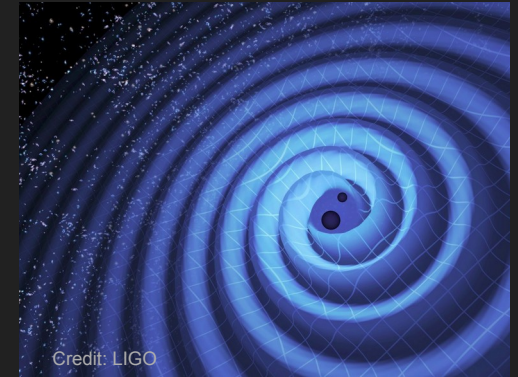
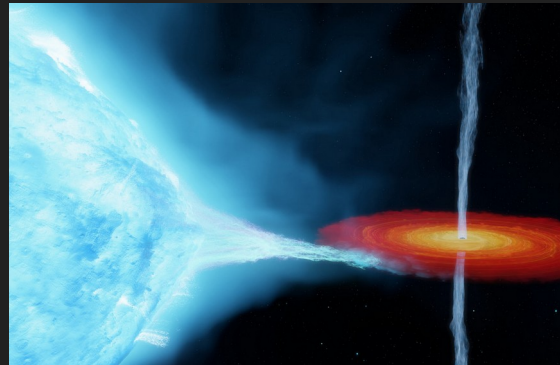


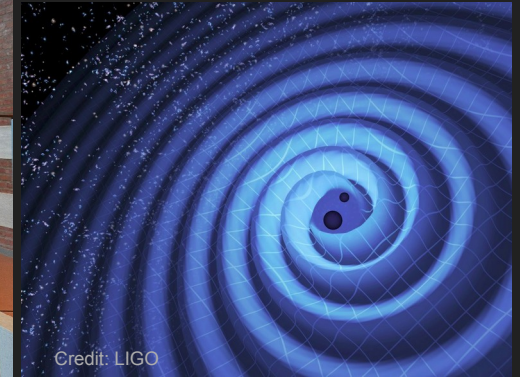
Binary Evolution



Lecturer: Eva Laplace

TAs: Hannah Brinkman, Vincent Bronner,
Harim Jin, Amadeusz Miszuda

Binary Evolution



Lecturer: Eva Laplace

TAs: Hannah Brinkman, Vincent Bronner,
Harim Jin, Amadeusz Miszuda

Draco

M82
NGC 3077
M81



Ursa Major

Canes Venatici

Arab Eye Test

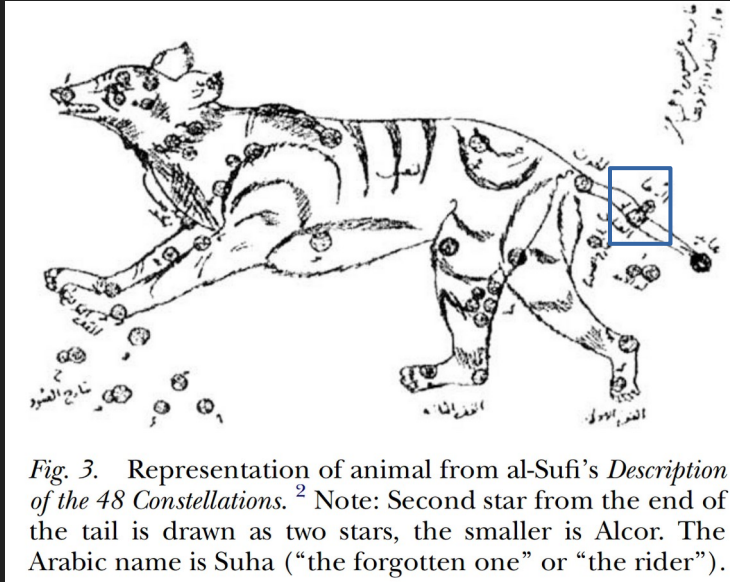
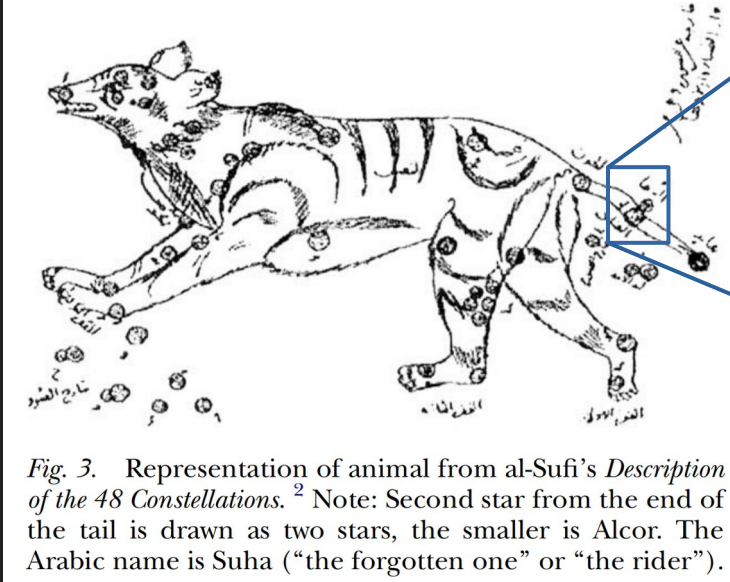


Fig. 3. Representation of animal from al-Sufi's *Description of the 48 Constellations*.² Note: Second star from the end of the tail is drawn as two stars, the smaller is Alcor. The Arabic name is Suha ("the forgotten one" or "the rider").

G. Bohigian 2008, History of Ophthalmology

Arab Eye Test



G. Bohigian 2008, History of Ophthalmology



Mizar “wrapper/cover” &
Alcor “the forgotten one /the rider”

Arab Eye Test



Fig. 3. Representation of animal from al-Sufi's *Description of the 48 Constellations*.² Note: Second star from the end of the tail is drawn as two stars, the smaller is Alcor. The Arabic name is Suha ("the forgotten one" or "the rider").

G. Bohigian 2008, History of Ophthalmology



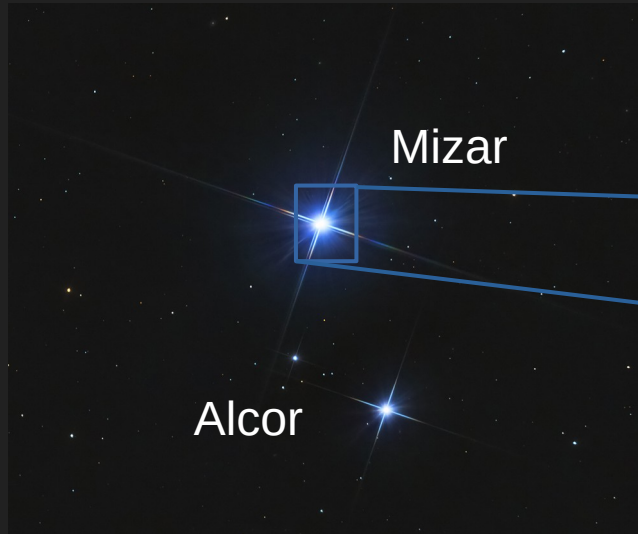
Mizar “wrapper/cover” &
Alcor “the forgotten one /the rider”

The Arab Eye Test using the double star of Mizar and Alcor remains a practical test of visual acuity and visual function as it was over 1000 years ago. This test is somewhat equivalent to the 20/20 in the Snellen visual acuity nomenclature. This is the first

Better observations: a triple!

1617

Benedetto Castelli (student of Galileo Galilei)
Discovery of Mizar A and Mizar B



Mizar A & B

Better observations: a quadruple!

1890

Antonia Maury: Discovery of the first spectroscopic binary system Mizar A
Pickering (1890)



Credit: Model - Bob King, Sky & Telescope

Better observations: a quintuple!

1908

Ludendorff 1908/Frost 1908: Discovery of a spectroscopic binary in Mizar B

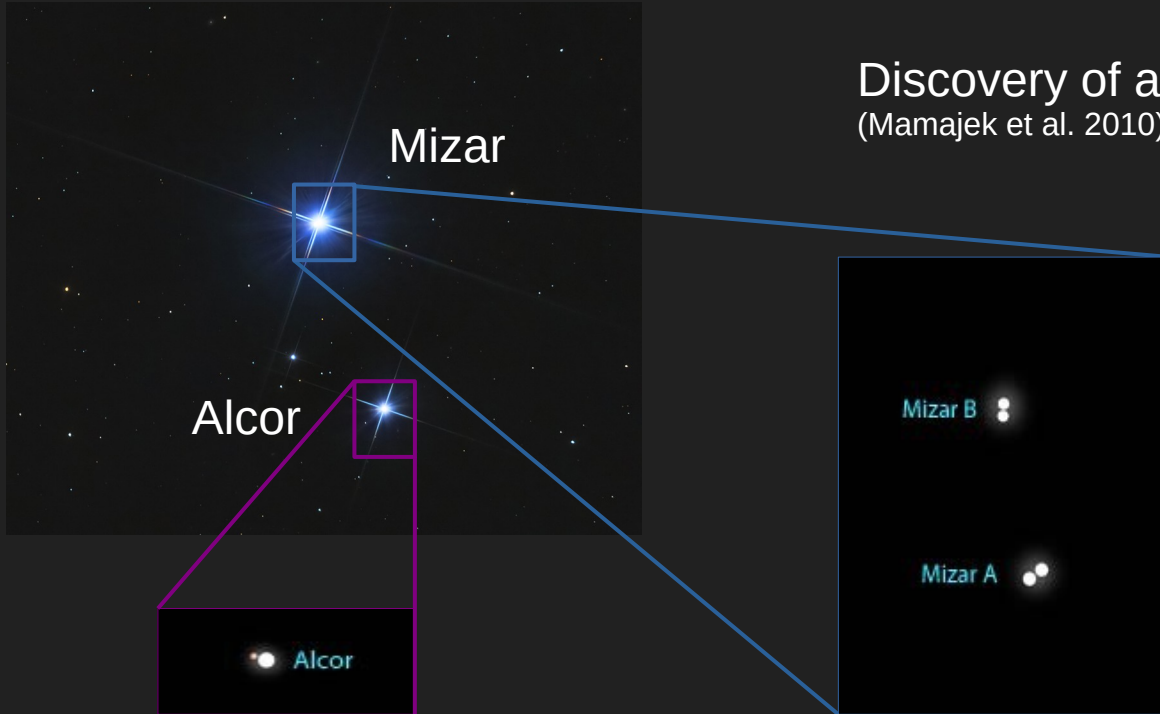


Credit: Model - Bob King, Sky & Telescope

Better observations: a sextuple!

2010

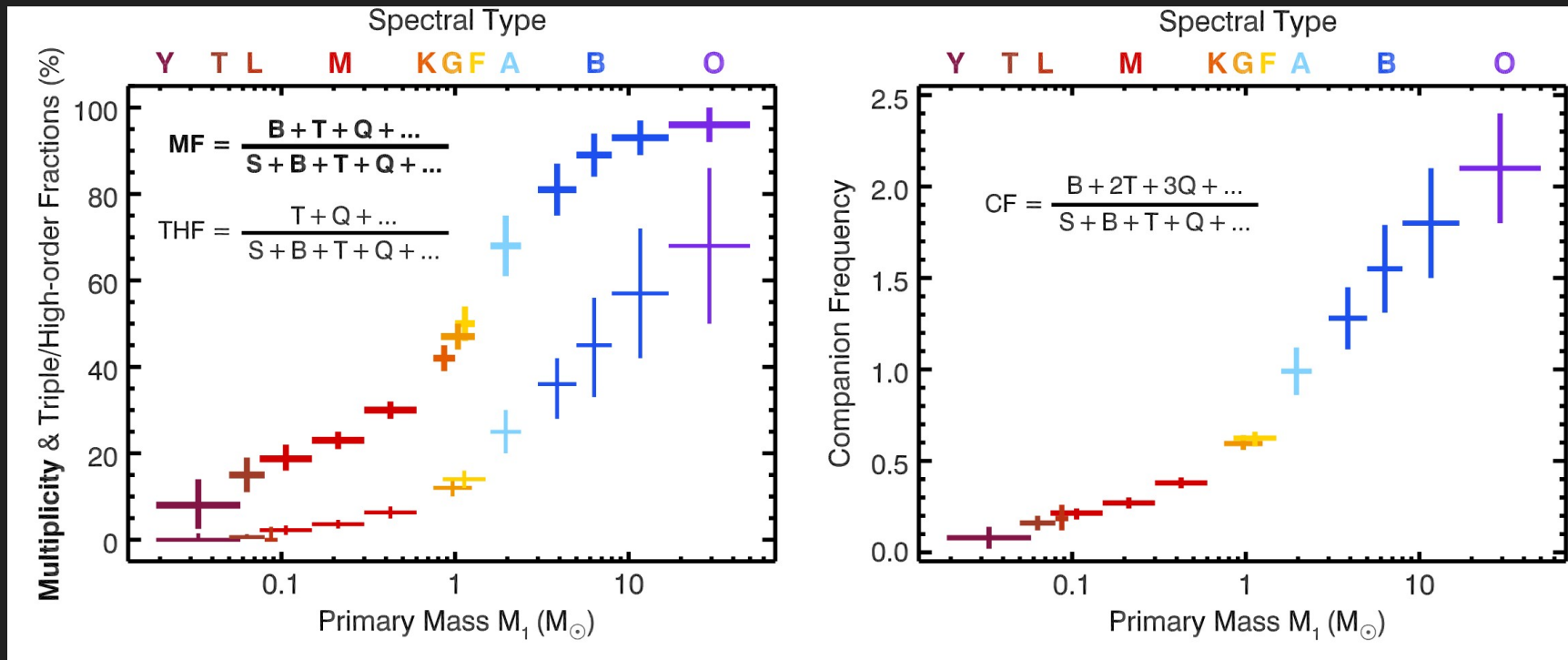
Discovery of a faint companion to Alcor
(Mamajek et al. 2010)



