Light curve analysis of eclipsing sdB+dM/BD systems

Research workshop on evolved stars

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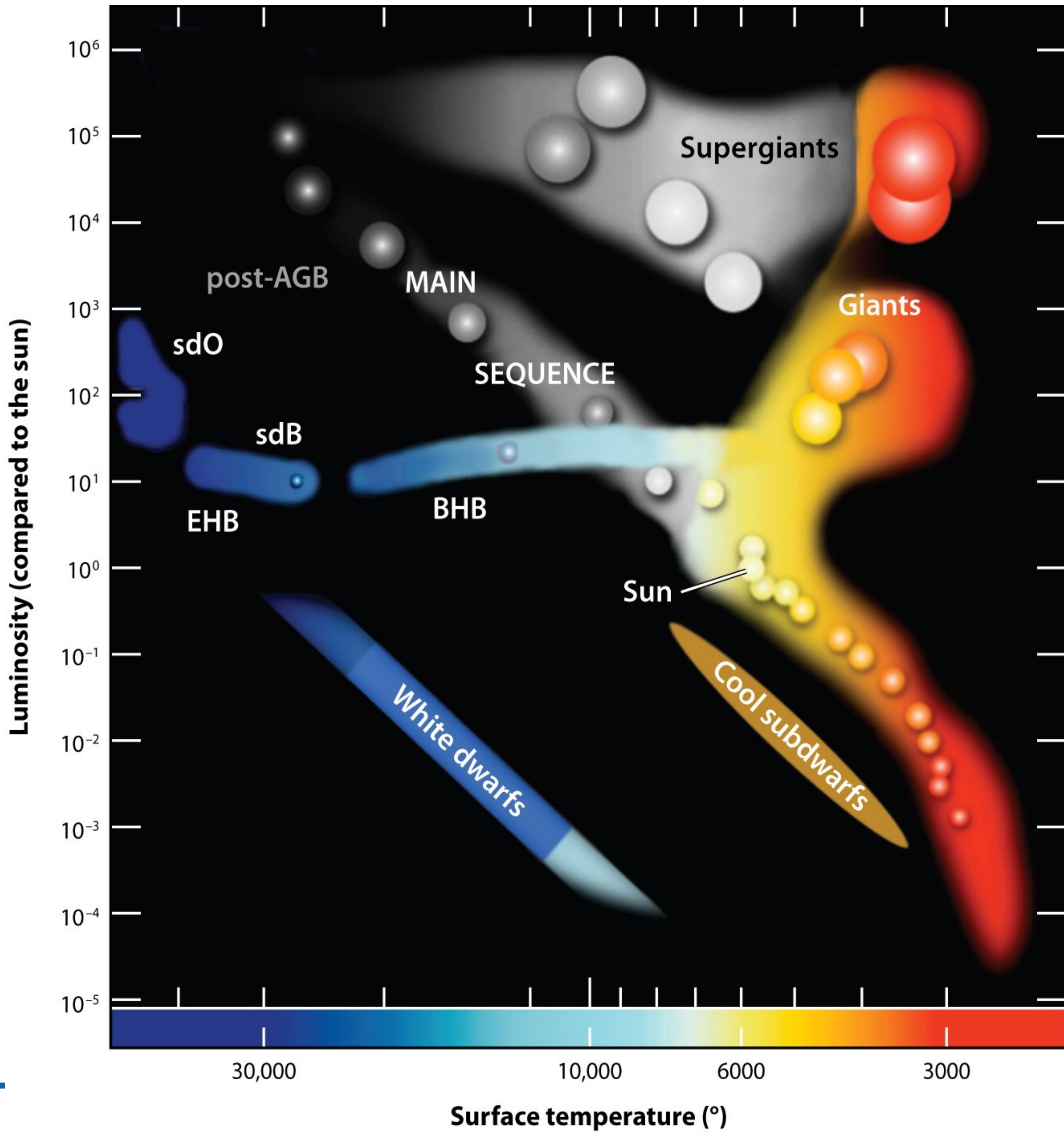
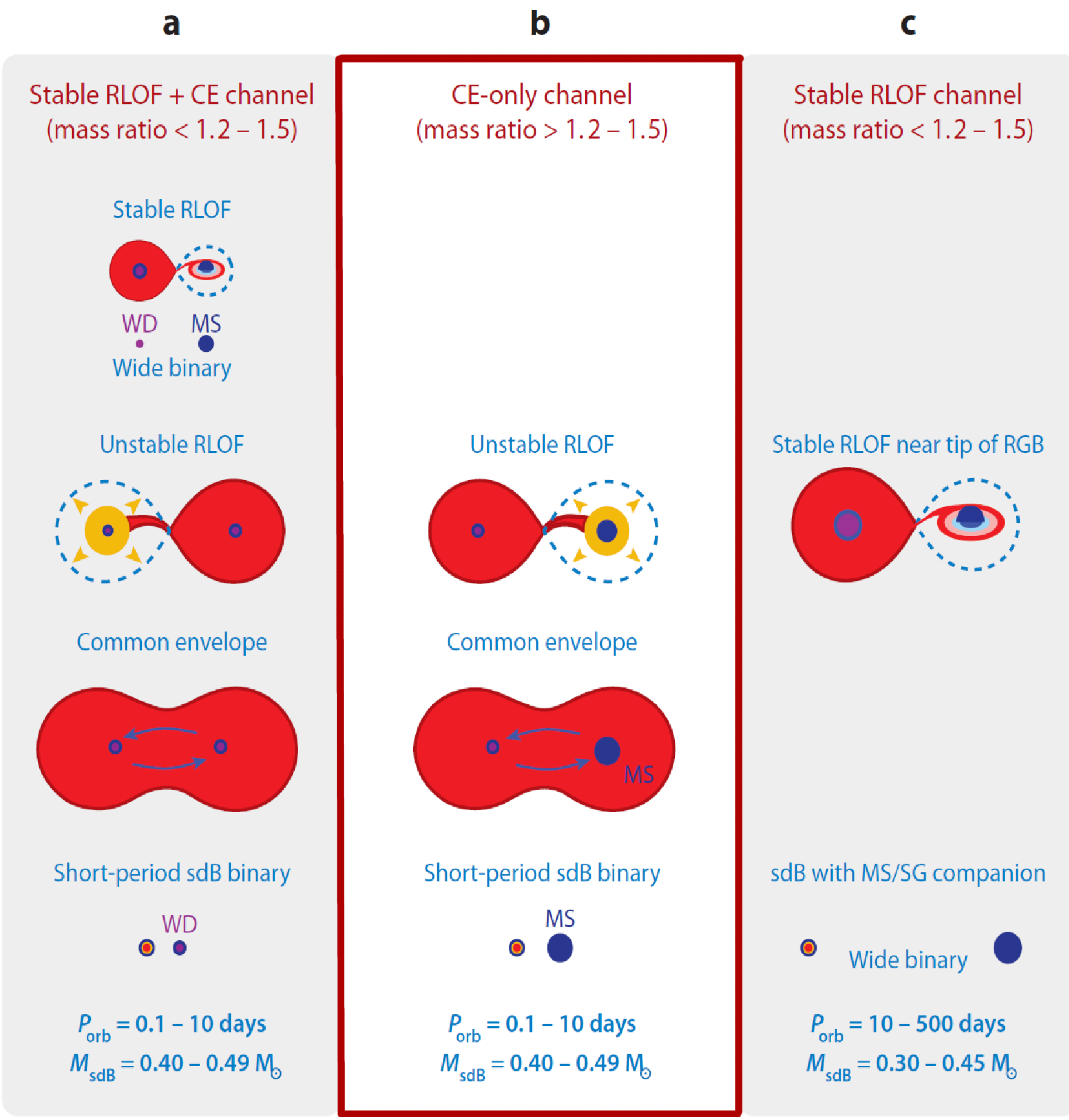
Introduction

