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Low-mass Contact Close Binary Systems and Their Stability

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- **Stellar mergers** are usually associated with compact binary systems – close binaries in which both components are **compact objects** (the final phases of stellar evolution): white dwarfs (WD), neutron stars (NS) and black holes (BH)

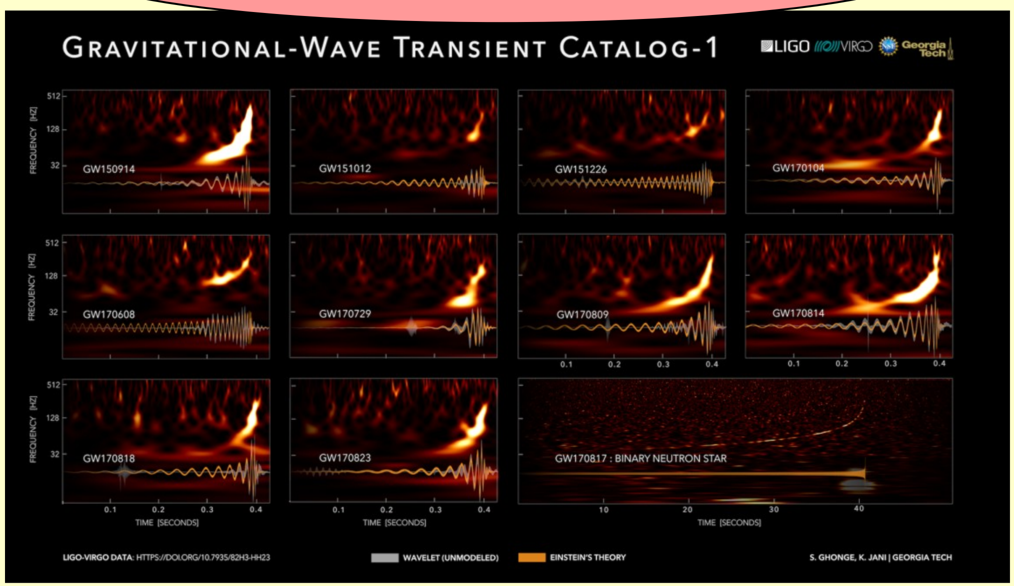
- Known systems: WD+WD, WD+NS, NS+NS

- Detection of systems: WD+BH, NS+BH i BH+BH ?

