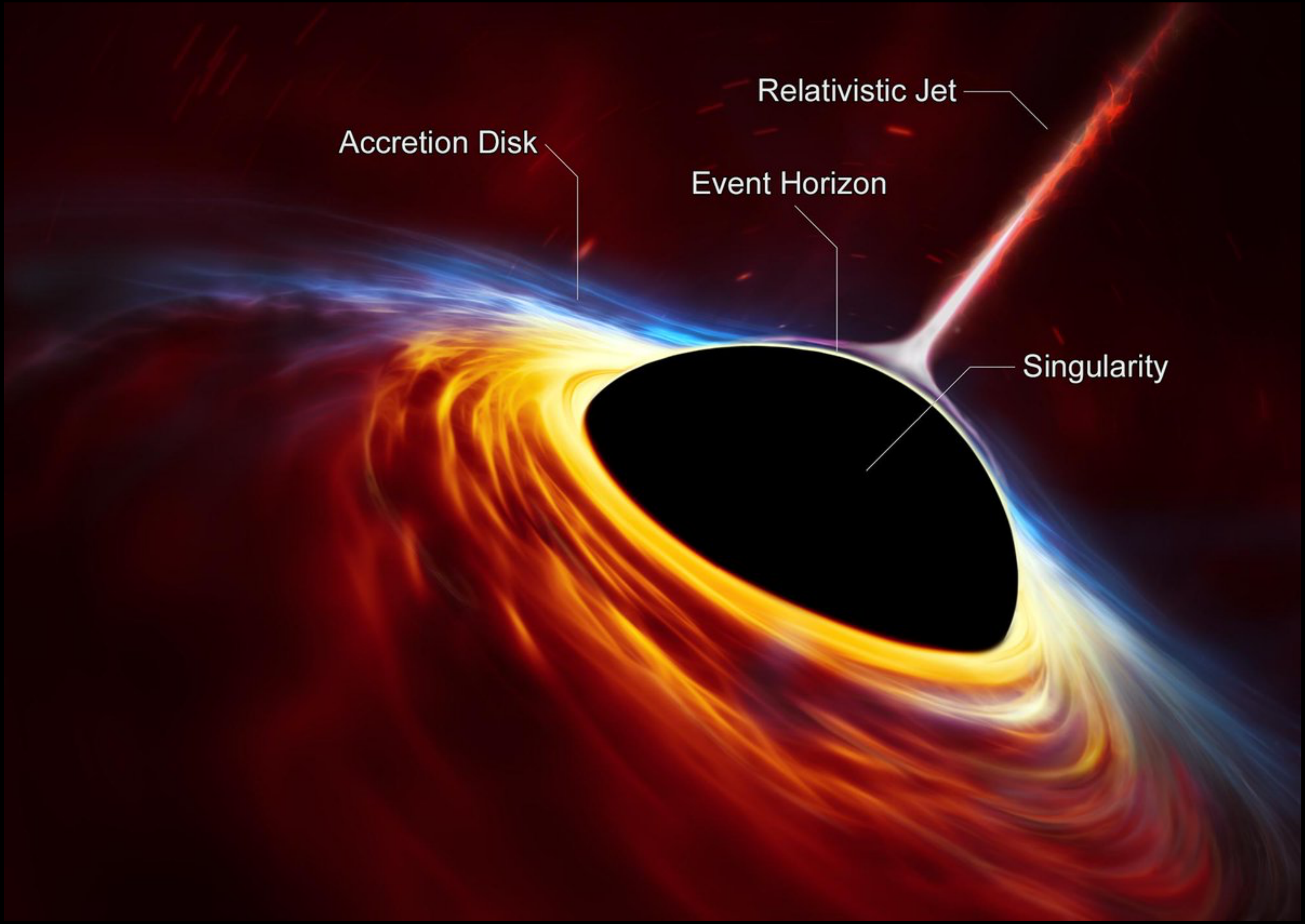

Relativistic Jet
Accretion Disk
Event Horizon
Singularity

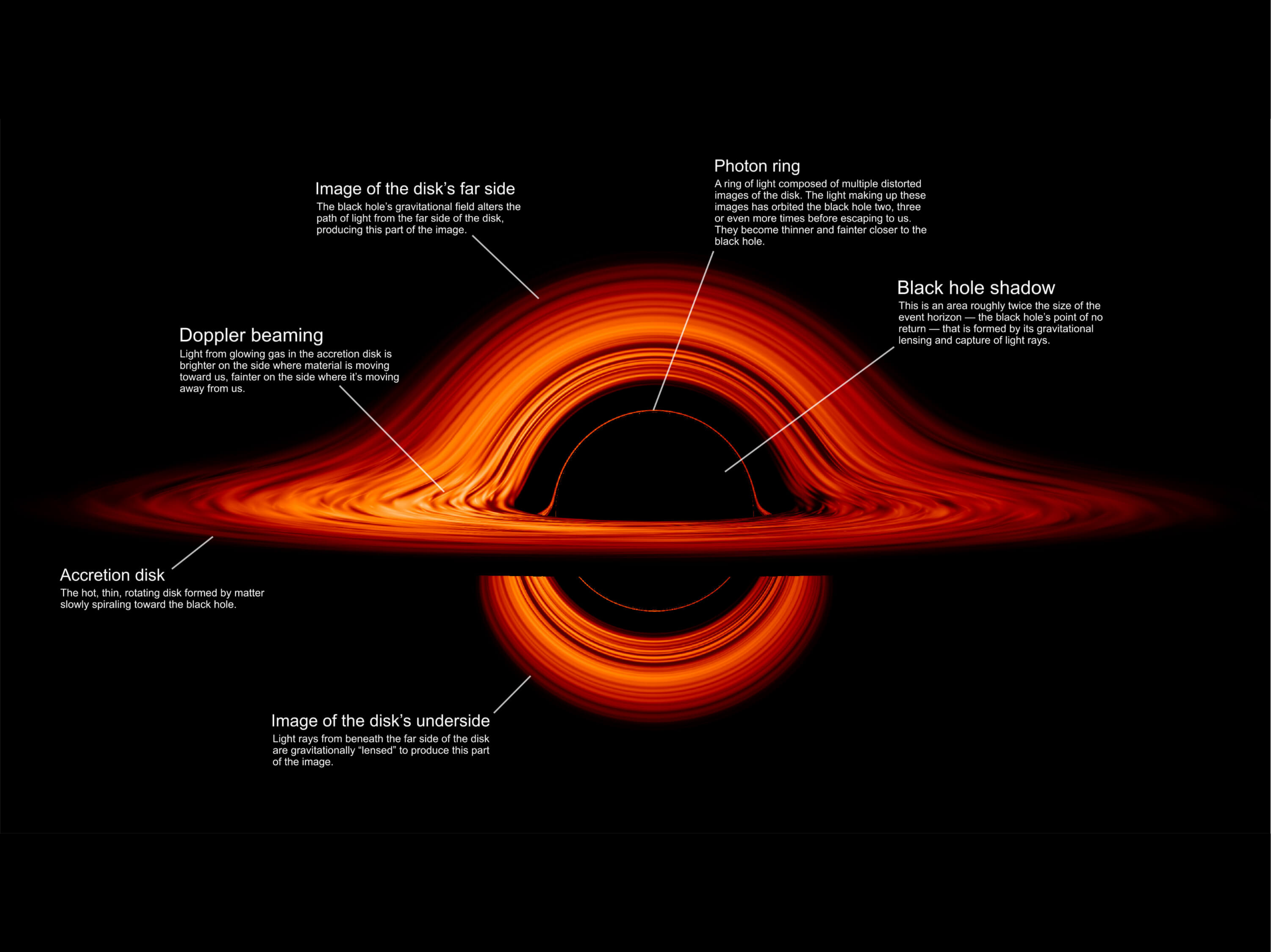
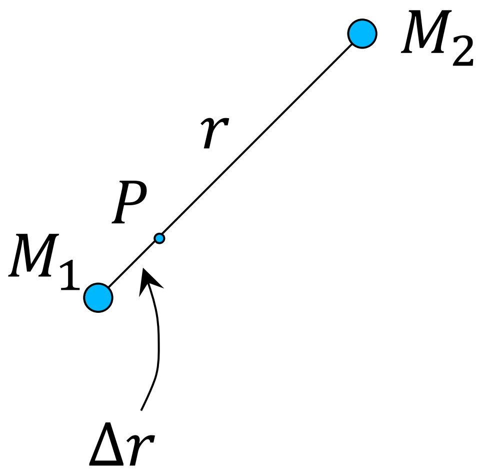


Image of the disk's far side
The black hole's gravitational field alters the path of light from the far side of the disk, producing this part of the image.
Photon ring
A ring of light composed of multiple distorted images of the disk. The light making up these images has orbited the black hole two, three or even more times before escaping to us. They become thinner and fainter closer to the black hole.
Black hole shadow
This is an area roughly twice the size of the event horizon — the black hole's point of no return — that is formed by its gravitational lensing and capture of light rays.
Doppler beaming
Light from glowing gas in the accretion disk is brighter on the side where material is moving toward us, fainter on the side where it's moving away from us.
Accretion disk
The hot, thin, rotating disk formed by matter slowly spiraling toward the black hole.
Image of the disk's underside
Light rays from beneath the far side of the disk are gravitationally "lensed" to produce this part of the image.

