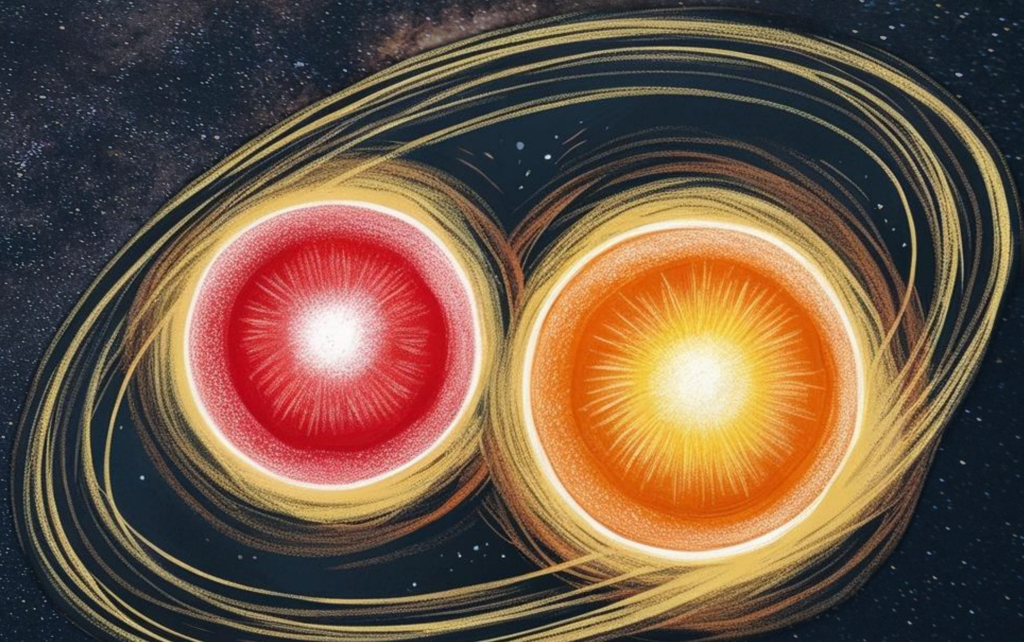
Binary and Multiple Stars in the Era of Big Sky Surveys,
Litomyšl, 2024

A novel q-PED method: precise physical properties of a merger-origin binary Cepheid OGLE-LMC-CEP-1347

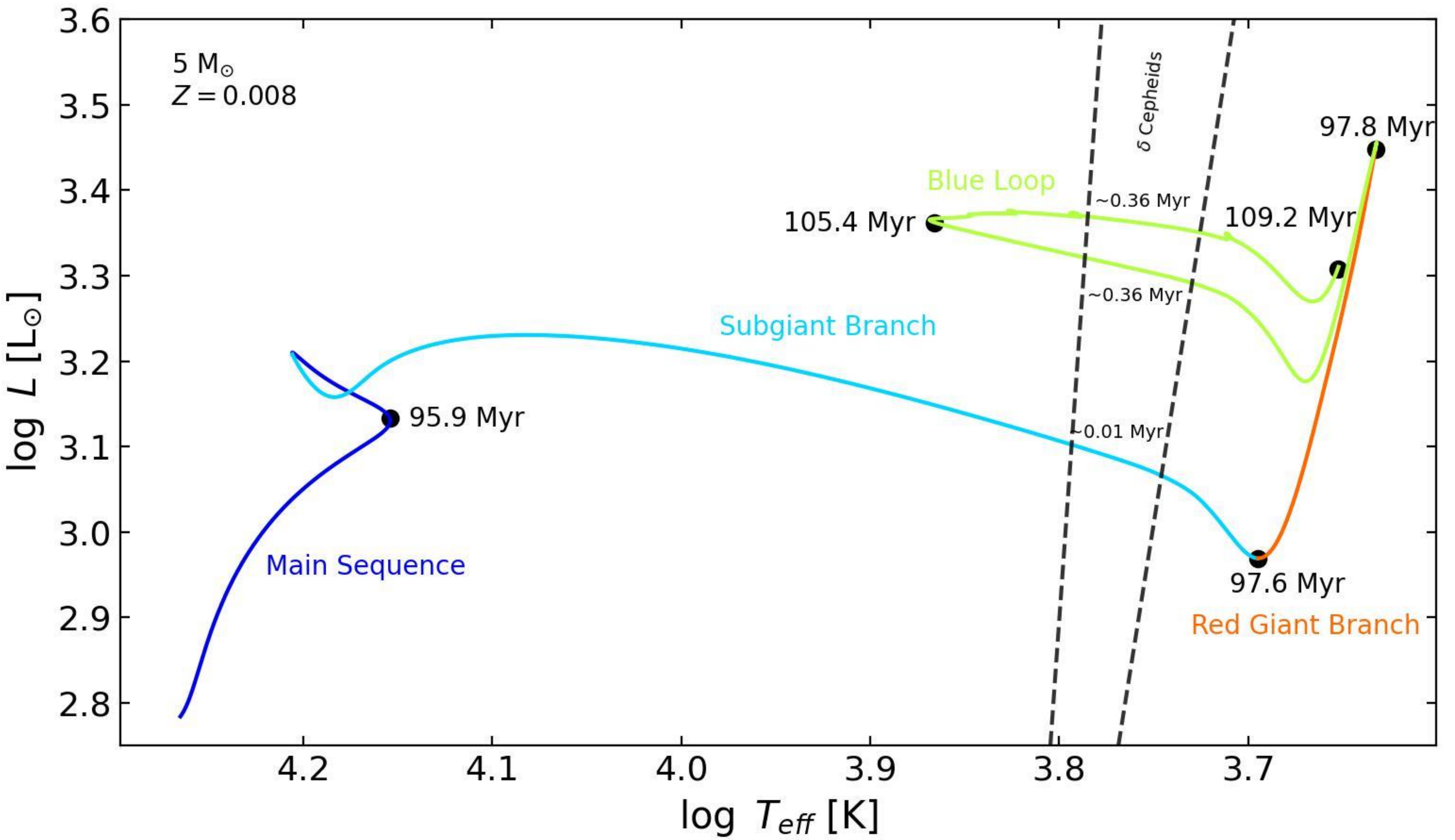


Felipe Espinoza Arancibia
Supervisor: Bogumił Pilecki

CAMK PAN

Classical Cepheids

- ➢ $\sim 3\ - 13\ M_{\odot}$
- ➢ Located in the classical instability strip (IS)
- ➢ Pulsations are excited by the κ - γ mechanism



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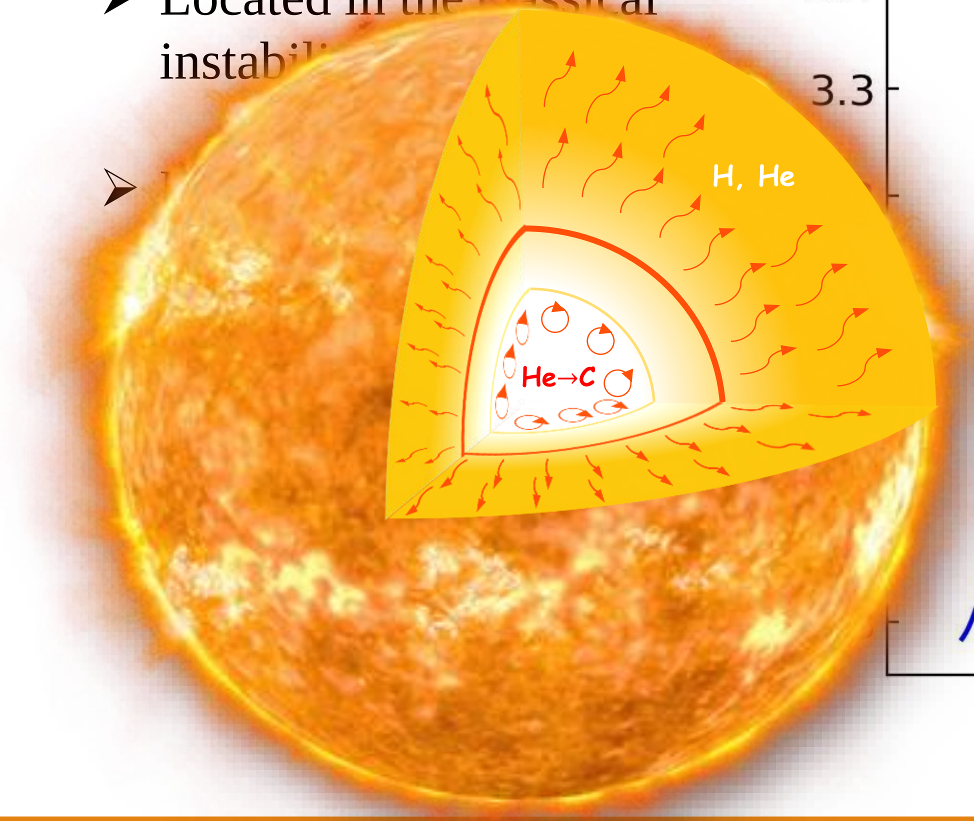