Credit: Model - Bob King, Sky & Telescope

Multiple systems are common! It is important to understand stellar interactions

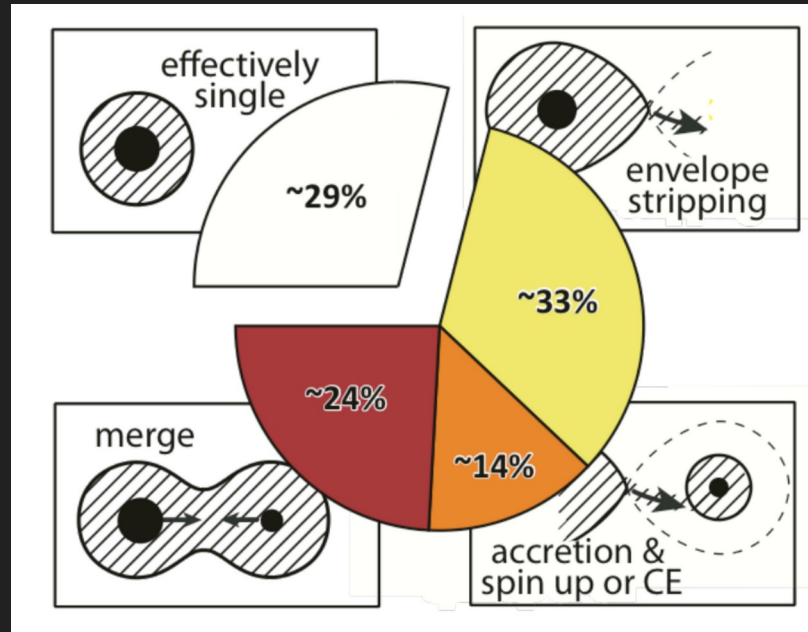
Paradigm shift: Most stars are born in multiples



Offner+2023; Moe & di Stefano 2017

The multiplicity fraction increases as a function of mass

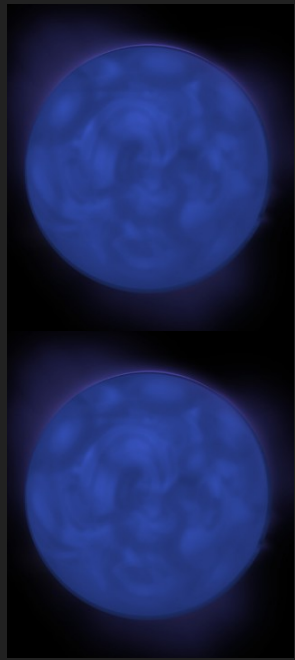
Paradigm shift: Most stars are born in multiples



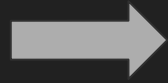
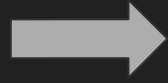
Sana+2012

Most massive stars will interact with a companion during their lifetime!

Renewed interest in binaries



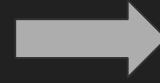
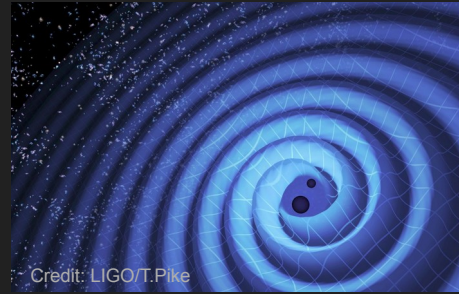
Binary stars



Binary black holes



Gravitational waves (GWs)



More massive
black hole

Simulating binaries with MESA (see Matthias' dev lecture)



+



+

Binary effects!
(binary module)

Two 1D models

Simulating binaries with MESA (see Matthias' dev lecture)



+



+

Binary effects!
(binary module)

Two 1D models

Which binary effects?

- Mass transfer
- Tides (close binaries)
- GW radiation (close binaries)
- Magnetic braking
- Kicks (supernovae)

Effects on stars + orbit!

Mass loss/gain

Changing composition

Changing rotation

Deformation

Widening / Shrinking

Eccentricity / spin /
variations

Collisions / Merging

Binary mass transfer (MT)

Mass transfer typically induced when material from one star (“donor”) reaches its Roche lobe. This material can then be accreted by (transferred to) its companion (“accretor”)

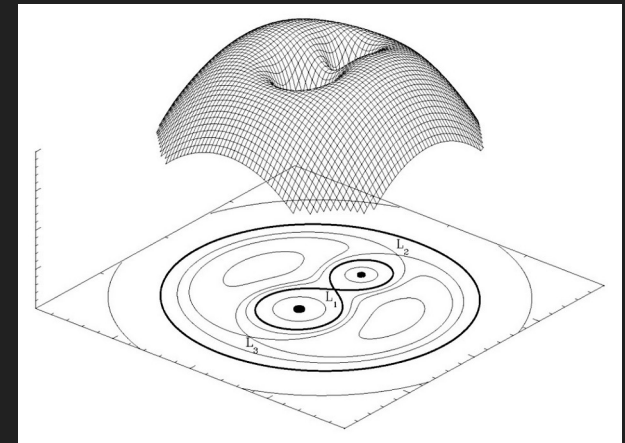
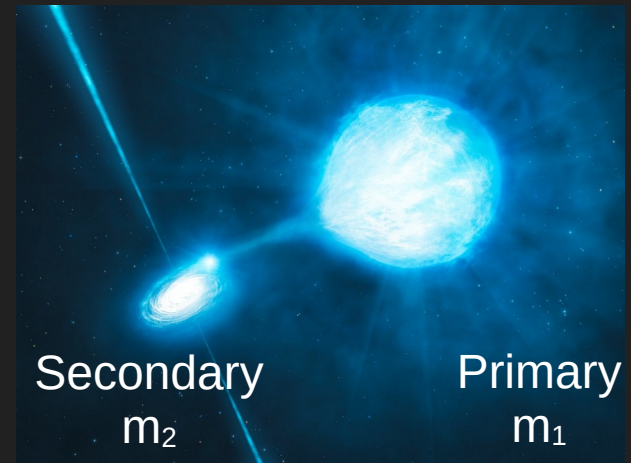
Intrinsically a 3D problem, but good 1D approximations exist

$$R_{\text{RL},1} = \frac{0.49q^{-2/3}}{0.6q^{-2/3} + \ln(1 + q^{-1/3})} a$$

R_L : Effective Roche-lobe radius

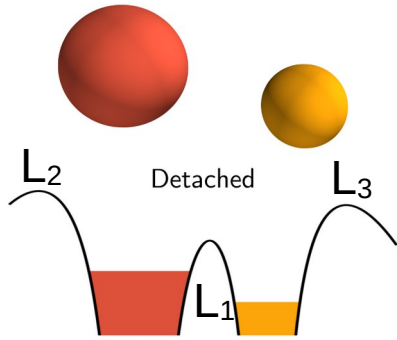
a : separation

$q = m_2/m_1$



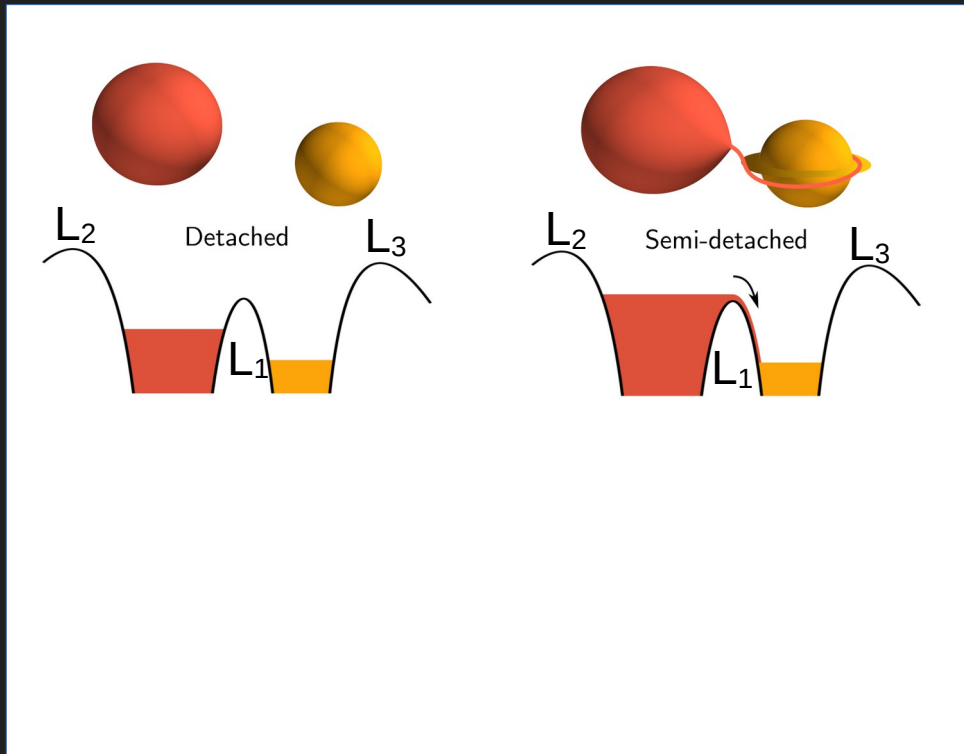
By Marc van der Sluys

Binary mass transfer (MT): binary configurations



- **Detached**: MT through winds ($R_d < R_L$)
 - Fast wind (hot stars): only a fraction of the wind is captured by the binary Bondi-Hoyle accretion)
 - Slow wind (cool stars): atmospheric RLOF (similar to a slow RLOF)

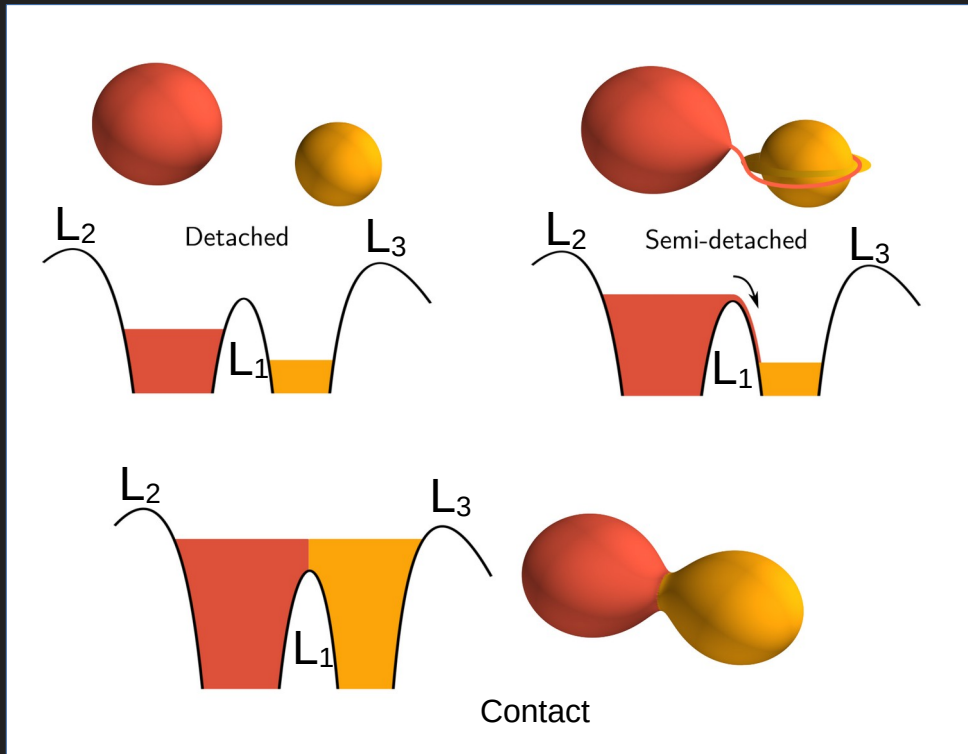
Binary mass transfer (MT): binary configurations



- **Detached:** MT through winds ($R_d < R_L$)
 - Fast wind (hot stars): only a fraction of the wind is captured by the binary Bondi-Hoyle accretion)
 - Slow wind (cool stars): atmospheric RLOF (similar to a slow RLOF)
- **Semi-detached:** Roche-lobe overflow (RLOF) – MT through inner L1 point. Difference between optically-thin MT ($R_d \sim R_L$, Ritter+1988) and optically-thick MT ($R_d > R_L$, Kolb+1990)