Hot subdwarf stars of spectral type B (sdB)



Formation of sdB binary



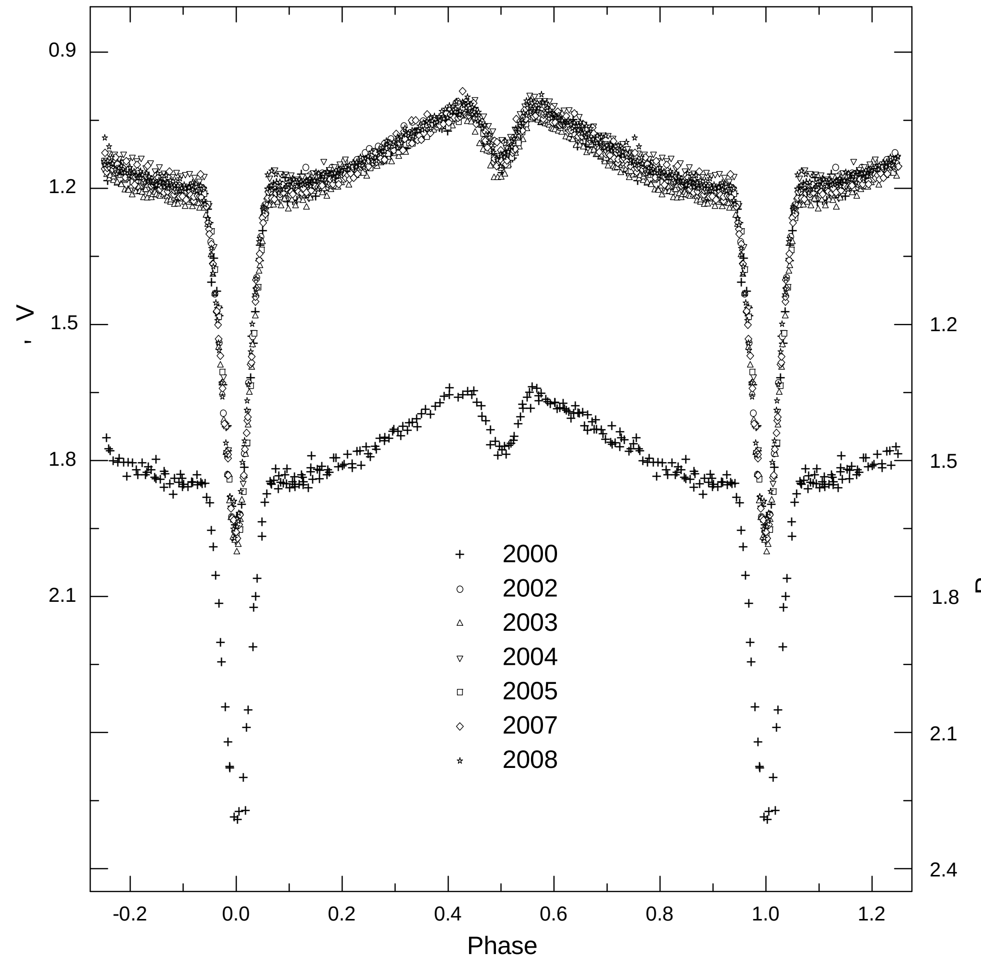
Han et al. (2002,2003)

HW Virginis systems

- Eclipsing binaries consisting of sdB and cool, low mass stellar or substellar companion
- ~200 HW Vir systems known
- Very short period ~1.5 - 6 h (separation ~1 $R_\odot$)

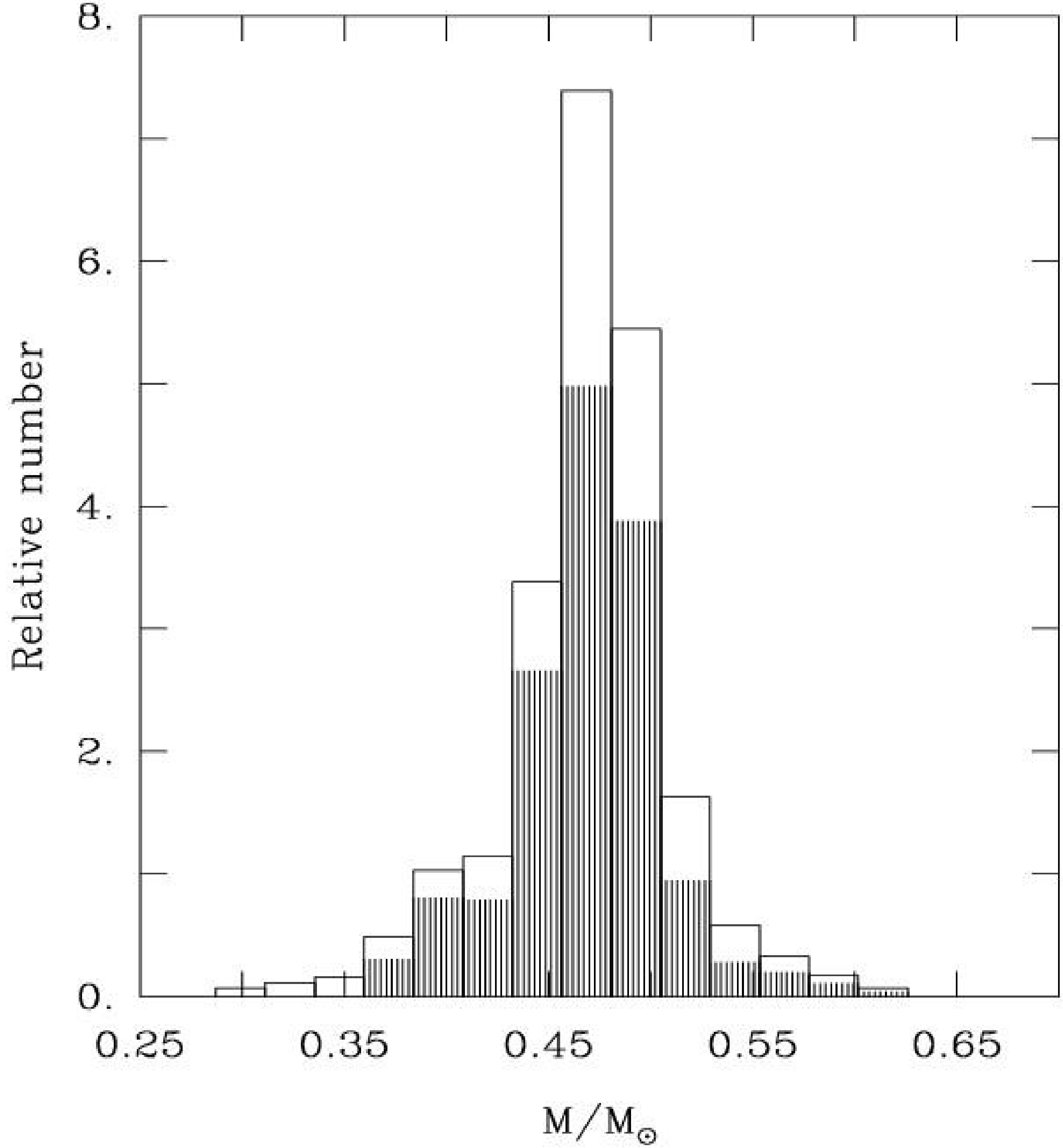
  ⇒ post common envelope system
- Only the sdB is visible in spectrum
- They display a unique-ish lightcurve

