Light curve analysis of eclipsing sdB+dM/BD systems

Research workshop on evolved stars

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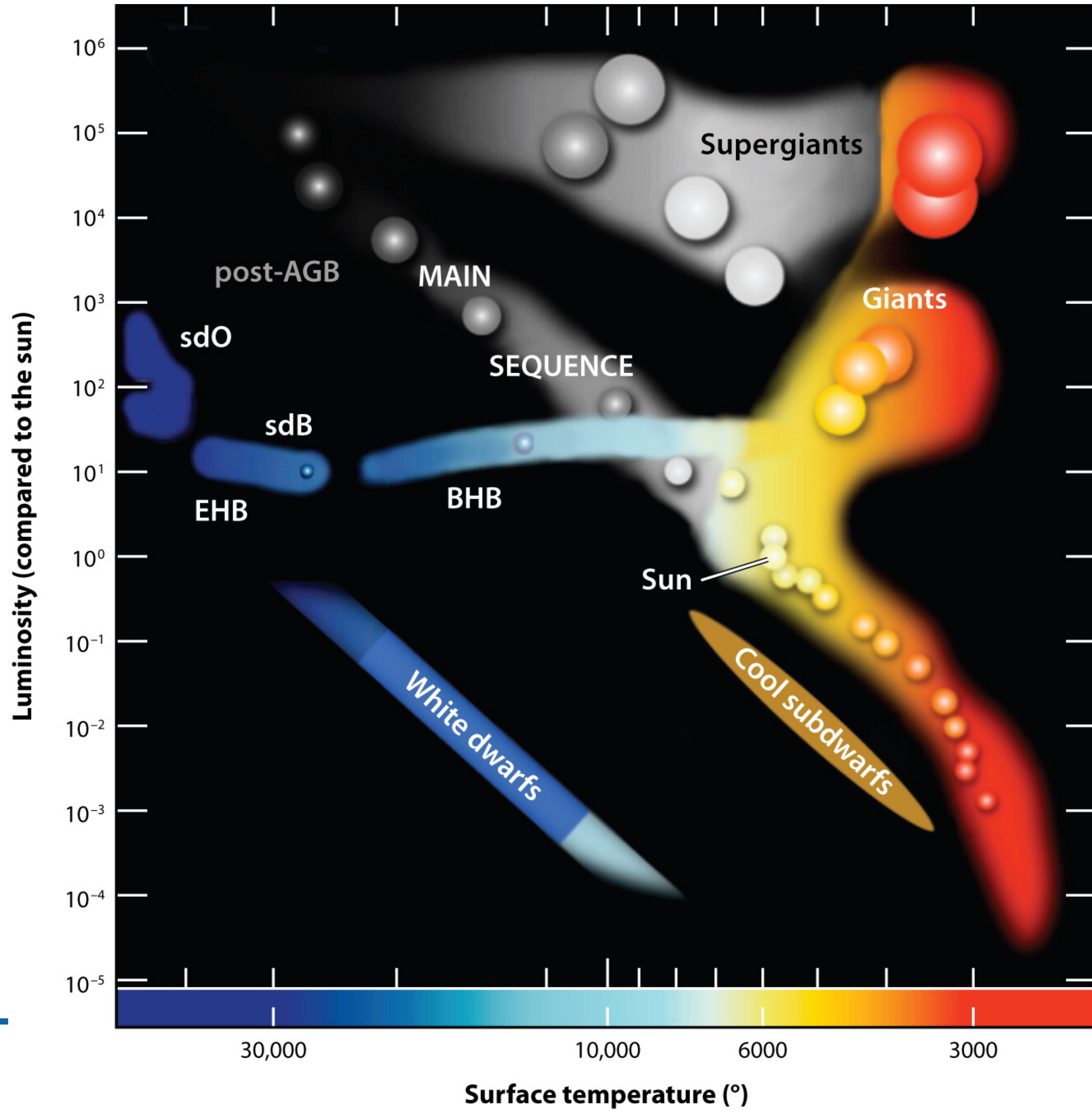
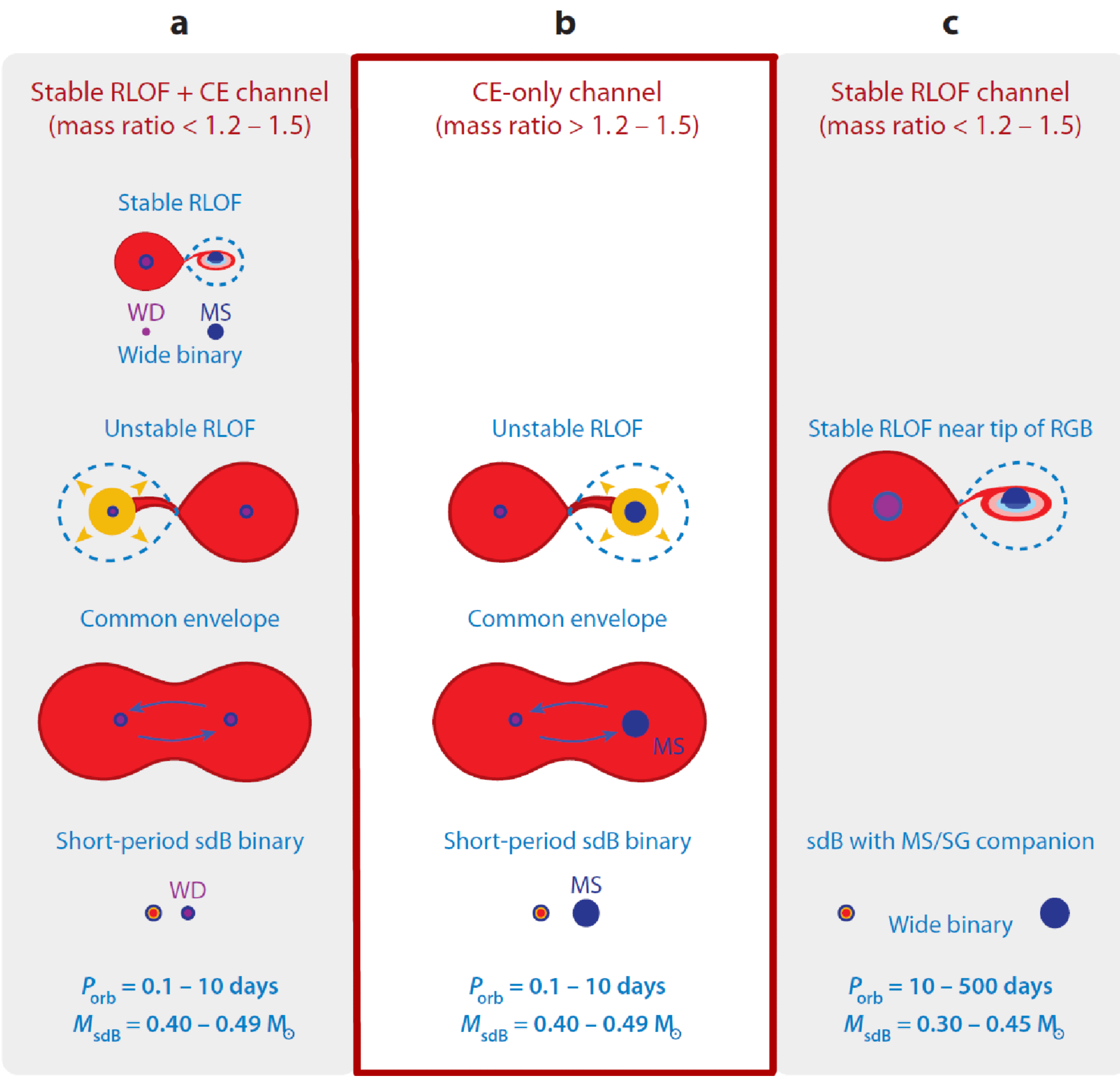
Introduction