Credit: M. Fabry, PhD thesis

Binary mass transfer (MT): binary configurations

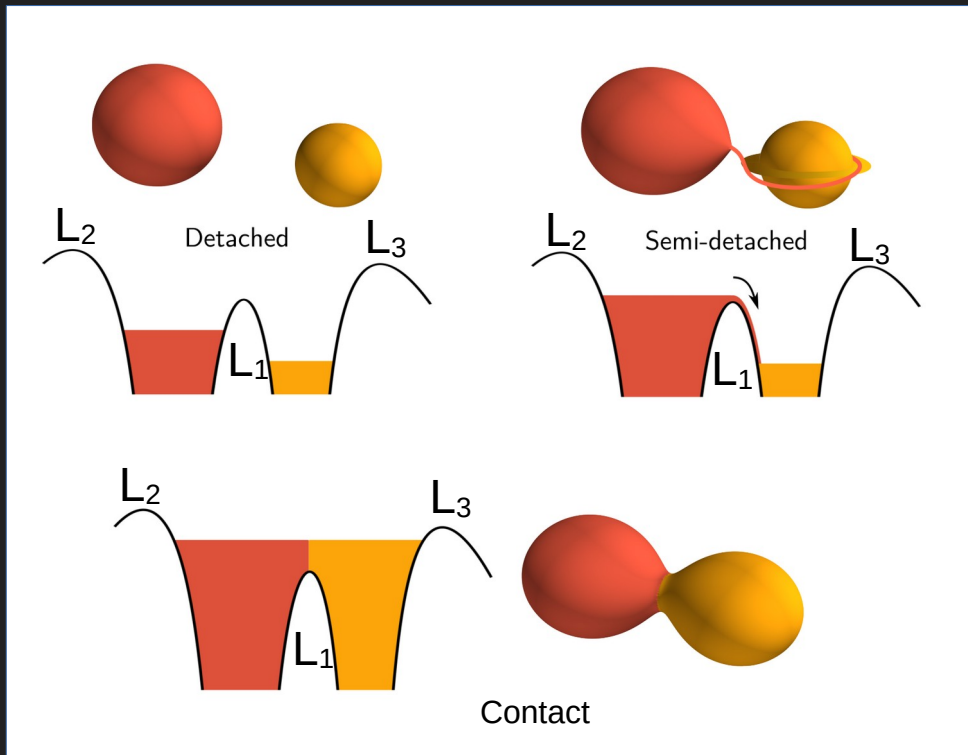


Credit: M. Fabry, PhD thesis

- **Detached:** MT through winds ($R_d < R_L$)
 - Fast wind (hot stars): only a fraction of the wind is captured by the binary Bondi-Hoyle accretion)
 - Slow wind (cool stars): atmospheric RLOF (similar to a slow RLOF)
- **Semi-detached:** Roche-lobe overflow (RLOF) – MT through inner L1 point. Difference between optically-thin MT ($R_d \sim R_L$, Ritter+1988) and optically-thick MT ($R_d > R_L$, Kolb+1990)
- **Contact (overcontact):** Stars share an envelope and are “peanut” shaped. Difficult to simulate in 1D, but still possible! (Marchant+2016, Fabry+2022,2023)

In MESA: Type of MT is controlled by `mdot_scheme`

Binary mass transfer (MT): consequences

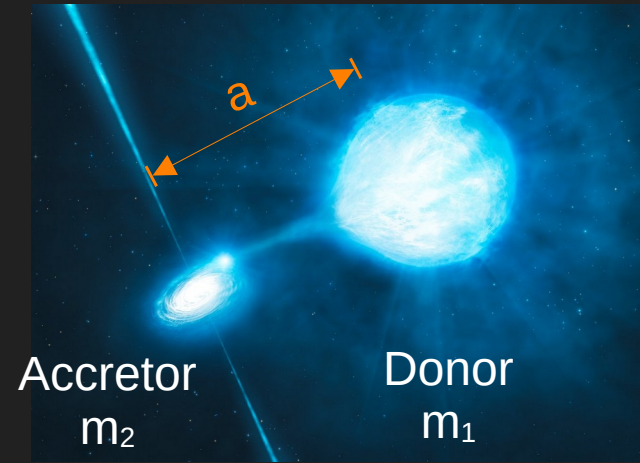


- Transfer both **matter** and **angular momentum**
- Large and very different consequences for the **structures of both stars** (Lab 1)
- Effect on the **binary orbit** (Lab 2) and **rotation of each star**
- In some cases: **unstable mass transfer** leading to common-envelope evolution (more on this in Lab 3)

Cases of mass transfer (MT)

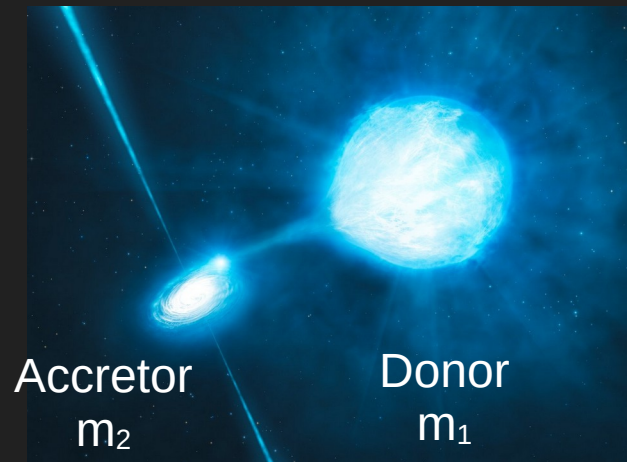
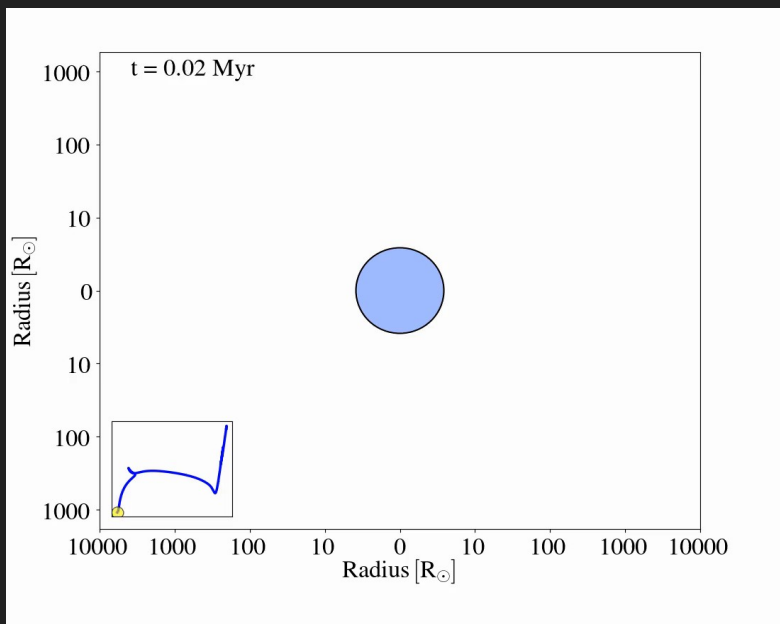
Lab 1: When and how does mass transfer happen and what are the consequences for the stars?

- Case A : Donor is core H burning
- Case B: Donor is post core H-burning, and before the end of core He burning “Hertzsprung-gap phase”
- Case C: Donor is post core He burning
(Note: these definitions can vary in the literature)



Cases of mass transfer (MT)

Lab 1: When and how does mass transfer happen and what are the consequences for the stars?



Visualizing MESA output (bonus task)

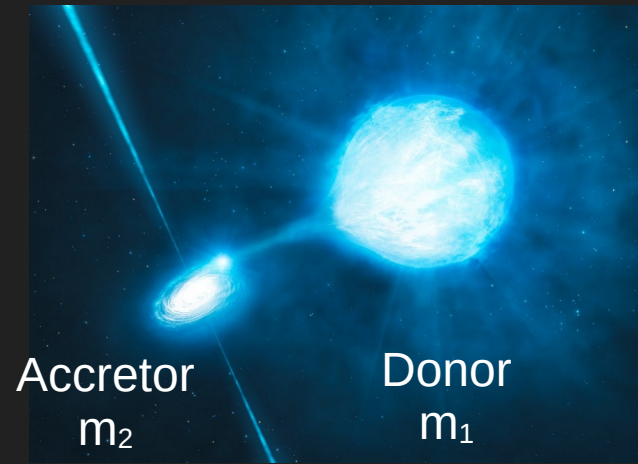


TULIPS

Tool for Understanding the Lives, Interiors, and Physics of Stars

Cases of mass transfer (MT)

Lab 1: When and how does mass transfer happen and what are the consequences for the stars?



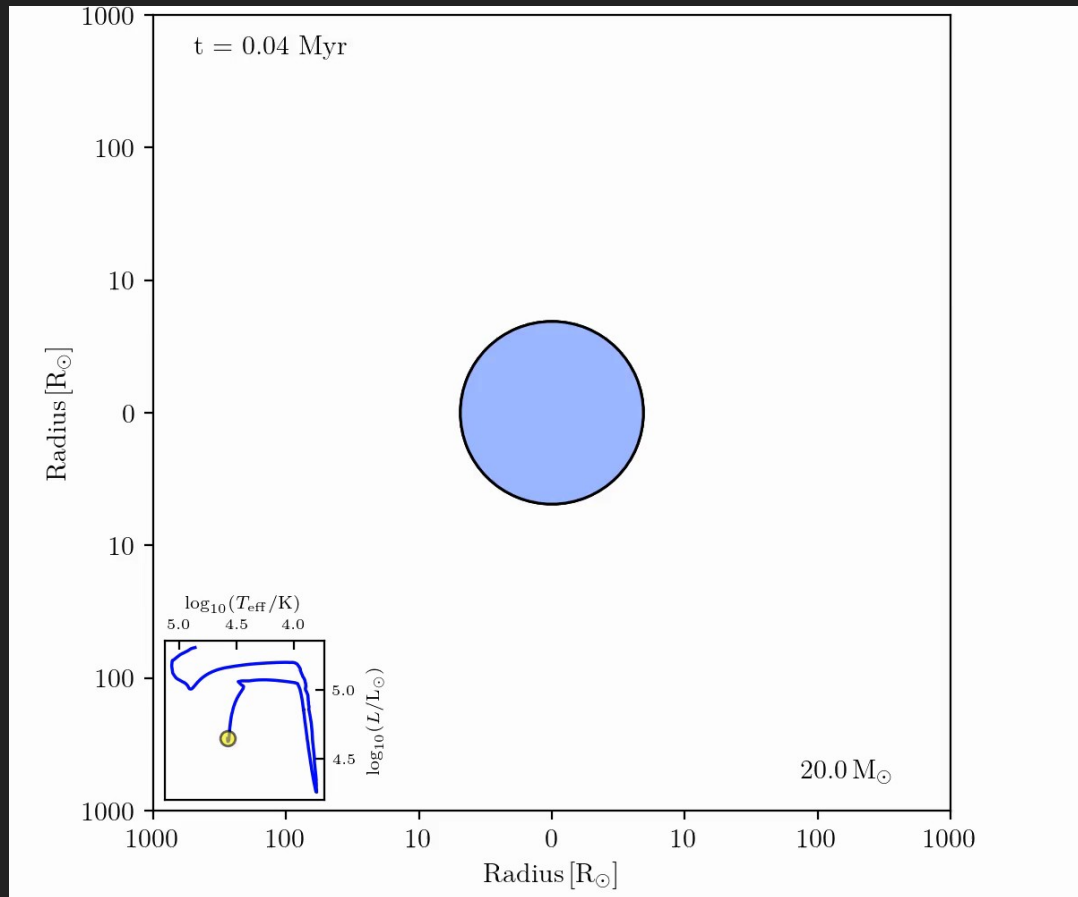
- Case A : Donor is core H burning
- Case B: Donor is post core H-burning, and before the end of core He burning “Hertzsprung-gap phase”
- Case C: Donor is post core He burning
(Note: these definitions can vary in the literature)

BEFORE STARTING LAB 1
Write down your hypotheses for:

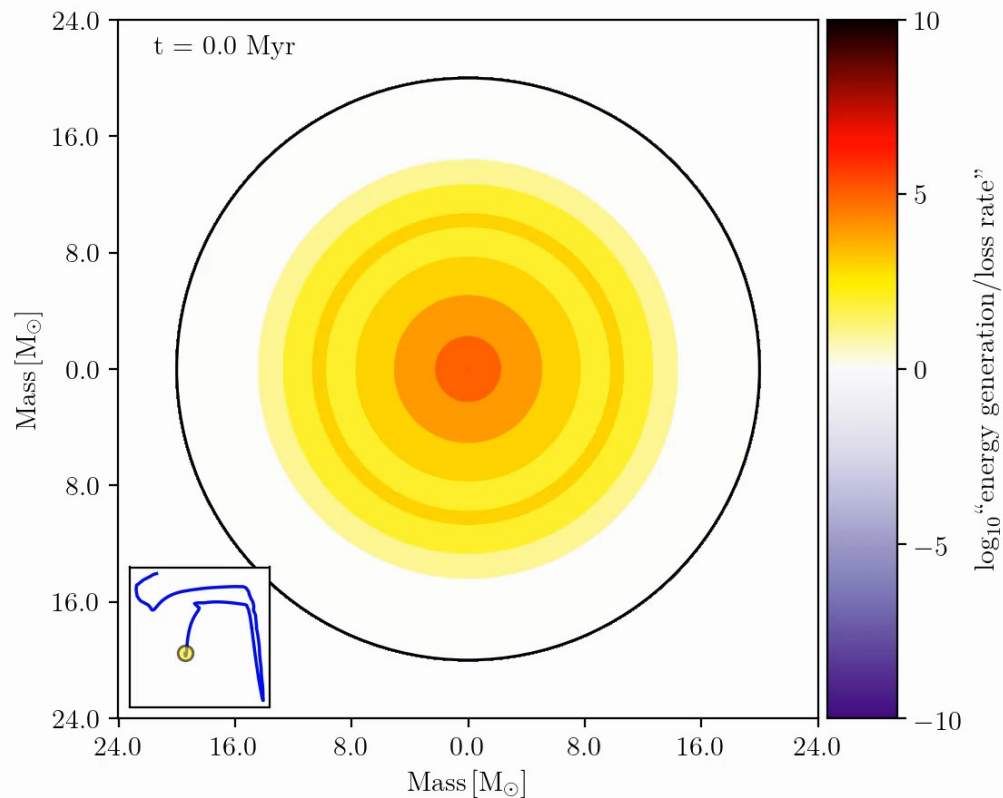
- 1) The effect of MT on each star**
- 2) What makes MT unstable**
- 3) The role of binary separation and mass ratio on the cases of MT**

