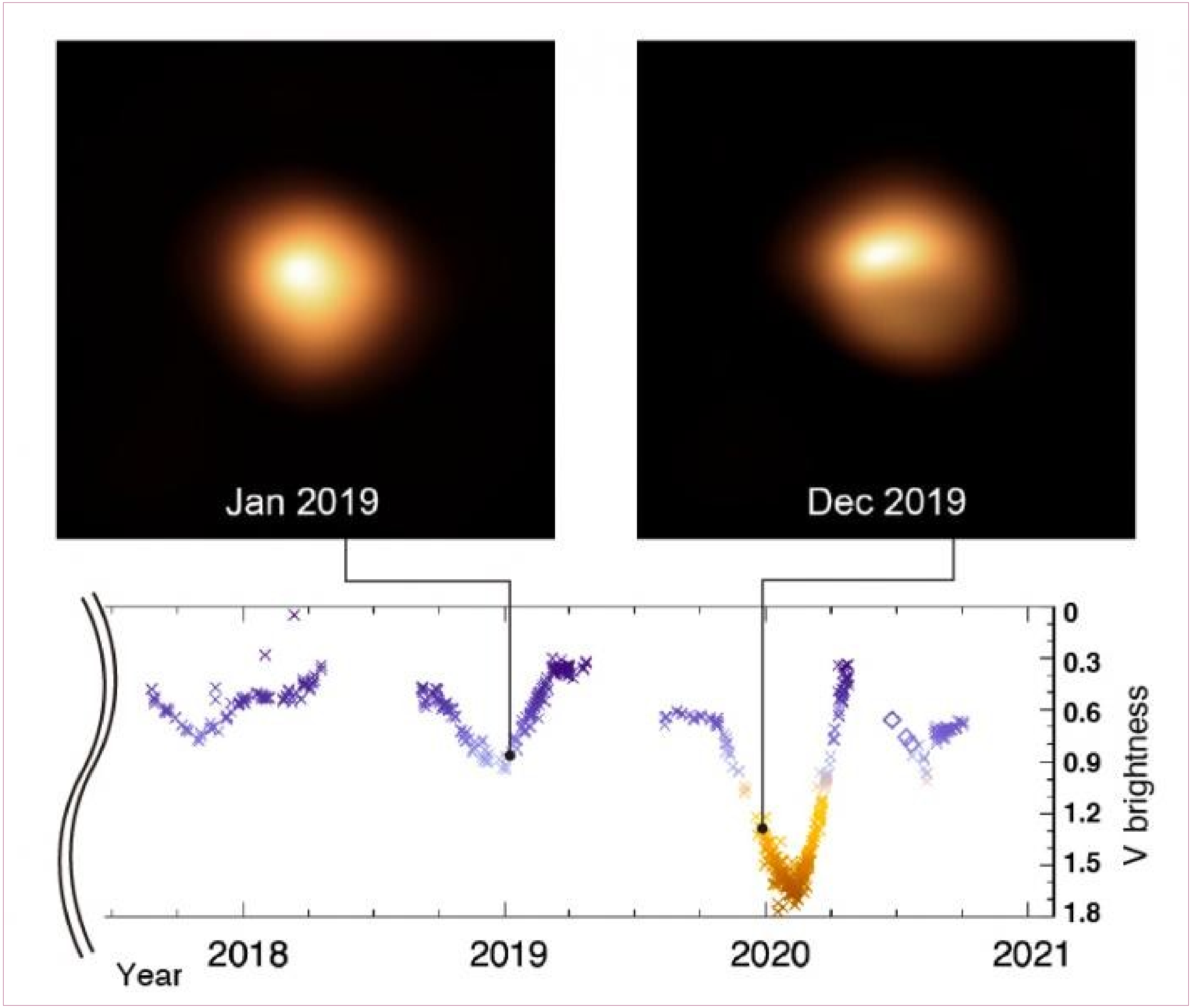
Ages are hard! Be careful with math.

BONUS: Betelgeuse MLT content

Late 2019: unprecedented brightness drop



Press release: Kavli IPMU Toyko, Japan

Our Approach (one of many):

Reproduce this lightcurve via simulation to understand why Betelgeuse became dim or rule out causes

