# *Photometric variability of binaries*

Research workshop on evolved stars

Prof. Stephan Geier
&
Harry Dawson

27.08.2024

Institute for Physics and Astronomy
Email: sgeier@astro.physik.uni-potsdam.de
hdawson@astro.physik.uni-potsdam.de

Universität Potsdam

# *Introduction*

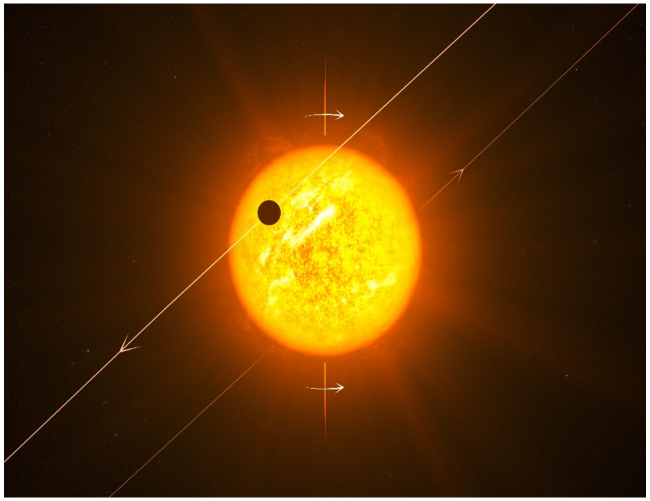
# What are variable stars?

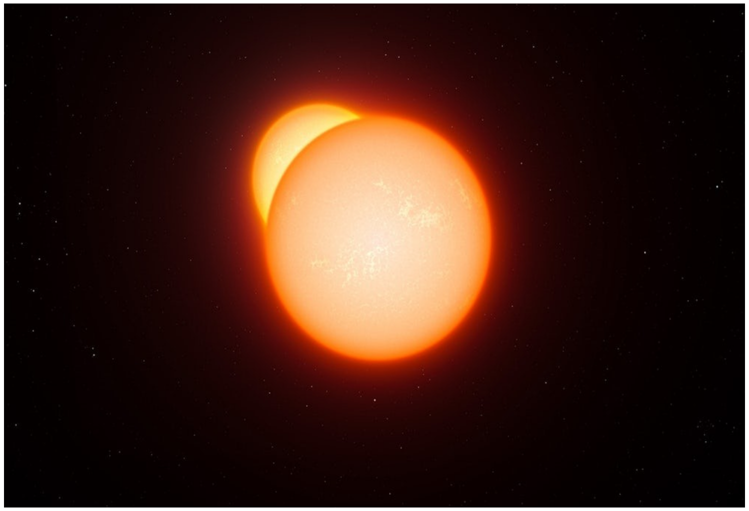
Stars, whose brightness vary periodically, semi-periodically or irregularly as seen from earth

- extrinsic variables: variability is due to the eclipse of one star by another or the effect of stellar rotation
- intrinsic variables: variation is due to physical changes in the star or stellar system

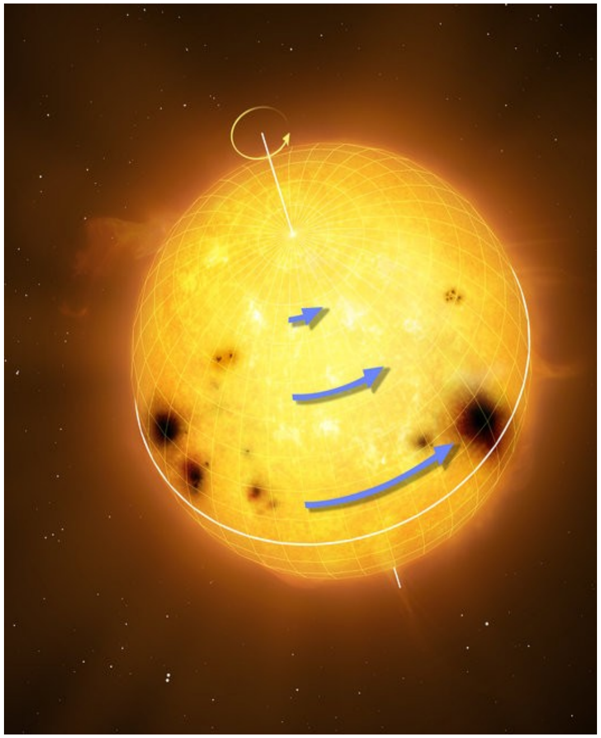
# Extrinsic variables

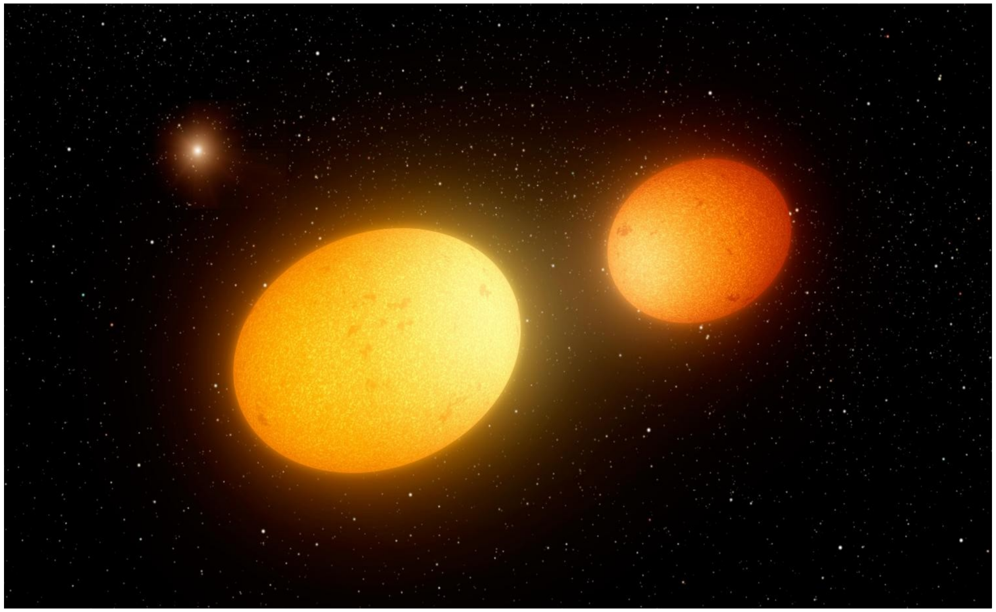
## Transiting planets/Eclipsing binaries





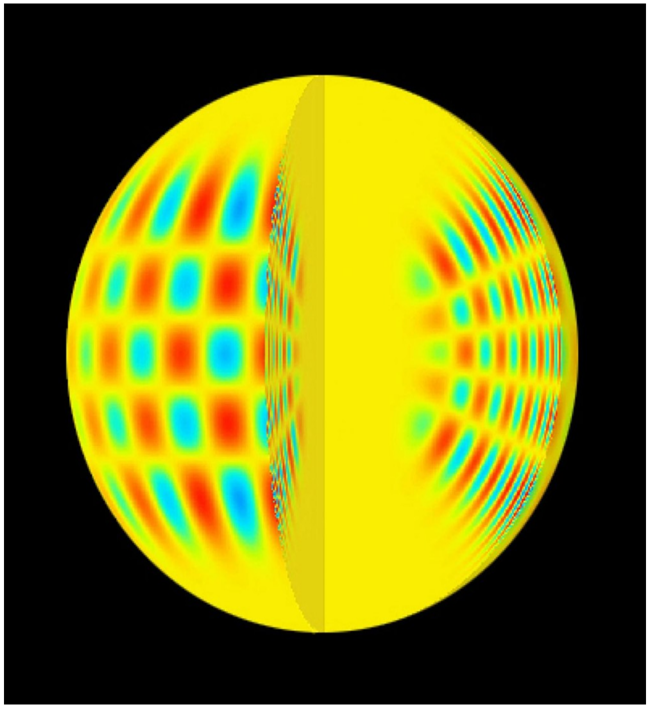
## Rotating variables



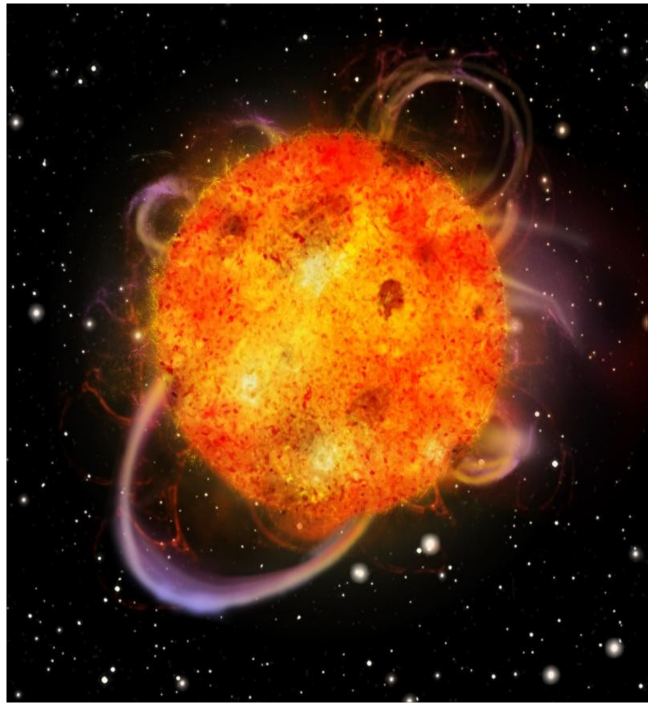


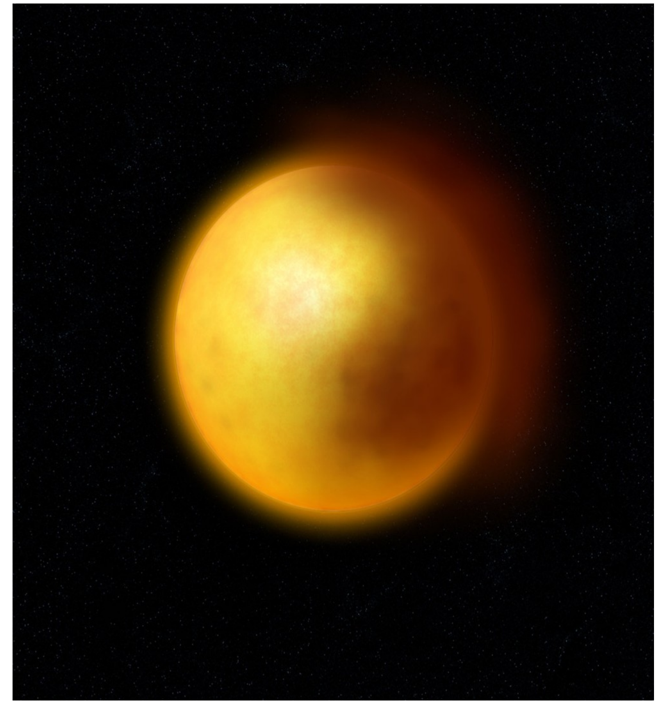
# Intrinsic variables

## Pulsating variables

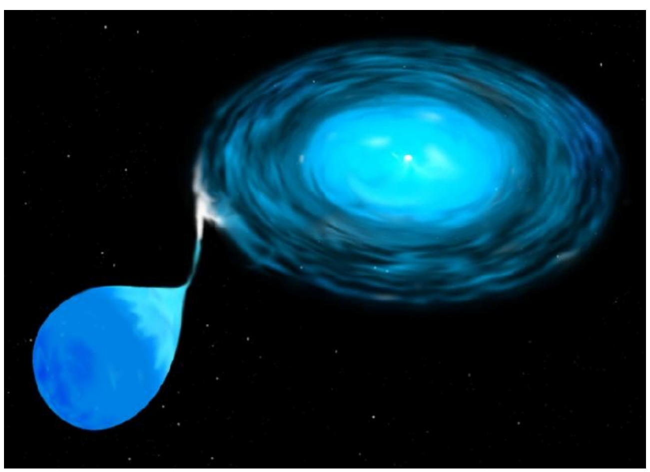


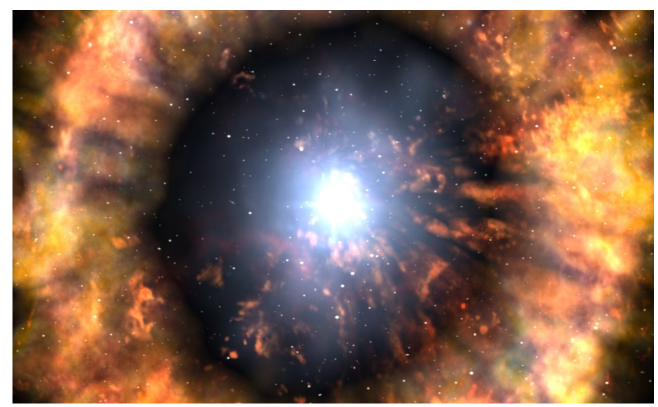
## Eruptive variables





## Cataclysmic variables

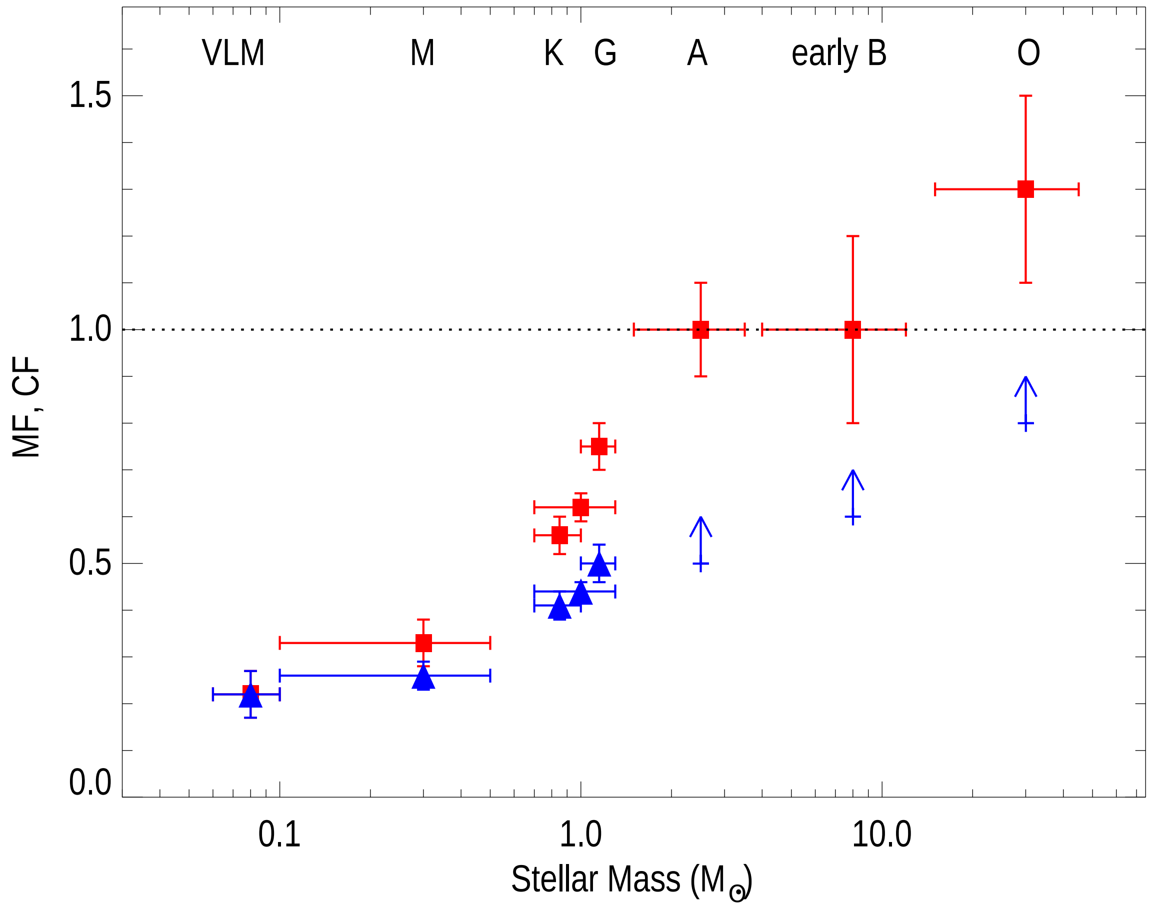




*Binary Stars: Overview*

# Binaries

50% – 80% of all stars in the solar neighbourhood belong to multiple systems.




Duchene & Kraus 2013

→ stellar evolution cannot be understood without understanding binary evolution

# Types of Binaries

Rough classification:

**apparent binaries**: stars are *not* physically associated, just happen to lie along same line of sight ("optical doubles").

**visual binaries**: bound system that can be resolved into multiple stars (e.g., Mizar); can image orbital motion, periods typically 1 year to several 1000 years.

**spectroscopic binaries**: bound systems, cannot resolve image into multiple stars, but see Doppler effect in stellar spectrum; often short periods (hours. . . months).

# Mass determination in binaries

To determine stellar masses, use Kepler's 3rd law:

$$\frac{a^3}{P^2} = \frac{G}{4\pi^2}(m_1 + m_2)$$

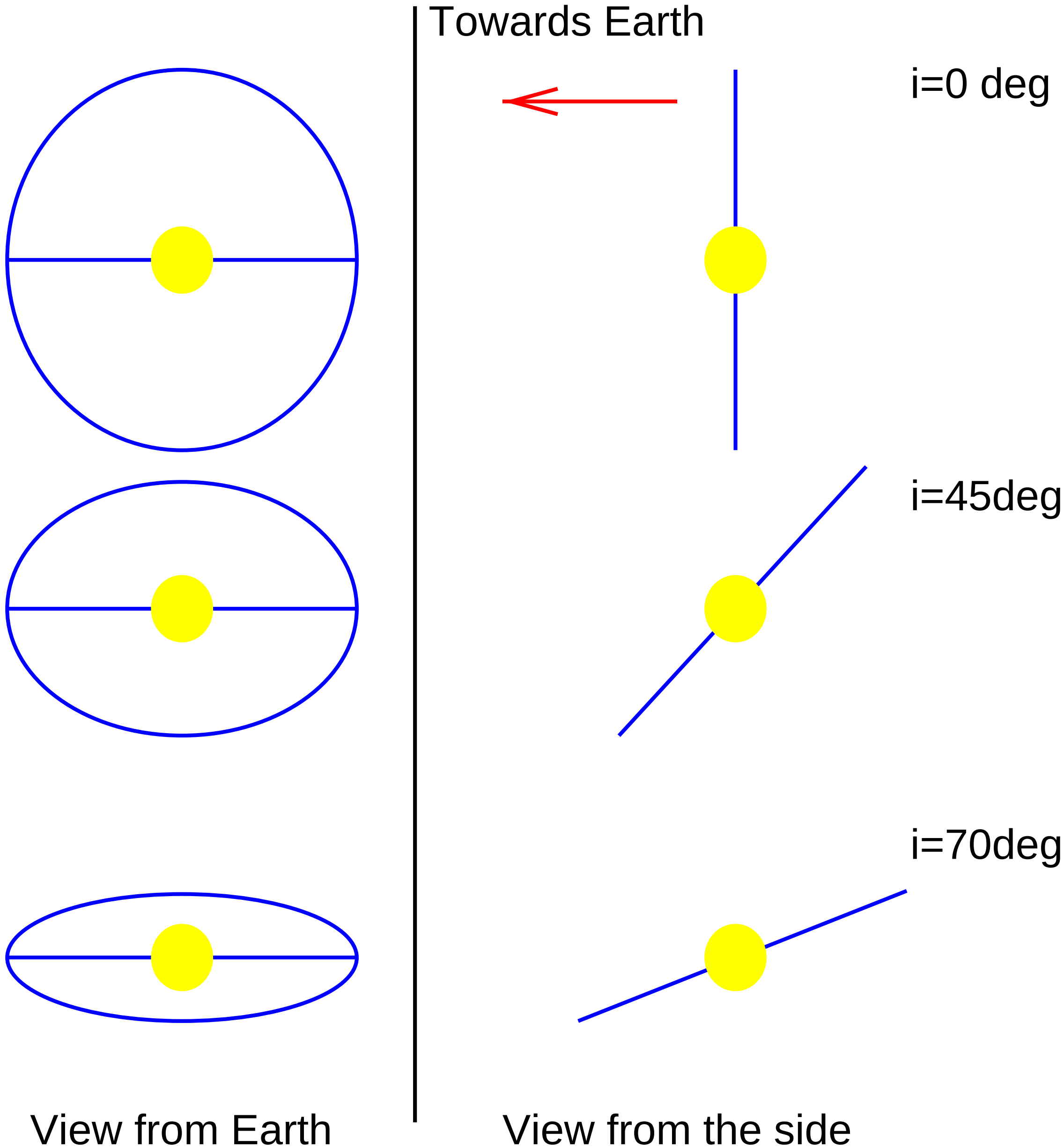
where

- $M_{1,2}$: masses
- $P$: period
- $a$: semimajor axis

Observational quantities:

- $P$ – directly measurable
- $a$ – measurable from image *if and only if* distance to binary and the inclination are known

# Mass determination in binaries

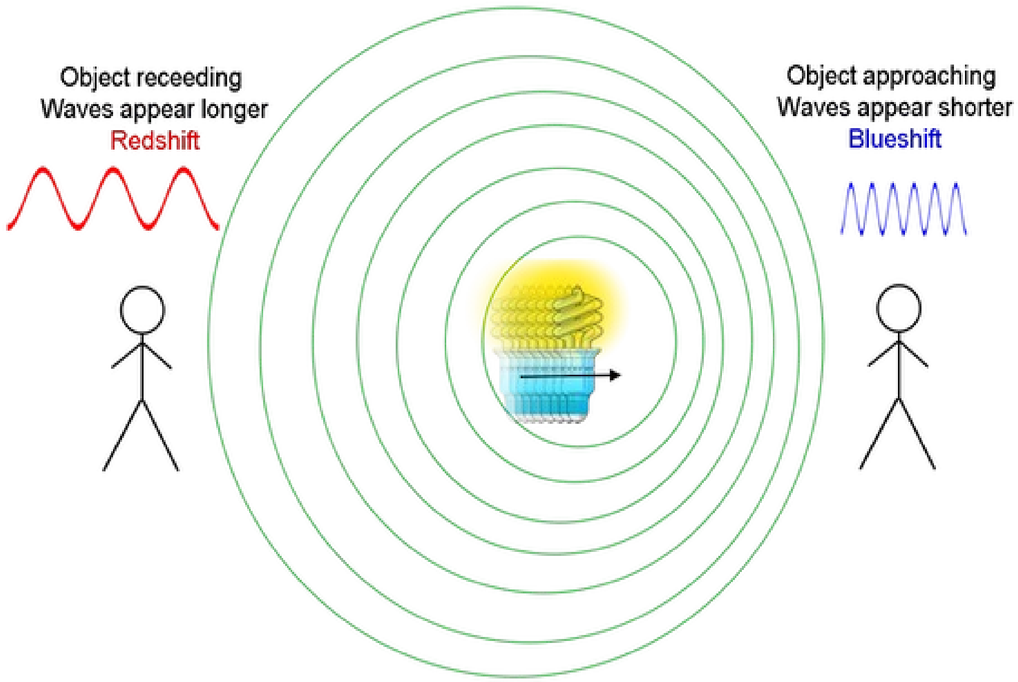



Problem when analysing orbits: orientation of orbit in space: “inclination”

