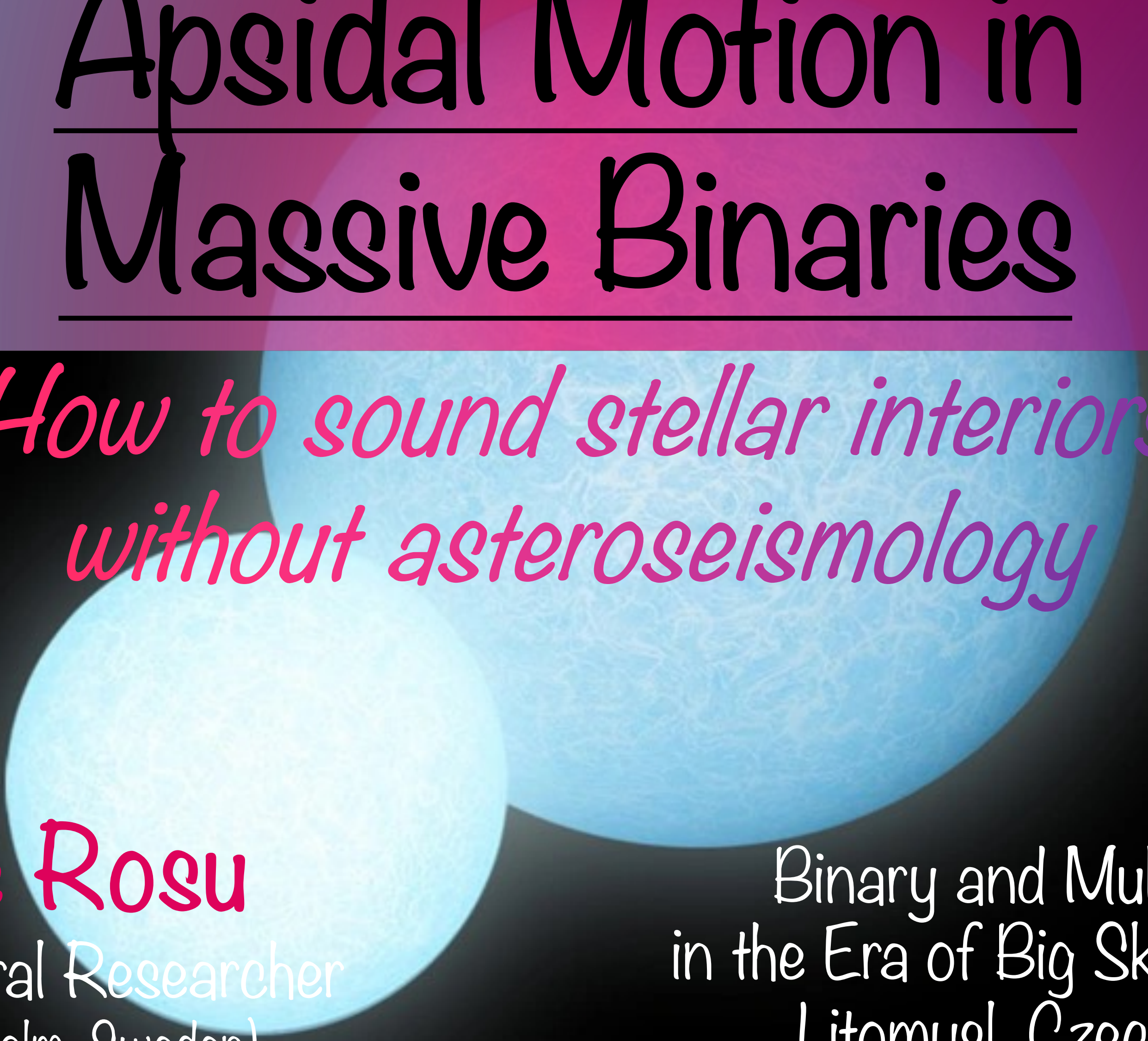
Apsidal Motion in Massive Binaries

How to sound stellar interiors without asteroseismology



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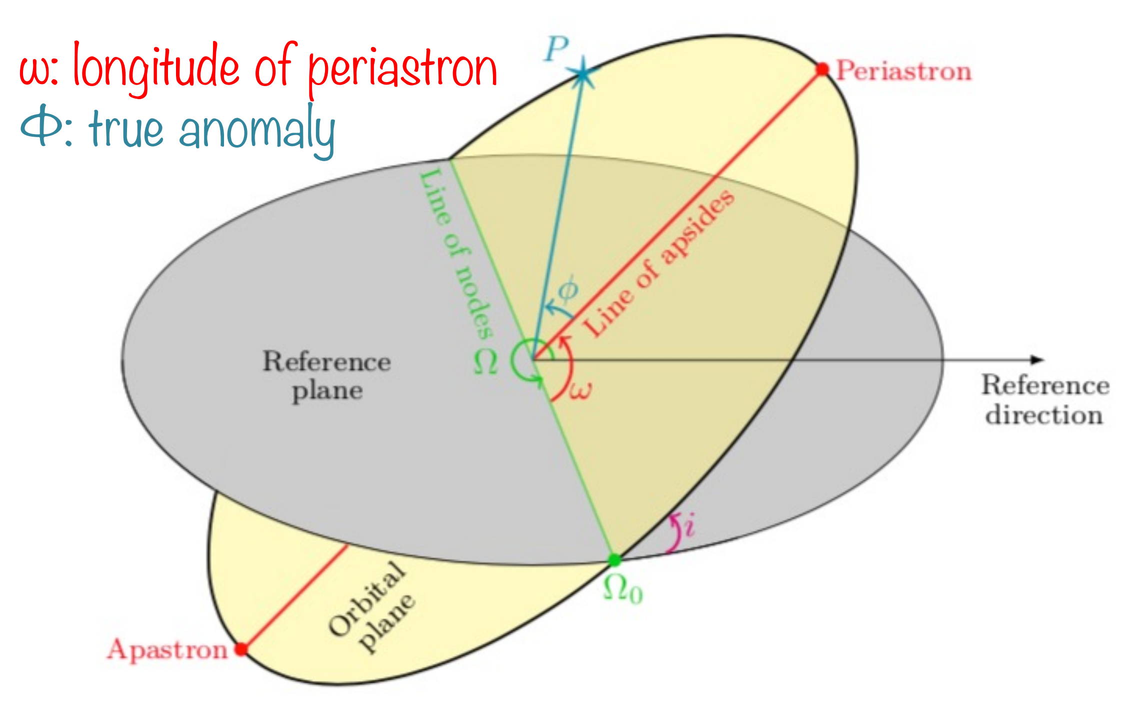
Binary and Multiple Stars
in the Era of Big Sky Surveys
Litomysl, Czech Republic
10th September 2024