  ⇒ huge-ish reflection effect



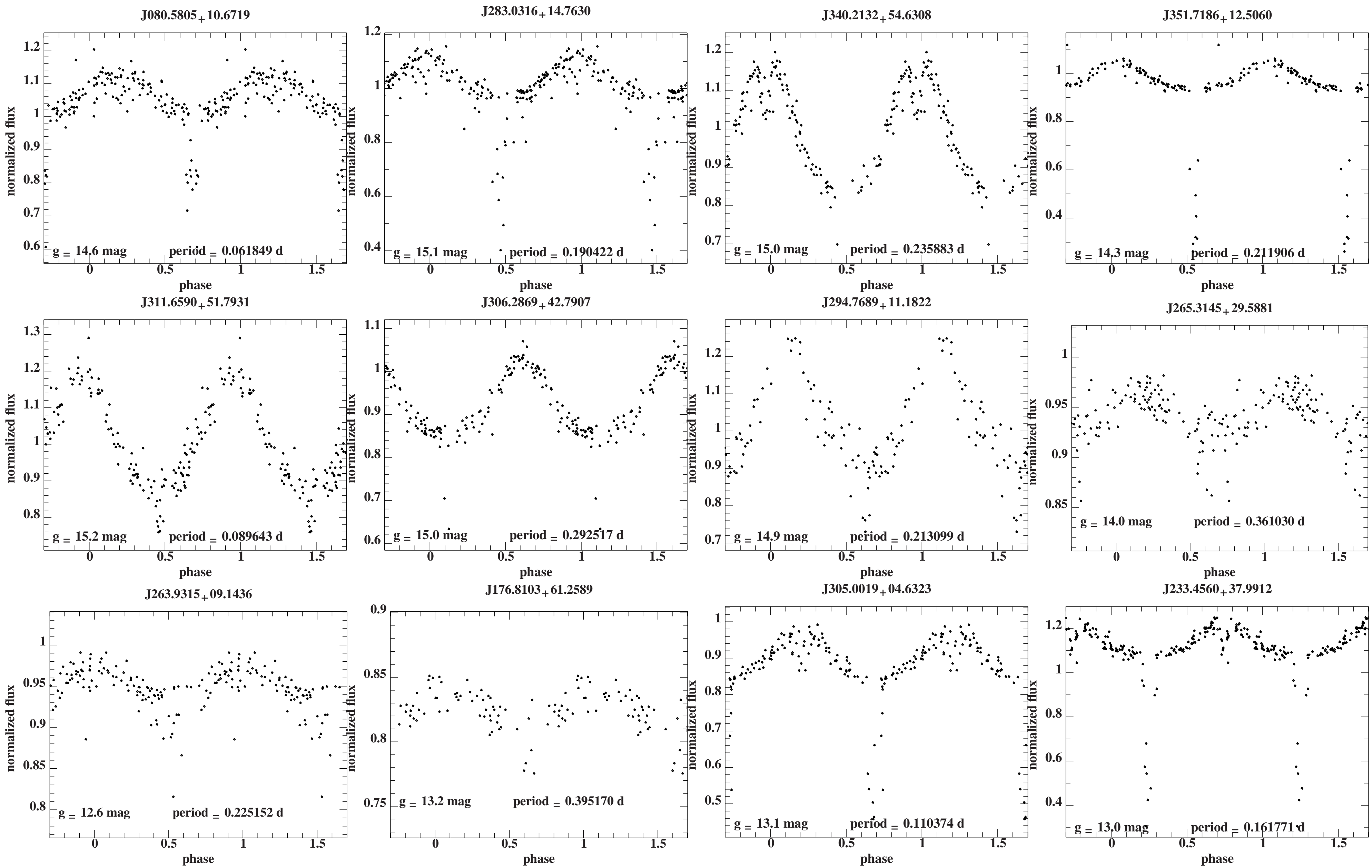
Lightcurve of HW Virginis (Lee et al. 2009)

Observed mass distribution of sdBs



Fontaine et al. 2012

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



Schaffenroth et al. 2019

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 ($T_{\rm eff}$, log g) and system parameters (a, P)

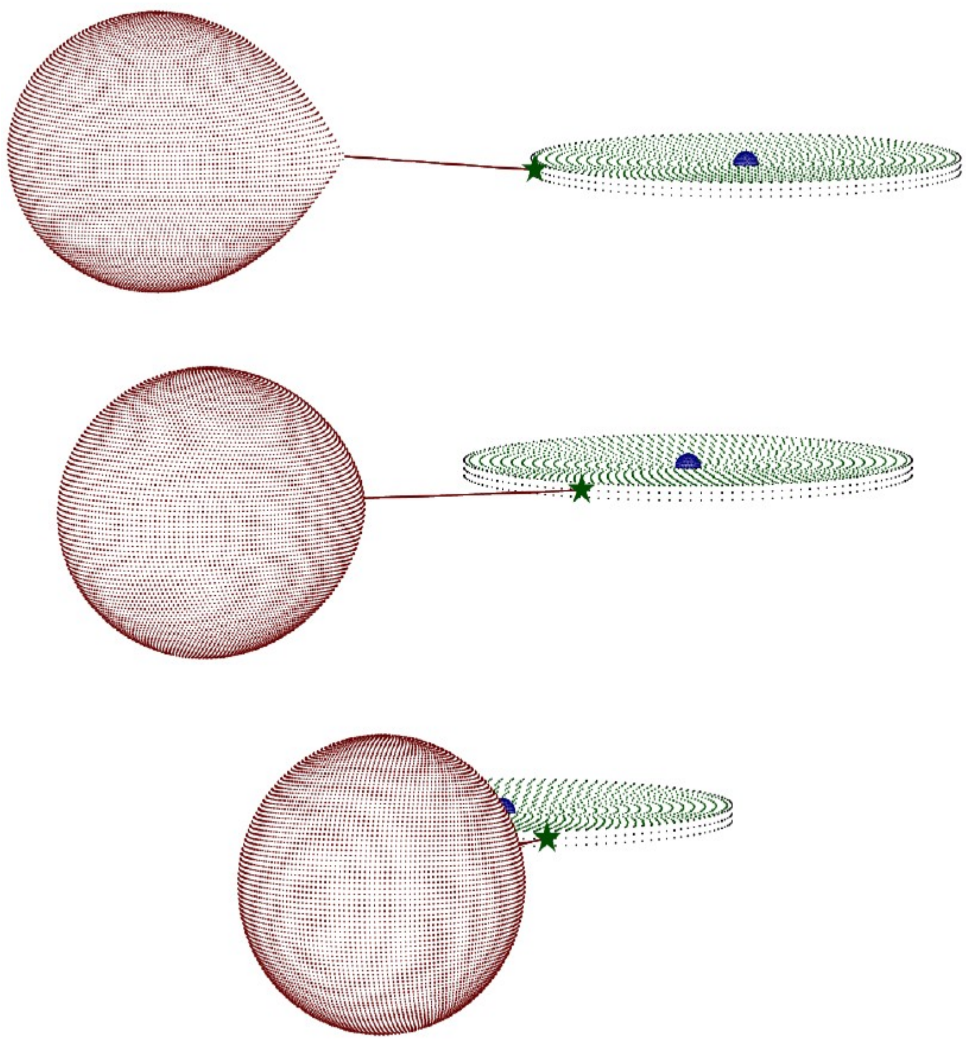
Key questions:

- 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

Lightcurve analysis with ***lcurve***

Generating a lightcurve



A light curve can be generated as follows:

- Generate grids covering all objects (stars, disc, etc...)
- Set their surface brightness including all effects, e.g. limb darkening, gravity darkening, reflection effect, Doppler beaming, ...
- At every phase compute what can and cannot be seen, add up the fluxes.