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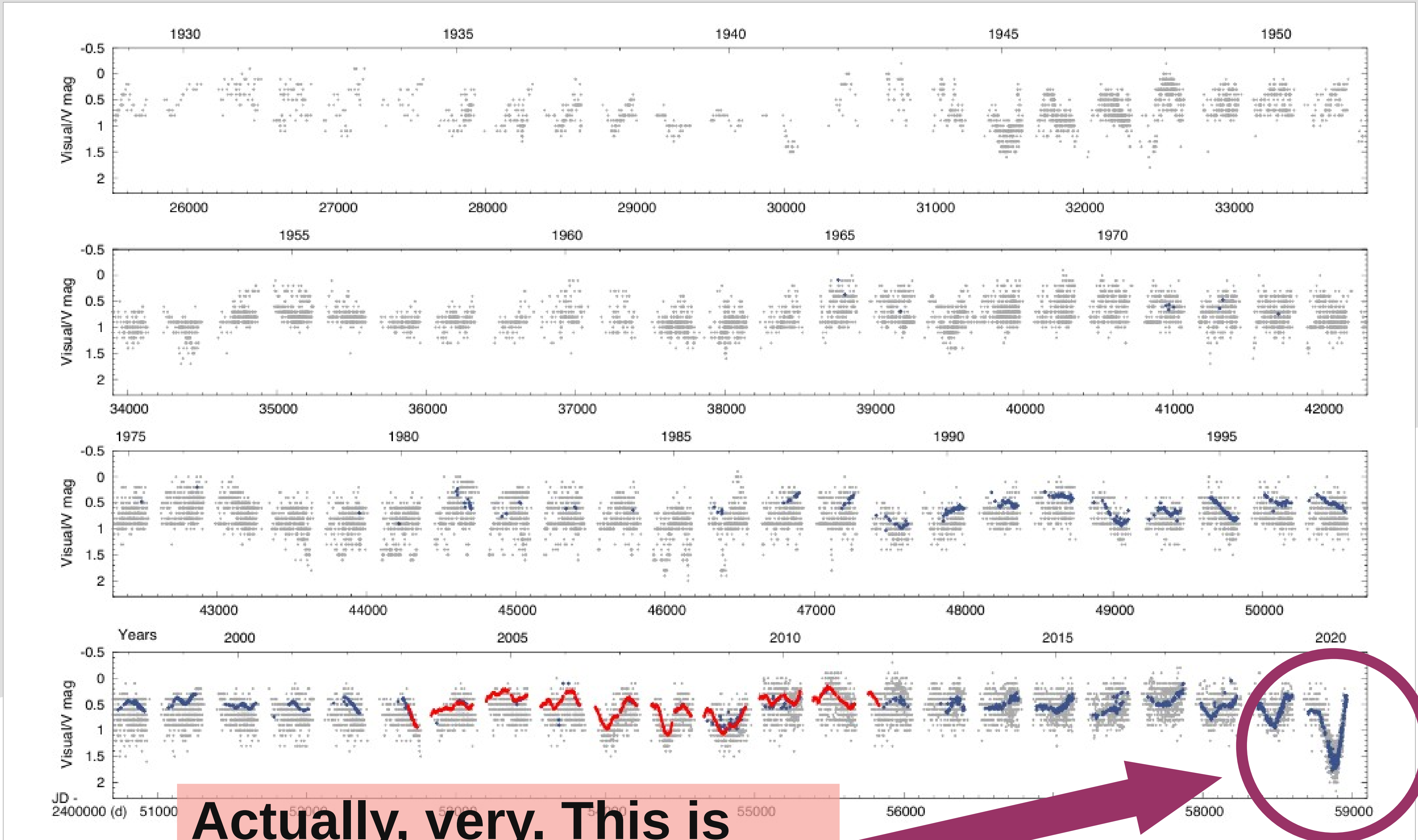
Reproduce this lightcurve via simulation to understand why Betelgeuse became dim or rule out causes

...but in order to understand why this dimming event was “unprecedented,” we must first understand Betelgeuse’s normal periodic variations

The ‘unprecedented’ dimming of Betelgeuse
-First question: How unprecedented, *really*?



Actually, very. This is the dimmest it’s been in nearly 100 years

What patterns do we detect in the frequencies?

From new and archival photometry we find periodicities (variabilities):
- 416 days
- 185 days
- 5.6 years

Determining the drivers of different frequencies tells us about the structure of the star

What we want to know...
Is the 416-day periodicity the fundamental mode?

Is the 185-day periodicity the first overtone?

