Cepheid Blue Loops and Nonlinear Pulsations

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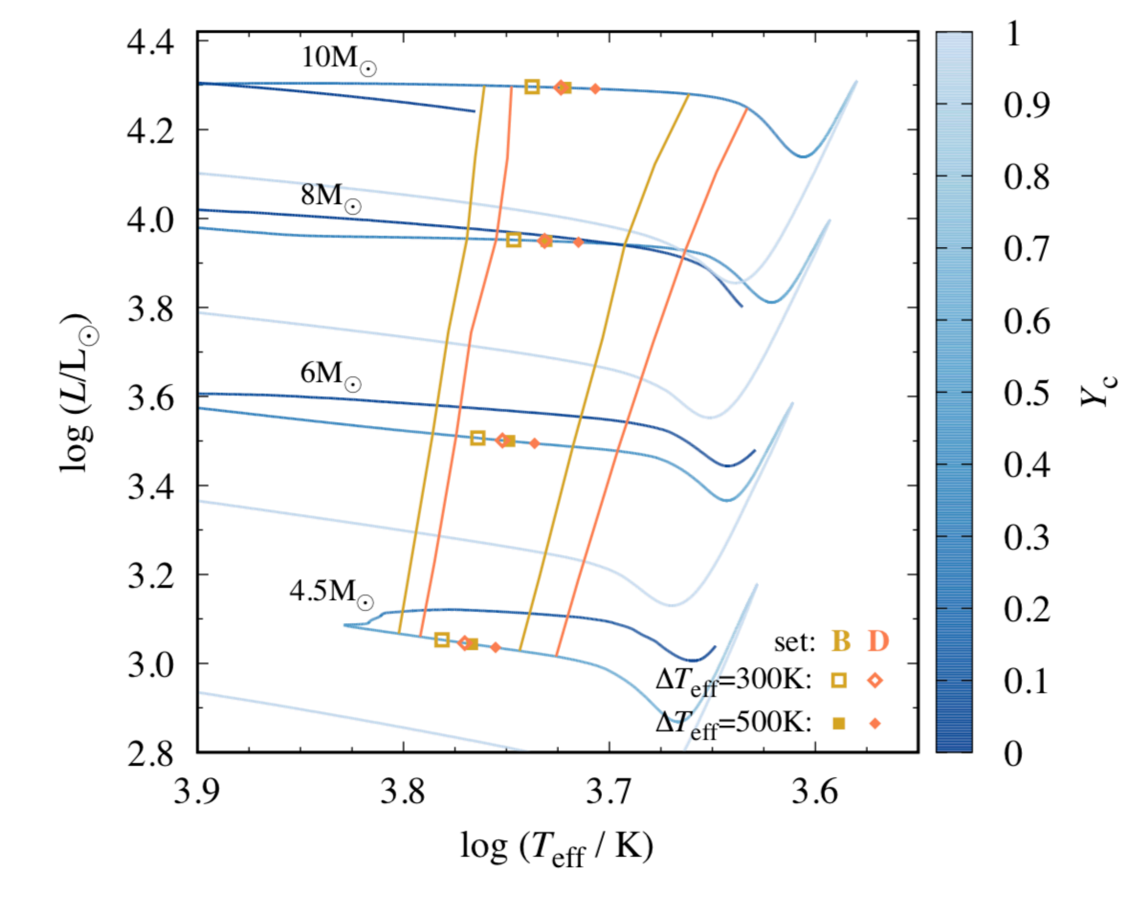

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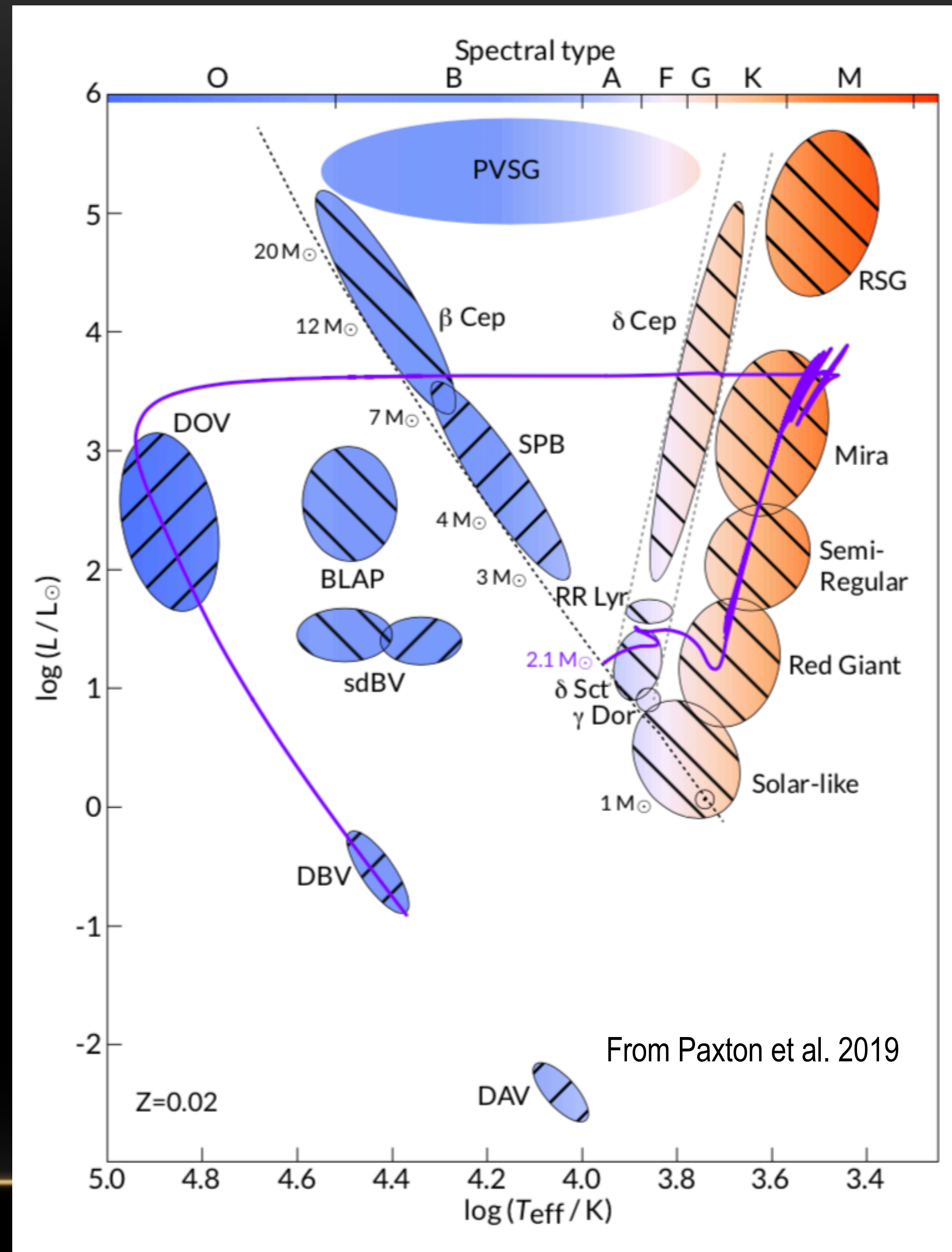
What are Cepheids?

- Prototype δ Cep
- 5-15 M_{sun}, core helium burning
- Pulsation periods ~3 to 100 days
- Pulsation driving via the kappa (opacity) mechanism in second helium ionization zone ~50,000 K
- Radial, first overtone, 2nd overtone (rare) or some combination
- Found in MW Galaxy, LMC, and SMC



