Better Stellar Modeling:

Numerical Tools and Techniques for the Modern Observational Landscape

IPMU, Kashiwa, Japan

15 January 2020

1D 3D
MESA2HYDRO

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In this talk:

Stellar Structure and Evolution (SSE) Programs

- ➔ Explanation and examples
- ➔ The Modules for Experiments in Stellar Astrophysics (MESA) software suite

Insights from precision 1D stellar modeling

- ➔ calibrators for convection in the stellar interior
- ➔ Predicting the near-future behavior of T Ursae Minoris through seismic evolution models

^{1D}MESA2HYDRO^{3D}

- ➔ Translating the customizable physics of 1D SSE codes to 3D smoothed-particle hydrodynamics initial conditions

Questions for the audience:

Who here has used a stellar track, isochrone, or synthetic frequency spectrum?

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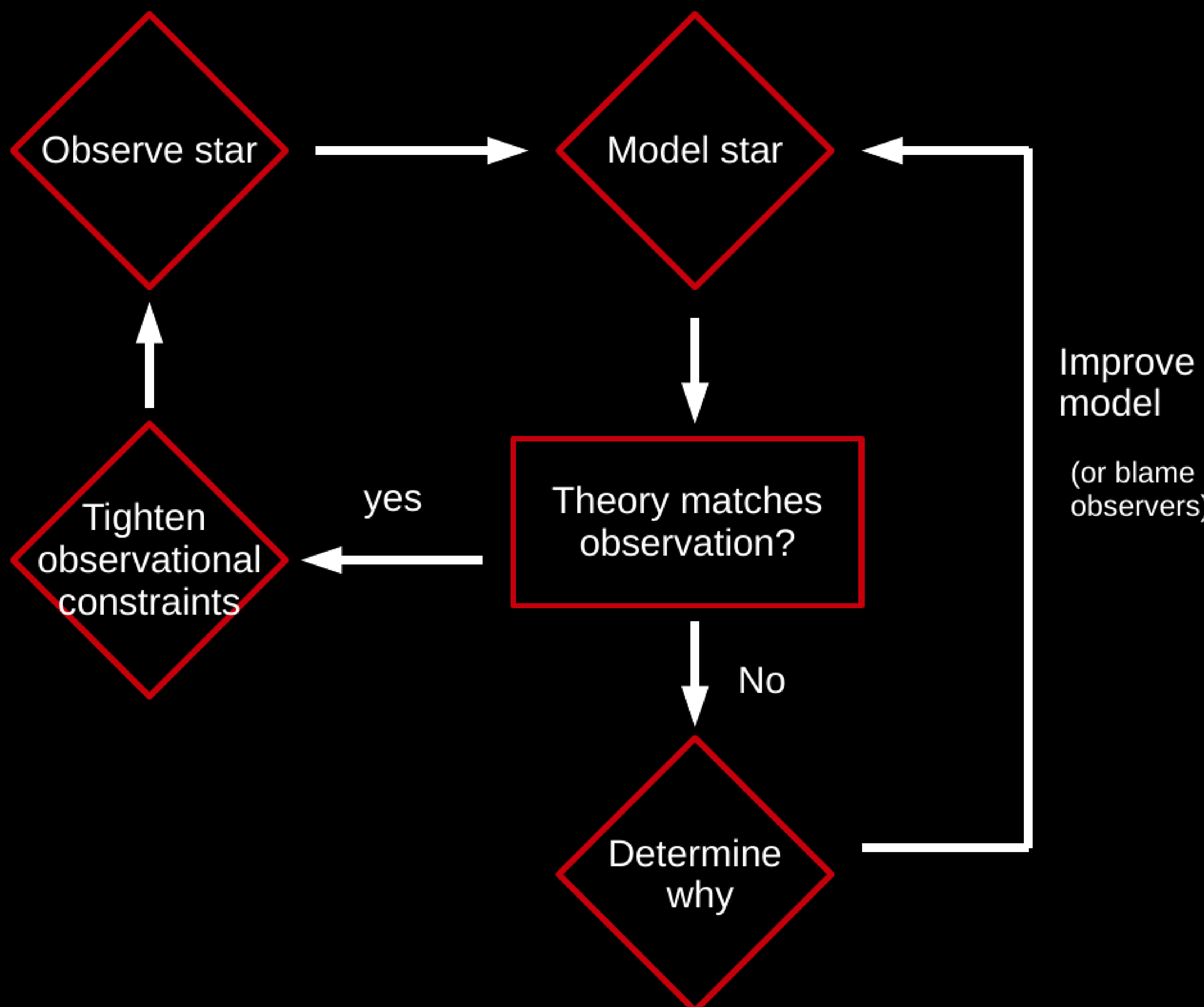
Like any instrument, stellar structure and evolution codes are subject to calibration errors, biases, and “black-box” treatment

The cycle of computational stellar astrophysics



Stellar Structure and Evolution (SSE) codes/programs:

We all need them, but do we really understand what they do?

How do stellar models work?

Mathematical Statement	Physical Principle
$\rho \frac{d\mathbf{v}}{dt} = -\nabla P - \rho \nabla \Phi$	Momentum conservation
$\nabla^2 \Phi = 4\pi G \rho$	Gravitation
$\frac{dP}{dr} = -\rho \frac{d\Phi}{dr}$	Hydrostatic equilibrium
$\frac{dM}{dr} = 4\pi r^2 \rho$	Mass continuity
$\frac{dL}{dr} = 4\pi r^2 \rho \varepsilon(\rho, T, \mu)$	Conservation of energy
$\frac{dT}{dr} = -\frac{3}{16\pi ac} \frac{\kappa \rho L}{r^2 T^3}$	Radiative energy transport
$= -\frac{GM}{c_p r^2}$	Adiabatic convective energy transport
$\frac{d\rho_i}{dt} = Q_i$	Nuclear energy generation.

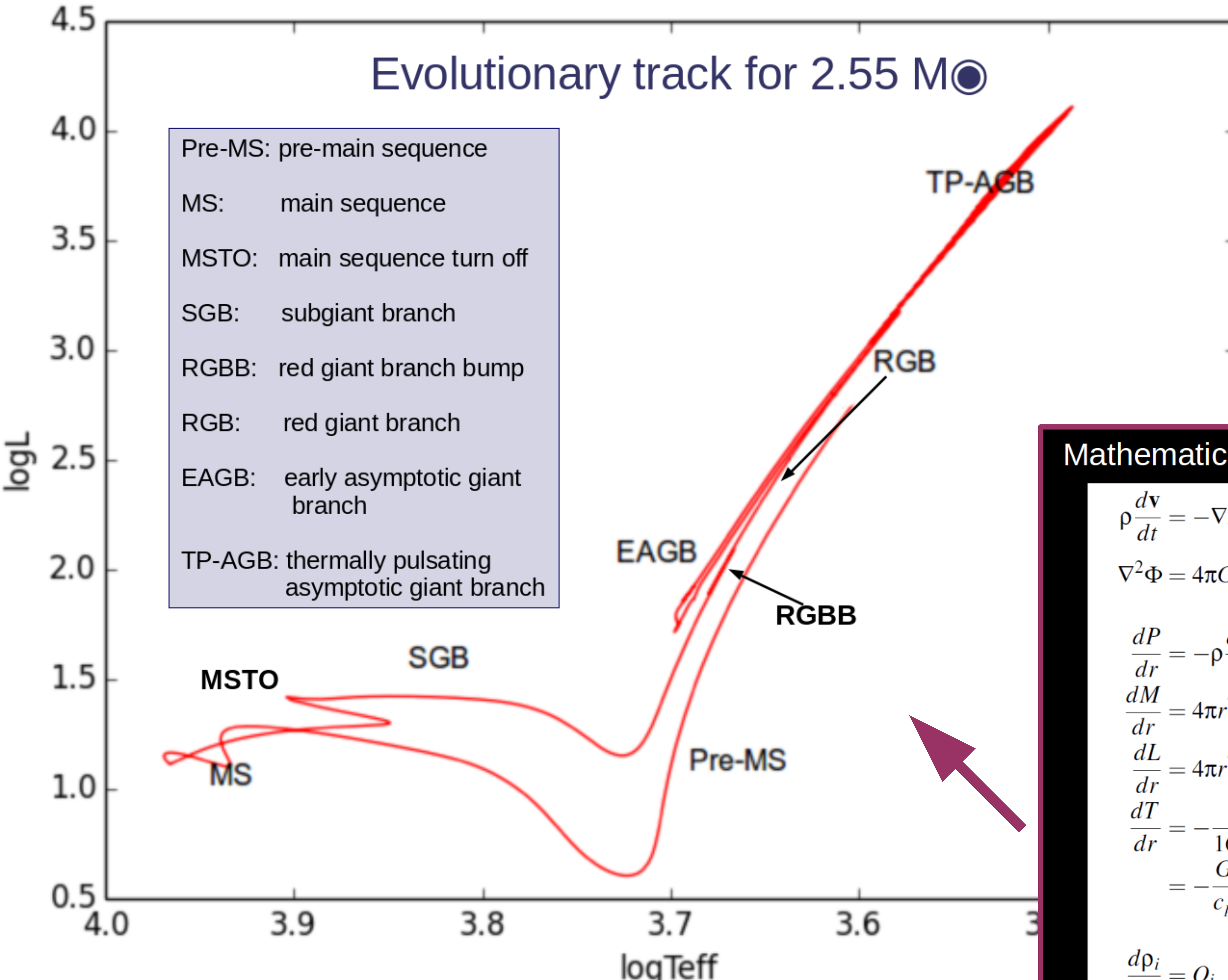
Simplest model of a star

A form of Poisson's equation describes a self-gravitating, spherically symmetric ball of fluid
Dimensionless form: Lane—Emden equation $$\frac{1}{\xi^2}\frac{d}{d\xi}\left(\xi^2\frac{d\theta}{d\xi}\right)+\theta^n=0$$

Solve this under an equation of state relating certain physical quantities (e.g. ideal gas law) to obtain the radial profile, or stellar structure, described by P(r), ρ(r), m(r)
Simplest: polytropic EOS $$P=K\rho^{1+\frac{1}{n}}$$

Compute the structure of this sphere at many times t under prescribed conditions for energy transport to see changes in state variables: Luminosity (L), temperature (T), composition (μ)

A map of the state variables over time constitutes the evolution of the model



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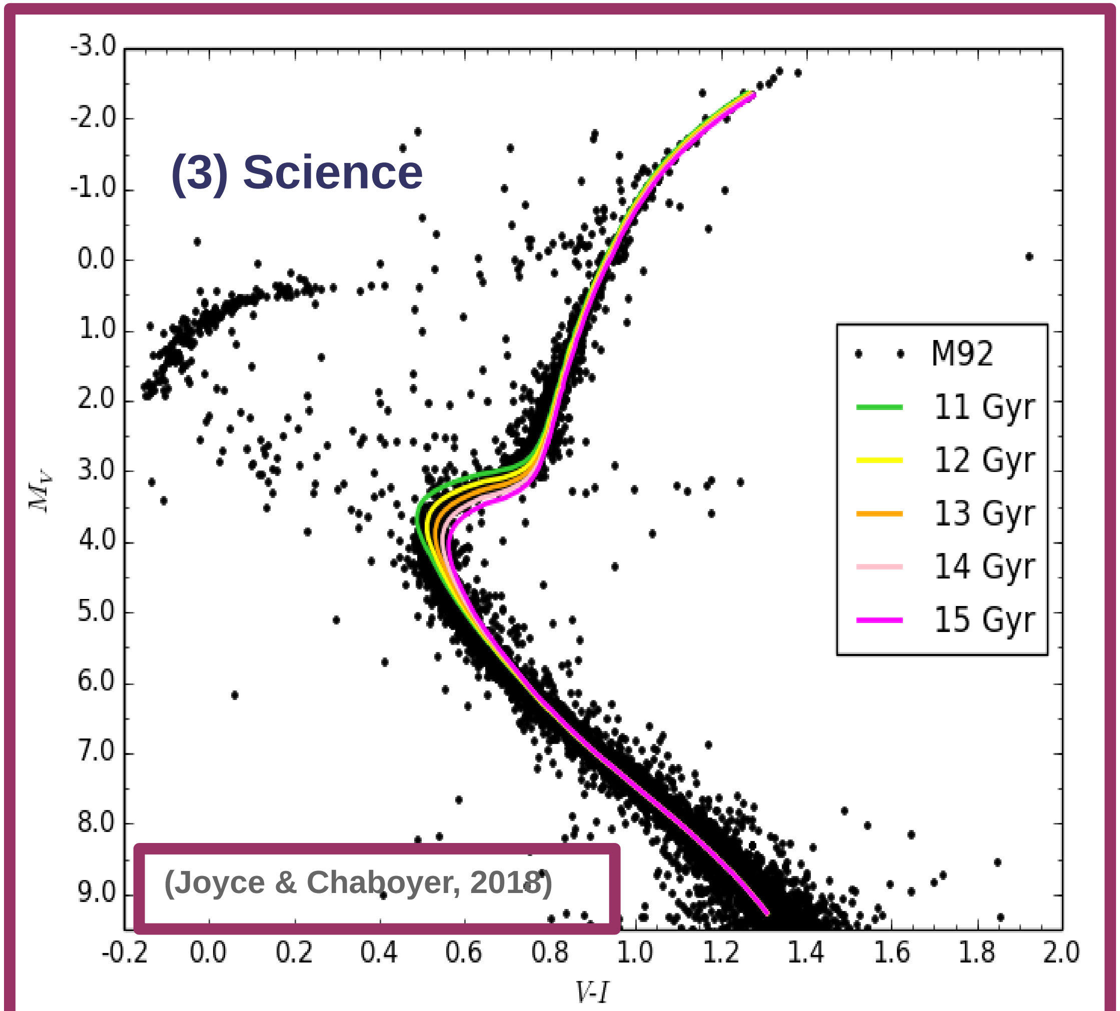
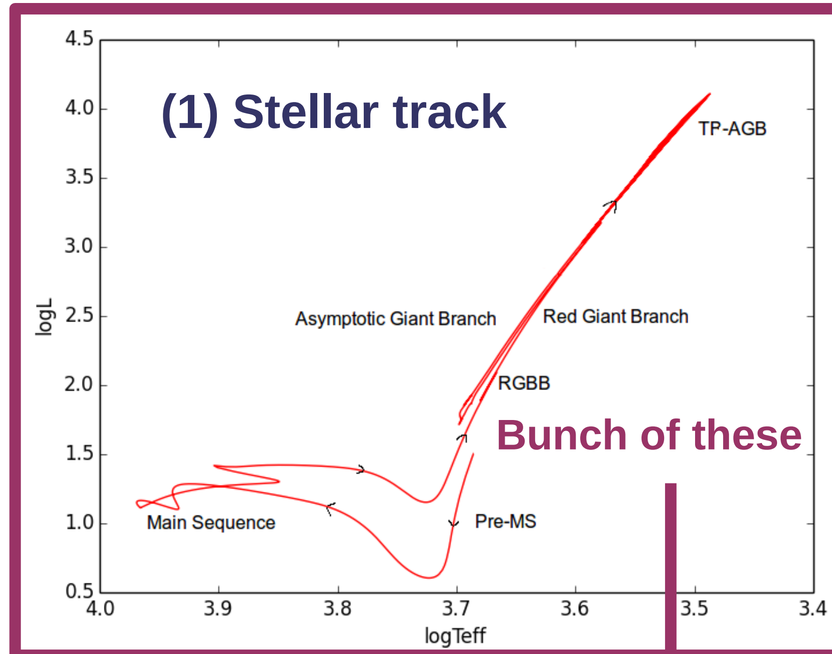
$$\frac{dL}{dr} = 4\pi r^2 \rho \varepsilon(\rho, T, \mu)$$

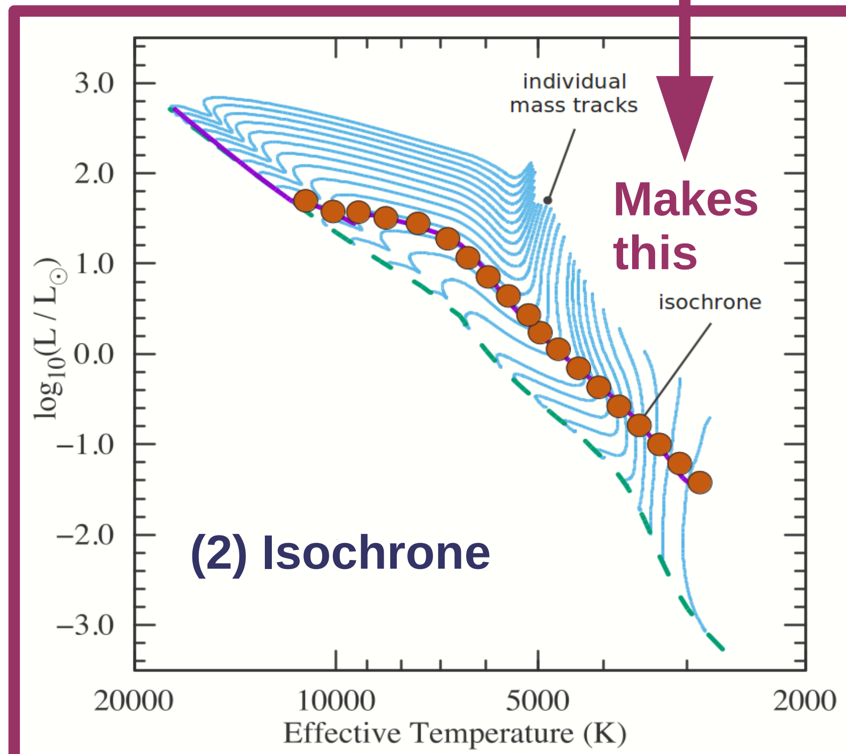
$$\frac{dT}{dr} = -\frac{3}{16\pi a c} \frac{\kappa \rho L}{r^2 T^3} = -\frac{GM}{c_p r^2}$$

$$\frac{d\rho_i}{dt} = Q_i$$

Math to Astronomy

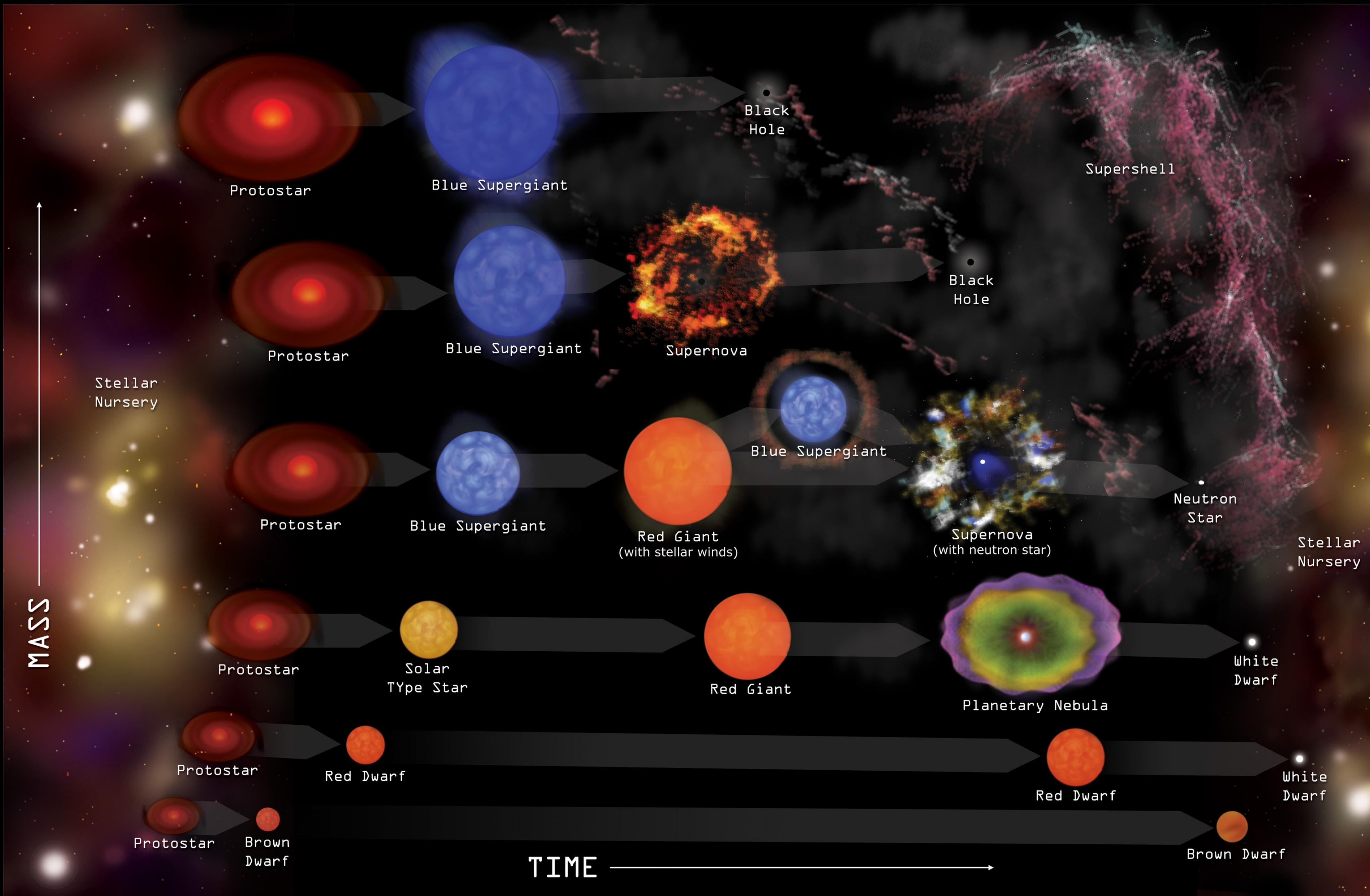






Derive fundamental parameters for both individual stars and stellar populations

→ allows us to study how stars live and die



We have had functional models of stellar structure and evolution for several decades...

What’s left to learn?

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What's left to learn?

Many things.

Let me convince you.

Two (of many) SSE programs with different benefits:

D S E P

Dartmouth Stellar Evolution Program

written by Brian Chaboyer (my PhD adviser)
w/ updated release by Aaron Dotter and contributions from Greg Feiden and myself

Pros:

-excellent for low mass stars (~0.5–2.5 Msolar)
-best code for reproducing the observed mass-radius relation on the main sequence
-good for metal-poor stars
-uses heavy element diffusion (Thoul et al., 1994)
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-not user friendly
-not open source
-only ~4 people have contributed to its development
-difficult to add extensions

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MESA

Paxton et al., 2011–2019; 5 paper releases and numerous code releases

Pros:
- -widest scope in astrophysics—everything from large planets to black hole progenitor systems
- -open source
- -modular: easy to add features
- -large user base
- -actively maintained and documented

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Pros:

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-modular: easy to add features
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Cons:

-slower run time
-“broad” rather than “deep” in its physics
-steep learning curve
-installation and technical barriers can be intimidating

But it is worth it!

Modules for Experiments in Stellar Astrophysics

MESA

*You may also want to visit **the MESA marketplace**, where users share the inlists from their published results, tools & utilities, and teaching materials.*

Why a new 1D stellar evolution code?

The MESA Manifesto discusses the motivation for the MESA project, outlines a MESA code of conduct, and describes the establishment of a MESA Council. Before using MESA, you should read the **manifesto document**. Here's a brief extract of some of the key points

Stellar evolution calculations remain a basic tool of broad impact for astrophysics. New observations constantly test the models, even in 1D. The continued demand requires the construction of a general, modern stellar evolution code that combines the following advantages:

- **Openness**: anyone can download sources from the website.
- **Modularity**: independent modules for physics and for numerical algorithms; the parts can be used stand-alone.
- **Wide Applicability**: capable of calculating the evolution of stars in a wide range of environments.
- **Modern Techniques**: advanced AMR, fully coupled solution for composition and abundances, mass loss and gain, etc.
- **Comprehensive Microphysics**: up-to-date, wide-ranging, flexible, and independently useable microphysics modules.
- **Performance**: runs well on a personal computer and makes effective use of parallelism with multi-core architectures.

Latest News

- 10 Sep 2019 » **Release 12115**
- 30 Aug 2019 » **New MESA SDK Version**
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- 04 Mar 2019 » **Instrument Paper 5**
- 11 Jan 2019 » **Summer School 2019**
- 21 Mar 2018 » **Release 10398**

- O underlying program is a 1 dimensional stellar structure solver
- O widest breadth of physical conditions available in any code
- O software development is:
  - -lead by an actual computer scientist
  - - collaborative effort between ~13 world experts in diverse subfields of computational astrophysics
  - - driven by demand from a broad user base

Modules for Experiments in Stellar Astrophysics

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What are the official roles in MESA?

There are a few defined roles in the MESA community.

1st Author

- **Bill Paxton**

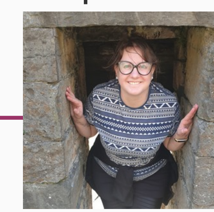
The 1st author is the primary developer of MESA and the first author on the MESA instrument papers

Developers

Current developers:

- **Warrick Ball**
- Evan Bauer
- **Lars Bildsten**
- **Matteo Cantiello**
- Aaron Dotter
- **Robert Farmer**
- **Adam Jermyn**
- **Meridith Joyce**
- Pablo Marchant
- **Josiah Schwab**
- **Radek Smolec**
- Anne Thoul
- **Frank Timmes**
- **Rich Townsend**
- **Bill Wolf**

Me: most recent developer



(still learning!)