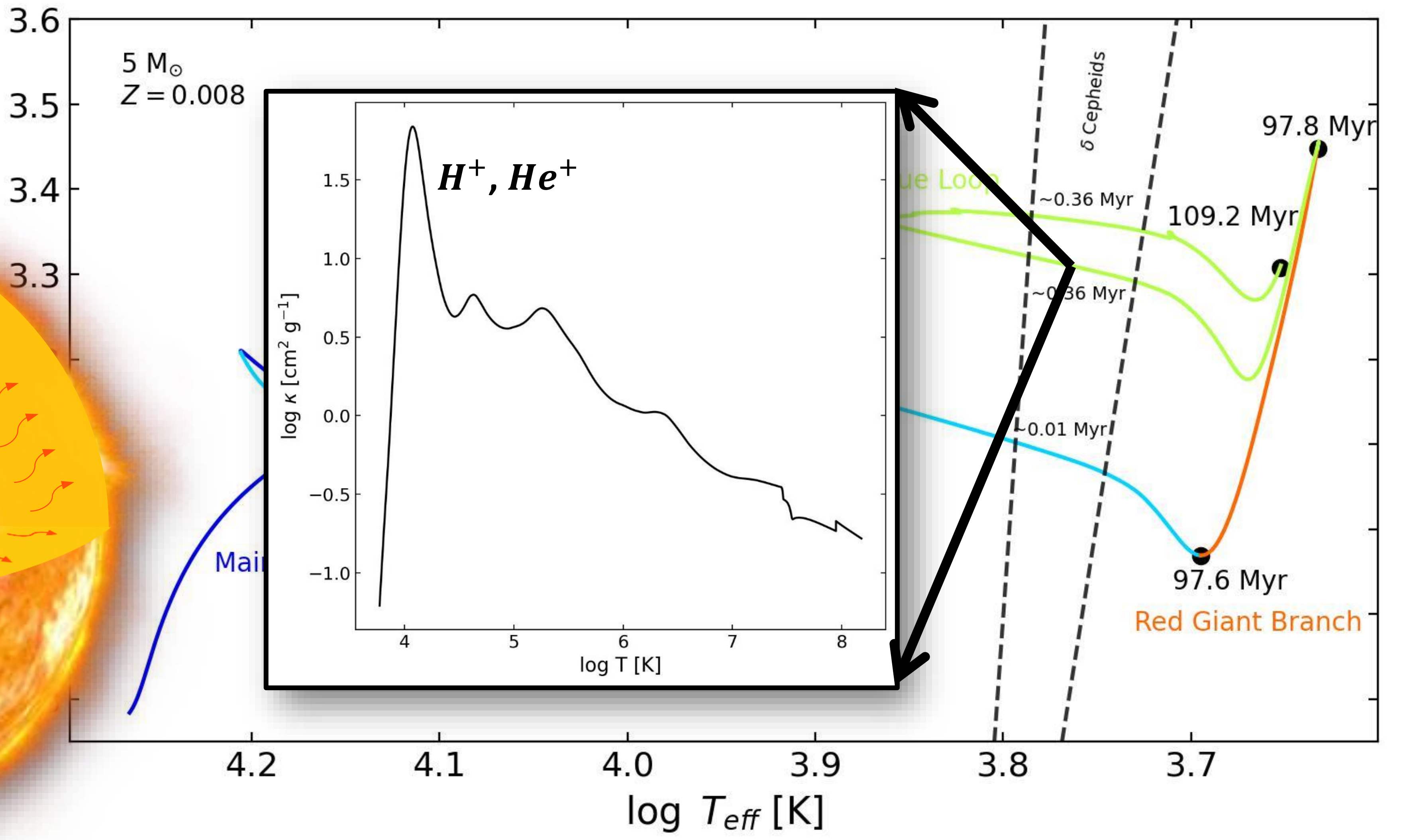

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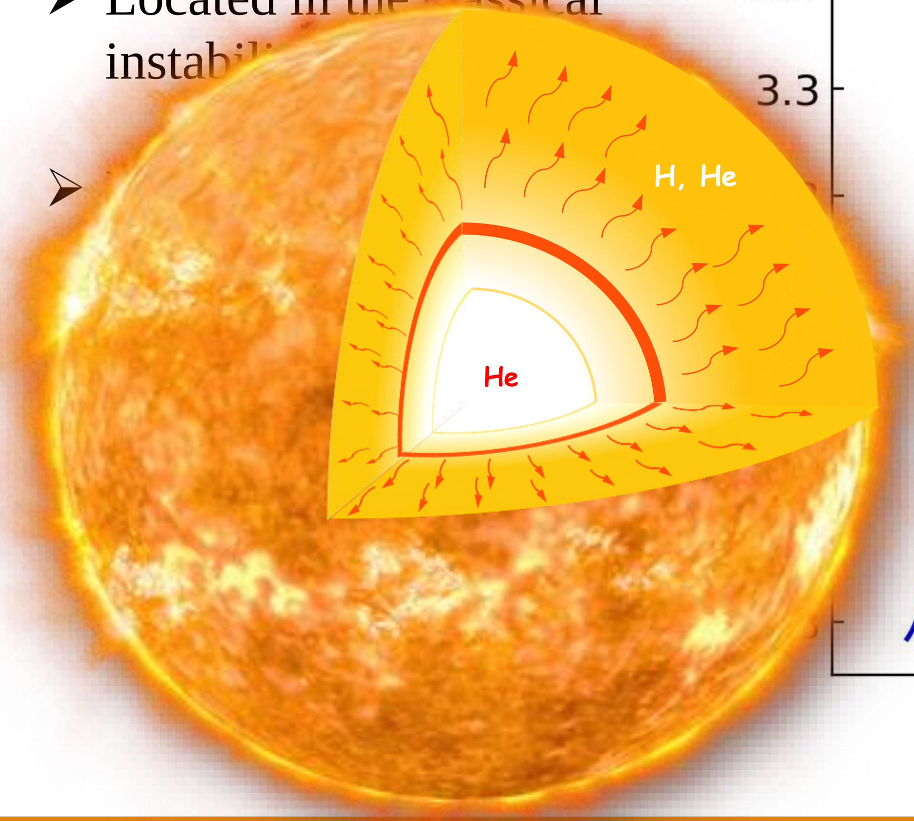
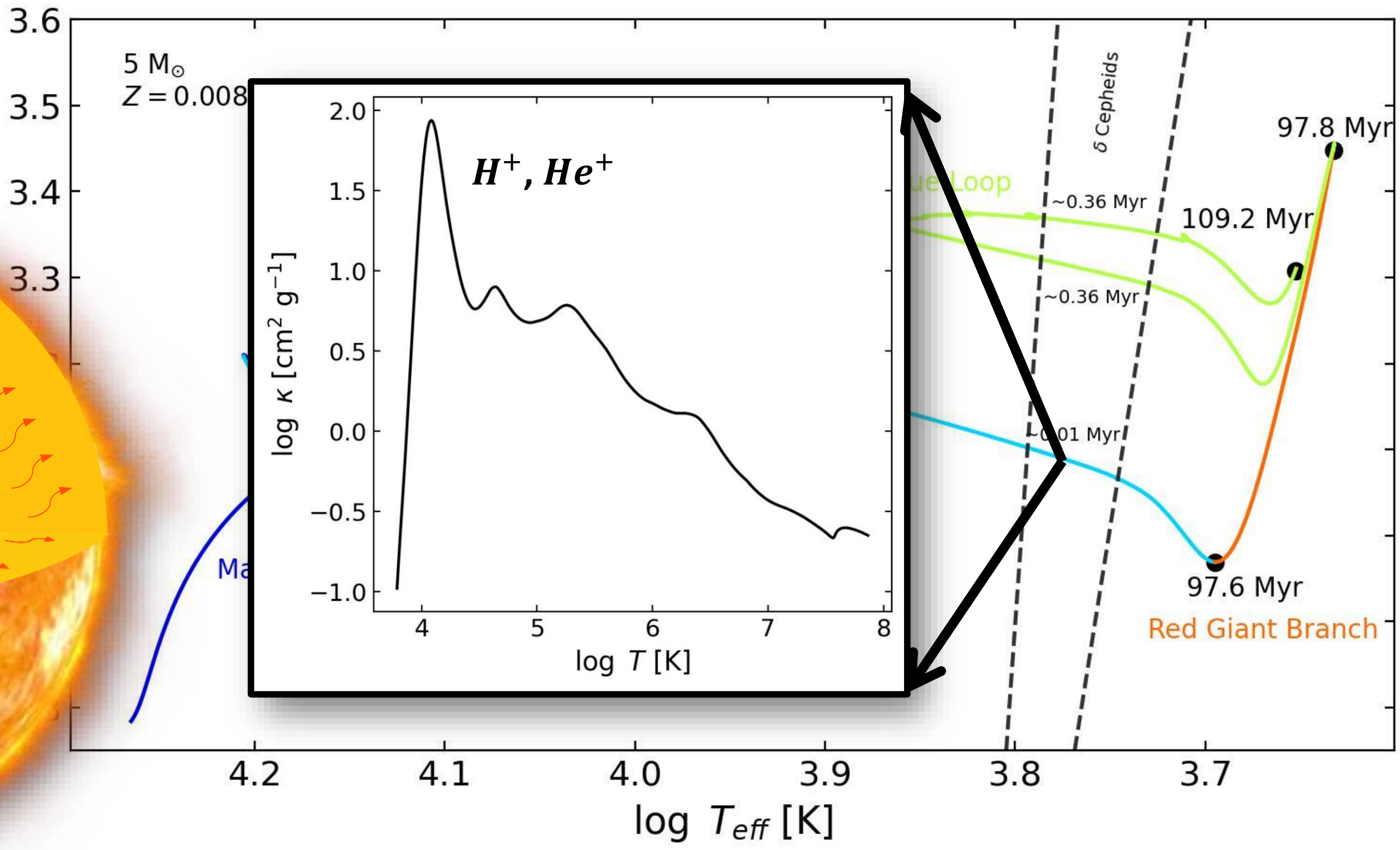