From Paxton et al. 2019

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

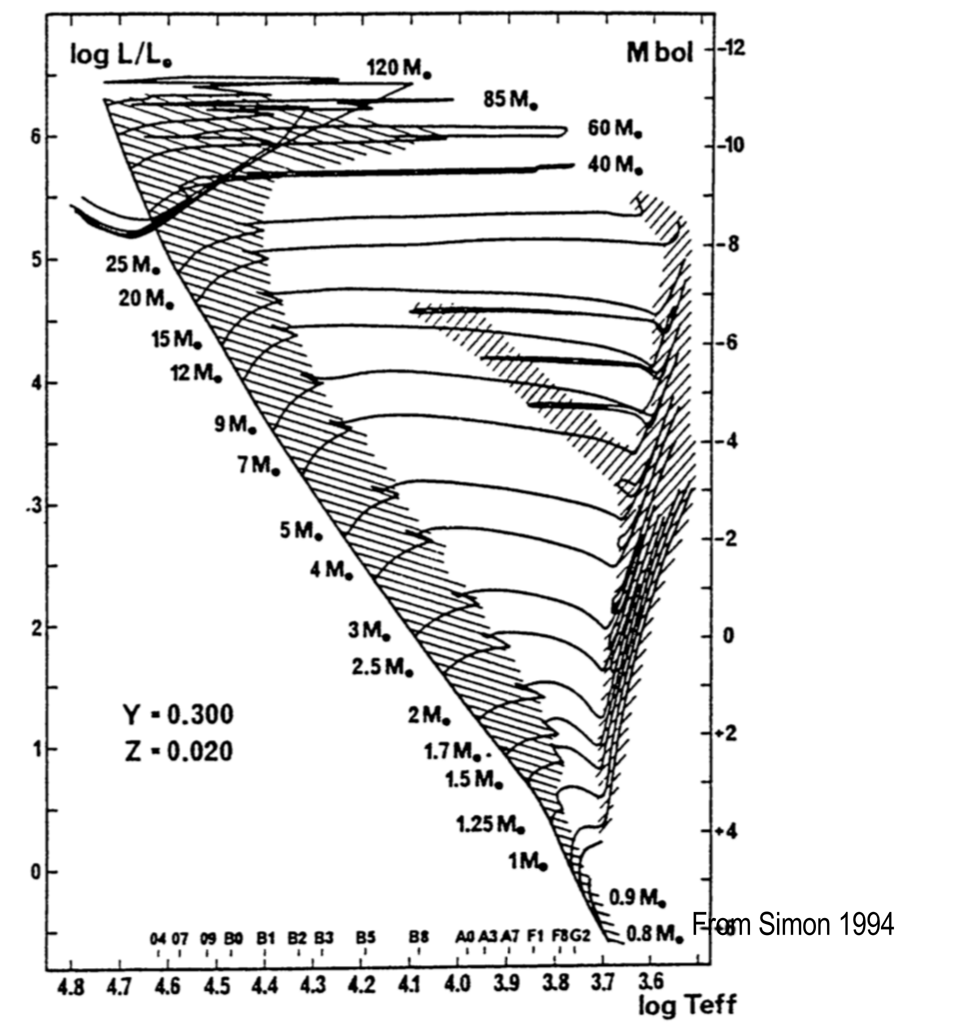
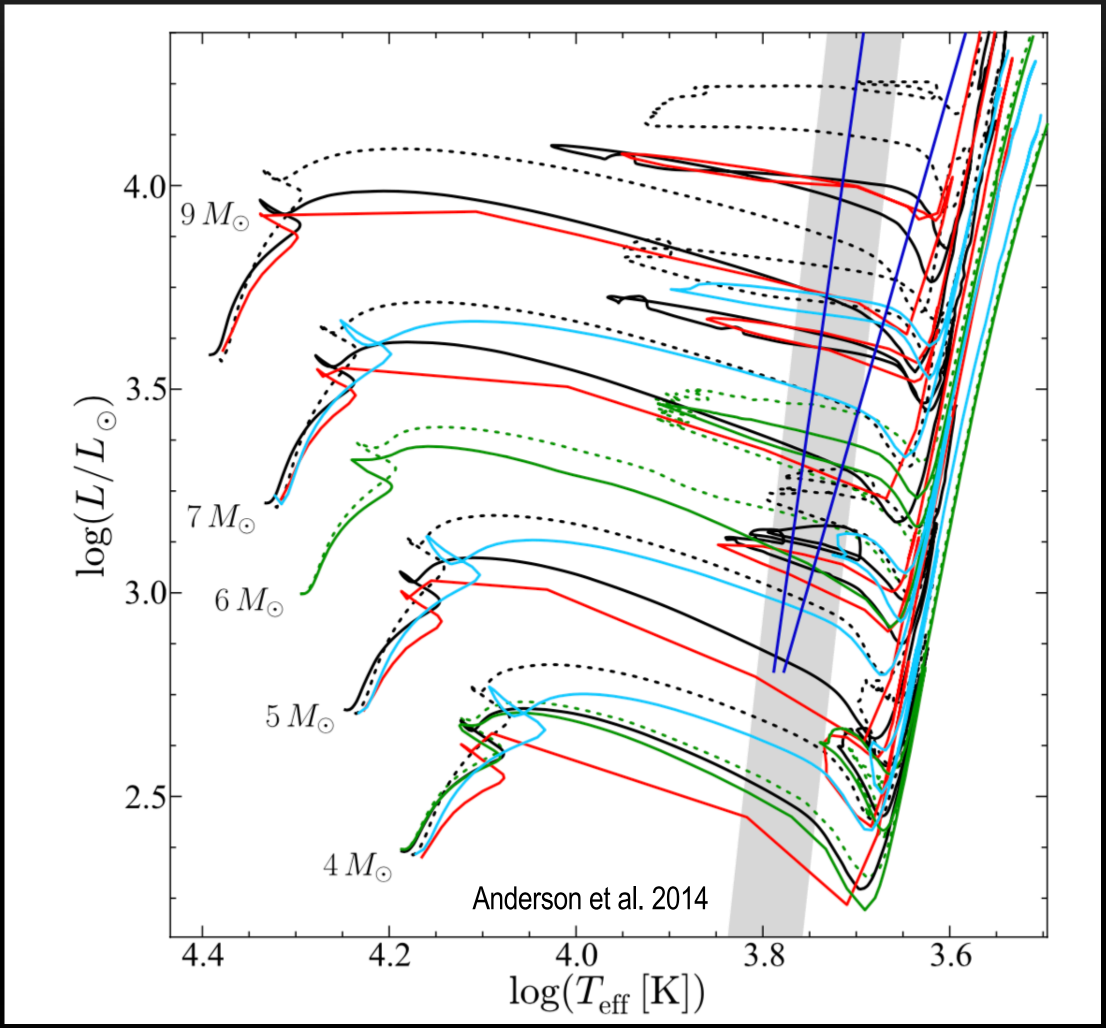


Fig. 6. Geneva tracks for Z = 0.02, reproduced from Schaller et al. (1992). Crosshatched regions indicate “slow” phases of nuclear burning.

Evolution Models and Cepheid Pulsation Instability Regions

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



Why are Cepheids important?

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

- Determine Hubble Constant
- Discrepancy between Hubble constant derived via Cepheid calibrations vs.from Cosmic Microwave Background observations (~4 sigma difference)

“Laboratory” to test stellar input physics

- Cepheid mass discrepancy
- ’Beat’ (1st overtone/F) and ‘bump’ (2nd overtone/F) Cepheid period ratios

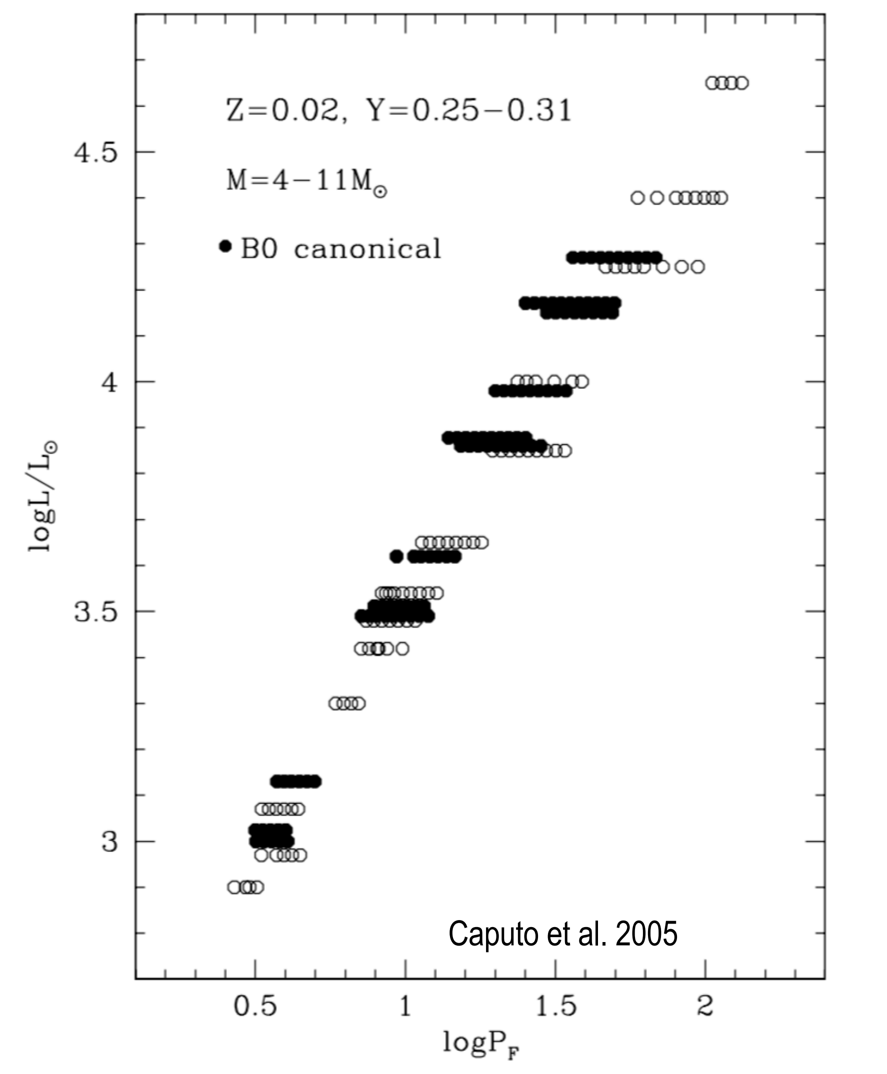
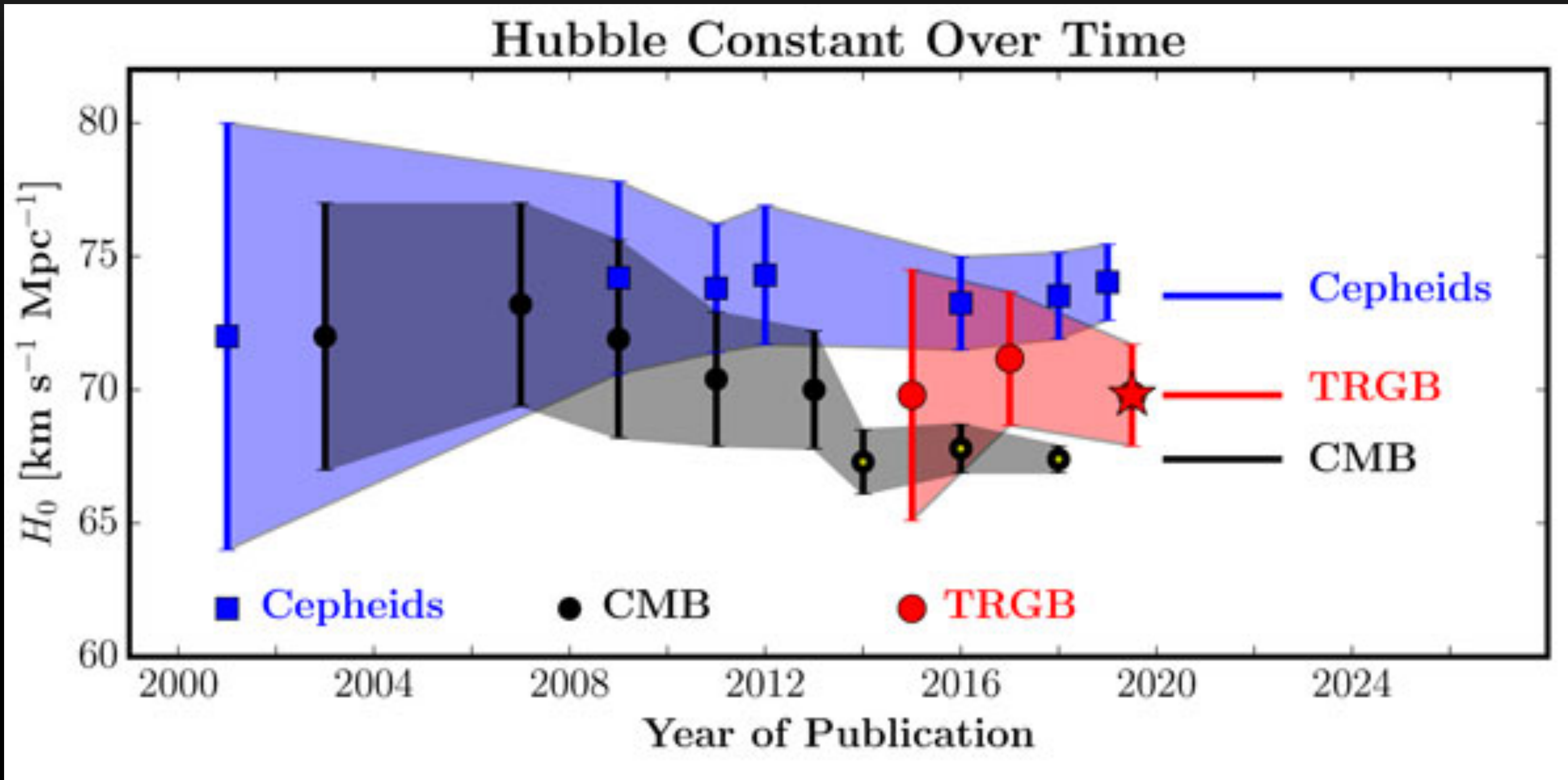


