Uncertainties on the evolutionary tracks of medium mass stars

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Our group

Classical Cepheids as testbeds for stellar evolution and pulsation theories

Radek Smolec - Radial Stellar Pulsations (RSP), MESA developer, constructing a huge grid of evolutionary models of Cepheids

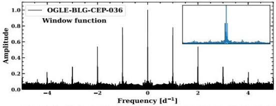
Vincent Hocdé - Estimates for metallicity of Cepheids from the shape of light curves, evolution of the Cepheid Y Oph, radial velocity curves

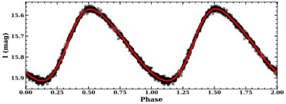
Rajeev Singh Rathour - Finding pulsation flavours in Cepheids, Non-evolutionary period changes

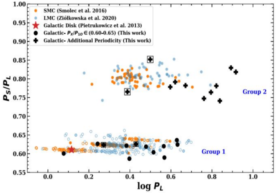
Oliwia Ziółkowska - Uncertainties on evolutionary tracks of medium mass stars, Cepheids in double-lined eclipsing binaries

Our group - Rajeev Singh Rathour

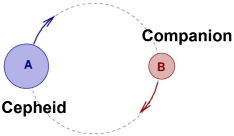
Finding and characterizing pulsation flavors in Cepheids

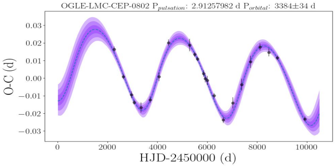




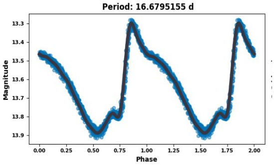


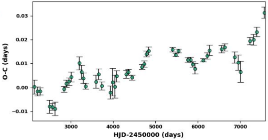
Searching Cepheids in binary systems





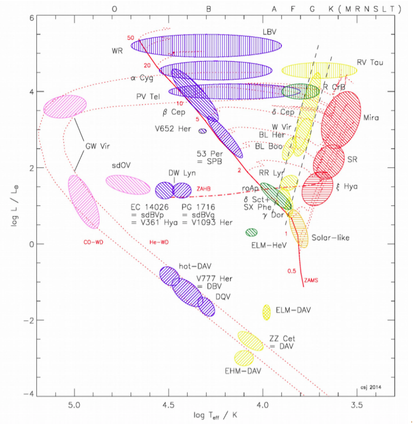
Mechanism explaining erratic Period changes in Cepheids





Classical Cepheids

- ⋆ young, medium mass stars ($\sim$ 3-14 $M_\odot$);
- ⋆ classical pulsators, crossing the instability strip (IS) 3 times;
- ⋆ most of them are on the blue loop, burning helium in the core;
- ⋆ pulsate radially with high amplitudes;
- ⋆ period-luminosity relation;
- ⋆ excellent laboratories for evolution and pulsation theories;



Jeffery&Saio (2016)

More about them in **Felipe's** talk tomorrow morning!

Motivation

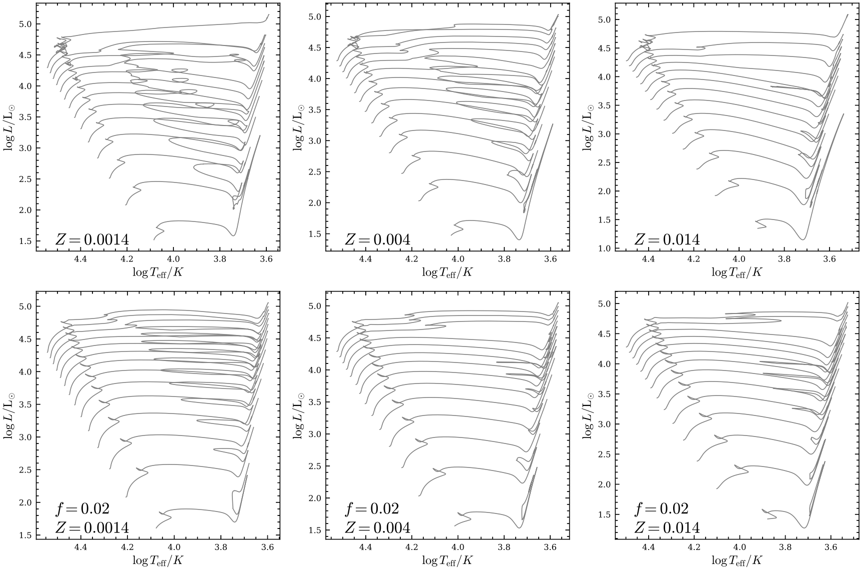
- ⋆ free parameters;
- ⋆ simplified descriptions of physical effects;
- ⋆ many, equally valid recipes for microphysics.