Interacting Binary Stars

- many stars are found in binary systems
- close binaries generally have circular orbits
- compact binaries are extremely important to astrophysics

Interacting Binary Stars



- acceleration at P due to M_1

$$a_{grav} = \frac{GM_1}{(\Delta r)^2}$$

- differential (tidal) acceleration of P relative to M_1 due to M_2

$$a_{tide} = GM_2\left(\frac{1}{(r-\Delta r)^2} - \frac{1}{r^2}\right)$$

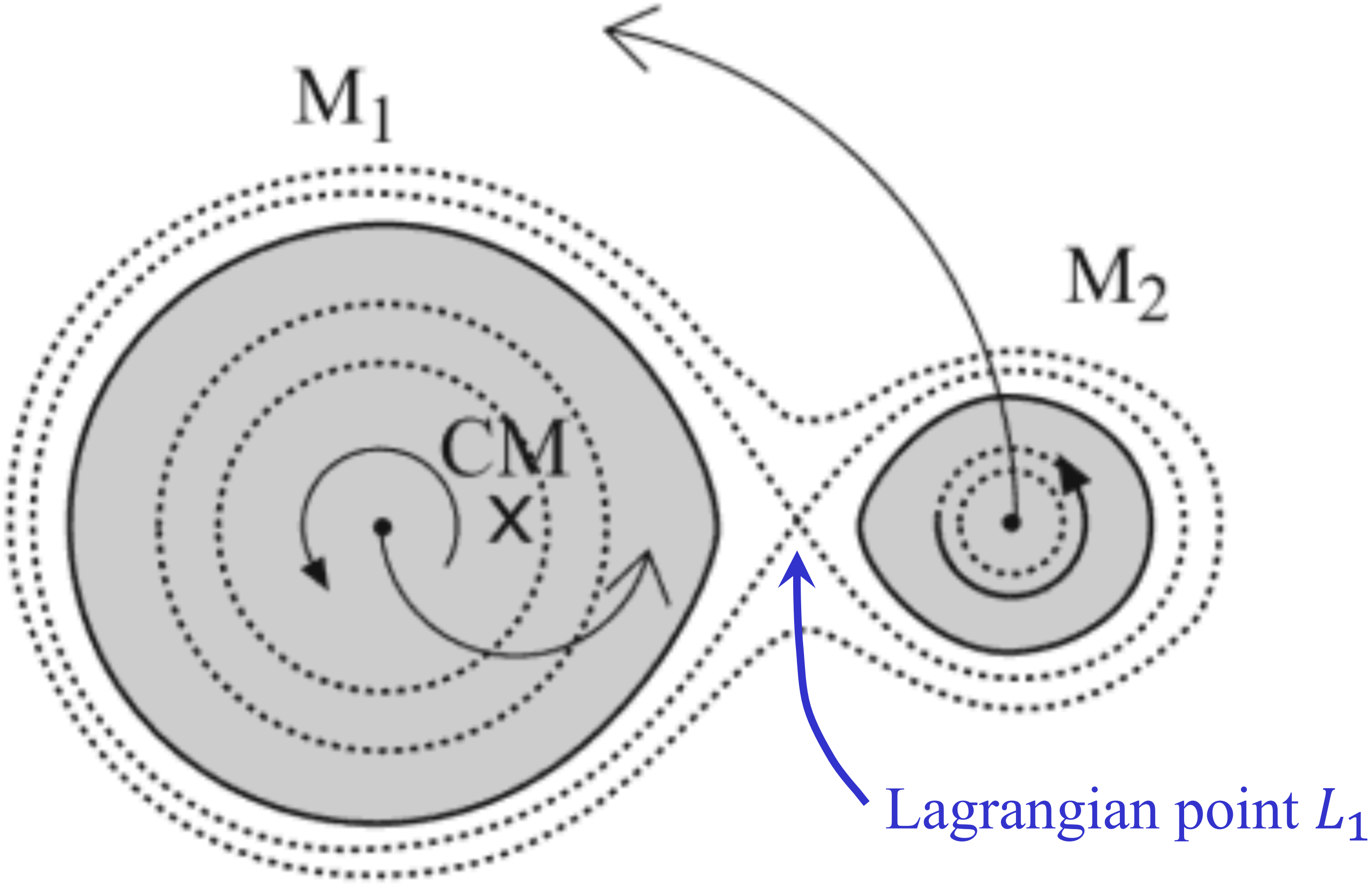
$$\approx \frac{2GM_2\Delta r}{r^3}$$

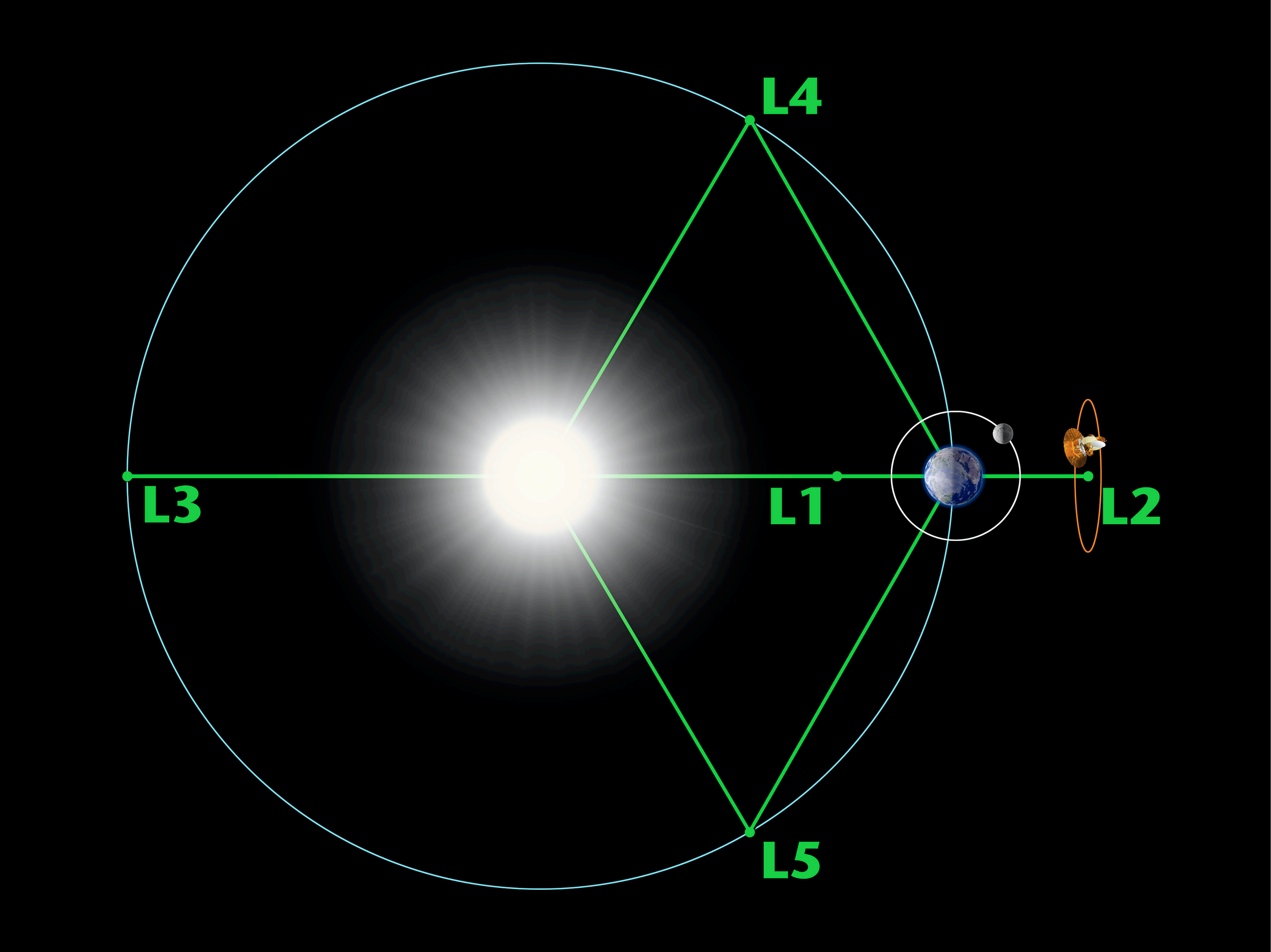
- ratio

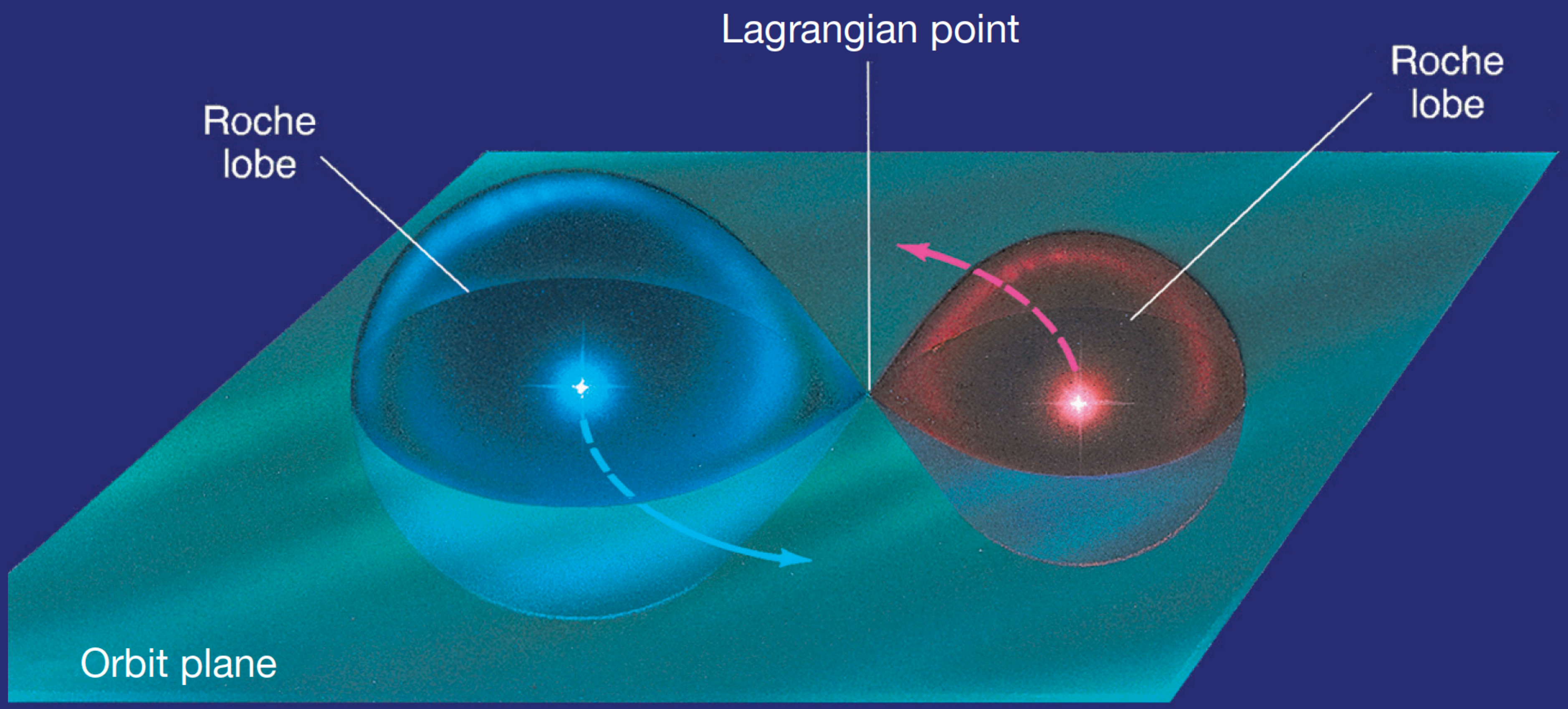
$$\left|\frac{a_{tide}}{a_{grav}}\right| = \frac{2M_2}{M_1}\left(\frac{\Delta r}{r}\right)^3$$