FIG. 1.—PL distribution of fundamental pulsators with fixed metal content ($Z = 0.02$) and helium abundance ranging from $Y = 0.25$ to 0.31. Filled circles display Cepheid models computed by adopting the B00 canonical ML relation.

Cepheids and the Hubble Constant



Sky and Telescope July 24, 2019

Cepheid Mass Discrepancy

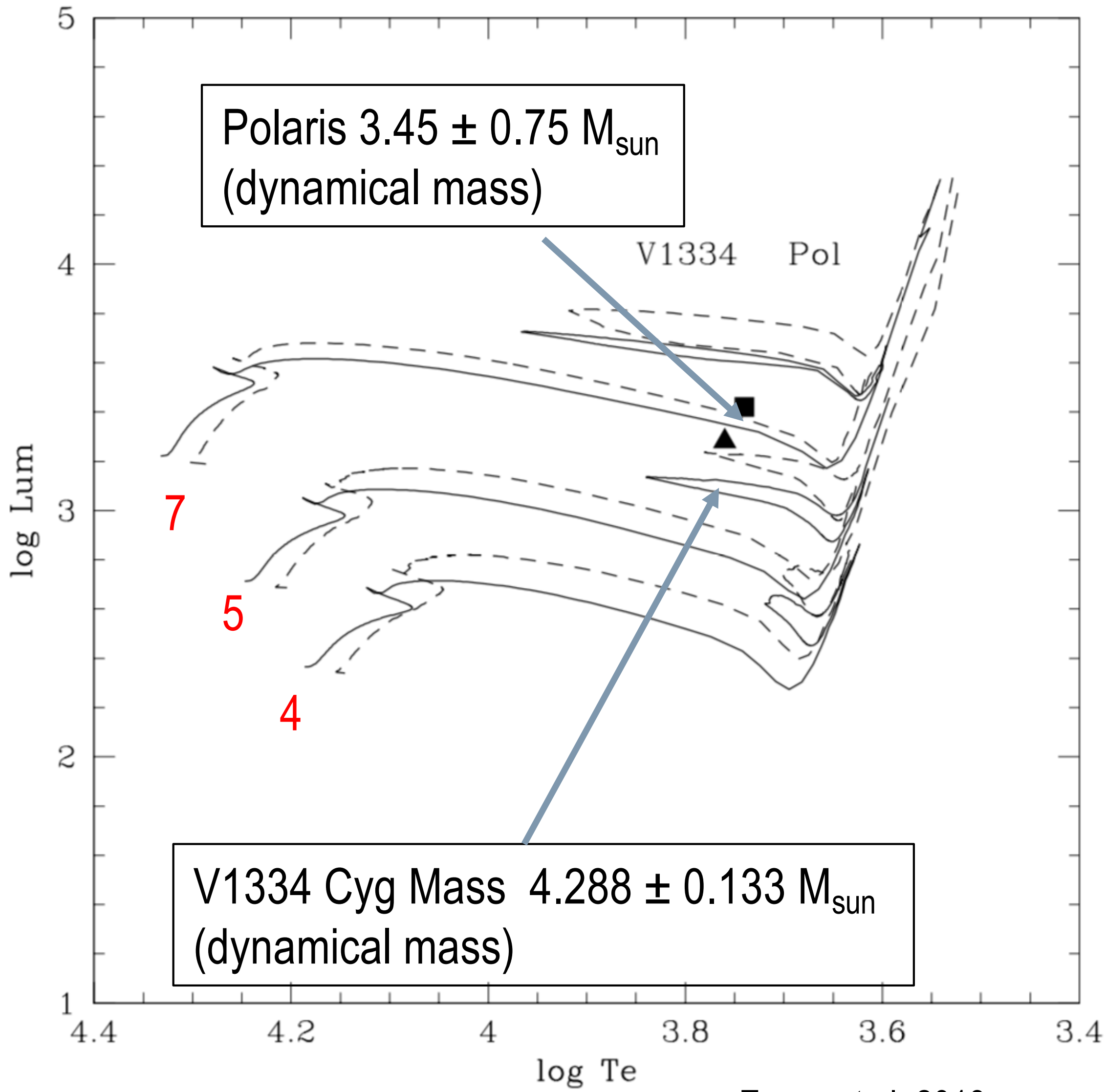
Pulsation and dynamical masses do not agree with evolution mass

Pulsation mass: Period proportional to 1/sqrt(mean density)~1/sqrt(M/R^3)

- Obtain R from L and T_{eff}
- Measure Period, can constrain Mass

Dynamical Mass: Obtain masses from binary orbit analyses

Observed luminosity is too high compared to the evolution track for the determined mass



Evans et al. 2018

Evolution masses of Galactic Cepheids are larger than pulsation masses

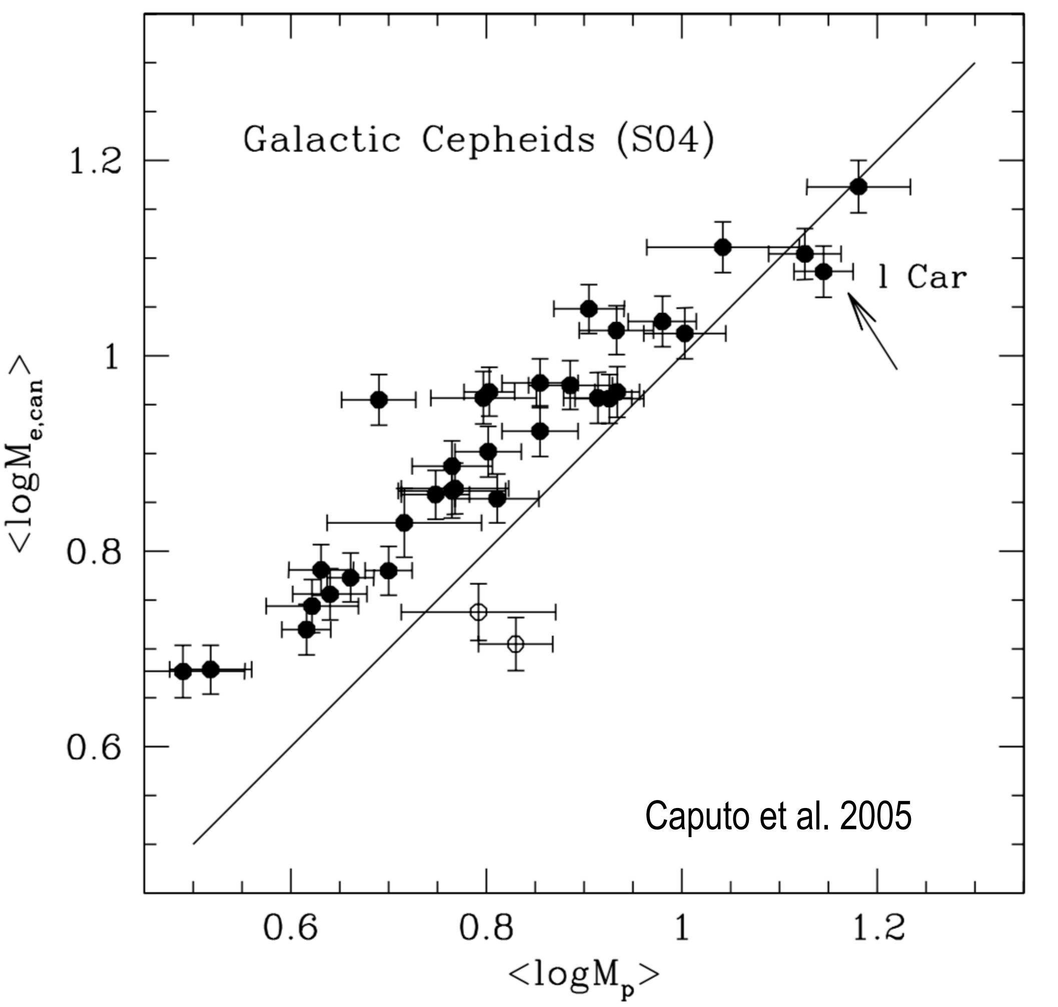


FIG. 8.—Mean pulsation mass of Galactic Cepheids vs. the mean canonical evolutionary one. Open circles mark the short-period Cepheids SU Cas and EV Sct, while the small arrow marks the long-period variable l Car.

