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Modeling Cepheid Variable Stars Using the Open-Source MESA Code

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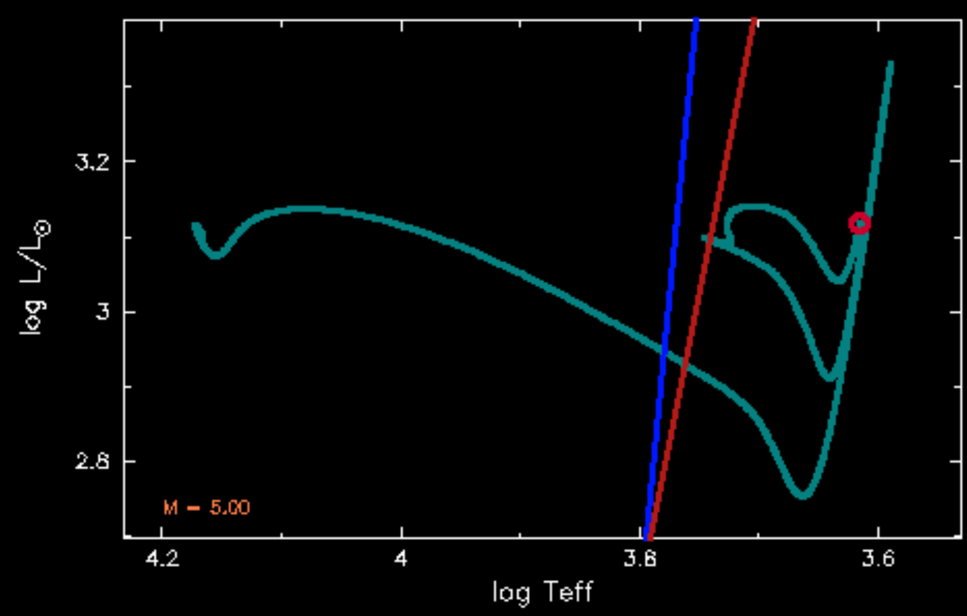
October 19, 2019



Los Alamos National Laboratory LA-UR-19-30082

Abstract

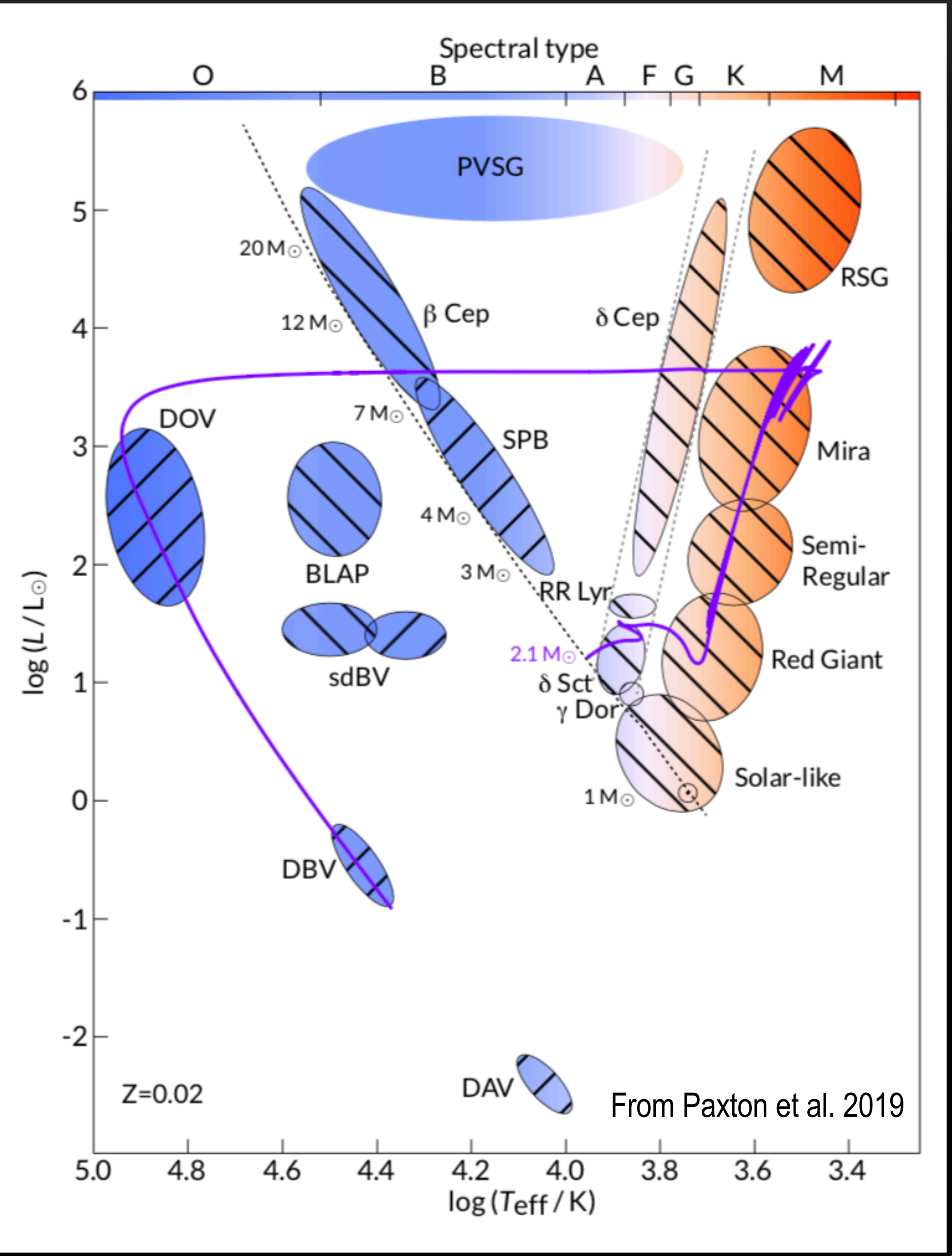
Cepheid variable stars are core helium-burning stars of around 4 to 15 solar masses that show radial pulsations with typical periods of a few days to a few weeks, and magnitude variations of a few tenths to up to 2 magnitudes per pulsation cycle. Cepheids are well within the reach of amateur observers, with over 200 Galactic Cepheids brighter than 10th magnitude, and have been the target of numerous AAVSO observations.

Cepheids show a period-luminosity relation, discovered by Henrietta Leavitt in 1908, that has been used to determine distances within the Galaxy and to galaxies beyond the Milky Way. Cepheids are also a laboratory to test stellar interior physics, such as nuclear reaction rates for helium burning, turbulence models, and opacities, under conditions not easily accessible in laboratories on Earth. Current problems in Cepheid research include the discrepancy between the Hubble constant derived from the Cepheid period-luminosity relation, and that derived from cosmic microwave background observations; and 2) the discrepancy between Cepheid masses derived from pulsation periods or binary dynamics and that derived using stellar evolution models.

Here we show how the open-source MESA (Modules for Experiments in Stellar Astrophysics) code (Paxton et al. 2011, 2013, 2015, 2018, 2019, http://mesa.sourceforge.net/) can be used to explore Cepheid evolution. We will also show results using the new radial stellar pulsation (RSP) capability in MESA to model the hydrodynamics of Cepheid envelopes during their pulsations, and simulate light curve and radial velocity variations. We will compare models with observations of Cepheids with well-known properties such as delta Cep, Polaris, and V1334 Cyg. These stellar modeling capabilities are accessible to anyone with a laptop computer, following the directions in the MESA tutorial for installation, and starting with the examples in the MESA test suite.

What are Classical Cepheids?

- Pulsating variable stars, prototype delta (δ) Cep
- 4-15 M_{sun}, core helium burning
- Pulsation periods 3 to 100 days
- Pulsations driven via the 'kappa' (opacity) mechanism in envelope helium ionization zone ~50,000 K
- Radial fundamental, 1st overtone, or 2nd overtone (rare) pulsations



Why are Cepheids important?

- Period-luminosity relation (Leavitt 1908) used to calibrate distance scale for universe

  Determine Hubble Constant

- "Laboratory" to test stellar physics

  Cepheid mass discrepancy

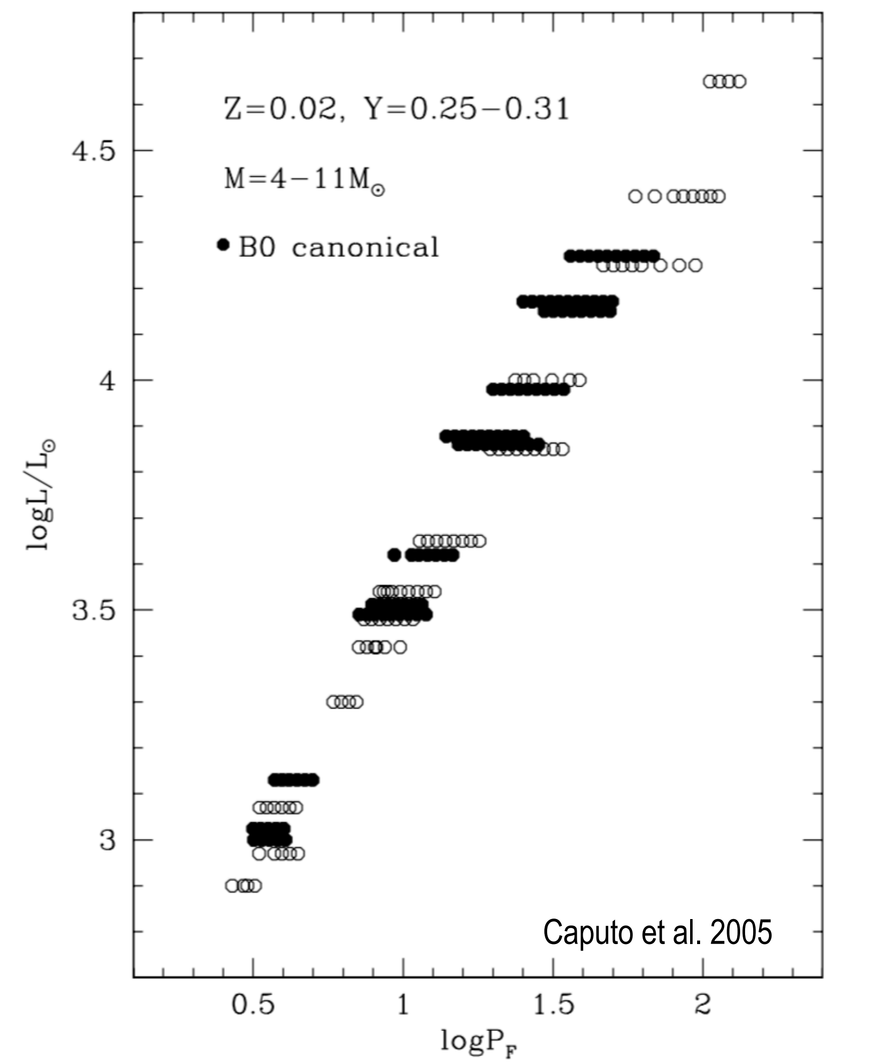
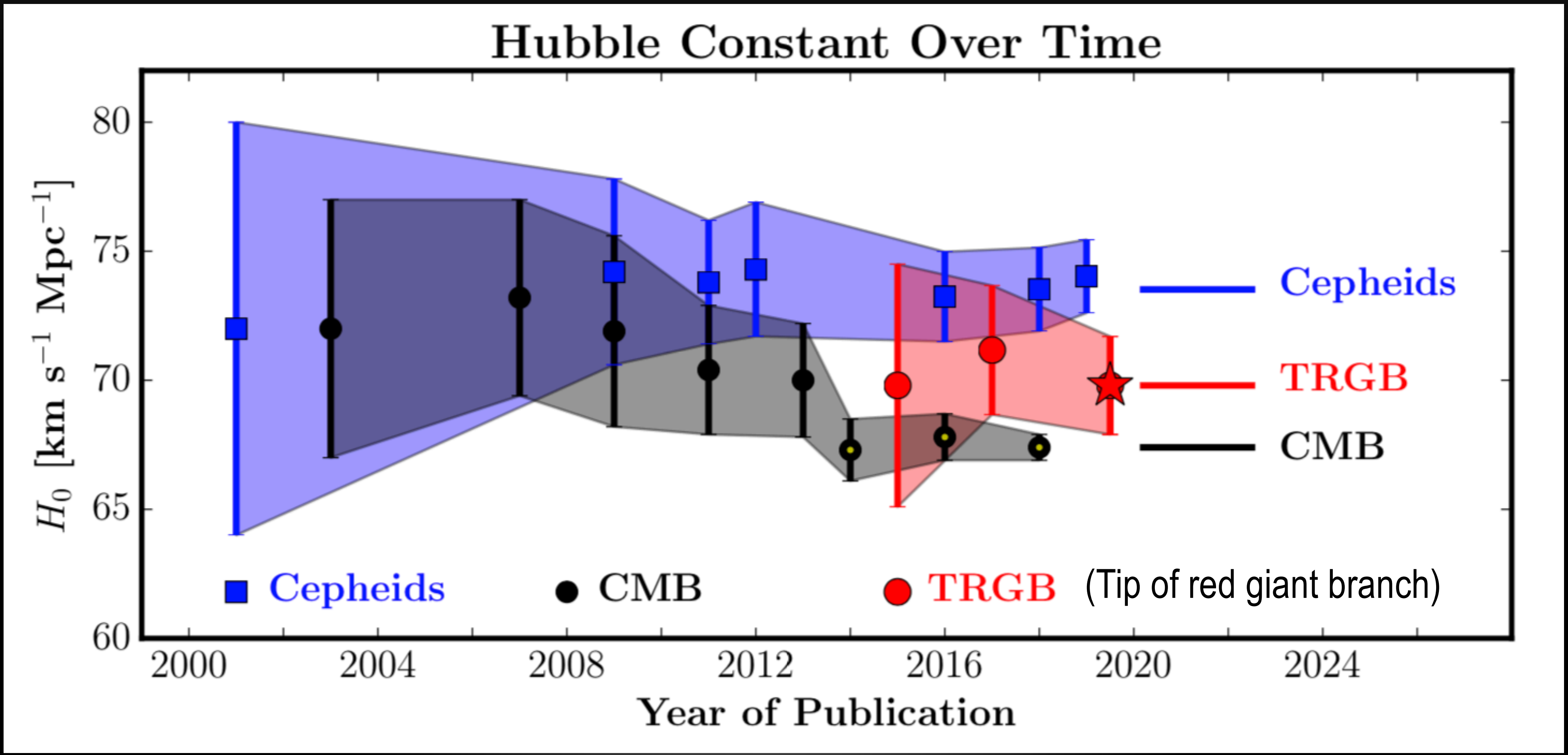


