Physical properties and evolutionary status of Cepheids in eclipsing binaries in the LMC

Bogumił Pilecki

Centrum Astronomiczne im. M. Kopernika PAN, Warsaw, Poland

Collaborators: W. Gieren, G. Pietrzyński, I. Thomson, R. Smolec,
A. Dervisoglu, M. Taormina, D. Graczyk, I. Soszyński, et al.

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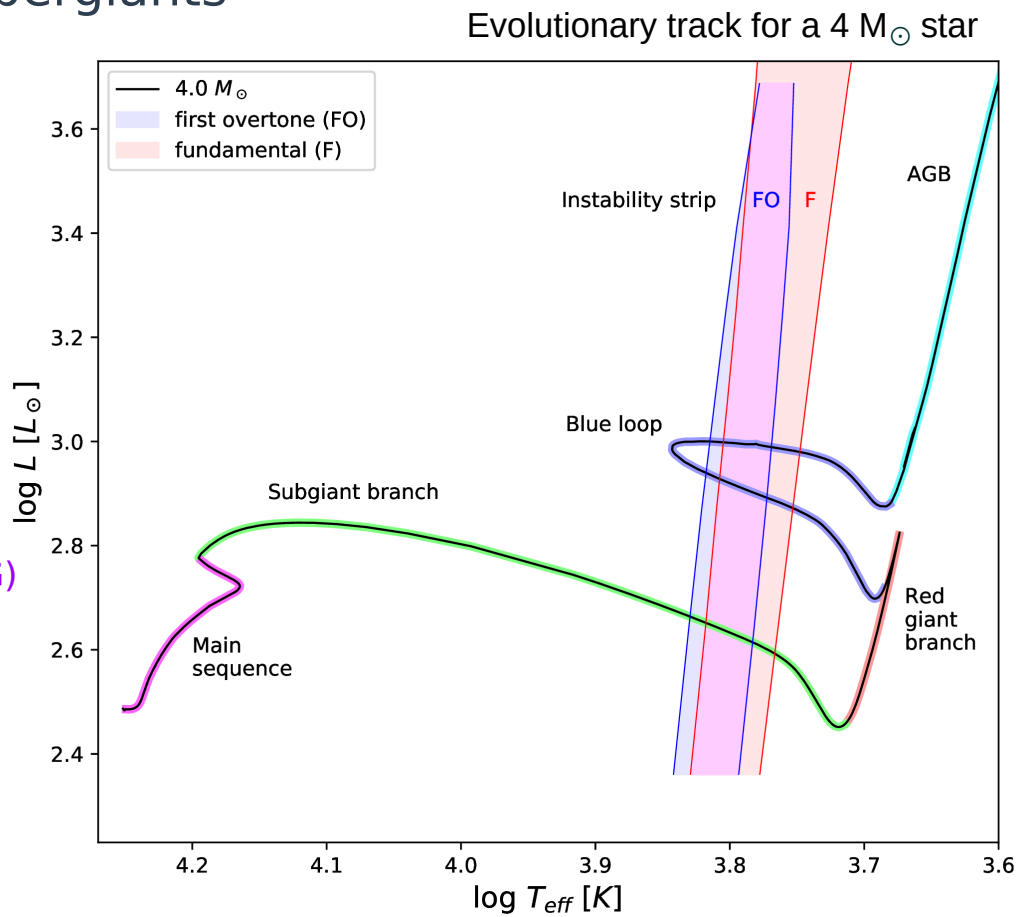
Araucaria PROJECT

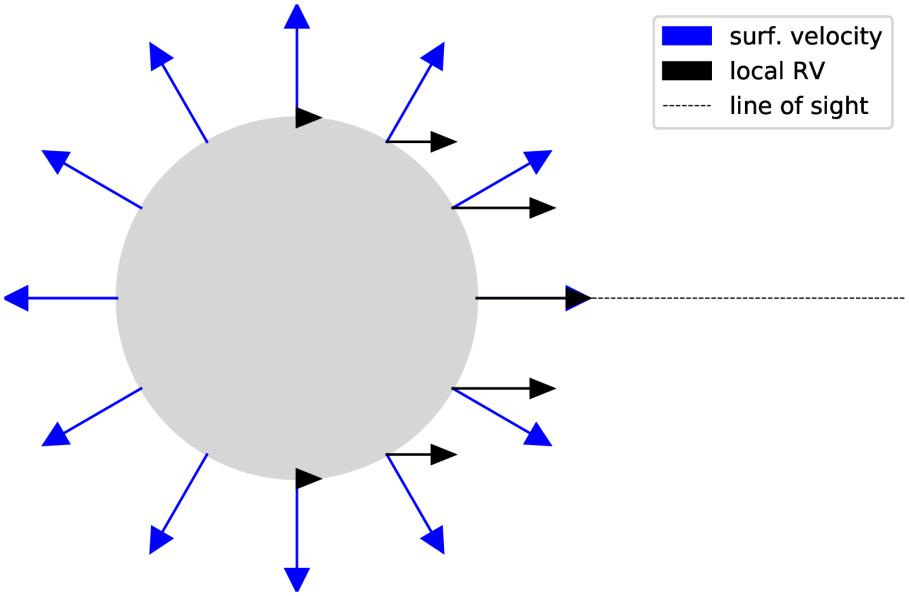
Cepheid variables
classical and type-II Cepheids

- **Classical Cepheids**
  - radially pulsating giants and supergiants
  - ~3.5–10 M_{sun}
- **type II Cepheids**
  - ~ 0.5-0.6 M_{sun}
- **Problems**:
  - mass (e.g. mass discrepancy) (talk by RIA)
  - P-L zero point / ~[Fe/H] (talk by WG)
  - p-factor => B-W methods
  - binarity (type II: pWVir)
  - evolutionary status (type II)



Projection factor

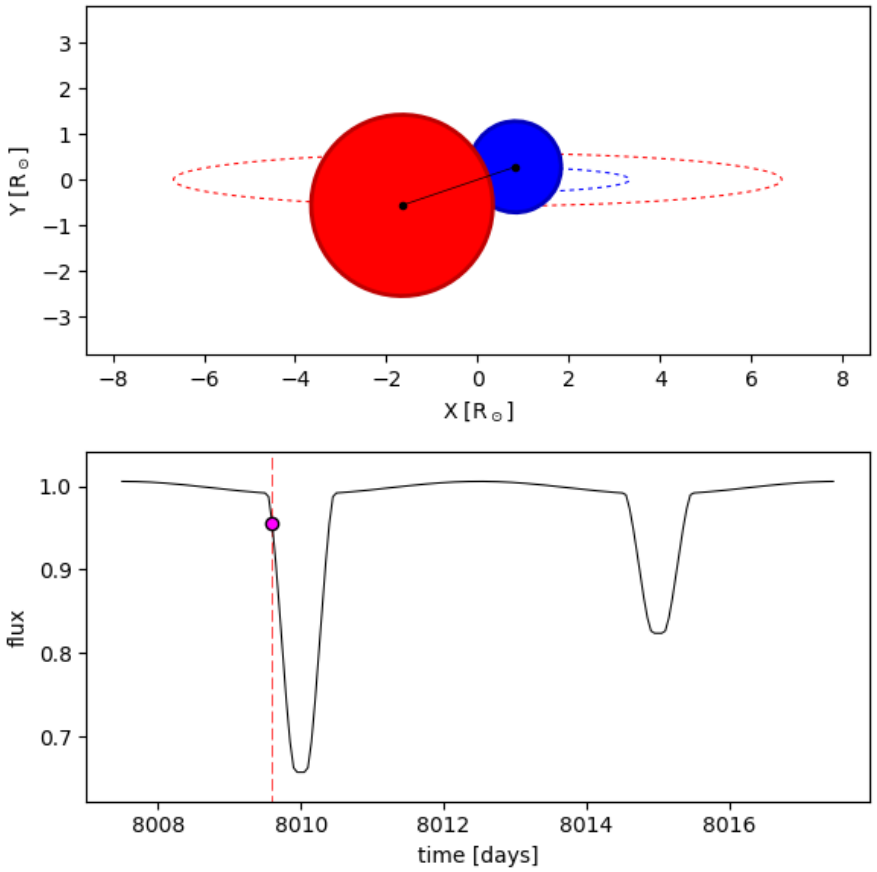
projection (p) factor –
a conversion factor between the integrated pulsational radial velocity (projected on the line of sight) and the velocity of the pulsating star's photosphere.



- geometric factor: 1.5
- athmospheric properties also matter (LD, vel. gradients, etc.)
- ***p*** very important for B-W methods of distance determination

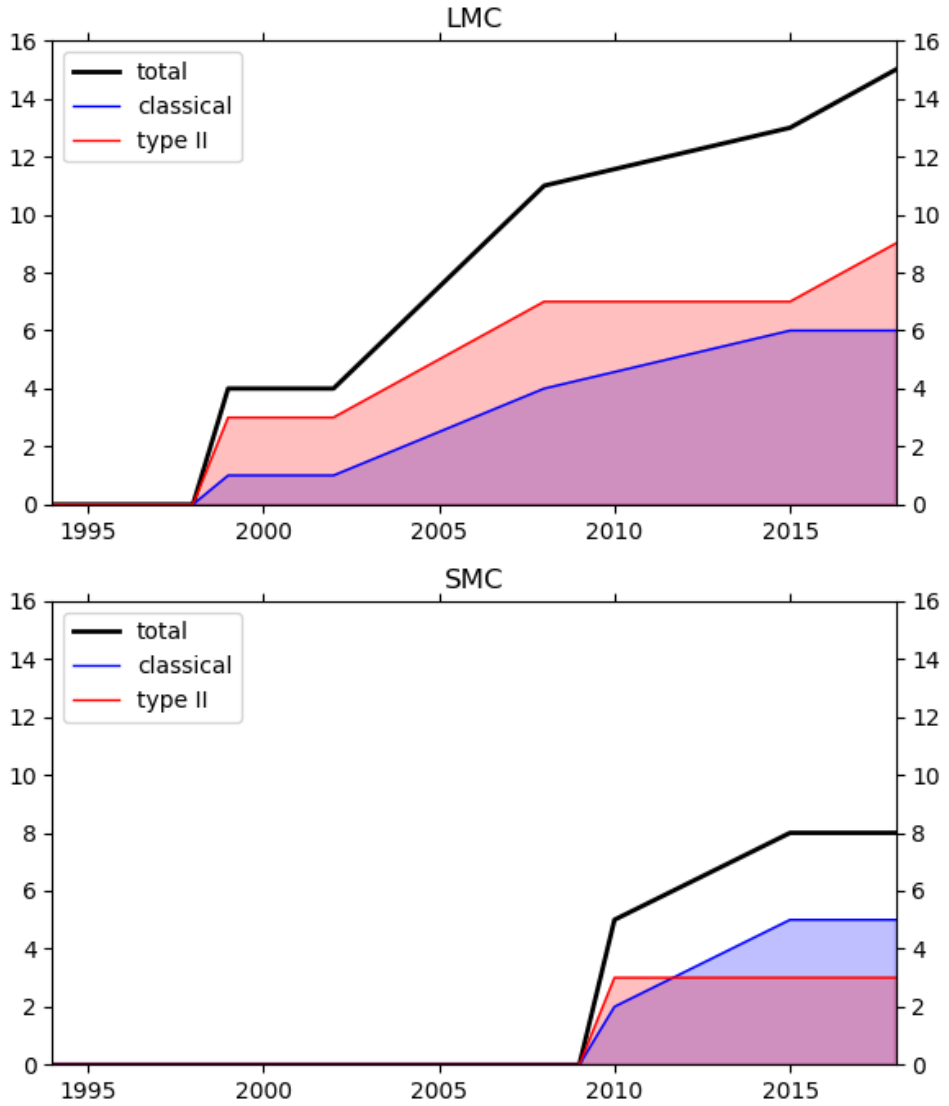
(Eclipsing) binary systems

- **Binarity of Cepheids** (65-80%) *Evans+2013, Kervella+2019*
- orbit inclination → eclipses
- lines of both components (SB2)
- Best tool for determination of physical parameters
- **Advantages for Cepheids:**
  - accurate mass
  - star size
  - radius change → p-factor
  - luminosity
  - evolutionary status
  - geometric distance



Cepheids in EBs
History

- **History**
  - Milky Way (non-eclipsing, e.g. Moore 1929 – Polaris, Abt 1959 – FF Aql, Evans+2019 – V350 Sgr)
  - LMC → OGLE (14), MACHO (1)
  - SMC → OGLE (8)
- **Data/quality**
  - spectroscopic confirmation
  - both ecl., SB2, high S/N
  - LMC: 3 CC / 0 T2C
  - SMC: 0 CC / 0 T2C



