Tópicos

Close binary stars

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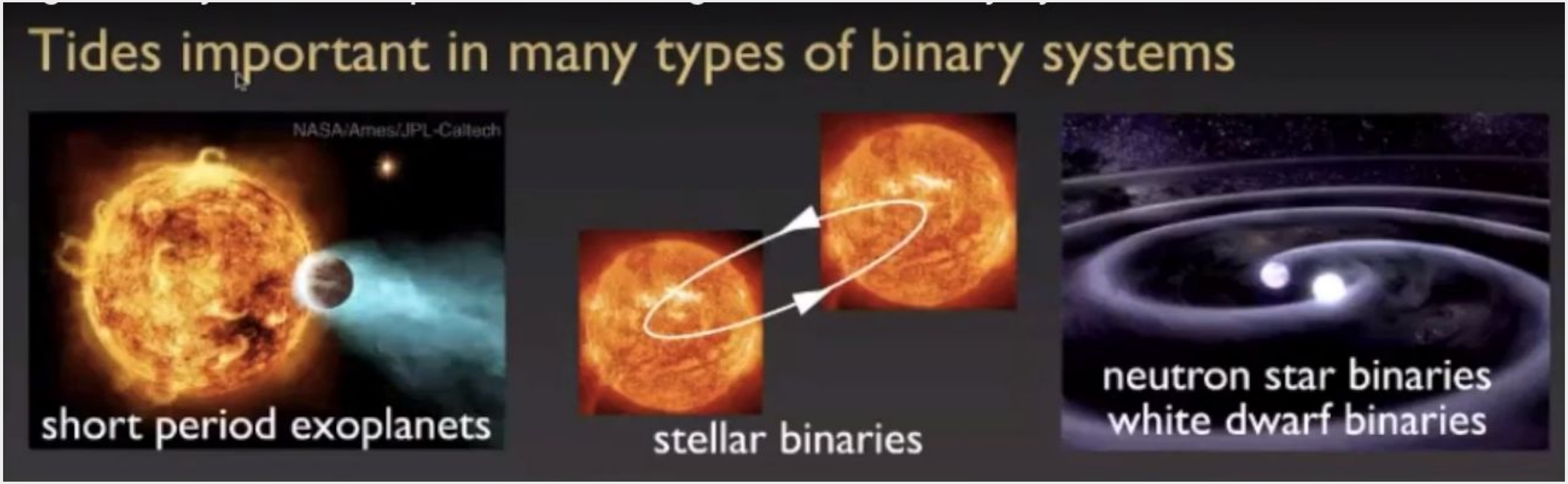
Lecture 6

28/08

Close (interacting) binaries:
Tidal effects



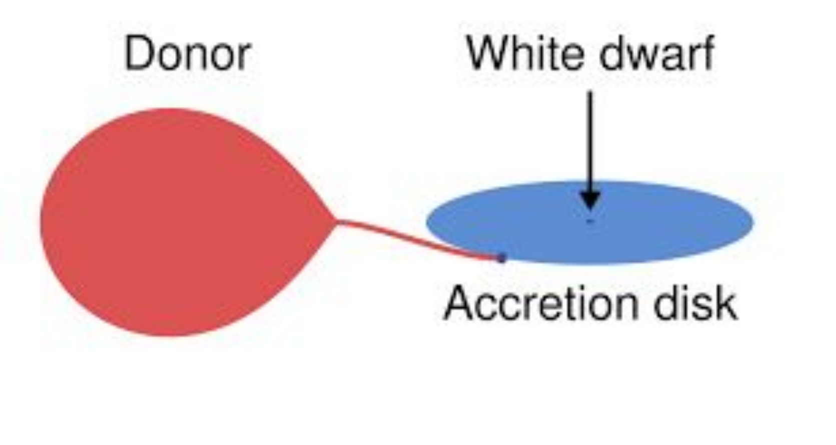
Orbital synchronization

The components of close binaries ($P \lesssim 10d$) usually (not always) rotate much more slowly than single stars of the same spectral type.

Observations prove that many stars in very close binary systems are **synchronized** with the orbital movement:

$$P_{orb} = P_{rot}$$

Example:
Donor (MS) star in cataclysmic variables but not the WD (unless it is strongly magnetic)



Example: Earth-Moon tidal evolution

- The Moon is already tidally locked to Earth ($P_{orb} = P_{rot}$) → we always see the same face

- Tidal forces gradually slow Earth's rotation, lengthening the day.

- As Earth slows, the Moon gains angular momentum and recedes into a higher, slower orbit, altering the rate of tidal interaction.

- In ~50 billion years, Earth and Moon should both be synchronised with a period of ~47 days.
  This state will not be reached, as the Sun will become a red giant long before then.

Orbital synchronization

	Prot[d]
Mercury	58.646
Venus	-243.023
Earth	0.997
Mars	1.026
Jupiter	0.414
Saturn	0.440
Uranus	-0.718
Neptune	0.671
Moon	27.322

What about planets?

The 2 closest planets to the Sun rotate much slowly.

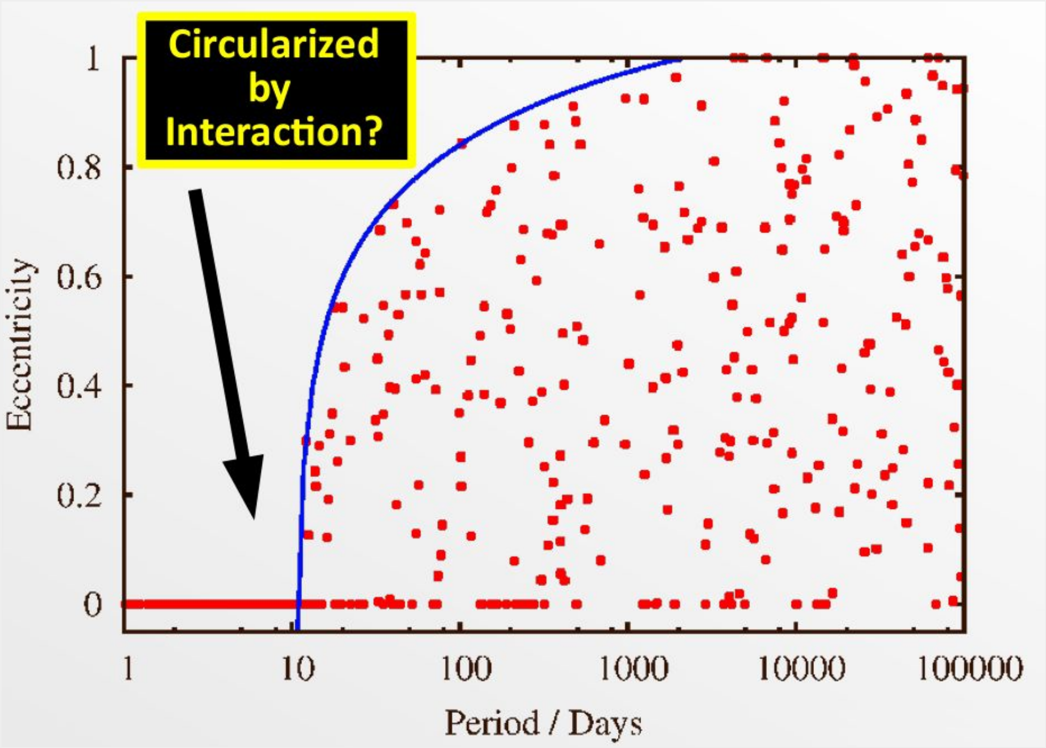
Mercury is not synchronized, but tidally locked with the Sun in a 3:2 spin-orbit resonance ($2P_{orb} = 3P_{rot}$). Mercury's relatively high eccentricity (~0.206) favours this stable 3:2 resonance instead of the 1:1.

Venus:
- has an extremely slow retrograde rotation: ~243 days.
- Its orbital period is ~224.7 days.
- These periods are nearly synchronised with Earth's orbit, so that at inferior conjunction (when Sun-Venus-Earth are aligned) Venus presents almost the same face towards Earth.
- Is not true tidal locking, but the result of complex interactions between Venus, Earth, the Sun, and Venus's massive, rotating atmosphere.

Orbital circularization

Also, very close binary stars typically are in **circular orbit**.

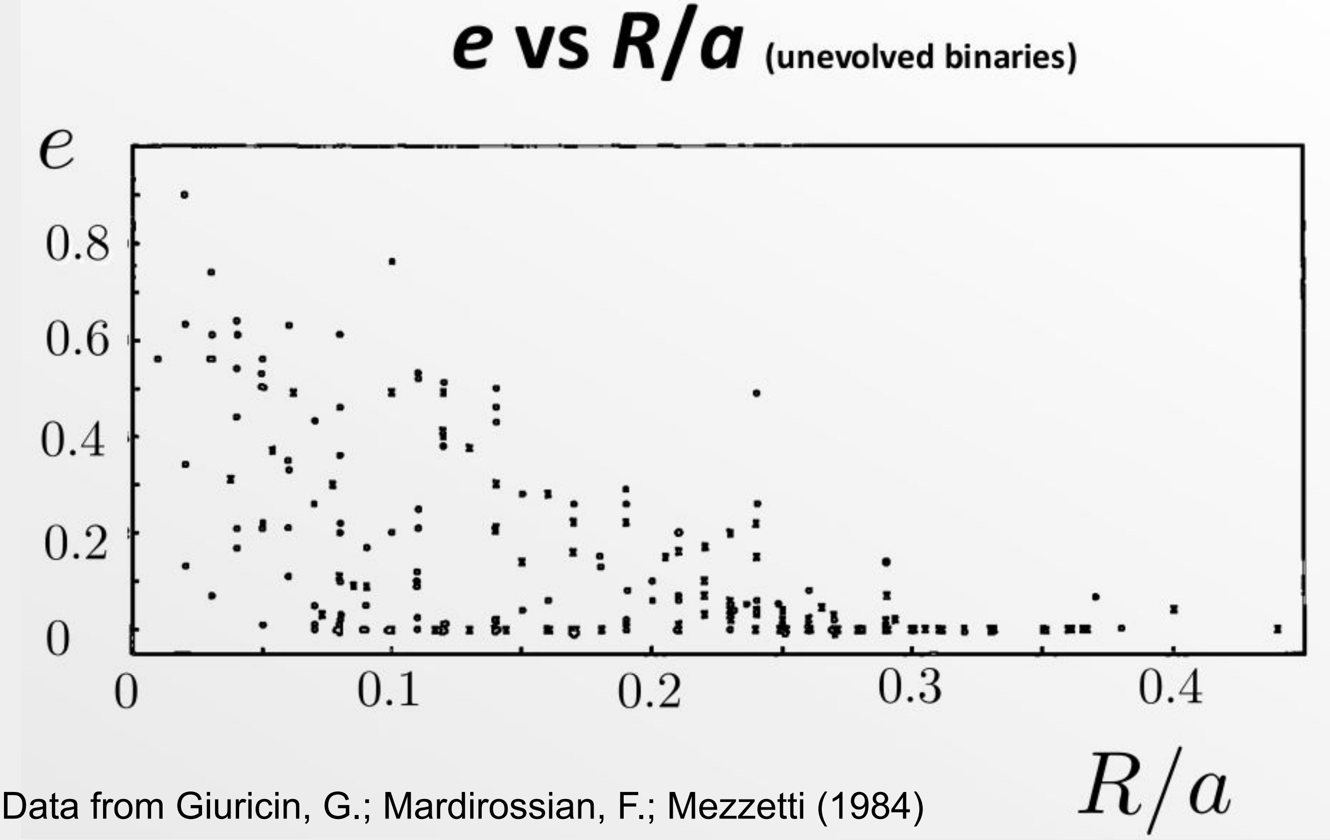
Remember period/eccentricity plots.



The closest binaries have e = 0
(P $\lesssim$ 10d, exact value depends on age of the population)

Orbital circularization

Circularization depends on radius v/s a.