Proposed Resolutions for Cepheid Mass Discrepancy

Core convective overshoot (which parameters and treatment?)

Rotation (potential problem with too-high abundances from dredge-up on RGB)

Binary merger (proposed for Polaris, increases Y abundance and luminosity)

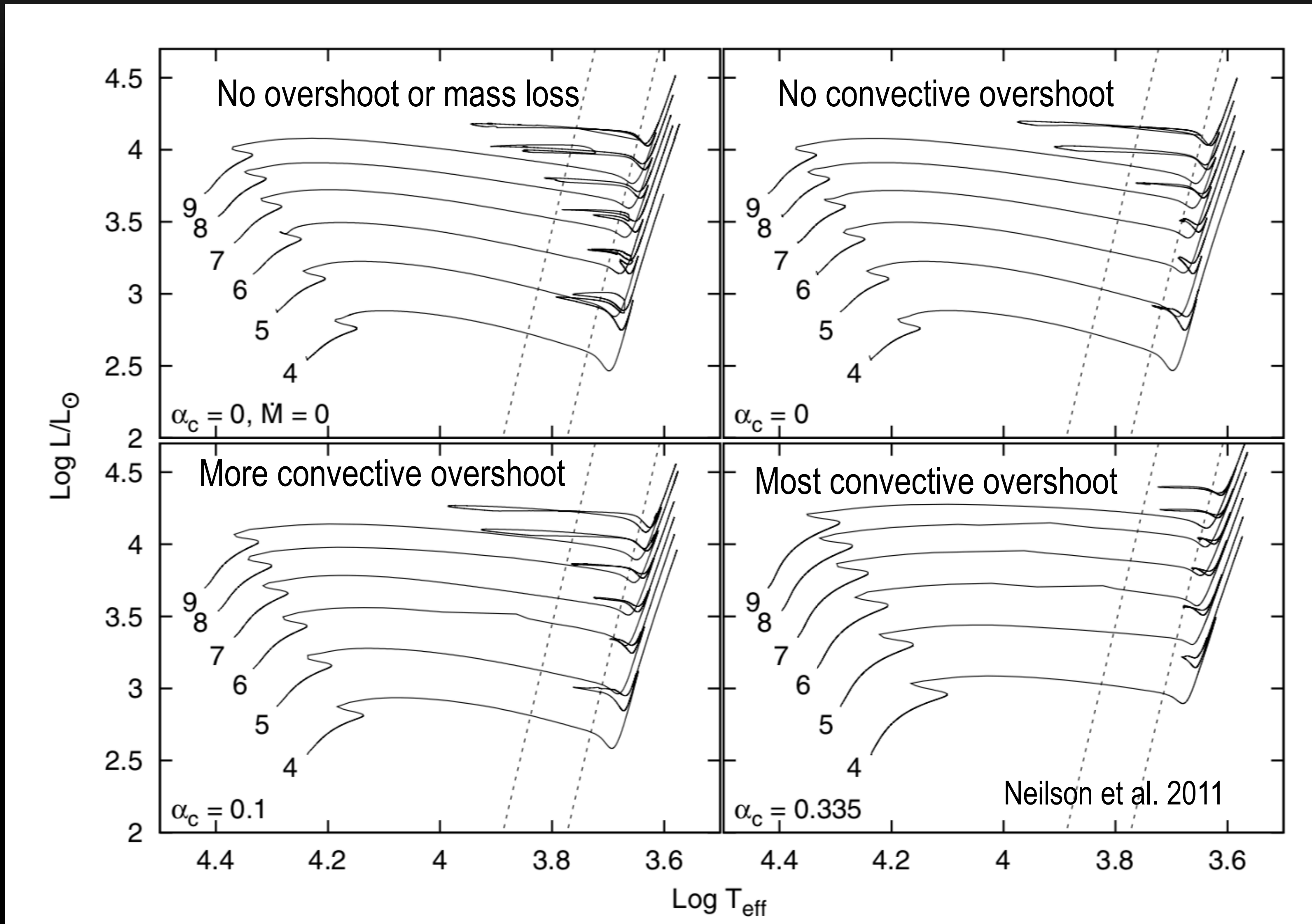
Mass loss driven by Cepheid pulsations (need rate ~> 10^{-7} M_{sun}/year)

Nuclear reaction rates during He burning (change blue loops; higher rates increase luminosity in Cepheid phase)

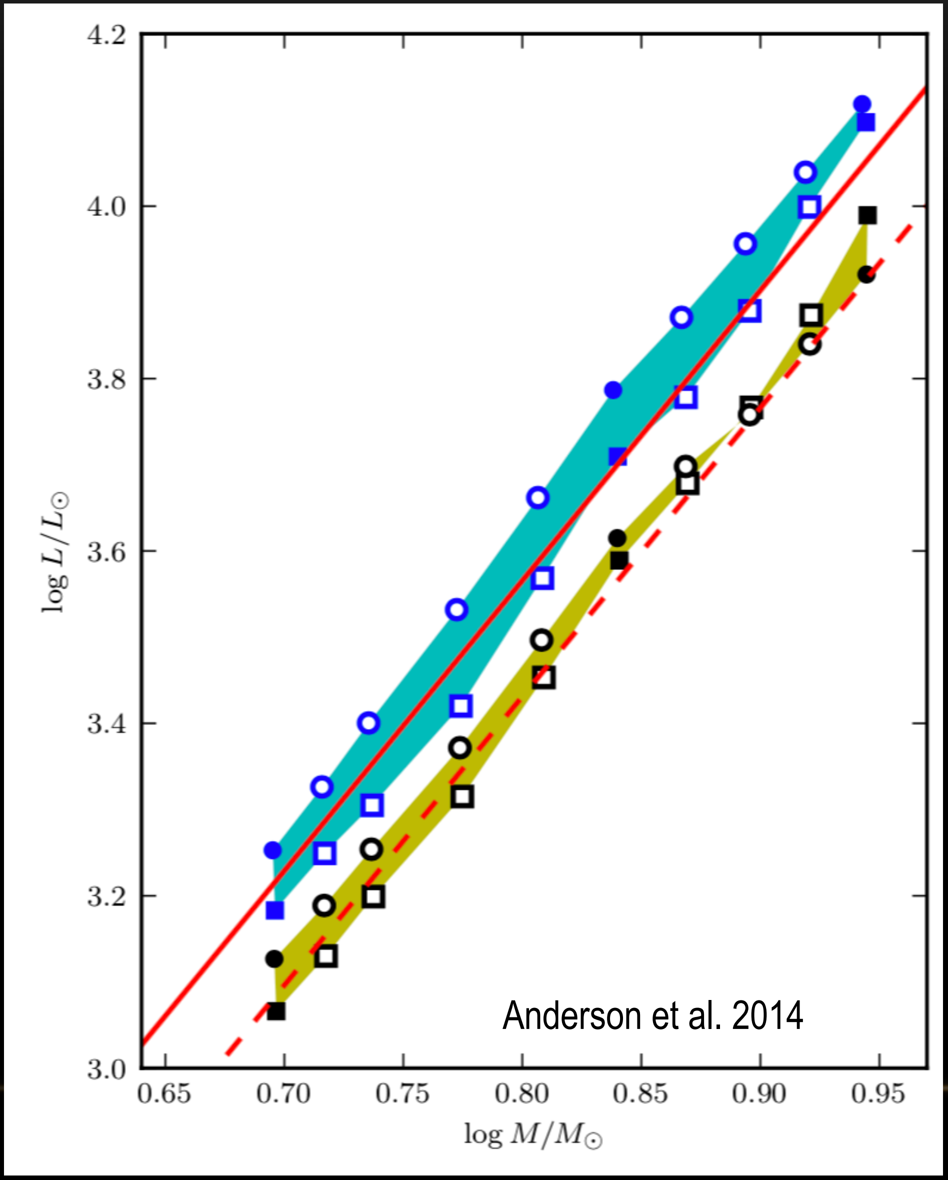
- Triple-alpha (helium burning)
- $^{12}C(\alpha,\gamma)^{16}O$

Opacity modifications (Motivation? T, ρ dependent)

