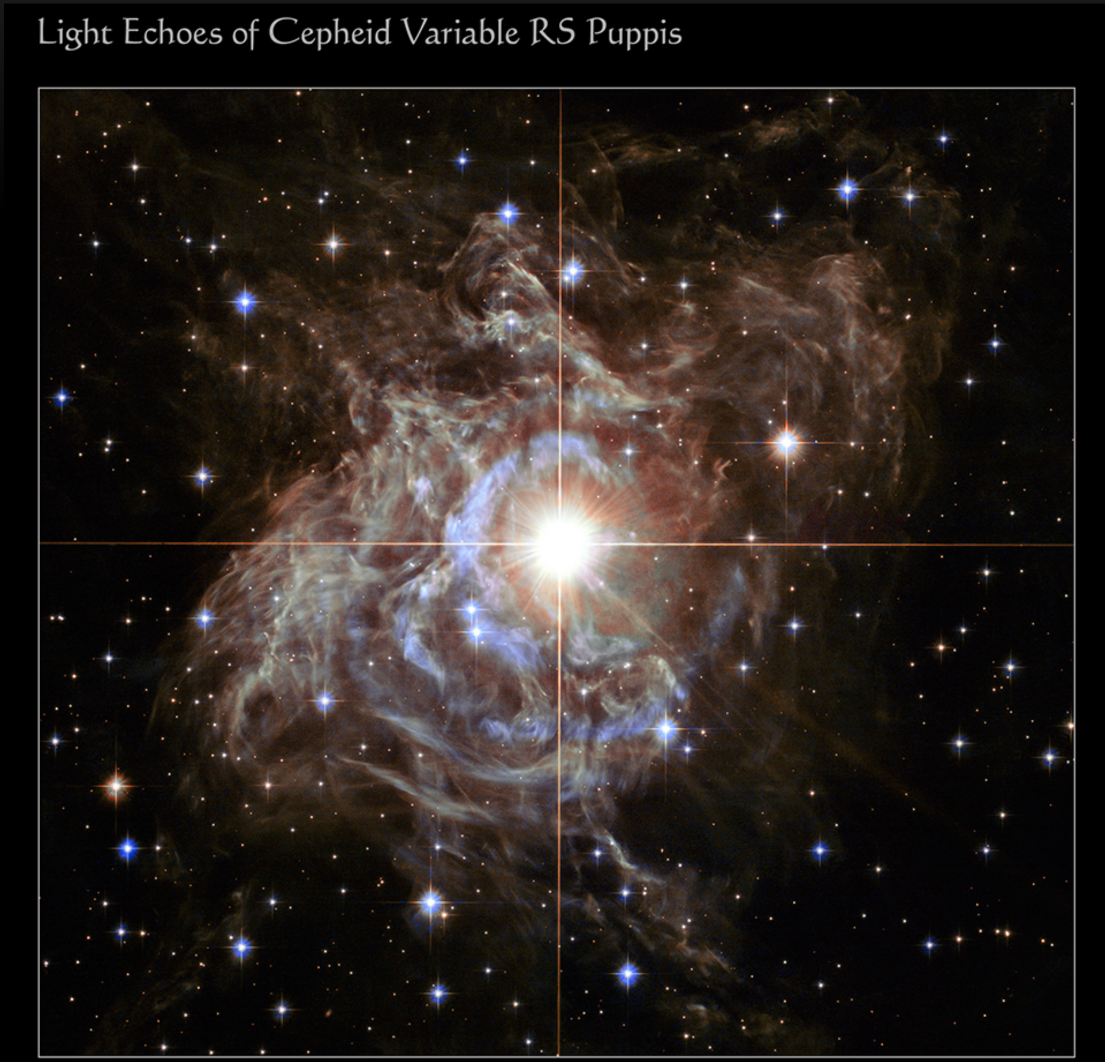
# Modeling Pulsations of Cepheid Variables using the Open-Source MESA Code




NASA, ESA, and the Hubble Heritage Team (STScI/AURA)-Hubble/Europe Collaboration. Acknowledgment: H. Bond (STScI and Penn State University)

*Joyce Ann Guzik*

*E. Farag, J. Ostrowski, N.R. Evans, H. Neilson, S. Moschou, and J.J. Drake*

*35th Annual New Mexico Symposium*

*February 21, 2020*

# What are (classical) Cepheids?

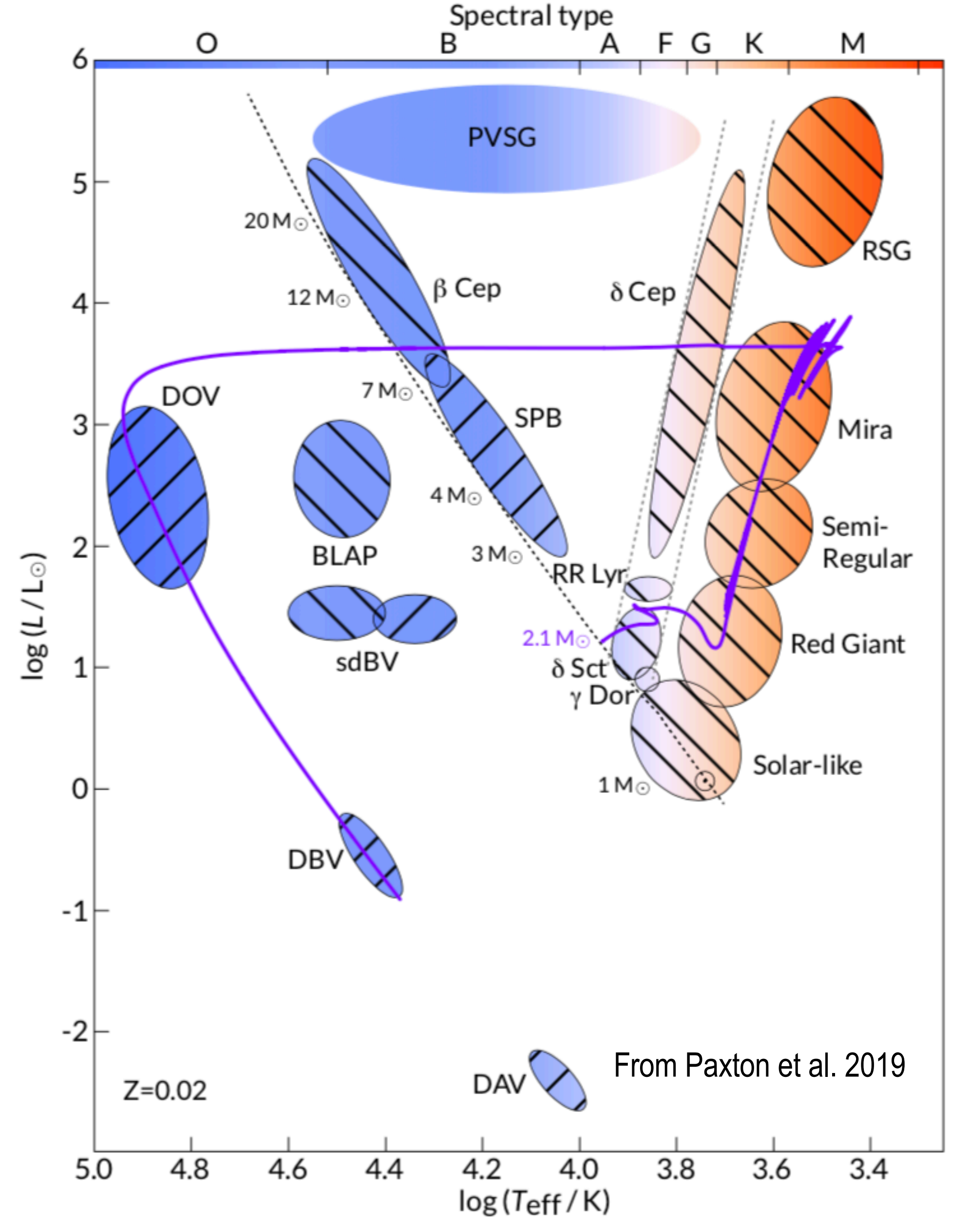
- Pulsating variable stars
- Prototype δ Cep discovered 1784 (J. Goodricke)

- 4 to 15 x mass of Sun
- Fusing helium to carbon and oxygen in cores

- 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 2$^{nd}$ overtone (rare) pulsations




From Paxton et al. 2019

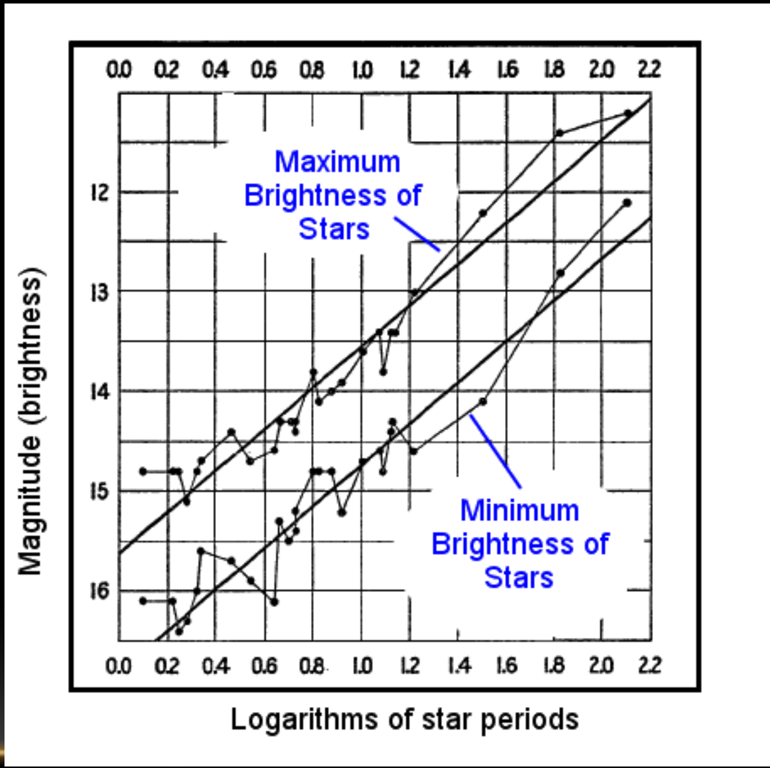
# Why are Cepheids important?

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

  *Determine Hubble Constant*

- "Laboratory" to test stellar physics

  *Cepheid mass discrepancy*



# The Cepheid period-luminosity relation must be calibrated by using Cepheids with known distances

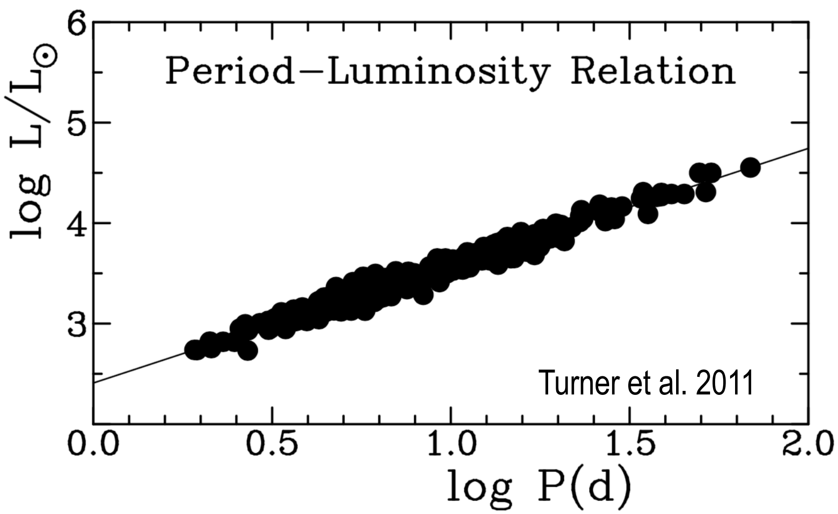



Fig. 3.— The period-luminosity relation defined by Cepheids of well-established reddening.

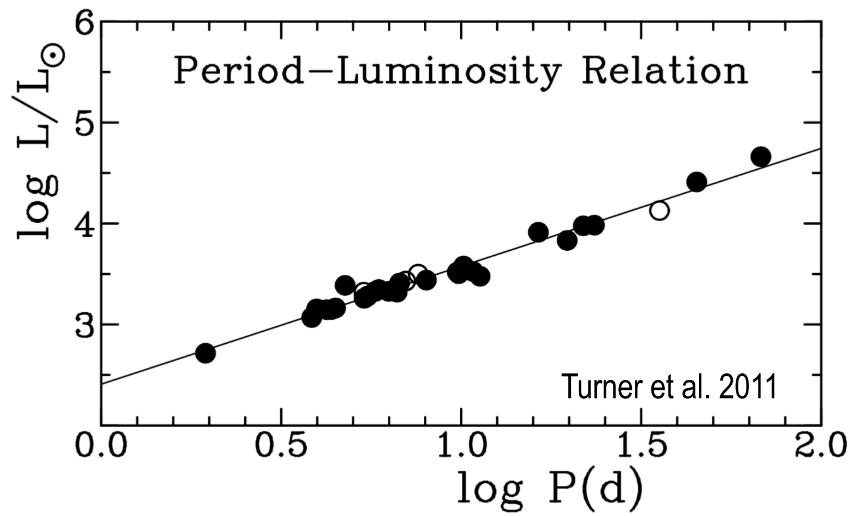
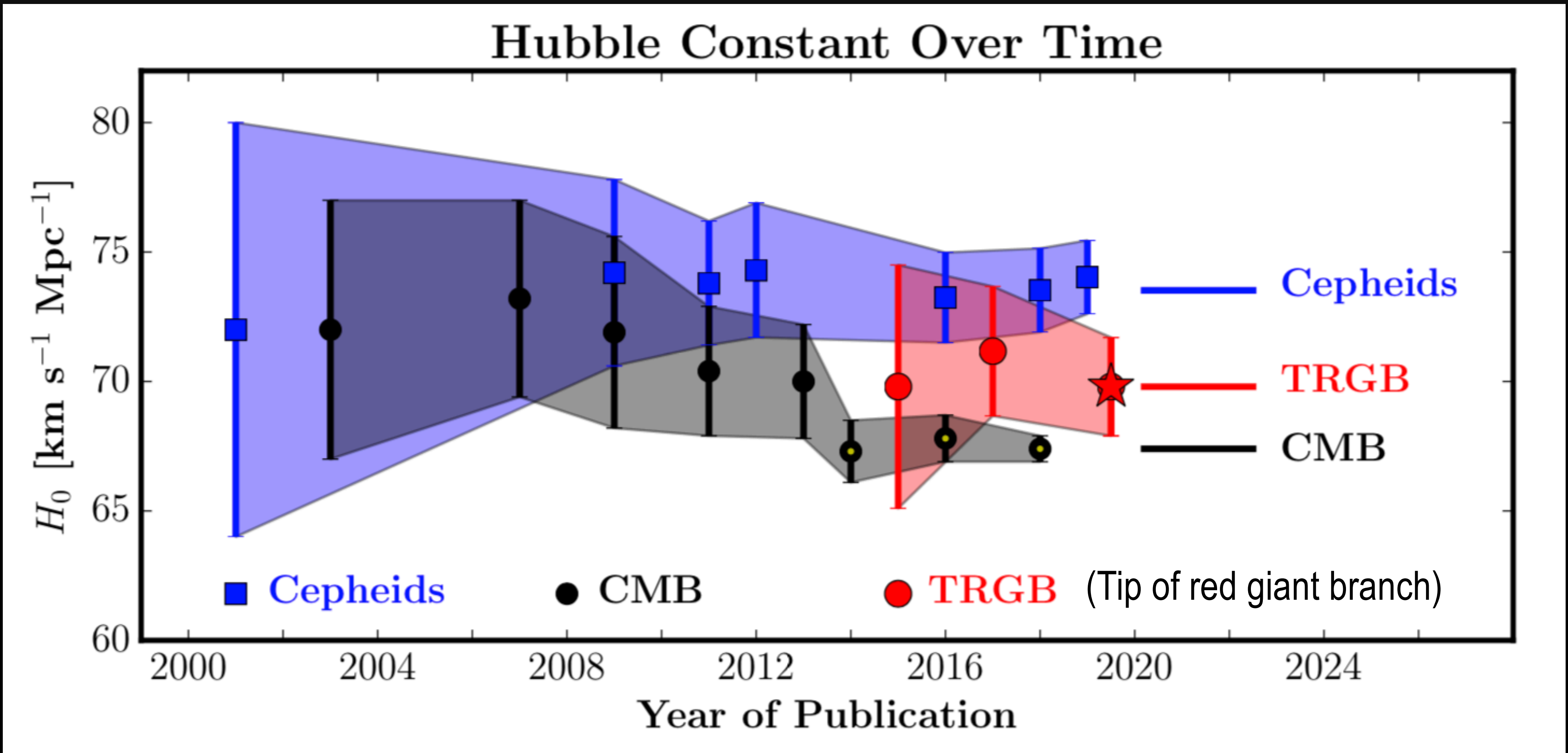



Fig. 4.— The period-luminosity relation defined by cluster (filled circles) and HST parallax (open circles) Cepheids.

