Tópicos

Close binary stars

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Lecture 1

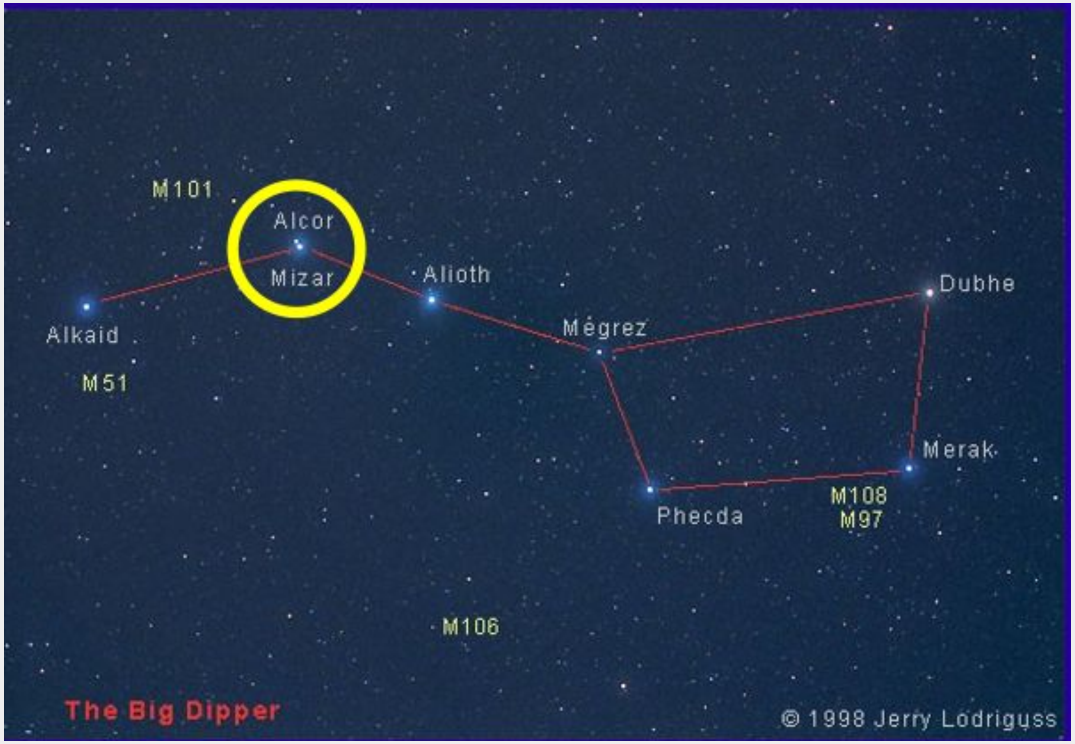
11/08

A bit of history

Soon after the construction of the first telescopes, also the first visual binary star was discovered. This was Mizar (ζ Ursae Majoris) discovered by the Italian astronomer J. B. Riccioli ~ 1650.

This and the subsequent discoveries were considered as mere curiosities of accidental line of sight coincidences.

Until **Isaac Newton** began publishing theories.



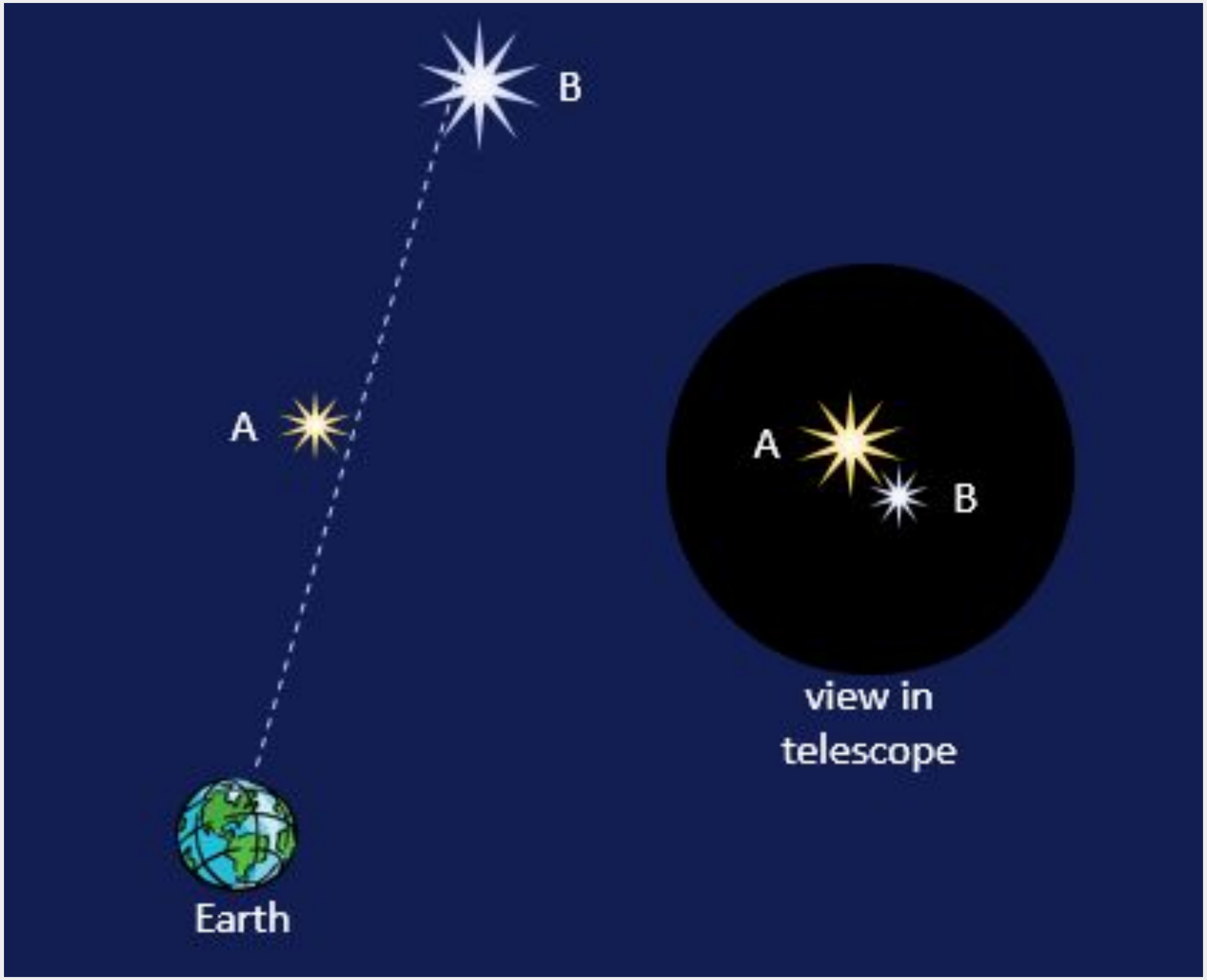
A bit of history

The first catalogue of binary stars, containing 80 systems, was published in 1781 by **C. Mayer**.
He speculated that “these stars could be small suns revolving around larger suns” (as predicted by I. Newton).

Wilhelm Herschel (1738–1822), owner of the largest telescope at that time, did not believe that binary stars may be physical systems.

Are binaries real?

Two stars that are not gravitationally bound but just appear close to each other through chance alignment with earth are known as **optical doubles** = fake (or coincident) binaries.

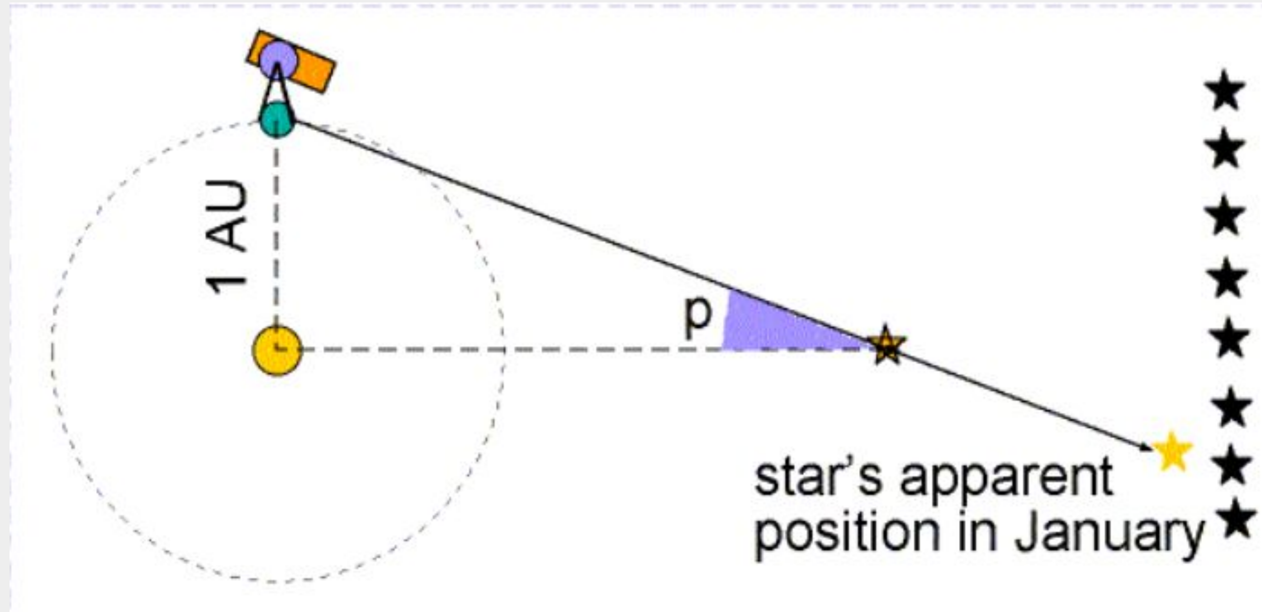


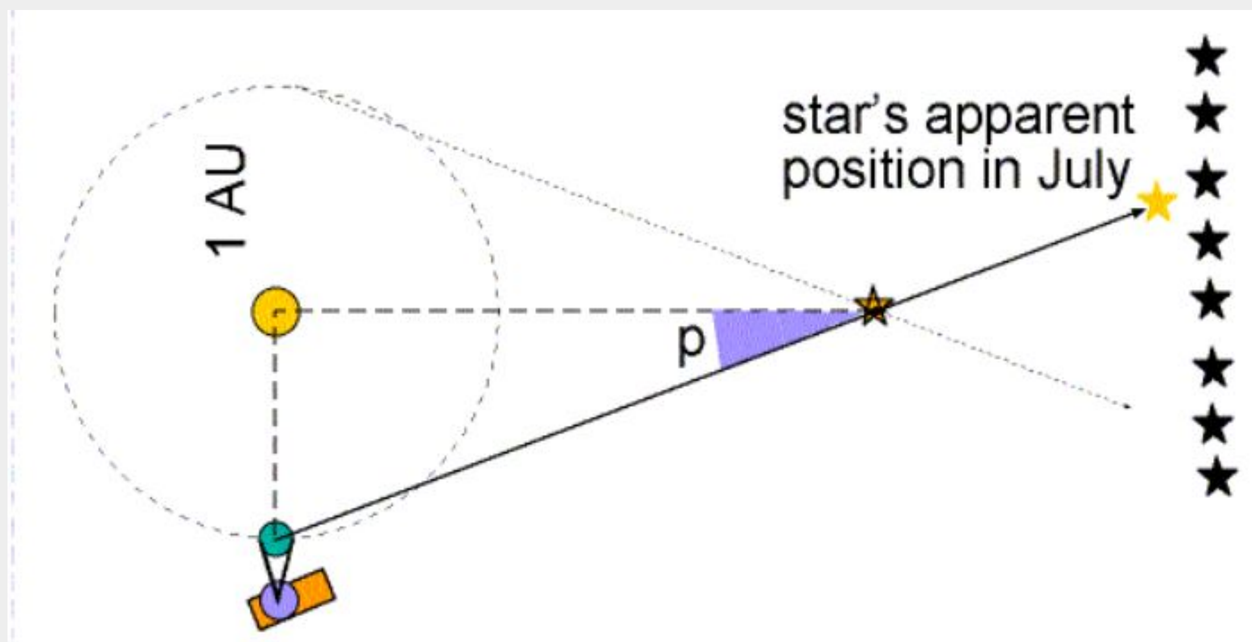
Parallax can prove it

Herschel wanted to observe binaries to find the distances to the stars (using parallaxes), in order to prove that they were just chance alignments.