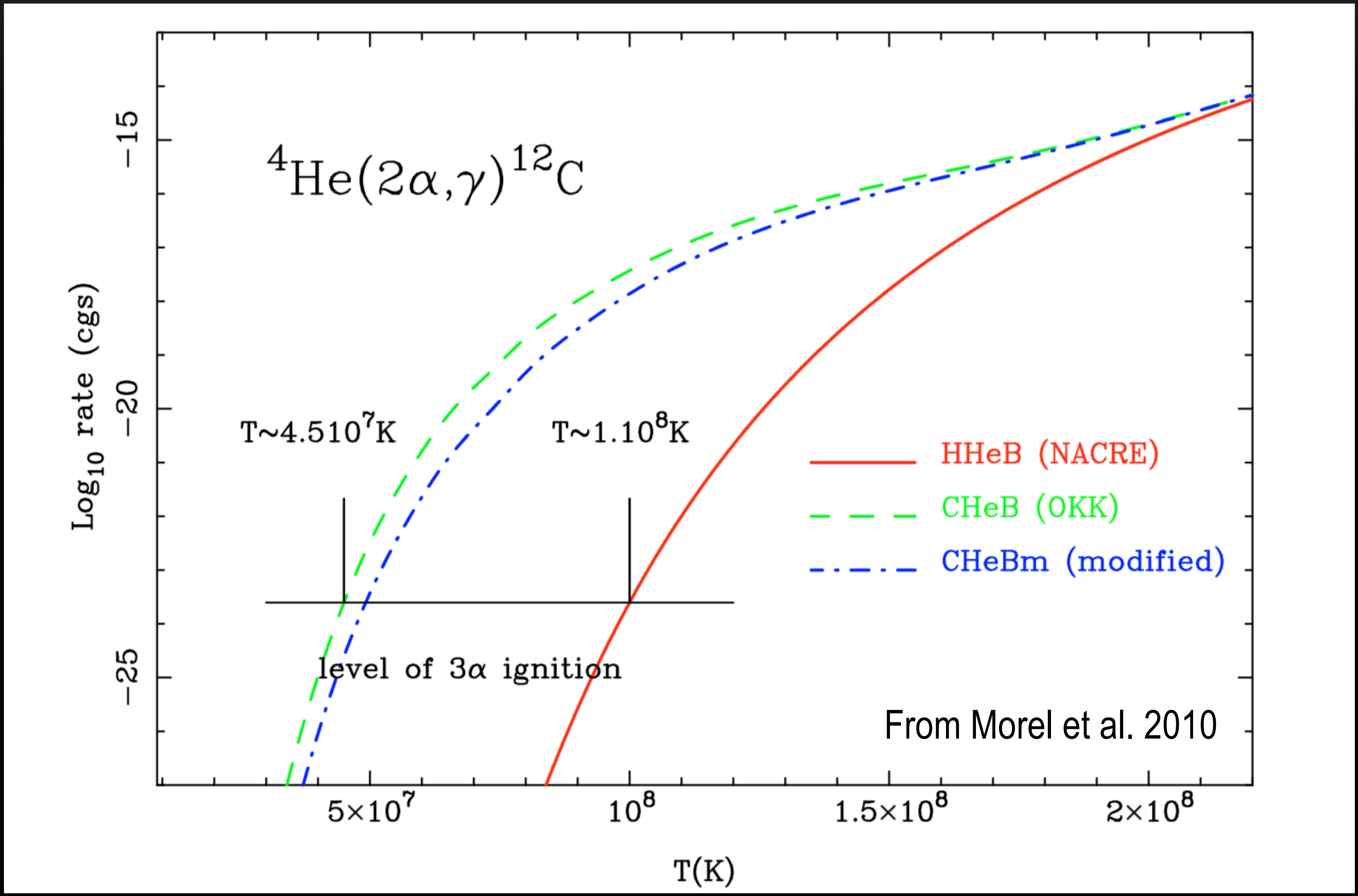
Effects of Pulsation-Driven Mass Loss and Convective Overshoot



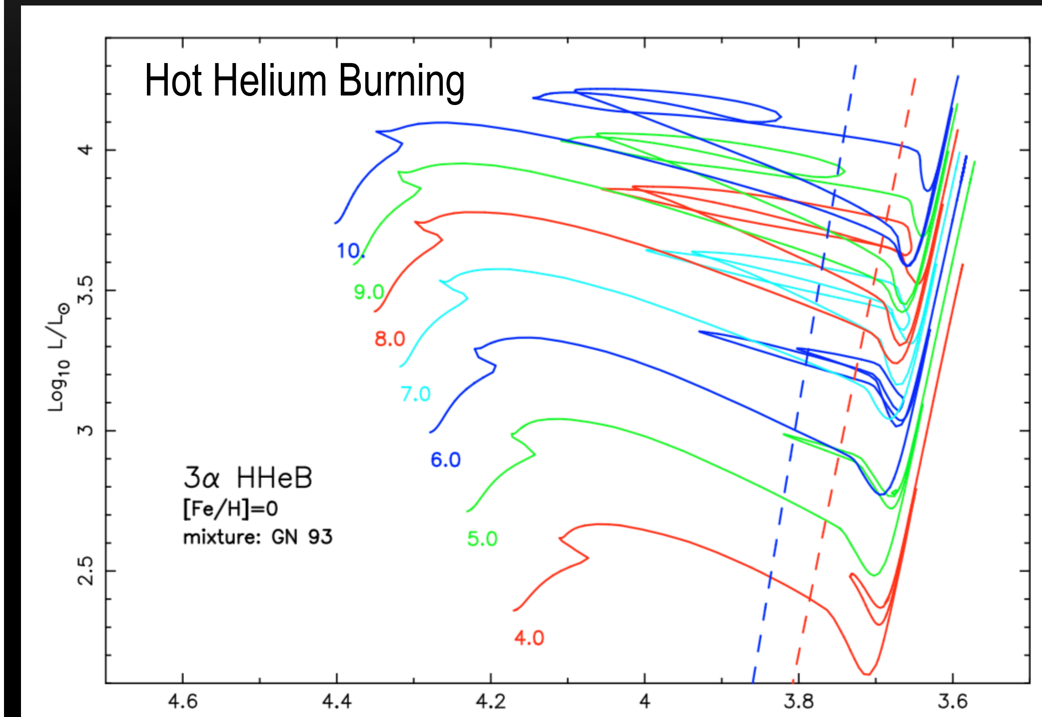
Cepheid models with rotation and overshoot have higher luminosities for the same mass

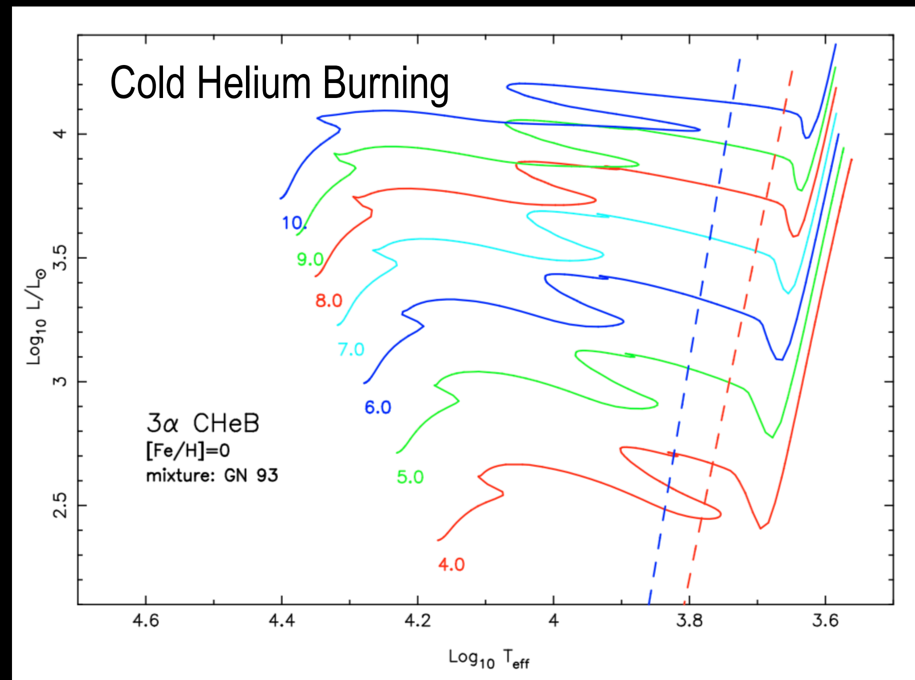


Proposed change to triple-alpha reaction causes onset of helium burning at lower temperatures



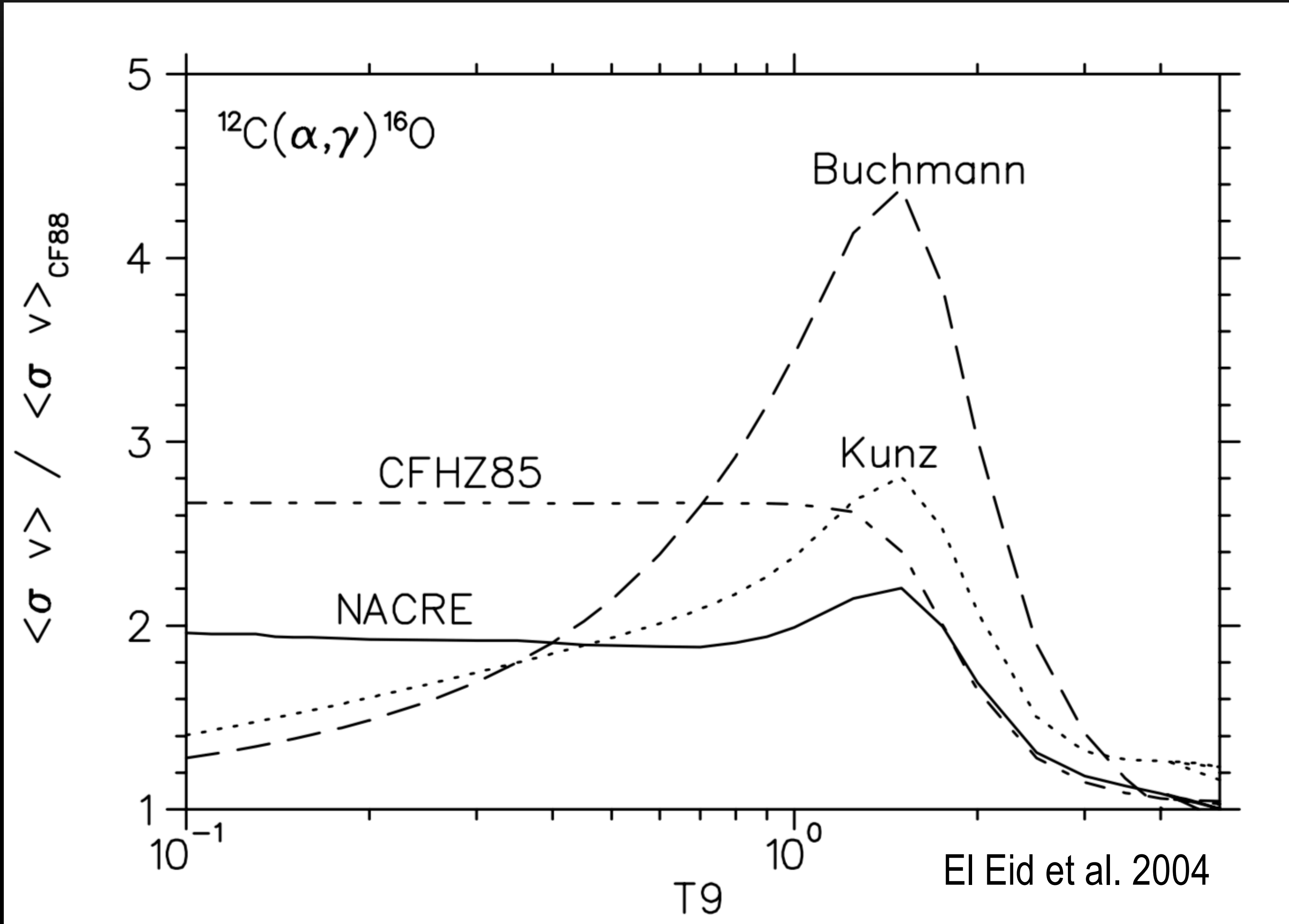
Proposed helium ignition at lower temperatures drastically changes blue loops