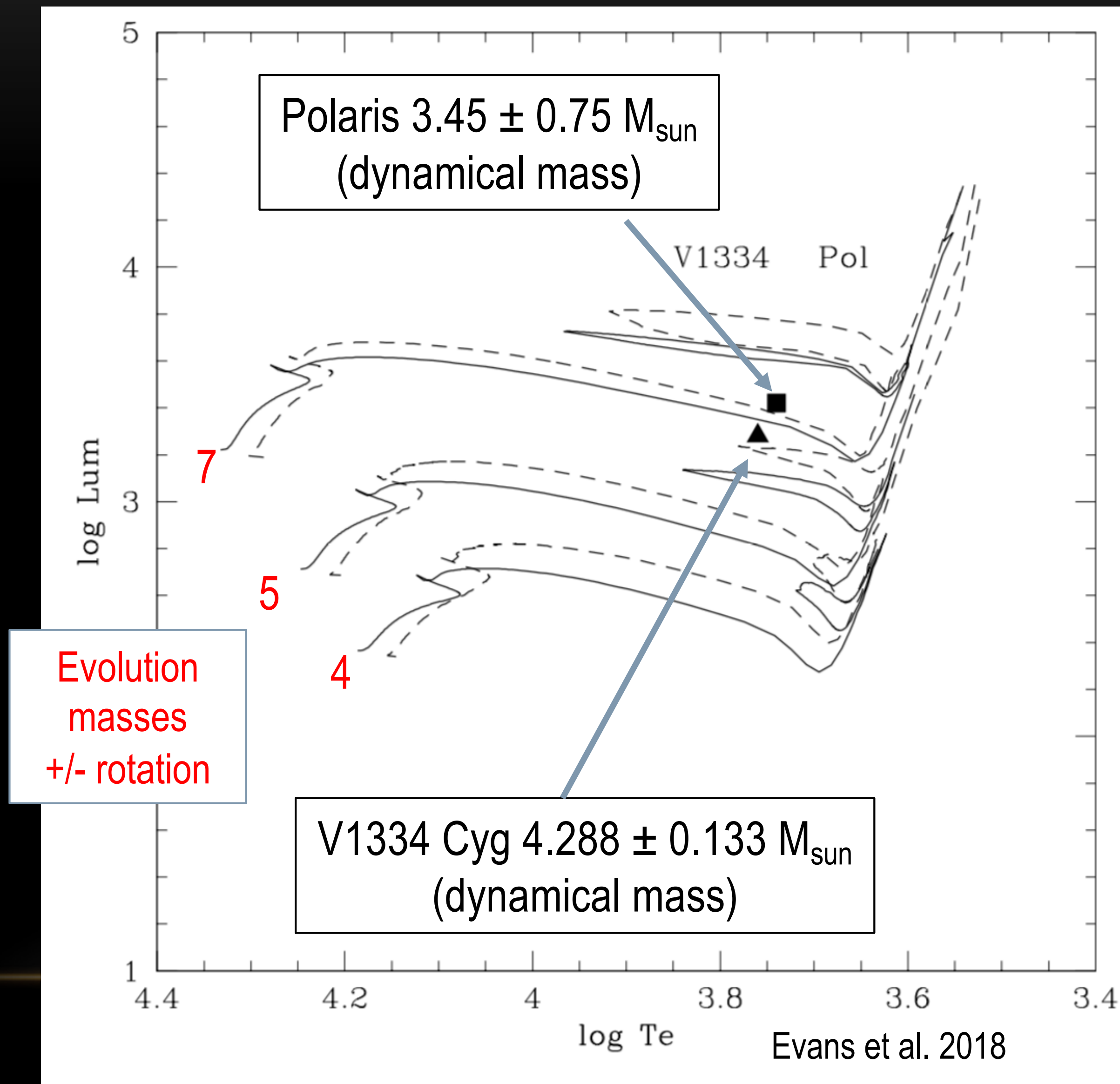
FIG. 1.—PL distribution of fundamental pulsators with fixed metal content ($Z = 0.02$) and helium abundance ranging from $Y = 0.25$ to 0.31. Filled circles display Cepheid models computed by adopting the B00 canonical ML relation.

The Hubble Constant derived using Cepheids is higher than that measured using the Cosmic Microwave Background



Freedman et al., ApJ 2019

Cepheid masses determined from binary dynamics are lower than evolution model masses



What is MESA?

- MESA = Modules for Experiments in Stellar Astrophysics
- Open-source stellar evolution code (Paxton et al. 2011, 2013, 2015, 2018, 2019)
- New 2019 capability to calculate radial hydrodynamic pulsations of stellar envelope models (RSP)
- Directions and tutorials on mesa.sourceforge.net
- Runs on desktops and laptops (e.g., my Mac laptop!)
- Used to calculate Cepheid evolution models by following

  ‘getting started’ tutorial and example

  star/test_suite/5M_cepheid_blue_loop
- Used to calculate Cepheid envelope pulsation models

  star/test_suite/rsp_Cepheid

MESA page on mesa.sourceforge.net

mesa.sourceforge.net/index.html

Most Visited | Getting Started | Outlook | Ambient Weather | Web Mail Messages | Facebook | Breaking News, Wor... | Los Alamos Daily Po... | MESA home | The Future of Aster... | Specific Help for AR... | Inbox

MESA
Modules for Experiments in Stellar Astrophysics

MESA home
code capabilities
prereqs & installation
getting started
using pgstar
using MESA output
extending MESA
troubleshooting
FAQ
best practices
star_job defaults
controls defaults
pgstar defaults
binary_controls defaults
news archive
documentation archive

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

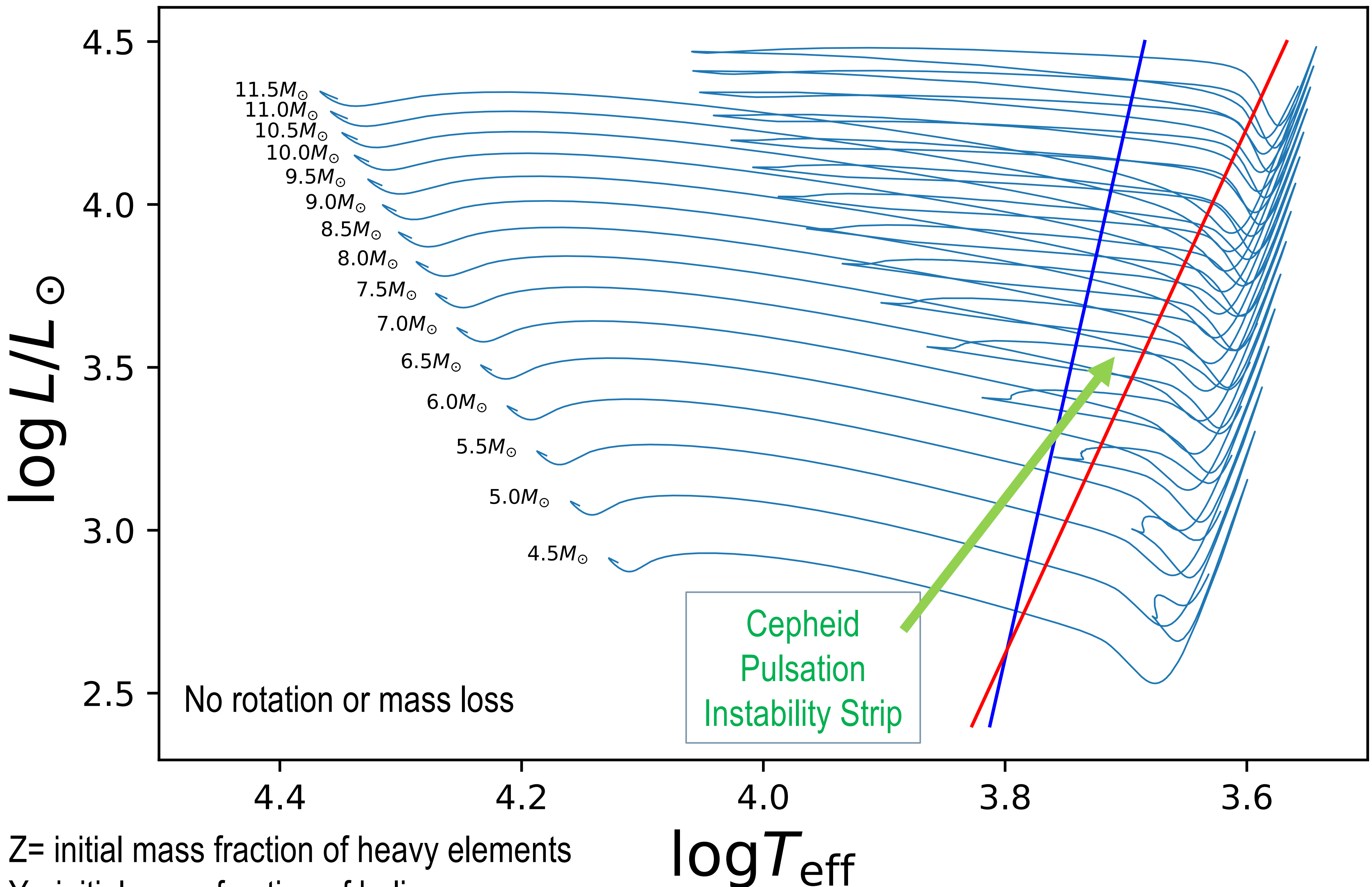
Stellar evolution calculations remain a basic tool of broad impact for astrophysics. New observations constantly test the models, even in 1D. The continued demand requires the construction of a general, modern stellar evolution code that combines the following advantages:

