Triple Systems
in PHOEBE
(coming soon... someday)

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Universe of Binaries, Binaries in the Universe
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Telc, Czech Republic

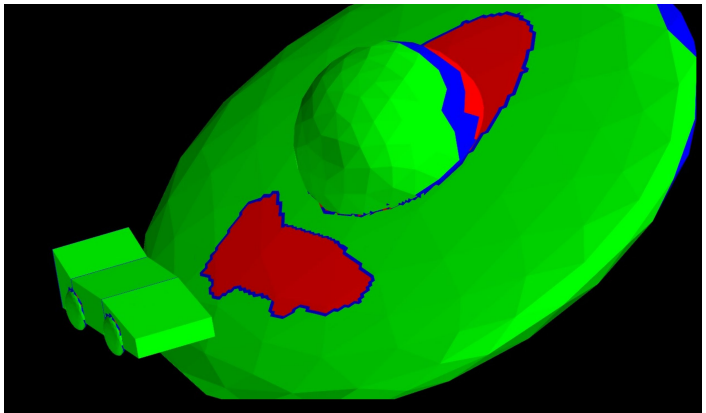
History of PHOEBE

0.2 (2003) - original version of PHOEBE released by Andrej

0.3 (2007) - now referred to as PHOEBE legacy or PHOEBE 1

2010 - Pieter DeGroote and Steven Bloemen pitch python wrapper to Andrej

2011 - Begin complete rewrite of a general framework for modeling EBs



History of PHOEBE

2.0 (2017) - Initial release of complete-rewrite with Python framework

2.1 (2018) - Support for spin-orbit misalignment and spectral line profiles

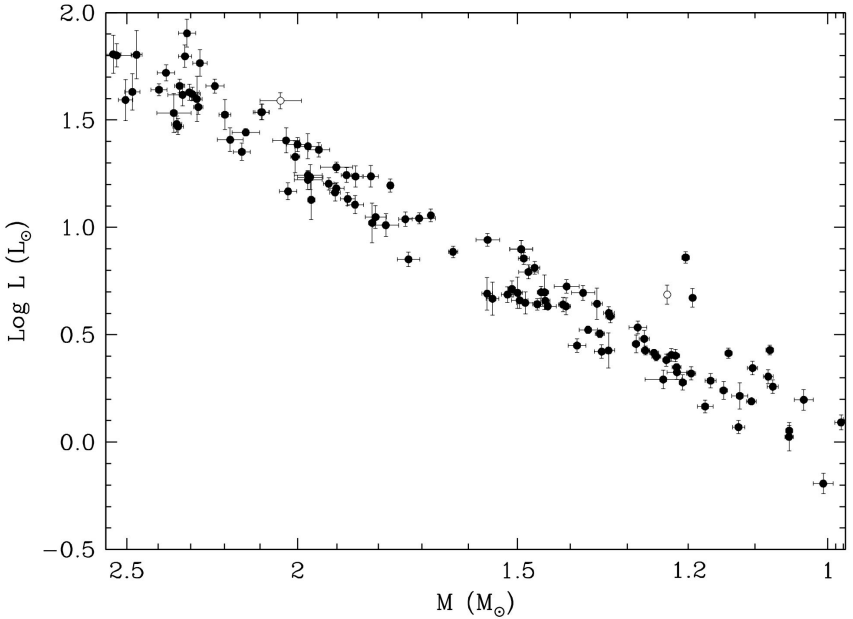
2.2 (soon) - Interstellar extinction and better atmosphere support

In progress:

- **Triples & Multiples**
- Pulsations
- Bayesian Fitting
- GUI and web-based UI

Benefits to Modeling Triples

Benchmark EBs: 2-3% uncertainties in fundamental parameters



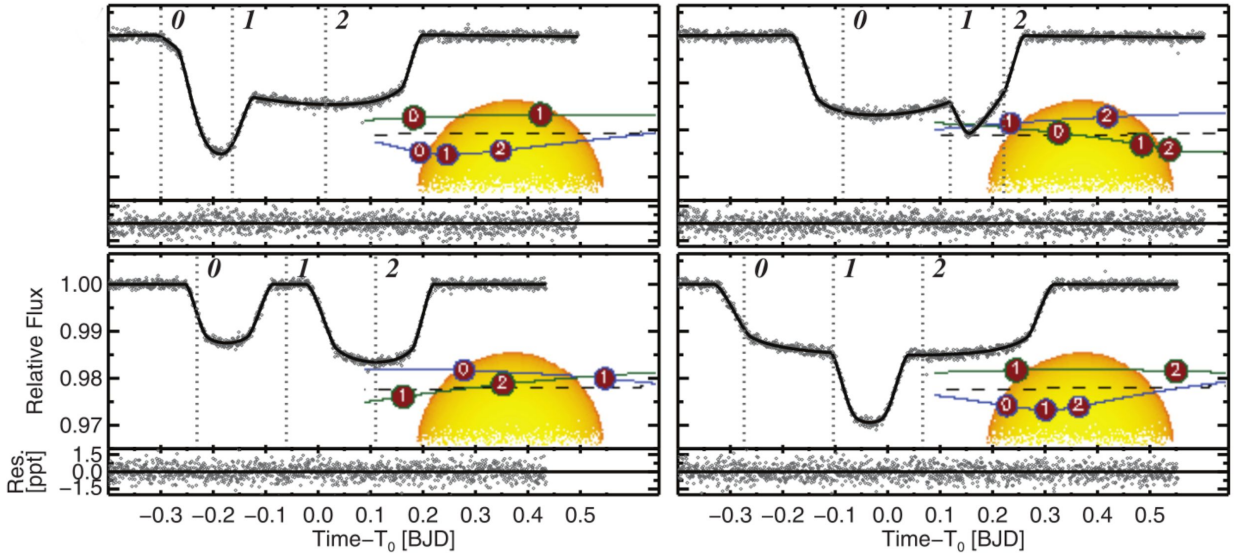
Torres+ 2010

calibration of stellar models and relationships would benefit by an increase in precision, but our precision is limited by:

- uncertainties in data (fixed by Kepler)
- precision of model (goal of PHOEBE)
- **inherent degeneracies** (radius vs incl)

Benefits to Modeling Triples

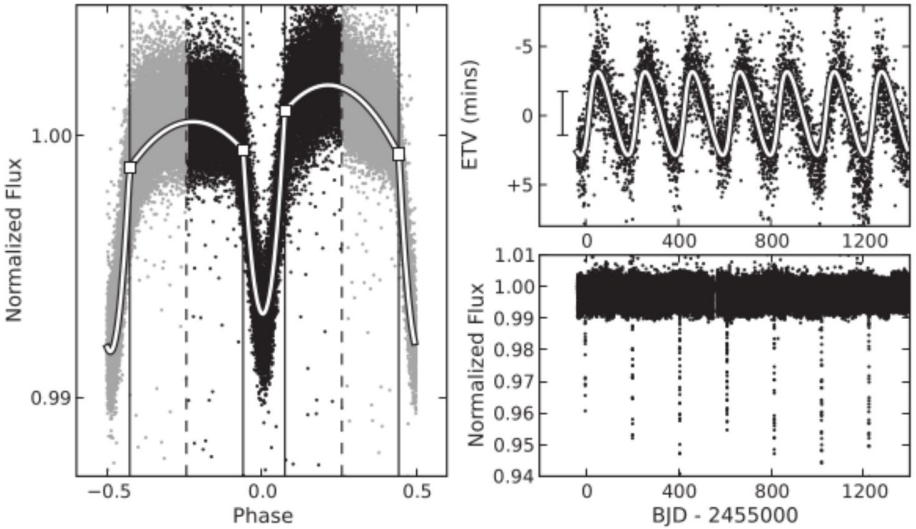
Benchmark EBs: 2-3% uncertainties in fundamental parameters (Torres+ 2010)
Kepler multiples: <1%



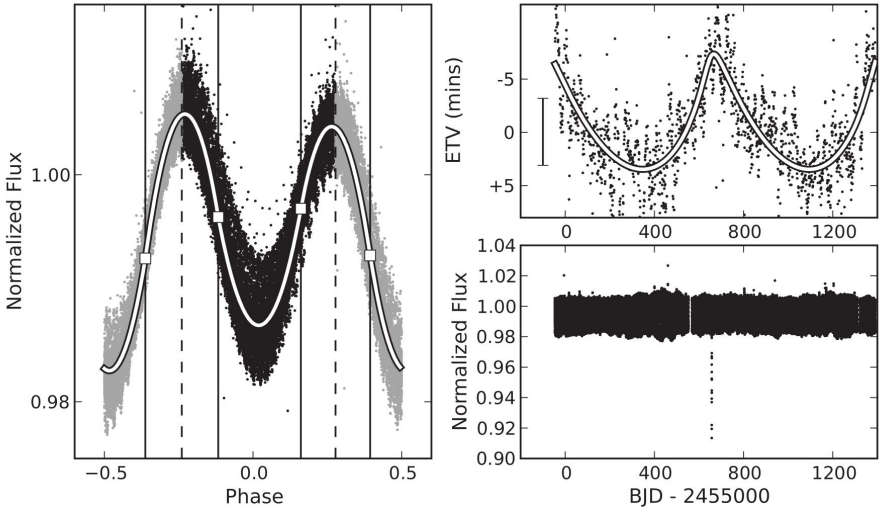
	Star 1	Star 2	Star 3
Mass [MSun]	1.347 +/- 0.032	0.241 +/- 0.003	0.213 +/- 0.003
Radius [RSun]	2.025 +/- 0.010	0.254 +/- 0.001	0.232 +/- 0.001
Density [kg/l]	0.229 +/- 0.003	20.70 +/- 0.19	24.09 +/- 0.20