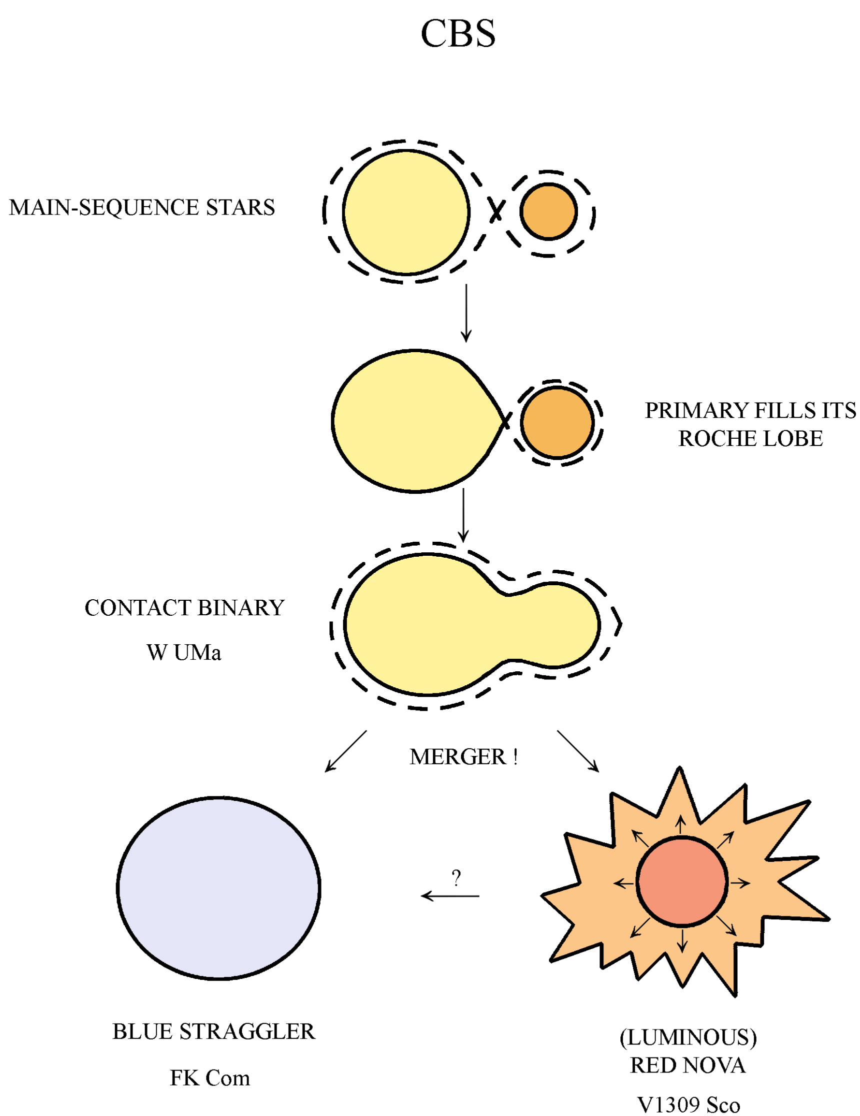
Short gamma-ray bursts

Alternative model for type Ia SNe

Gravitatational waves

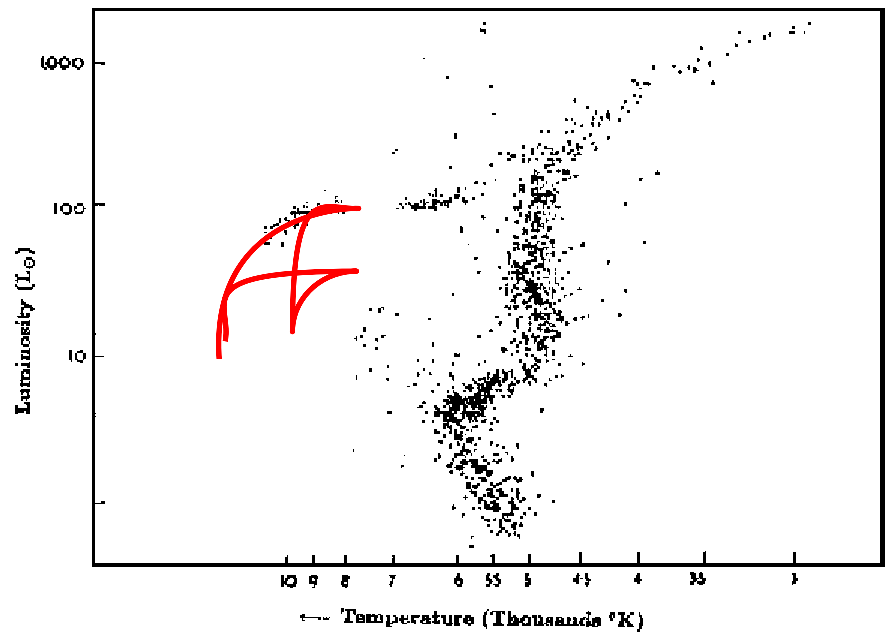


- **But mergers can also happen with "normal stars"**



- blue stragglers