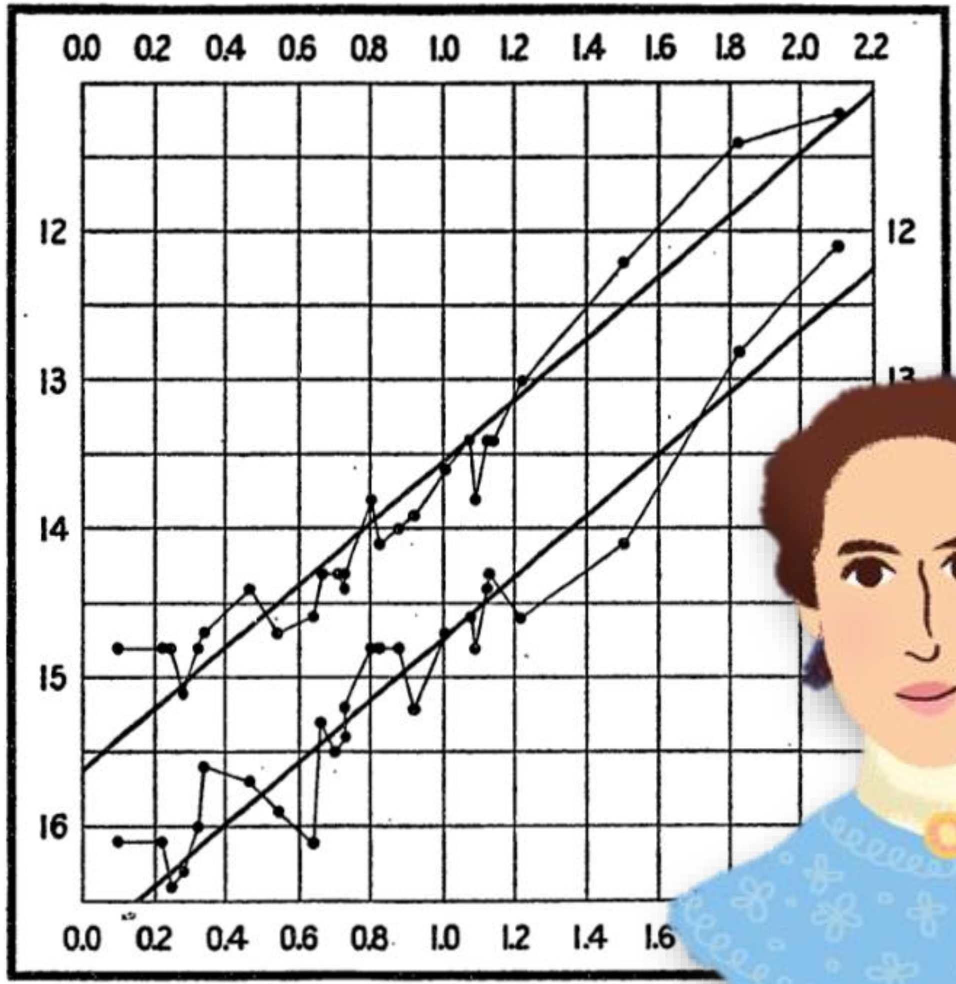


Classical Cepheids

- $\sim 3 - 13\ M_{\odot}$
- Located in the classical instability strip (IS)
- Pulsations are excited by the κ - γ mechanism
- In 1912, Henrietta Leavitt discovered that variables with longer periods had brighter magnitudes.

$$M = \alpha \log P + \delta + \gamma[Fe/H]$$

Leavitt & Pickering (1912, Harv. Obs. Circ., 173)



Source: Abigail Malate

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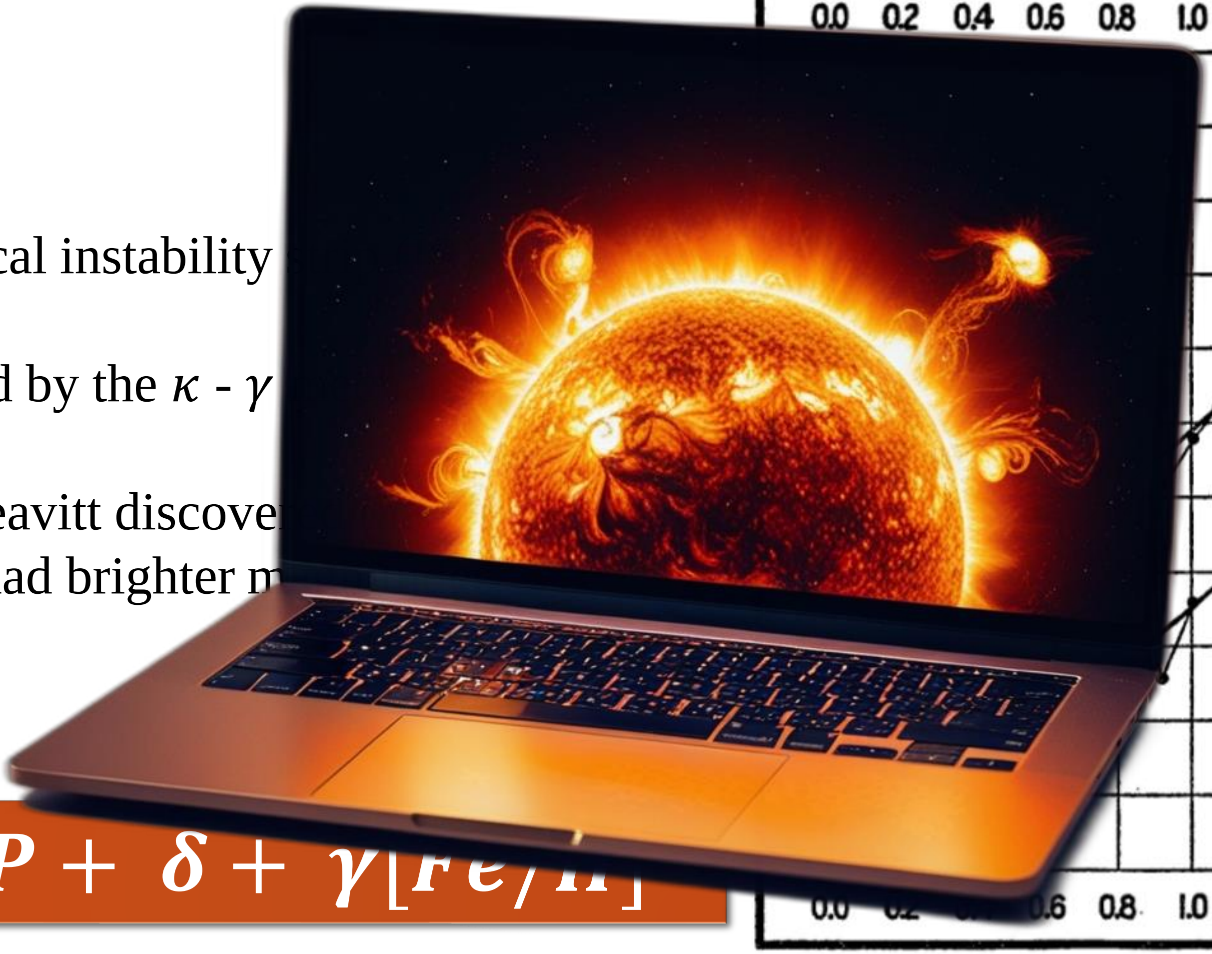