$$d = \frac{1\ \text{AU}}{\tan p}$$

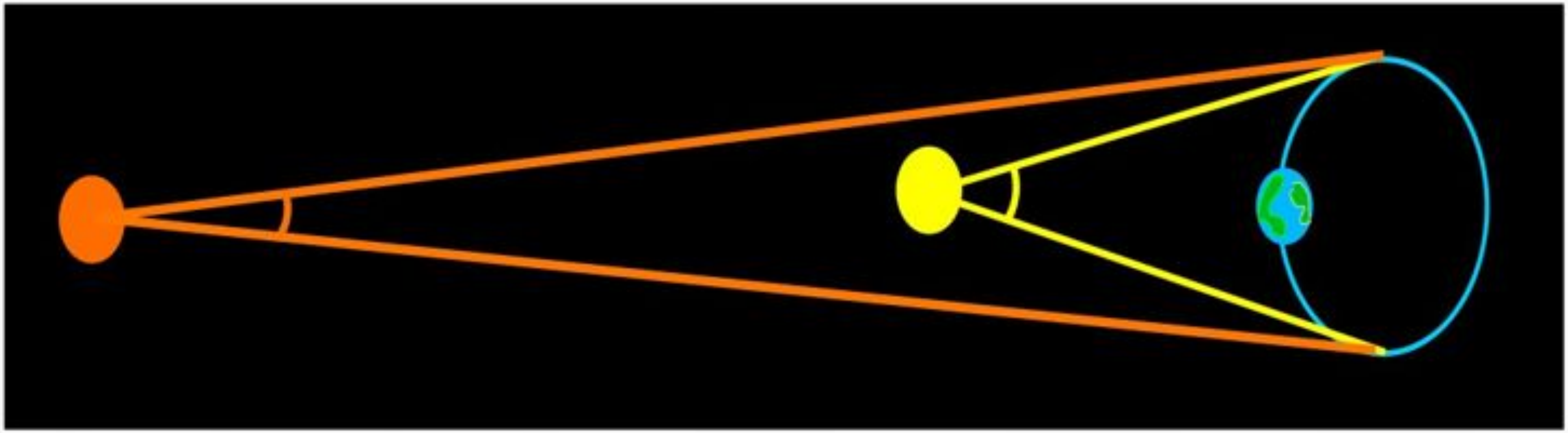
$$d = \frac{1}{p''}\ \text{pc}$$





Parallax can prove it

Fake or coincident binaries have different parallax (closer stars have larger parallax)



Herschel never succeeded in measuring the parallax, because at that time it was believed that all stars were alike (i.e. fainter stars were more distant).

However, during this study, Herschell noticed that the number of close pairs in the sky was too large to be just produced by chance alignment.

Together with his sister Caroline he compiled a very accurate **catalog of “pairs of stars”**, where they recorded positions of the stars on different nights for a long time.

Since he had many values of the positions, he then noticed that they moved in the sky as if they were orbiting one around the other!

But that meant that they were actually close to each other in real space, not just projected.

And if they were close then they were part of the same system, a binary stellar system!

Real binaries: history

Herschel discovered more than 800 double stars. He called these star systems **binary stars**.

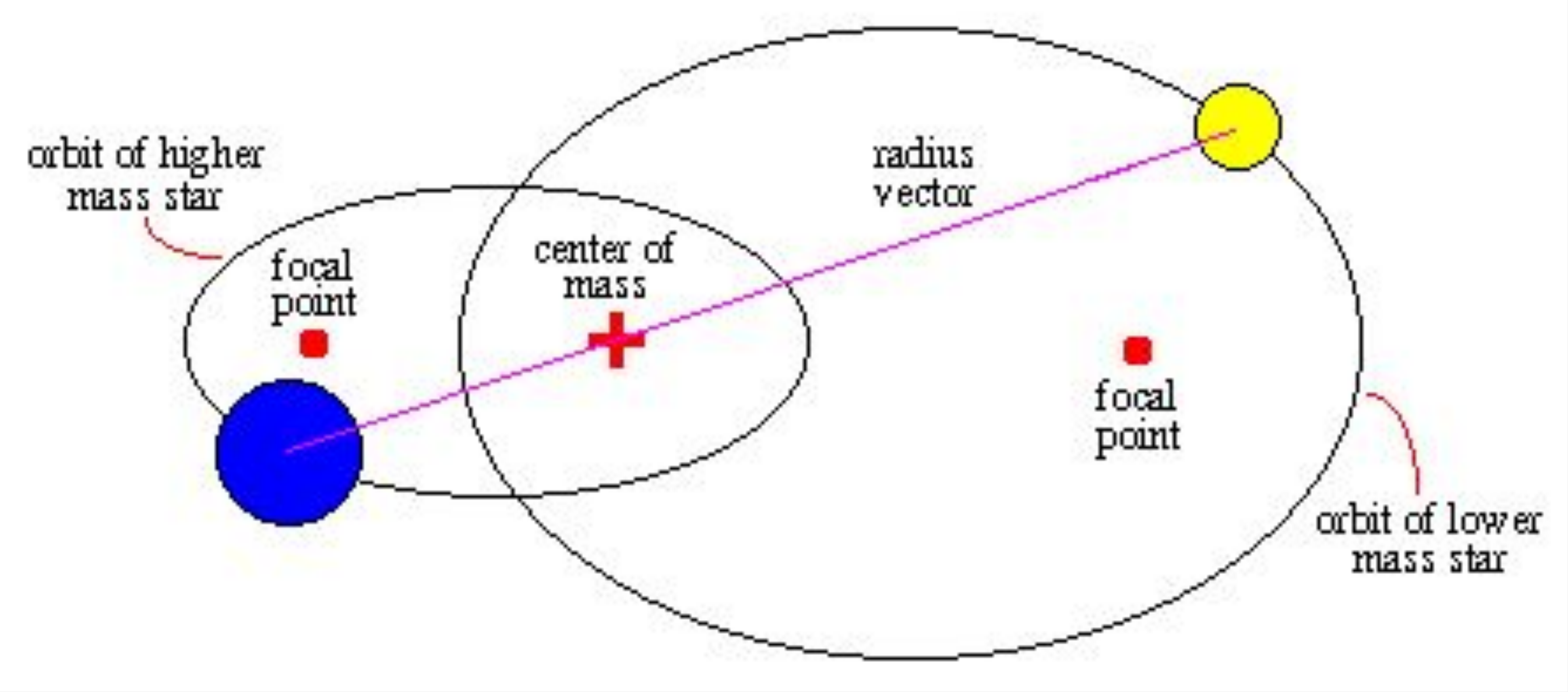
Provided the first evidence of the universality of Newton's law of gravitational attraction

→ gravity exists outside our solar system!!!

His son, John Herschel (1792–1871), continued the search for binaries and catalogued over 10,000 systems of two or more stars.

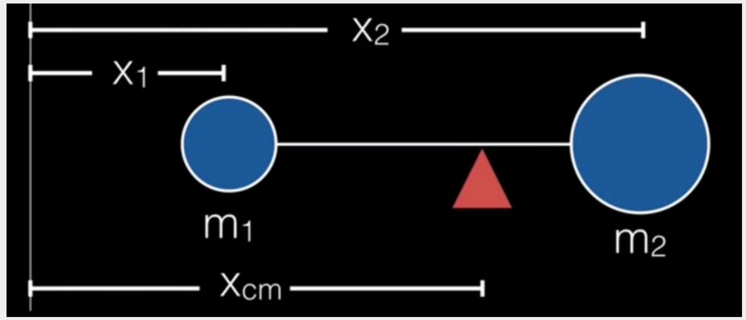
Real binaries

A binary star is a star system in which **two stars linked by their mutual gravity orbit around a common center of mass**.



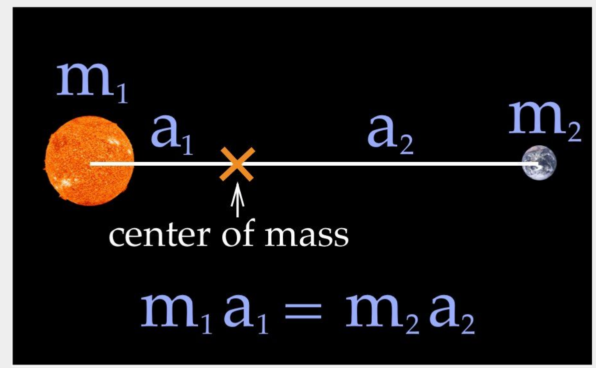
Center of mass

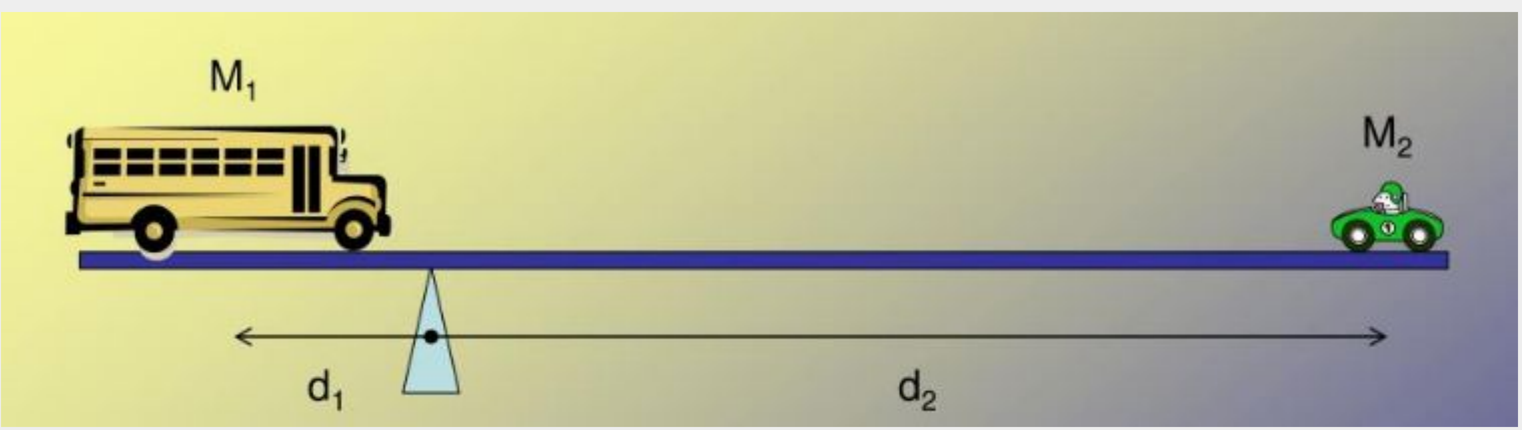
Measured from an arbitrary point, at a distance X_{CM} from the center of mass:



