# The Ages of Stars and Other Stories:

## Redefining the Standard for 1D Stellar Modeling

Smith College Research Talk

~~8~~ 15 December, 2022

@MeridithJoyceGR

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Dr Meridith Joyce

Marie Curie Widening Fellow: MATISSE
CSFK Konkoly Observatory, Budapest

MESA Developers

# About Me:

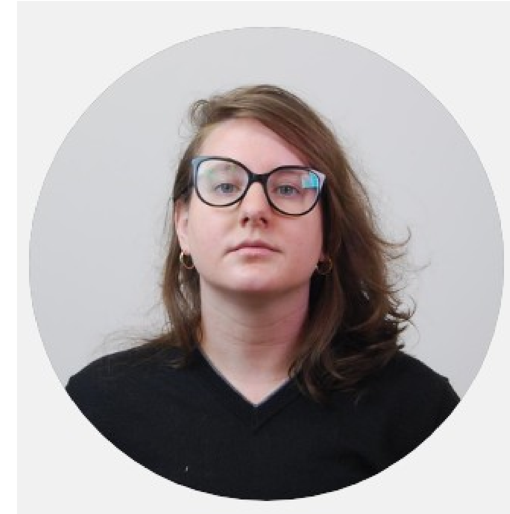
## Aspiring international sensation

I have enjoyed work and life all over the world, and now I’m working on a Marie Curie (WF) in Europe!

# About Me:

## Astronomy software developer

Modules for Experiments in Stellar Astrophysics (MESA)




MESA

GYRE

1D 3D
MESA2HYDRO

# About Me:

Part-time D-list science celebrity

SKY&TELESCOPE
THE ESSENTIAL GUIDE TO ASTRONOMY

TOOLS COMMUNITY

STELLAR SCIENCE

## HOW BIG IS BETELGEUSE REALLY?

BY: MONICA YOUNG | NOVEMBER 6, 2020 | 12

Knowing Betelgeuse's size is crucial to understanding its recent bizarre behavior — and predicting when it will go su

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## Red supergiant Betelgeuse not so bright, not so giant, not so far away

CNN World Africa Americas Asia Australia China Europe India Middle East United Kingdom Edition

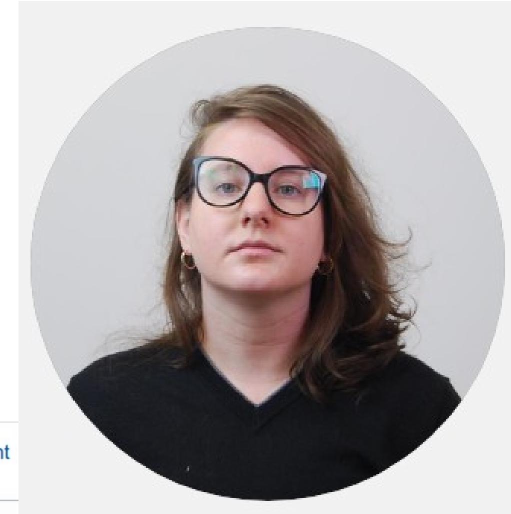
SPACE + SCIENCE

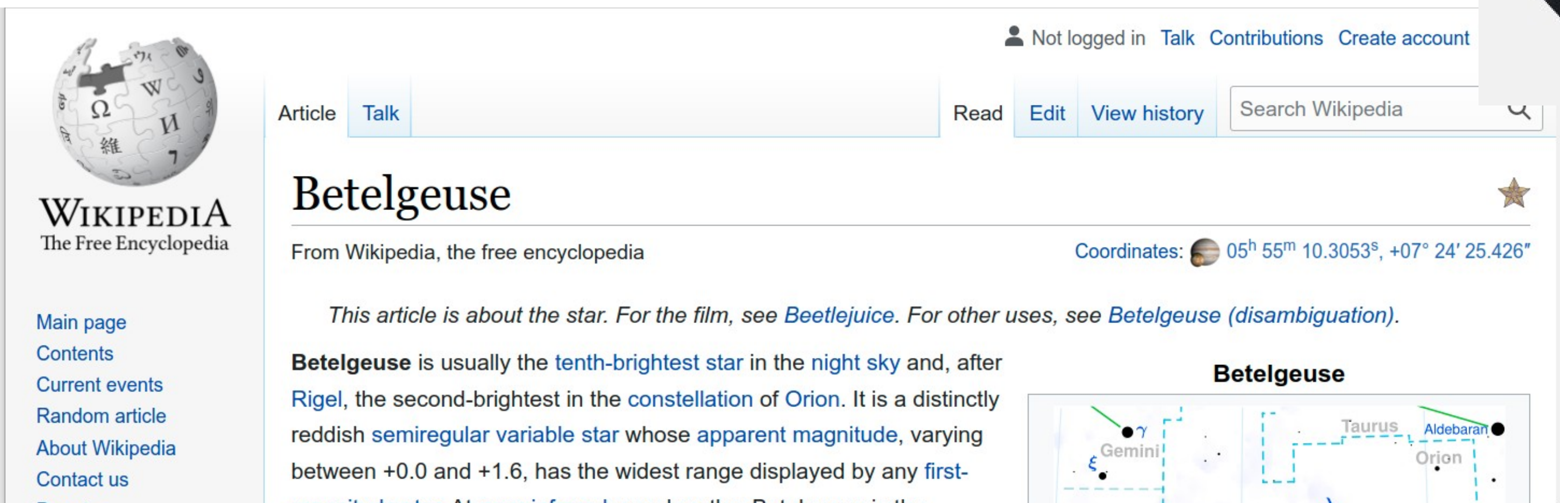
## Betelgeuse, the unusually dimming star, is smaller and closer than scientists thought

By Ashley Strickland, CNN
Updated 1640 GMT (0040 HKT) October 19, 2020

# About Me:

...and dubious Wikipedia source!





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# Betelgeuse

From Wikipedia, the free encyclopedia

Coordinates: $05^h\ 55^m\ 10.3053^s$, +07° 24′ 25.426″

*This article is about the star. For the film, see Beetlejuice. For other uses, see Betelgeuse (disambiguation).*

**Betelgeuse** is usually the tenth-brightest star in the night sky and, after Rigel, the second-brightest in the constellation of Orion. It is a distinctly reddish semiregular variable star whose apparent magnitude, varying between +0.0 and +1.6, has the widest range displayed by any first-magnitude star. At near-infrared wavelengths, Betelgeuse is the

**Betelgeuse**



In 2020, new observational data from the space-based *Solar Mass Ejection Imager* aboard the Coriolis satellite and three different modeling techniques produced a refined parallax of $5.95^{+0.58}_{-0.85}$ mas, a radius of $764^{+116}_{-62}\,R_\odot$, and a distance of $168.1^{+27.5}_{-14.4}$ pc or $548^{+90}_{-49}$ ly, which, if accurate, would mean Betelgeuse is nearly 25% smaller and 25% closer to Earth than previously thought.[11]

All of astronomy and cosmology hinges on results from stellar models.

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No matter what you study, your work likely relies on results from stellar models

# But this should concern you...

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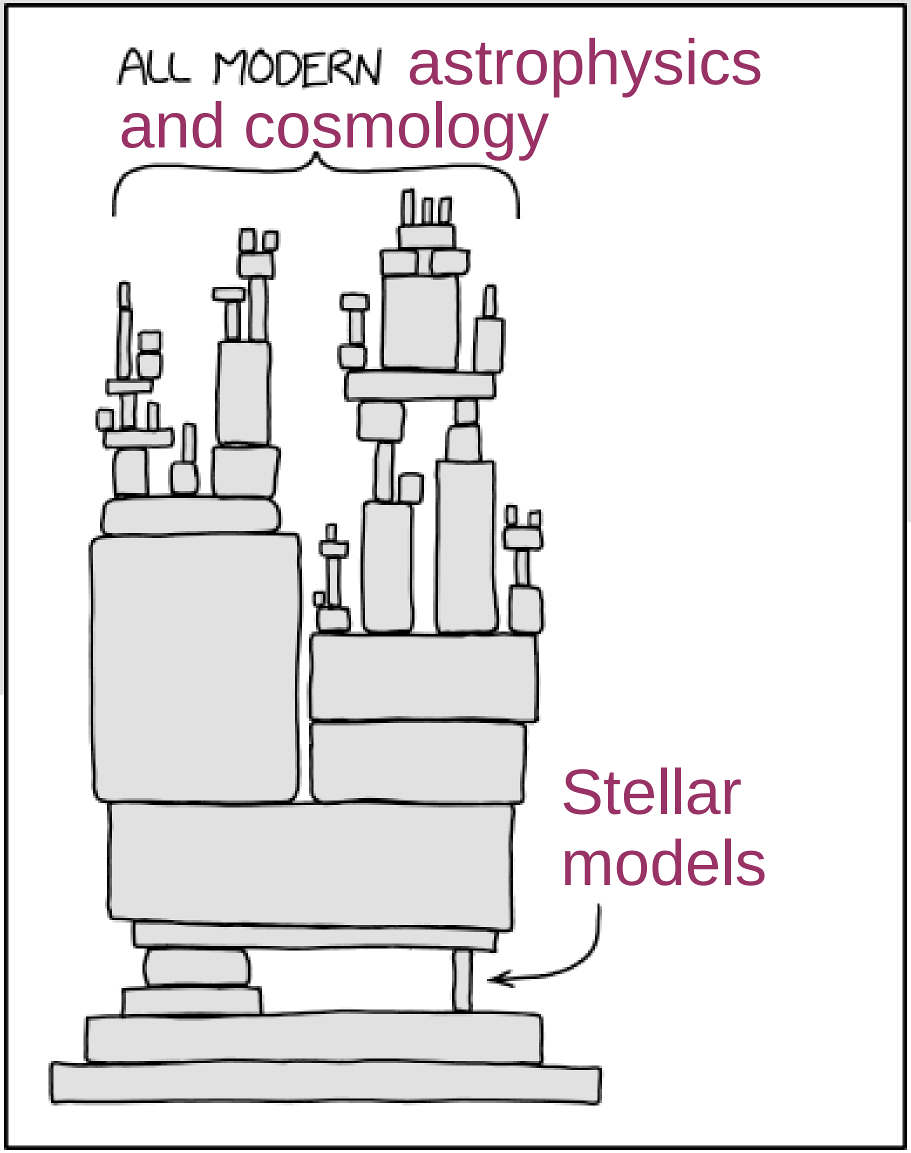



Source: modified from XKCD’s “Dependency”

Together, we can fix them.

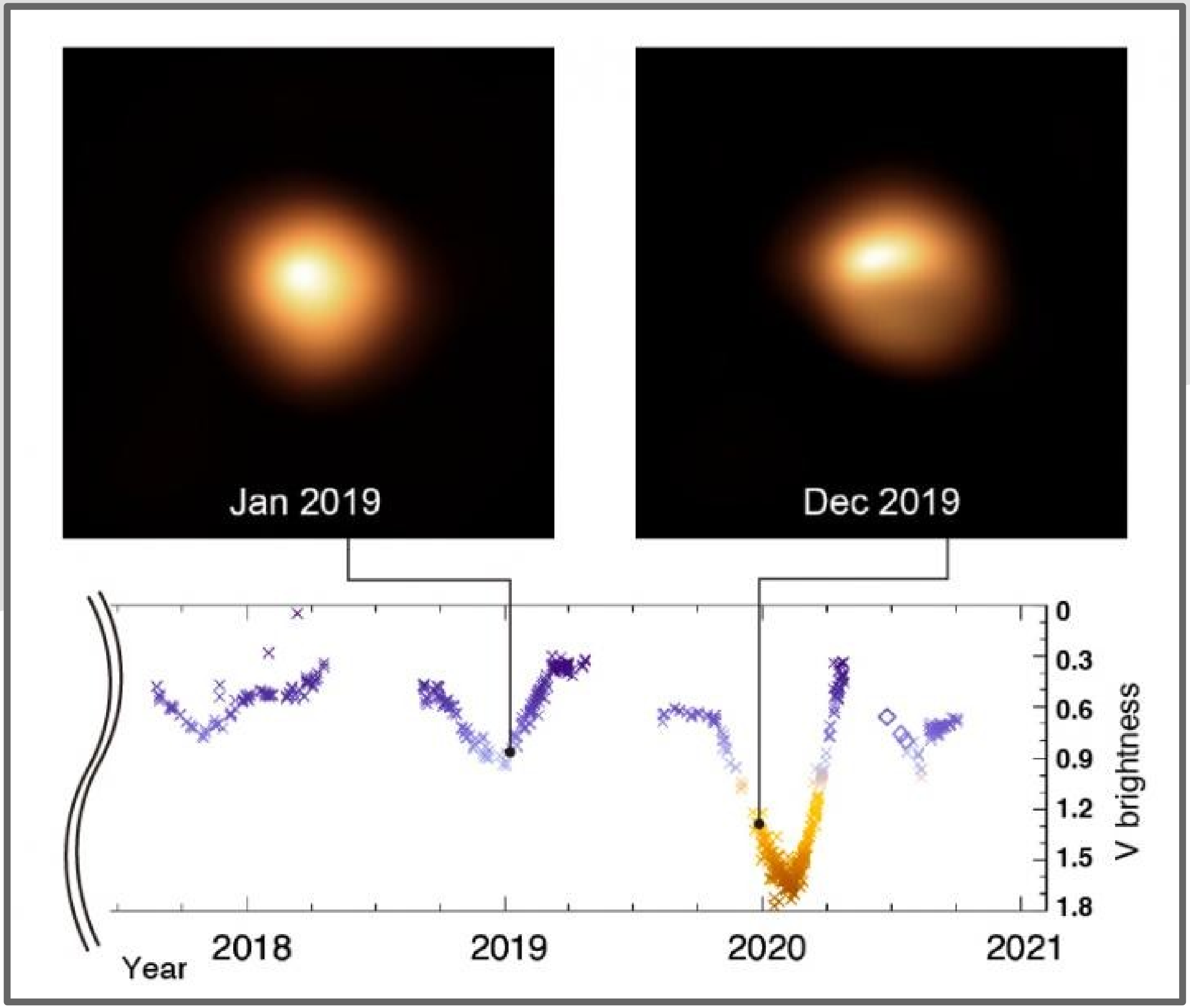
# The power of stellar models and statistical inference in practice: determining the fundamental properties of

# Betelgeuse

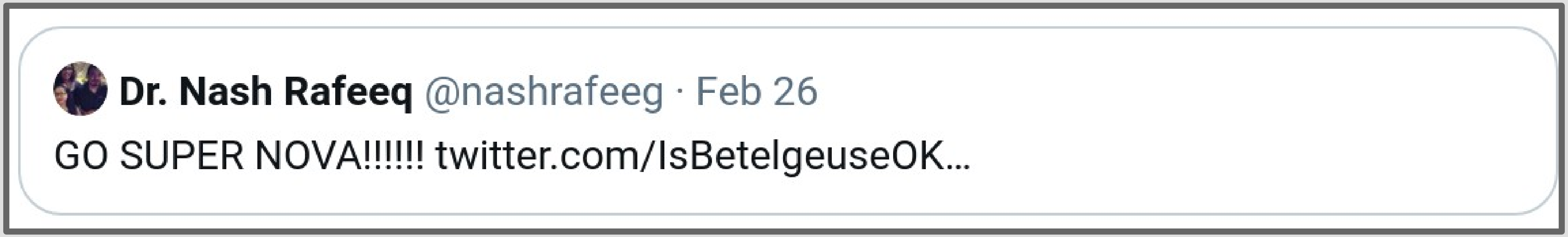
*Standing on the shoulders of giants: New mass and distance estimates for Betelgeuse through a combination of evolutionary, asteroseismic, and hydrodynamical simulations with MESA*

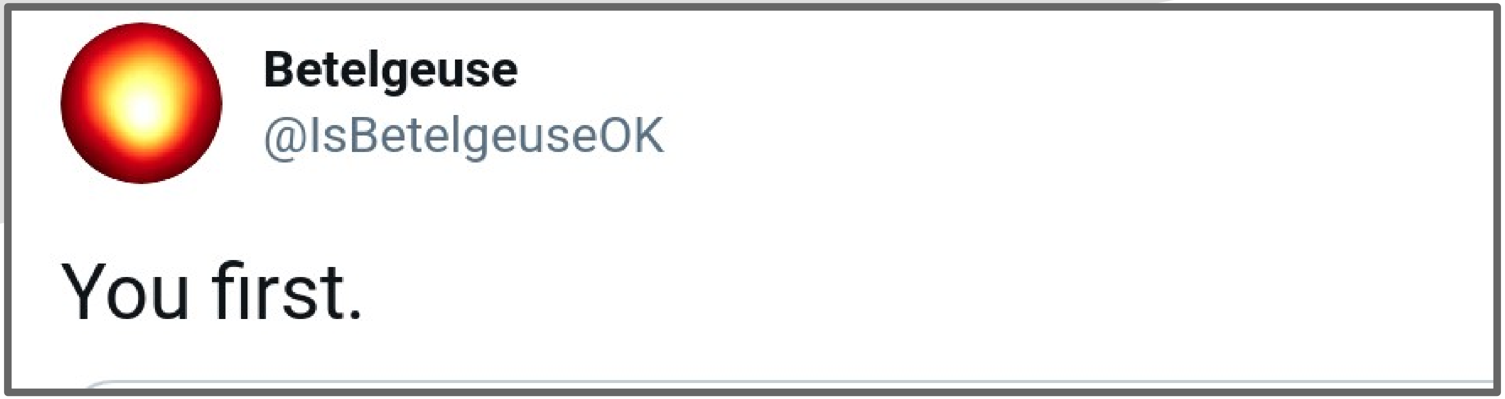
**Meridith Joyce,** Shing-Chi Leung, László Molnár,
Michael J. Ireland, Chiaki Kobayashi, and Ken'ichi Nomoto
**ApJ**, *2020*

# From November 2019 to January 2020, Betelgeuse underwent a huge brightness drop—The “Great Dimming”



# Such severe brightness changes are thought to precede supernovae



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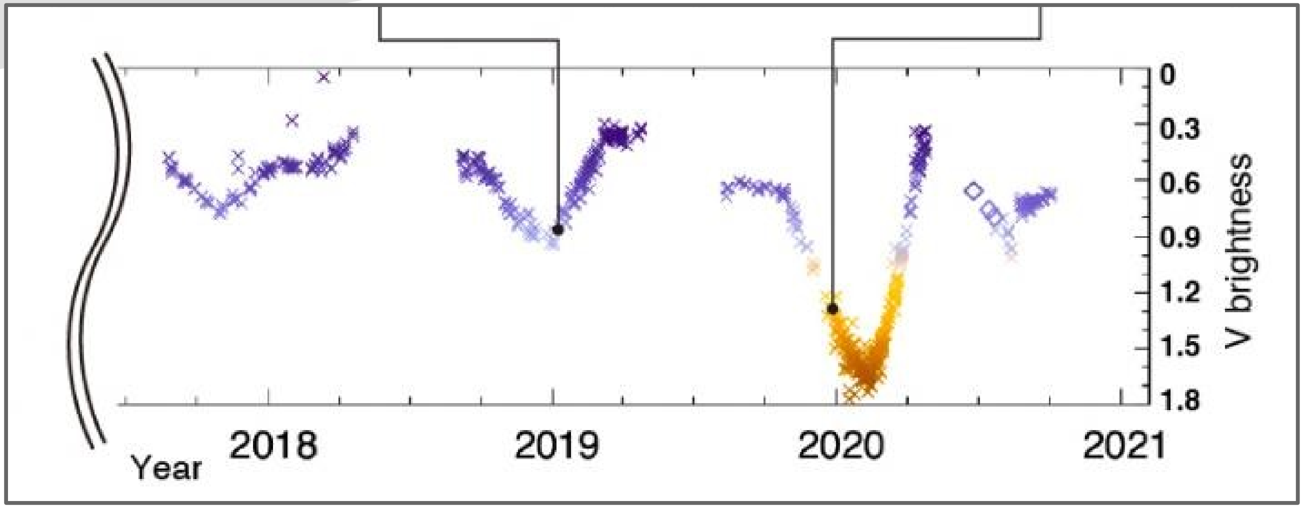
**My approach:** reproduce this lightcurve via simulation to understand why Betelgeuse became dim or rule out causes



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**My approach:** 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

# Key tools:

MESA

*Modules for Experiments in Stellar Astrophysics*
Generates structural, evolutionary, hydrodynamic models

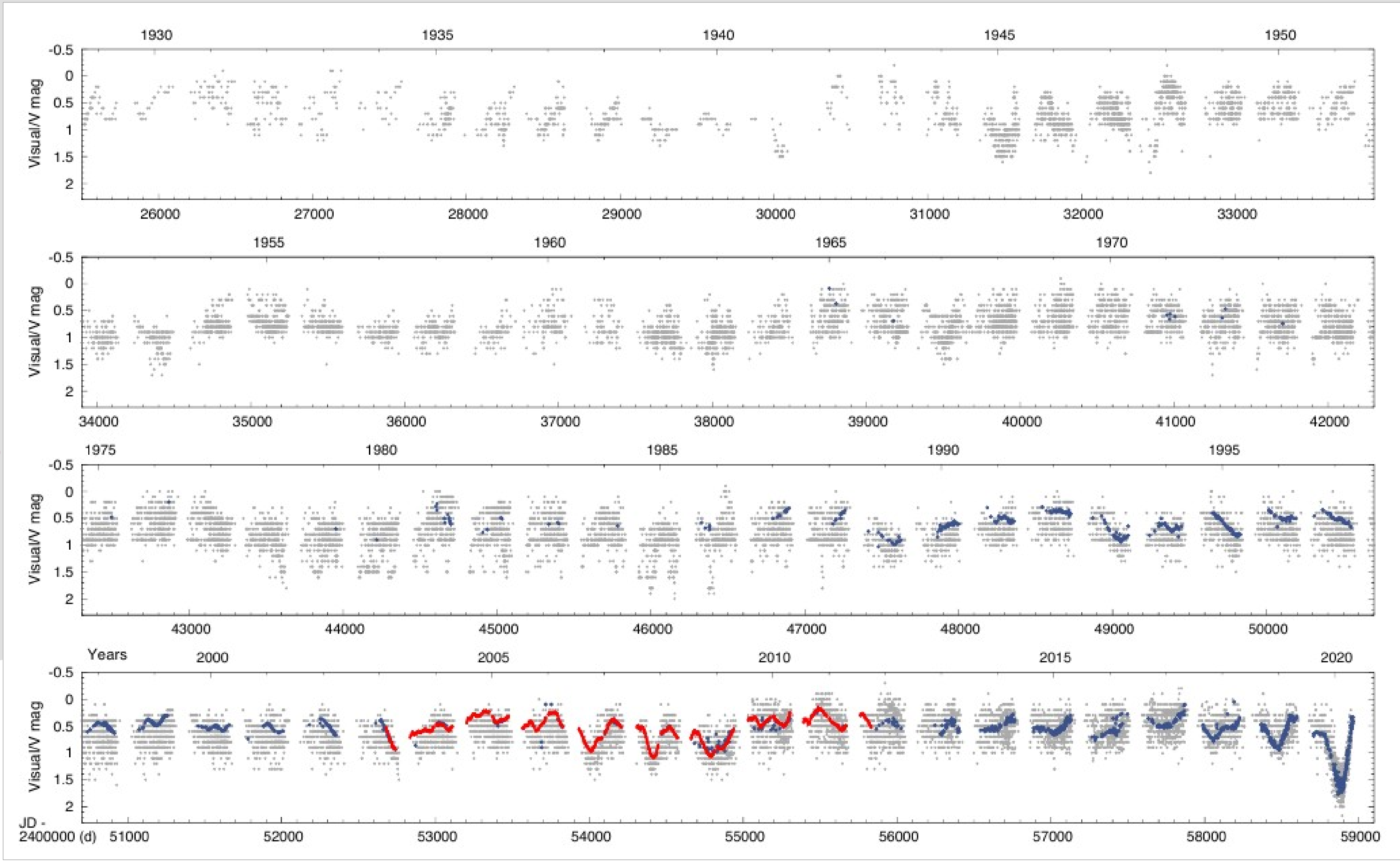
GYRE

Solves the oscillation equations to predict a body's response to perturbations, generating a theoretical frequency spectrum

→ in this case, the "body" is a model of **Betelgeuse**

# Part 1: Observational analysis
# Betelgeuse's brightness variability over 100 years

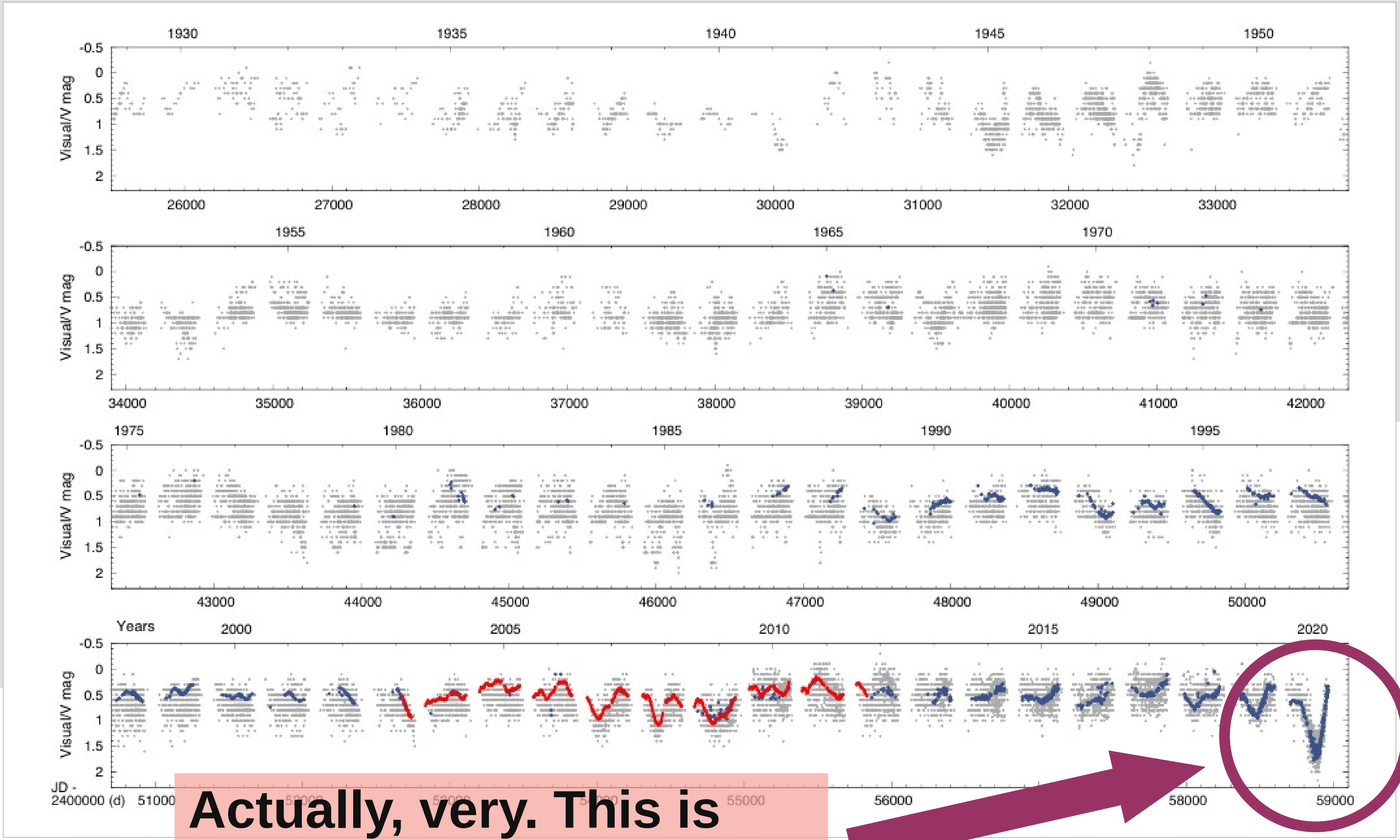
Brightness




Time

Fig by László Molnár

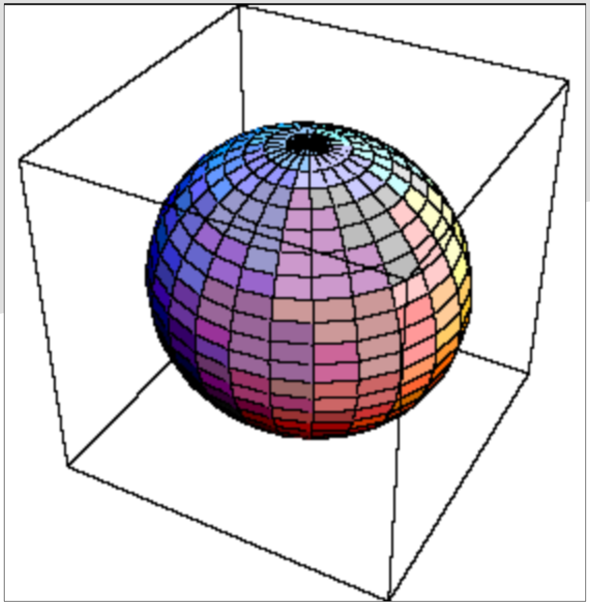
# The ‘unprecedented’ dimming of Betelgeuse
# -First question: How unprecedented, *really*?