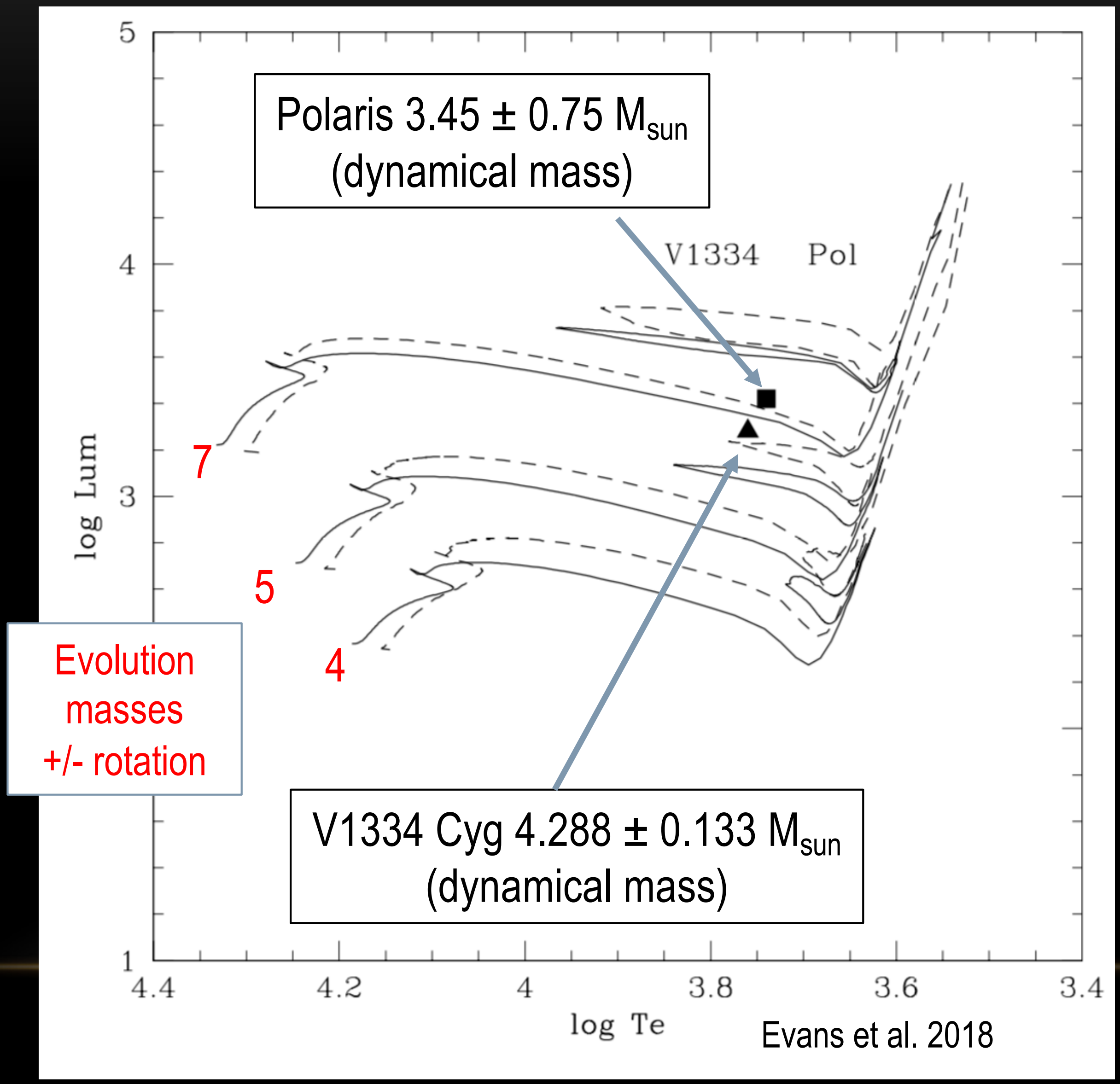
The slope and intercept of the straight-line fit are uncertain

# 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 orbit dynamics are lower than evolution model masses



# The Open Source MESA code was used to model Cepheid evolution and pulsation

- 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

**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?

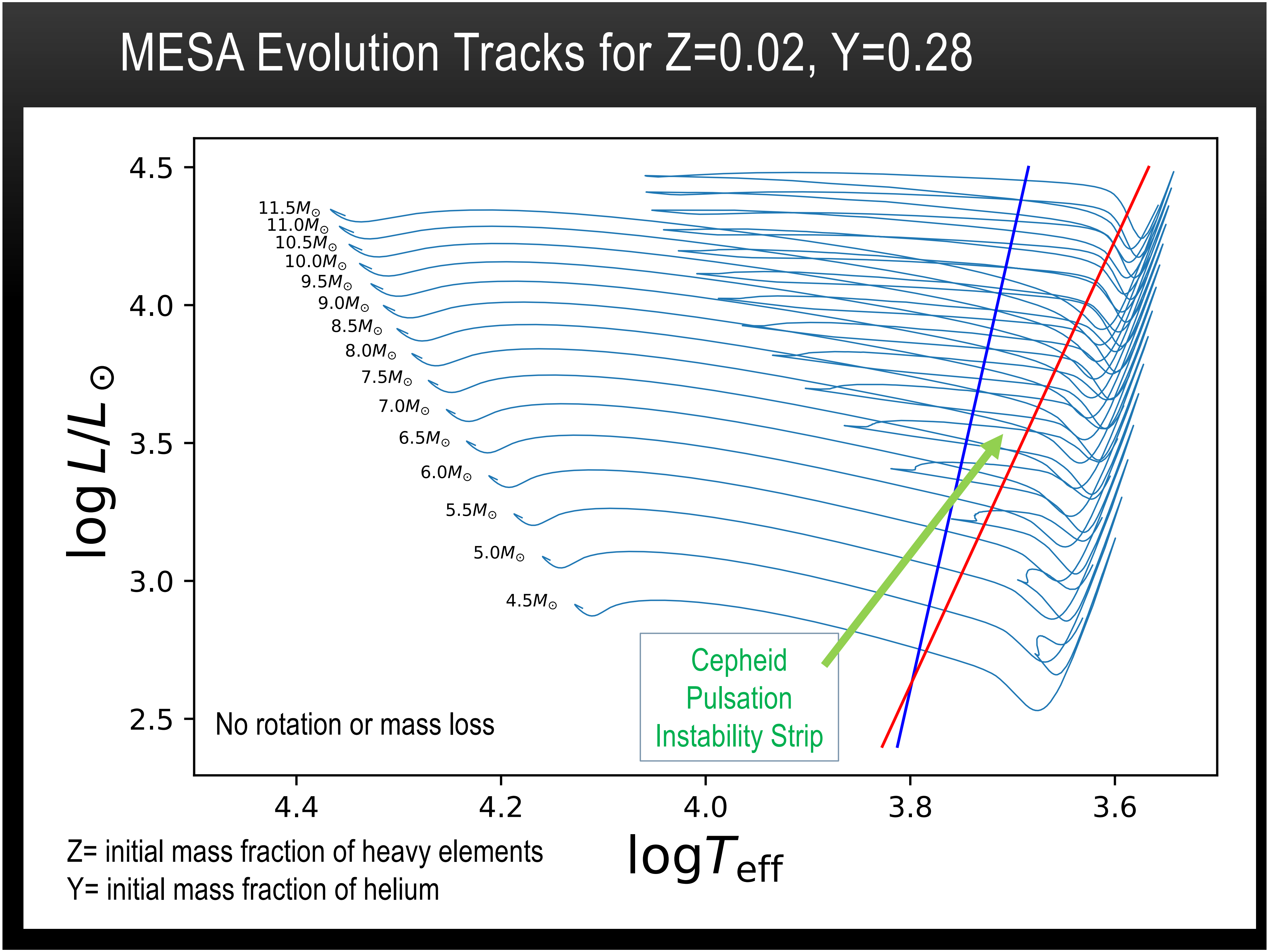
The MESA Manifesto discusses the motivation for the MESA project, outlines a MESA code of conduct, and describes the establishment of a MESA Council. Before using MESA, you should read the **manifesto document**. Here's a brief extract of some of the key points

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.