- **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

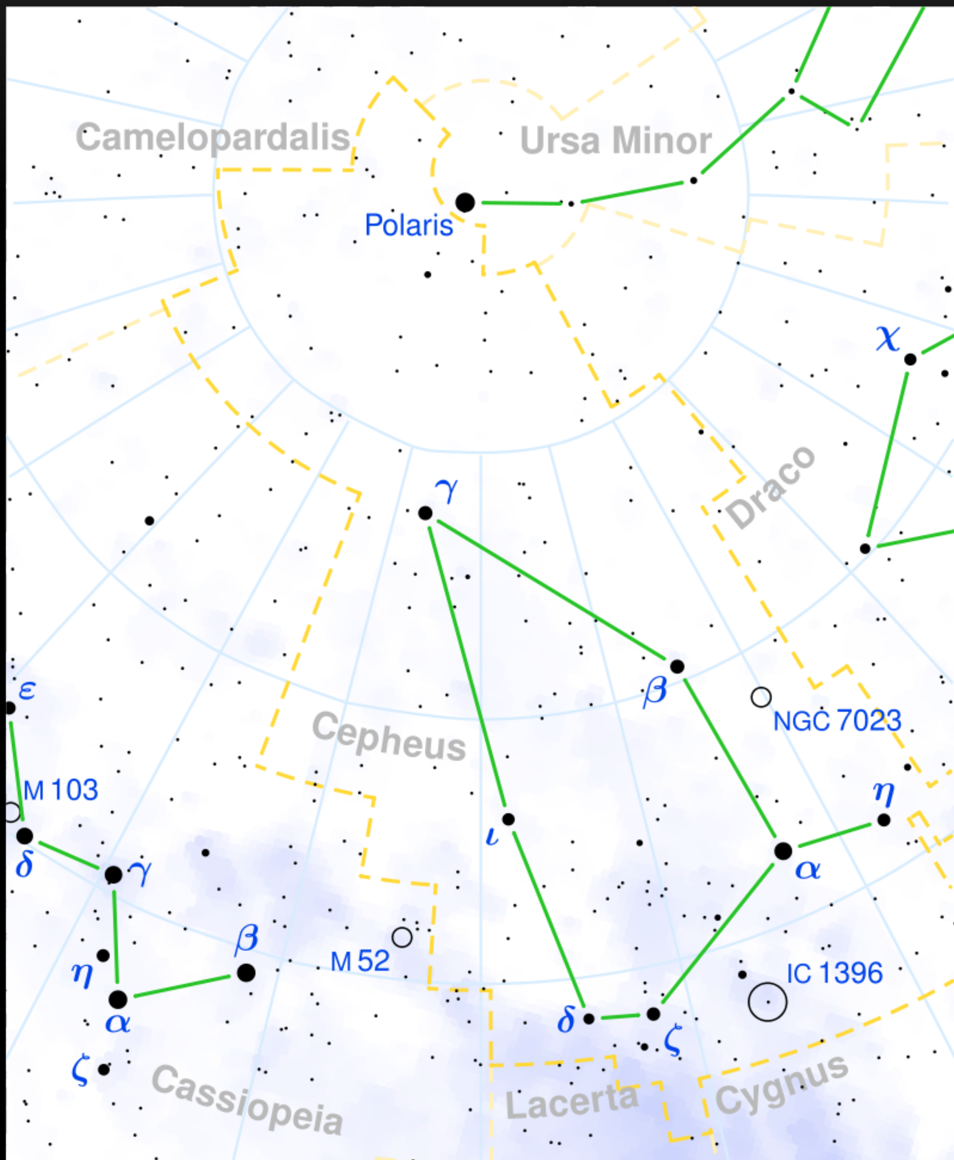
- 10 Sep 2019
  » **Release 12115**
- 30 Aug 2019
  » **New MESA SDK Version**
- 03 May 2019
  » **Release 11701**
- 03 May 2019
  » **New MESA SDK Version**
- 15 Mar 2019
  » **Release 11554**
- 15 Mar 2019
  » **New MESA SDK Version**
- 04 Mar 2019
  » **Release 11532**
- 04 Mar 2019
  » **Instrument Paper 5**
- 11 Jan 2019
  » **Summer School 2019**
- 21 Mar 2018
  » **Release 10398**

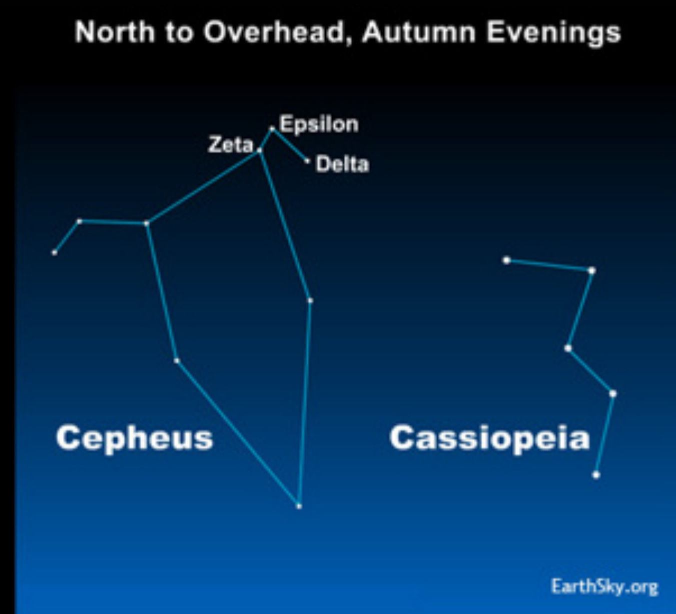
MESA Evolution Tracks for Z=0.02, Y=0.28



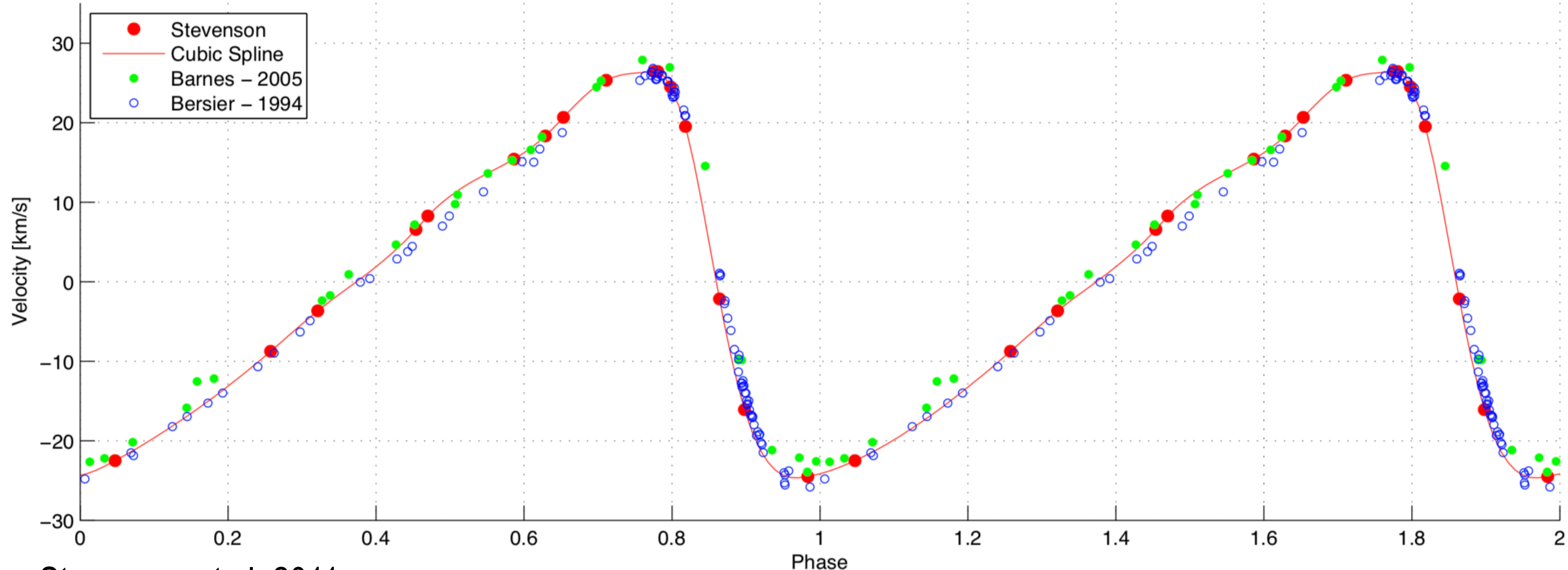
Z= initial mass fraction of heavy elements
Y= initial mass fraction of helium

The prototype Cepheid delta Cep varies from V=3.48 to 4.37 mag with period 5.36 days





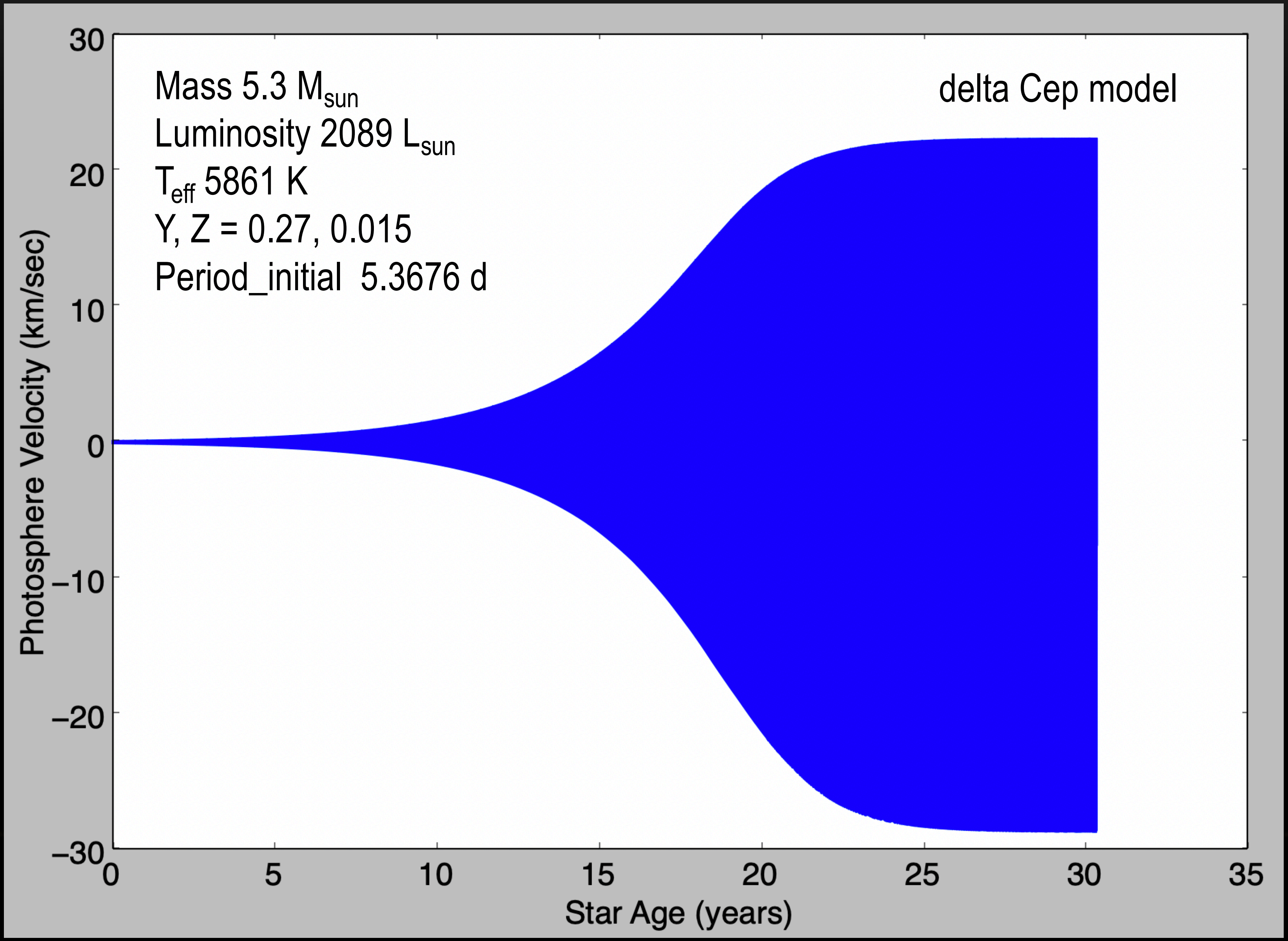
The radial velocity curve of delta Cep has a 'sawtooth' shape with amplitude > 20 km/sec