In simplest case: real semi-major axis:

$$a_{\text{observed}} = a_{\text{real}} \cos i$$

# Spectroscopic Binaries



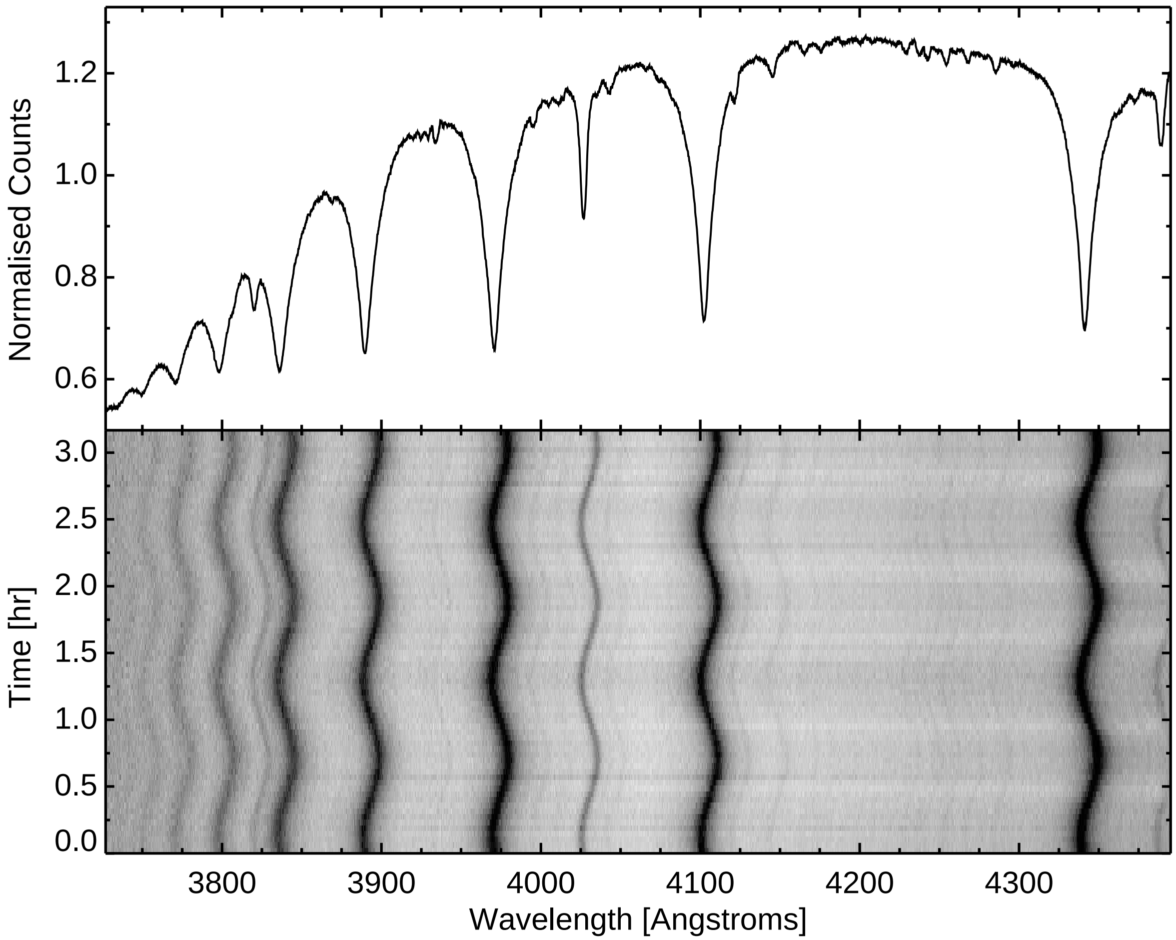

Spectroscopic binaries: Components close together: orbital motion via periodic Doppler shift of spectral lines.

SB2 = both spectra are visible

SB1 = only one spectrum visible

in **eclipsing** SB2 systems the inclination (close to $i=90^\circ$) and masses for both components can be determined.

# Spectroscopic binaries




CD−30°11223 (Geier, ..., Schaffenroth et al. 2013, A&A 554, 10)

Motion of star visible through Doppler shift in stellar spectrum:

$$\frac{\Delta\lambda}{\lambda} = \frac{v_\mathrm{r}}{c} = \frac{v \sin i}{c} \sin \frac{2\pi}{P} t$$

# Spectroscopic binaries

## Double-lined spectra, case SB2

Assume circular orbit ($e = 0$)

| | |
|---|---|
| $K_1, K_2$ | velocity half amplitudes of components 1 & 2 |
| $P$ | orbital period |
| $2\pi a_{1/2}$ | orbital radii of components 1 & 2 |

$$K_{1/2} = \frac{2\pi a_{1/2}}{P} \sin i$$

$$\Longrightarrow a_{1/2} \sin i = \frac{P}{2\pi} K_{1/2}$$

again $\sin i$ remains undetermined

# Spectroscopic binaries

Centre of mass law:

$$\frac{M_1}{M_2} = \frac{a_2}{a_1} = \frac{K_2}{K_1}$$

Kepler's third law:

$$M_1 + M_2 = \frac{4\pi^2}{G\,P^2}a^3,$$

$$a = a_1 + a_2 = \frac{P}{2\pi}(K_1 + \frac{P}{2\pi}K_2)/\sin i$$

$$\Longrightarrow M_1 + M_2 = \frac{4\pi^2}{G\,P^2}\frac{P^3}{(2\pi)^3}\frac{(K_1+K_2)^3}{(\sin i)^3}(\star)$$

$$\Longrightarrow M_1 + M_2 = \frac{P}{2\pi G}\frac{(K_1+K_2)^3}{(\sin i)^3}$$

$$(M_1 + M_2)(\sin i)^3 = \frac{P}{2\pi G}(K_1 + K_2)^3$$

$\Longrightarrow$ two equations for three unknowns ( $M_1 + M_2$, $\sin i$ ),
sin $i$ can only be determined for eclipsing binaries

# Spectroscopic binaries

**Single-lined spectra, case SB1**

(only one spectrum visible):

$K_2$ Unknown: $K_2 = K_1 \frac{M_1}{M_2}$

Insert in equation ($\star$):

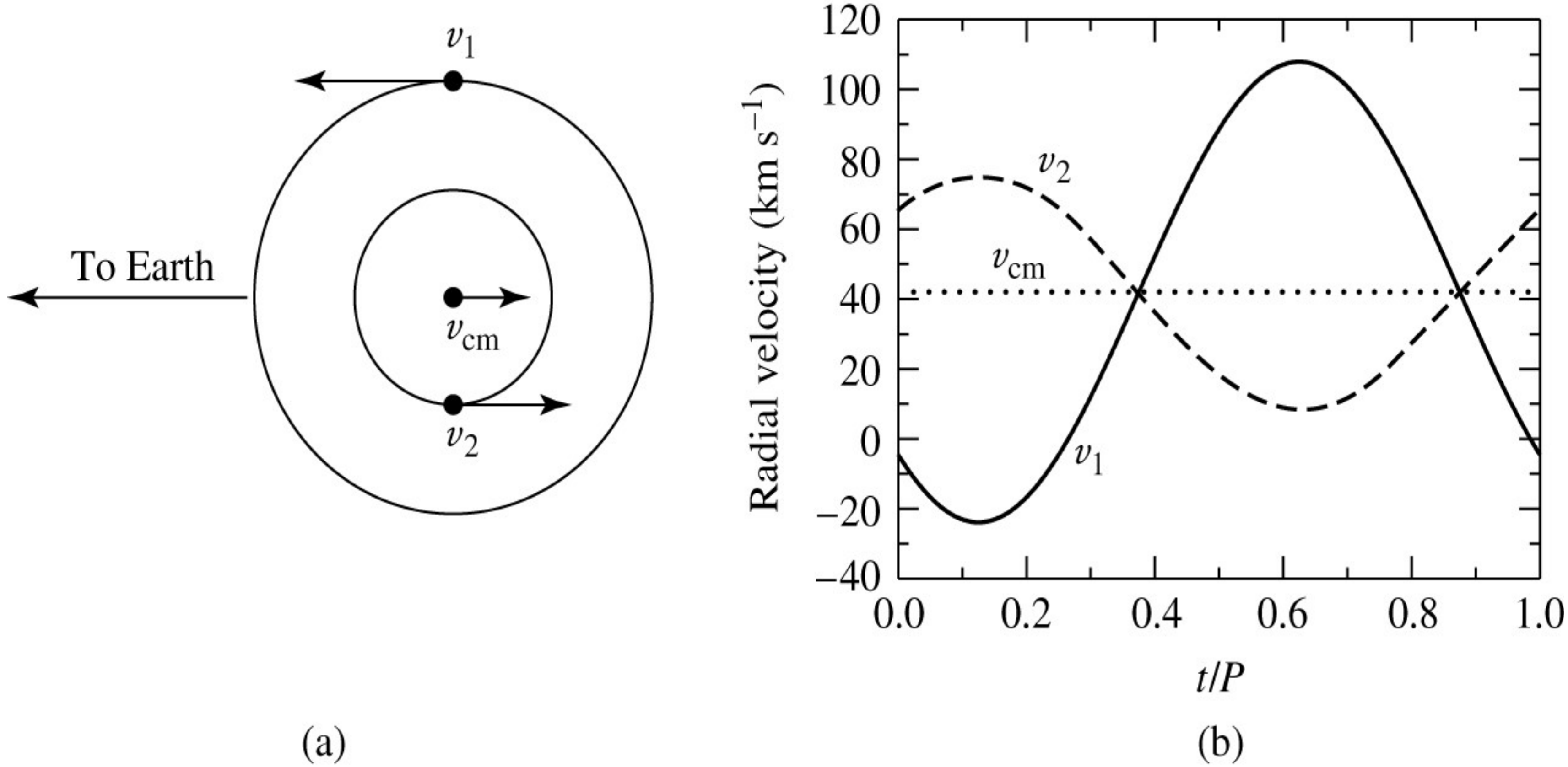
$$(M_1 + M_2)(\sin i)^3 = \frac{P}{2\pi G}\left(K_1 + K_1 \frac{M_1}{M_2}\right)^3$$

$$\frac{M_2\left(1 + \frac{M_1}{M_2}\right)(\sin i)^3}{\left(1 + \frac{M_1}{M_2}\right)^3} = \frac{P K_1^3}{2\pi G}$$

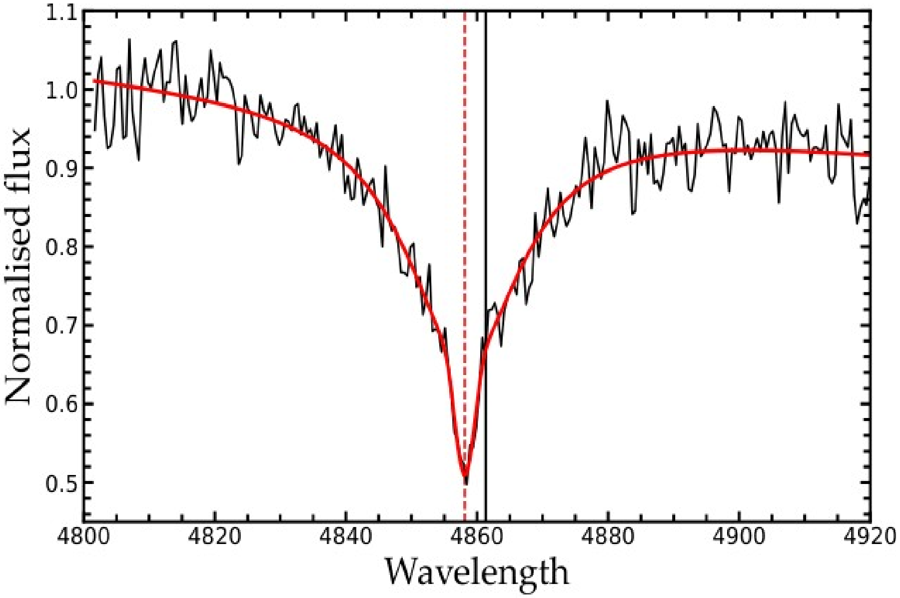
Mass function $f(M)$:

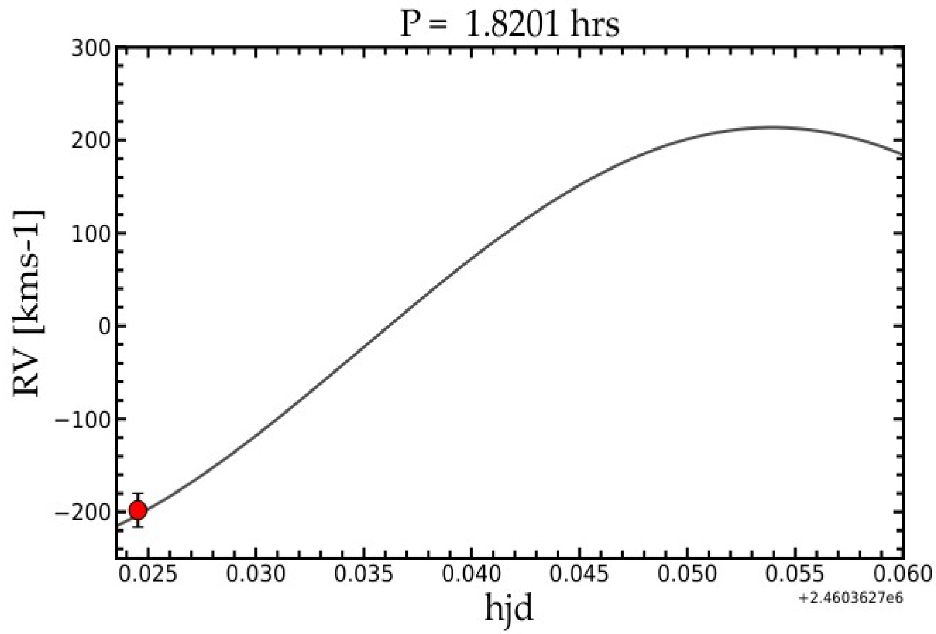
$$f(M) = \frac{M_2(\sin i)^3}{\left(1+\frac{M_1}{M_2}\right)^2} = \frac{P K_1^3}{2\pi G}$$

# Spectroscopic binaries: Radial velocity curve



# Spectroscopic binaries: Radial velocity curve



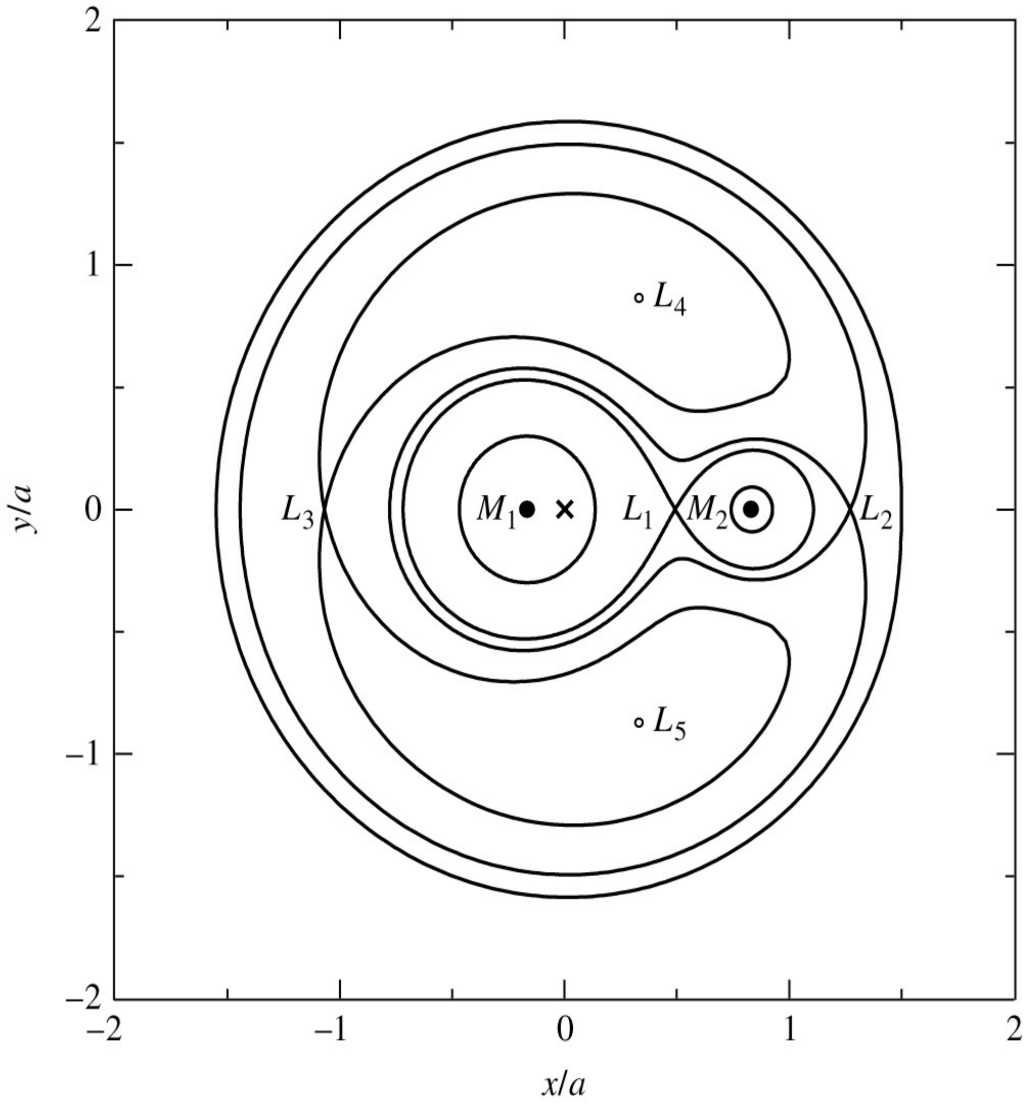




**Try out these interactive simulators!**

http://astro.unl.edu/naap/esp/animations/radialVelocitySimulator.html
https://astro-apps.org/BinaryStarSystem/index.html

# *Light Curves of Eclipsing Binary Stars*

# The Roche Model




In a close binary system: Gravitational potential described by the Roche potential:

$$\Phi_R(\mathbf{r}) = -\frac{GM_1}{|\mathbf{r}-\mathbf{r}_1|} - \frac{GM_2}{|\mathbf{r}-\mathbf{r}_2|} - \frac{1}{2}(\omega \times \mathbf{r})^2$$

and where

$$\omega = \left(\frac{GM}{a^3}\right)^{1/2}$$

Stellar surfaces are isosurfaces of this potential

=⇒ stars are non-spherical

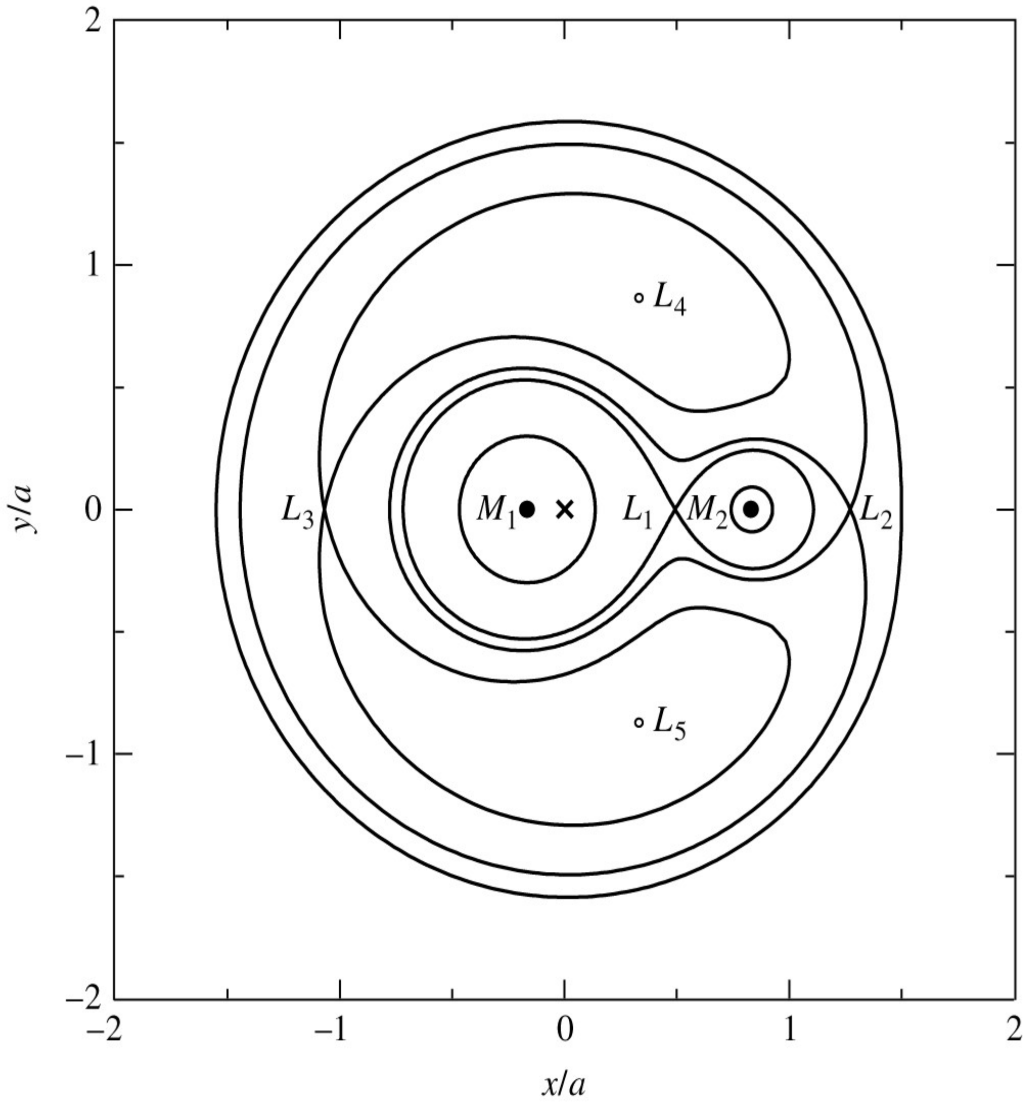
=⇒ Stellar magnitude changes with orbit.