Hot subdwarf stars of spectral type B (sdB)



Formation of sdB binary



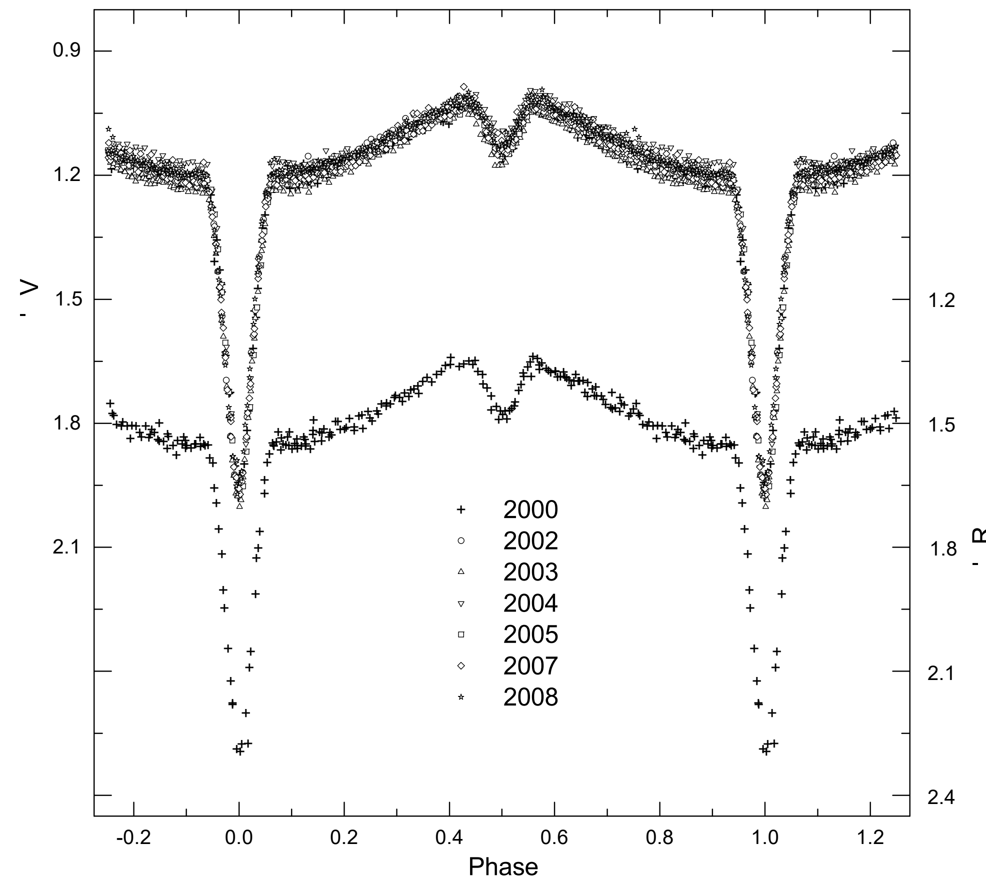
Han et al. (2002,2003)

HW Virginis systems

- eclipsing binaries consisting of sdB and cool, low mass stellar or substellar companion
- ~20 HW Vir systems published
- very short period $\sim$ 1.5-6 h (separation $\sim 1\,R_\odot$)

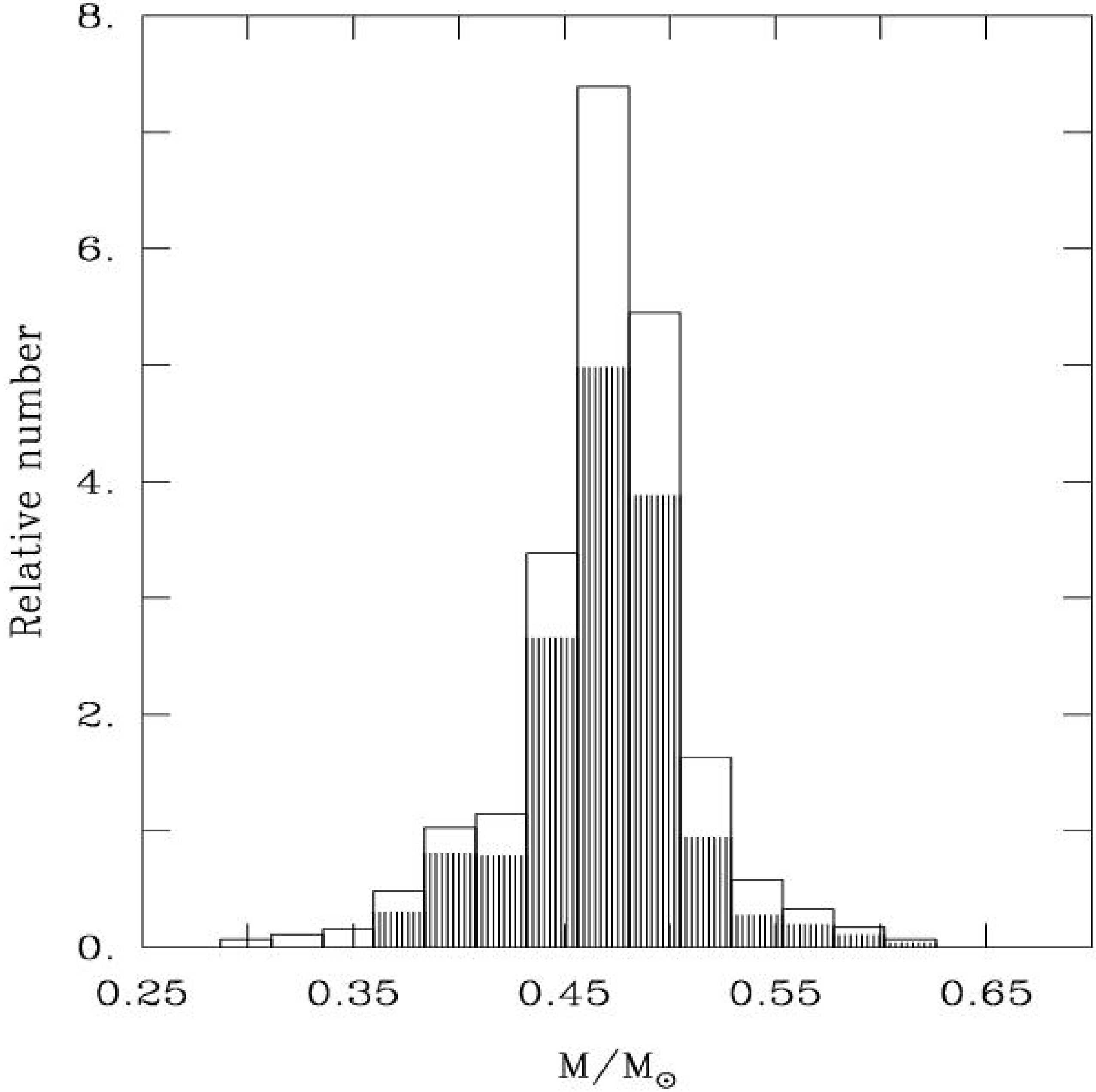
  $\Rightarrow$ post common envelope system
- only sdB visible in spectrum
- unique lightcurve

