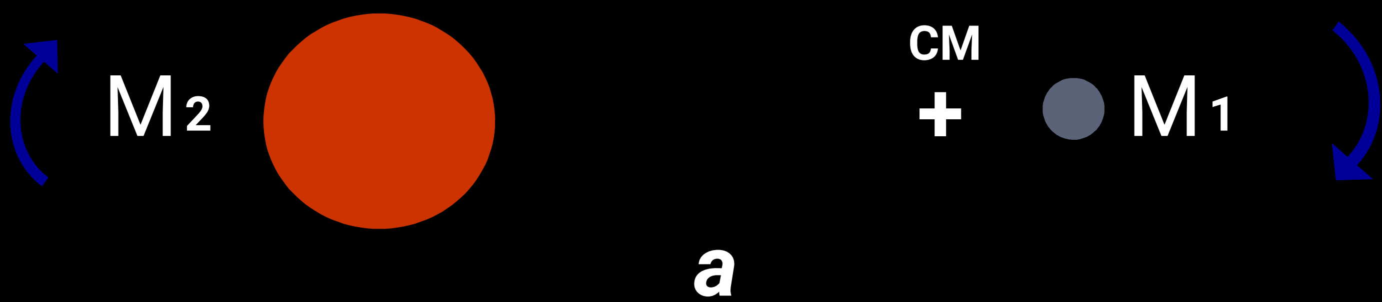
Accretion in binary systems

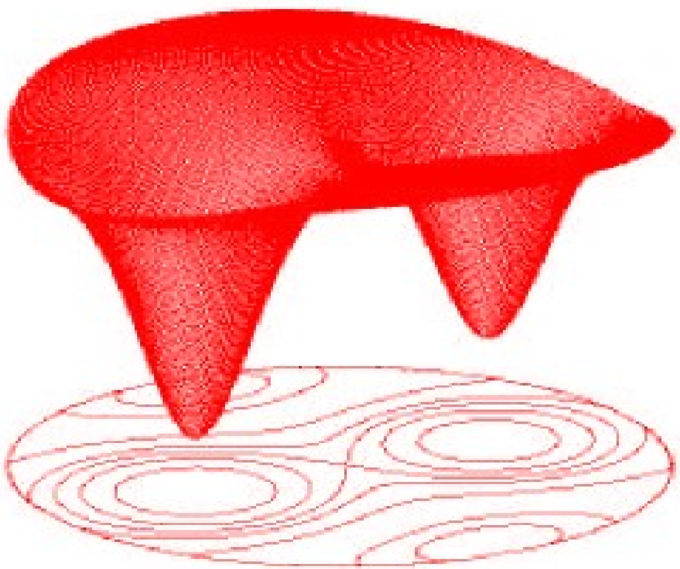
Compact star M , normal star M with $M_2 < M_1$

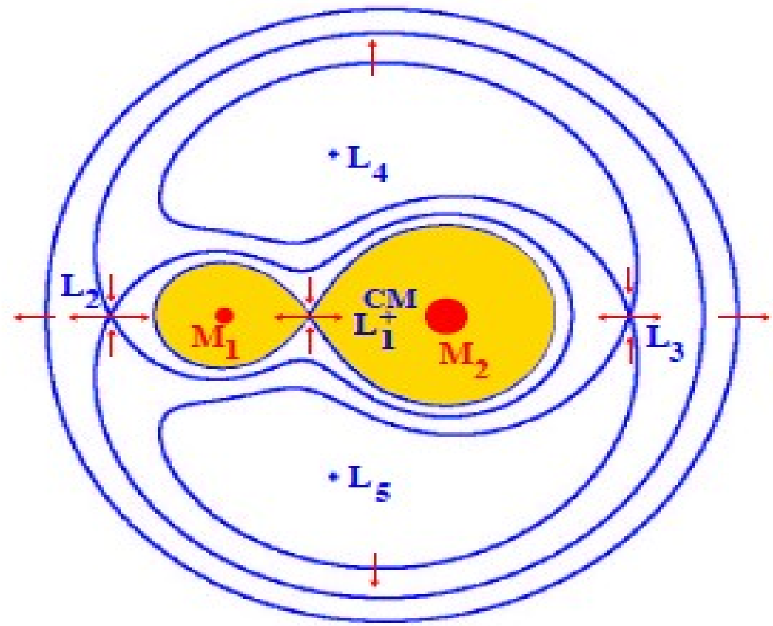


Normal star expanded or binary separation decreased => normal star feeds compact star