Roche radius:

$$\frac{R_L}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})} \qquad (3.11)$$

R. Hynes

# The Roche Model

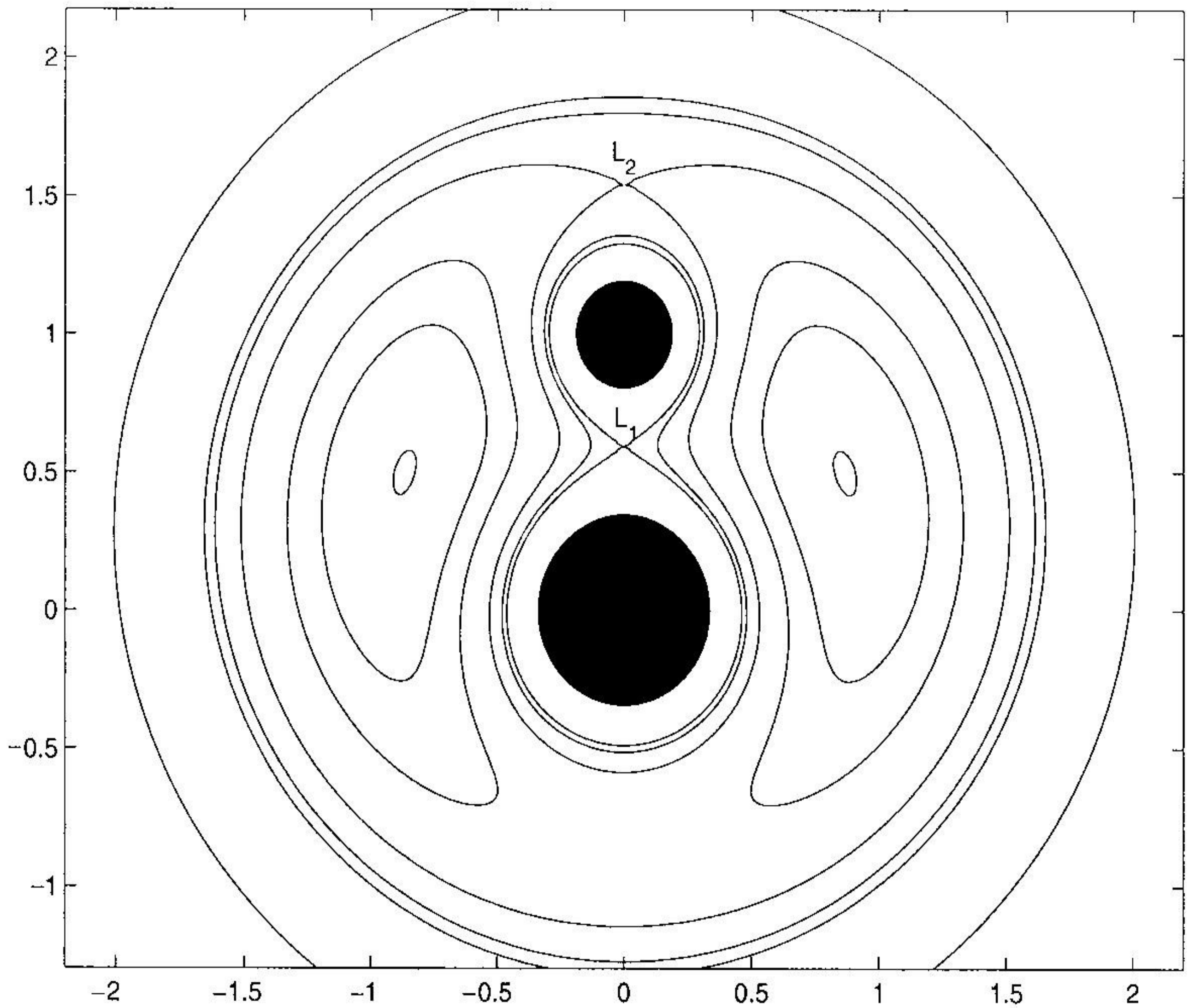



Carroll & Ostlie

Approximations:

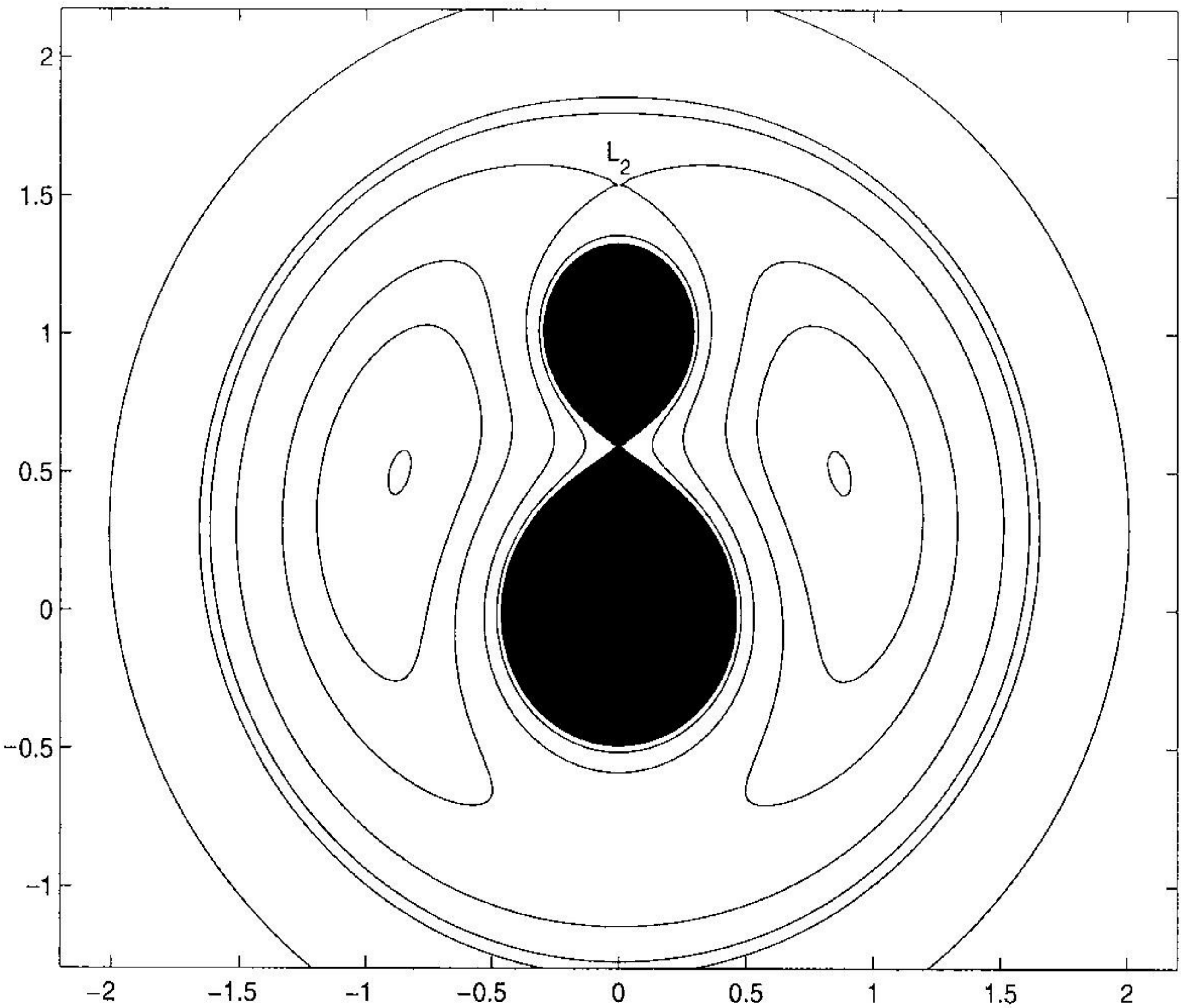
- stellar potentials are point-like (most of the stellar mass is concentrated in its core)
- Orbits are circularised (quickly established by tidal forces)
- rotation axes are perpendicular to the orbital plane
- stellar rotation is synchronous (tidally locked to the orbit)

# The Roche Model

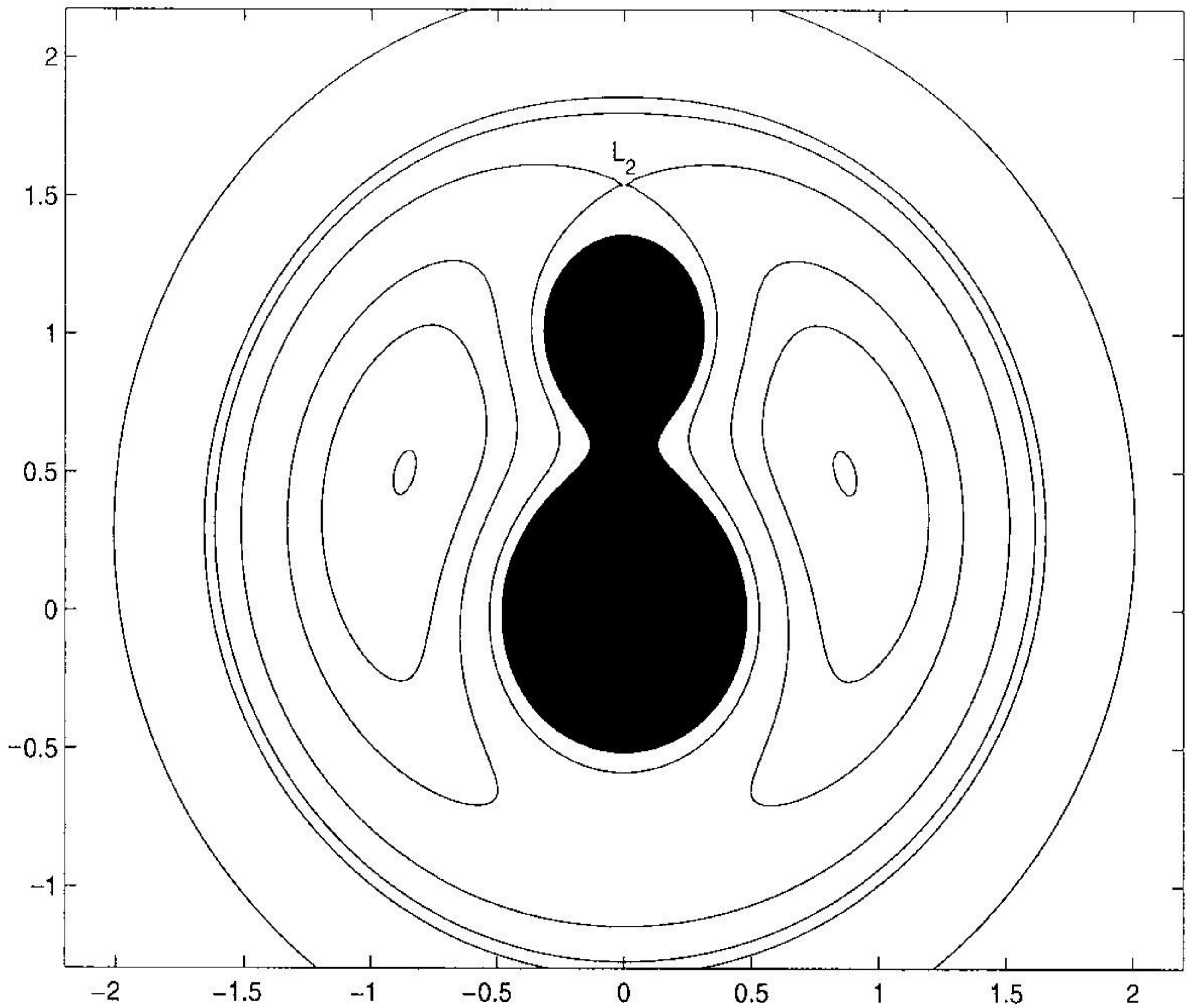



Detached Binaries

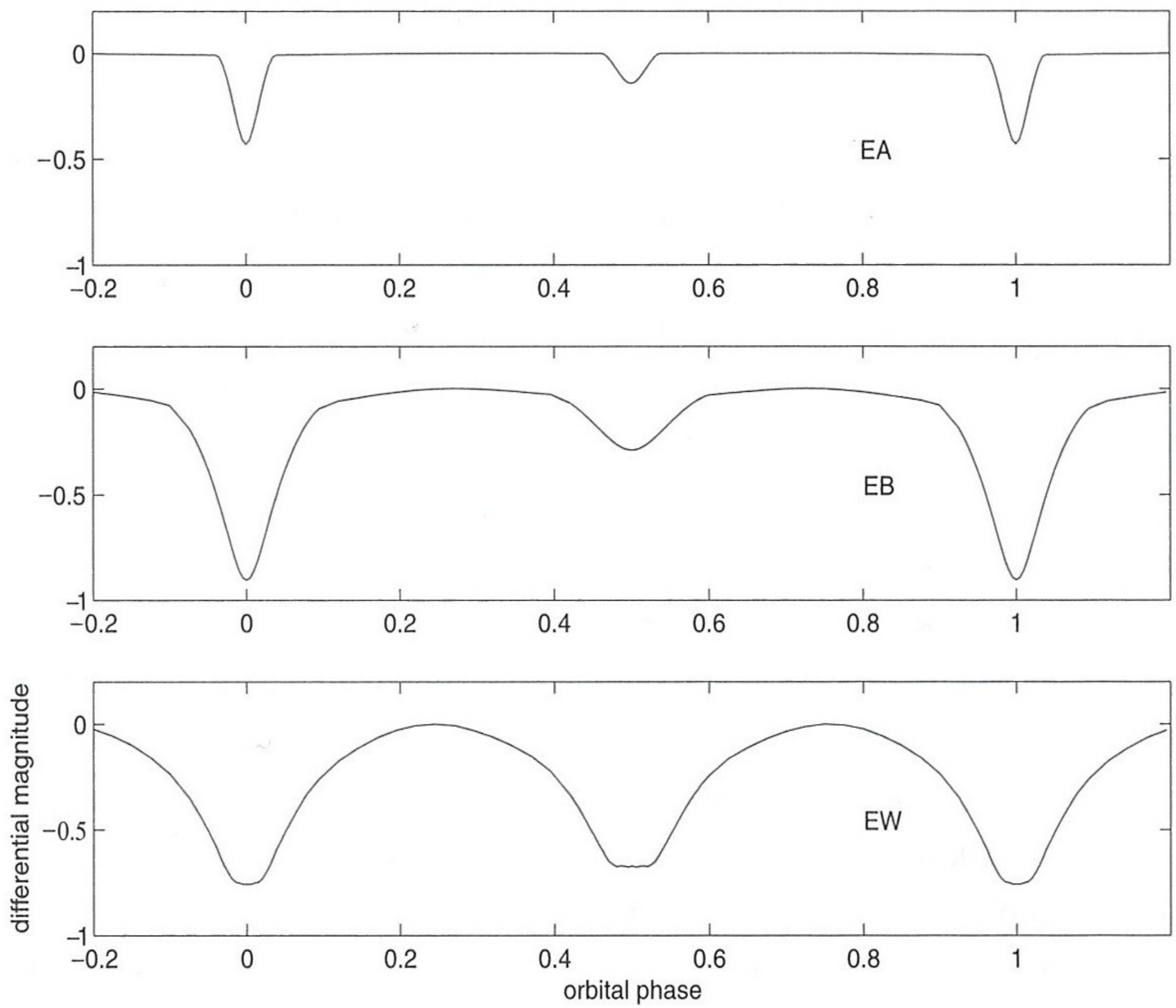
# The Roche Model



# The Roche Model



# The Roche Model




light curves of eclipsing binaries: detached, contact, overcontact (top to bottom)

# Limb darkening

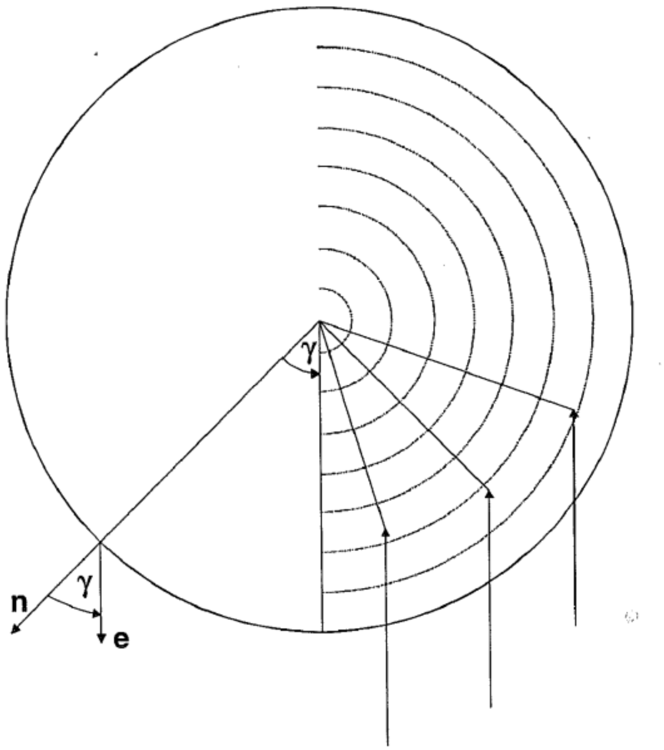
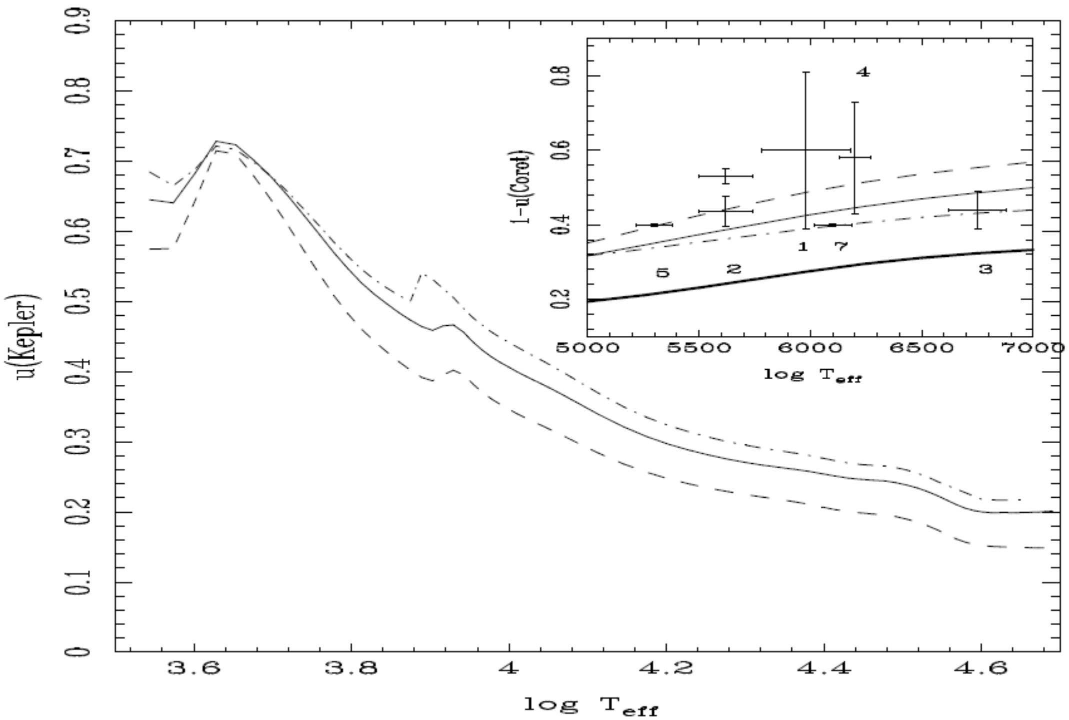



FIGURE 3.17. Center-to-limb variation. This figure shows the aspect angle $\gamma$ (angle between normal vector **n** and radiation emission direction **e**) appearing in the mathematical formulation of the limb-darkening. The right part of the figure illustrates that the depth of the atmosphere region (and thus temperature) accessible to an observer varies with the aspect angle $\gamma$.

Kallrath & Milone (1999)

- intensity of the stellar disk decreases from the centre to the limb temperature is increaing with increasing photospheric depth
- can be measured for the sun
- can be measured by microlensing
- can be calculated from model atmospheres
- linear law: $I = I_0(1 - \epsilon + \epsilon \cos\theta)$
  $\epsilon$ = limb darkening factor, wavelength dependent
  sun in the UV ($<$ 1600Å): limb brightening due to chromospheric temperature rise

# Limb darkening




Claret & Bloemen (2011, A&A 529, A75)

- limb darkening coefficient is temperature dependent
- other laws in use

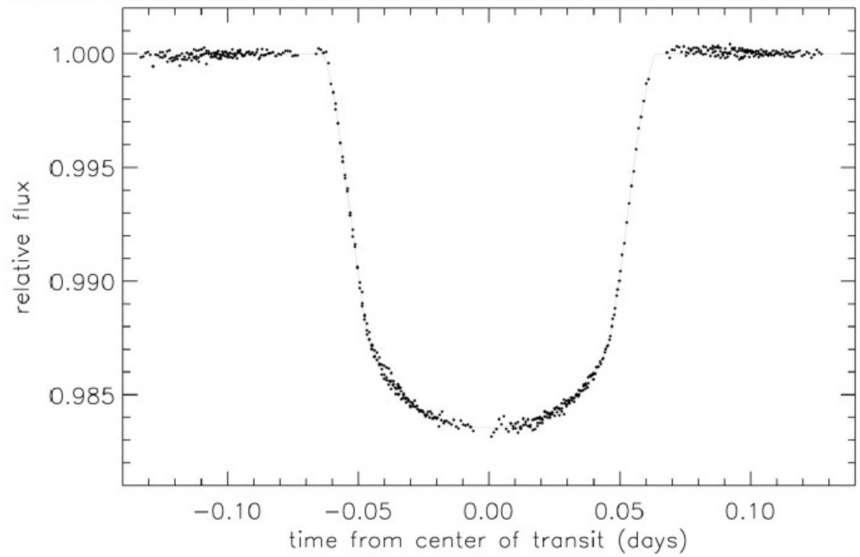
Claret's law:

$$I/I_0 = 1 - a_1(1 - \mu^{1/2}) - a_2(1 - \mu) - a_3(1 - \mu^{3/2}) - a_4(1 - \mu^2) \qquad (3.12)$$

$\mu = \cos \gamma$

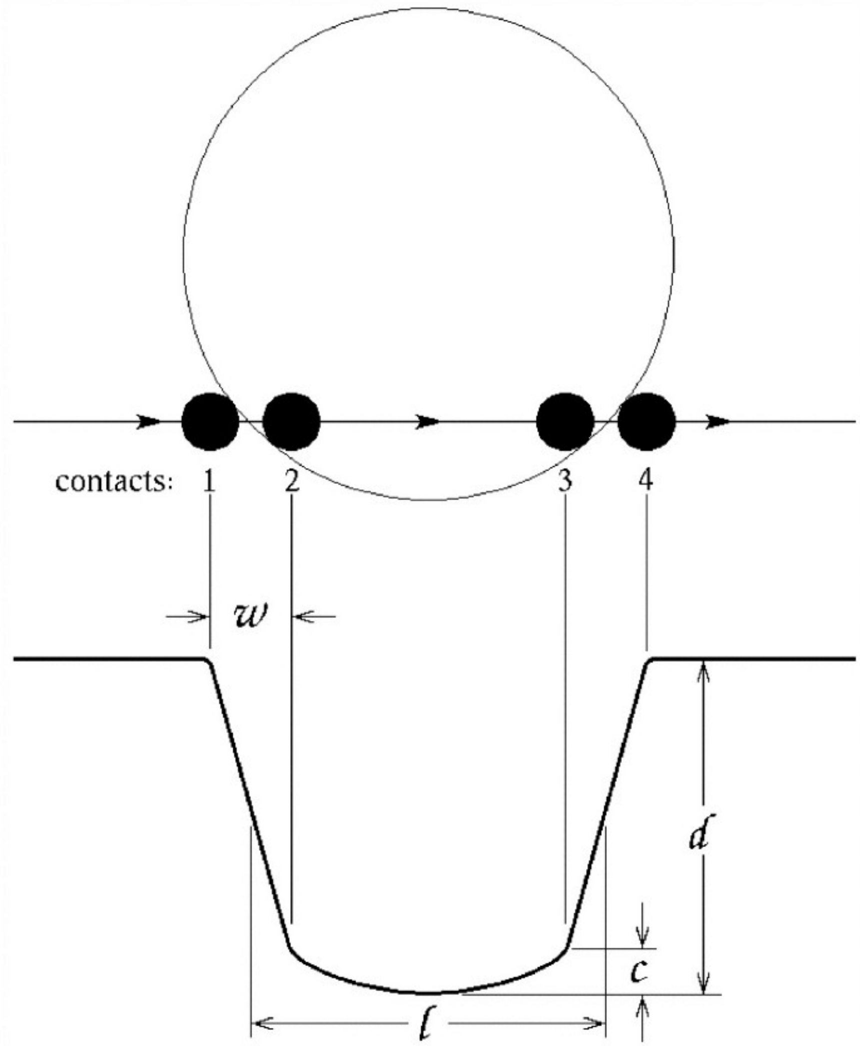
# Limb darkening

HD 209458b: the first transiting exo-planet discovered, HST light curve:

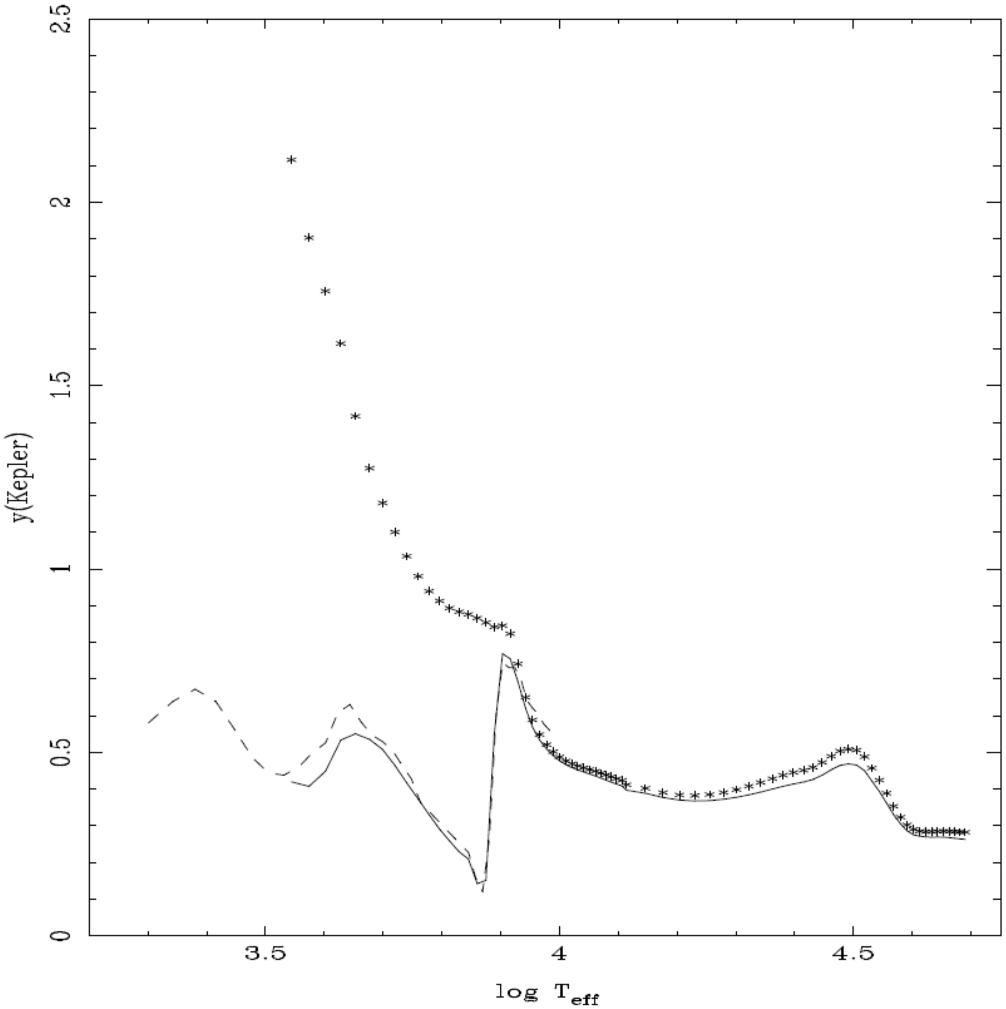



- Transit is not central
- transit depth is not constant
- → caused by limb darkening

Brown et al. (2001, ApJ 552:699)



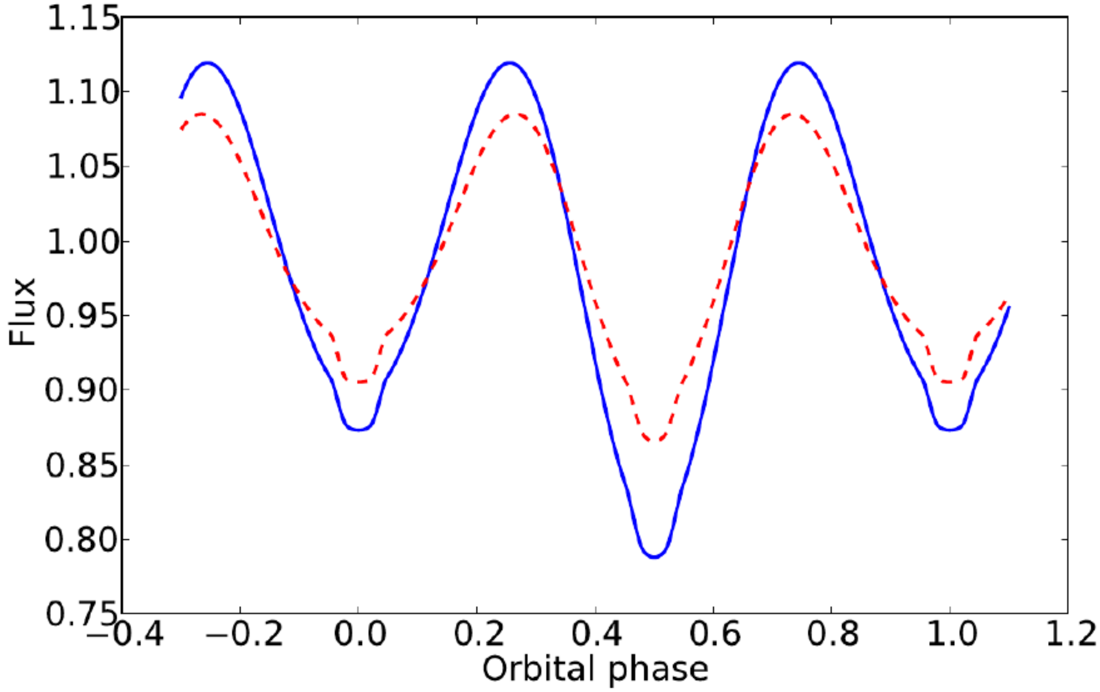
# Gravity darkening




Claret & Bloemen (2011, A&A 529, A75)

- non-spherical stars, surface gravity varies across the surface
- von Zeipel's Theorem: radiative atmospheres: black body: diffusion equation
- due to temperature gradient in star Flux $F_R \propto \nabla B \propto \frac{dB}{d\Phi} \propto g$
- in the convective case F $\approx g^{0.32}$ (Lucy's law, 1967)
- derive numerically from appropriate model atmospheres
- $F \propto g^y$ (tables by Claret & Bloemen, 2011)

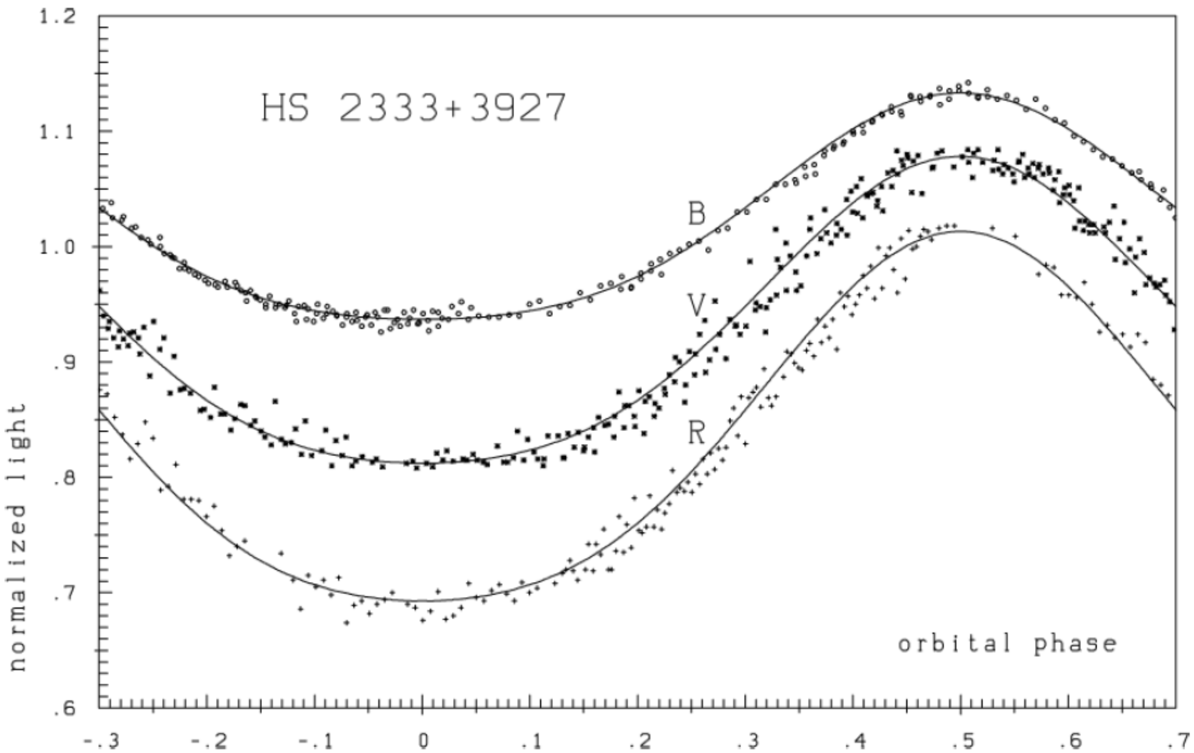
# Gravity darkening




Tidally-distorted, limb-darkened, eclipsing, with and without gravity darkening.

- non-spherical stars, surface gravity varies across the surface
- derive numerically from appropriate model atmospheres
- $F \propto g^y$ (tables by Claret & Bloemen, 2011)

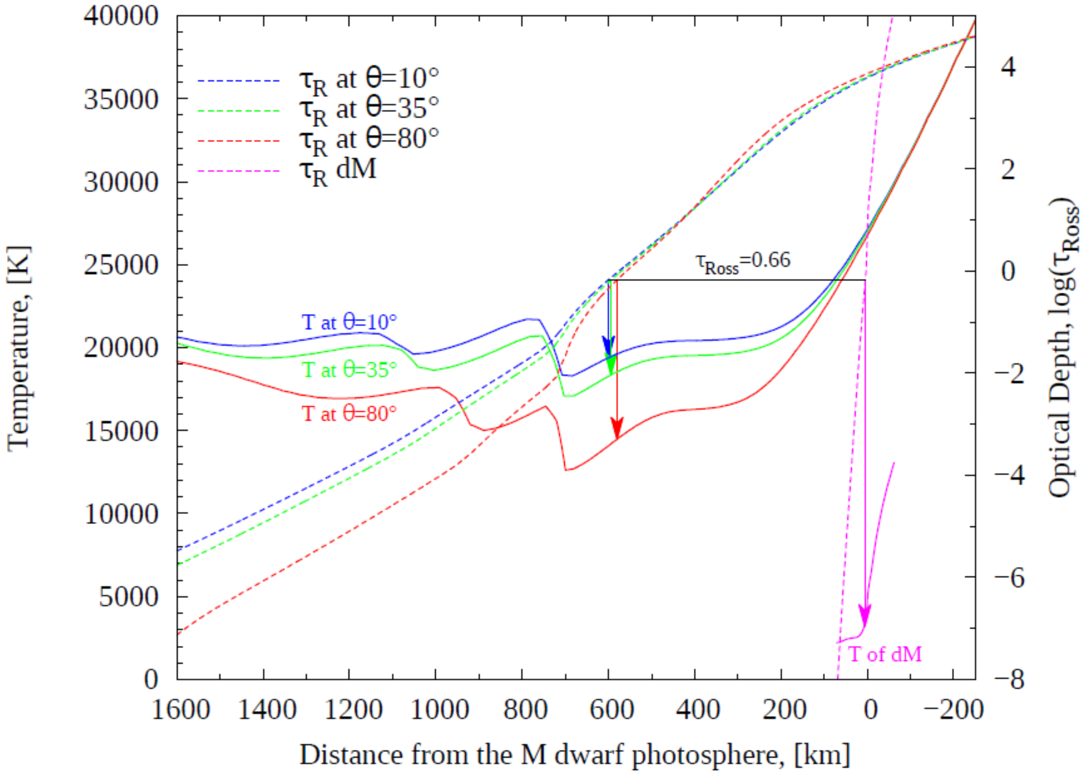
# Reflection effect




Heber et al. 2004, A&A 420, 251

- light variation by irradiated hemi-sphere of the companion
- companion has phases like the moon or Venus
- e.g. HS2333+3927: Hot star (33000K) & cool star (3000K)
- Albedo: percentage of light ref-elected from the irradiated surface.

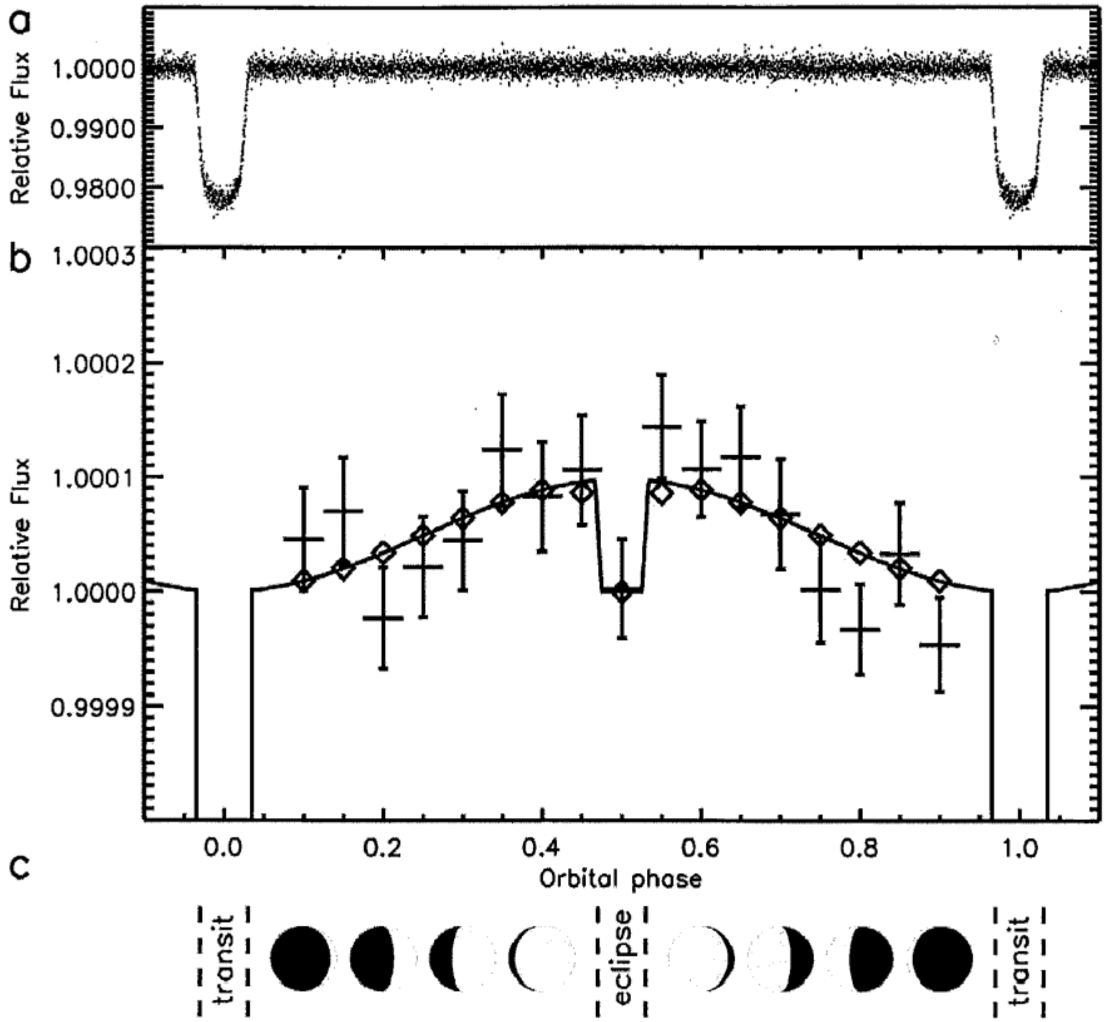
# Refection effect




Vuckovic et al. 2016

- The refelction effect is not simply re-flected light
- the irradiated hemisphere is strongly heated
- e.g. AA Dor: A hot subdwarf (40000K) & brown dwarf (3000K)
- hemisphere is heated to more than 20000K
- redistribution of flux from one wave-lengths range to the other
  → albedo can be larger than 1 (100%)
- synchronised rotation, no heat ex-change expected

# Reflection effect



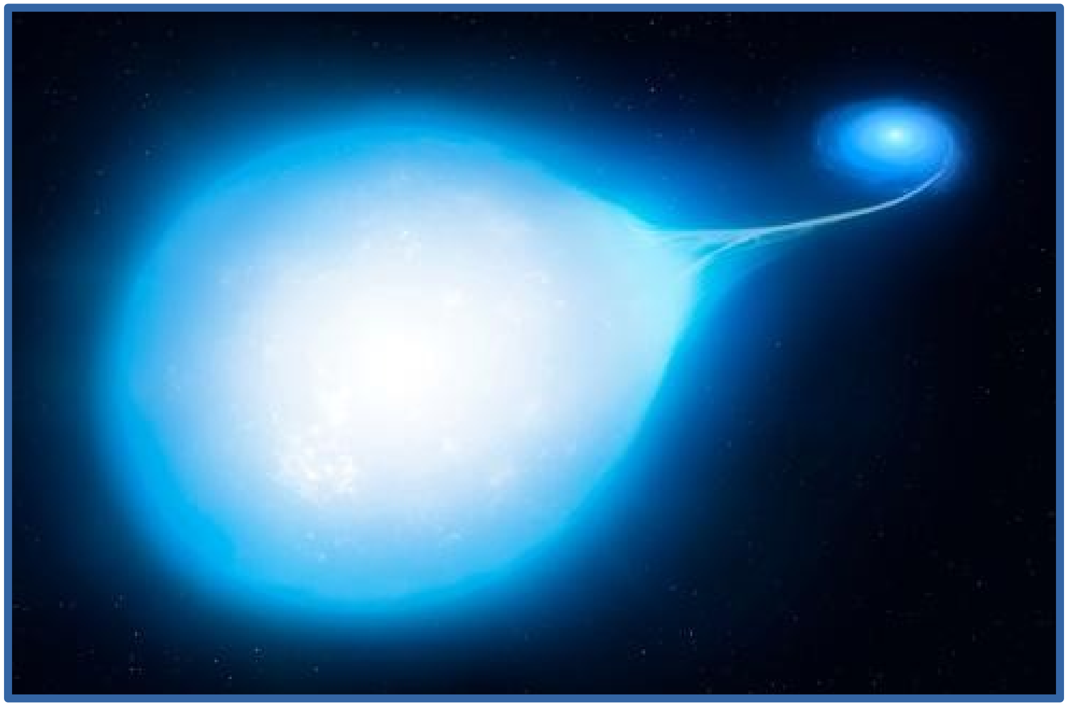

Snellen et al., 2009, Nature 459,543

- CoRoT 1b: Hot Jupiter: mass $M=1.03M_{Jup}$; radius: $R=1.49\ R_{Jup}$
- CoRoT 1b: Reflection effect and eclipse of a transiting planet discovered for the first time (Snellen et al. 2009)
- Orbital period 1.509 d, light variation 0.01%

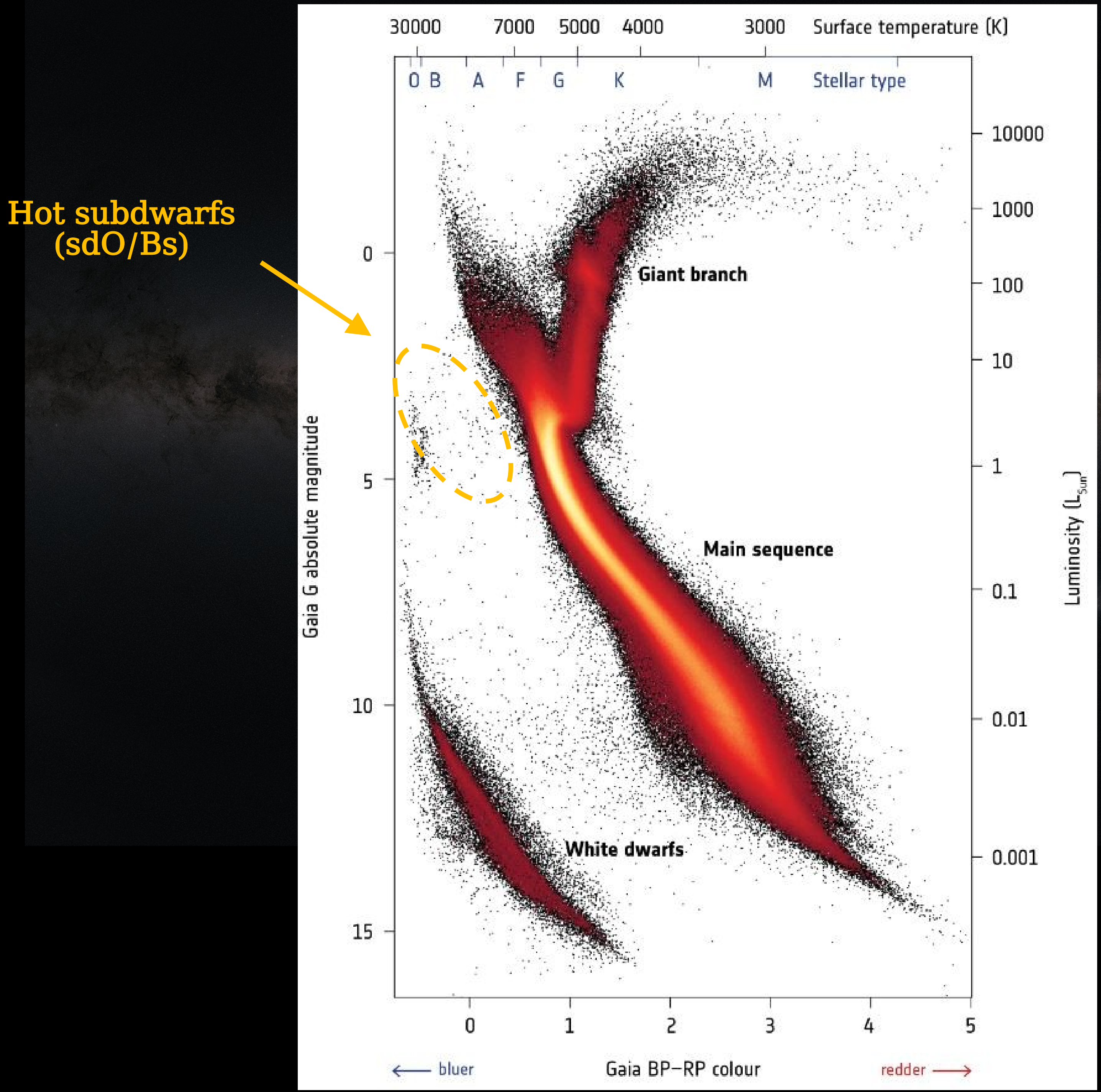
$$T_{2,new} = T_2 \left( 1 + \alpha \left( \frac{T_1}{T_2} \right)^4 \left( \frac{R_1}{a} \right)^2 \right)^{0.25} \quad (3.13)$$