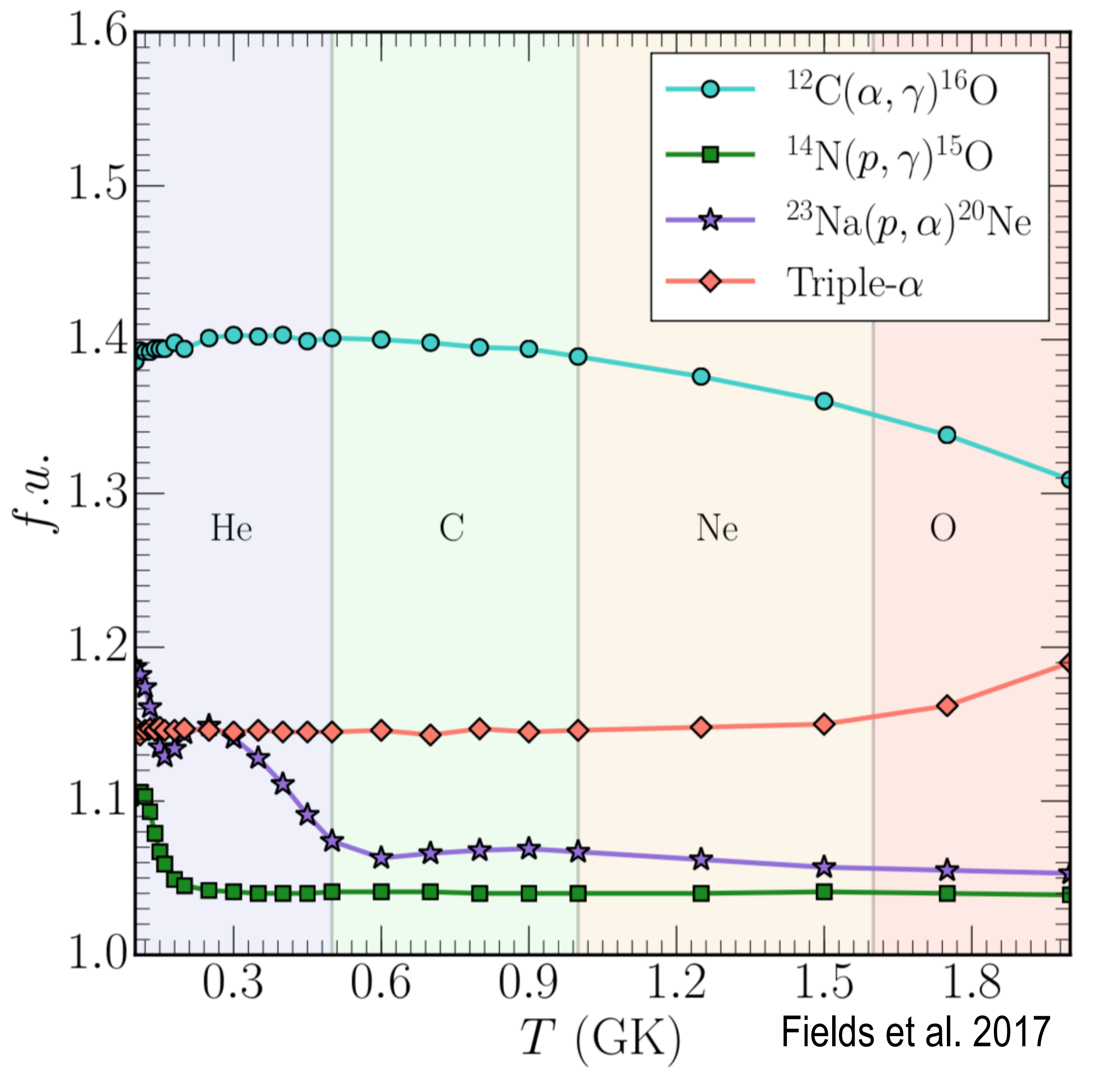


Morel et al. 2010

$^{12}C(\alpha,\gamma)^{16}O$ rate varies for different reaction rate sets



Assessed uncertainties in $^{12}C(\alpha,\gamma)^{16}O$ and 3α rates are modest



Fields et al. 2017

Minilab 1

a) Examine nominal evolution of model from Terminal-Age Main Sequence through core Helium burning

- $Z=0.02$, $Y=0.28$
- AGSS09 Opacities

b) Explore effects of nuclear reaction rate multipliers

Opacity Enhancements

- Proposed to explain hybrid pulsations of SPB/β Cep stars, 5-11 M_{sun} main-sequence stars that will become Cepheids
- Daszynska-Daszkiewicz et al. (2017) consider OPAL (LLNL), OP, and OPLIB (LANL) opacities, find best fit to SPB/β Cep star ν Eri pulsation observations with modified opacities with different temperature-dependent for each set of tables
- There is no atomic physics motivation for the opacity modifications, although those calculating opacities are searching for possible sources of error

Higher OPAL opacities introduced in 1992 reduced extent of blue loops and lowered luminosities for 5 M_{sun} evolution models. They also helped explain the 'bump' and 'beat' Cepheid period ratios.

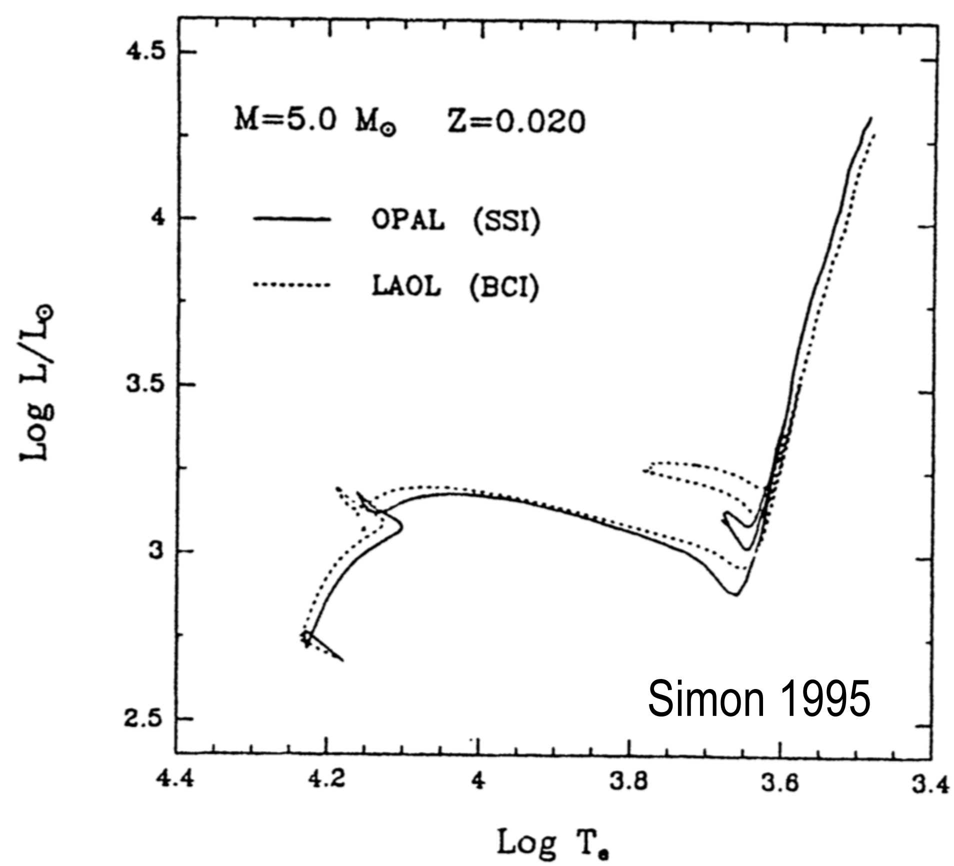
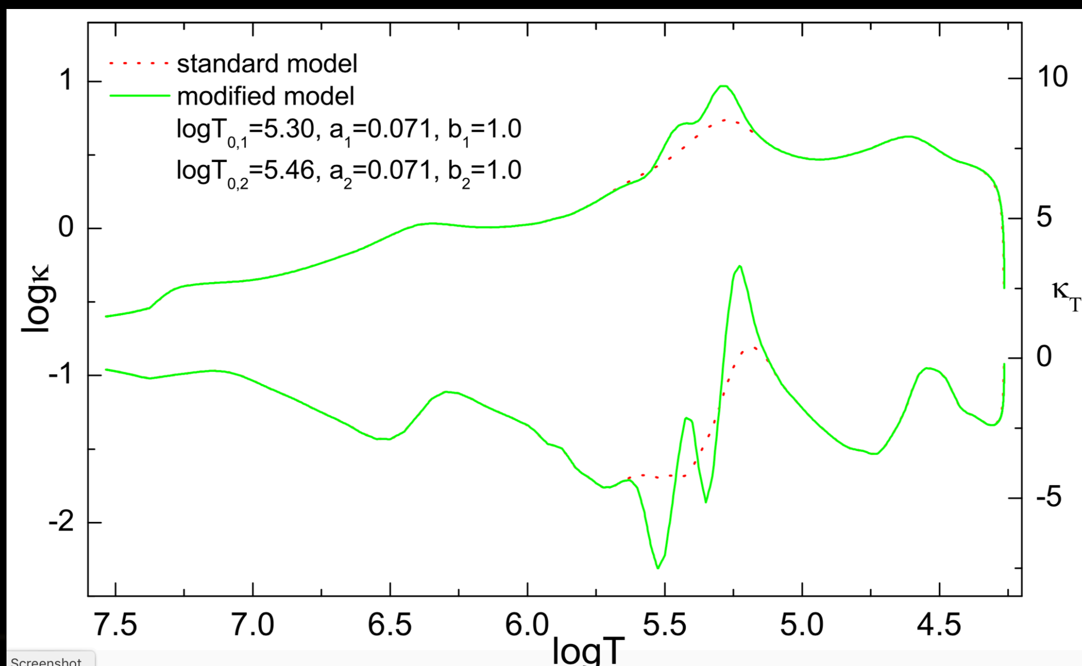