Lab 1 summary

Lab 1 summary: donor

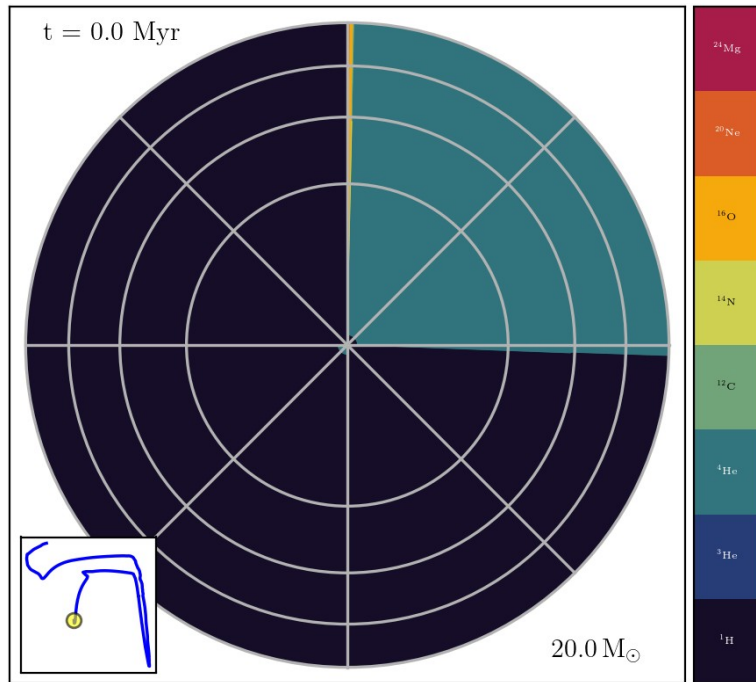


Lab 1 summary: donor



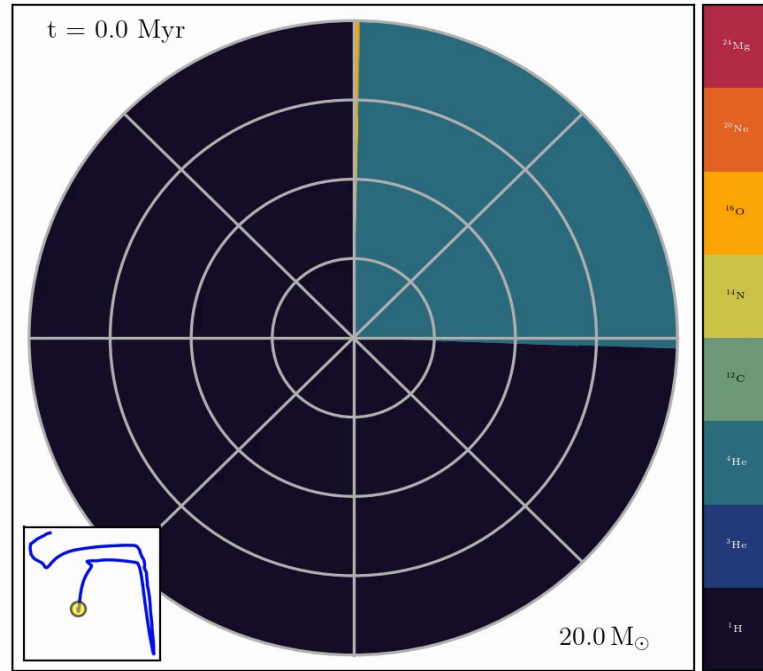
- Becomes a stripped star! (high T_{eff} , high L , $1 R_{\text{sun}}$, almost no H in envelope)

Lab 1 summary: donor



- Becomes a stripped star! (high T_{eff} , high L , $1 R_{\text{sun}}$, almost no H in envelope)

Lab 1 summary: donor



- Becomes a stripped star! (high T_{eff} , high L , $1 R_{\text{sun}}$, almost no H in envelope)

Lab 1 summary: donor

- Stripped stars were predicted since the 1960s but only very recently discovered!

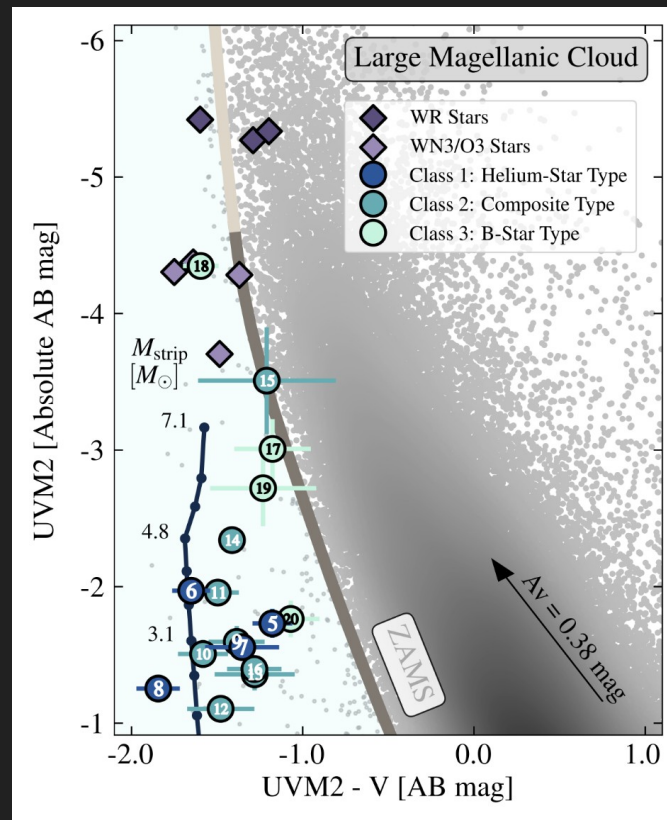
(e.g. Kippenhahn+1967)

- Important sources of ionizing photons, progenitors of stripped-envelope SNe, lead to different compact objects and different nucleosynthesis

(Eldridge+2013, Göteborg+2017, 2018, Klencki+2021, Laplace+2021, Farmer+2021, 2023)

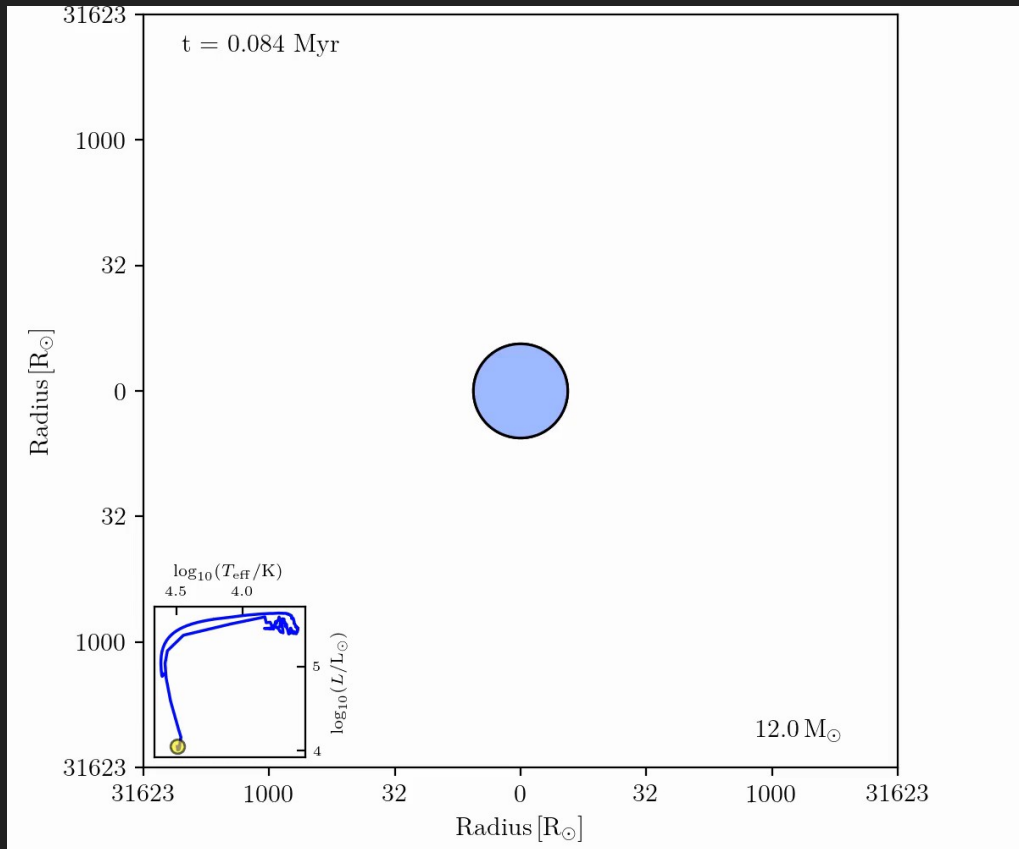
- Now also partially-stripped stars discovered

(Bodensteiner+2023, Shenar+2024, El-Badry+2024, Pauli+2024, Ramachandran+2024)



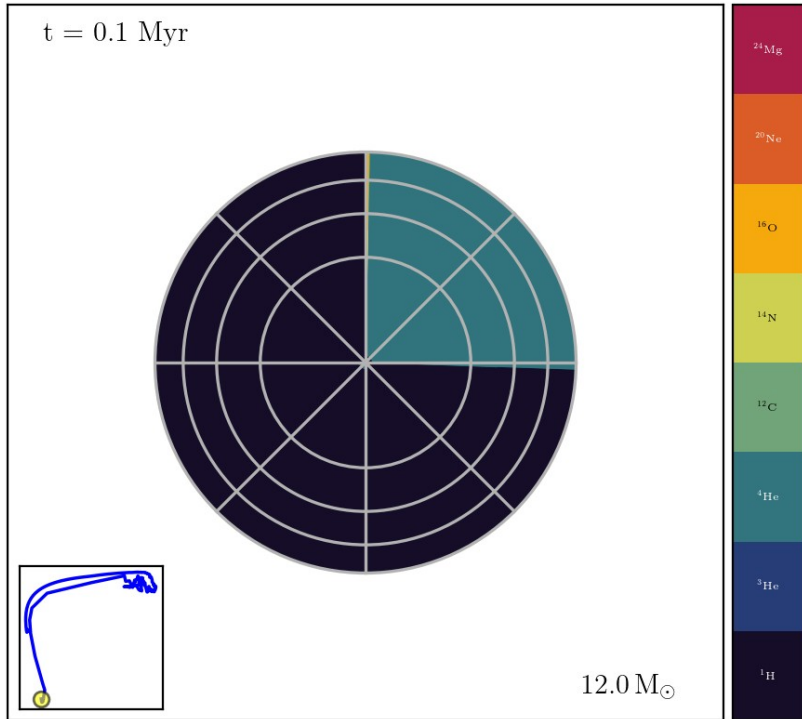
Drout & Göteborg et al. 2023, Science;
Ludwig+2025

Lab 1 summary: accretor



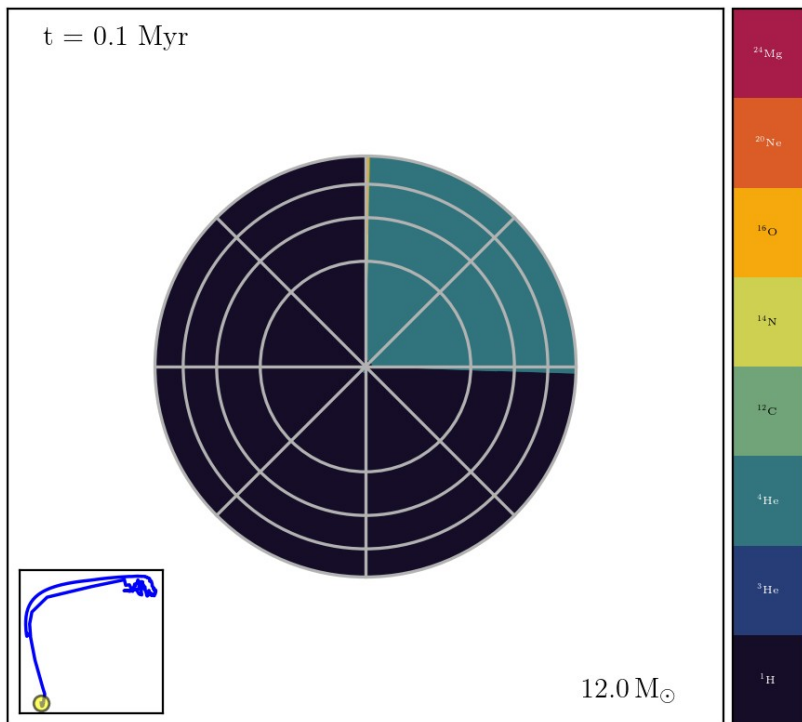
- Becomes a more luminous and hotter star → equivalent to an initially higher-mass star!

Lab 1 summary: accretor



- Becomes a more luminous and hotter star → equivalent to an initially higher-mass star!