Is the 416-day period **driven by the kappa mechanism?**

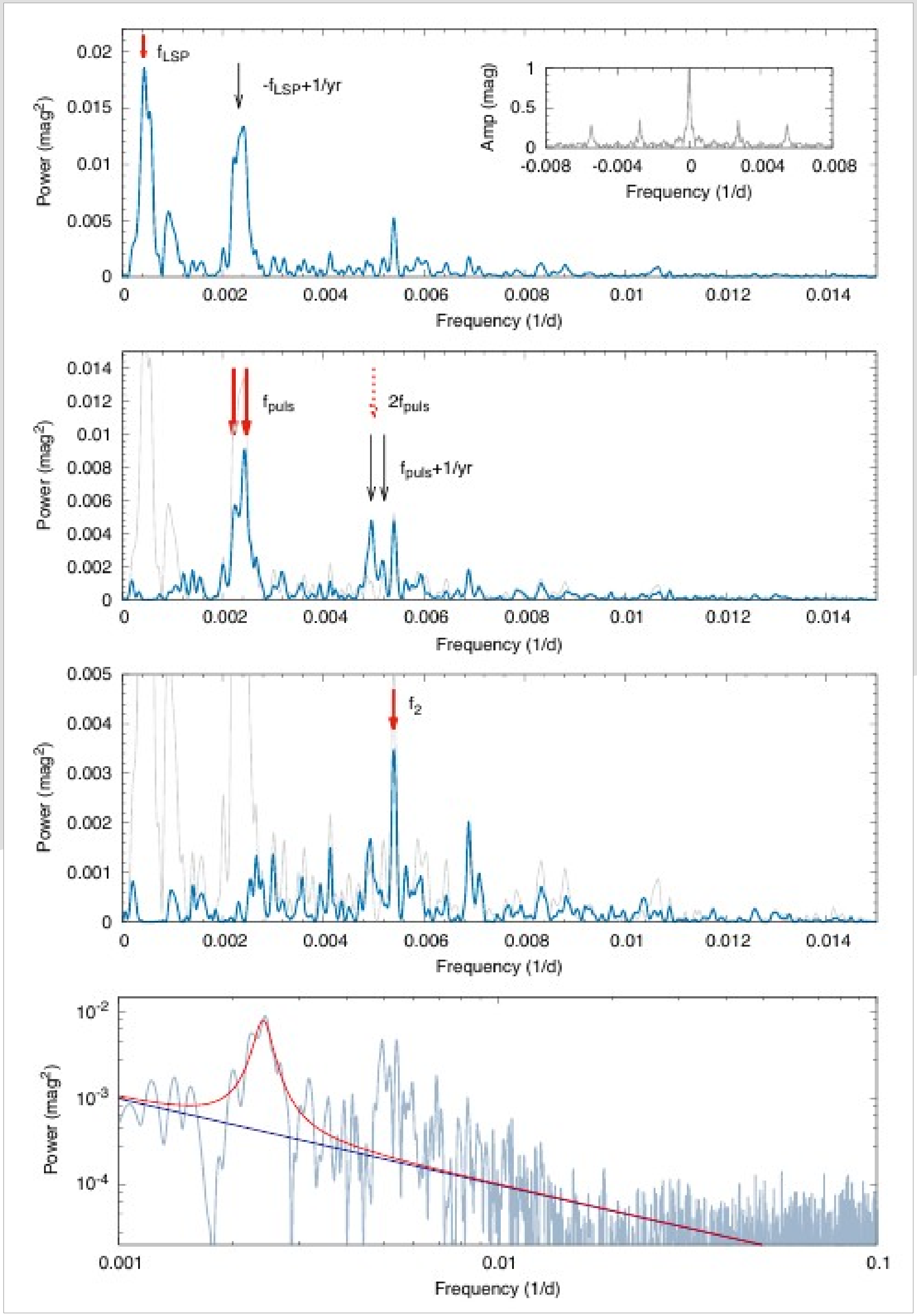