- ⋆ The goal: estimate uncertainties rising from this freedom.

MESA

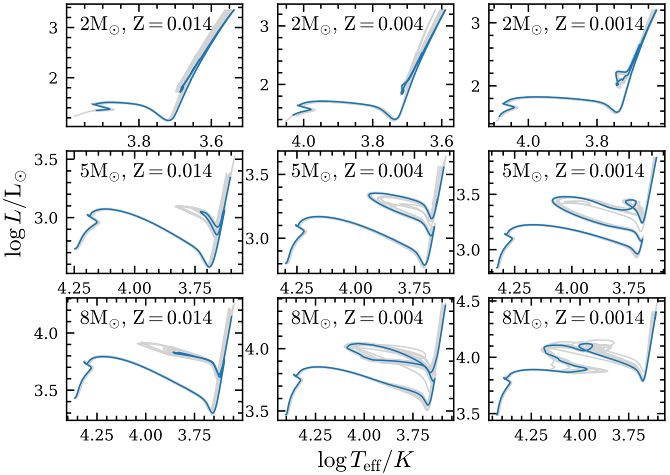
- ⋆ Modules for Experiments in Stellar Astrophysics v. r.21.12.1;
- ⋆ Calculated models for M=2-15 $M_{\odot}$ and Z=0.0014, 0.004, 0.014,
- ⋆ for two values of overshooting from the convective core on the main sequence $f = 0.00$, 0.02

Reference tracks calculated with MESA



Evolutionary tracks calculated with MESA

For each M, Z we have a reference model and 22 other models (grey) from various sets.

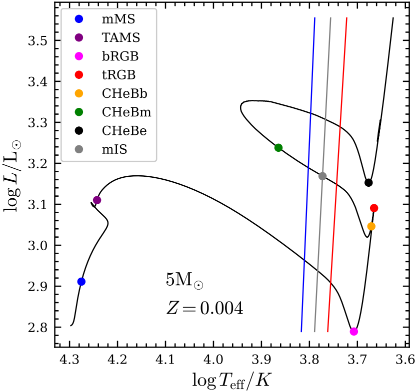


Set	Varied options
RES_A	`time_delta_coeff = 0.50` + `mesh_delta_coeff = 0.50`
RES_B	`time_delta_coeff = 0.25` + `mesh_delta_coeff = 0.50`
RES_C	`time_delta_coeff = 0.50` + `mesh_delta_coeff = 0.25`
RES_D	`time_delta_coeff = 0.25` + `mesh_delta_coeff = 0.25`
RES_E	`time_delta_coeff = 1.00` + `mesh_delta_coeff = 1.00` + default MESA resolution controls
MLT_A	Henyey (Henyey et al. 1965)
MLT_B	ML1 (Böhm-Vitense 1958)
MLT_C	Cox (Cox & Giuli 1968)
MLT_D	Mihalas (Mihalas 1978)
ATM_A	model atmosphere tables (Hauschildt et al. 1999a,b; Castelli & Kurucz 2003)
ATM_B	$T-\tau$ relation Eddington
ATM_C	$T-\tau$ relation Krishna_Swamy (Krishna Swamy 1966)
ATM_D	$T-\tau$ relation solar_Hopf (Paxton et al. 2013)
ATM_E	$T-\tau$ relation Trampedach_solar (Ball 2021; Trampedach et al. 2014)
NET_A	$^{12}C(\alpha,\gamma)^{16}O$ from Kunz et al. (2002) + $^{14}N(\alpha,\gamma)^{15}O$ from Cyburt et al. (2010) + pp_and_cno_extras.net
NET_B	$^{12}C(\alpha,\gamma)^{16}O$ from Kunz et al. (2002) + $^{14}N(\alpha,\gamma)^{15}O$ from Cyburt et al. (2010) + mesa49.net
NET_C	$^{12}C(\alpha,\gamma)^{16}O$ from Angulo et al. (1999) + $^{14}N(\alpha,\gamma)^{15}O$ from Cyburt et al. (2010) + pp_and_cno_extras.net
NET_D	$^{12}C(\alpha,\gamma)^{16}O$ from Kunz et al. (2002) + $^{14}N(\alpha,\gamma)^{15}O$ from Angulo et al. (1999) + pp_and_cno_extras.net
NET_E	$^{12}C(\alpha,\gamma)^{16}O$ from Angulo et al. (1999) + $^{14}N(\alpha,\gamma)^{15}O$ from Angulo et al. (1999) + pp_and_cno_extras.net
CONV_A	Predictive Mixing + Schwarzschild criterion
CONV_B	Predictive Mixing + Ledous criterion
CONV_C	Sign Change + Schwarzschild criterion
CONV_D	Predictive Mixing + Schwarzschild criterion + including predictive mixing in the envelope
MIX_A	Asplund et al. (2009)
MIX_B	Grevesse & Sauval (1998)
MIX_C	Grevesse & Noels (1993)
DIFF_A	atomic diffusion off
DIFF_B	atomic diffusion on
INT3_A	cubic interpolation of opacity tables off
INT3_B	cubic interpolation of opacity tables on