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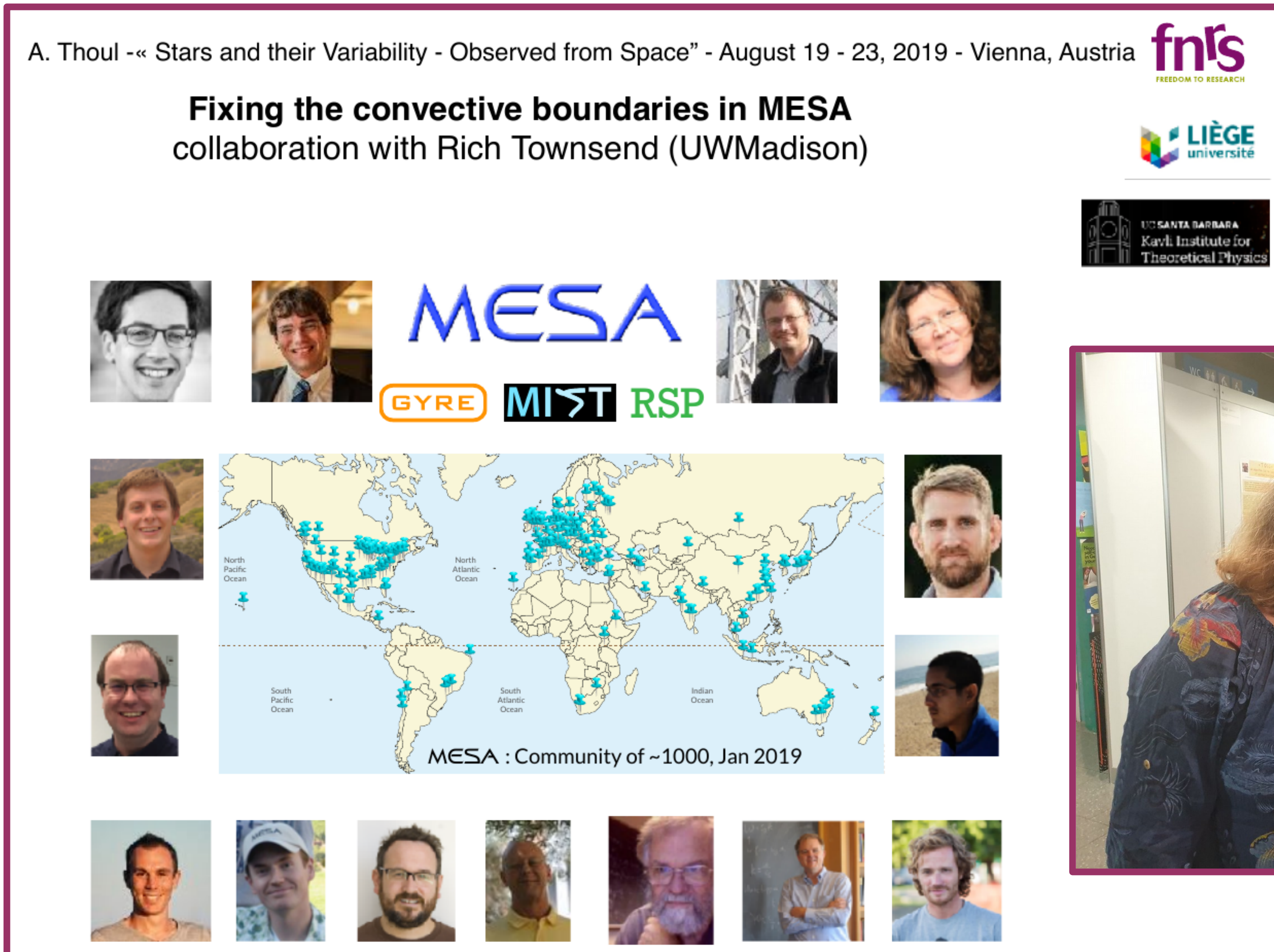
How I got involved with MESA:

-wrote a software package that interfaces with MESA (Joyce et al., 2019, ApJ)

-talked w/ first female developer, Anne Thoul, after her presentation on implementing convective boundaries in MESA at “Stars and Their Variability,” University of Vienna

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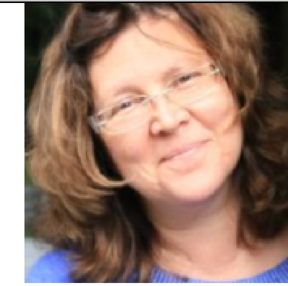
Anne Thoul


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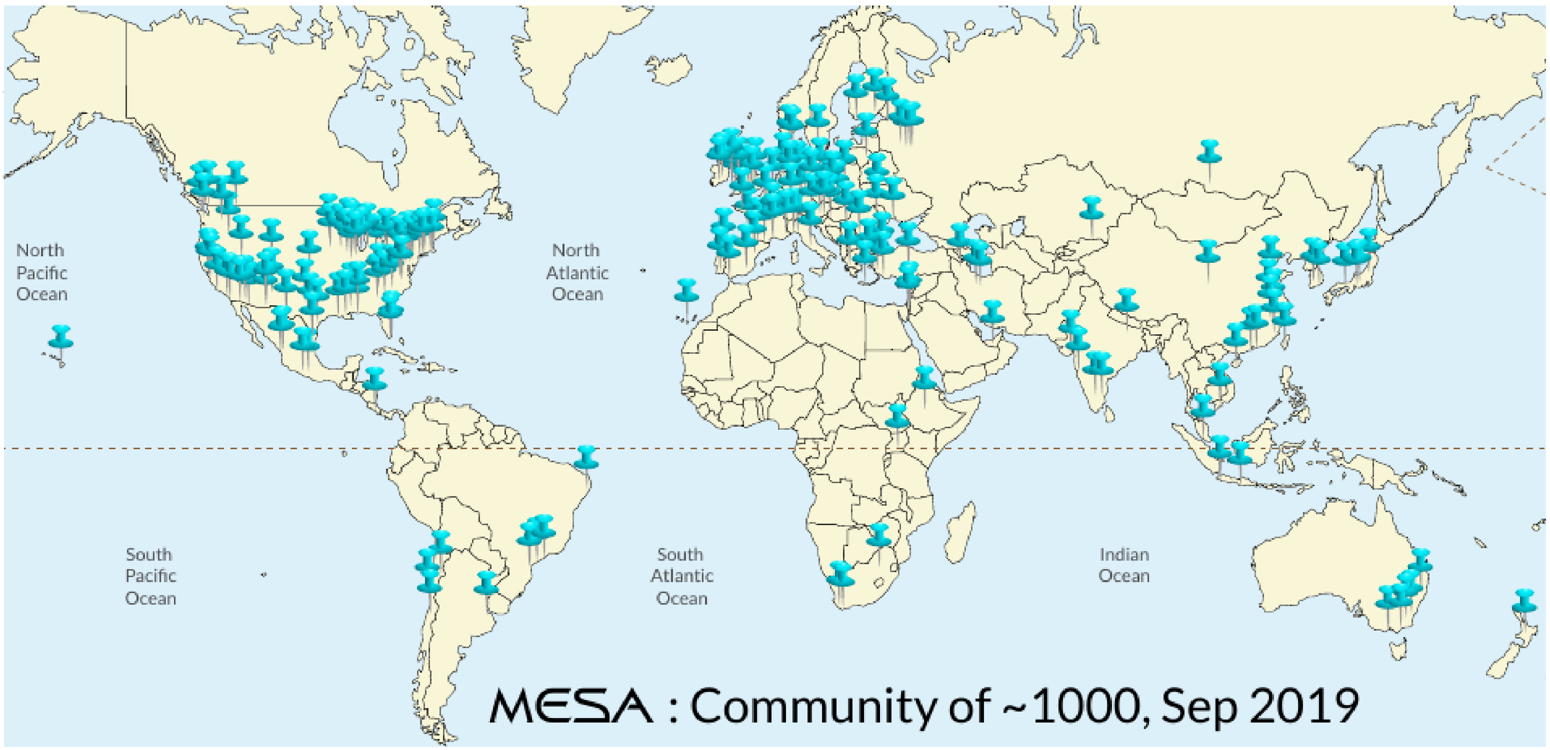


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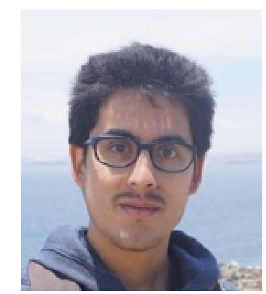
Pablo Marchant


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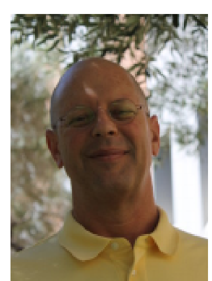
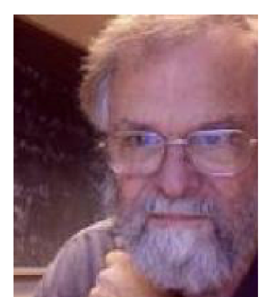

Frank Timmes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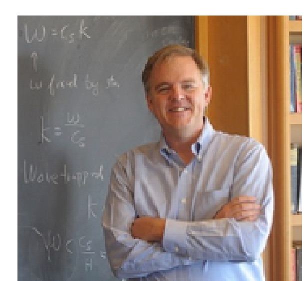

Lars Bildsten

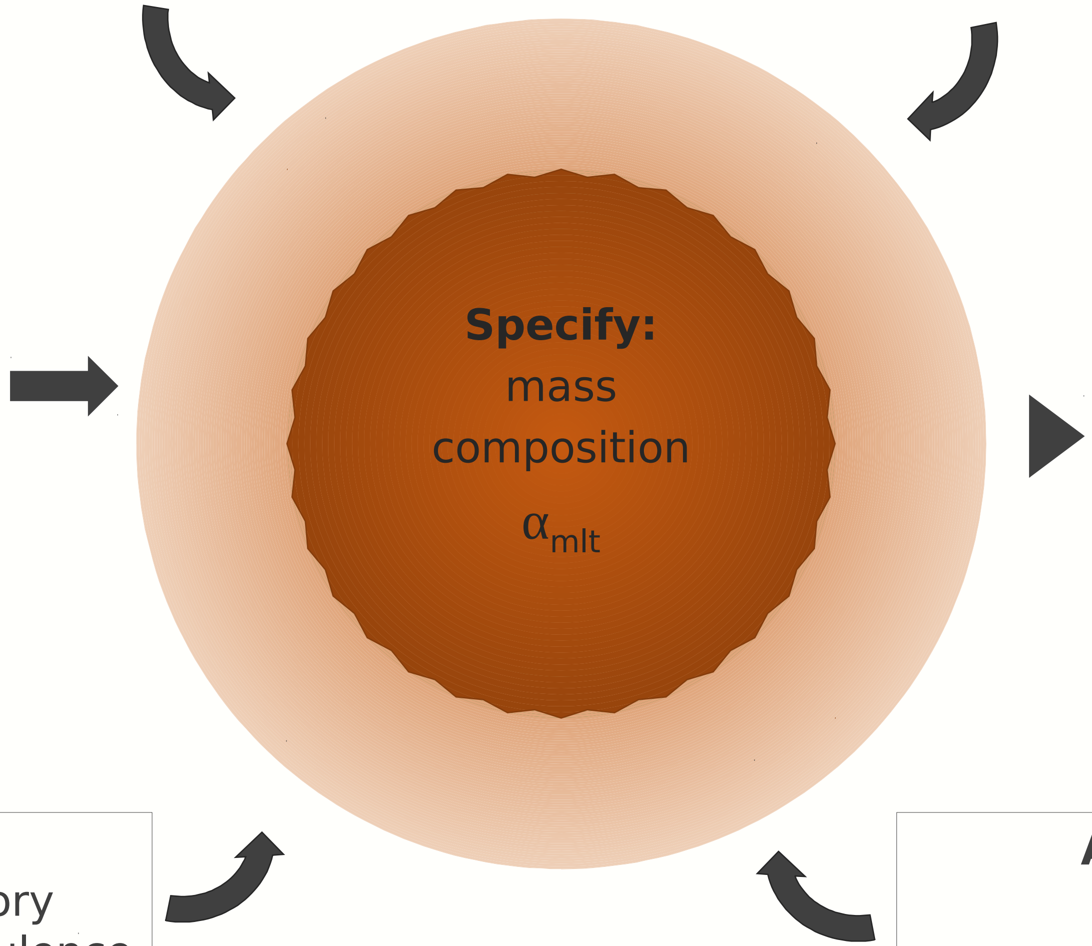

Matteo Cantiello

Components of a Stellar Structure and Evolution Code

Standard Equations:
mass & energy conservation
hydrostatic equilibrium
energy transport

Surface Boundary Conditions:
grey – Eddington $T(\tau)$
grey – Krishna Swamy $T(\tau)$
non-grey – stellar atmospheres

Microphysics:
opacities
equation of state
nuclear reactions



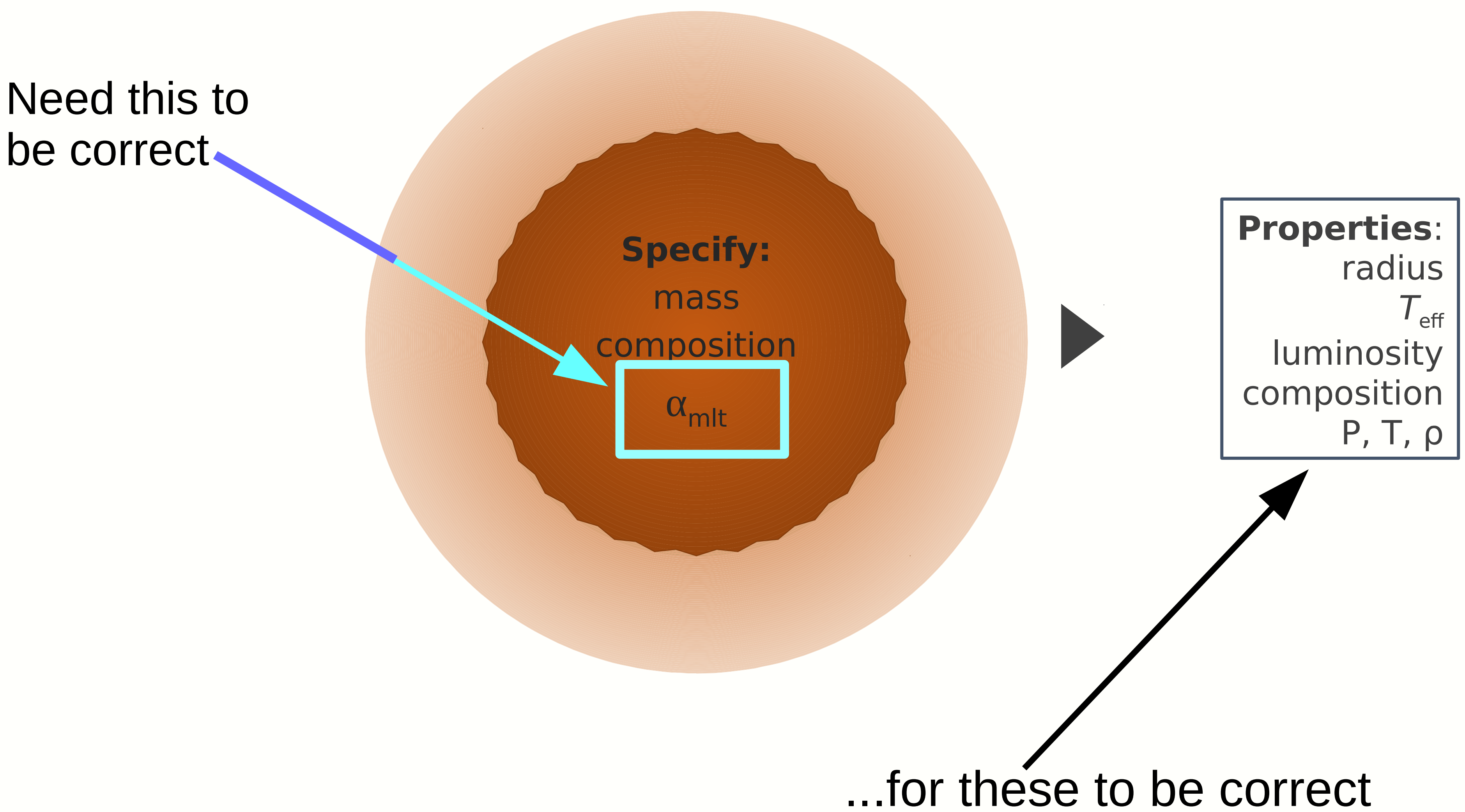
Properties:
radius
T_{eff}
luminosity
composition
P, T, ρ

Convection:
mixing length theory
full spectrum turbulence

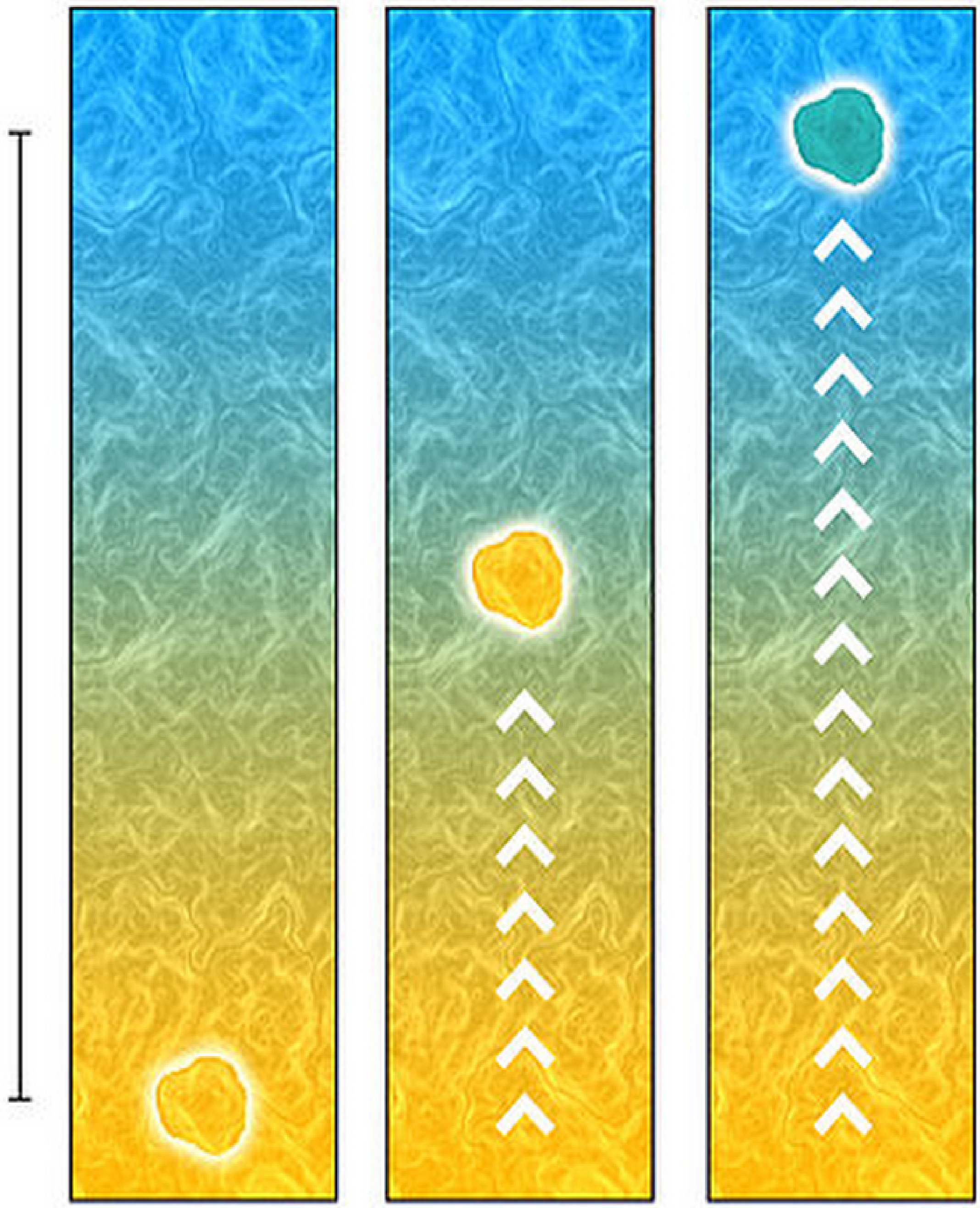
Additional Physics:
diffusion
variable mass
rotation
magnetic fields / activity

Slide credit: Greg Feiden

Components of a Stellar Structure and Evolution Code



Mixing Length Theory (MLT) Formalism



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

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

-discrete parcels consist of fluid which are in pressure, but not thermal, equilibrium

-parcels move along vertical trajectories

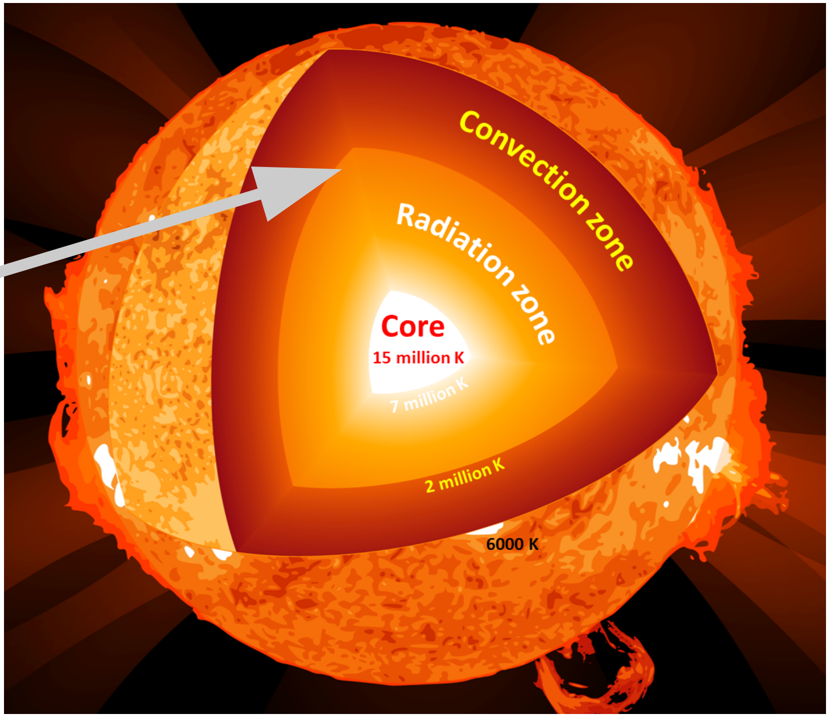
- “mixing length:” average distance which parcels can travel before denaturing

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

MLT calibrations are tedious, difficult, and only possible in a specific regime, but using uncalibrated values introduces modeling errors

Because it is a free parameter, α_{MLT} absorbs **modeling inconsistencies**

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



Two separate science questions:

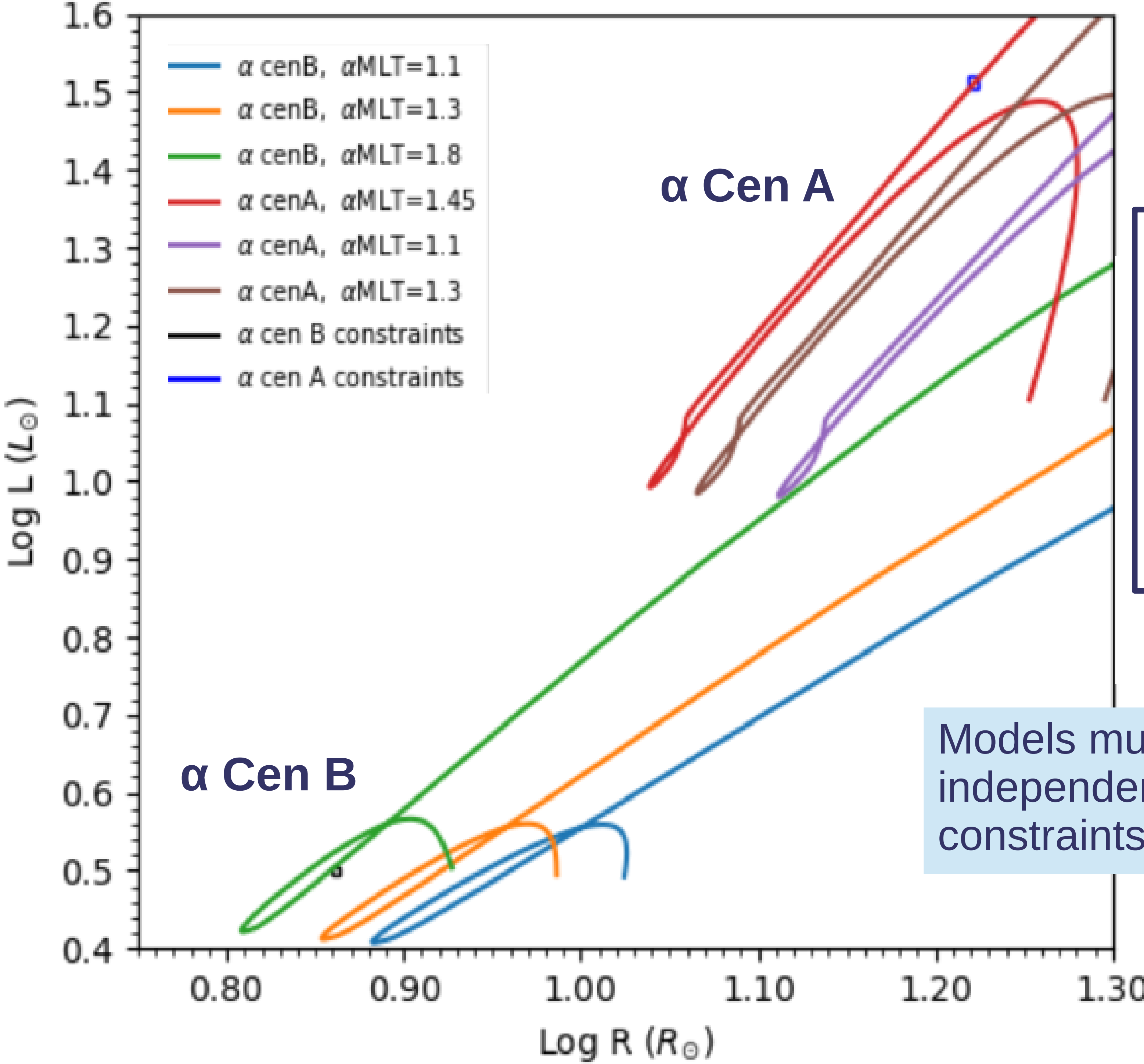
(1) How does α_{MLT} vary among stars with different global properties?

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

MLT Calibrations with Seismic Binaries

α Centauri A & B

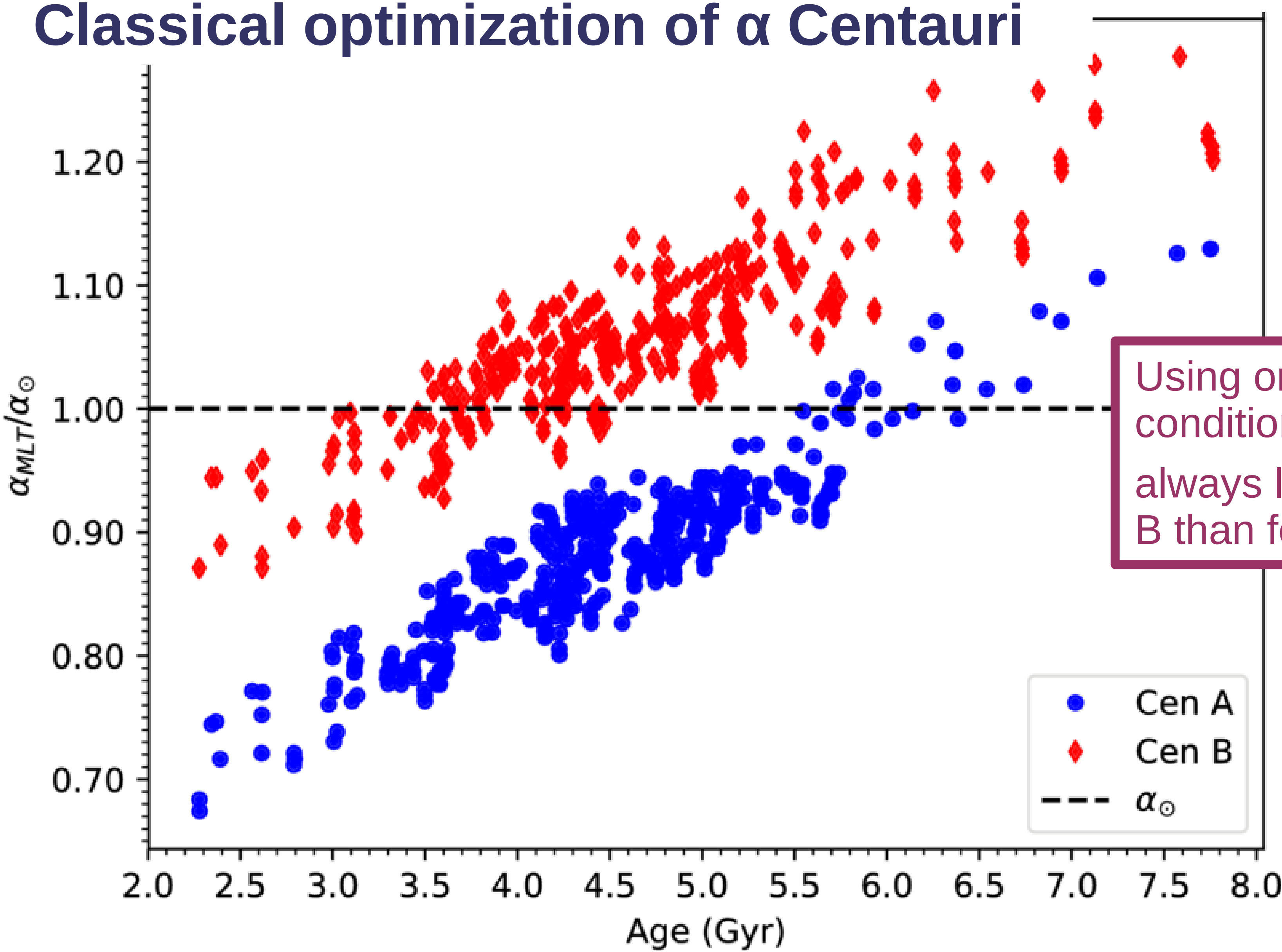
Classical optimization of α Centauri



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

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

Classical optimization of α Centauri



Using only these 7 conditions, α_{MLT} is always larger for α Cen B than for α Cen A