Interacting Binary Stars

- equipotentials in co-orbital frame




L4
L3
L1
L2
L5


Lagrangian point
Roche
lobe
Roche
lobe
Orbit plane

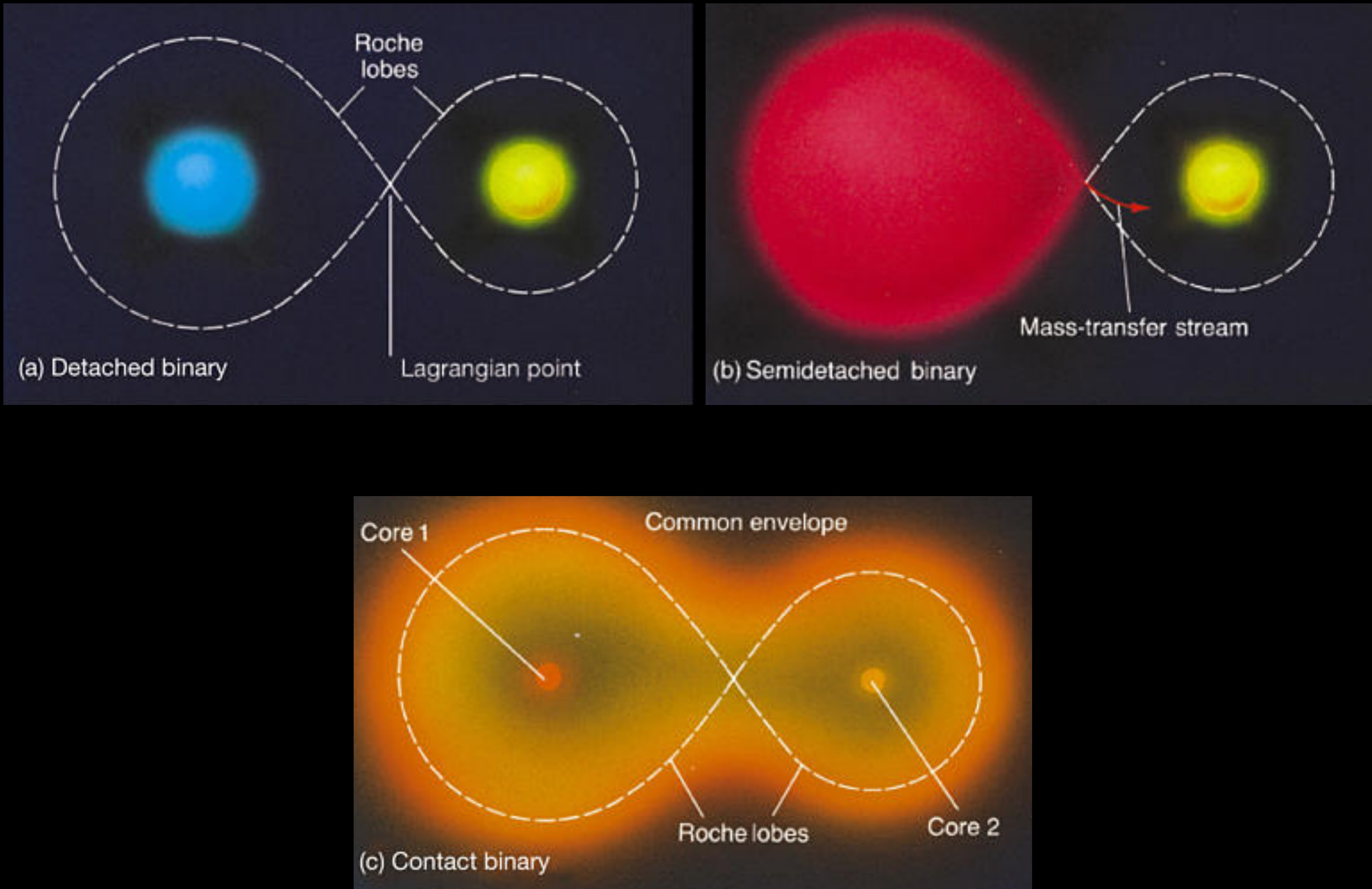
Interacting Binary Stars

- classification
  - detached

    - both stars lie within their Roche lobes
  - semidetached

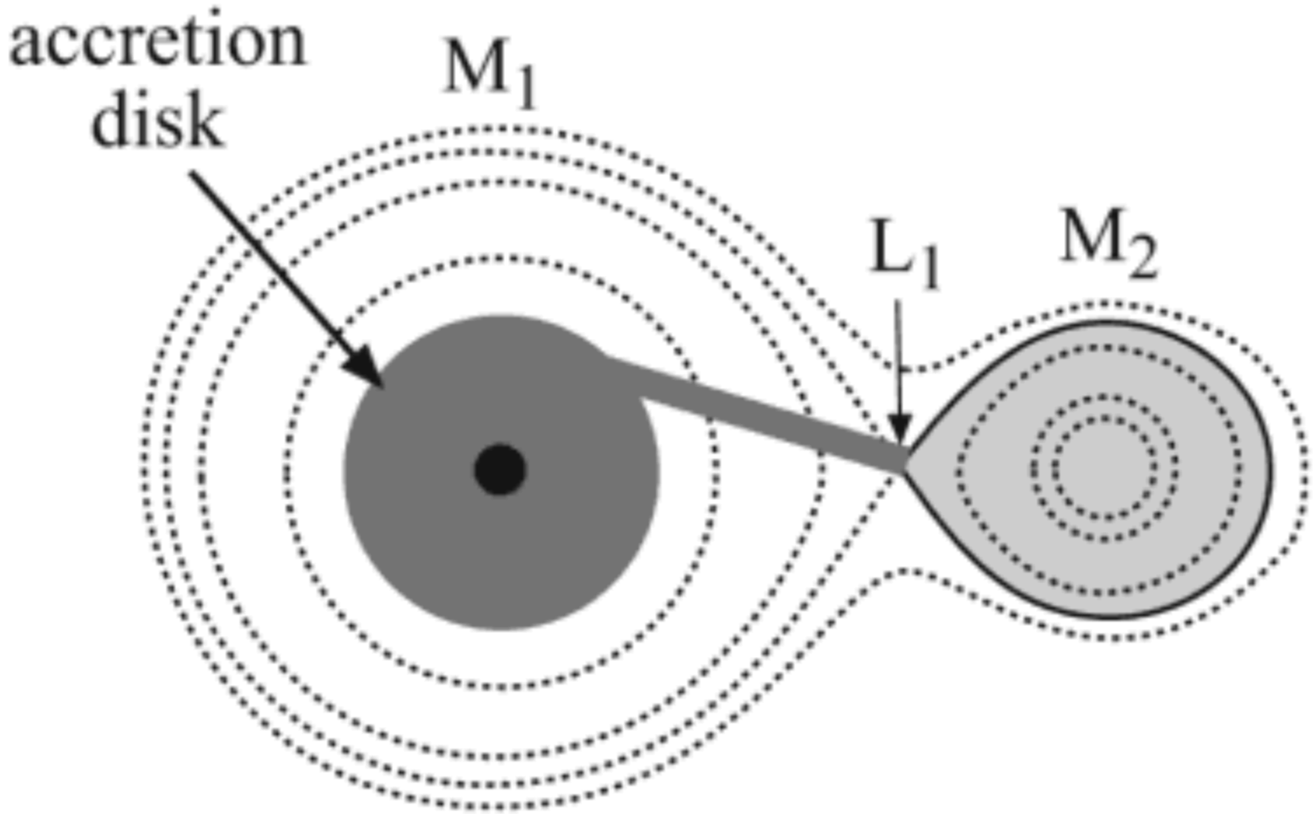
    - one star fills its Roche lobe
  - contact/common envelope

    - both stars overflow their Roche lobes

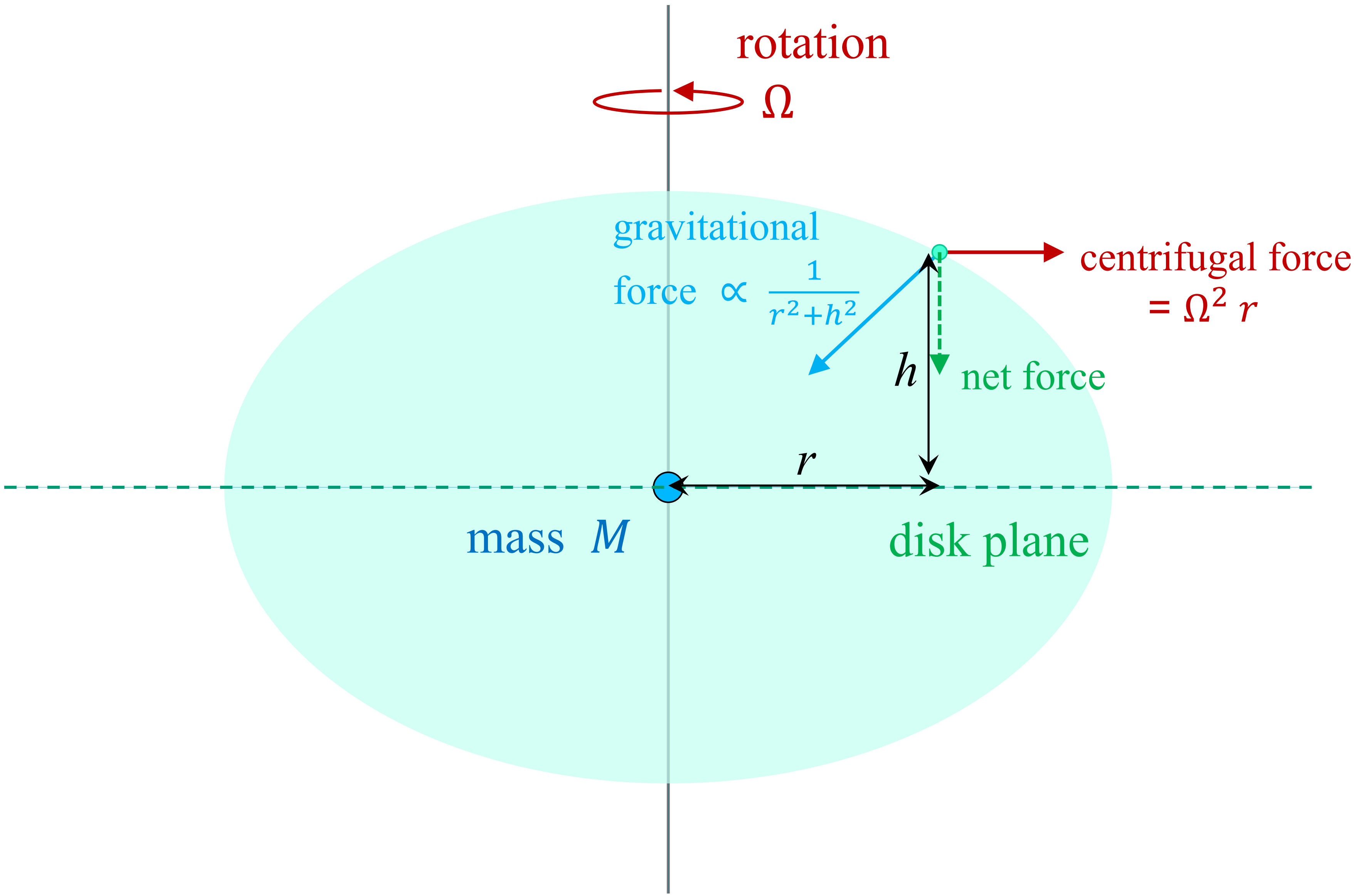

Roche
lobes
(a) Detached binary
Lagrangian point
Mass-transfer stream
(b) Semidetached binary
Common envelope
Core 1
Roche lobes
Core 2
(c) Contact binary