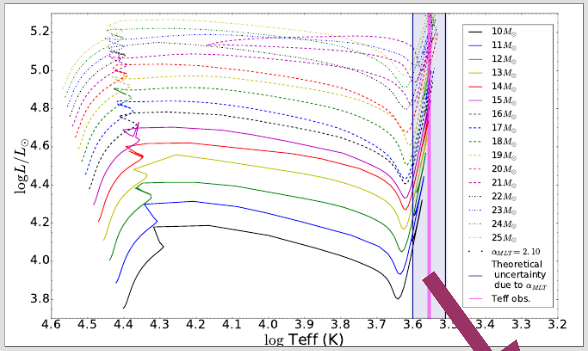
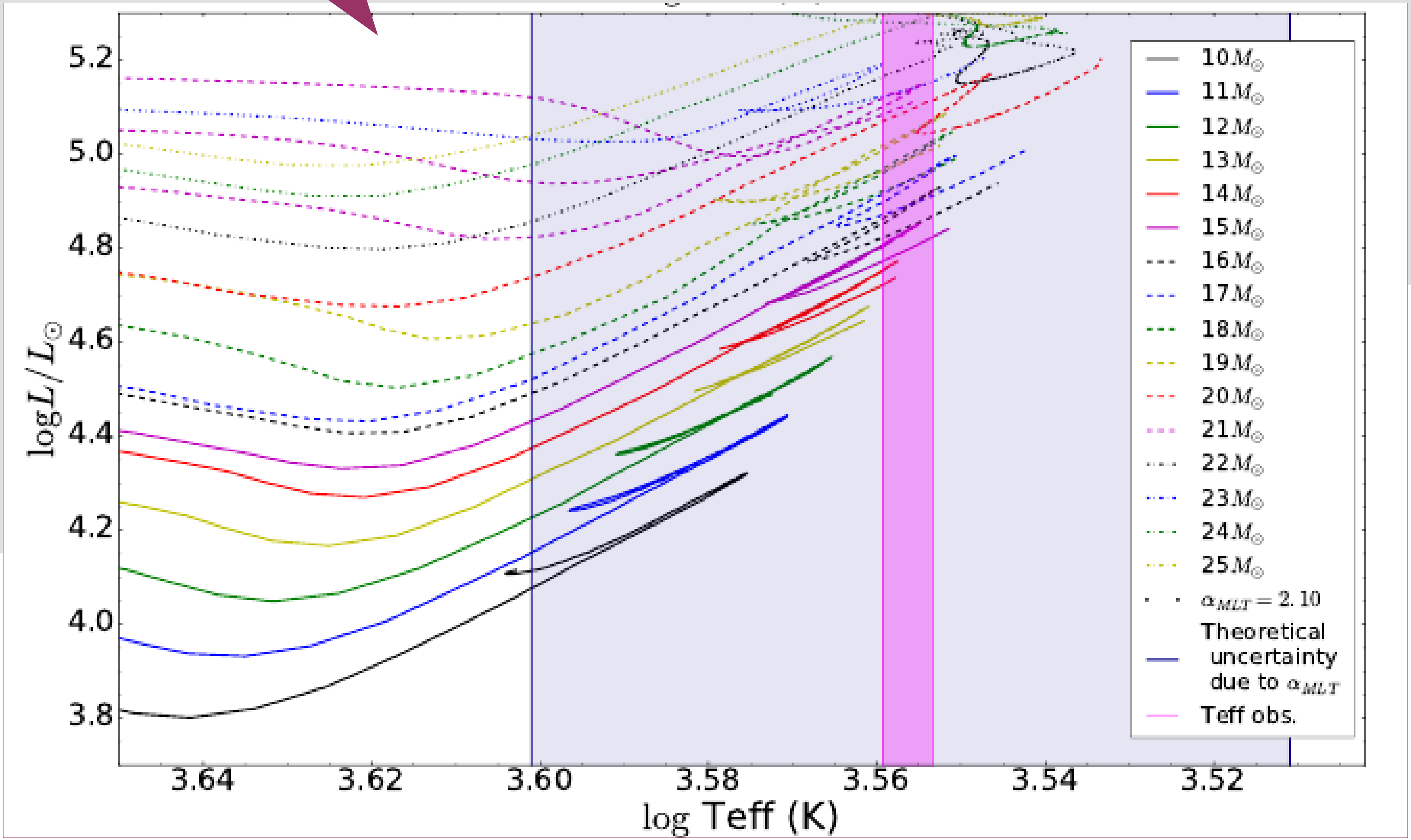
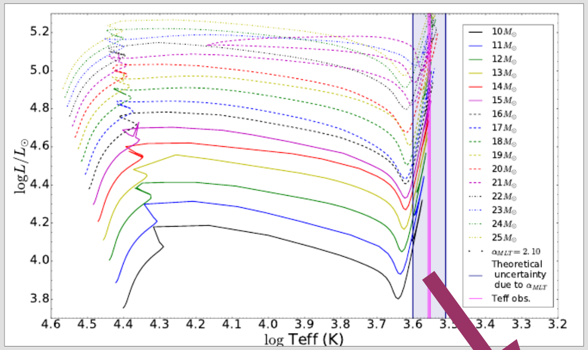