Data file

Data file

- Can be in any time units or phase 'process_lightcurve.sh' returns hjd.
- Must be in normalized flux not magnitudes
- Combining data from different nights by phasing the data
- For deriving the period use Lomb-Scargle algorithm
- Binning improves the S/N

Careful with combining data from different nights

- Check normalization
- Check for trends due to atmospheric dispersion

Data file

Data file

- You'll get something like this:

HJD	Mag	Mag_error
2460550.34769	4.6703	0.0093
2460550.34804	0.0233	0.0141
2460550.34839	0.0283	0.0141
2460550.34874	-1.4350	0.4881
2460550.34908	-1.5350	0.6131
2460550.34943	0.0317	0.0141
2460550.34978	-1.4397	0.2932
2460550.35013	-1.8227	1.5760
2460550.35048	0.0707	0.0141
2460550.35083	-1.5020	0.4082
2460550.35118	-1.2940	0.2374
2460550.35153	-1.3310	0.4831
2460550.35187	-1.4510	0.7690
2460550.35222	0.2037	0.0145
2460550.35257	0.2280	0.0145
2460550.35291	0.2410	0.0145

Data file

```
#phase   delta_phase  flux  flux_error weight factor
0.000000 0.005000 0.998687 0.000039 1 1
0.005000 0.005000 0.998429 0.000039 1 1
0.010000 0.005000 0.998627 0.000040 1 1
0.015000 0.005000 0.998445 0.000039 1 1
0.020000 0.005000 0.998252 0.000039 1 1
0.025000 0.005000 0.998146 0.000039 1 1
0.030000 0.005000 0.997968 0.000039 1 1
0.035000 0.005000 0.997922 0.000039 1 1
0.040000 0.005000 0.997763 0.000039 1 1
0.045000 0.005000 0.997587 0.000040 1 1
0.050000 0.005000 0.997578 0.000039 1 1
0.055000 0.005000 0.997595 0.000039 1 1
0.060000 0.005000 0.997497 0.000039 1 1
```

Data file

```
#hjd   delta_phase  flux  flux_error weight factor
2460550.49777 0.005000 0.998687 0.000039 1 1
2460550.50228 0.005000 0.998429 0.000039 1 1
2460550.50309 0.005000 0.998627 0.000040 1 1
2460550.5039 0.005000 0.998445 0.000039 1 1
2460550.50471 0.005000 0.998252 0.000039 1 1
2460550.50552 0.005000 0.998146 0.000039 1 1
2460550.50633 0.005000 0.997968 0.000039 1 1
2460550.50714 0.005000 0.997922 0.000039 1 1
2460550.50795 0.005000 0.997763 0.000039 1 1
2460550.50876 0.005000 0.997587 0.000040 1 1
2460550.50957 0.005000 0.997578 0.000039 1 1
2460550.51038 0.005000 0.997595 0.000039 1 1
2460550.51119 0.005000 0.997497 0.000039 1 1
```

Model file – ‘example/example.json’

```
{
  "data_file_path": "ondrejov_lc_testing/J018.4128+22.9608_night1/I_lightcurve_modified.txt",
  "output_file_path": "output_J018.txt",
  "plot_device": "qt",
  "mcmc_steps": 10000,
  "mcmc_burn_in": 2500,
  "chain_out_path": "chain_out_J018.txt",
  "use_priors": false,
  "true_period": 0.2574,
  "priors": {
    "vrad1_obs": "130 100 80",
    "m1": "0.44 0.15 0.15",
    "m2_min": "0.34 0.3 0.3",
    "r1": "0.22 0.11 0.11"
  },
```

If false, lines below are ignored

Prior distributions can be used to set physical limits

Data file

Model file – ‘example/example.json’

1 = freeze; 0 = free

Relative radii! r / a

Limb darkening coefficients (use linear)

```
"model_parameters": {
  "q": "0.75 0.002 0.0001 1 1",
  "iangle": "75 1 0.01 1 1",
  "r1": "0.31 0.001 0.0001 1 1",
  "r2": "0.20 0.01 0.0001 1 1",
  "t1": "32290 1000 10 0 1",
  "t2": "3424.761 1000 10 1 1",
  "ldc1_1": "0.2121 0.02 0.0001 0 1",
  "ldc1_2": "0 0.02 0.003 0 1",
  "ldc1_3": "0 0.02 0.003 0 1",
  "ldc1_4": "0 0.02 0.003 0 1",
  "ldc2_1": "0.5315 0.02 0.0001 0 1",
  "ldc2_2": "0 0.02 0.0001 0 1",
  "ldc2_3": "0 0.02 0.0001 0 1",
  "ldc2_4": "0 0.02 0.0001 0 1",
  "velocity_scale": "200.0 1 1.0 1 1",
  "beam_factor1": "1 0.1 0.01 0 1",
  "beam_factor2": "1 0.1 0.01 0 1",
  "t0": "0.38 1e-05 0.0001 1 1",
  "period": "0.09040 0.0001 1e-08 1 1",
  "tperiod": "0.09040",
  "pdot": "0 0.01 1e-05 0 1",
  "deltat": "0 0.0001 0.0001 0 1",
  "gravity_dark1": "0.32 0.01 1e-06 0 1",
  "gravity_dark2": "0.08 0.01 1e-06 0 1",
  "absorb": "0.5 0.1 0.01 0 1",
```

Just get comfortable with changing various parameter to see how they affect they lightcurve!