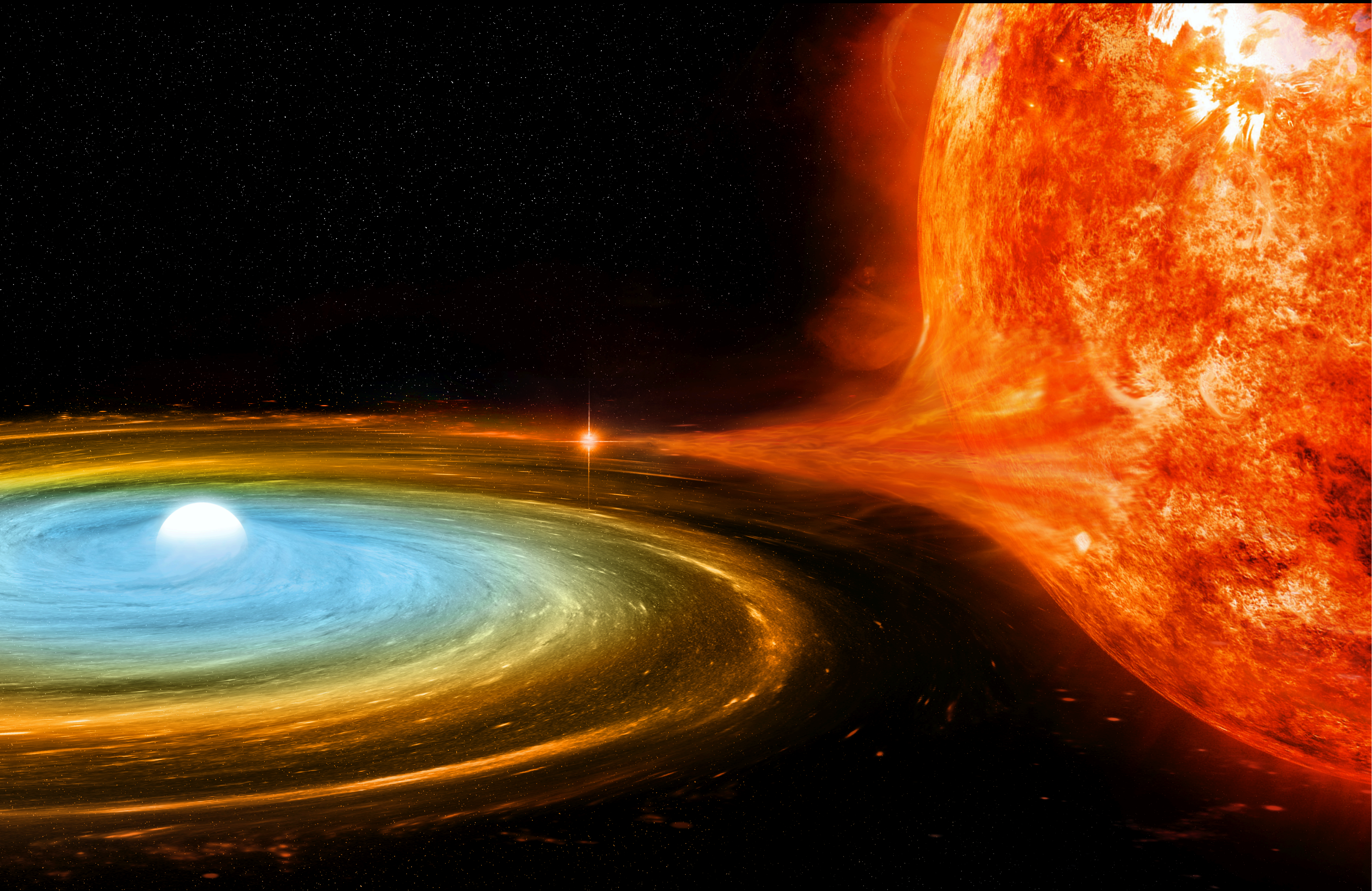
Interacting Binary Stars

- mass transfer in semidetached system

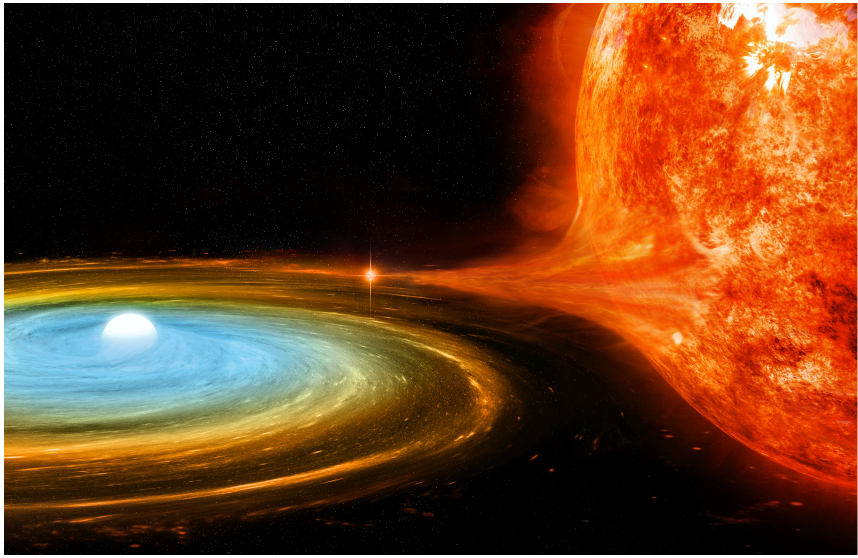


$\Omega \propto r^{-2}$ (conservation of angular momentum)





Accretion Disk



- gas sinks from $r+dr$ to r

$$dE_{th} = \frac{1}{2}\left(\frac{GMdM}{r} - \frac{GMdM}{r+dr}\right)$$

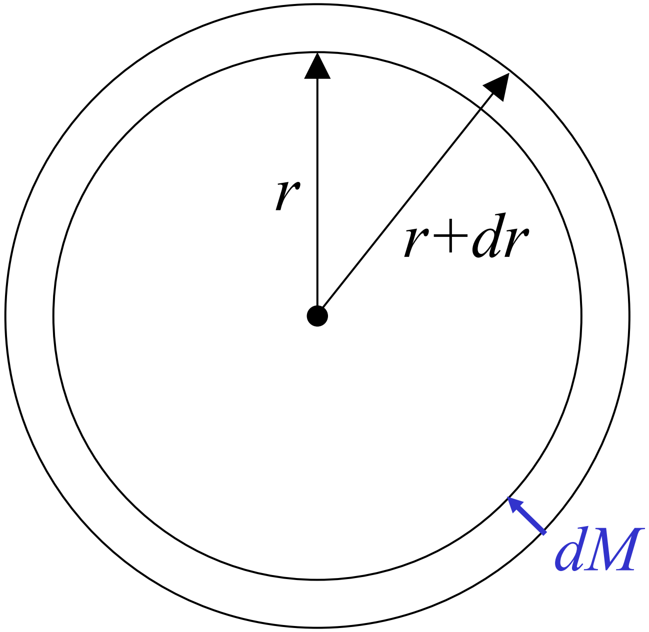
- radiates excess energy away

$$dL = \frac{dE_{th}}{dt} = \frac{GM}{2}\frac{dM}{dt}\left(\frac{1}{r} - \frac{1}{r+dr}\right)$$

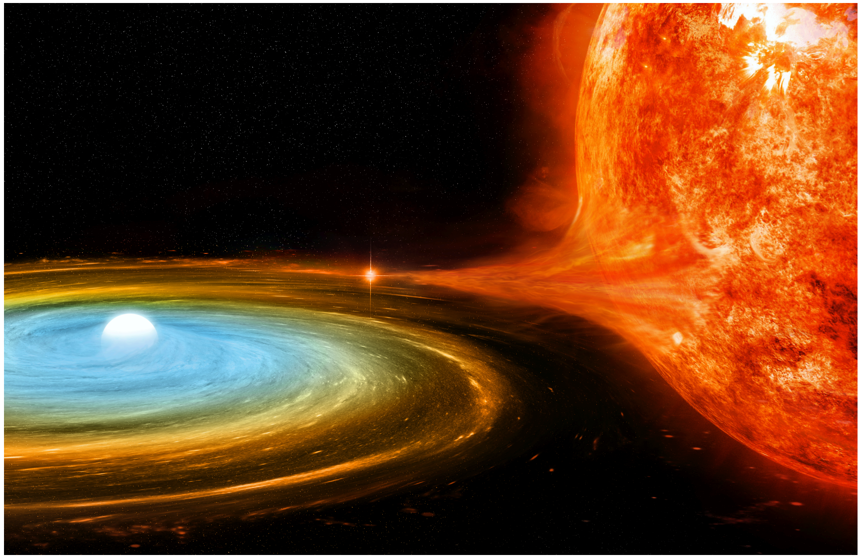
$$= \frac{1}{2}GM\dot{M}\frac{dr}{r^2}$$

$$= 2(2\pi r)dr\,\sigma T^4$$

$$\Longrightarrow T(r) = \left(\frac{GM\dot{M}}{8\pi\sigma}\right)^{1/4} \mathrm{r}^{-3/4}$$