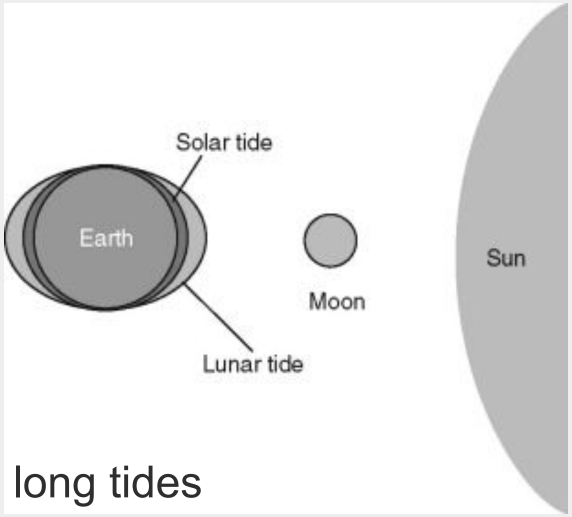
Data from Giuricin, G.; Mardirossian, F.; Mezzetti (1984)

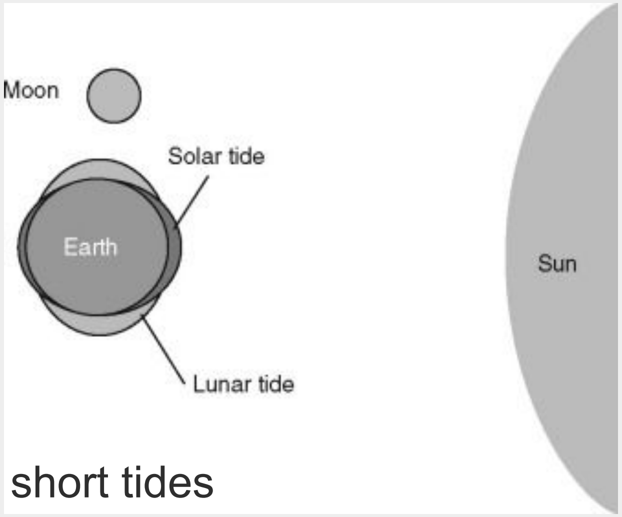
If radius is closer to orbital separation, the deformation of the star is larger, and circularization is faster. → faster in “normal” stars than in degenerate objects (same for synchronization, tides affect less the compact objects)

Tidal effects
circularization and synchronization

Circular and synchronized orbit correspond to the minimum energy configuration.

Both results are attributed to the effects of **tidal forces**. We call them this way, because is the same effect that produces tides in the Earth's ocean (but here we have the combined action of the Moon and Sun).

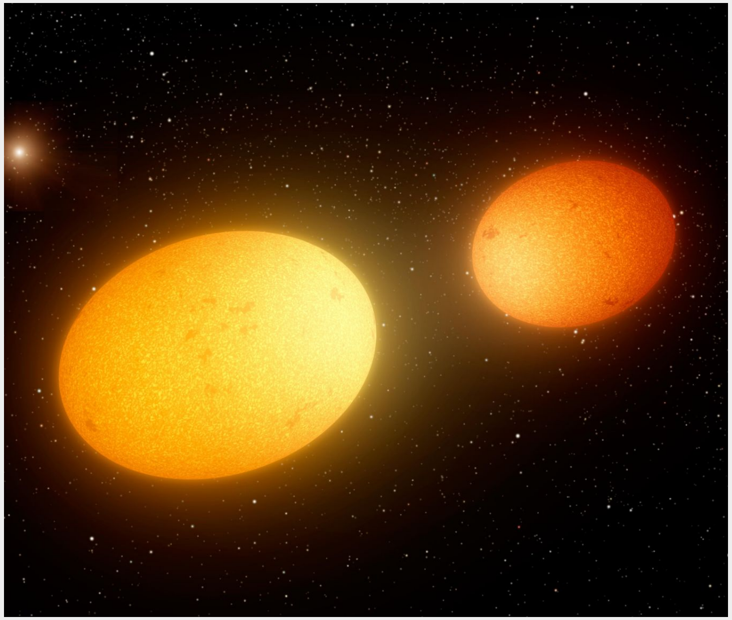




Observations show that tidal effects can be important in close binaries.

Tidal effects
circularization and synchronization

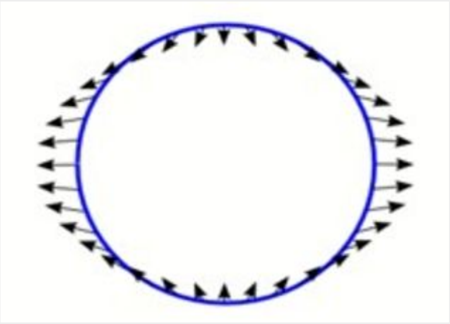
Whenever the two components of a binary are located closely to each other, the tidal forces (gravitational pull) can distort one or both of the components.
In this case, the gravitational potential is no longer a simple function of 1/r but extra terms are showing up.



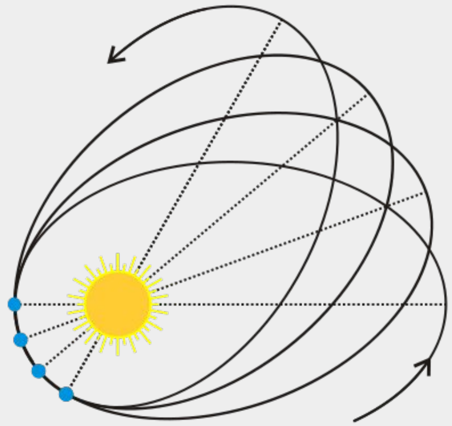
These extra terms appear because **the mass distribution is no longer spherically symmetric** in the disturbed companion (or in both components).

Tidal effects
circularization and synchronization

The extra terms in the gravitational potential cause a variation of the order of a few percent. When the stars are moving around each other, the extra terms produce a force that **causes a variation in energy and angular momentum of the orbital**.
(Tidal torque → Energy dissipation)



Among other things, this variation causes the movement of the line of the apsides, so the orbit is no longer a closed ellipse.
The binary will evolve into a circular system.

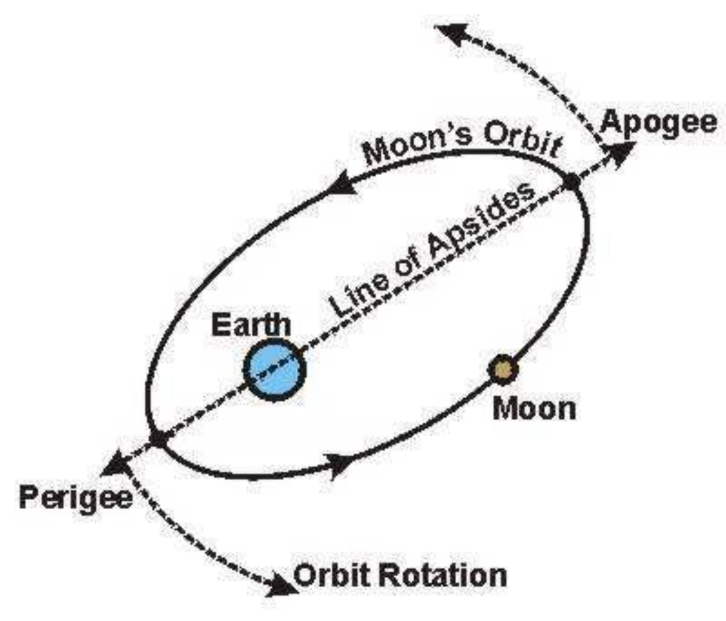


Tidal effects
circularization and synchronization

Apsides = two points on an elliptical orbit that are nearest to, and farthest from, the center of mass (in case of a planet around a star, this are periastron and apastron).

The **line of apsides**, connects the two apsides = is the <u>major axis</u> of the orbit.

Example: Moon's line of apsides:



Equilibrium tides

The study of tides in close binaries started in the first half of the 20th century. Those first studies about the deformation of close binary components caused by tides only described **equilibrium tides**:

- assumes the stars are in hydrostatic equilibrium
- the relative orbit of the companion must be **circular**
- the rotation of the primary component is **synchronized** with the orbital movement of the companion.

So, the distortion of the primary component is static in relation to a coordinate system rotating with the star.

In general, the tidal force is time dependent. Tides in a component of a close binary are then called dynamic tides.

Dynamic tides

Compute reaction of a star on dynamic tidal force due to companion: complicated theory, resonances,...

Dynamical effects due to tides determined by gravity field:

- Gravitational pull between mass centres
- Forces due to non-spherical mass distribution

Also depends on the mode of energy transport (convective or radiative envelope) in the deformed star envelope.

Effects of dynamic tides

The full treatment of dynamic tides and tidal friction in close binaries was treated in the seminal paper by J.-P. Zahn, 1977, "Tidal Friction in Close Binary Stars". https://ui.adsabs.harvard.edu/abs/1977A&A....57..383Z

Stars in an eccentric orbit and/or stars not co-rotating in a circular orbit will remain subordinate to tidal forces with a variable amplitude
→ stars are forced to pulsate!

The tidal potentials create tidal torques and transfer energy and angular momentum from the stars (rotation) to the orbit until rotation and orbital periods match → synchronous rotation.

Other recommended papers:

Hut (1980) "Stability of the Tidal Equilibrium"
https://ui.adsabs.harvard.edu/abs/1980A%26A....92..167H

Hut (1981) "Tidal evolution in close binary systems"
https://ui.adsabs.harvard.edu/abs/1981A%26A....99..126H

Tides depends on the mode of energy transport

It is generally accepted that two mechanisms can explain synchronization in close binaries, which depend on the mode of energy transport in the deformed star envelope:

Deep **convective** envelope: turbulent convection

Radiative envelope: oscillations are damped by viscous effect, dissipating the pulsation energy and exerting torque (not easy to derive).

Timescales

Zahn (1977) deduced expressions for the time scales of synchronization and circularization of the orbit. For stars with **convective** envelopes (like the sun, or pre-MS stars):

- Circularization time scale:

$$1{,}000{,}000 \times (1/q)[(1+q)/2]^{5/3}\ P^{16/3}$$

extremely dependent on orbital period

- Synchronisation time scale:

$$10{,}000 \times [(1+q)/2q]^{2}\ P^{4}$$

Also faster for shorter periods.

Conclusion: **synchronization faster than circularization**

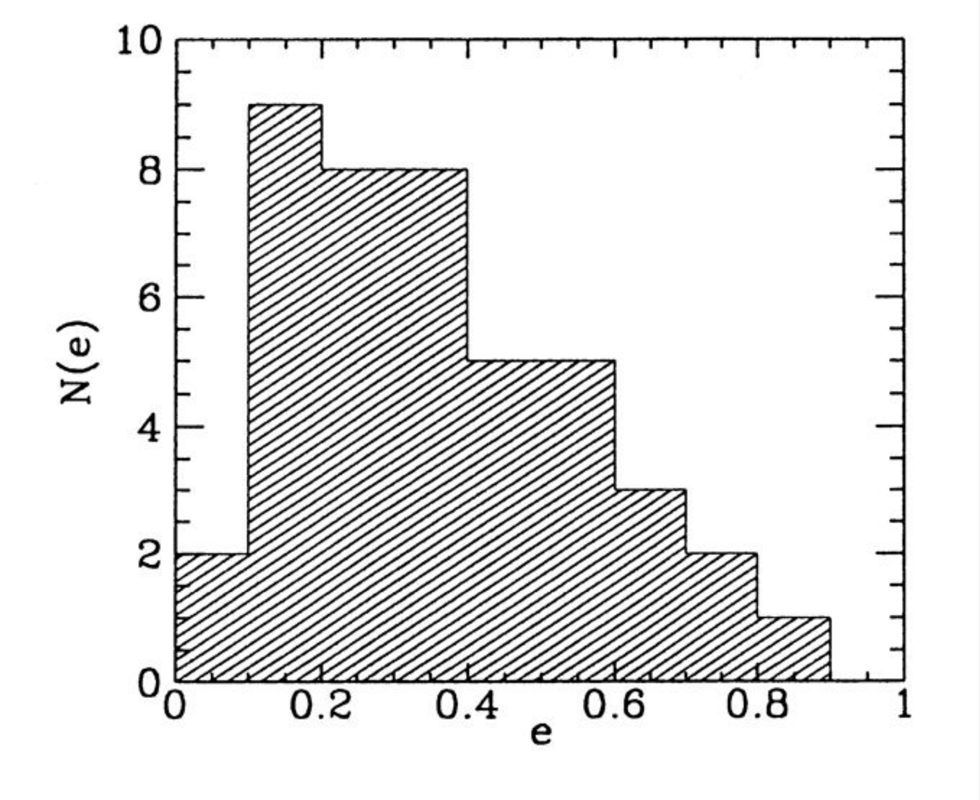
*The orbital periods in these formulae must be expressed in days; in that case, the results of these time scales is expressed in year

Circularization is observed!

Duquennoy & Mayor (1992): sample of 164 close binaries in the galactic plane (open clusters), with orbital periods ranging from 7-8 hours up to 3000 days.
Mainly main-sequence stars with masses of about a solar mass (F-G-K-dwarfs).

They found a clear cut-off period at 11.6 days. All binary systems with a shorter orbital period are circular or quasi-circular ($e < 0.03$). Systems with a longer period are all eccentric, having an average value of $e = 0.31 \pm 0.04$.

This finding corresponds with the fact that **binaries are born eccentric**, and in most close systems the tidal effects are strong.



distribution of eccentricities for 43 open cluster stars with an orbital period between 10 and 1000 days

Circularization is observed!

Dividing the sample depending on the binaries age:

- For pre-main-sequence binaries the cut off P is ~ 4 days.
- In the Pleiades (relatively young cluster), binaries with P < 7.1 days have circular orbits.
- For M67 (older open cluster) the cut-off period is ~ 12.4 days.
- Binary stars in the halo of our Milky Way Galaxy (much older) have a much longer cut-off period, between 12-19 days.