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

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

Incorporating seismic constraints

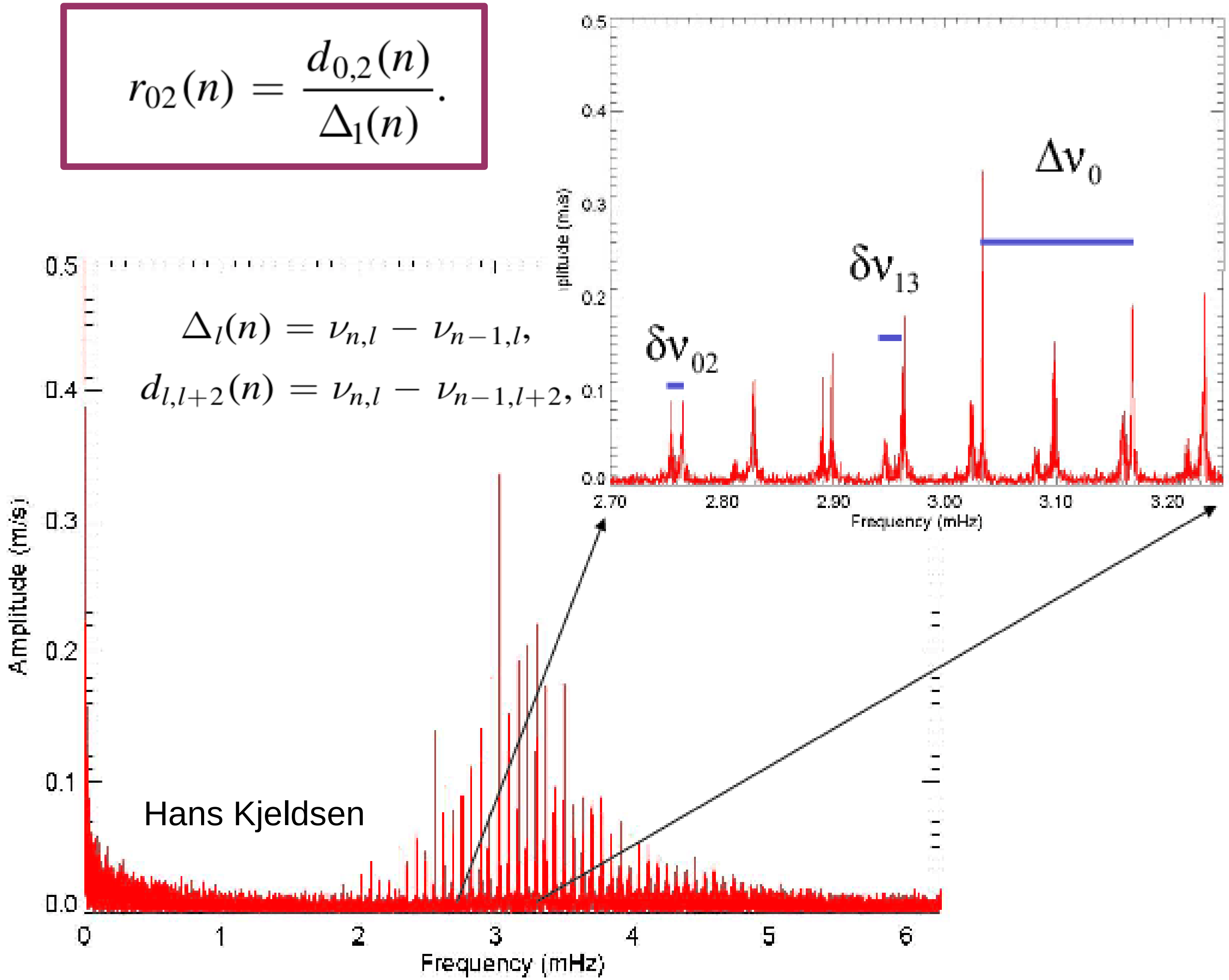
-Ratio between small and large frequency separation tells us about the sound speed in the interior

-can be computed from observations and obtained theoretically using GYRE

-r_{02} corrects "surface effects"—the known deviation of ridges in observed vs theoretical Echelle diagrams caused by approximate atmospheric modeling

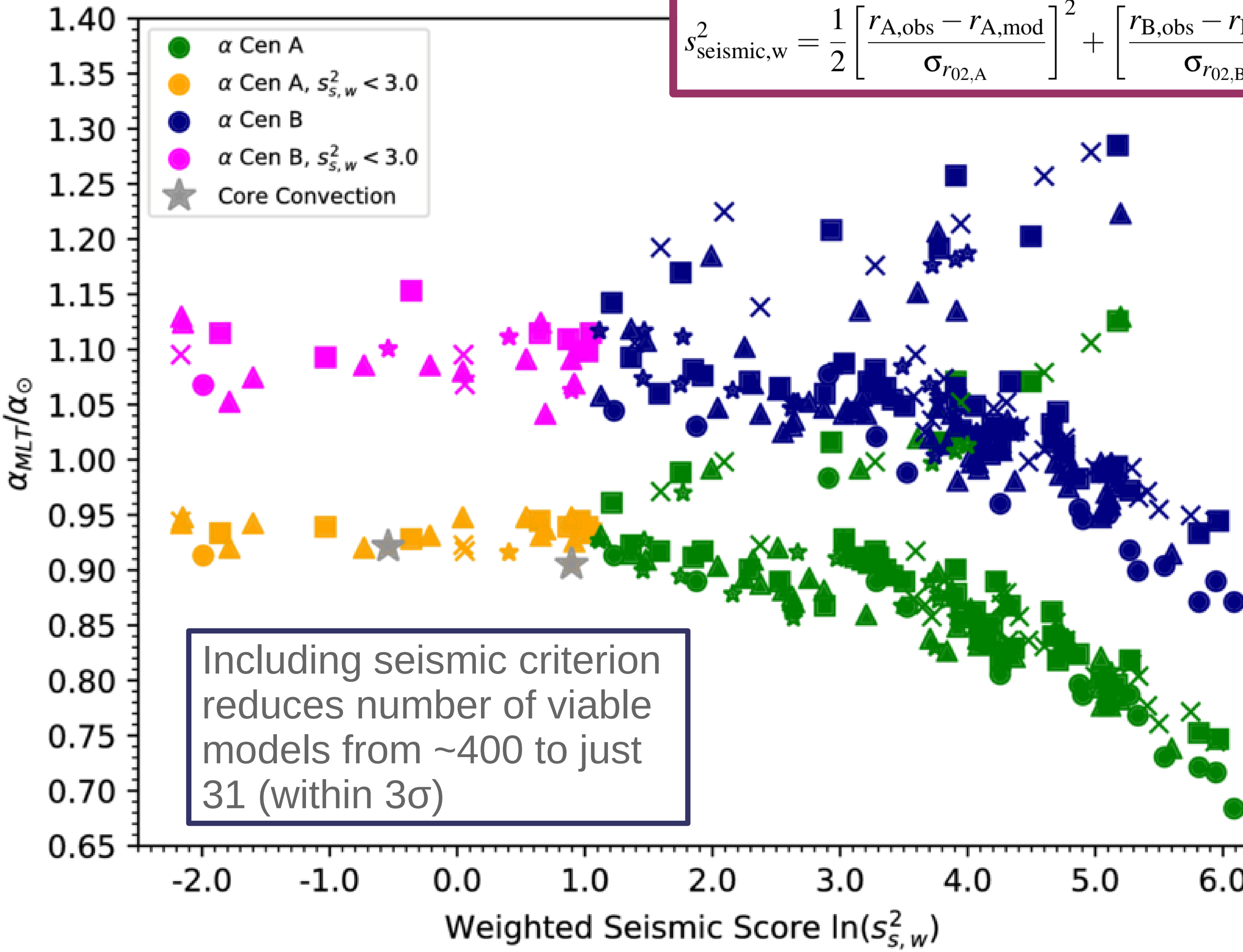
$$r_{02}(n) = \frac{d_{0,2}(n)}{\Delta_1(n)}.$$

$$\Delta_l(n) = \nu_{n,l} - \nu_{n-1,l},$$
$$d_{l,l+2}(n) = \nu_{n,l} - \nu_{n-1,l+2},$$



Incorporating seismic constraints

$$s^2_{\text{seismic,w}} = \frac{1}{2}\left[\frac{r_{\text{A,obs}} - r_{\text{A,mod}}}{\sigma_{r_{02,\text{A}}}}\right]^2 + \left[\frac{r_{\text{B,obs}} - r_{\text{B,mod}}}{\sigma_{r_{02,\text{B}}}}\right]^2$$

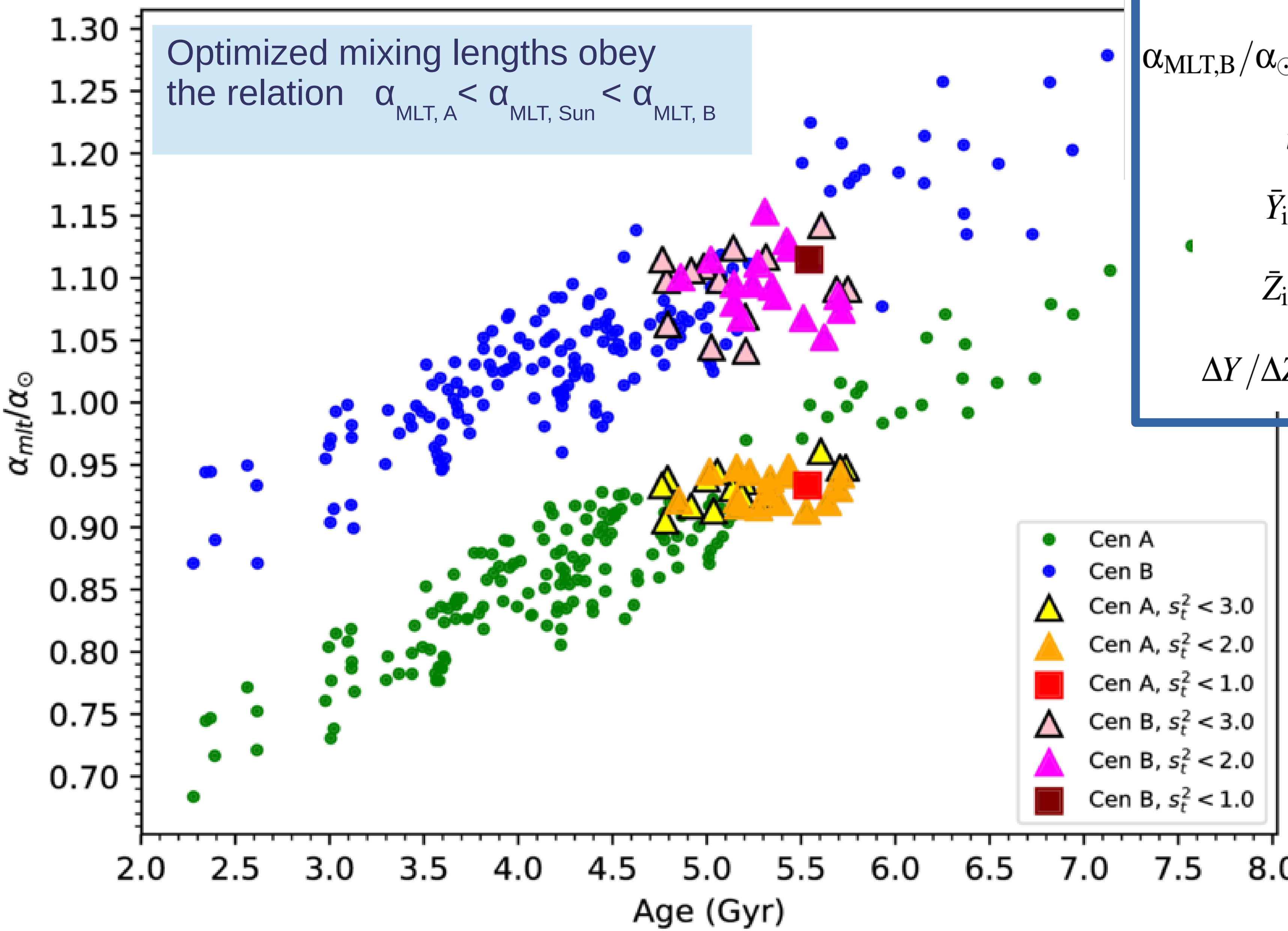


Including seismic criterion reduces number of viable models from ~400 to just 31 (within 3σ)

Results:

-refined fundamental parameters of α Centauri A & B

-new method for age estimation



$$\alpha_{\mathrm{MLT,A}}/\alpha_{\odot} = 0.932 \pm 0.17;$$

$$\alpha_{\mathrm{MLT,B}}/\alpha_{\odot} = 1.095 \pm 0.20;$$

$$t = 5.26 \pm 0.95\,\mathrm{Gyr};$$

$$\bar{Y}_{\mathrm{in}} = 0.273 \pm 0.035;$$

$$\bar{Z}_{\mathrm{in}} = 0.027 \pm 0.005;$$

$$\Delta Y/\Delta Z = 0.90 \pm 0.12.$$

General Conclusions:

– seismic constraints severely restrict α_{MLT}, especially for α Cen A

– solar-normalized α_{MLT} converge to well-defined values in both stars!

– MLT calculations seem to be insensitive to variations in (1D) input physics; main effect is on the age estimate

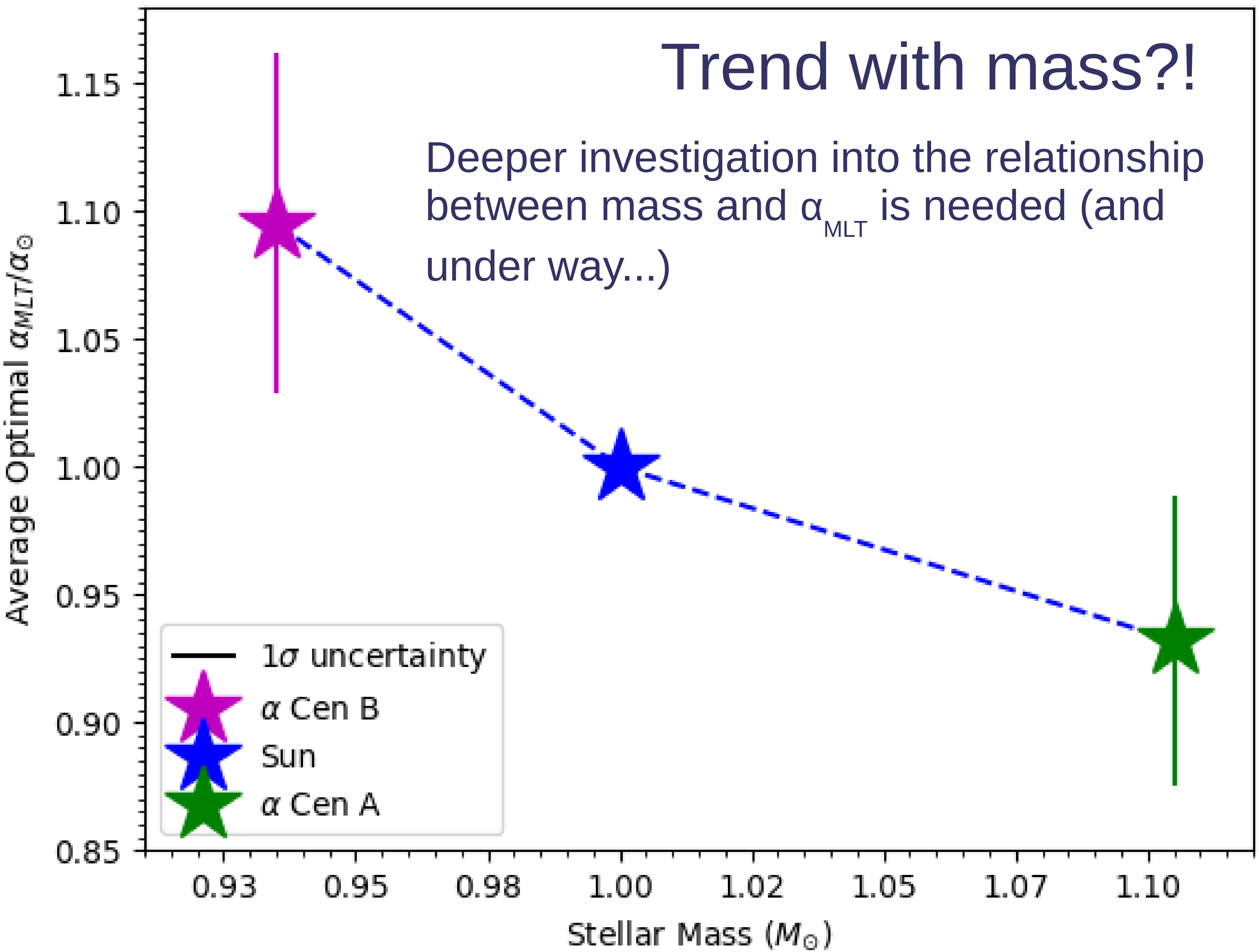
– under all conditions tested, the hotter and more massive star prefers smaller mixing length values than its cooler, lower-mass counterpart

Important to note: this directly contradicts trends found when using 3D atmospheres (e.g. Zhou, Asplund, et al in prep; STAGGER grid)

Our group's work on this discrepancy continues...

Trend with mass?!

Deeper investigation into the relationship between mass and α_{MLT} is needed (and under way...)



More MLT calibrations with seismic binaries

Kepler targets
Solar twins
& Procyon

What makes alpha Cen the perfect lab?

Independent measurements remove degrees of freedom and isolate MLT

Mass – kinematics

Radius – interferometry

Luminosity – photometry

Surface abundance – high resolution spectroscopy

Stellar interior constraints **from which surface effects can be removed** – seismology

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

Problem:

No other (known) system satisfies all of these conditions!

Other contenders:

– doubly oscillating *Kepler* targets: usually missing interferometry

– interferometric targets: usually cannot also be spectroscopic binaries

– stars with high resolution spectroscopy (HRS): powerful for determining input composition, but lack an interior constraint

– stars that DO satisfy the basics:

[X] typically only measurements for one component
[X] period too long for dynamical mass (e.g. 16 Cyg)
[X] difficult to model / incorrect region of the HRD
-wrong mass regime
-nested or inverted convective structure

How about….Procyon?

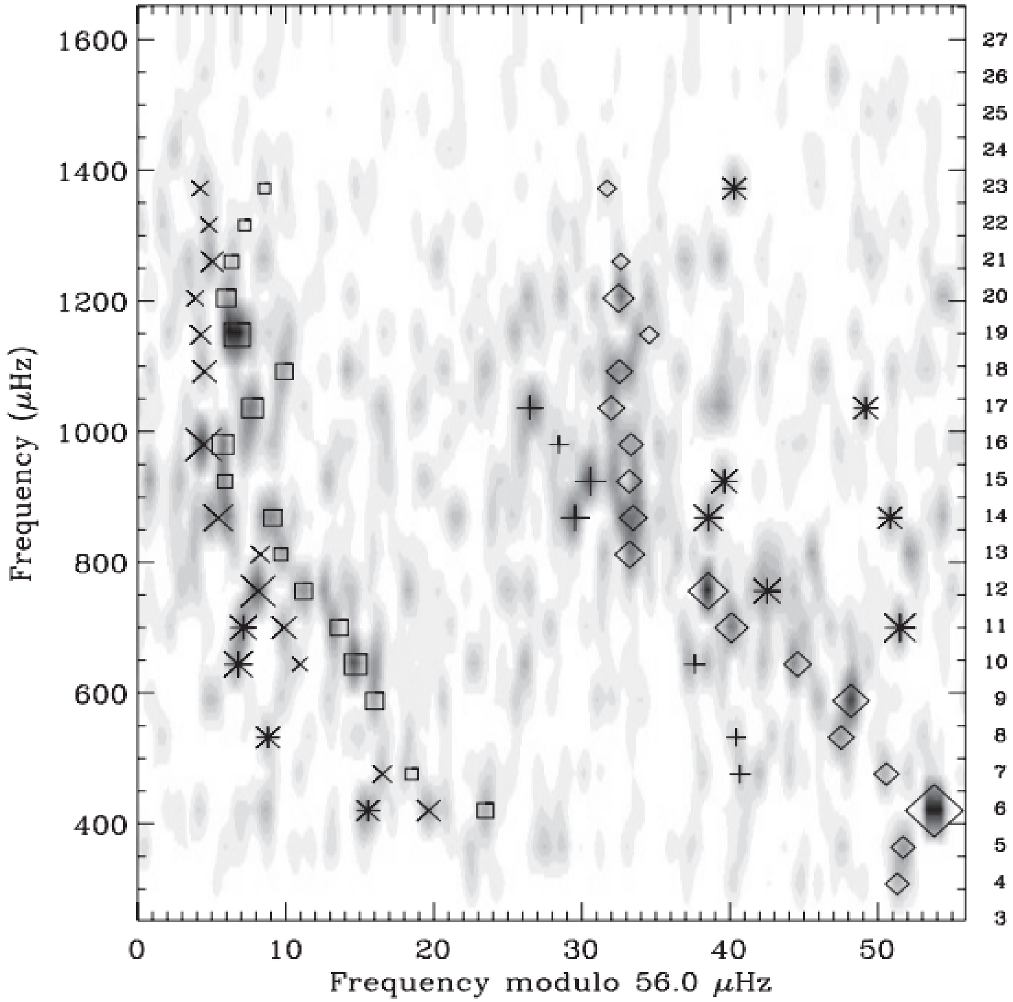


Figure 14. Power spectrum of Procyon overlaid with mode frequencies listed in Table 1. Symbols indicate angular degree (squares: $l = 0$; diamonds: $l = 1$; crosses: $l = 2$; pluses: $l = 3$). Asterisks show the peaks that have not been identified, as listed in Table 2.

Bedding et al. 2010

Challenges:

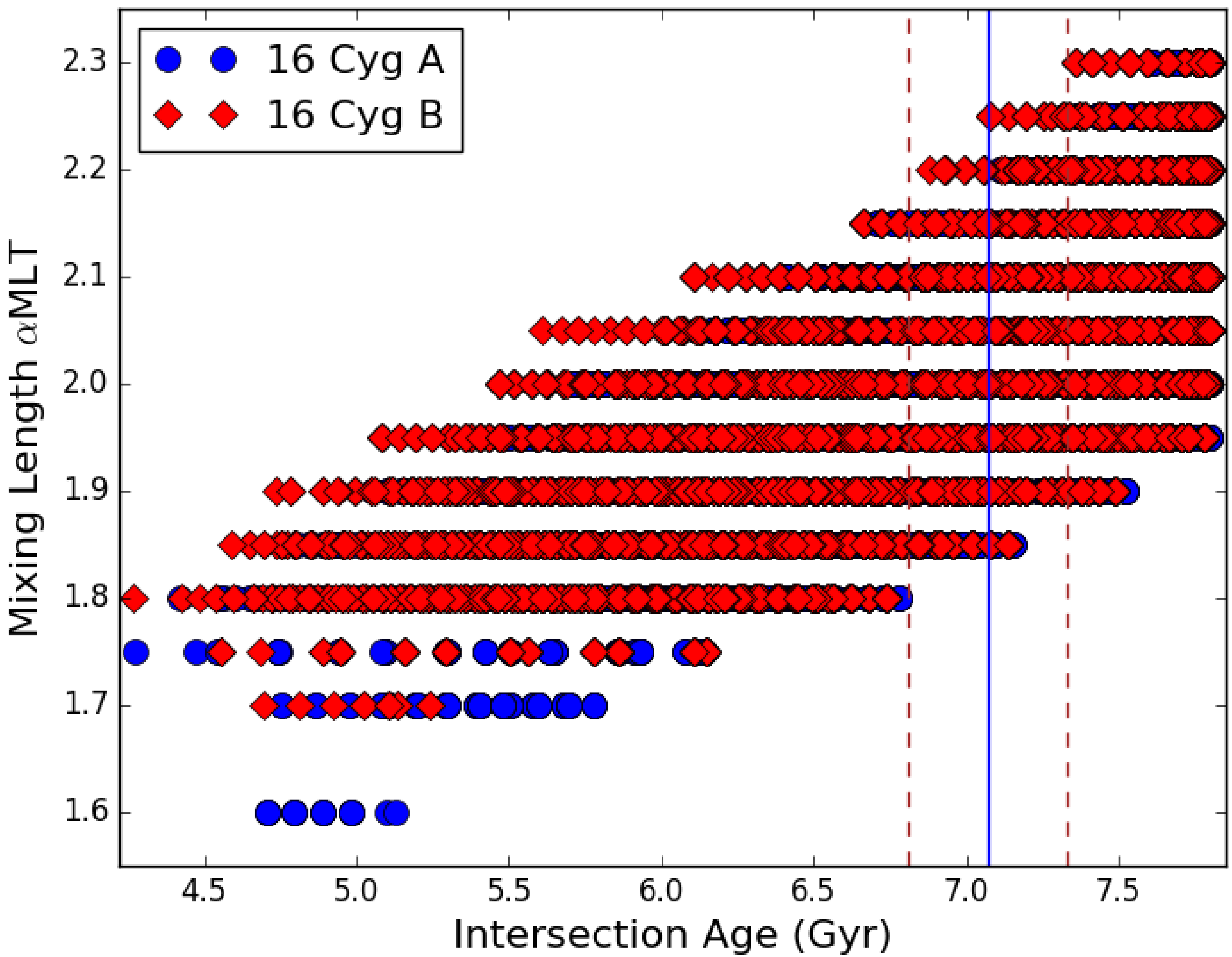
-**Ridge identification** is difficult observationally

-**p-mode behavior** in this part of the HRD is much more complicated

-**surface convection zone** in evolutionary models is very thin and therefore much less sensitive to changes in α mlt

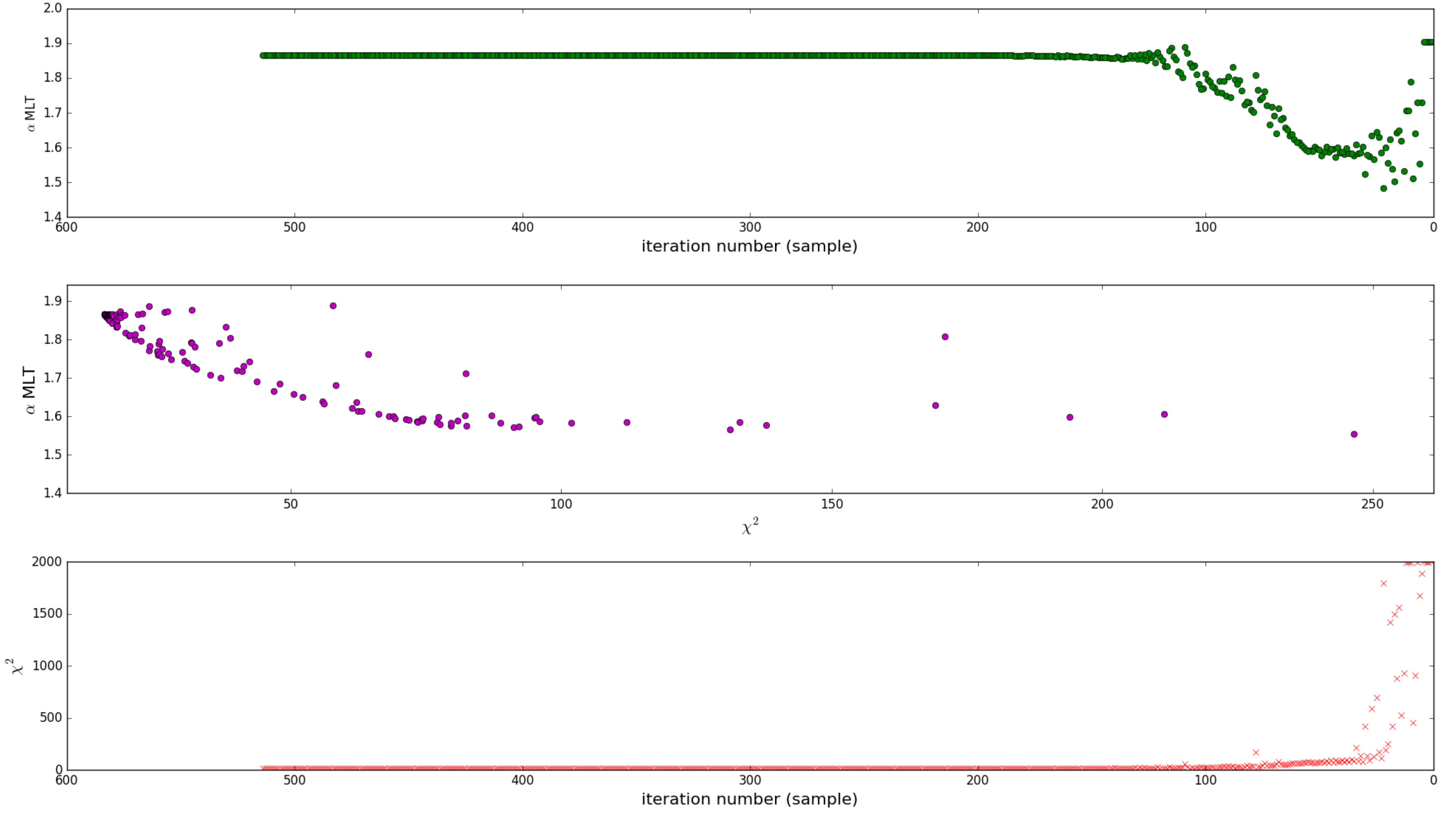
How about….16 Cyg A & B?