Roche lobe and Lagrangian points

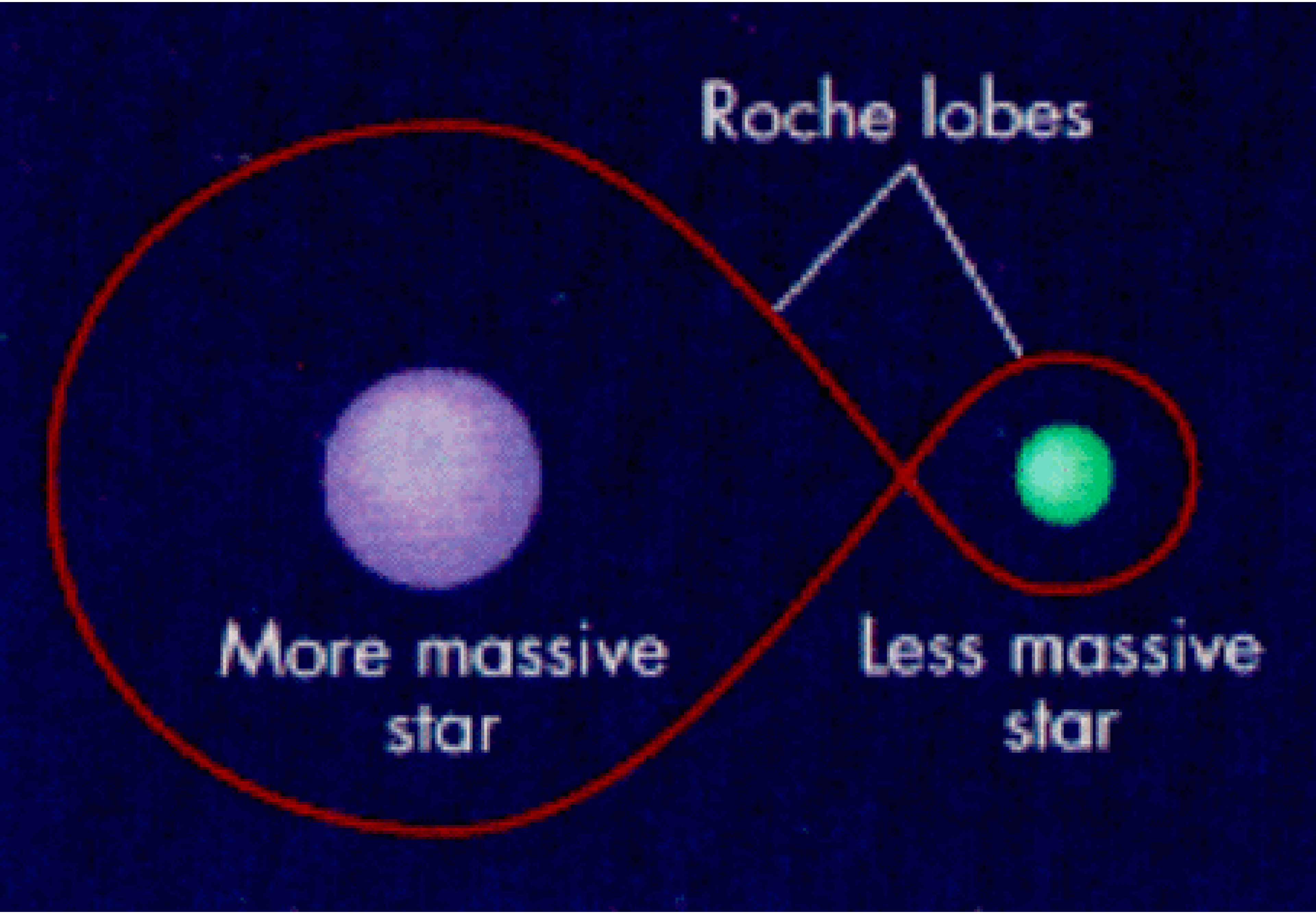
Test particle in binary system: equipotential surface