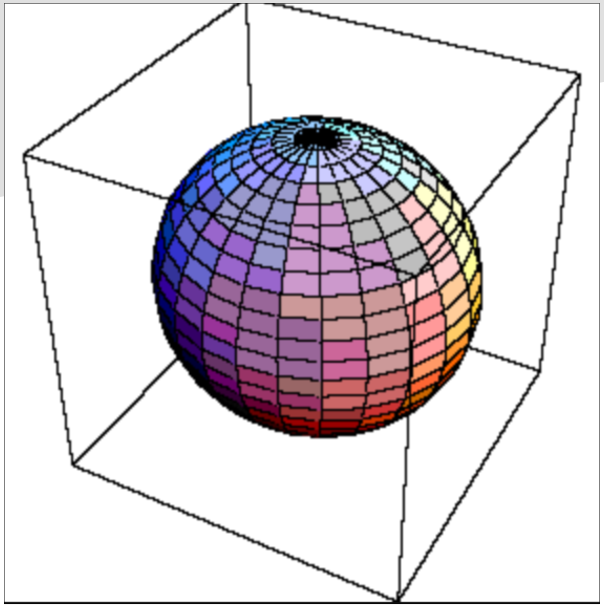


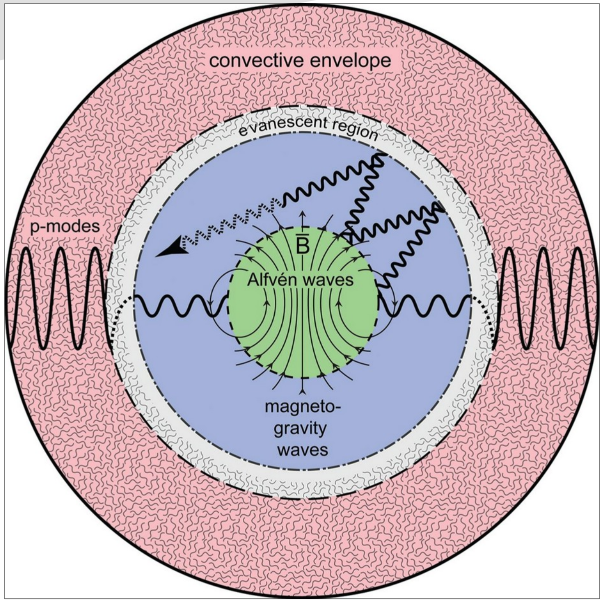

**Actually, very. This is the dimmest it’s been in nearly 100 years**

# Key Concept: Stars pulsate!

They “ring” like bells, in response to physical mechanisms causing waves inside them







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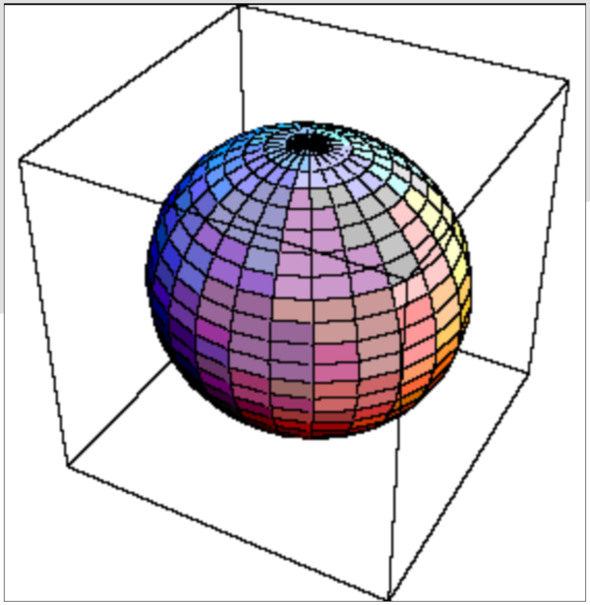
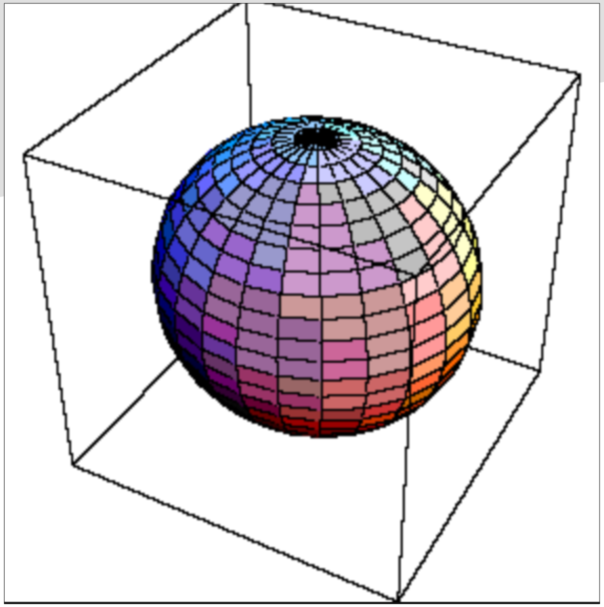
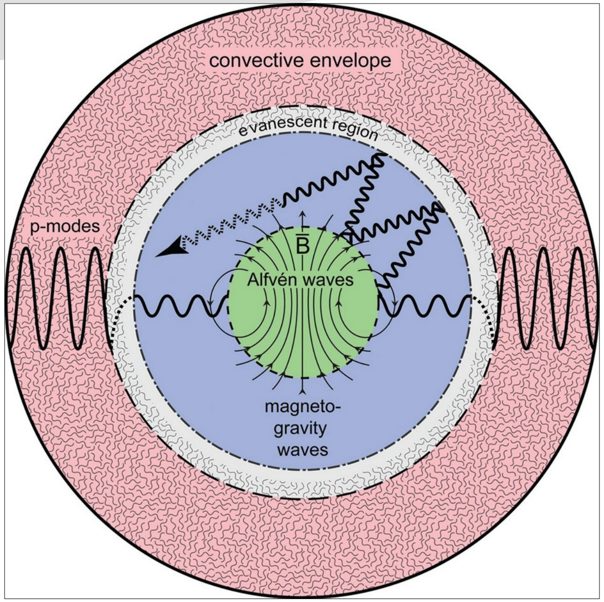
The frequencies (pitches) at which they ring can tell us what they’re made out of







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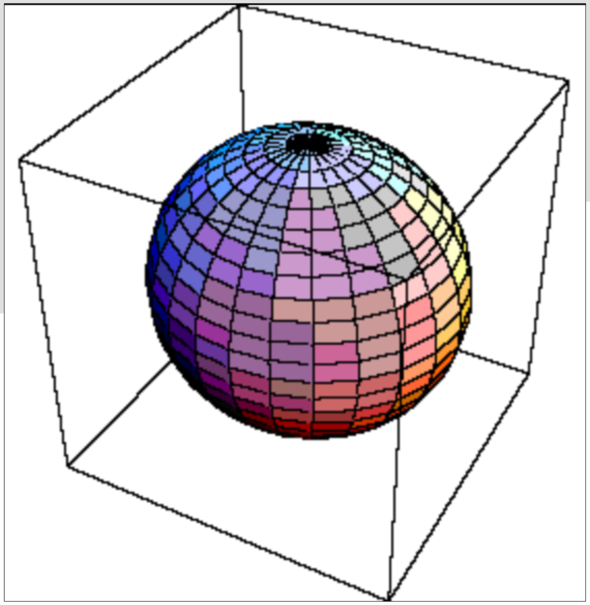
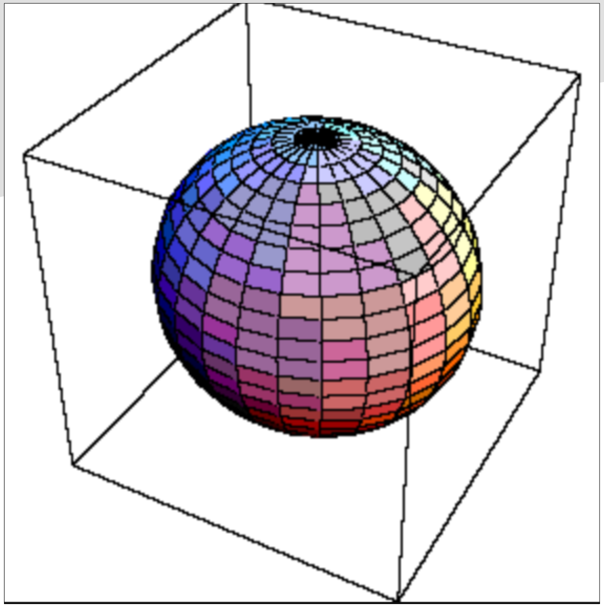
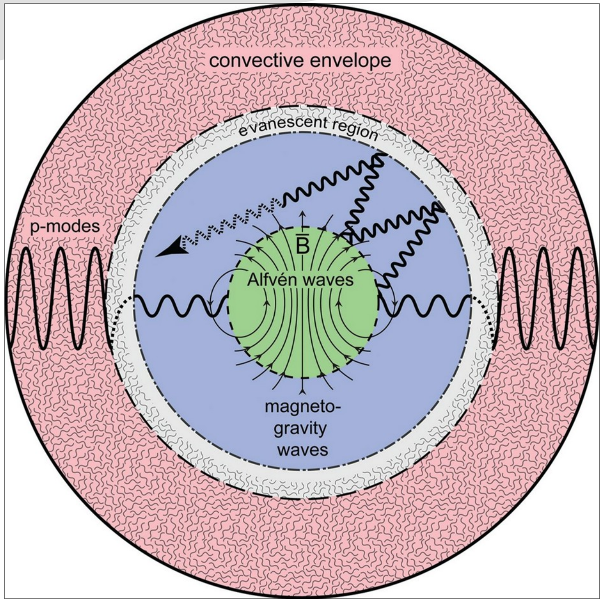
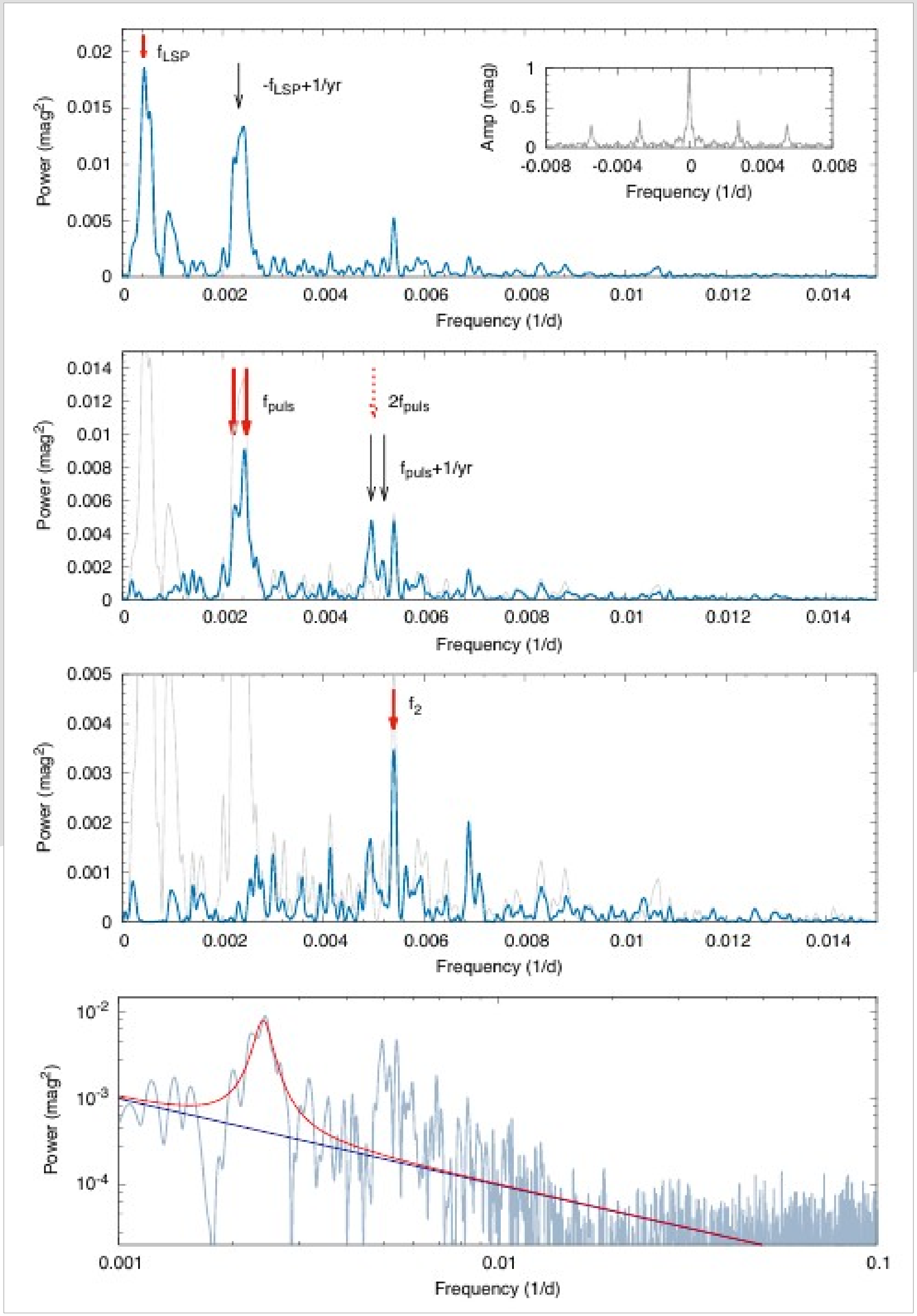
The use of these pulsations to learn about stellar structure is called **asteroseismology**







**Fourier Analysis:** What patterns do we detect in the frequency spectrum?



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From new and archival brightness measurements, we find strong periods at:

**- 416 days**
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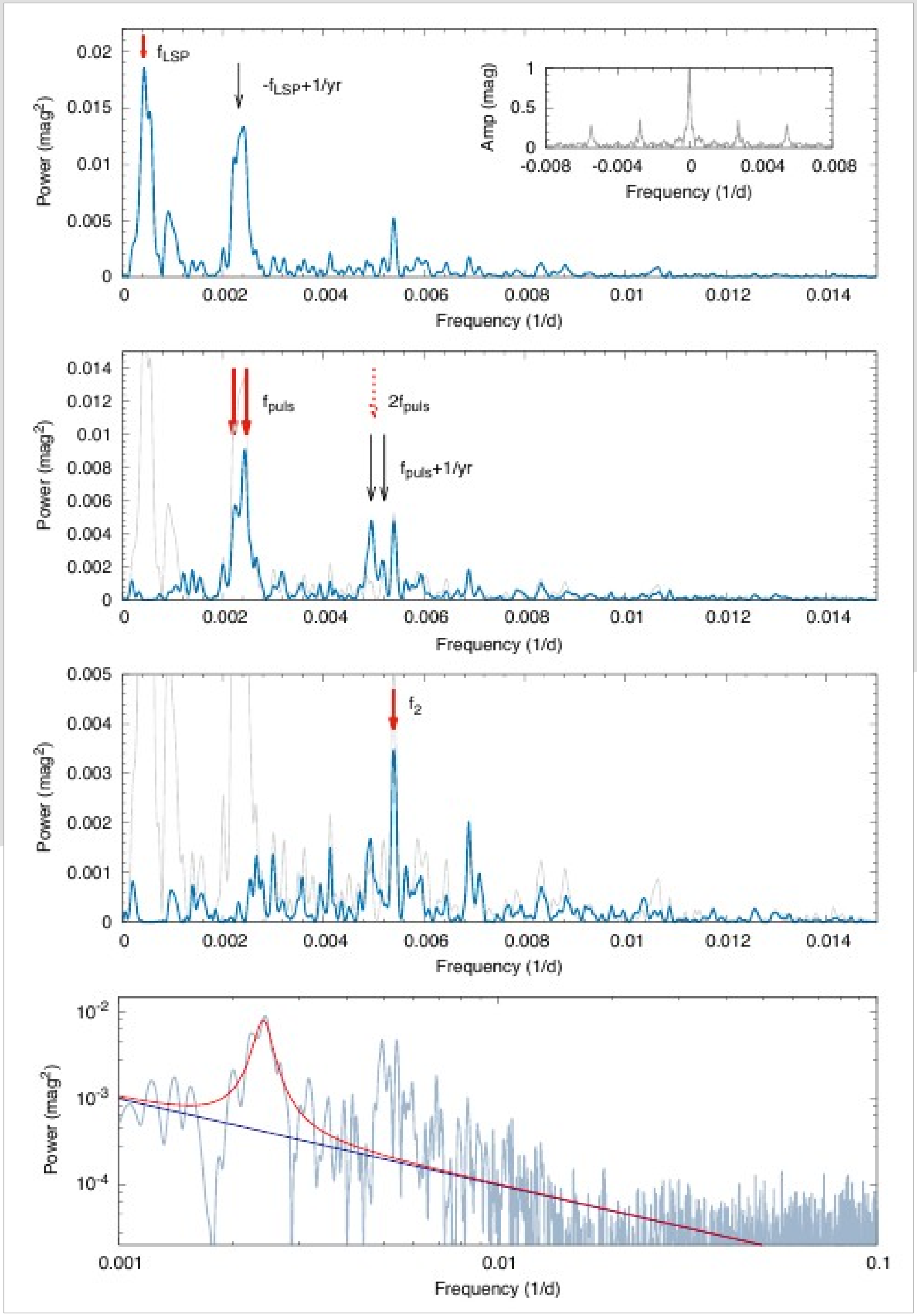
**- 5.6 years**



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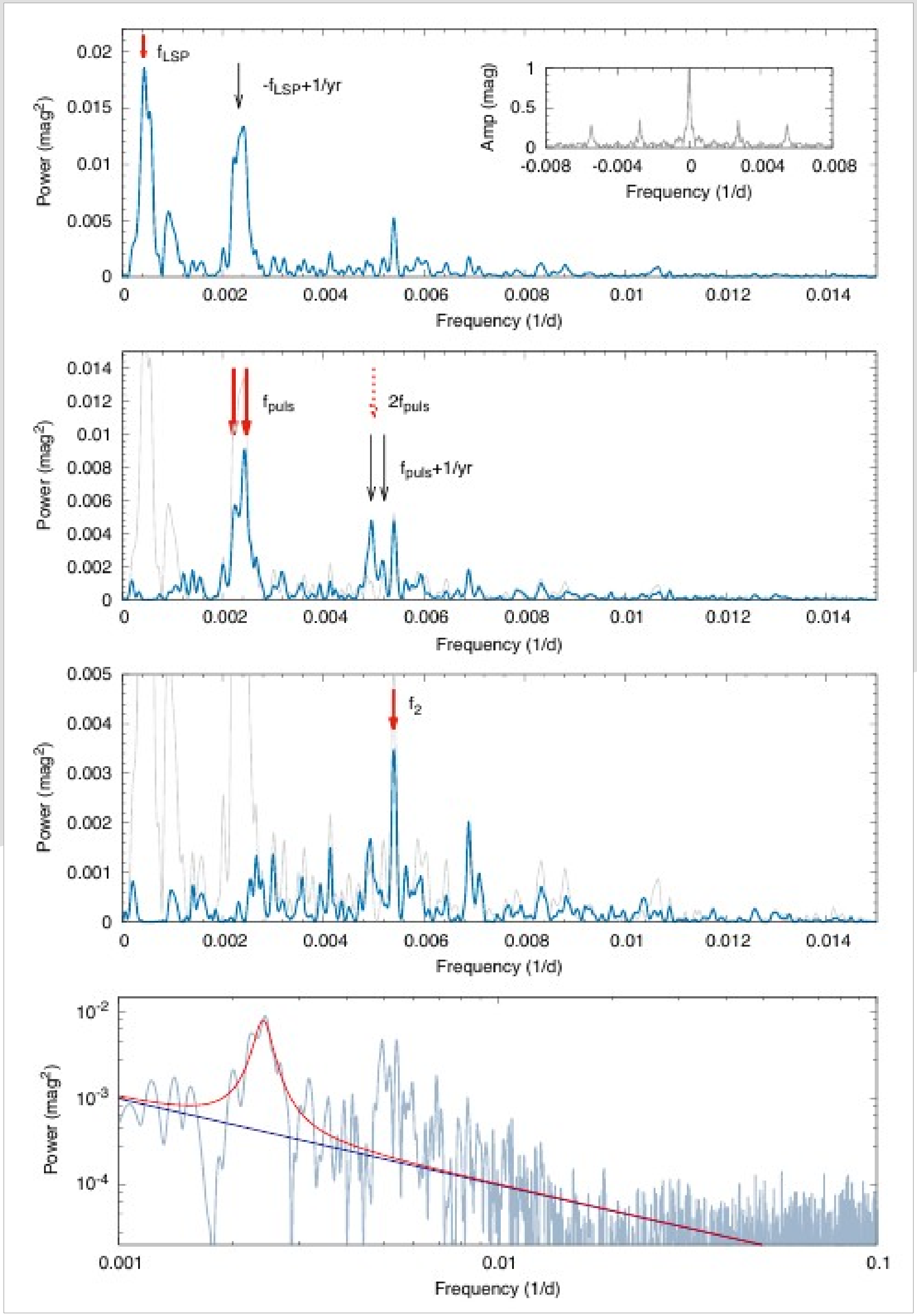

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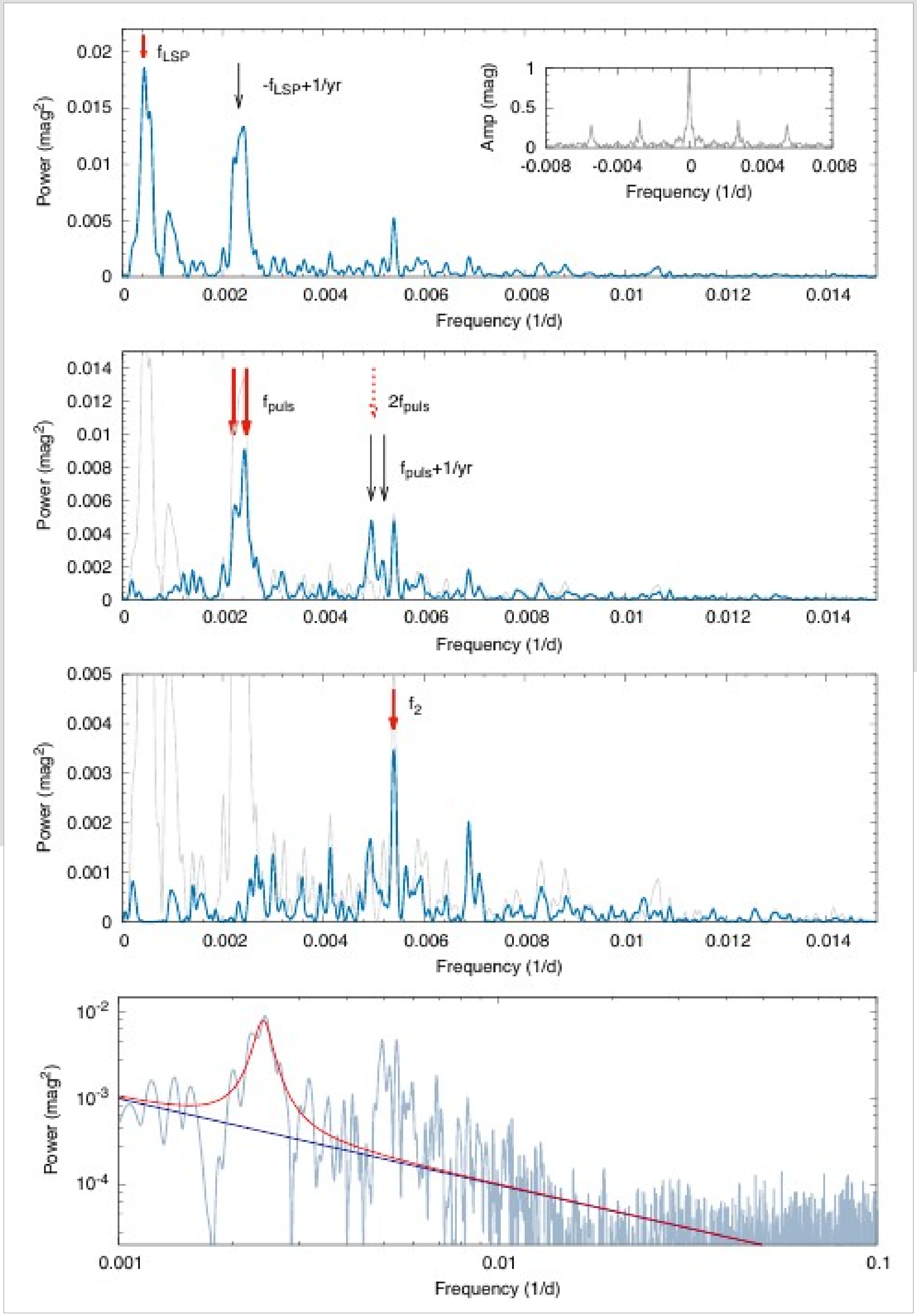
Is the 416-day periodicity a type of frequency called the ***fundamental mode***?



