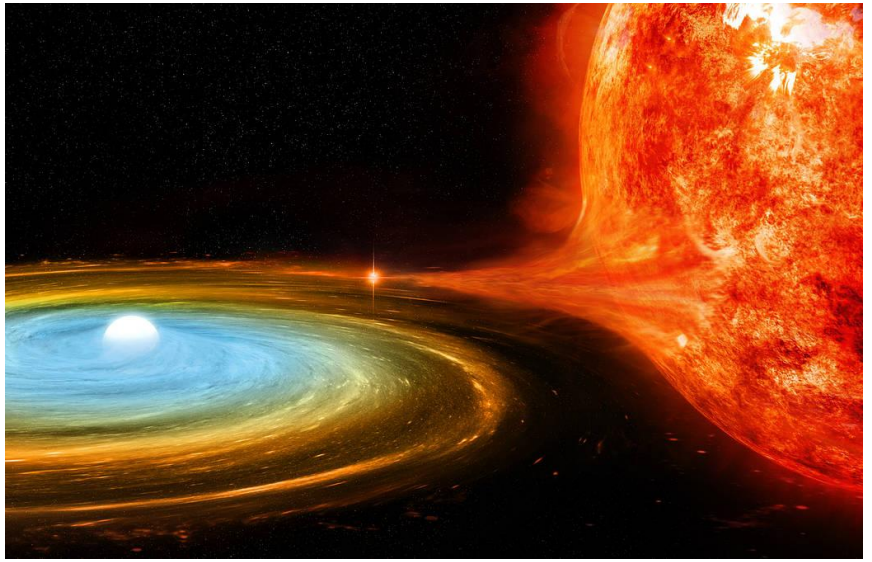
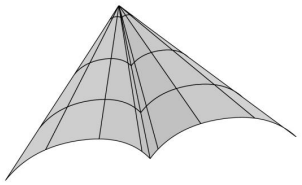
Multi-dimensional radiation-magneto-hydrodynamical simulations of the lives and deaths of interacting binary stars



Ondřej Pejcha
Institute of Theoretical Physics
Faculty of Mathematics and Physics, Charles University







StG 2019-2025: Cat-In-hAT

CoG 2025-2030: ROGALLO

(subset of) Team in Prague (2019-2025)



Damien Gagnier
(postdoc 2021-2024)
→ Heidelberg
3D fluid dynamics



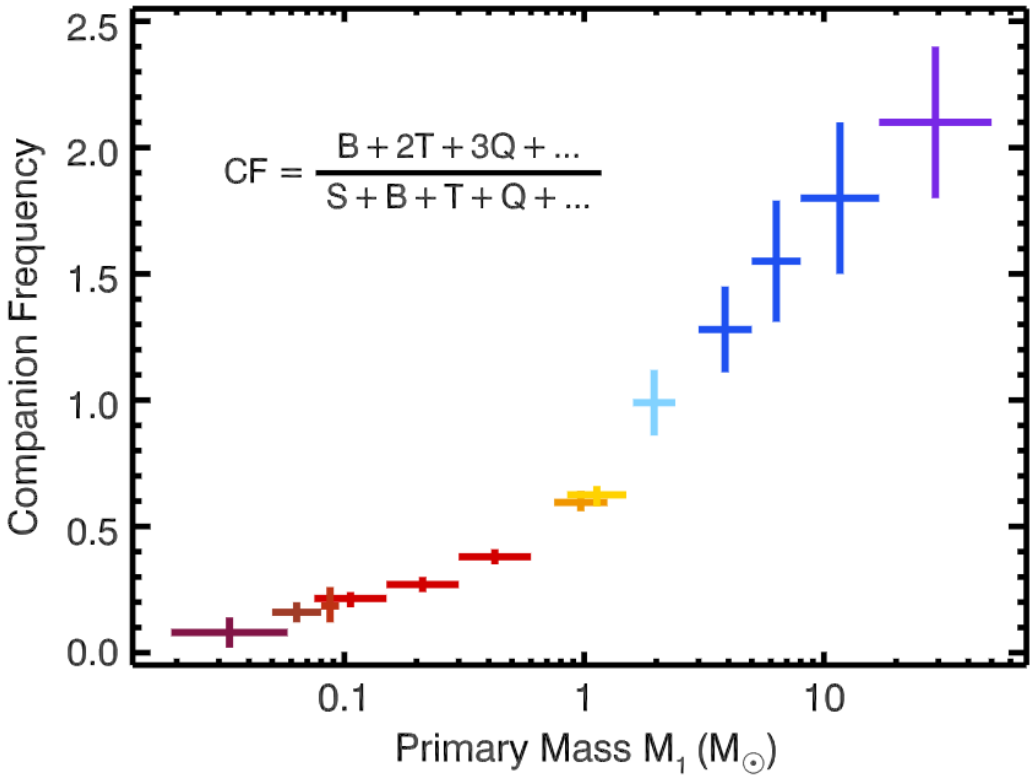
Diego Calderón
(postdoc 2019-2023)
→ Hamburg/Max Planck Garching Humboldt Fellow
→ MSCA Fellow (Prague)
Radiation hydrodynamics