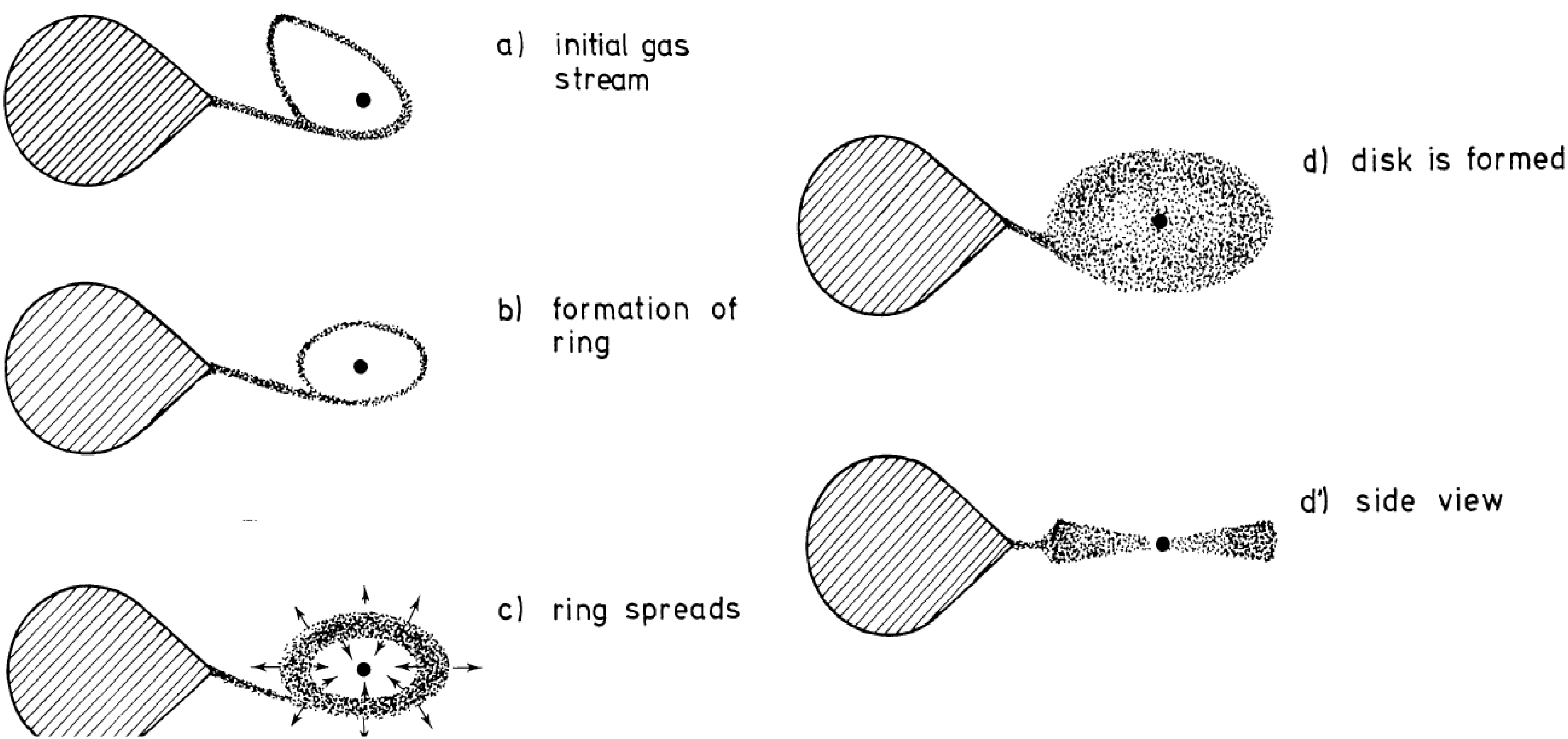


5 equilibrium points: Lagrangian points

If a star fills its Roche lobe ⇒ mass transfer ⇒ accretion

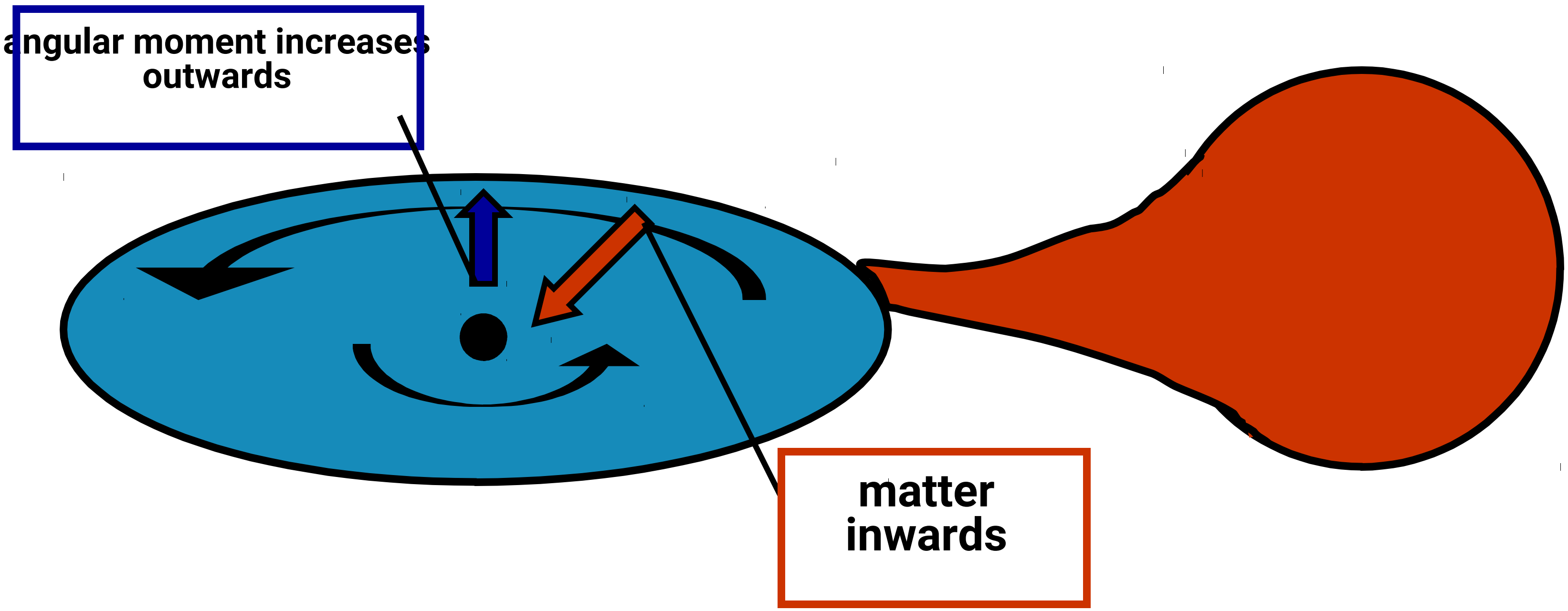

Roche lobes
More massive
star
Less massive
star

Formation of an accretion disc



Accretion disk formation

Matter circulates around the compact object:



Accretion disk

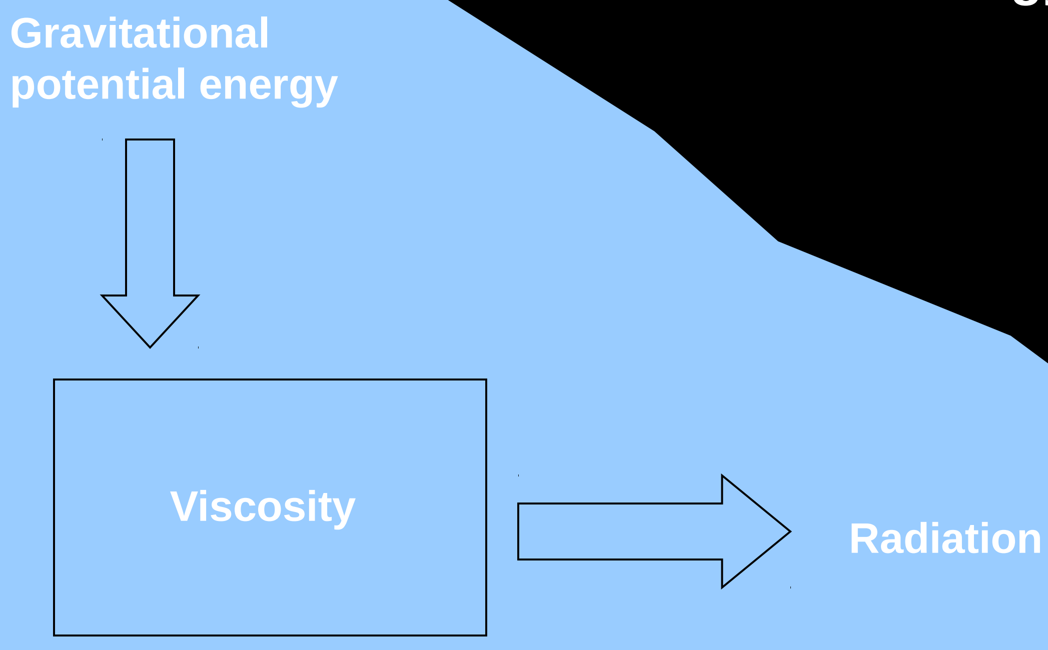
- Material transferred has high **angular momentum** so must lose it before accreting => disk forms
- Gas loses angular momentum through collisions, shocks, **viscosity** and magnetic fields: kinetic energy converted into **heat** and radiated.
- Matter sinks deeper into **gravity** of compact object

Viscosity

Accretion Disc ← Disc+ viscosity

- **Converts shear to heat**
- **Heat radiated away**
- **Energy being lost**

⇨ **Gas sinks deeper in the potential well**



Gravitational (potential) energy

surface gravity: $g = \frac{GM}{r^2}$

grav. force: $F = mg$

work: $dE = Fdr$

total work / potential energy: $E = m \int_R^\infty g dr = m \int_R^\infty \frac{GM}{r^2} dr$

$$E = m \left[\frac{GM}{r} \right]_R^\infty$$

$$\boxed{E = \frac{GMm}{R}}$$

Accretion: gravitational power plant

potential energy: $\frac{GM_c m}{R_c}$

$\longrightarrow$ kinetic energy: $\frac{1}{2}mv^2$

$\longrightarrow$ thermal energy: $\frac{3}{2}kT$

$\longrightarrow$ radiation: $h\nu$

Accretion Disk Luminosity

- For most accretion disks, total mass of gas in the disk is << *M* so we may **neglect self-gravity**
- Hence the disk material is in circular **Keplerian orbits** with angular velocity

$$\Omega = (GM/R^3)/2 = v/R$$

- Energy of **particle** with mass *m* in the Kepler orbit of radius *R* just grazing the compact object is