Preliminary results are UNLIKE α Cen A & B: **--> no age bifurcation**



New method: Simplex Optimizer with MESA

Work in progress using the ASTERO and SIMPLEX_SOLAR_CALIBRATION modules, to which I am currently contributing



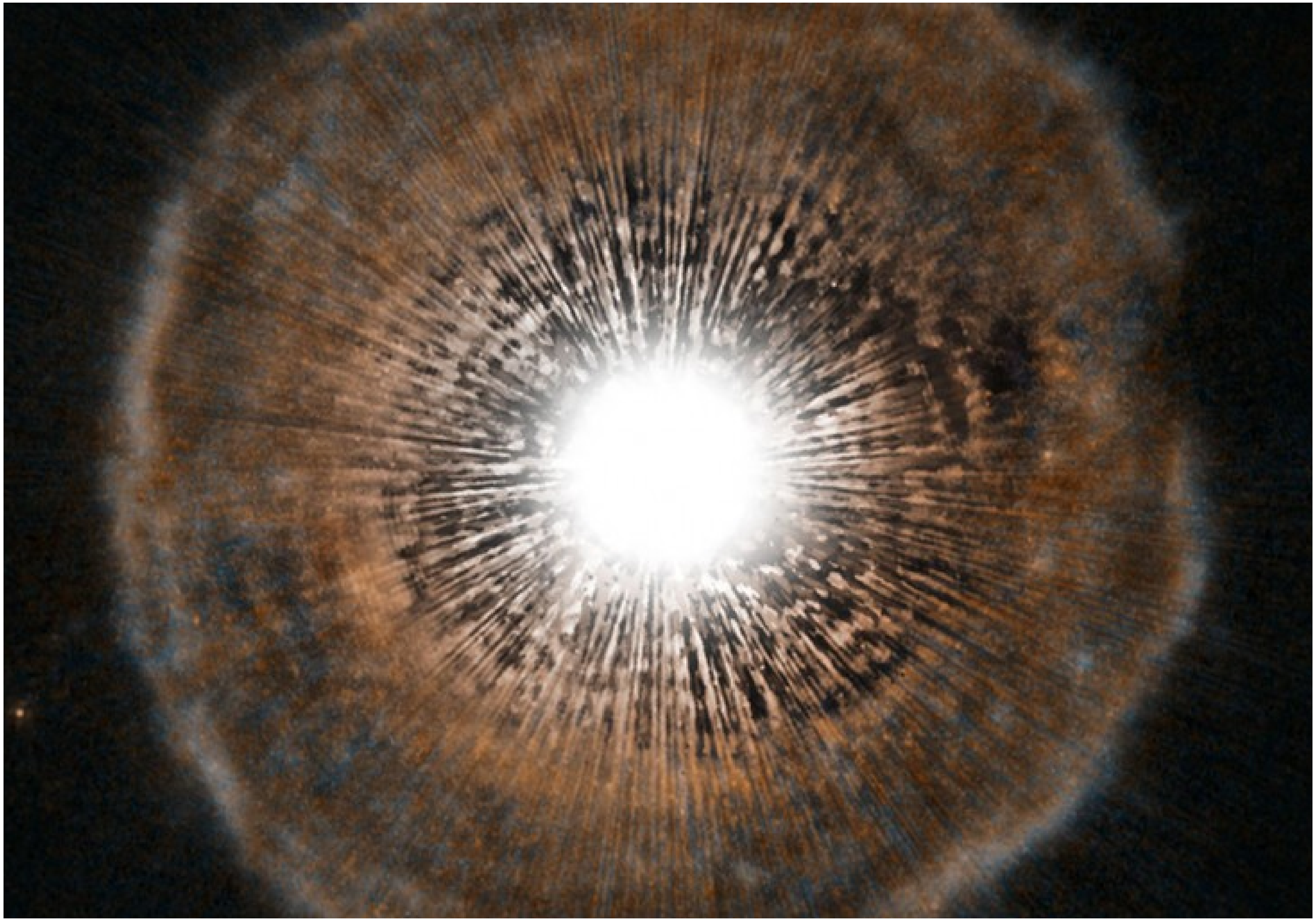
High precision seismic evolution

AGB stars
& T Ursae Minoris

The dying breaths of a Sun-like star

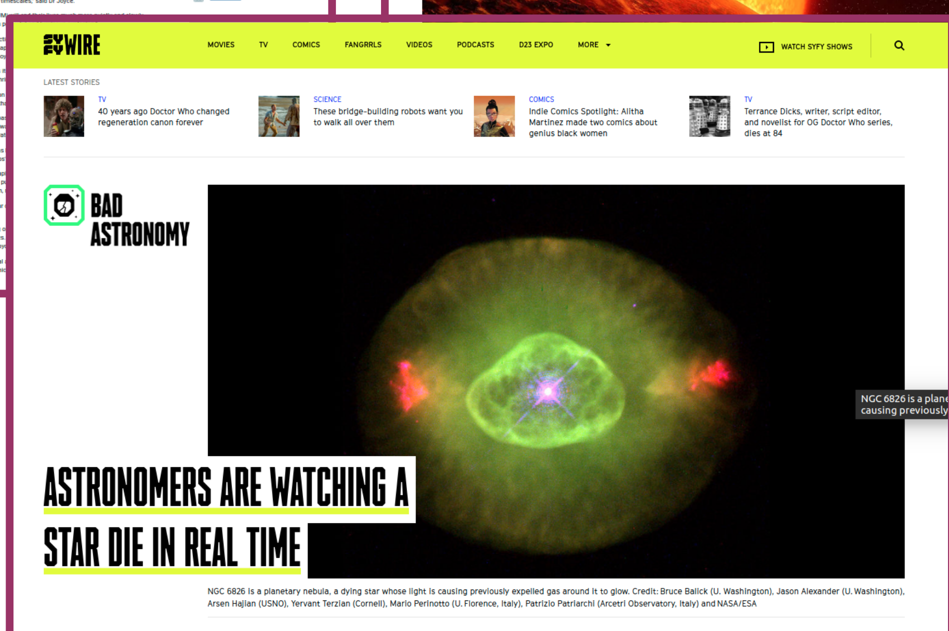
Live

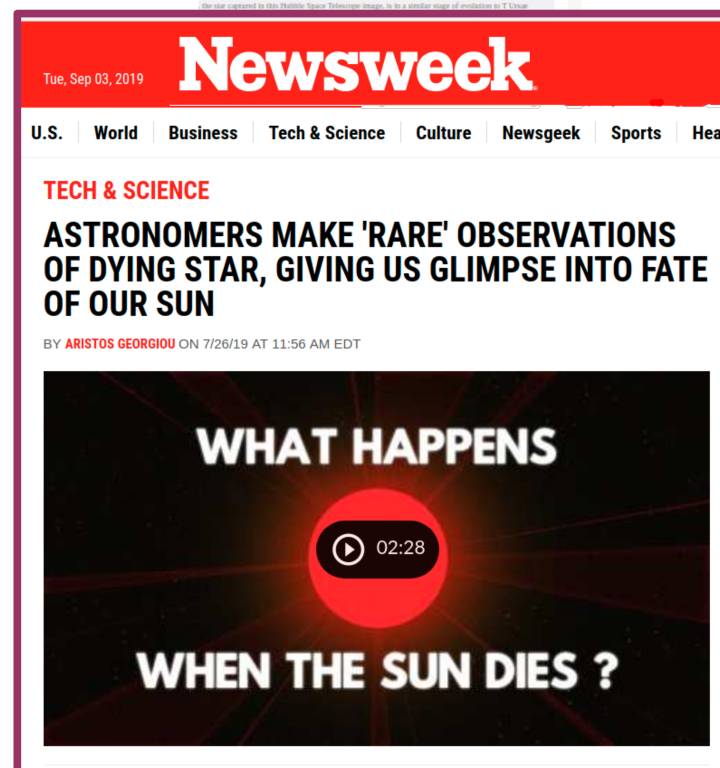
Studied: T Ursae Minoris

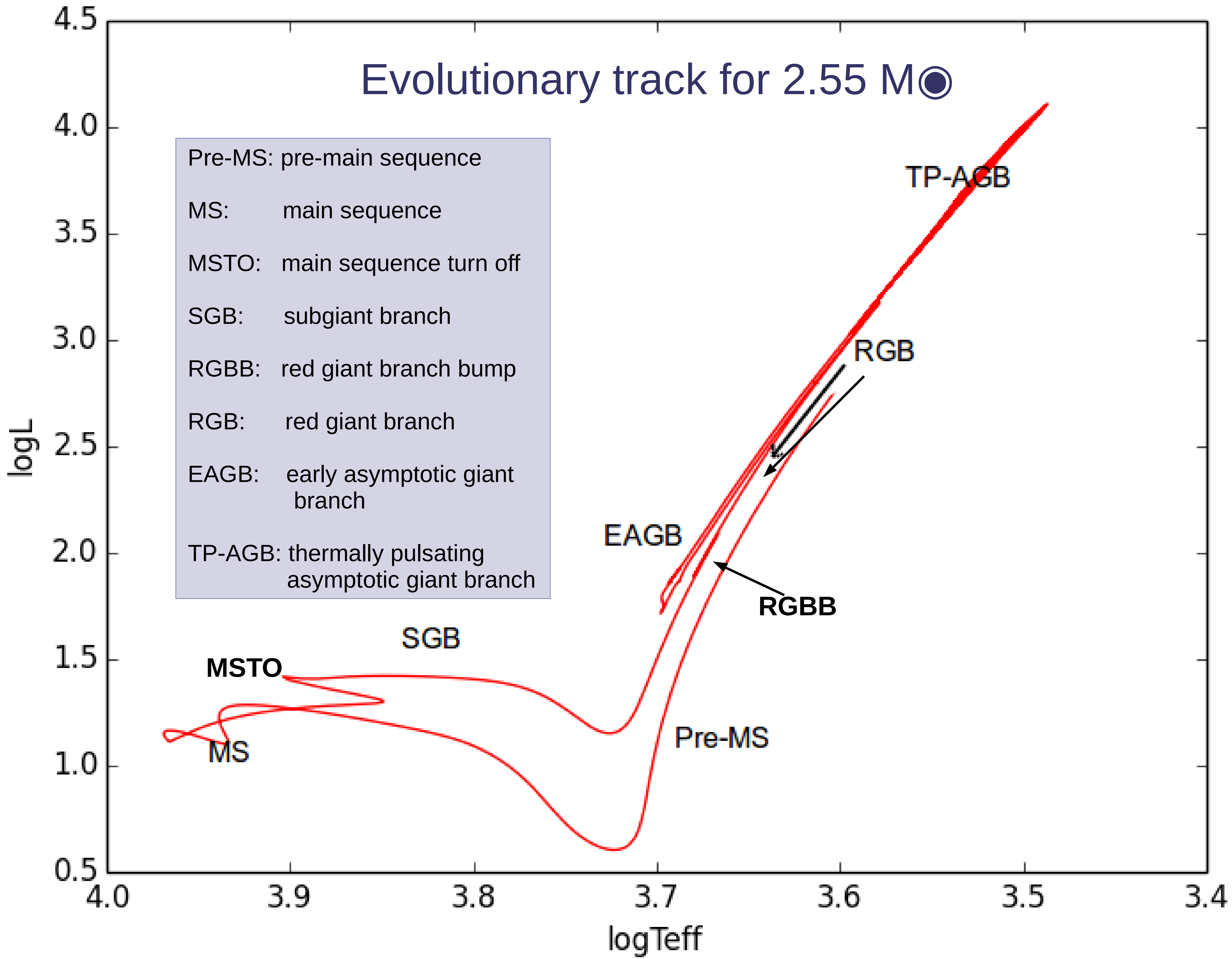


Pictured: U Camelopardalis, a similar TP-AGB star

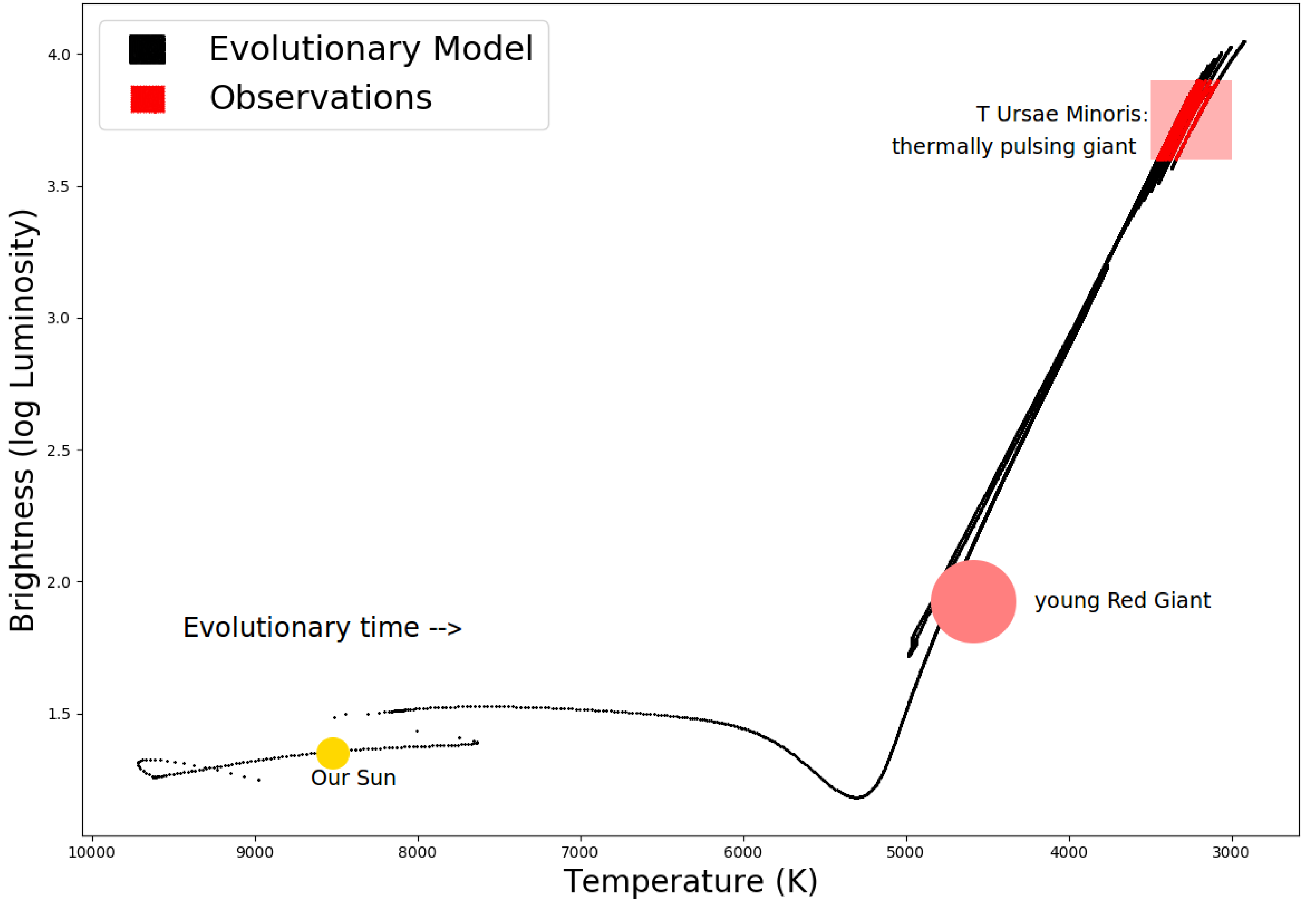
As seen in recent pop science coverage...



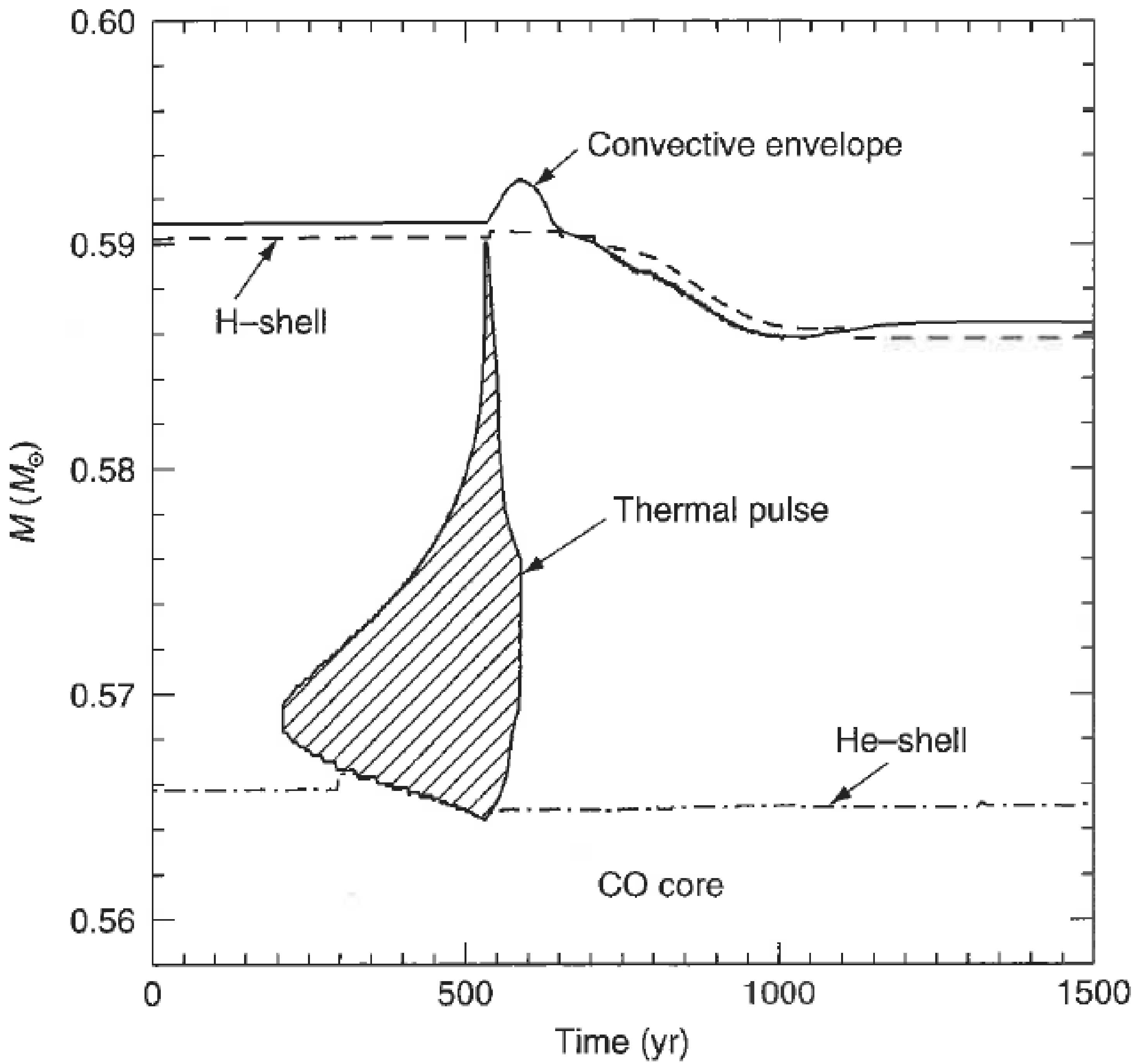



Evolutionary track for 2.55 M◉
Pre-MS: pre-main sequence
MS: main sequence
MSTO: main sequence turn off
SGB: subgiant branch
RGBB: red giant branch bump
RGB: red giant branch
EAGB: early asymptotic giant branch
TP-AGB: thermally pulsating asymptotic giant branch
TP-AGB
RGB
EAGB
RGBB
SGB
MSTO
MS
Pre-MS
logL
logTeff
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
4.0
3.9
3.8
3.7
3.6
3.5
3.4

T Ursae Minoris: Evolutionary Context



Anatomy of a Thermal Pulse



T Ursae Minoris: why this star?

(1) 100+ years of visual observations

(2) undergoing dramatic changes while we’re watching

(3) turns out to be located in a very special and short-lived part of the evolutionary diagram, a region amenable to capturing its **seismic evolution**

(4) evolutionary trajectory is similar to the Sun’s

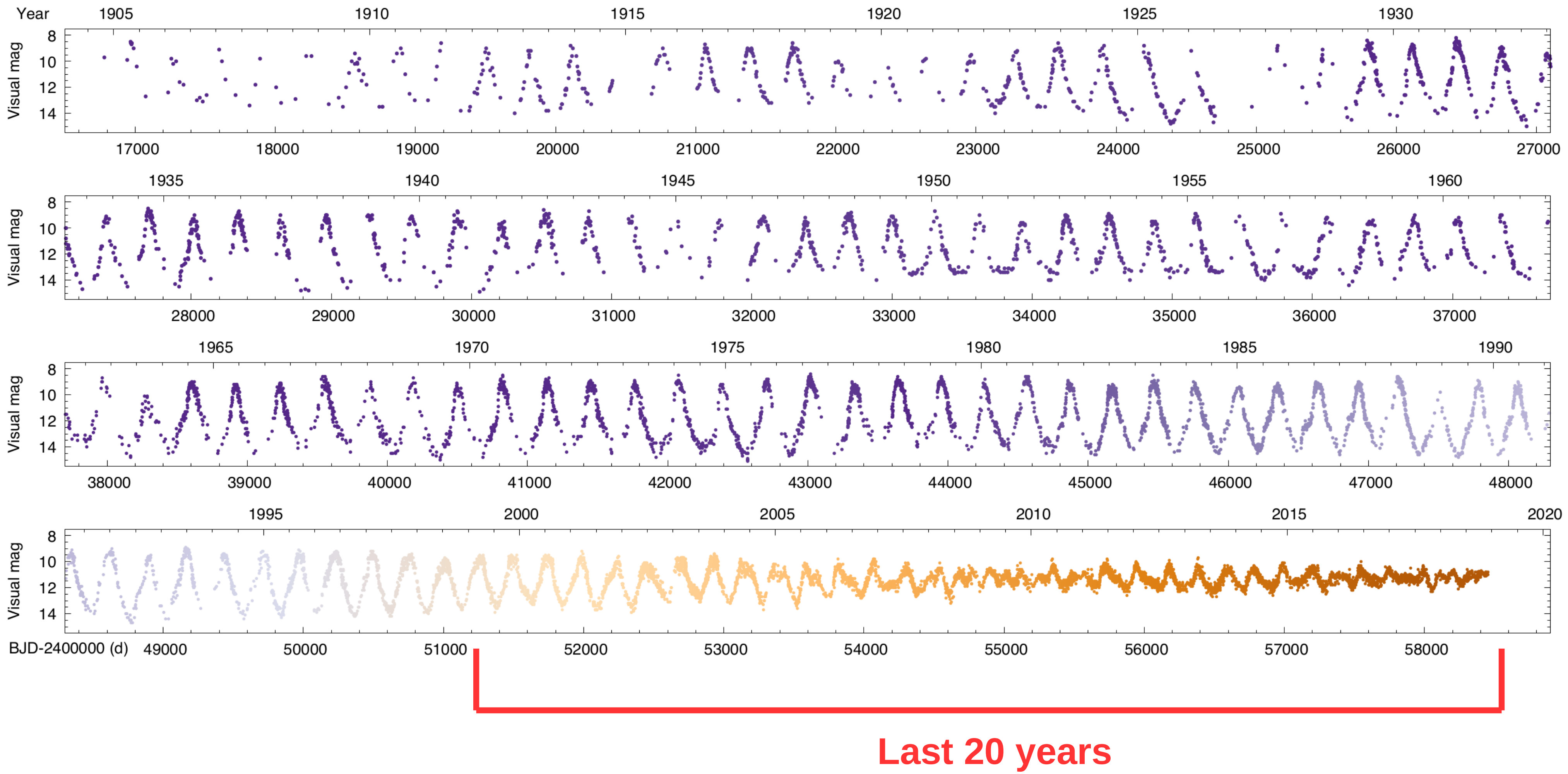
Important distinction:

Pulse—helium shell flash episode (evolutionary behavior)

Pulsation—coherent global oscillation in the envelope (seismic behavior)

→ T UMi is experiencing both

Lightcurve: dramatic change in amplitude of oscillations in visual mag over last ~30 years



Difference in T UMi's period spectrum then-to-now suggests need for reclassification