## *The search for new hot subdwarf binaries*

Research workshop on evolved stars

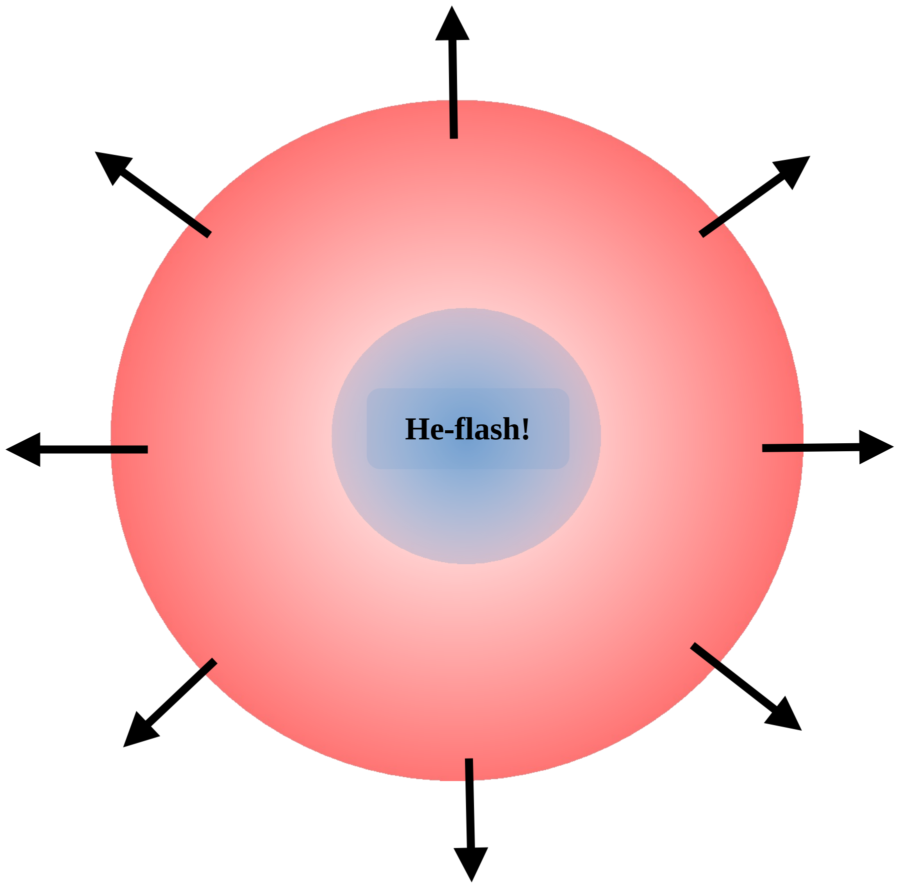


Universität Potsdam



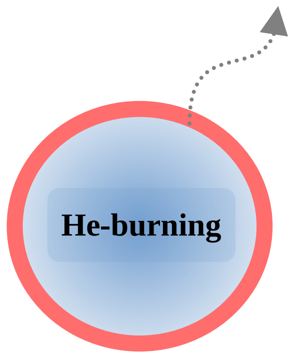
Hot subdwarfs
(sdO/Bs)
30000
7000
5000
4000
3000
Surface temperature (K)
O B A F G K M Stellar type
Giant branch
Main sequence
White dwarfs
Gaia G absolute magnitude
0
5
10
15
10000
1000
100
10
1
0.1
0.01
0.001
Luminosity (L_Sun)
0 1 2 3 4 5
← bluer
Gaia BP–RP colour
redder →

# Hot subdwarf = He-burning stripped star




Extreme mass-loss is difficult for single star evolution to explain!

Thin hydrogen envelope remaining (~0.01 $M_\odot$)



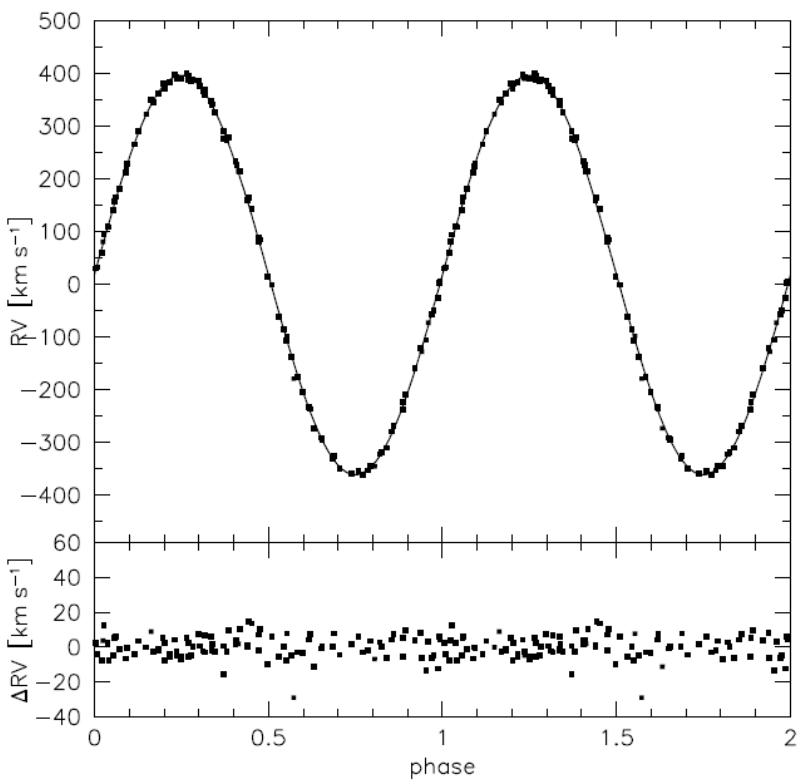

**Mass** ~0.47 $M_\odot$

**Radius** ~0.1 - 0.3 $R_\odot$

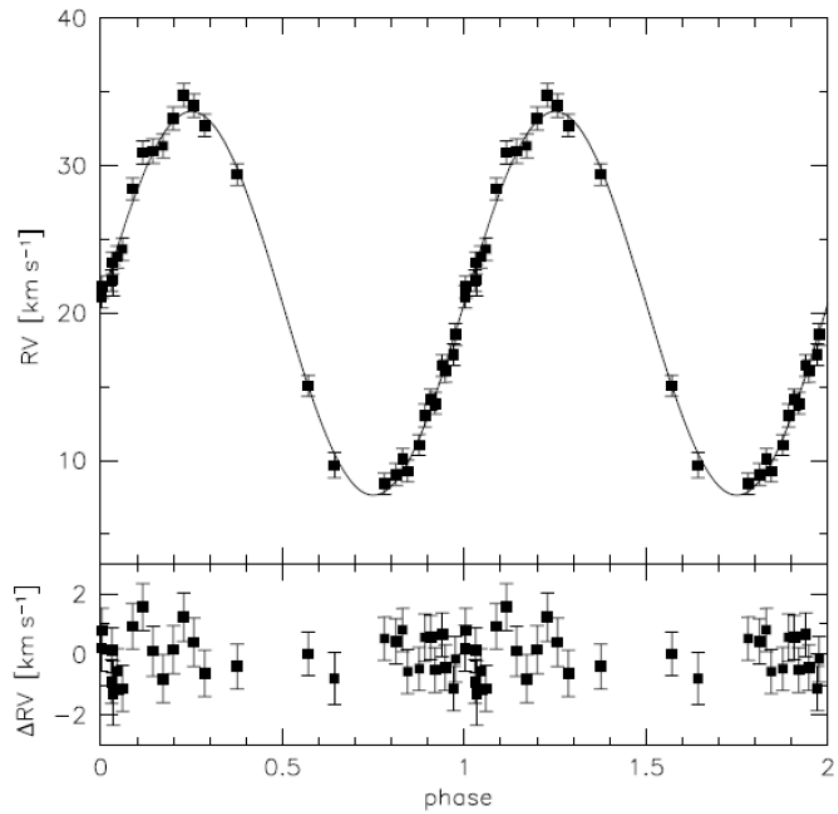
**Effective temperature** ~ 20 – 100 kK

# Hot subdwarfs in binaries

Hot subdwarfs in binaries with unseen companion discovered by RV method




CD-30° 1122, $P$ = 0.0498 d (Geier et al. 2013)

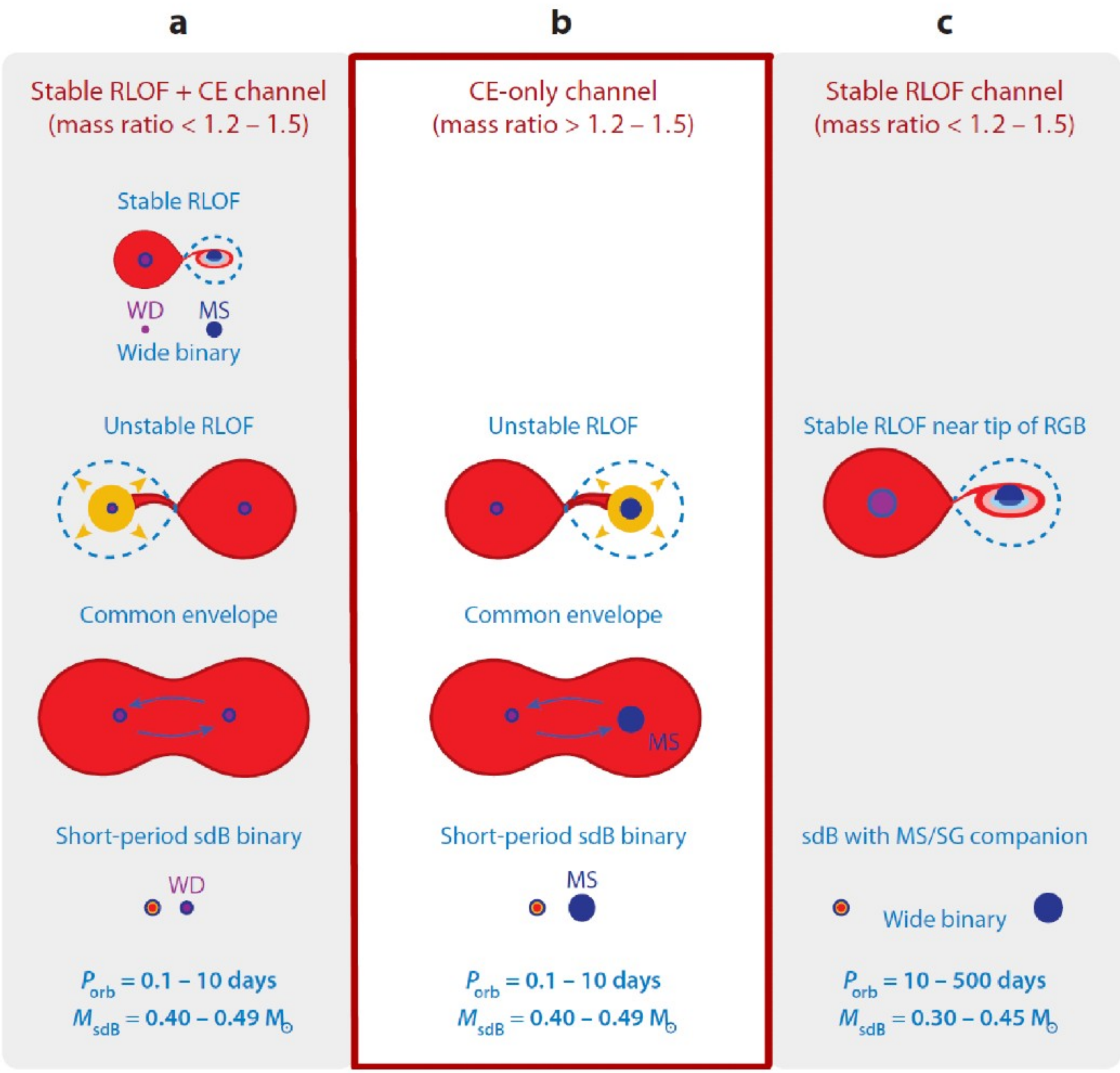



PHL 457, $P$ = 0.3131 d (Schaffenroth et al. 2014)

$$f(m) = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{K_1^3 P}{2\pi G}$$

more than 50% of sdBs in close binaries ($P < 1$ d)

# Formation of sdB binary




Han et al. (2002,2003)

# Formation of sdBs by substellar objects

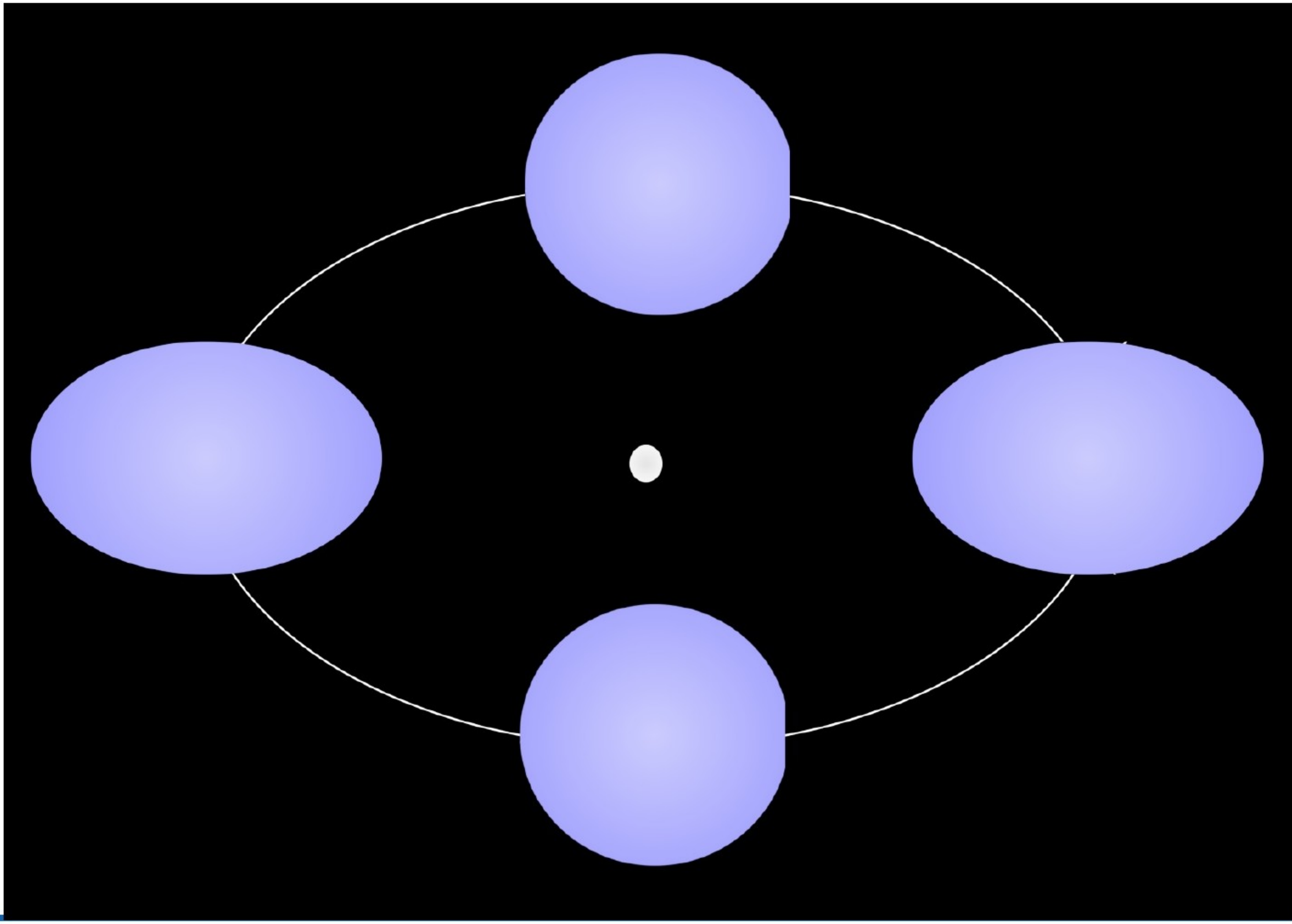
Soker 1998 AJ

- Orbit of planet in envelope of evolved star
- fate of planet:
  - evaporation
  - merger with the core
  - survival for $\geq\ 10 M_{\text{Jupiter}}$ depending on separation
    → ejection of envelope

Â© Mark Garlick / HELAS

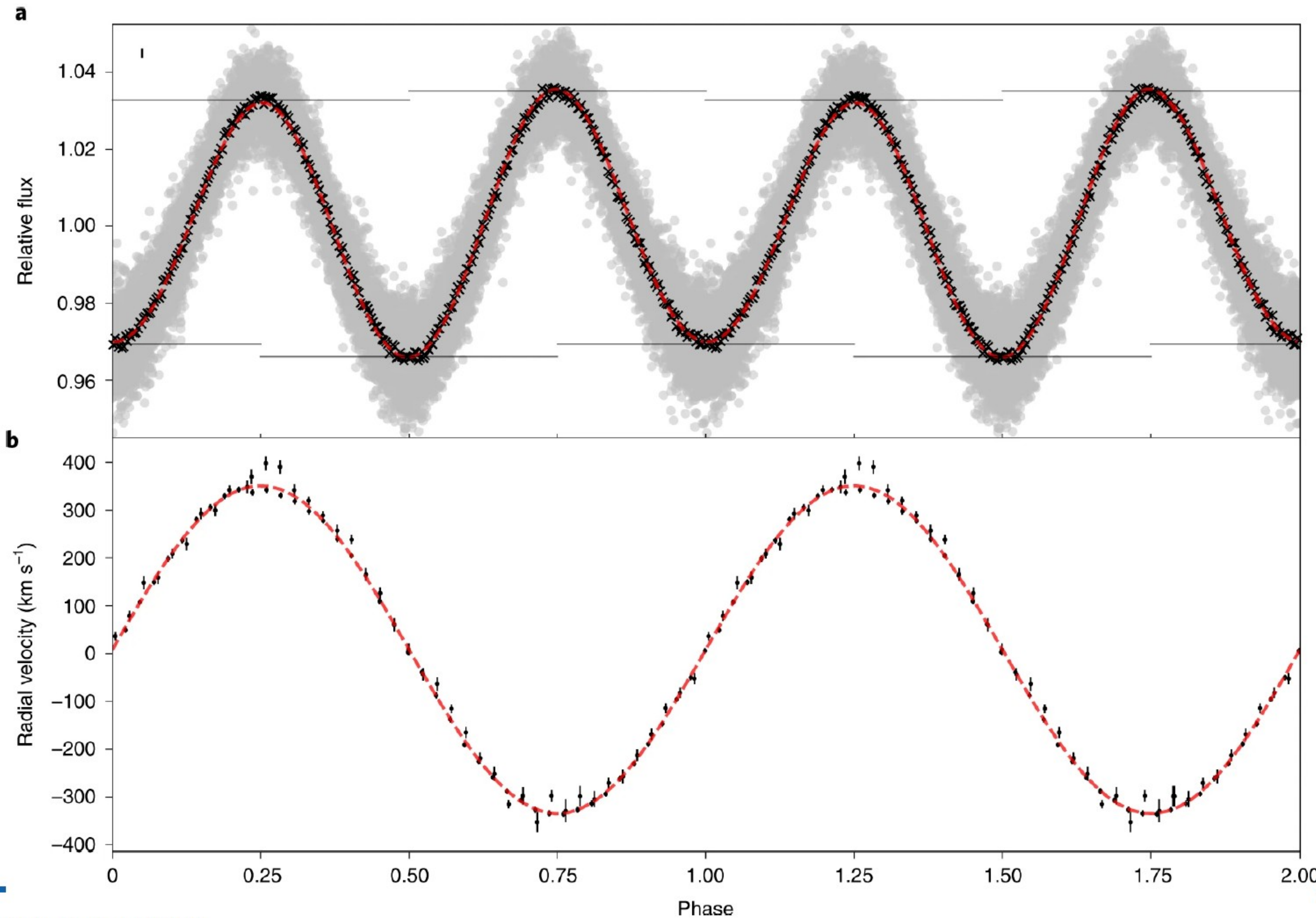
→ **studying the influence of planets on stellar evolution**

# Light variation of compact sdB binaries



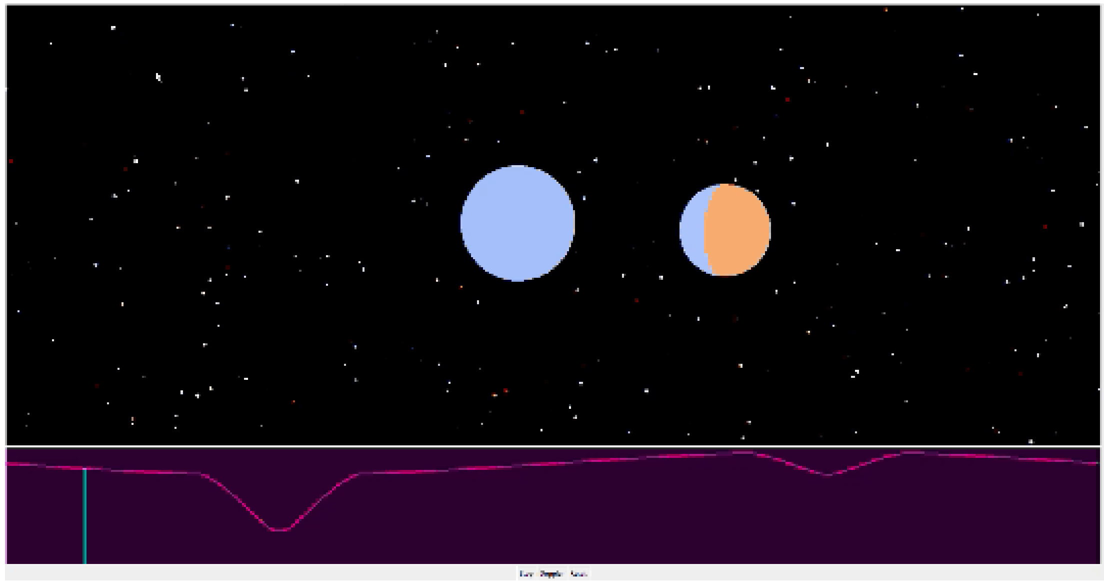
Ellipsoidal Variations

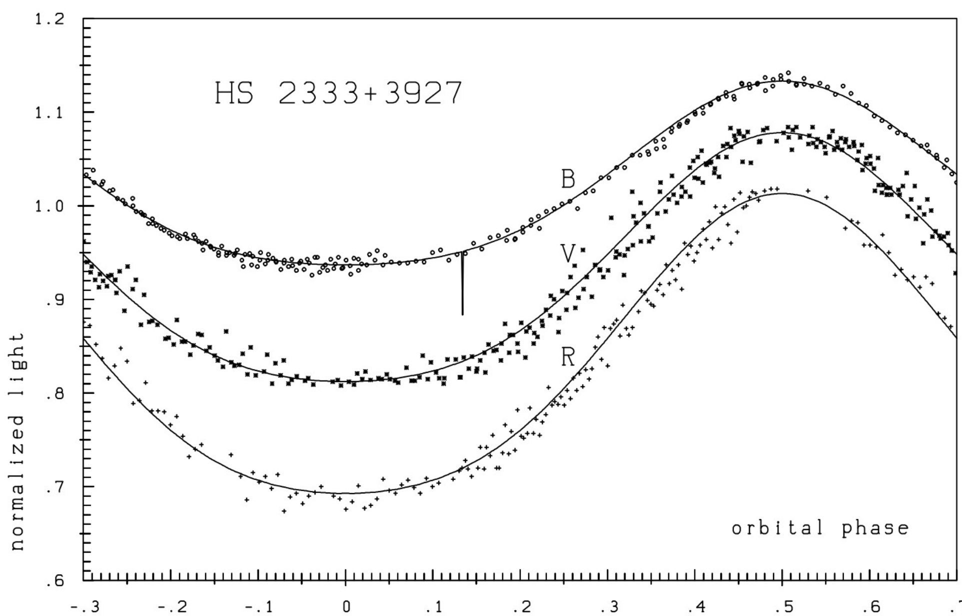
# Ellipsoidal modulation and Doppler beaming (sdB+WD)