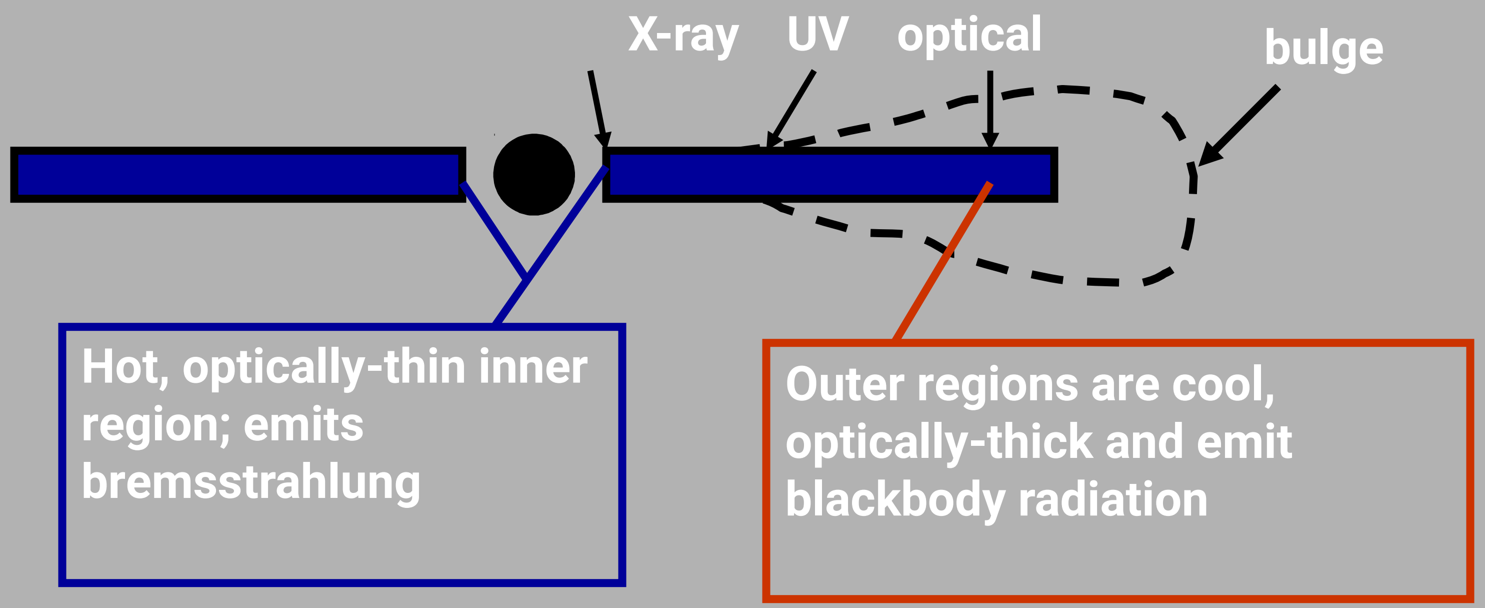
$$\frac{1}{2}mv^2 = \frac{1}{2}m\frac{GM}{R} = \frac{1}{2}E_{acc}$$

- Gas particles start at large distances with negligible energy, thus

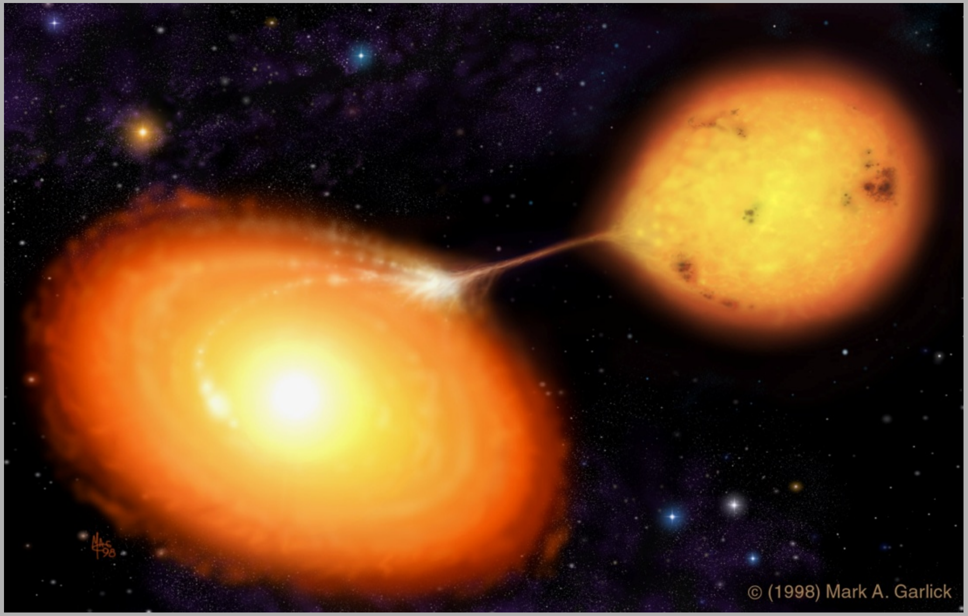
$$L_{disk} = \frac{GM\dot{M}}{2R} = \frac{1}{2}L_{acc}$$

Disk structure

The other half of the accretion luminosity is released very close to the star.