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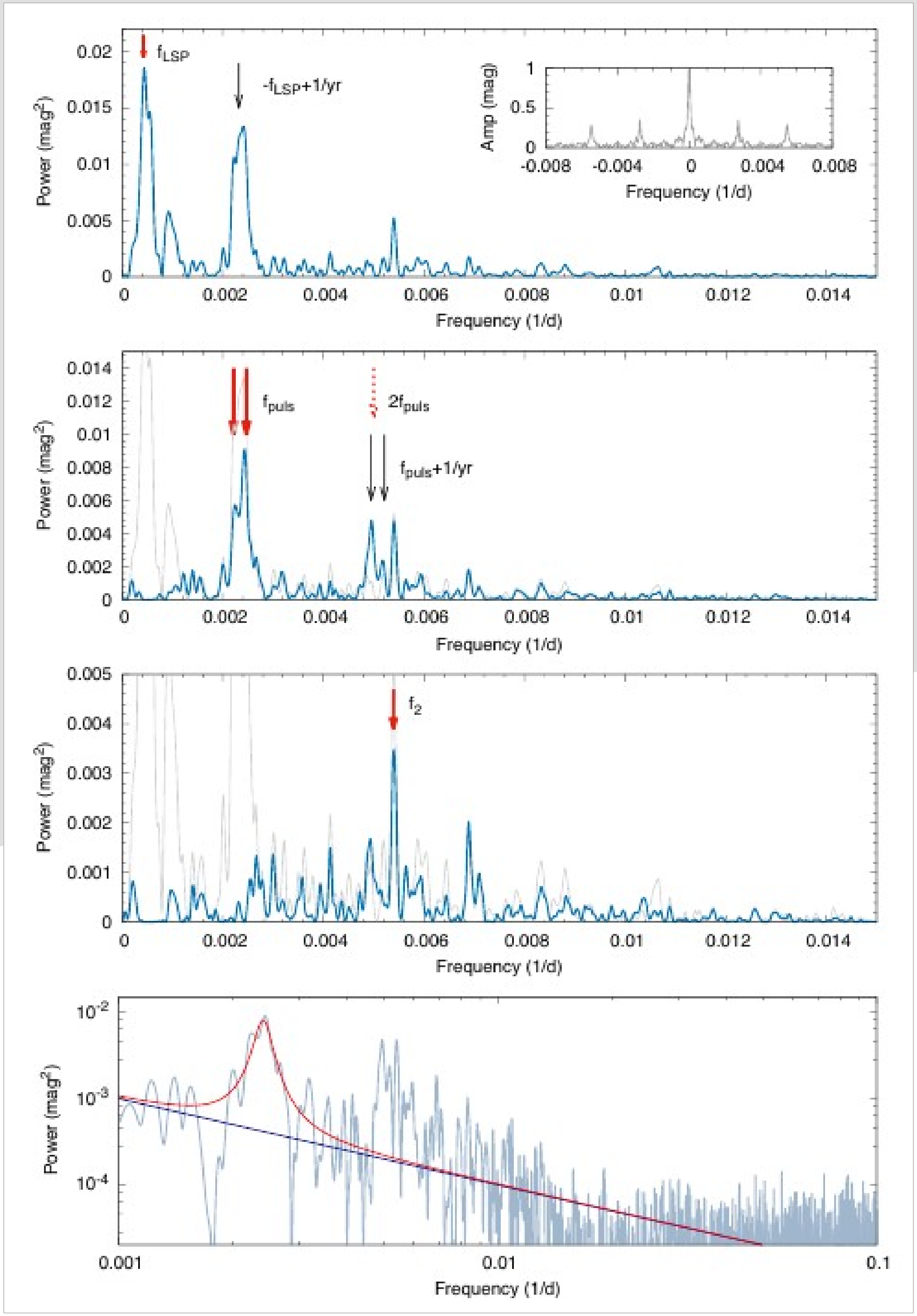

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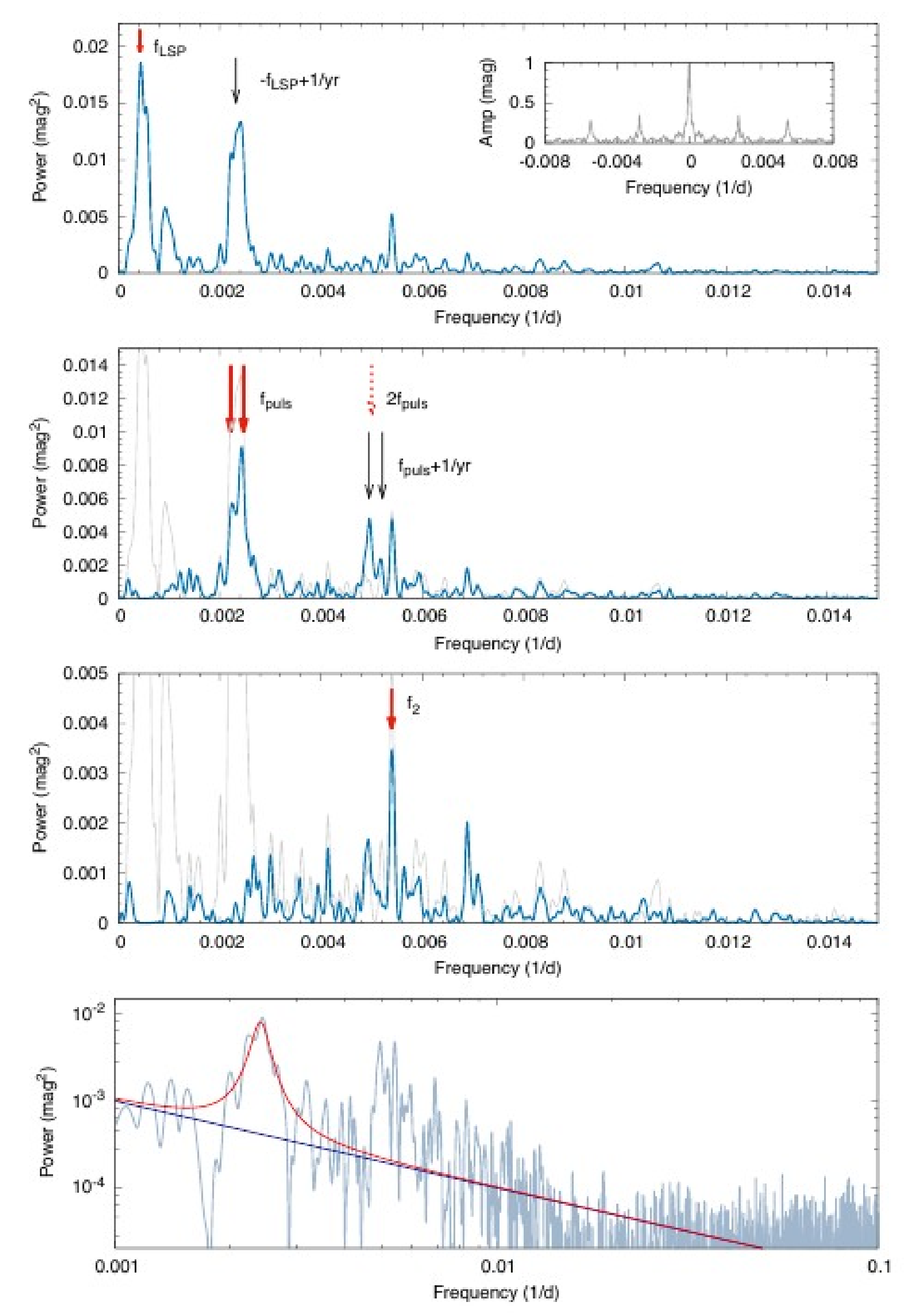
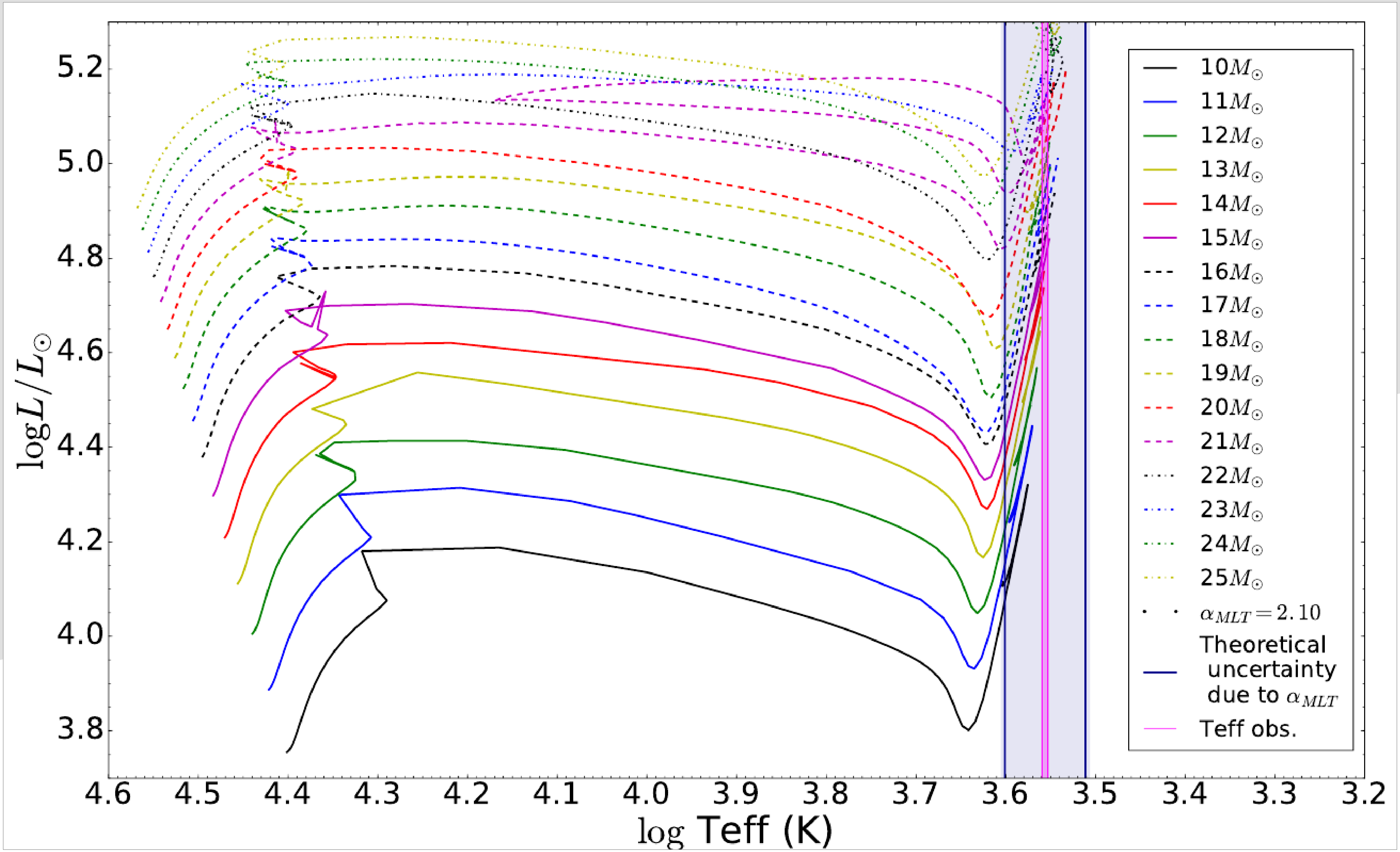
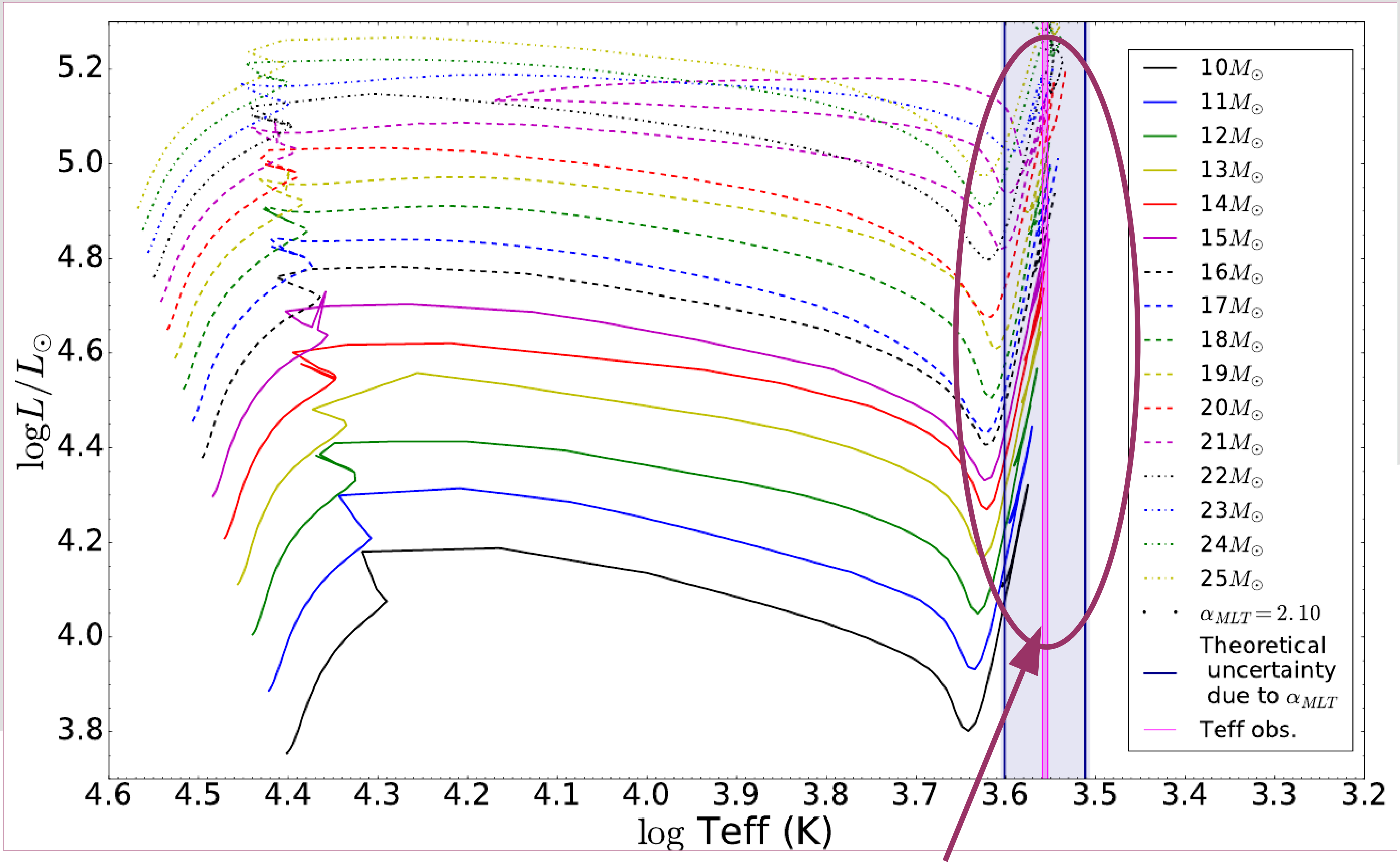
We can answer these questions by determining whether the 416-day periodicity is **driven by the kappa mechanism**



# Step 2: Build evolutionary models that agree with observations

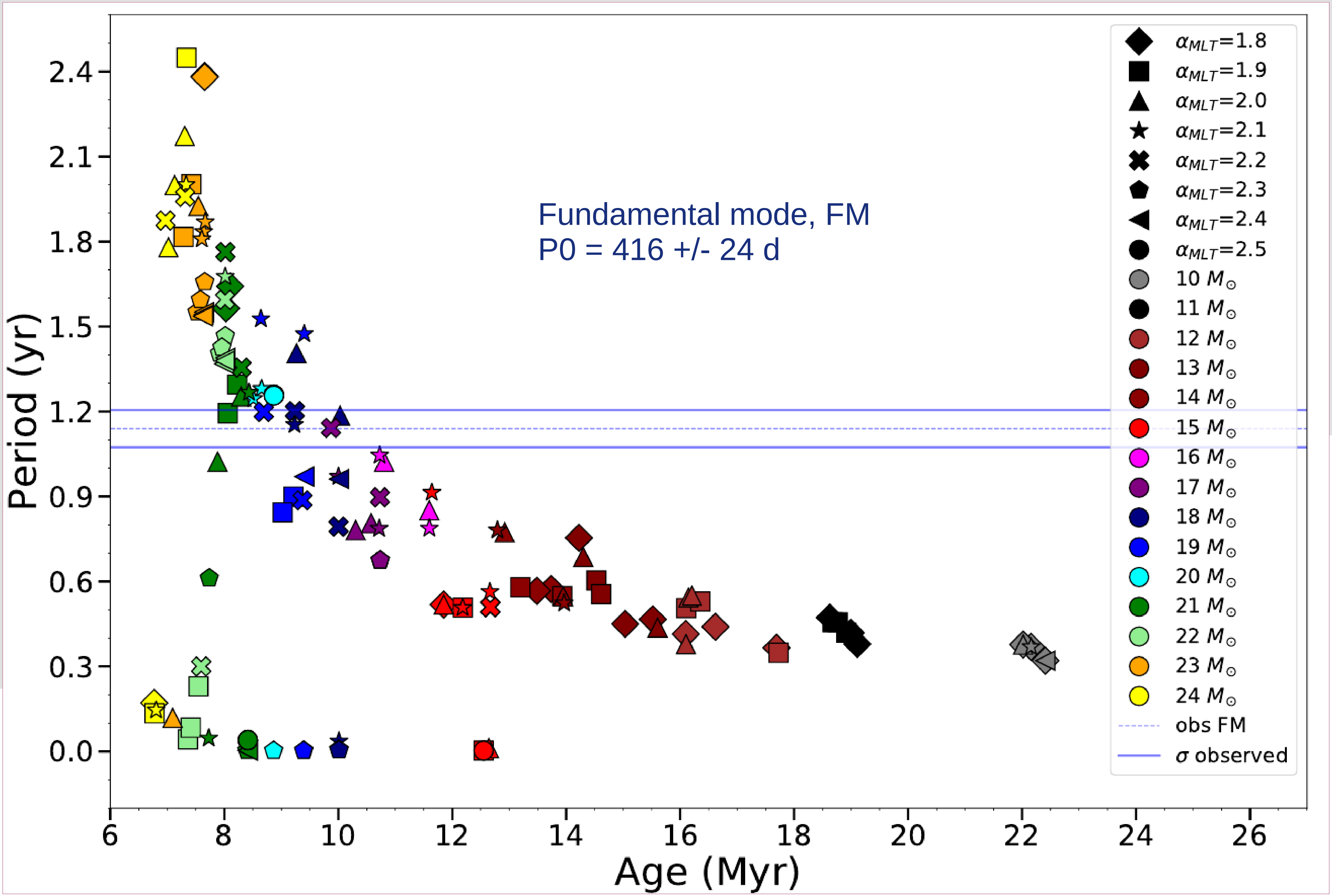


# Part 3: Add in asteroseismology




Use GYRE to perform linear seismic analysis on observationally consistent tracks: those which intersect the temperature constraints and their uncertainties

# Determining which models are seismically compatible



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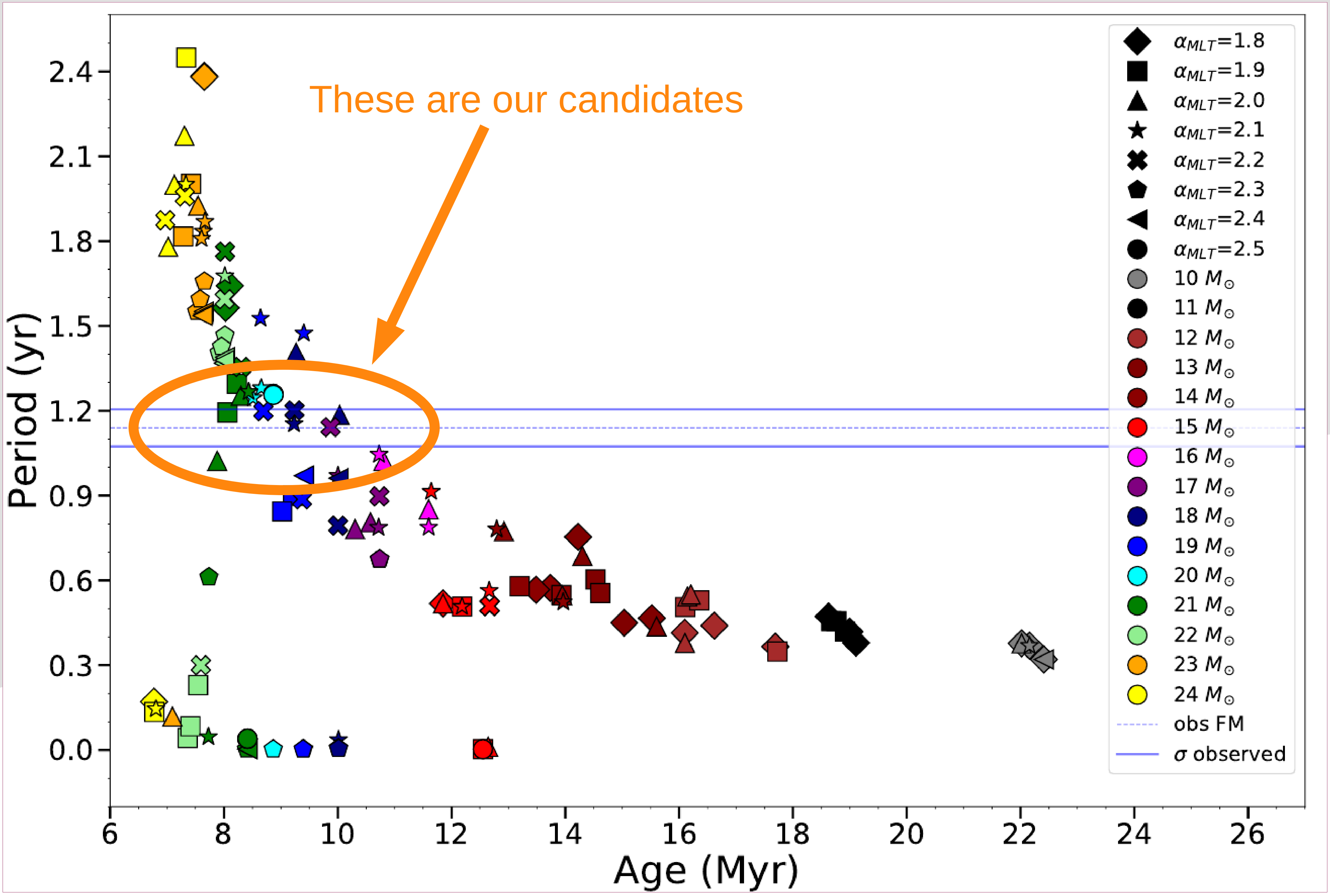
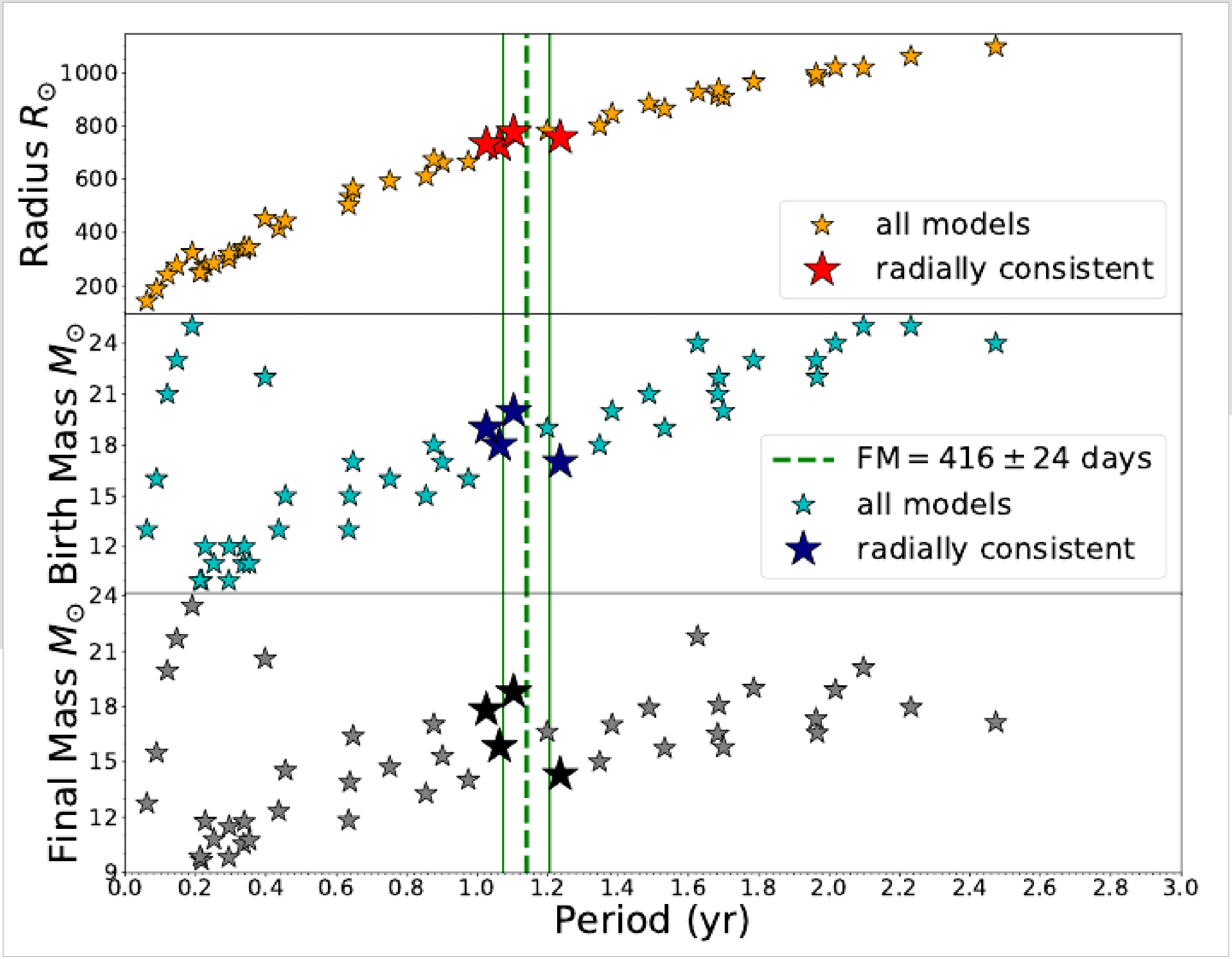