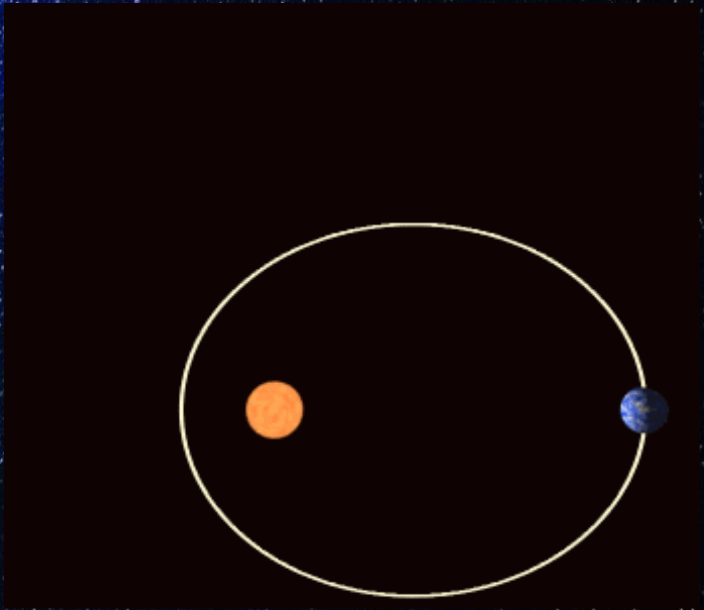
Apsidal Motion


ω: longitude of periastron
Φ: true anomaly

Tidal interactions
Exchange of angular momentum

Stellar deformations

Gravitational potential:
~~spherically symmetric~~

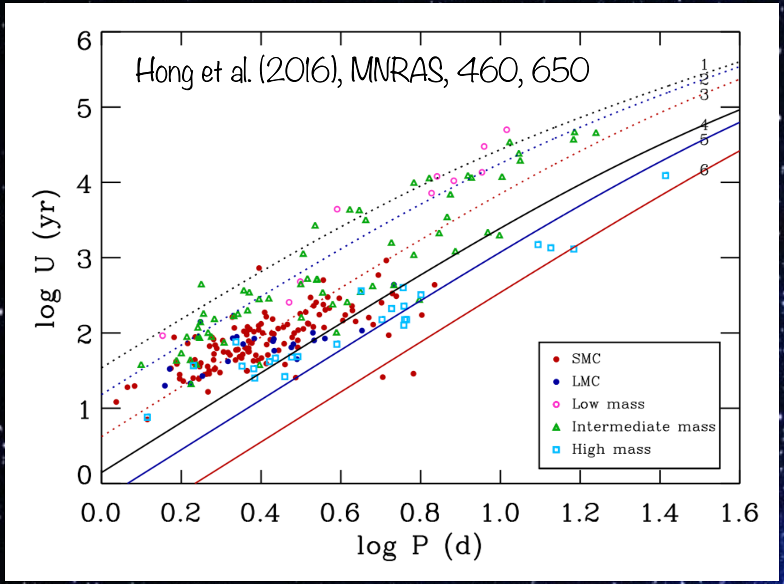


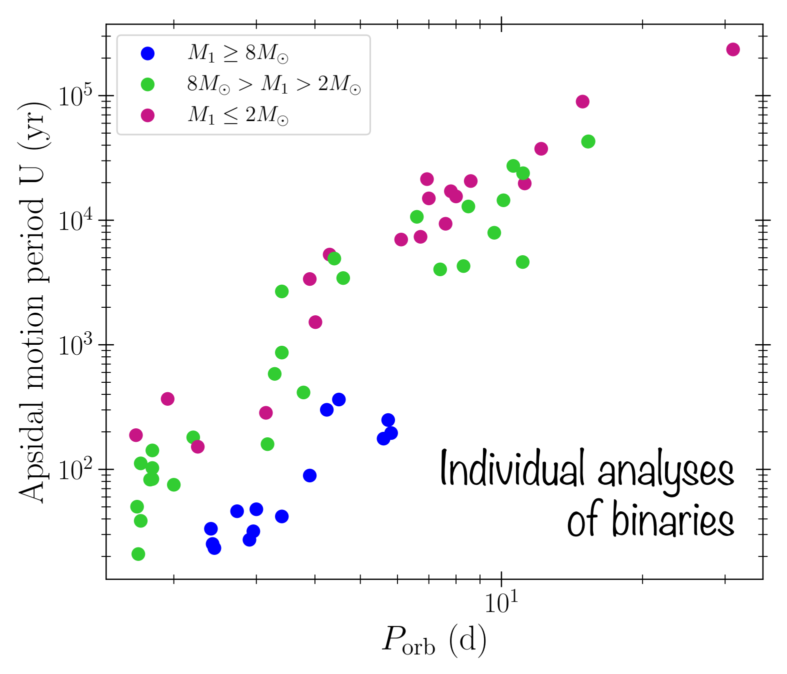
Rate: dω/dt

Slow motion: few °/yr

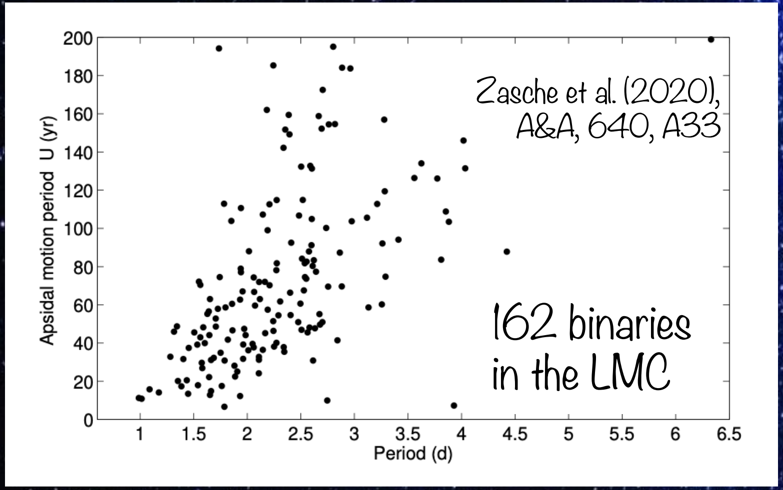
Non-Keplerian movement
(+ general relativistic contribution)

Is the apsidal motion observed and measured? YES!


Hong et al. (2016), MNRAS, 460, 650



Individual analyses of binaries


Zasche et al. (2020), A&A, 640, A33

162 binaries in the LMC

How?

Double-line spectroscopic binary
Eclipsing binary

Determination of dω/dt

Double-line spectroscopic binary

Amplitudes of the RV curves

Apparent systemic velocities

$$RV_p(t) = K_p\,[\cos(\Phi(t)+\omega(t)) + e\cos(\omega(t))] + \gamma_p$$

$$RV_s(t) = -K_s\,[\cos(\Phi(t)+\omega(t)) + e\cos(\omega(t))] + \gamma_s$$

Kepler's equation with P_{orb}, e, T_0

Eccentricity

With apsidal motion:

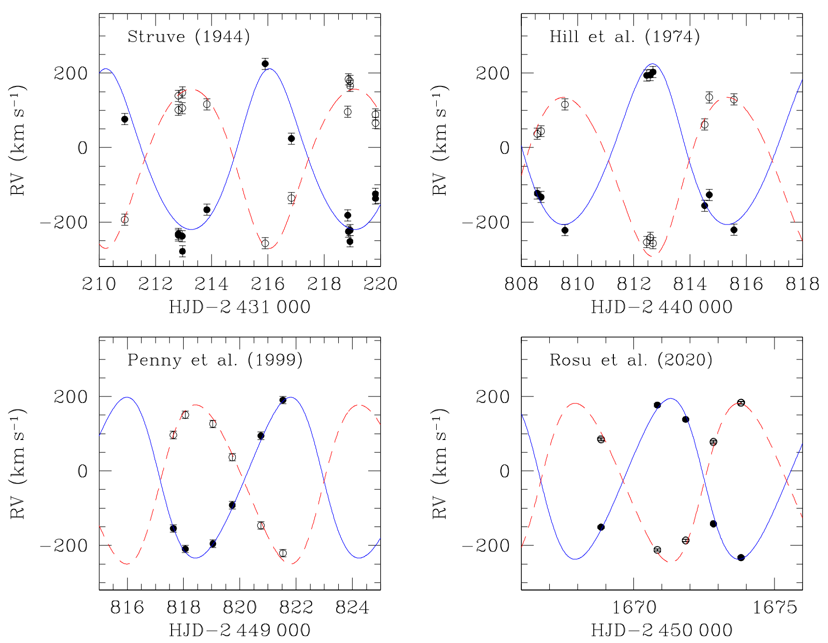
$$\omega(t) = \omega_0 + d\omega/dt\,(t - T_0)$$

Time of periastron passage

HD 152248

dω/dt = 1.84 ± 0.08 °/yr

Rosu et al. (2020), A&A, 635, A145



Determination of dω/dt

Eclipsing binary

If i < 90°:

Depth

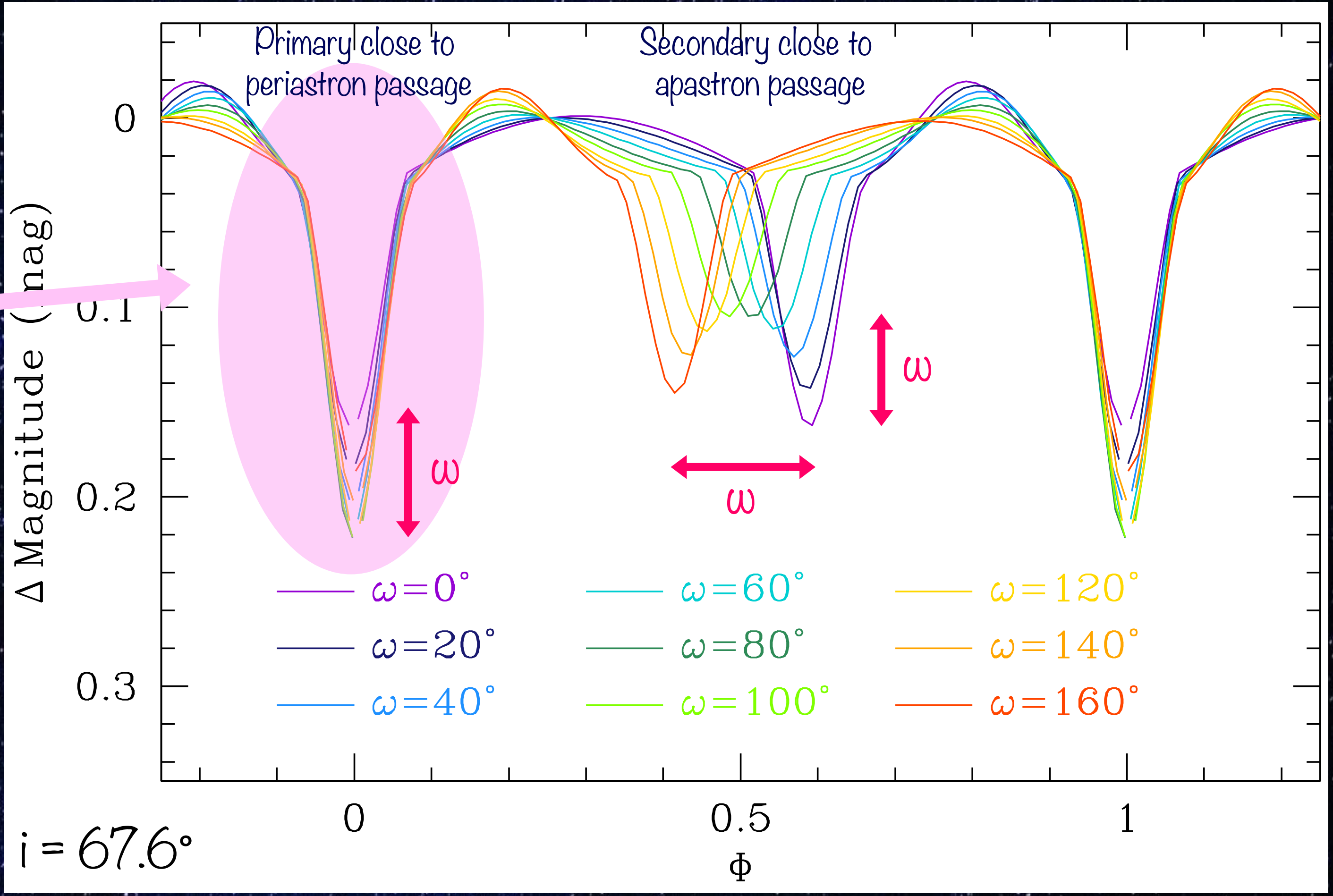
↑

Orbital separation at conjunction

↑

Orientation of ellipse w.r.t. line of sight (ω)