Examples: White dwarf



$M = 0.6\ M_{\odot}$

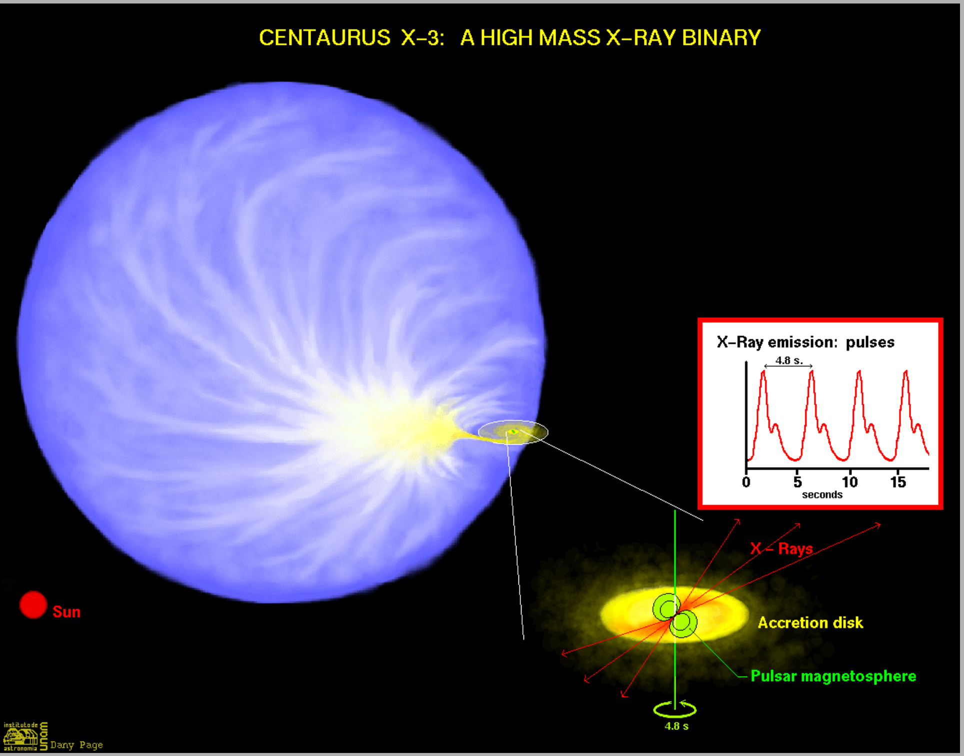
$R = 10\ 000$ km

$E = GMm/R$

$m = 1$ g $\Rightarrow$

$E \approx 8 \times 10^{16}$ erg

Example: Neutron star



$M = 1.4\ M_{\odot}$

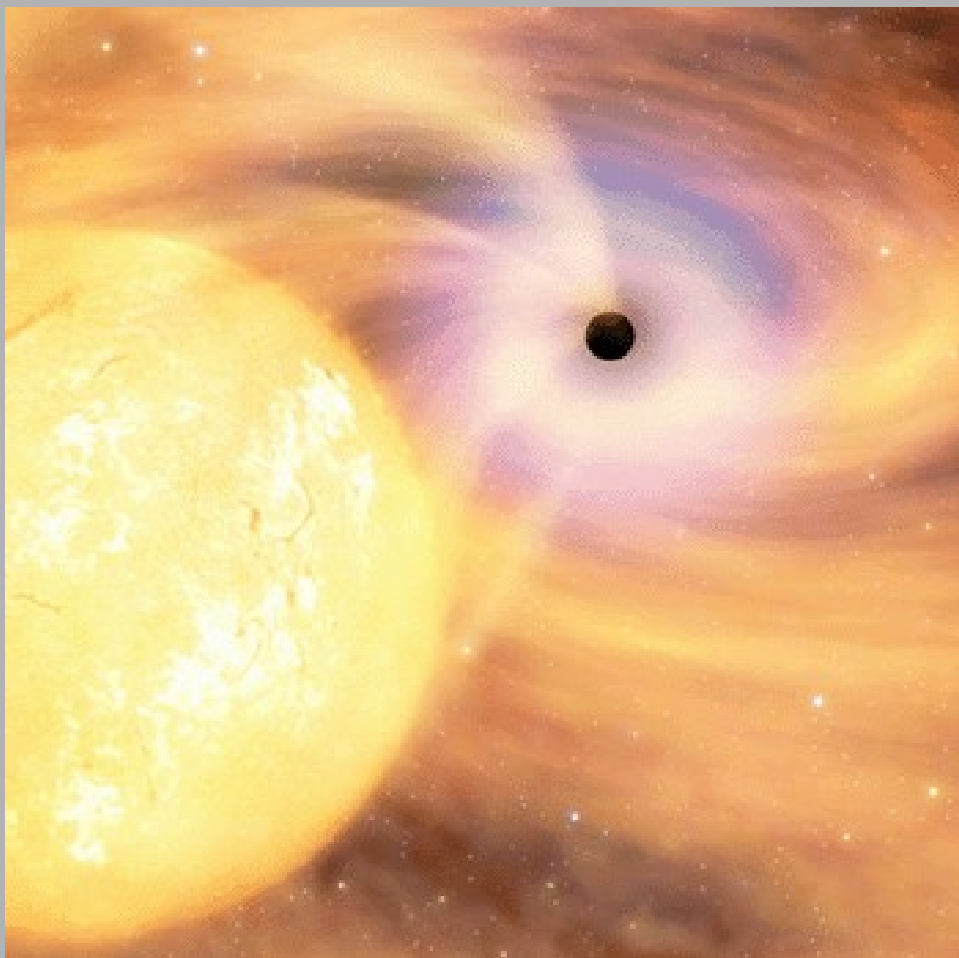
$R = 10$ km

$E = GMm/R$

$m = 1\ g \Rightarrow$

$E \approx 2 \times 10^{20}$ erg

Example: Stellar black hole