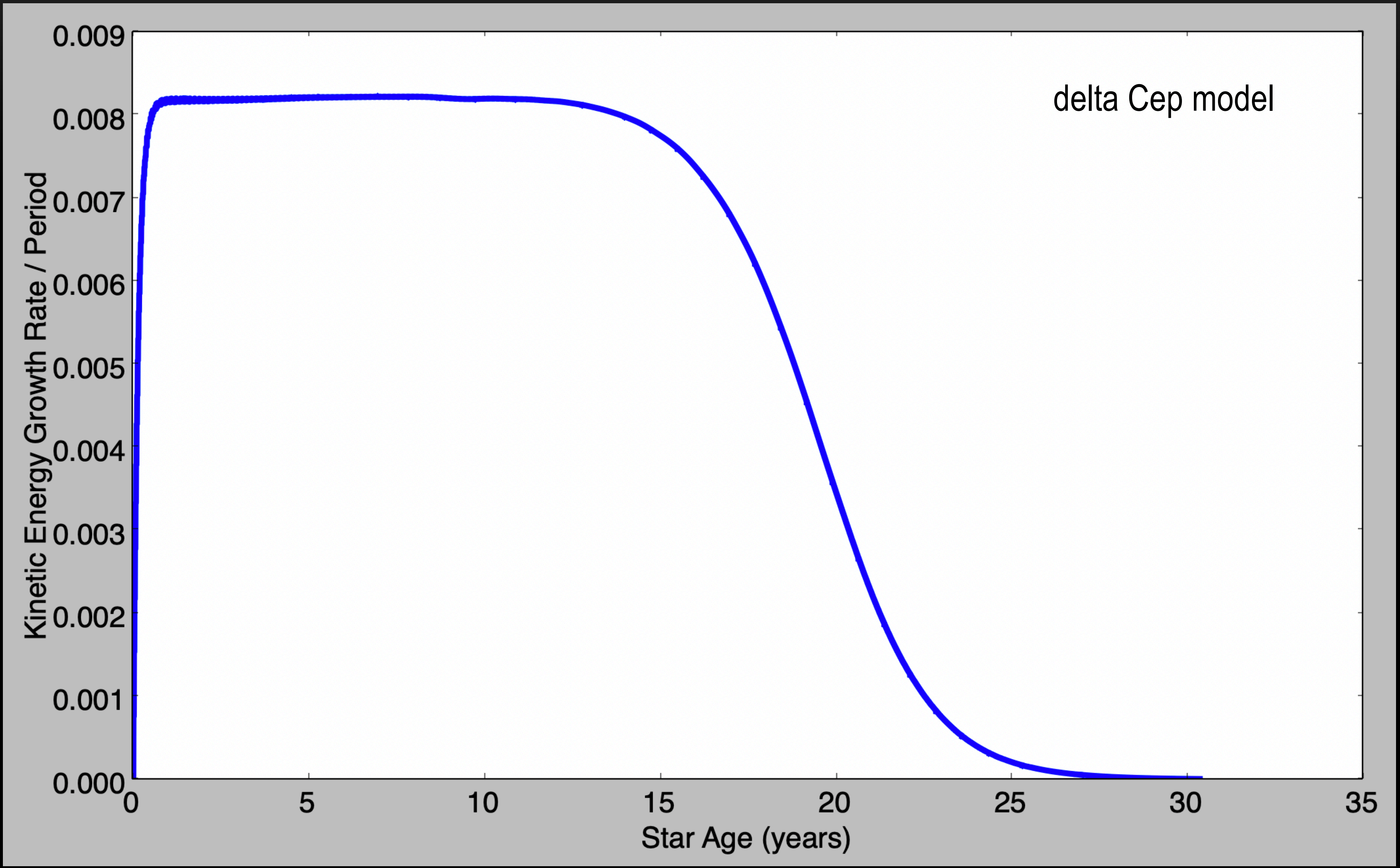
Stevenson et al. 2011

Period 5.3662 days, Fundamental radial mode

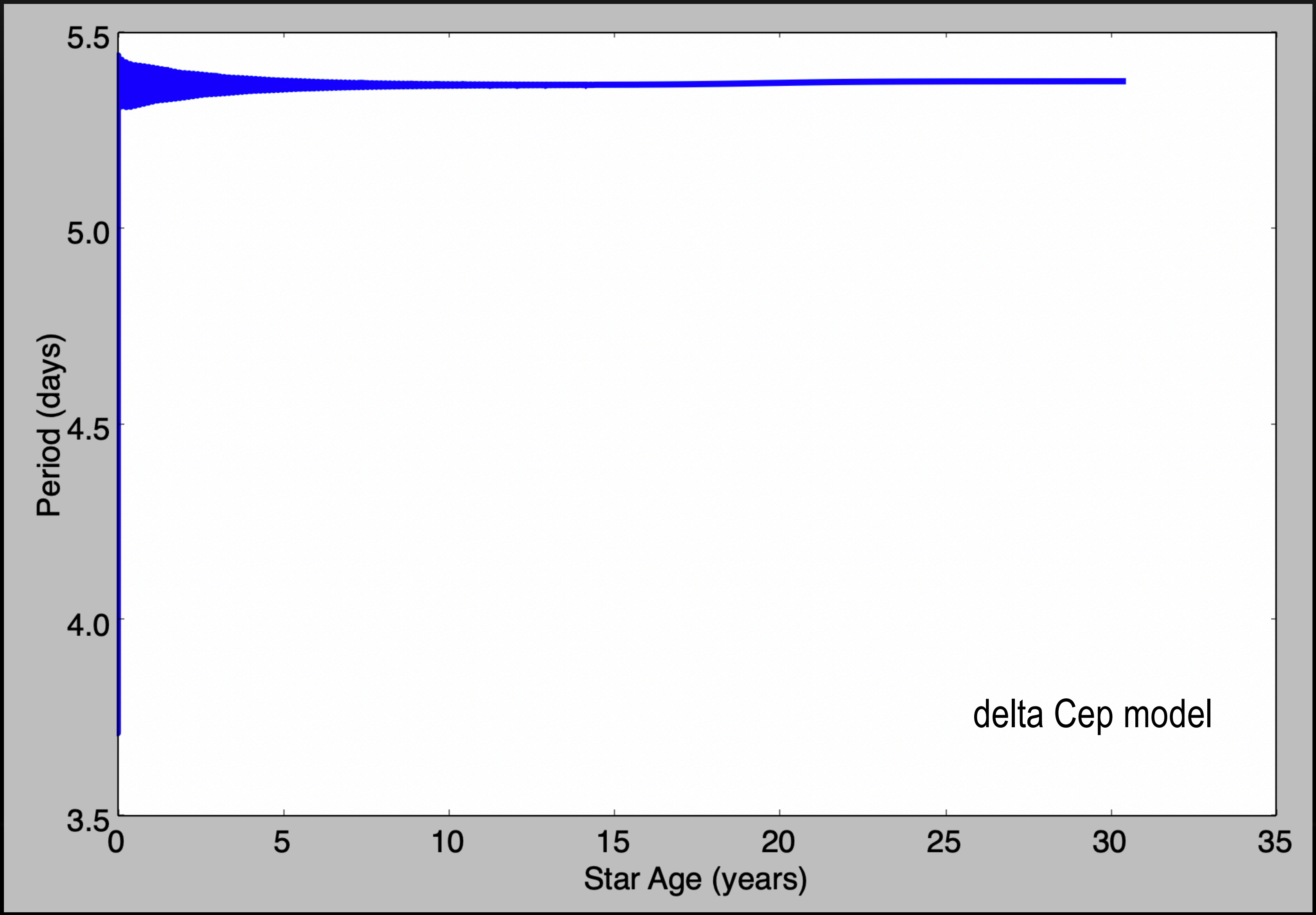
MESA RSP simulations initiated in fundamental mode at 0.1 km/sec grow to > 20 km/sec



The kinetic energy put into pulsations per period decreases to zero when radial velocity reaches limiting amplitude