The cut-off period (maximum period for circular binaries) is linked to the age of the ensemble of stars, because it is dependent on the time span during which the tidal forces have been acting.

The more time the tidal forces get to act, the longer the periods of orbits that are already circularized.

Conclusions on tidal effects

● Binary stars are born with eccentric orbits.

● Predictions of tidal effects are visible in the data.

● Test of circularisation fairly easy (P v/s e).

● Define cutoff period for a given age (e.g. in a cluster) = longest period of circular orbit, increasing for older populations (also, binaries born with high e need more time to circularise).

● Circularisation already achieved in pre MS stage? at TAMS? Depends on initial Porb and e.

● Synchronization should be faster, but more difficult to test because it is not that easy to measure the rotational period. (example: the Moon's orbit is synchronized but not yet circularized, e ~ 0.05)

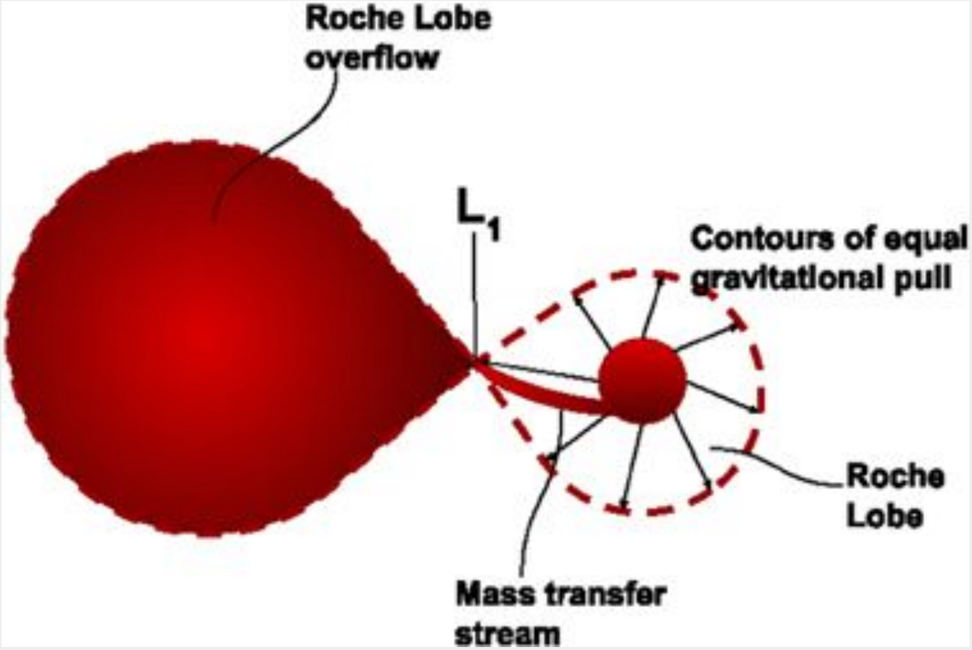
Roche Geometry

Interacting binaries

Binary stars may interact in many ways, such as

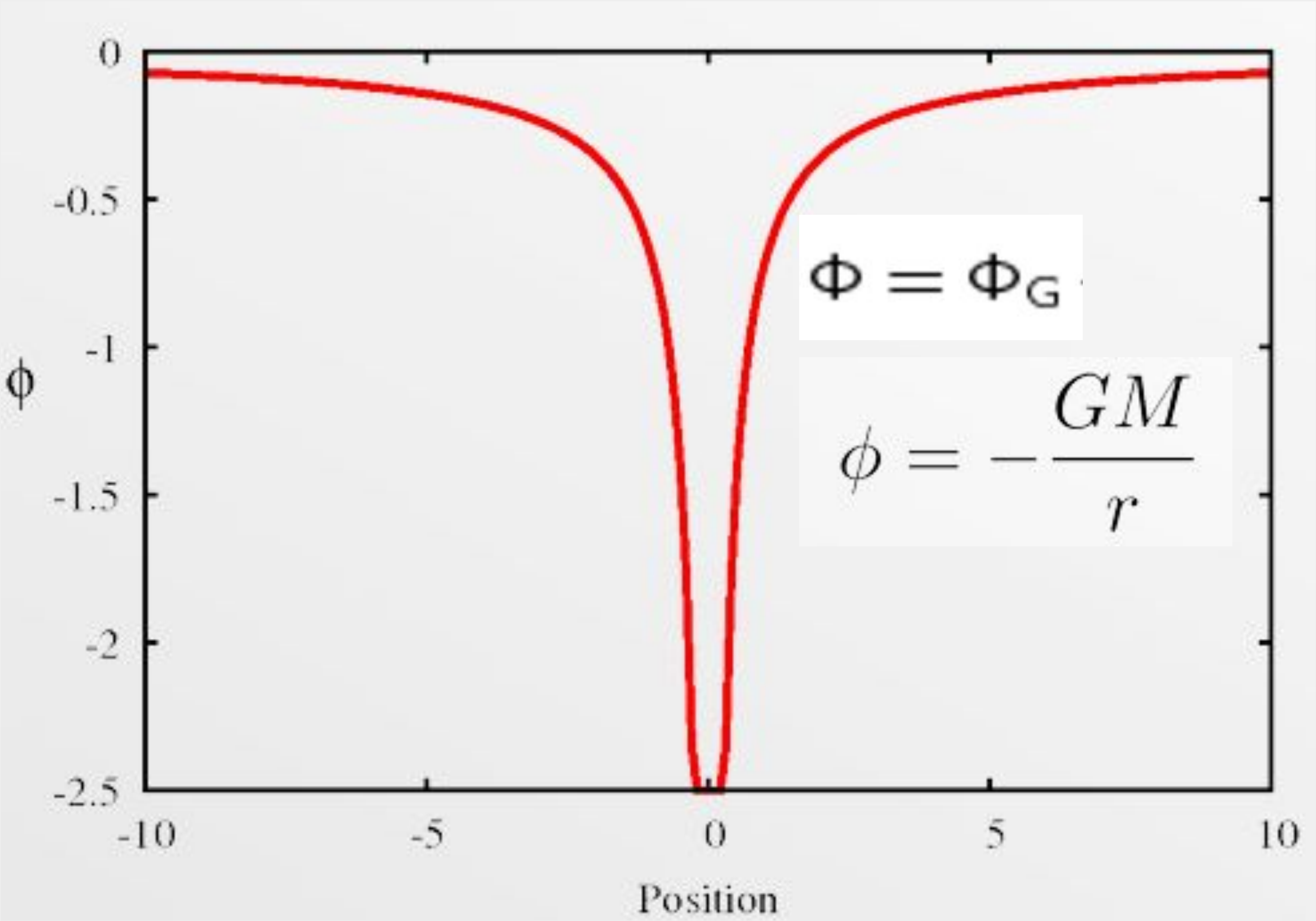
- Roche lobe overflow (RLOF)
- Stellar wind accretion
- Orbital angular momentum loss (AML) from gravitational wave radiation, magnetic braking.

RLOF is the most important interaction, which changes the destiny of a binary system.



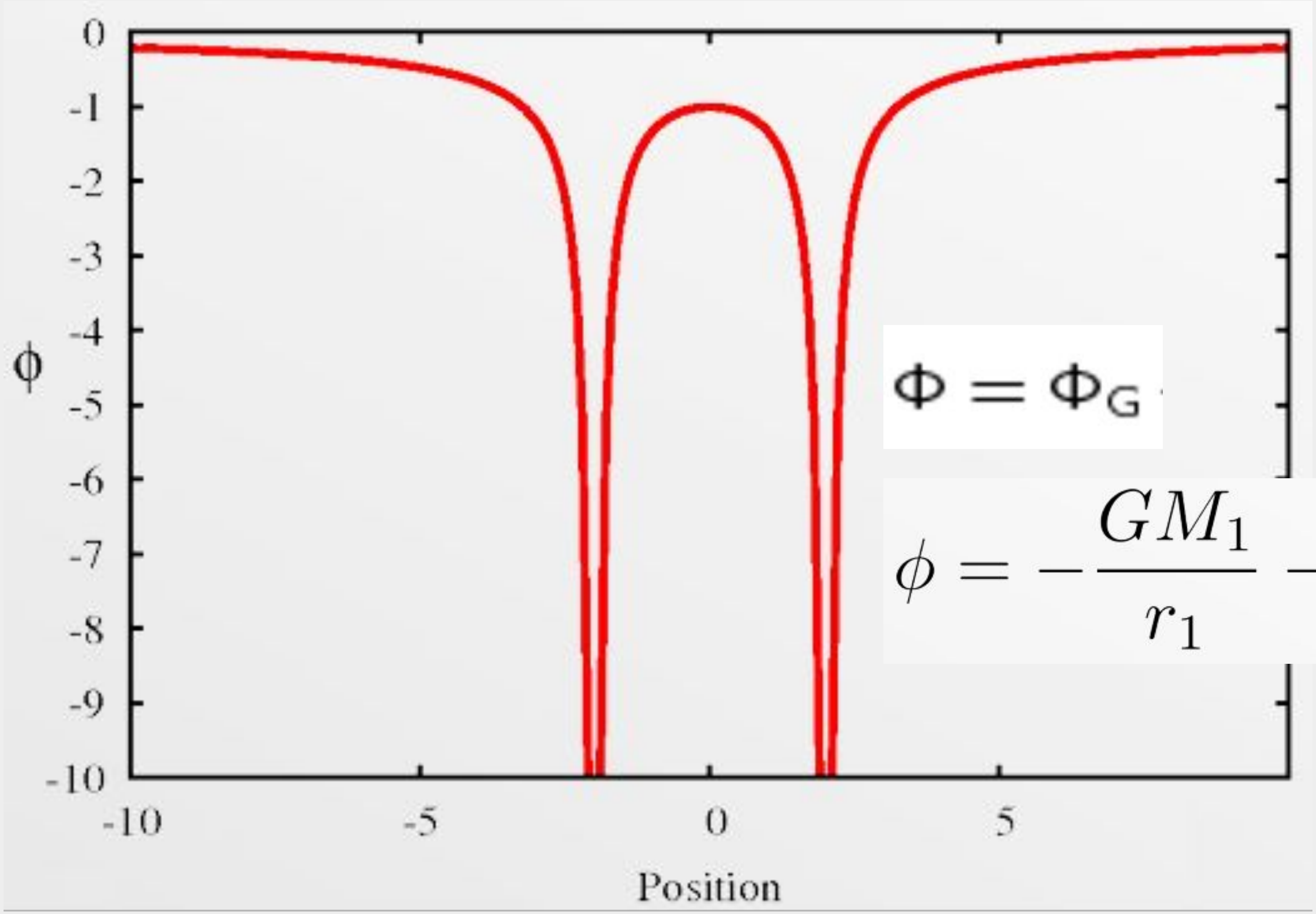
Potential

Potential due to a point mass:



Potential

Potential due to two point equal masses:



$$\Phi = \Phi_G$$

$$\phi = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2}$$

Potential

In a binary system, it is often useful to describe the system in a coordinate system that rotates along with the objects.

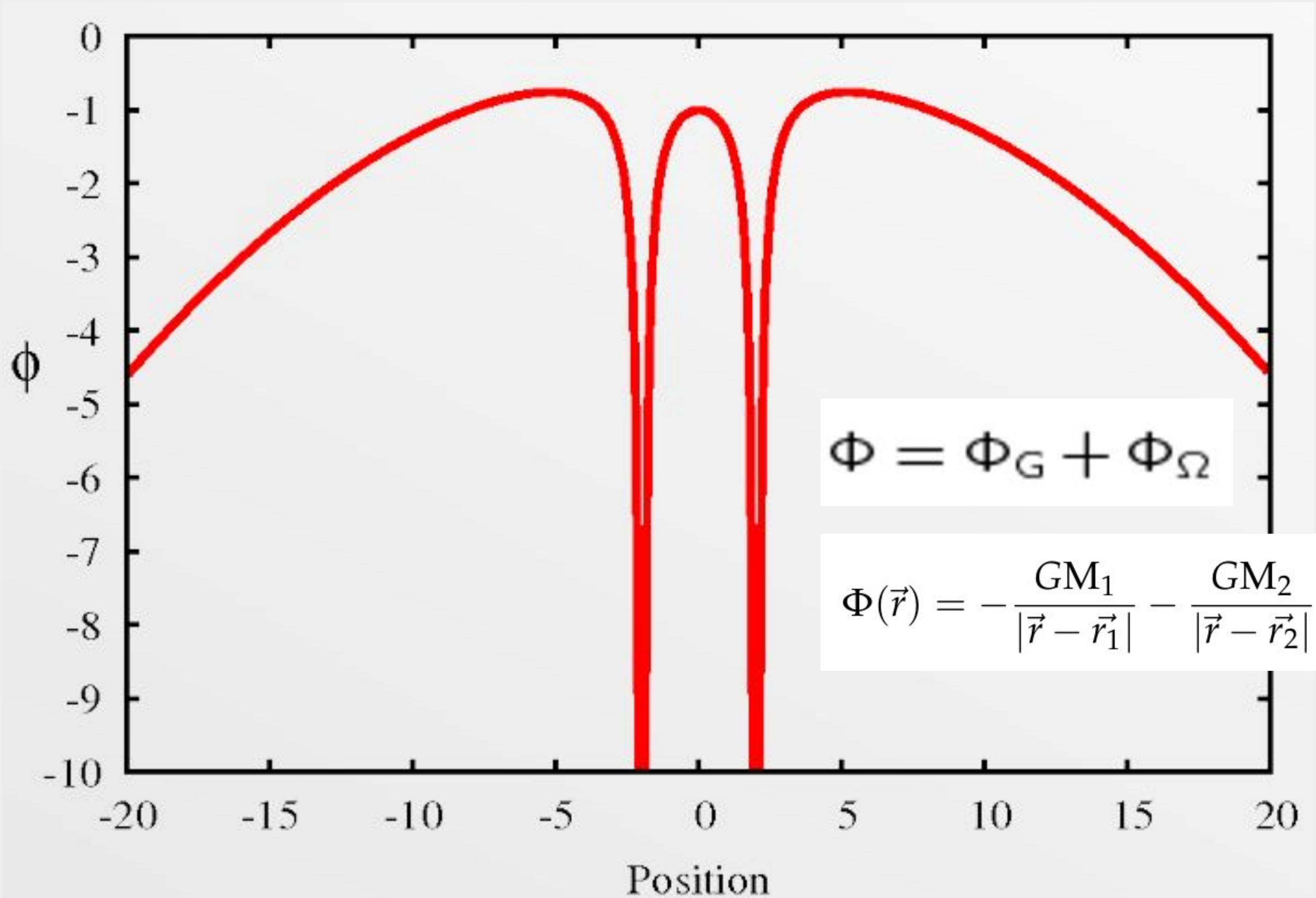
In this non-inertial frame, one must consider **centrifugal force** (not really a force) in addition to gravity.