Fig by László Molnár



Observations state 3600 +/- 25 K, yet we can move an evolutionary track by ~350 K just by changing **the convective mixing length** from 1.8x to 2.5x the pressure scale height





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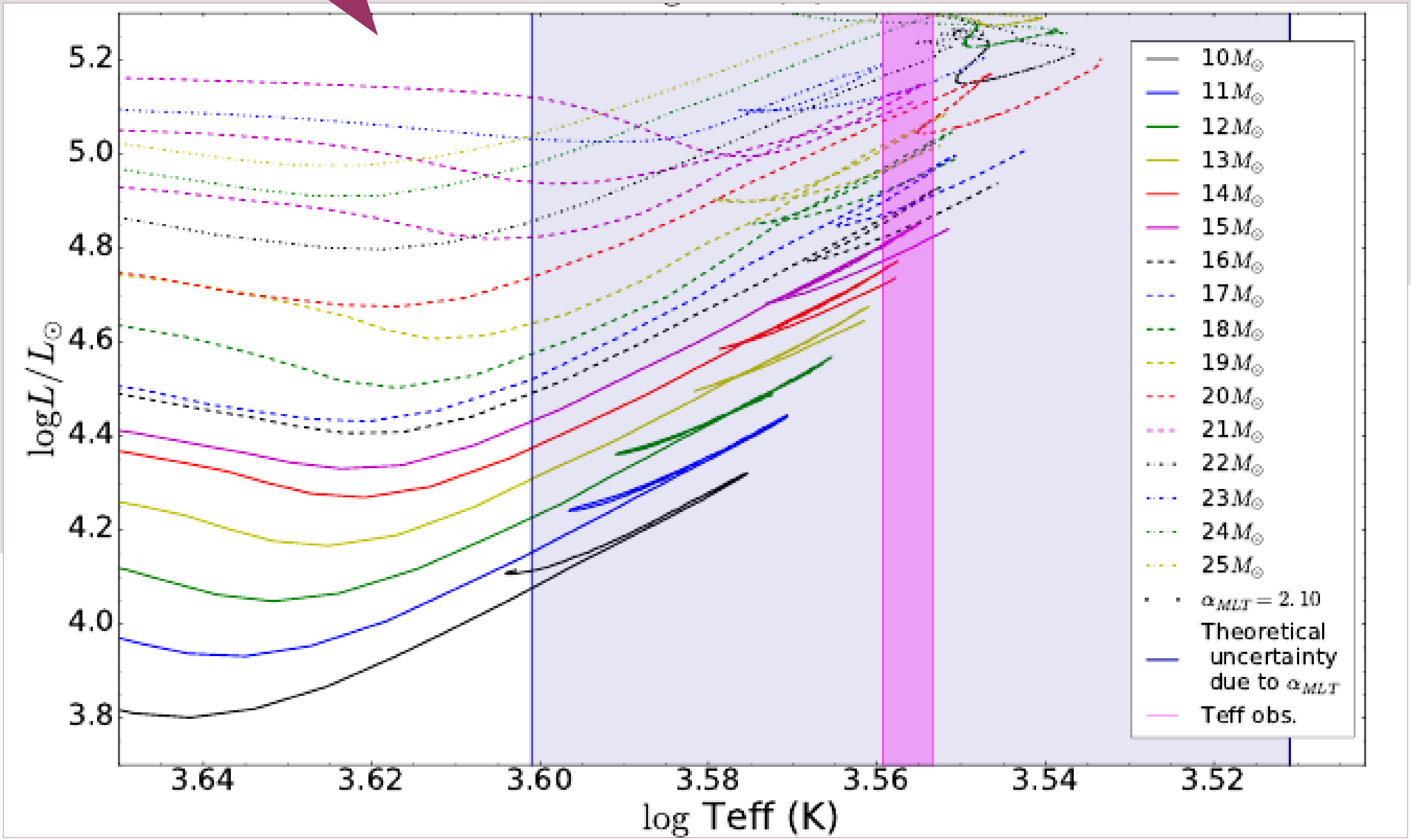
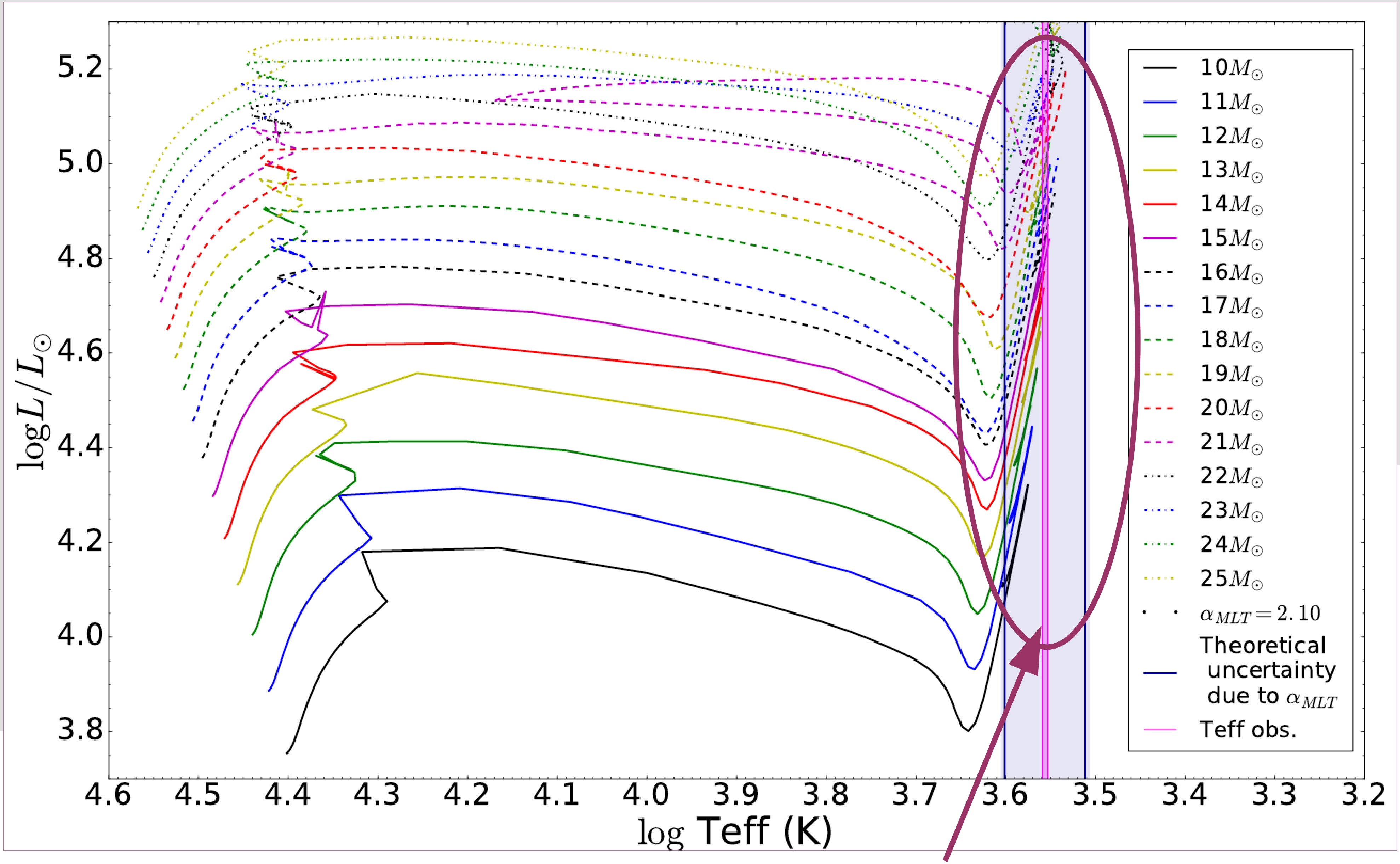
→ need to introduce new interpretation of temperature constraints that account for *ad hoc* modeling choices: region in blue