KOI 126 (Carter+ 2011)

Tight Inner-Binary Formation Theories



KIC 2856060
0.25 d inner-binary



KIC 2835289
0.9 d inner-binary

Conroy+ 2014

Overview of Existing Codes

Wilson-Devinney:

- modeling ETVs caused by third body

photodynam (Josh Carter):

- full dynamical treatment
- spherical stars
- quadratic limb-darkening

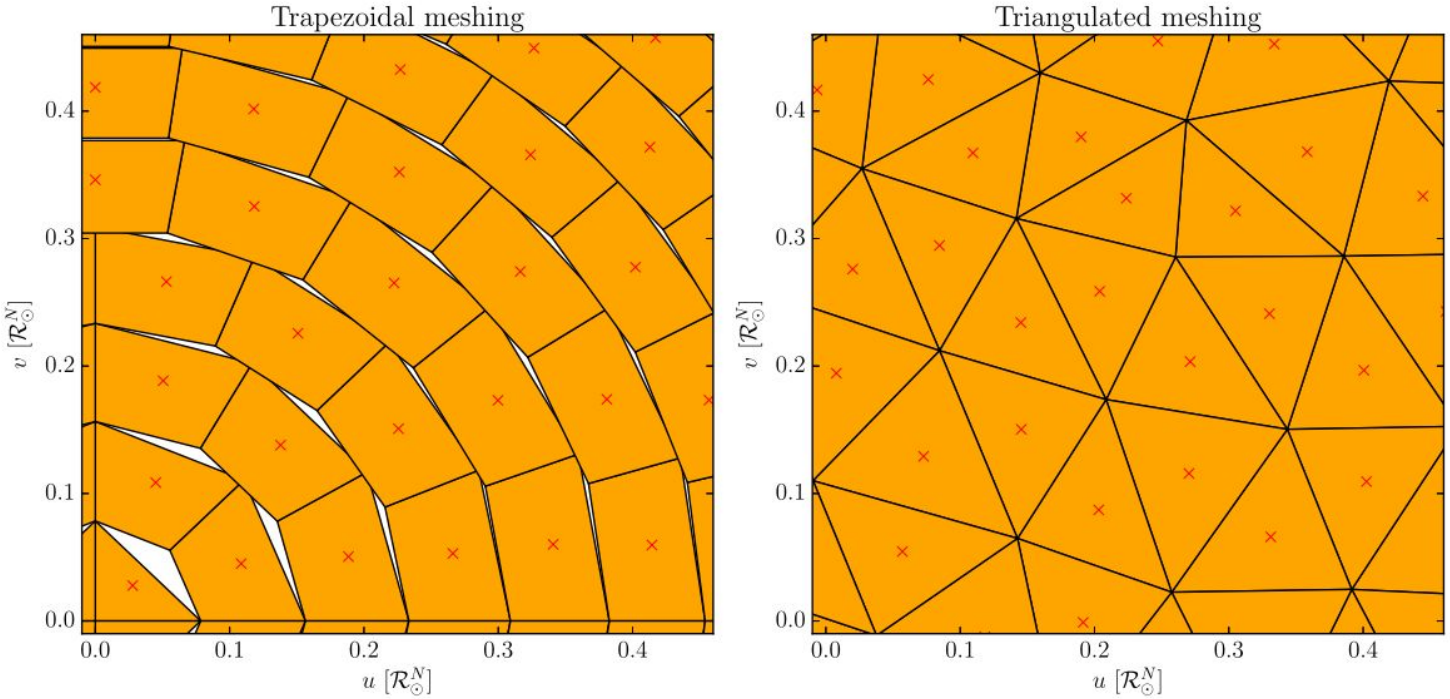
ELC (Jerry Orosz):

- up to 10 bodies
- “nested” only (with exception of double binary)
- UBVRIJHK passbands
- linear, logarithmic, and quadratic limb-darkening

lightcurvefactory (Tamas Borkovits)