Coordinate system in corotation with orbit: centrifugal and gravitational force combine into potential $\Phi = \Phi_G + \Phi_\Omega$

Also, Φ_G more complicated than for point masses, depends on density distribution in each of the stars.

Potential

Potential due to two point equal masses in co-rotating frame



$$\Phi = \Phi_G + \Phi_\Omega$$

$$\Phi(\vec{r}) = -\frac{GM_1}{|\vec{r}-\vec{r_1}|} - \frac{GM_2}{|\vec{r}-\vec{r_2}|} - \frac{1}{2}(\vec{\omega} \times \vec{r})^2$$

Reference frame with origin in the center of mass, corotating with the system at velocity $\omega = 2\pi/P_{orb}$ (also called Ω)

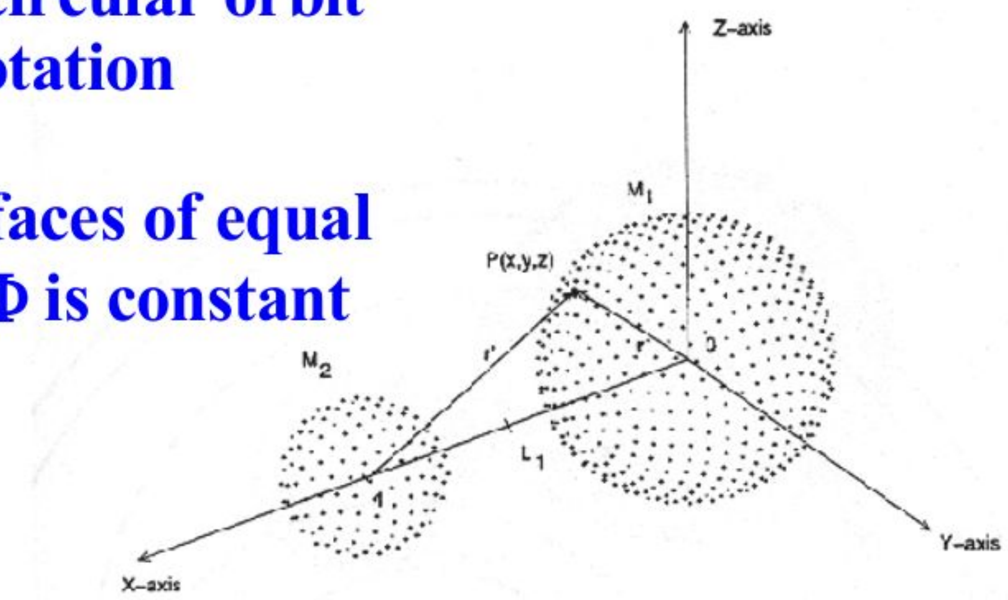
The Roche equipotential surfaces

Roche approximation: Simplification that assumes that the orbit is circular, both stars corrotate, and have spherically symmetry

Primary in (0,0,0)
Secondary in (a,0,0)

System in circular orbit and in corotation

Derive surfaces of equal potential: Φ is constant



Equation of Motion $:\frac{1}{\rho}\vec{\nabla}P + \vec{\nabla}\Phi = \vec{0}$ with $\Phi = \Phi_G + \Phi_\Omega$

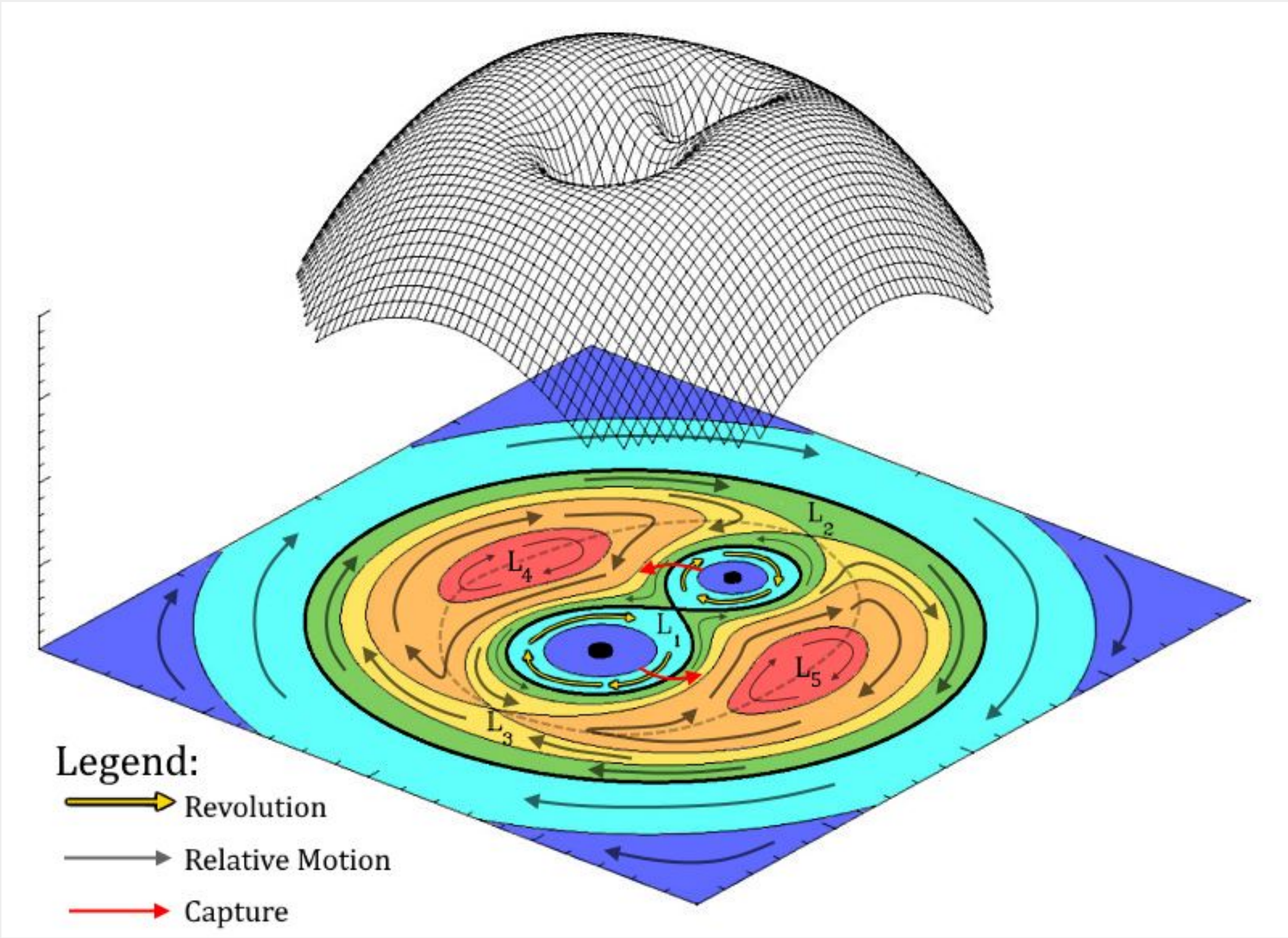
Mass Centre : $(\mu a, 0, 0)$, $\mu \equiv M_2/(M_1 + M_2)$

Roche Approximation $:\Phi_G = -\frac{GM_1}{|\vec{r} - \vec{r}_1|} - \frac{GM_2}{|\vec{r} - \vec{r}_2|}$

$$\Phi = \Phi_G + \Phi_\Omega = -\frac{GM_1}{(x^2 + y^2 + z^2)^{1/2}} - \frac{GM_2}{((x-a)^2 + y^2 + z^2)^{1/2}} - \frac{1}{2}\Omega^2\left[(x - \mu a)^2 + y^2\right]$$

Ω = ω in the previous slide

Roche Geometry



Close to each star, surfaces of equal gravitational potential are approximately spherical and concentric with the nearer star.

Far from the stellar system, the equipotentials are elongated due to tidal effects of the companion and inertia.

A critical equipotential intersects itself at **L1 = inner Lagrangian point**, forming a two-lobed figure-of-eight with one of the two stars at the center of each lobe. This critical equipotential defines the **Roche lobes.**

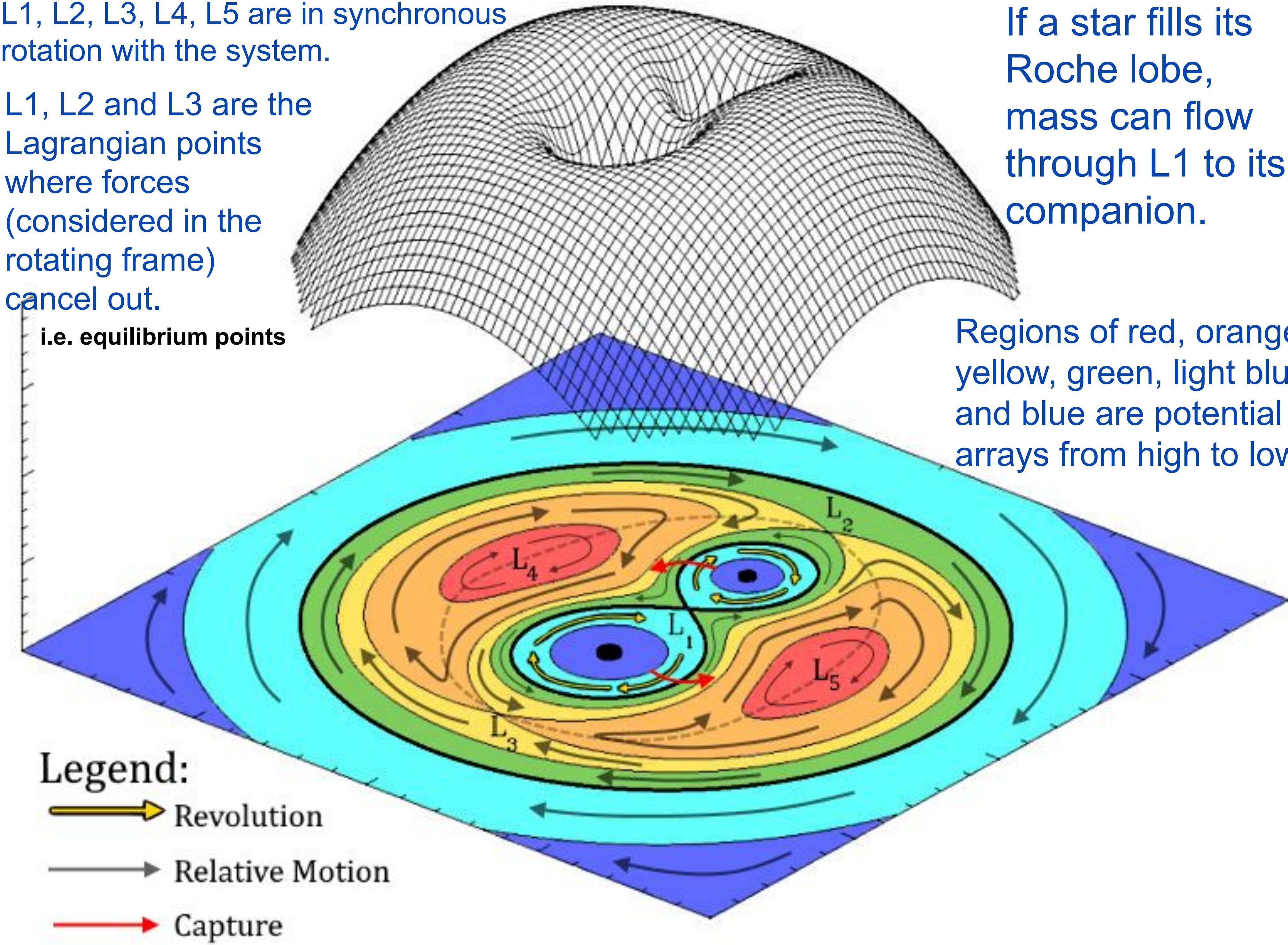
L1, L2, L3, L4, L5 are in synchronous rotation with the system.