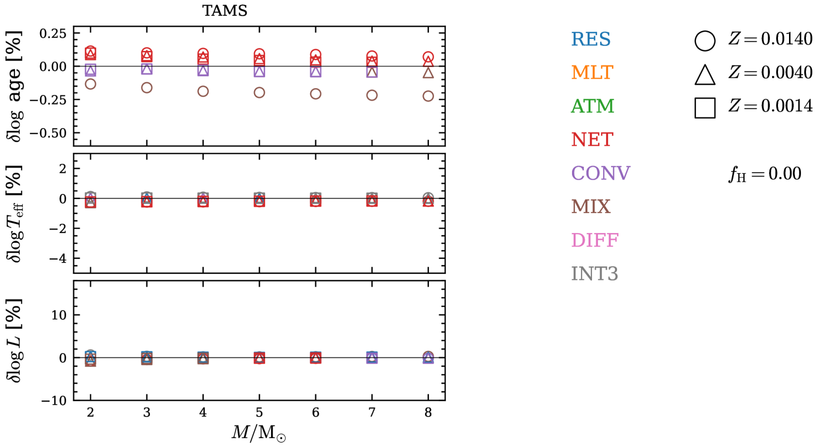
Benchmark points

We estimate uncertainties at 8 specific stages of evolution:

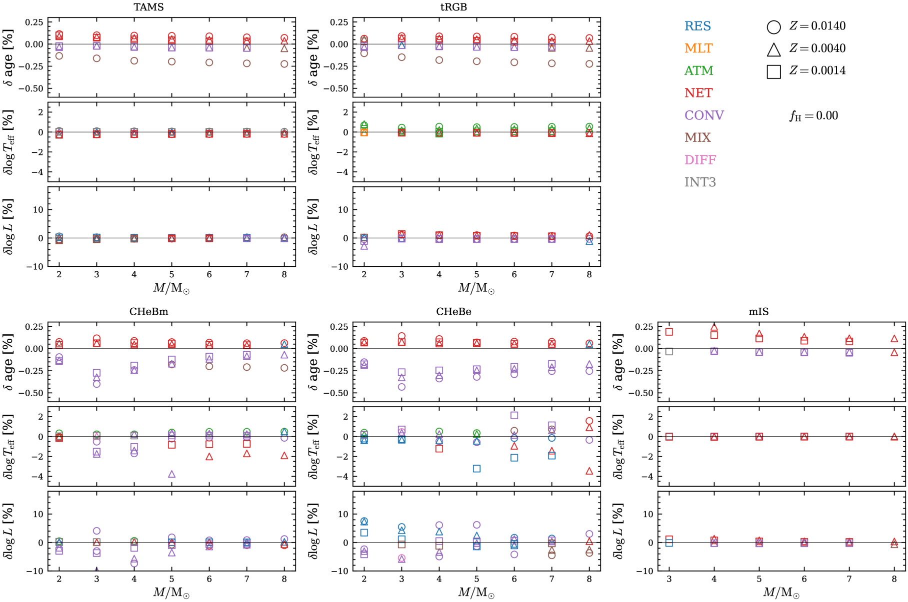
- ⋆ mMS (middle of Main Sequence)
- ⋆ TAMS (Terminal Age Main Sequence)
- ⋆ bRGB (base RGB)
- ⋆ tRGB (tip RGB)
- ⋆ CHeBb (Core Helium Burning, begin)
- ⋆ CheBm (Core Helium Burning, middle)
- ⋆ CheBe (Core Helium Burning, end)
- ⋆ mIS (middle of Instability Strip)