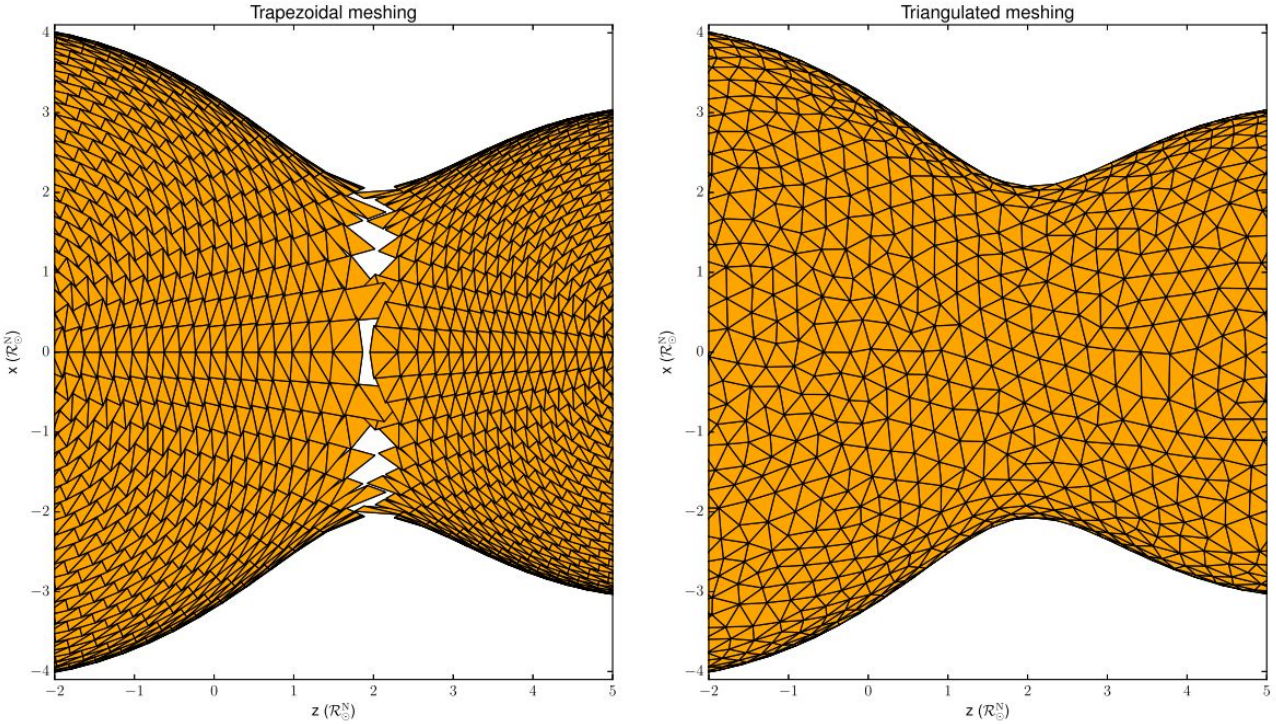
Cannot adequately model triples with tight inner-binaries!