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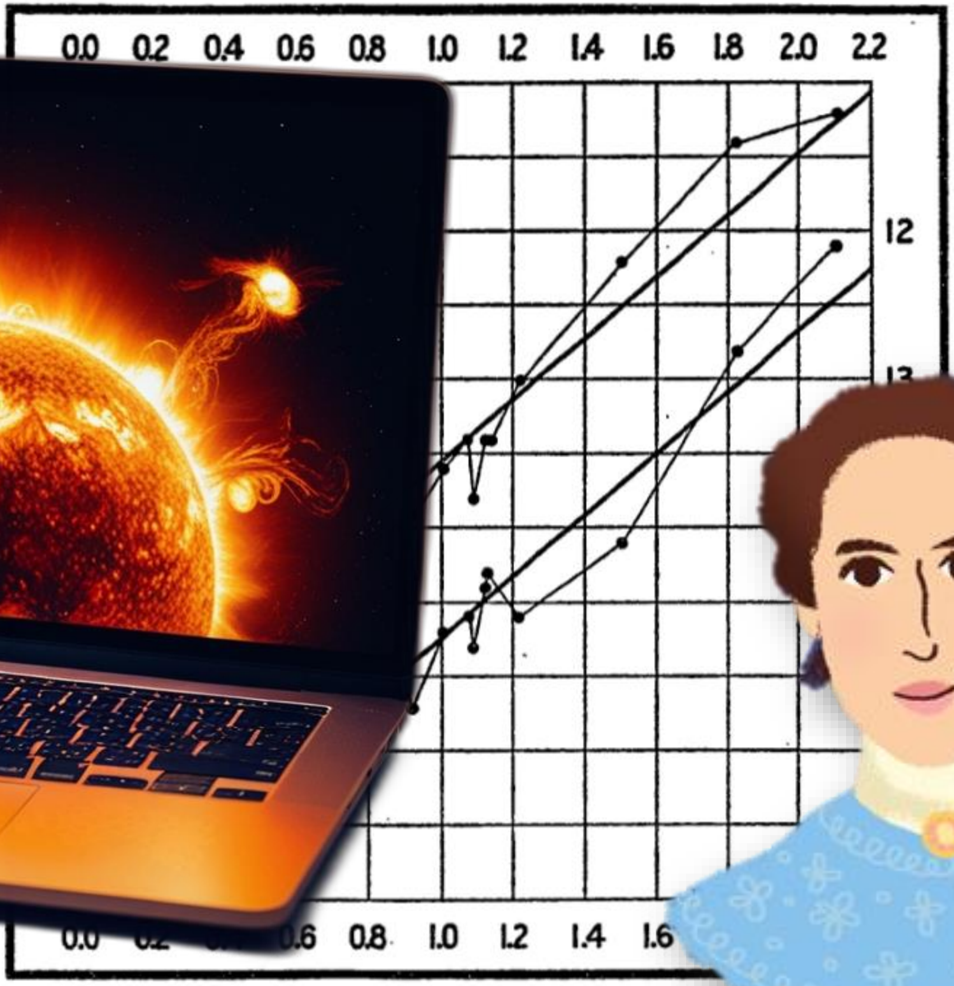


Source: Abigail Malate

$$M = \alpha \log P + \delta + \gamma[Fe/H]$$

MESA + RSP

Modules for Experiments in Stellar Astrophysics

- Mixing-length parameter $\boldsymbol{\alpha_{mlt} = 1.939}$.
- **Predictive mixing scheme** to determine the convective boundaries (Paxton et al. 2018).
- Exponential core and envelope overshooting with parameters $\boldsymbol{f_{core} = 0.015}$ and $\boldsymbol{f_{env} = 0.024}$.
- RBG mass-loss using Reimers (1975) prescription, with $\boldsymbol{\eta_R = 0.3}$.

Radial Stellar Pulsations

- Model large-amplitude, self-excited, nonlinear pulsations that stars develop when they cross instability domains in the HR diagram.

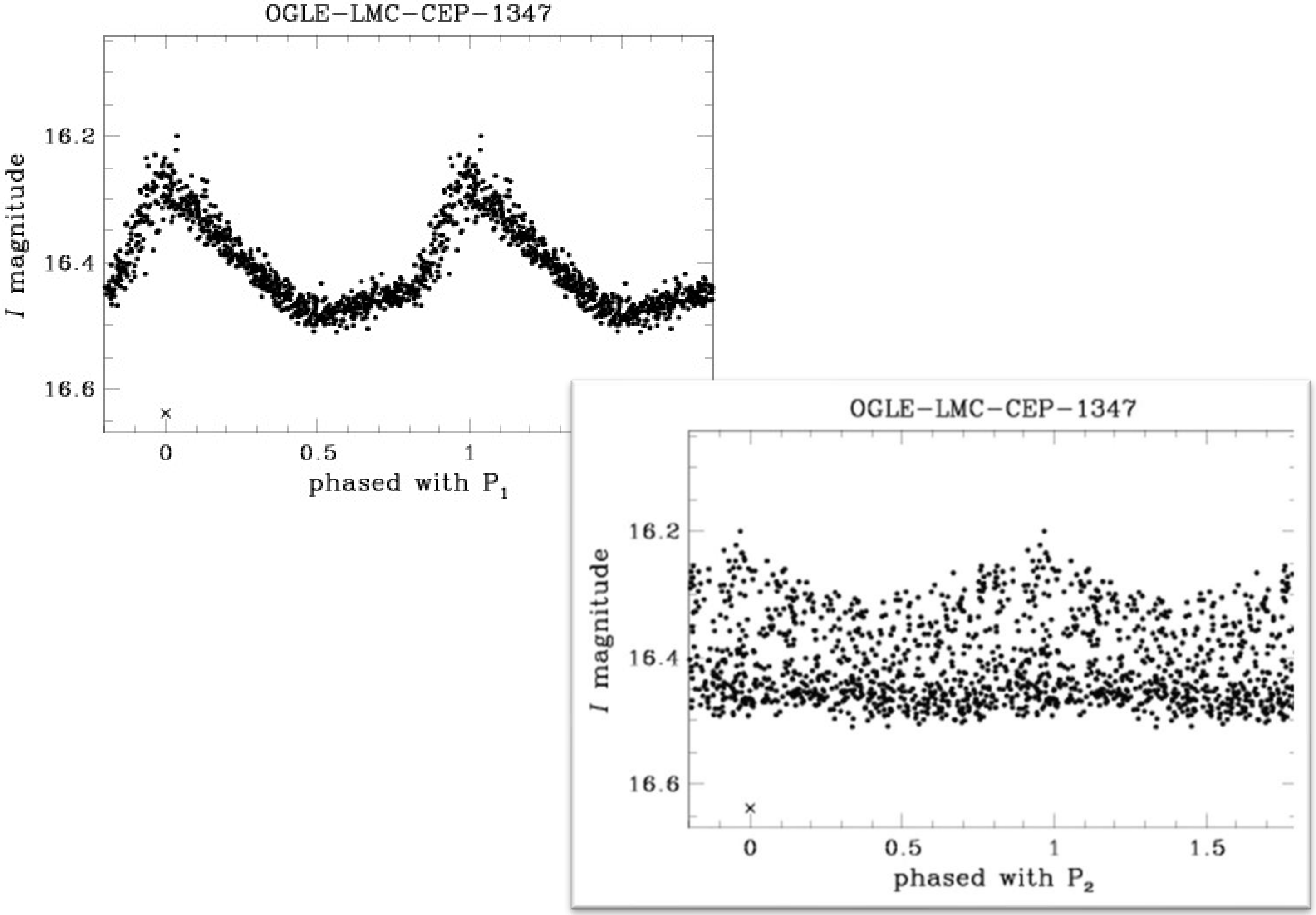
- From given stellar parameters ($\boldsymbol{M, L, T_{eff}, X}$, **and** $\boldsymbol{Z}$), RSP can obtain periods, and growth rates.

https://docs.mesastar.org/

OGLE-LMC-CEP-1347

- **Double-lined binary (SB2) system** from the sample of **41** SB2 candidates suitable for dynamical mass measurements of Pilecki et al. (2021).