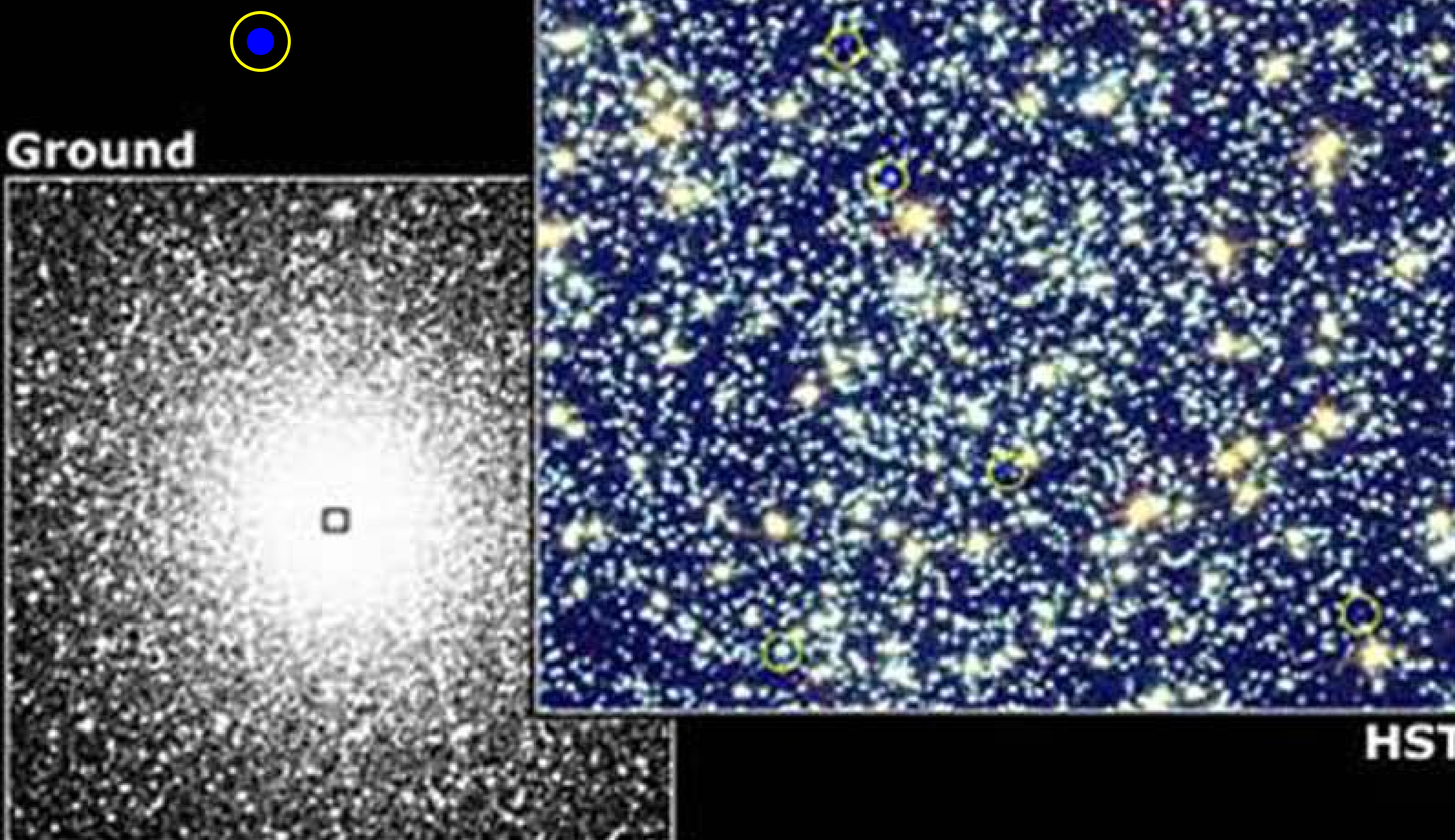
Globular cluster M3



- alternatively (or predominantly) blue stragglers in old open clusters may form via mass-transfer from an AGB or RGB companion (Leiner et al. 2019, 2021)

- direct collisions?