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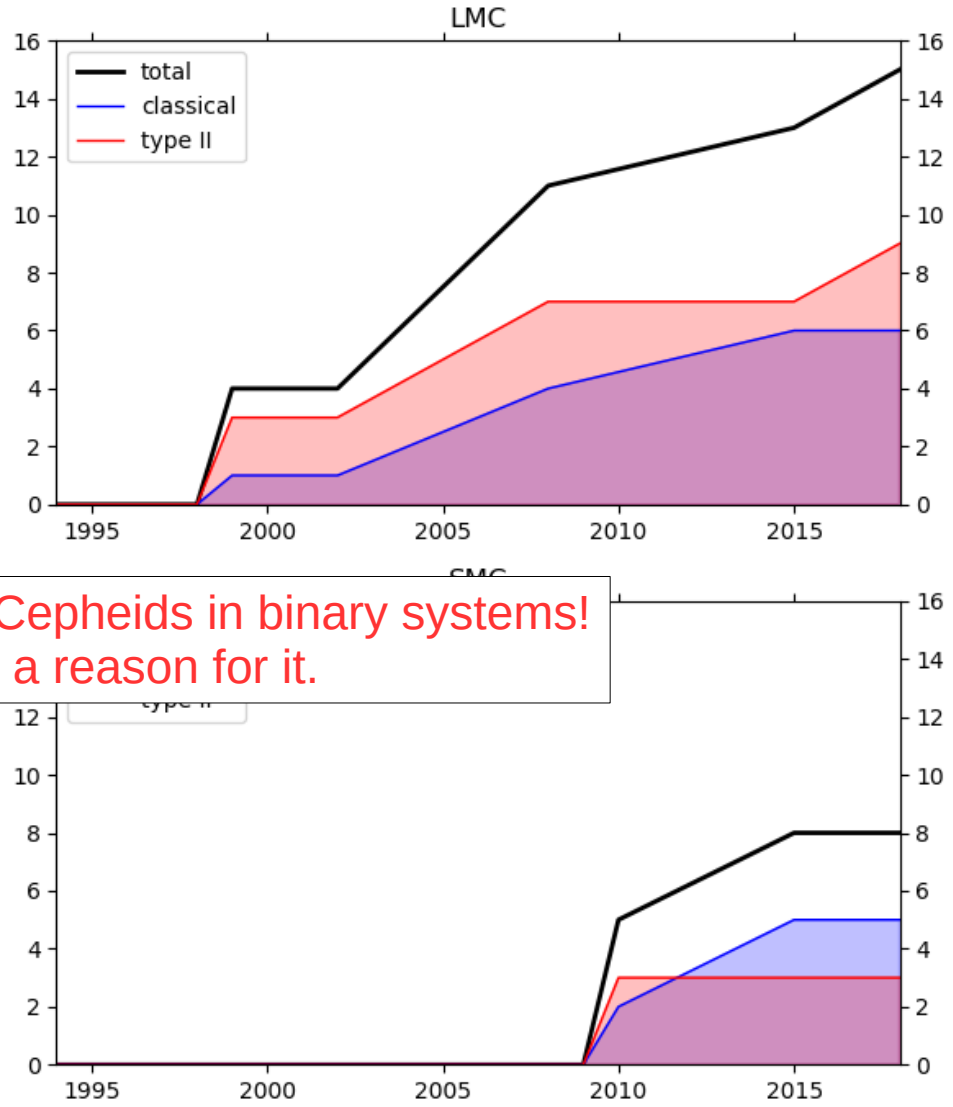
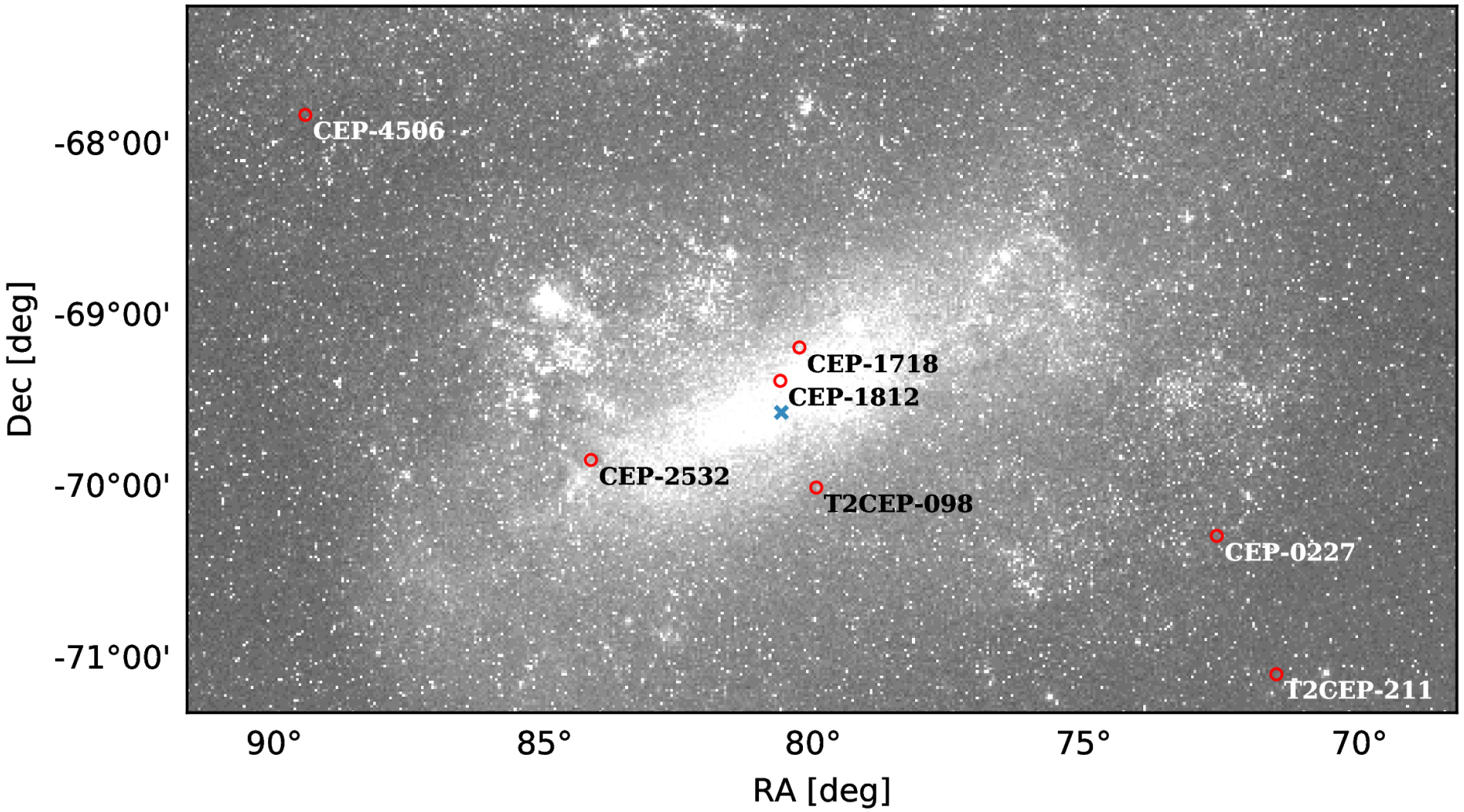


Only 2% of Cepheids in binary systems!
And there is a reason for it.