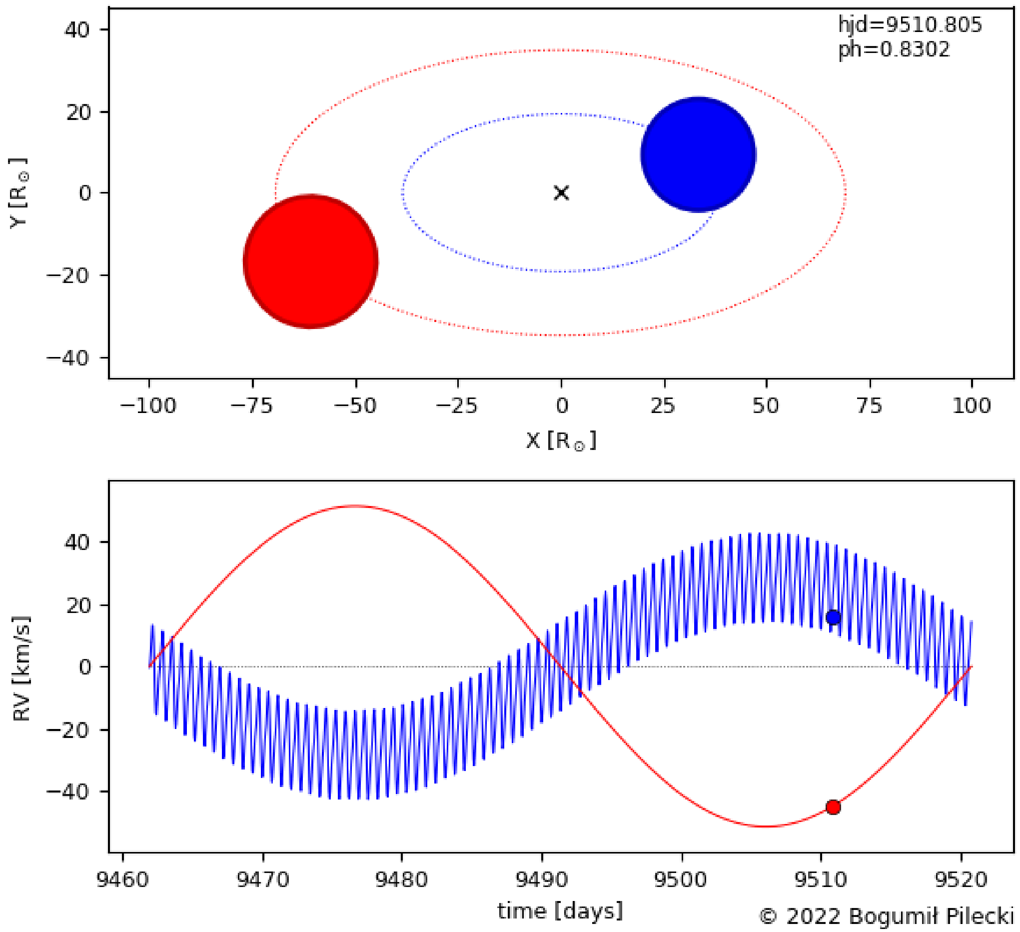
- CEP-1347 is a double-mode Cepheid with a first-overtone (1O) period of $\boldsymbol{P_1 = 0.690}$ **day** and second-overtone (2O) period of $\boldsymbol{P_2 = 0.556}$ **day** (Soszyński et al. 2017).



Pilecki B., Thompson, I. B., Espinoza-Arancibia, F. et al. 2022, ApJL, 940, L48

OGLE-LMC-CEP-1347

The orbital period ($P_{orb} = 59\ d$) of the system is **five times shorter than the shortest** known to date for a binary Cepheid



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OGLE-LMC-CEP-1347

Companion: at least two times fainter, redder and less massive than the Cepheid. Thus at the subgiant or more advanced evolutionary stage.

Cepheid: has to be a product of a merger of two less massive stars, to match the characteristics of the system

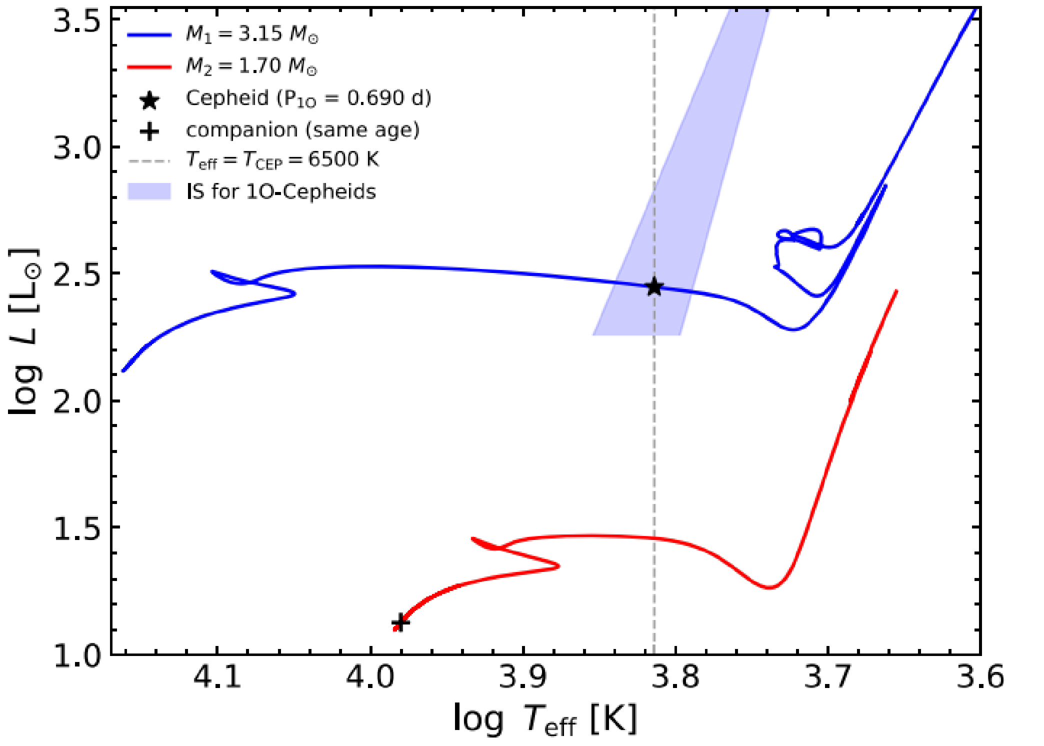


Figure 4. Example evolutionary tracks for stars with masses expected for components of OGLE-LMC-CEP-1347 assuming single star evolution. The position of the Cepheid with a 1*O* period of 0.690 day and the corresponding instability strip are shown. The hypothetical position of the companion with the same age as the Cepheid clearly contradicts the observational data (it should be cooler than the Cepheid).

Pilecki B., Thompson, I. B., Espinoza-Arancibia, F. et al. 2022, ApJL, 940, L48

Determining precise physical parameters of binary Cepheids

Pulsation + Evolutionary models

Mass ratio (q) + Distance (+ photometry)