Camille Landri
(PhD 2020-2024)
→ KU Leuven
Smoothed particle hydrodynamics,
3D simulations

VSB TECHNICAL UNIVERSITY OF OSTRAVA | IT4INNOVATIONS NATIONAL SUPERCOMPUTING CENTER

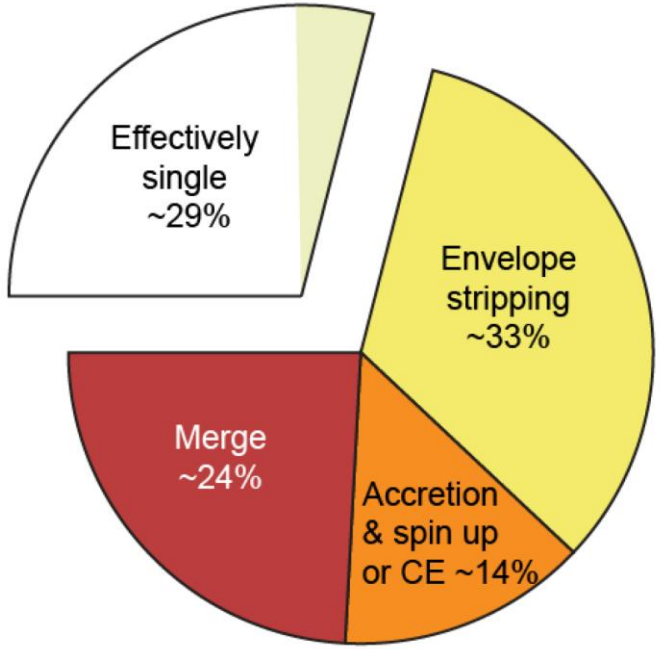
Binary stars are frequent



Offner et al. (2023)

Interactions in binaries are frequent

(high-mass stars)



Sana et al. (2012)