Limb darkening

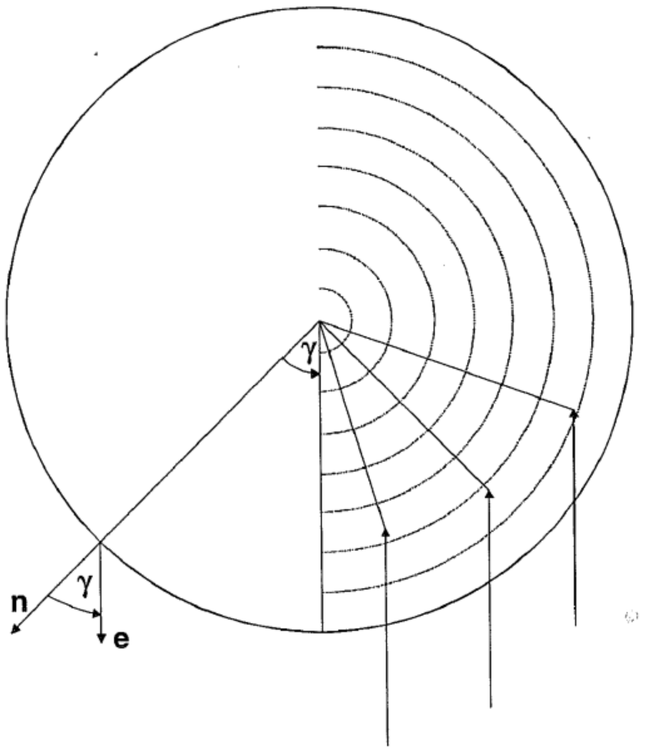


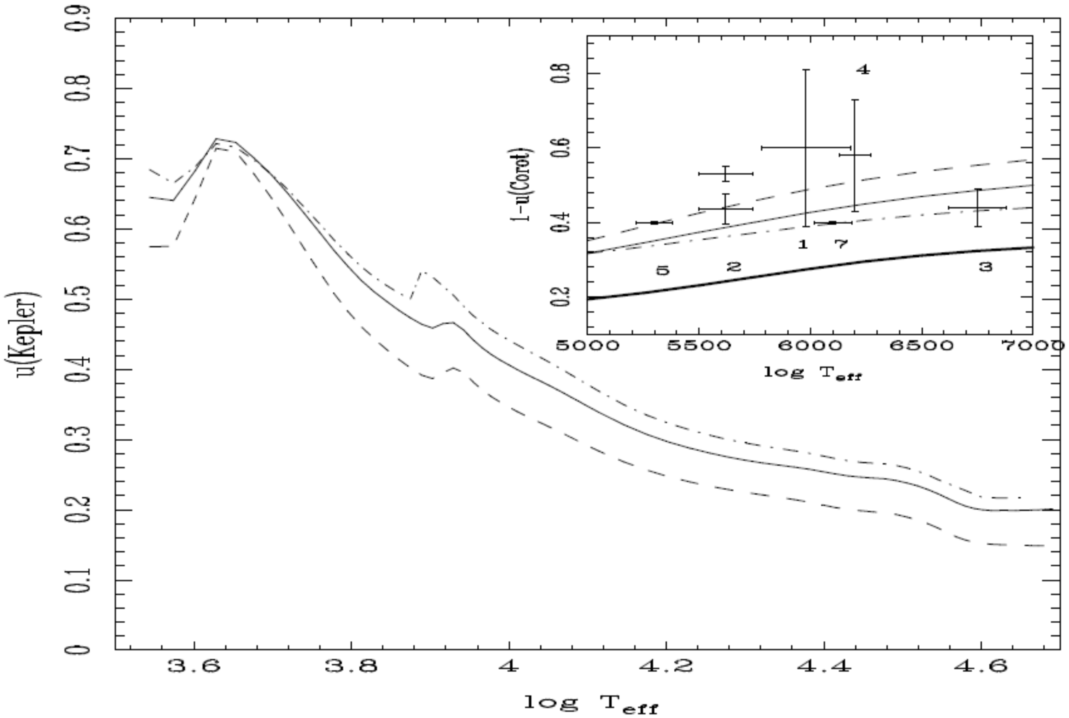
FIGURE 3.17. Center-to-limb variation. This figure shows the aspect angle γ (angle between normal vector **n** and radiation emission direction **e**) appearing in the mathematical formulation of the limb-darkening. The right part of the figure illustrates that the depth of the atmosphere region (and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

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: $I = I_0(1 - \epsilon + \epsilon \cos\theta)$
  ϵ = limb darkening factor, wavelength dependent
  sun in the UV ($<$ 1600Å): limb brightening due to chromospheric temperature rise

→ It will directly impact the shape of the LC, especially around the eclipses!

Limb darkening



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

→ You will need to look up the Claret Limb-darkening coefficients online!
The linear component is usually enough.

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

Claret's law:

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

$\mu = \cos\gamma$

Look up limb darkening coefficients in Vizier

→ https://vizier.cds.unistra.fr/viz-bin/VizieR

→ Search for ‘limb darkening coefficients for compact stars’

  → J/A+A/634/A93/tableu

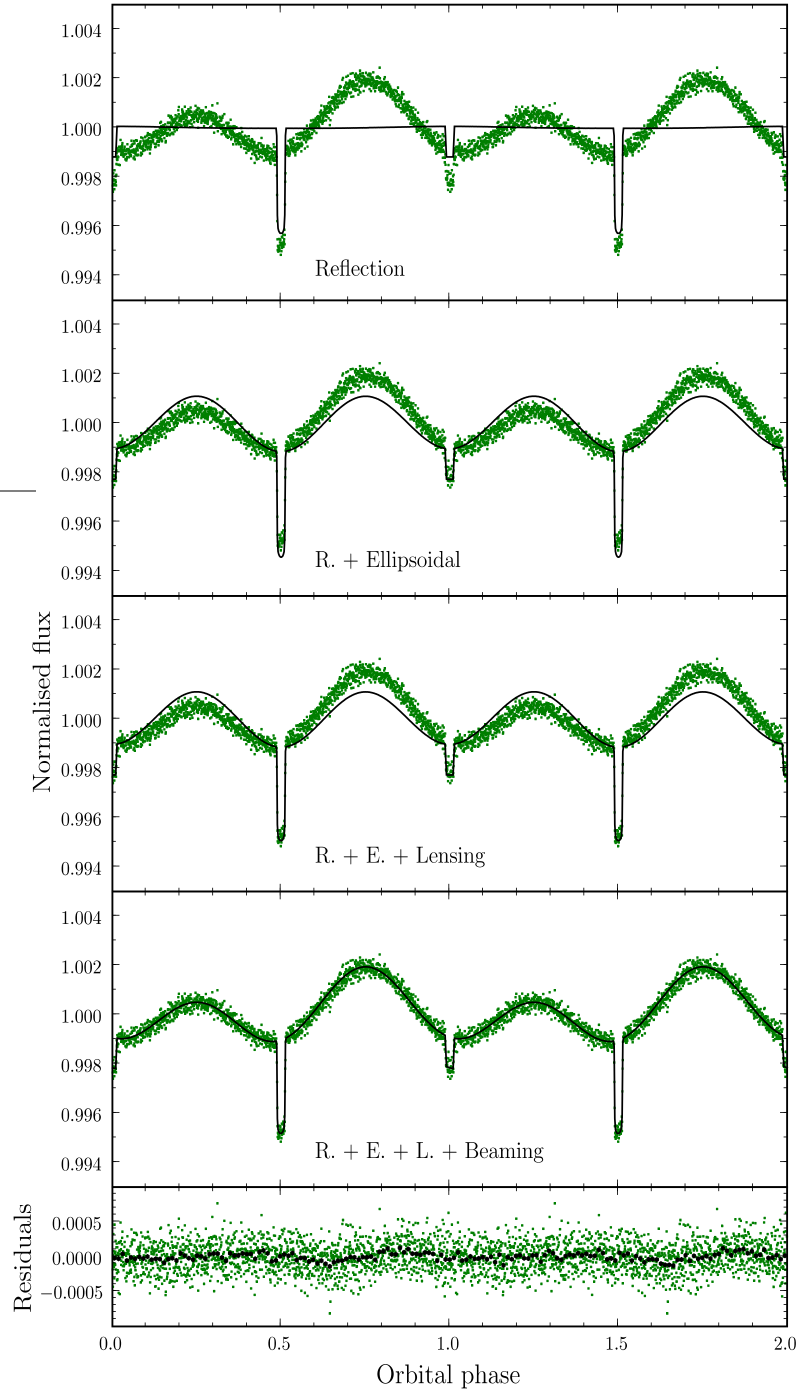
  → Search for appropriate logg and Teff ranges (and filter!)