$M = 6\ M_{\odot}$

$R \approx 2GM/c^2 \approx 18$ km

$E = GMm/R \approx 0.5\ mc^2$

$m = 1$ g $\Rightarrow$

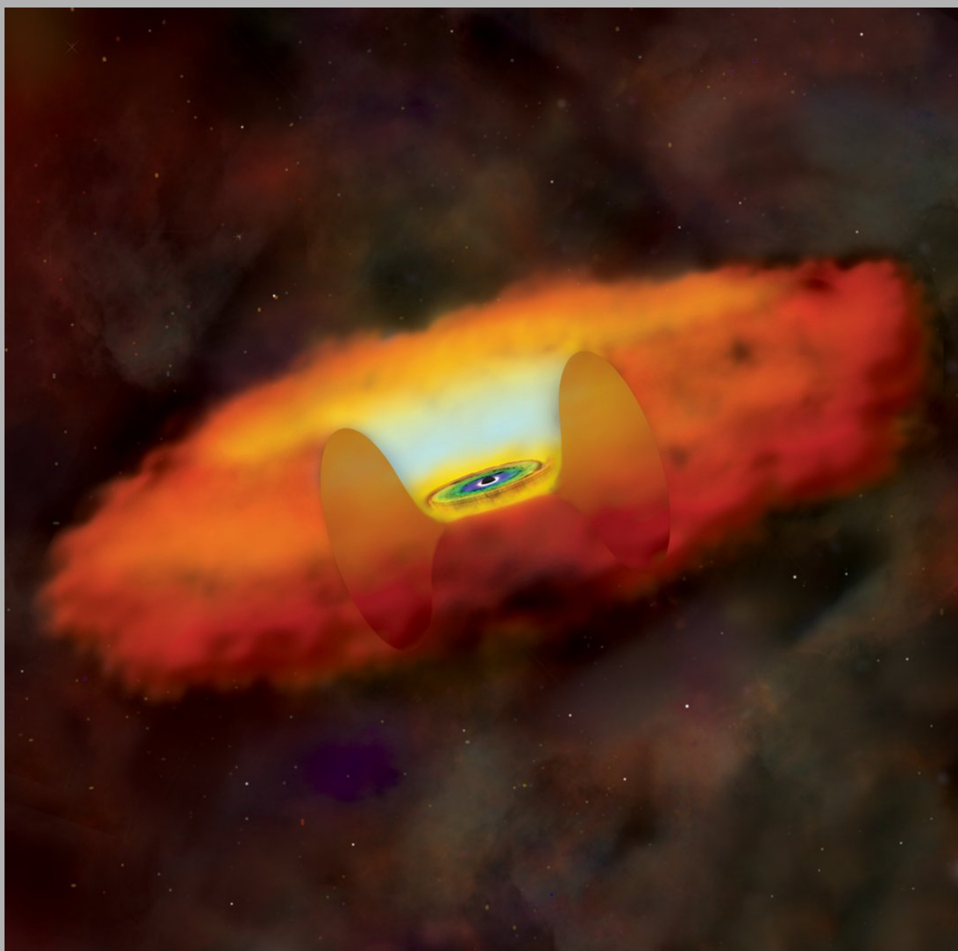
$E \approx 4 \times 10^{20}$ erg

$m = 1\ M_{\odot} \Rightarrow$

$E \approx 8 \times 10^{53}$ erg

⇒ If energy released in seconds/minutes: **GRB** luminosity (collapsar model)

Example: Active galactic nucleus (AGN)