Fig. 4. Two 5 $M_\odot$ evolutionary trucks reproduced from Bressan et al. (1993). The OPAL blue loop fails to penetrate the instability strip, which covers $3.8 \le \log T_{eff} \le 3.7$.

Temperature-dependent opacity modifications proposed to improve agreement with pulsation data for hybrid main-sequence SPB/β Cep star ν Eri

$$\kappa(T) = \kappa_0(T)\left[1 + \sum_{i=1}^{N} b_i \exp\left(-\frac{(\log T - \log T_{0,i})^2}{a_i^2}\right)\right]$$

(ii) OPAL: $\log T_{0,1} = 5.30, a_1 = 0.082, b_1 = 0.5;$
$\log T_{0,2} = 5.46, a_2 = 0.082, b_2 = 1.5,$



Daszynska-Daszkiewicz et al. 2017

Minilab 2

a) Examine effect of of 0.95 opacity multiplier

b) Write a subroutine to apply the temperature-dependent opacity multiplier of Daszynska-Daszkiewicz et al. 2017 in run_star_extras.f and examine effects on evolution

MESA Radial Stellar Pulsation (RSP) Capabilities (Paxton et al. 2019)

Evolution of Cepheids (see, e.g., test suite 5M_cepheid_blue_loop)

Paxton et al. 2019 considered Z=0.008 models (Large Magellanic Cloud metal abundance)

Instability strip boundaries were plotted for Z=0.008 on H-R diagram plots

Can determine M, L, T_{eff}, R, Z, Y, for an evolution model in the Cepheid instability strip and input into RSP to calculate nonlinear radial pulsations

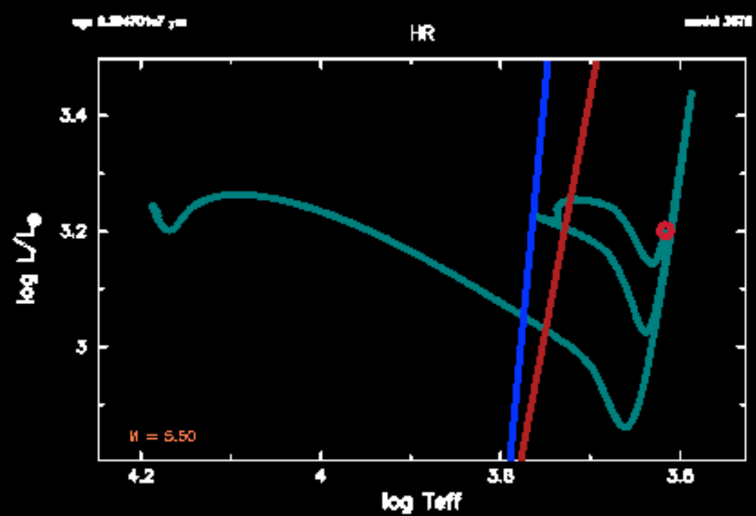
e.g., rsp_Cepheid in test suite

Cannot as yet input a composition profile directly from MESA evolution model; however, envelope composition is insignificantly changed during pre-AGB evolution, especially without mass loss

Envelope model includes about 150 zones from surface down to ~ 2 million K

May need to run 4000 or so RSP cycles to converge nonlinear model

Minilab Example H-R Diagrams for 5.5 and 8 M_{sun} Models



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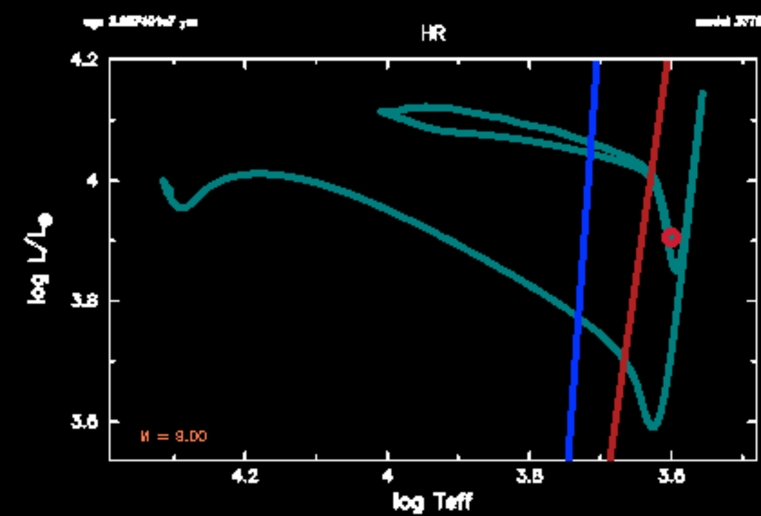

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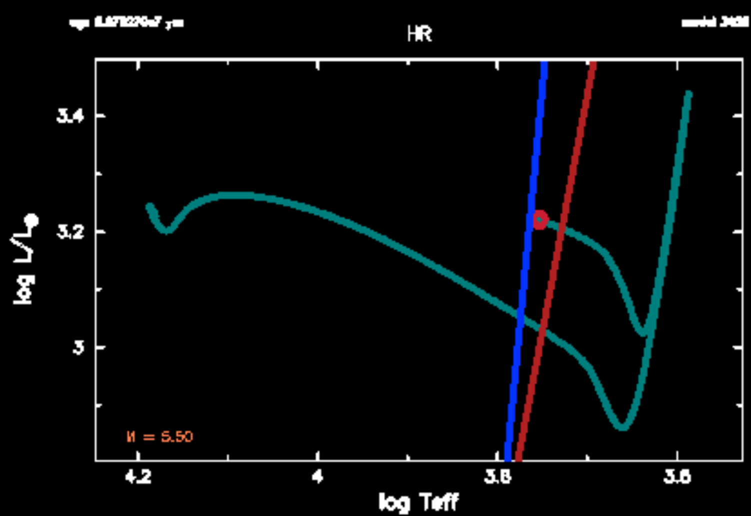

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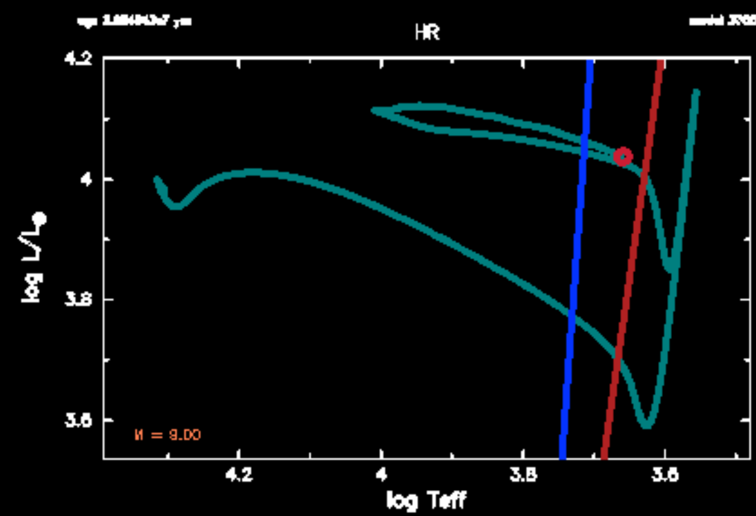