q-PED method

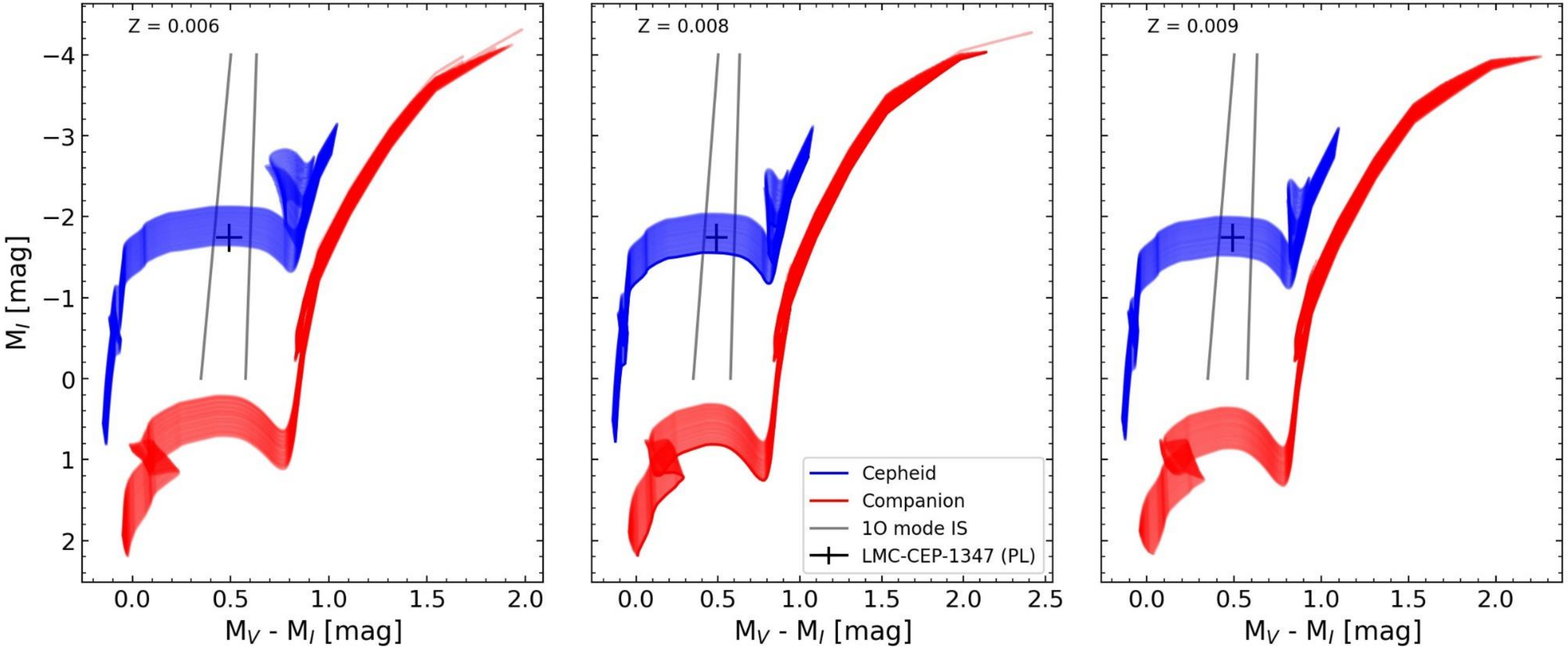
q-PED method on CEP-1347

1st step: Calculate evolutionary models considering the LMC metallicity

q-PED method on CEP-1347

Period-luminosity relations from Breuval et al. (2022)

$q = m_2/m_1 \approx 0.553$
(Pilecki et al. 2022)



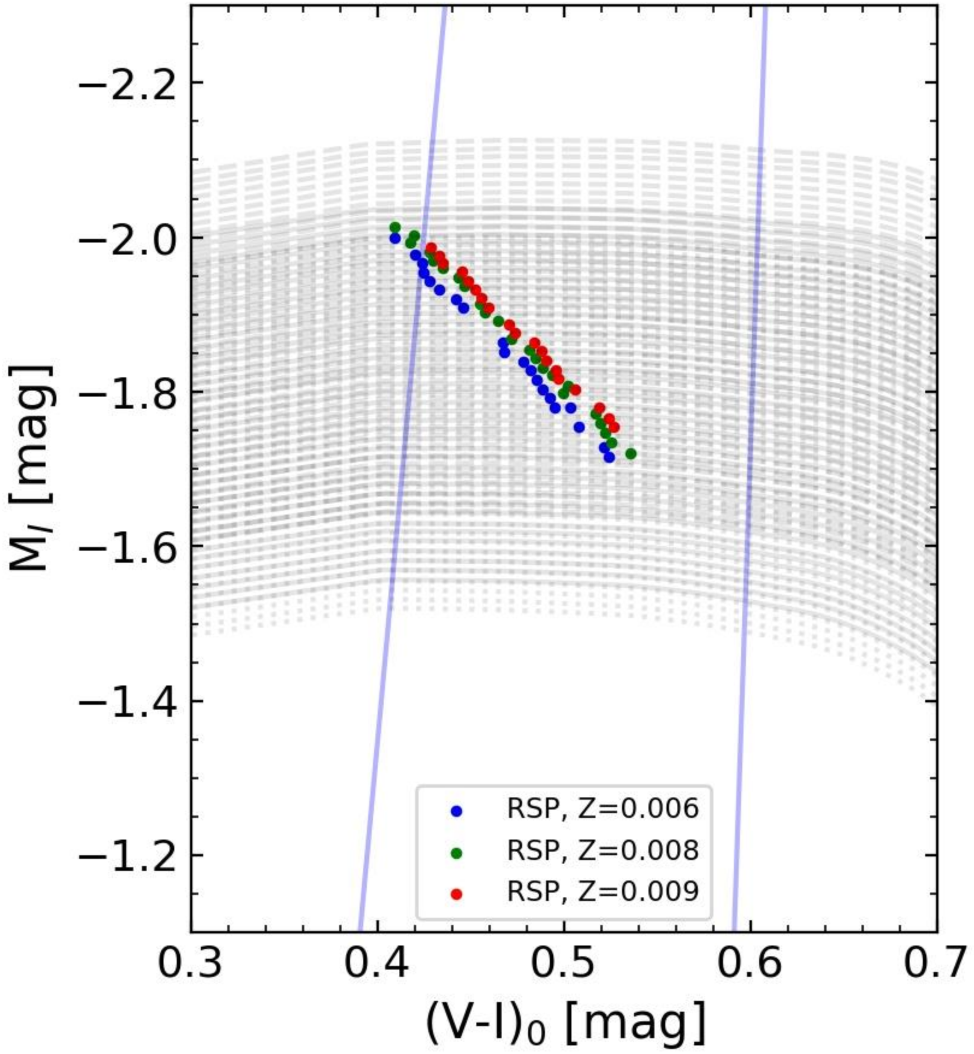
q-PED method on CEP-1347

1st step: Calculate evolutionary models considering the LMC metallicity

2nd step: Calculate pulsational models of the Cepheid

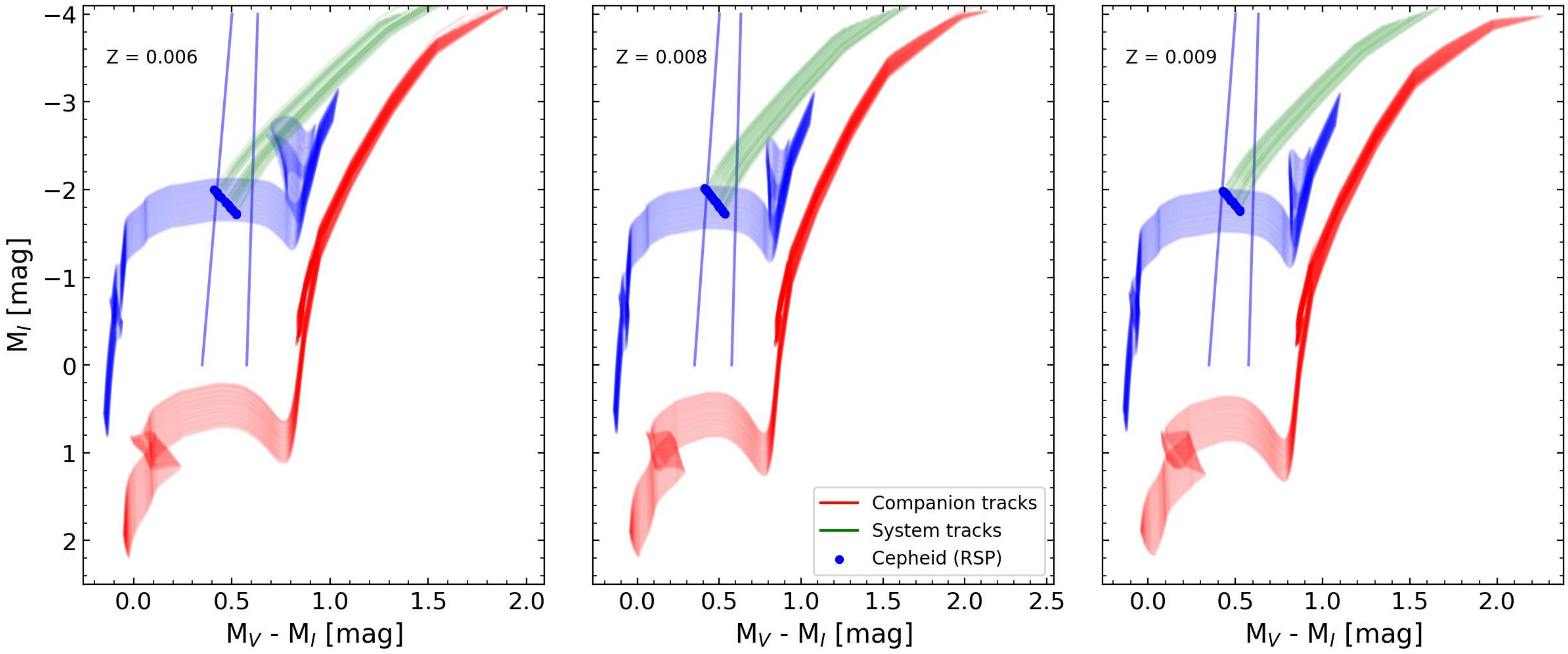
q-PED method on CEP-1347

CEP-1347:
$P_{1o} = 0.69\ d$
$P_{2O} = 0.556\ d$



RSP

q-PED method on CEP-1347



q-PED method on CEP-1347

1st step: Calculate evolutionary models considering the LMC metallicity

2nd step: Calculate pulsational models of the Cepheid

3rd step: Use the multi-band method to constrain our solution based on the known distance to the LMC

q-PED method on CEP-1347

Multi-band method (Gieren et al. 2005)