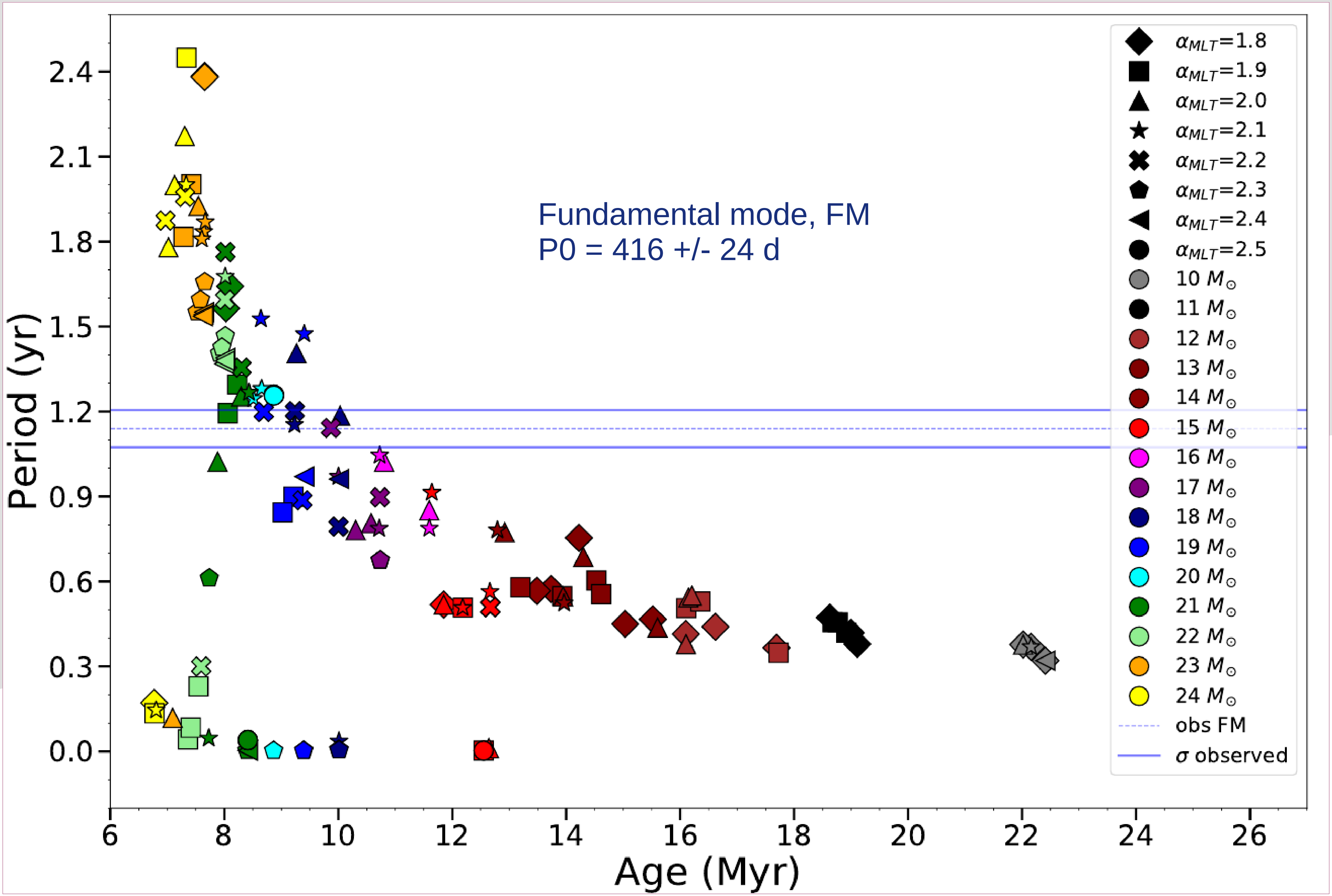


Add in asteroseismology

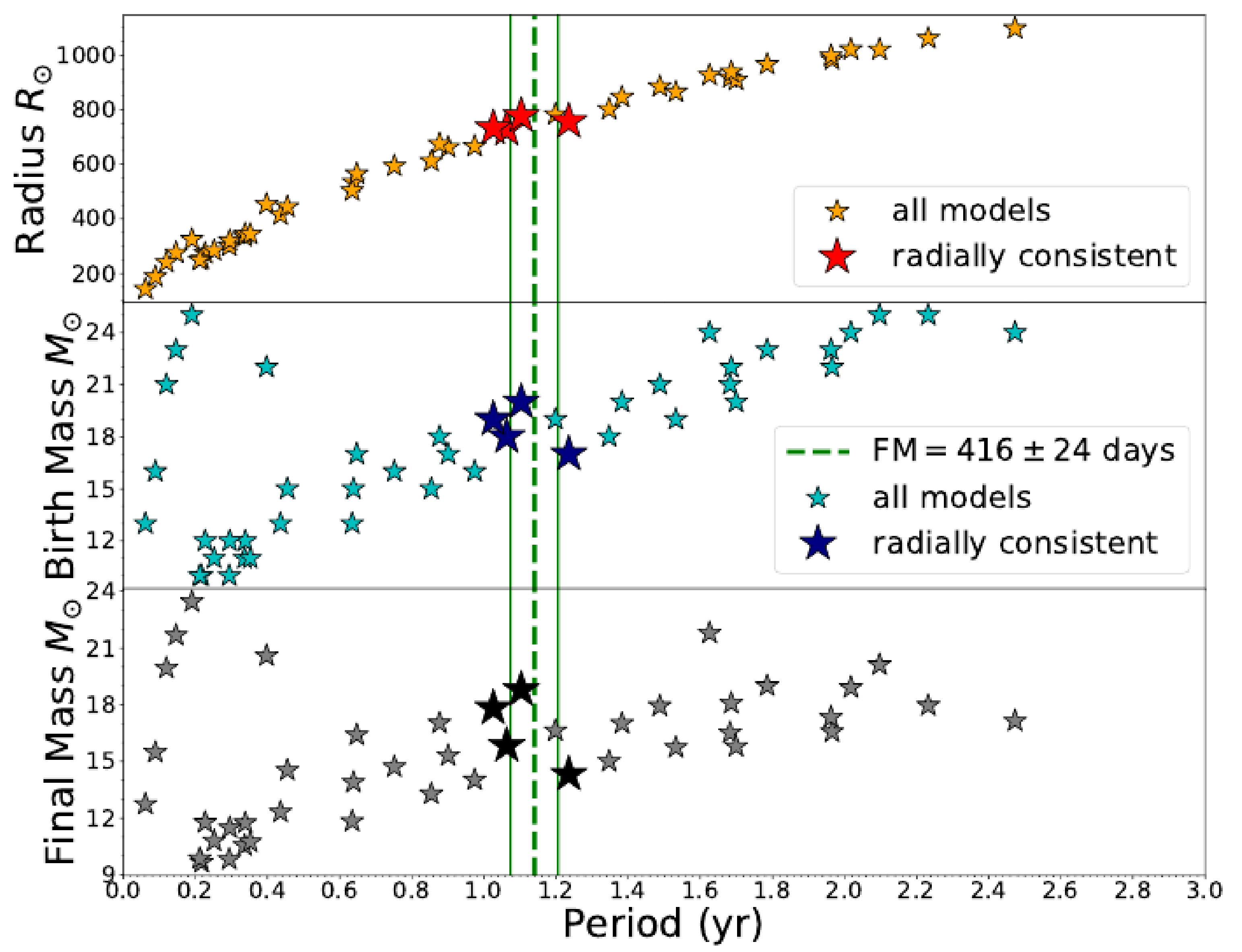


Use GYRE to perform linear seismic analysis on observationally consistent tracks (those which intersect the uncertainty-adjusted Teff constraints)

Determining which models are seismically compatible



This method constrains Betelgeuse's physical radius ...even more tightly than the traditional interferometry + parallax method



Graph 2: Fundamental mode; fixed mixing length

Classical & Seismic results:

General finding: on the (initial) mass of Betelgeuse, our results are consistent with other modeling efforts; not particularly more precise: 18-24 Msolar

...but our models permit only a **very small range** for the physical radius: a 3σ band of 150 Rsolar

In fact, this range is considerably smaller than predictions for the physical radius provided by traditional observational methods (interferometry + parallax)!

Unanticipated Bonus:
precision modelled radius + measured angular diameter
= new parallax distance estimate

Seismic parallax!!