  $\Rightarrow$ huge reflection effect



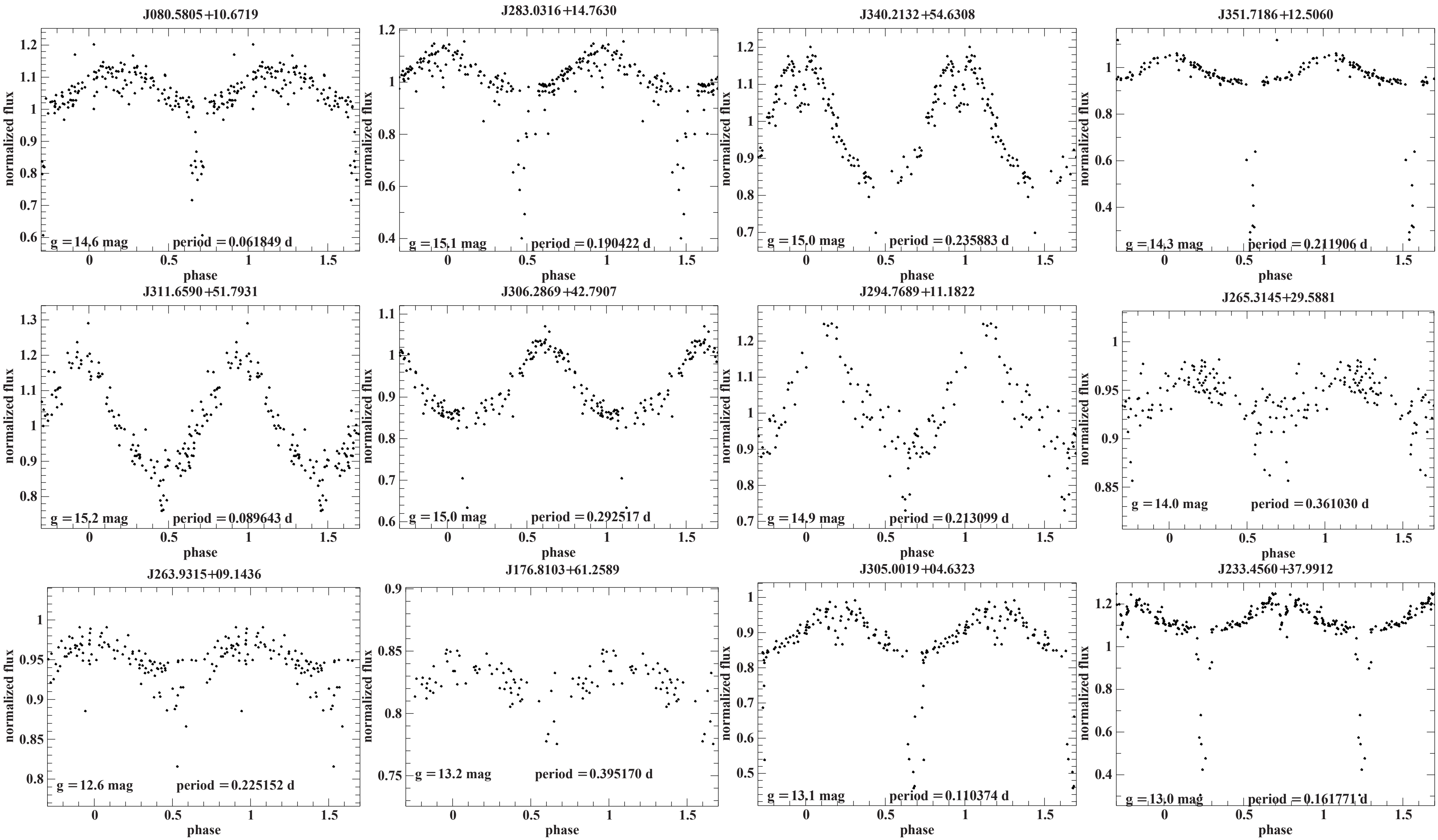
Lightcurve of HW Virginis (Lee et al. 2009)