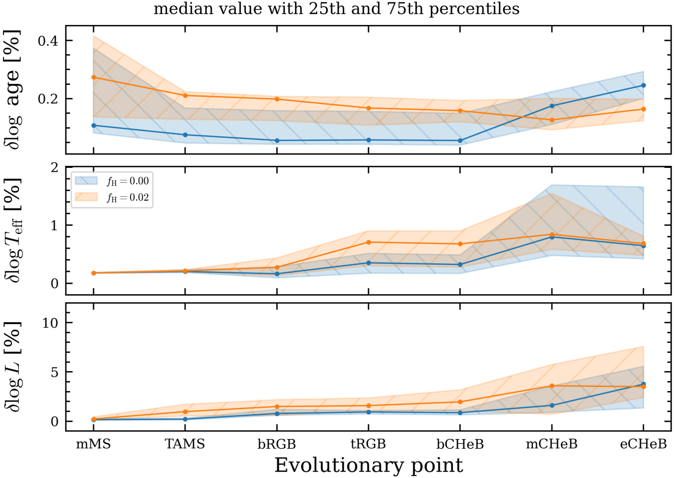
Uncertainties at TAMS - example



Evolution of the uncertainties



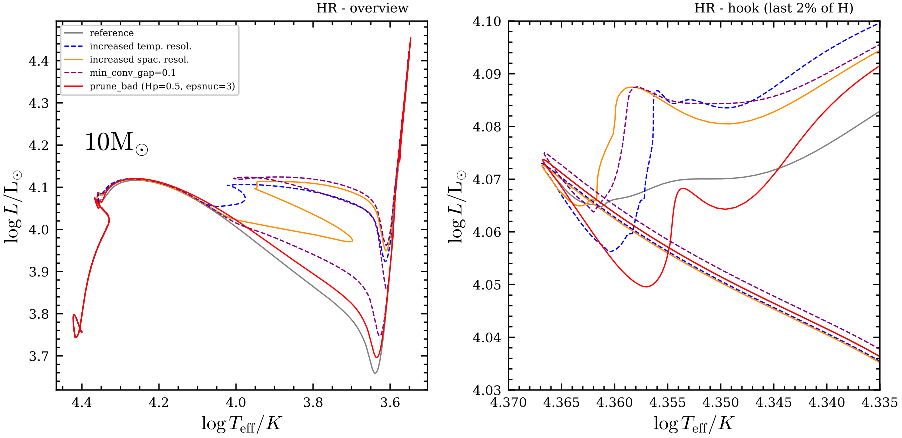
Median from all masses and metallicities; moderate vs. no overshooting



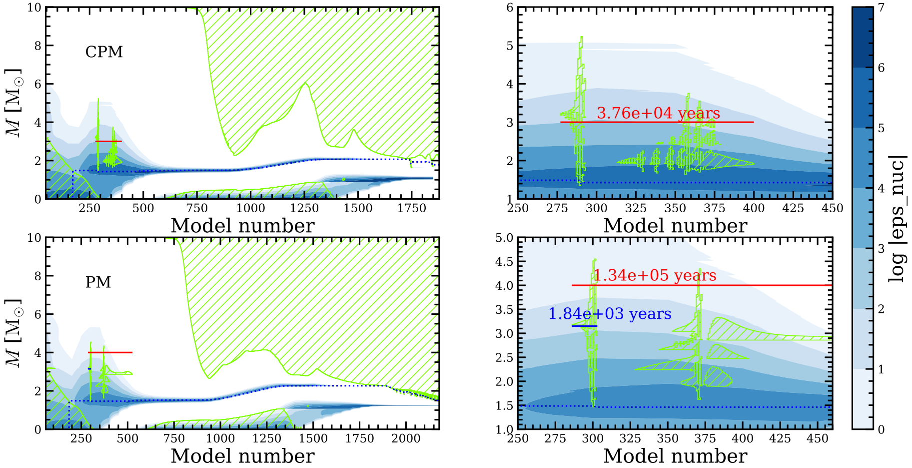
Conclusions for lower masses

- ⋆ No clear trends with M and Z;
- ⋆ For T_{eff} and L the biggest uncertainties appear for convective boundaries and nuclear reactions;
- ⋆ Uncertainties during CHeB are the highest;
- ⋆ The effects of core overshoot are strong at all evolutionary phases;

Higher masses - lack of convergence



Higher masses - lack of convergence - thin convective shells



Conclusions for higher masses

- ⋆ More massive models need to be investigated carefuly with Kippenhahn diagrams to asses how severe the thin shell problem is for a given M,Z and how it affects subsequent evolution;

- ⋆ Analysing the differences of surface CNO abundances is a very challenging task. Quite often there is no clear systematics across M,Z and evolutionary phase