L1, L2 and L3 are the Lagrangian points where forces (considered in the rotating frame) cancel out.

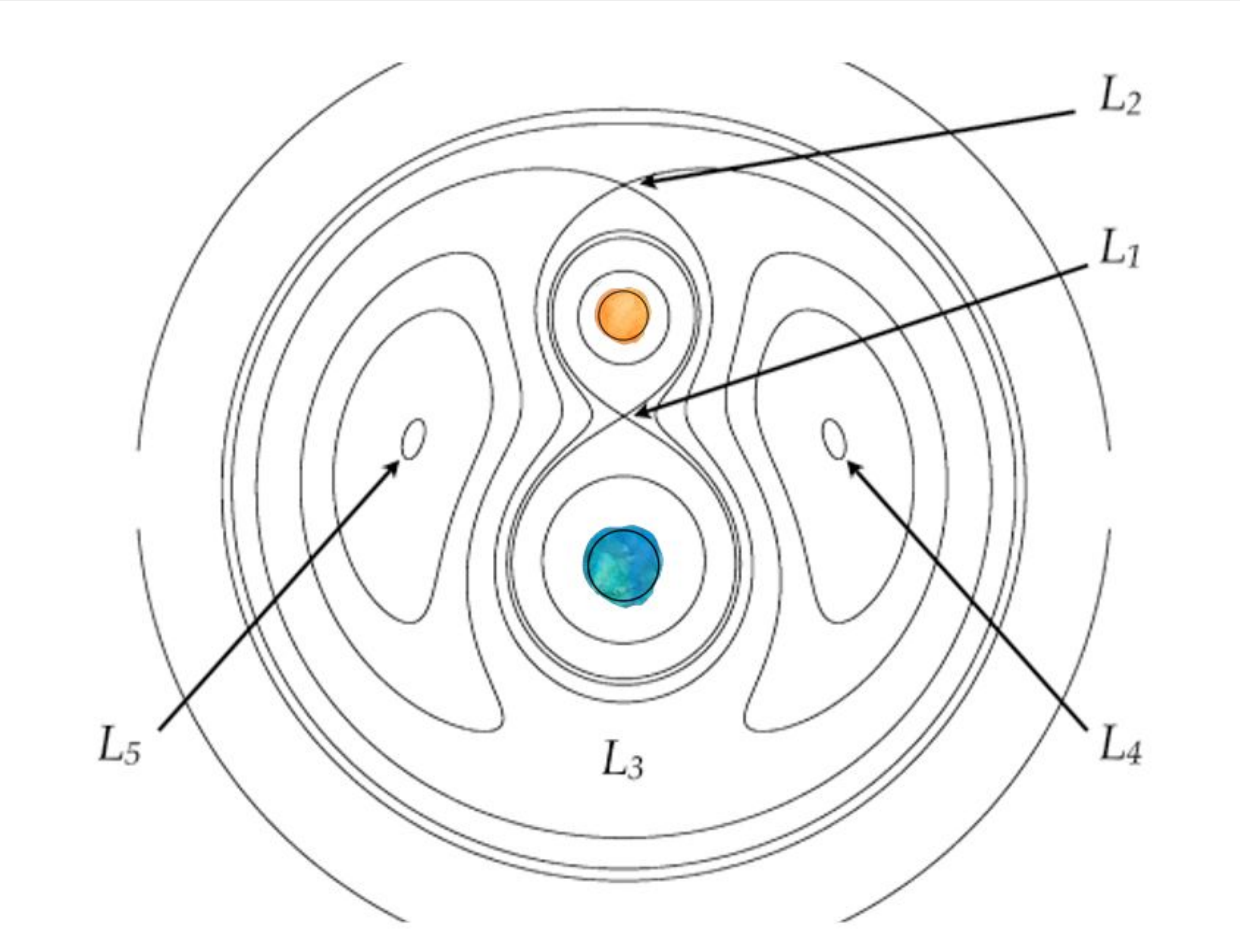
i.e. equilibrium points

If a star fills its Roche lobe, mass can flow through L1 to its companion.

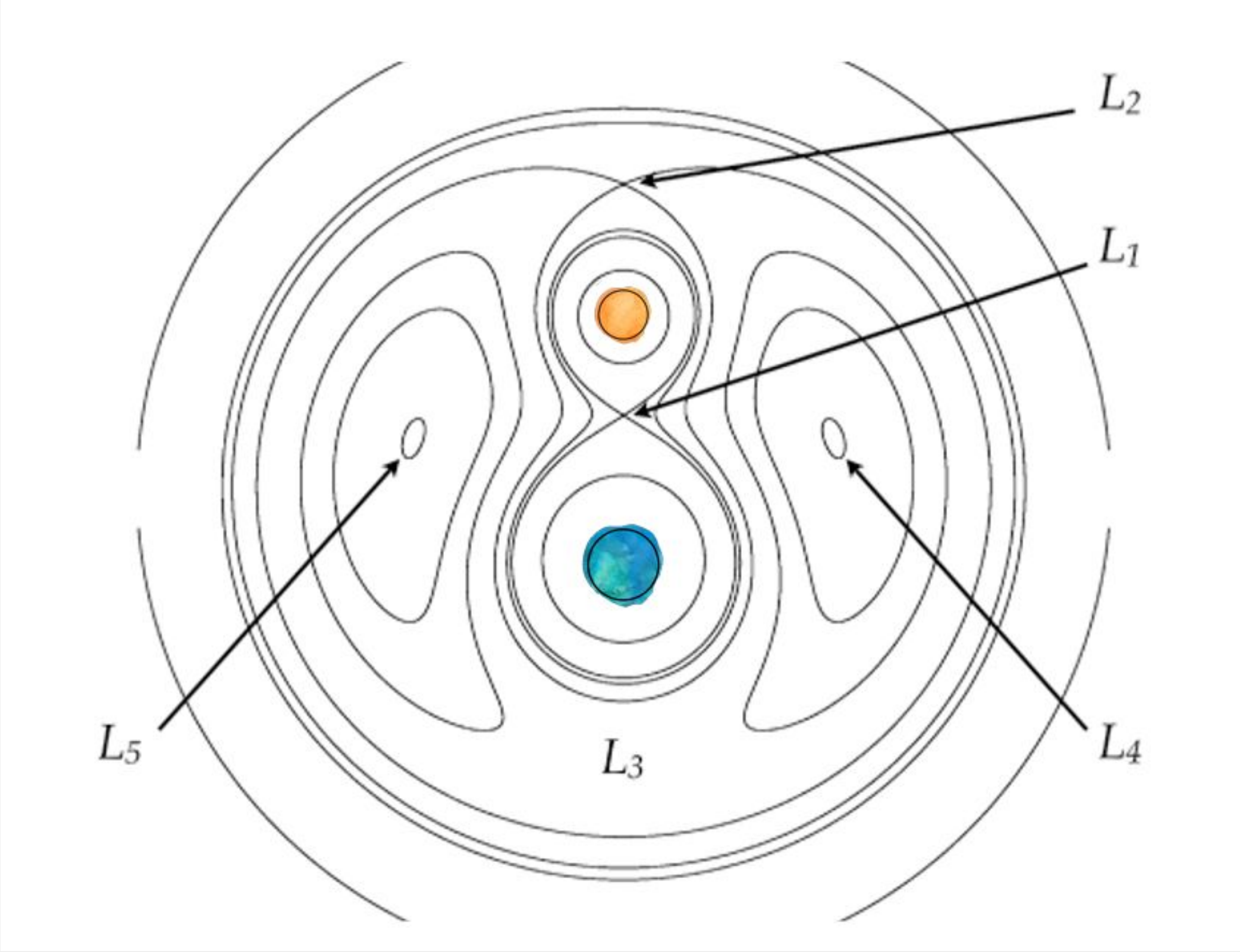
Regions of red, orange, yellow, green, light blue and blue are potential arrays from high to low.



The Roche equipotential surfaces



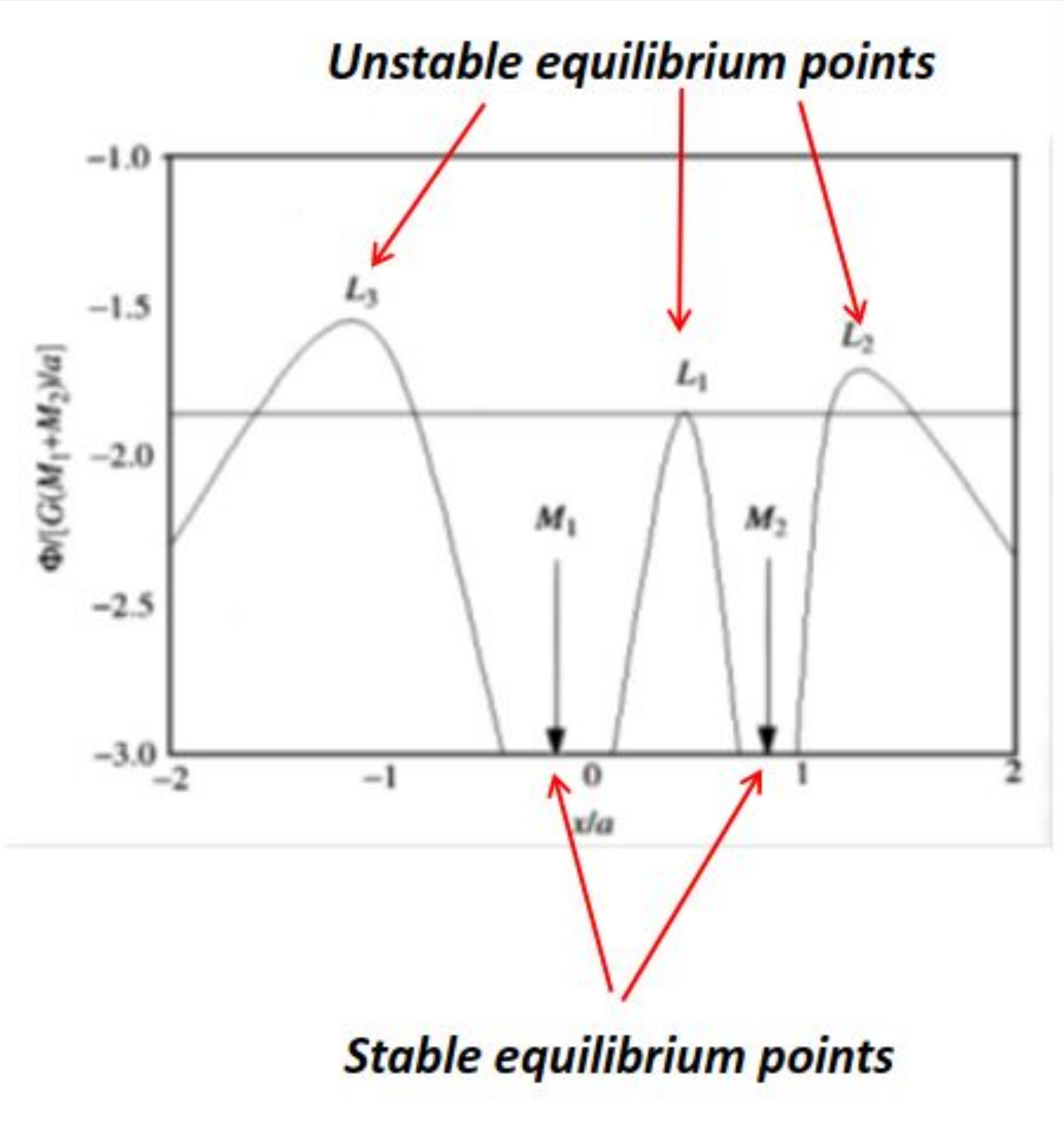
Roche Geometry



L2 and L3 are unstable equilibrium points. Through these points, matter can pass between the inner region of the binary and the external "figure-of-eight" region.

L4 and L5 are local minima of the effective potential. They are stable equilibrium points where material can remain trapped (e.g. Trojan asteroids).