Observed mass distribution of sdBs



Fontaine et al. 2012 *M*

200 HW Vir candidate systems: P = 0.05 − 1.26 d



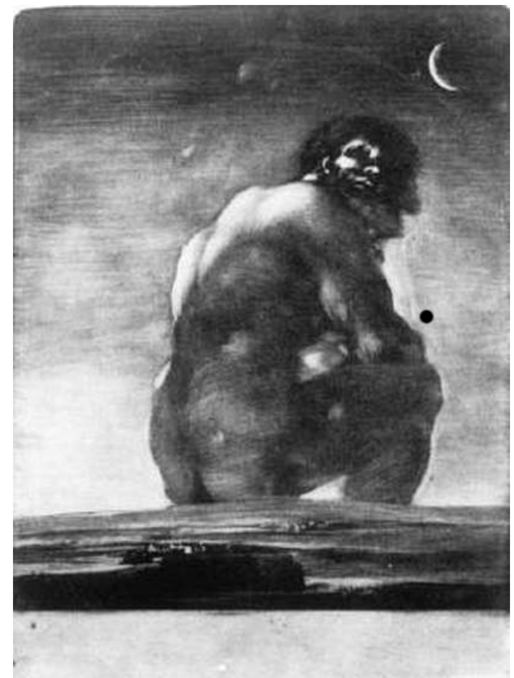
The EREBOS project

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 ($T_{\rm eff}$, $\log g$) and system parameters (a, P)
- spectroscopic and photometric follow-up

Key questions:

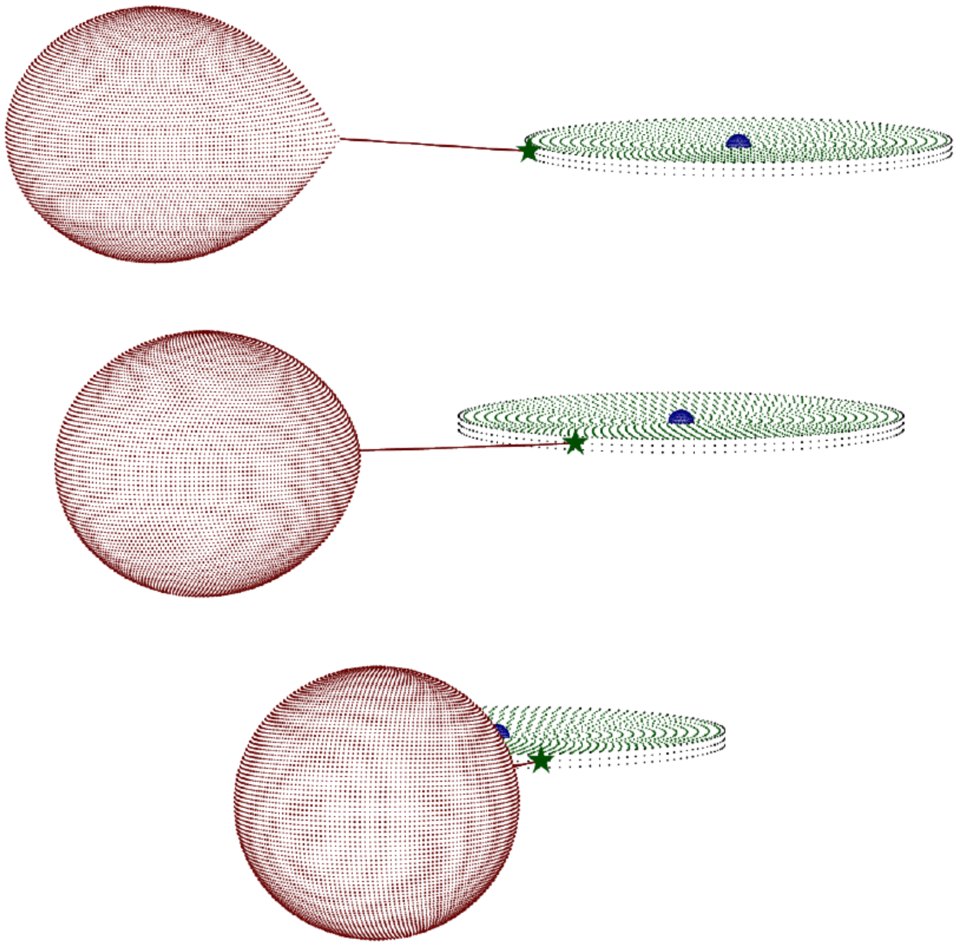
- minimum mass of the companion necessary to eject the common envelope?
- fraction of close substellar companions to sdB stars
- better understanding of the CE phase and the reflection effect