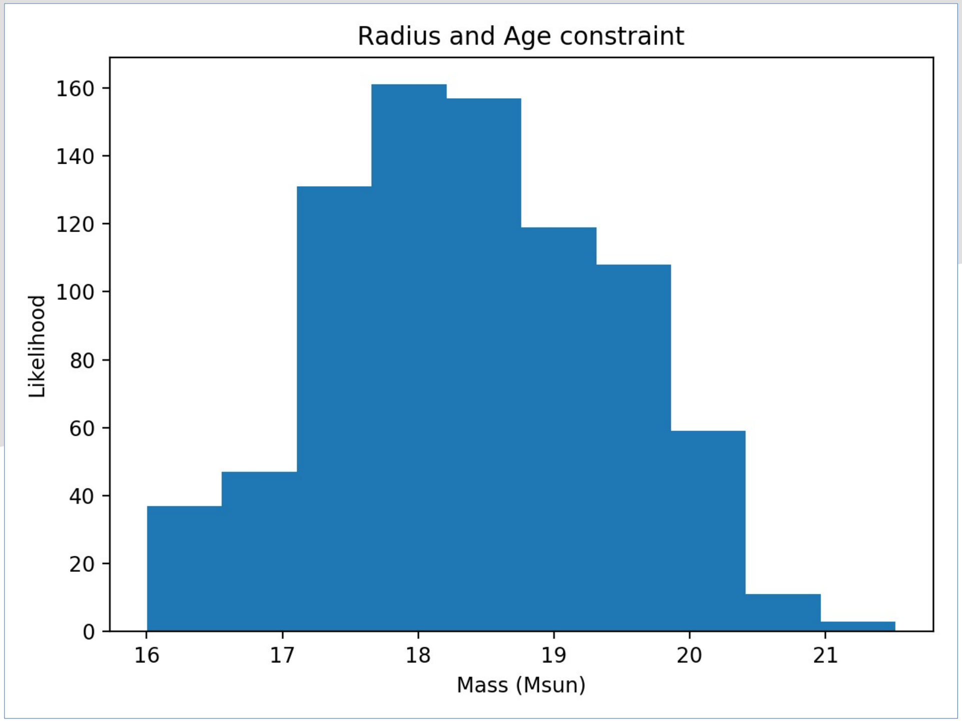
It turns out that this **theoretical and statistical method** constrains Betelgeuse's physical radius **better than traditional observational methods**

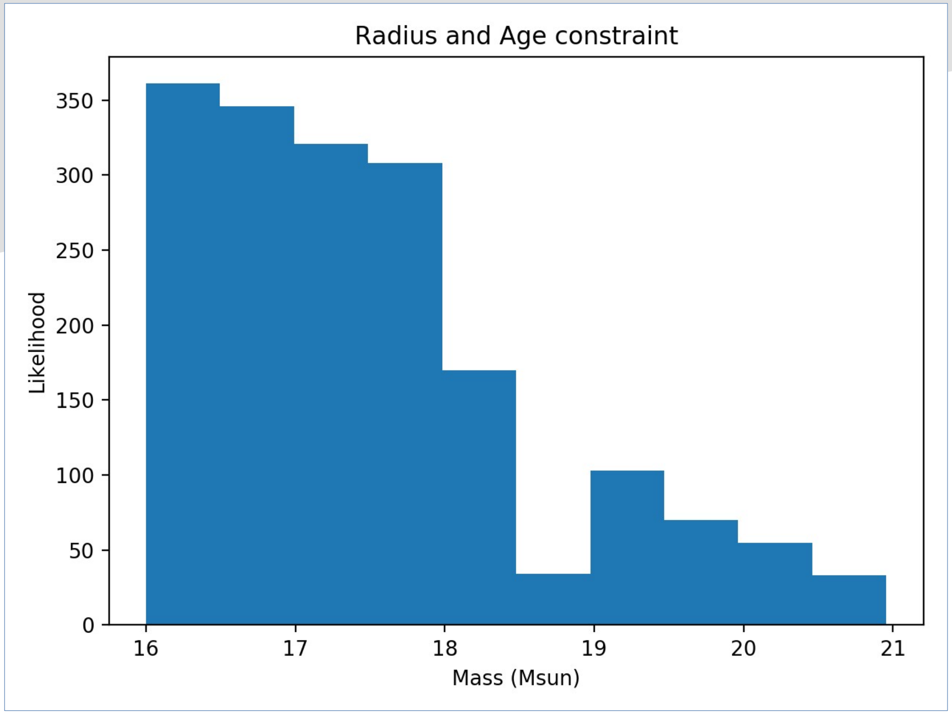


# Key insight from evolutionary models and statistical methods:

Statistically, it is most likely that Betelgeuse is in its core helium burning phase

→ we demonstrate this using a **Monte Carlo interpolation** over a grid of tracks spanning the masses, metallicities, and radii compatible with the observations




Figs by Mike Ireland

# 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

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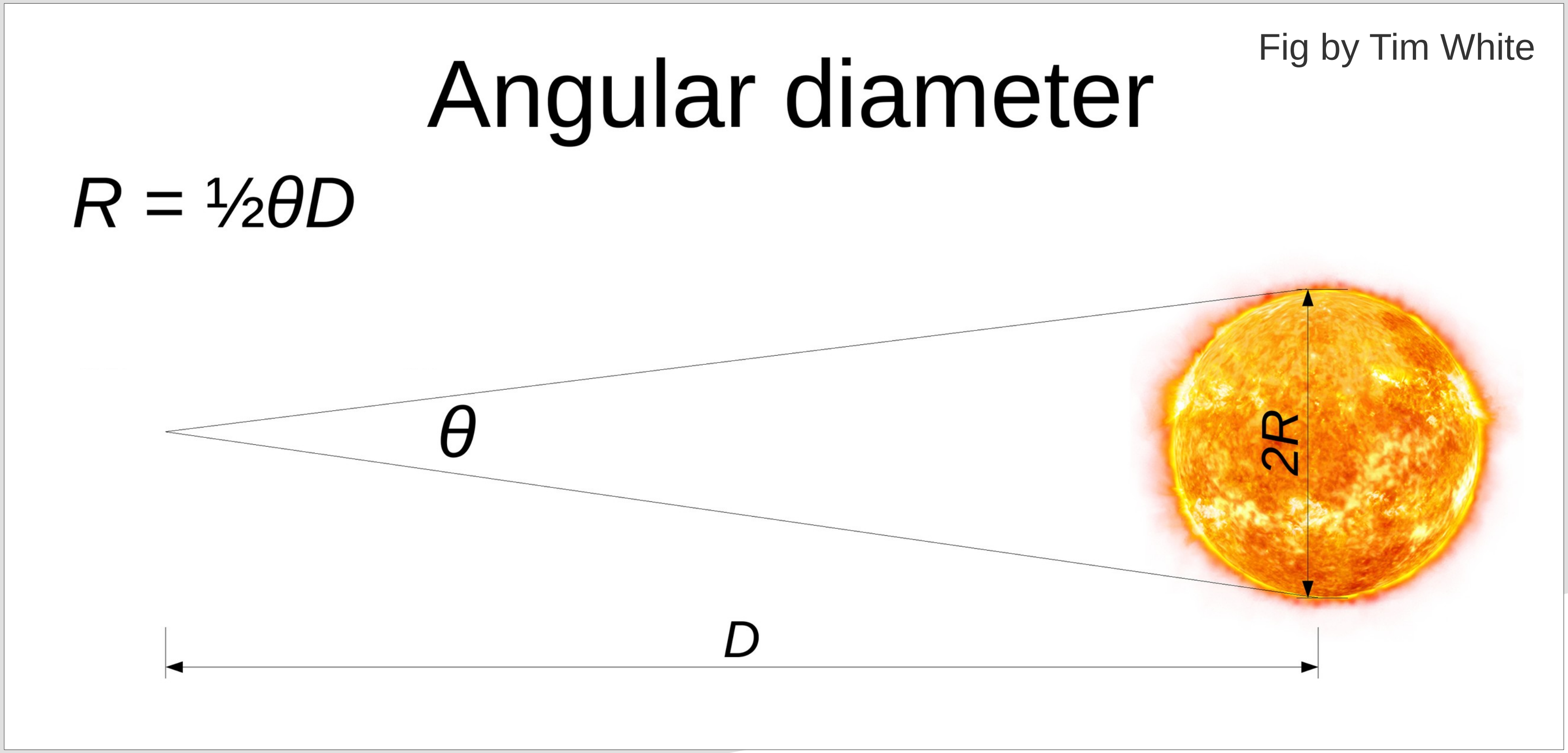
In fact, this range is considerably smaller than predictions for the physical radius provided by traditional observational methods!

# Inversion of the distance inference:




**Parallax (1/D) is a tricky trigonometric distance inference that can be combined with a measurement of the apparent size, or angular diameter (theta), of Betelgeuse on the sky to make a prediction for Betelgeuse's physical radius**

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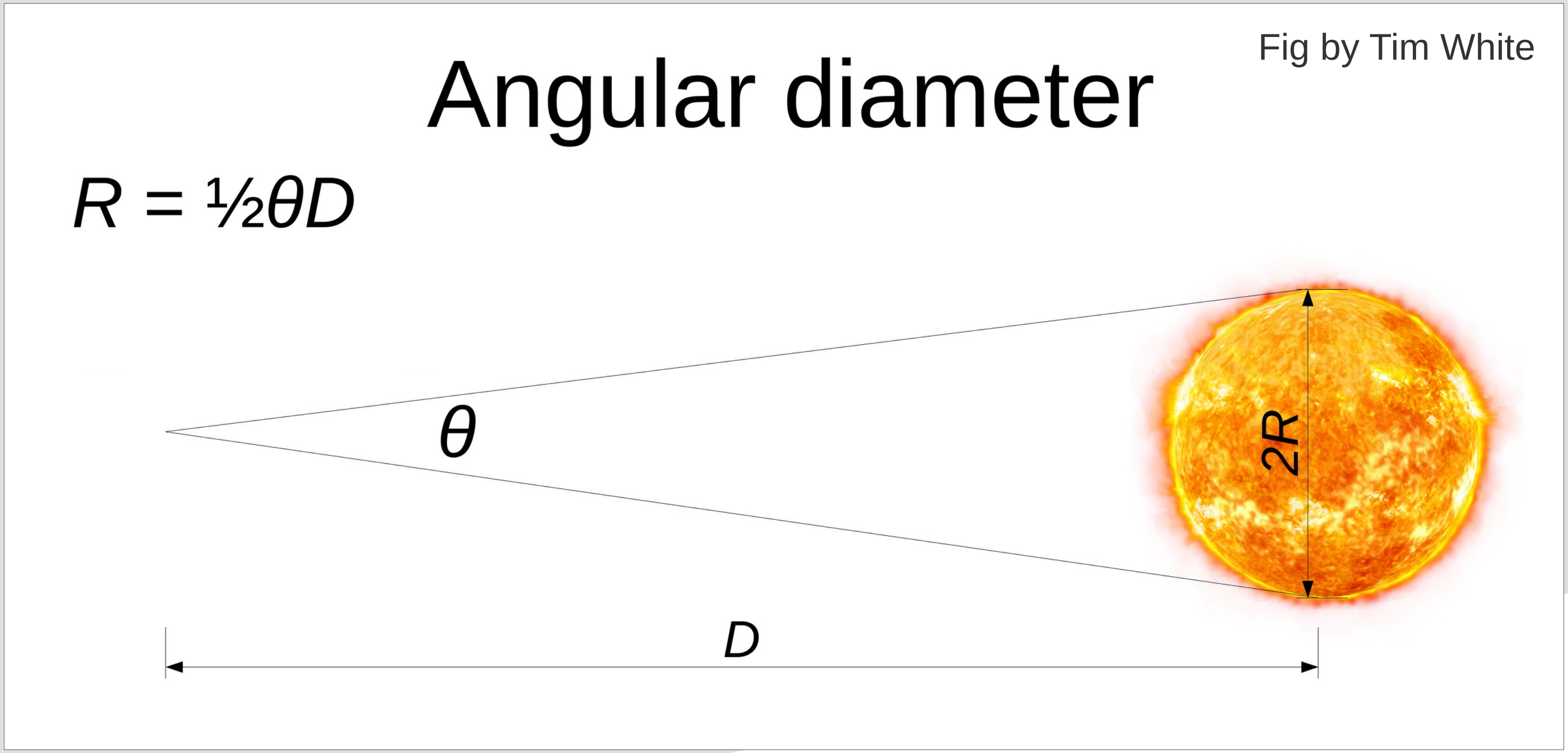


**But in our case, thanks to statistics and asteroseismology, we already have a theoretical value for Betelgeuse’s physical radius from our models...**

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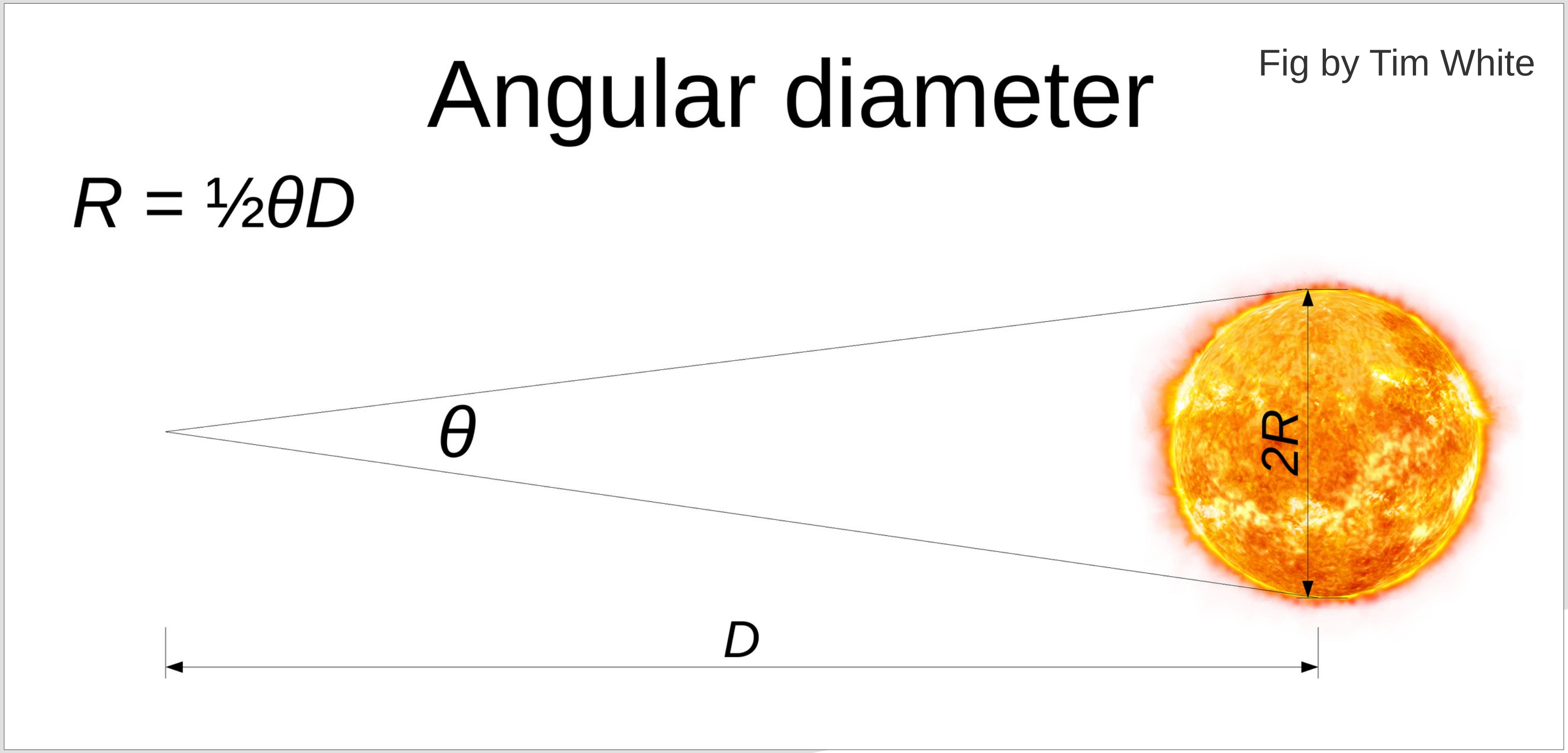


We may then invert the argument by combining
our theoretical radius (from calculations)
& the observed angular diameter (theta)
⟶ parallax (1/D)

So, we put the radius in and get the distance out, instead of the other way around

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

**Unanticipated Bonus:**

precision modelled radius + measured angular diameter

= **new parallax distance estimate**

**Seismic parallax!!**

# Revised distance from seismic parallax

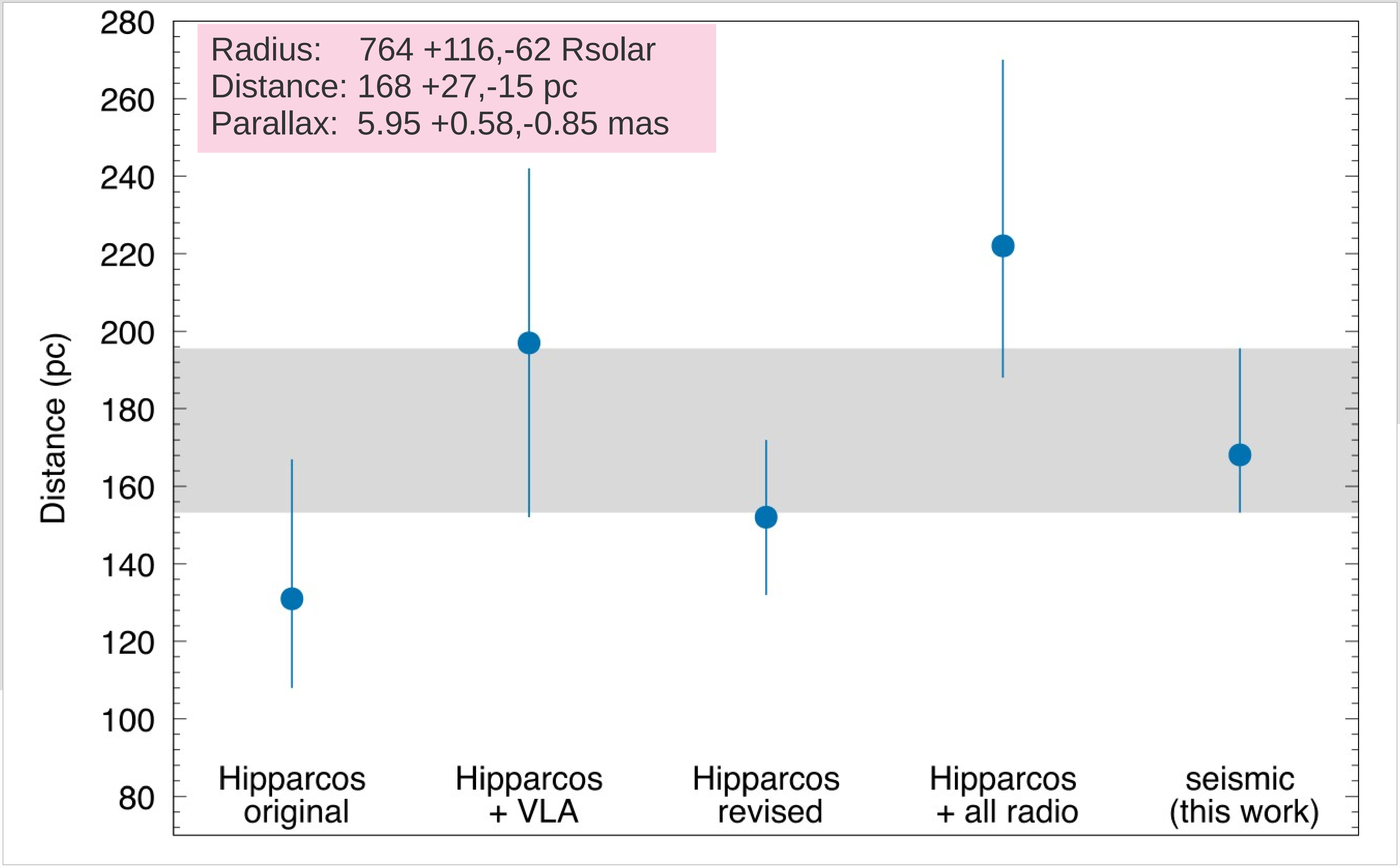



Fig by László Molnár

# Part 4: Hydrodynamical Simulations
# We can reproduce GYRE's linear mode classifications with hydrodynamics

Self-consistent mode classifications: From short-timescale hydro simulations, we can extract cycle lengths as a secondary means of estimating oscillation periods

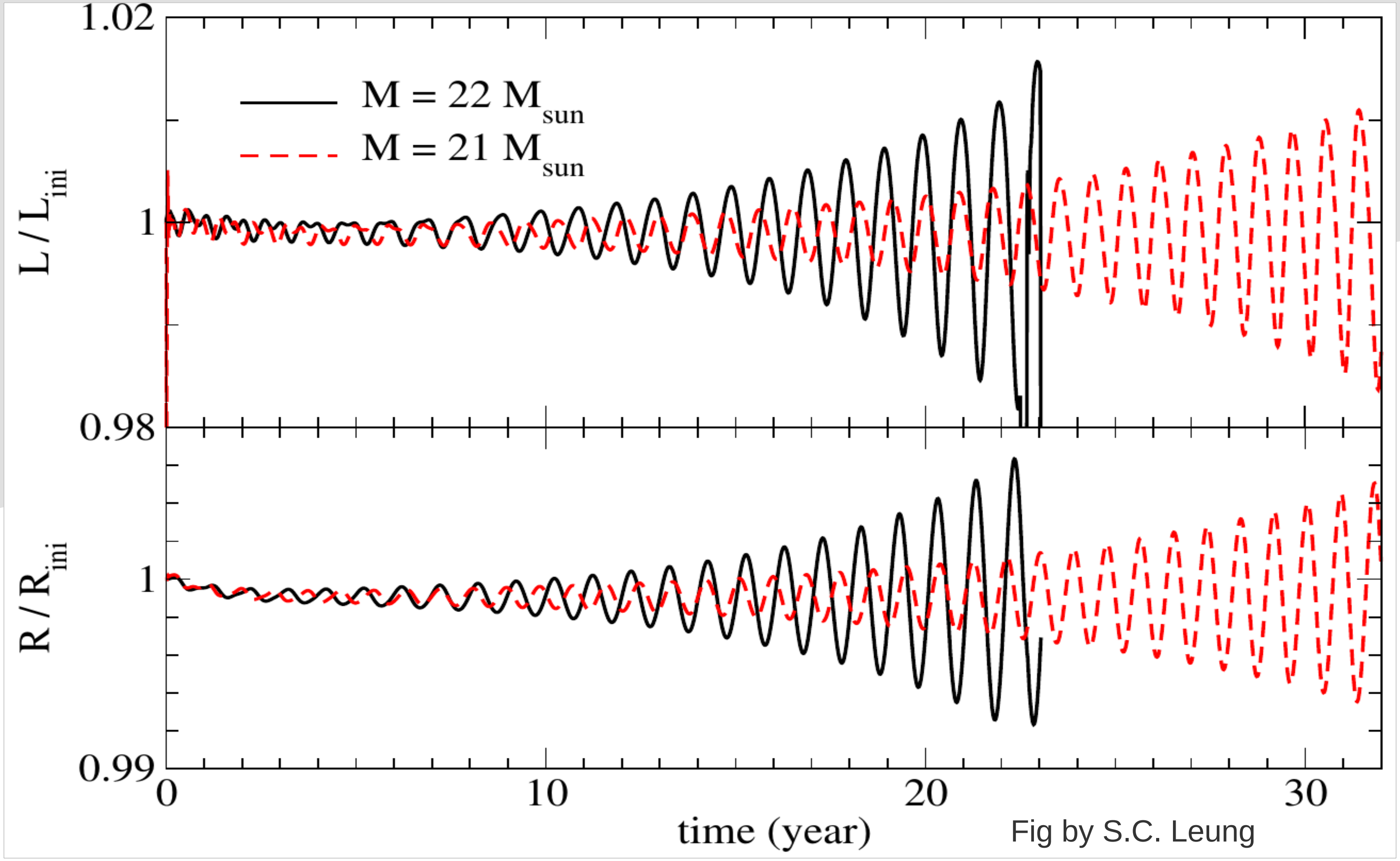



Fig by S.C. Leung

## With hydrodynamic calculations, can we...

(1) activate a mode consistent with the FM? → **yes**
(2) conclusively determine the driving physics of that mode? → **??**