Pelisoli et al. (2021)

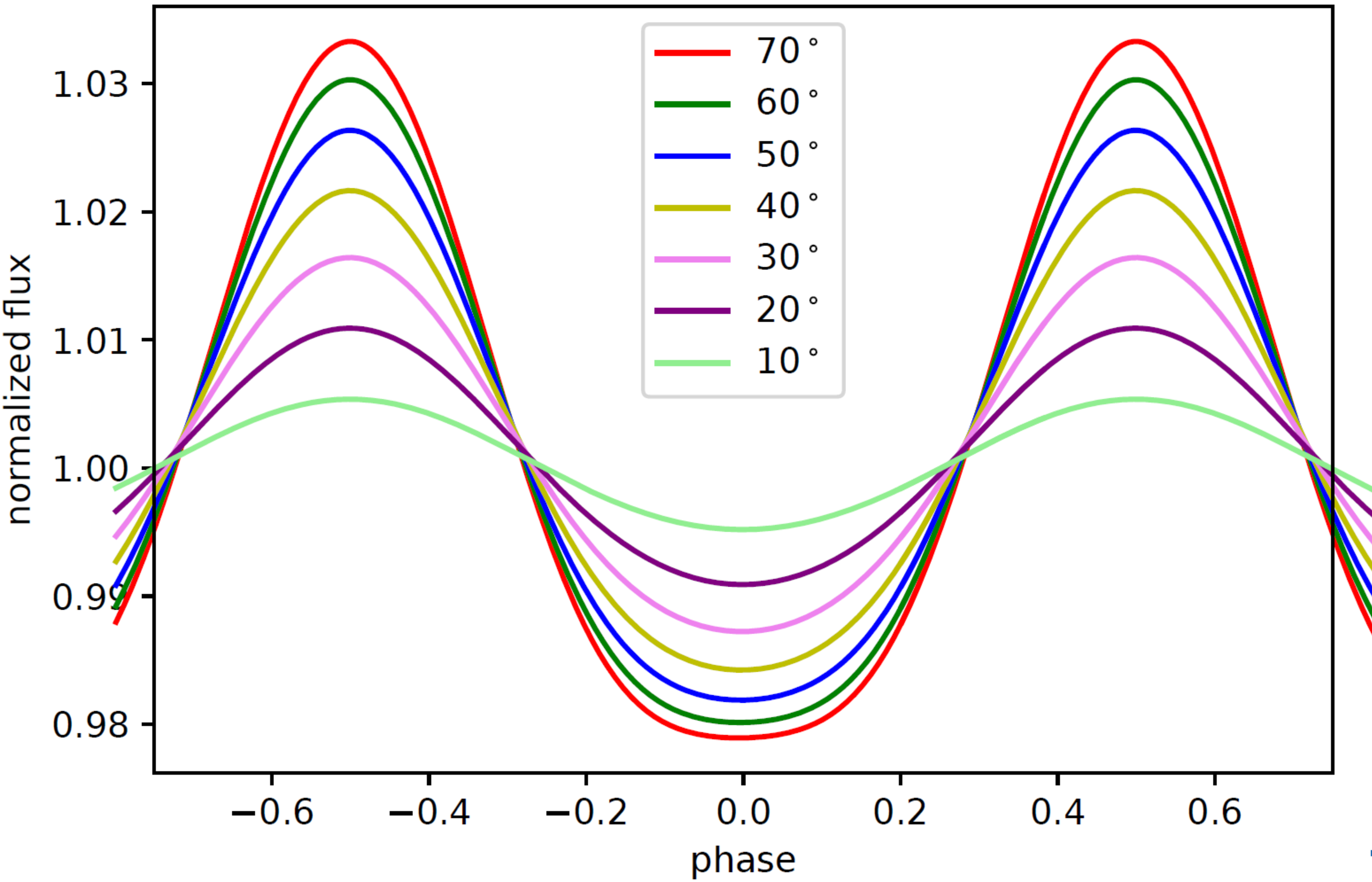
# Eclipsing Reflection effect (sdB+dM/BD) systems



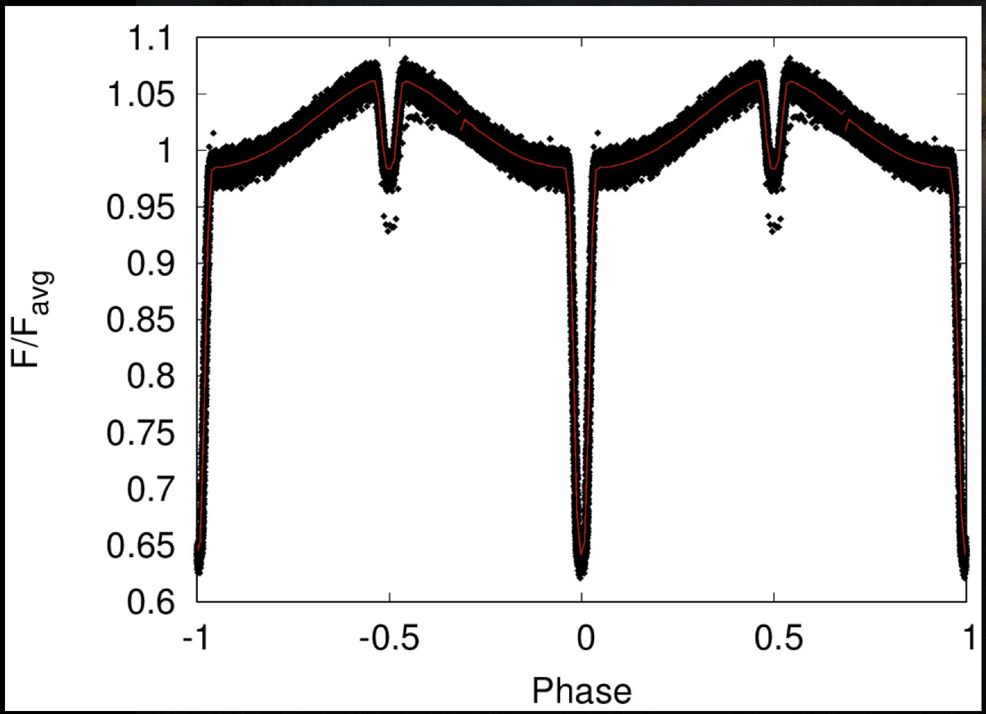



**Different amplitudes in different bands**

# Reflection effect



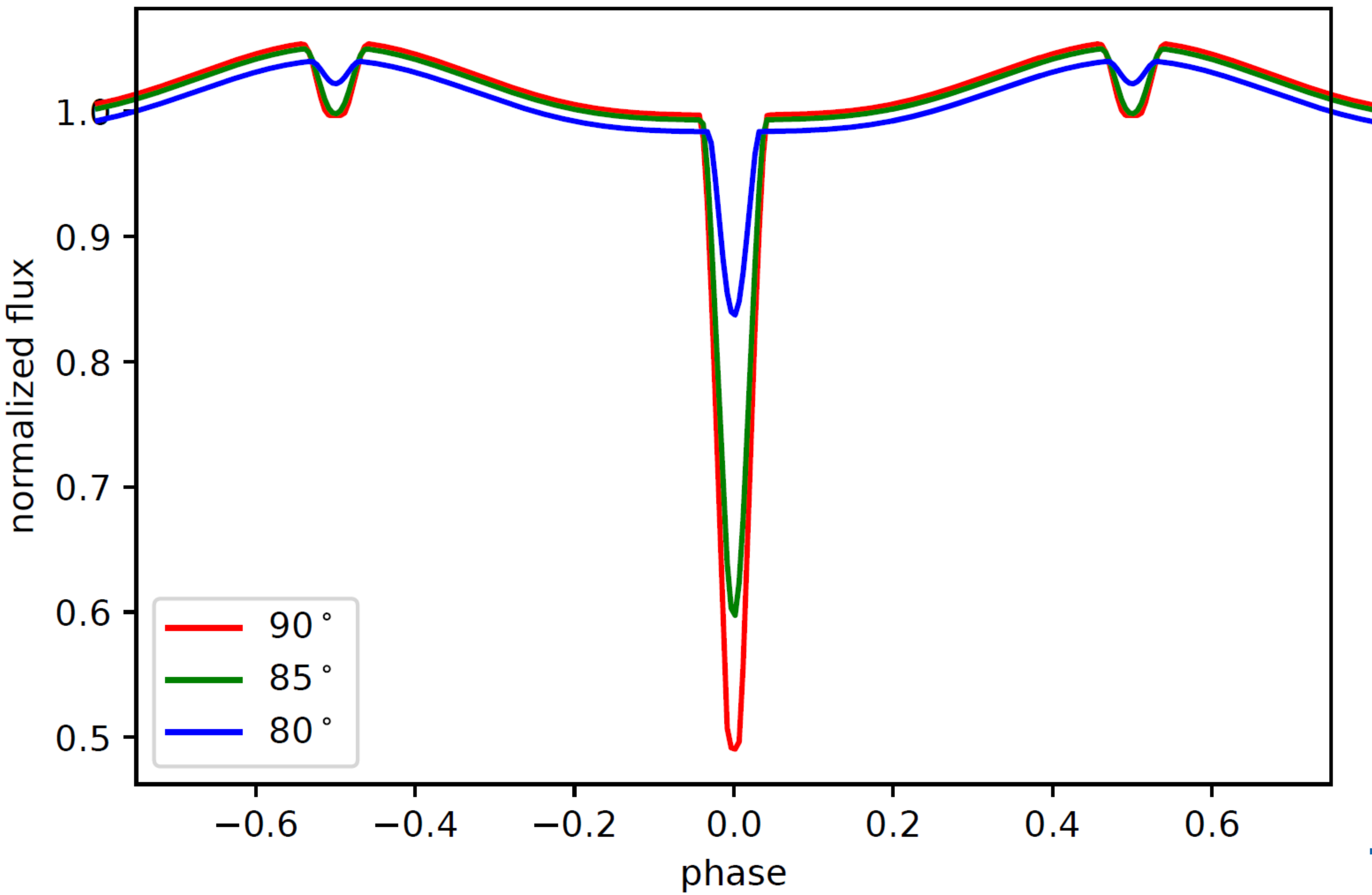
# HW Vir systems



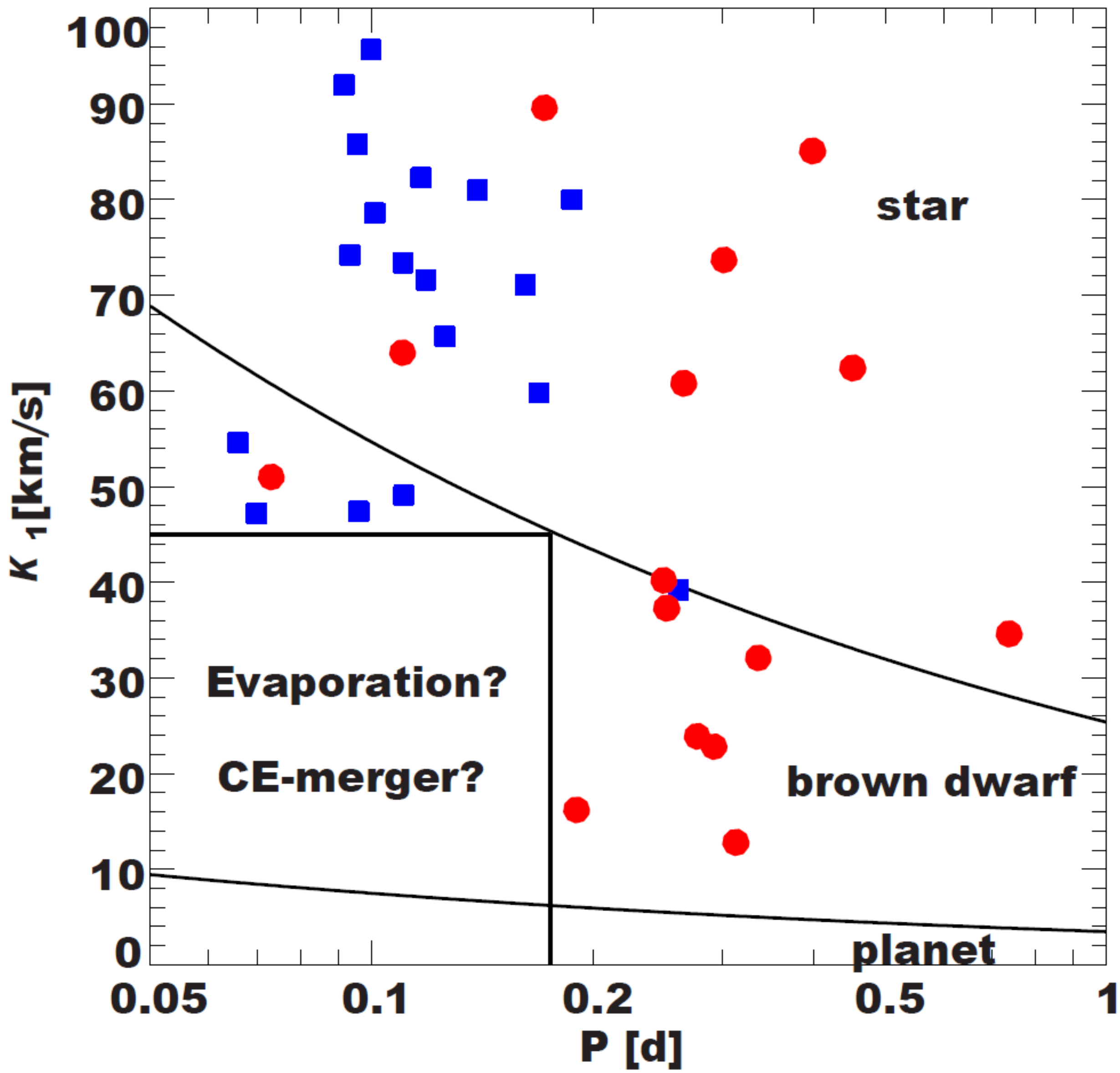

## Reflection + eclipsing

- Constrain inclination and radius
- + radial velocities → companion mass
- ~ 200 known
- Eclipse duration > 15-20 minutes
- Average period ~5 hours

# Eclipsing Reflection effect (HW Vir systems)



# Minimum companion masses of hot subdwarfs with cool companions



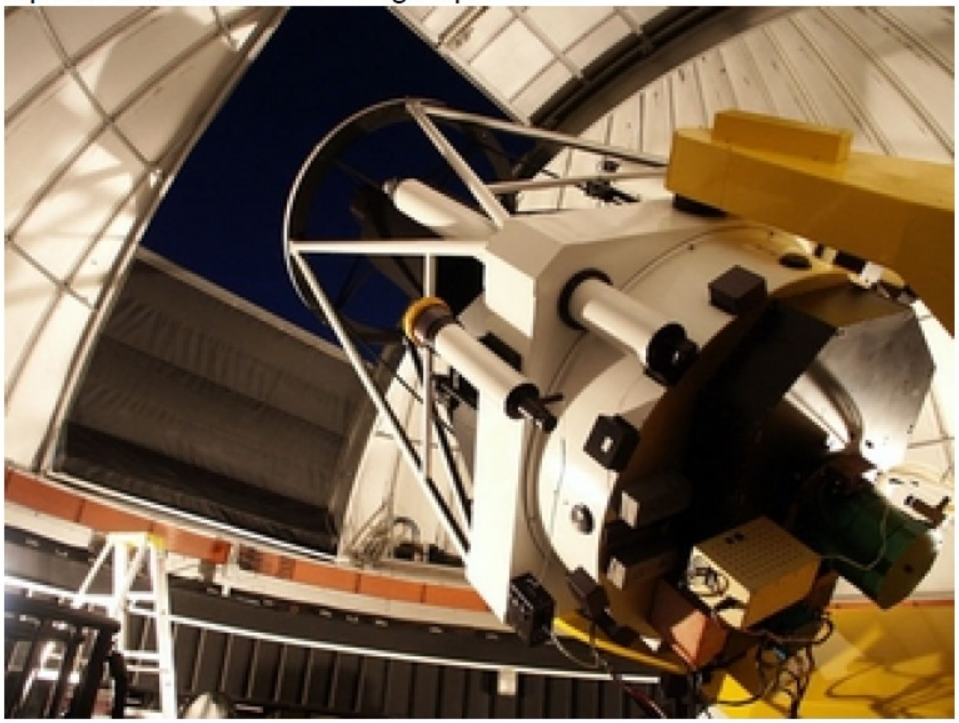

Schaffenroth et al. 2019 in press

$$f(m) = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{K_1^3 P}{2\pi G}$$

# Ground-based lightcurve surveys

## OGLE

Optical Gravitational Lensing Experiment



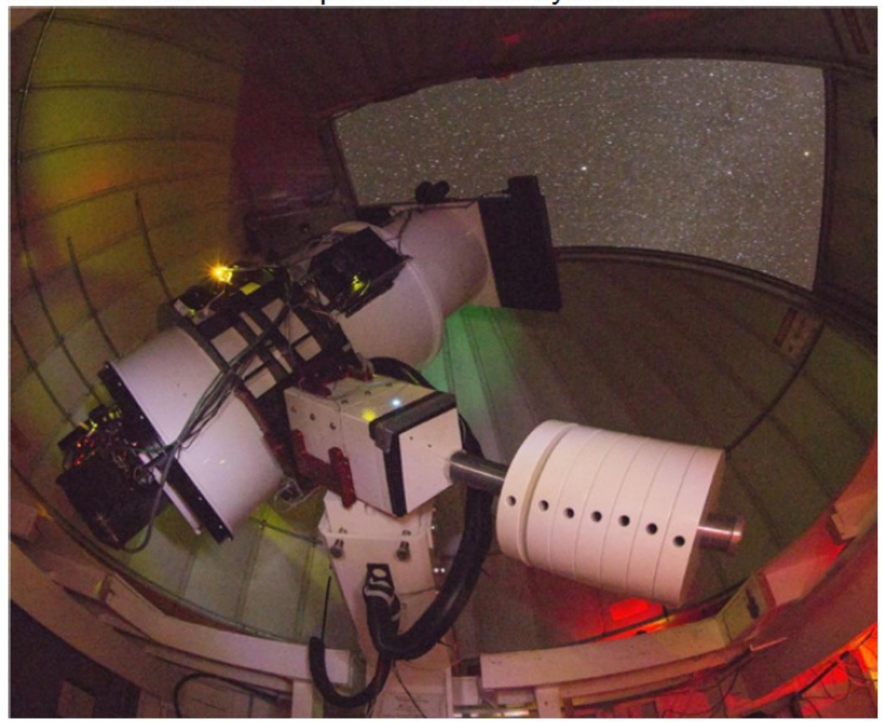
→ observation of the lightcurve of many stars in different fields

→ discovery of planetary transits, pulsators, eclipsing binaries

CRTS, PTF, ZTF, BlackGEM, ....

## ATLAS

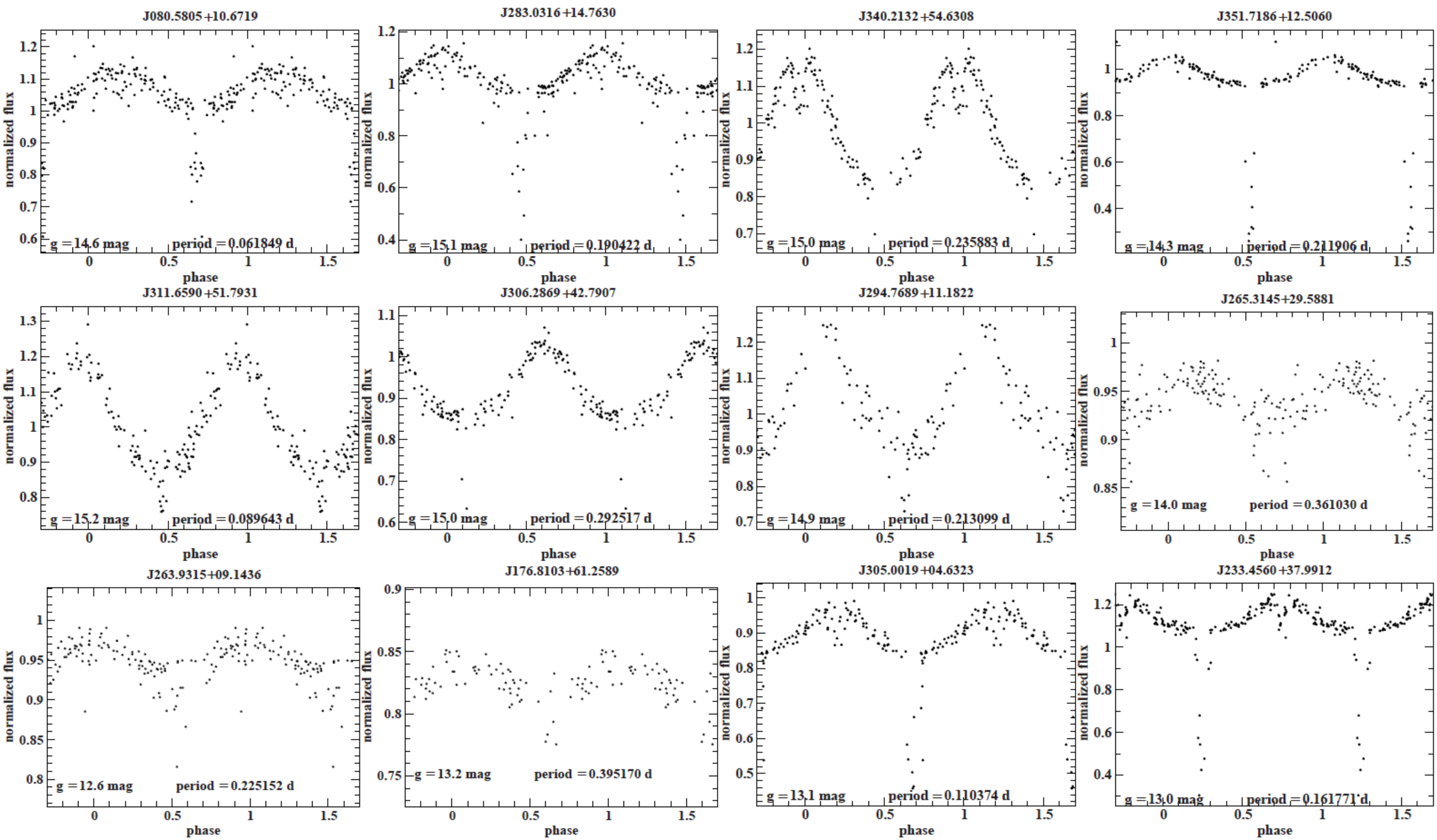
Asteroid Terrestrial-impact Last Alert System