EREBOS
God of darkness

*Lightcurve analysis with **lcurve***

Generating a lightcurve



A light curve can be generated as follows:

- Generate grids covering all objects (stars, disc, ...)
- 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.

Computation of the light-curve of a Roche distorted star

lroche computes the light curve equivalent to a model of a sphere and a Roche-distorted star to model a white dwarf or subdwarf/main-sequence binary and can optionally include a disc and bright-spot as well.
Other physics included: Doppler beaming, gravitational lensing, Roemer time delays, asynchronous rotation of the stellar components

Invocation

lroche model data noise seed nfile [output] (device)]]

noise	multiplier of the real error bars
seed	Seed integer
nfile	Number of files to store
output	File to save the results in the form of rows each with time, exposure time, flux and uncertainty
device	Plot device to use

Data file

Data file

- can be in any time units or phase
- 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

```
#phase   delta_phase  flux  flux_error weight fact
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
```

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. Extrapolate from Claret et al.
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.

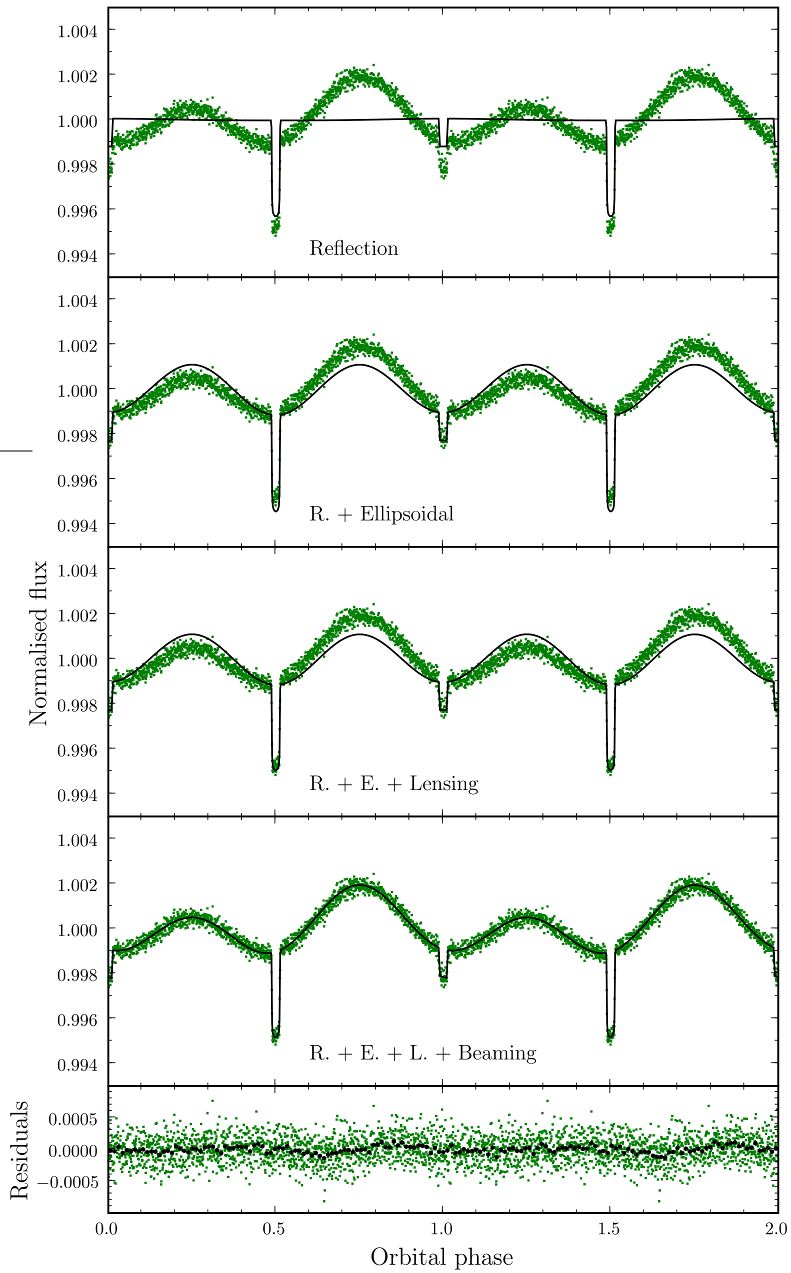
Parameter file – Physical parameters – General

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.