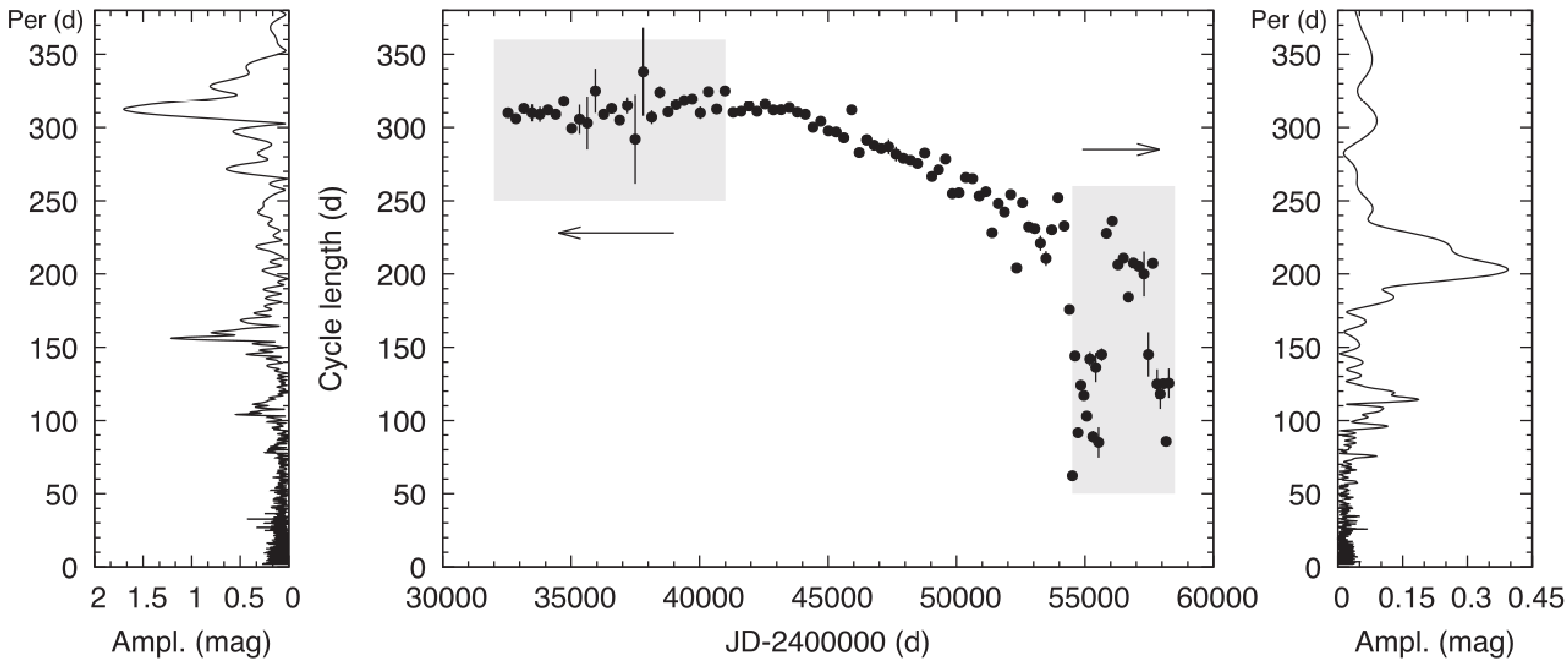
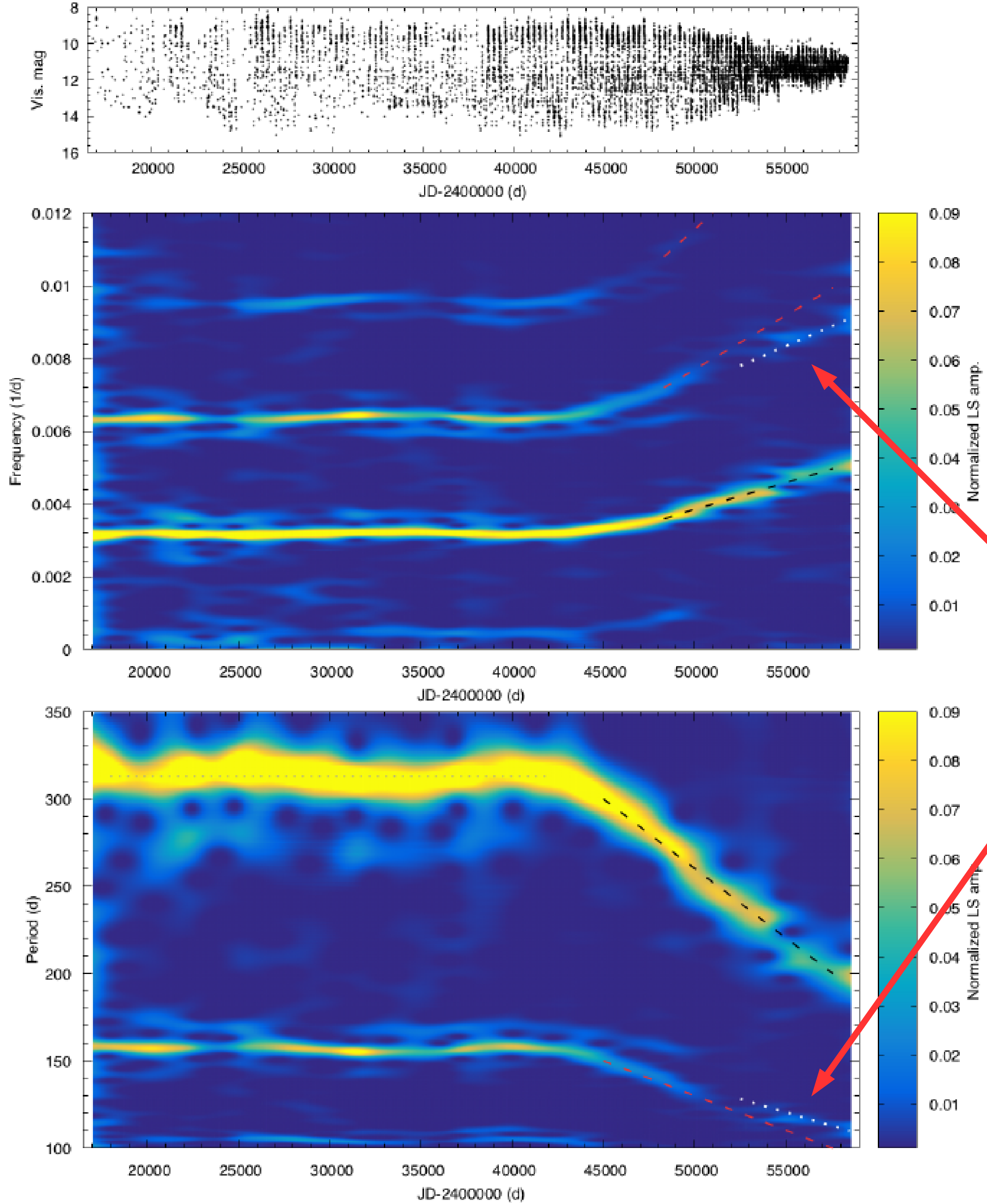


Figure 2. Middle: distances of successive (local) light maxima. Left and right: the corresponding periodograms from the early (gray highlighted region in the upper left of middle panel) and late (gray highlighted region in the lower right) sections of the light curve. The "early" region covers truncated JD 32,000 to 41,000 and the "late" region, 54,500 to 58,500.



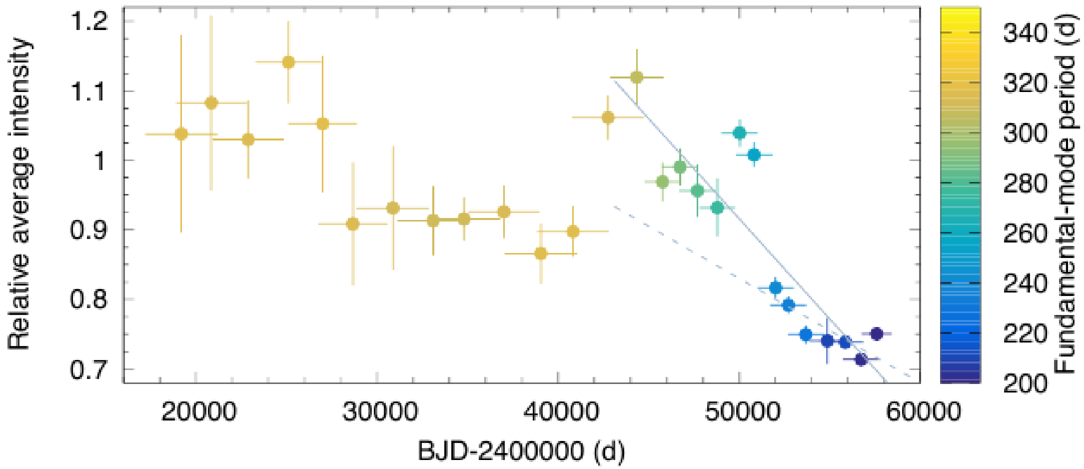
Visual Data

Time-frequency distribution

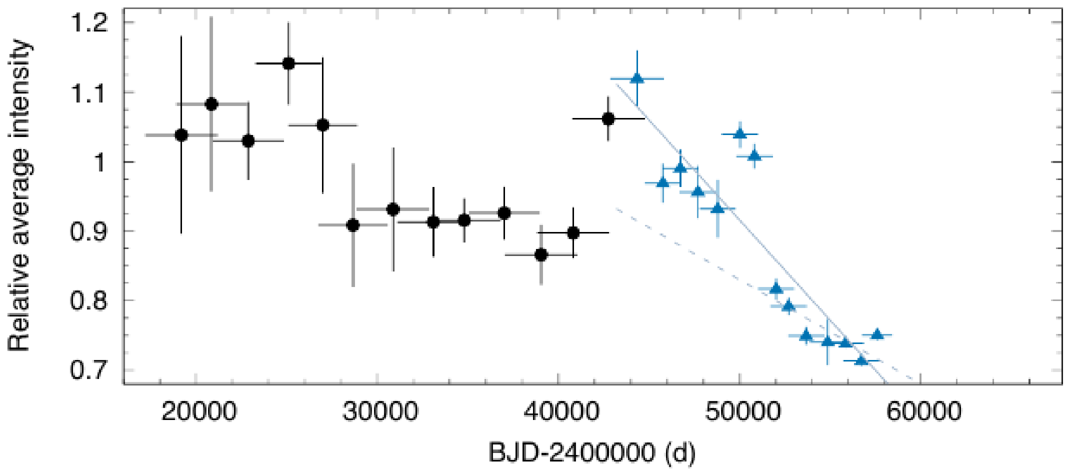
Emergence of new oscillation mode!

→ excellent news for seismic modeling

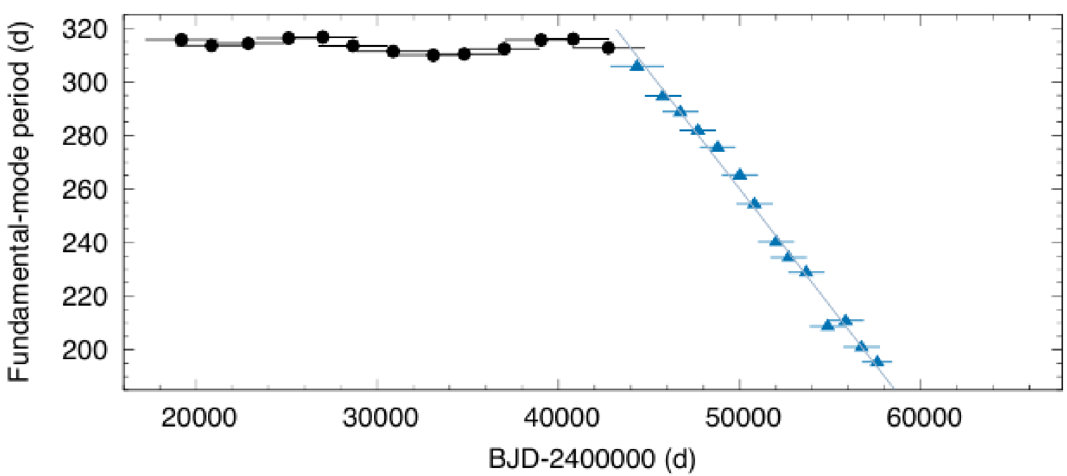
Time-period distribution



Visually, looks like it's just meandering
Seismically, there is a **rapid period decline**

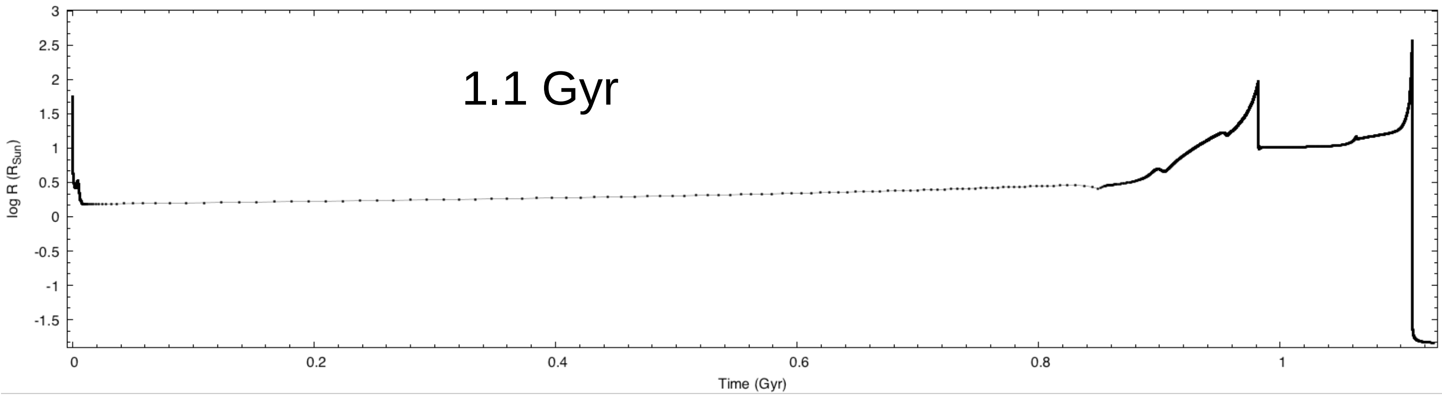


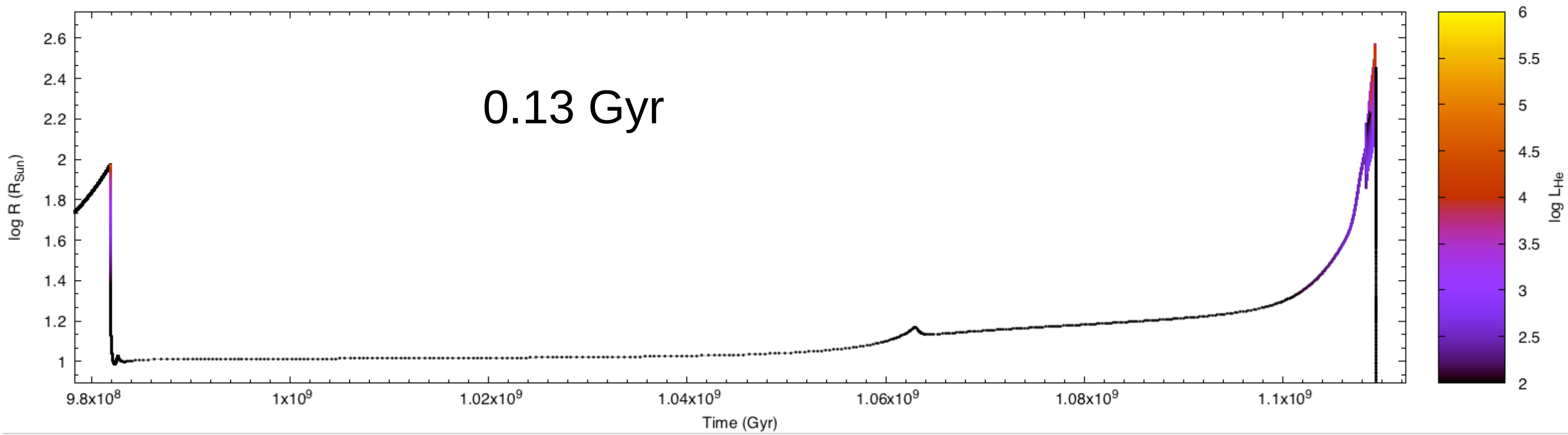
Same data, divided into **before (black) / after (blue)** the rapid period change

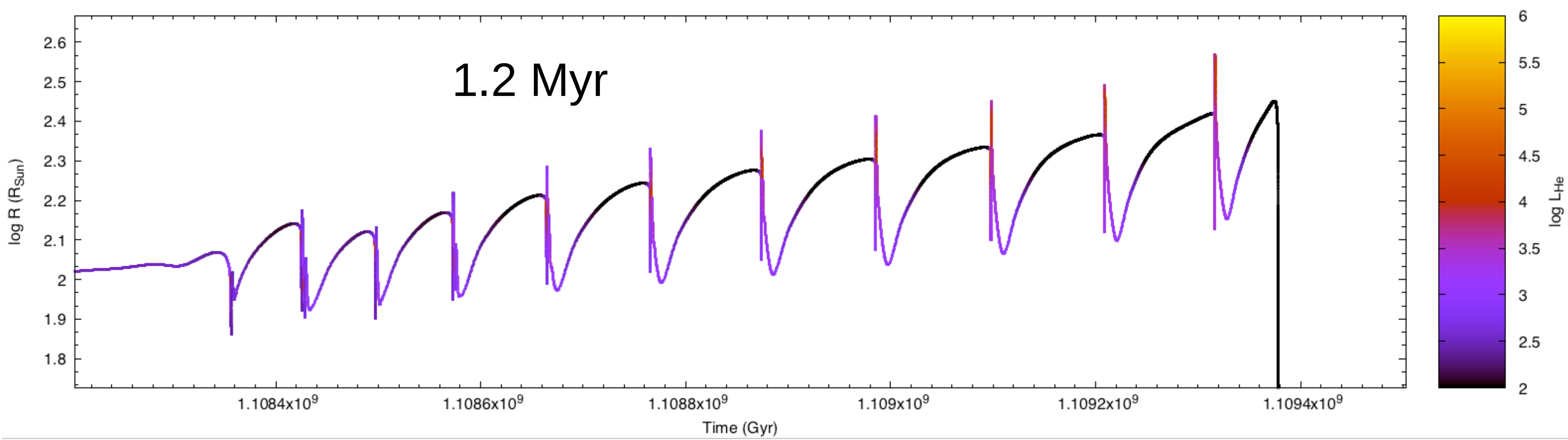


Same data, shown in terms of **fundamental mode period**

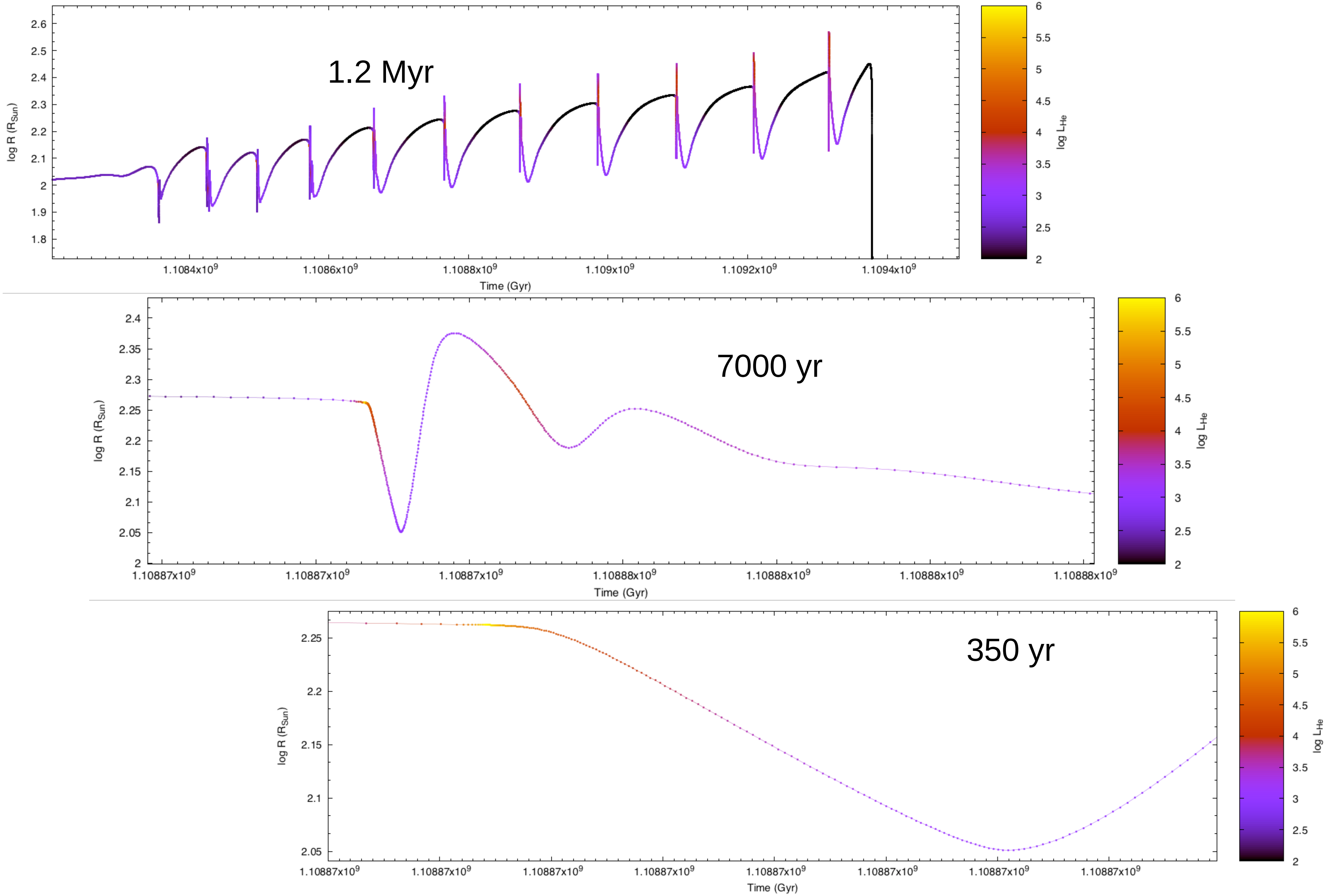
Let’s model it!







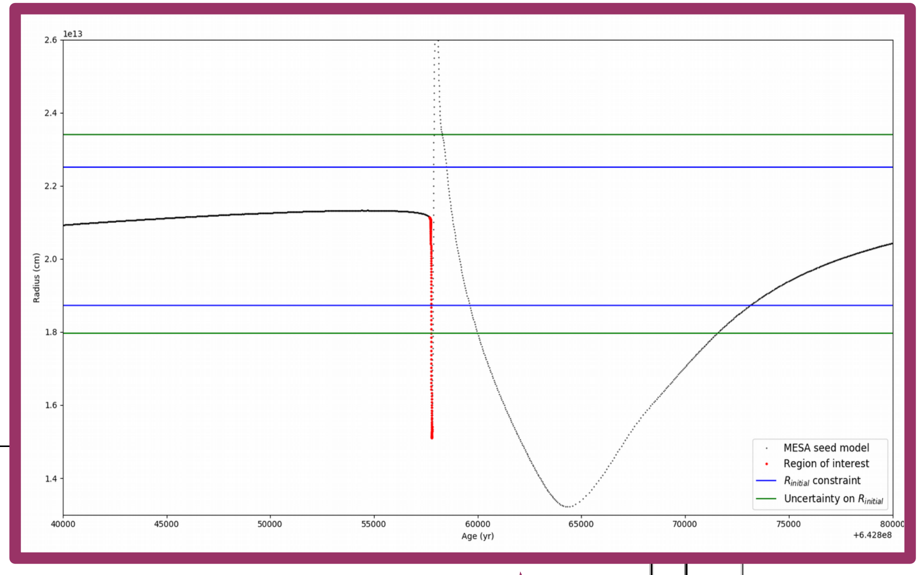
Let’s model it!

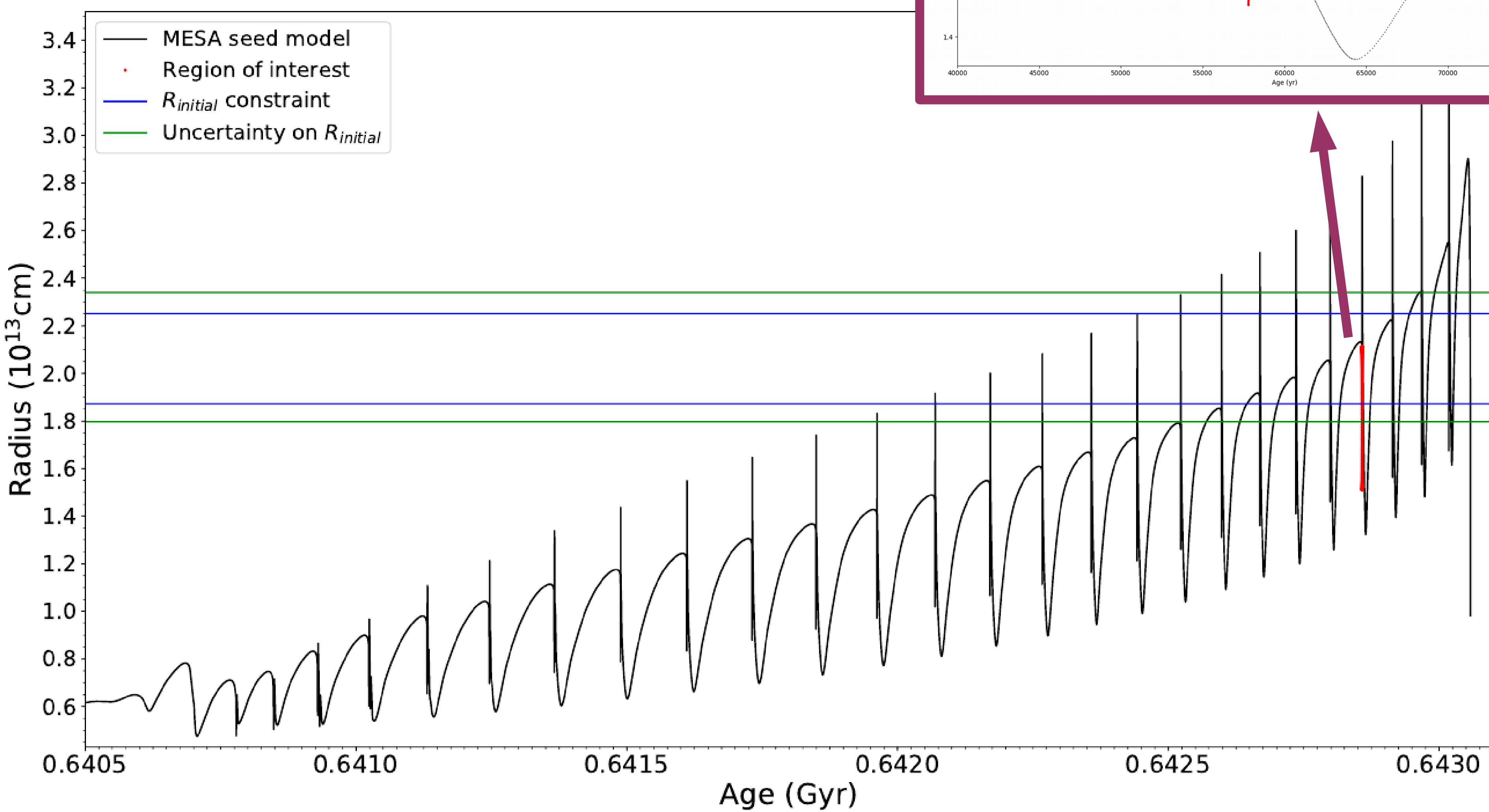


Let’s model it!

- The region over which we want to compute frequency spectra is ~50 years long (out of a 5 billion year evolutionary track)
- Isolating that region reliably—much less sampling it—is actually hard
- Only in the last year has anyone else tried to map seismic evolution onto stellar evolution: uncharted territory!