Full	Mod	logg [cm/s+2]	Teff K	Z [-]	u	sig	I mW/m2/Hz/sr	Be	Filter
1	DB	5.00	20000.0	-10.0000	0.3392	0.0762	4.60845e-04	0.6764	u'
2	DB	5.00	30000.0	-10.0000	0.2871	0.0700	1.02056e-03	1.1831	u'
3	DB	6.00	20000.0	-10.0000	0.3427	0.0792	4.68302e-04	0.6764	u'
4	DB	6.00	30000.0	-10.0000	0.2741	0.0594	9.69334e-04	1.1831	u'
5	DA	5.00	20000.0	0.0000	0.3819	0.0944	4.10262e-04	0.6765	u'
6	DA	5.00	30000.0	0.0000	0.3311	0.1246	1.17205e-03	1.1832	u'
7	DA	6.00	20000.0	0.0000	0.3757	0.0841	4.03678e-04	0.6765	u'
8	DA	6.00	30000.0	0.0000	0.3186	0.1102	1.13520e-03	1.1832	u'
9	DB	5.00	20000.0	-10.0000	0.3168	0.0962	4.18859e-04	1.0683	g'
10	DB	5.00	30000.0	-10.0000	0.2590	0.0701	7.60893e-04	1.4175	g'
11	DB	6.00	20000.0	-10.0000	0.3028	0.1197	4.22035e-04	1.0683	g'
12	DB	6.00	30000.0	-10.0000	0.2478	0.0640	7.38280e-04	1.4175	g'
13	DA	5.00	20000.0	0.0000	0.3617	0.1388	4.16084e-04	1.0683	g'
14	DA	5.00	30000.0	0.0000	0.2986	0.1300	8.81566e-04	1.4175	g'
15	DA	6.00	20000.0	0.0000	0.3517	0.1338	4.14478e-04	1.0683	g'
16	DA	6.00	30000.0	0.0000	0.2811	0.1126	8.61365e-04	1.4175	g'

G filter.
Select the right one for you.

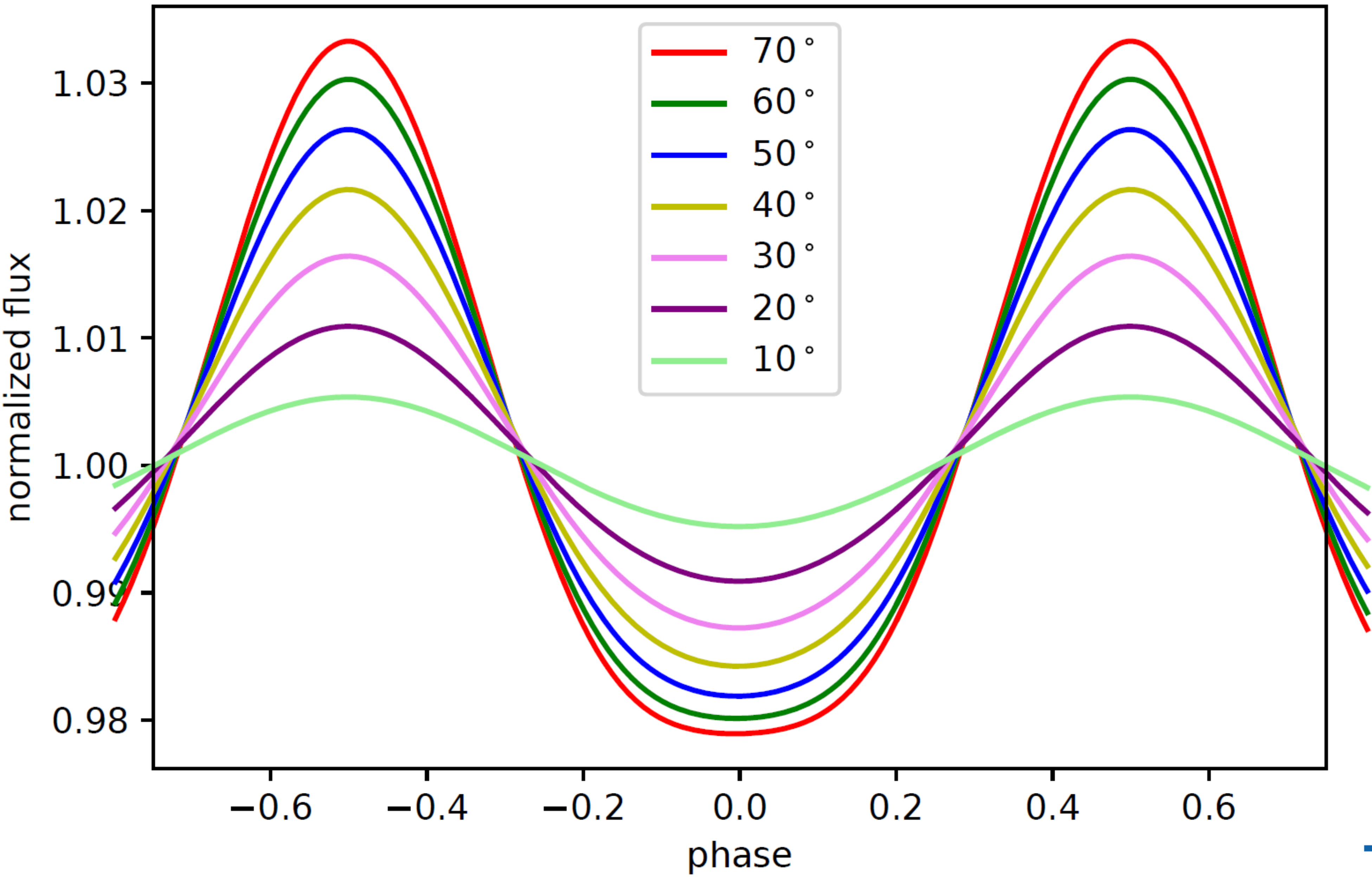
This is for the primary hot subdwarf → do the same for the companion star!