Blue stragglers



Interesting systems

V838 Mon

- atypical nova, (luminous) red nova?

- the eruption on a main sequence B stars in a close binary orbit with another B star, resulting in a cool (L-type) supergiant, $L \sim 10^4$ *Lo*, $R \sim 10^3$ *Ro*

- *e*volution of light echo

- merger in a triple system (Kaminski et al. 2021)

V1309 Sco

- red nova, OGLE observations 2001 – 2008 (outburst)

- Roseta stone of contact binary mergers (Tylenda et al. 2011)

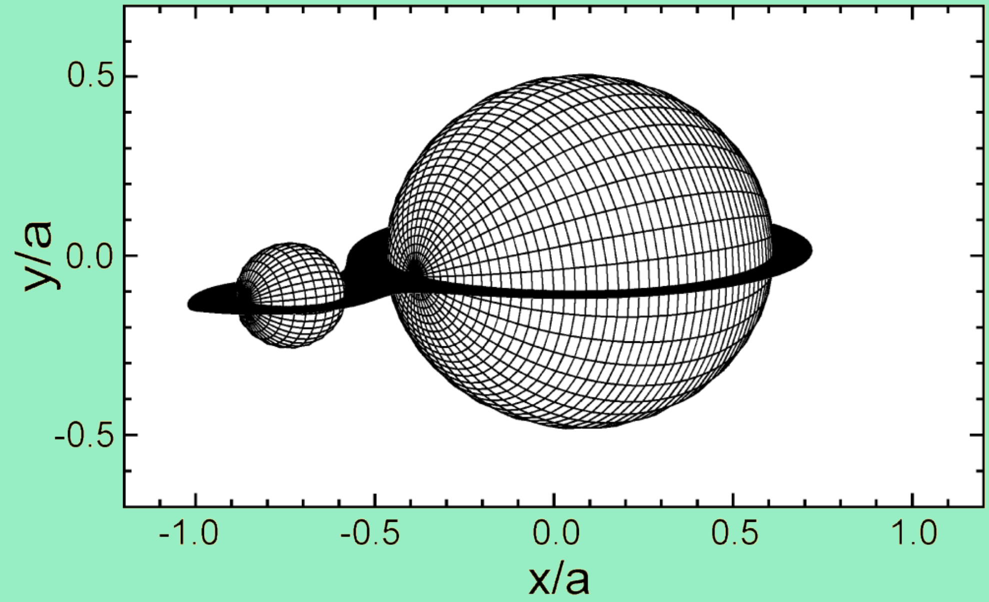
- K-type progenitor, initial period of 1.4 d with exponential decay $P \sim \exp(\tau/(t-t_0)$

- search for similar systems (Kurtenkov 2017, Wadhwa et al. 2021, 2022a,b, Lee et al. 2022)