PHOEBE's precision and advanced effects



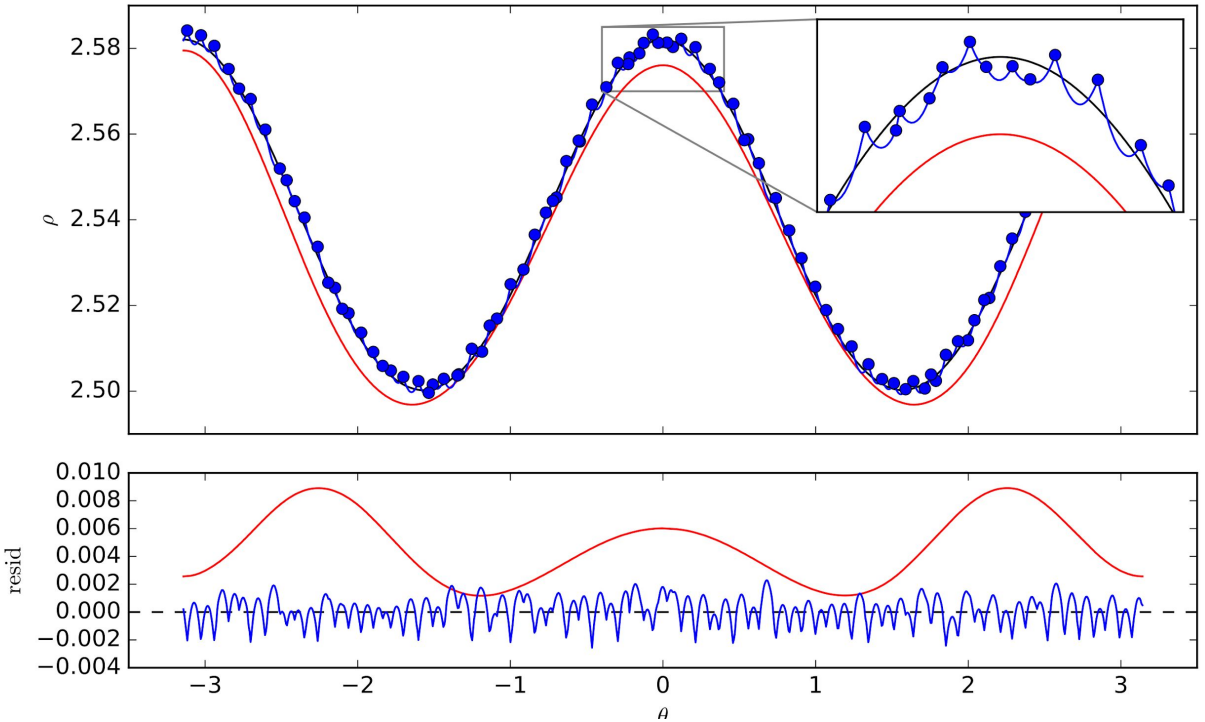
Prsa+ 2016

PHOEBE's precision and advanced effects



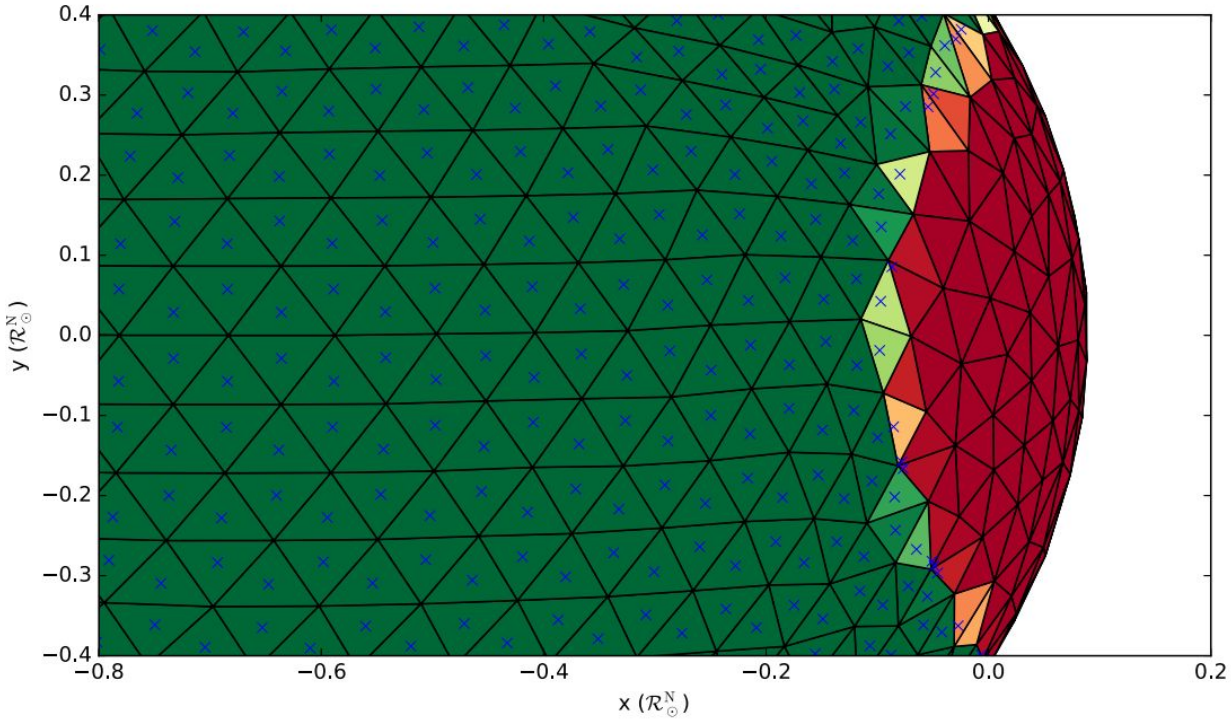
Prsa+ 2016

PHOEBE's precision and advanced effects



Prsa+ 2016

PHOEBE's precision and advanced effects



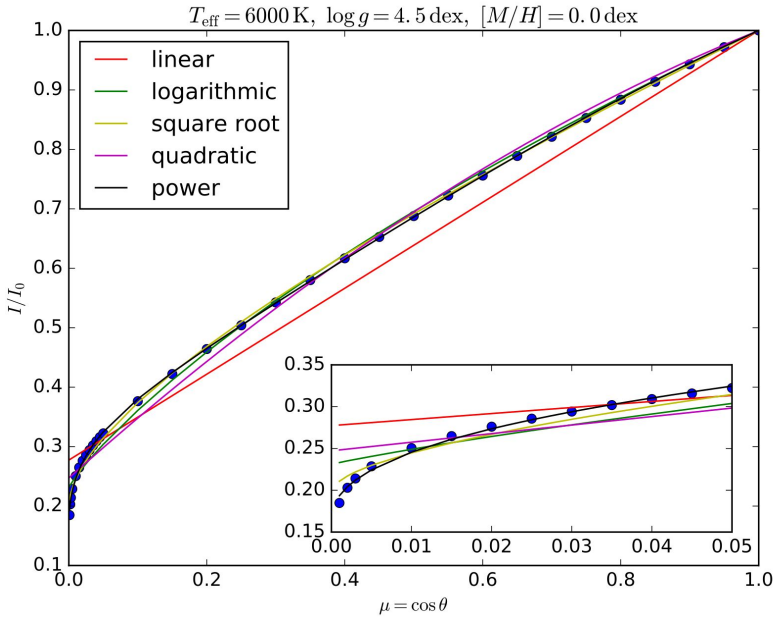
Prsa+ 2016

PHOEBE's precision and advanced effects

Atmospheres:

- Castelli-Kurucz or blackbody
- Interpolated or analytical limb-darkening
- ~50 passbands, including Kepler, LSST, TESS

- Doppler boosting
- Spin-orbit misalignment
- Irradiation with Lambert scattering



Prsa+ 2016

Support for “alternate backends”

All of these things come at a cost… **computational efficiency**

Goal:

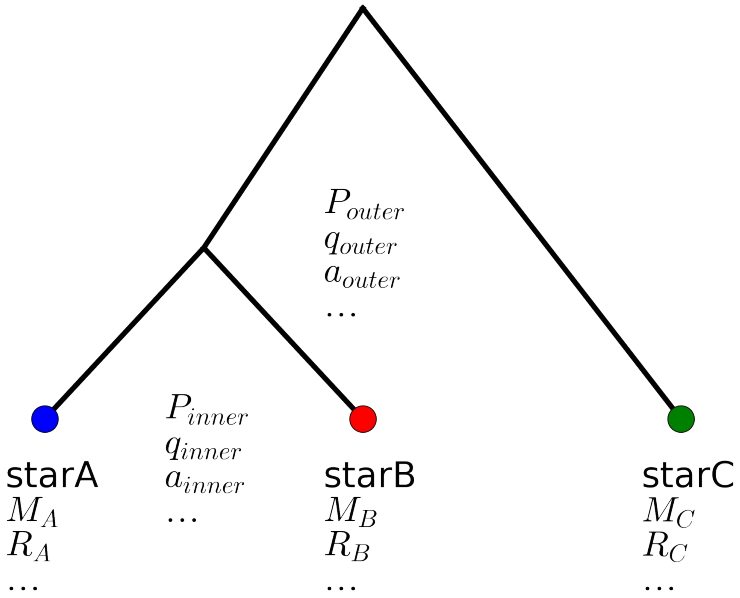
- support triples in PHOEBE to benefit from these high-precision (but expensive) effects
- continue to develop support for “alternate backends” to both compare models and to explore parameter space with “cheaper” codes before switching to more-expensive but hopefully more-robust treatment in PHOEBE

Considerations in applying to multiples

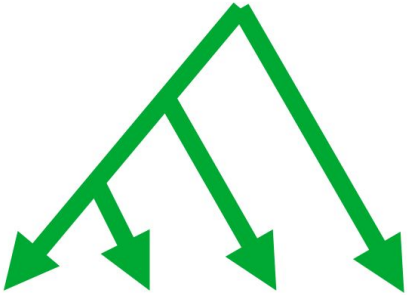
- Flexible hierarchies (1+2, 2+1, 2+2, etc)
- Treat dynamics as either hierarchical Keplerian orbits or fully dynamical via N-body treatment
- Account for tidal effects in dynamics???
- Allow for distortion effects (for both Keplerian and Nbody)
- Ability to model ETVs

Plan for supporting generic multiple hierarchies in PHOEBE

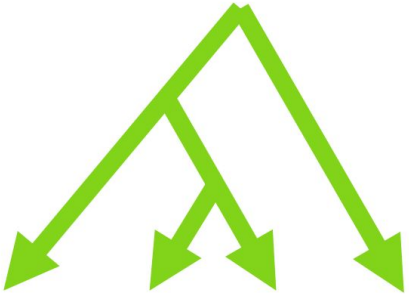
Hierarchy


P_{outer}
q_{outer}
a_{outer}
…
P_{inner}
q_{inner}
a_{inner}
…
starA
M_A
R_A
…
starB
M_B
R_B
…
starC
M_C
R_C
…