Need evolutionary resolution of 5-10 years for seismic calculations





Constraints & Considerations

Scientific:

- luminosity change must be consistent with longitudinal brightness decrease in observations

- need to match starting period ratio (function of radius) as well as **rate of change** of decay

- period ratio implies a certain range of acceptable starting radii depending on initial mass

- no metal enhancement: weak spectroscopic constraints suggest solar or slightly sub-solar metallicity

- T UMi is not a carbon star → evolutionary profiles should not produce strange abundances (Li, Tc)

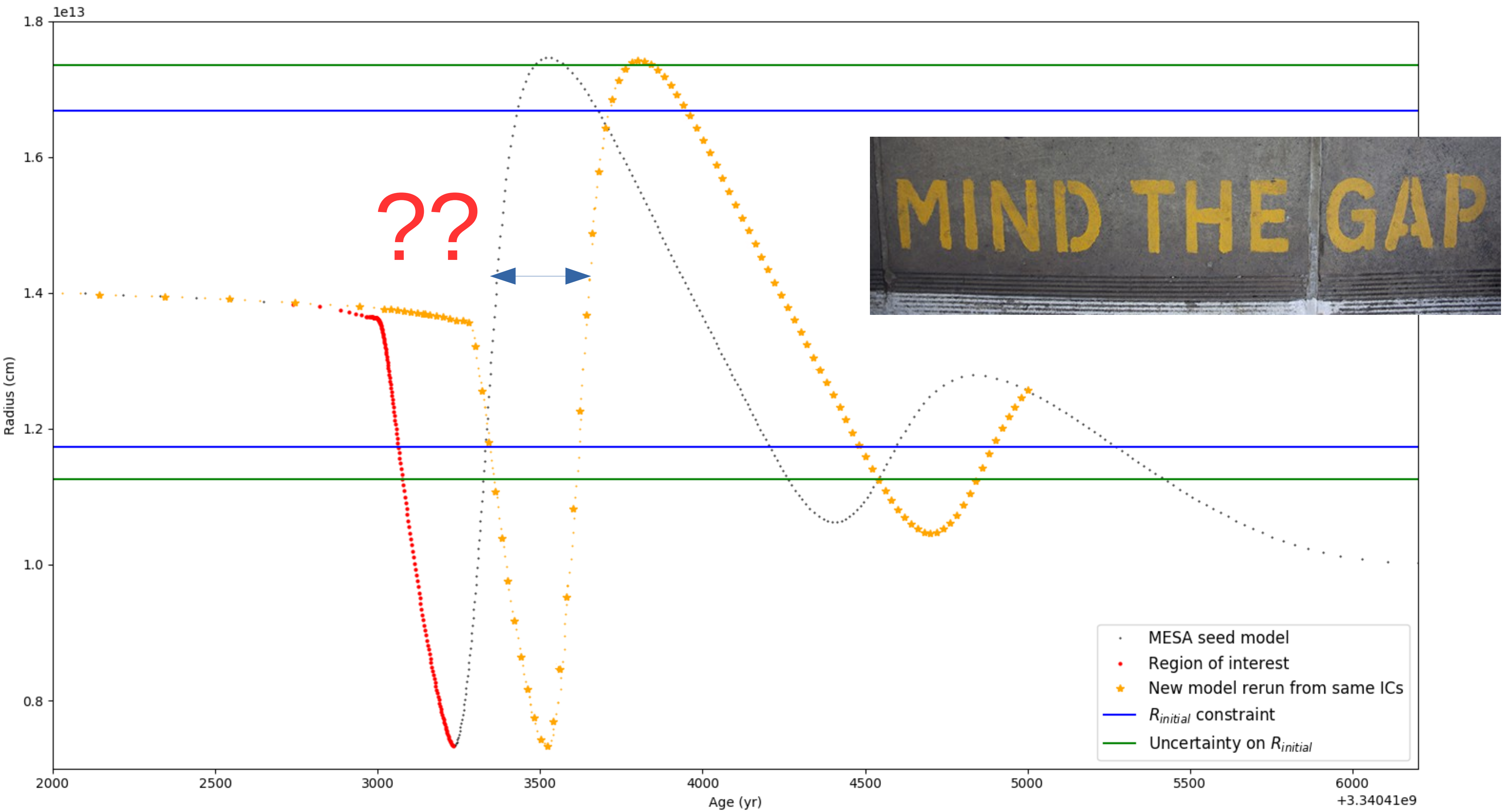
- number of pulses we find in seed model should be roughly consistent with other theorists' calculations, to verify appropriate convective parameters

Practical:

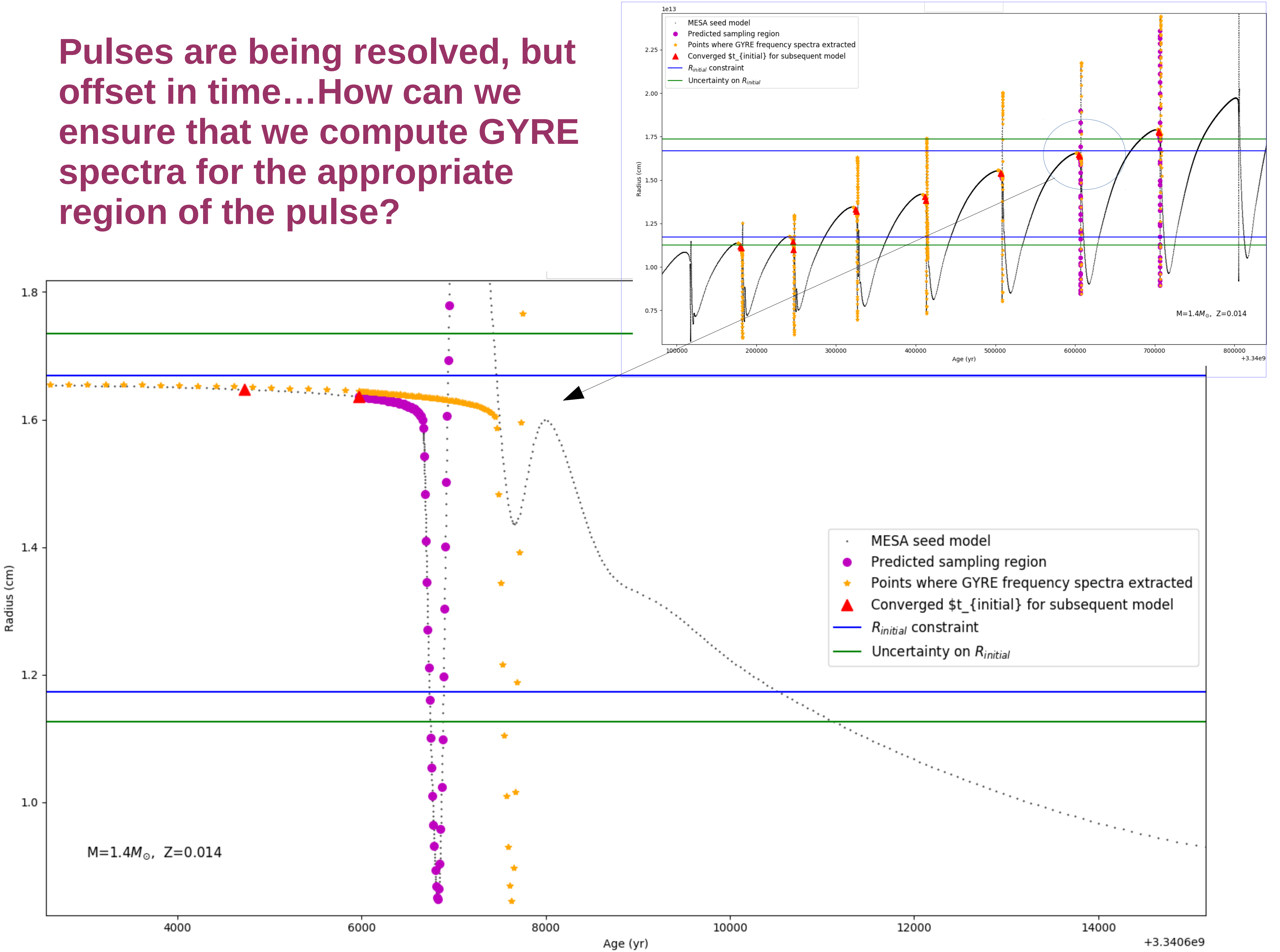
- COMPUTING TIME
- automation
- avoiding excess data production
- timestep issues

Meeting most of these conditions is “easy” enough, but one is not

→ MESA’s timestepping procedure has difficulty with this precision

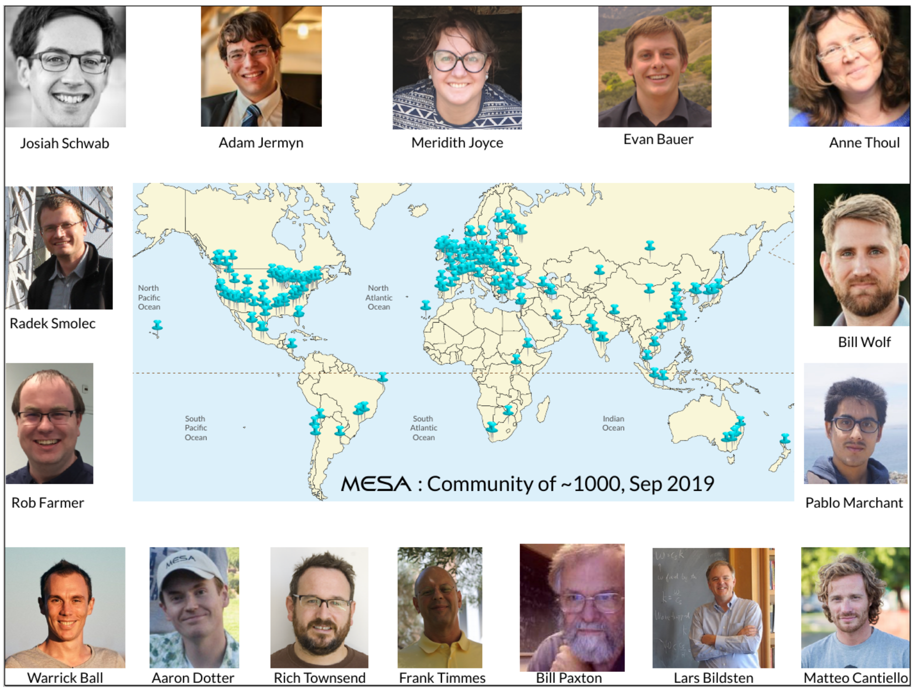


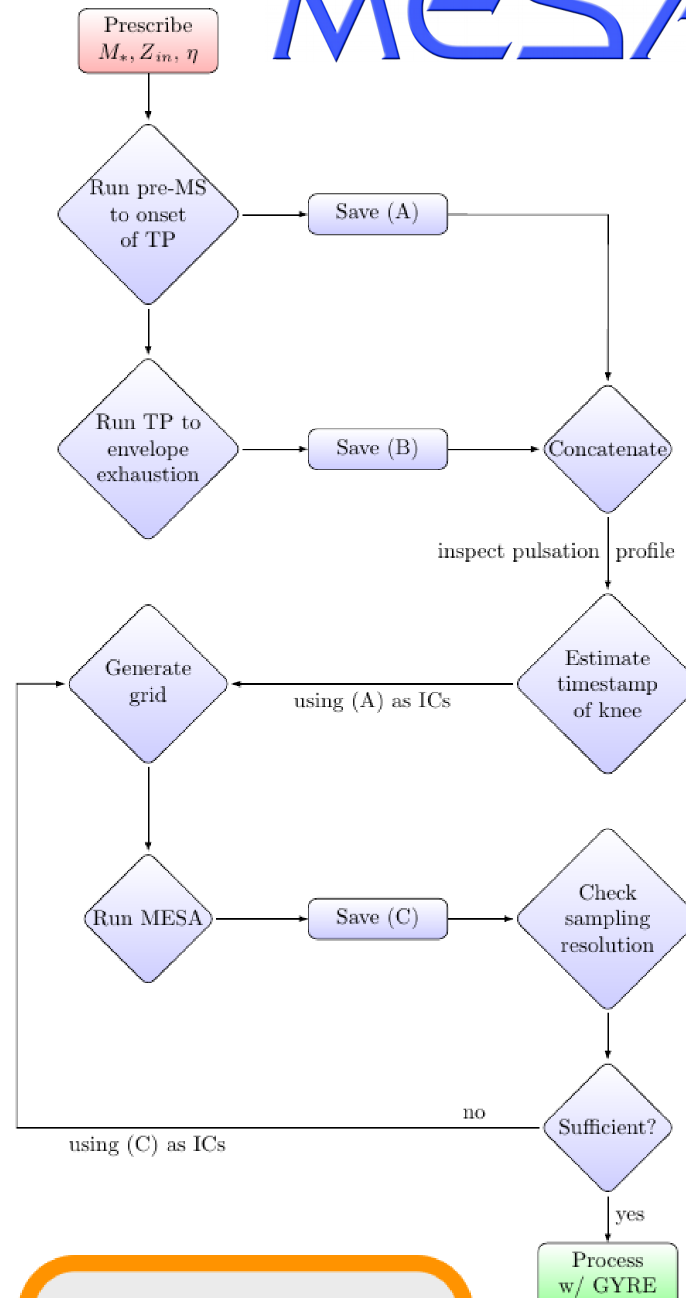
Pulses are being resolved, but offset in time…How can we ensure that we compute GYRE spectra for the appropriate region of the pulse?



MESA and an external adaptive time sampling algorithm

MESA

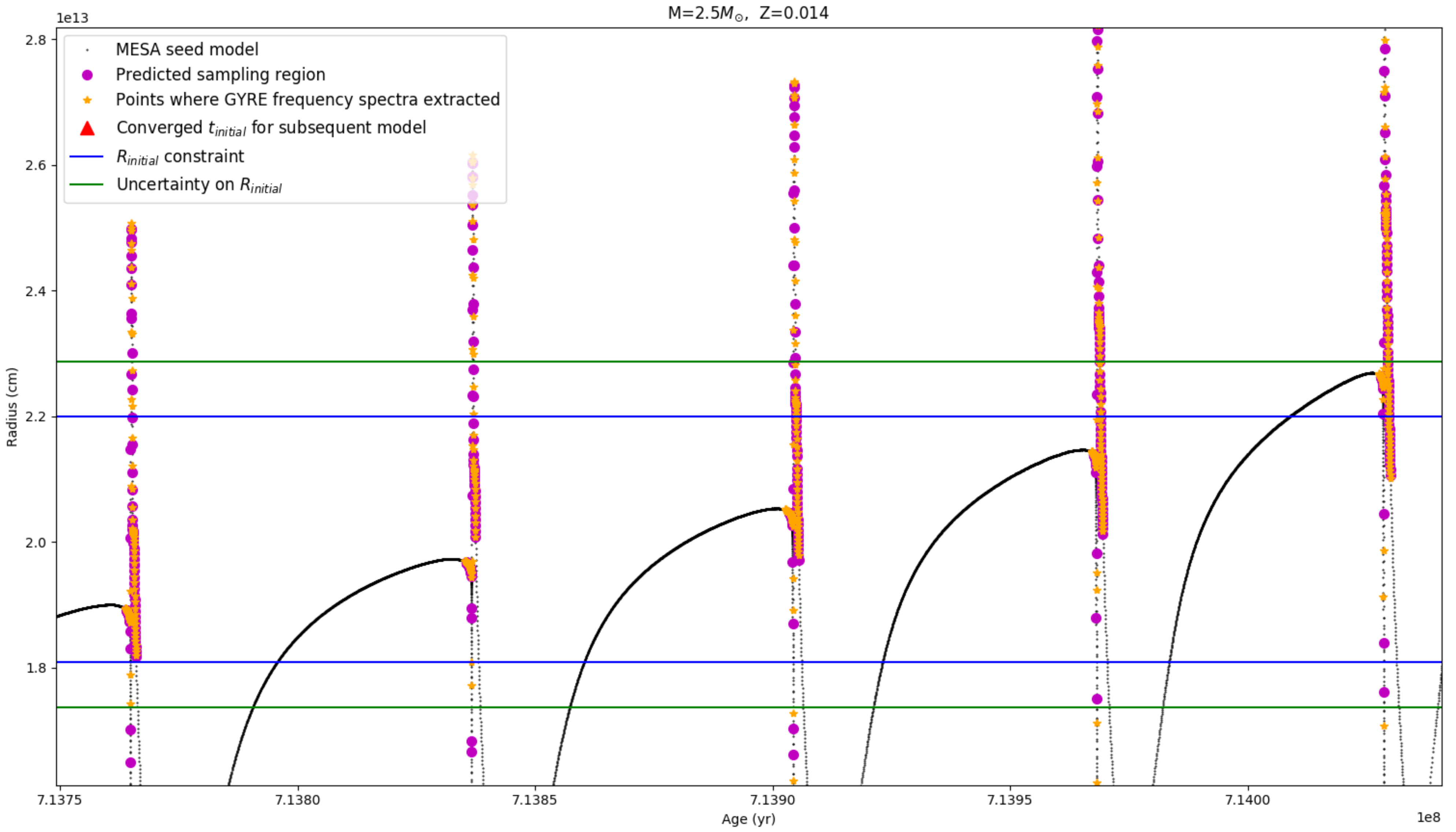




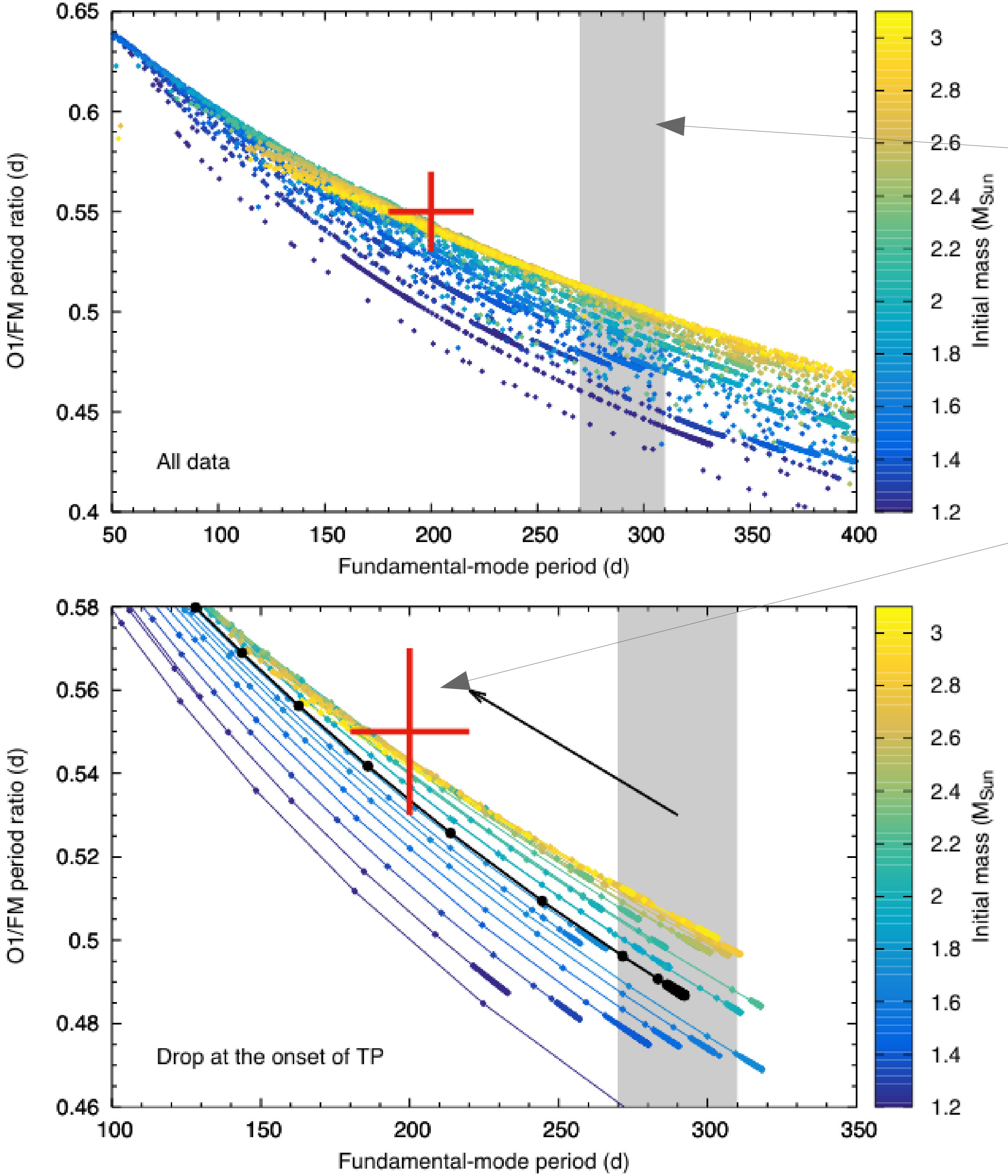
GYRE

Result of successful iteration scheme:

GYRE spectra are computed for critical pulse regions under variable radial constraints while working around MESA's local timestep resolution, without wasting storage and time on inter-pulse regions



Utility of seismic constraints



Models need to match initial period range

and the intersection of fundamental mode period (horizontal) O1/FM period ratio(vertical)

This is highly constraining over the whole parameter space!

Major Result:

(Possibly) the best ZAMS mass and age estimate for a single AGB star:

$2.0 \pm 0.15\ M_{Sun}$

1.17 ± 0.21 Gyr

Other parameters:

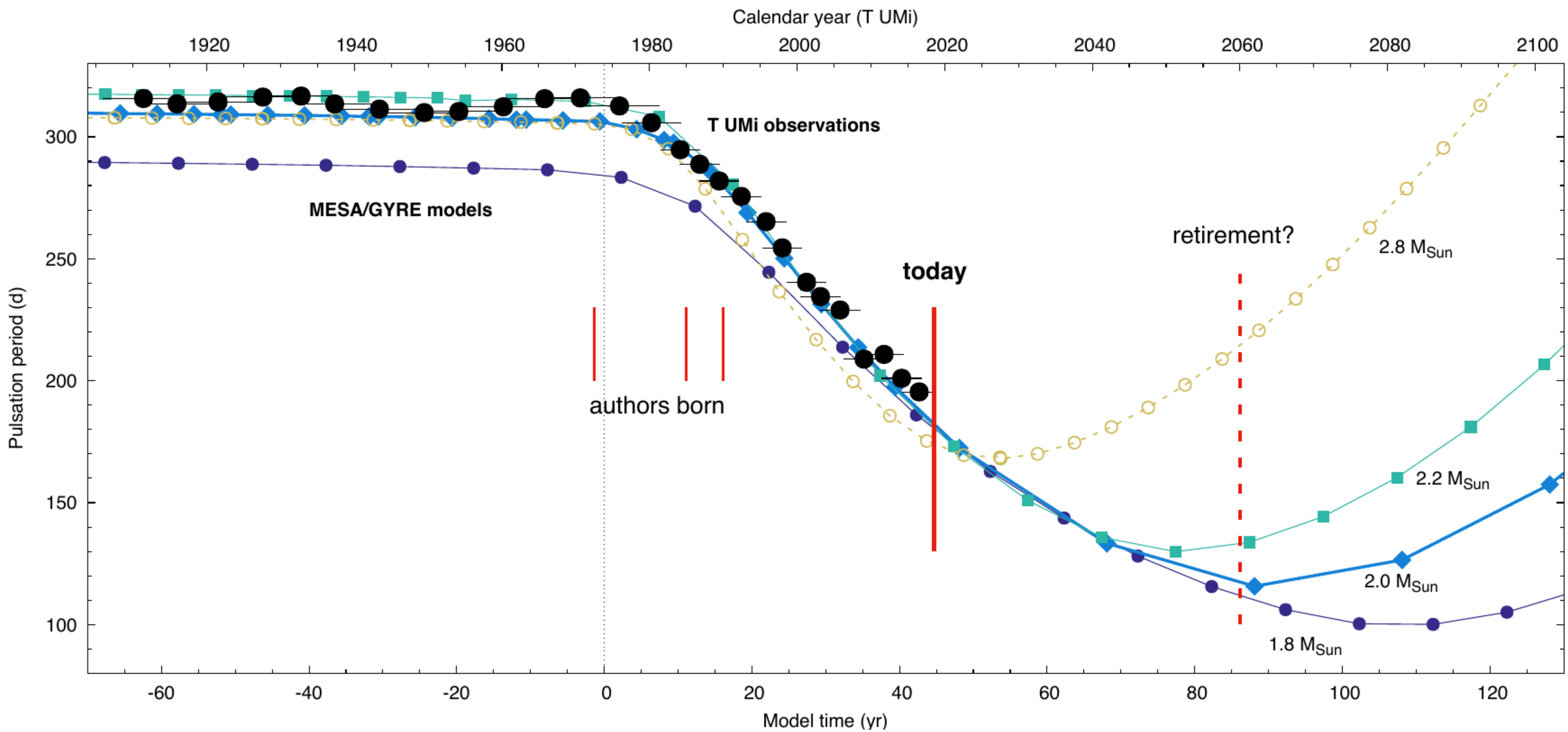
$R = 290 \pm 15\ R_{Sun}$,

$M = 1.66 \pm 0.10\ M_{sun}$,

$T_{eff} = 3200 \pm 30$ K

...but these are highly dependent on modeling choices for e.g. convective parameters, mass loss, etc

We have testable predictions for its behavior over the next few decades!



In Short...

Mira has transitioned to semi-regular pulsator: identification of non-harmonic pulsation mode

Period dropped dramatically in last few decades and **first overtone (O1) oscillation mode emerged**

MESA + GYRE model grid exploited to fit mode periods, Pdot, and luminosity
→ sampling at this resolution is **very hard!**

First “confirmation” of ongoing **thermal pulse** via direct observation

Obtained most precise ZAMS mass (**2.0±0.15 Ms**) and age (**1.17±0.21 Gyr**) for a single AGB star...ever(?)

Modeling implies **Pdot should reverse in 40-60 years**—evidence within our lifetimes

^{1D}MESA2HYDRO^{3D}

a Python interface tying stellar evolution calculations to 3D hydrodynamic simulations

Co-developers:

Lianne Lairmore (lead) packaging, portability, software development, upgrade to Python3

Dan Price integration with Phantom

Thomas Reichardt Ohlmann et al. 2017 damping scheme, dispersion analysis

1D 3D
MESA2HYDRO

Supporters and contributors:

Tom Jarrett 3D data visualization (VIDEO!)

Amanda Karakas AGB expertise and outreach

Orsola De Marco Phantom

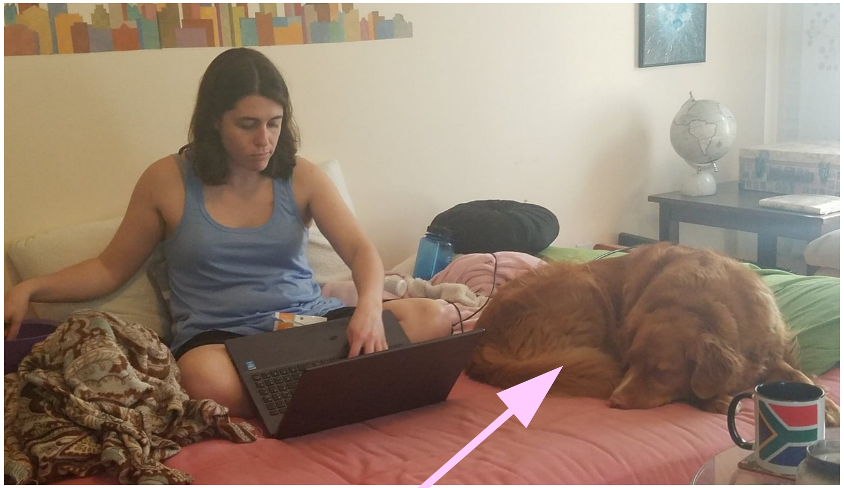
Phil Taylor & Zhengwei Liu soft testing with GADGET-2

Martin Asplund resources & supervision

Shazrene Mohamed project inception & oversight at SAAO

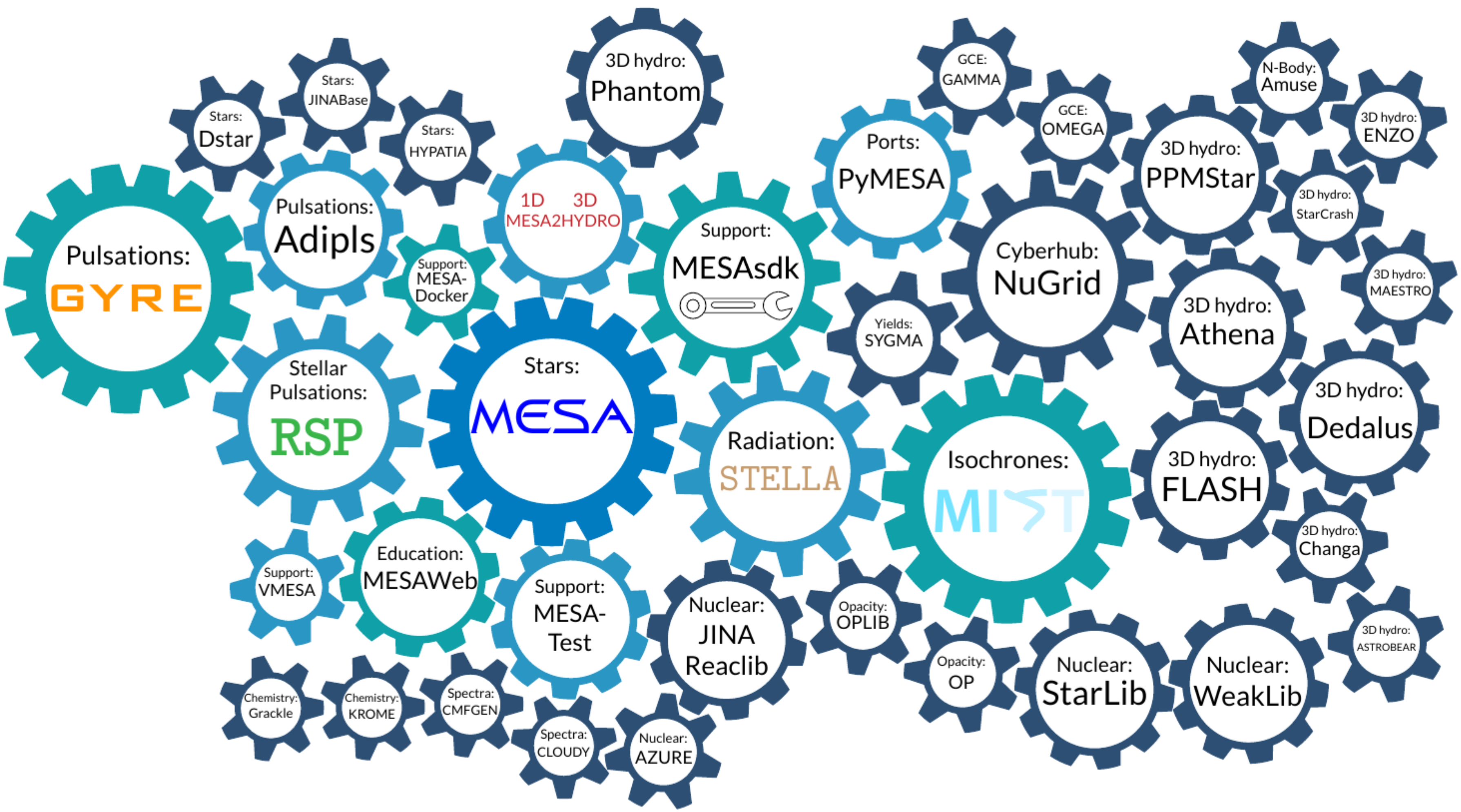
Computing & IT at ANU patience & technical support!