~0.2 mergers/year in the Galaxy

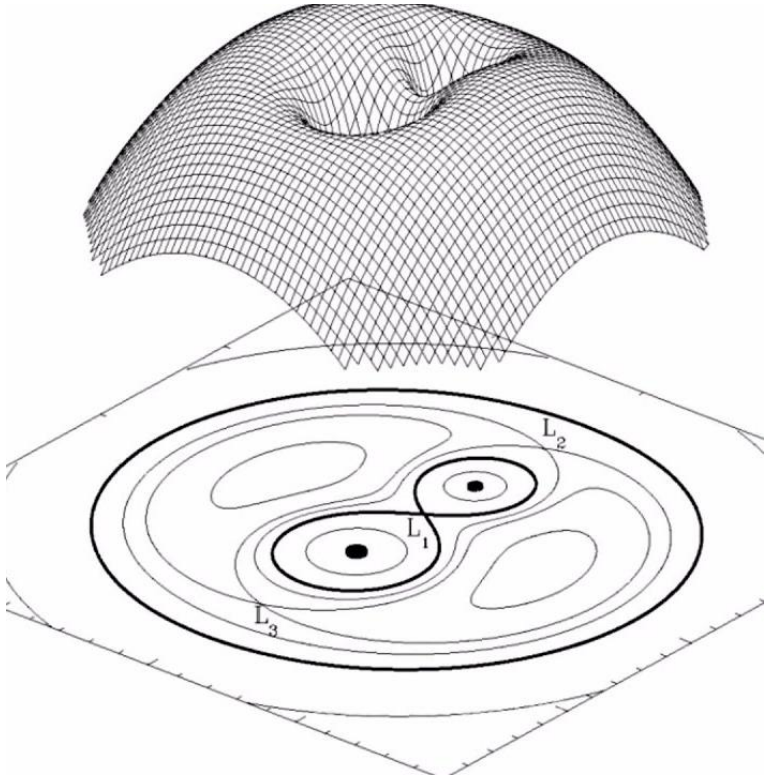
(Kochanek et al. 2014)

Structure of binary stars: lack of symmetry

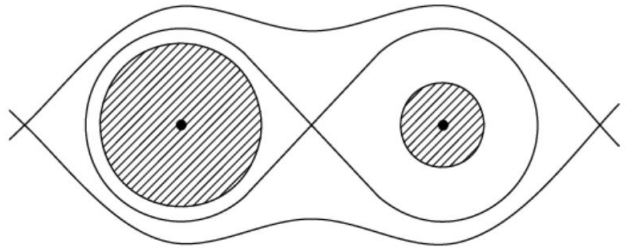
Roche potential

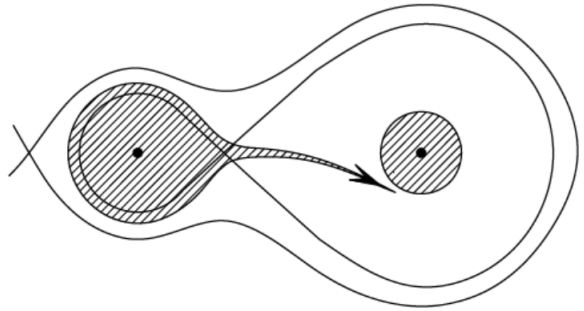
$$\ddot{\mathbf{r}} = -\nabla\phi_R(\mathbf{r}) - 2\boldsymbol{\omega}\times\dot{\mathbf{r}},$$

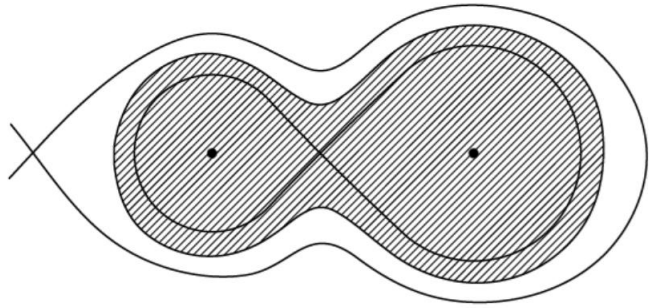
$$\phi_R(\mathbf{r}) = -\frac{GM_1}{|\mathbf{r}-\mathbf{r_1}|} - \frac{GM_2}{|\mathbf{r}-\mathbf{r_2}|} + \frac{1}{2}|\boldsymbol{\omega}\times\mathbf{r}|^2$$