Data to model

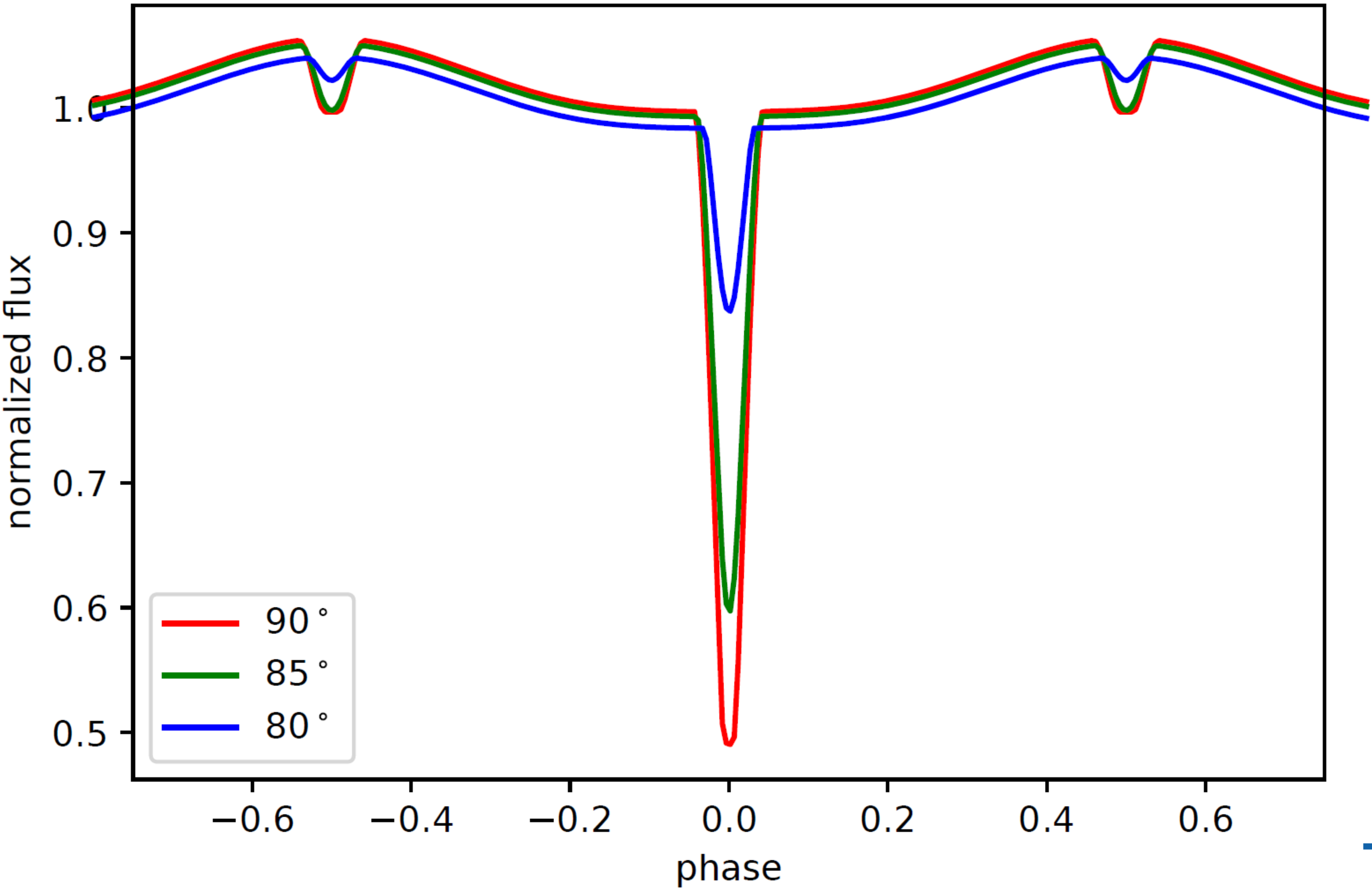


- find which models are consistent with the data, statistical and computational task
- different methods: Levenberg-Marquardt method, simplex method, Markov Chain Monte Carlo (MCMC)
- much harder to find uncertainties in the parameters, than the best-fitting model itself.

Reflection effect



Eclipsing Reflection effect (HW Vir systems)



Degeneracy in the light curve analysis

If a change in one parameter causes a change in the predicted light curve that can be matched by a change in another or several others, then the fit will be degenerate.

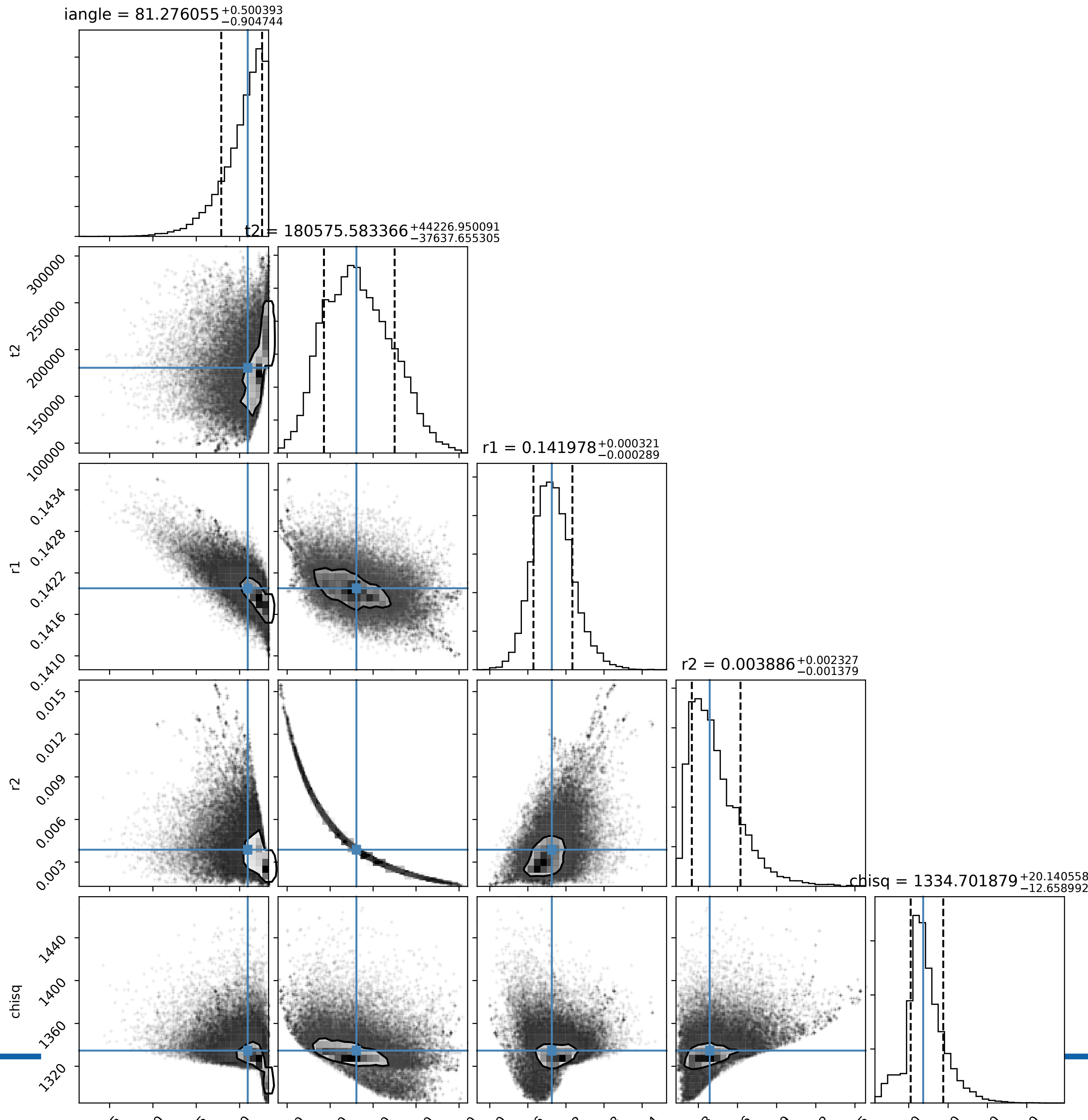
For a parameter to be well-defined, its effect on the light curve must be unique.

Degeneracy can

- make it impossible to uniquely constrain parameters,
- lead to strong correlations between multiple parameters,
- cause minimisation algorithms (e.g. Levenberg-Marquardt) to fail.

Bayesian methodology allows one to include prior information!
Use as many known parameters as possible from theory or spectroscopic observation (T_1, $\log g$ limb darkening coefficients, ...)