Deeper



HD 152248

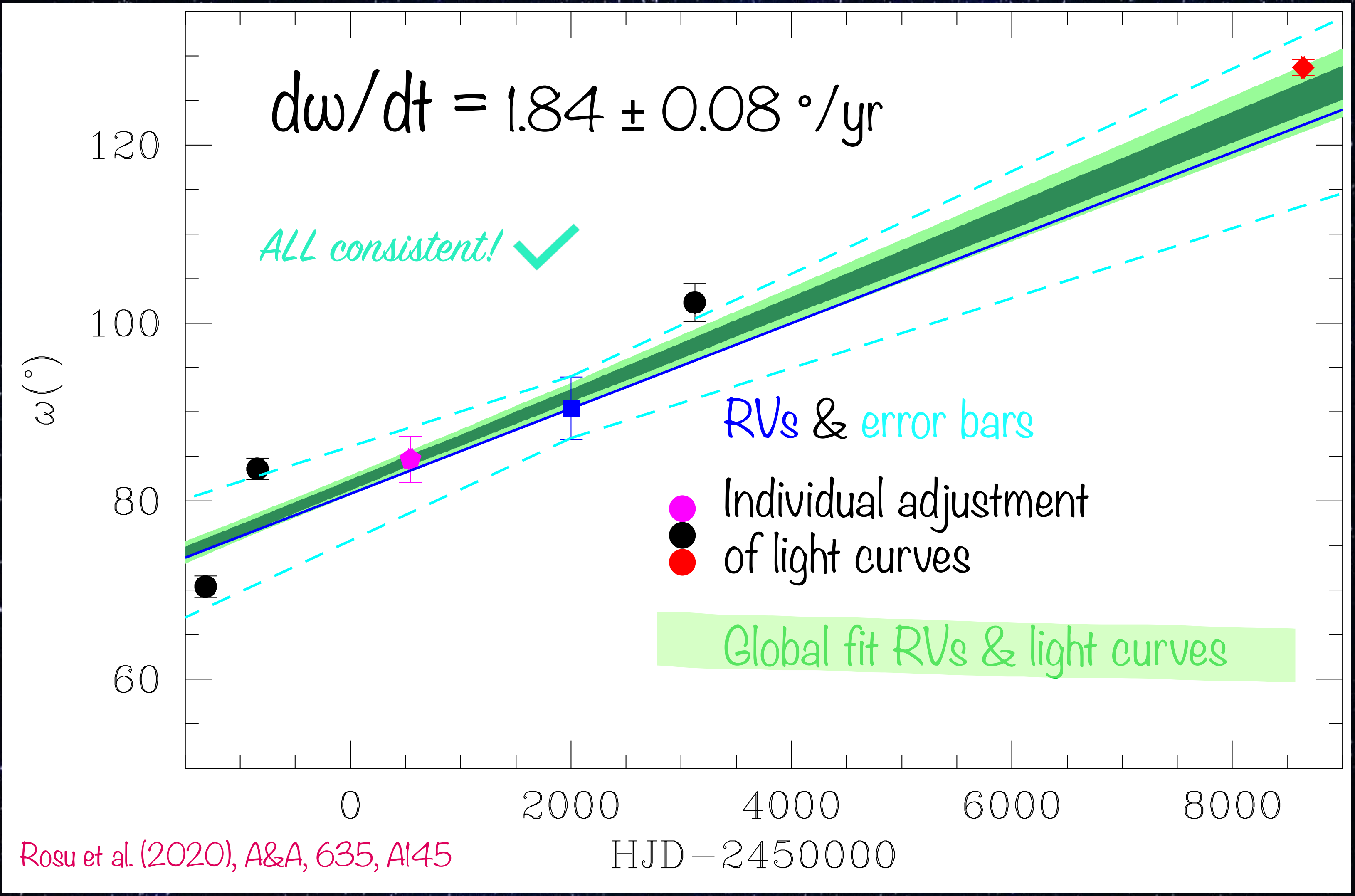
Twin system → All parameters identical

Rosu 2021, Bulletin de la Société Royale des Sciences de Liège, 90, 1

Determination of dω/dt

Spectroscopic + Eclipsing binary

HD 152248



$d\omega/dt = 1.84 \pm 0.08$ °/yr

ALL consistent! ✓

RVs & error bars

● ● ● Individual adjustment of light curves

Global fit RVs & light curves

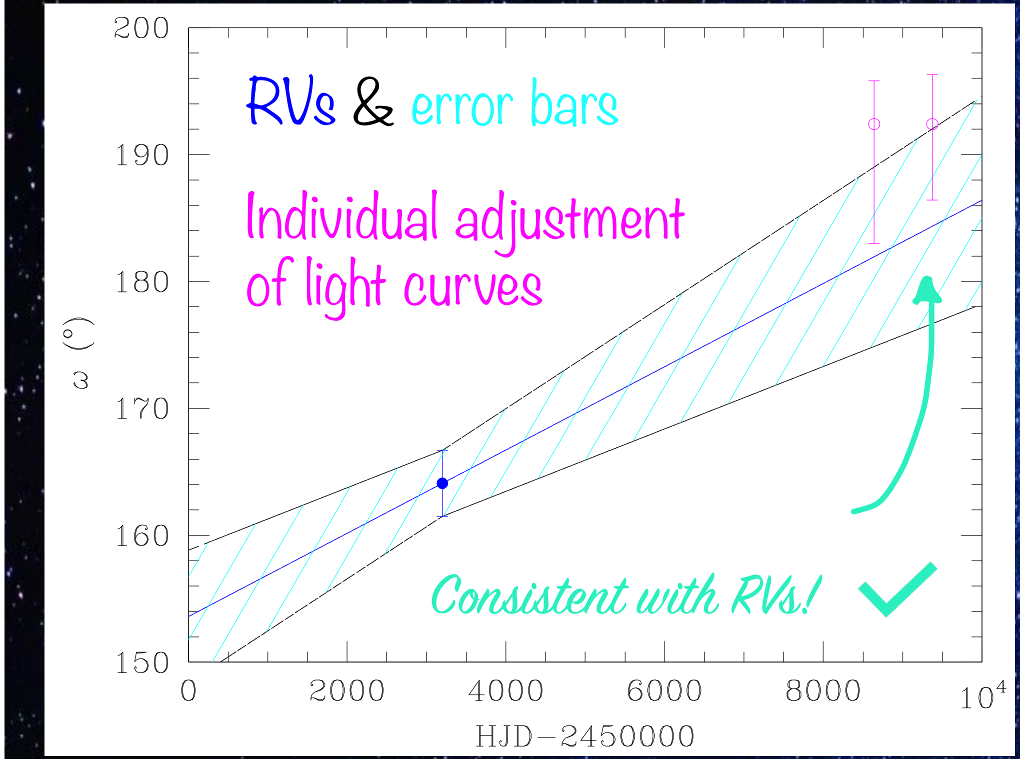
Rosu et al. (2020), A&A, 635, A145

Determination of dω/dt

Spectroscopic + Eclipsing binary

HD 152219

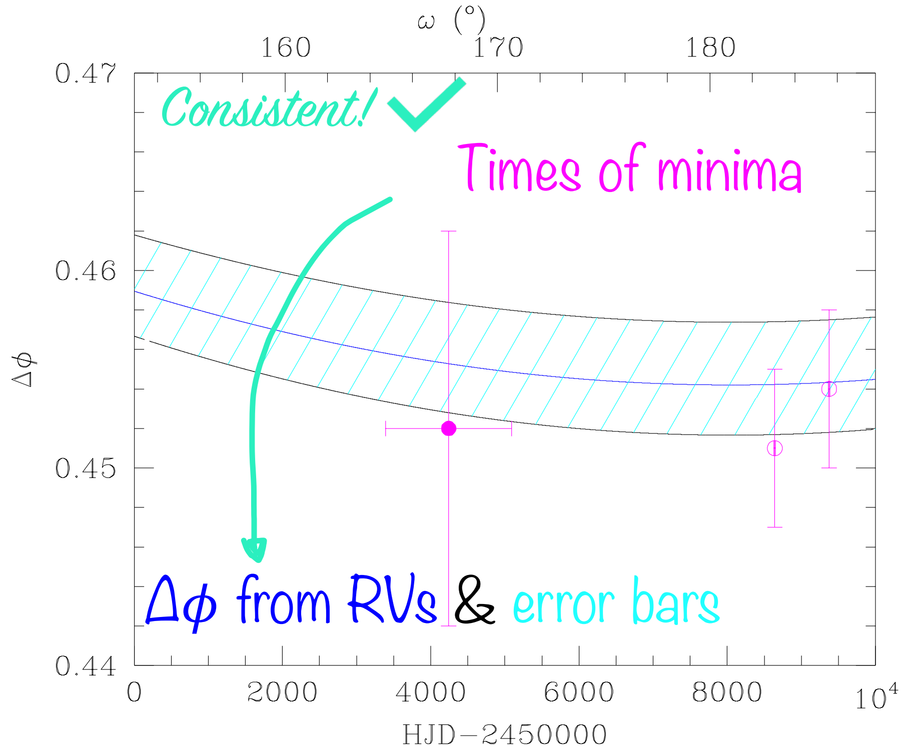
$d\omega/dt = 1.20 \pm 0.30$ °/yr



RVs & error bars

Individual adjustment of light curves

Consistent with RVs! ✓



Consistent! ✓

Times of minima

Δϕ from RVs & error bars

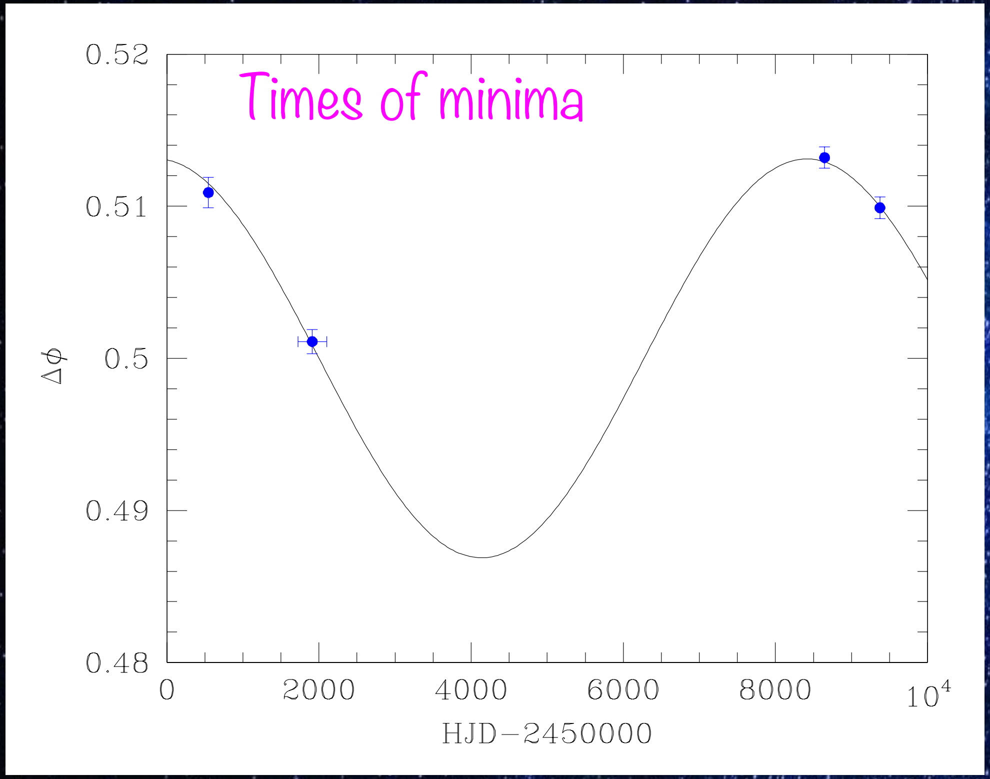
Rosu et al. (2022), A&A, 660, A120

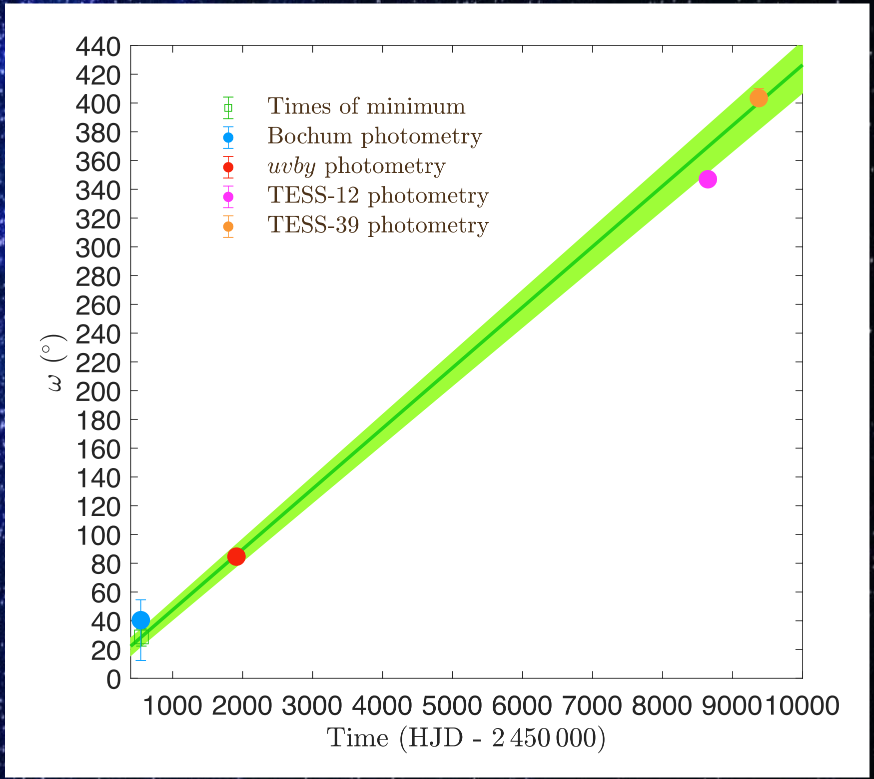
Determination of dω/dt

Spectroscopic + Eclipsing binary

CPD-41° 7742

$d\omega/dt = 15.38 \pm 0.51$ °/yr





Times of minima and individual light curves consistent! ✓