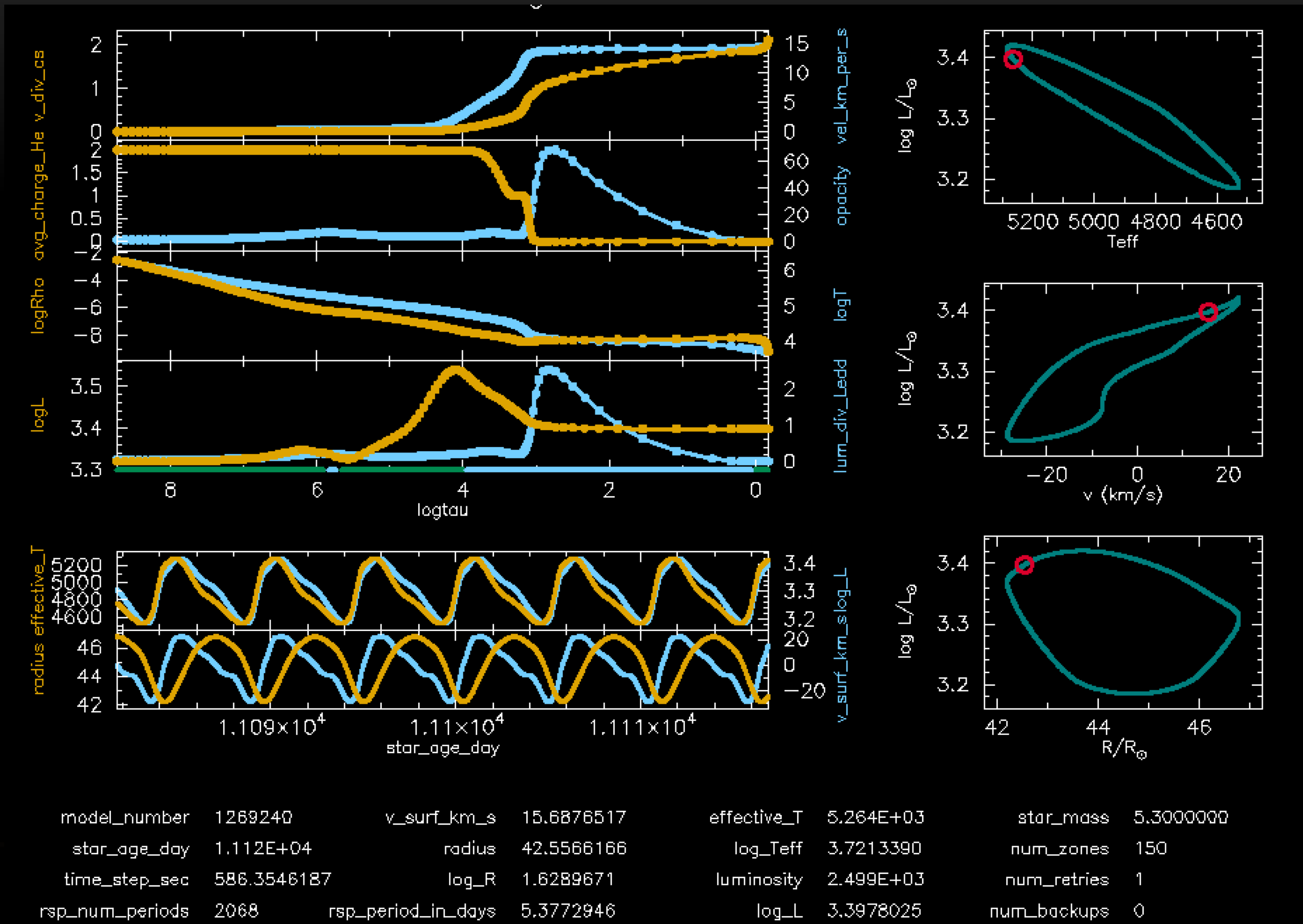


The pulsation period oscillates before reaching a constant value

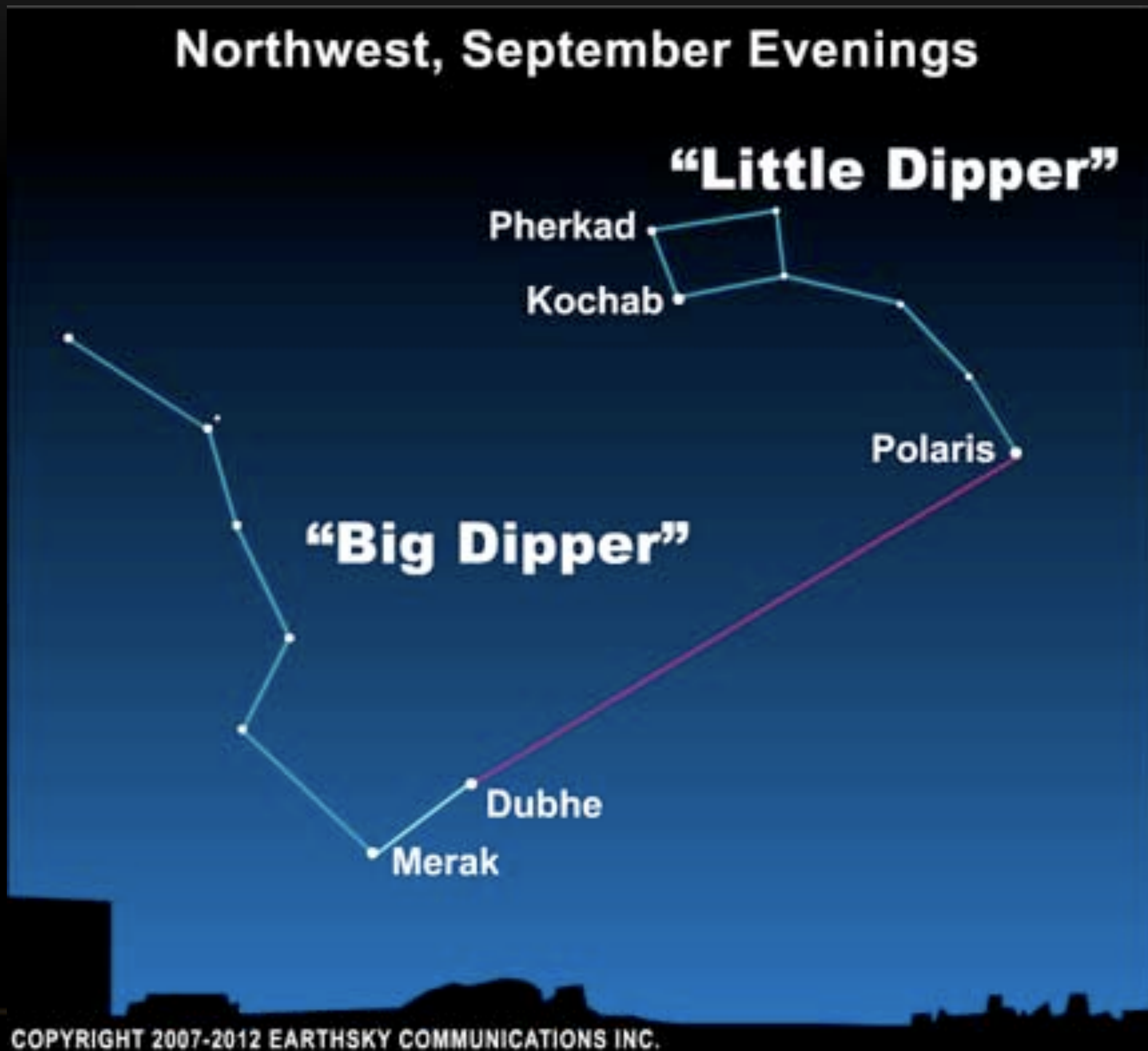


A ‘dashboard’ shows pulsation properties during the simulation

delta Cep model



Polaris varies between magnitude V = 1.86 and 2.13 with period 3.972 days



Polaris has a smaller radial velocity amplitude of only one to a few km/sec

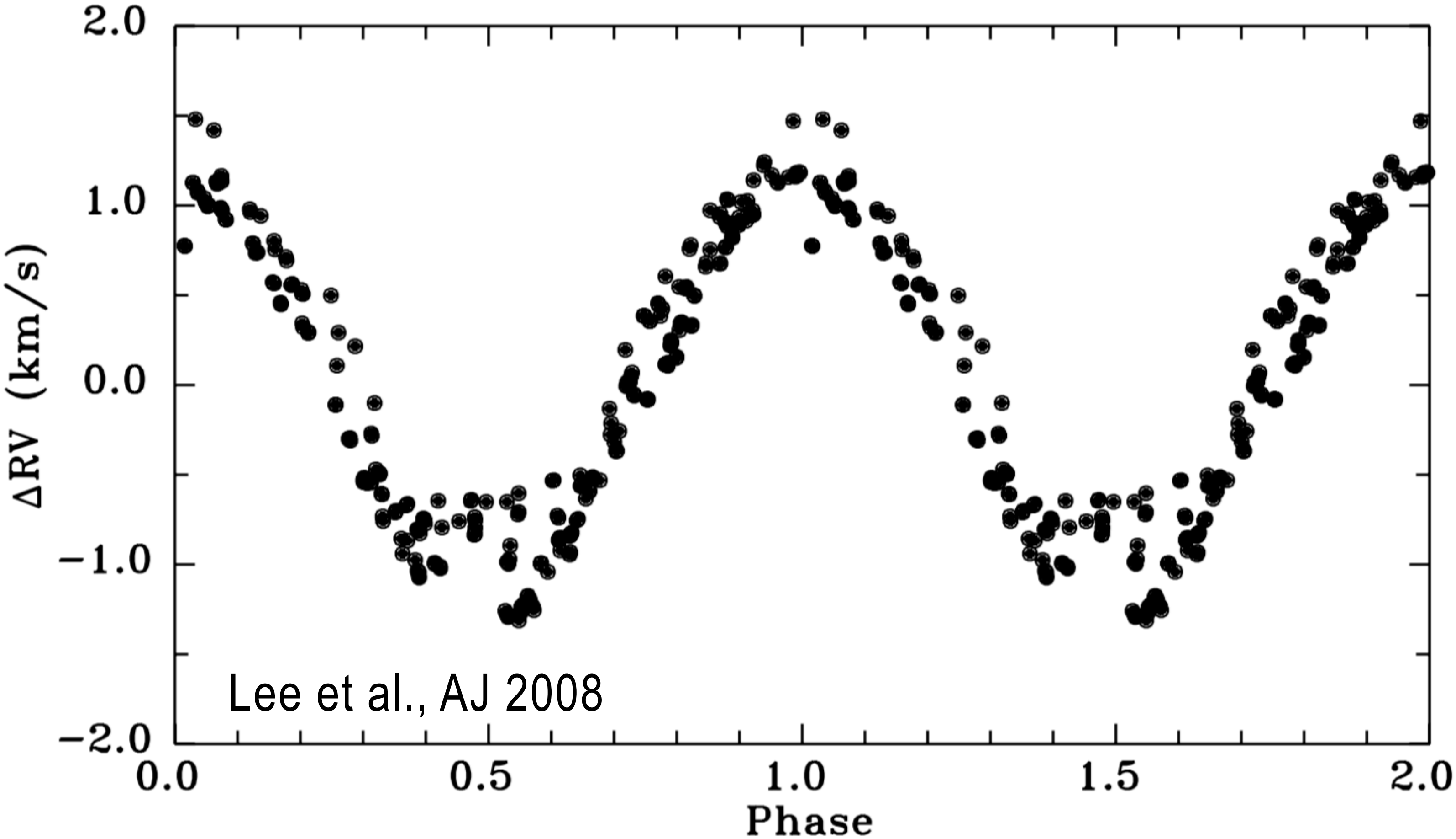
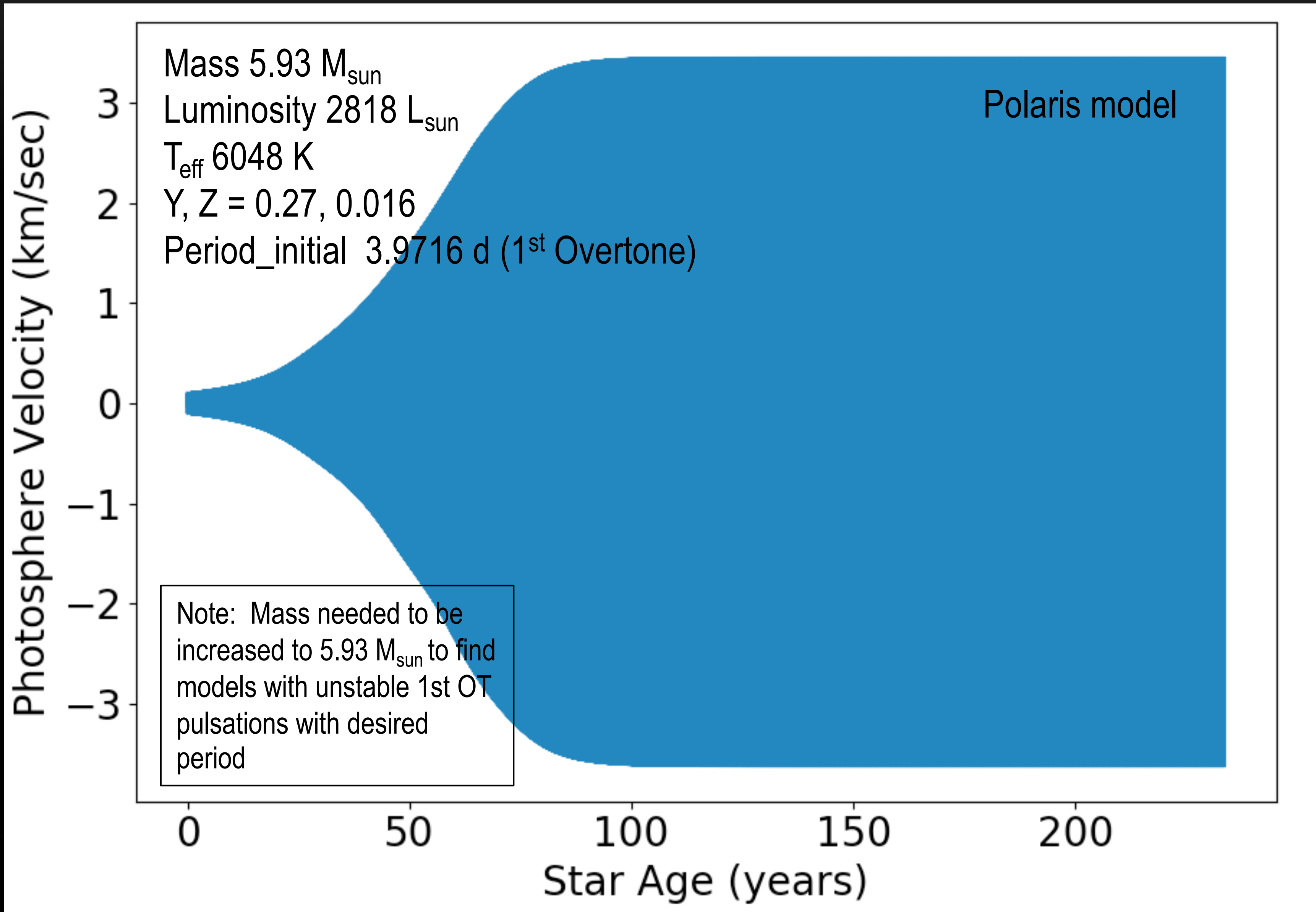
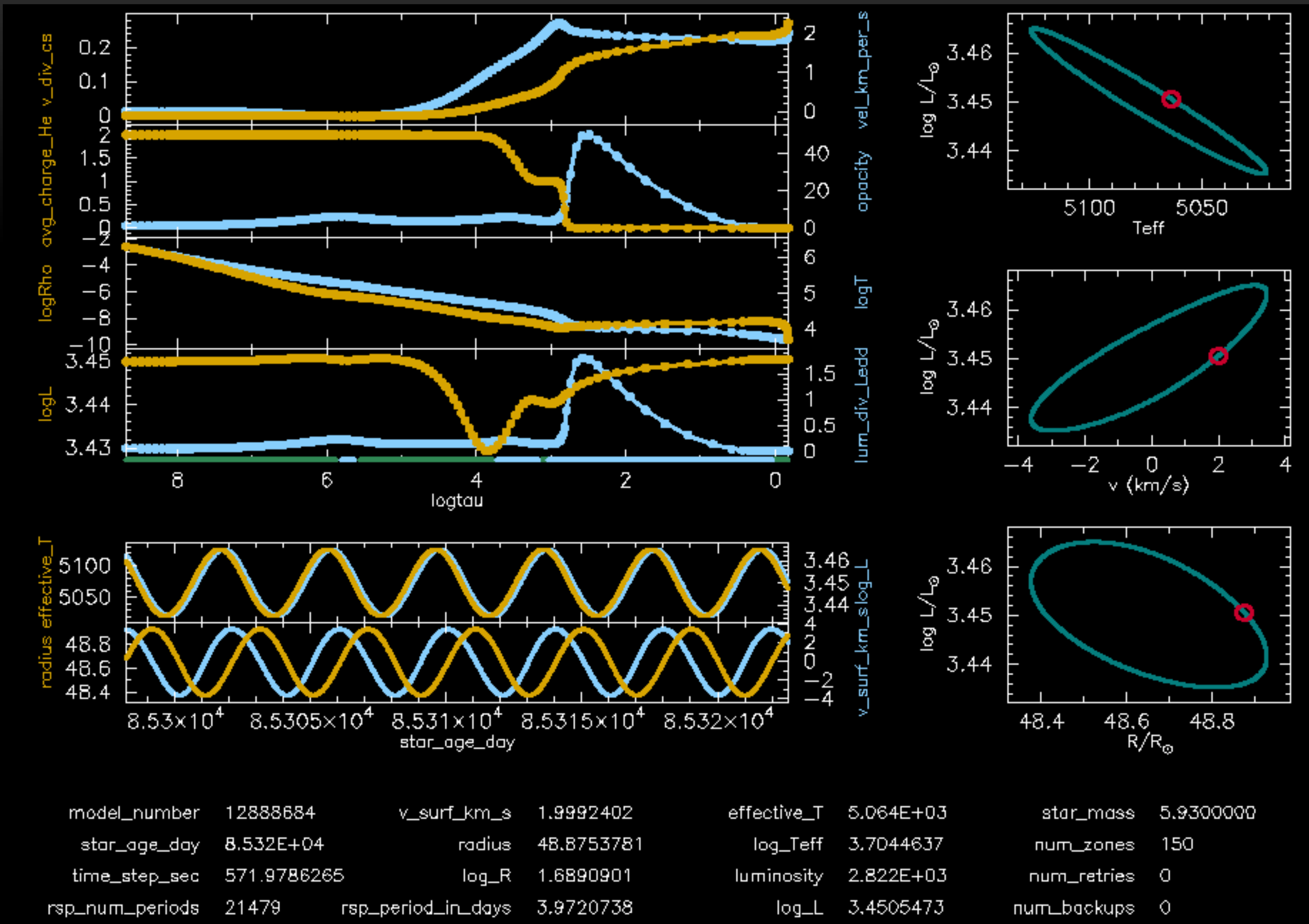


Figure 4. Phase curve of the original data phased to the best-fit period $P_1 =$ 3.97208 days. 1st Overtone Mode