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.

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.

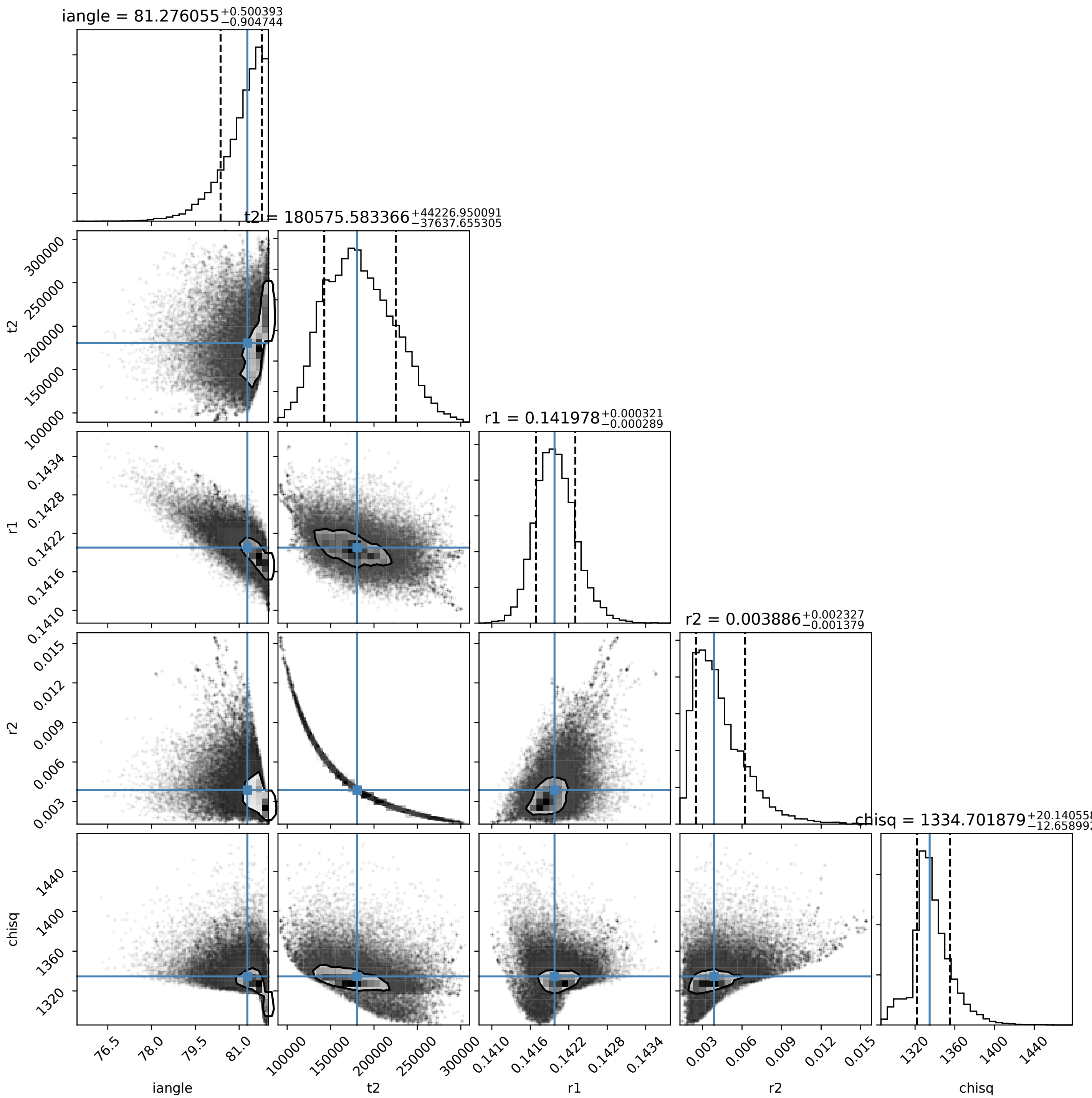
For a parameter to be well-defined, its effect on the light curve must be unique.