MESA developers, MESA collaboration, & Phantom community



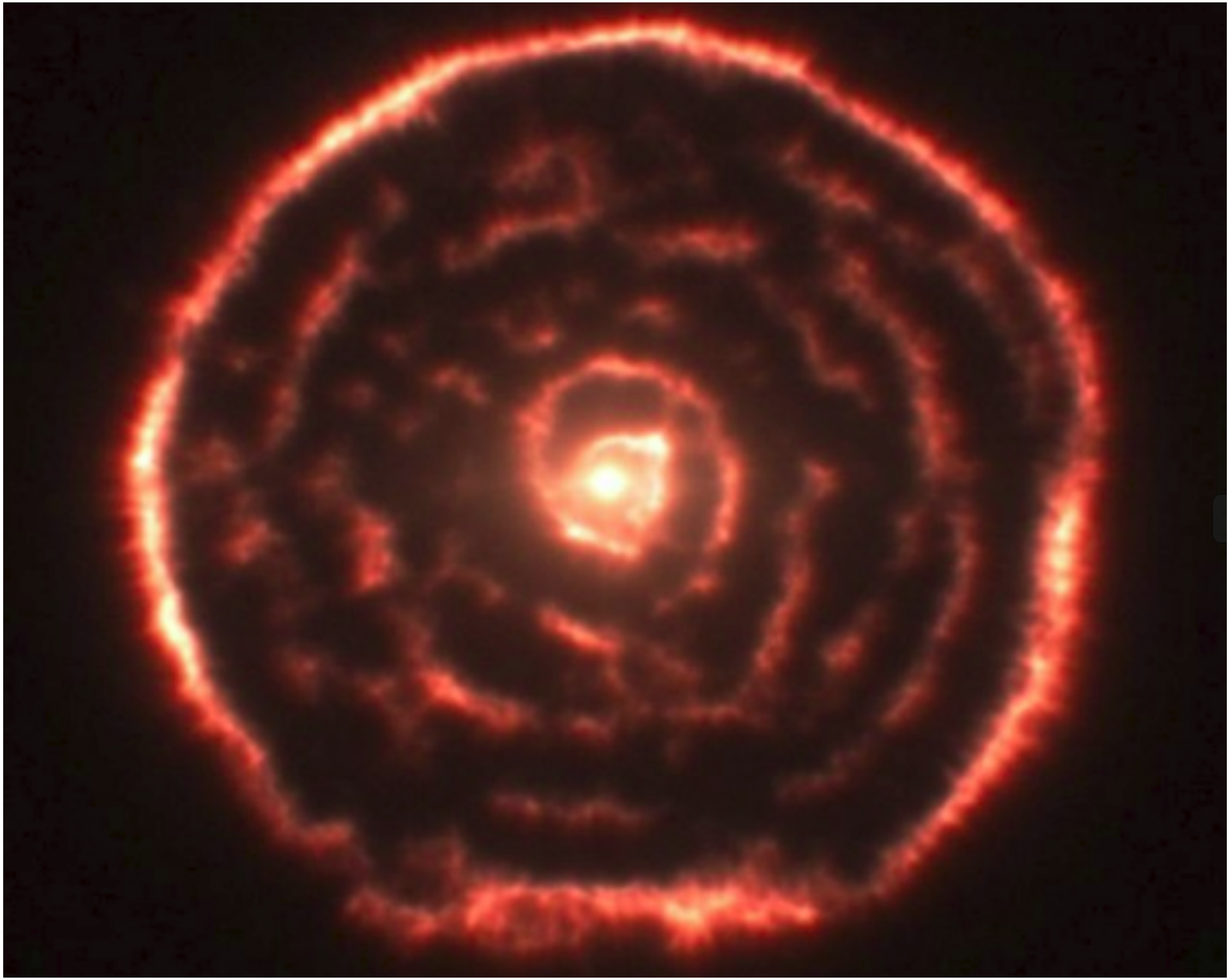
Good dog, bad developer

Gaia LIGO SDSS Hubble JWST LSST TESS LCOGT NuSTAR

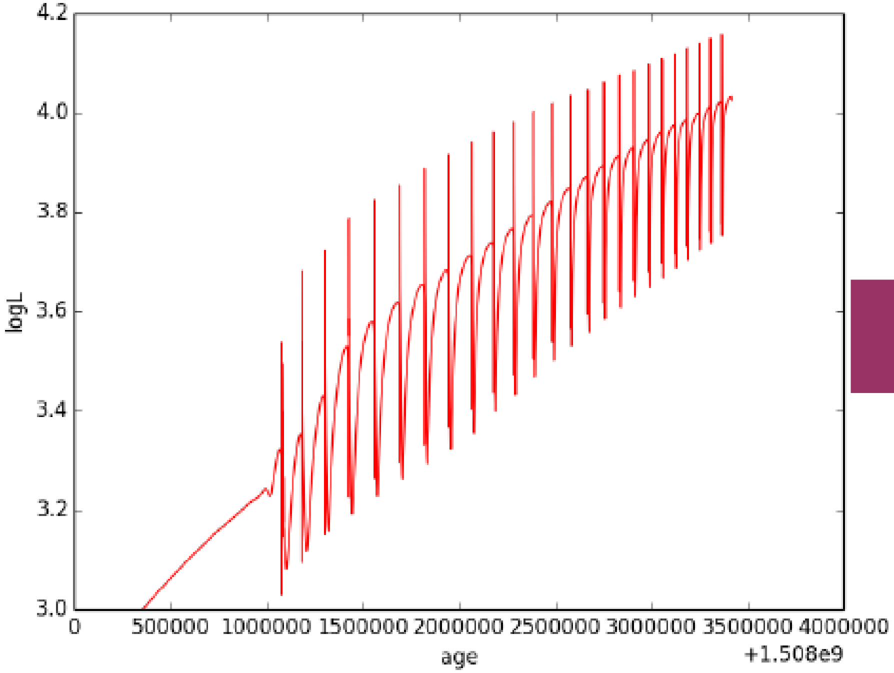


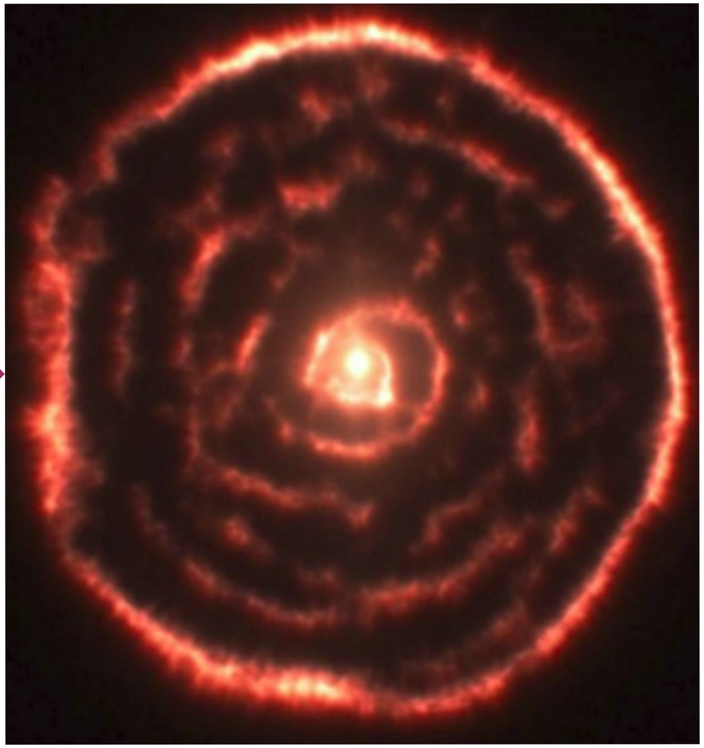
Laboratory Astrophysics

M2H’s original motivation:
translate AGB capabilities of 1D SSECs to hydro models



MESA2HYDRO: Motivation





How can we combine the benefits of both types of simulation?

Mapping radially extended stars: not easy

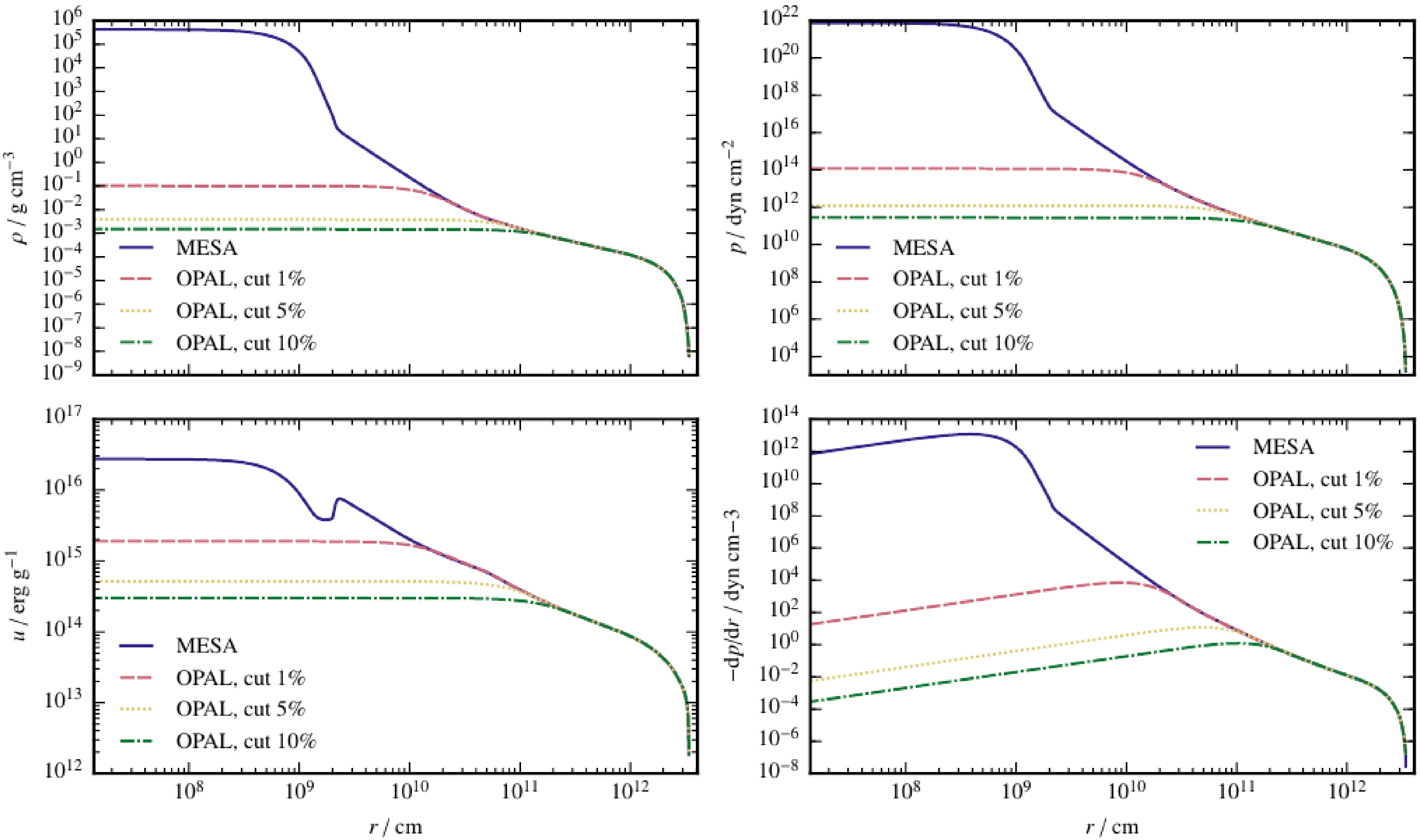
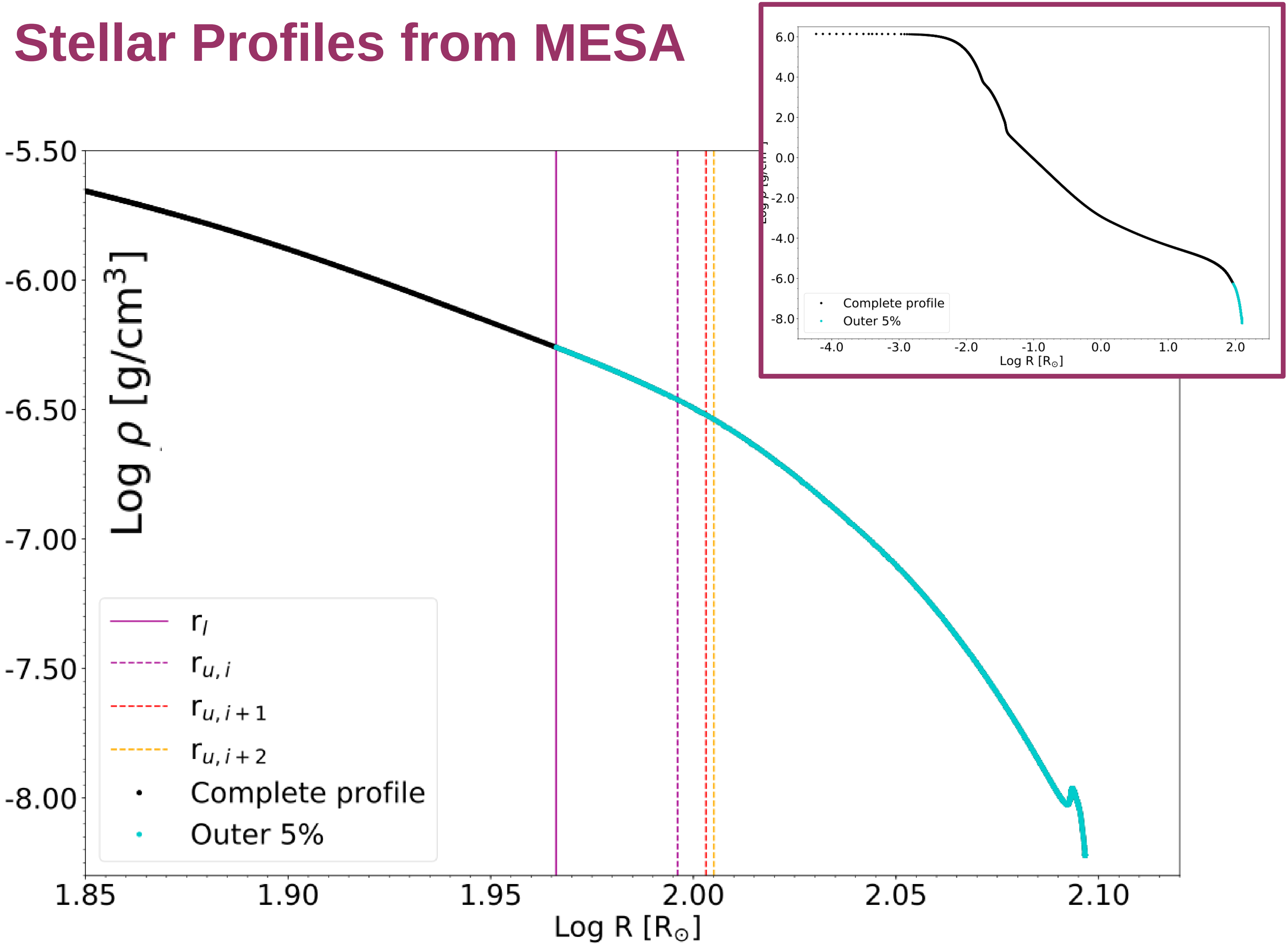


Fig. 4. Comparison of density (*upper left*), pressure (*upper right*), internal energy (*lower left*) and derivative of pressure (*lower right*) for a 2 $M_\odot$ RG with a ~0.4 $M_\odot$ He core. Shown is the original profile from the MESA stellar evolution code as well as approximate profiles for cut radii of 1%, 5%, and 10% of the total radius. The approximate profiles were computed using a polytropic index of $n = 3$ for the interior part.

Ohlmann et al., 2017

Stellar Profiles from MESA

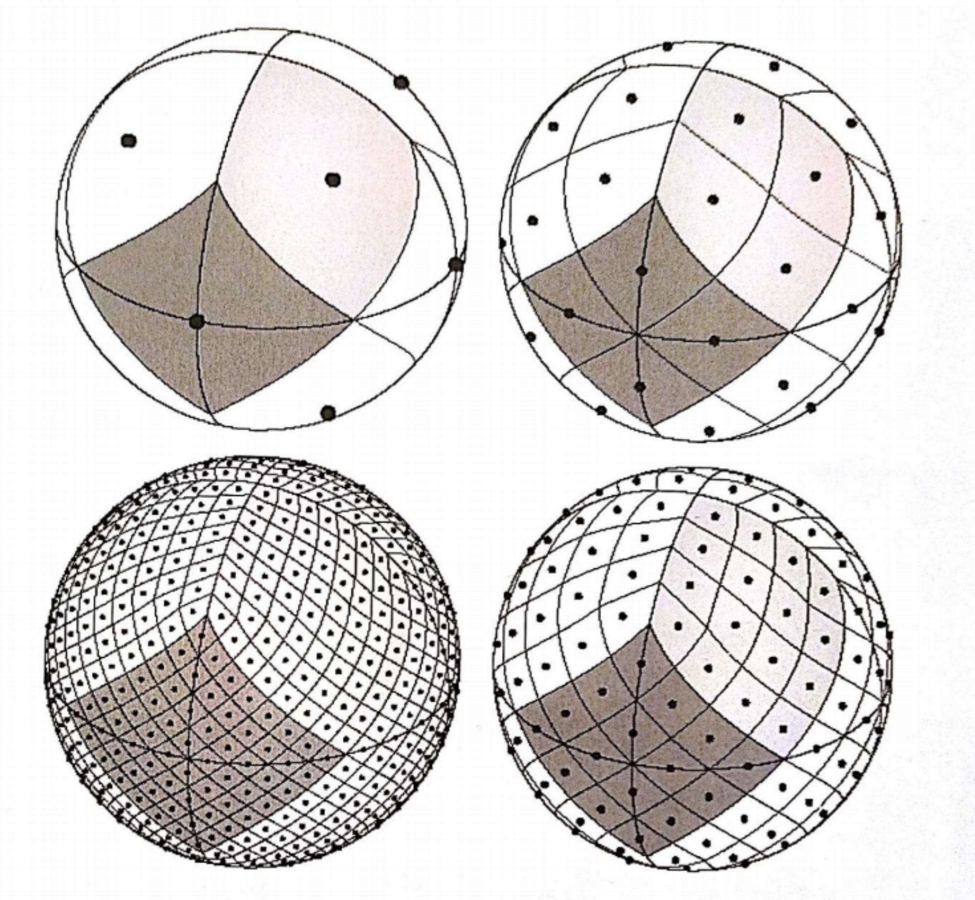


HEALPix:

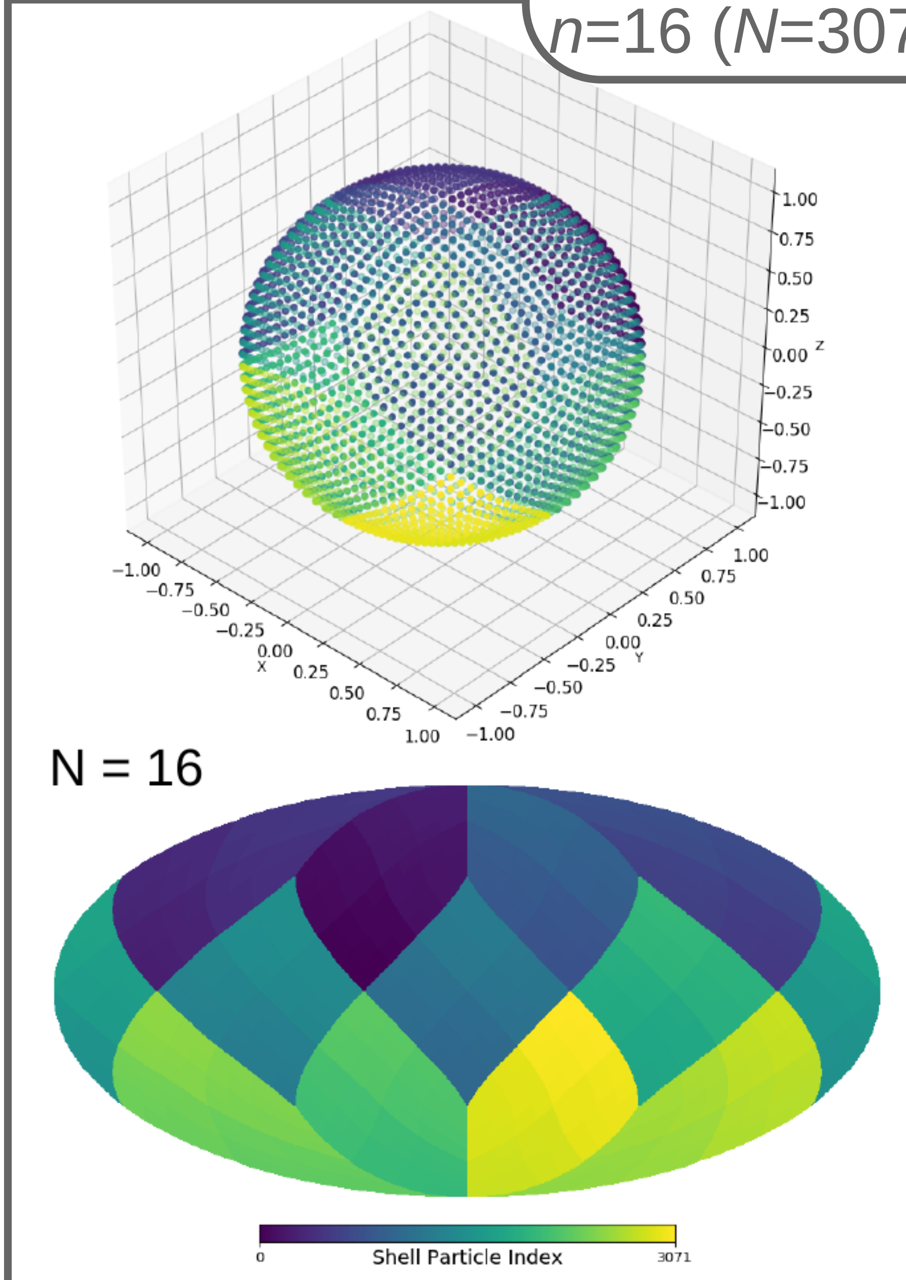
Hierarchical Equal Area iso-Latitude Pixelization

tessellation for n=16 (N=3072)

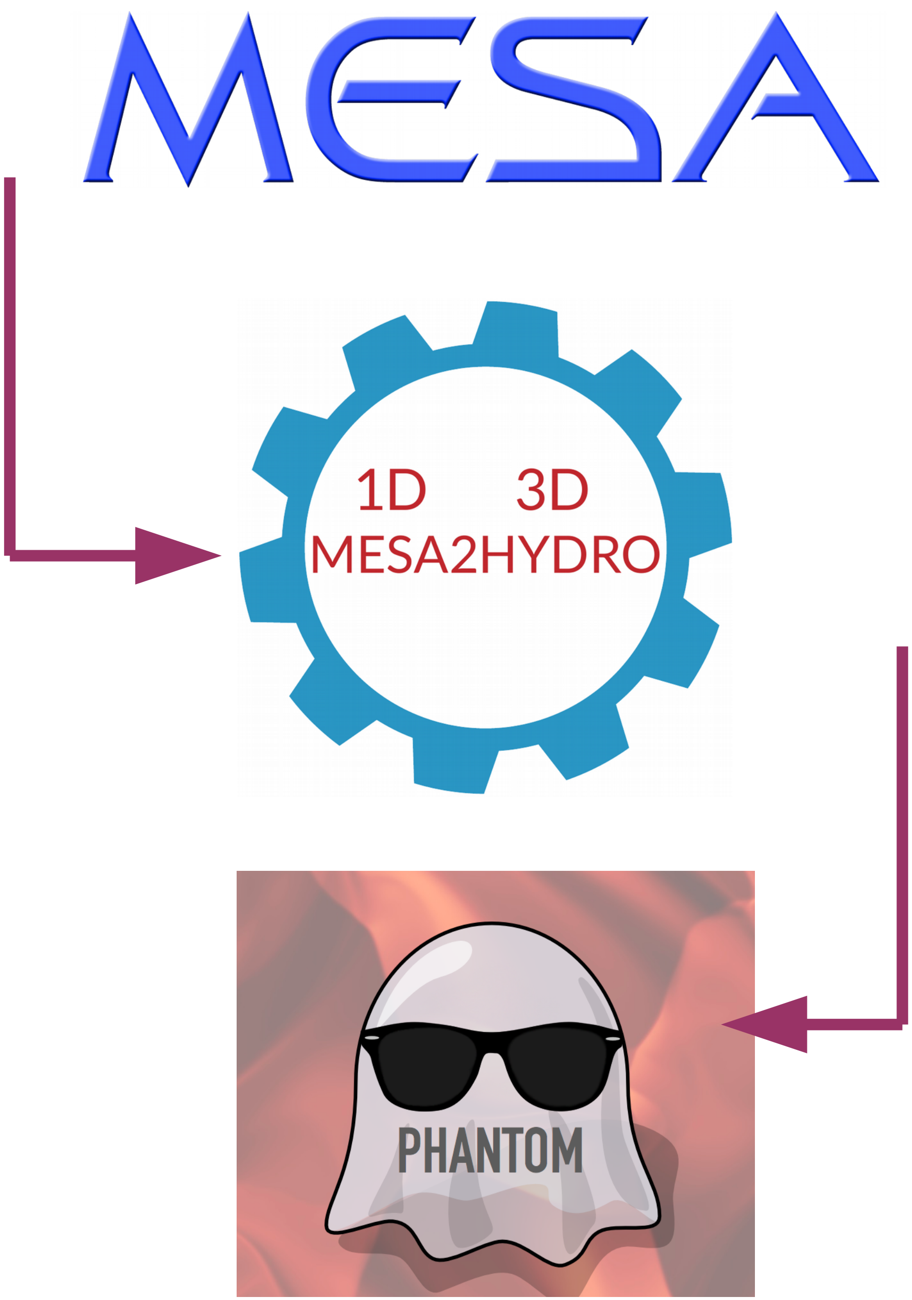
Pakmor et al. (2012): use HEALPix to construct 3D white dwarfs using concentric shells