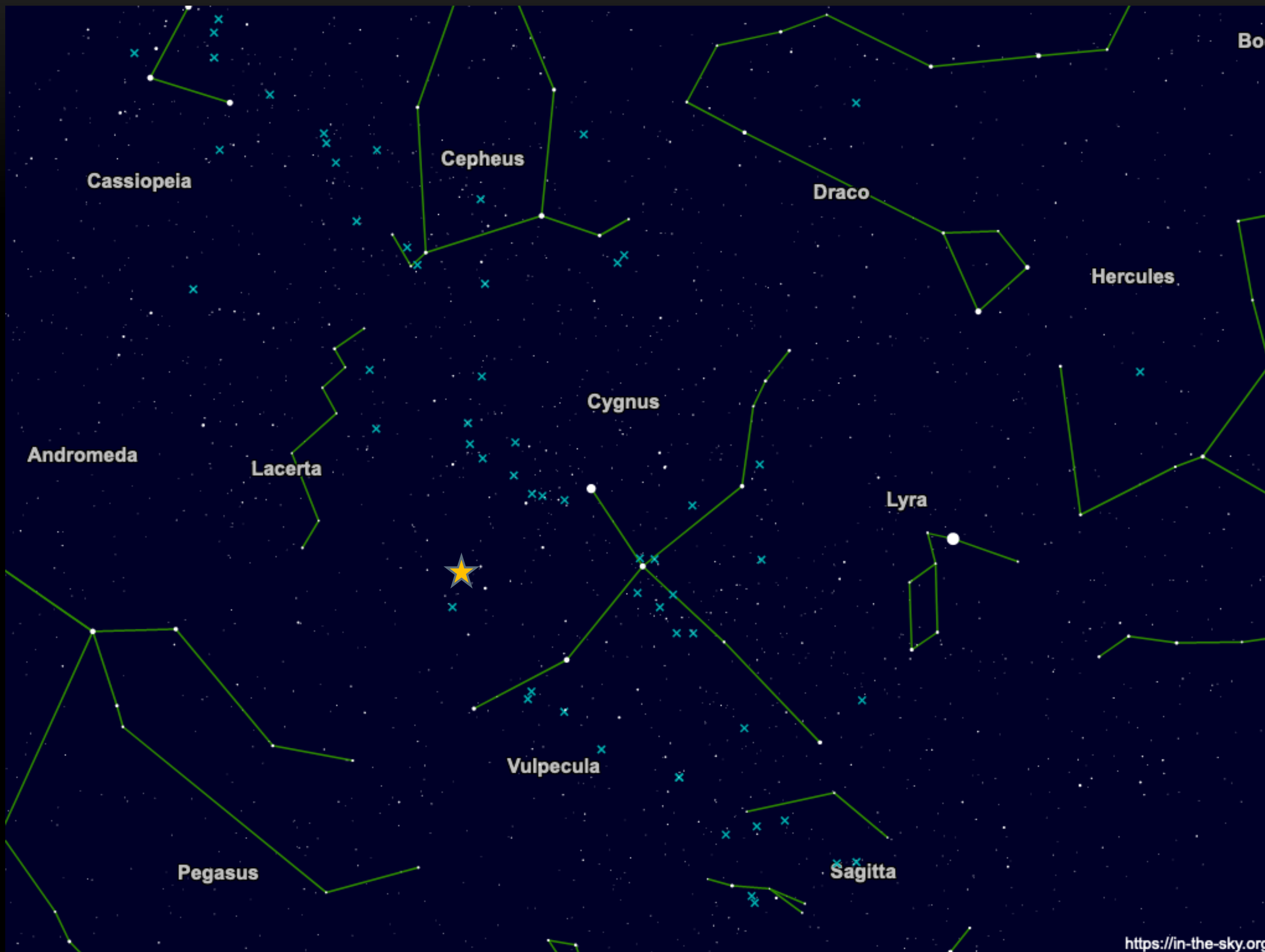
MESA RSP Polaris simulations initiated in 1st Overtone at 0.1 km/sec grow to > 3 km/sec



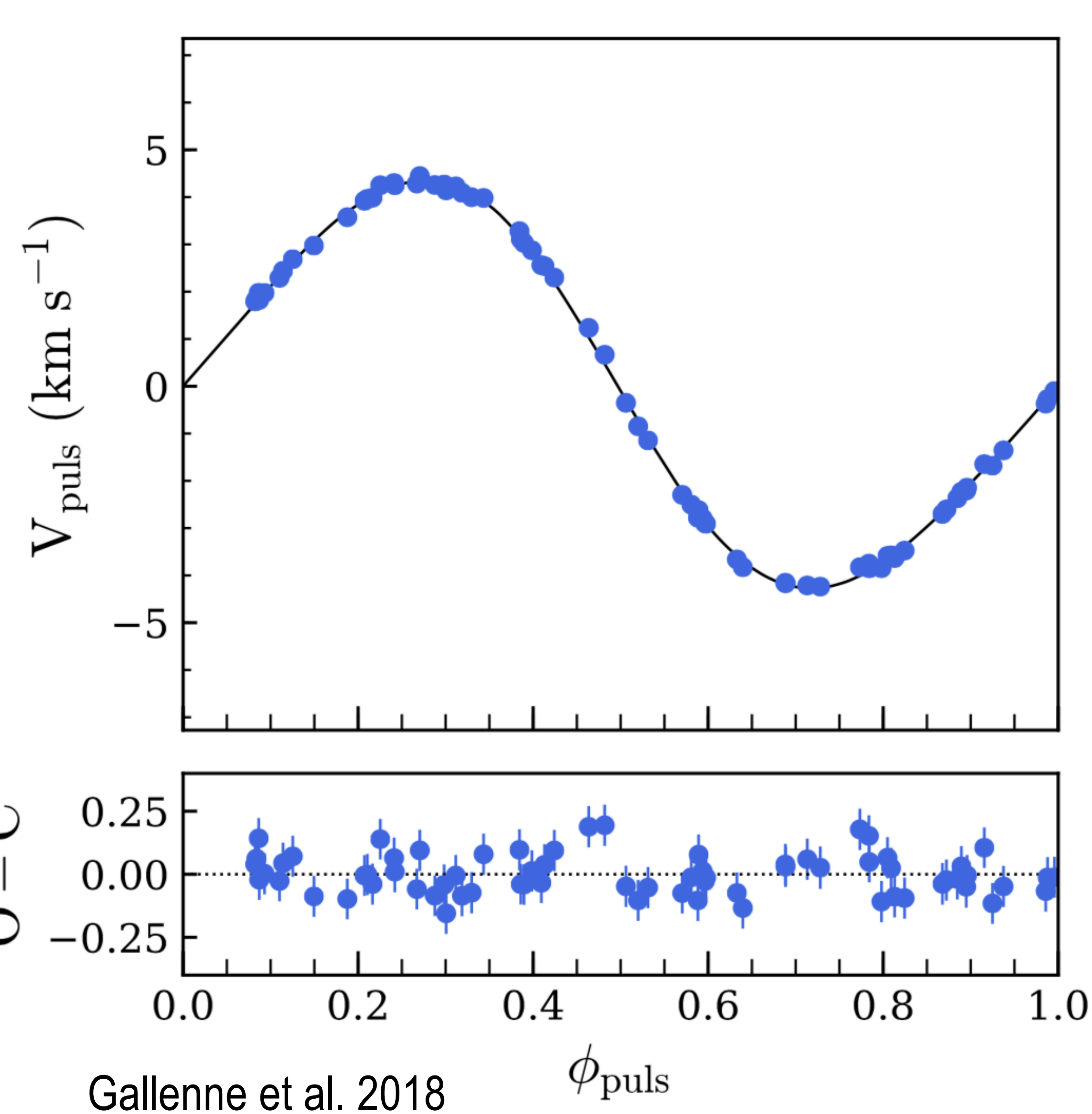
Polaris ‘dashboard’



V1334 Cyg (V=5.89 mag) pulsates with period 3.332 days

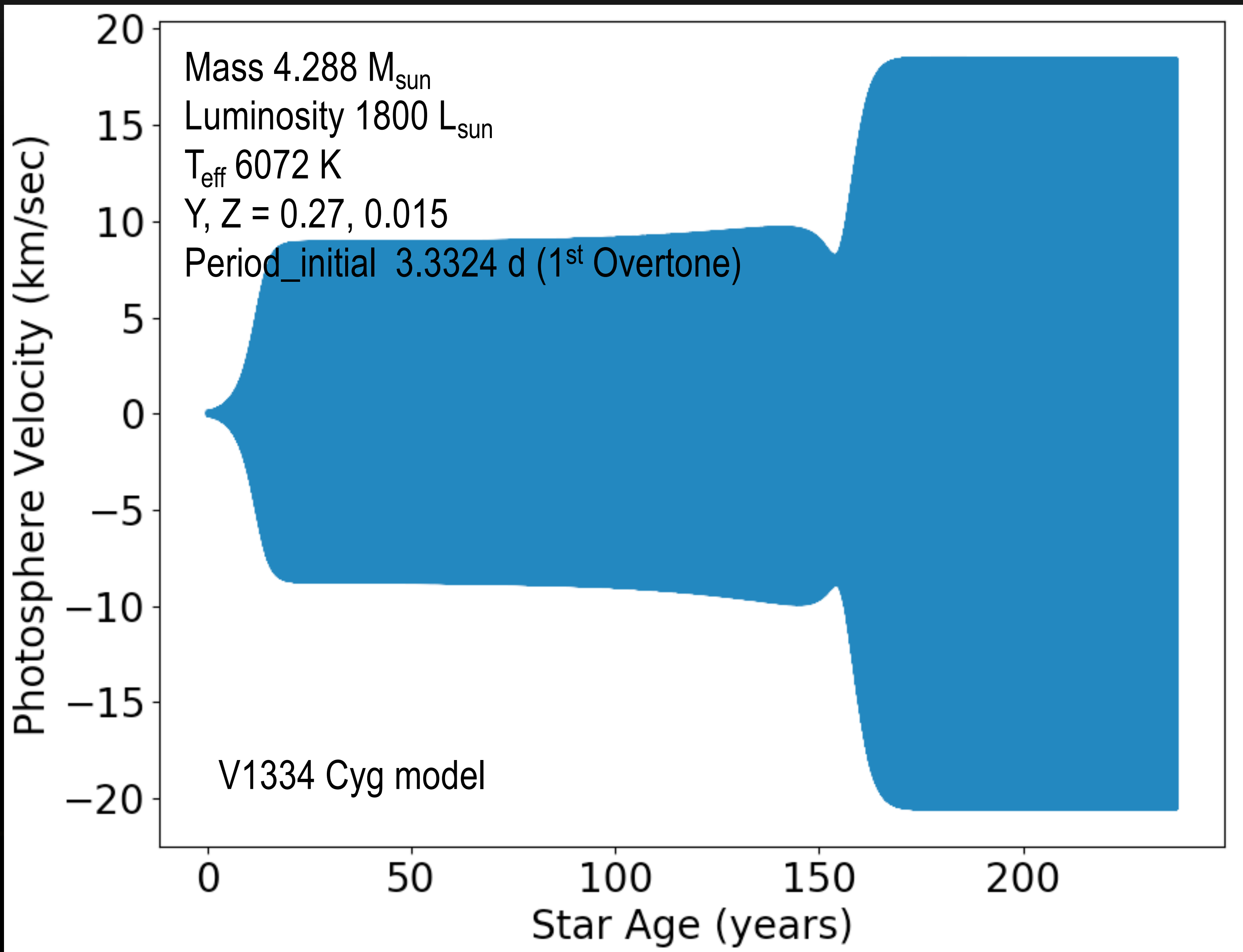


V1334 Cyg has a low radial velocity amplitude of about 5 km/sec (1st OT)