$$X_{cm} = \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2}$$

If the origin is at the center of mass →





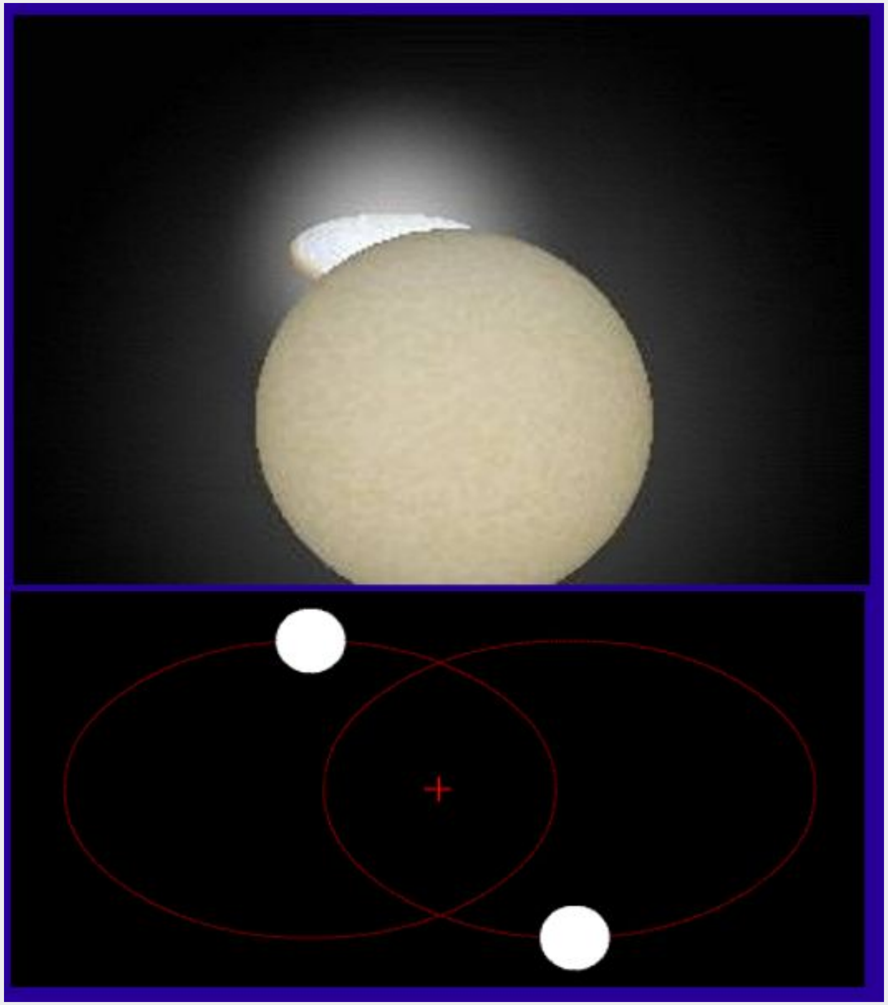
$$M_1 d_1 = M_2 d_2$$

Real binaries: wide range of separation

Some stars in binaries are so close to each other that their surfaces almost touch.

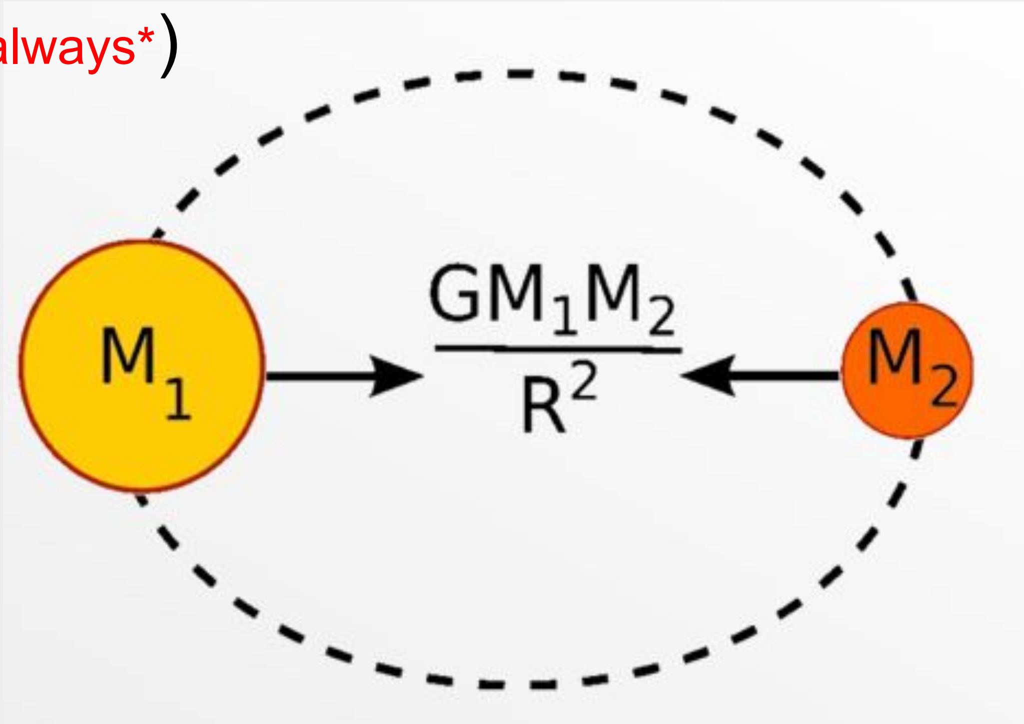
Others can be several 1000 AU away from each other and take hundreds of years to complete one orbit about the common center of mass.

Large period range: From minutes in the case of close double WDs (or even less for more massive remnants just before merge) to several thousands of years (longest documented is ~ 32,000 yr).



Nomenclature

Primary: the brightest (caution: not always*)
Secondary: companion



M_1: Mass of primary star
M_2: Mass of secondary star
Mass ratio: **q** = M_2/M_1
a: orbital separation
P: orbital period
e: Eccentricity
i: inclination (Face on = 0°, edge on = 90°)

Usually $q < 1$, but not always true (e.g. Algol paradox: the brightest star is a subgiant star, while the more massive companion is still on the main-sequence).

* some authors called the more massive star "primary", even if it is fainter, so that q is always below 1.

Formation

Formation of multiple systems

Different theories

Fission: a rapidly rotating object, already in hydrostatic equilibrium, breaks up by dynamical instability.

Capture: One star captures another initially unbound star into a bound orbit.

Fragmentation: collapsing cloud breaks up into several pieces during collapse, each of which forms a separate star.
Or form one protostar + disk, which subsequently breaks up.

Fission

- As a star contracts toward the main sequence, after disk accretion has been completed it tends to spin up

$$E_{grav} = \frac{GM^2}{R} \qquad E_{rot} = \frac{1}{2} I\Omega^2 \qquad I = kMR^2 \qquad \Omega \propto M^{-1}R^{-2}$$

Moment of inertia   Angular velocity

If angular momentum ($L = I\Omega$) is conserved, E_{rot} increases as the star contracts toward the MS → the ratio $\beta = E_{rot}/E_{grav}$ increases

- When β obtains a critical value (break up velocity), the star becomes unstable to perturbations that are not axisymmetric.

- Fission hypothesizes that non-axisymmetric perturbations will breakup the star.

- This mechanism would produce close binaries.

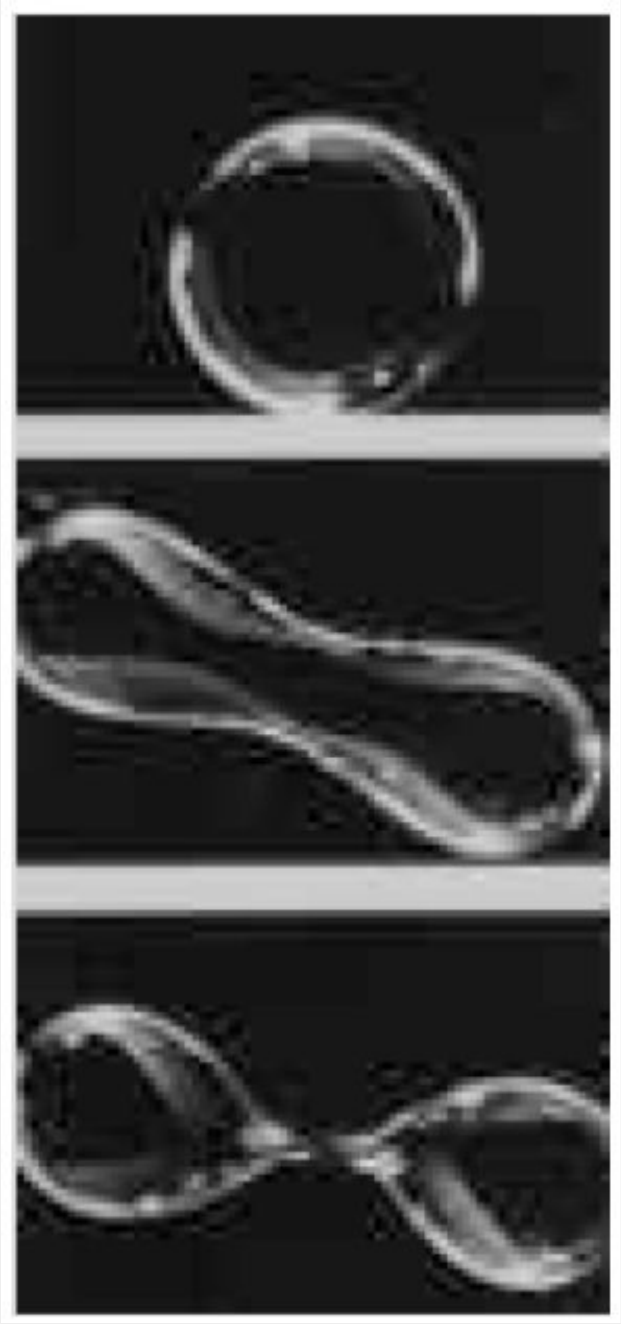
Fission

Equilibrium shapes of rotating bodies of incompressible fluids are well known: Spheres, Oblate spheroids & Ellipsoids

For example, water is an incompressible fluid. When drops spun up in zero gravity they fission into two