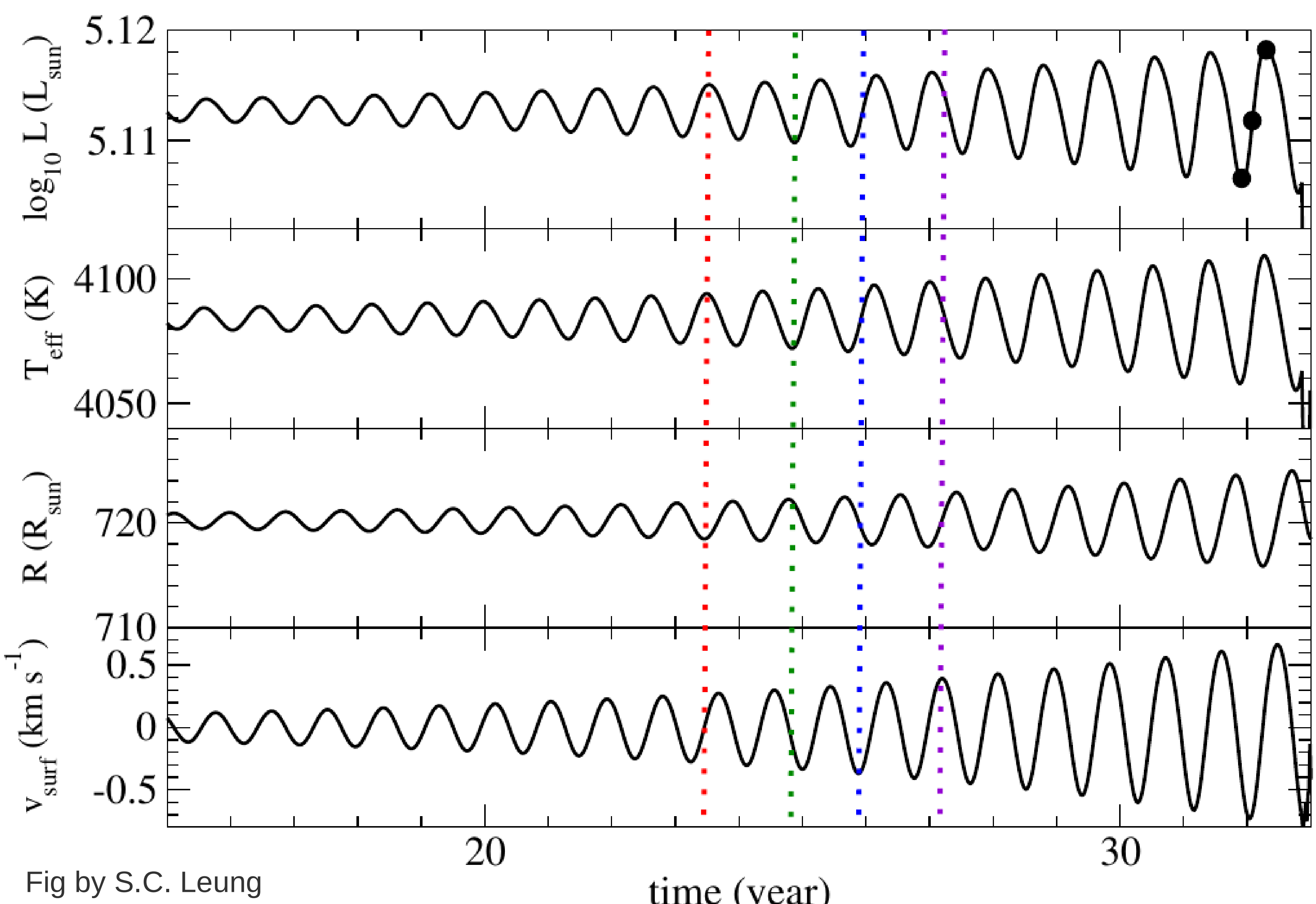
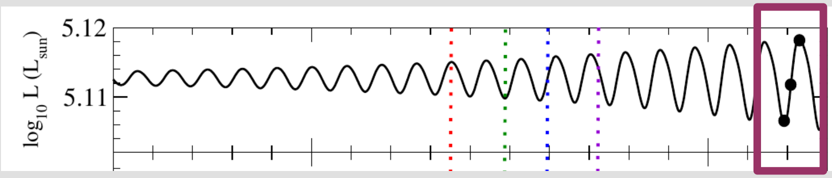
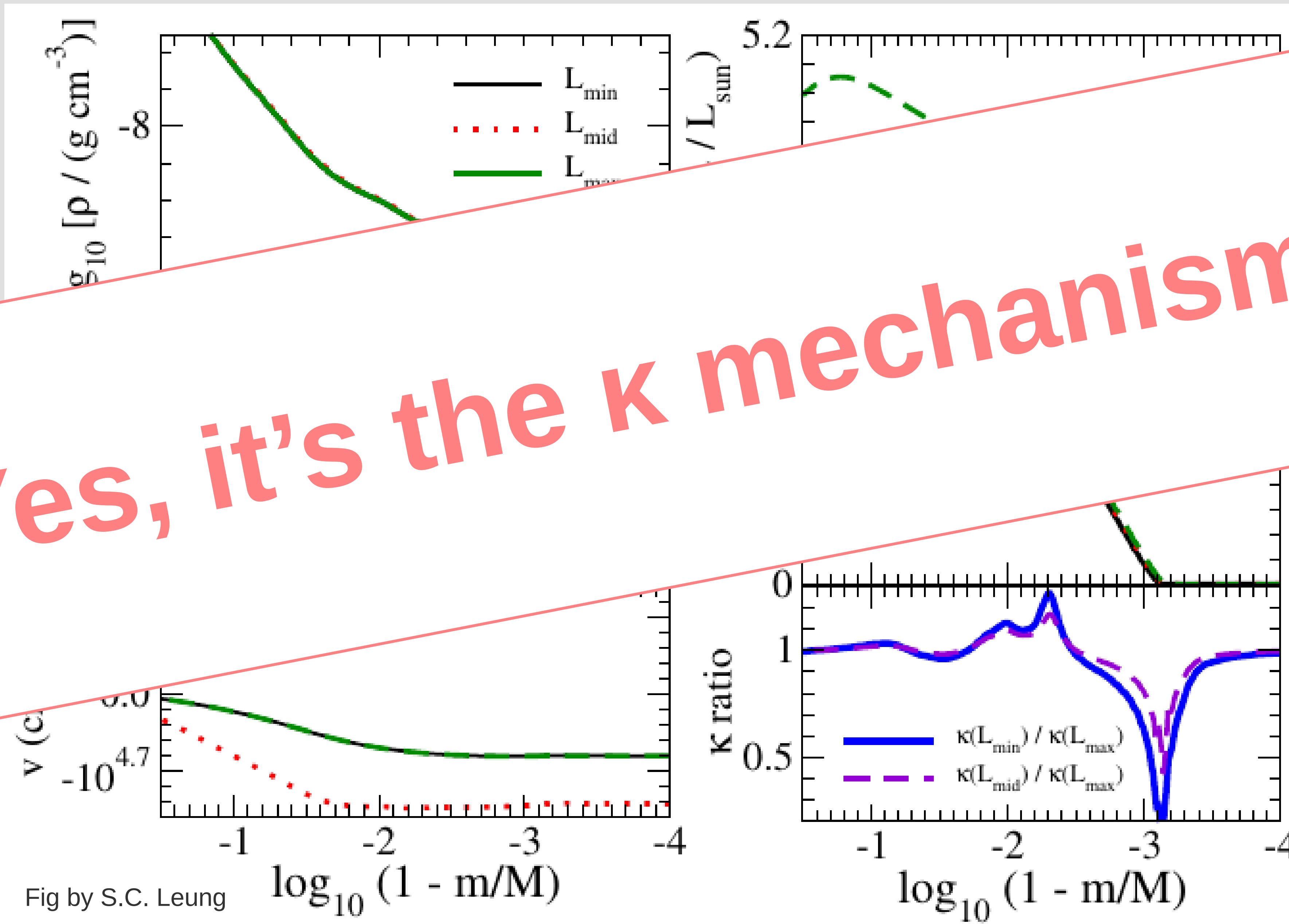



Fig by S.C. Leung

# Examine the envelope structure at critical points in the pulsation cycle

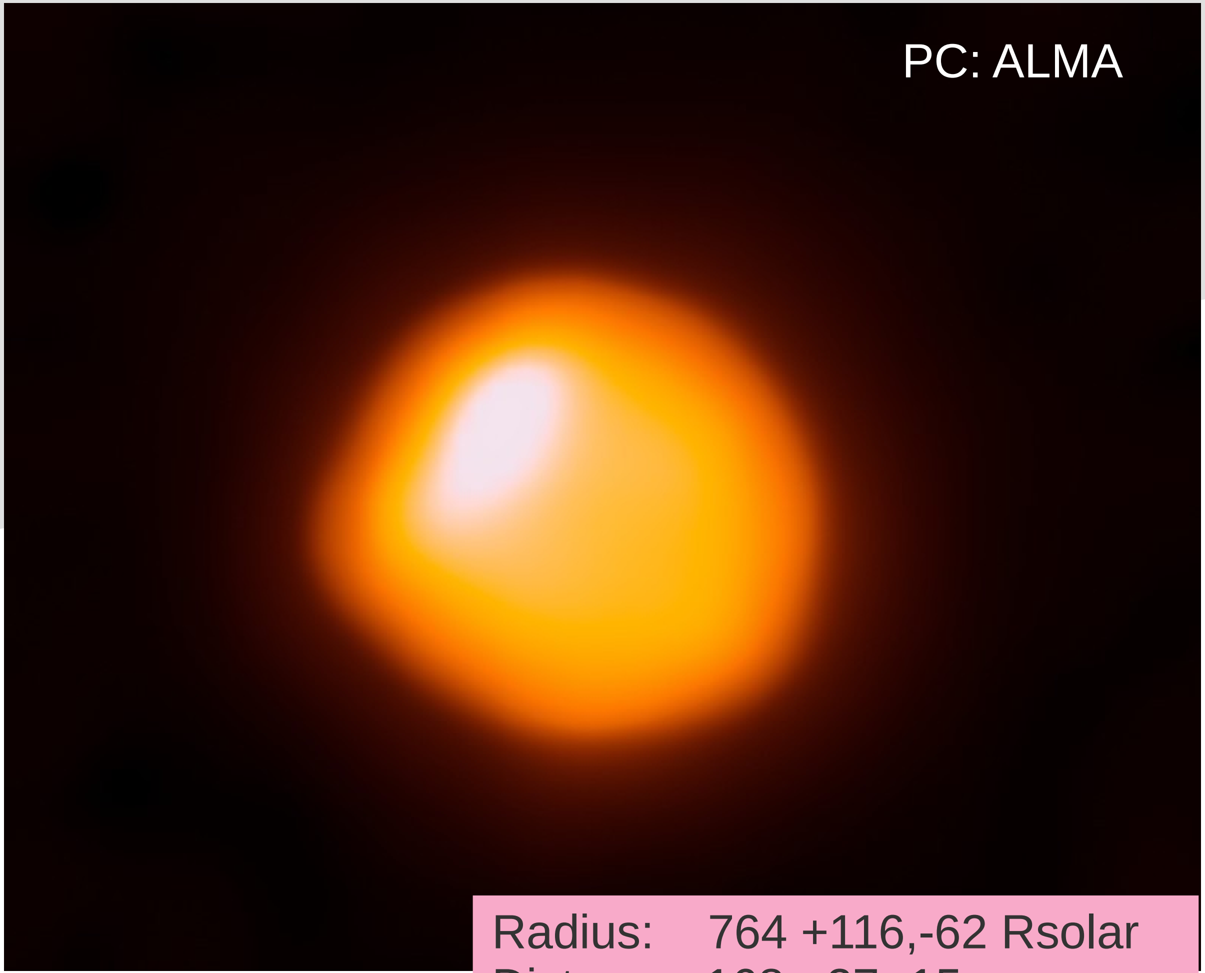



**Yes, it's the κ mechanism**

Fig by S.C. Leung

# Key results from four analysis methods:




Radius: 764 +116,-62 Rsolar
Distance: 168 +27,-15 pc
Parallax: 5.95 +0.58,-0.85 mas

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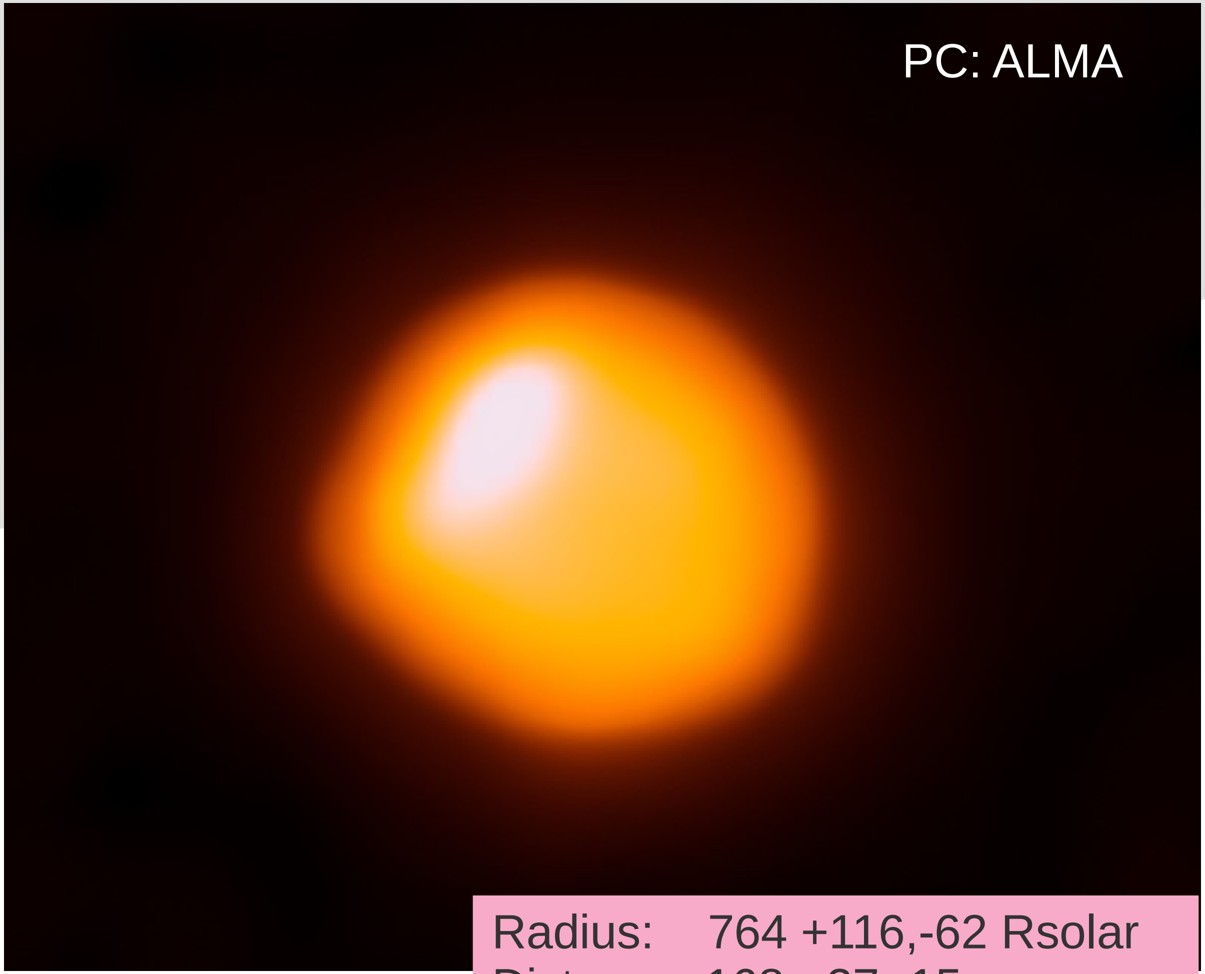


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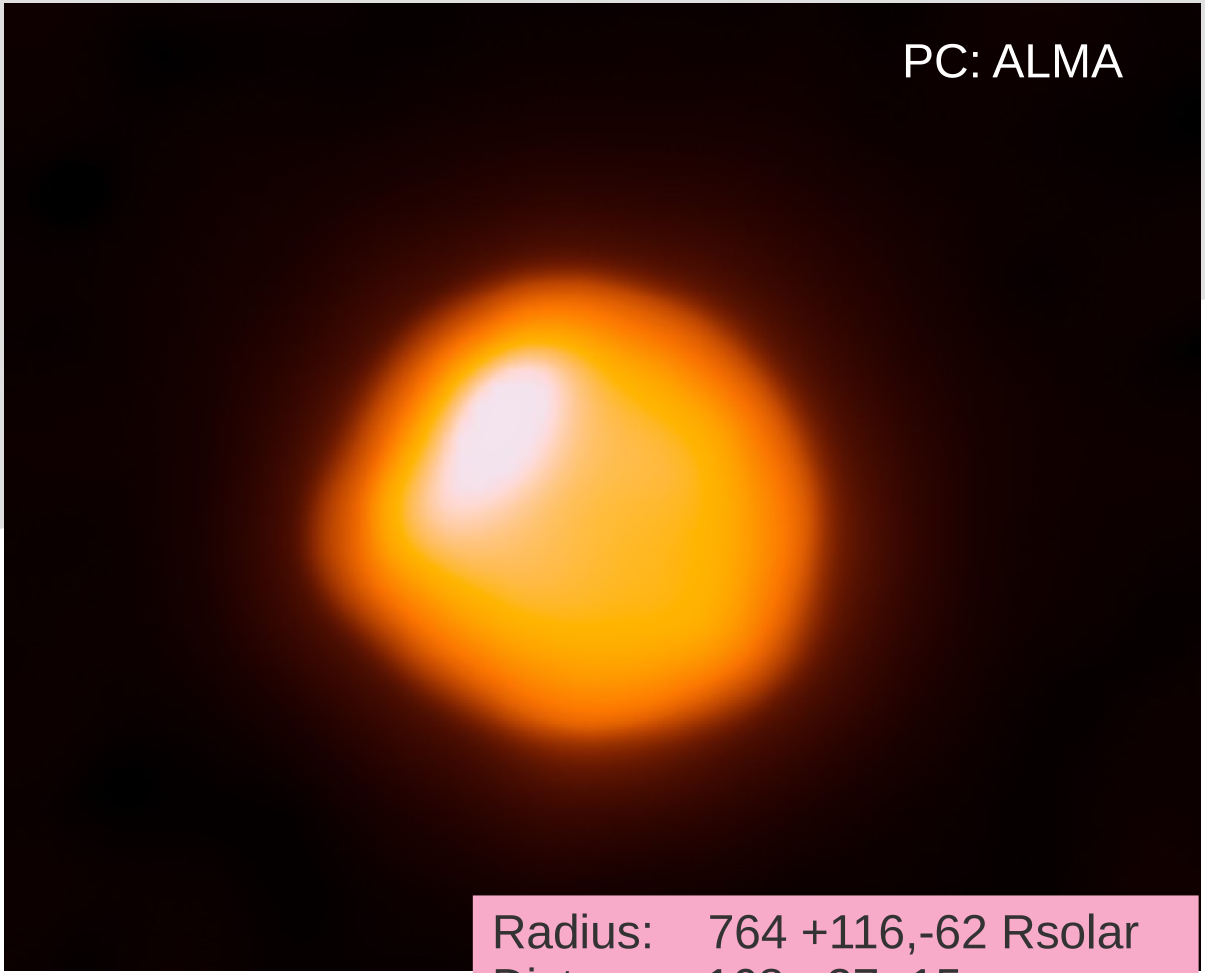


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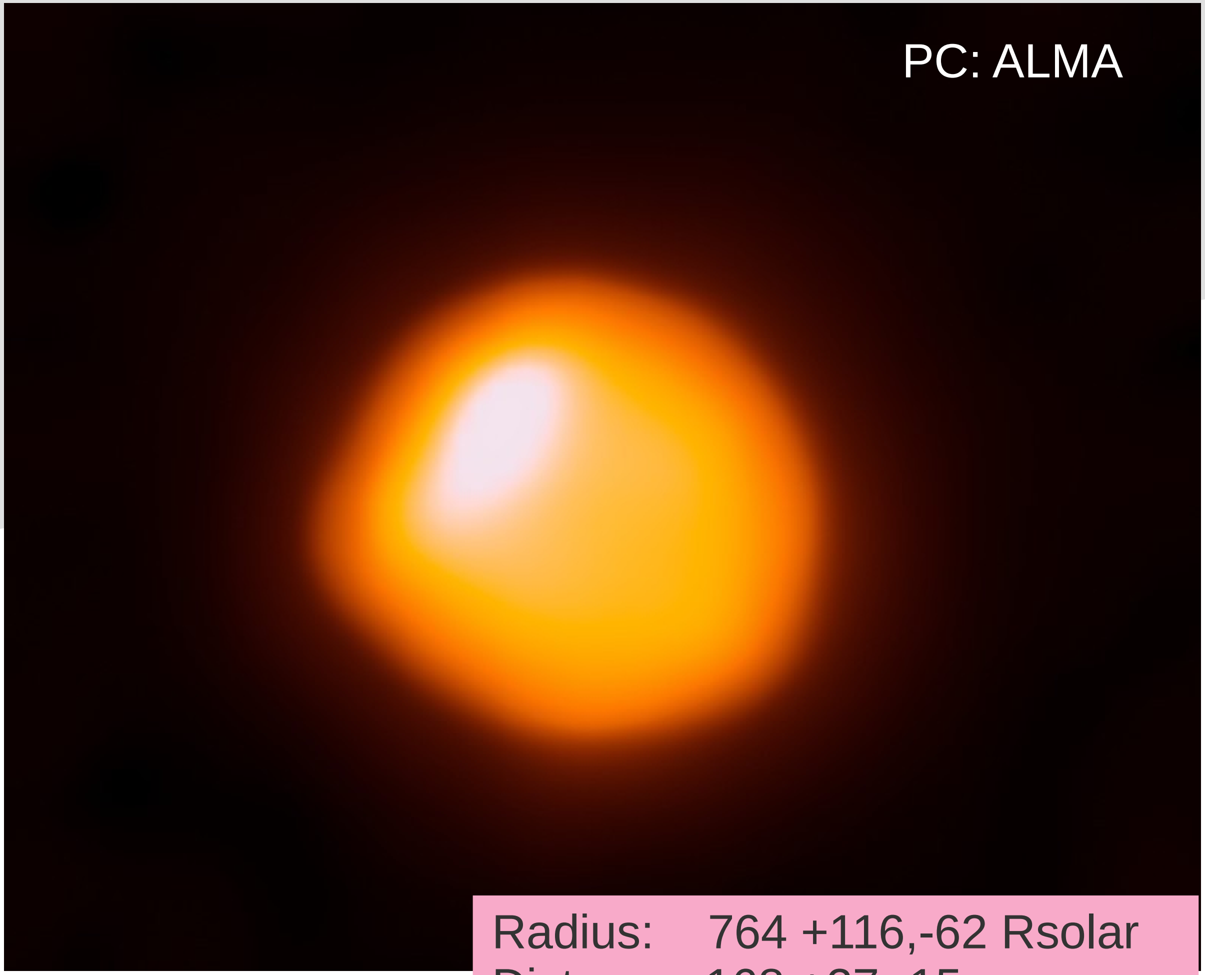