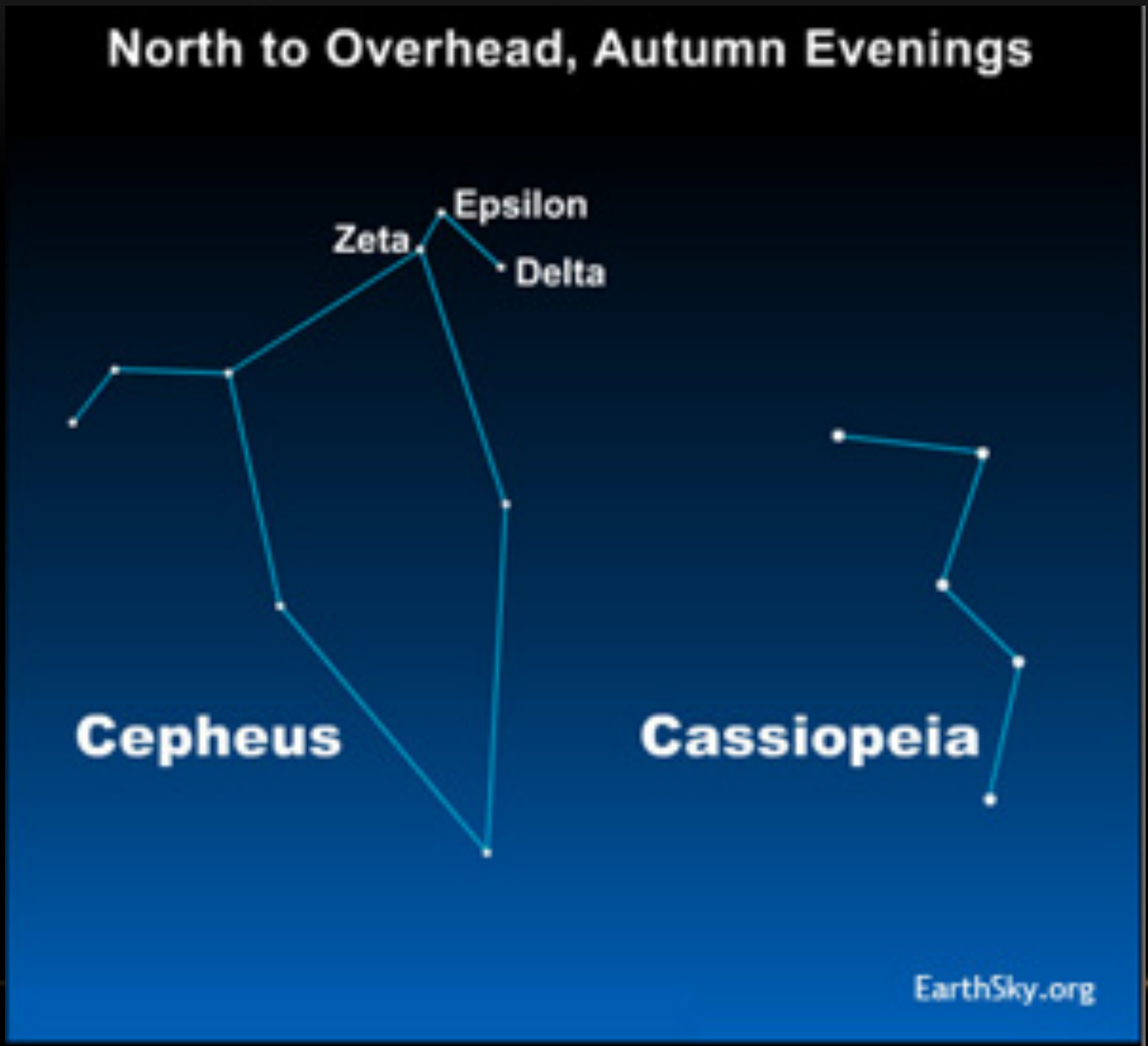
### Latest News

- 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**



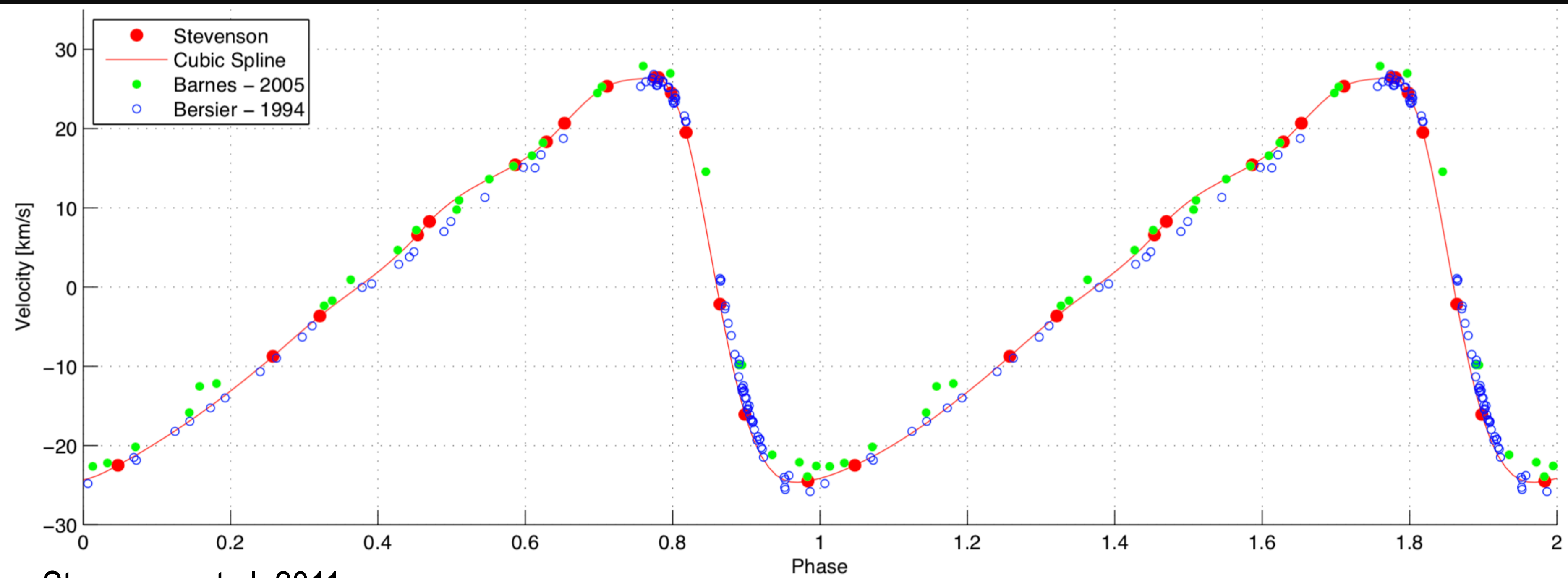
MESA Evolution Tracks for Z=0.02, Y=0.28
log $L/L_\odot$
4.5
4.0
3.5
3.0
2.5
$11.5M_\odot$
$11.0M_\odot$
$10.5M_\odot$
$10.0M_\odot$
$9.5M_\odot$
$9.0M_\odot$
$8.5M_\odot$
$8.0M_\odot$
$7.5M_\odot$
$7.0M_\odot$
$6.5M_\odot$
$6.0M_\odot$
$5.5M_\odot$
$5.0M_\odot$
$4.5M_\odot$
No rotation or mass loss
Cepheid
Pulsation
Instability Strip
4.4
4.2
4.0
3.8
3.6
log $T_{eff}$
Z= initial mass fraction of heavy elements
Y= initial mass fraction of helium

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




By Cepheus_constellation_map.png: Torsten Bronger. Cepheus_constellation_map.png, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=10827910

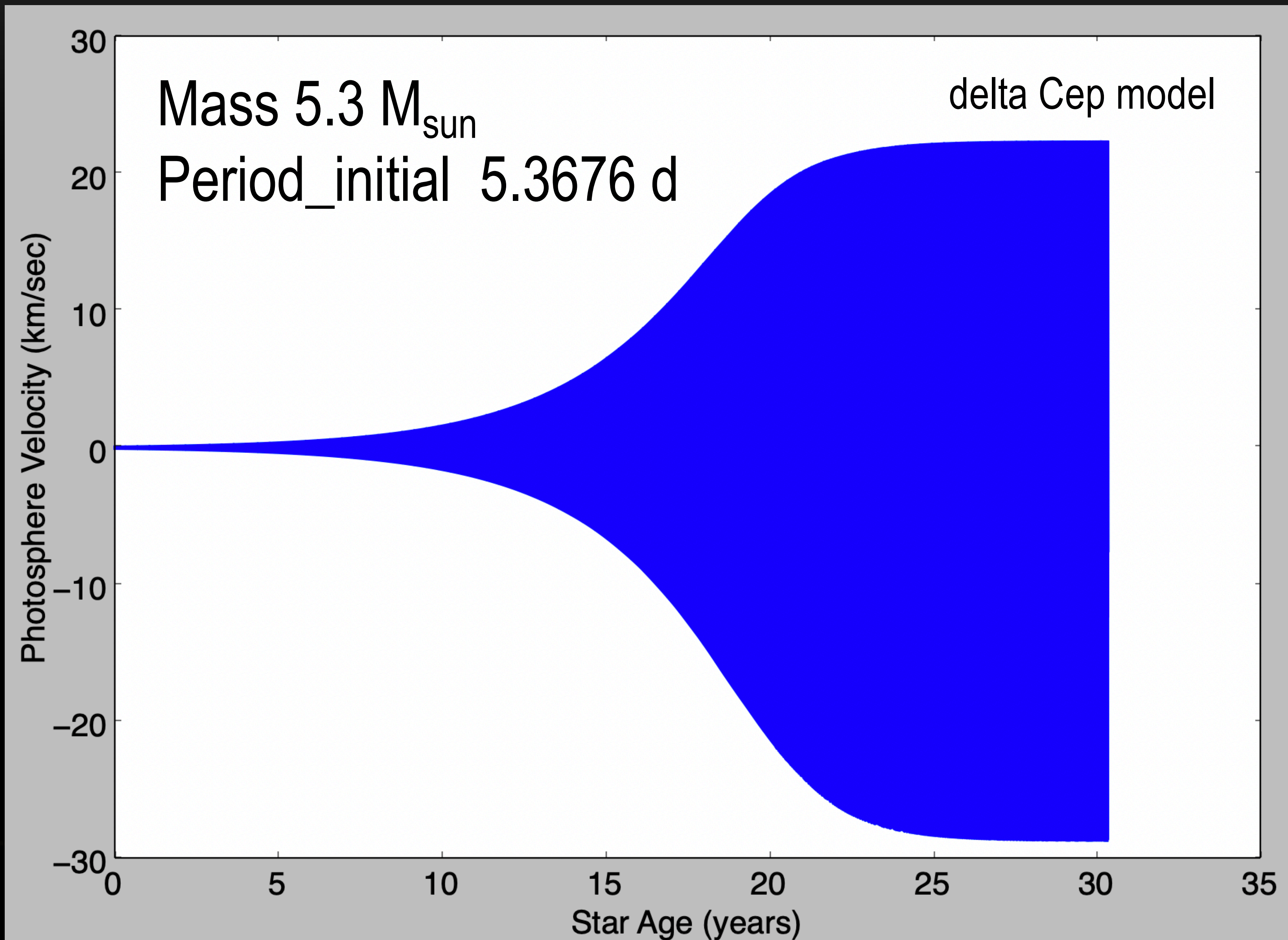
# The radial velocity curve of delta Cep has a ‘sawtooth’ shape with amplitude > 20 km/sec (45,000 miles/hour)