Rosu et al. (2022), A&A, 664, A98

> “One of the most reliable means of studying the stellar interior is through the apsidal motion in double line eclipsing binary systems”

- A. Claret, A&A, 674, A67 (2023)

Perturbative case

Apsidal motion equations

- ★ Total rate of apsidal motion

$$\dot{\omega} = \dot{\omega}_{\mathrm{N}} + \dot{\omega}_{\mathrm{GR}}$$

- ★ General relativistic contribution

$$\dot{\omega}_{\mathrm{GR}} = \left(\frac{2\pi}{P_{\mathrm{orb}}}\right)^{5/3} \frac{3(G(m_1+m_2))^{2/3}}{c^2(1-e^2)}$$

Sterne (1939), MNRAS, 99, 451

- ★ Newtonian contribution: tidal deformations & stellar rotation

$$\dot{\omega}_{\mathrm{N}} = \frac{2\pi}{P_{\mathrm{orb}}}\left[15 f(e)\left\{k_{2,1} q \left(\frac{R_1}{a}\right)^5 + \frac{k_{2,2}}{q}\left(\frac{R_2}{a}\right)^5\right\} + g(e)\left\{k_{2,1}(1+q)\left(\frac{R_1}{a}\right)^5\left(\frac{P_{\mathrm{orb}}}{P_{\mathrm{rot},1}}\right)^2 + k_{2,2}\frac{1+q}{q}\left(\frac{R_2}{a}\right)^5\left(\frac{P_{\mathrm{orb}}}{P_{\mathrm{rot},2}}\right)^2\right\}\right]$$