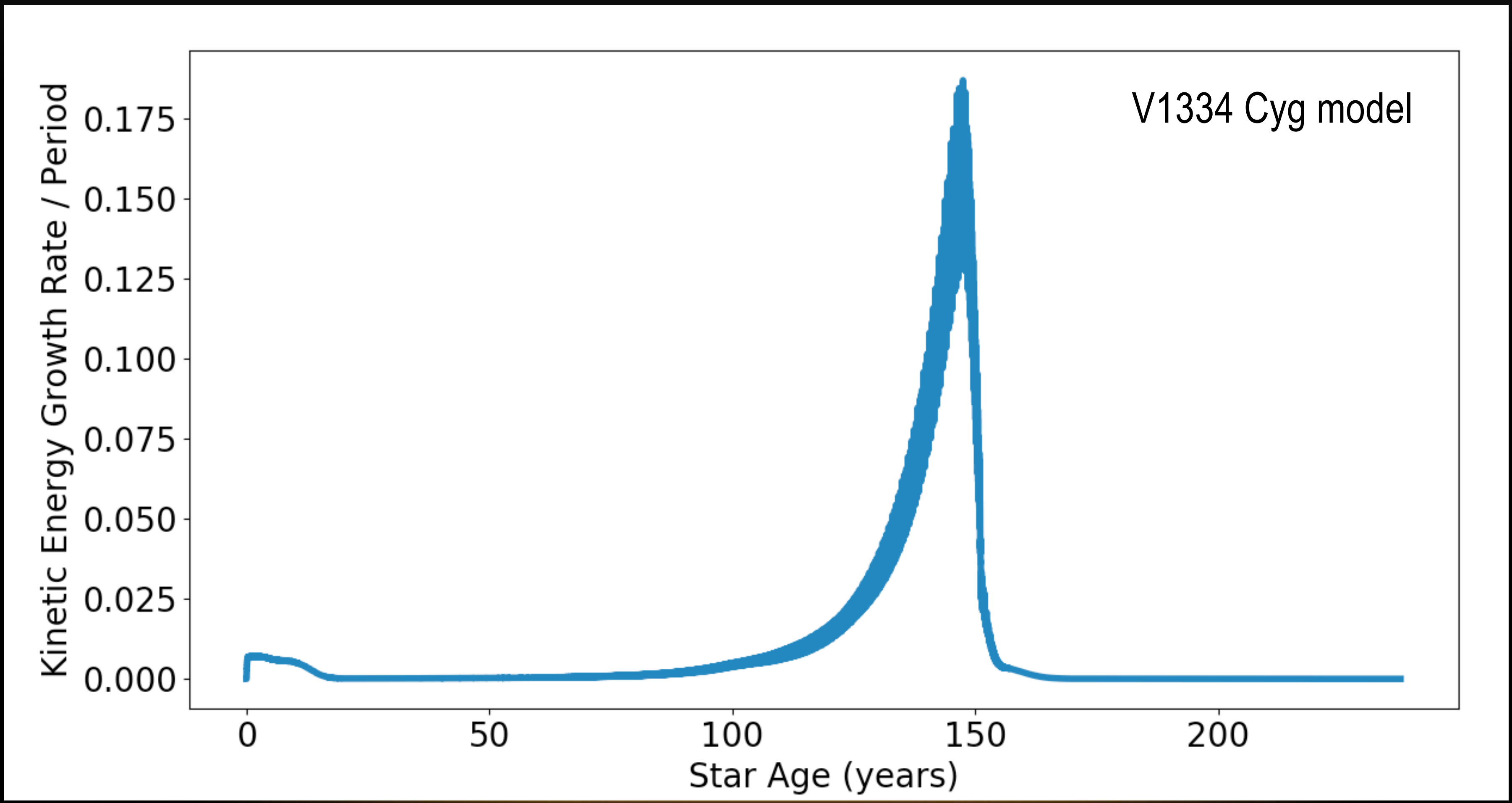


Gallenne et al. 2018

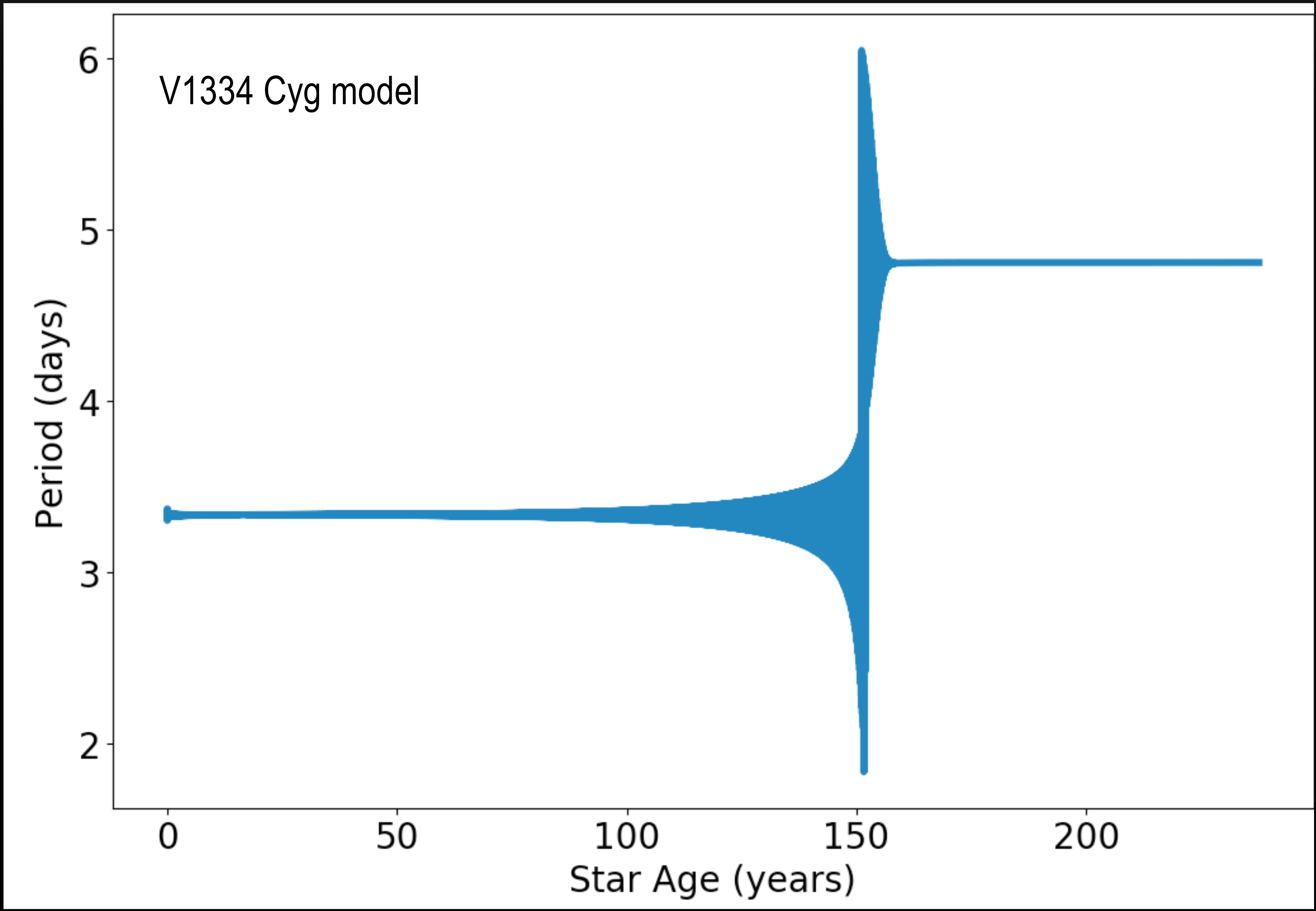
V1334 Cyg radial velocity initiated in 1st OT at 0.1 km/sec grows to nearly 10 km/sec, but then model switches to fundamental mode, with radial velocity amplitude 18 km/sec!



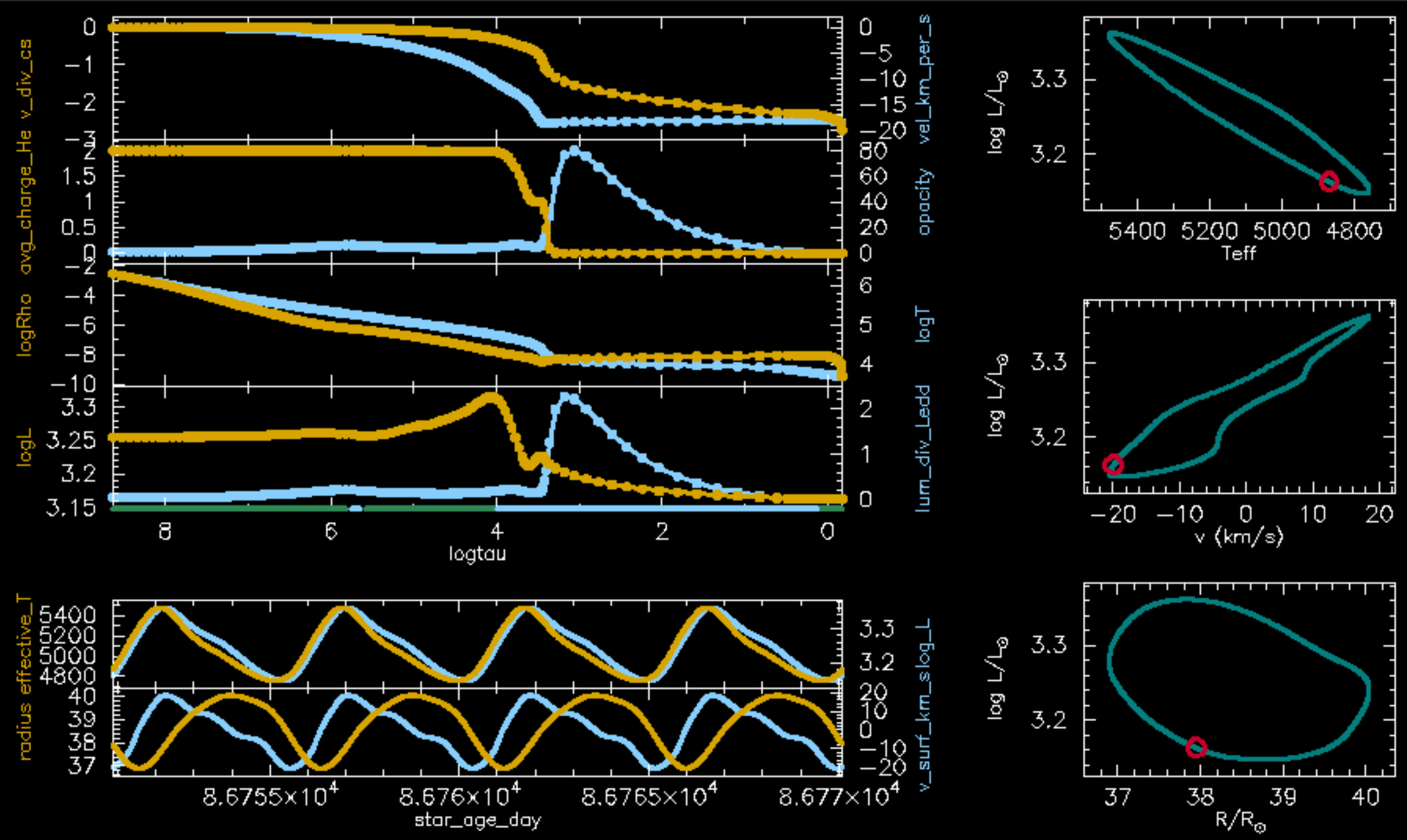
The kinetic energy growth rate begins to decrease as model settles into 1st OT mode, but then increases while model switches to F mode!



The pulsation period starts to converge to a 1st OT period, but then switches to fundamental mode!



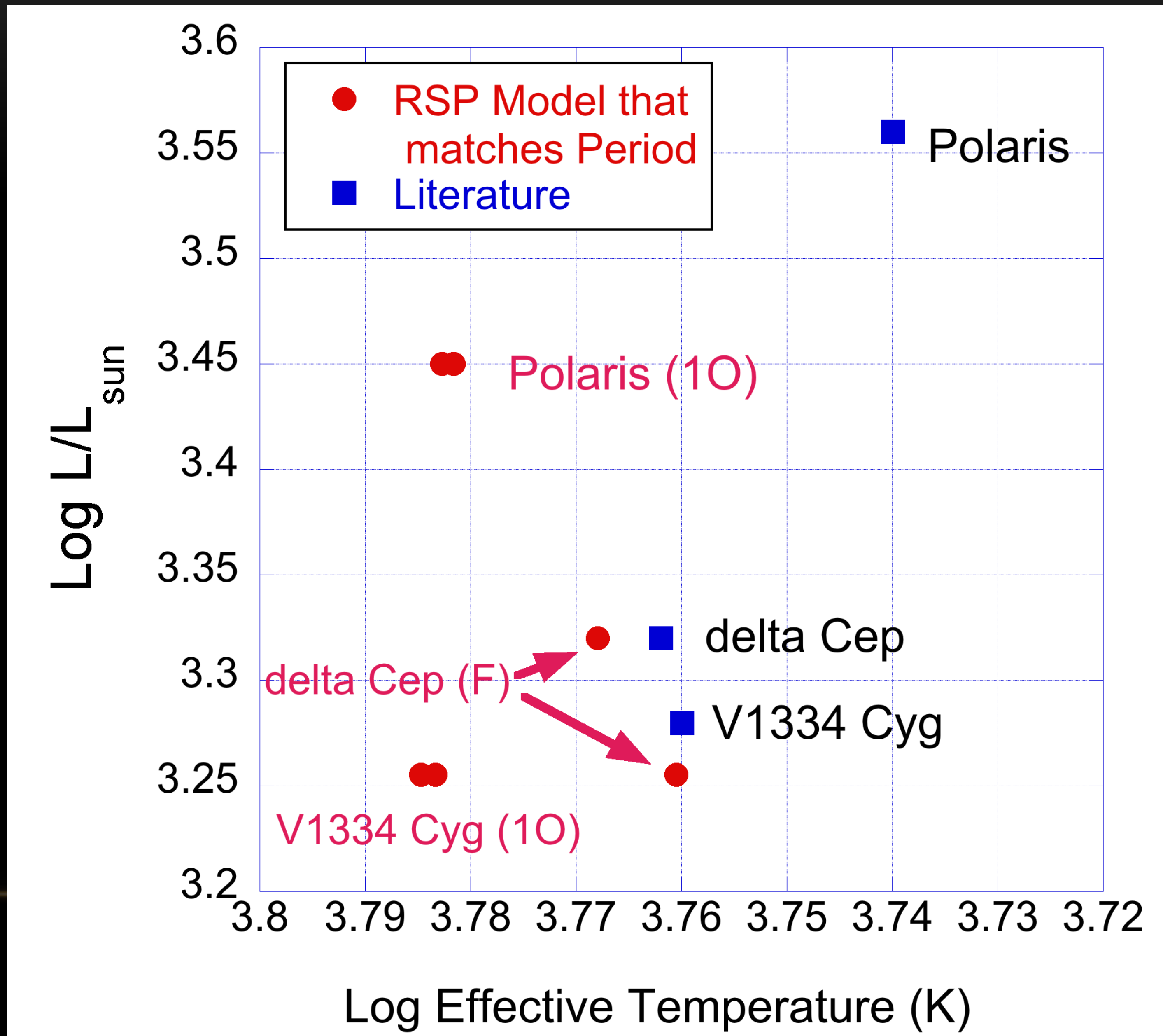
V1334 Cyg ‘dashboard’



model_number	14212620	v_surf_km_s	−19.9195368	effective_T	4.869E+03	star_mass	4.2880000
star_age_day	8.677E+04	radius	37.9474109	log_Teff	3.6874163	num_zones	150
time_step_sec	692.5085208	log_R	1.5791822	luminosity	1.454E+03	num_retries	0
rsp_num_periods	23132	rsp_period_in_days	4.8090869	log_L	3.1625419	num_backups	0