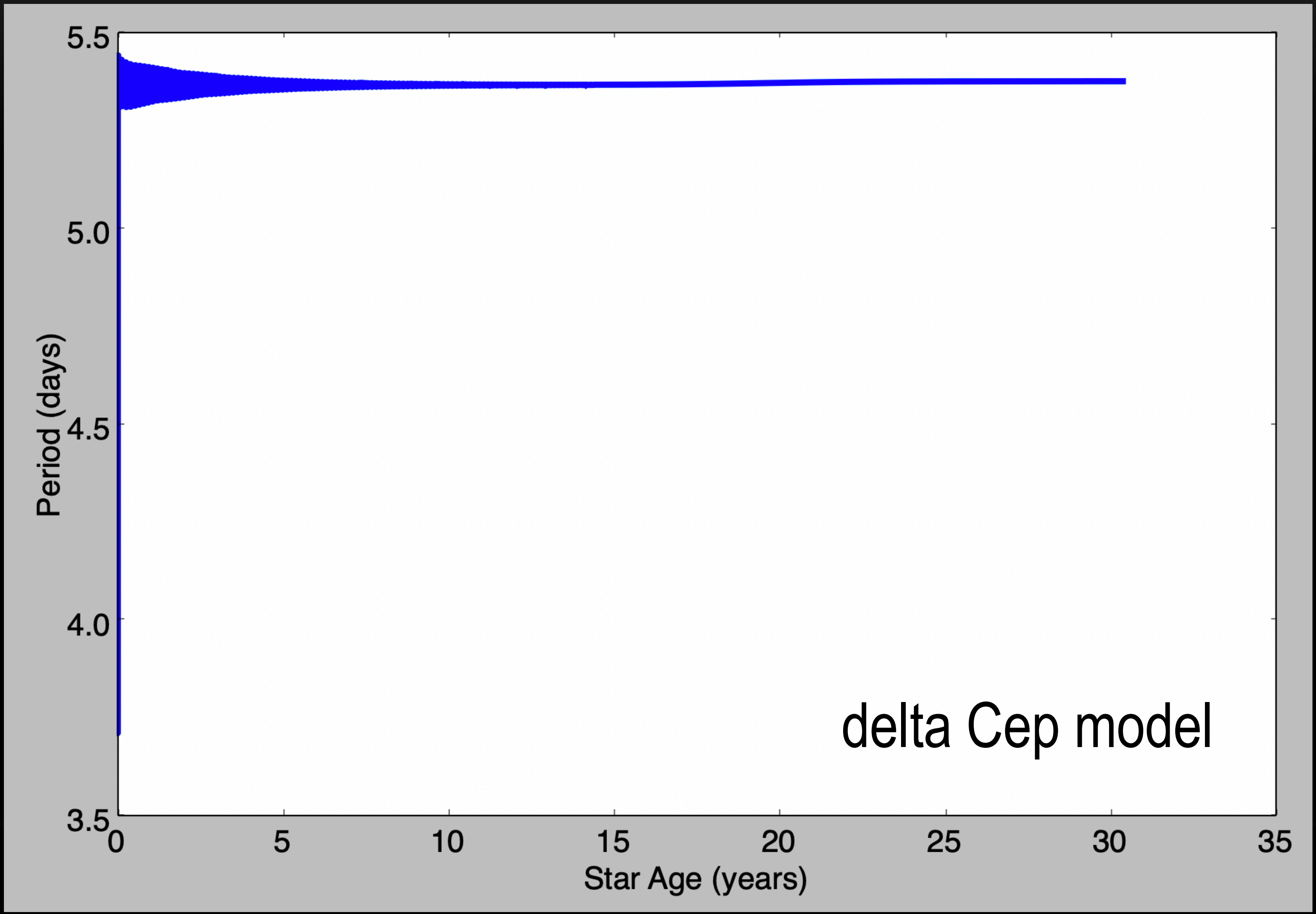

Stevenson et al. 2011

Period 5.3662 days, Radial fundamental mode

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

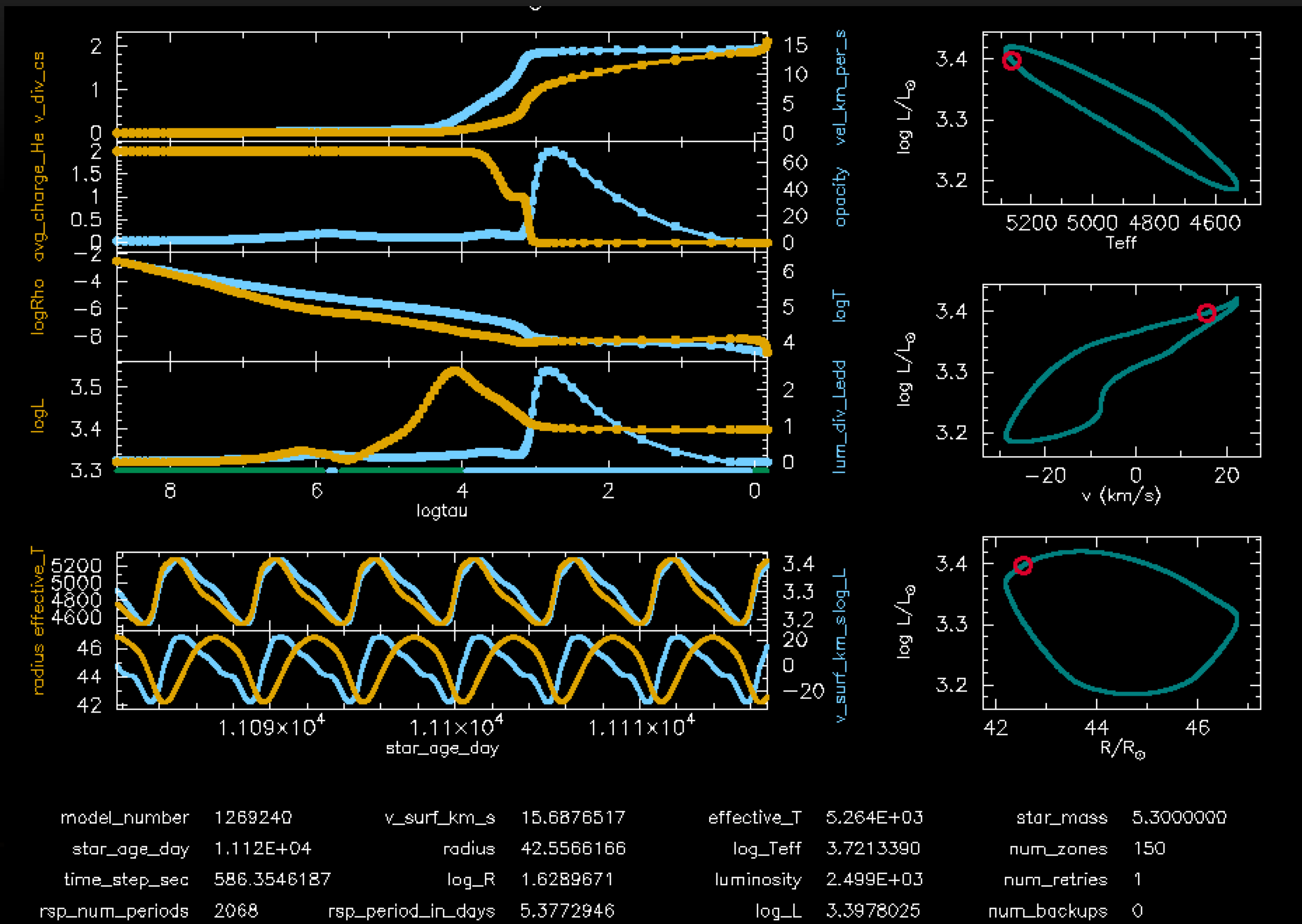


# The pulsation period oscillates before reaching a constant value

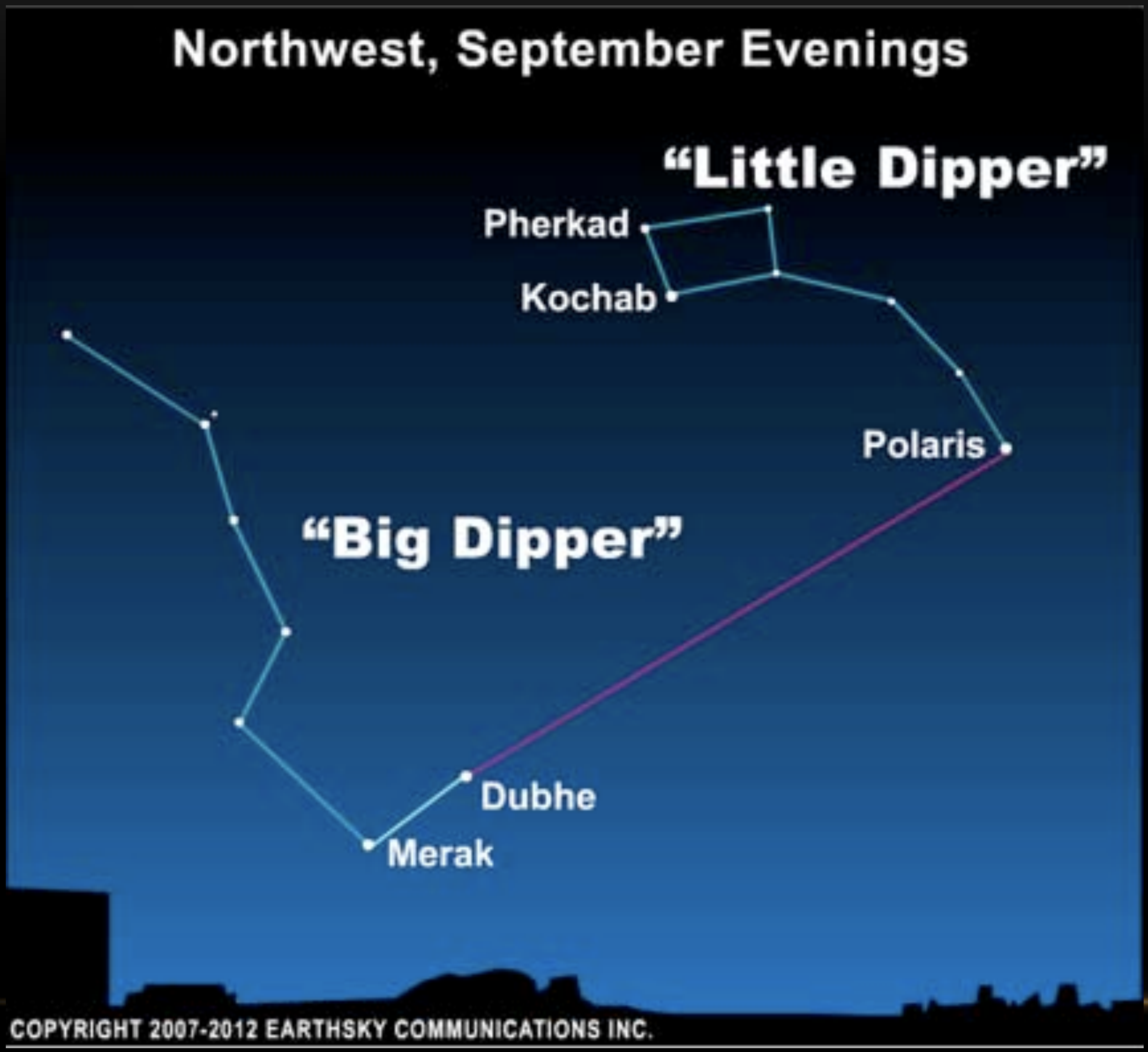


# A ‘dashboard’ shows pulsation properties during the simulation

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

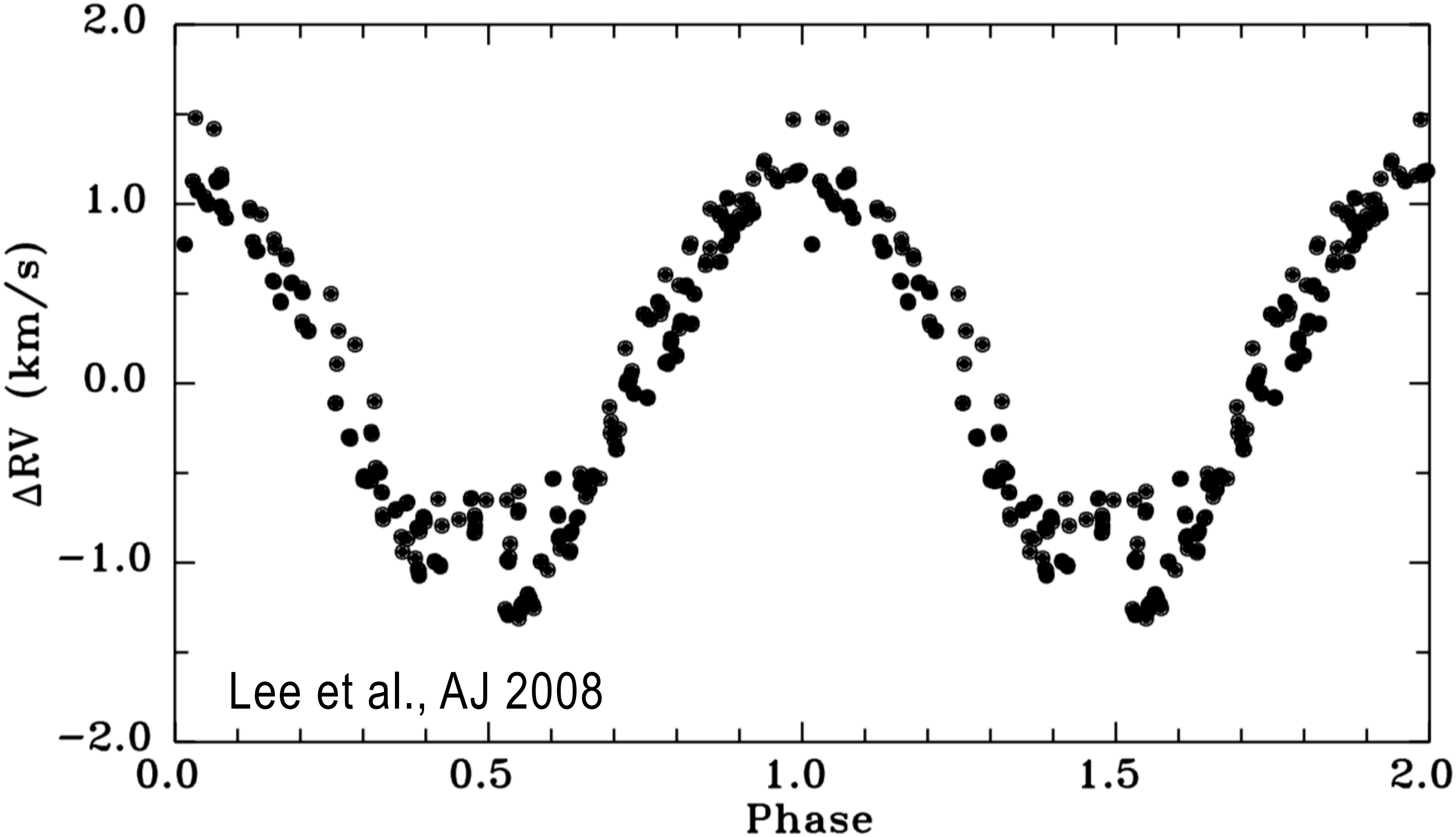
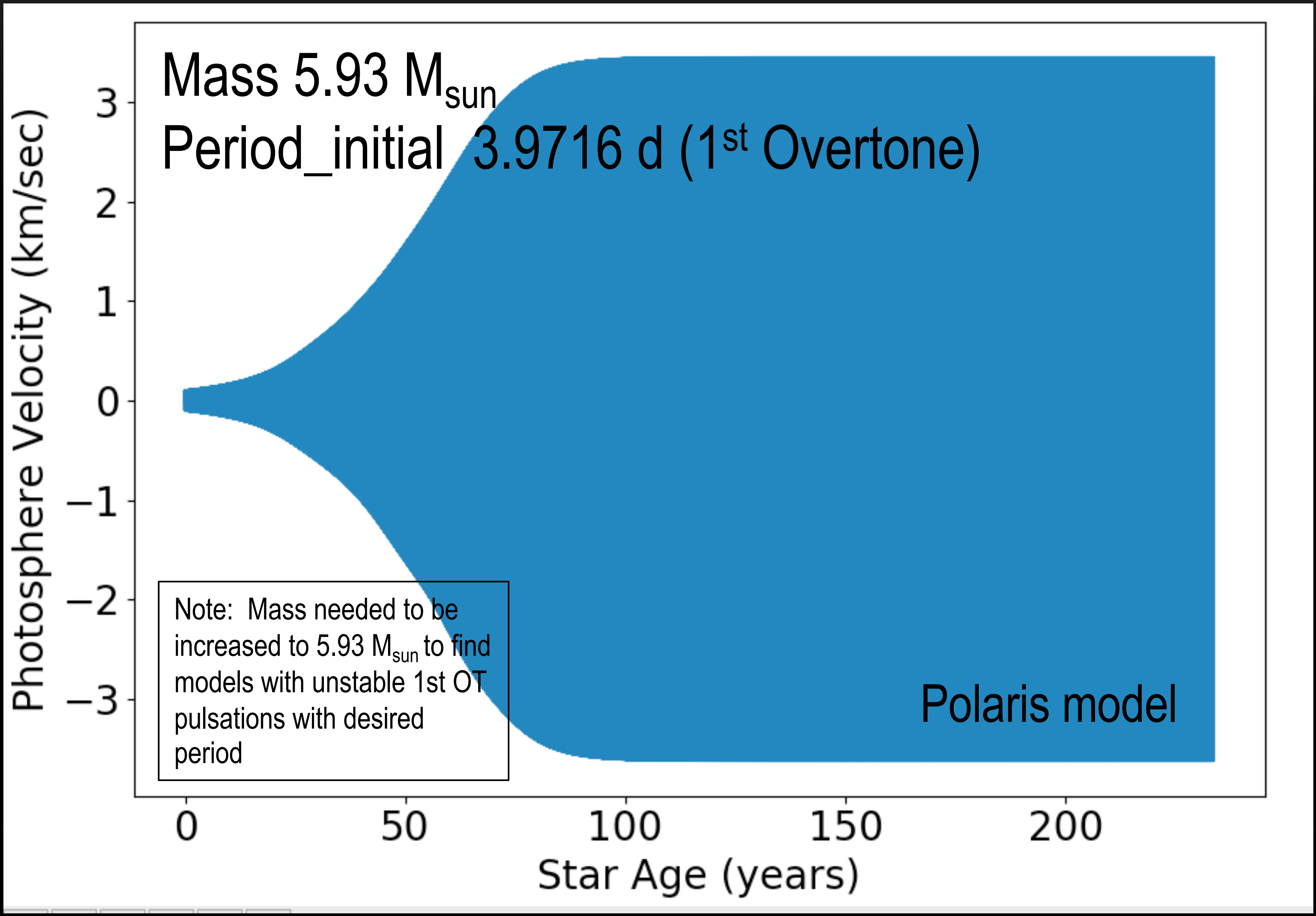
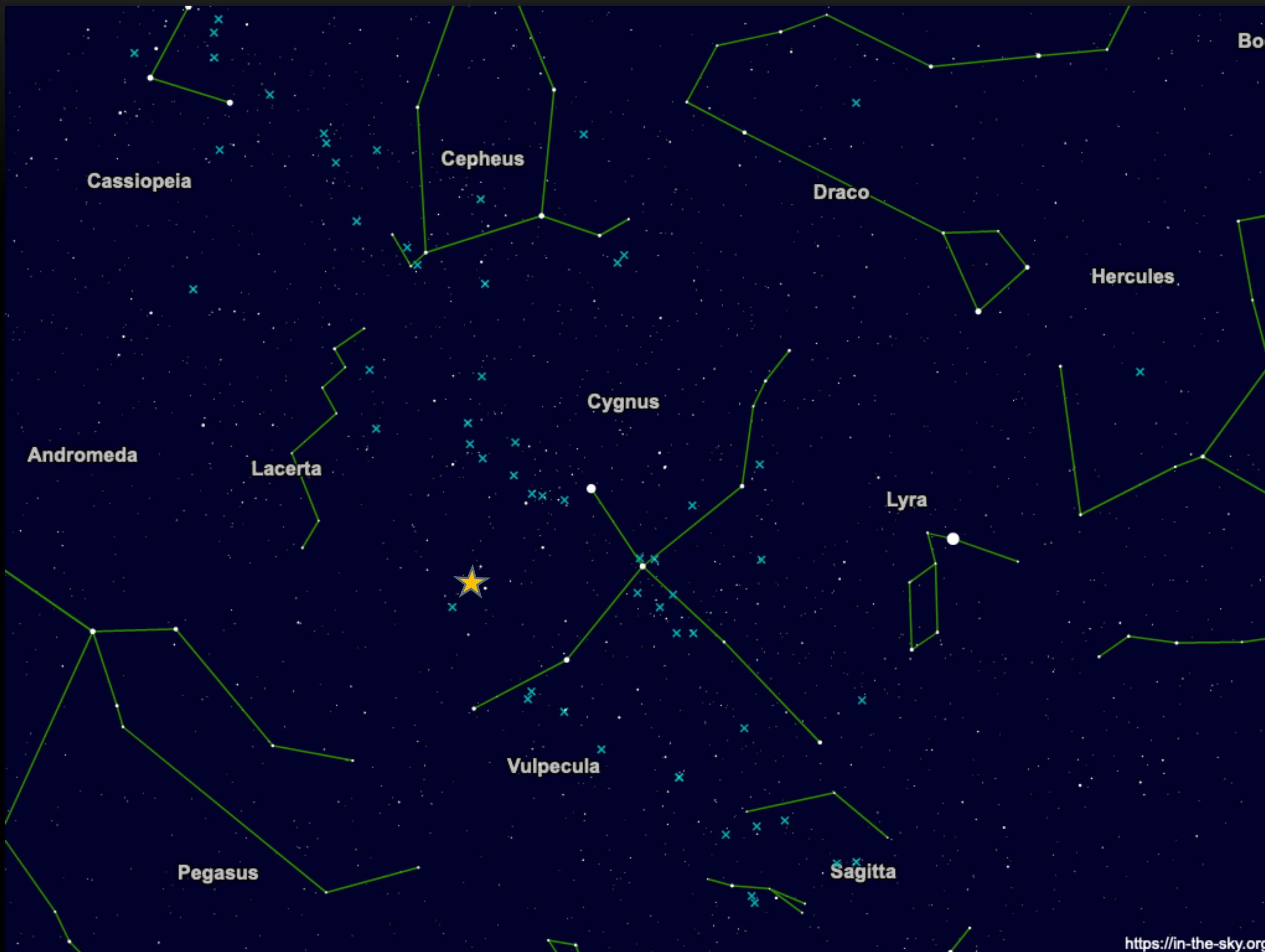