→ a robotic astronomical survey looking for near-earth objects

→ located in Hawaii

# 200 HW Vir candidate systems: $P$ = 0.05 – 1.26 d



# The EREBOS project

EREBOS (Eclipsing Reflection Effect Binaries from **Optical** Surveys)

- homogeneous data analysis of all newly discovered HW Vir systems
- photometric and spectroscopic follow-up of all targets to determine fundamental ($M$, $R$), atmospheric ($T_{\text{eff}}$, $\log g$) and system parameters ($a$, $P$)
- spectroscopic and photometric follow-up

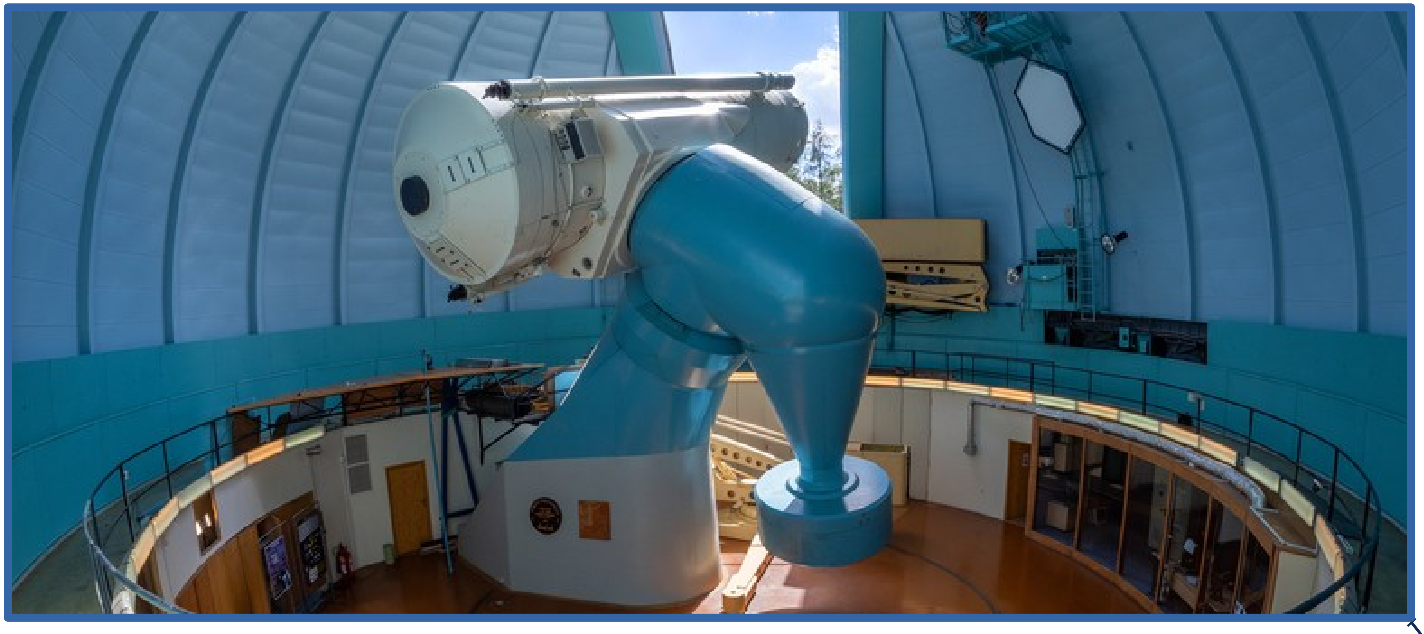
**Key questions**:

- minimum mass of the companion necessary to eject the common envelope?
- fraction of close substellar companions to sdB stars
- better understanding of the CE phase and the reflection effect

EREBOS
God of darkness

## *The photometry project*

Over to you!

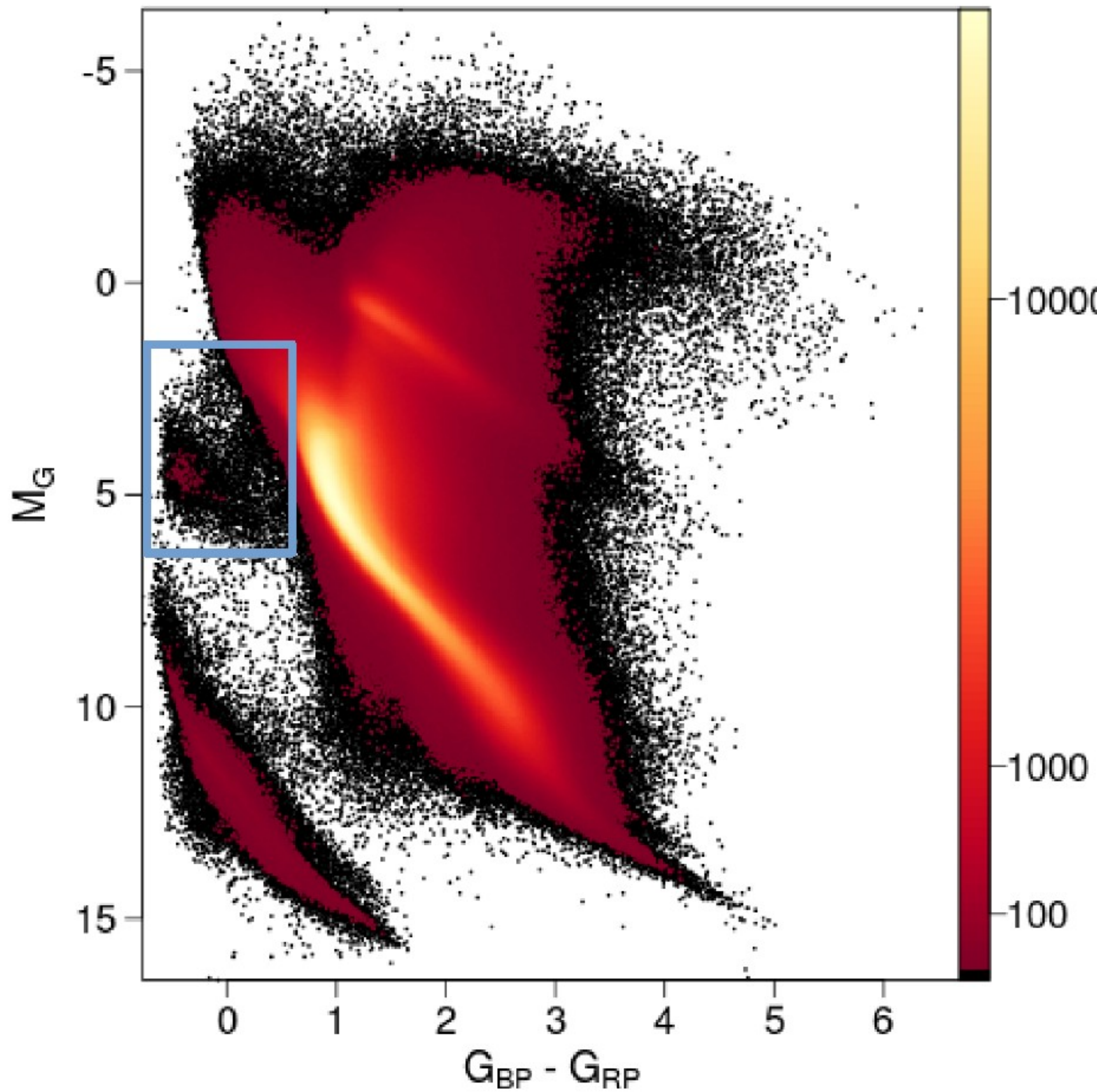


# Target selection – Gaia catalogue of hot subdwarf candidates

Selected based on colour, absolute magnitude and reduced proper motion.

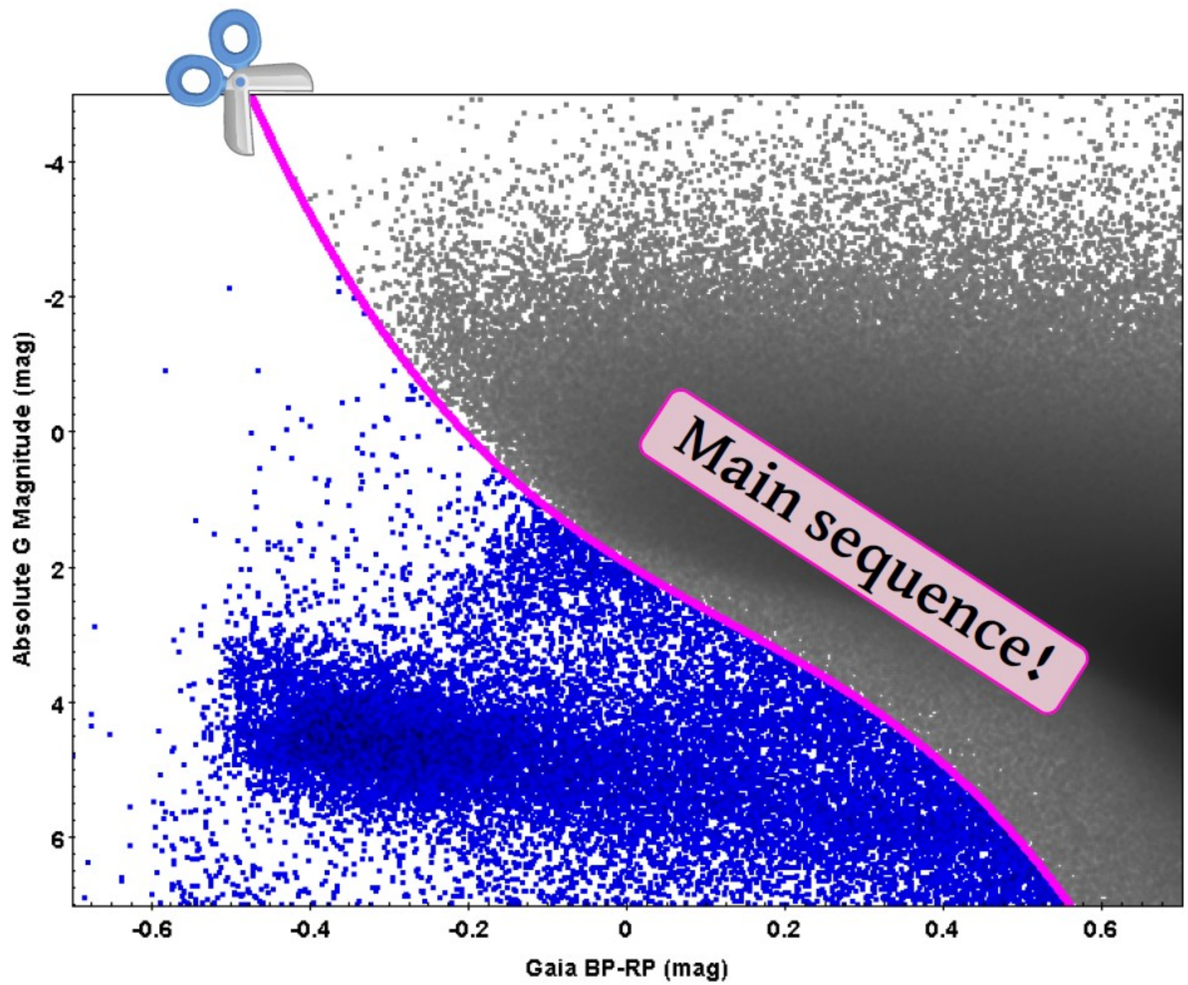
Limited to Gaia G~21.7 mag

All-sky and complete out to ~1.5 kpc



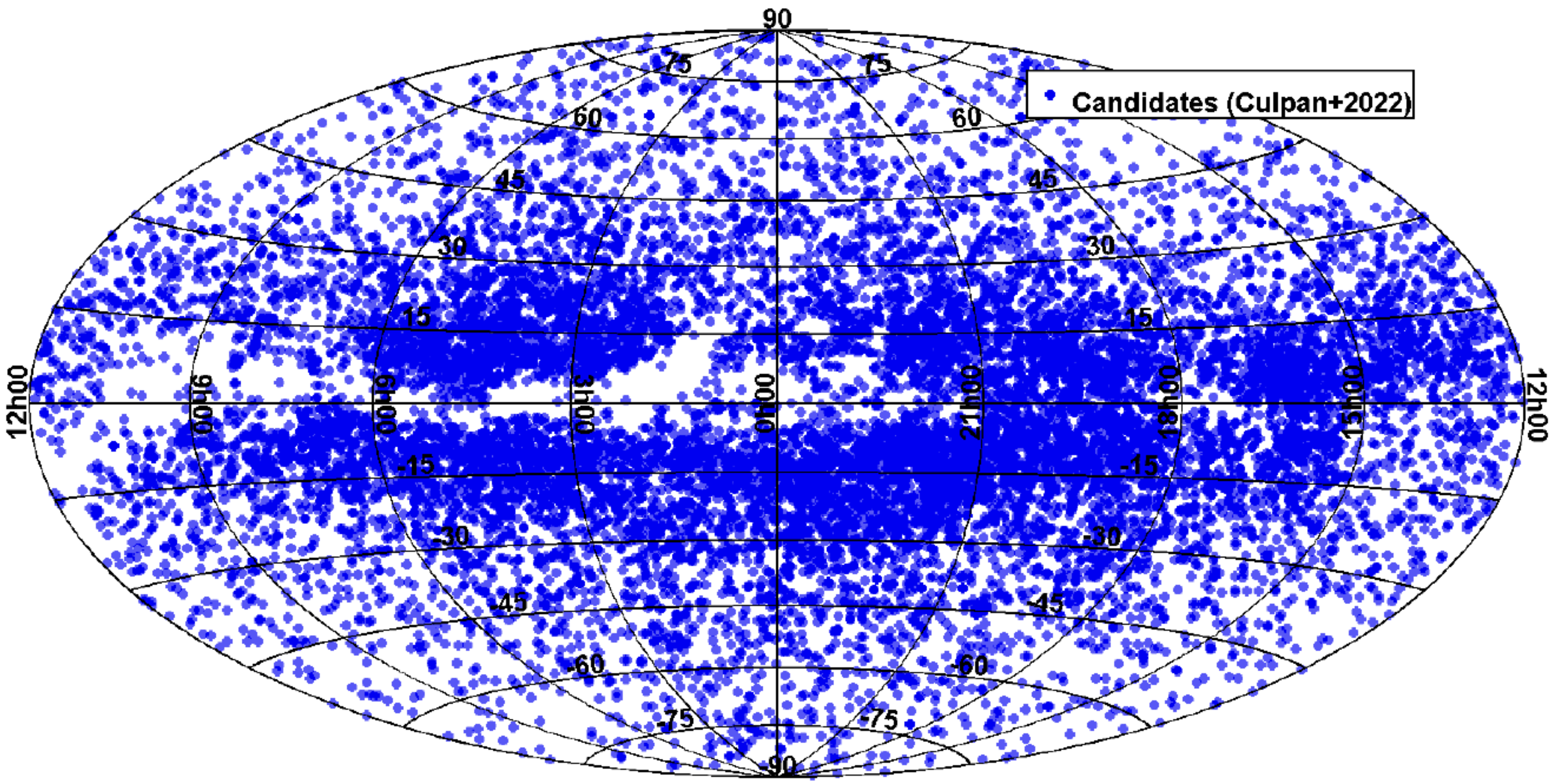

Gaia collaboration 2018

# Target selection – Gaia catalogue of hot subdwarf candidates

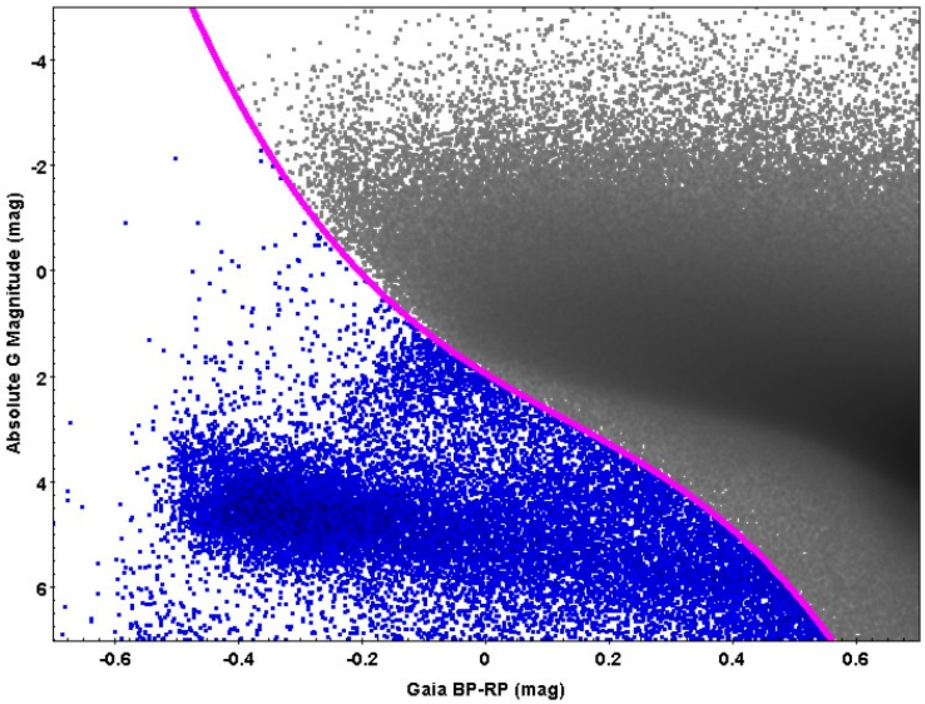


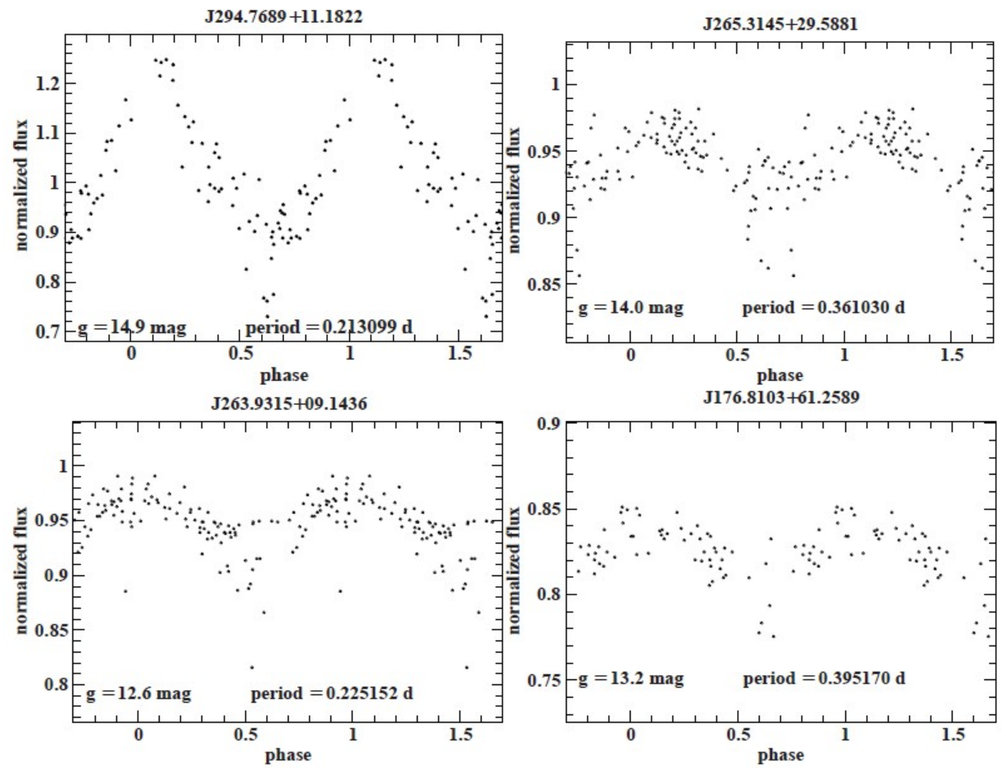

Culpan+2022

# Target selection – Gaia catalogue of hot subdwarf candidates



# Photometric project



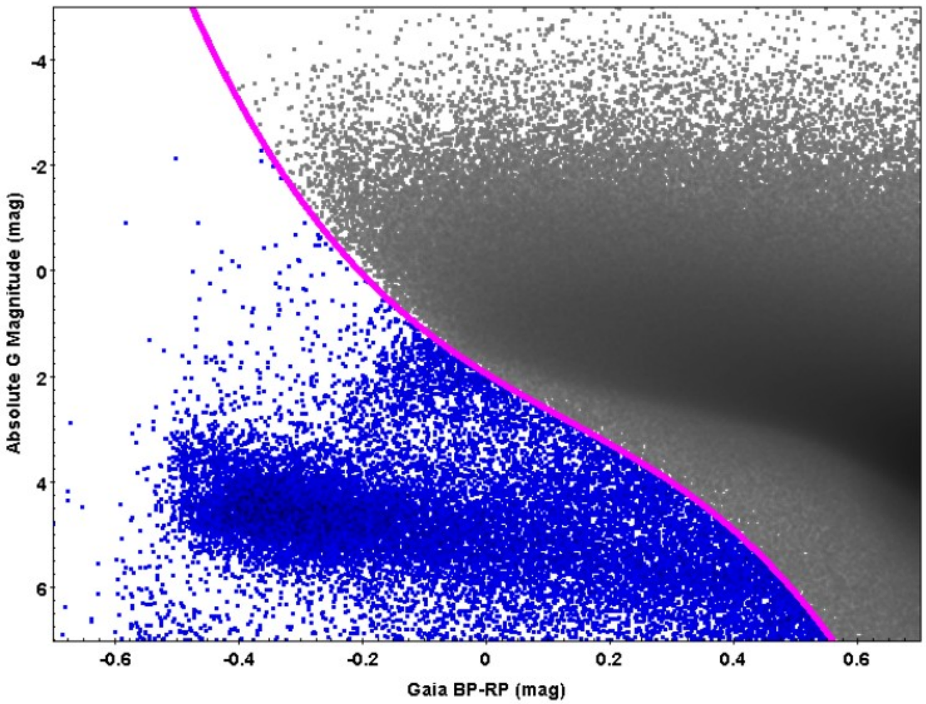

Culpan+2022

→ *We want to observe* ***hot subdwarf stars with suspected variability.***

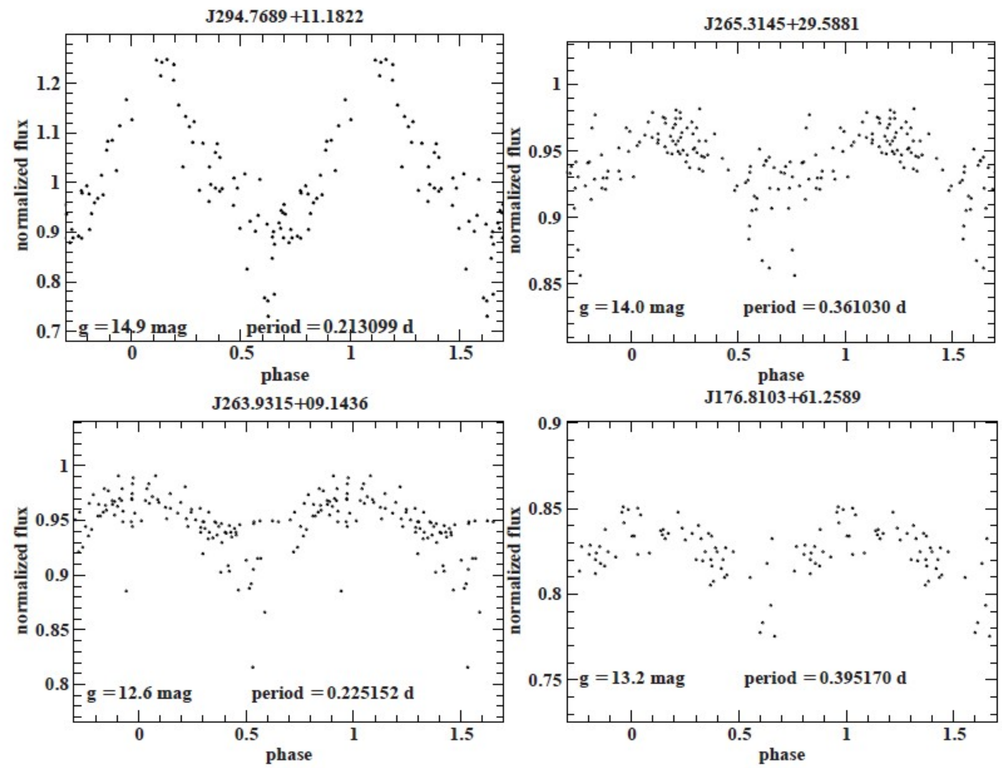
→ Crossmatch with photometric surveys – search for, follow-up observation of and light curve analysis of HW Vir system candidates to derive fundamental parameters