Shakura (1985), Sov. Astron. Lett., 11, 224

Stellar rotation axes perpendicular to orbital plane

Perturbative case

Internal stellar structure constant

$$k_2 = \frac{3 - \eta_2(R_*)}{4 + 2\eta_2(R_*)}$$

Hejlesen (1987), A&AS, 69, 251

★ Clairaut-Radau differential equation

Density at a distance r

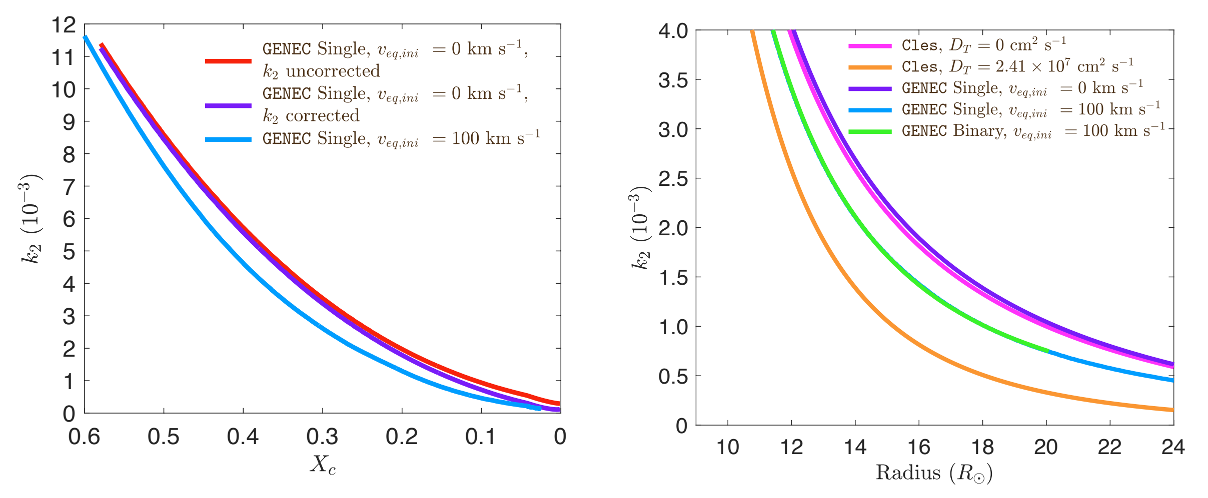
$$r\frac{d\eta_2(r)}{dr} + \eta_2^2(r) - \eta_2(r) + 6\frac{\rho(r)}{\bar{\rho}(r)}(\eta_2(r)+1) - 6 = 0$$

Distance from the centre

Mean density in sphere of radius r

Rosu et al. (2020), A&A, 642, A221

31 $M_\odot$

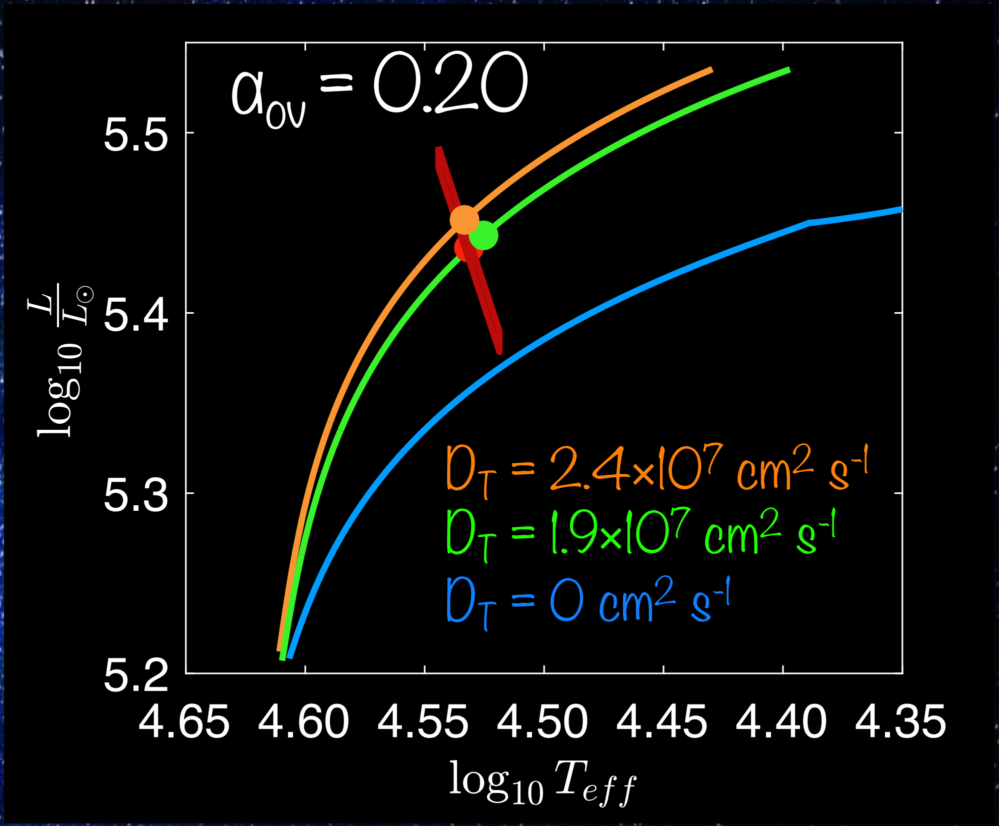


- Density stratification inside the star
- Decreases with time
- Good indicator of stellar evolution

Internal structure of massive stars

HD 152248

$M_\star = 29.5\ M_\odot$
$R_\star = 15\ R_\odot$
$d\omega/dt = 1.84°/yr$
$k_{2,\star} = 0.001$



Standard models:

Too high k_2
Too low density contrast

→ **Enhanced mixing**

Rosu et al. (2020), A&A, 642, A221

Internal structure of massive stars

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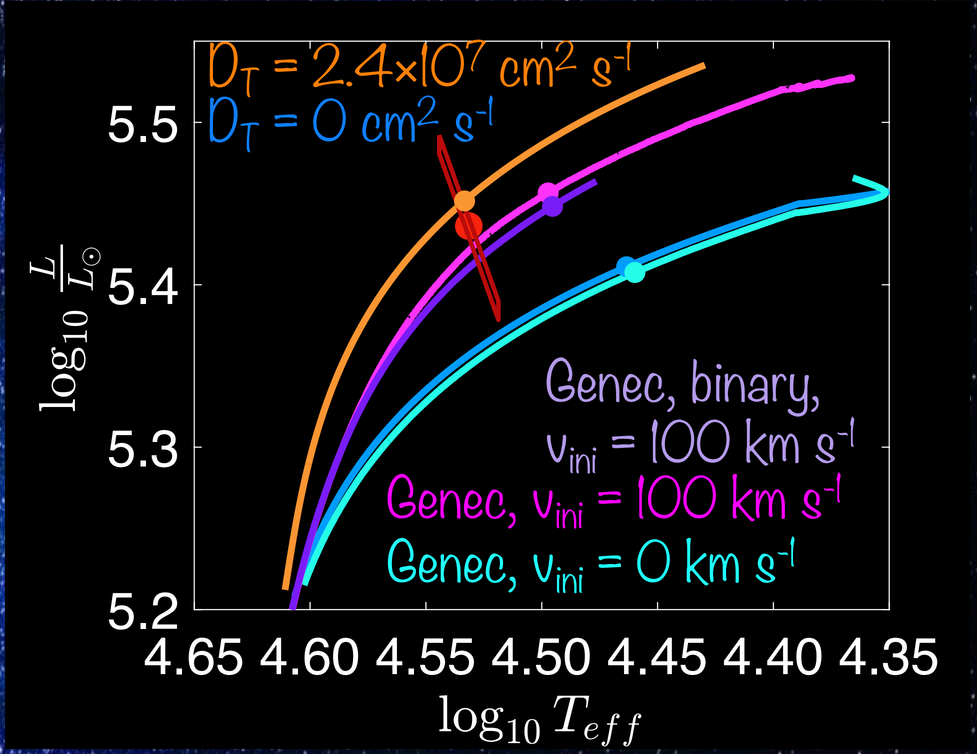


Standard models:

Too high k_2
Too low density contrast

→ **Enhanced mixing**

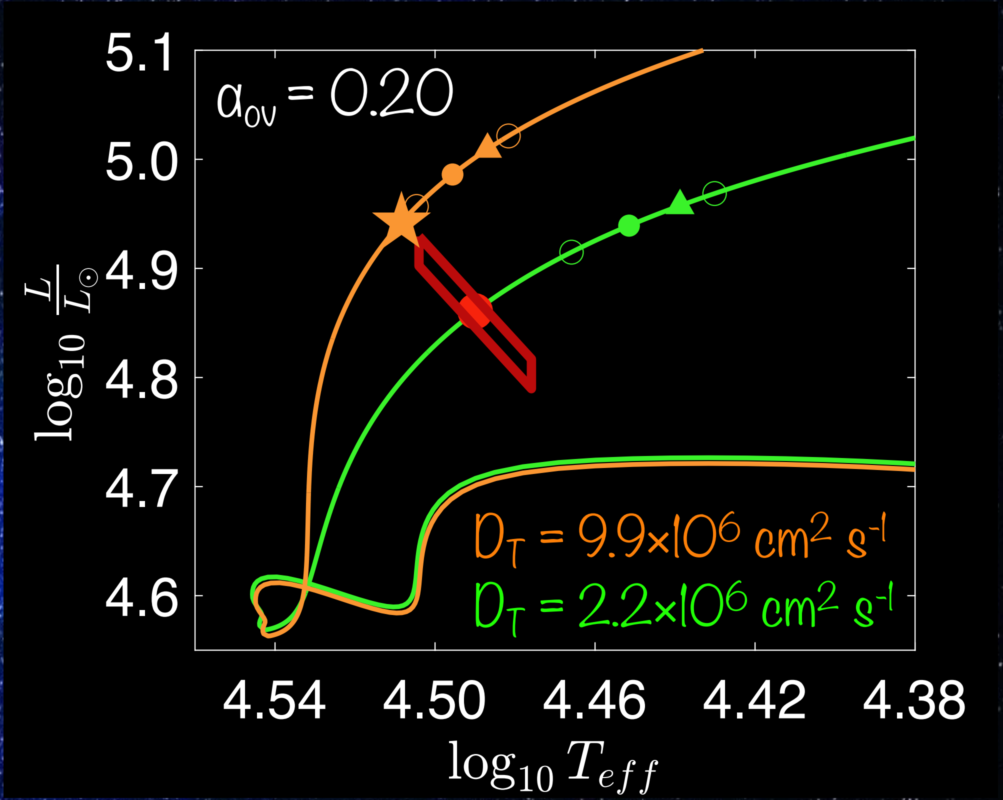
Turbulent diffusion
↕
Stellar rotation

Rosu et al. (2020), A&A, 642, A221

Internal structure of massive stars

HD 152219

$M_{\star 1} = 18.7\ M_\odot$
$R_{\star 1} = 9.7\ R_\odot$
$M_{\star 2} = 7.7\ M_\odot$
$R_{\star 2} = 4.3\ R_\odot$
$d\omega/dt = 1.20°/yr$
$k_{2,mean} = 0.0015$



Standard models:

Too high k_2, too low density contrast

→ **Enhanced mixing**

But not sufficient…

Rosu et al. (2022), A&A, 660, A120

Is that due to the inherent 1D stellar modelling?

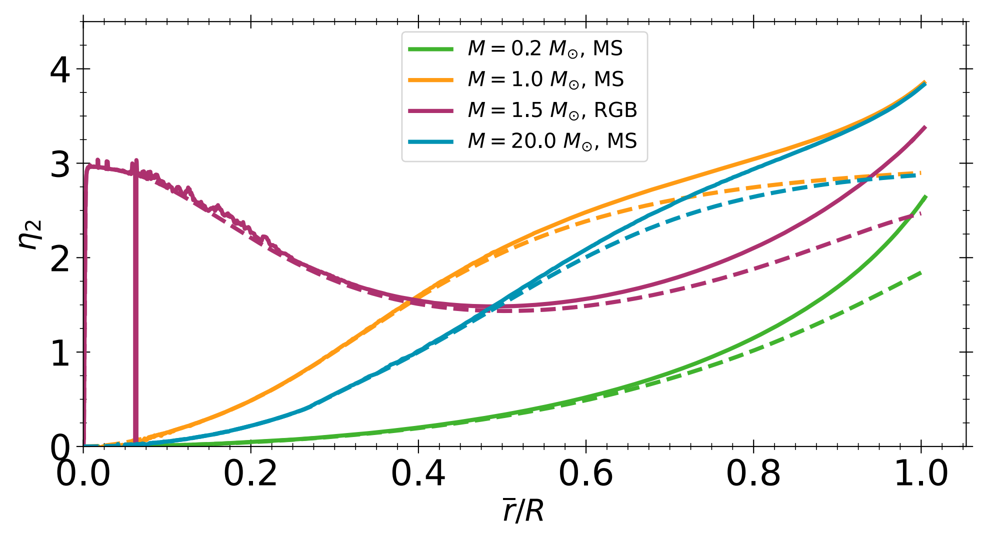
MoBiDICT code

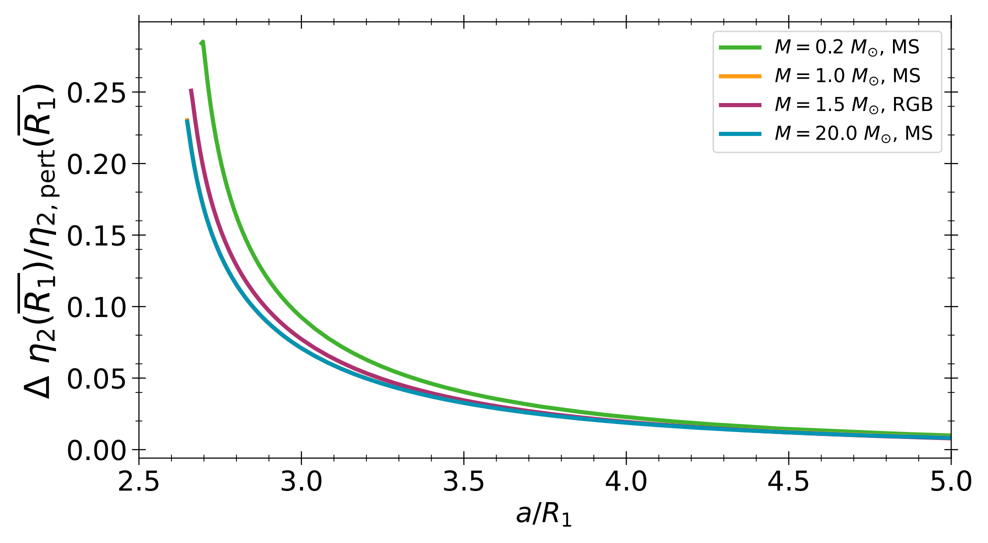
Modelling Binaries Deformations Induced by Centrifugal and Tidal forces
Non-perturbative method

- **Entire precise 3D structure** of each component
- Calculate **instantaneous tidal acceleration perturbation** and consequence on apsidal motion