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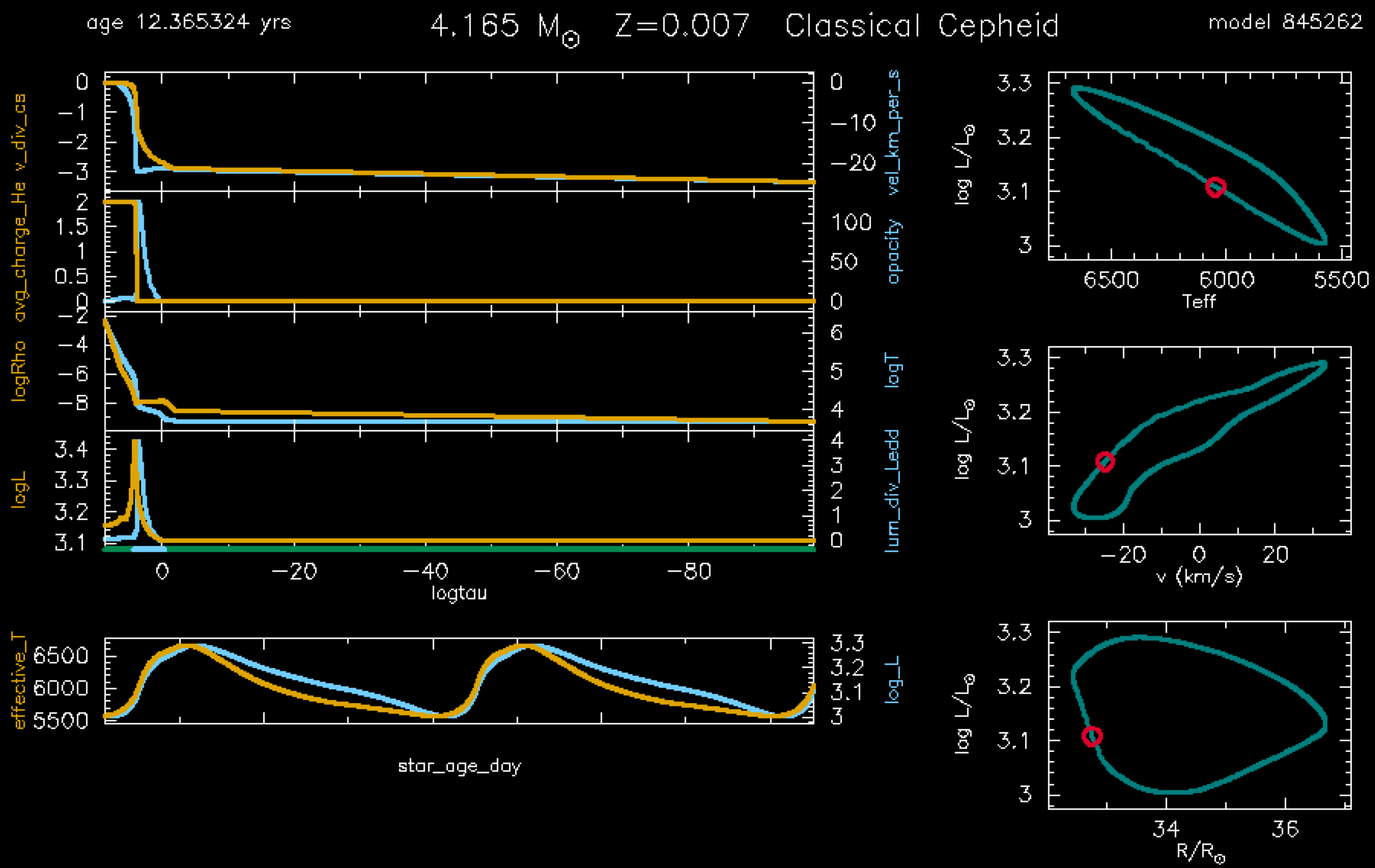
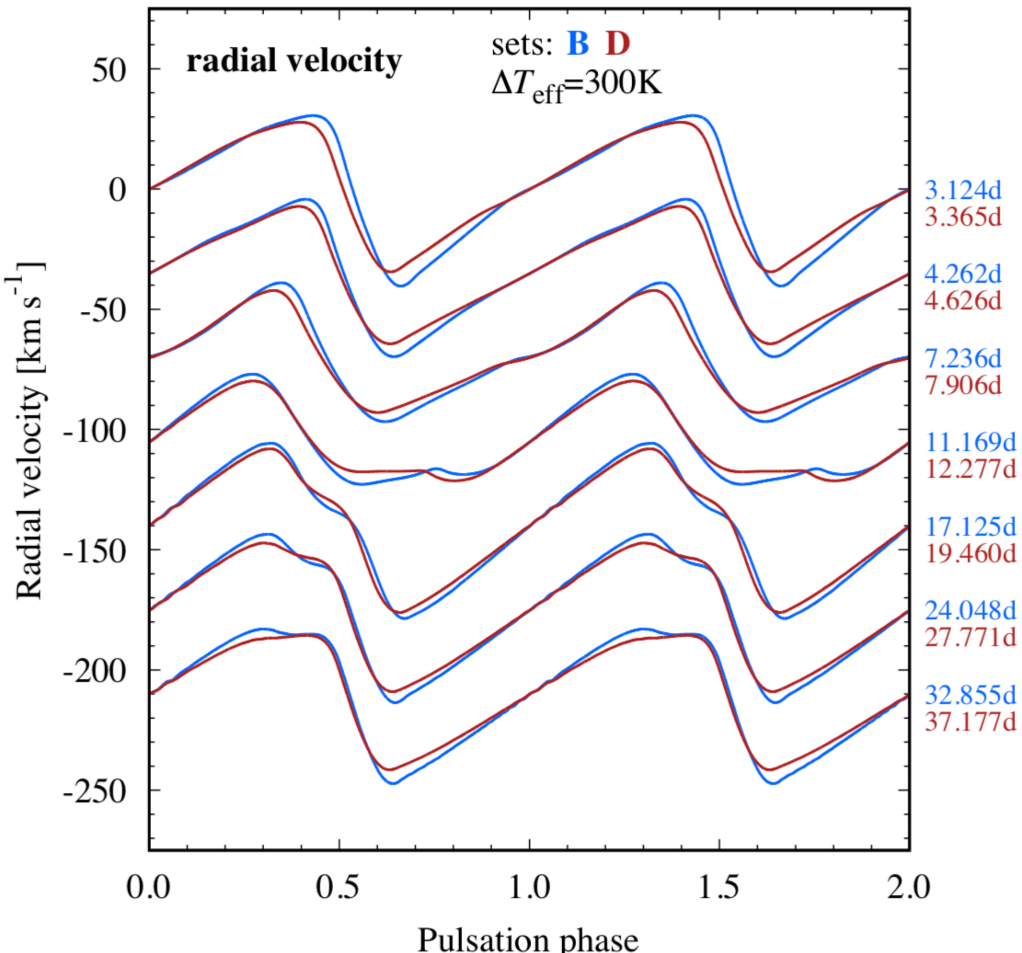
Example RSP PGSTAR Plot After Convergence



model_number	845262	v_surf_km_s	−24.6581705	effective_T	6.048E+03	star_mass	4.1650000
star_age_day	4.517E+03	radius	32.7596129	log_Teff	3.7816312	num_zones	150
time_step_sec	575.5057543	log_R	1.5153388	luminosity	1.284E+03	num_retries	0
rsp_num_periods	1394	rsp_period_in_days	3.9965677	log_L	3.1086388	num_backups	0

Cepheid Radial Velocity vs. Phase using RSP



Paxton et al. (2019)

Figure 14. *I*-band light curves (upper panel) and radial velocity curves (lower panel) for the Cepheid models with a $\Delta T_{\rm eff} = 300\,{\rm K}$ offset from the blue edge and convective sets B and D. Light curves are labelled with their pulsation periods and offset vertically by 0.5 mag or 35 $\rm km\,s^{-1}$ to facilitate comparison. Radial velocity curves follow the same order.

RSP models of 4.5, 5.0, 6.0, 7.0, 8.0, 9.0, and 10.0 M_{sun}

X=0.736, Z=0.008

Maxilab rsp (crowdsource)

Calculate nonlinear radial stellar pulsation envelope models for models in Cepheid instability strip

Divide models among those at table:

a) Nominal model

b) Model with reaction-rate multipliers x 3

c) Model with opacity multiplier x 0.95

Report results on google docs

Abstract (1)

Since the discovery of the Cepheid Period-Luminosity relation by Henrietta Leavitt in 1908, pulsating Cepheid variables have been used to determine distances around the Milky Way, to the LMC and SMC, and to nearby galaxies, and to cross-correlate with other distance indicators such as Type Ia supernovae.

Classical Cepheids are core-helium burning stars of masses 4 to ~15 M_{sun}. In the H-R diagram, in most stellar evolution simulations, these stars 'blue loop' to hotter temperatures during the core helium-burning phase. Cepheid pulsations are driven by the kappa (opacity) mechanism in the second helium ionization region in the stellar envelope around 50,000 K. They pulsate in radial, first overtone, or second overtone modes with typical periods of 5-10 days.

Several problems persist in the calibration of the distance scale and interpretation of Cepheid observations. First, the Hubble constant derived from distance scales based on Cepheids differs from that obtained using observations of the cosmic microwave background by about four sigma. Second, Cepheid masses derived from pulsation periods or binary dynamics are generally lower than those derived from stellar evolution models. Third, problems with reproducing period ratios of 'bump' and 'beat' Cepheids were largely resolved by increased opacities in the early 1990s, but some discrepancies still remain.

Abstract (2)

Recent efforts have been dedicated to investigating the effects of metallicity, helium abundance, pulsation-driven mass loss, rotation, convection and overshooting prescriptions for modifying the evolution tracks to reduce or remove the Cepheid mass discrepancy. While these approaches are promising, either alone or in combination, to solve the problem, more work is required to distinguish between possible solutions.

Here we investigate the effects of opacity modifications and nuclear reaction rates on Cepheid evolution using the MESA stellar evolution code (Paxton et al. 2011, 2013, 2015, 2019). We explore the consequences of varying the triple-alpha and the ^{12}C(alpha, gamma)^{16}O rate. We also consider the effects of an overall opacity multiplier, or, alternatively, a temperature-dependent multiplier on the opacity profile motivated by main-sequence β Cep variables (e.g., Daszynska-Daszkiewicz et al. 2017) that will evolve into Cepheids. We make use of MESA's new nonlinear radial pulsation capability including time-dependent convection to calculate Cepheid light curves, radial velocities and periods.