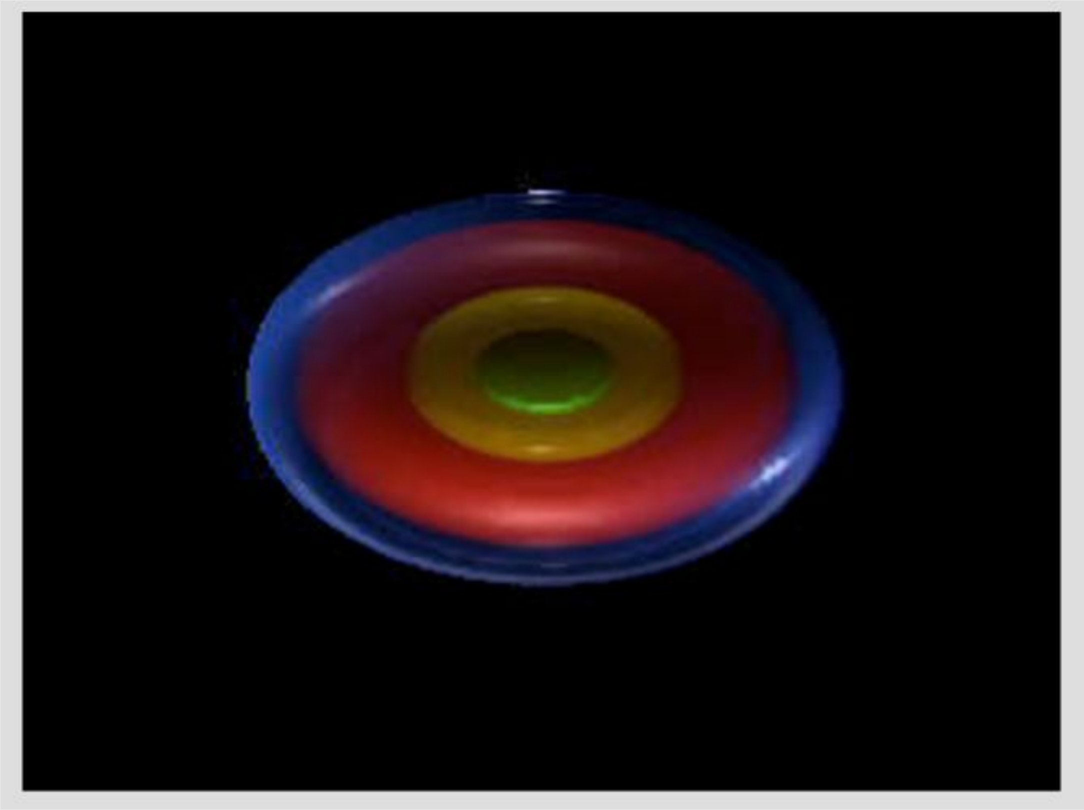
● Is this a way to form binary stars?

No, stars are compressible (much denser near the center than at the outside)
Do not have the surface tension like the droplet.



Fission

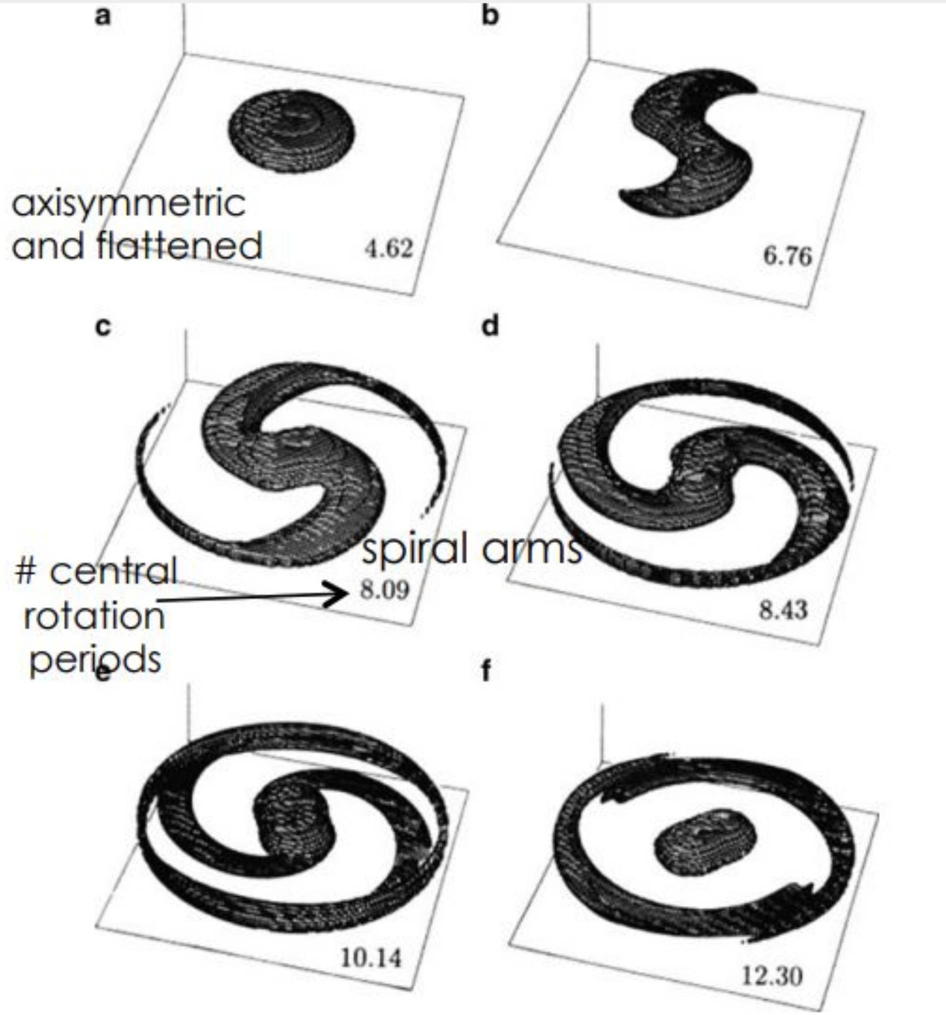
Difference: stars are compressible - much denser near the center than at the outside. Try spinning a star up...



Conclude: stars don’t fission - lose angular momentum in spiral arms instead.

Fission: example

- Figure on the right shows a calculation starting from a
  - Rapidly rotating polytrope of index 0.8
  - $\beta = 0.31$
- The figure shows that on a time scale of about 10 central rotation periods
  - System develops spiral arms
  - Spiral arms exert torques on the central object
  - Outcome is more slowly rotating central object plus a ring
- Don't get the right initial conditions for Fission, but it does give you a constraint on the maximum rotation rate of a star

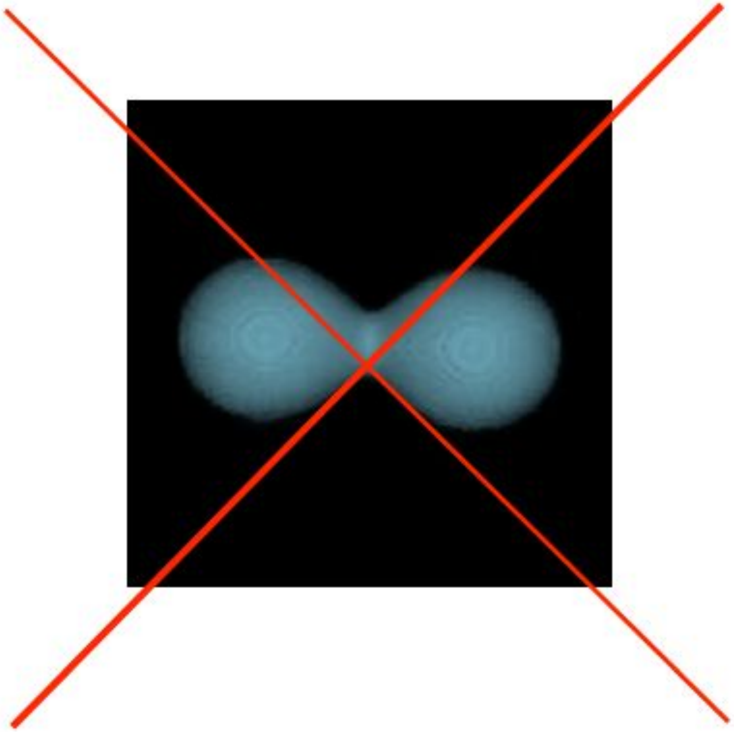


Numerical simulation of the evolution of a rapidly rotating polytrope of index 0.8 with initial $\beta = 0.31$. Times are indicated on each frame in units of the initial central rotation period.

Source: H. Williams, J.E. Tohline, ApJ **334**, 449 (1988)

Fission: summary

- **Stars do not Fission**
- Don't get the initial conditions needed for Fission
- Fission gives you a constraint on the maximum rotation



Formation of multiple systems

Different theories

~~**Fission**: a rapidly rotating object, already in hydrostatic equilibrium, breaks up by dynamical instability.~~

Capture: One star captures another initially unbound star into a bound orbit.

Fragmentation: collapsing cloud breaks up into several pieces during collapse, each of which forms a separate star.
Or form one protostar + disk, which subsequently breaks up.

Capture

Consider two stars isolated from all other stars.
If we can ignore the internal structure of the stars then:

Total energy = Potential energy + Kinetic energy, is conserved

- If $E_{total} < 0$: stars are bound
- If $E_{total} > 0$: stars are unbound and will remain so

For one star to capture another and form a binary, need to somehow lose energy from the system:
- into internal energy / fluid motion of the stars
- give energy to a third star

Tidal Capture

A very close approach of two stars can lead to:

- tidal distortion of the stars
- energy loss into internal energy within the stars
- formation of a bound system - tidal capture

Nearby passage with energy tidal dissipation → gravitationally bound pair.

The impact parameter has to be just right:

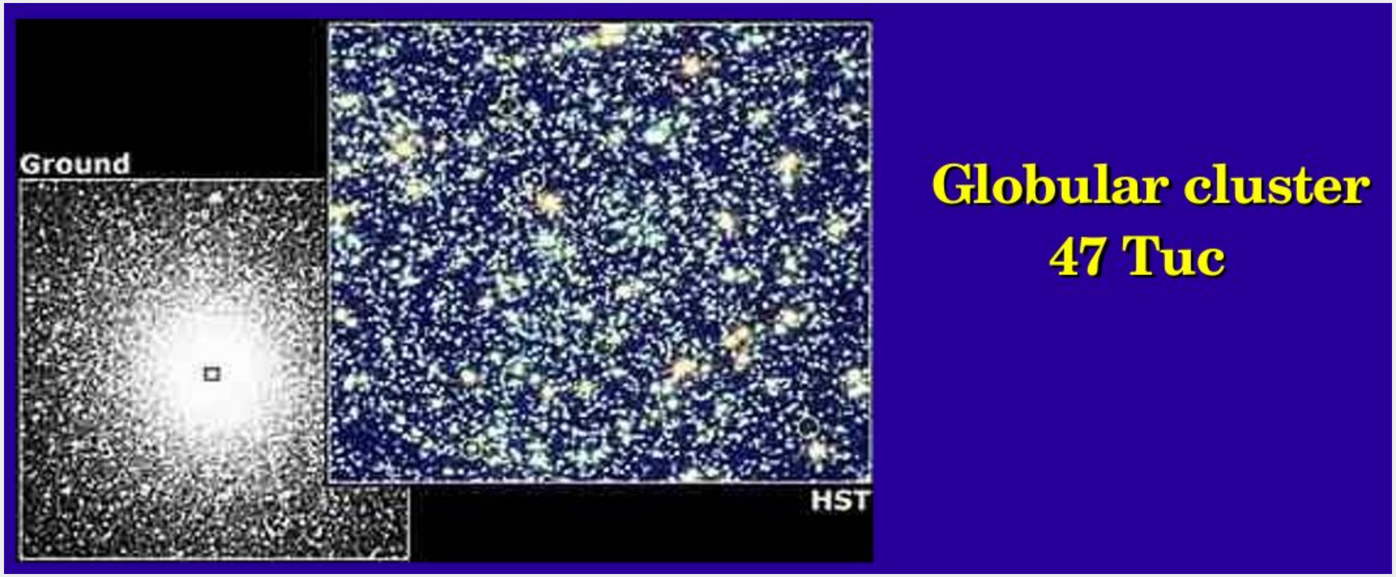
- Too close an approach: merger
- Too distant: insufficient energy dissipation to form binary

Tidal Capture

● Tidal capture requires extremely high stellar densities, like in globular clusters

Possible as a formation route for rare objects in the cores of globular clusters, but not as a general binary formation process.