Accretion Disk

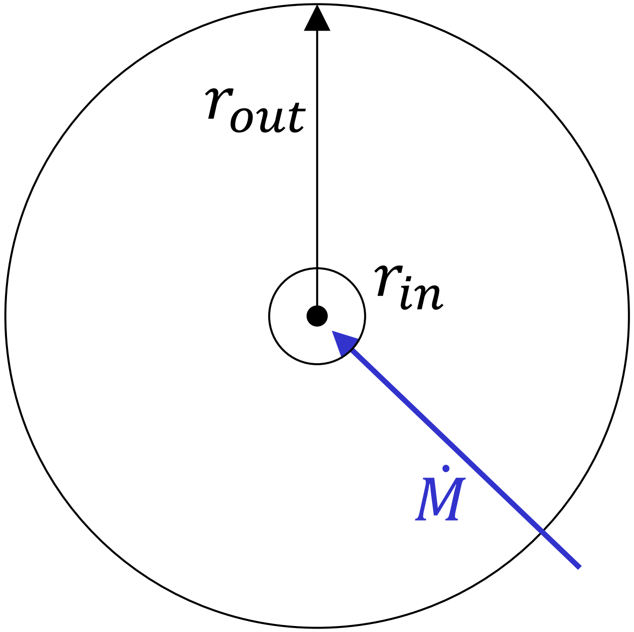


- total luminosity

$$L = \int_{r_{in}}^{r_{out}} 2(2\pi r)\sigma T(r)^4 dr$$

$$= \frac{1}{2} G M \dot{M} \left(\frac{1}{r_{in}} - \frac{1}{r_{out}} \right)$$

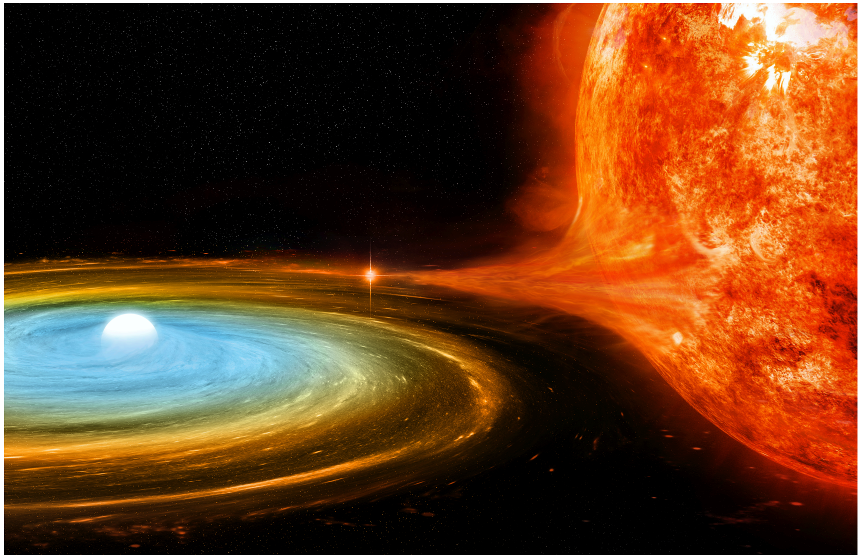
$$\approx \frac{1}{2} \frac{G M \dot{M}}{r_{in}}$$



- efficiency

$$\eta = \frac{L}{\dot{M} c^2} = \frac{1}{2} \frac{GM}{c^2 r_{in}}$$

Accretion Efficiency



- neutron star

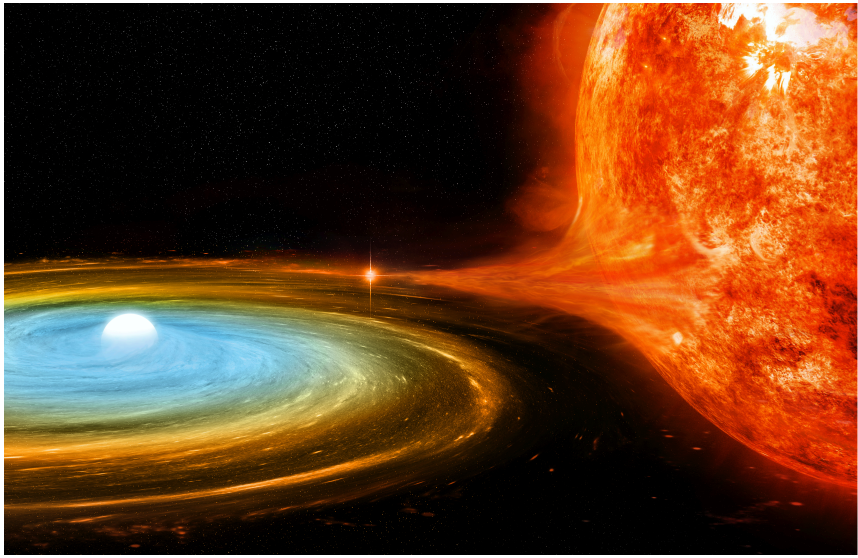
$$M = 1.4\, M_{\odot}$$
$$R = 10 \text{ km}$$
$$r_{in} \approx R$$
$$\Longrightarrow \eta \approx 0.10$$

$$\eta_{pp} = 0.007$$

- black hole

$$M = 10\, M_{\odot}$$
$$r_{in} \approx 3r_s = 90 \text{ km}$$
$$\Longrightarrow \eta \approx 0.08$$

Accretion Luminosity



- white dwarf

$$M = M_{\odot}$$

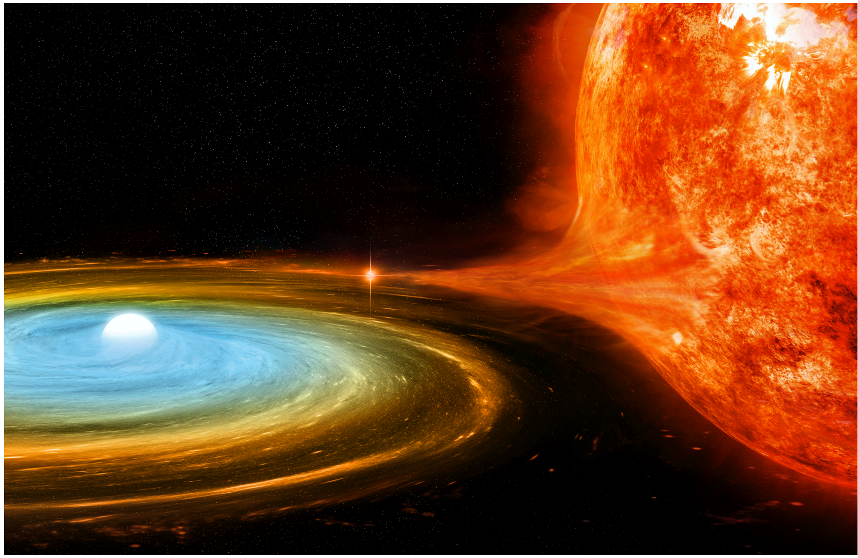
$$r_{in} \approx 10^4 \text{ km}$$

$$\dot{M} \approx 10^{-9} M_{\odot}/\text{yr}$$

$$\Longrightarrow L \approx 4\times10^{30} \text{ W} \approx L_{\odot}$$

$$T \approx 5\times10^{4}\text{K} \qquad \text{ultraviolet}$$

Accretion Luminosity



- neutron star

$$M = 1.4\, M_\odot$$

$$r_{in} \approx 10\text{ km}$$

$$\dot{M} \approx 10^{-9} M_\odot/\text{yr}$$

$$\Longrightarrow L \approx 10^{34}\text{ W} \approx 1000\, L_\odot$$

$$T \approx 10^{7}\text{ K}$$ X-ray

Eddington Luminosity

- luminosity L_ν, spherical geometry
- photon flux

$$n_{ph} = \frac{L_\nu}{4\pi r^2 c h \nu}$$

- Thomson scattering rate on electron

$$R_{scat} = n_{ph} \sigma_T c$$

- radiative force

$$\frac{dp}{dt} = R_{scat} \frac{h\nu}{c} = \frac{L_\nu \sigma_T}{4\pi r^2 c} \qquad \rightarrow \frac{L\sigma_T}{4\pi r^2 c} \text{ total}$$