Roche Geometry



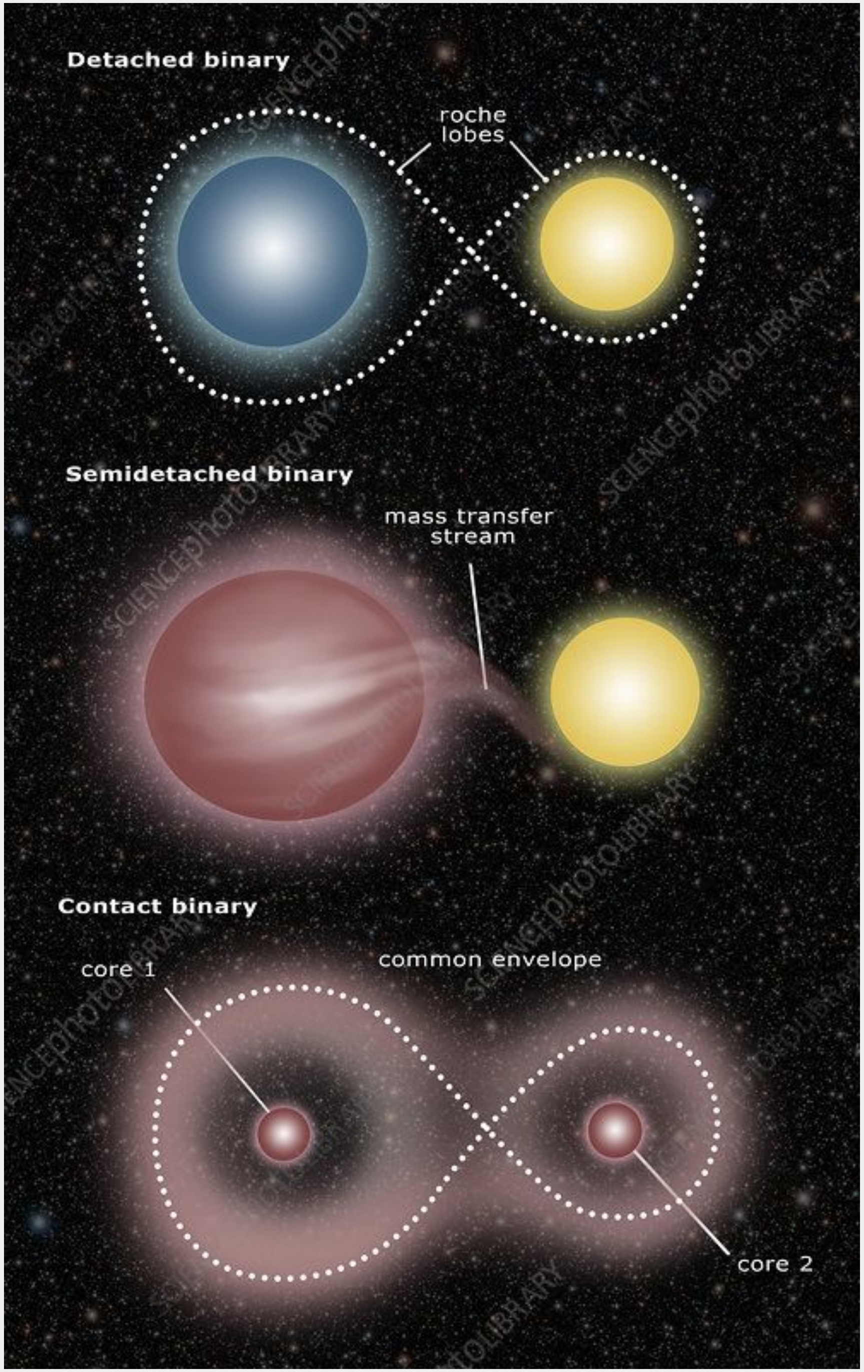
Example with $M_1 > M_2$

Any mass located near an unstable equilibrium point may be channelled between the stars (L1) or flow out of the Roche lobes into the external region of the system (L2, L3), from where it can potentially escape.

Roche Geometry

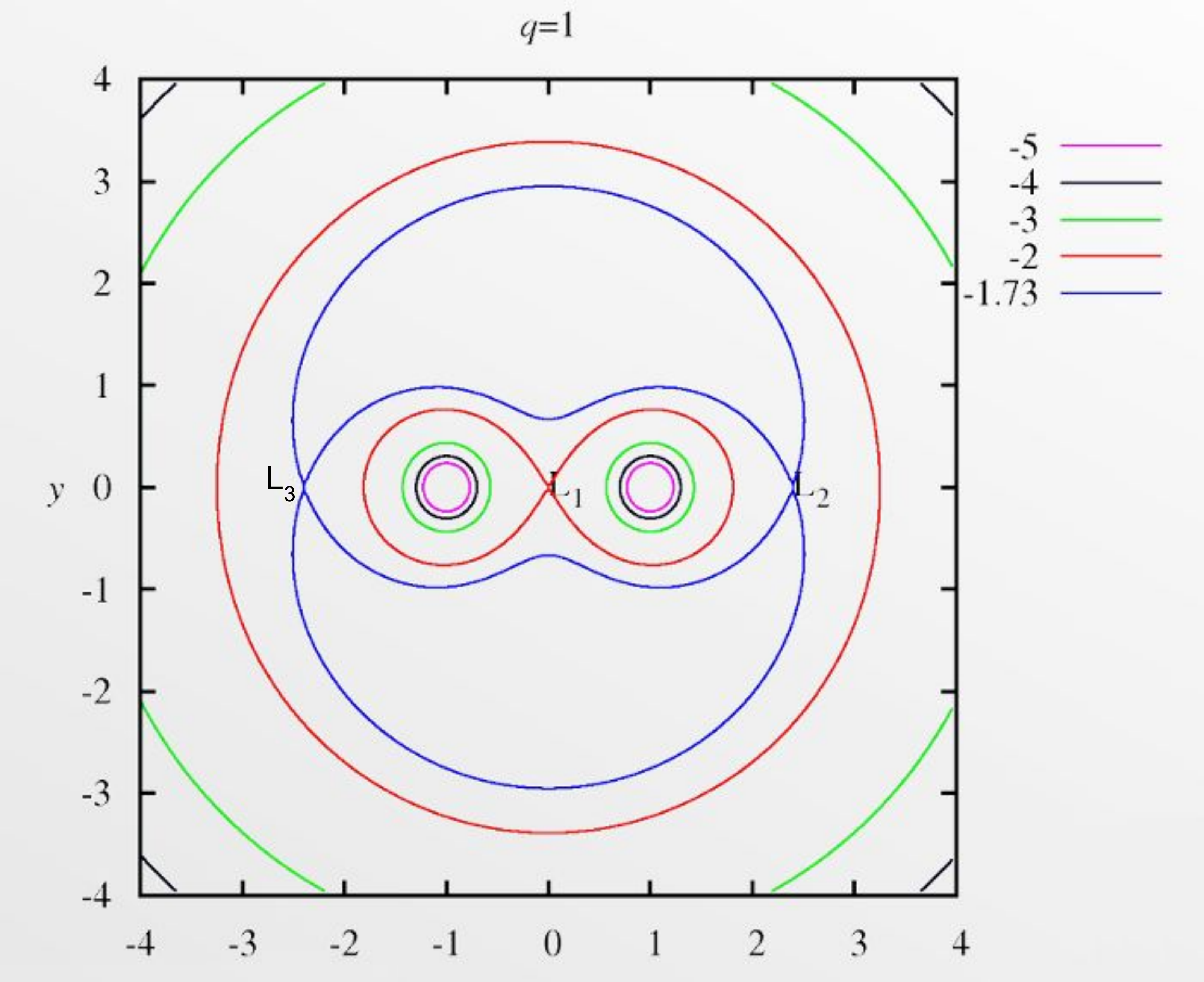
So, from the point of view of binary evolution, the most important equipotential surface is the one which defines the **two Roche lobes** (touching at the the inner Lagrangian point L1).

RL classification is based on this.



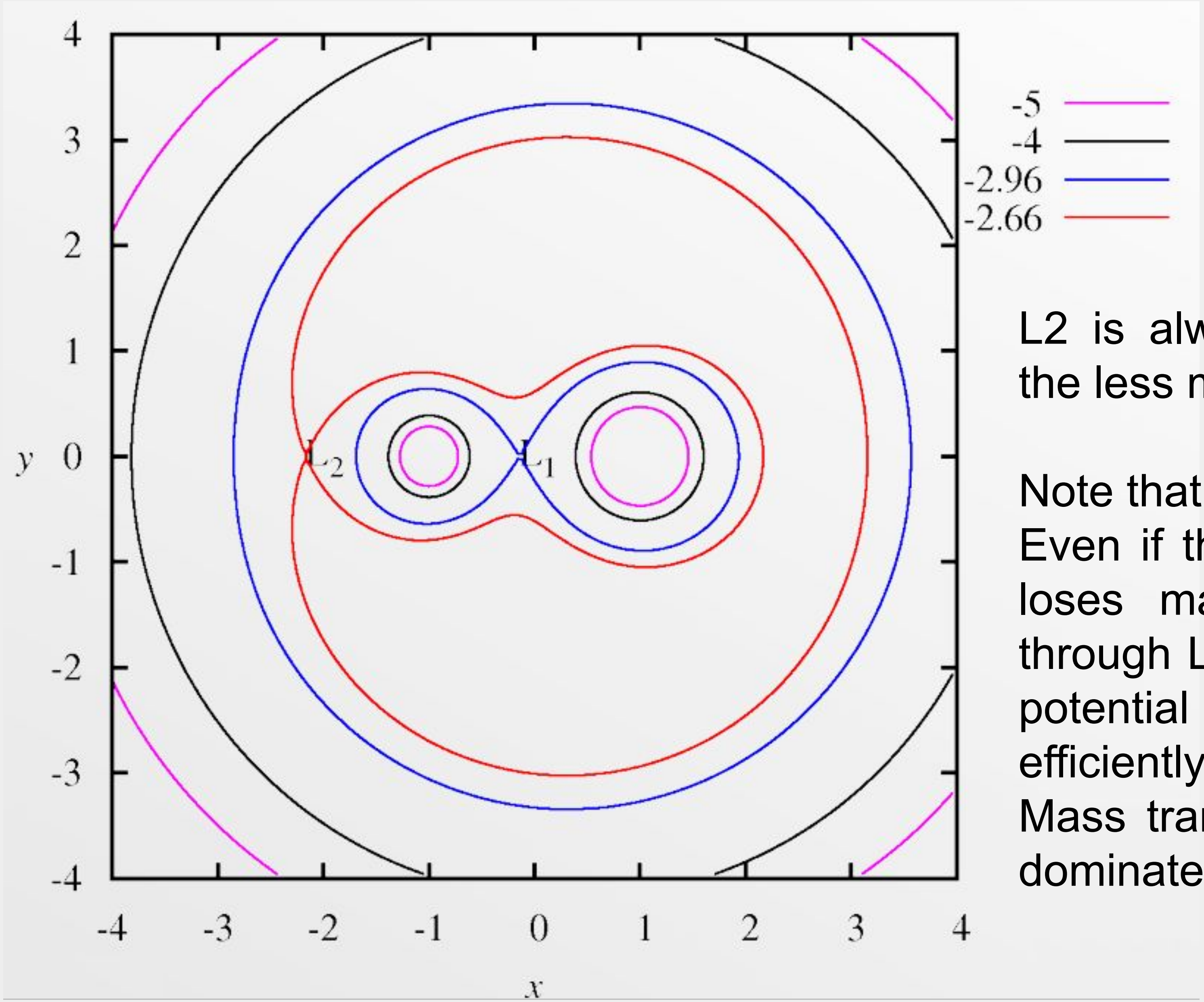
Roche Geometry dependes on q

Example equal masses (q = 1)