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, $\log g_1$, y, 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
- $\log g_1$

Lightcurve

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

Calculation of fundamental parameters

orbital separation

$$a = \frac{P}{2}\frac{K_1}{\sin(i)}(1/q + 1) \tag{2.1}$$

radii

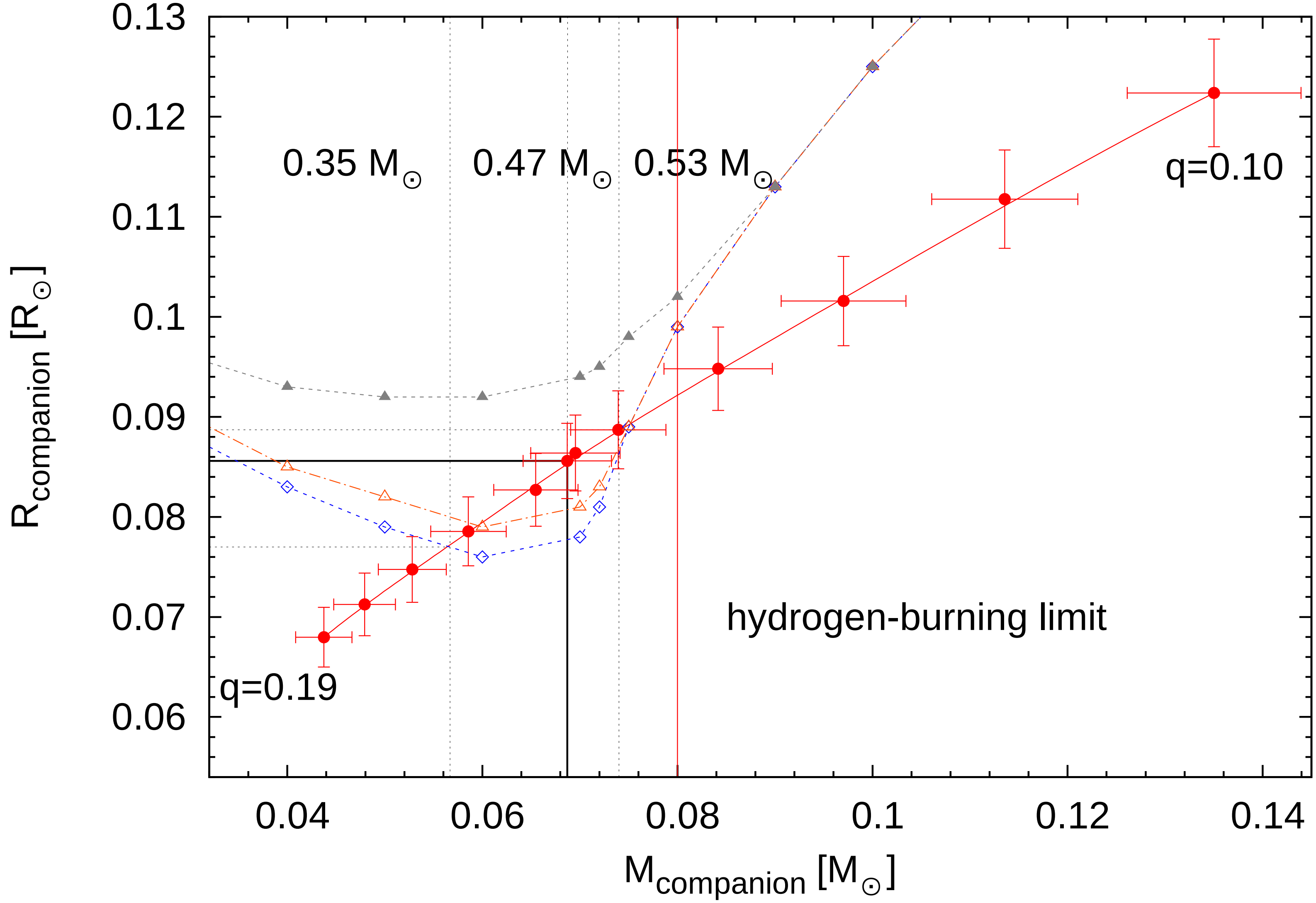
$$R_{1/2} = \frac{r_{1/2}}{a} \cdot a \tag{2.2}$$

masses

$$M_1 = \frac{P}{2\ G}\frac{K_1^3(q+1)^2}{(q \sin i)^3} \tag{2.3}$$

$$M_2 = q \cdot M_1 \tag{2.4}$$

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



Schaffenroth et al. 2017

Fit the data

- Login: **ssh -X blockcourse@carina.astro.physik-uni.potsdam.de**
  password: **late_stellar_evolution**
- First play around with lroche to get a feeling which parameters change what
- to invoke simplex algorithm: **simplex** model data
- when you found a good model use the Levenberg-Marquardt algorithm to estimate the error
- **levmarq** model data
- calculate the best model with **lroche** to plot results
- with **visualise** model you get a nice visualization of both stars and their orbit