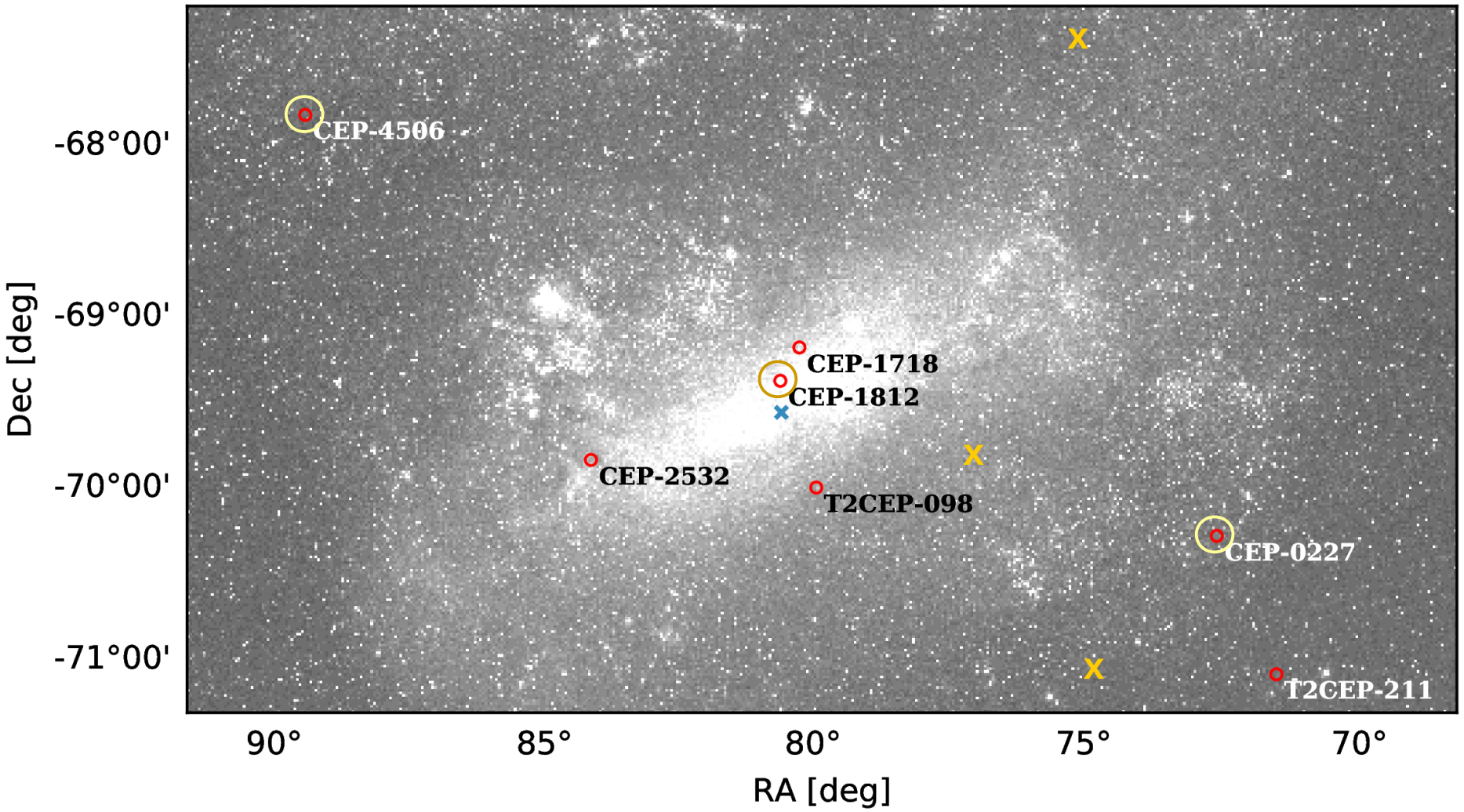
LMC binary Cepheids



OGLE-LMC-#ID#

Pilecki+2018ab

LMC binary Cepheids



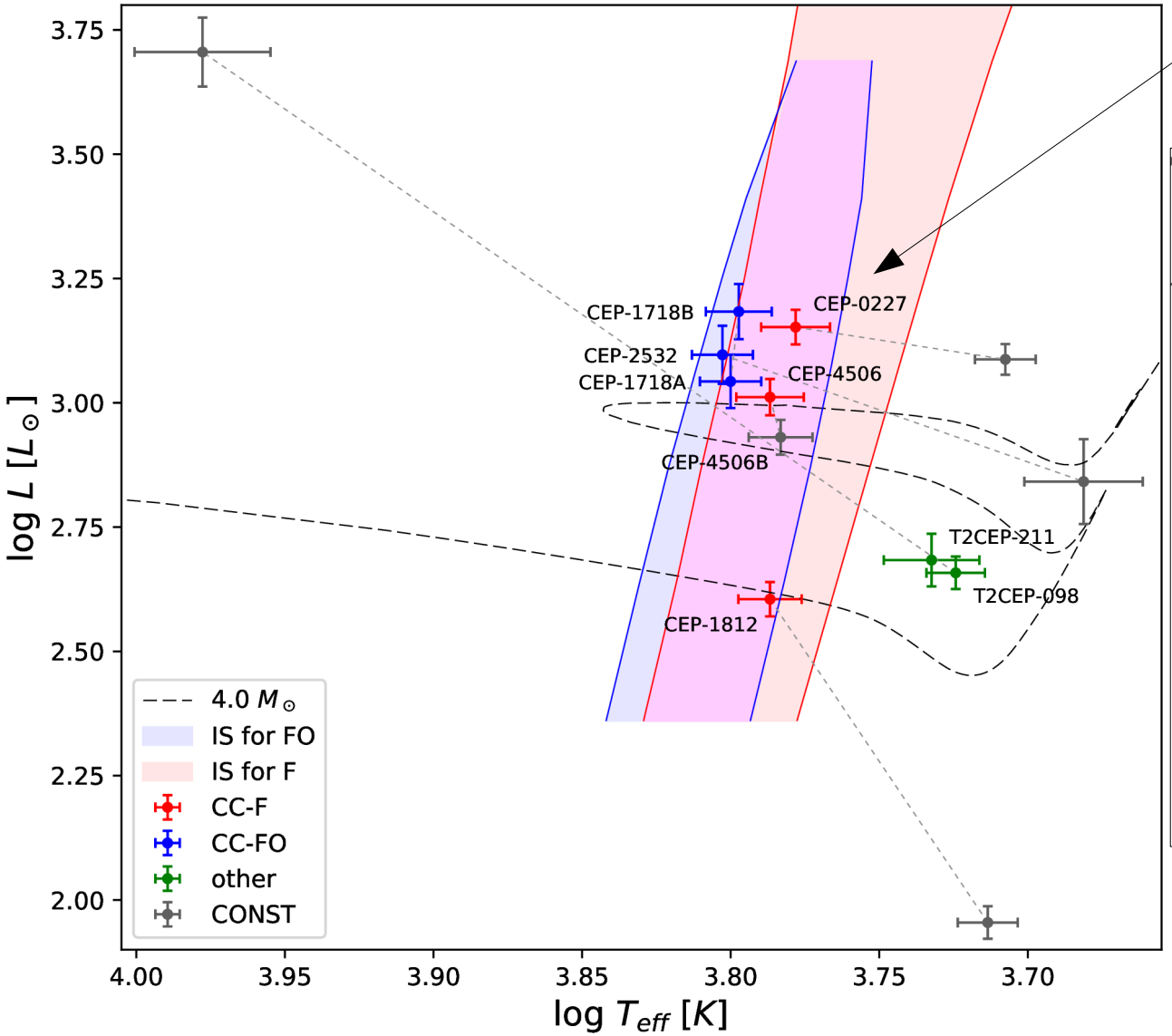
OGLE-LMC-#ID#

Pilecki+2018ab

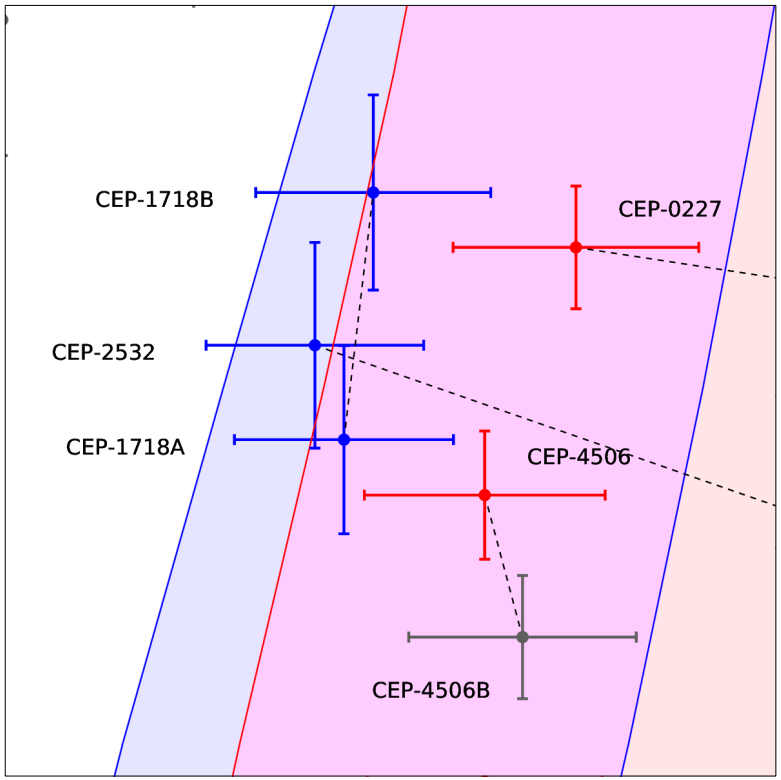
Result overview

- **Dynamical masses for various Cepheids:**
  - the first one (OGLE-LMC-CEP-0227)
  - important step in solving the Cepheid “mass discrepancy" problem
- **Accurate radii and other physical parameters:**
  - p-factor (calibration of B-W method)
  - empirical relations: P-L, P-R, P-R-M
- **Interesting cases:**
  - two Cepheids in one system
  - one-of-its-kind Cepheid
- **Evolutionary state of Cepheids:**
  - one first-crossing Cepheid, maybe merger
  - binary interactions

HR diagram
CEP-0227 - first dynamical mass

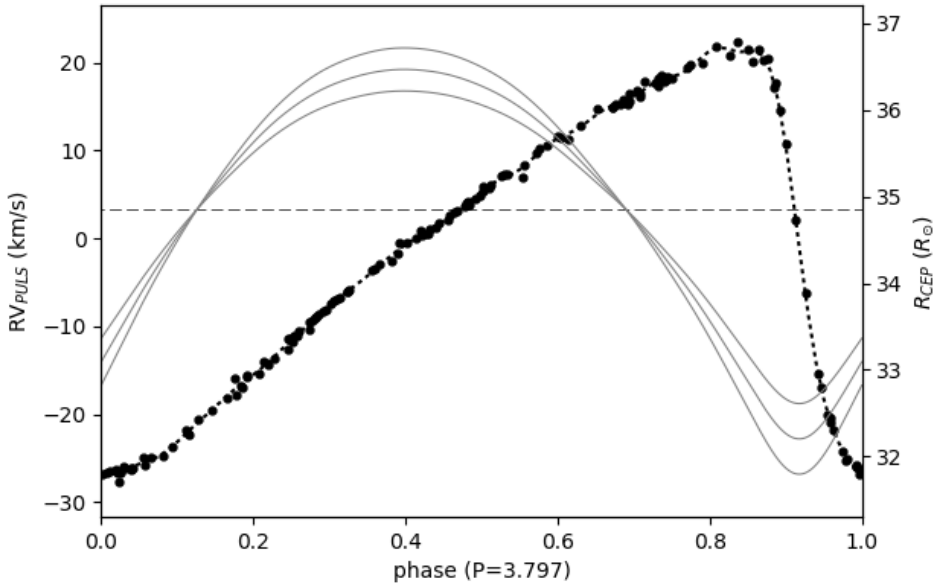


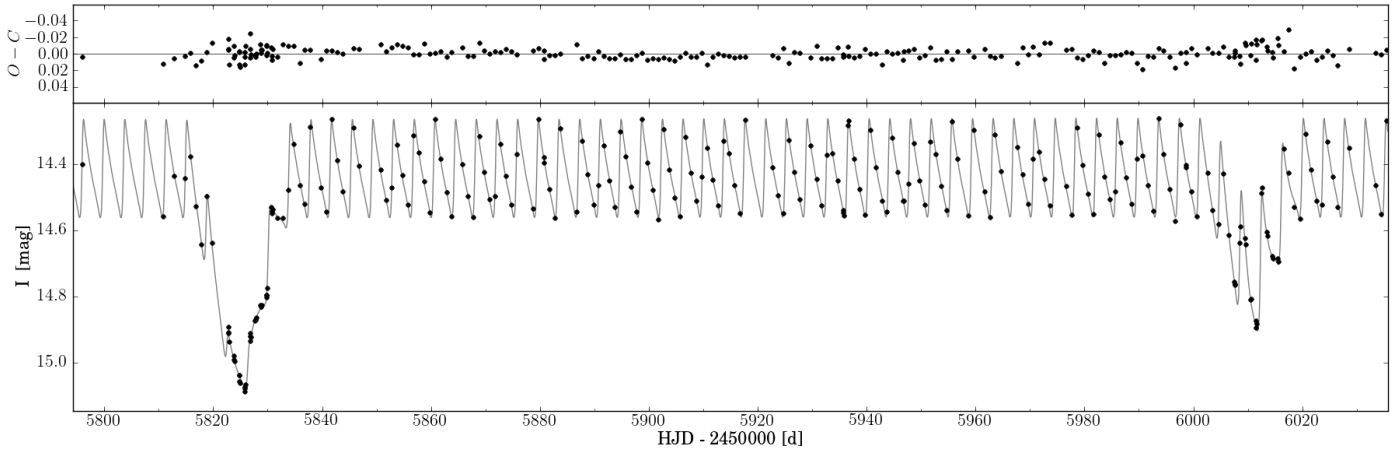
first dynamical mass
first geom. p-factor



OGLE-LMC-CEP-0227
first p-factor

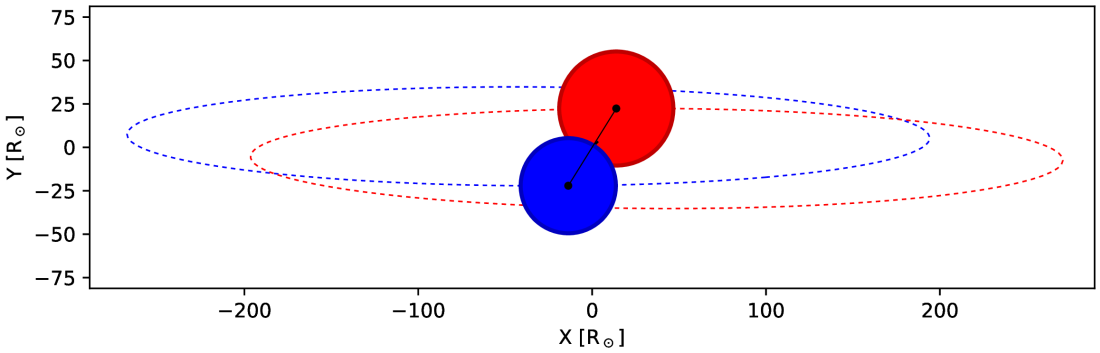
- Dynamical mass!
  (Pietrzyński+2010, Pilecki+2013,2018)
  - Up to now (Pilecki+2018):
    7 dynamical masses
    (5 accurate to < 1%)
- P-factor:
  - 1.21 +/- 0.03 (stat.) +/- 0.04 (syst.)
  - direct, geometrical, distance-independent
  - 4 p-factors in total