**Figure 4.** Phase curve of the original data phased to the best-fit period $P_1$ = 3.97208 days. 1st Overtone Mode

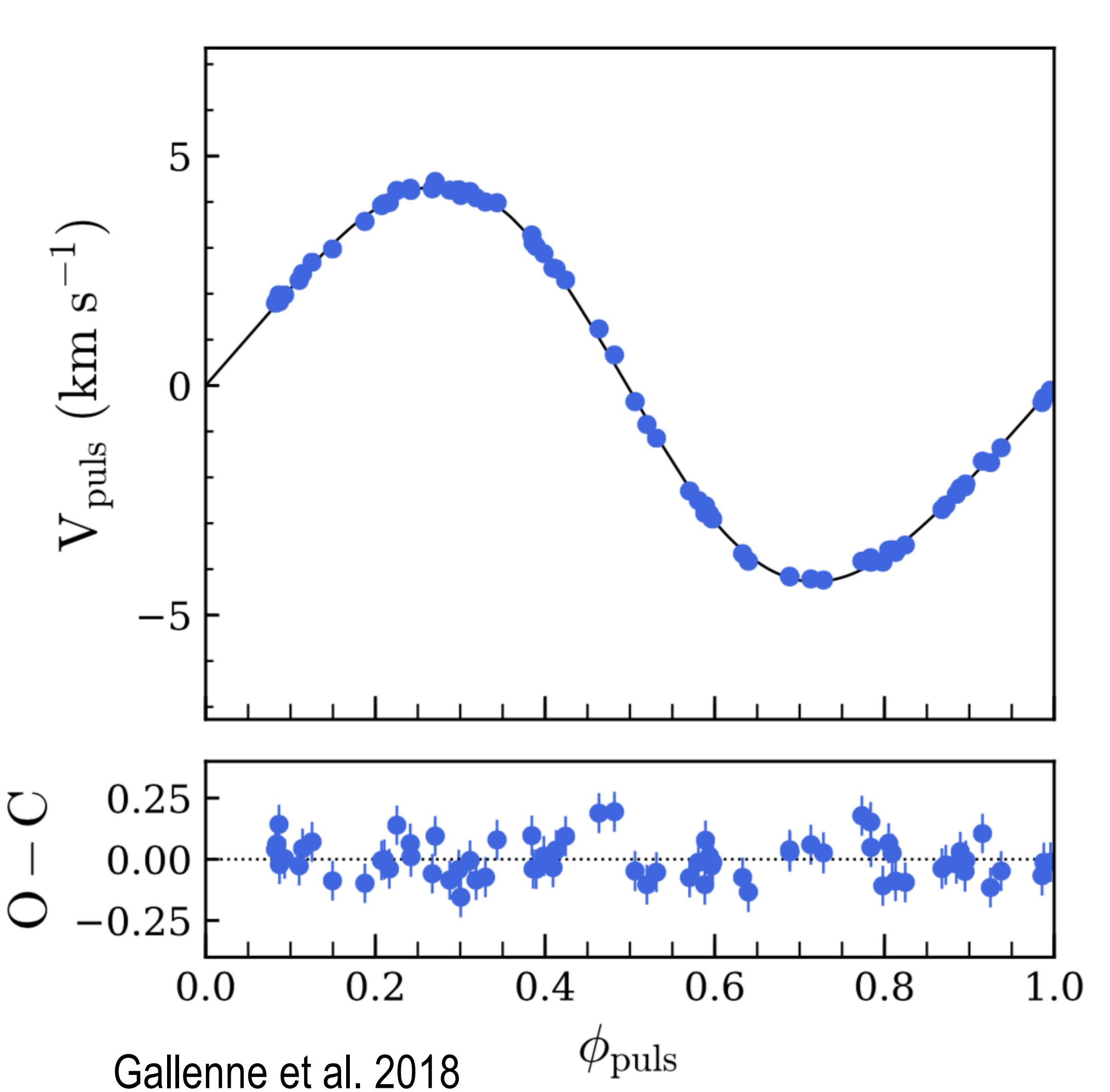
# MESA RSP Polaris simulations initiated in 1st Overtone at 0.1 km/sec grow to > 3 km/sec



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

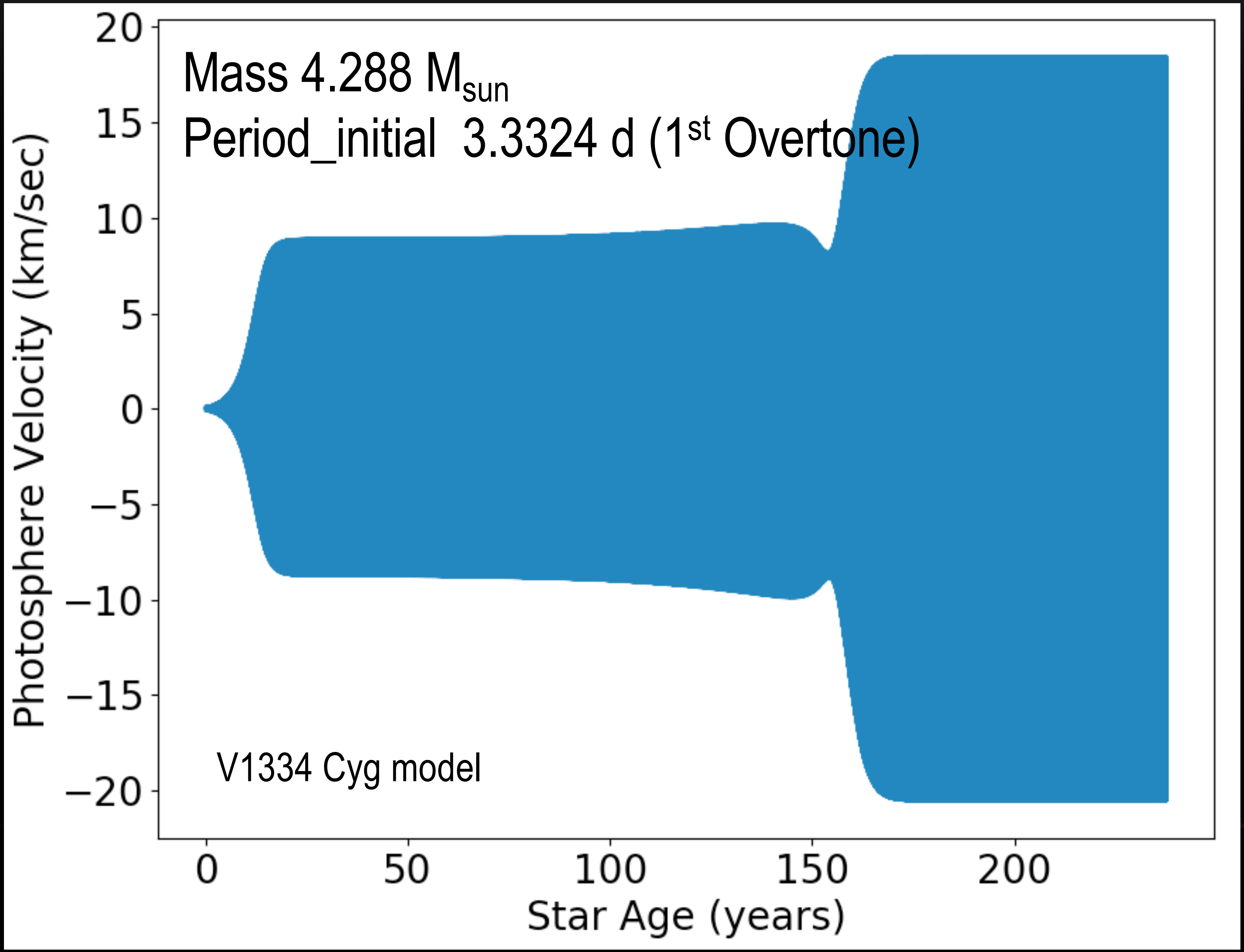


# V1334 Cyg has a low radial velocity amplitude of about 5 km/sec (1st OT)

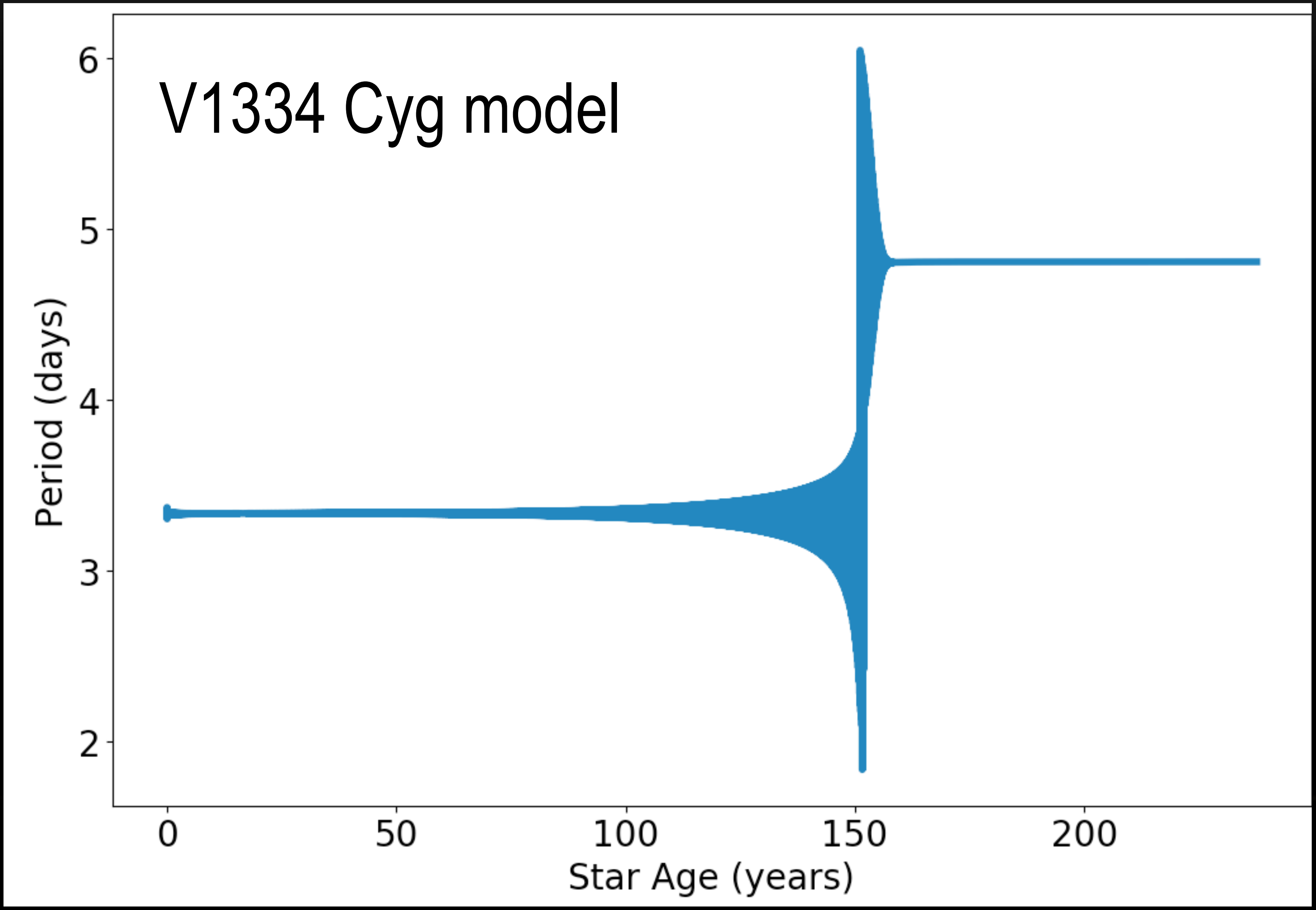


Gallenne et al. 2018

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!

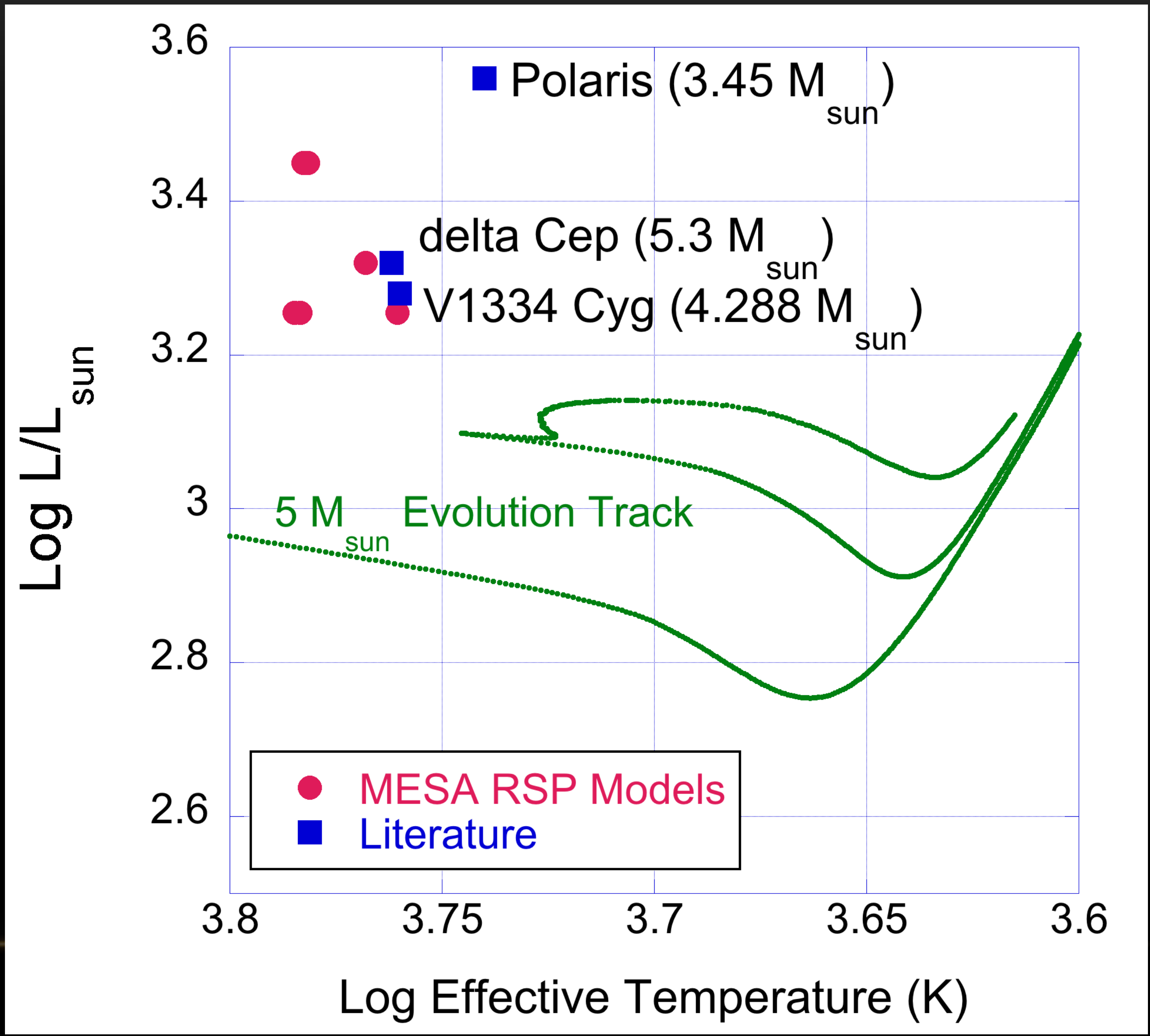


The pulsation period starts to converge to a 1st OT period, but then switches to fundamental mode!