Lab 1 summary: accretor



- Becomes a more luminous and hotter star → equivalent to an initially higher-mass star!
- Rejuvenates: more hydrogen fuel, lifetime is extended (note this sensitively depends on internal mixing and timing of accretion)

Lab 1 summary: accretor



Credit: NASA, JPL-Caltech,
Spitzer Space Telescope

Zeta Ophiuci, example of a likely accretor

Renzo & Göberg 2021

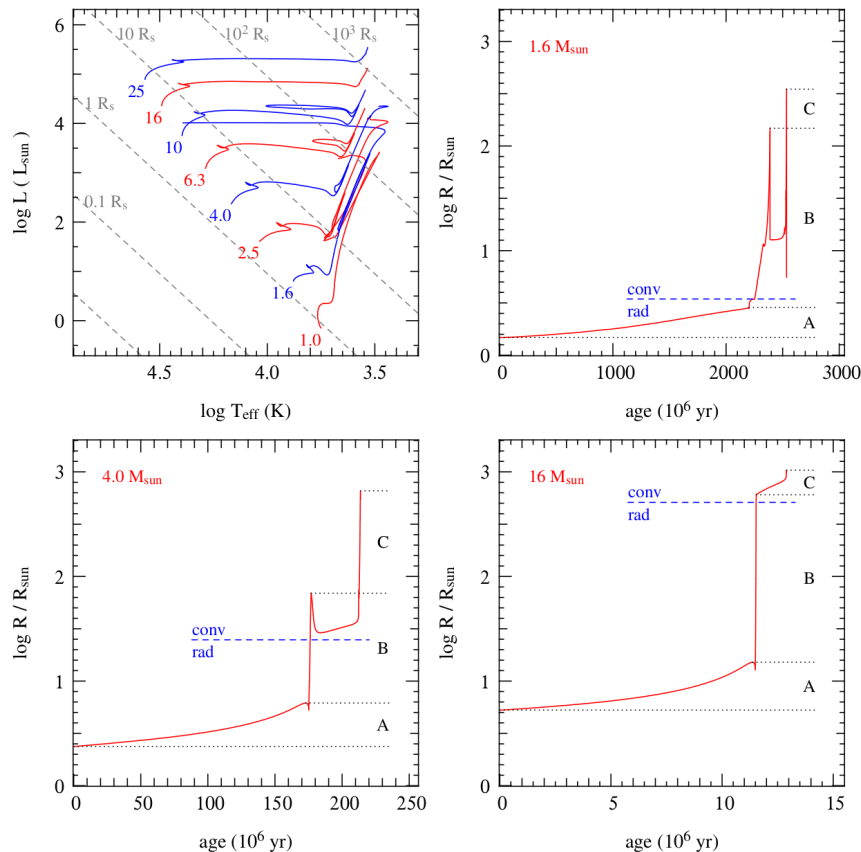
- Typically fast rotating, unusual age / luminosity compared to average population
- Many Be stars (rapidly rotating) can well be explained by accretion (e.g., Bodensteiner+2021)
- Surviving companions of exploded donor stars. Can lead to different compact objects (Renzo & Göberg+2021, Schneider+2024)
- Still many uncertainties regarding accretion process (angular momentum transfer, composition of accreted material, etc..)

Lab 1 summary

- Case A : Donor is core H burning
 - short periods/separations. MT on long (nuclear) timescale
- Case B: Donor is post core H-burning, and before the end of core He burning “Hertzsprung-gap phase”
 - intermediate periods/separations. MT on short (thermal) timescale
- Case C: Donor is post core He burning
 - large periods/separations, MT on dynamical or thermal timescale depending on envelope structure

Lab 1 summary

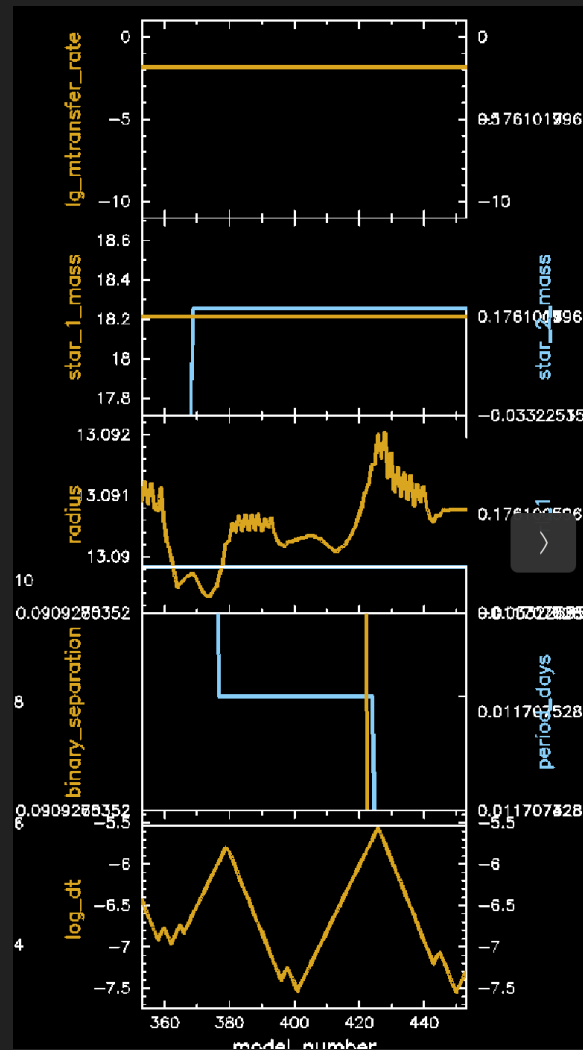
- Case A : Donor is core H burning
 - short periods/separations. MT on long (nuclear) timescale
- Case B: Donor is post core H-burning, and before the end of core He burning “Hertzsprung-gap phase”
 - intermediate periods/separations. MT on short (thermal) timescale
- Case C: Donor is post core He burning
 - large periods/separations, MT on dynamical or thermal timescale depending on envelope structure



Lab 1 summary:

Mass transfer stability depends on the mass ratio and the property of the envelope!

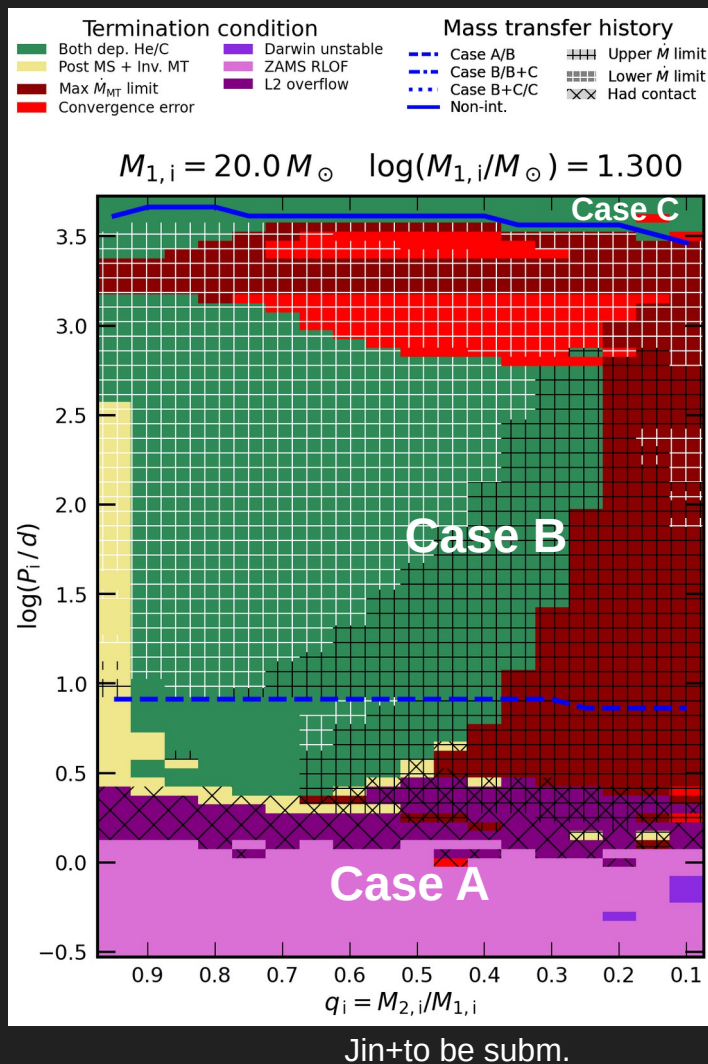
- More extreme mass ratio \rightarrow unstable
- Radiative envelope (low density in outer layers): envelope typically **shrinks** during MT
- Convective envelope (higher density, : envelope typically **expands** during MT \rightarrow can lead to runaway unstable MT and result in common envelope (see Lab 3)



Lab 1 summary:

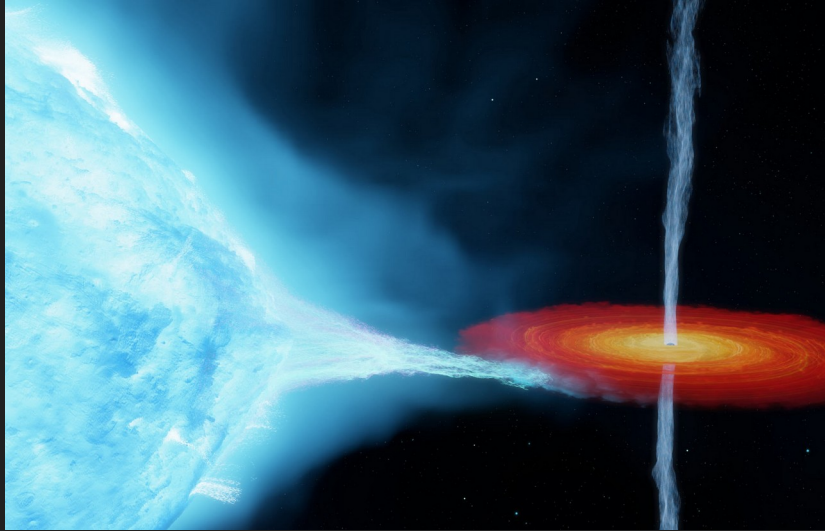
Mass transfer stability depends on the mass ratio and the property of the envelope!

- More extreme mass ratio \rightarrow unstable
- Radiative envelope: envelope typically **shrinks** during MT
- Convective envelope: envelope typically **expands** during MT \rightarrow can lead to runaway unstable MT and result in common envelope (see Lab 3)



Lab 2

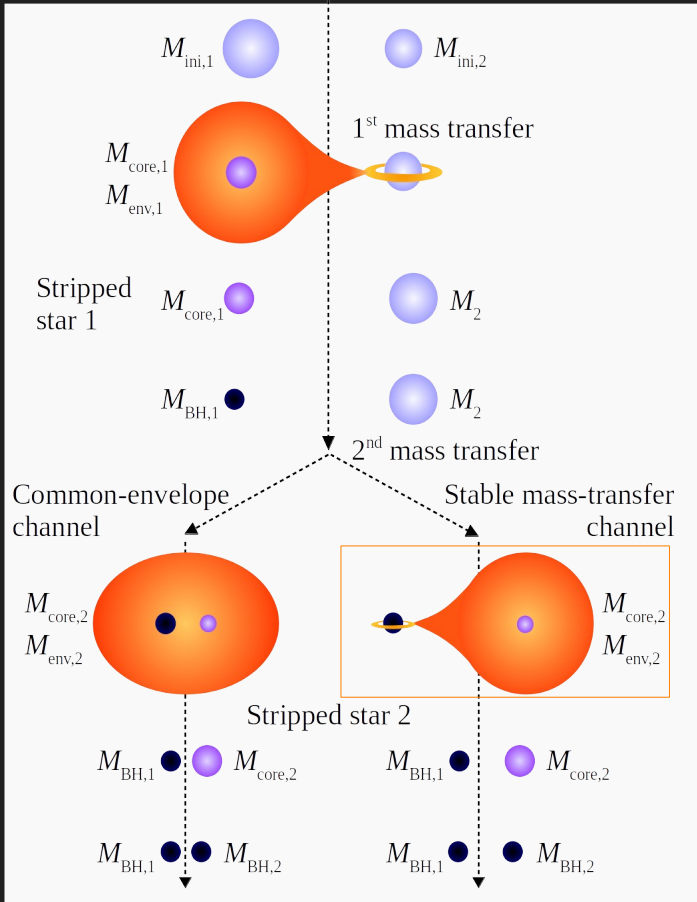
Lab 2 – Reproducing the properties of Cyg X-1



- X-ray binary: black hole + companion star. Bright X-rays from accretion process
- First black hole ever discovered $\sim 18 M_{\text{sun}}$ BH with $\sim 30M_{\text{sun}}$ O-type supergiant companion in a 5d orbit.
- **DRAWING EXERCISE**
What is a likely evolutionary history of this binary system? What will its future evolution look like?