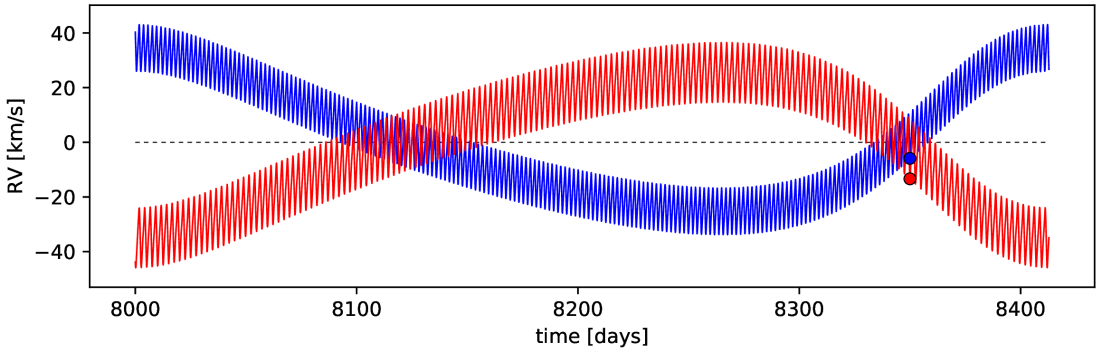


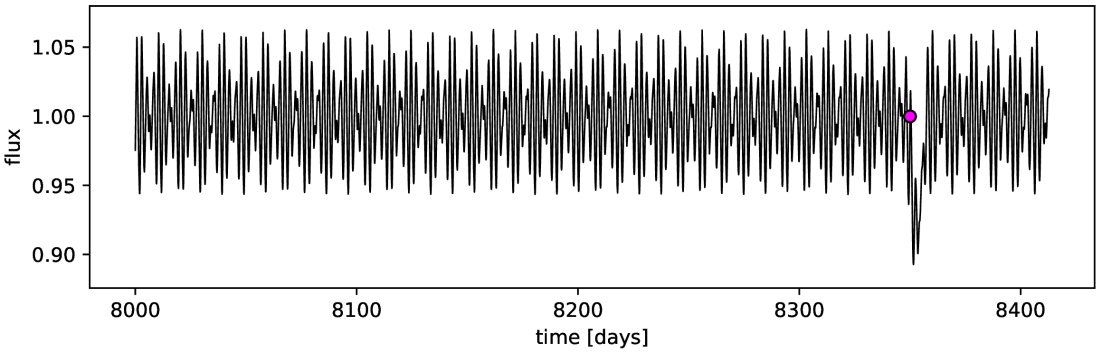


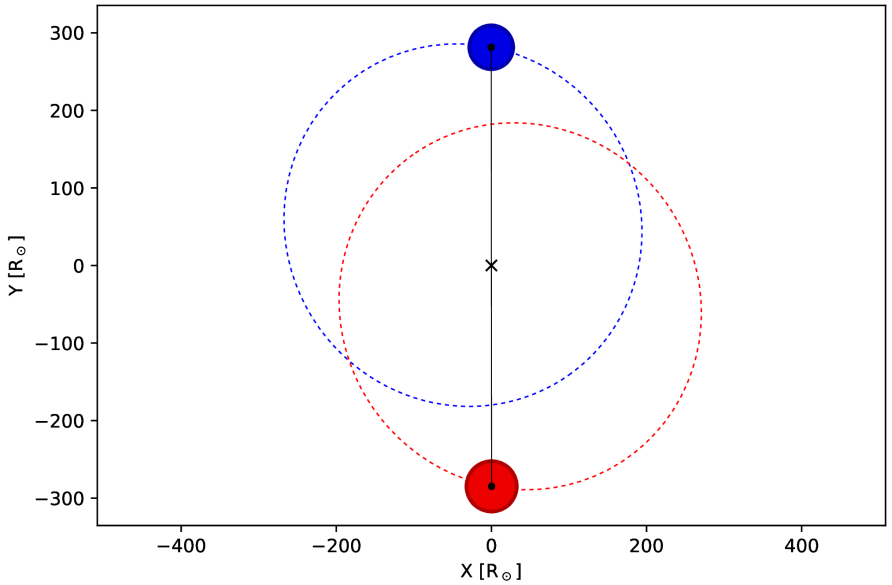
OGLE-LMC-CEP-1718

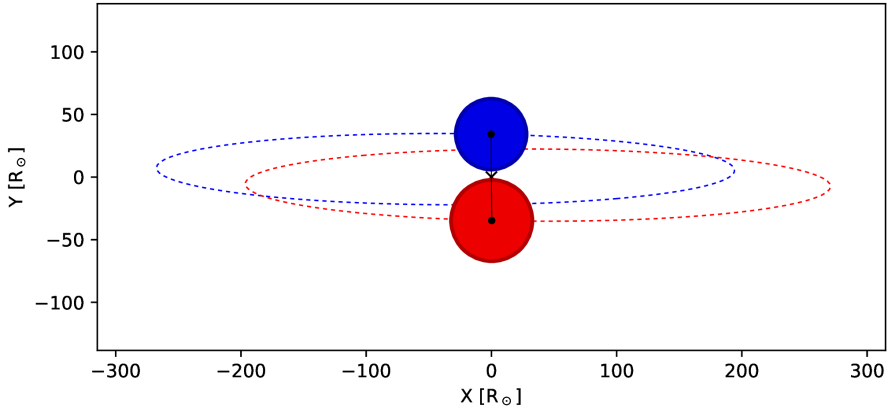
double Cepheid, one eclipse











OGLE-LMC-CEP-1718

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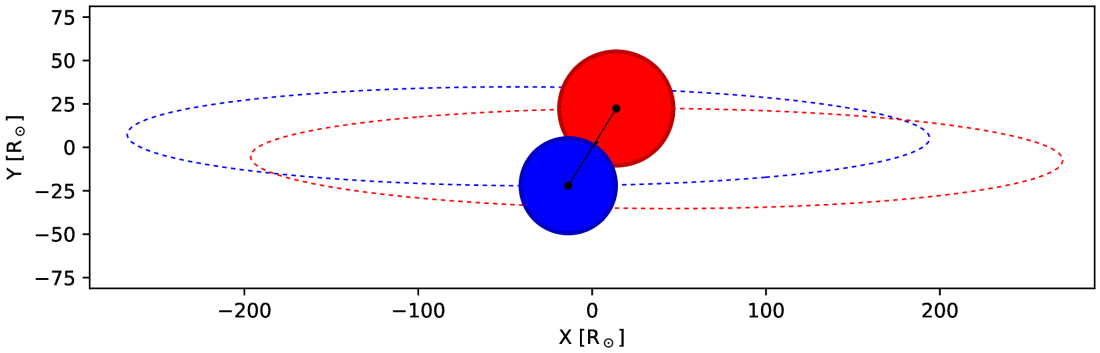
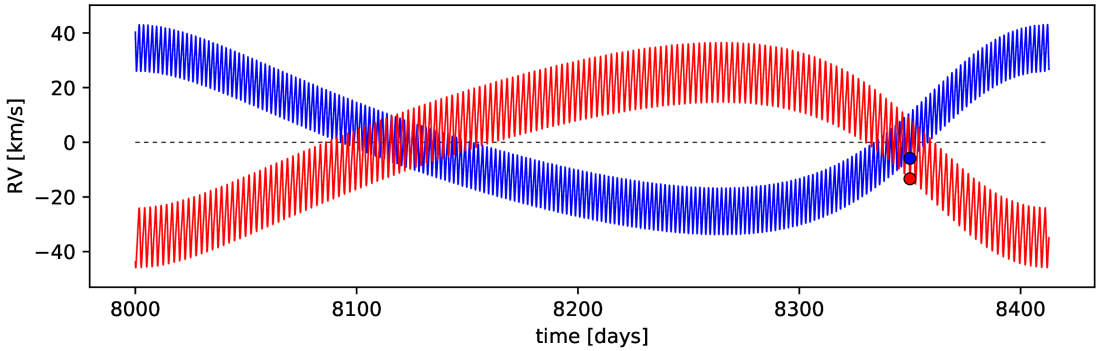
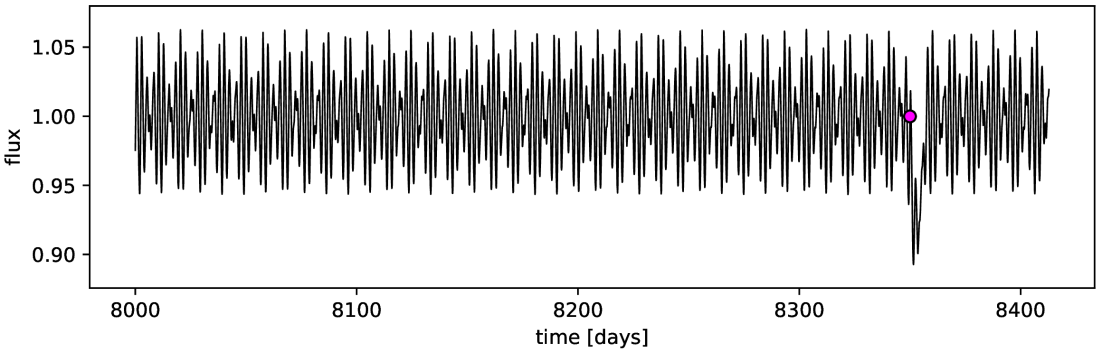
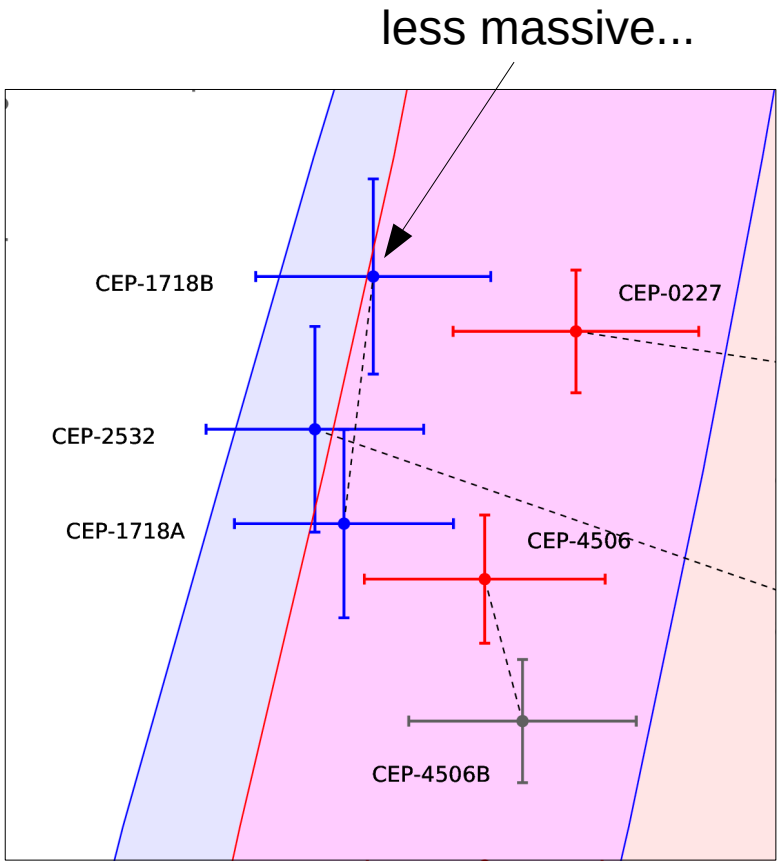