Górski et al., 2005



Flow of Control



The Astrophysical Journal, 882:63 (14pp), 2019 September 1

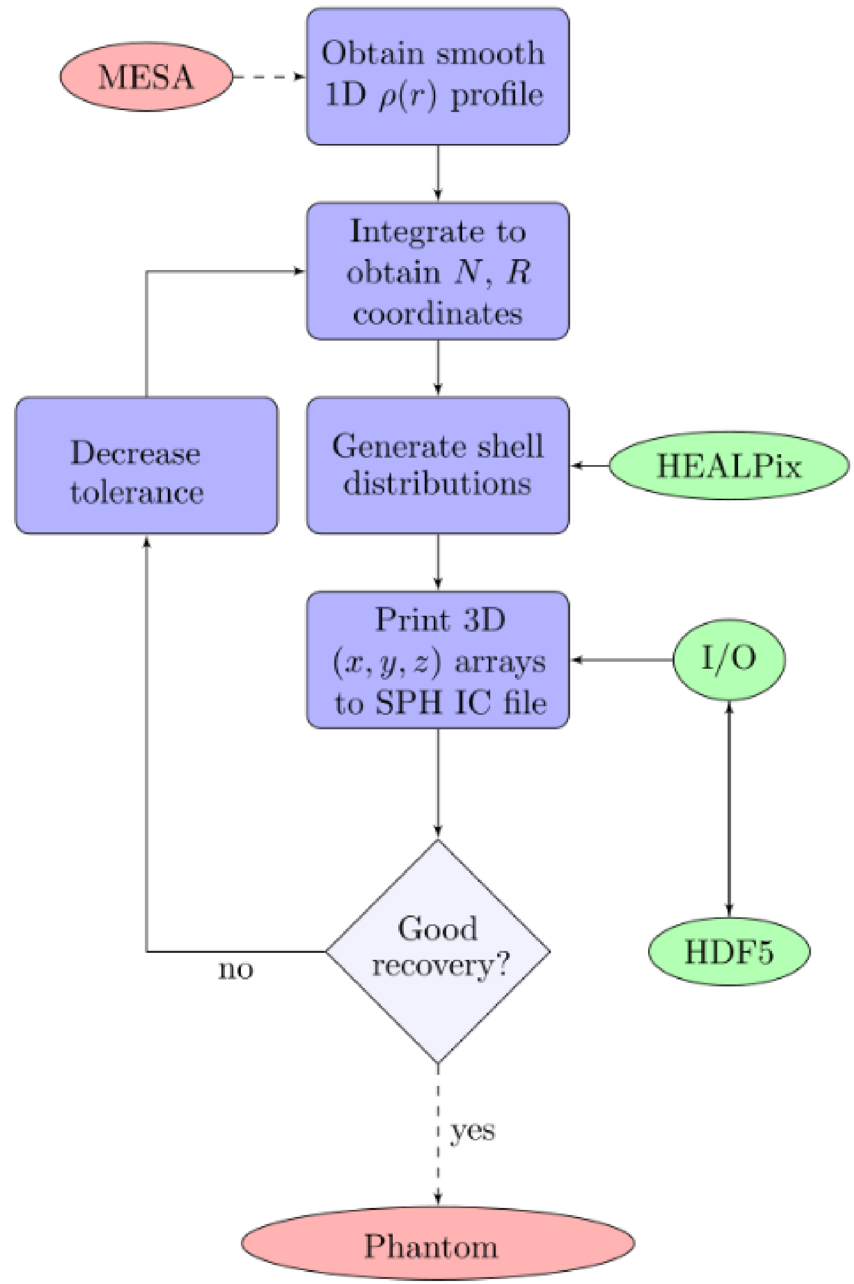
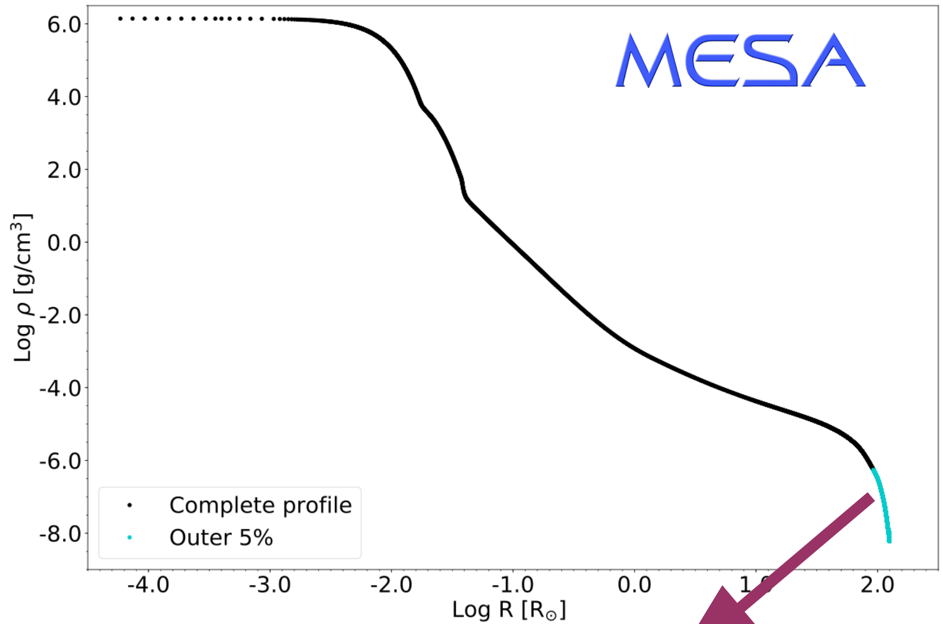
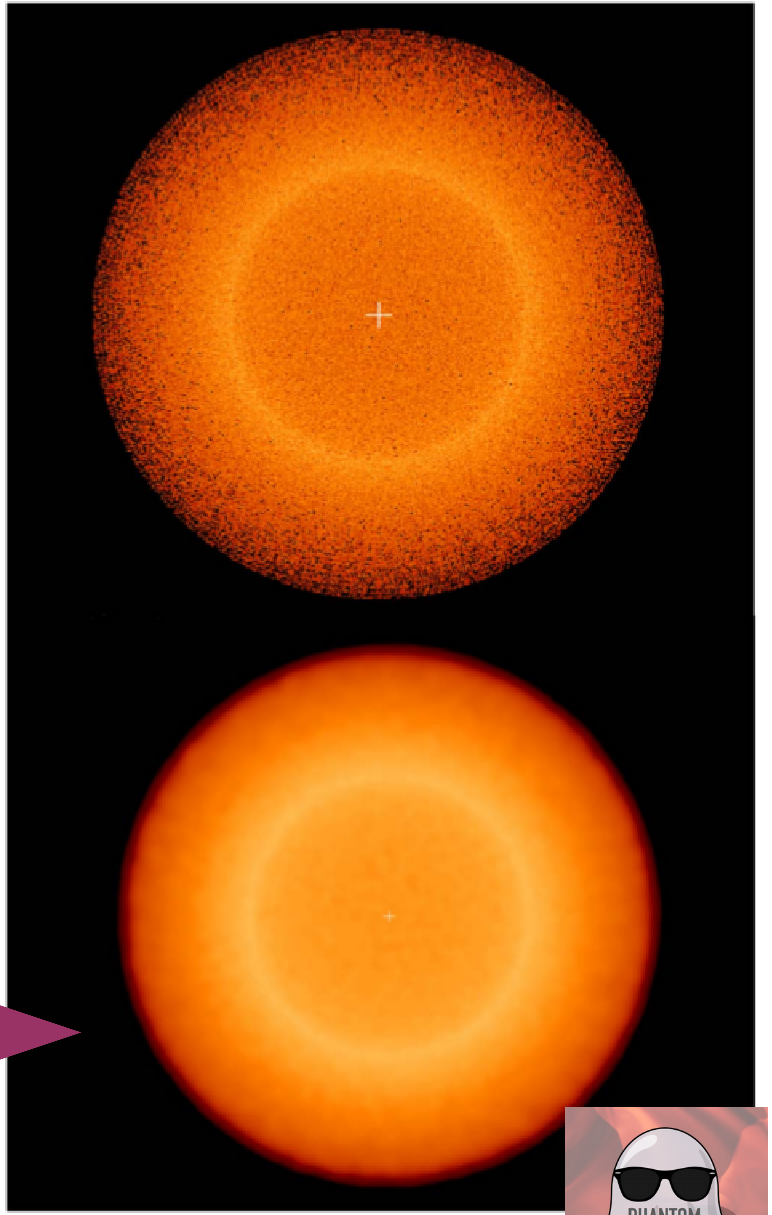


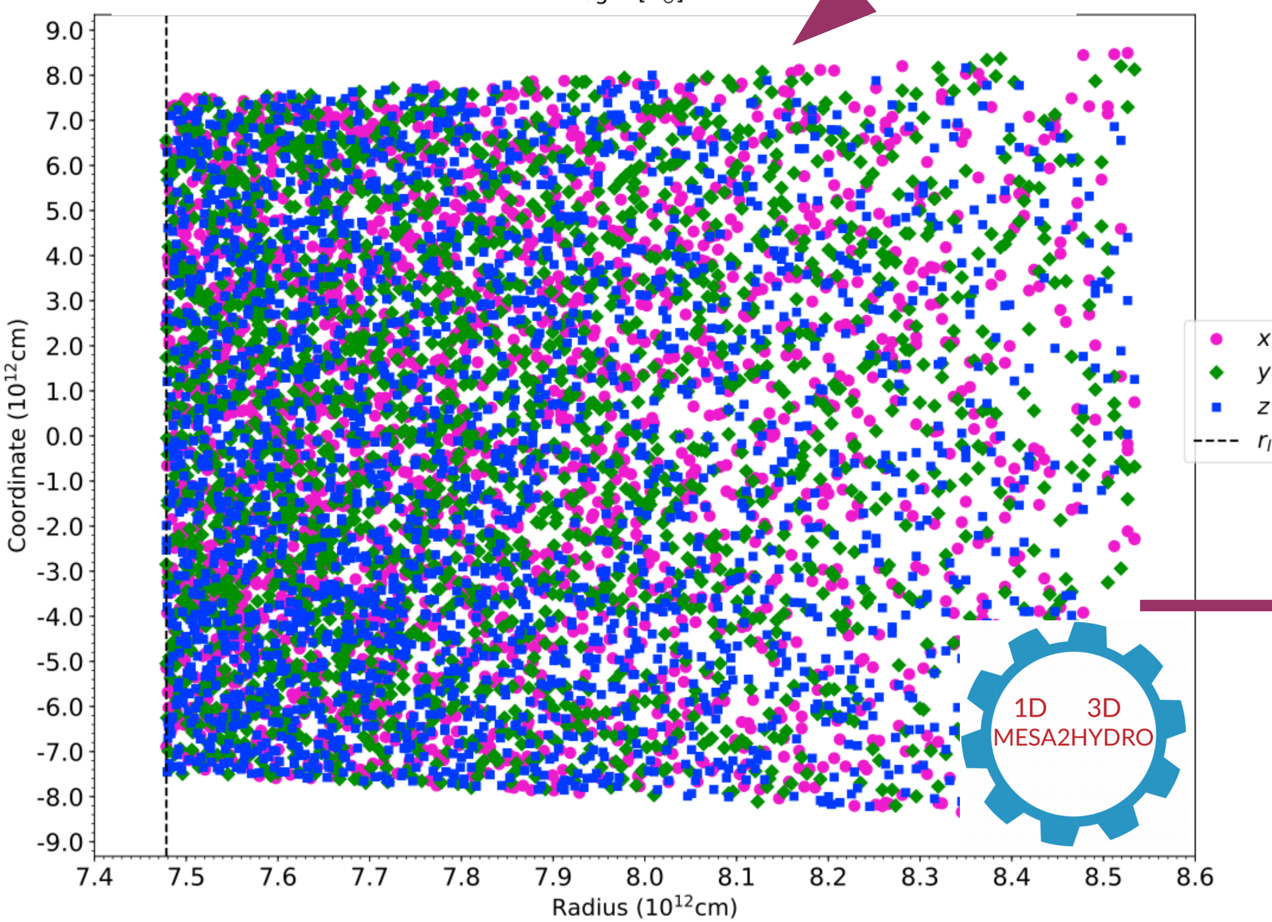
Figure 3. Flow of control diagram for ^{1D}MESA2HYDRO^{3D}.



Log ρ [g/cm³]
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
Log R [R☉]
Complete profile
Outer 5%

Result

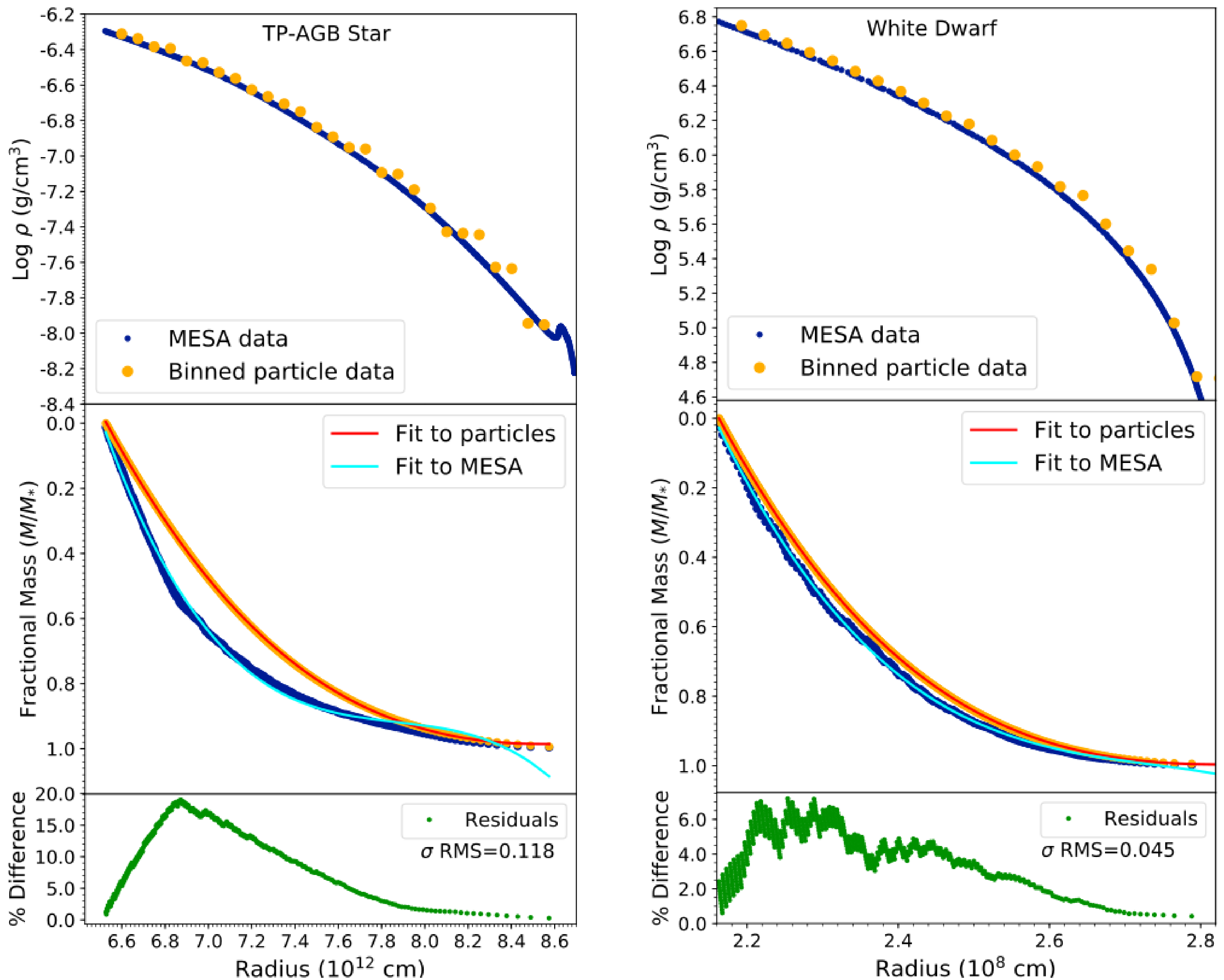




Coordinate (10¹²cm)
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
-9.0
7.4
7.5
7.6
7.7
7.8
7.9
8.0
8.1
8.2
8.3
8.4
8.5
8.6
Radius (10¹²cm)
x
y
z
r_l

Agreement between MESA input and M2H-rendered distributions

THE ASTROPHYSICAL JOURNAL, 882:63 (14pp), 2019 September 1 Joyce et al.

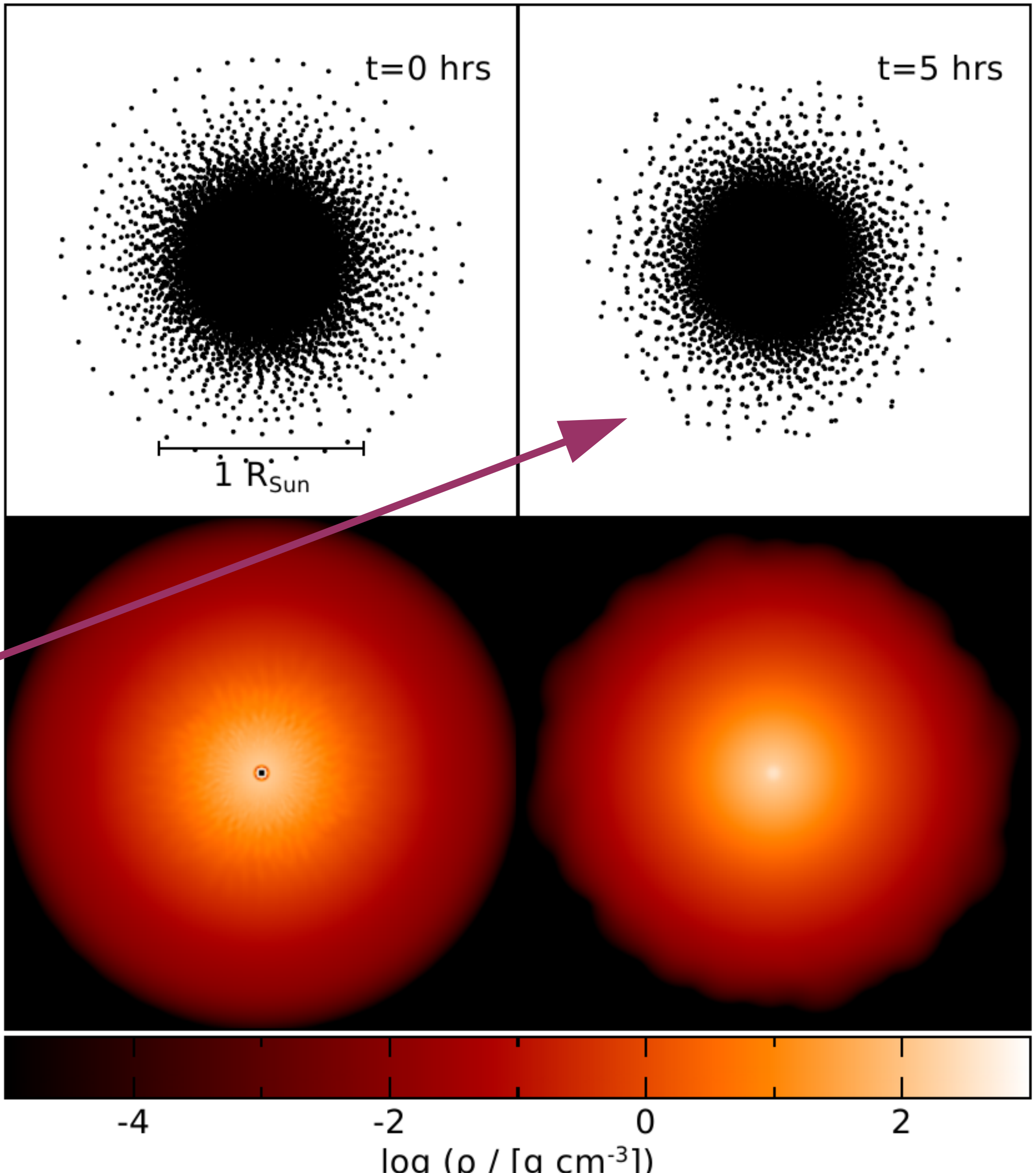


Stability Assessment

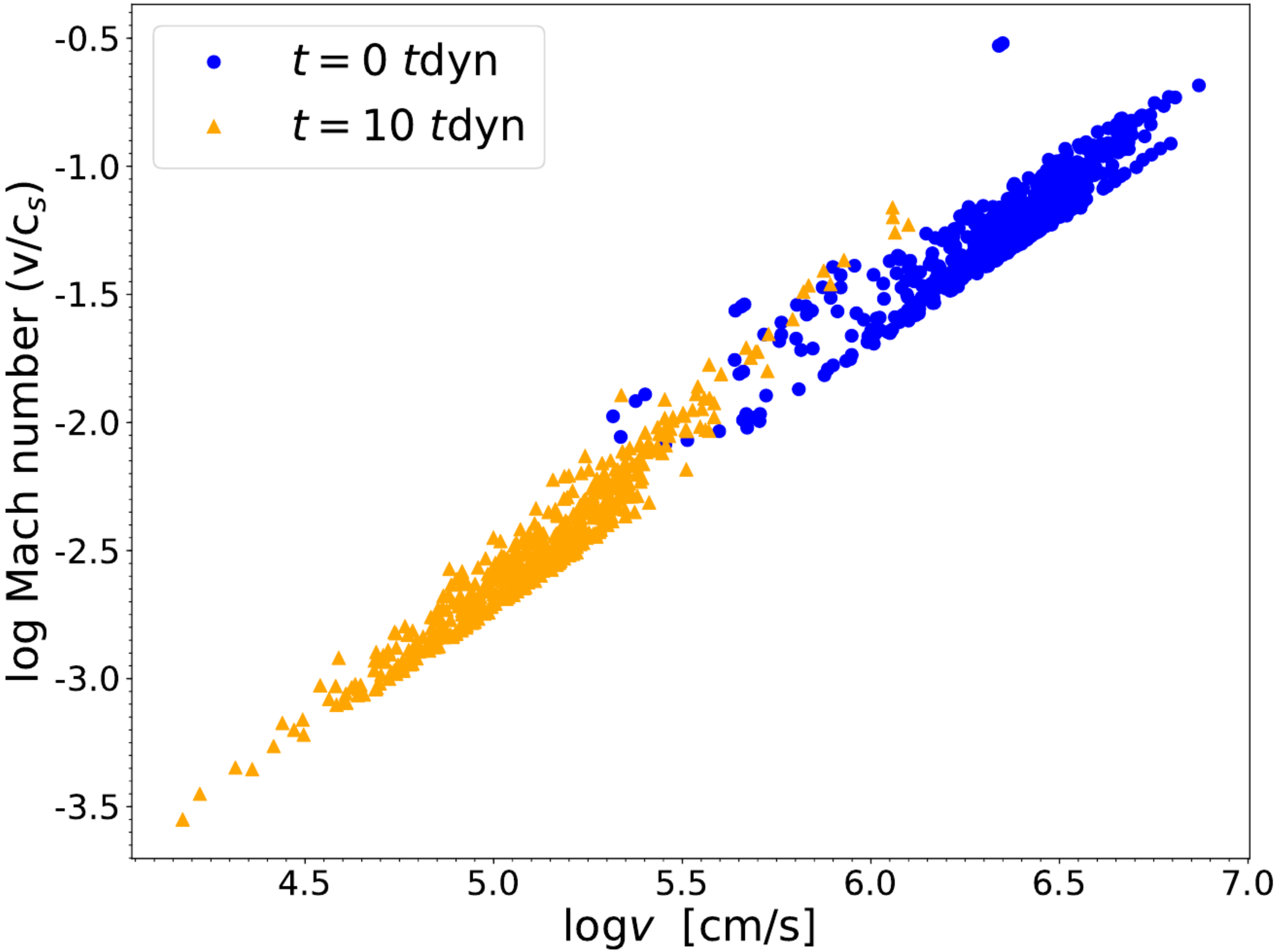
We evolve the distributions for 10 dynamical timescales ($\tau_{\rm dyn}$), following the damping prescription of Ohlmann et al.'s (2017) Equation (9), implemented in Phantom by Reichardt (2019):

$$\tau(t) = \begin{cases} \tau_1, & t < 2t_{\rm dyn} \\ \tau_1 \left(\frac{\tau_2}{\tau_1}\right)^{\frac{t-2t_{\rm dyn}}{3t_{\rm dyn}}}, & 2t_{\rm dyn} < t < 5t_{\rm dyn} \\ \infty, & t > 5t_{\rm dyn}. \end{cases}$$

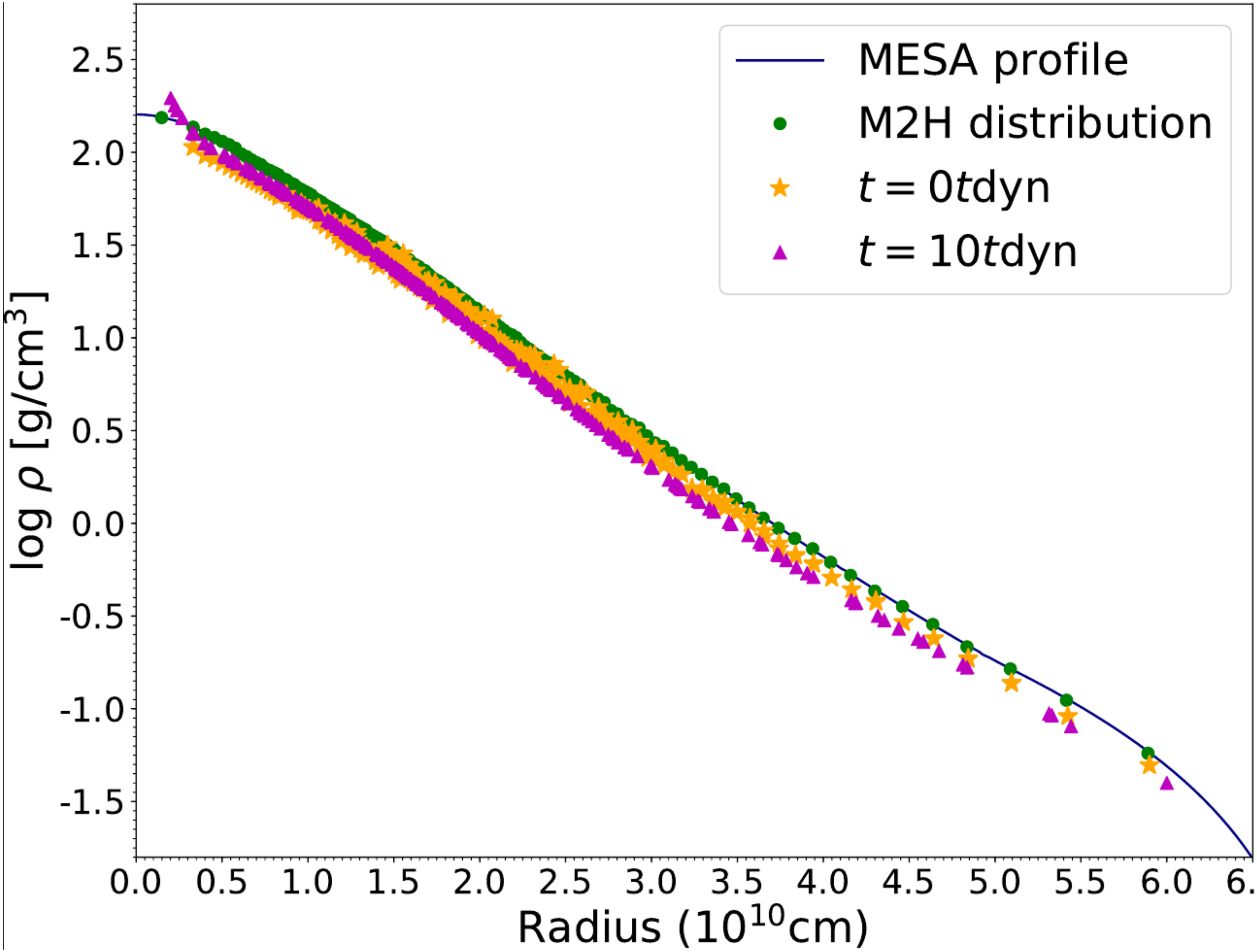
Configuration after relaxation and undamped evolution



Stability Assessment:
velocity field after 10 dynamical timescales



Agreement between MESA input, M2H-rendered distributions, and Phantom-evolved distributions (back-projected to 1D)



In Summary:

Precision 1D stellar modeling: plenty of innovation to come!

➔ Much work remains to be done calibrating stellar convection zones

➔ Predicting the near-future behavior of T Ursae Minoris through **seismic evolution models** has laid foundation for further attempts at modeling dynamical behavior in 1D

➔ **^{1D}MESA2HYDRO^{3D} : Extending 1D**

➔ Great potential in combining the customizable physics of 1D SSE codes with hydrodynamical modeling

Last Comment

MESA has been used successfully to model numerous high-energy phenomena, including...

- core-collapse supernova explosions
- x-ray bursts
- massive binaries as gravitational wave sources
- tidal disruption events
- modified theories of gravity
- new elementary particles (scalar and vector)
- universes without the weak force

D S E P
Dartmouth Stellar Evolution Program

MESA

GYRE

If you are interested in using MESA for your projects, please take advantage while I am here!

ありがとうございました