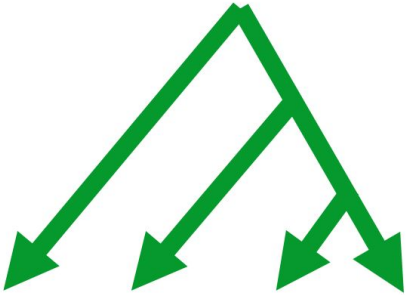
Hierarchy



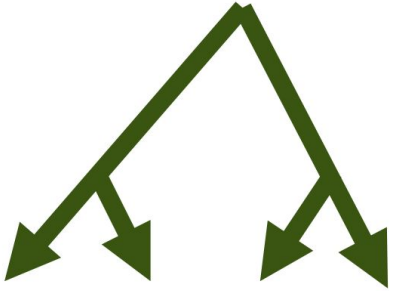
2+1+1



1+2+1



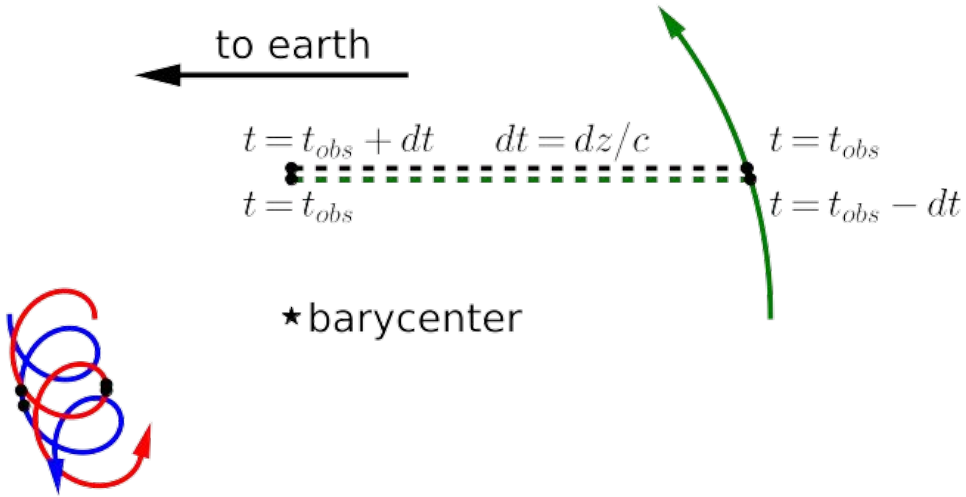
1+1+2



2+2

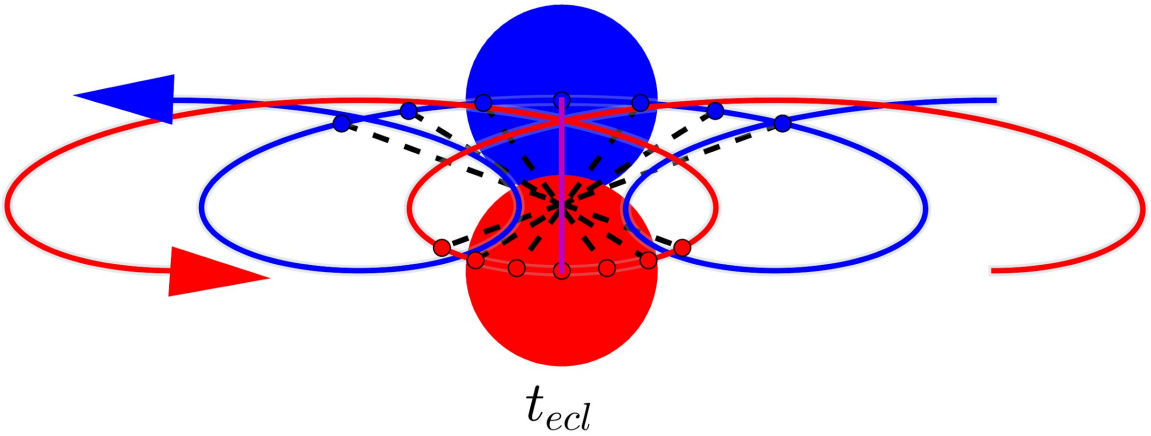
Dynamics

N-body **-or-** nested Keplerian orbits, with LTTE

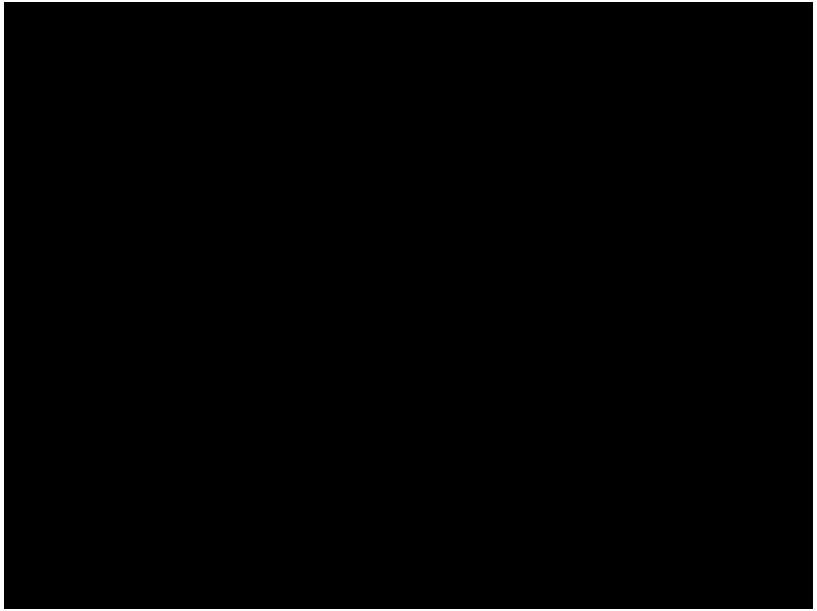


Numerical ETVs

Eclipse times determined by “crossing times” numerically without needing to simulate entire eclipse light curve.