Configurations of binary stars

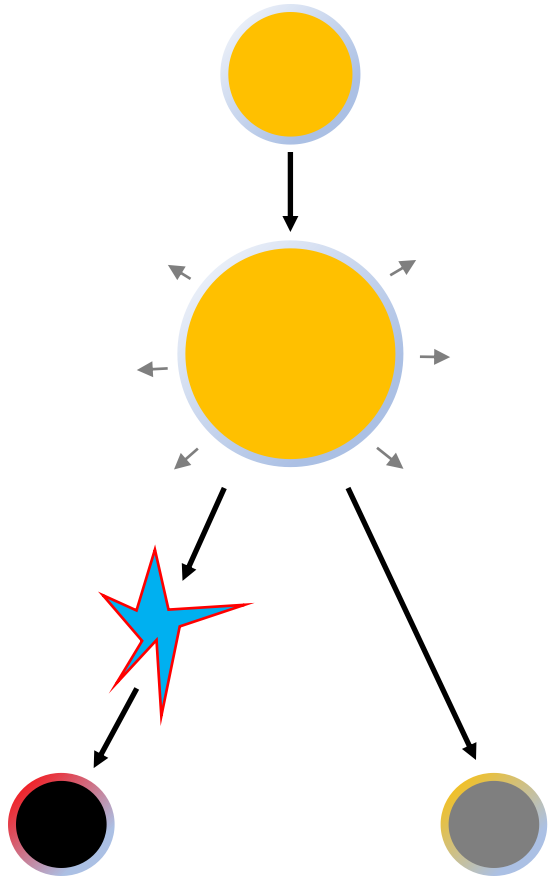






Importance of interacting binary stars: evolutionary outcomes not achievable in single star evolution