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

Note: Polaris modeled with mass 5.93 $M_{sun}$

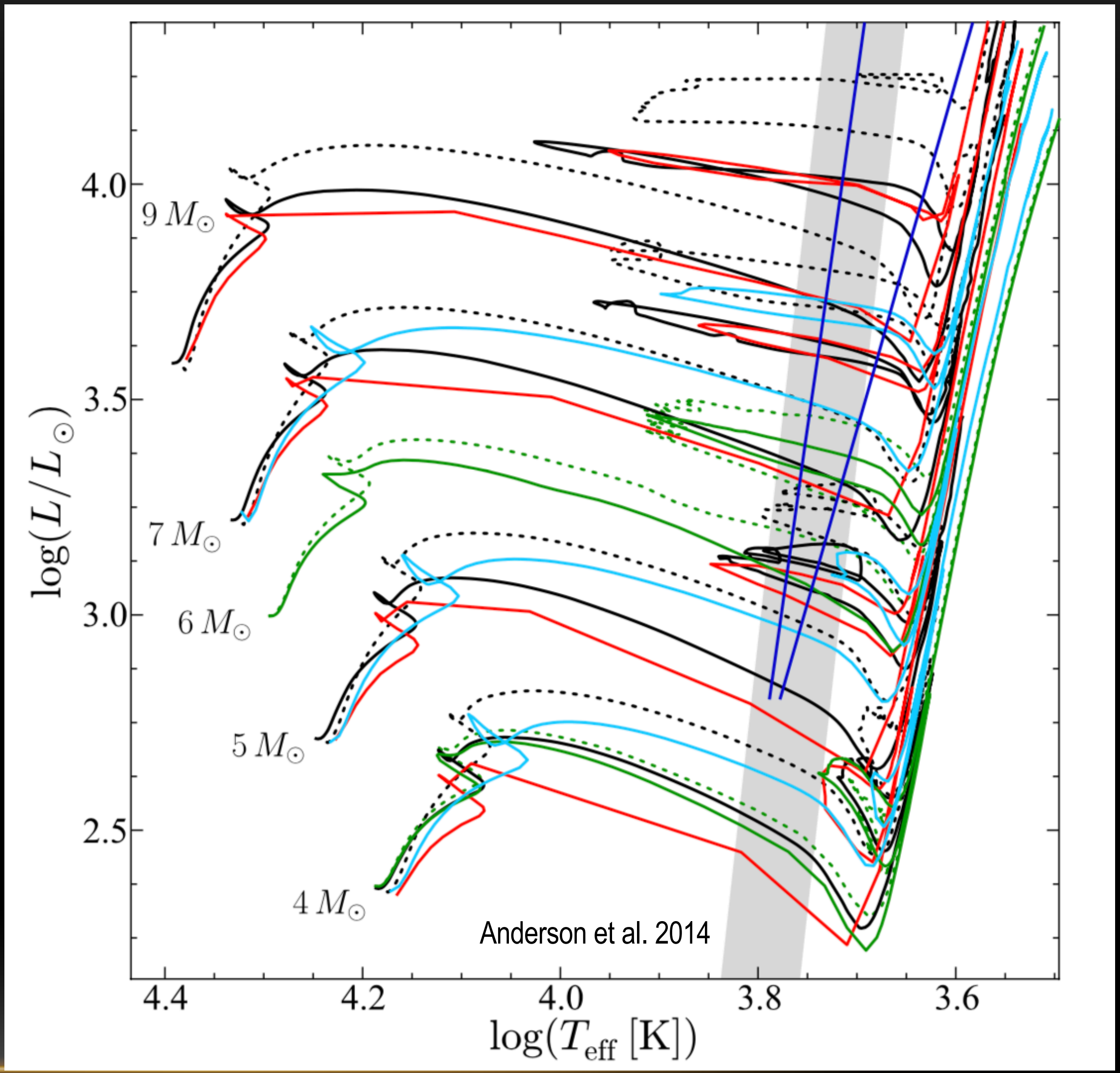


# Conclusions from MESA models of Polaris, δ Cep, and V1334 Cyg

- Limiting radial velocity of 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

# MESA can be used to explore changes in input physics to attempt to resolve this Cepheid mass discrepancy

- Helium and metal abundances
- Convective overshoot
- Mass loss
- Rotation
- Opacities
- Nuclear reaction rates



# Backup Slides

# 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

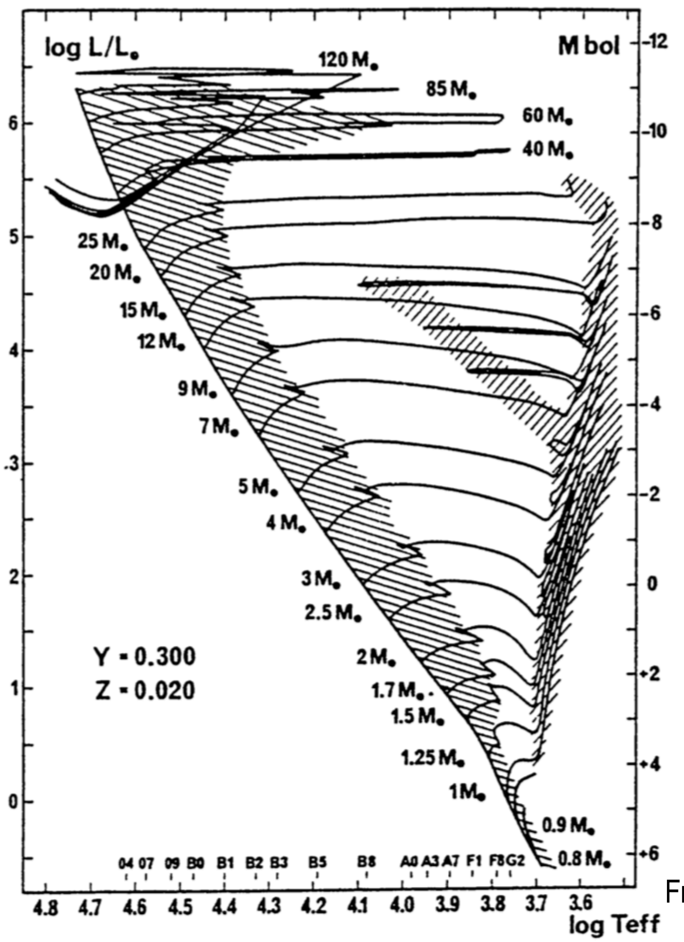
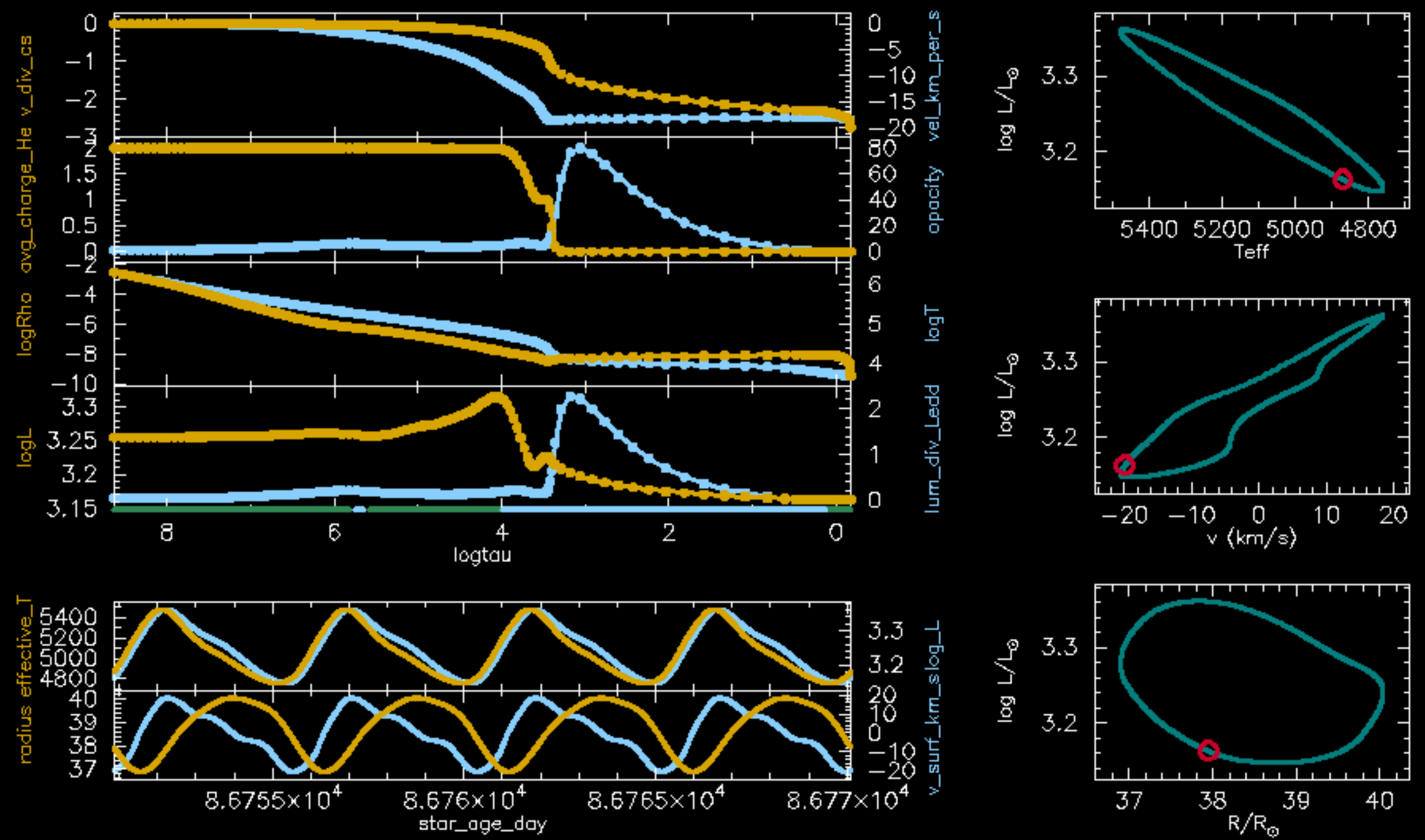



Fig. 6. Geneva tracks for Z = 0.02, reproduced from Schaller et al. (1992). Crosshatched regions indicate “slow” phases of nuclear burning.

From Simon 1994

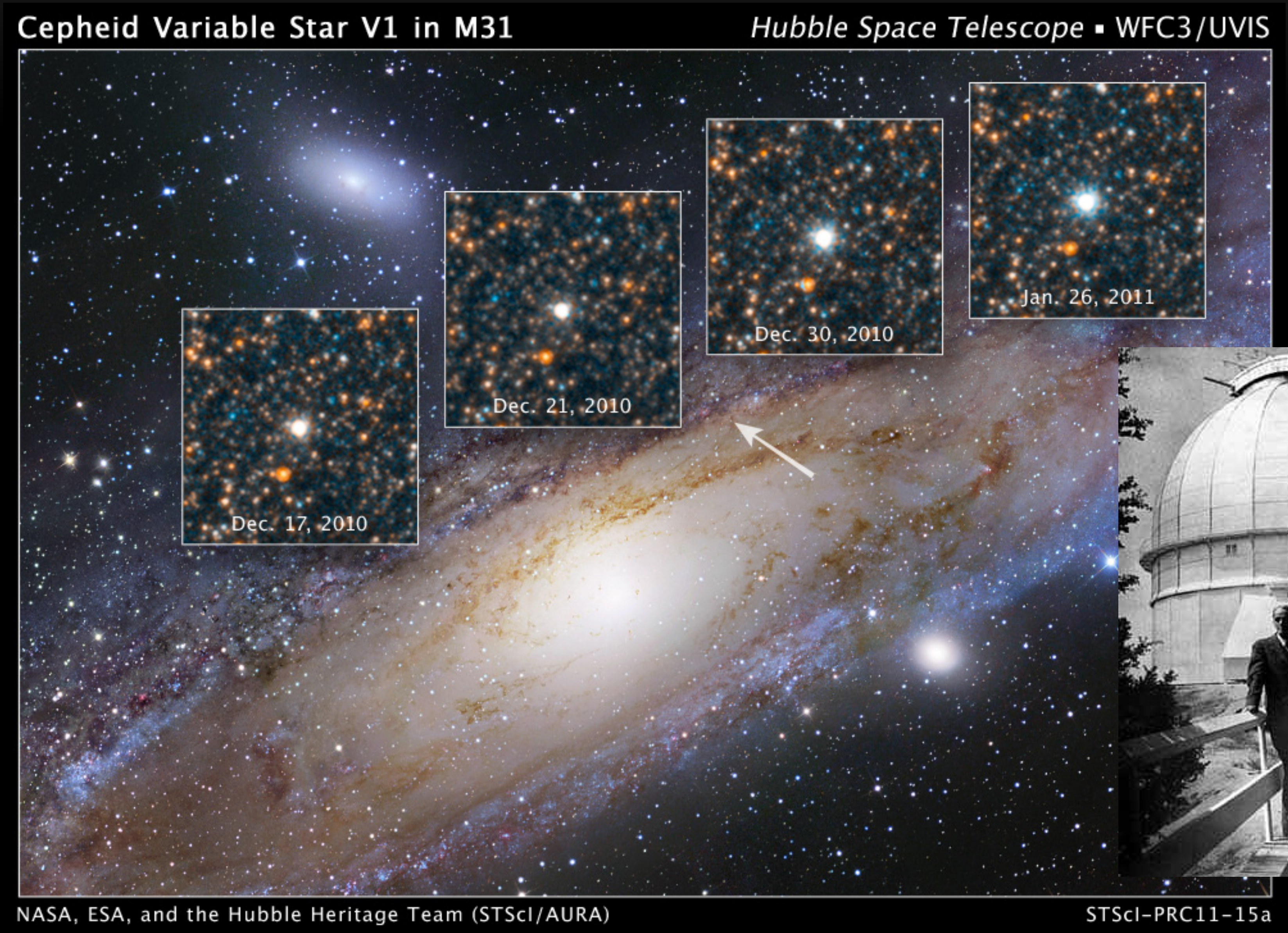
# V1334 Cyg ‘dashboard’