Eddington Luminosity

- total radiative force

$$F_{\mathrm{rad}} = \frac{L\sigma_T}{4\pi r^2 c}$$

- total gravitational force

$$F_{\mathrm{grav}} = \frac{GMm_p}{r^2}$$

- force balance when

$$\frac{L\sigma_T}{4\pi r^2 c} = \frac{GMm_p}{r^2}$$

$$\Longrightarrow \quad L = L_E = \frac{4\pi c G M m_p}{\sigma_T}$$

Eddington luminosity

$$= 3.3\times10^4 L_\odot \left(\frac{M}{M_\odot}\right)$$

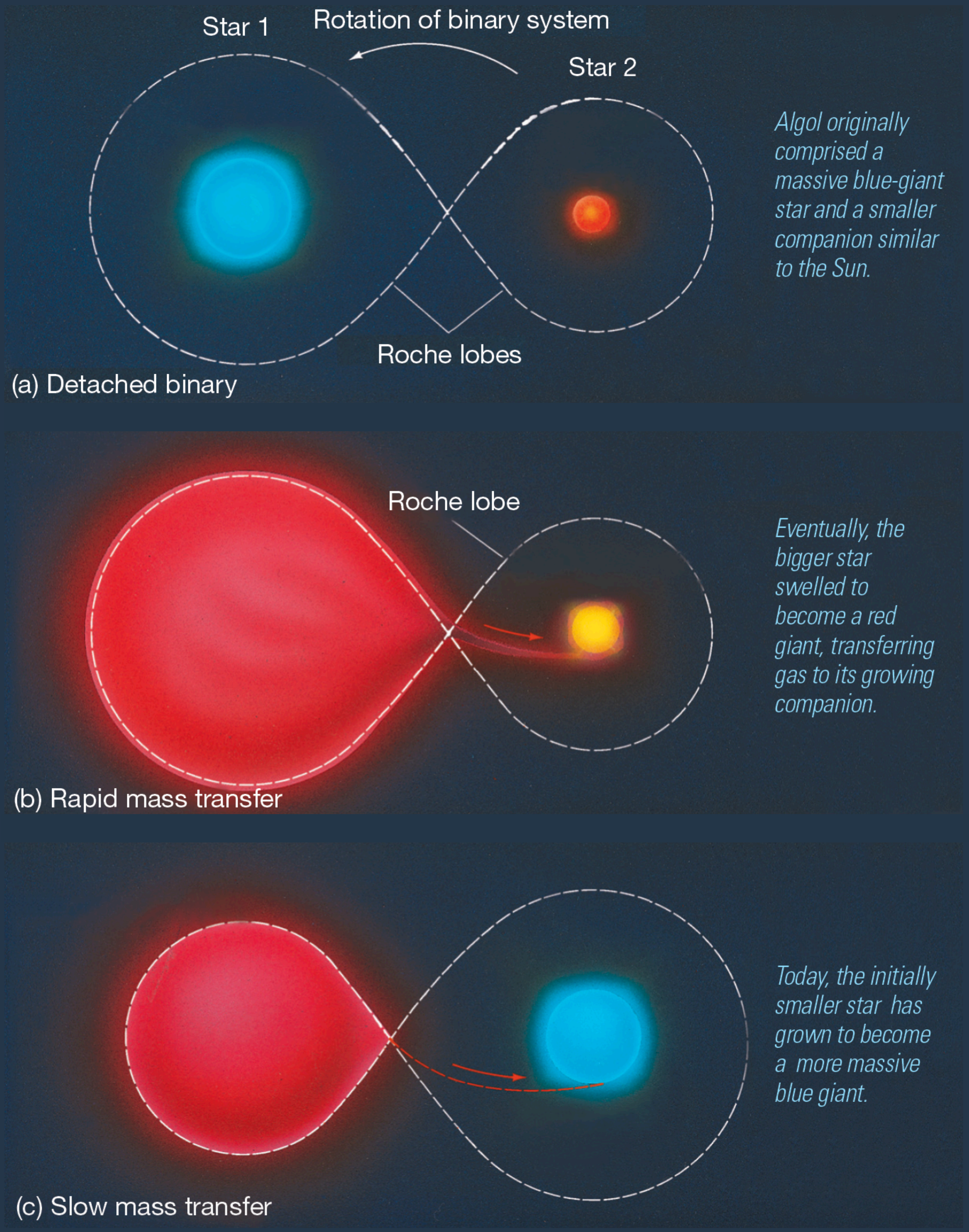
Orbital Evolution

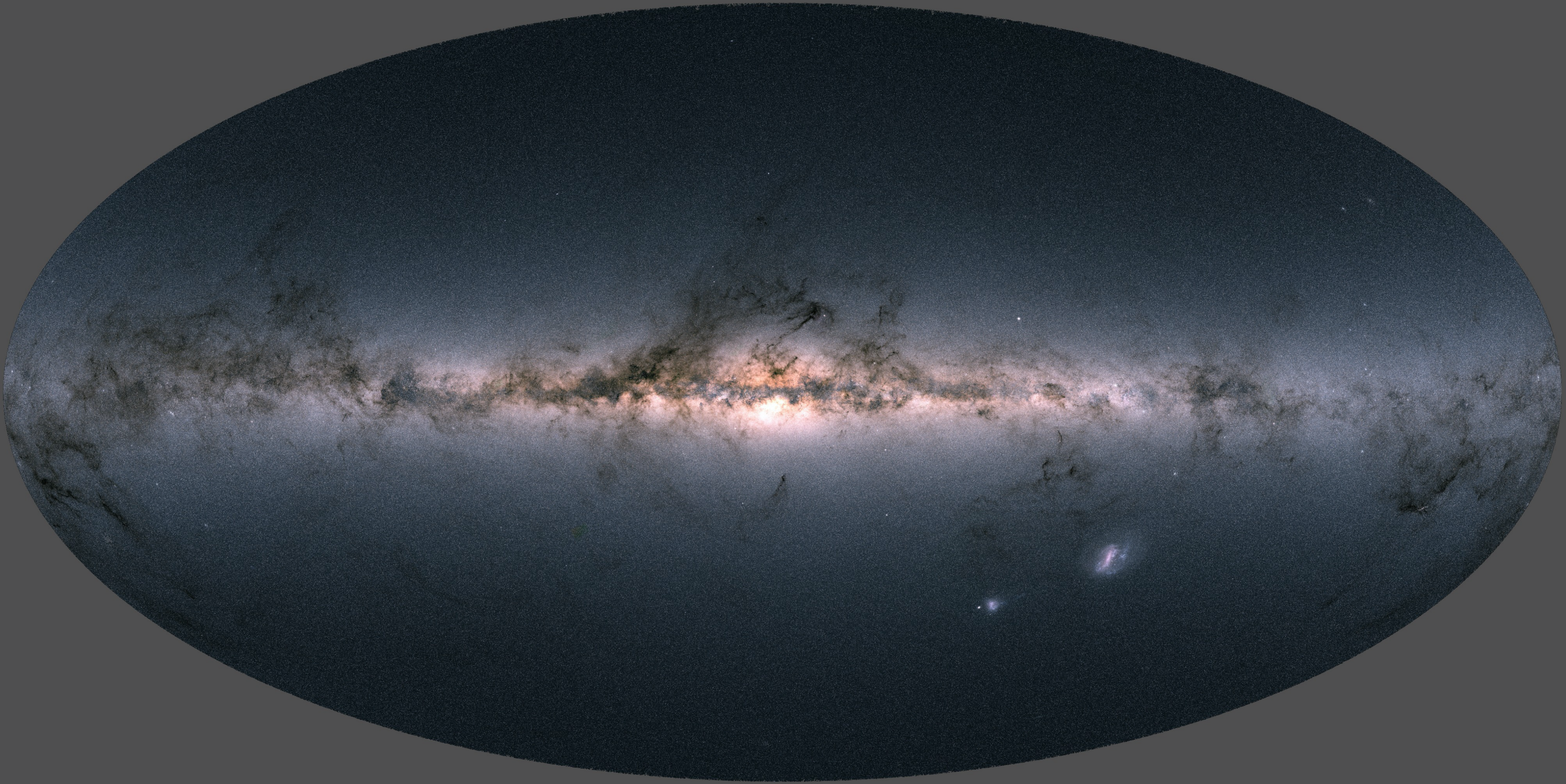
- mass transfer changes the binary separation