Roche Geometry dependes on q

Example q = 0.5

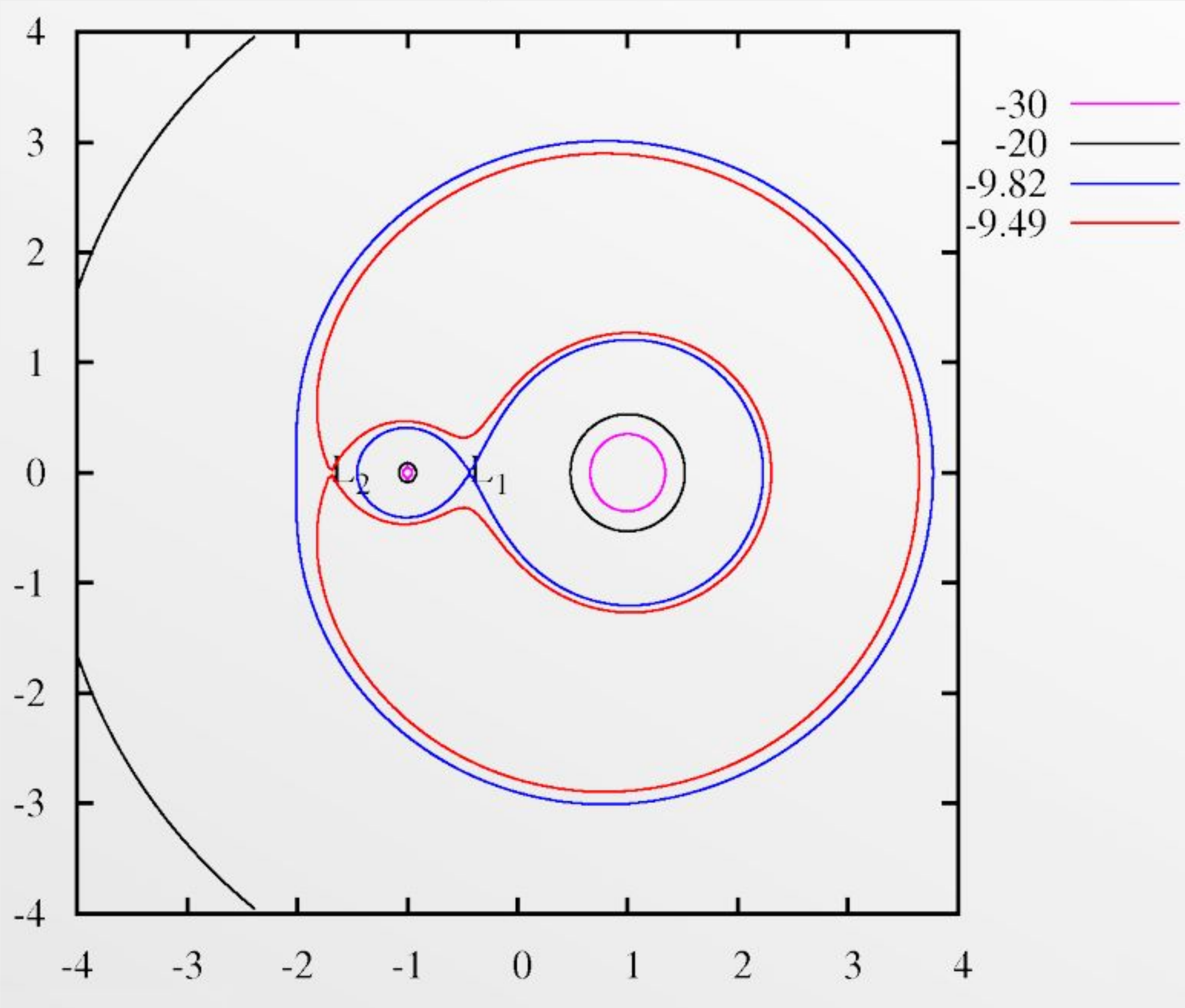


L2 is always located “behind” the less massive star.

Note that L3 is not shown.
Even if the more massive star loses mass, any mass loss through L3 is negligible, as the potential gradient does not efficiently channel material. Mass transfer and escape are dominated by L1 and L2.

Roche Geometry

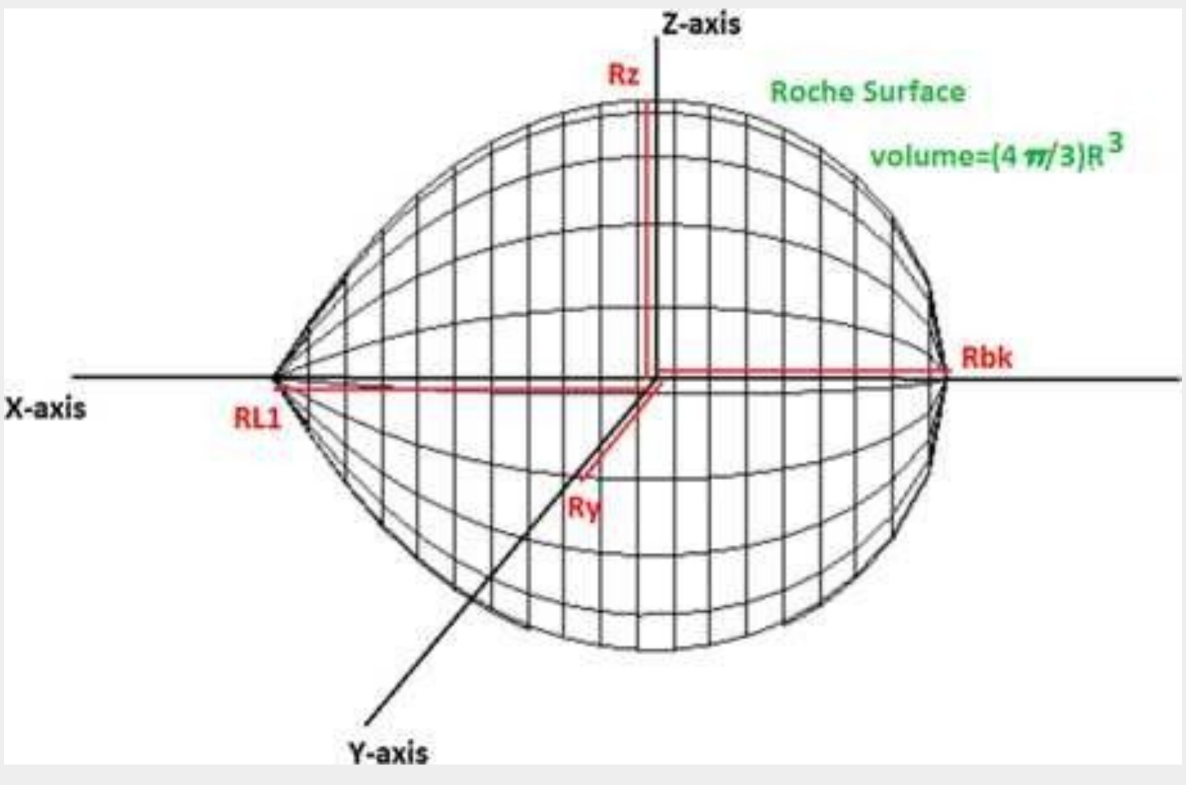
Example q = 0.1



The Roche Radius

The stars (especially in close systems) are non-spherical due to the Roche deformation, this is, the radius varies depending on along which angle to the orbital plane it is measured.

Eggleton (1983), defined the Roche radius as the **radius of a sphere with** volume equal to the **volume of the Roche-lobe**.



$$V_{R1} = \frac{4}{3}\pi R_{L1}^{3}$$

Approximations to Roche Lobe Radius

from Eggleton 1983, *ApJ*, 268, 368

$$\frac{R_{\rm L}}{a} \approx \frac{0.49\,q^{2/3}}{0.6\,q^{2/3} + \ln(1+q^{1/3})} \approx \frac{0.44\,q^{0.33}}{(1+q)^{0.2}}$$

Good to 1%
for $0 < q < \infty$

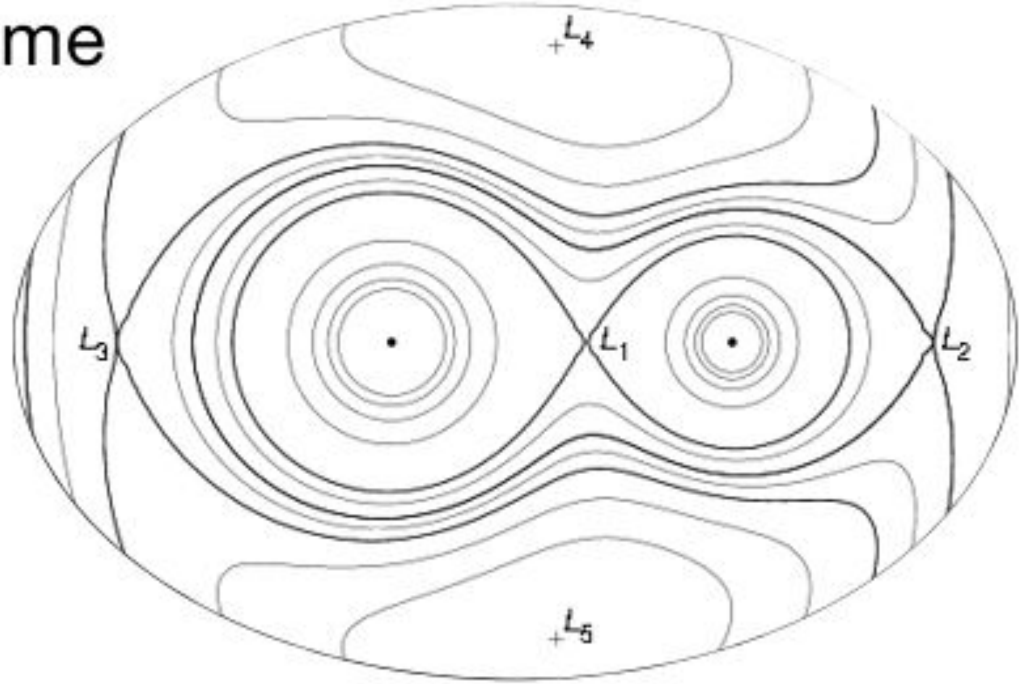
Good to a few%
for $0.1 < q < 10$

works for both stars.
If q = M1/M2 → RL1
If q = M2/M1 → RL2

Reproduces Roche lobe volume

q = binary mass ratio
(controls shape)

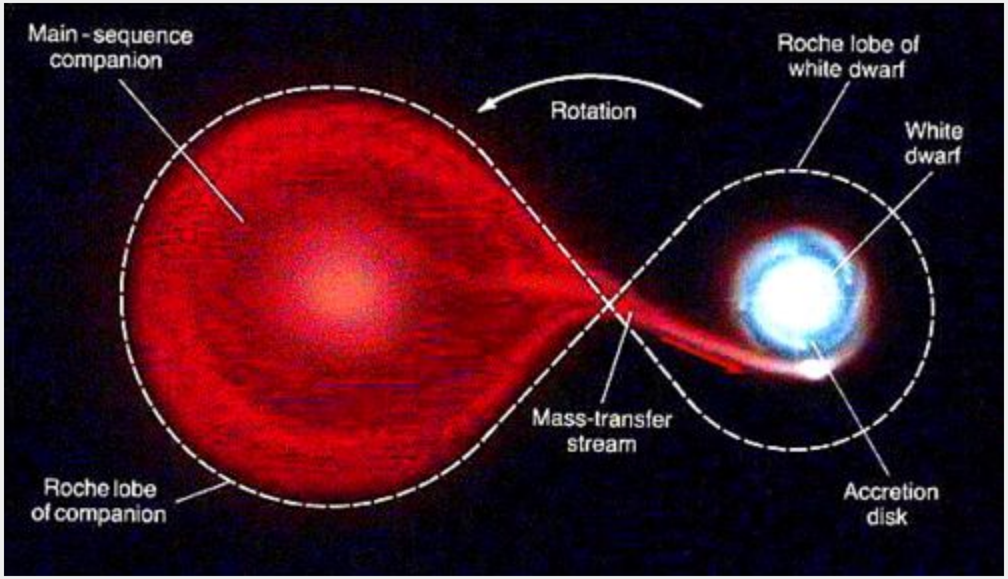
α = orbital separation
(controls scale)



Roche Lobe Overflow (RLOF)

When a star radius exceeds its Roche radius the material which lies outside can "fall off" into the other object's Roche lobe via the first Lagrangian point, which is referred to as **mass transfer via Roche-lobe overflow.**

This is responsible for a number of astronomical phenomena, including Algol systems, recurring novae, X-ray binaries and millisecond pulsars.



Roche Lobe Overflow (RLOF)

After mass transfer begins, the size of the Roche lobes will change, due to the change in q.

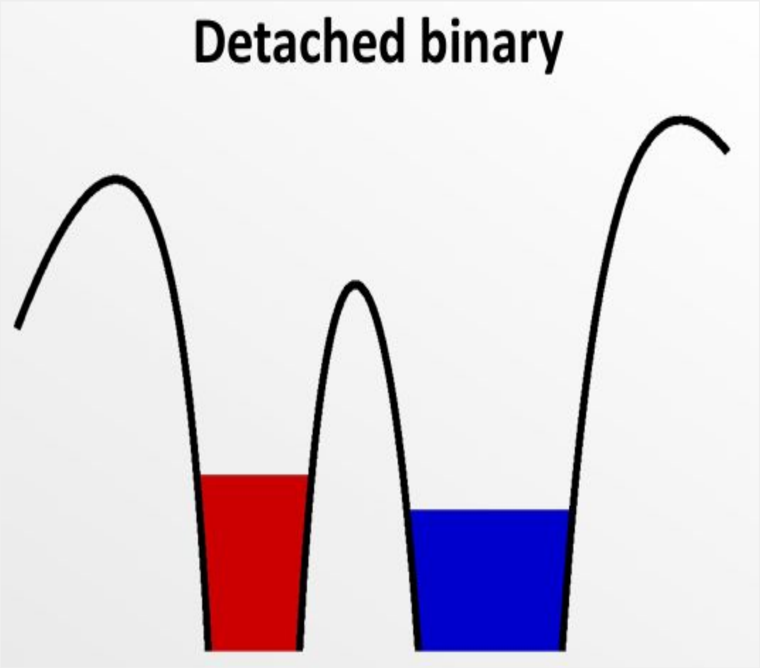
- If a star loses mass too quickly, it's Roche lobe will shrink faster than the physical star and mass transfer becomes dinamically unstable.