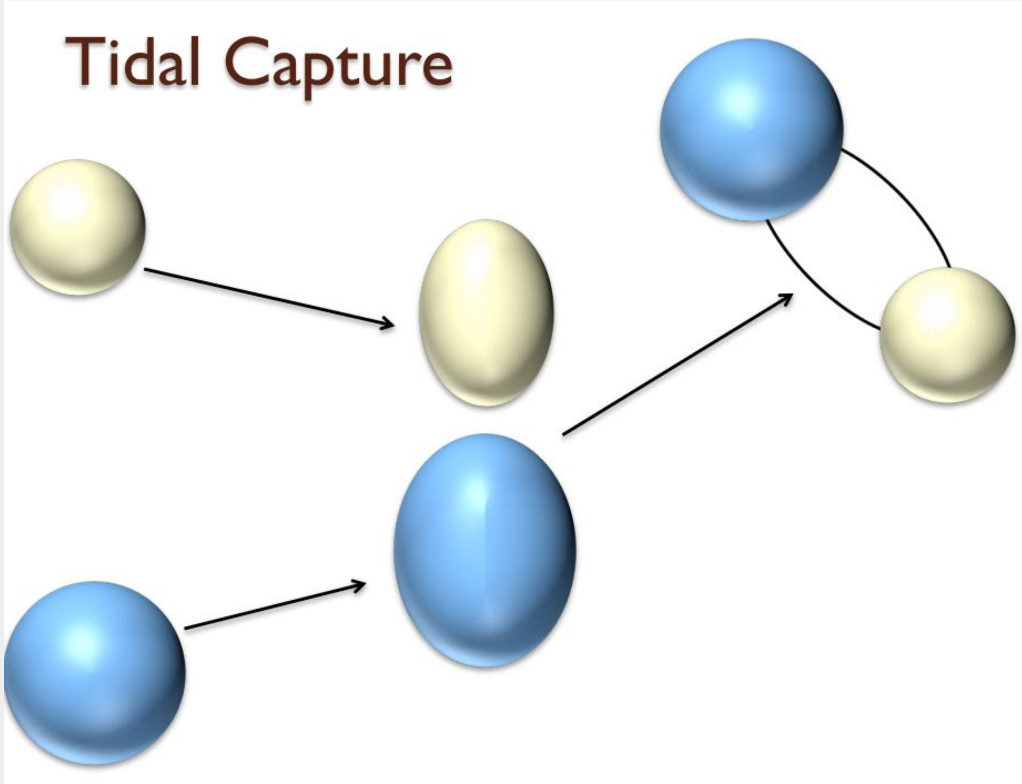
● Results in binaries whose separation is of the same order as their radii (i.e. close binaries)



Tidal Capture

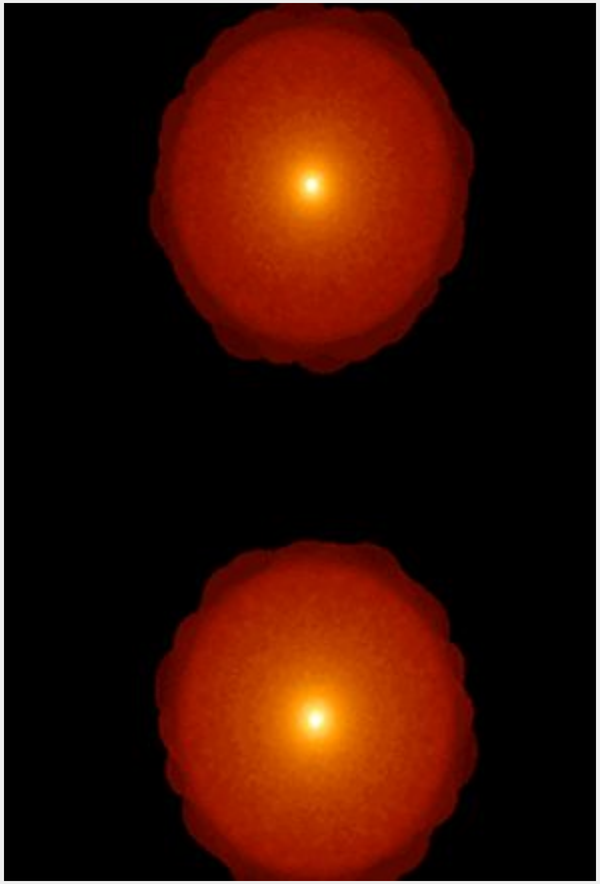
The capture cross-section can be explained geometrically as the area under the critical impact parameter (depends on mass and velocity).

- Cross sections are far too low in the galactic disk.
- May be important in dense young clusters.
- Would produce very tight binaries (Bodenheimer, 2011).



Dissipative Capture

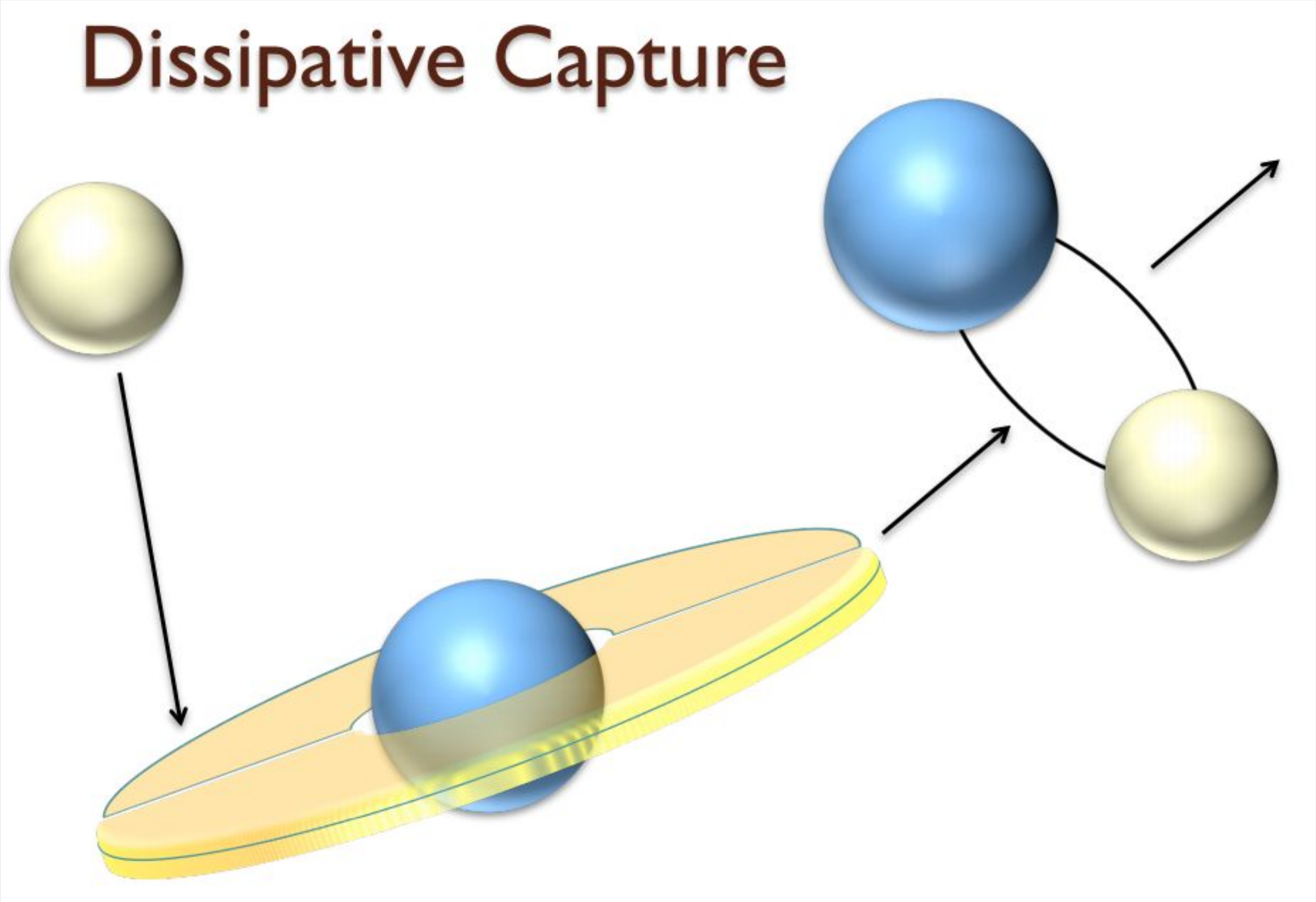
Another idea is to make the stars larger targets - form binaries via capture early on when the stars still have massive disks around them:



Still requires high densities of stars but may be feasible in young, small clusters.

Dissipative Capture

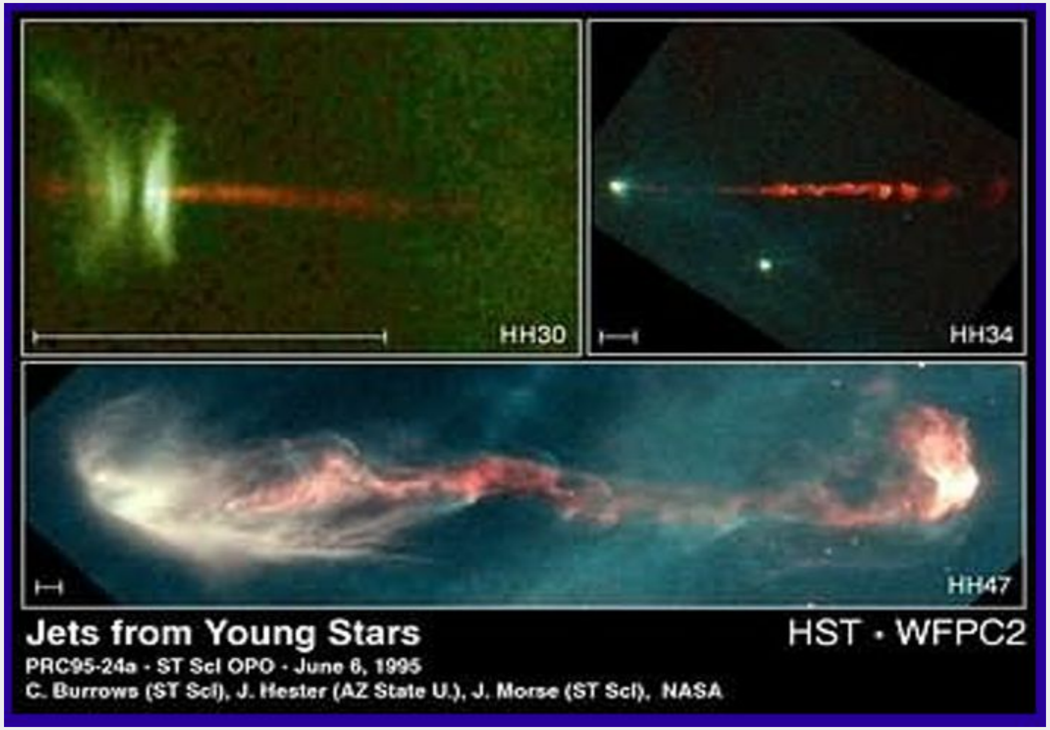
- More distant encounters can cause capture than for tidal capture.
- Only occurs in young clusters that are still forming stars (Bodenheimer, 2011).