Interesting systems

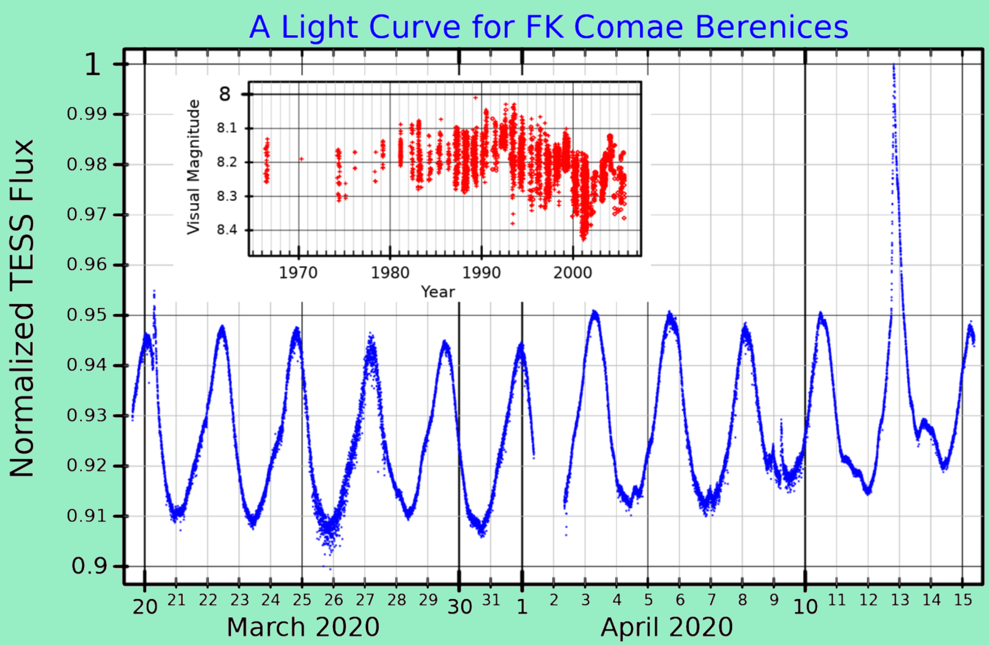
AW UMa

- Paczyncki's star, discovered in 1964
- Extremely low mass ratio q=0.075 (Rucinski 1992)
- Pribulla & Rucinski (2008) find higher mass ratio q = 0.1 and suggest that AW UMa may not be a contact binary?



FK Com

- Prototype of a class of variables
- A giant (G4 III) with large cool spots, unusually fast rotation and magnetic activity
- May be the result of of merger of a W UMa- type contact binary (Ayres et al. 2016 and ref. therein)
- long term variability (Panov & Dimitrov 2007)



CBs of W UMa-type

- contact systems

- Roche model:

$$\Phi_{eff} = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \tfrac{1}{2}\Omega^2 R$$

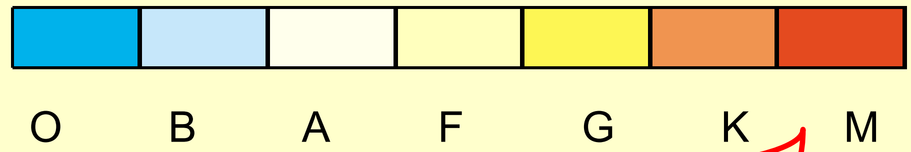
$$\Omega^2 = \frac{G(M_1 + M_2)}{a^3}$$

- spectral type: late F-K

- common convective envelope, nearly equal temperatures (although $q = M_2/M_1 \sim 0.5$)

- two sub-types: A and W

- primary components seems to be normal MS stars, secondaries are oversized for their ZAMS masses, and can be found *left* from the main-sequence (see e.g. Hilditch 2001)

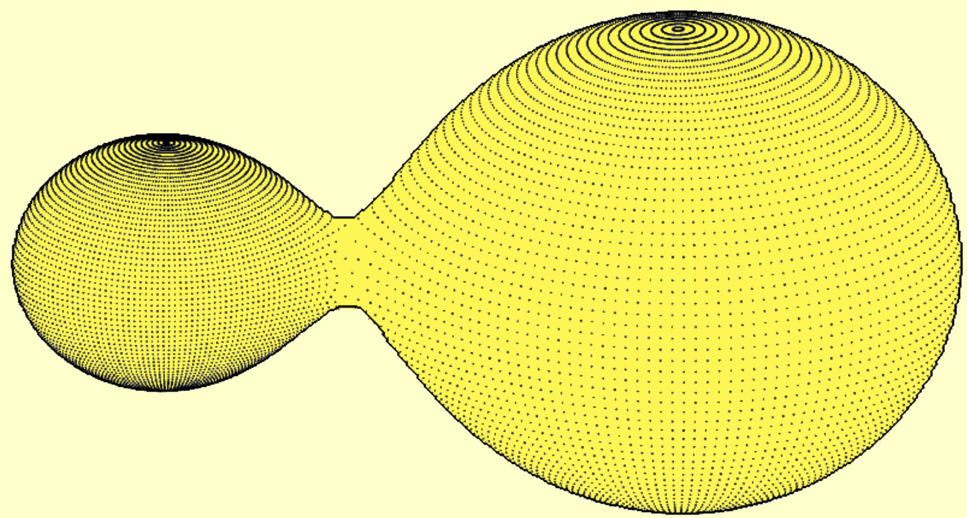


- critical equipotential surfaces (*Roche lobes*):