Revised distance from seismic parallax

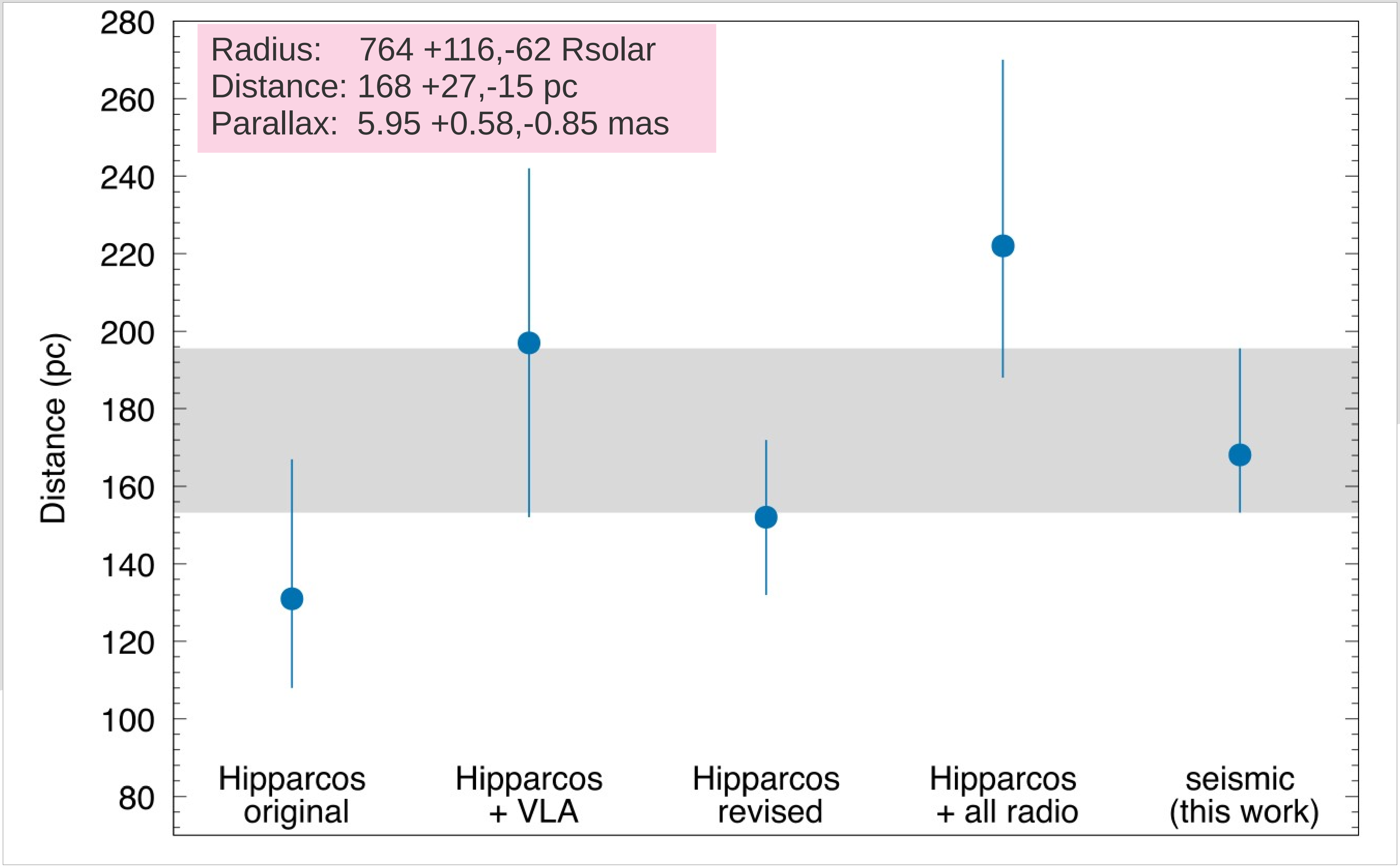


Fig by László Molnár

Ultra bonus content: you can do statistics for sociology of science, too

Gender Disparity in Publishing Six Months after the KITP Workshop *Probes of Transport in Stars*

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ABSTRACT

Conferences and workshops shape scientific discourse. The Kavli Institute for Theoretical Physics (KITP) hosts long-term workshops to stimulate scientific collaboration that would not otherwise have taken place. One goal of KITP programs is to increase diversity in the next generation of scientists.

arXiv: 2206.10617 (also published in PASP)

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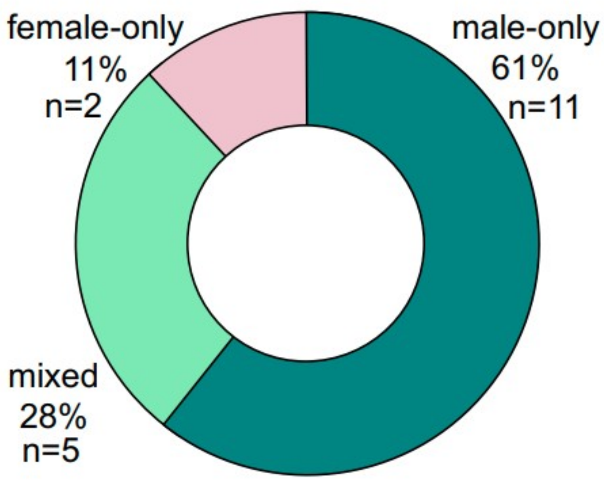
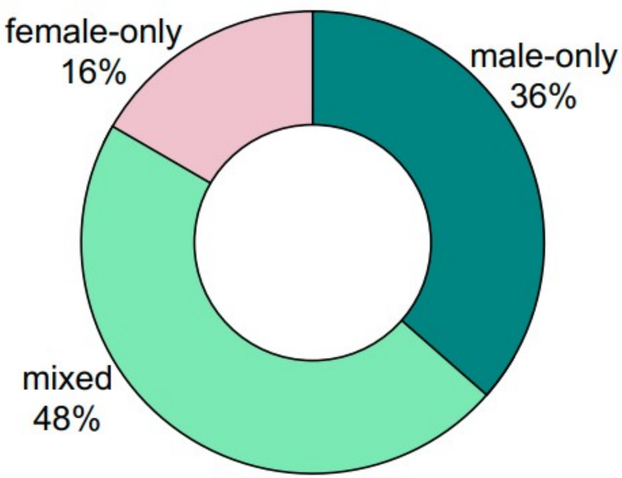
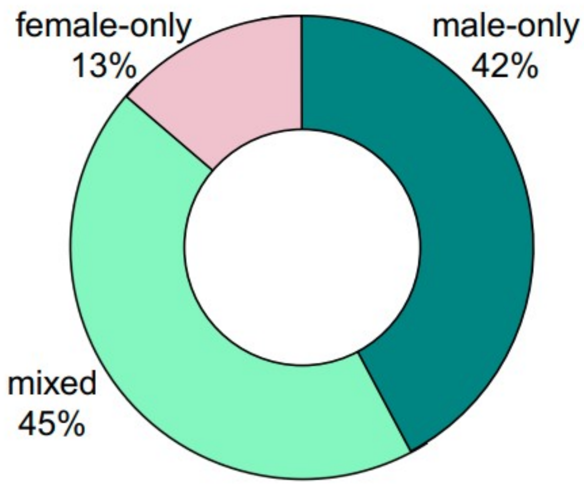