$M = 10^{8} M_{\odot}$

$R = 2GM/c^{2}$

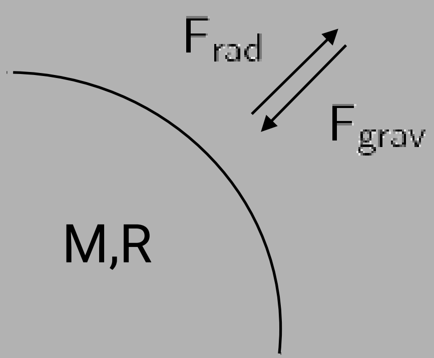
$E = GMm/R \approx 0.5\, mc^{2}$

$m = 1\ g \Rightarrow$

$E \approx 4 \times 10^{20}$ erg

⇒ Are stellar BH as bright as AGN?!

The Eddington luminosity



$$L = 4\pi R^2 F \implies F_{rad} = \frac{\sigma_T L}{4\pi R^2 c}$$

$$m_p = 1830 m_e \implies F_{grav} = \frac{GMm_p}{R^2}$$

$$F_{rad} = F_{grav} \implies \boxed{L_E = \frac{4\pi GMm_p c}{\sigma_T}}$$

Accretion rate: $\dot{M}$ (measured in [g/s] or [M□/yr])

Accretion luminosity: $L_{acc} = \frac{GM\dot{M}}{R}$ [erg/s]

Maximum accretion rate onto a **neutron star**:

$$L_{E,NS} \approx 1.8 \times 10^{38} \text{ erg/s} \Rightarrow \dot{M}_{E,NS} = \frac{L_{E,NS} R}{GM} \approx 1.5 \times 10^{-8} \quad \mathbf{M_{0/yr}}$$

Maximum accretion onto a **supermassive** (10^8) **black hole**:

$$L_{E,AGN} \approx 10^{46} \text{ erg/s} \Rightarrow \dot{M}_{E,AGN} \approx 0.5 \quad \mathbf{M_{o/yr}}$$

Characteristic temperatures

- Define temperature T such that hν ~ kT
- Define 'effective' BB temp T

b

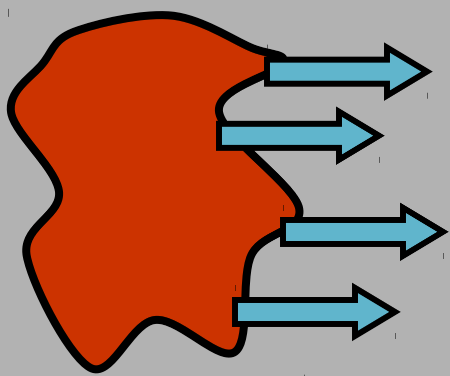
$$T_b = (L_{acc} / 4\pi R^2 \sigma)^{1/4}$$

- Thermal temperature, T such that:

$$G\frac{M(m_p + m_e)}{R} = 2 \times \frac{3}{2} kT_{th} \quad \Rightarrow \quad T_{th} = \frac{GMm_p}{3kR}$$

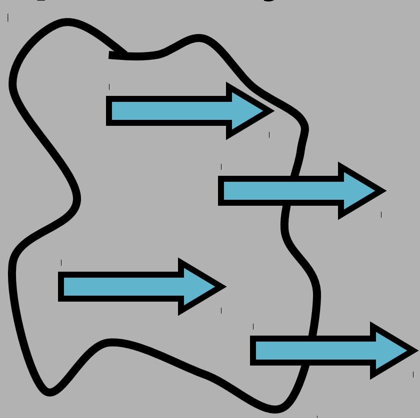
Accretion temperatures

- Optically-thick flow:



$$T_{rad} \sim T_b$$

- Optically-thin flow:



$$T_{rad} \sim T_{th}$$

Computing accretion temperatures

- In general, $$T_b \le T_{rad} \le T_{th}$$
- For a neutron star:

$$T_{th} = \frac{GMm_p}{3kR} \approx 7.5 \times 10^{11} K$$

$$T_b = (L_{acc} / 4\pi R^2 \sigma)^{1/4} \approx 2 \times 10^7 K$$

assuming:

$$L_{acc} \approx L_{Edd} = 1.3 \times 10^{38} \left(\frac{M}{M_{Sun}} \right) \text{erg/s}$$

Accreting NS and WD spectrum

- Thus expect photon energies in range:

$$1\ \mathrm{keV} \leq h\nu \leq 100\ \mathrm{MeV}$$

- Similarly for a stellar mass black hole

- For **white dwarf**, $L_{acc} \sim 10^{33}$ erg/s, $M \sim M_\odot$ $R = 5\times10^{8}$ cm,

$$1\ \varepsilon\varsigma \leq h\nu \leq 100\ \mathrm{keV}$$

=> optical, UV, X-ray sources

Accreting White Dwarfs in binary systems are called **Cataclismic Variables (CVs)**