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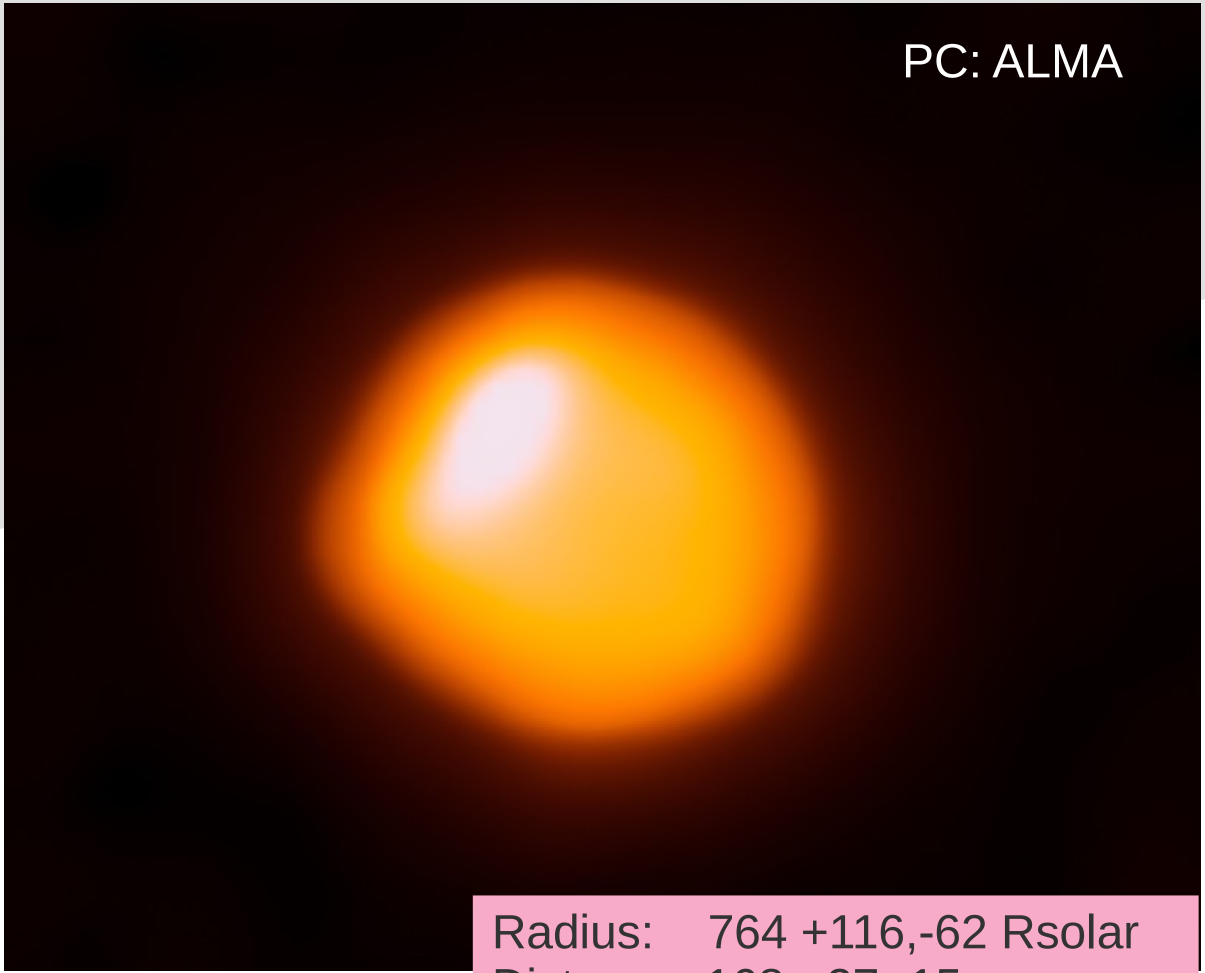


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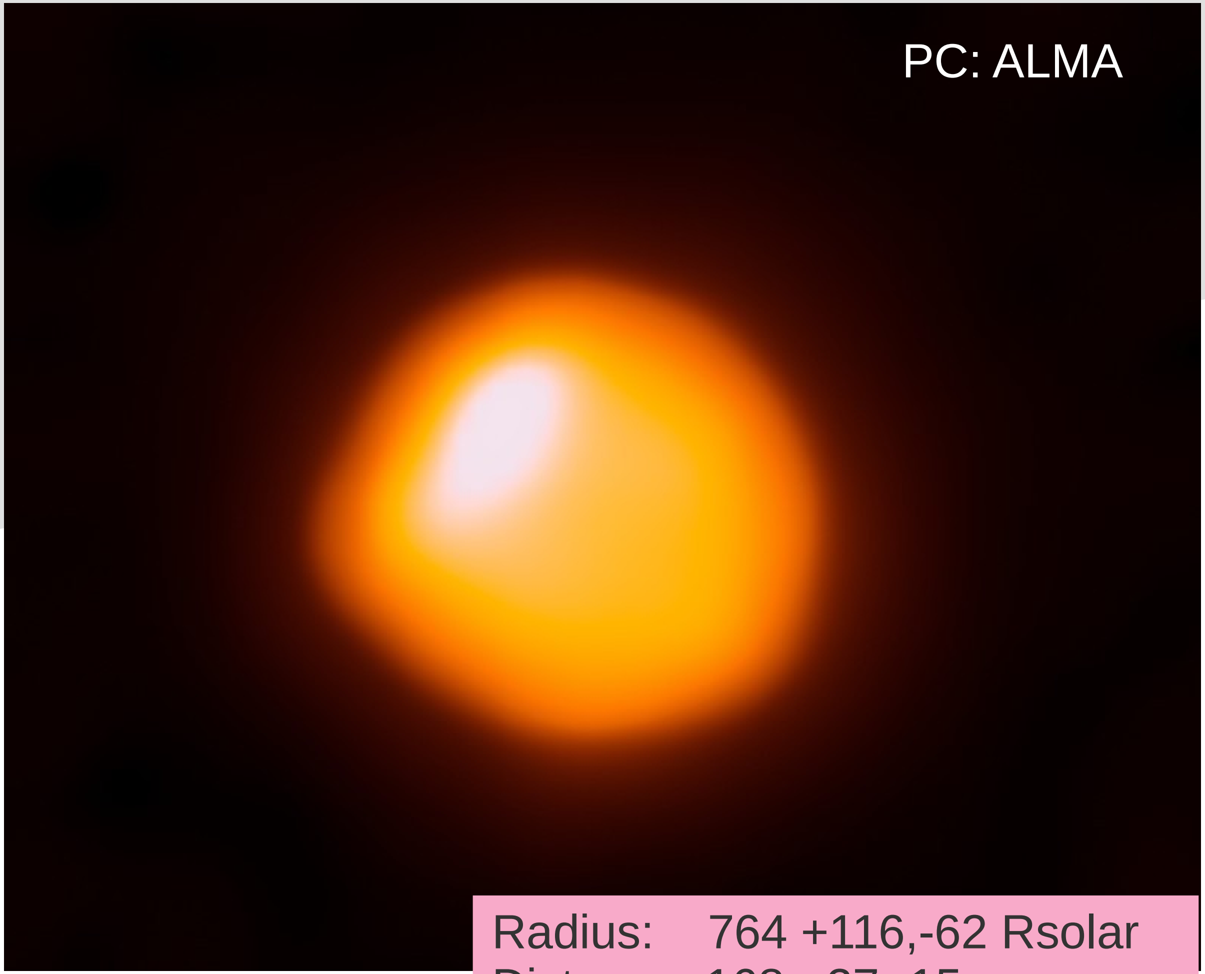


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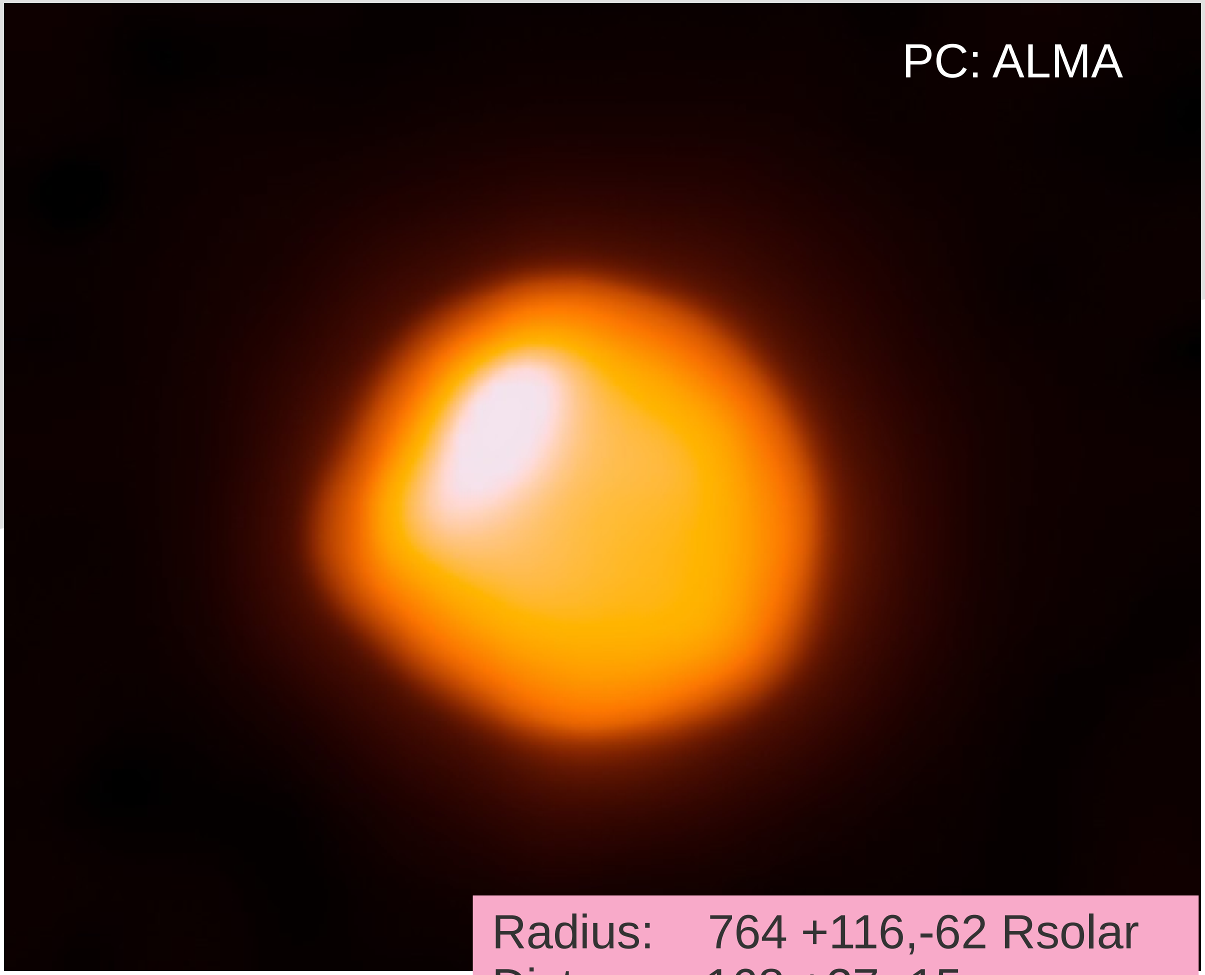
**Seismic parameters were the key to the modeling problem**

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- behind the scenes: we used **grid modeling, multi-dimensional parameter optimization, error propagation techniques, and high performance computing to generate the different bases of models used to fit to Betelgeuse, and then again to determine the *best* fit**

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- find better ways to create the models. Make running the stellar structure and evolution software obsolete. Replace ancient partial differential equation solvers—which is what stellar structure and evolution programs are, by and large—with machine learning parameter generators trained on stellar models instead

Is it really a “fundamental tension,” or is it a matter of error bars?

# The Age of the Galactic Bulge

*The Ages of Galactic Bulge Stars with Realistic Uncertainties*

**Meridith Joyce, Christian I Johnson**, Tommaso Marchetti,
R. Michael Rich, Iulia Simion, and John Bourke
**ApJ** (in revision), *2022*

# In 2017, a catalog of ages for 91 micro-lensed subdwarfs was put forth by T. Bensby and collaborators:

**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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We played with this data set in our mock class

In 2017, a catalog of ages for 91 micro-lensed subdwarfs was put forth by T. Bensby and collaborators

...that suggested the presence of a significant population of young stars in the Galactic Bulge

# Young stars in the Galactic bulge?

## Why is this contentious?

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- presence of young stars implies prolonged star formation, and our understanding of the Galaxy is not consistent with recent star formation episodes in this region

- 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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## Big picture:

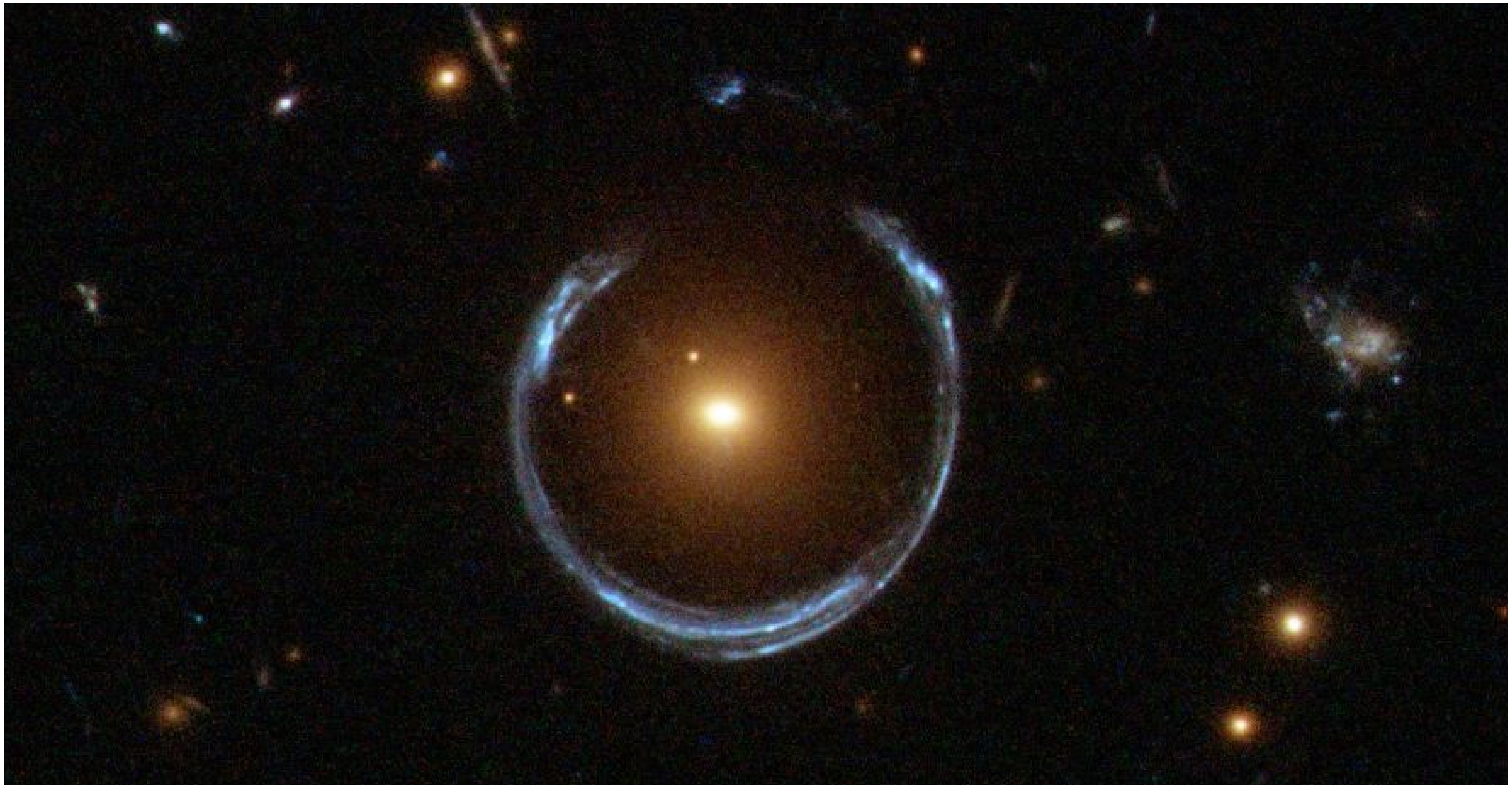
There is tension in the literature between ages derived from **photometry**, which claims a **uniformly old bulge**

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

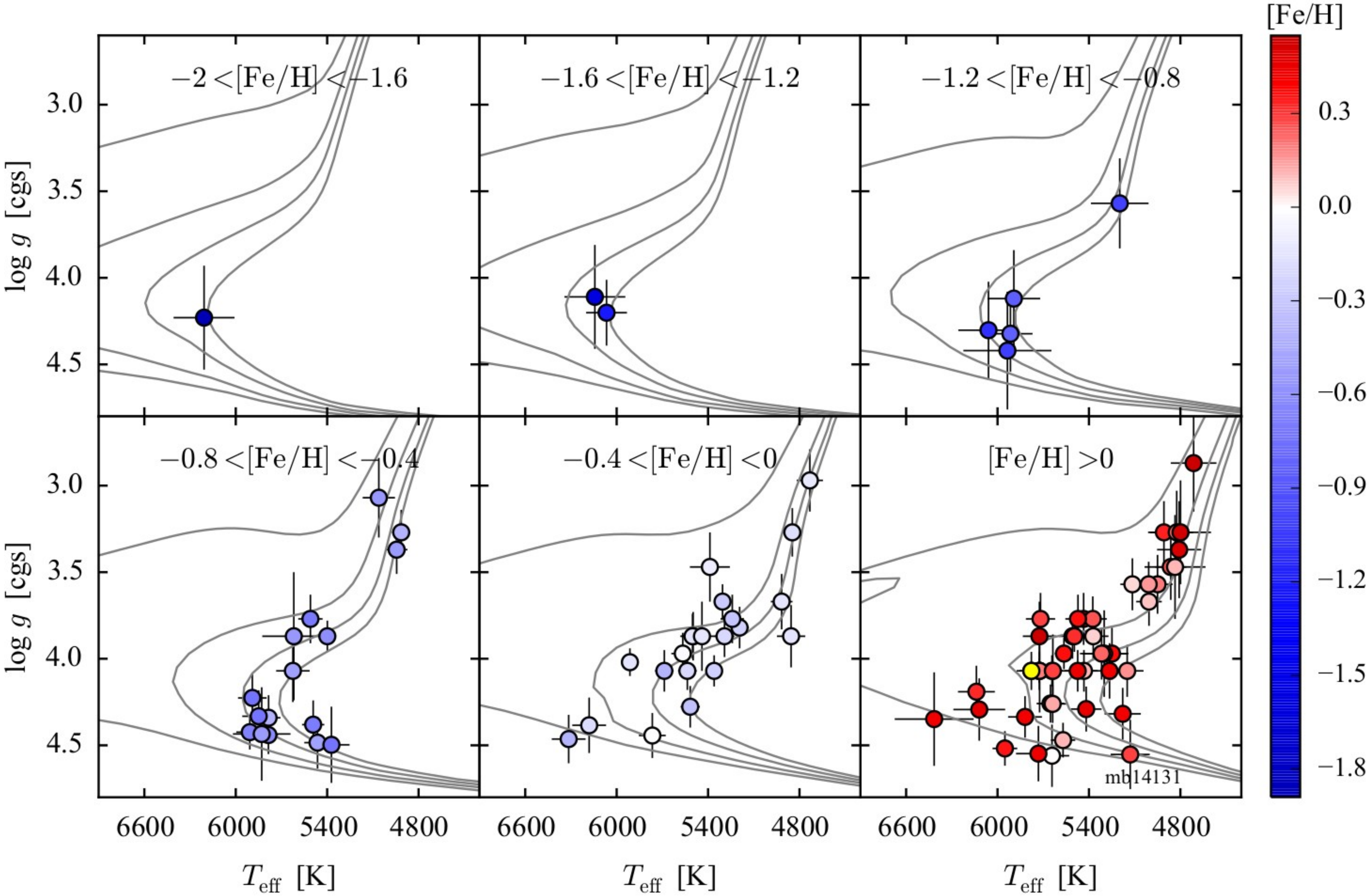
...but in order for something to be true, **it must be true regardless of inference method**

# A rare and powerful dataset

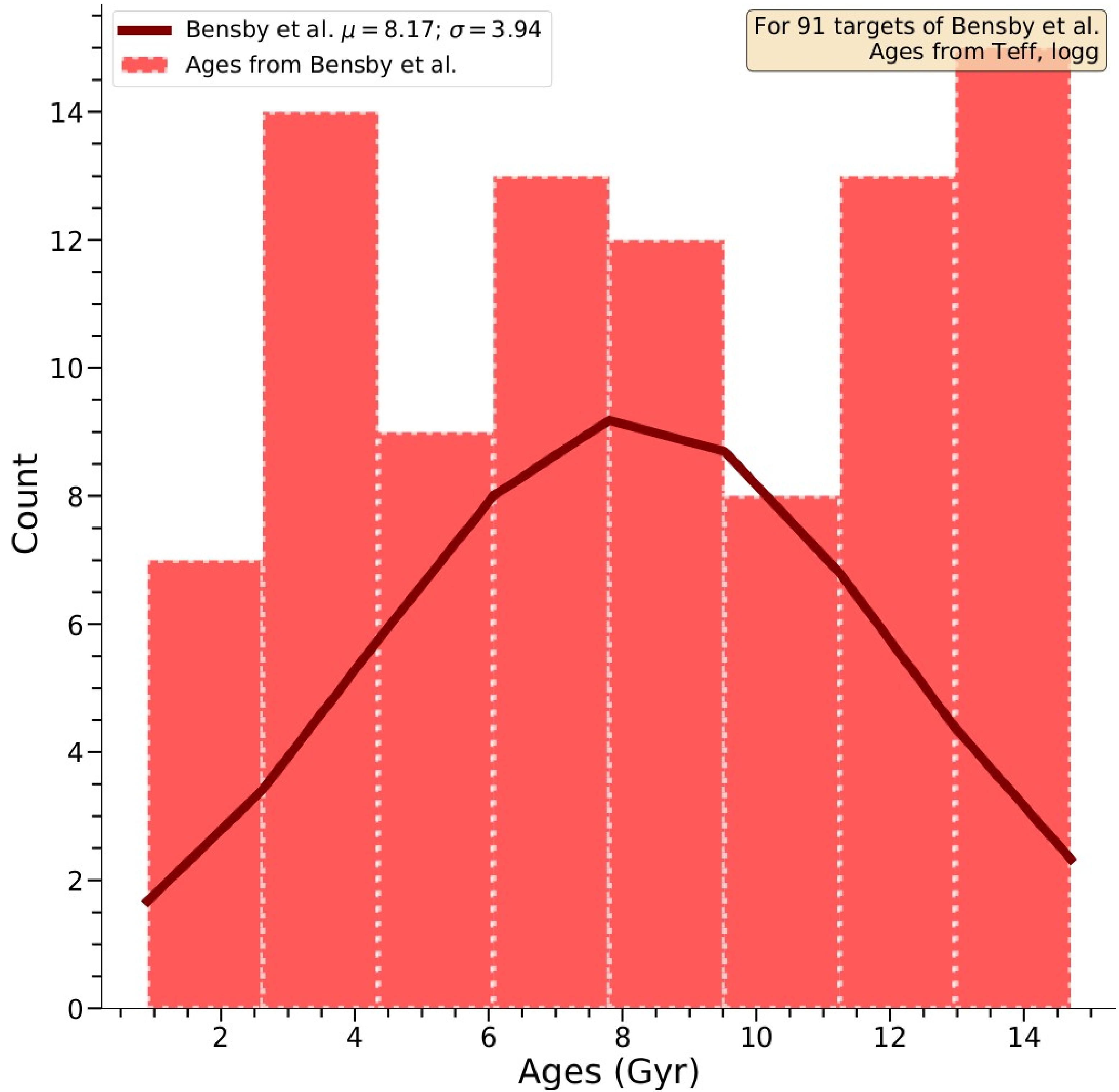
Microlensing permits the direct inference of physical, spectroscopic coordinates (Teff, logg) of faint, cool stars due to the 10-1000x brightness magnification they experience during these events



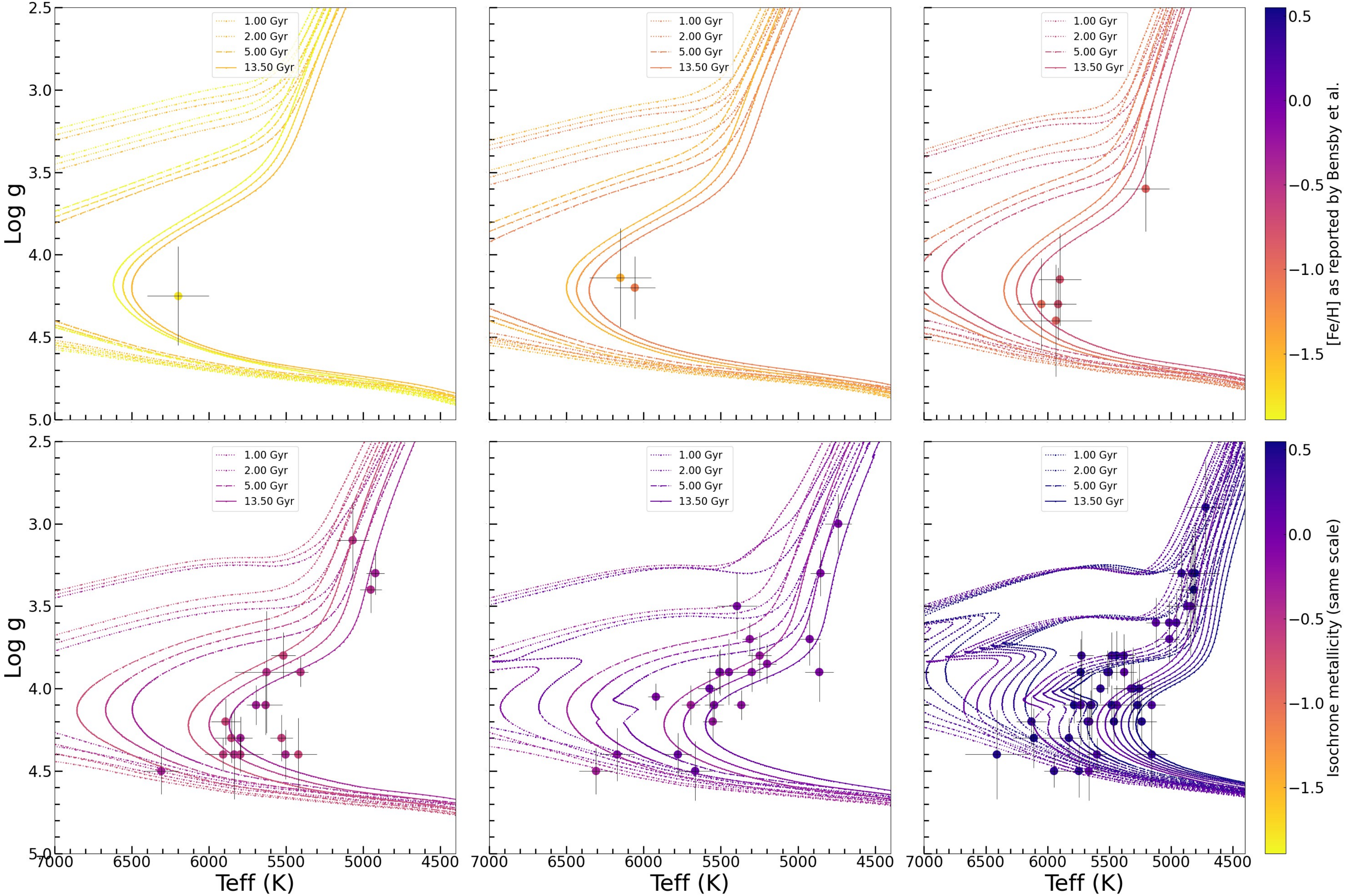
# Fig 6, Bensby et al. 2017: 91 stars on Yale isochrones