$$\Phi_{IL}, \Phi_{OL}$$

- degree of contact *(overcontact degree):*

$$f = \frac{\Phi - \Phi_{IL}}{\Phi_{OL} - \Phi_{IL}}$$



Dynamical evolution

- driven presumably by angular momentum loss (AML)

- magnetic activity, starspots, magnetized stellar wind

- secular, tidal or Darwin instability

Sir George Howard Darwin (1845-1912)

- tidal forces → circulization and synchronization

- if the timescale for the synchronization is smaller that the AML timescale, system will remain synchronized and orbit will shrink until, at some critical separation, the instability sets in

- rotational and orbital angular momentum become comparable

- instability condition: $d\,J_{tot} = 0$ ($J_{orb} = 3\,J_{spin}$) (Rasio 1995, Rasio & Shapiro 1995)

- MERGER!

W UMa → blue stragglers (Stepien & Kiraga 2015)

- a significant number of W UMa-type binary systems among blue stragglers in open and globular clusters (Kaluzny & Shara 1988).

The minimum mass ratio for W UMa-type CBs

$$J_{\rm spin} = k_1^2 M_1 R_1^2 \Omega + k_2^2 M_2 R_2^2 \Omega$$

$$J_{\rm orb} = \mu a^2 \Omega = \frac{q\sqrt{GM^3 a}}{(1+q)^2}$$

$$\mu = M_1 M_2 / M,\ M = M_1 + M_2,\ q = M_2/M_1$$

$$J_{\rm tot} = J_{\rm orb} + J_{\rm spin}$$

$$\mathrm{d}J_{\rm tot} = 0 \qquad J_{\rm orb} = 3J_{\rm spin}$$

$$\frac{a_{\rm inst}}{R_1} = k_1 \sqrt{\frac{3(1+q)}{q}}$$ - critical separation (Rasio 1995)

- k is dimensionless gyration radius which depends on the density distribution (for homogenous sphere $k^2 = 2/5$)

$$n = 3 \quad (\Gamma_1 = 4/3),\ k^2 \approx 0.075$$

$$n = 1.5 \quad (\Gamma_1 = 5/3),\ k^2 \approx 0.205$$

- Sun $\quad k_\odot^2 = 0.059 \approx 0.06$

$$\frac{R_{{\rm IL}i}}{a} = \begin{cases} \frac{0.49q^{-2/3}}{0.6q^{-2/3}+\ln(1+q^{-1/3})}, & i=1 \\ \frac{0.49q^{2/3}}{0.6q^{2/3}+\ln(1+q^{1/3})}, & i=2, \end{cases}$$

$$\frac{R_{{\rm OL}i}}{a} = \begin{cases} \frac{0.49q^{-2/3}+0.15}{0.6q^{-2/3}+\ln(1+q^{-1/3})}, & i=1 \\ \frac{0.49q^{2/3}+0.27q-0.12q^{4/3}}{0.6q^{2/3}+\ln(1+q^{1/3})}, & i=2. \end{cases}$$

(Eggleton 1983, Yakut & Eggleton 2005)

- $q_{\rm min}$ = 0.085-0.095

- AW UMa, q = 0.075

(Paczynski 1964,
Rucinski 1992,
Pribulla & Rucinski 2008)