Lab 2 – Summary

Tauris & van den Heuvel 2023



Case B

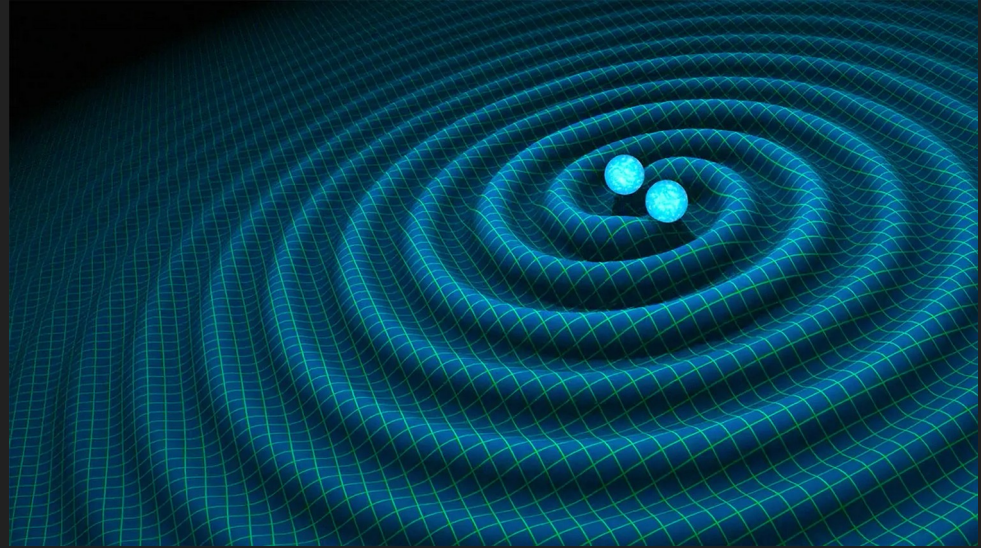
- The black hole in Cyg X-1 likely comes from the initial **primary star!**
- The companion is the initial secondary post accretion
- Likely progenitor of a double compact object (but merger time larger than age of the Universe). A favorable kick during compact object formation could change this

Cyg X-1!

Lab 2 – Gravitational-wave (GW) radiation

GR prediction: Emitted by massive objects accelerated in a non-spherically symmetric way (changing quadrupole moment)

→ orbital decay and eventual merger



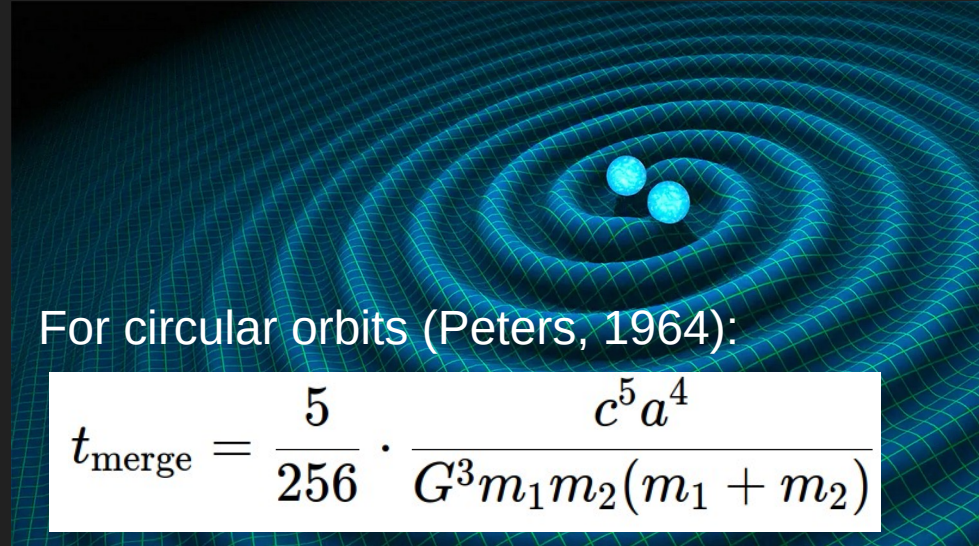
Two Nobel prizes:

- 1993: Hulse-Taylor pulsar orbital decay
- 2017: direct measurement of GWs from merging black holes by LIGO/Virgo

Lab 2 – Gravitational-wave (GW) radiation

GR prediction: Emitted by massive objects accelerated in a non-spherically symmetric way (changing quadrupole moment)

→ orbital decay and eventual merger

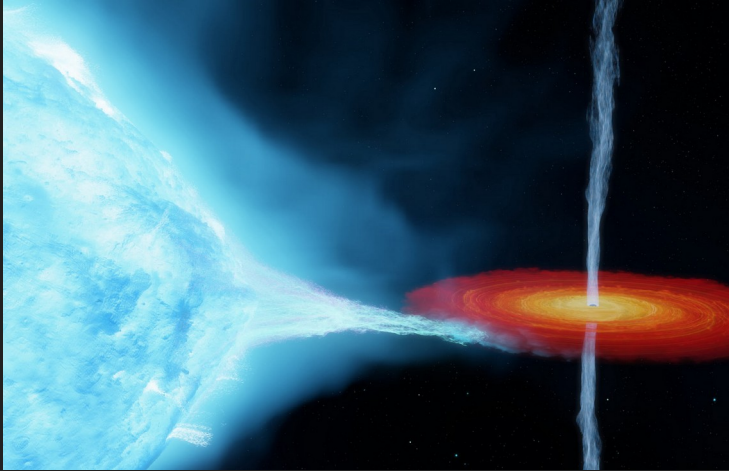


Will Cyg X-1 be a GW source in the future?

Two Nobel prizes:

- 1993: Hulse-Taylor pulsar orbital decay
- 2017: direct measurement of GWs from merging black holes by LIGO/Virgo

Lab 2 – Accretion efficiency

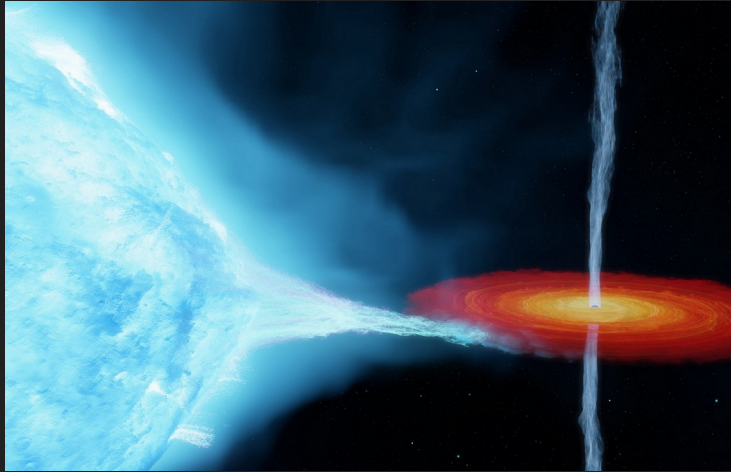


- Accretion Efficiency = fraction of accreted matter

$$\eta = (1 - \alpha - \beta - \delta)$$

Eddington-limited:
Maximum rate of accretion balanced by radiation pressure

Lab 2 – Accretion efficiency



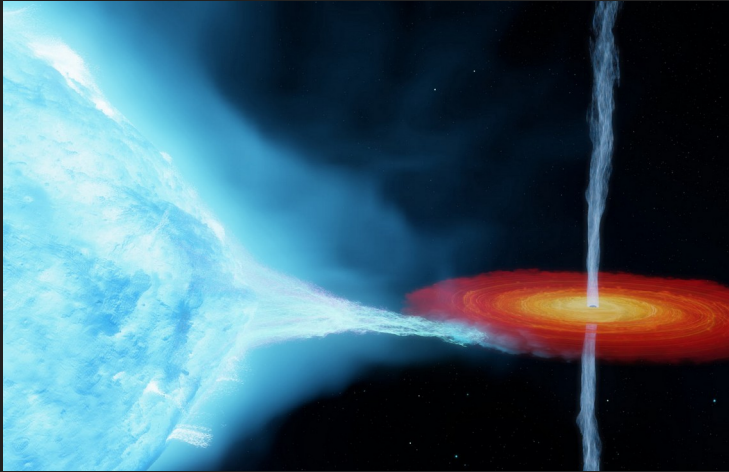
Eddington-limited:
Maximum rate of
accretion balanced by
radiation pressure

- Accretion Efficiency = fraction of accreted matter

$$\eta = (1 - \alpha - \beta - \delta)$$

- alpha: Fraction ejected from donor (fast wind / Jeans mode)
 - beta: Fraction ejected close to accretor (jet / isotropic re-emission)
 - delta: Fraction flowing away slowly from the system (circumbinary disk / ring)
- gamma: radius of circumbinary disk

Lab 2 – Accretion efficiency



Eddington-limited:
Maximum rate of
accretion balanced by
radiation pressure

- Accretion efficiency = fraction of accreted matter

$$\eta = (1 - \alpha - \beta - \delta)$$

This lab

- alpha: Fraction ejected from donor (fast wind / Jeans mode)
 - beta: Fraction ejected close to accretor (jet / isotropic re-emission)
 - delta: Fraction flowing away slowly from the system (circumbinary disk / ring)
- gamma: radius of circumbinary disk

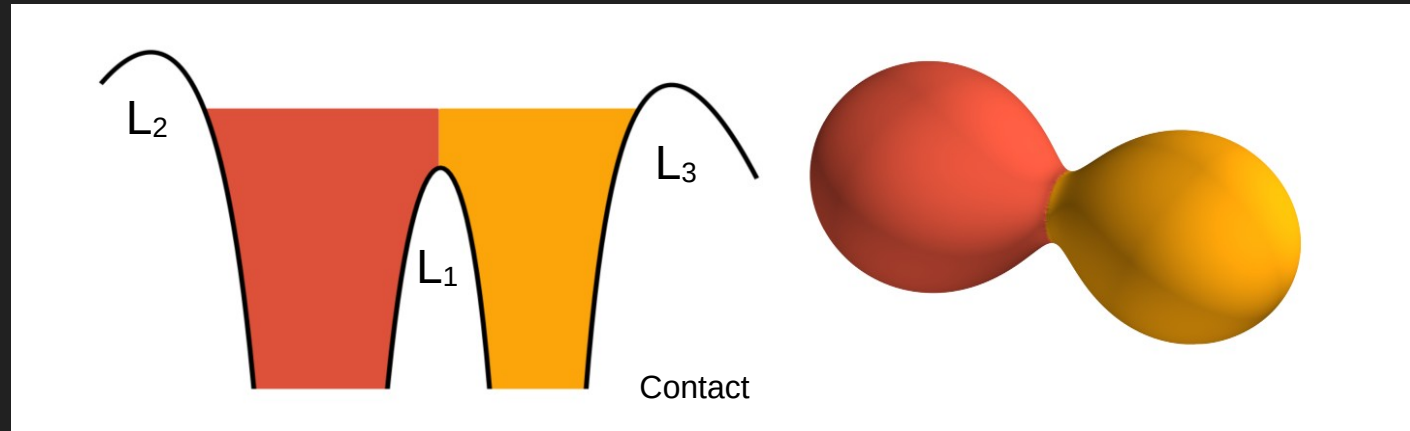
Extra bonus task: reproduce the Ups Sag system

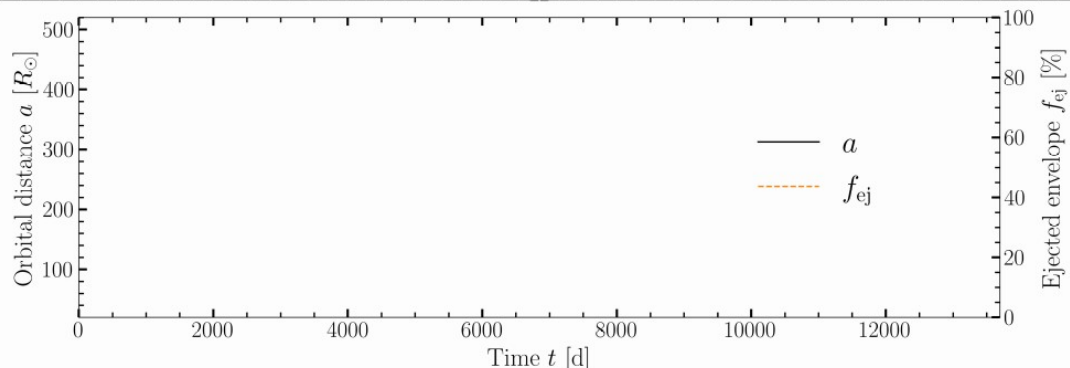
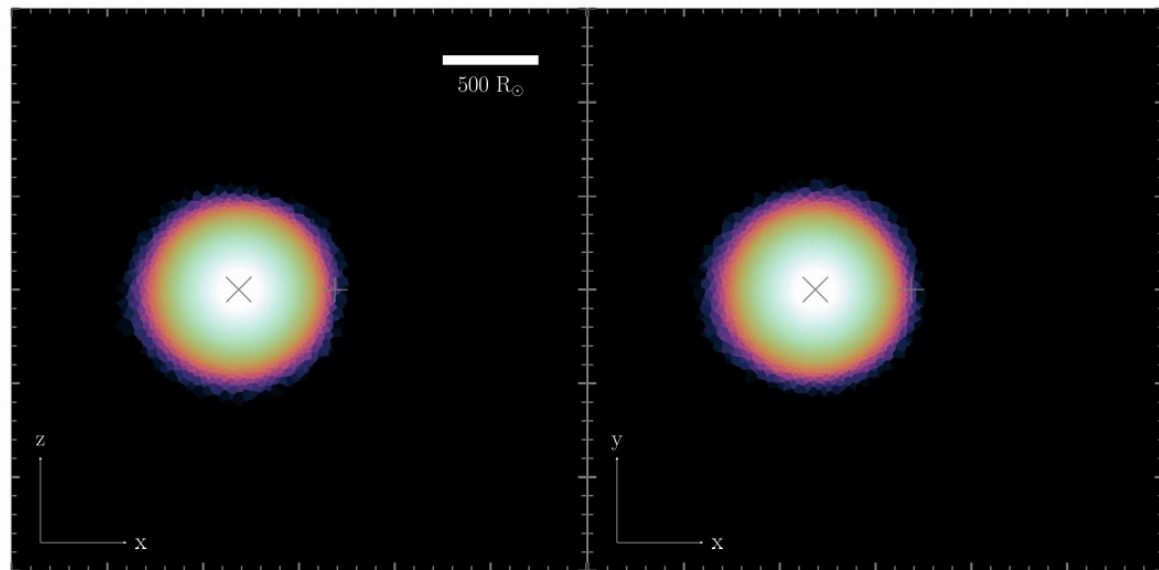
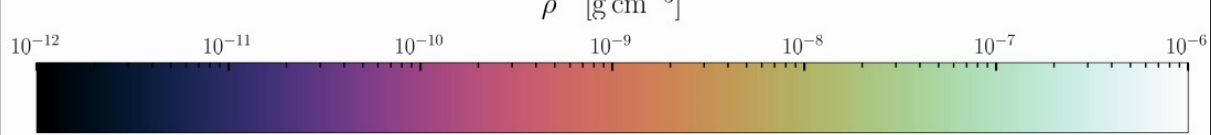
Lab 2: Summary