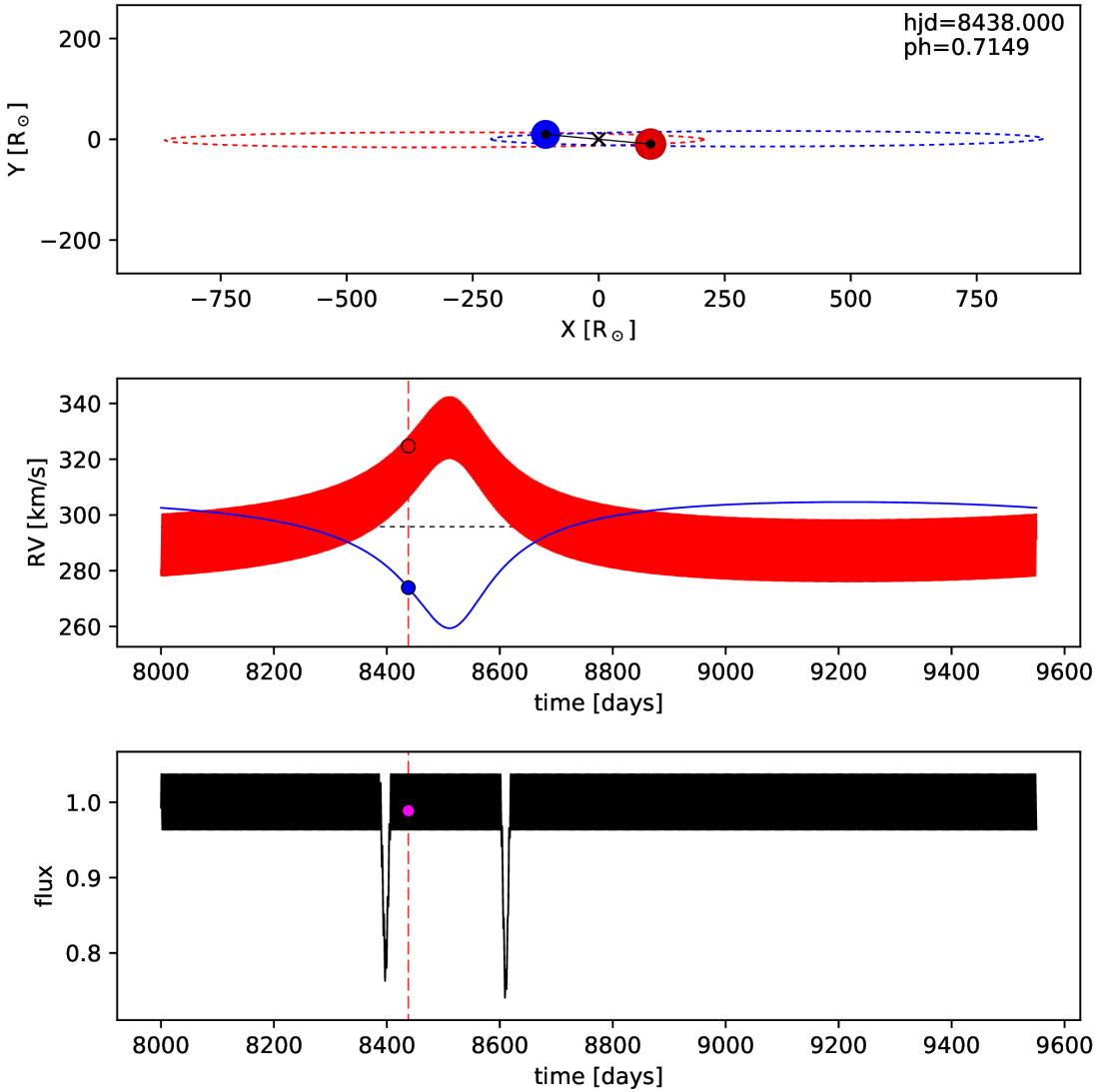


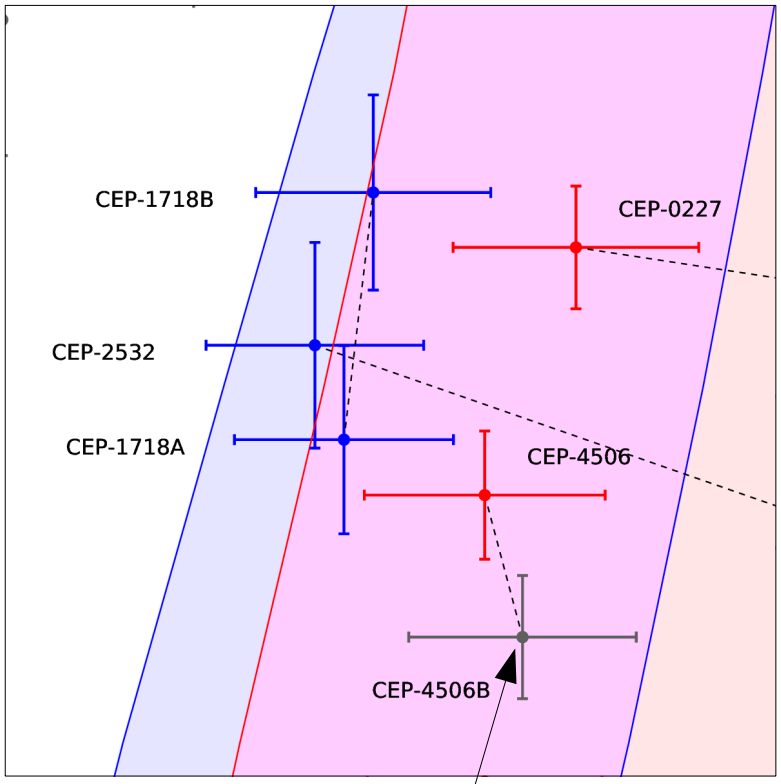




OGLE-LMC-CEP-4506

eccentric, long-period

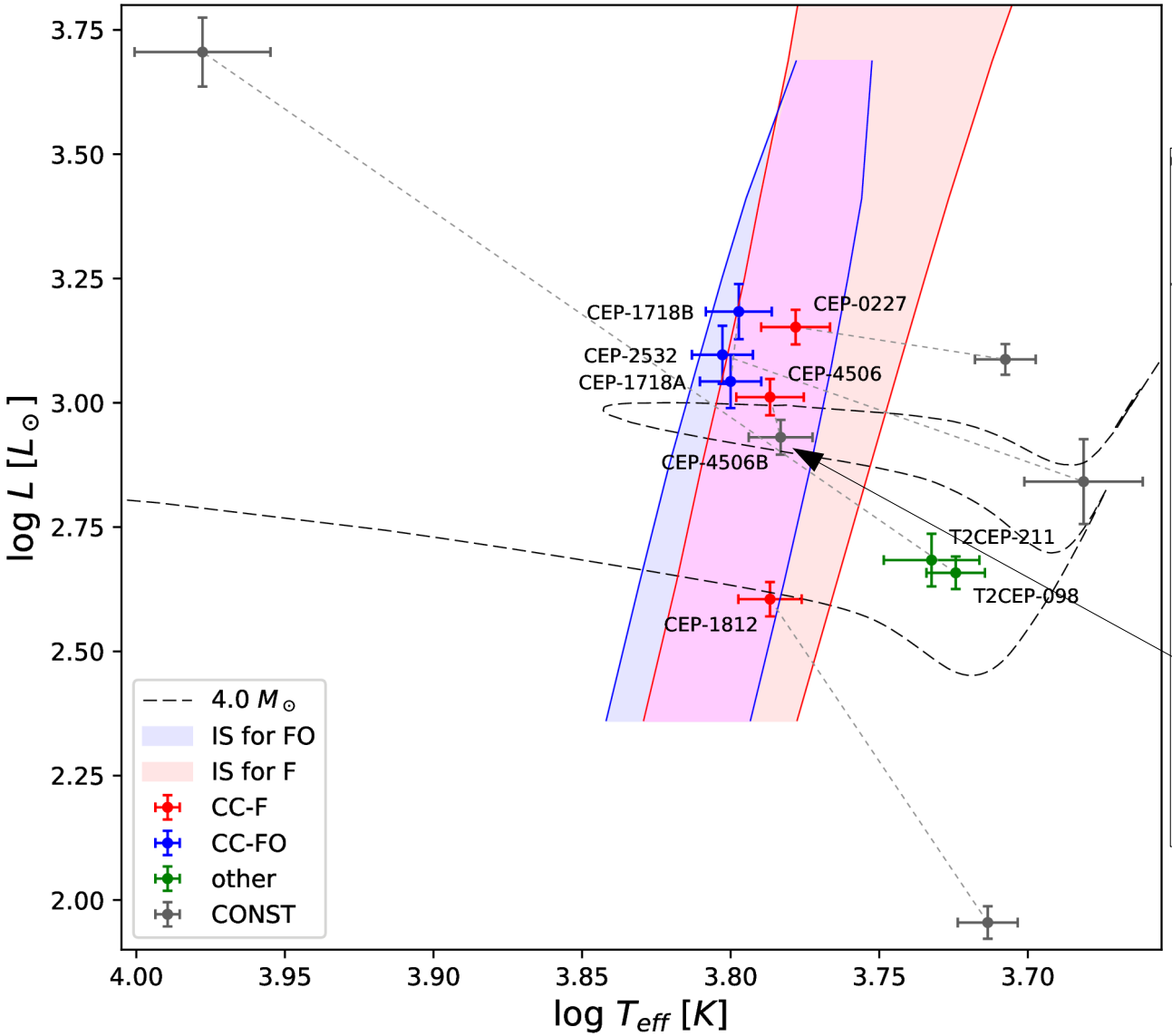


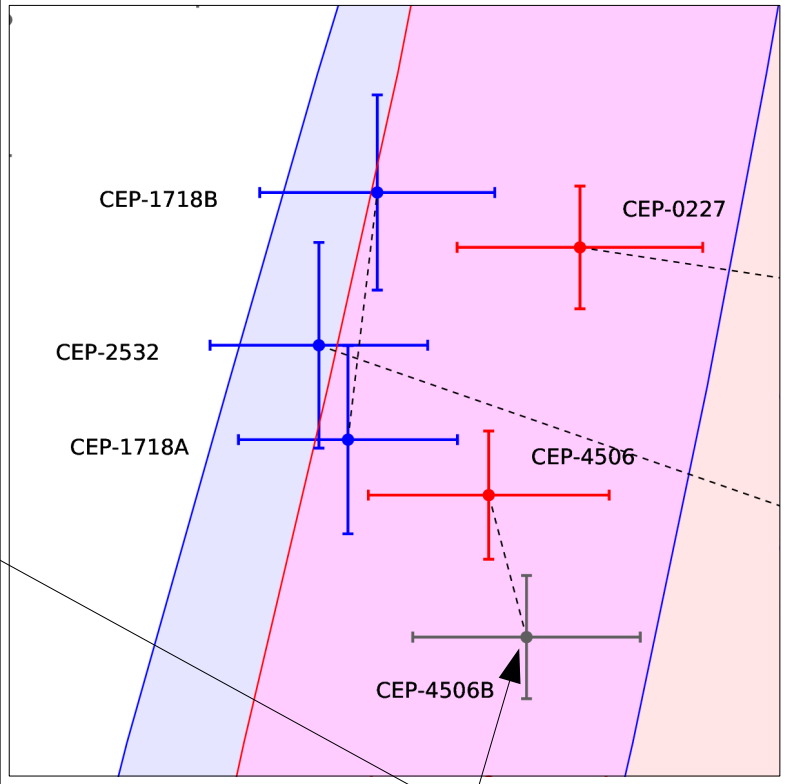


non-pulsating!

OGLE-LMC-CEP-4506

eccentric, long-period

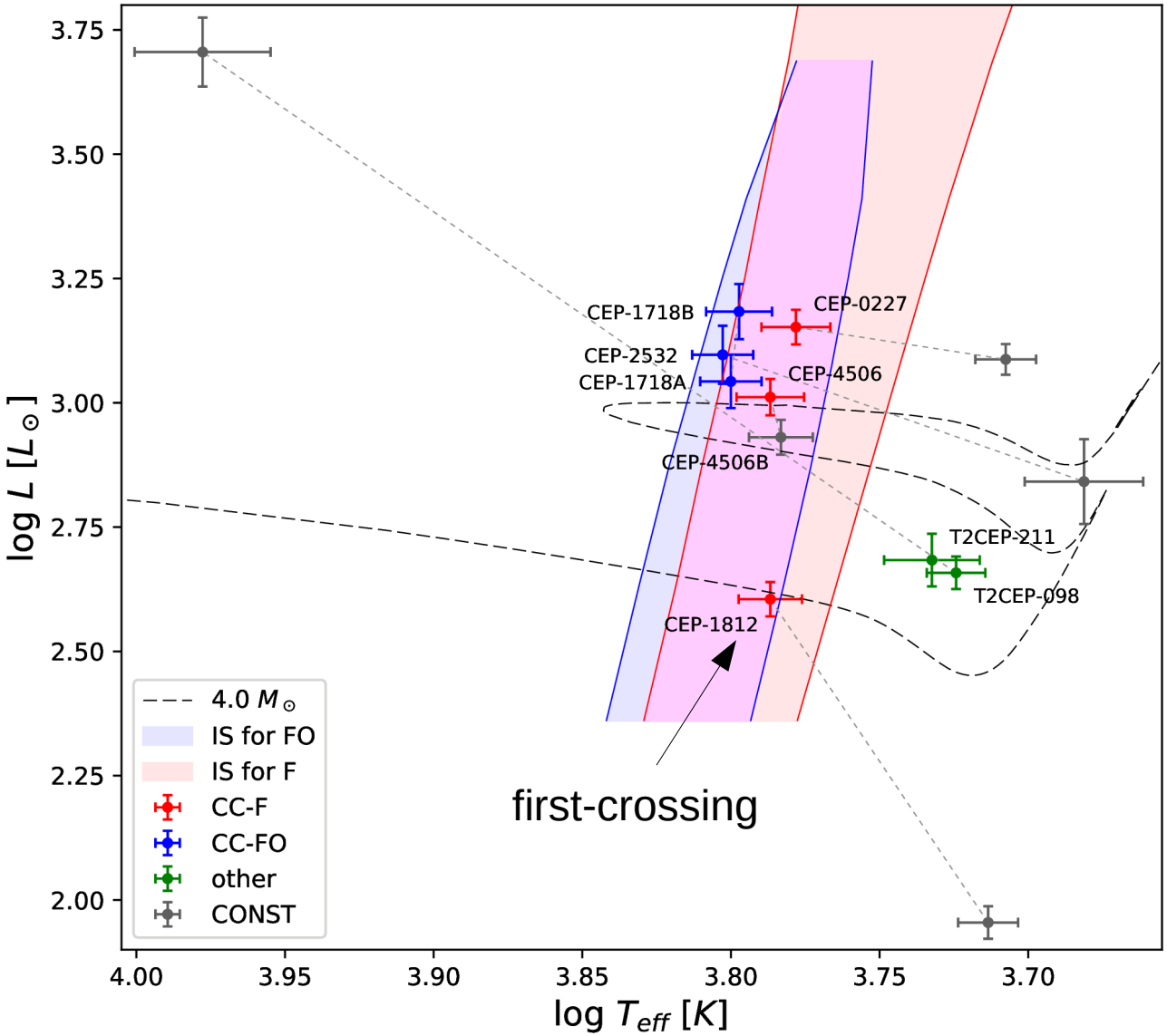


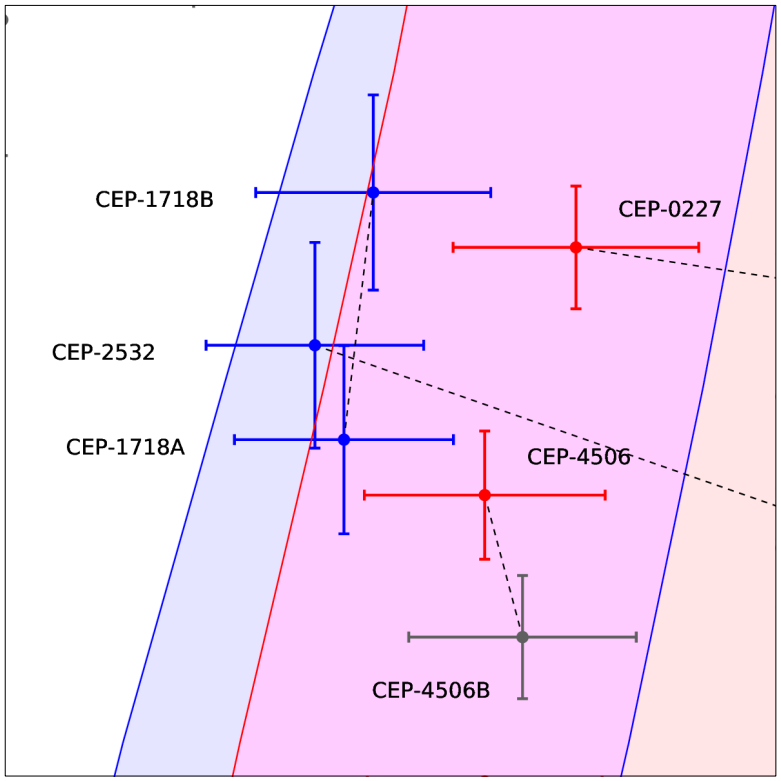


non-pulsating!