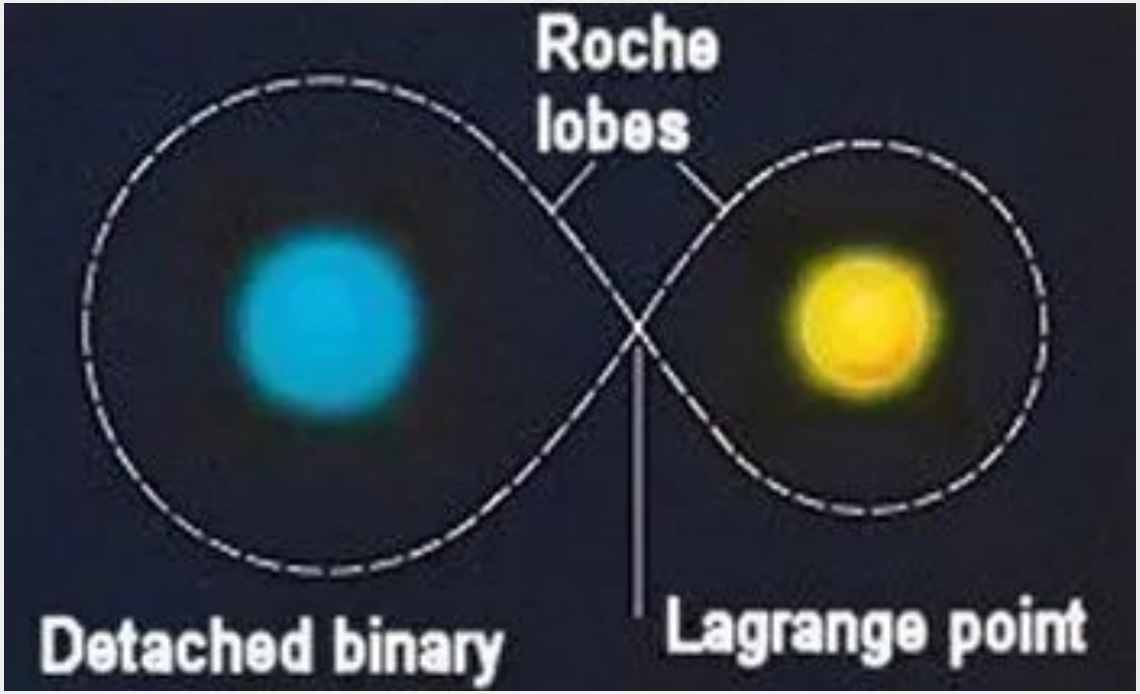
- If a star loses mass too slowly, it will shrink down to a size smaller than its Roche lobe, ending mass transfer.

In order for a steady (stable) mass transfer to occur, the size of the star must remain equal to its Roche lobe → semi-detached binary

Types of binaries based on RL

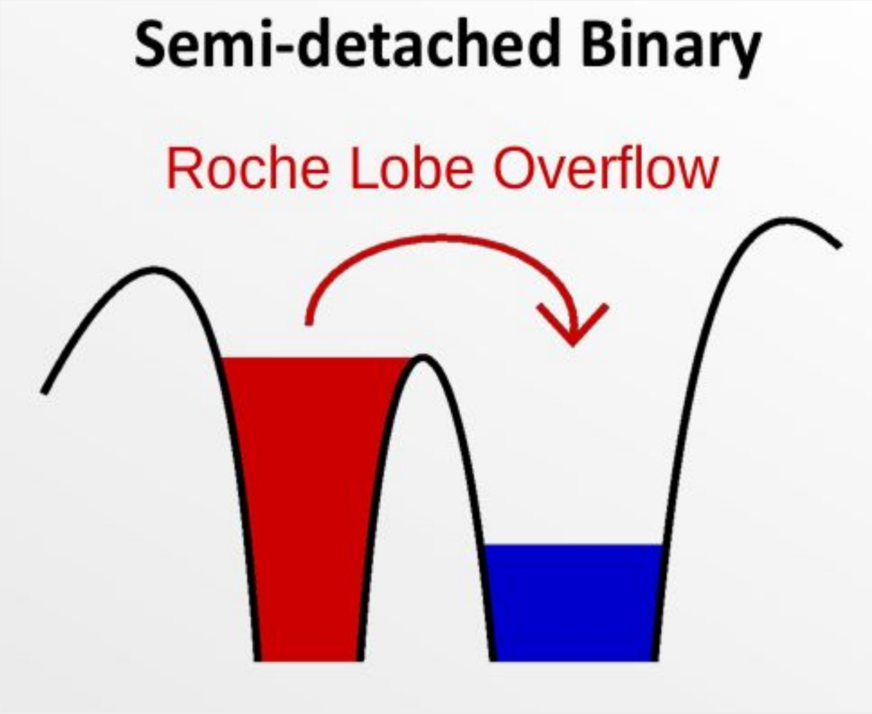
Detached binary: the two stars are both within their Roche lobes. Stellar evolution typically proceeds just as it would if the two stars evolved separately. BUT, it is also possible that tidal forces, circularization, co-rotation or wind interaction still occur.

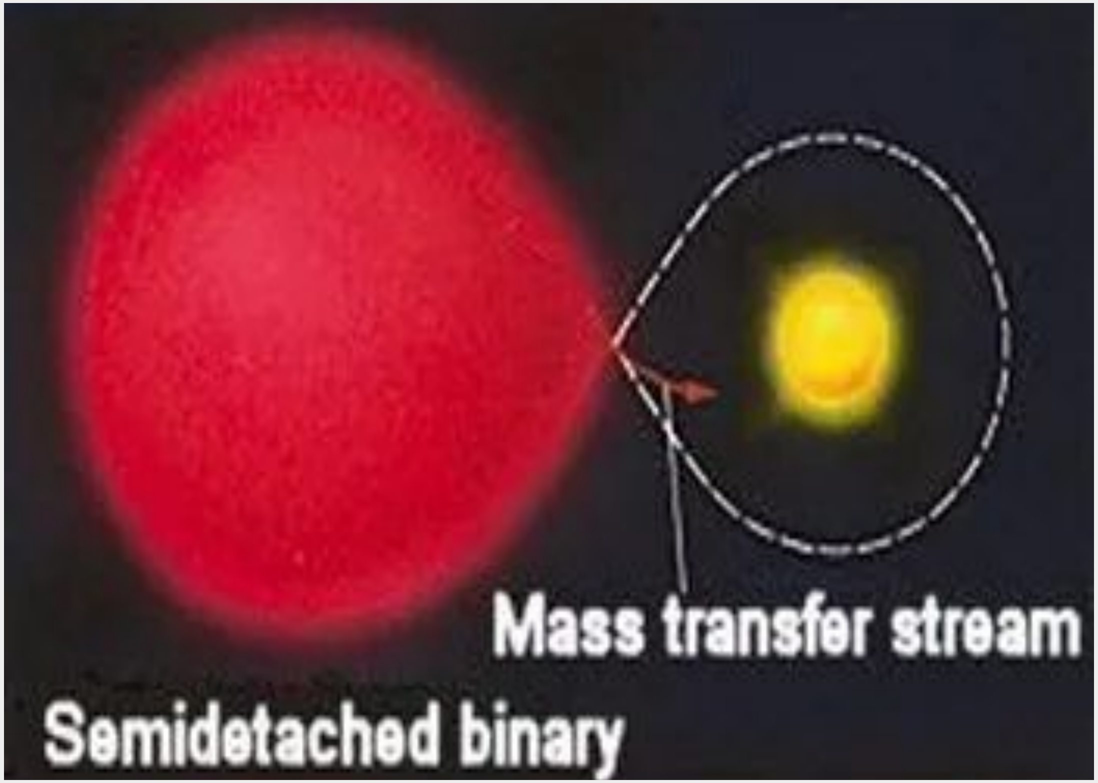




Types of binaries based on RL

Semi-detached binary: one star is "just" filling its Roche lobe and transfers mass stably to the other, which is not filling.



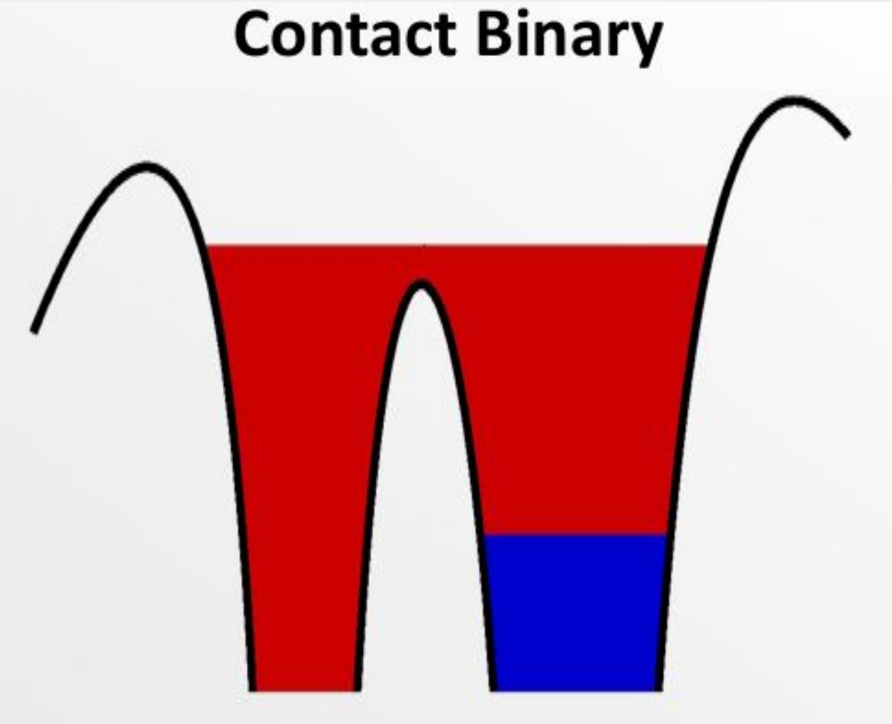


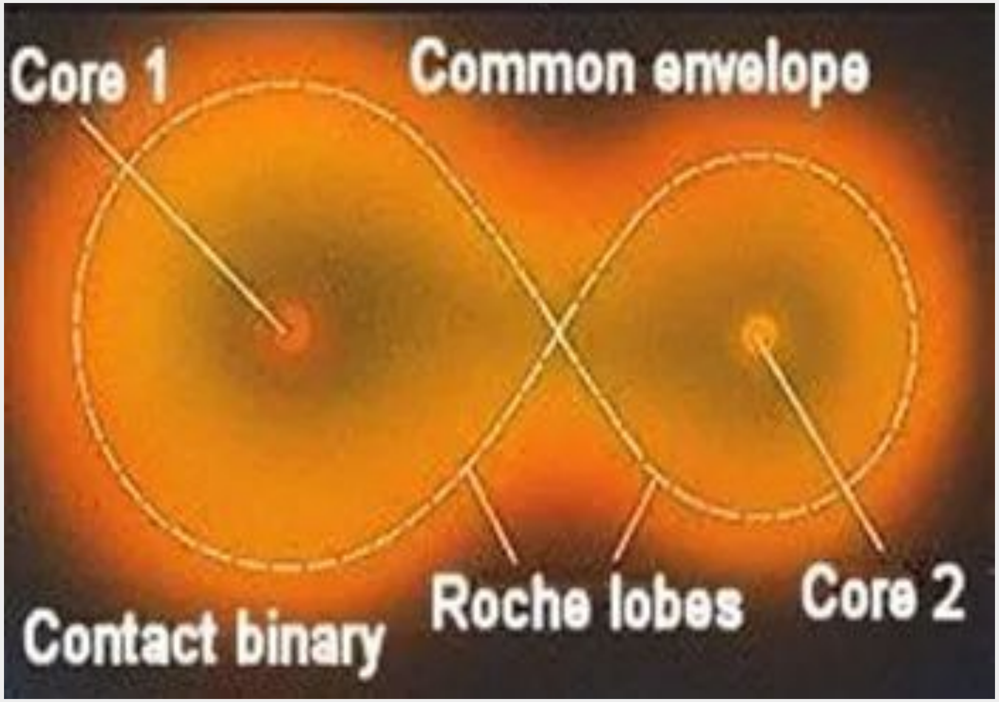
In many cases the inflowing material forms an accretion disc around the mass gainer.

Types of binaries based on RL

Contact binaries: both stars are overfilling their Roche lobes. The uppermost part of the atmosphere forms a **common envelope** that surrounds both stars.

Drag forces within the core of the stars and the envelope causes a loss of orbital energy, causing a reduction in the orbital separation (and can merge into a single rapidly-rotating star)





Next class: mass transfer