Lab 3: Simulating common envelope evolution in MESA

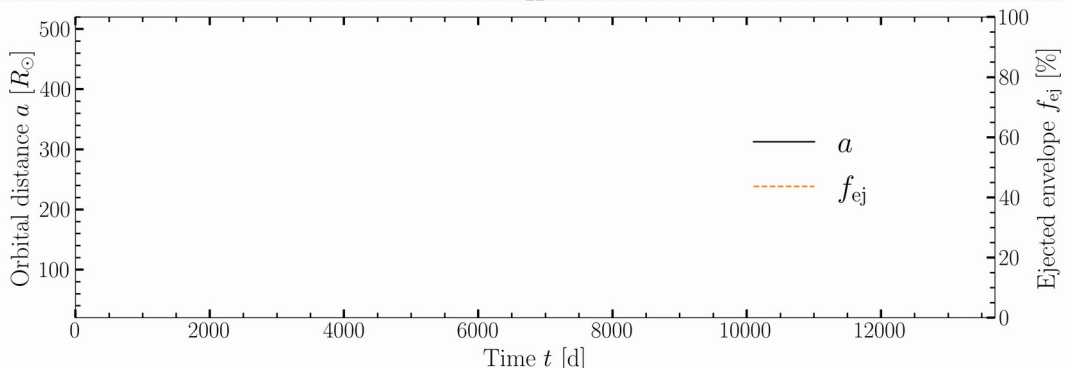
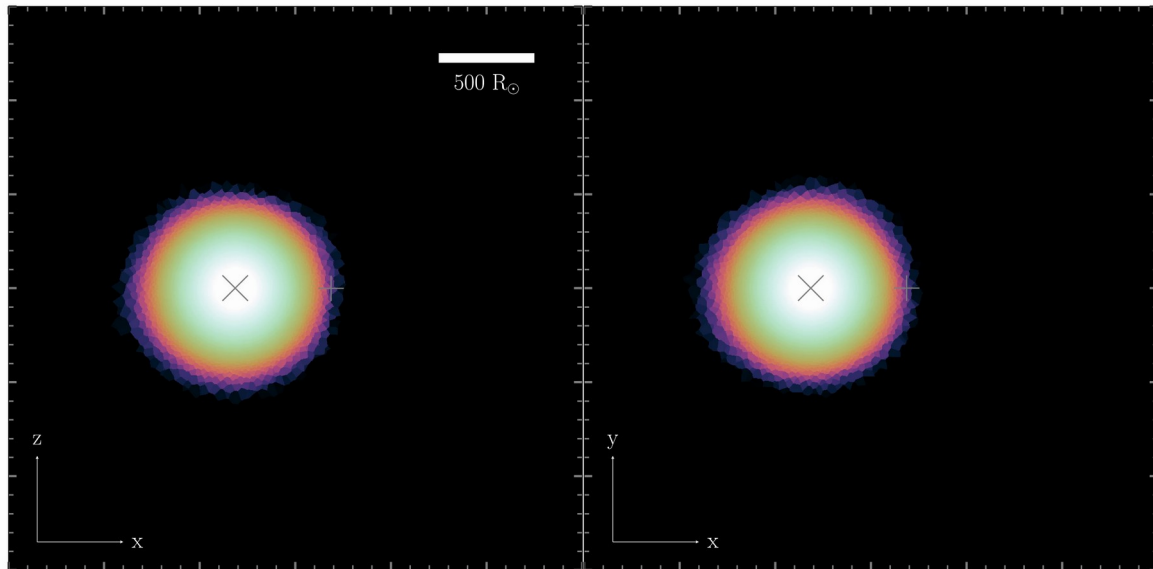
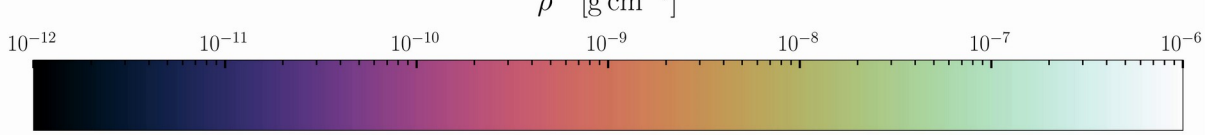
Lab 3: Common-envelope evolution

Starting from stable configuration \rightarrow unstable MT



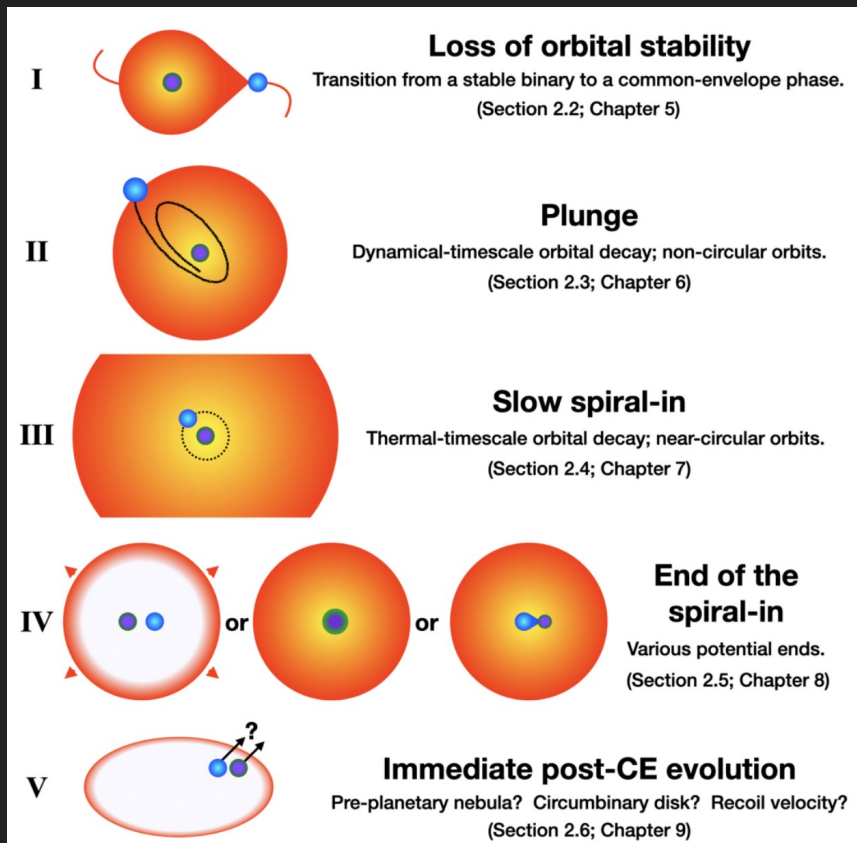


Credit:
Marco Vetter

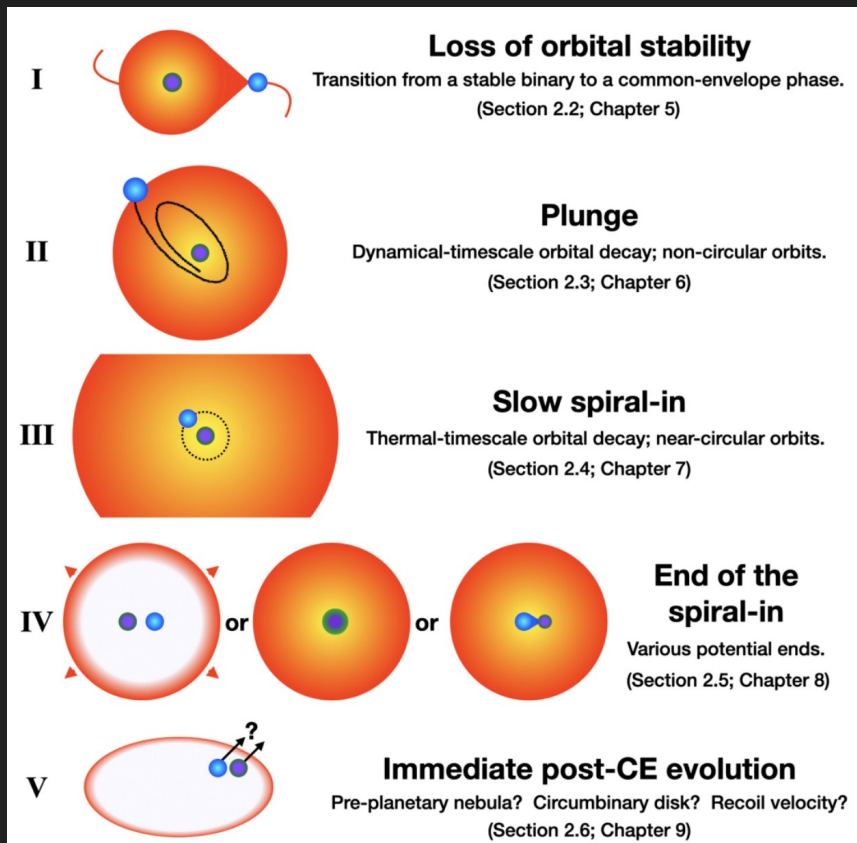


Credit:
Marco Vetter

Lab 3: Common-envelope evolution



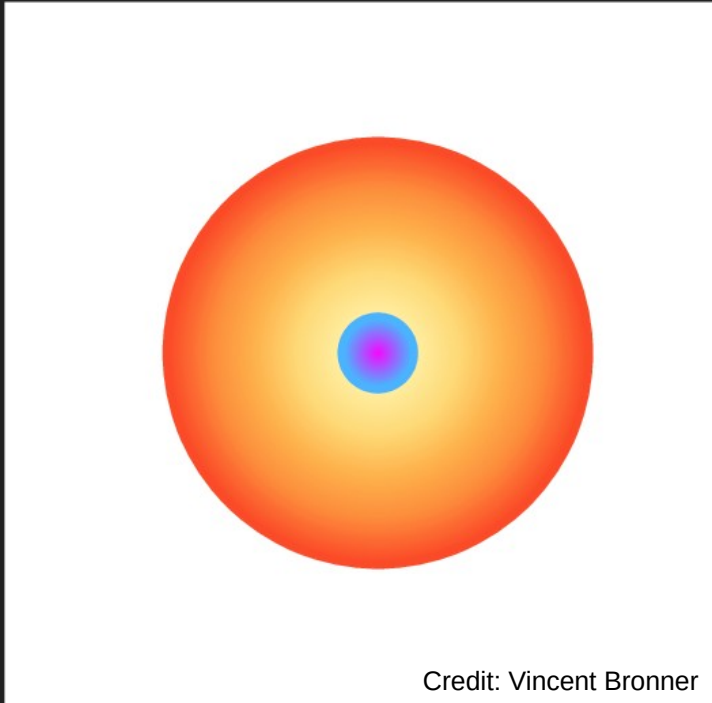
Lab 3: Common-envelope evolution



- Common and important process in binary stellar evolution
- Successful ejection determined by:
 - How tightly bound the envelope is
 - How efficiently orbital energy can be converted to unbinding the envelope

- If $\alpha_{\text{CE}} \Delta E_{\text{orb}} \geq E_{\text{bind}} \rightarrow$ **Envelope is ejected**
- If $\alpha_{\text{CE}} \Delta E_{\text{orb}} < E_{\text{bind}} \rightarrow$ **Merger occurs**

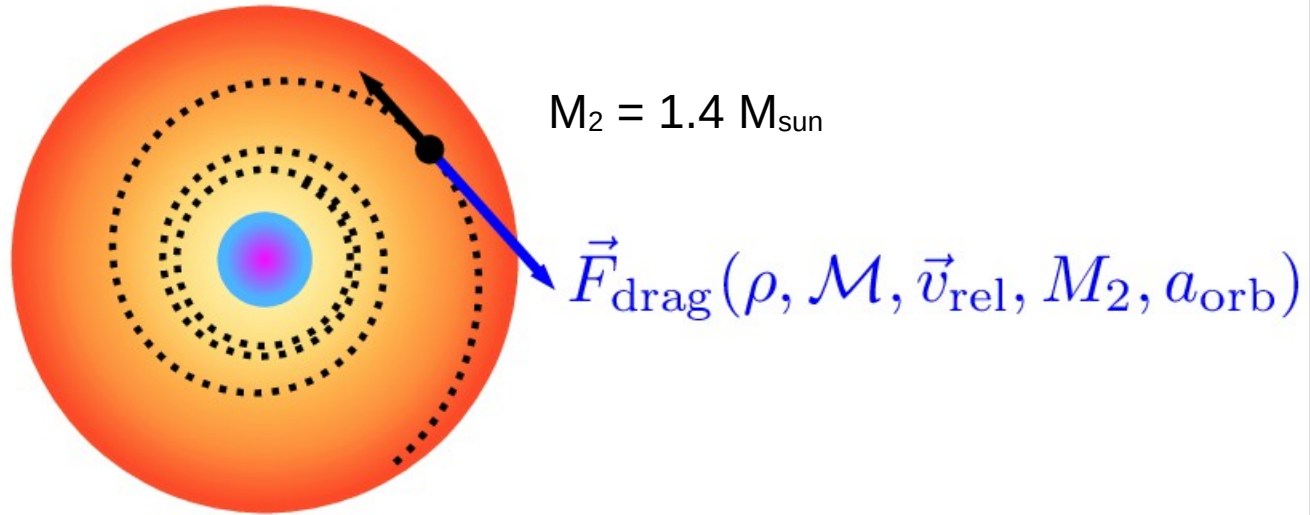
Lab 3: Simulating common envelope evolution in MESA