new candidates in LMC – see Narloch+2019

HR diagram
CEP-1812 - first crossing

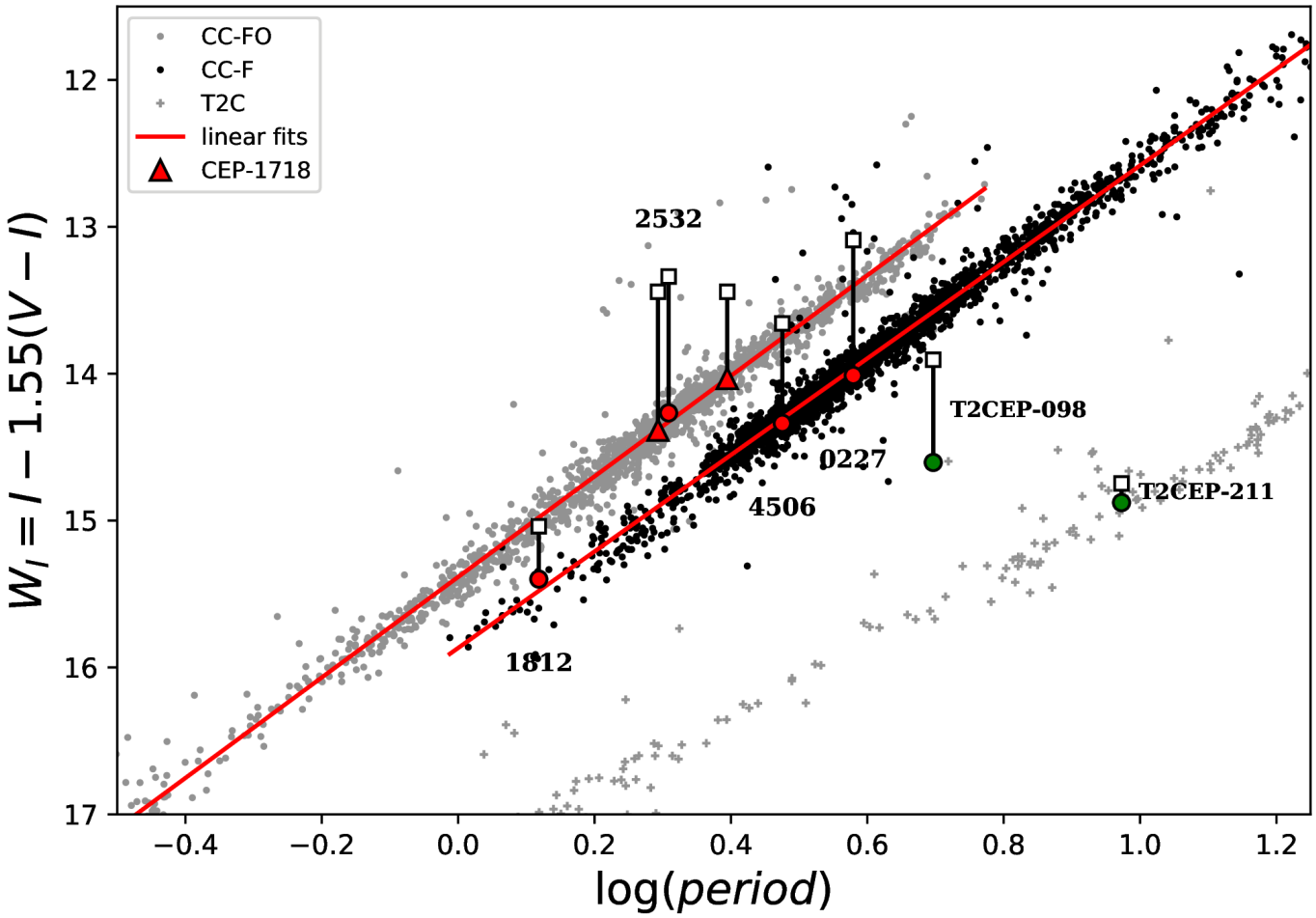




And probably a merger too.
(10-30% of Cepheids may be mergers!)
Sana+2012

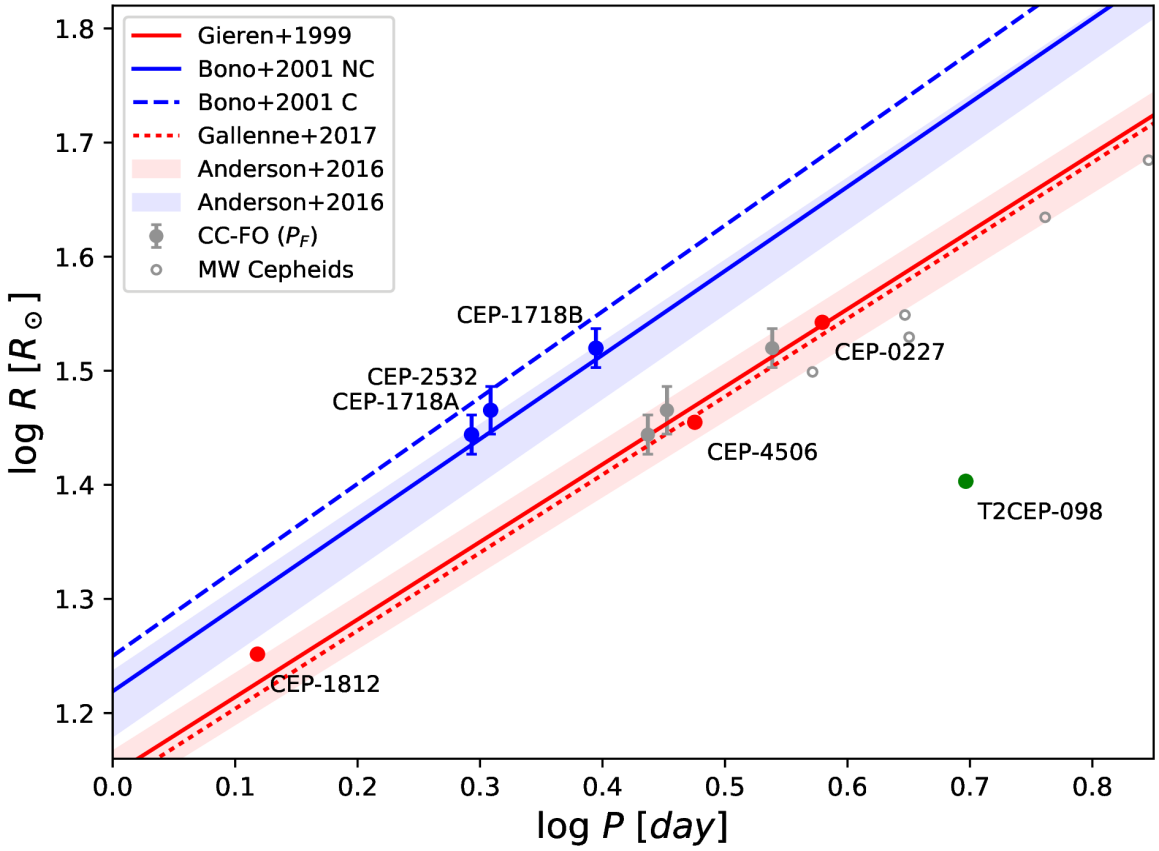
LMC binary Cepheids
P-L diagram

- Statistics:
  - 3 FO-mode CC
  - 3 F-mode CC
  - 2 type-II Cep
- corrected mag. on P-L
- T2CEP-098:
  - mass: 1.5$M_\odot$ new class ? LP Anom. Cep.?



Period-radius relation

- Empirical P-R
  based on radii from EB
- Consistent with others
  (theo. and obs.) relations
- FO CC more consistent
  with non-canonical
  models
- CEP-1812 somewhat
  oversized
- MW Cepheids seem
  systematically smaller

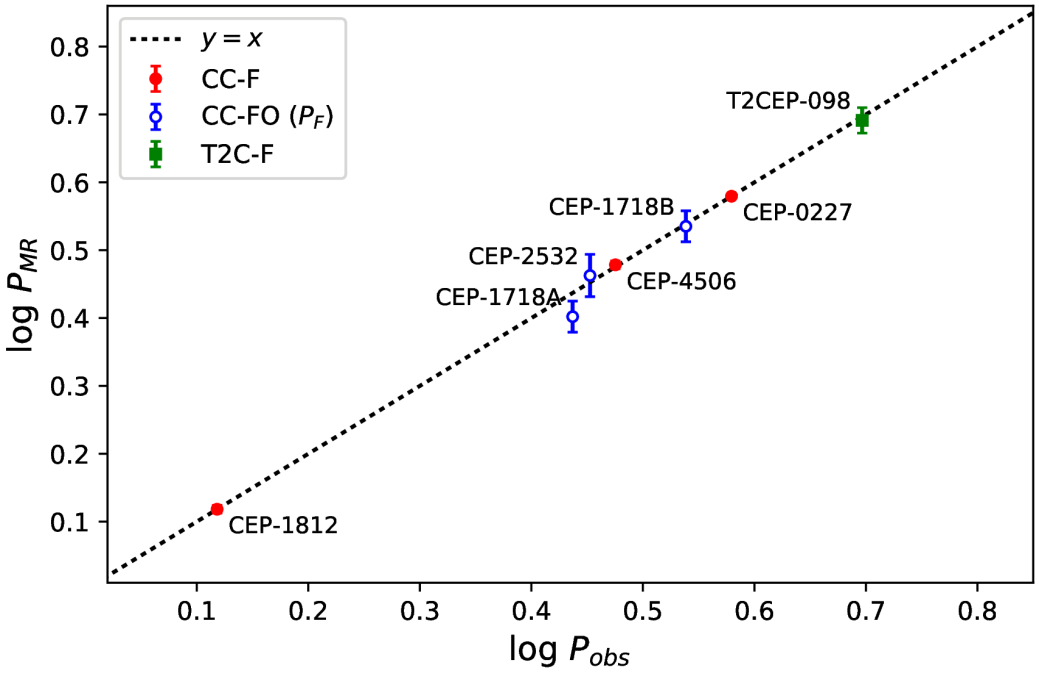


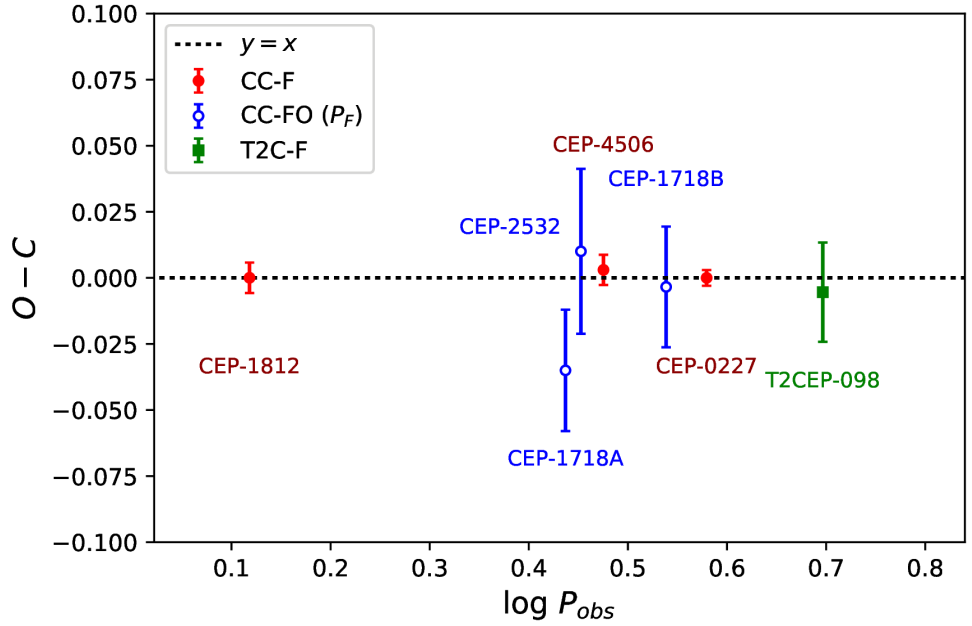
Pilecki+2018a

Period-mass-radius relation

- Precise empirical P-M-R relation
- Based mostly on 3 CC-F, but consistent with all Cepheids
- => Masses for single Cepheids ! (kappa Pav, 0.56 +/- 0.08 M_{sun})

$$\log \boldsymbol{P_{MR}} = -1.56\ (4) - 0.80\ (4) \log \boldsymbol{M} + 1.70\ (3) \log \boldsymbol{R}$$





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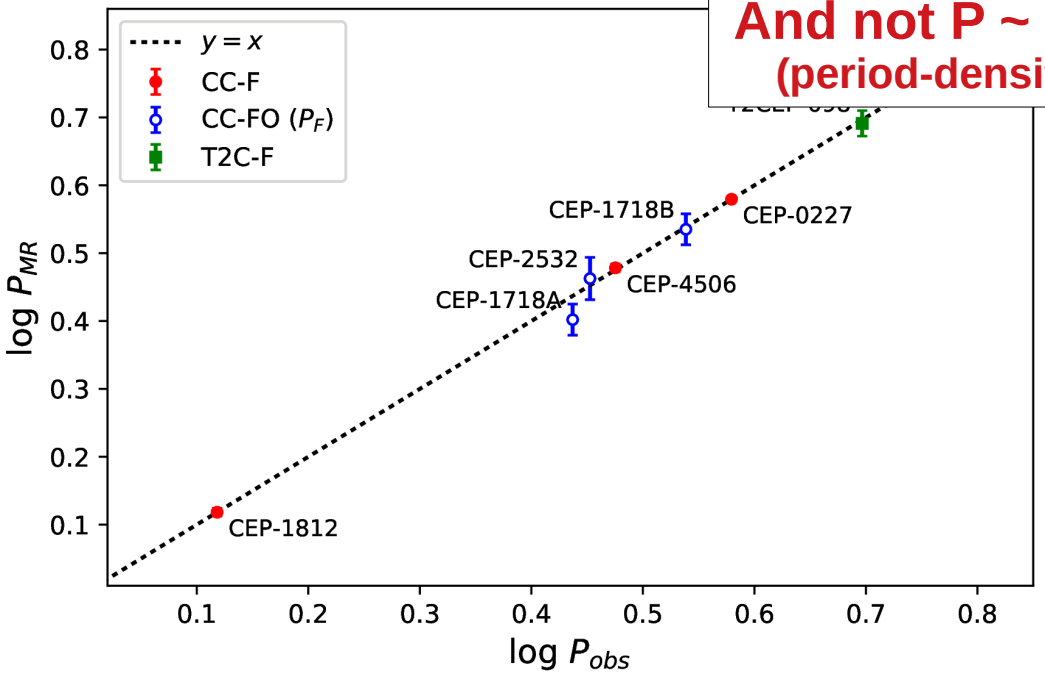
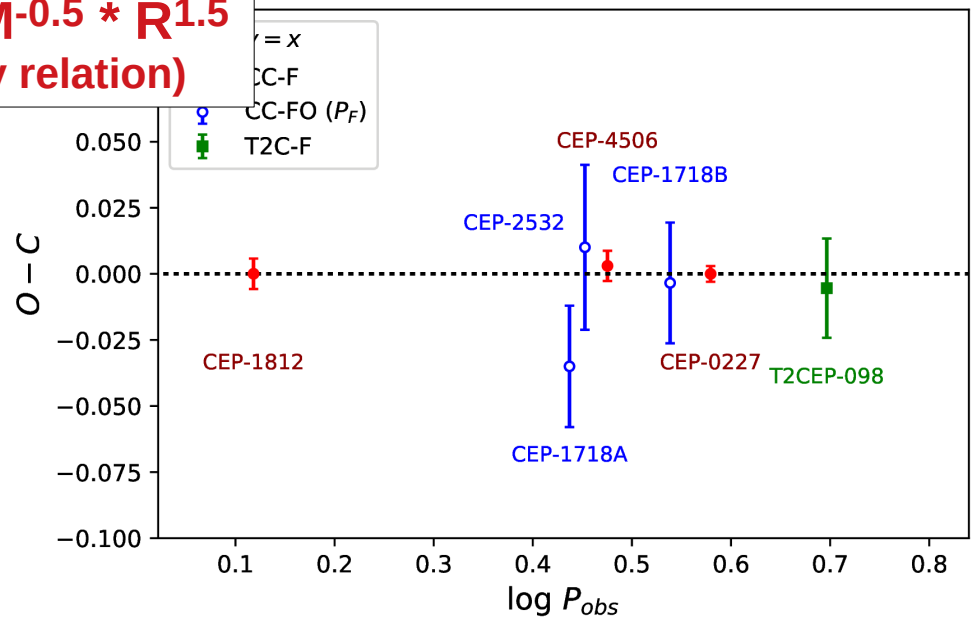
And not P ~ $M^{-0.5} * R^{1.5}$
(period-density relation)