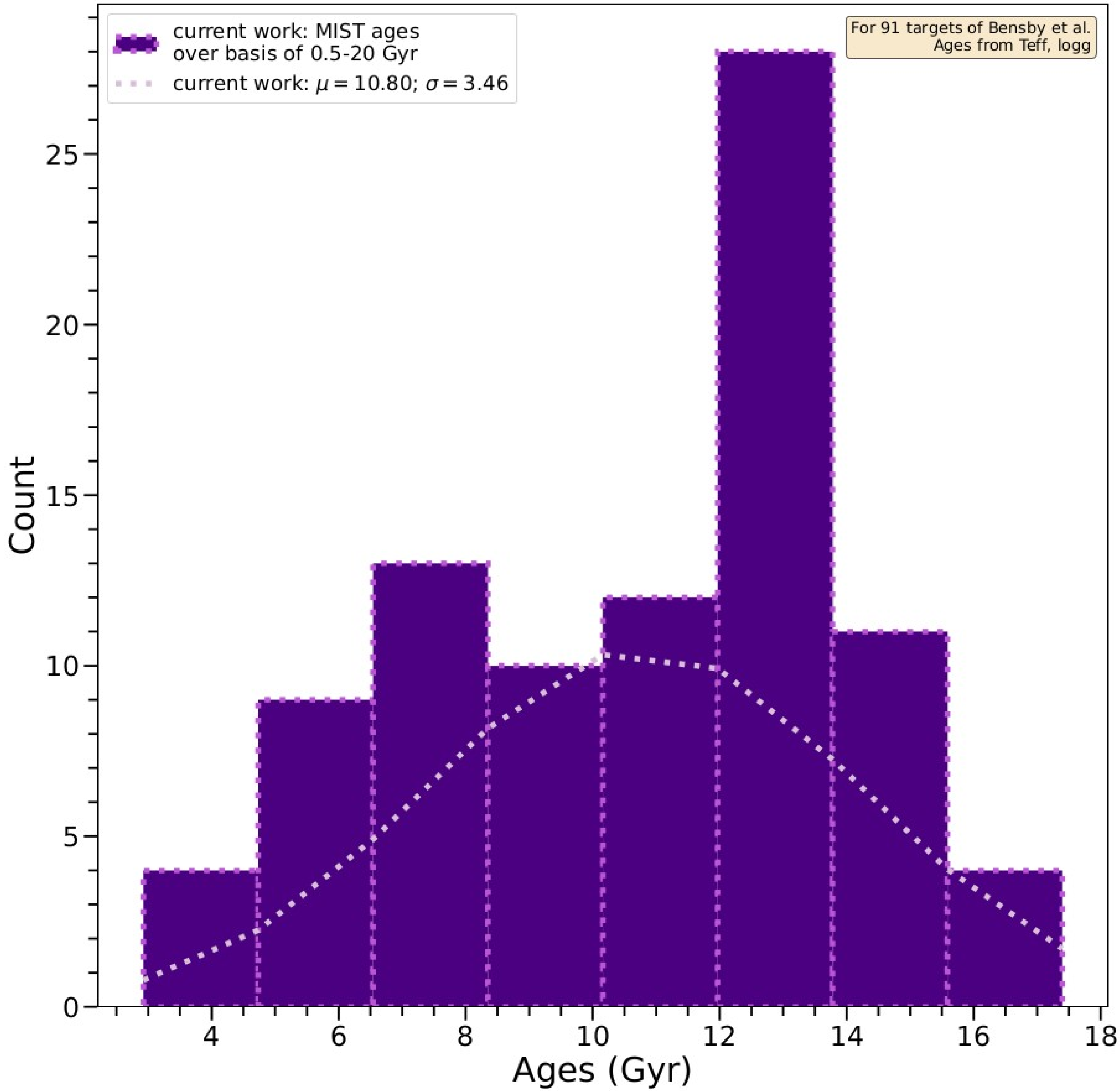
# Resulting age distribution (Bensby et al.; Yale)



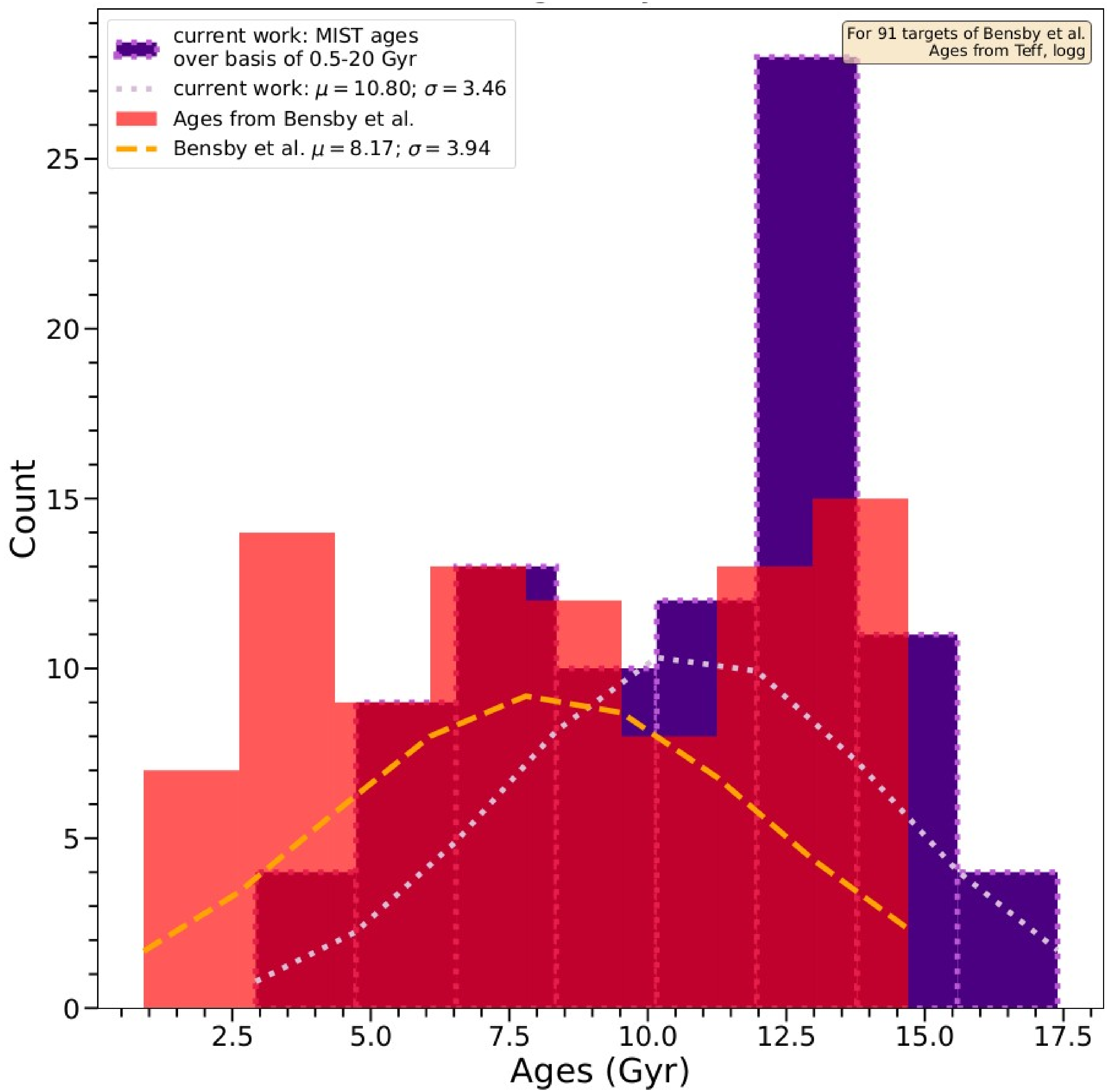
# Reproduction with MIST isochrones

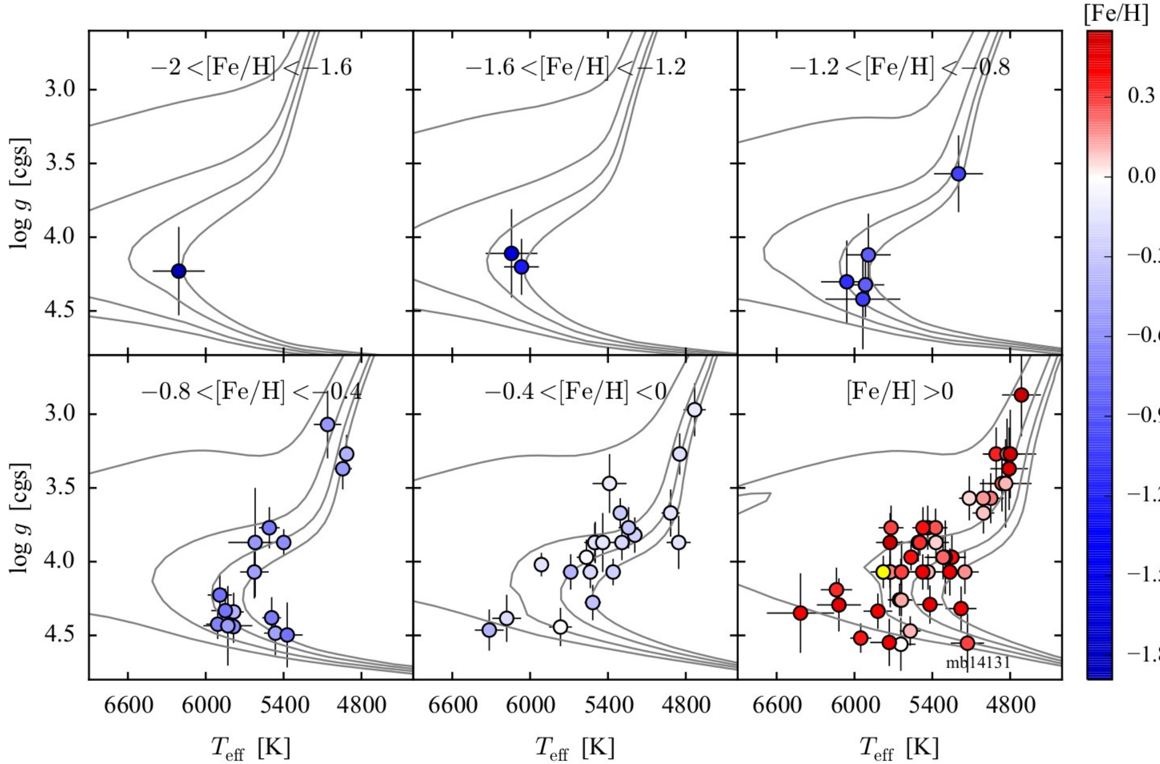


Resulting age distribution (Joyce et al; MIST)

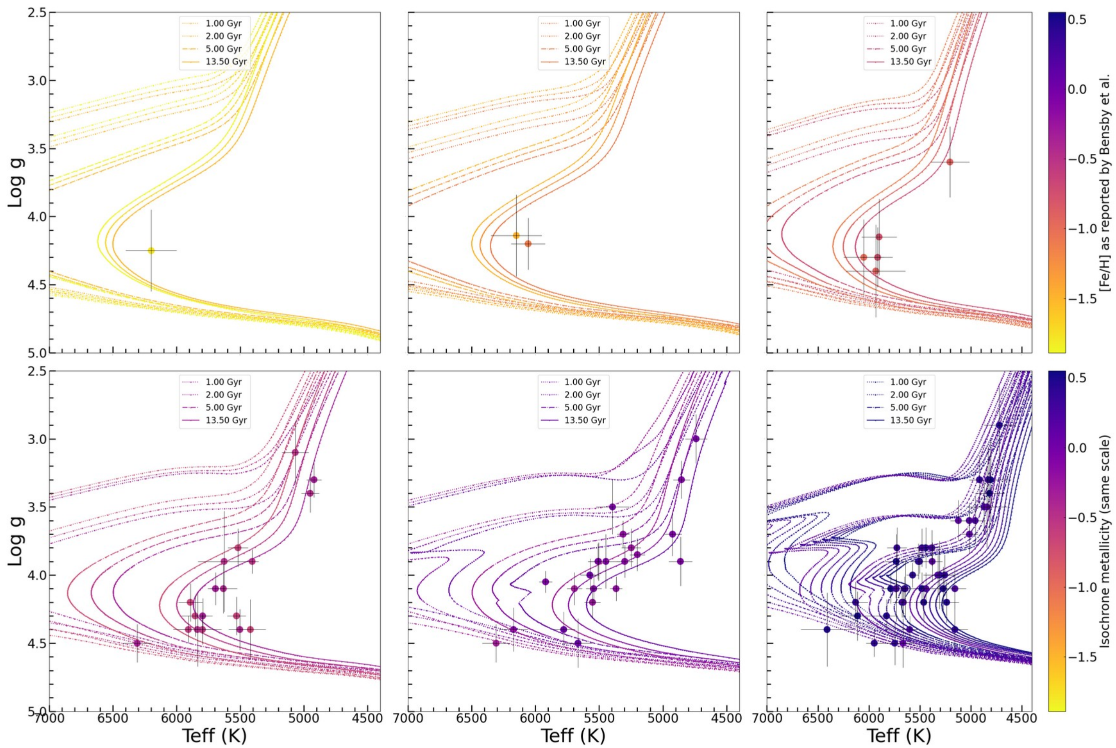


Distributions overlaid





−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]
[Fe/H]

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 physical assumptions and therefore yield different ages?

→ No

Is it because we use more sophisticated assumptions about the chemical distribution of the Galaxy in our isochrones and the other age determinations do not?

→ Also no

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

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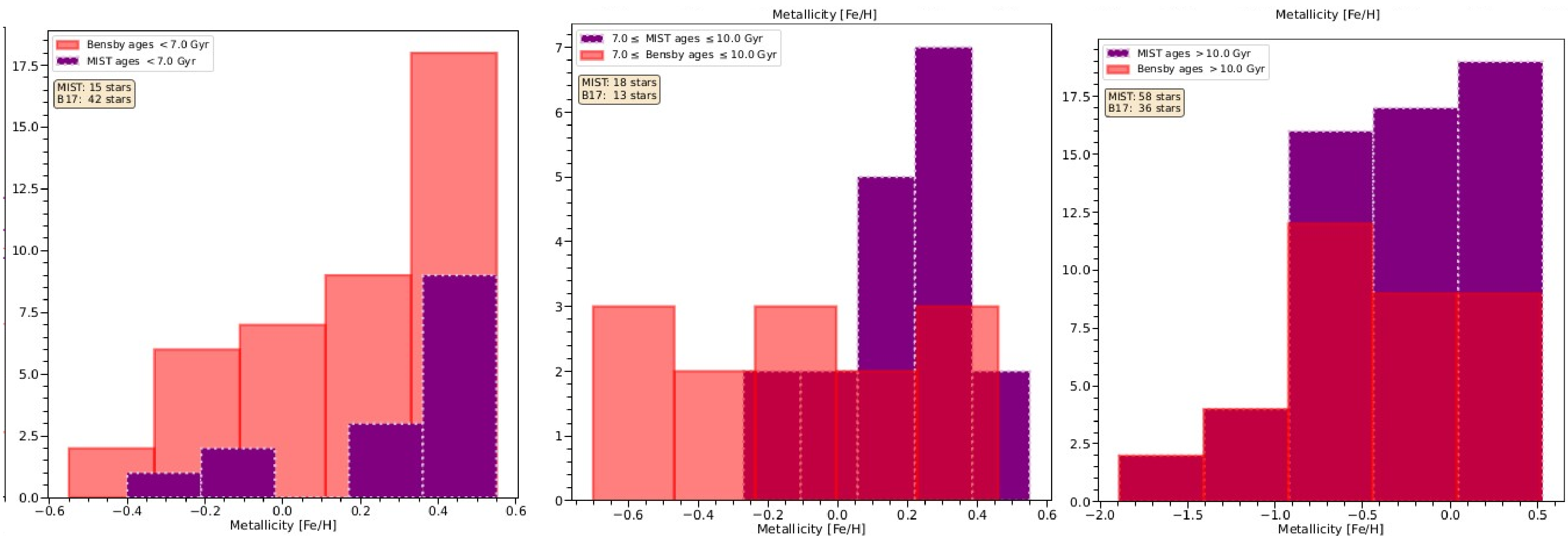
A huge part of my research is the art of *ruling out* explanations for discrepancies, using statistics, probability, and computer modeling

Research is not just about finding a model that works, it’s about demonstrating mathematically why other explanations are not viable

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




**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

# 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 $1\sigma$ 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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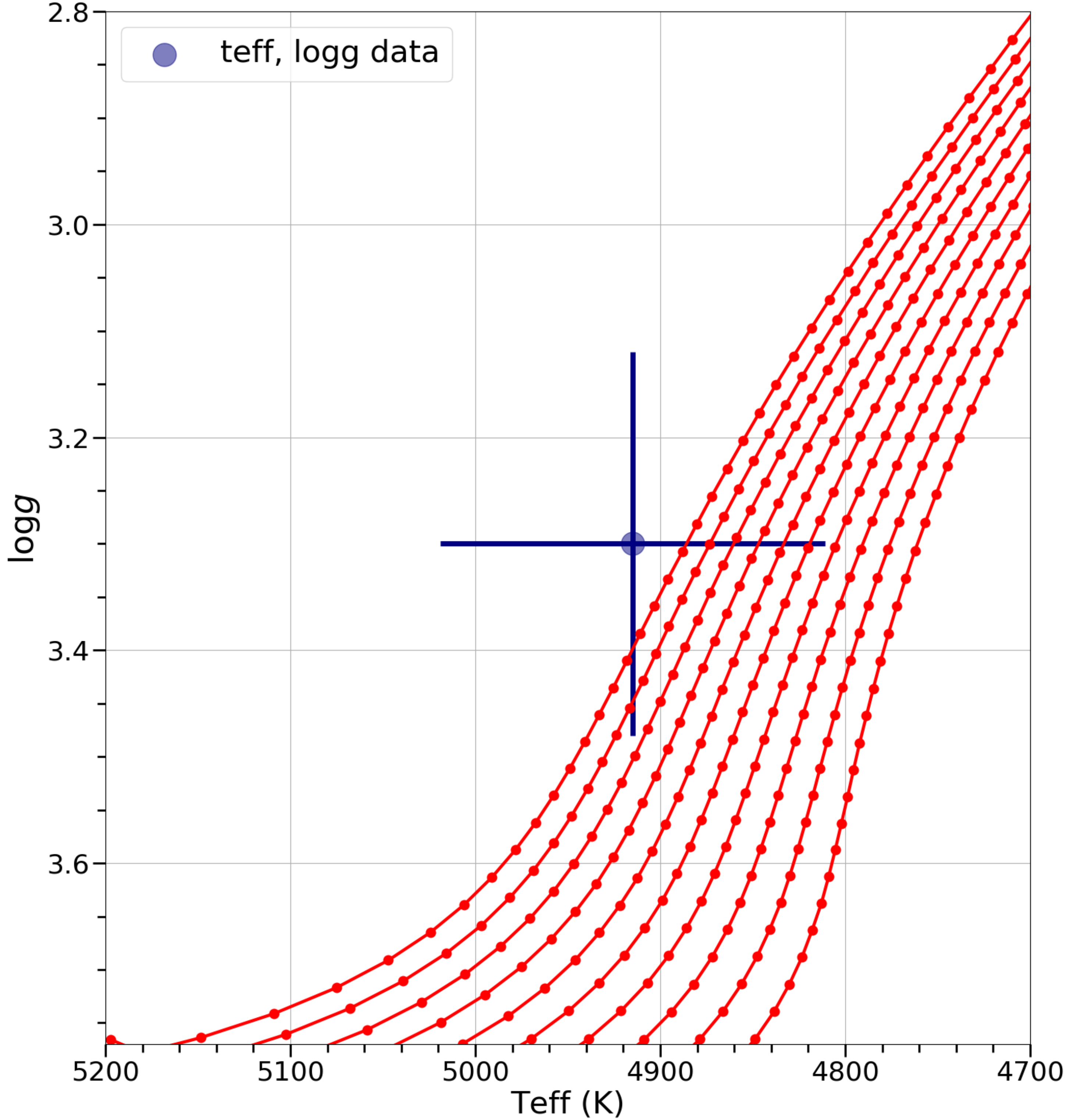
teff, logg data
logg
Teff (K)
2.8
3.0
3.2
3.4
3.6
5200
5100
5000
4900
4800
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# For the enthusiasts:

To compute the *weighted-average age* of a given star, we apply a combination of a **frequentist approach**, **goodness-of-fit**, and **maximum likelihood analysis**

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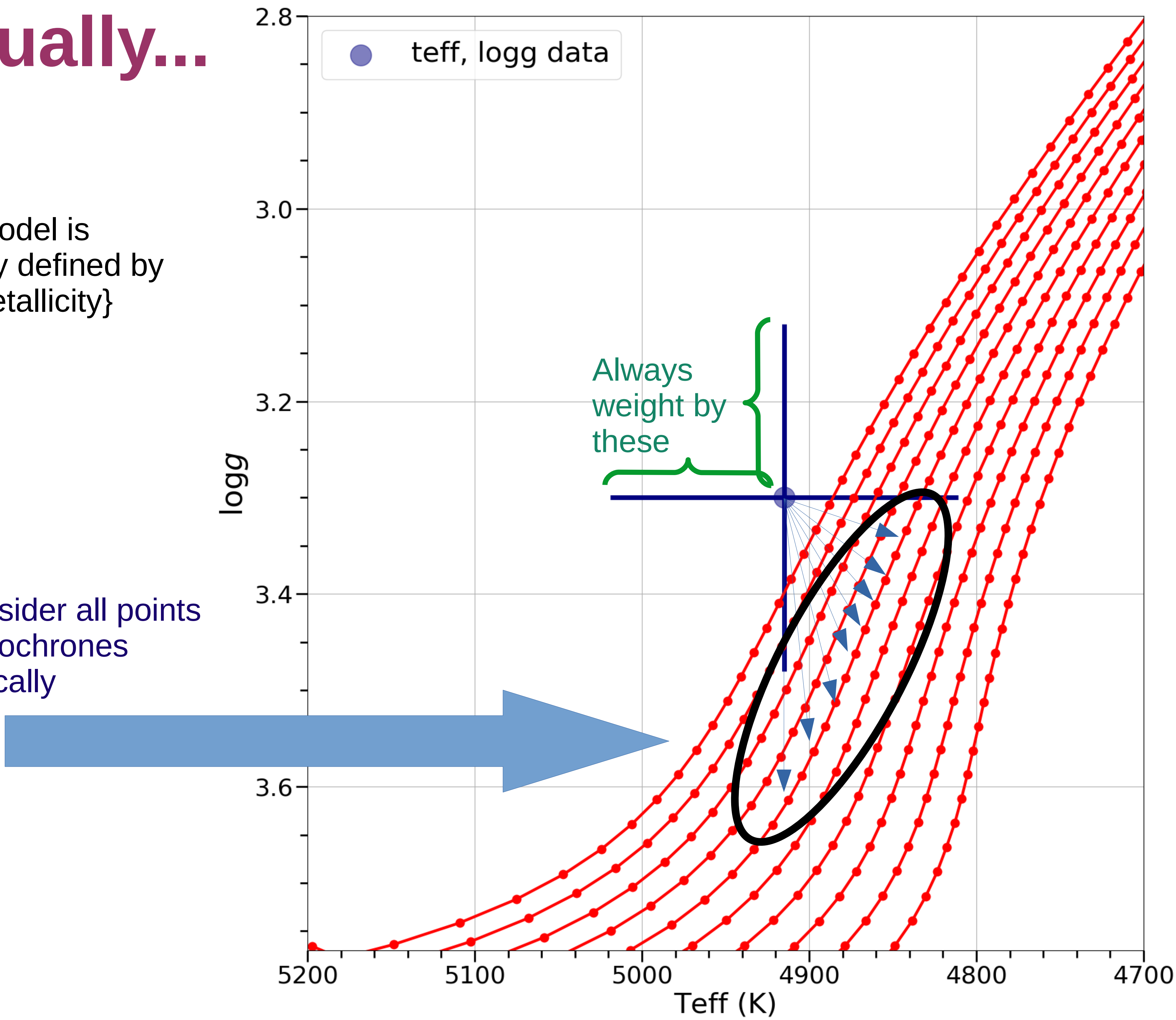
(3) - Compute a weighted average over all candidate hypotheses (each point on each isochrone)
- A point with age $t_n$ is weighted by its likelihood, $p_n$, of being an appropriate fit to the star
- The final weighted average, $t_S$, is our estimate for the age of the star

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

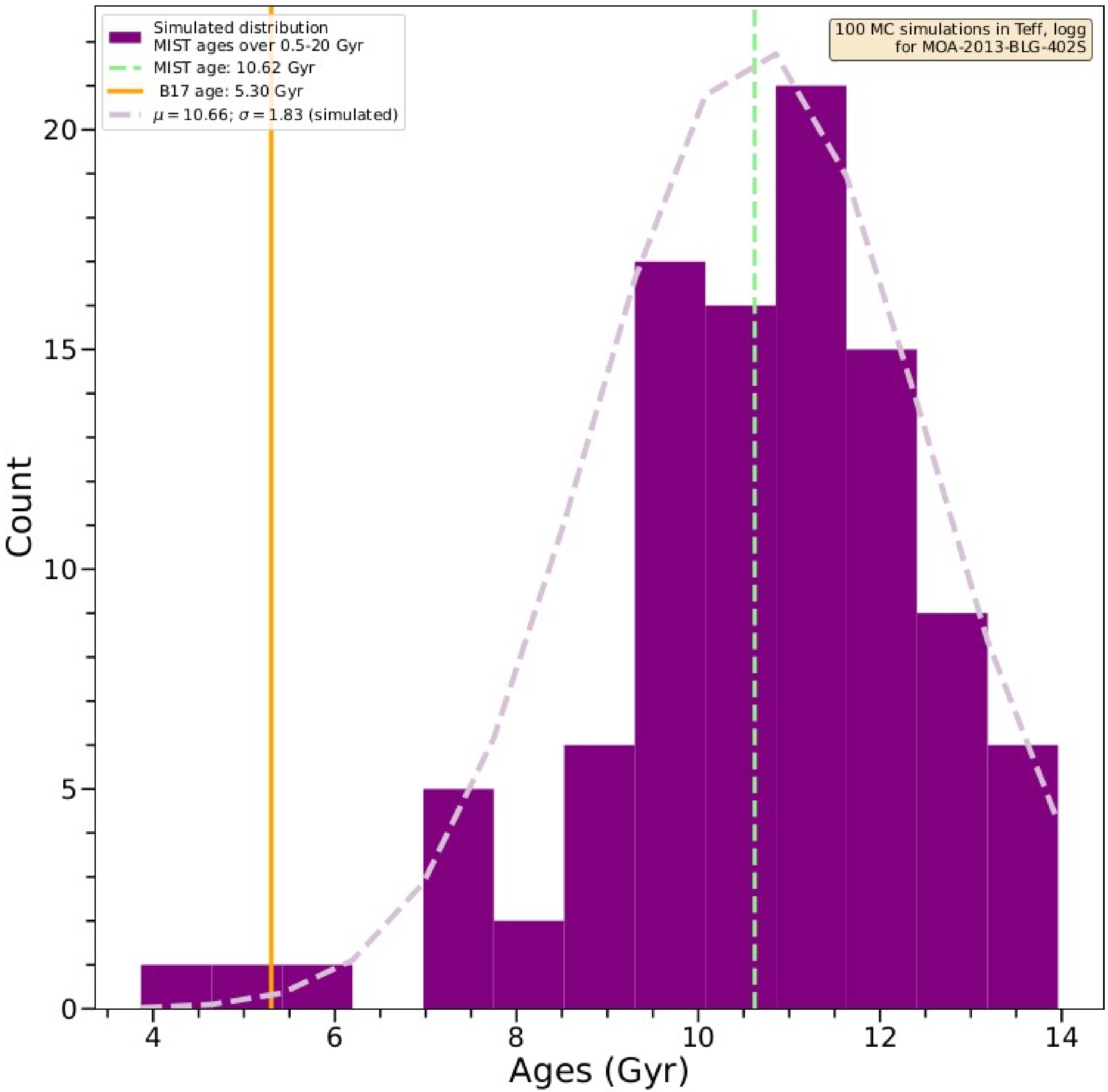
# Visually...