Observed outcome



Predicted by “Random Authors” Model



Predicted by “Random Coauthors” Model

arXiv: 2206.10617 (also published in PASP)

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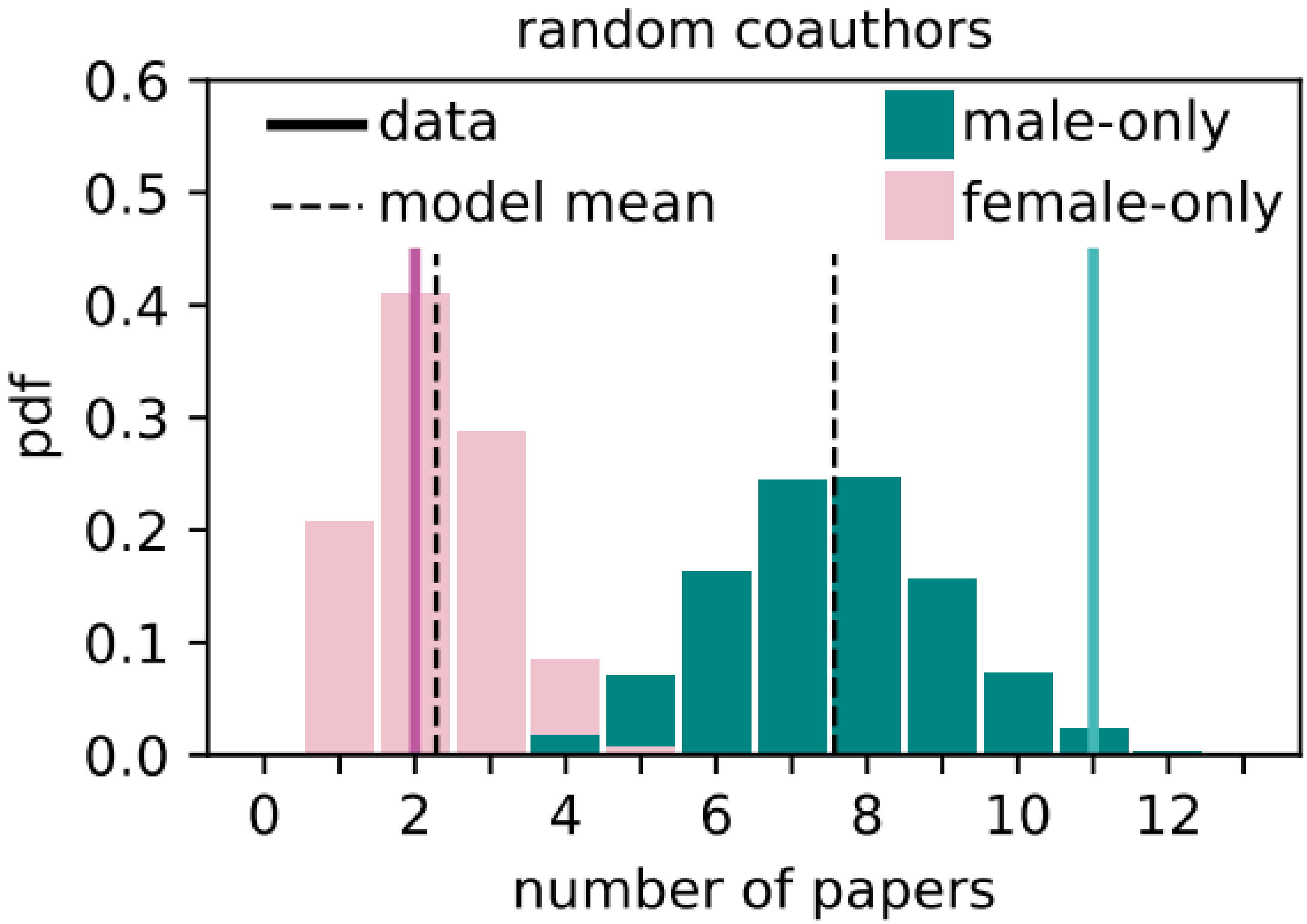

The number of observed all-female* papers is about the same as predicted by our (most generous) model, whereas the number of observed all-male* papers is highly outlying (p<0.05)

(see paper for detailed discussion of assumptions)

*genders as reported by participants; “non-binary” and “another not included” options were available


Fin
Tack

Bulge Age Conclusions: reprise

Bensby+ 2017 (Yale isochrones) find a large population of metal-rich, young stars in the bulge, suggesting prolonged star formation in the region, which is in conflict with previous/other understanding of the formation history of the Galaxy

Joyce (me)+ 2022 (MIST isochrones) do not find a large constituency of metal-rich young stars in this region, despite using Bensby+2017's parameters verbatim

There is no significant discrepancy between the physical assumptions adopted between both isochrone databases, nor can differences in alpha-abundance scale explain the striking difference in derived age distributions

Bensby+2017's age distribution is statistically consistent with a uniform distribution across 1 to 15 Gyr, whereas Joyce+2022 finds a clear peak at 13 Gyr and a median of 10.8 Gyr.

While still showing some slight age spread, Joyce+2022 results are **more consistent with photometric analyses of this region** despite being **based on the same spectroscopic, microlensed sample** analyzed in Bensby+2017

Have we resolved the spectroscopic/photometric tension? Not entirely, but careful application of statistics puts the picture in better focus

Ages are hard! Be careful with math.