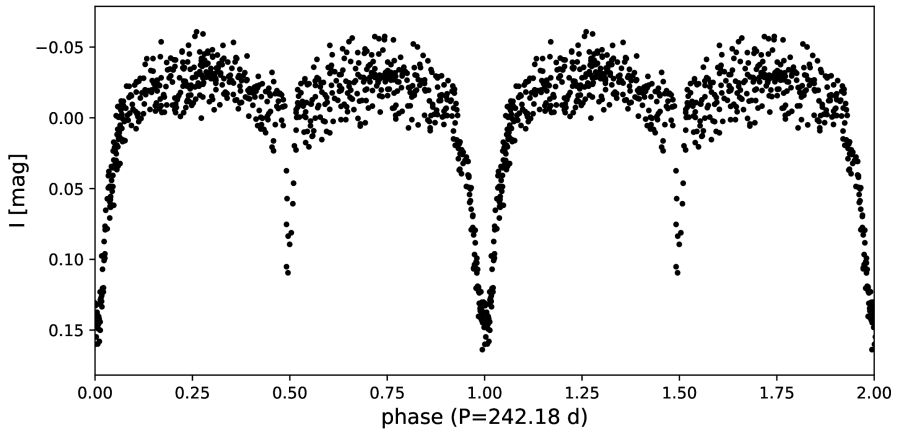


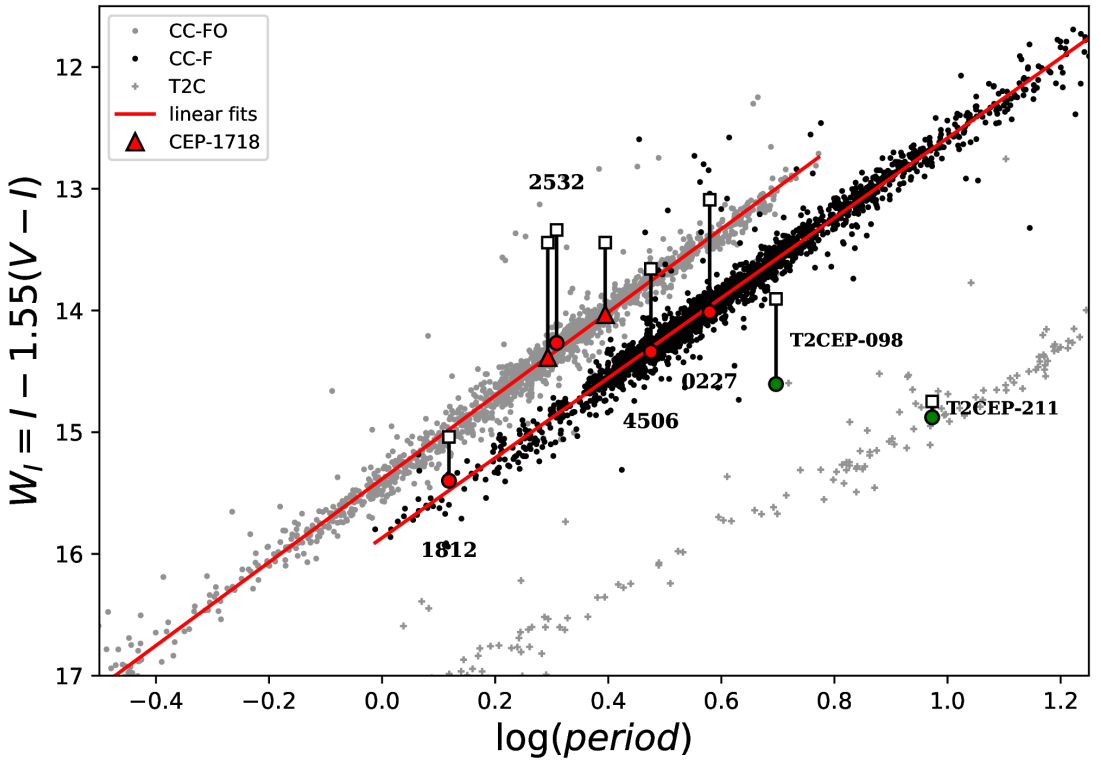


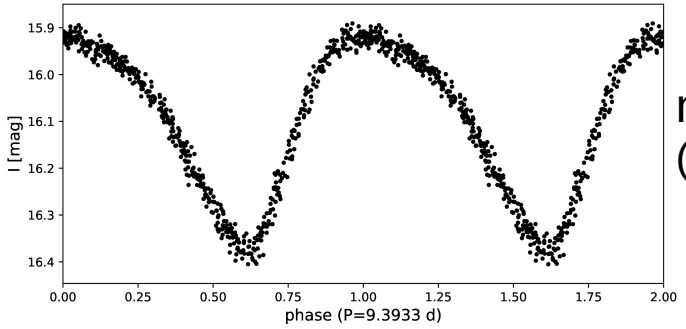
Pilecki+2018a

P-L diagram
OGLE-LMC-T2CEP-211

- **OGLE LMC-T2CEP-211**
  - peculiar W Vir (OGLE class.) [related to binarity]
- **eclipsing LC**
  - primary eclipse much wider than the secondary eclipse
  - => disk presence



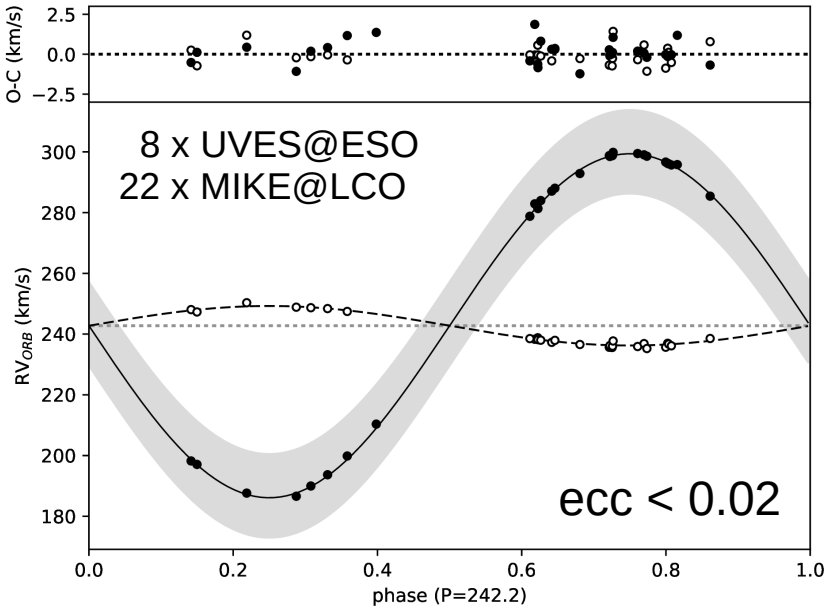


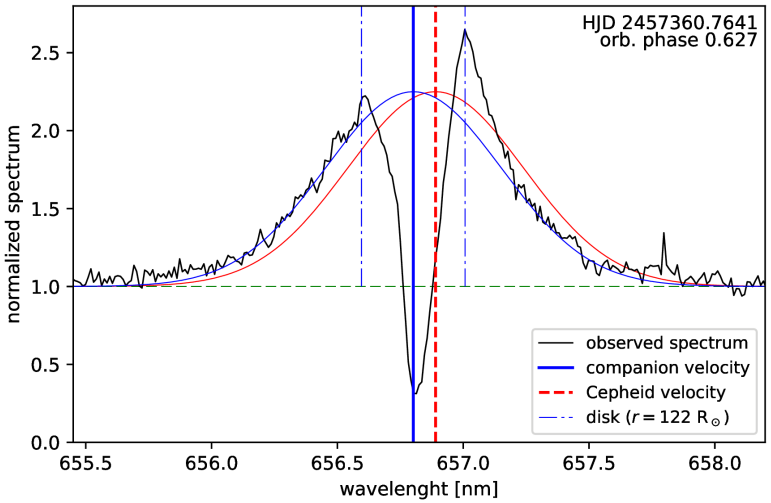


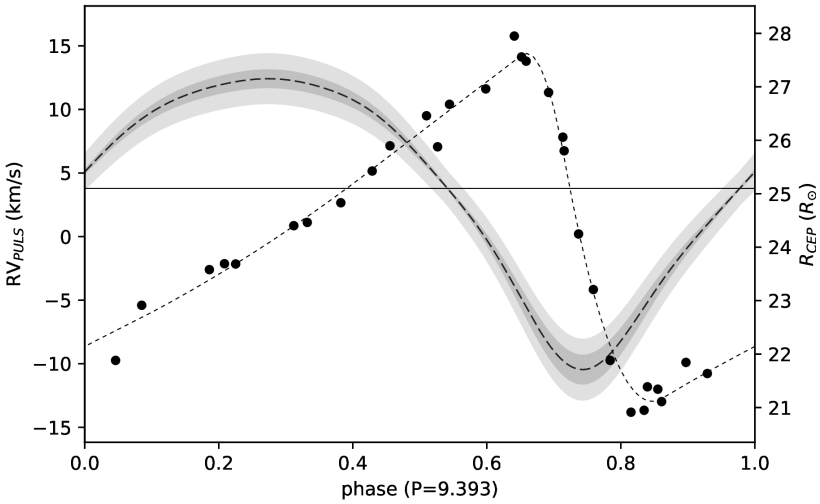
not a typical W Vir (asc. branch steeper)

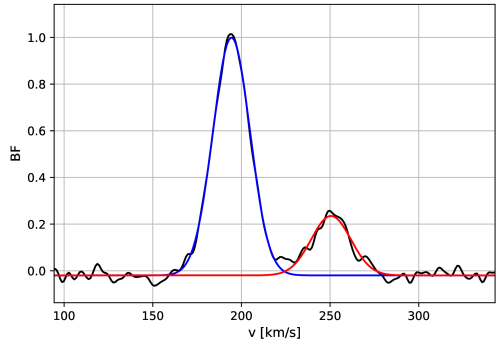
Spectroscopy
Radial velocity curves

- **SB2 - dynamical mass !**
  - Cepheid: 0.64 ± 0.02 $M_\odot$
  - companion: 5.67 ± 0.06 $M_\odot$
  - mass ratio ~ 9 !
- **high amplitude** of radius change (25%)
- **Hα emission** – Be shell star (disk)





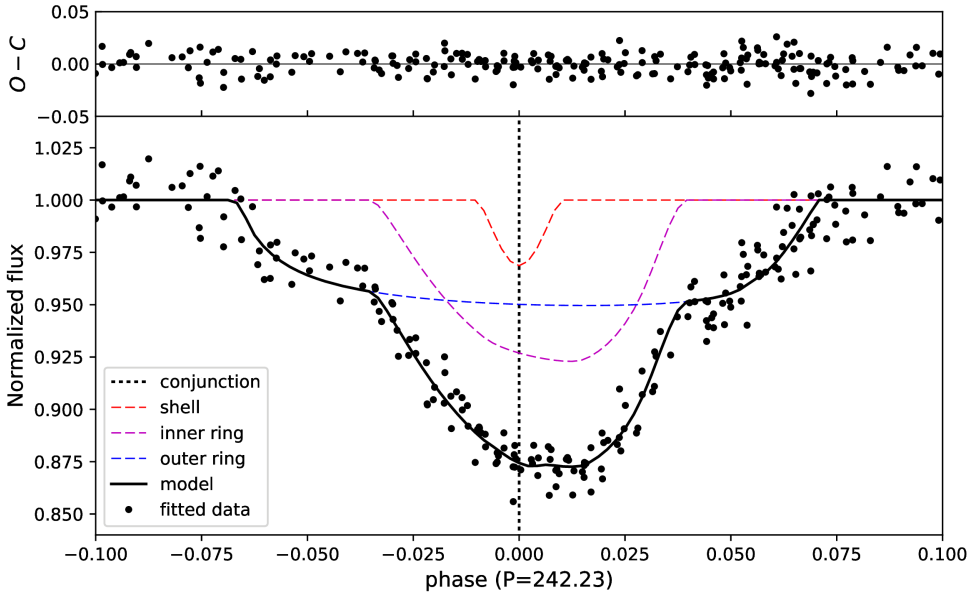


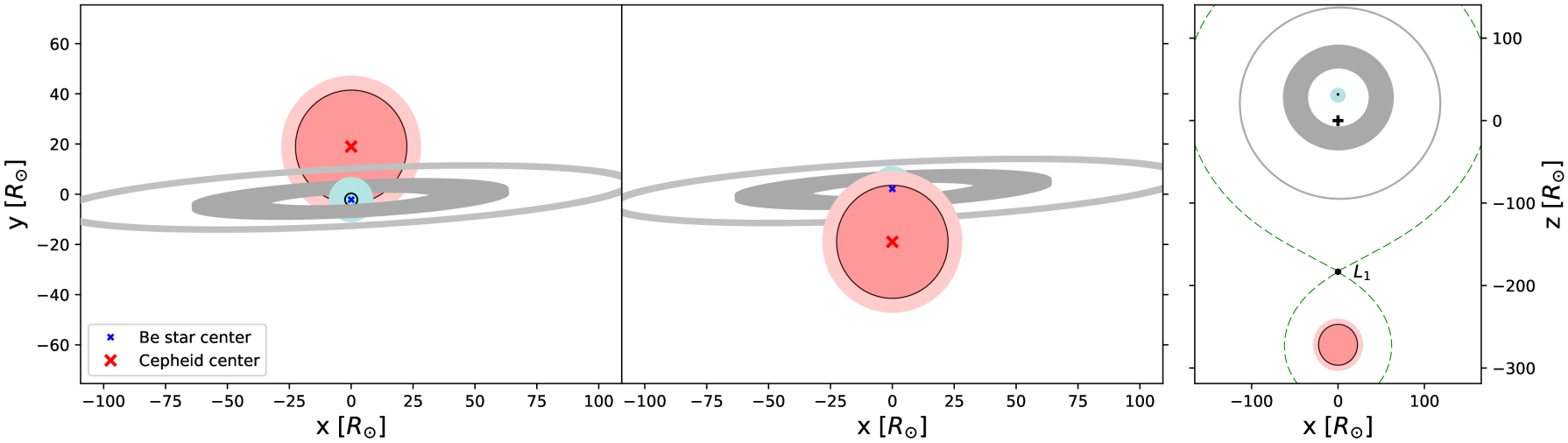


Broadening Function
for RV measurements

Light curve model
2-ring disk without pulsations

- **RVC + LC + puls. theory:**
  - R_{cep} = 25.1 ± 0.3 $R_\odot$
  - R_{comp} = 9 ± 2 $R_\odot$ (Be shell star)
  - ecc ~ 0.0
- **two-ring disk: R ~ 116 $R_\odot$**