Dissipative Capture

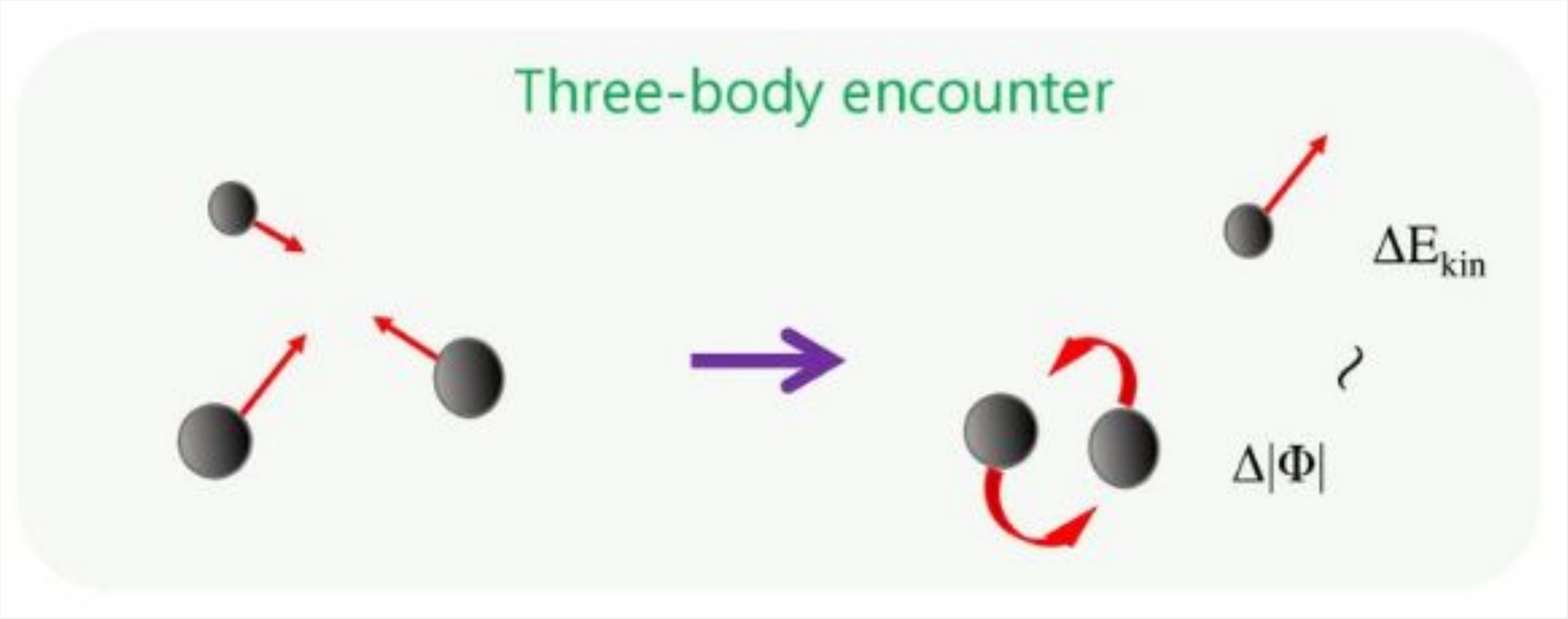
During the pre-main-sequence phase, T Tauri stars and Herbig Ae/Be stars indeed include circumstellar disks that are composed of the remainders of the star formation process. The presence of such a disk can increase the possibility of tidal capture considerably, when a star comes close to a disk around one of its neighbours.

Close encounter of a star to disks of protostars, such as Herbig Ae/Be or T Tauri stars results in a wide binary.



Three-Body Capture

In a triple star encounter, one star can take away extra kinetic energy, while the other two get bound.



- Cross sections are far too low in the galactic disk (again).
- Maybe important in dense young clusters.
- Would produce wide binaries (Bodenheimer, 2011).

Formation of multiple systems

Different theories

~~**Fission**: a rapidly rotating object, already in hydrostatic equilibrium, breaks up by dynamical instability.~~

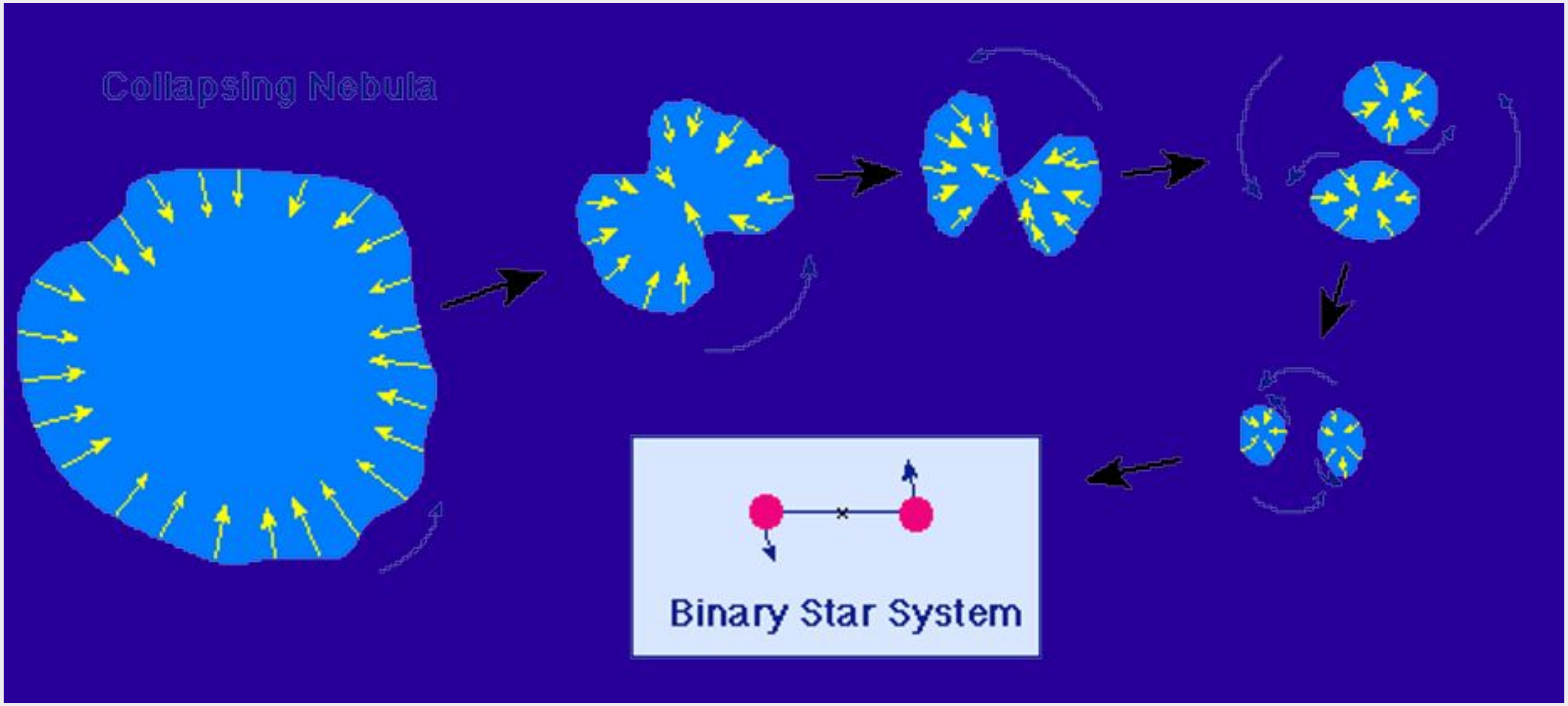
Capture: Tidal, dissipative or three body capture. Not impossible but also not very likely. <u>Needs dense environment.</u>

Fragmentation: ?

Fragmentation

Star formation: collapse of molecular cloud followed by fragmentation process (remember: isothermal collapse, jeans mass)

Fragmentation can lead to binary/multiple systems



Cloud collapse

molecular cloud collapses under self-gravity

if $M > M_J \sim 1.2 \times 10^5\, M_\odot \, \left(\frac{T}{100\ \mathrm{K}}\right)^{3/2} \left(\frac{\rho_0}{10^{-24}\ \mathrm{g\ cm^{-3}}}\right)^{-1/2} \mu^{-3/2}$

μ: mean molecular weight, M_J: Jeans Mass

Formation of multiple systems

Unless fragments form quickly, collapse will cause them to merge again later.

Need to start from initial conditions (pre-collapse) that are:

- not too strongly centrally concentrated
- have significant departures from spherical symmetry.

There are three types of fragmentation processes that can result in a binary:

a) prior to collapse

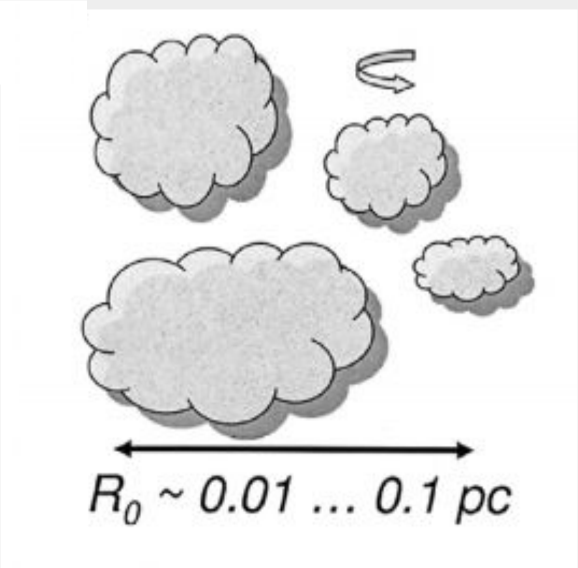
b) during isothermal collapse

c) disc fragmentation

a) Fragmentation prior to collapse (prompt fragmentation)

Depends critically on initial conditions (density, rotation, geometry and temperature of the cloud + any initial perturbations in density, shape, and velocity).

Most favorable case: when there are large density variations in the initial molecular cloud (sometimes called prompt fragmentation).