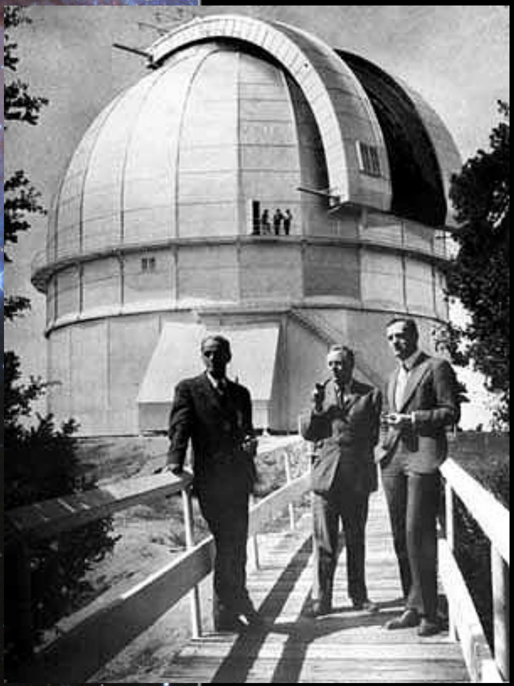



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| model_number | 14212620 | v_surf_km_s | −19.9195368 | effective_T | 4.869E+03 | star_mass | 4.2880000 |
| star_age_day | 8.677E+04 | radius | 37.9474109 | log_Teff | 3.6874163 | num_zones | 150 |
| time_step_sec | 692.5085208 | log_R | 1.5791822 |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

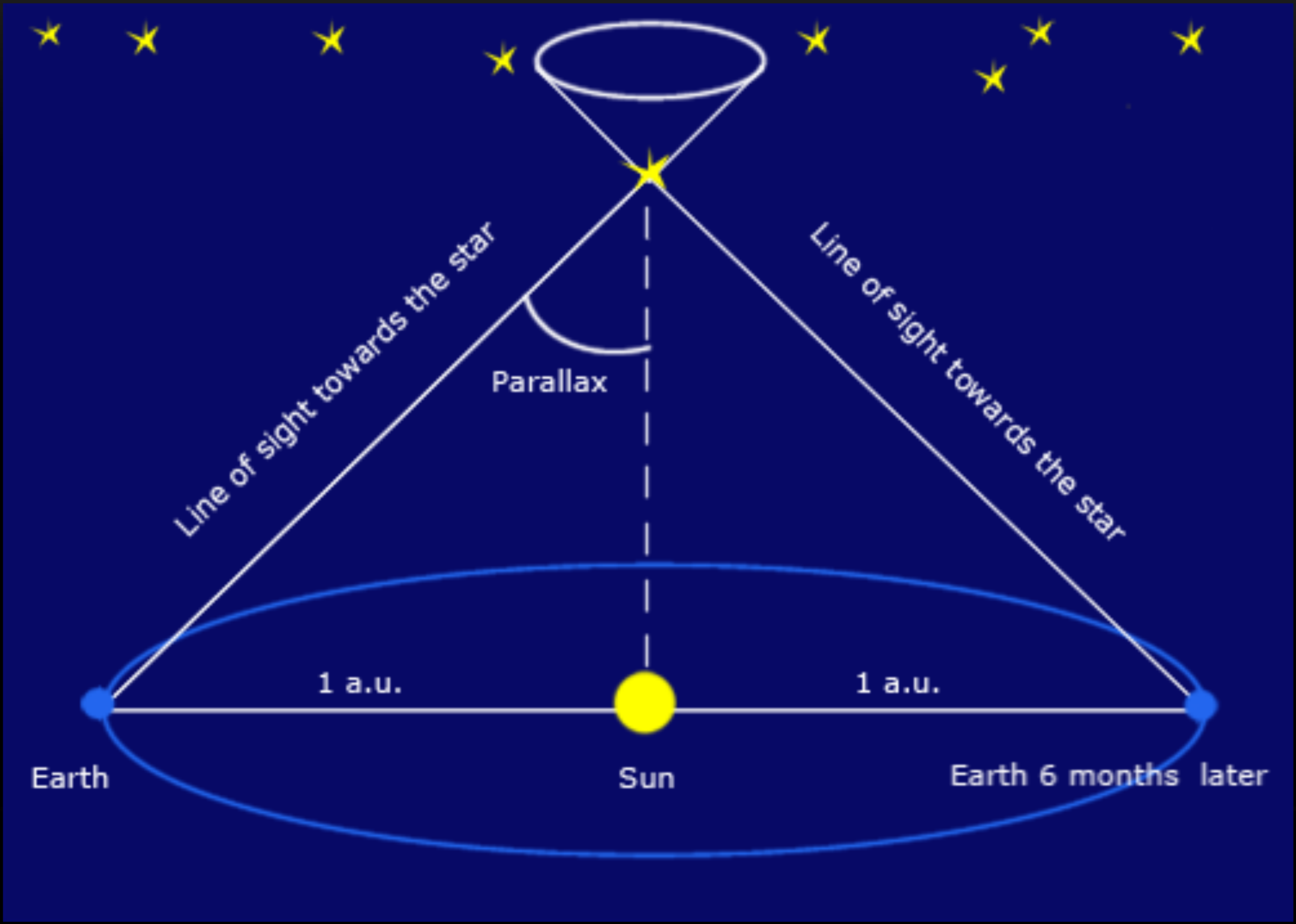
# Small and large Magellanic clouds are satellite galaxies to the Milky Way Galaxy

# Edwin Hubble in early 1920s found Cepheids in Andromeda Galaxy, showing that galaxies are far outside the Milky Way

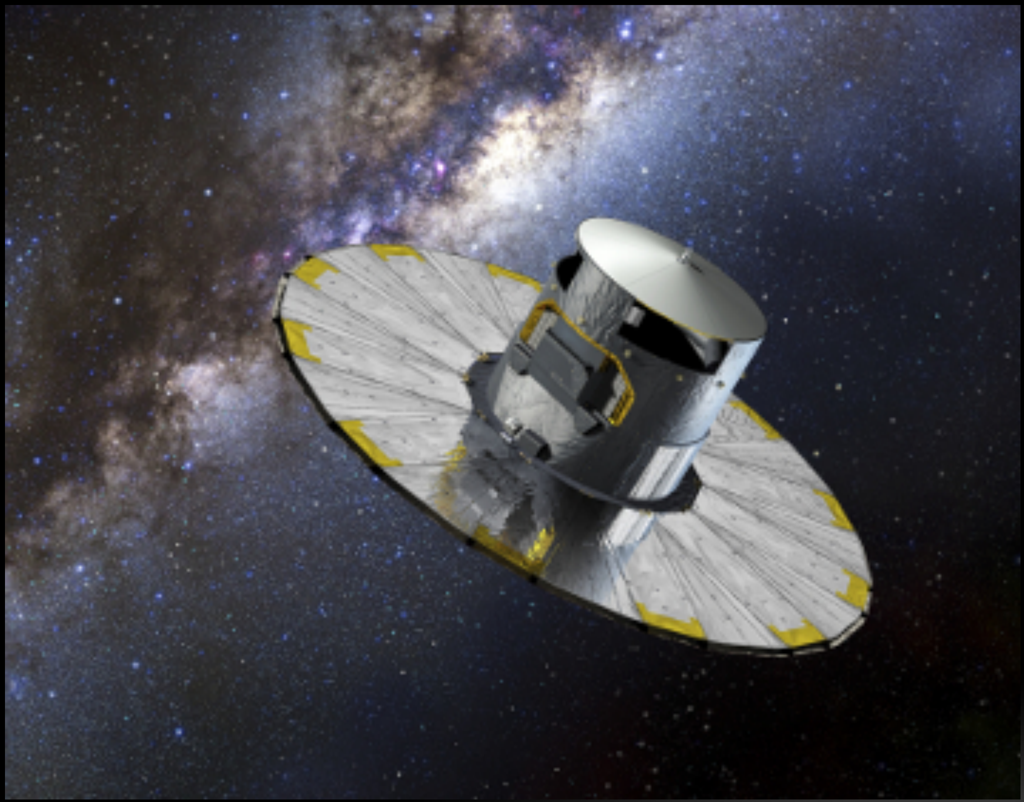


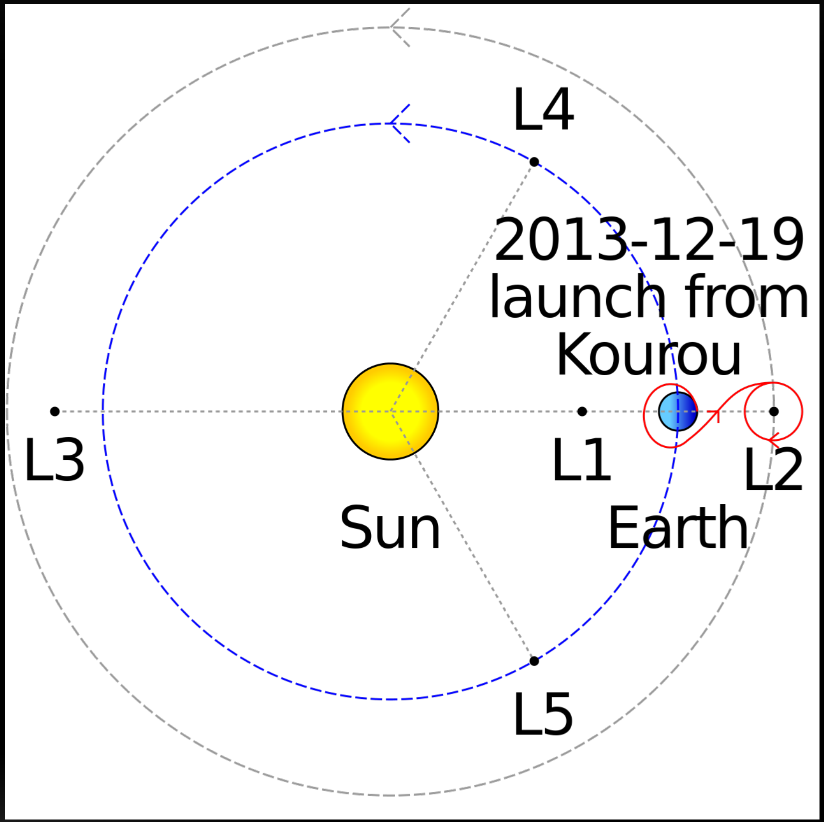
# Absolute distances of Cepheids can be measured using ‘parallax’



# Gaia spacecraft will measure distances of stars in Milky Way, including nearby Cepheids, to higher precision

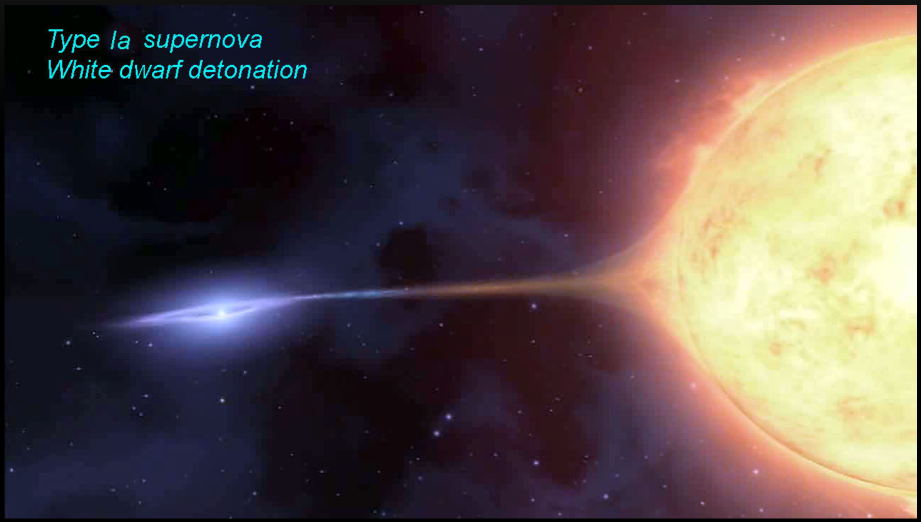


By Source (WP:NFCC#4), Fair use, https://en.wikipedia.org/w/index.php?curid=39342811




By Cmglee - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=30257831

# Type Ia supernovae can be seen in the most distant galaxies, and are used to determine universe's expansion rate (Hubble Constant)





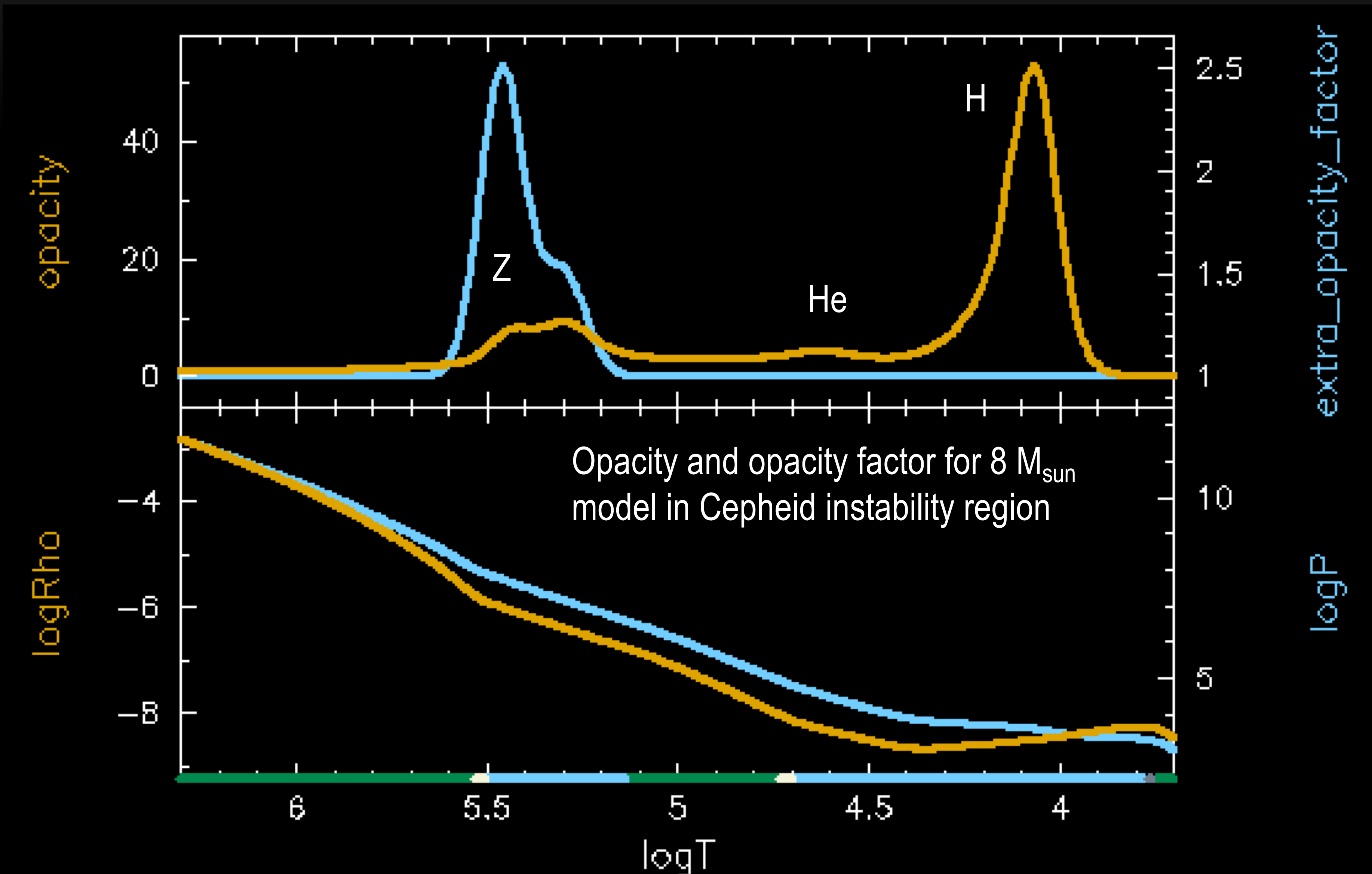

Type Ia SN in Pinwheel Galaxy
20 million light years from Earth

This galaxy also contains Cepheids, so distance scale using Type 1a SN could be calibrated