→ **Max will show you how to obtain this catalogue**

# Photometric project

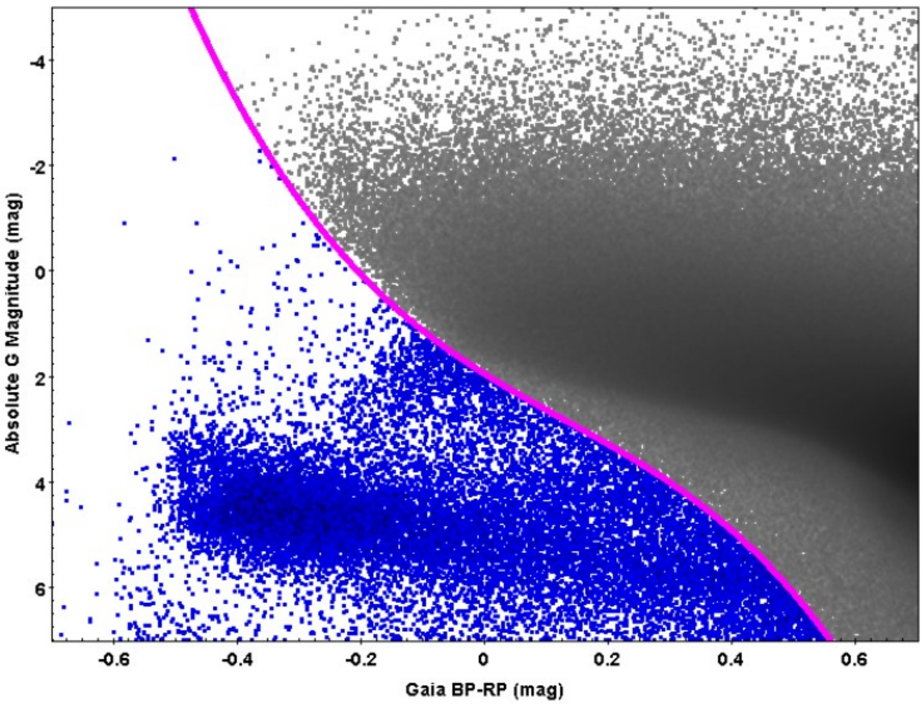



Culpan+2022

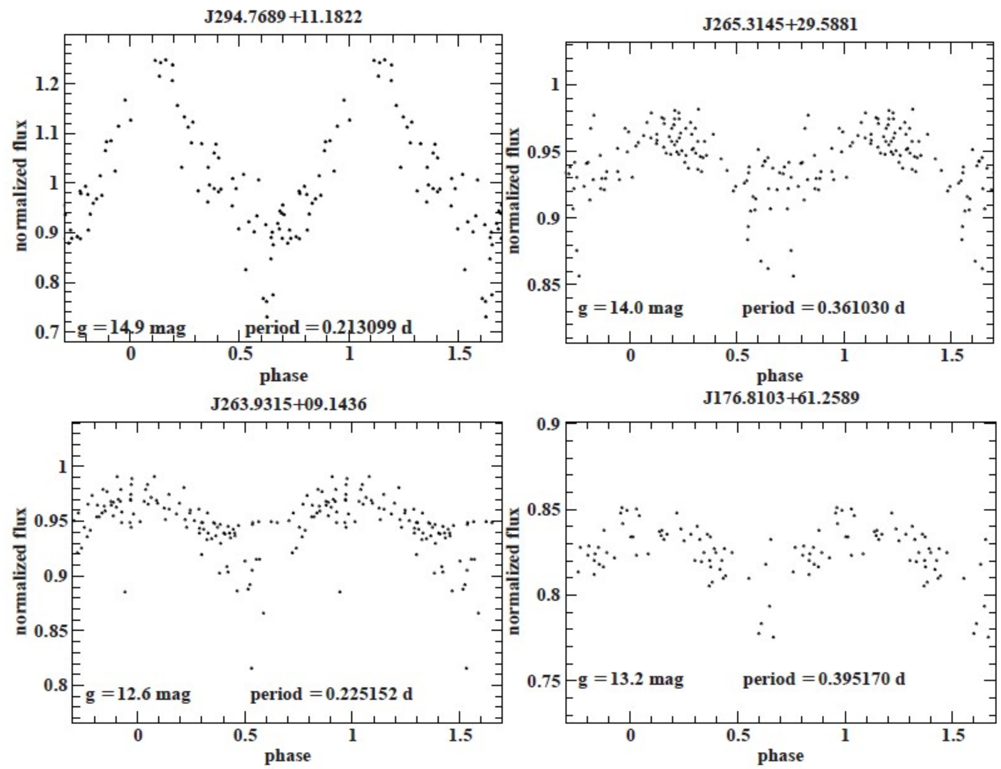



→ Faintest we can go with the Perek telescope is ~18.5 mag
→ We want to observe a complete orbital period
→ At least 100 data points per orbit (don’t go too faint!)
→ Always prepare backup targets in case of poor weather!

# Photometric project




Culpan+2022




→ To identify candidate variables, we will use the ATLAS catalogue

→ **Find 'ATLAS_cat.fits' in the virtual box (300MB).**

→ Find information about this here: https://archive.stsci.edu/prepds/atlas-var/

→ We will also check ZTF (different passbands)

→ **Find 'table_paper_publication_simplified.csv' in the virtual box.**

# Photometry project – preparing the target list

**TOPCAT**

**Tool for OPerations on Catalogues And Tables**

***Does what you want with tables***

**Max will show you how to use TOPCAT after lunch!**

# Photometry project – preparing the target list

… after lunch:

**Step 1:** import all three tables into TOPCAT

**Step 2:** select only relevant columns from the ATLAS table → 

→ There are 197 (!) columns in the full table – they describe many parameters in the variability search algorithm run by ATLAS.

→ Using the column metadata shortcut, all columns but the following are deselected:

- ATO_ID
- ra and dec (we need those to do a crossmatch)
- fp_period
- fp_fitrms
- fp_fitchi
- CLASS (this is the type of variation ATLAS identified)

> We are interested in short period binaries. These parameters describe the fitted period, root-mean-square, and chi-square of the short-period algorithm in ATLAS. However periods given by ATLAS are not always correct!!!.

# Photometry project – preparing the target list

**Step 3:** cross-match ATLAS with the catalogue of hot subdwarf candidates.
→ The resulting table tells us the list of hot subdwarf candidates that show some sort of variability in ATLAS.
They may not actually be hot subdwarfs!

**Step 4:** Now we need to select good candidates that are actually observable right now from Ondrejov.
→ Create a subset (or subsets) of observable candidates.
→ Consider the right ascension, declination and 'fb_period' from ATLAS (this the fitted from ATLAS, we should set it to **fb_period > 0**.

**Step 5:** We want to find the best targets from this final list

→ To do this you will inspect the light curves and do a period search (Lomb-Scargle periodogram).
Two python scripts have been created for you to check ATLAS and ZTF

**ATLAS_auto.py and ZTF_interactive.ipynb**

**Automatic!**
Save a csv .txt file of all you candidates
In TOPCAT to create all ATLAS LCs

**Step 5:** We want to find the best targets from this final list

→ To do this you will inspect the light curves and do a period search (Lomb-Scargle periodogram).
Two python scripts have been created for you to check ATLAS and ZTF

**ATLAS_auto.py and ZTF_interactive.ipynb**

**Automatic!**
Save a csv .txt file of all you candidates
In TOPCAT to create all ATLAS LCs

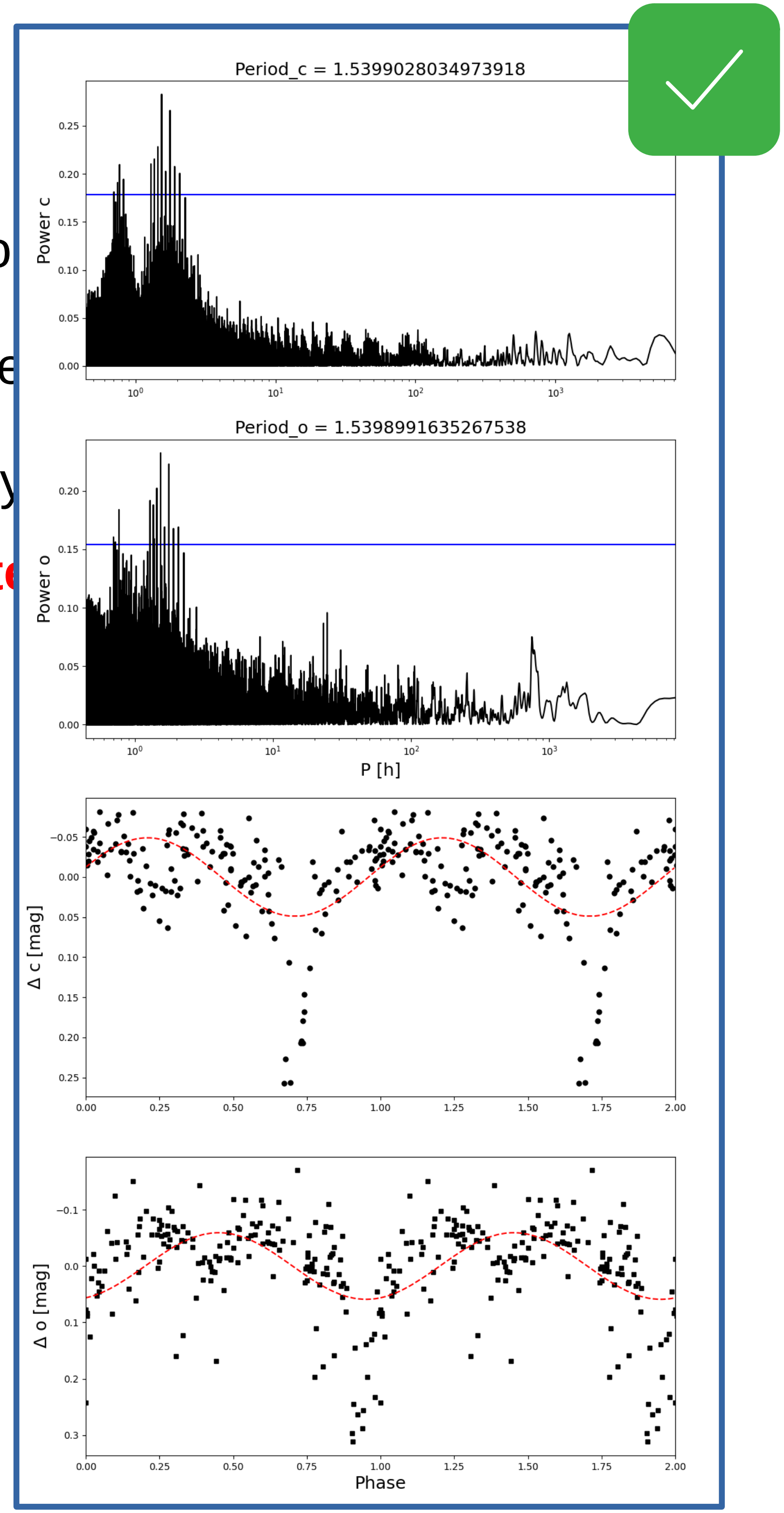
```
Successfully found J333.0713+52.0217
Period is 3.8445591503968948 hours from c filter and 3.8445001834344397 from o filter.
Successfully found J316.0059+34.6100
Period is 2.8451963667191524 hours from c filter and 2.8684006505576365 from o filter.
### The following files were not found: ###
['ATO_ID']
### The following files caused errors: ###
[]
```

**Step 5:** We want to find the best targets fro

→ To do this you will inspect the light curve
(Lomb-Scargle periodogram).
Two python scripts have been created for y

**ATLAS_auto.py** **and** **ZTF_inte**

**Automatic!**
Save a csv .txt file of all you candidates
In TOPCAT to create all ATLAS LCs



**Step 5:** We want to find the best targets from

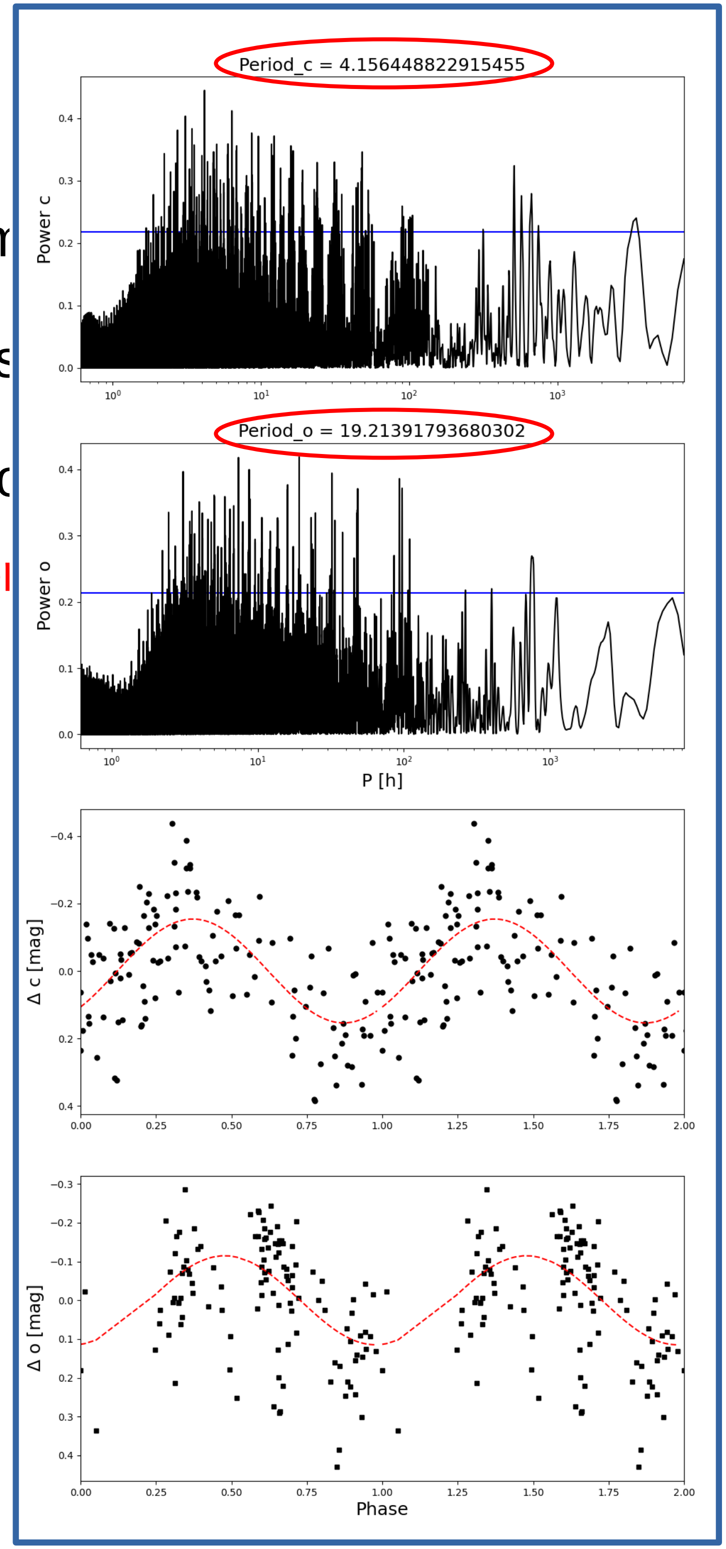
→ To do this you will inspect the light curves
(Lomb-Scargle periodogram).
Two python scripts have been created for yo

**ATLAS_auto.py and ZTF_inter**

**Automatic!**

Save a csv .txt file of all you candidates
In TOPCAT to create all ATLAS LCs

**An interactive script is also provided**
**ATLAS_interactive.ipynb**



**Step 5:** We want to find the best targets from this final list

→ To do this you will inspect the light curves and do a period search (Lomb-Scargle periodogram).
Two python scripts have been created for you to check ATLAS and ZTF

**ATLAS_auto.py and ZTF_interactive.ipynb**

**Interactive!**
Sources need to be downloaded and inspected one-by-one...

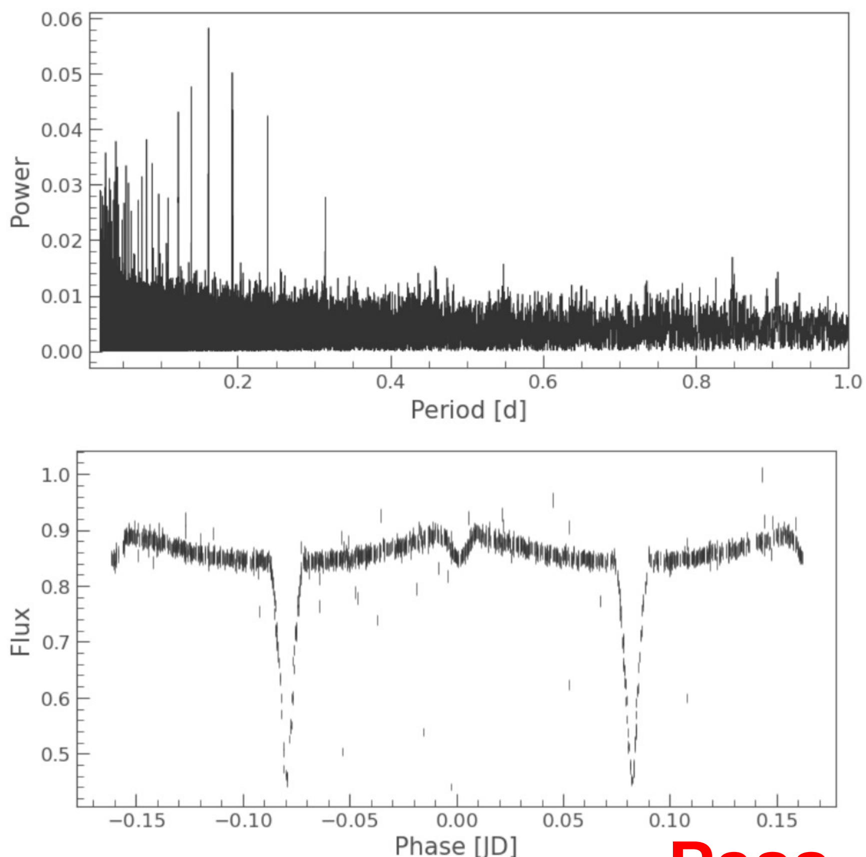
```
ra=296.1785753341851
dec=54.8285736956544
radius=5
target=2138663782338254464
```

First create a directory called ‘ZTF’
**mkdir ZTF**
Where the data will be saved

**Step 5:** We want to find the best targets from this final list

→ To do this you will inspect the light curves and do a period search (Lomb-Scargle periodogram).
Two python scripts have been created for you to check ATLAS and ZTF

**ATLAS_auto.py and ZTF_interactive.ipynb**




**Pass...**

**Interactive!**
Sources need to be downloaded and inspected one-by-one...

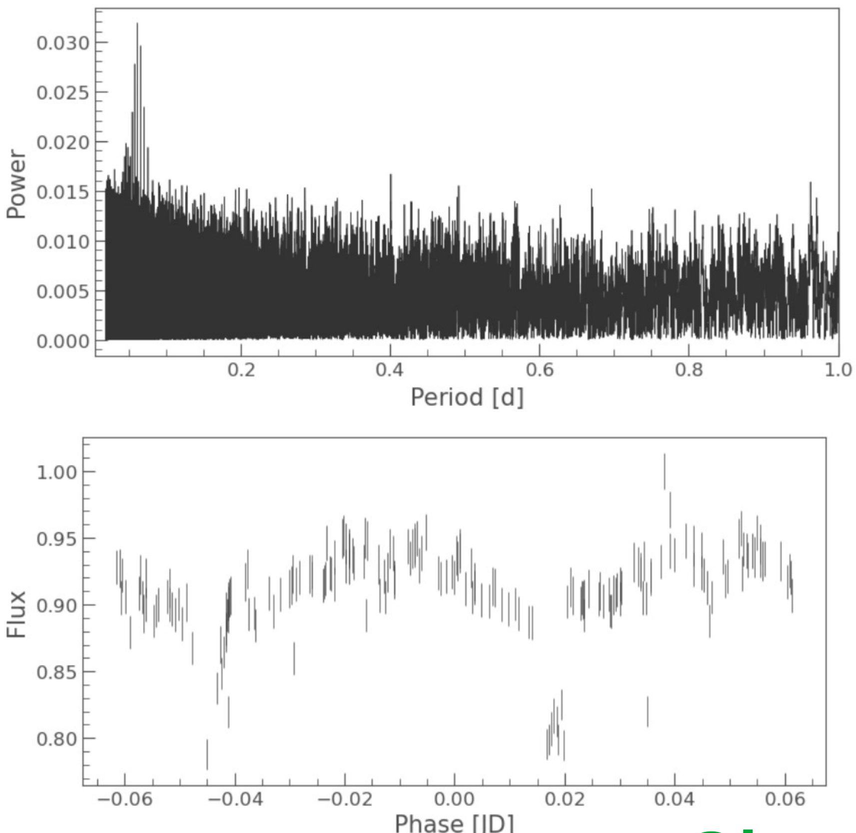
```
ra=296.1785753341851
dec=54.8285736956544
radius=5
target=2138663782338254464
```

First create a directory called 'ZTF'
**mkdir ZTF**
Where the data will be saved

**Step 5:** We want to find the best targets from this final list

→ To do this you will inspect the light curves and do a period search (Lomb-Scargle periodogram).
Two python scripts have been created for you to check ATLAS and ZTF

**ATLAS_auto.py and ZTF_interactive.ipynb**




**Interactive!**
Sources need to be downloaded and inspected one-by-one...

```
ra=296.1785753341851
dec=54.8285736956544
radius=5
target=2138663782338254464
```

First create a directory called ‘ZTF’
**mkdir ZTF**
Where the data will be saved

**Observe!**