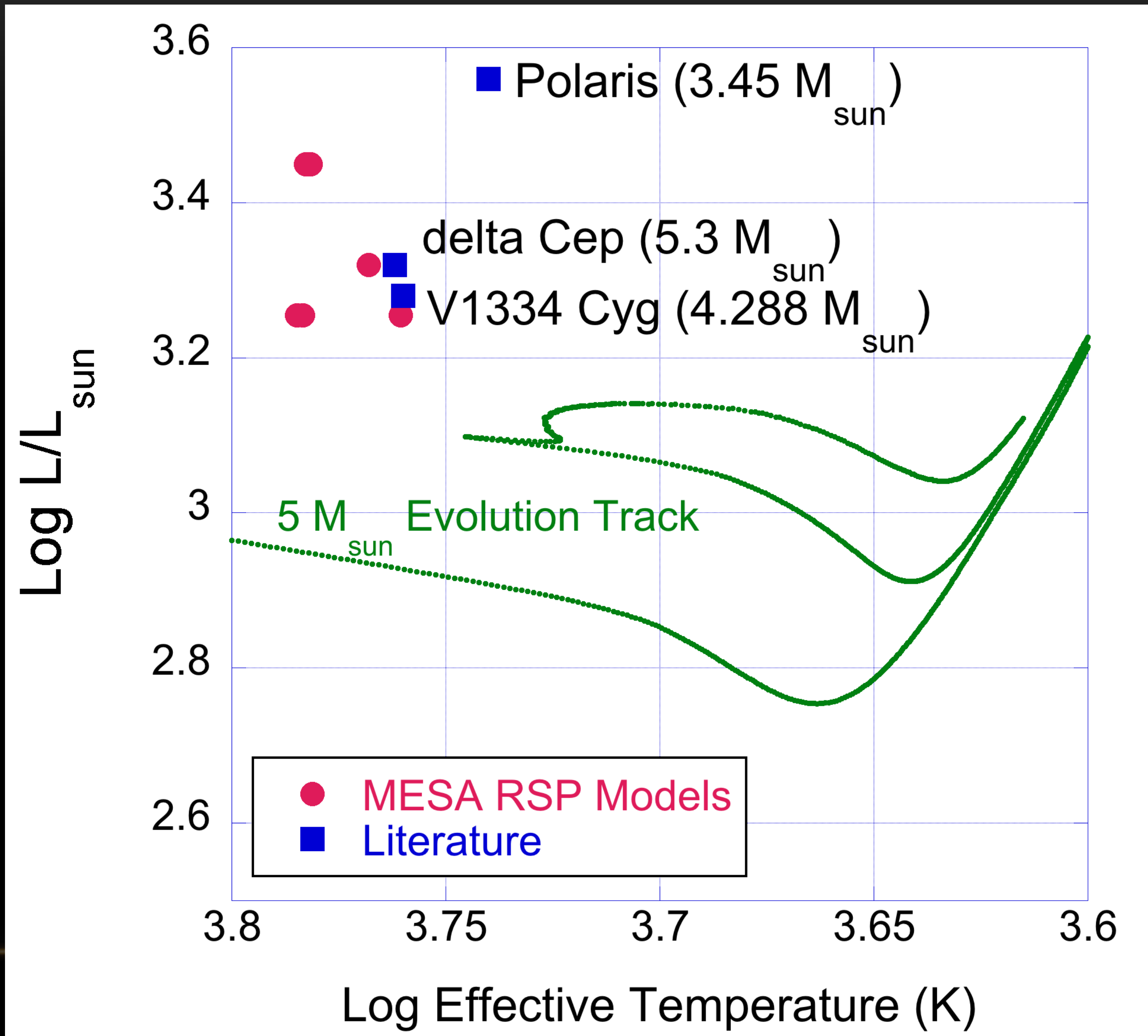
MESA RSP models that match pulsation periods usually are hotter and/or less luminous than literature values

Note: Polaris modeled with mass 5.93 M_{sun}



Models lie above MESA evolution track for 5 M_{sun}

Note: Polaris modeled with mass 5.93 M_{sun}



Conclusions

The MESA code is a useful tool to explore Cepheid evolution and pulsation modeling

- Open source, widely used, well supported
- Runs on desktop/laptops
- Documentation with tutorials and examples
- Allows changes in input physics to explore solutions to, e.g., Cepheid mass discrepancy
- New radial stellar pulsation capability to calculate nonlinear hydrodynamic envelope models

MESA RSP was used to model Galactic Cepheids Polaris, delta Cep, and V1334 Cyg

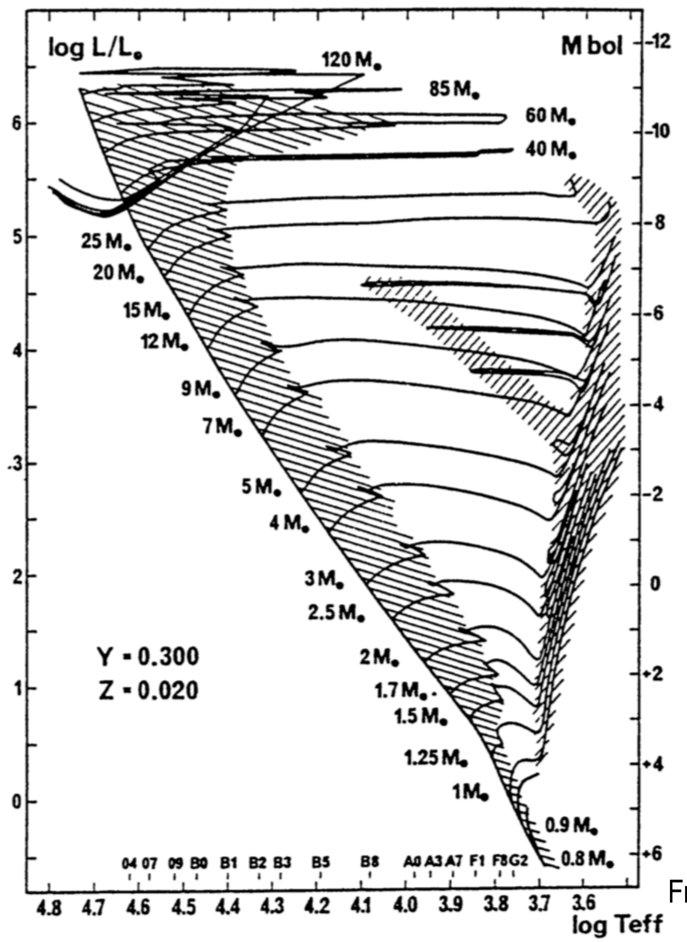
- Limiting radial velocity amplitudes of these first RSP models agree well with observed amplitudes
- RSP models that match observed pulsation periods have higher effective temperature and/or lower luminosity than observed values
- The Polaris and V1334 Cyg RSP models with periods matching observations have positions in the H-R diagram above a 5 solar mass evolution track, inconsistent with their dynamical masses

Backup slides follow

Cepheid Evolution

Stars of 5-15 M_{sun} can 'blue loop' to hotter temperatures after crossing to the red giant branch

During the 'blue loop' they spend a significant fraction of their lifetime in the core helium burning phase before evolving to the red to become asymptotic giant branch stars



From Simon 1994

Fig. 6. Geneva tracks for Z = 0.02, reproduced from Schaller et al. (1992). Crosshatched regions indicate "slow" phases of nuclear burning.

Pulsation masses of Milky Way Galactic Cepheids are lower than evolution masses

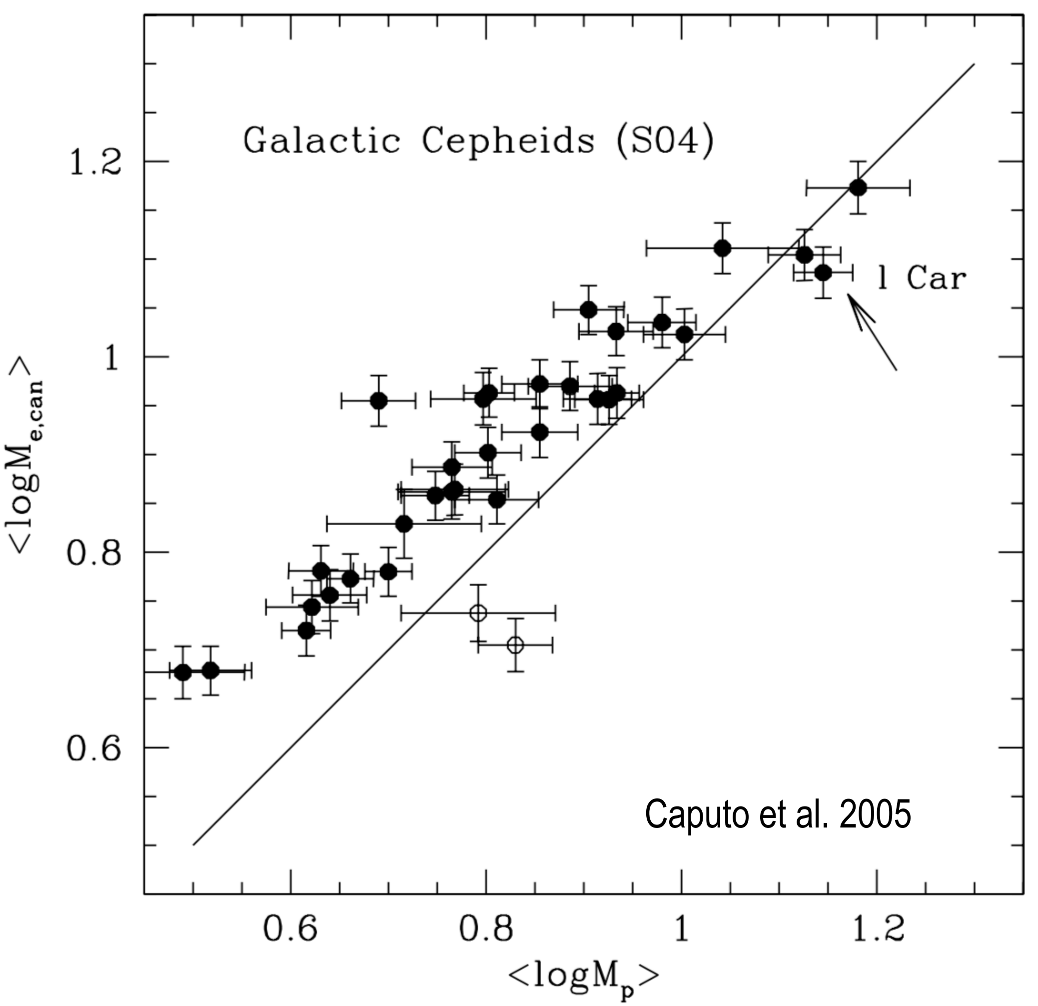


FIG. 8.—Mean pulsation mass of Galactic Cepheids vs. the mean canonical evolutionary one. Open circles mark the short-period Cepheids SU Cas and EV Sct, while the small arrow marks the long-period variable l Car.

Evolution Models and Cepheid Pulsation Instability Regions

Cepheid luminosities, extent of ‘blue loops’, and calculated instability region edges depend on element abundances and input physics of evolution and pulsation models

- Overshoot
- Mass loss
- Rotation
- Opacities
- Nuclear reaction rates