Degeneracy in the light curve analysis



Calculation of fundamental parameters

Spectrum

- Radial velocity curve K_1 and ideally $K_2 \Rightarrow q = K1/K2$
- effective temperature T_1
- $\log g$

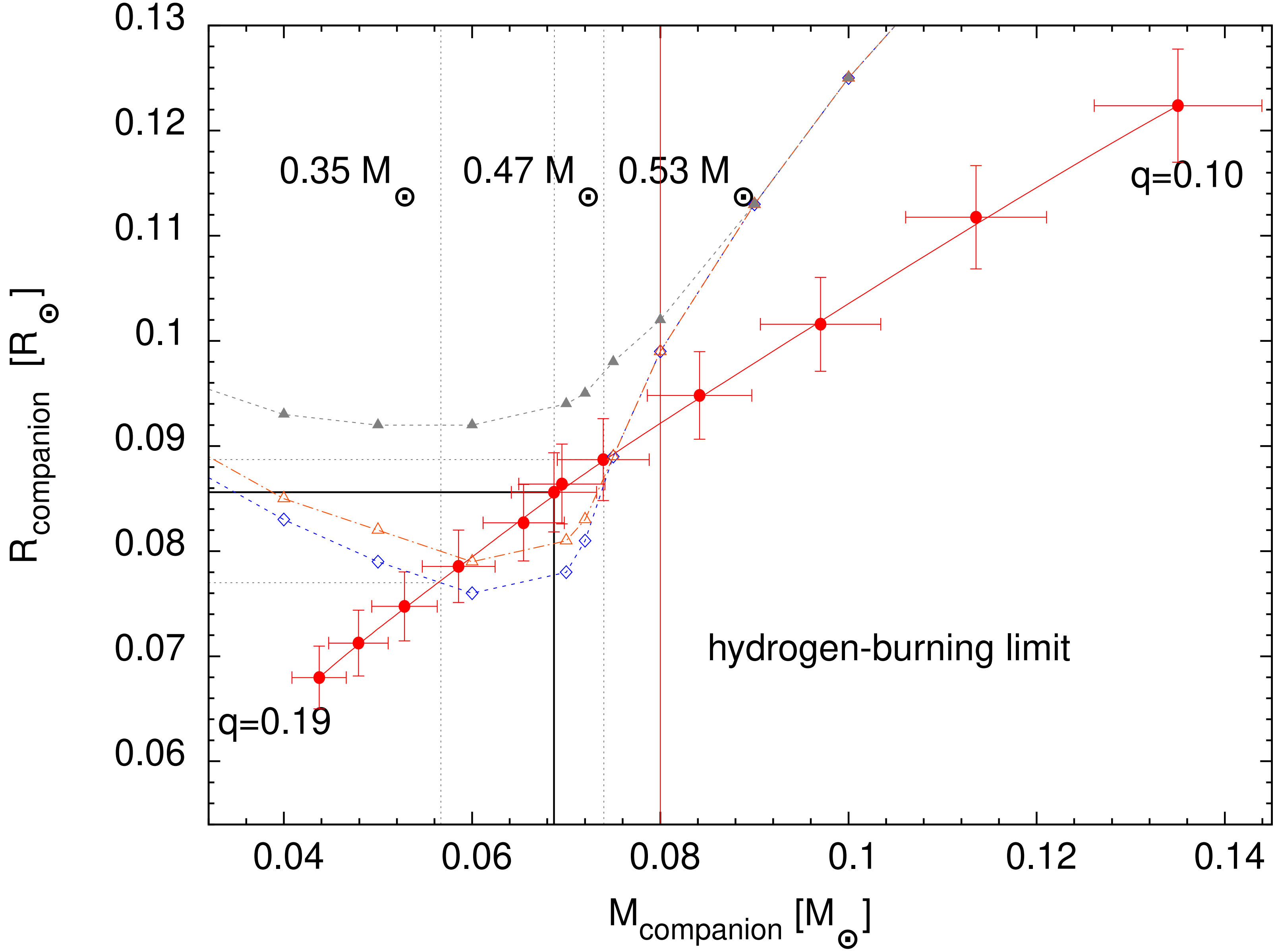
We don't have spectra so we have to assume these!

Lightcurve

- orbital period P
- mass ratio (ish) q
- inclination i
- effective temperature T_2
- relative radius r_1/a
- relative radius r_2/a
- albedo

Your job: derive T_2, relative radii, inclination, and the minimum mass of the companion. For M_2, you will need to solve the binary mass function ;)

Mass-radius relation for the companion Baraffe et al. 2003



Schaffenroth et al. 2017

Fit the data

- Find the **lcurve_re** folder in the virtual machine.
- Make a copy of the example/example.json file and edit it.
- Generate a light curve with your chosen parameters with:
  lcurve_re example/example.json
- Play around with it to get a feeling which parameters change what.
- to invoke the simplex algorithm: **lcurve_simplex example/example.json**
- when you found a good model use: **lcurve_mcmc example/example.json** algorithm to estimate the uncertainties.
- with **visualise** model you get a nice visualization of both stars and their orbit

Parameter file – Physical parameters – Binary and stars

x = initial_value param_space steps fitting(True/False) ignore_param(True/False)

q	Mass ratio, q = M2/M1
iangle	Inclination angle, degrees
r1	Radius of star 1, scaled by the binary separation
r2	Radius of star 2, scaled by the binary separation
t1	Temperature of star 1, K, This is a substitute for surface brightness, which is set assuming a black-body given this parameter.
t2	Temperature of star 2, Kelvin.
ldc1_1, etc	Limb darkening for stars is quite hard to specify precisely.

velocity_scale sum of unprojected orbital speeds, used for accounting for Doppler beaming and gravitational lensing.

beam_factor 3-alpha factor that multiplies -v_r/c in the standard beaming formula where alpha is related to the spectral shape. Use of this parameter requires the velocity_scale to be set.

Parameter file – Physical parameters – General

t0	Zero point of ephemeris, marking time of mid-eclipse
period	Orbital period, same units as times.
pdot	Quadratic coefficient of ephemeris, same units as times
deltat	Time shift between the primary and secondary eclipses to allow for small eccentricities and Roemer delays in the orbit. Delay of -deltat/P by the secondary eclipse.
gravity_dark	Gravity darkening coefficient. Only matters for the Roche distorted case. set gdark_bolom (see below) to 0. Use Claret et al.
absorb	The fraction of the irradiating flux from star 1 absorbed by star 2
slope, quad, cube	factors to help cope with any trends in the data as a result of e.g. airmass effects. The fit is multiplied by (1+x*(slope+x*(quad+x*cube)))
third	Third light contribution. Simply adds to whatever flux is calculated and will be subject to auto-scaling like other flux. It only applies if global scaling rather than individual component scaling is used. Third light is assumed strictly constant

Computational parameters

delta_phase	Accuracy in phase of eclipse computations
nlat1/2f	number of latitudes for star 1/2's fine grid. This is used around the phase of primary eclipse
nlat1/2c	number of latitudes for star 1's coarse grid. This is used away from primary eclipse.
phase1	This defines when star 1's fine grid is used abs(phase) < phase1. phase1 = 0.05 will restrict the fine grid use to phase 0.95 to 0.05.
phase2	this defines when star 2's fine grid is used phase2 until 1-phase2. phase2 = 0.45 will restrict the fine grid use to phase 0.45 to 0.55.
wavelength	Wavelength (nm)
tperiod	The true orbital period in days. This is required, with velocity_scale, if gravitational lensing is applied to calculate proper dimensions.
gdark_bolom	True, if gravity darkening coefficient represents the bolometric value
limb1/2	'Poly' or 'Claret' determining the type of limb darkening law. See comments on ldc1_1 above.