Pre-collapse cloud cores: observations reveal typical scales of $\approx$ 0.01−0.1 pc, $\rho \approx 10^{-18}$ g/cm^3, and T $\approx$ 10 K.

a) Fragmentation prior to collapse (prompt fragmentation)

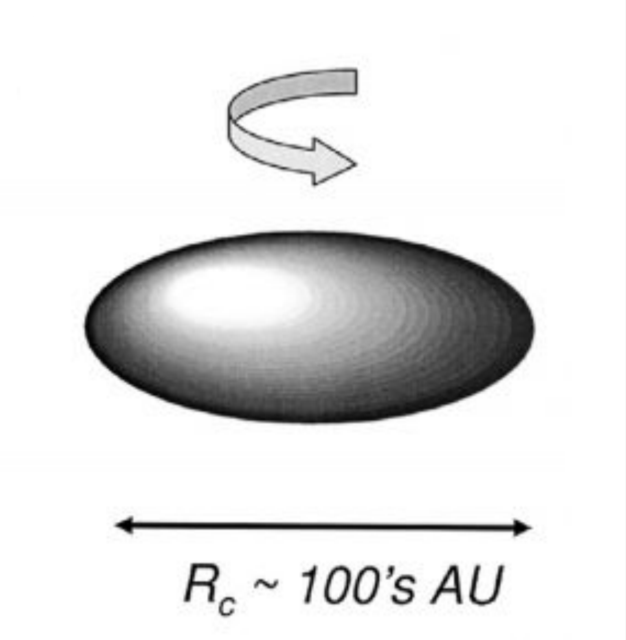
Fragments, arisen from the same molecular cloud, could end up so near to each other that they form a bound system

→ Interaction between the fragments can take place before the beginning of the definitive collapse into a protostar.
During this process energy can be dissipated so the fragments approach one another before protostars are formed.

→ **Wide binaries** can be produced this way

b) Fragmentation during isothermal collapse (rotational fragmentation)

First collapse phase nearly homologous isothermal.
Conservation of angular momentum evolves the object into an oblate, compact, fast rotating spheroid.

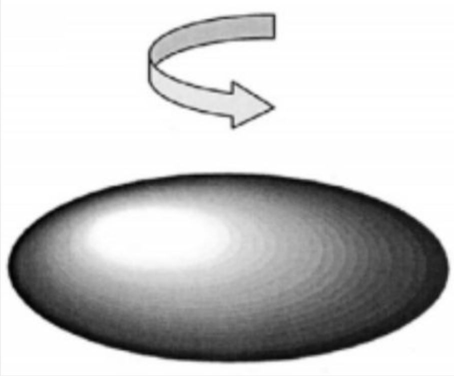


At the end of the isothermal phase $\rho \approx 10^{-13}$ g/cm^3

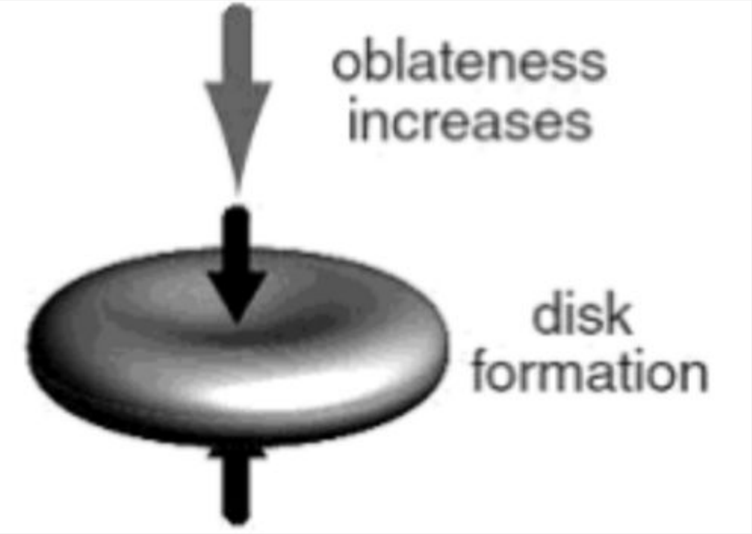
When, and under what conditions, does the collapsed core then fragment?

b) Fragmentation during isothermal collapse (rotational fragmentation)

This split is caused by fast rotation and is sometimes called rotational fragmentation.



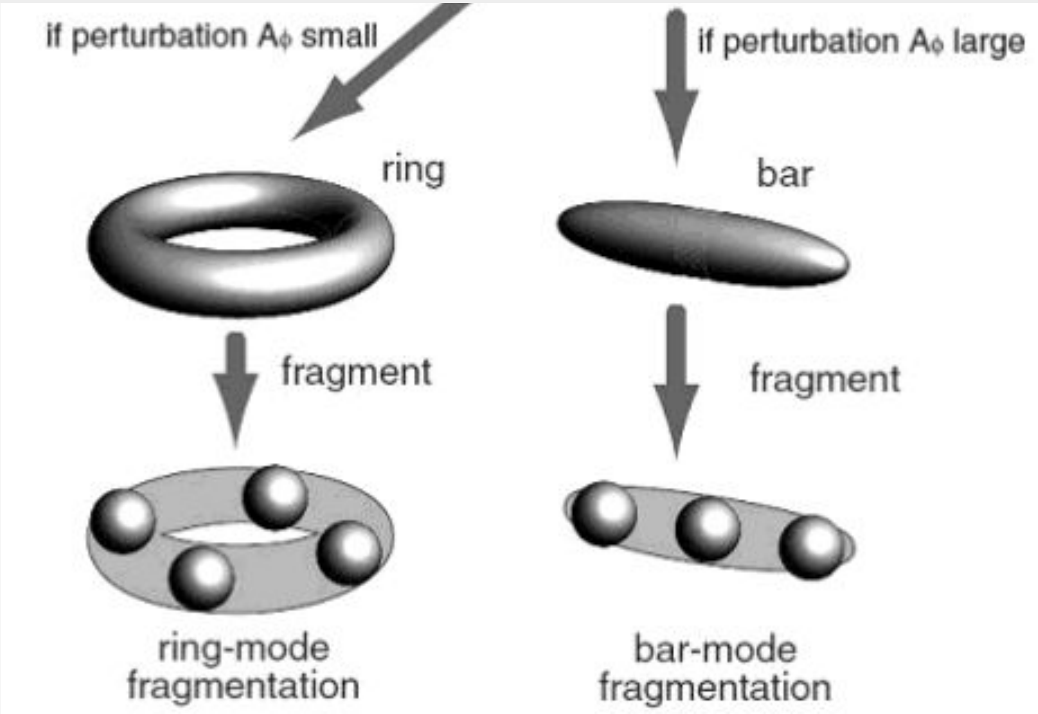
When a developing protostar is rotating at a high rate, the "*centrifugal forces*" (inertia) prevent the further collapse onto the central object.



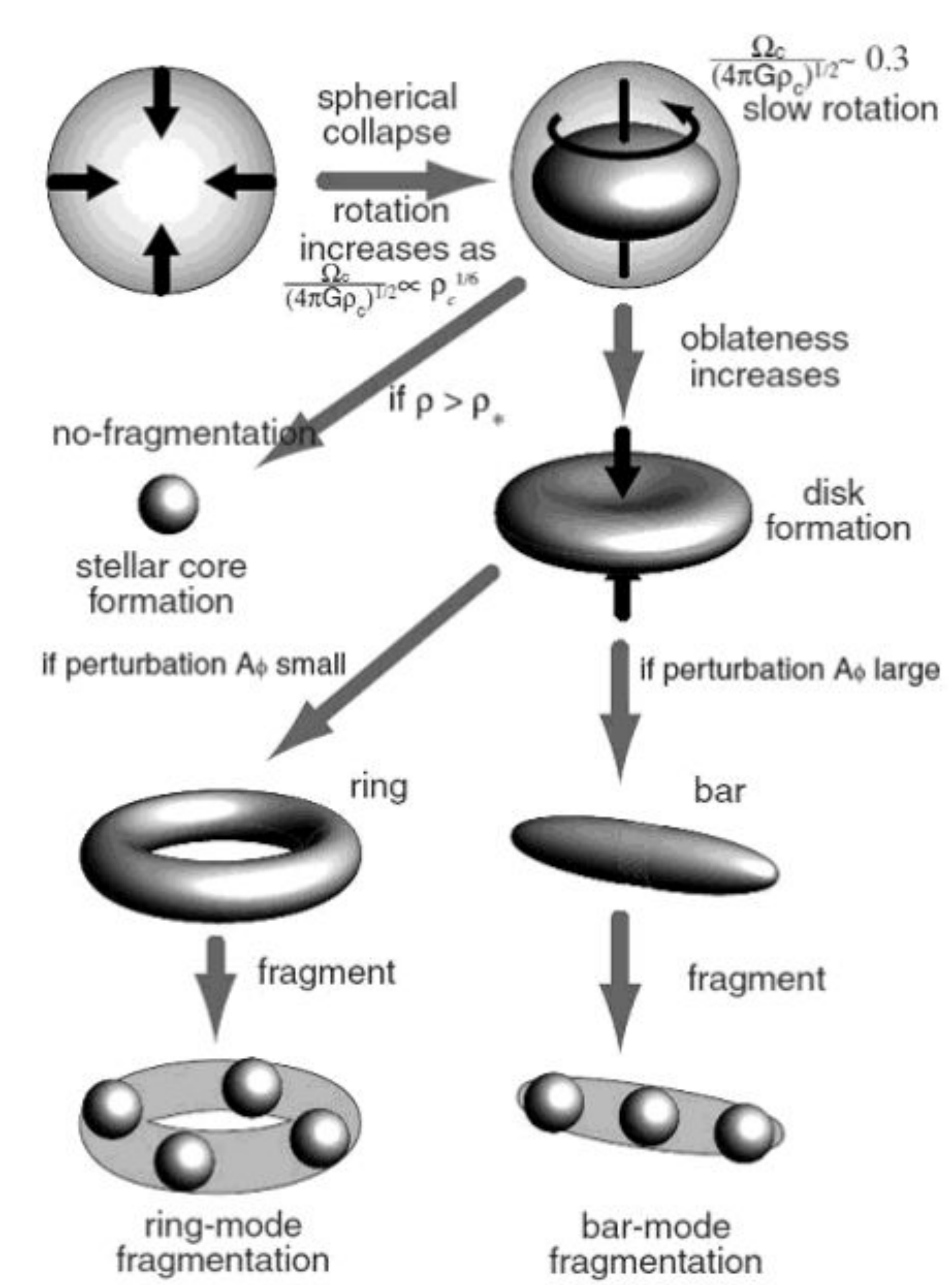
Rotationally-driven fragmentation occurs when the cloud achieves a high value of β (rotational to gravitational energy) **during isothermal collapse**, before the onset of adiabatic evolution, i.e. before density gets too high.
(according to simulations, $\beta_{crit} \approx 0.02$)

b) Fragmentation during isothermal collapse (rotational fragmentation)

The protostar keeps on accreting mass from the disk, but the quick rotation prevents the mass from falling into the dense core, producing a ring-shaped or bar-shaped configuration.



Disruptions in this bar/ring can then cause an asymmetrical mass distribution, which finally collapses separately



Schematic for the evolution of rotating cores.

If the core reaches the stellar density ρ_* before the disk formation (due to critical rotation), it does not fragment.
(remember, fission of stars does not work!)

Otherwise, it fragments in the bar mode or ring mode, depending on the amplitude of the bar-mode perturbation at the time of disk formation.