Dynamical Distortion



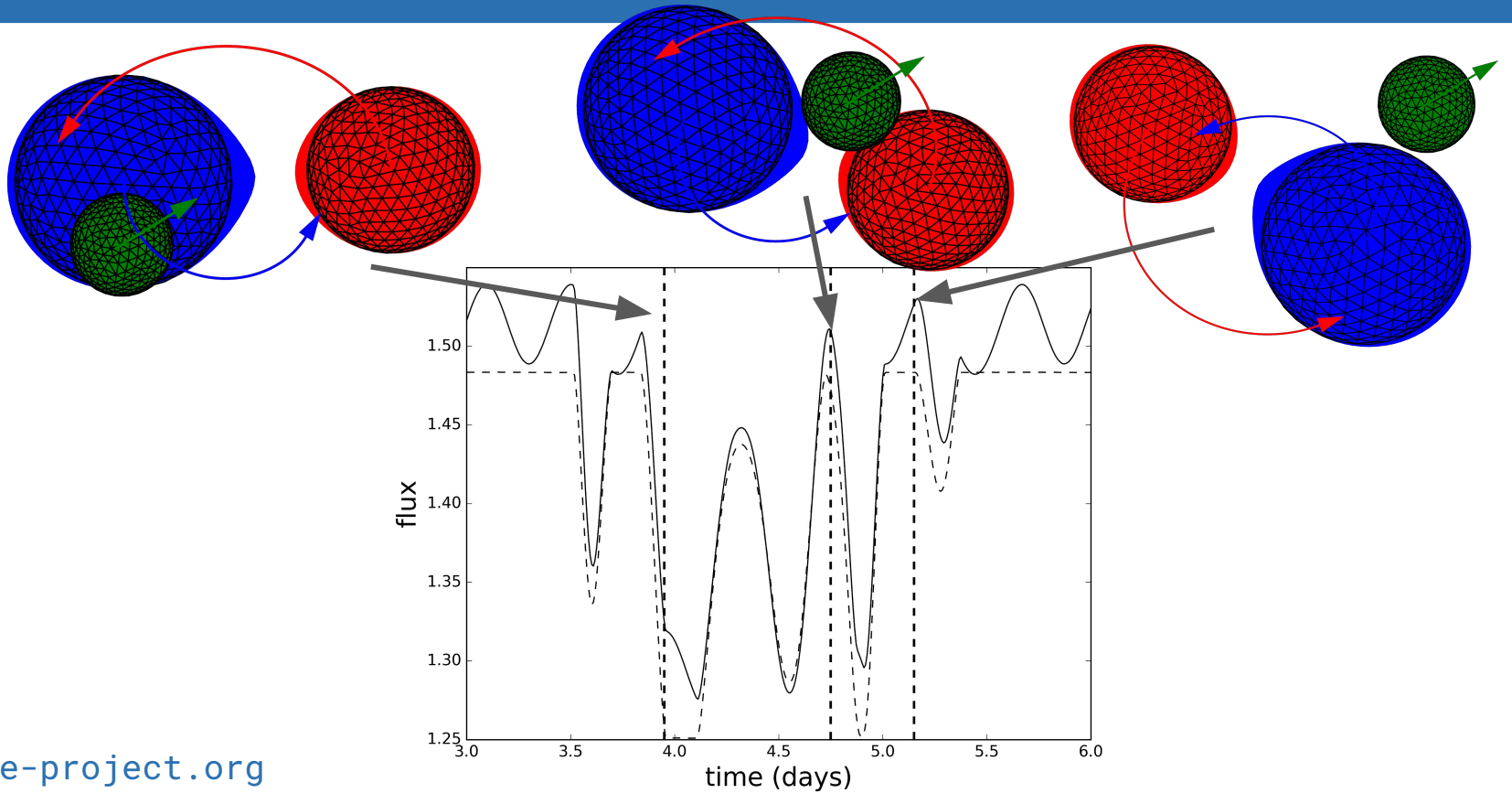
Fit an instantaneous Keplerian orbit to each star from Nbody positions & velocities.

- P (period)
- a (semi-major axis)
- e (eccentricity)

Then, compute instantaneous values for Roche parameters:

- q (mass-ratio, fixed)
- F (Porb / Prot, Prot is fixed)
- δ (instantaneous separation)
- Ω (volume fixed)

Dynamical Distortion



Summary

Once complete, PHOEBE will support a robust (but slow) treatment of triples with **dynamics**, tidal **distortion**, and **full atmosphere/passband** treatment.

Alternate backends will allow directly comparing multiple codes from a unified parameterization.

- Don’t need expensive treatment: use the fast model and compare against the full treatment to make sure assumptions don’t affect results.
- Otherwise: use the fast model to search parameter space and then switch to PHOEBE for final convergence.