- Considering a single-star model of a $12 M_{\text{sun}}$ red supergiant
- Using MESA hydrodynamic mode (considering the velocity terms in stellar structure equations)

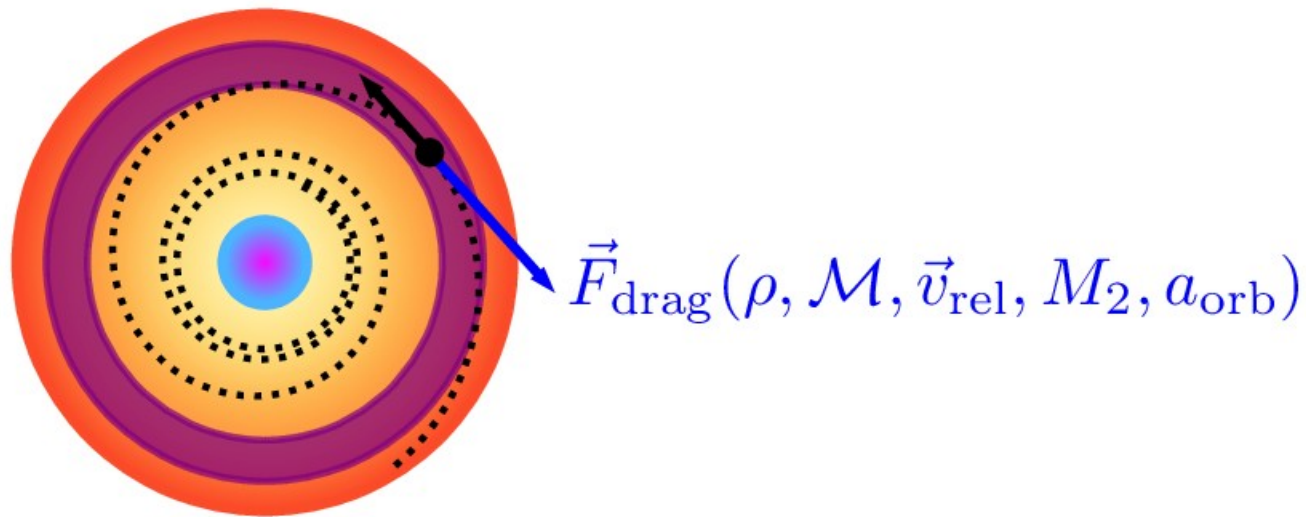
```
change_v_flag = .true.  
new_v_flag = .true.
```
- Adding a point-mass neutron-star companion on a circular orbit “by hand” through `run_star_extras` and solving equations of motion

Lab 3: Simulating common envelope evolution in MESA



Drag force: dissipates $E_{\text{orb}} \rightarrow$ shorter a_{orb}

Lab 3: Simulating common envelope evolution in MESA

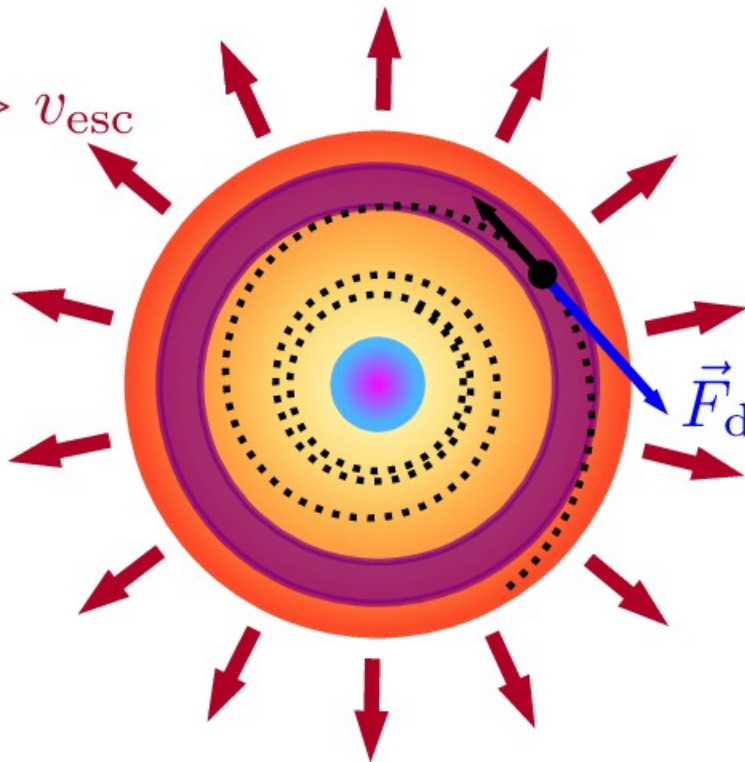


Drag force: loss of $E_{\text{orb}} =$ heating of the envelope (at radius R_a)

Credit: Vincent Bronner

Lab 3: Simulating common envelope evolution in MESA

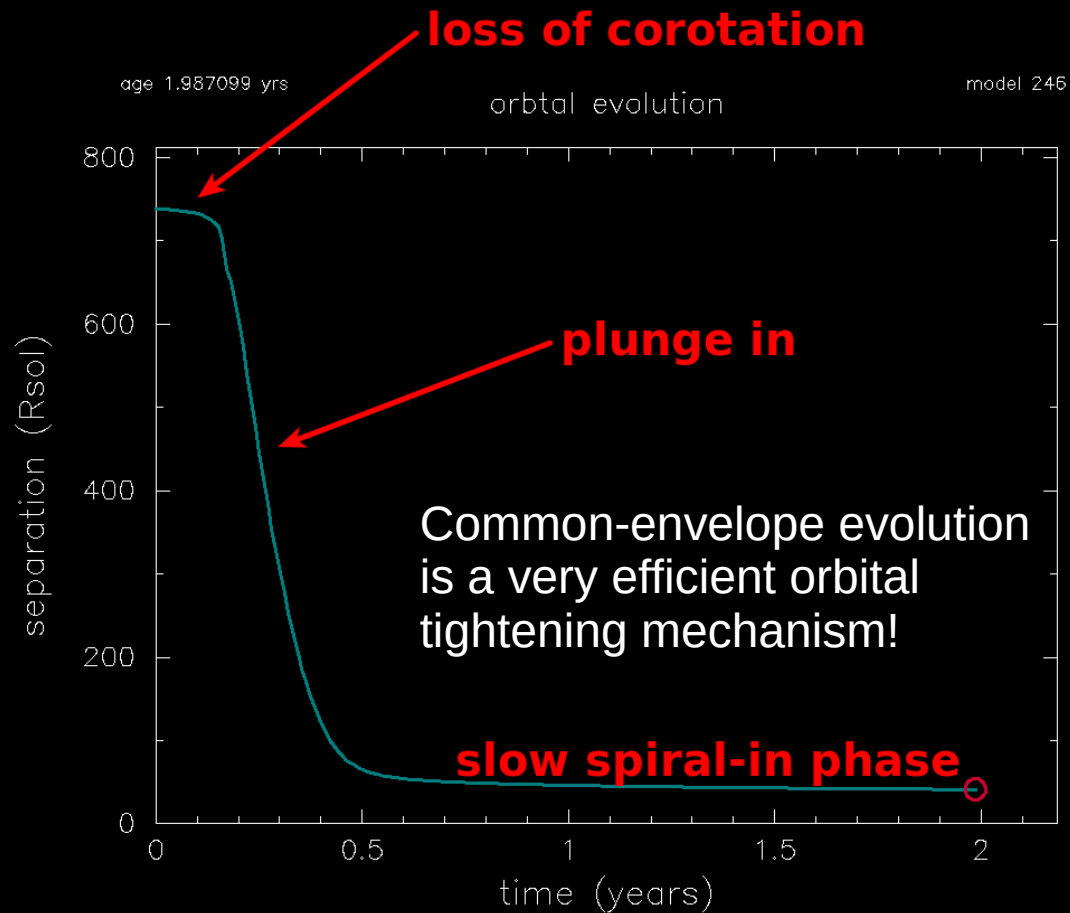
$$v_r > v_{\text{esc}}$$



Heating: Perturbation of hydrostatic equilibrium
→ star expands, ejection of layers with $v_r > v_{\text{esc}}$
(not simulated here)

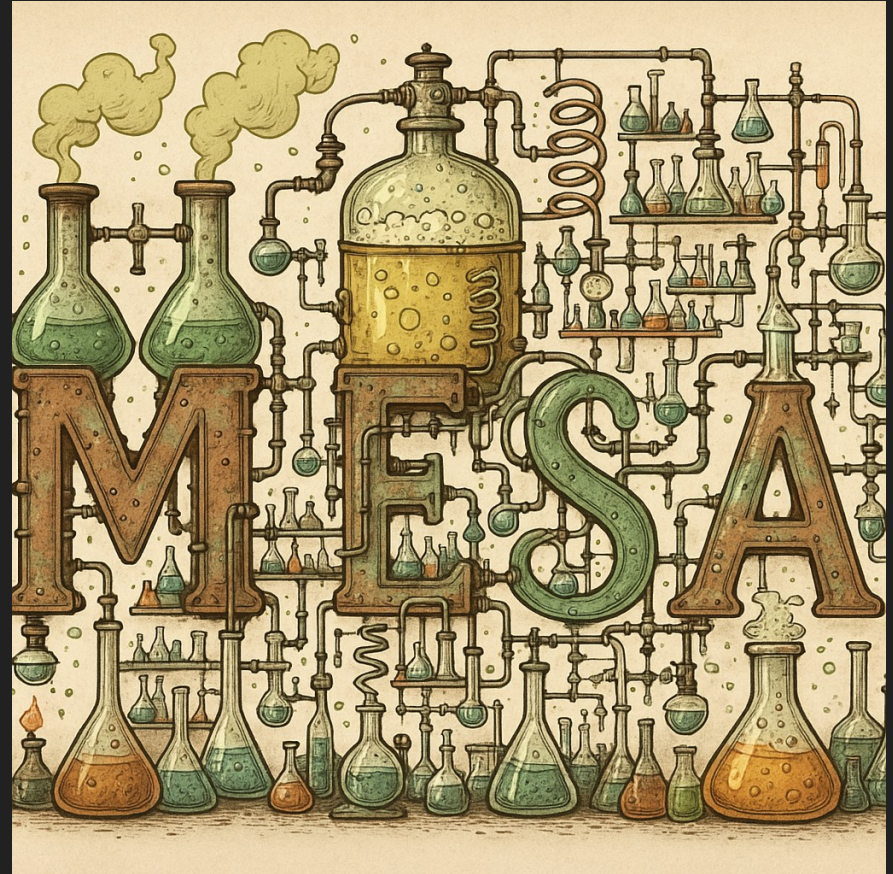
$$\vec{F}_{\text{drag}}(\rho, \mathcal{M}, \vec{v}_{\text{rel}}, M_2, a_{\text{orb}})$$

Lab 3 summary



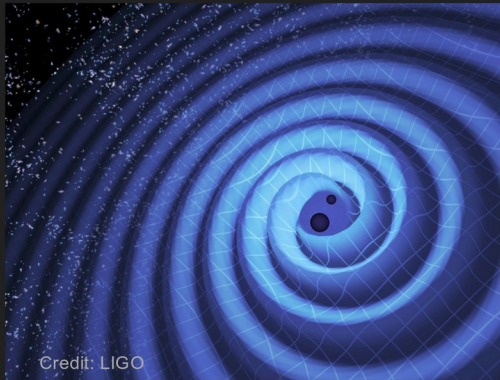
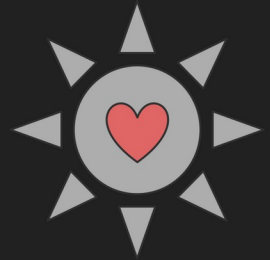
Thoughts on MESA

- It can be helpful to treat MESA runs as experiments in a fantastic virtual lab. Write down your hypotheses and the outcome.
- Sometimes, MESA crashes for a good reason! Be careful with “removing problematic layers”
- Sanity checks pay off!
- Check the documentation



Hiring 2 PhD candidates soon!

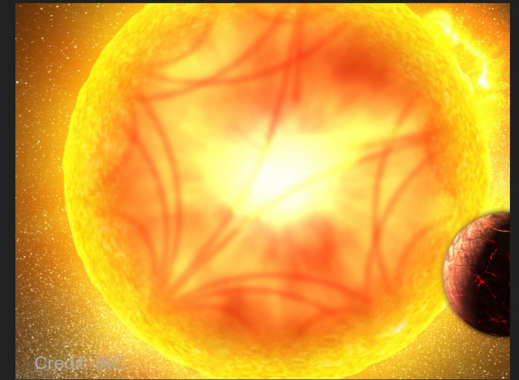
StarHearts



Gravitational-wave progenitors



Explosions and implosions of binaries



Stellar "heartbeats" (asteroseismology)