Each model is uniquely defined by {age,metallicity}

But consider all points on all isochrones agnostically



# 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

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

# Observational vs global uncertainties

There is an entire, second set of systematics we must understand in order to perform fully correct age determinations:

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There is an entire, second set of systematics we must understand in order to perform fully correct age determinations:


...the intrinsic uncertainty of the stellar models themselves

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**Convective & energy transport parameters:**
- mixing efficiency → convective mixing length
- convective overshoot
- convective boundaries; how the Schwarzschild/Ledoux criterion is evaluated

**Heavy element diffusion:**
- is it included, and where?
- how is it implemented?
- gravitational settling?
- 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?

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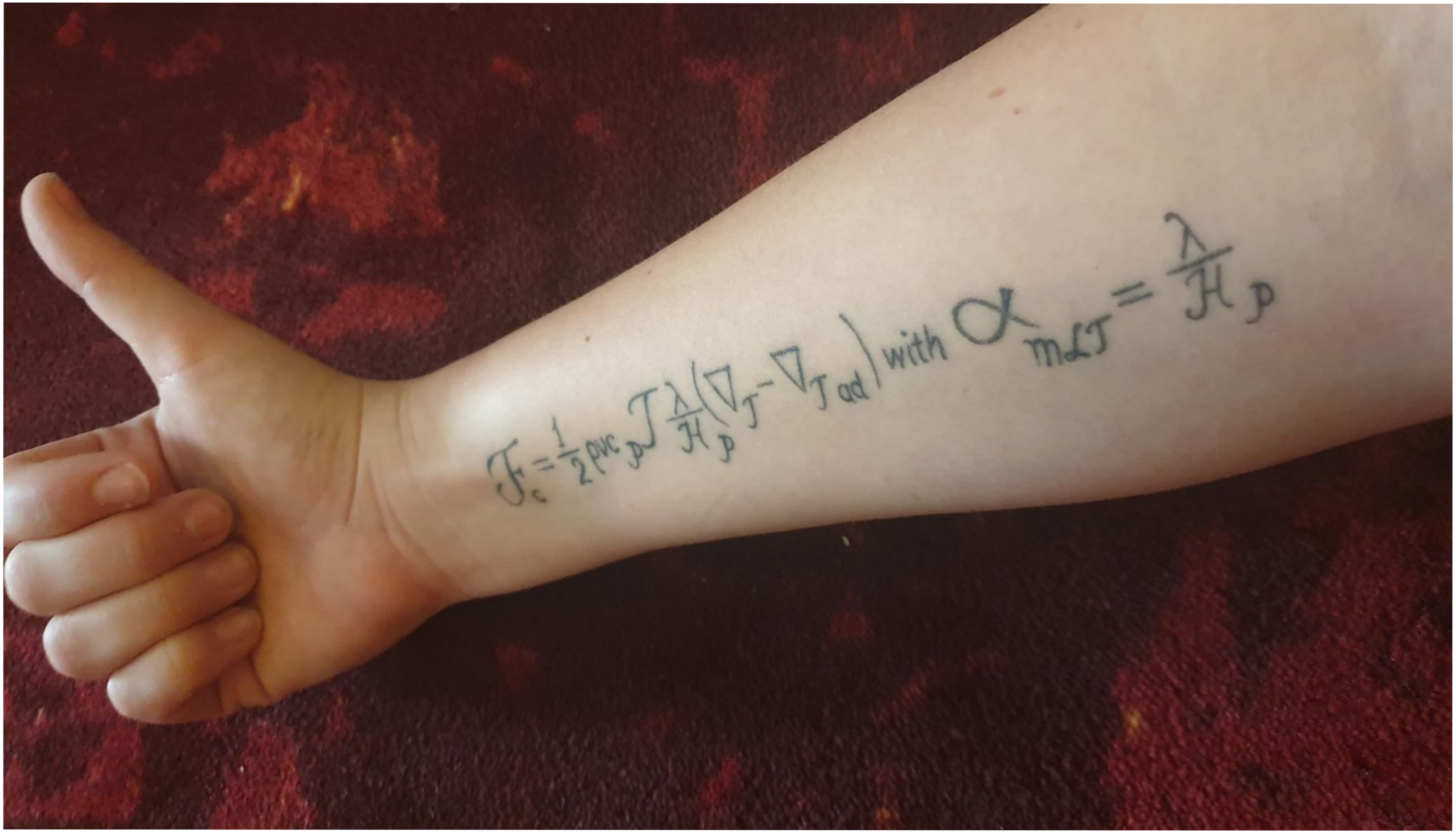
- if instead using a table-based treatment from external simulations (e.g. PHOENIX, Kurucz), what solar scale and other physics were used in those simulations? Are they self-consistent with the assumptions in the stellar models?

# We choose to use the convective mixing length, $\alpha_{MLT}$, for demonstration



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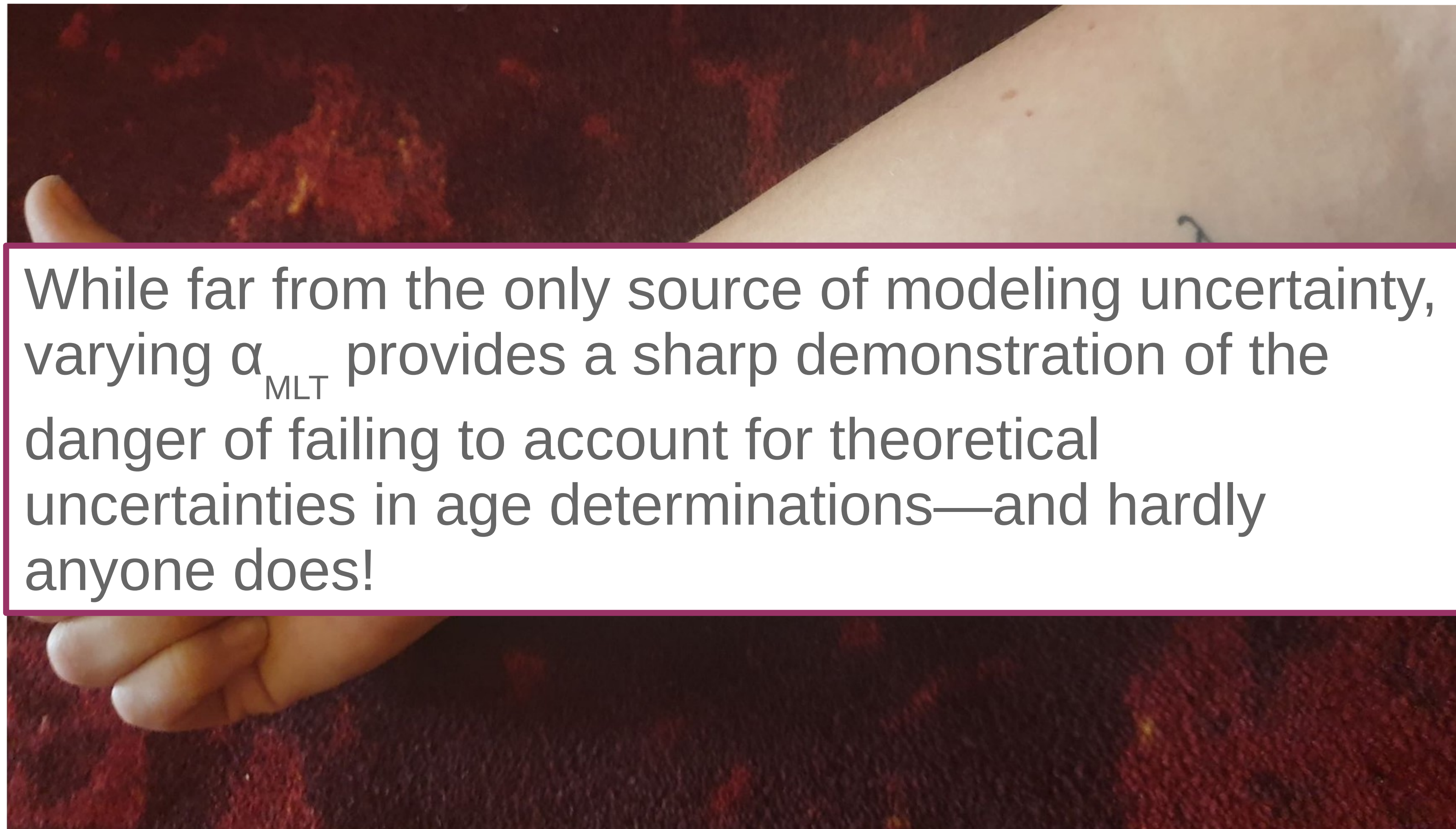
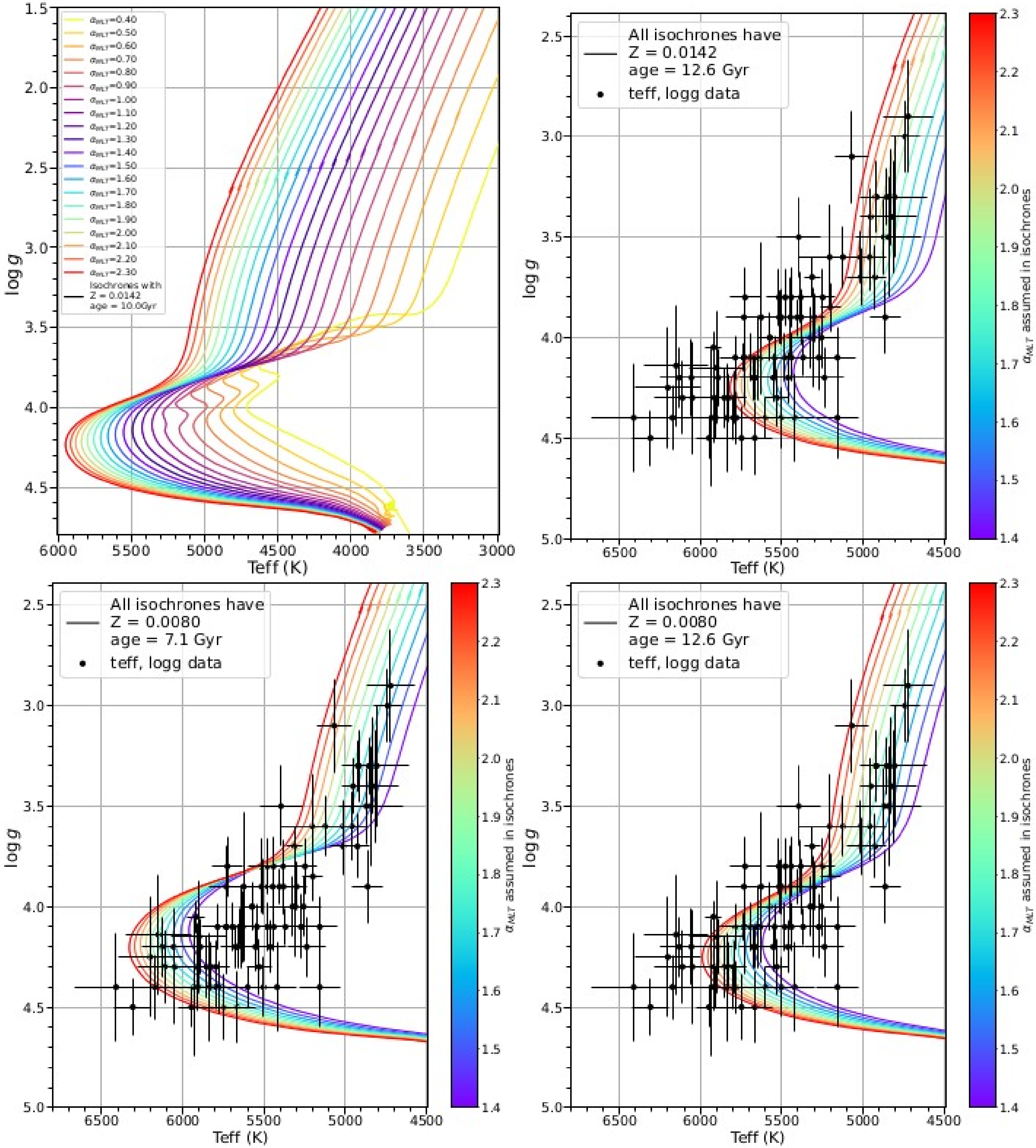


While far from the only source of modeling uncertainty, varying $\alpha_{MLT}$ provides a sharp demonstration of the danger of failing to account for theoretical uncertainties in age determinations—and hardly anyone does!

# The impact of αMLT



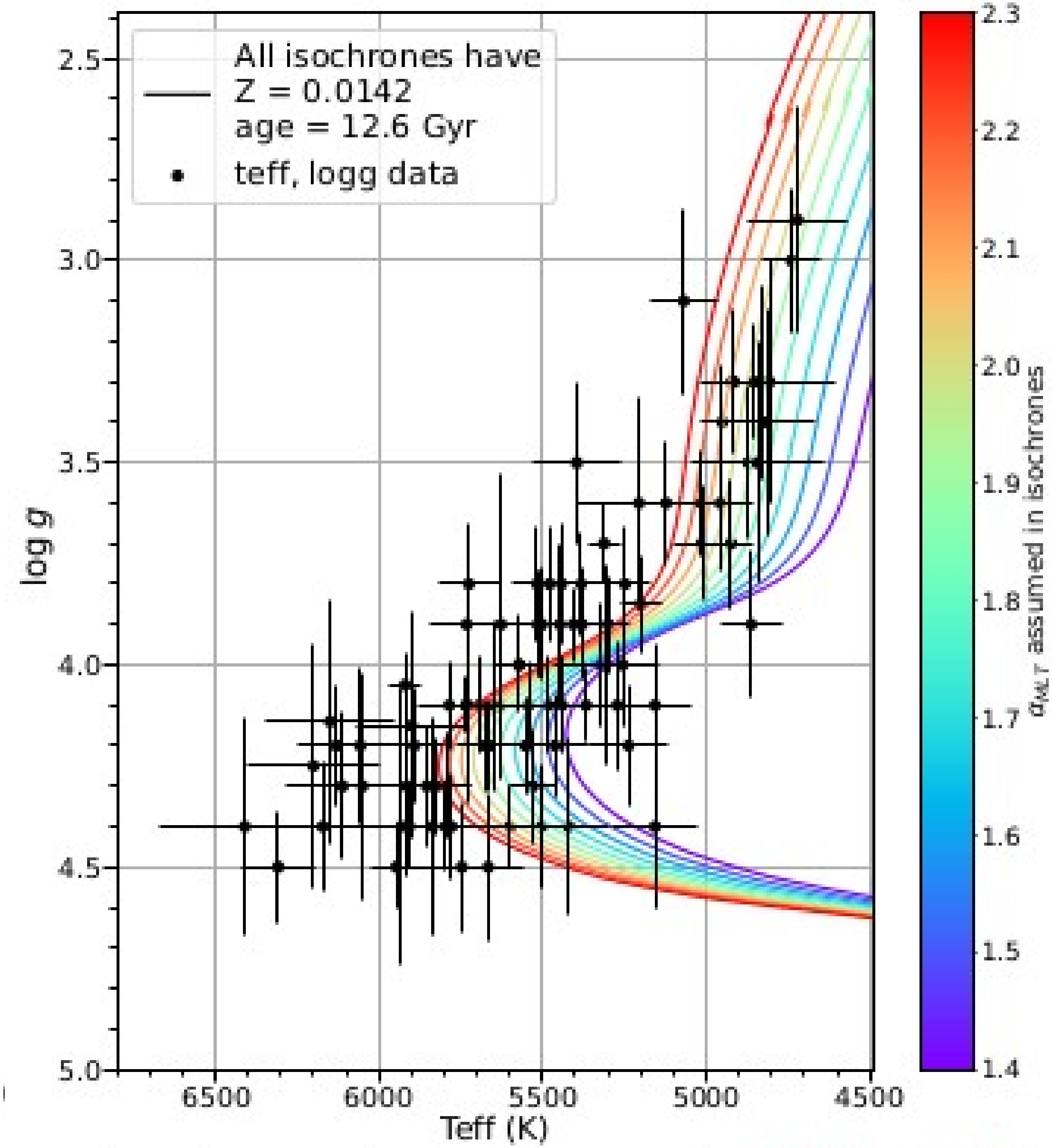
# Incorporating the isochrones' "shift" in our error simulations

Uniformly shift the isochrones according to the sampling of normal distributions given by

$$\mu = 0, \quad \sigma = \sigma_{T_{\rm eff,th}}$$
$$\mu = 0, \quad \sigma = \sigma_{\log g_{\rm th}},$$

sigma_logg = 0.17 dex

sigma_Teff = 200 K



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

| | Name | .. $\alpha$-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 | [illegible] ± 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 | 1[illegible].4 ± 1.5 |
| 9 | MOA-2011-BLG-034S | 14.6 ± 1.9 | 1[illegible].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 | 1[illegible].4 ± 2.7 |
| 13 | MOA-2011-BLG-104S | 13.3 ± 1.2 | 1[illegible].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 | [illegible]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 |
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| 8 | OGLE-2011-BL[illegible] | [illegible] | [illegible] |
| 9 | MO[illegible] | [illegible] | [illegible] |
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uncertainties increase by a factor of 1.5 - 2x

# Tension between inference methods?

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Ages are hard! Be careful with math.

# How can students get involved in research like this?

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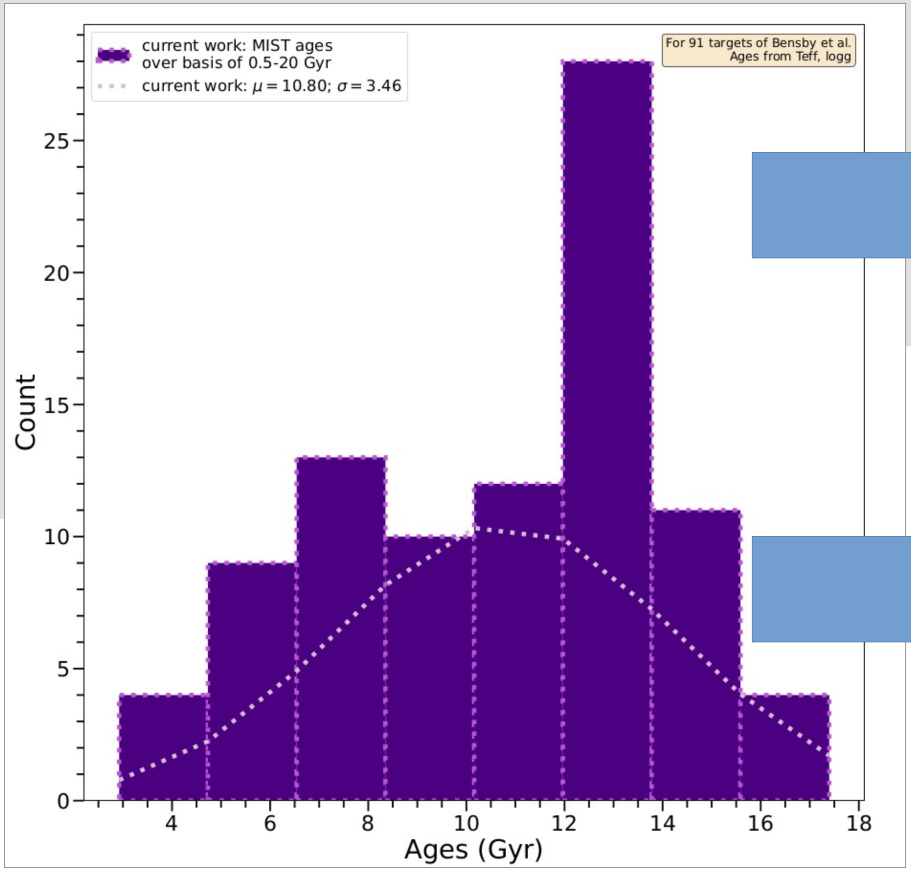
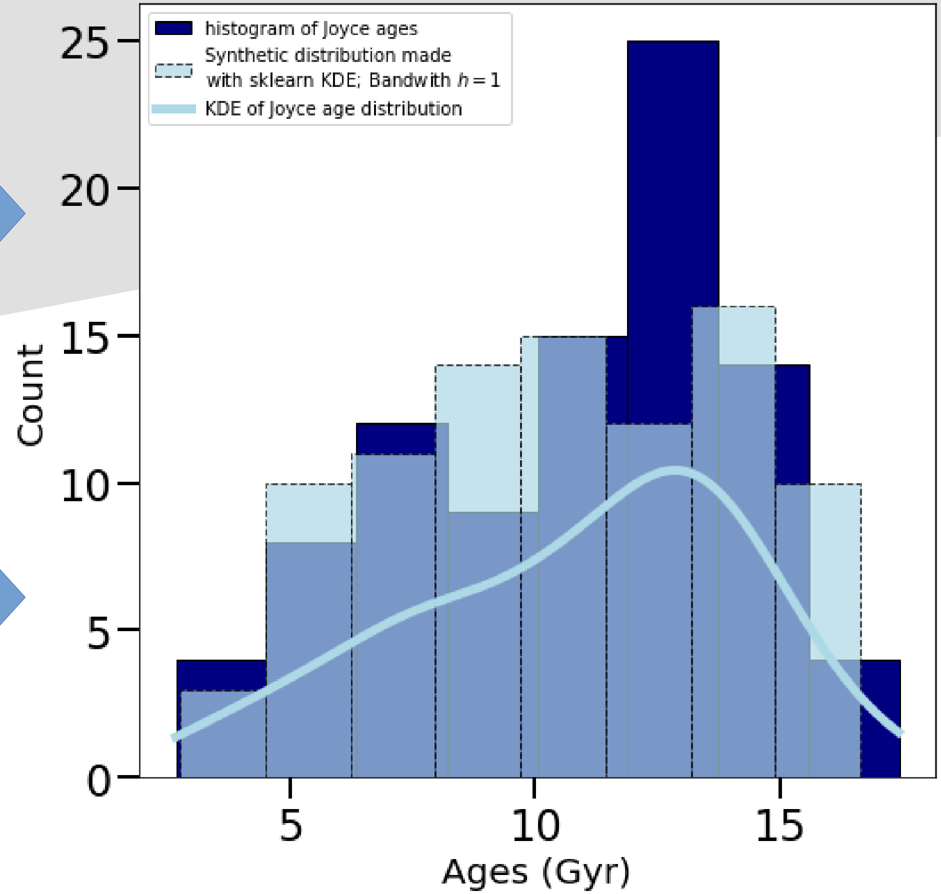
# You already were, in our mock class!



## The necessity of stellar structure and evolution (SSE) programs as tools of inference

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

But like any instrument, stellar structure and evolution codes are subject to calibration errors, biases, and “black-box” treatment

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**These are powerful tools, but only if we use them properly and understand their limitations!**