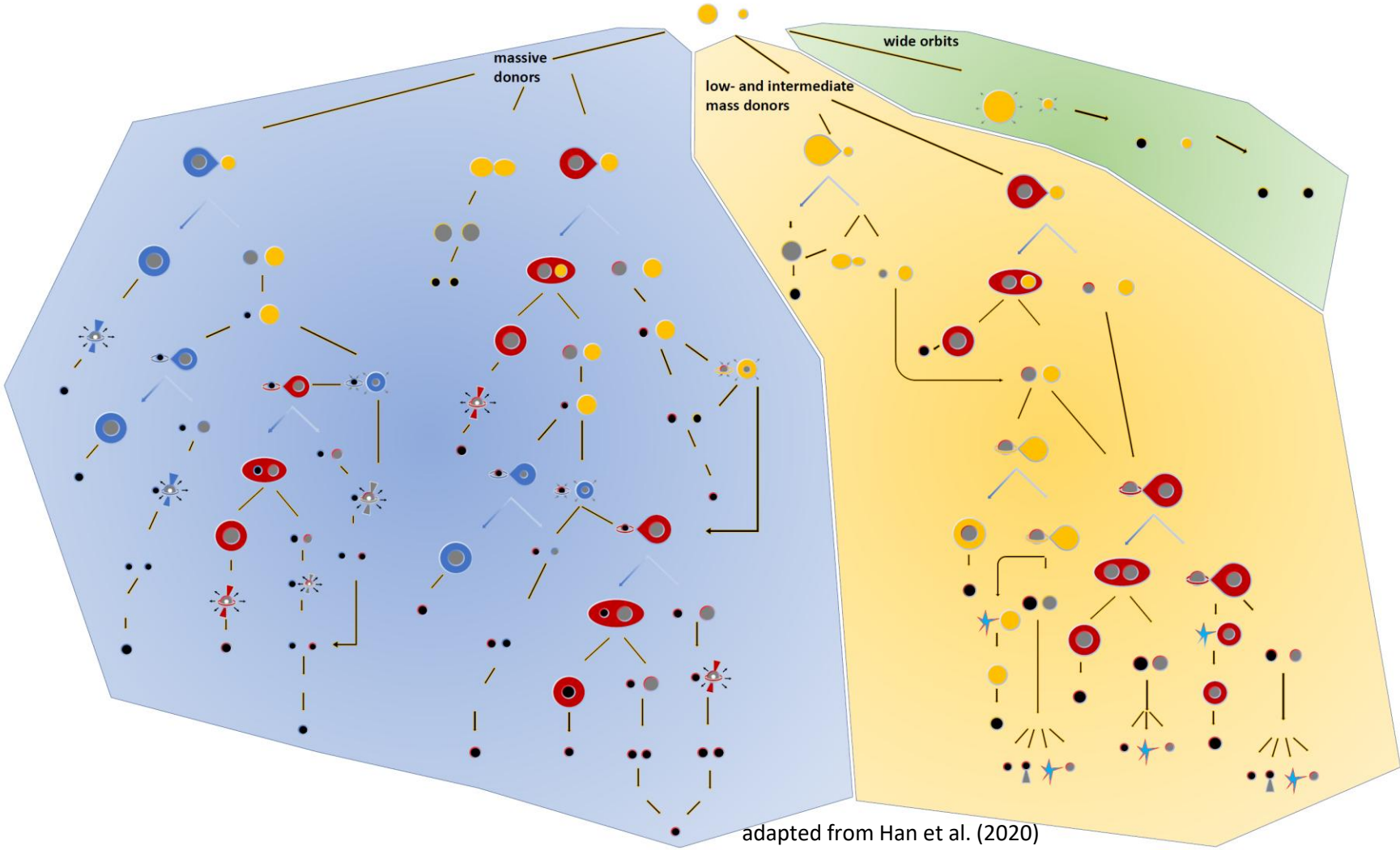
Single star evolution



neutron star/
black hole

white dwarf

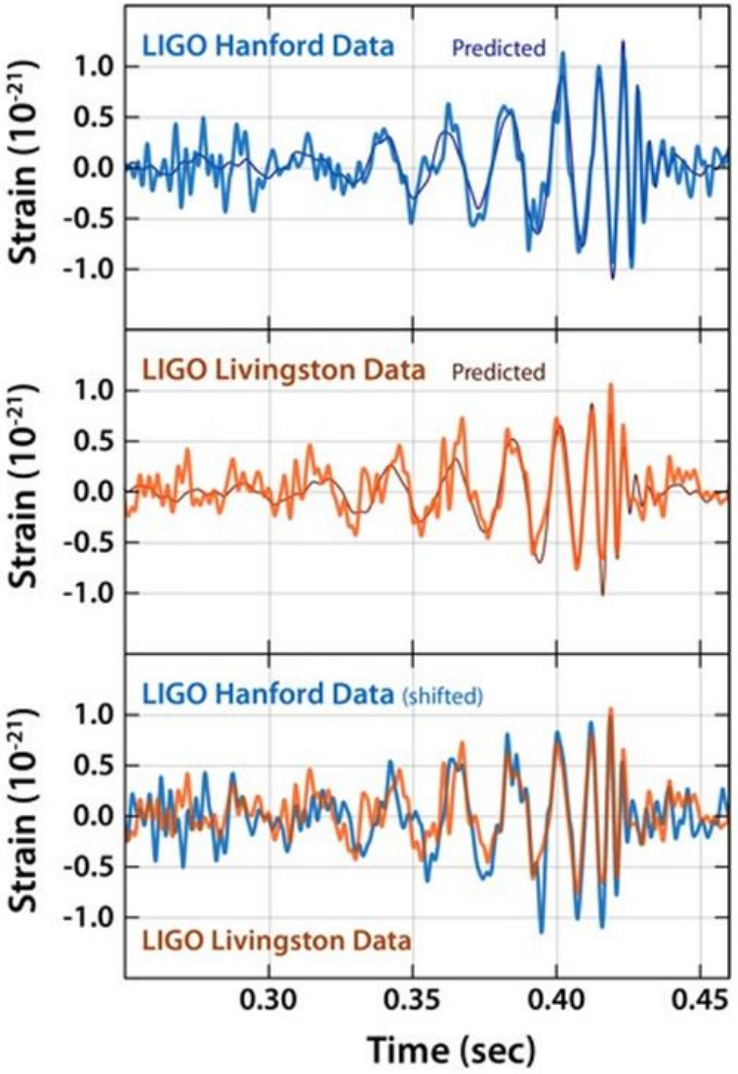
Binary star evolution



adapted from Han et al. (2020)