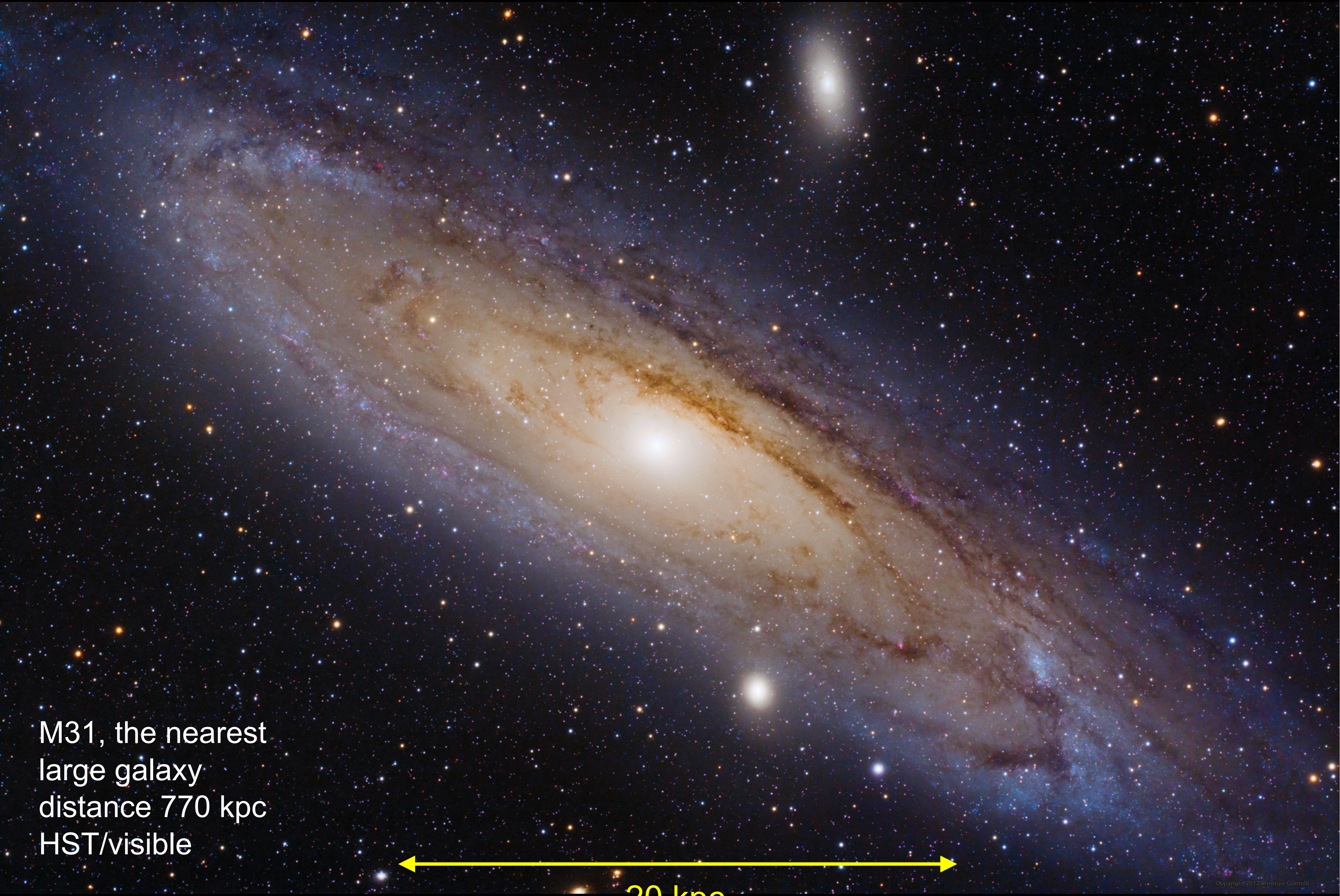
$$\frac{1}{a}\frac{da}{dt} = 2\dot{M}_1 \frac{M_1 - M_2}{M_1 M_2}$$

- e.g. $M_1 > M_2$, mass transfer $1 \rightarrow 2 \implies \frac{da}{dt} < 0$
- binary evolution can lead to outcomes inaccessible by normal stellar evolution channels

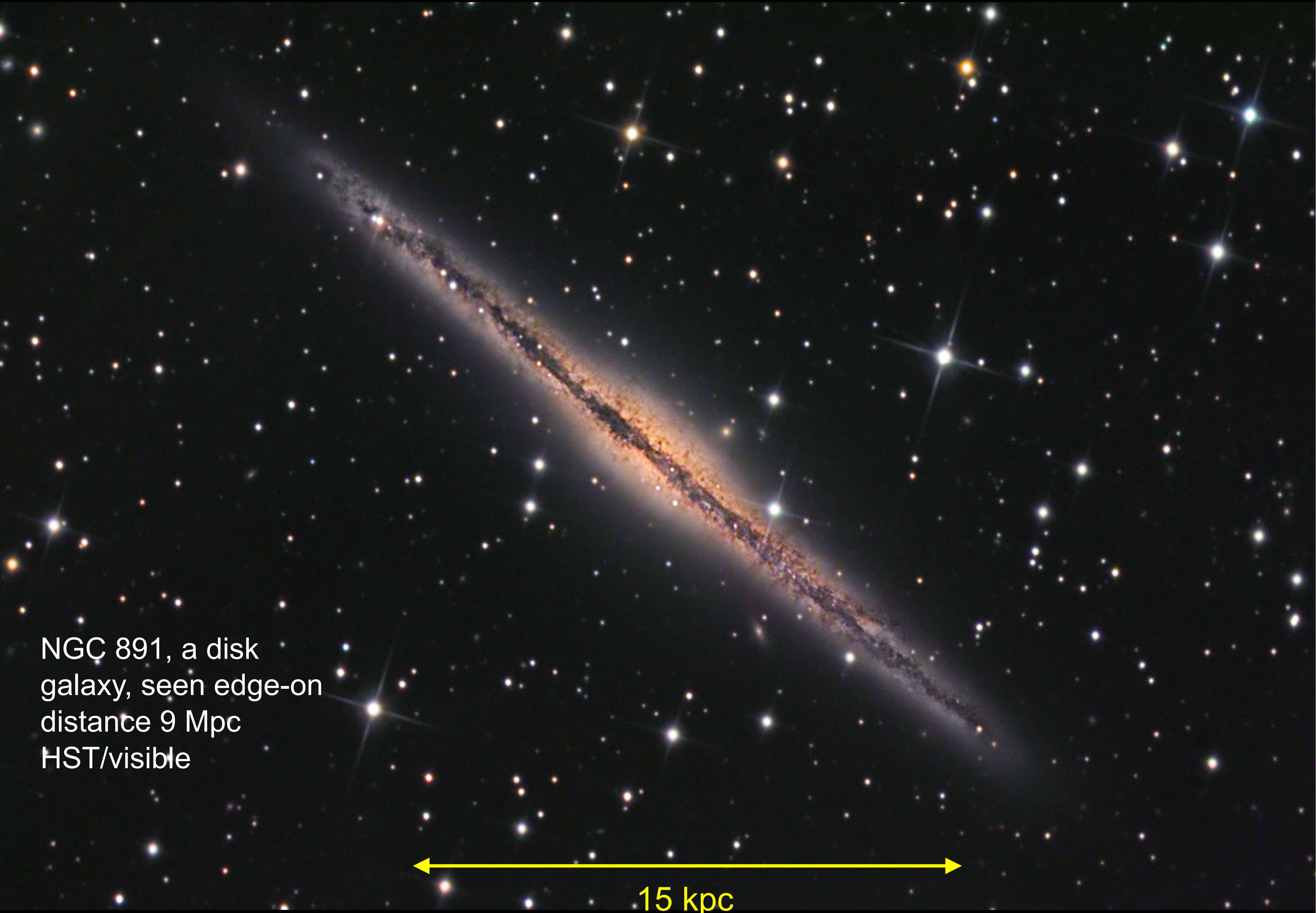
Algol System






M31, the nearest
large galaxy
distance 770 kpc
HST/visible
20 kpc


25 kpc


NGC 891, a disk
galaxy, seen edge-on
distance 9 Mpc
HST/visible
15 kpc