Machida et al. 2008

b) Fragmentation during isothermal collapse (rotational fragmentation)

Sterzik et al. (2003):

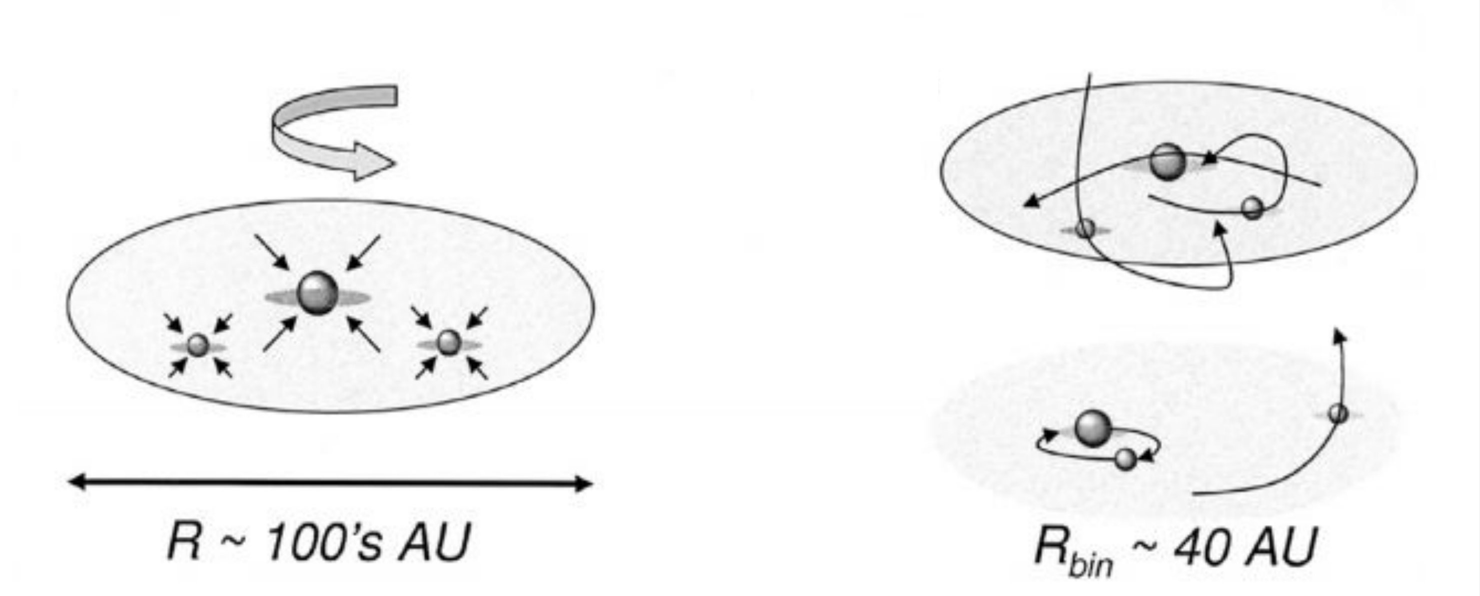
How do binary separations depend on cloud initial conditions?
https://www.aanda.org/articles/aa/pdf/2003/45/aa0219.pdf

The typical separation scale of binaries produced via this mechanism is too large.

Additional processes must be invoked to reduce the final characteristic scale of the binaries in order to populate the short-period part of the binary distribution.

Dynamical interactions within multiple systems (KL, tidal friction, escaping stars) are an essential ingredient.

Interactions after fragmentation



Sterzik et al. (2003)

The authors assumed a few (<10) fragments will survive independently and form protostars. The spatial distribution of the individual protostars is, initially, confined by the volume of the isothermal core (≈ 100's AU)

By that time, dynamical interactions between the individual protostars become important.

In multiple systems, some stars can take away energy and escape, tightening the orbit of others

c) Disk Fragmentation

The material in the circumstellar disk of a protostar clumps together, fragmenting to form a companion in orbit around the first protostar (similar to planet formation).

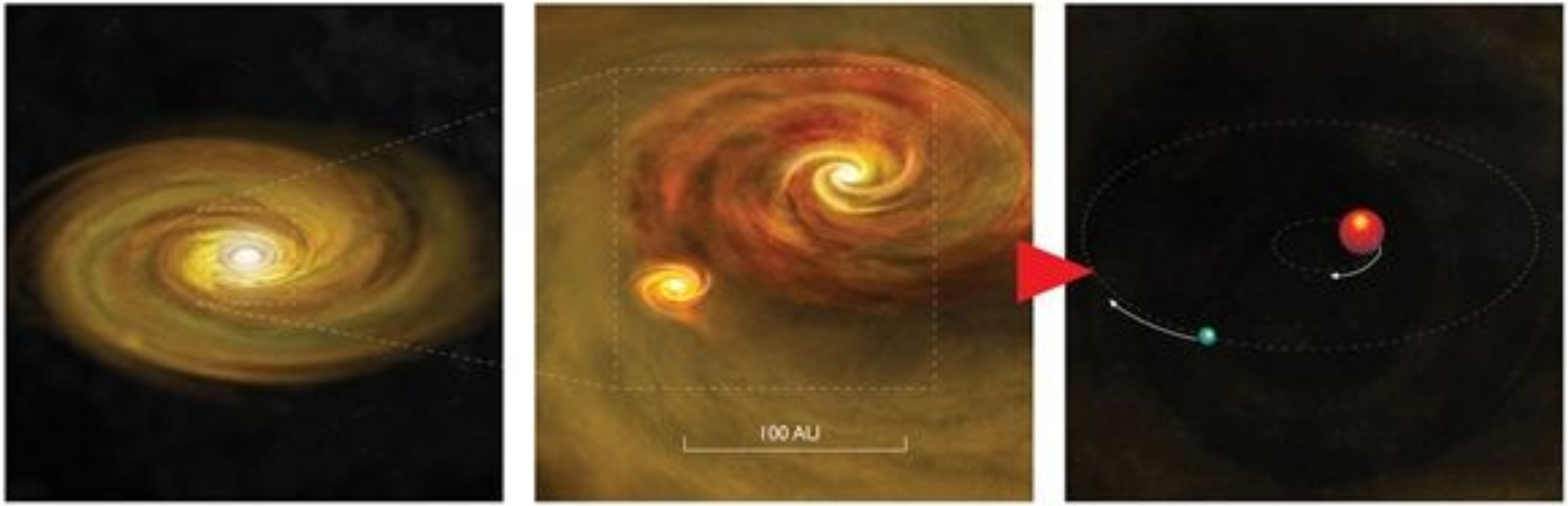
This mechanism only works properly if there is **enough mass in the disk**. So this is only possible during the **early stages of disk formation**.

For M1 > $1M_{\odot}$, disk fragmentation is progressively more likely with increasing primary mass (Kratter et al. 2006, 2011)

There is observational support!

*Is not the same as rotational fragmentation, because here you already have a central protostar.

c) Disk Fragmentation



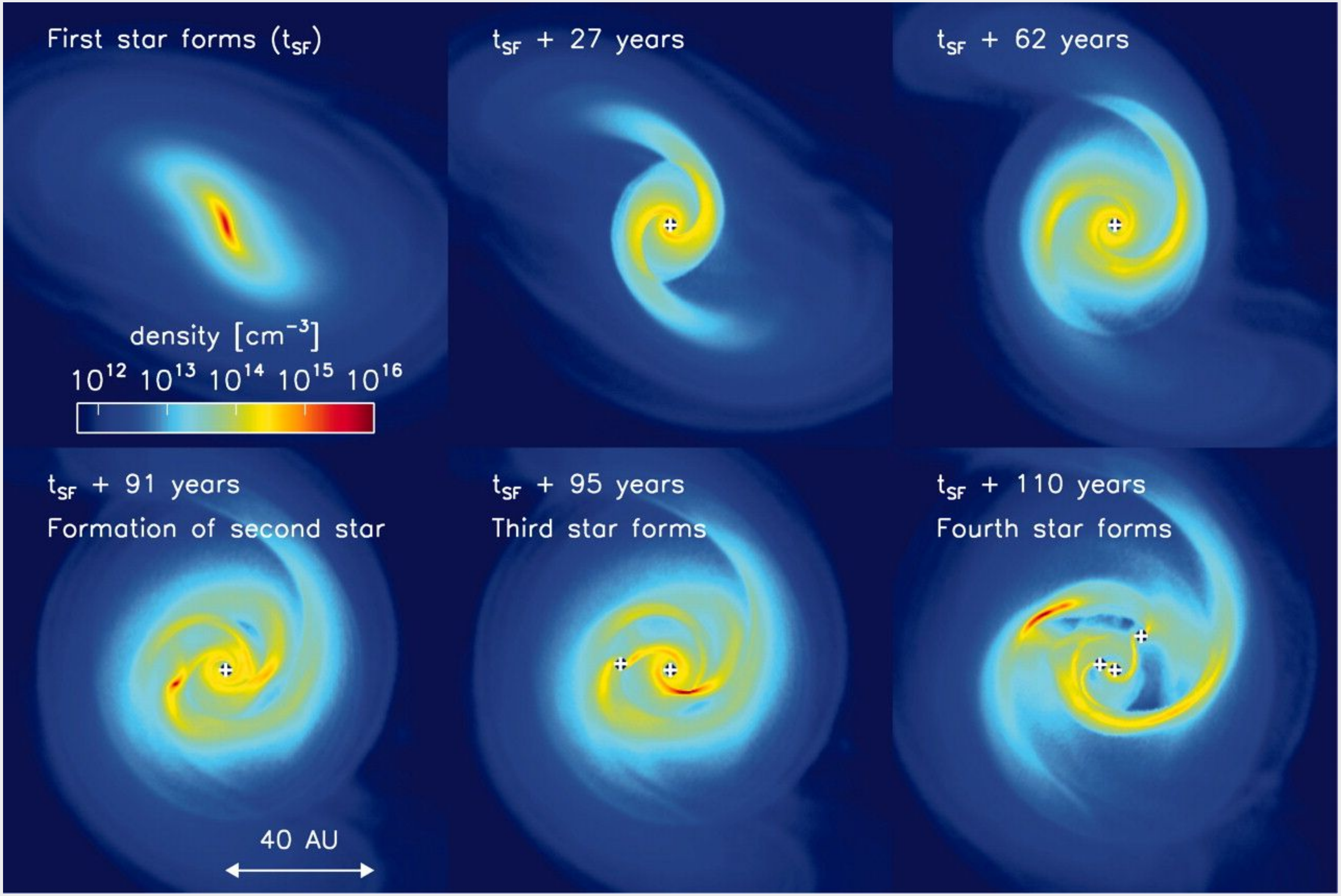
Young star surrounded by a rotating disk of gas and dust (left).

The disk fragments under its own gravity, with a second star forming within the disk (~100 AU) surrounded by its own disk (center)

The two stars form an orbiting pair.

Bill Saxton, NRAO/AUI/NSF

c) Disk Fragmentation



Density evolution in a 120 AU region around the first protostar, showing the buildup of the protostellar disk and its eventual fragmentation (Clark et al 2011)

Summarizing:

Formation of binary systems:

- ~~Fission~~ (does not work)
- Capture (tidal, dissipative, three-body). More likely in dense environments.
- Fragmentation (promt fragmentation, rotational fragmentation, disk fragmentation)

Next class

- Statistics: Statistics: Binary Fraction
- Triple/multiple systems
- Initial parameters distributions