Fit: $(m - M)_0 = (m - M)_\lambda - E_{B-V} R_\lambda$

Observations and MESA absolute magnitudes

Known from Breuval et al. (2022)

Result: estimated distance and reddening

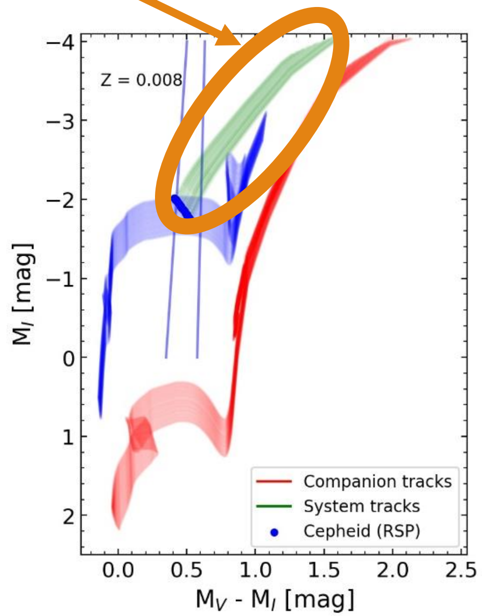
q-PED method on CEP-1347

Multi-band method (Gieren et al. 2005)

Fit: $(m - M)_0 = (m - M)_\lambda - E_{B-V} R_\lambda$

Known from Breuval et al. (2022)

Photometric band	Reference
V	OGLE-IV (Soszyński et al. 2015)
I	OGLE-IV (Soszyński et al. 2015)
J	Ripepi et al. (2022)
K	Ripepi et al. (2022)
H	2MASS 6X Point Source Working Database (Cutri et al. 2012)

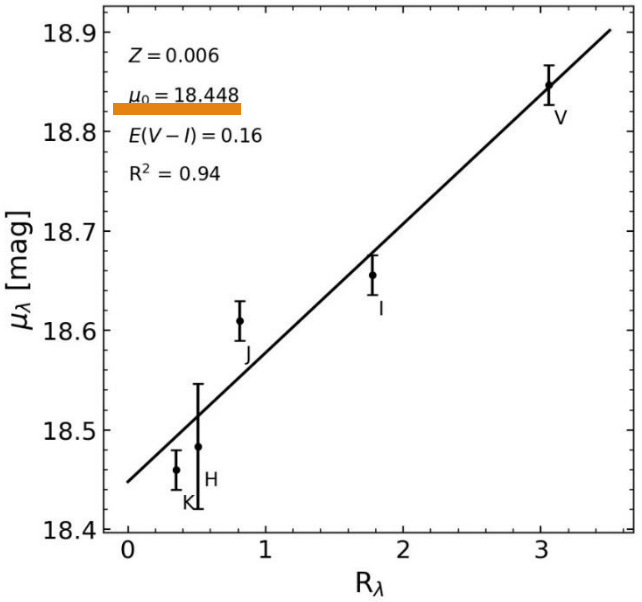


q-PED method on CEP-1347

Multi-band method (Gieren et al. 2005)

Fit: $(m-M)_0 = (m-M)_\lambda - E_{B-V} R_\lambda$

Example:

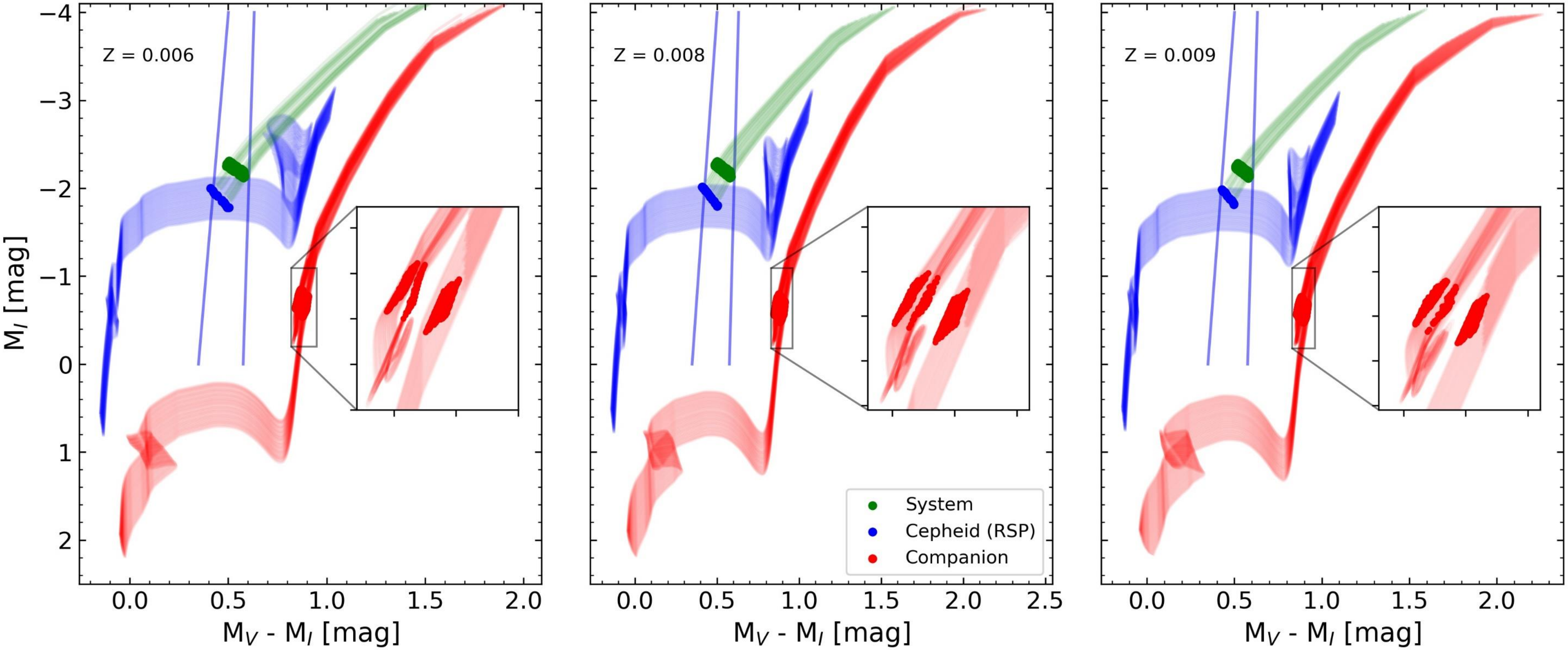


We limited our results to:

$\boldsymbol{\mu_0 = 18.487 \pm 0.04}$
(Pietrzyński et al. 2019)

and positive reddening

Results: HRD


Z = 0.006
Z = 0.008
Z = 0.009
M_I [mag]
M_V - M_I [mag]
System
Cepheid (RSP)
Companion
−4
−3
−2
−1
0
1
2
0.0
0.5
1.0
1.5
2.0
2.5

Results: Precise parameters of the system

Parameter	Cepheid	Companion	Unit
Mass	3.42 ± 0.08	1.87 ± 0.04	$M_{\odot}$
Radius	13.62 ± 0.12	12.26 ± 0.41	$R_{\odot}$
Log g	2.707 ± 0.003	2.534 ± 0.032	cgs
Temperature	6518 ± 99	4974 ± 78	K
Log L	2.48 ± 0.03	1.92 ± 0.03	$L_{\odot}$
Age	0.23 ± 0.01	1.11 ± 0.09	Gyr
E(V-I)	0.11 ± 0.03		mag