- contribution of the rotational AM of the secondary (Li & Zhang 2006, Arbutina 2007)

$$R_2 = R_2(R_1, a, q) \qquad k_1^2 \neq k_2^2$$

- $q_{\rm min}$ = 0.094-0.109

- deformation of the primary due to rotation and companion – nonzero quadrupole moment – "apsidal motion constant" ratio (Arbutina 2009)

$$J_{\rm orb} = \mu a^2 \Omega \qquad J_{\rm spin} = k_1^2 M_1 R_1^2 \Omega + \frac{2}{3}\left(\frac{\Omega^2}{3G} + \frac{M_2}{2a^3}\right)\tilde{A}_1 \Omega \qquad \tilde{A}_1 = \frac{R_1^5 \tilde{Q}_1}{1-\tilde{Q}_1}, \qquad k_{\rm AM} = \frac{1}{2}\frac{\tilde{Q}}{1-\tilde{Q}}$$

$$\Omega^2 = \frac{GM}{a^3}\left(1 + \frac{\tilde{A}_1 \omega_1^2}{2GM_1 a^2} + \frac{3\tilde{A}_1 M_2}{M_1 a^5} + \frac{\tilde{A}_2 \omega_2^2}{2GM_2 a^2} + \frac{3\tilde{A}_2 M_1}{M_2 a^5} + \frac{3GM}{c^2 a}\right), \qquad \omega_1 = \omega_2 = \Omega$$

- $q_{\rm min}$ = 0.091-0.103 $\quad k_{\rm AM} \approx 0.015$

- structure of the primary (k depends on the central condensation)

$$\rho \nabla \Phi_{\rm eff} = -\nabla P,$$

$$\triangle \Phi_{\rm eff} = 4\pi G \rho - 2\Omega^2,$$

$$P = K\rho^{1+1/n},$$

$$\Phi_{\rm eff} = \Phi - \frac{1}{2}\Omega^2 \varrho^2 - \frac{GM_2}{r_2}$$

$$\Omega = \sqrt{GM/a^3}.$$

- "spherical symmetry", $r \rightarrow R$ volume radius, see Eggleton (2006)

$$\underline{\underline{k_1^2 = k_1^2(a/R_1, q)\,,\ k_{\rm AM} = k_{\rm AM}(a/R_1, q)}}$$

$$k_1^2 = \frac{0.07536(a/R_1)^3 - 0.0184(1+q)}{(a/R_1)^3 + 0.1297(1+q)},$$

$$\frac{{\rm d}k_1^2}{{\rm d}(a/R_1)} = \frac{0.0845(1+q)(a/R_1)^2}{\left[(a/R_1)^3 + 0.1297(1+q)\right]^2},$$

$$k_{\rm AM} = 7.563\ k_1^4 - 0.4644\ k_1^2 + 0.0065.$$

- instability condition: $\frac{{\rm d}J_{\rm tot}}{{\rm d}(a/R_1)} = 0$

-significantly lower minimum mass ratio (Arbutina 2009) :

$q_{\rm min}$ = 0.070-0.074

- but we should include the secondary and take into account mass dependence *k=k(M)* (Wadhwa et al. 2021, 2022a) – the instability mass ratio

$$k_1 = -0.2392(M_1/M_\odot) + 0.527 \quad (0.6M_\odot < M_1 < 1.4M_\odot)$$
$$k_2 = -0.1985(M_2/M_\odot) + 0.485 \quad (0.09M_\odot < M_2 < 0.2M_\odot)$$

- for data from Landin (2009)

- room for improvement

$$n = n(M),\ k^2 = \frac{A(n)(a/R)^3 + B(n)}{1 + C(n)},\ k_{\rm AM} = D(n)k^4 + E(n)k^2 + F(n)$$

$$f = f(q, a/R), \quad f_1 = f_2\ \rightarrow\ R_2 = R_2(R_1, a, q)$$
$$q_{\rm inst} = q_{\rm inst}(M, f)$$

- Mochnacki (1984) tables

- **Work in progress!**

THANK YOU!