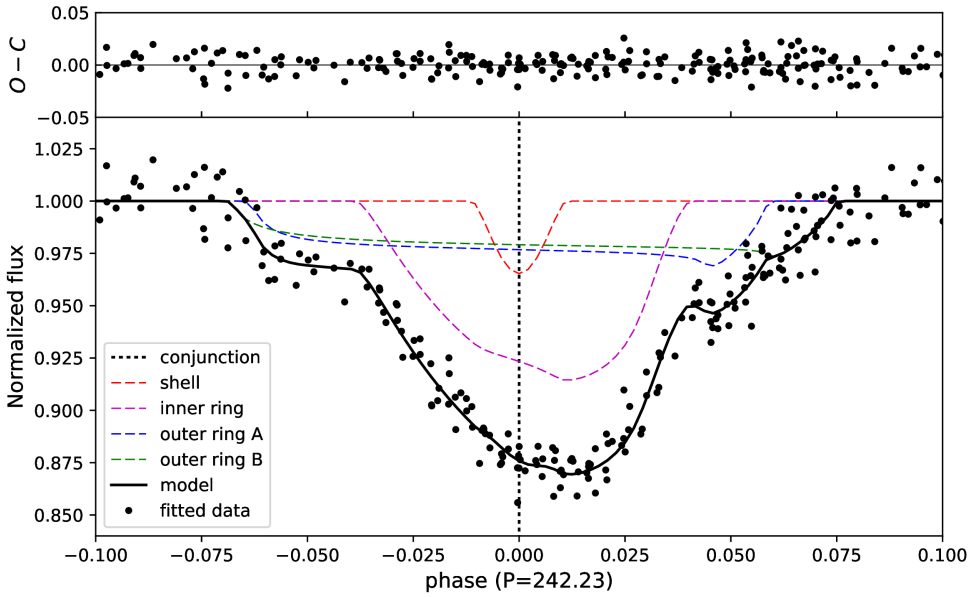


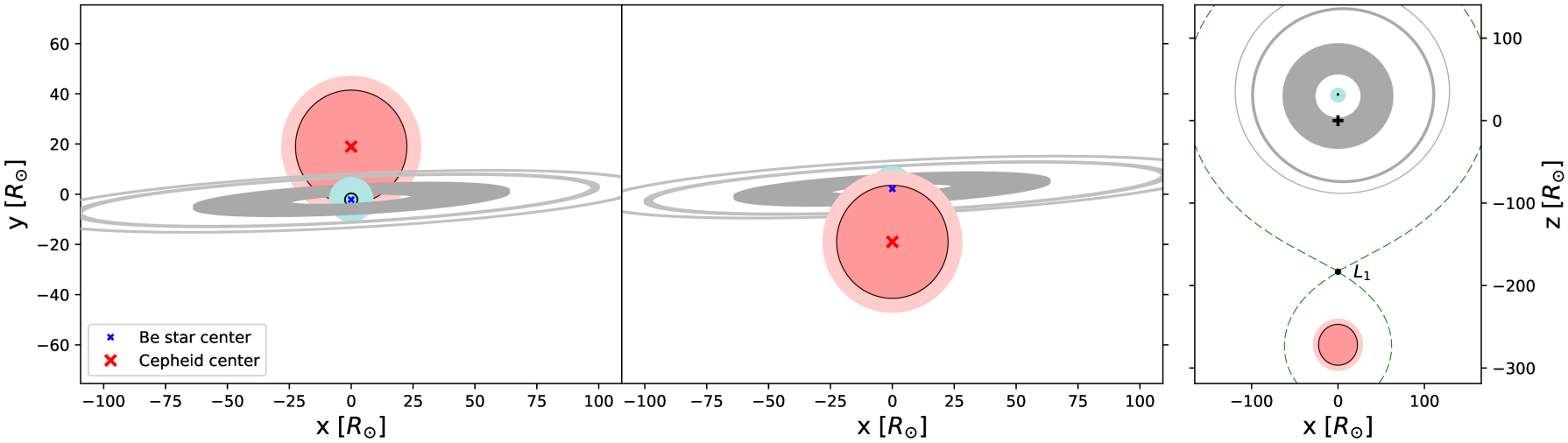


Light curve model
3-ring disk without pulsations

- **RVC + LC + puls. theory:**
  - $R_{cep} = 25.1 \pm 0.3\ R_\odot$
  - $R_{comp} = 9 \pm 2\ R_\odot$ (Be shell star)
  - ecc ~ 0.0
- **three-ring disk: R ~ 125 $R_\odot$**

  => prob. a complex (spiral?) structure

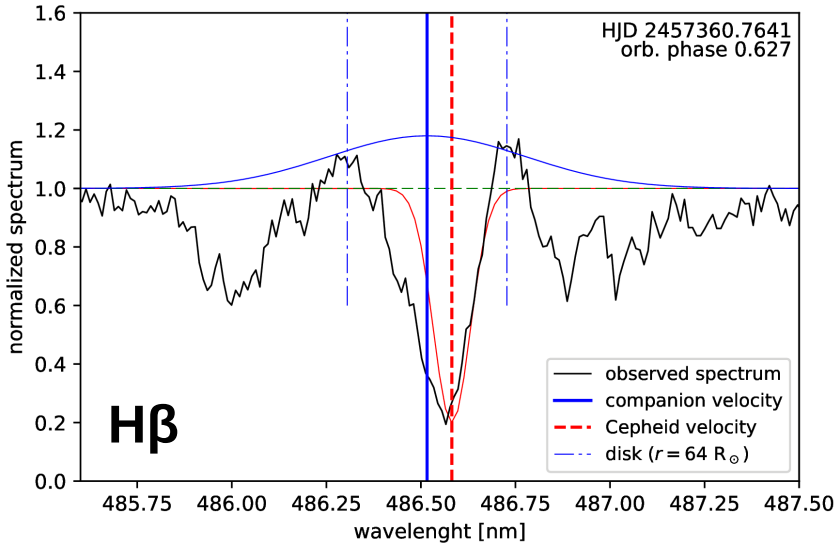


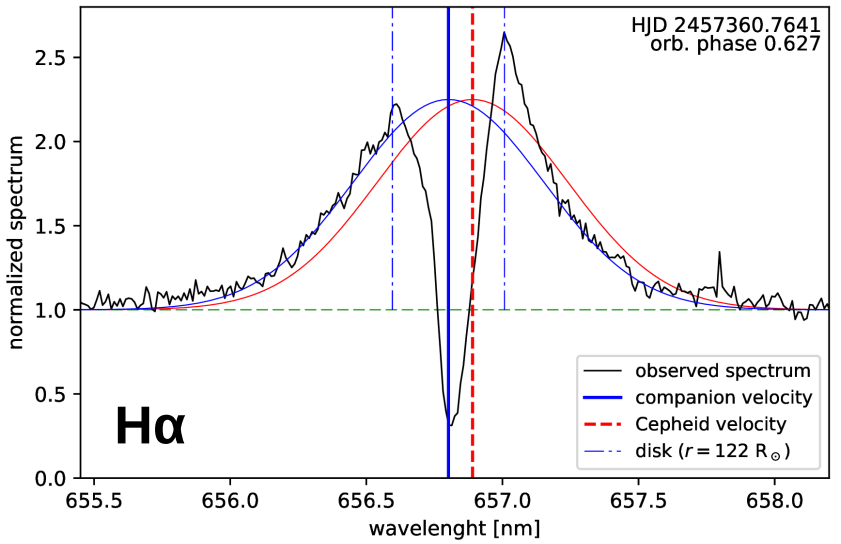


Spectral lines
Hα/Hβ emission

- **inner ring**
  - from ~30 to 64 $R_\odot$
- **outer ring(s)**
  - one outer ring R ~ 116 $R_\odot$

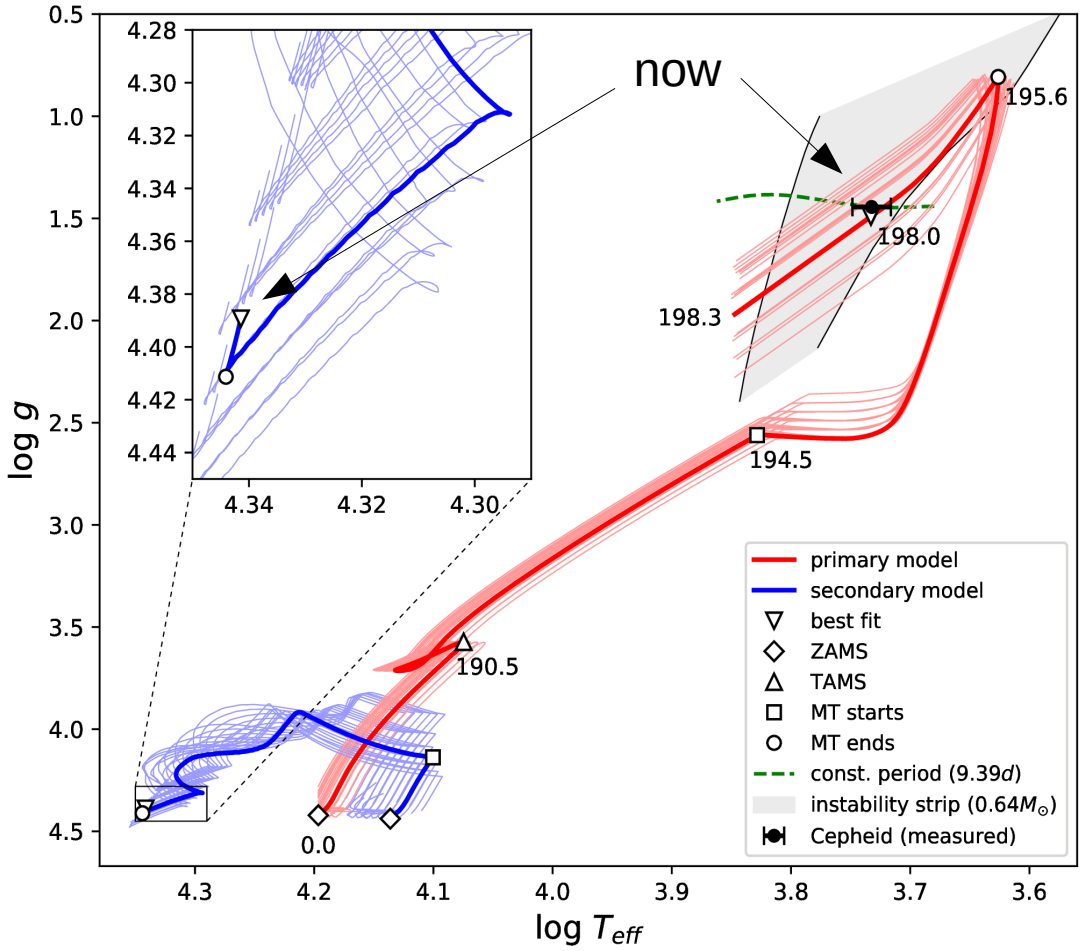
    or:
  - two outer rings R ~ 125 $R_\odot$
- **Hα emission**
  - max. at 113-122 $R_\odot$
- **Hβ emission**
  - max. at 64 $R_\odot$





Binary evolution scenario

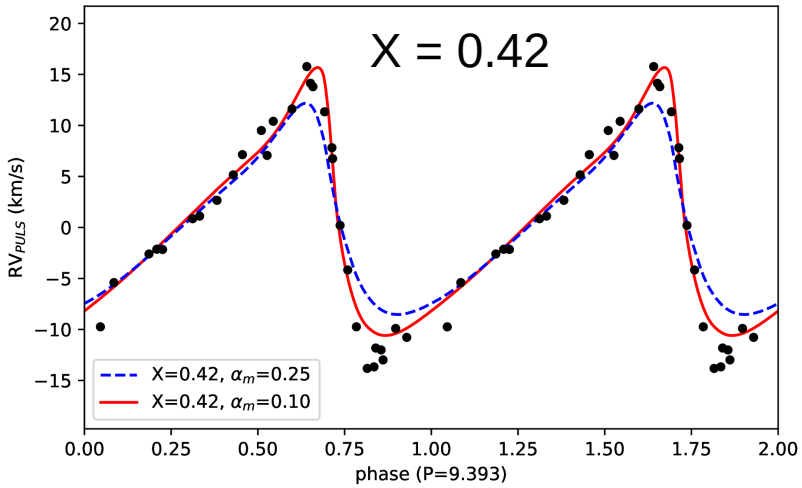
- **high q => mass transfer**
- **binary evolution**
  - STARS code (*A.D.*)
- **initial configuration**
  - orbital period: 12 days
  - M_1 (cep) = 3.52 $M_\odot$
  - M_2 (comp) = 2.82 $M_\odot$
- **now (~ 200 Myr):**
  - stripped of H (92% He)
  - passing through IS
  - companion: 2.5 $R_\odot$, T=22,000K (~ 9 $R_\odot$ from LC)

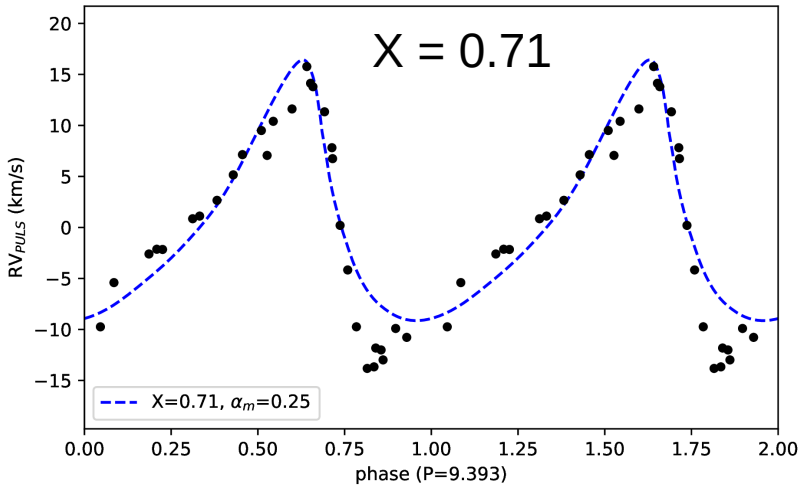


Relatively young objects (not population II) !

Consistency check
RVC comparison

- **Cepheid total mass:**
  - helium: 92%
- **Cepheid surface:**
  - hydrogen: 42%
  - helium: 57%
- **RVC comparison:**
  - observed (points)
  - puls. theory model (lines) (R.S.)
  - consistent for X=0.42
- **Confirms results from binary evolution**
- **<u>Plausible channel for all pWVir stars</u>**
  (but not yet for all type II Cepheids)





Disk origin

- **Decretion or accretion ?**
  - or both ?
- **Disk feeding:**
  - fast rotation of the early-type companion (Be shell star)
  - mass transfer in the past (inner ring?)
  - mass loss due to pulsations (outer ring?)
- **R_{disk}** slightly < **R_{max} = 130 $R_\odot$** (stable disk, P77)

See: Pilecki+2018b and https://users.camk.edu.pl/pilecki for more information on this system.