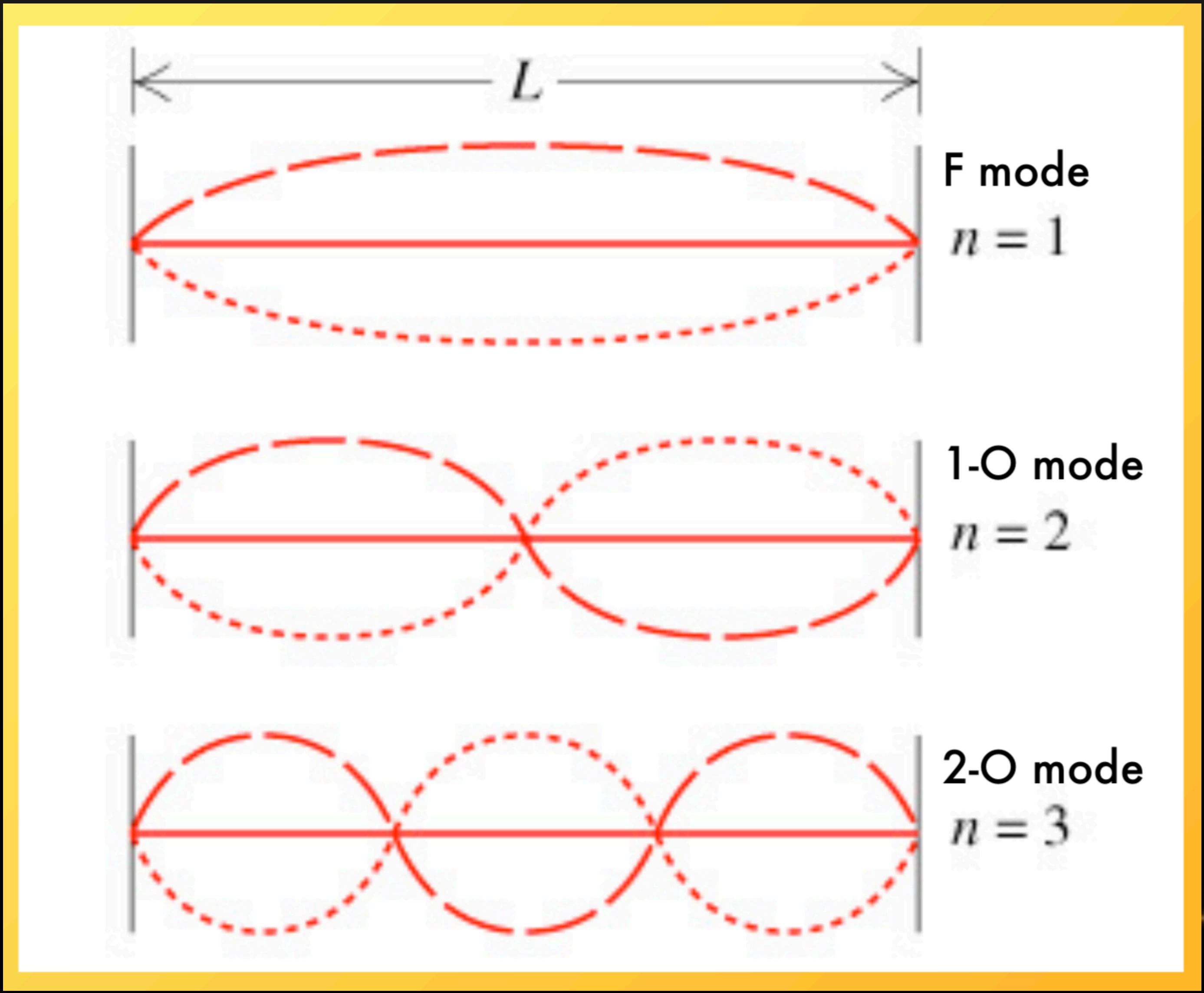
# Pulsation driving analogies

From Townsend 2019

# Cepheid pulsations are driven in region of helium ionization in stellar envelope

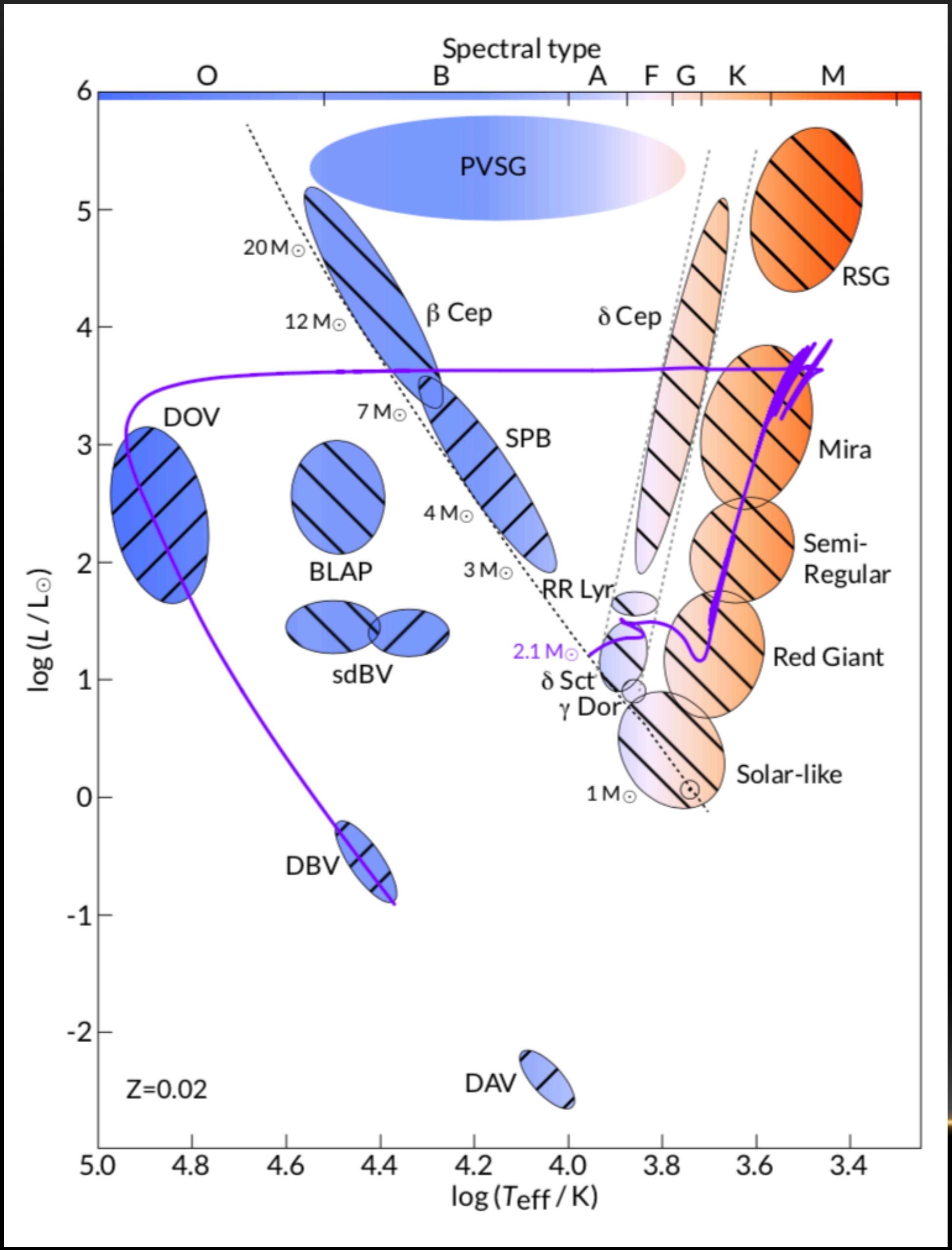


# Fundamental, first overtone, and second overtone modes on a string

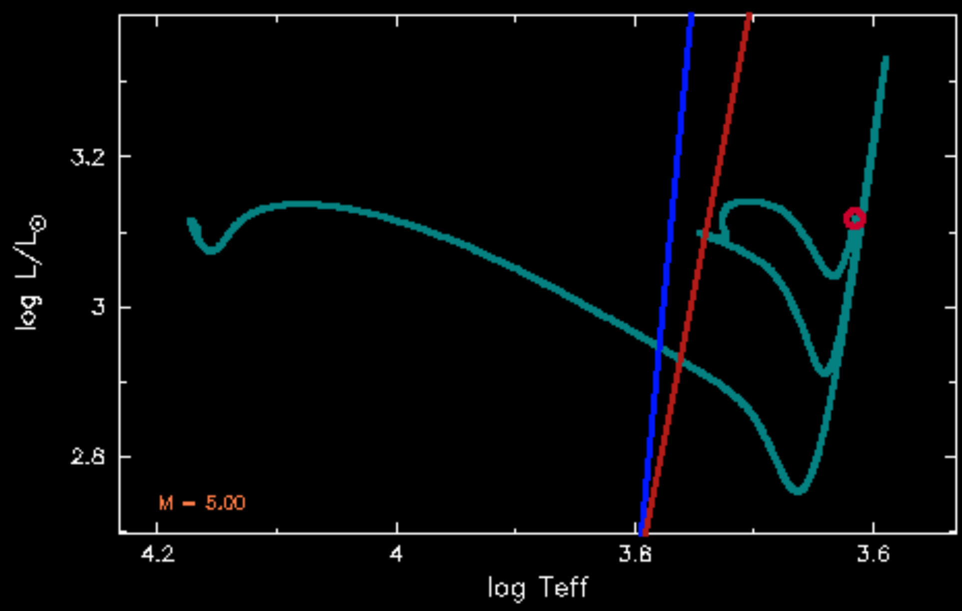



From Townsend 2019

# Why do Cepheids pulsate?




5 solar mass Cepheid evolution track



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

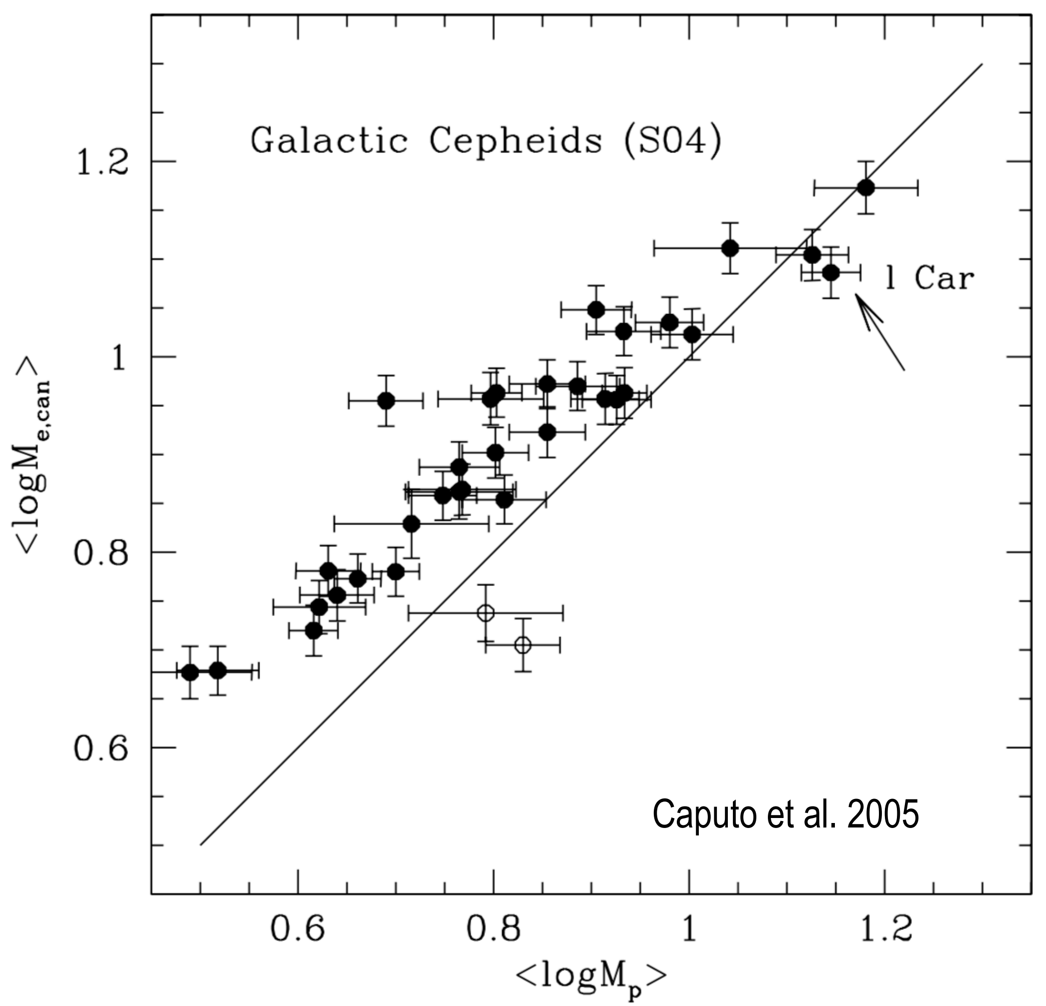



FIG. 8.—Mean pulsation mass of Galactic Cepheids vs. the mean canonical evolutionary one. Open circles mark the short-period Cepheids SU Cas and EV Sct, while the small arrow marks the long-period variable l Car.

# Abstract


Cepheid variable stars are core helium-burning stars of around 4 to 15 solar masses that show radial pulsations with periods of 3 to 100 days and magnitude variations of a few tenths to up to 2 magnitudes per pulsation cycle.

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 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 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 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.