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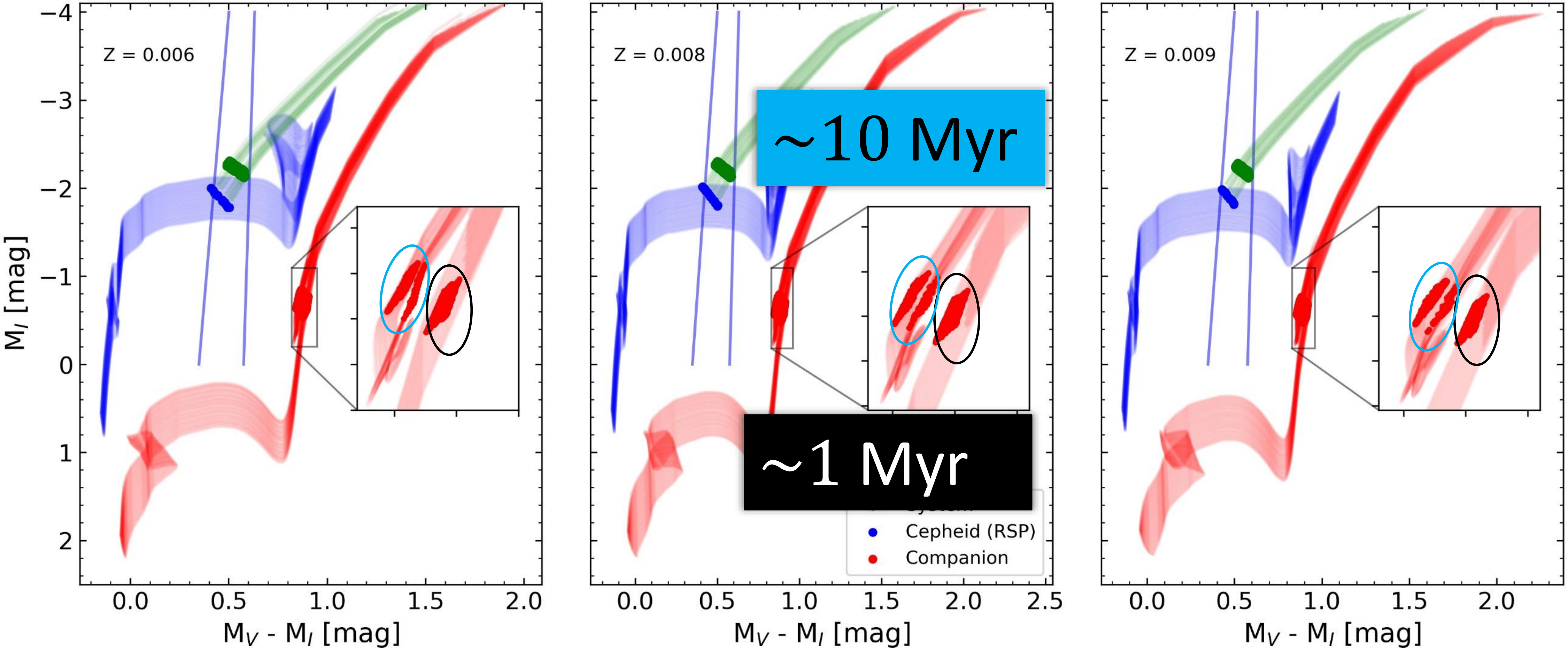
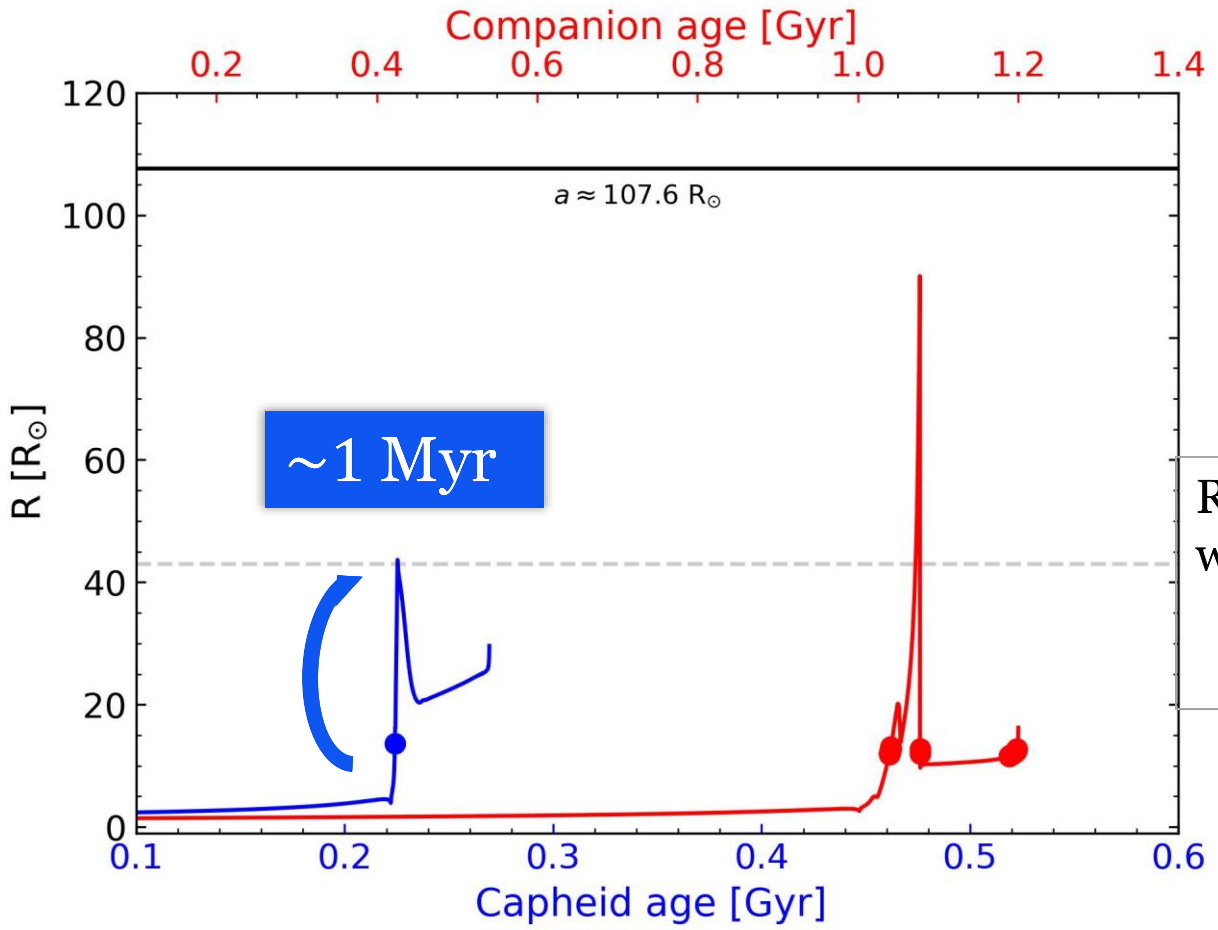
Results: Possible evolutionary phase



Results: Future evolution



Roche-lobe radius of a system with $q = 0.4$ (Nielson et al. 2015):

$$r_L \approx 0.4a$$

Calibration of q-PED method

Mass discrepancy problem → Evolutionary masses are larger than the ones computed from pulsation modeling (e.g Keller 2008)

OGLE-LMC-CEP-1812

- → Precise orbital (P_{orb} = 551.776 days) and physical parameters (Pilecki et al. 2018)
- → Has been suggested that the Cepheid is a merger of two low-mass stars (Nielson et al. 2015)
- → Very similar evolutionary state as CEP-1347

Calibration of q-PED method

Results for CEP-1812

	Cepheid		Companion		
Parameter	This work	Pilecki et al. (2018)	This work	Pilecki et al. (2018)	Unit
Mass	3.76 ± 0.08	3.76 ± 0.03	2.63 ± 0.05	2.62 ± 0.02	$M_\odot$
Radius	17.25 ± 0.14	17.85 ± 0.13	12.12 ± 0.6	11.83 ± 0.08	$R_\odot$
log g	2.546 ± 0.005	2.509 ± 0.007	2.692 ± 0.043	2.709 ± 0.007	cgs
Temperature	6278 ± 79	6120 ± 150	5246 ± 85	5170 ± 120	K
log L	2.61 ± 0.03	2.61 ± 0.04	2.00 ± 0.04	1.95 ± 0.04	$L_\odot$
Age	0.180 ± 0.007	0.190	0.484 ± 0.043	0.369	Gyr

Radius is 3.5% shorter

Conclusions

- We determined precise parameters of the components of OGLE-LMC-CEP-1347.

The Cepheid mass ($3.42 \pm 0.08\, M_{\odot}$) is lower than any other precisely determined Cepheid mass before.

- We confirmed the Cepheid merger-origin scenario.

The actual Cepheid age is 1.1 Gyr → **Significant fraction of Cepheids may be older than they appear!**

- Our method was able to closely reproduced the physical parameters of OGLE-LMC-CEP-1812.

Conclusions

- We determined precise parameters of the components of OGLE-LMC-CEP-1347.

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The actual Cepheid a... → **Significant fraction of Cepheids may be older than they appear!**

In the future: Study of a much larger sample (>20!)

- Our method was able to closely reproduced the physical parameters of OGLE-LMC-CEP-1812.

Thanks!