Fellay & Dupret (2023), A&A, 676, A22

MoBiDICT: impact on η_2





$\Delta\eta_2$

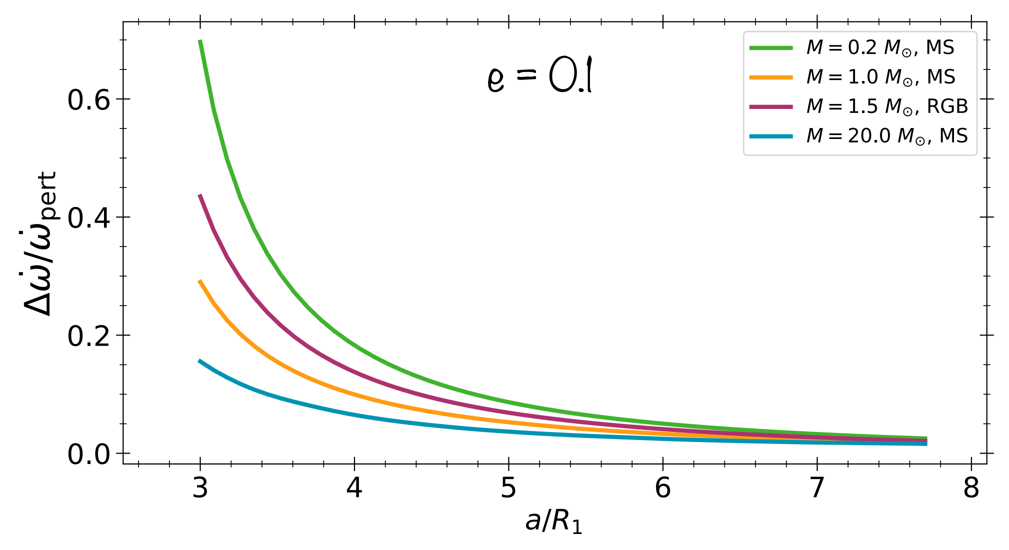
- Important for small orbital separation
- Almost independent of type of star

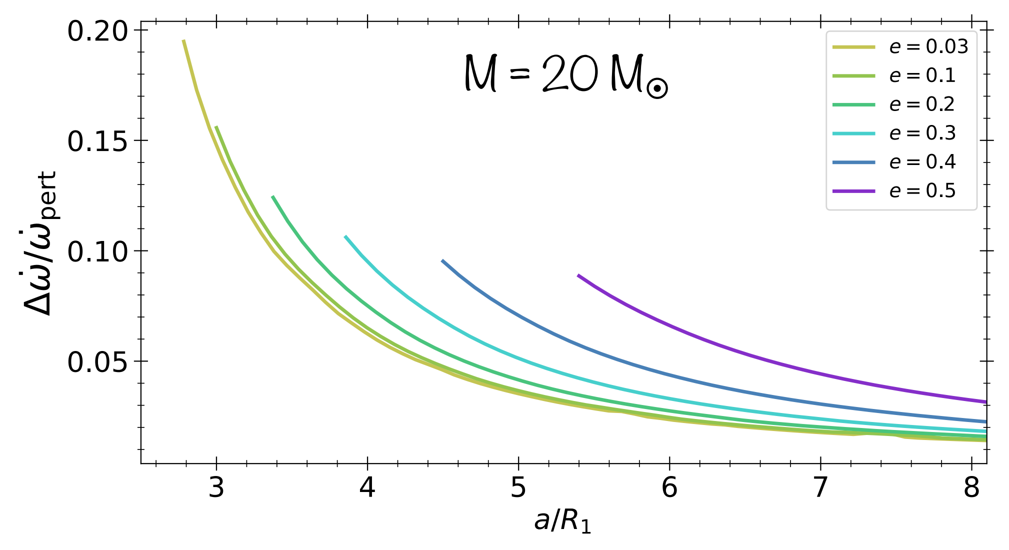
Direct impact on apsidal motion computation

Perturbative model assumption: not justified in high distortion cases (when $a < 5R_1$)

Fellay & Dupret (2023), A&A, 676, A22

MoBiDICT: theoretical apsidal motion

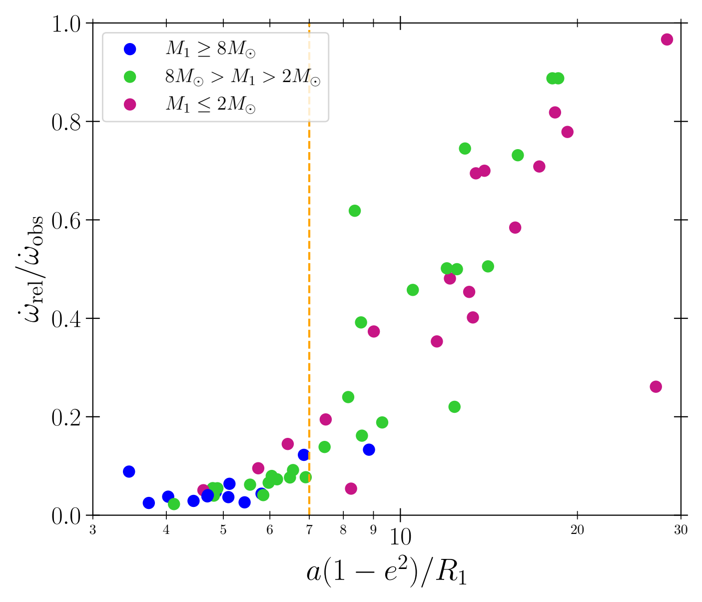




Fellay, Dupret, & Rosu (2024), A&A, 683, A210

Stars with highest M_{env}/M_{tot} are the most impacted

Perturbative model: underestimates apsidal motion when $a(1-e^2)/R_1 < 7$



MoBiDICT: still a lot of mixing…

Parameter	PV Cas	IM Per	Y Cyg	HD 152248
Mass ($M_\odot$)	2.78 ± 0.08	1.78 ± 0.01	17.72 ± 0.30	29.5 ± 0.5
P_{orb} (d)	1.78	2.25	3.00	5.82
a/R_1	4.80	4.60	4.95	3.47
Eccentricity	0.03	0.05	0.15	0.13
$d\omega/dt$ obs($^\circ$ yr^{-1})	4.35 ± 0.04	2.36 ± 0.06	7.54 ± 0.04	1.84 ± 0.08
α_{ov} (perturbatif) α_{ov} (MoBiDICT)	0.92 0.95	0.31 0.33	1.01 1.05	1.29 1.28
$d\omega/dt$ GR ($^\circ$ yr^{-1})	0.25	0.11	0.35	0.16
$d\omega/dt$ pert ($^\circ$ yr^{-1})	4.00	2.12	6.89	1.58
Δ $d\omega/dt$ non-pert ($^\circ$ yr^{-1})	0.17	0.13	0.30	0.11

Fellay, Dupret, & Rosu (2024), A&A, 683, A210

Take-away Message

Apsidal motion
(+ stellar and binary properties)

→ **Probe the interior of stars**

Double-line spectroscopic and/or eclipsing binary

↗ #Systems

Standard stellar evolution models

Too low density contrast
→ Enhanced mixing
Tidal interactions? MoBiDICT code

Supported by 2D hydrodynamical simulations of Baraffe et al. (2023), MNRAS, 519, 5333 of individual binaries and to reproduce the main-sequence width

In agreement with
Castro et al. (2014), A&A, 570, L13
Martinet et al. (2021), A&A, 648, A126

Thank you for your attention!!