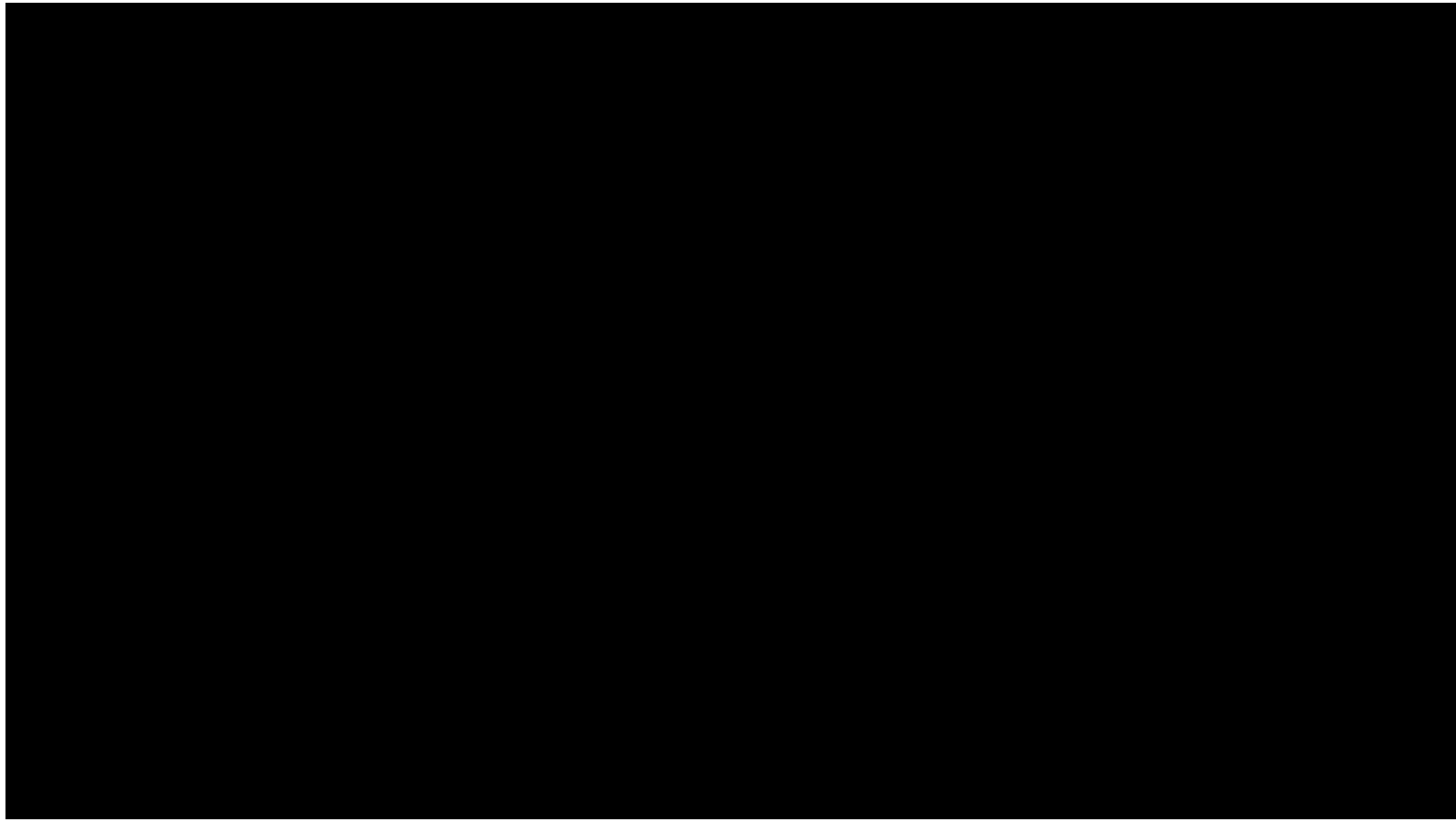
Importance of binary stars: origin of gravitational wave sources

GW150914 – collision of two black holes



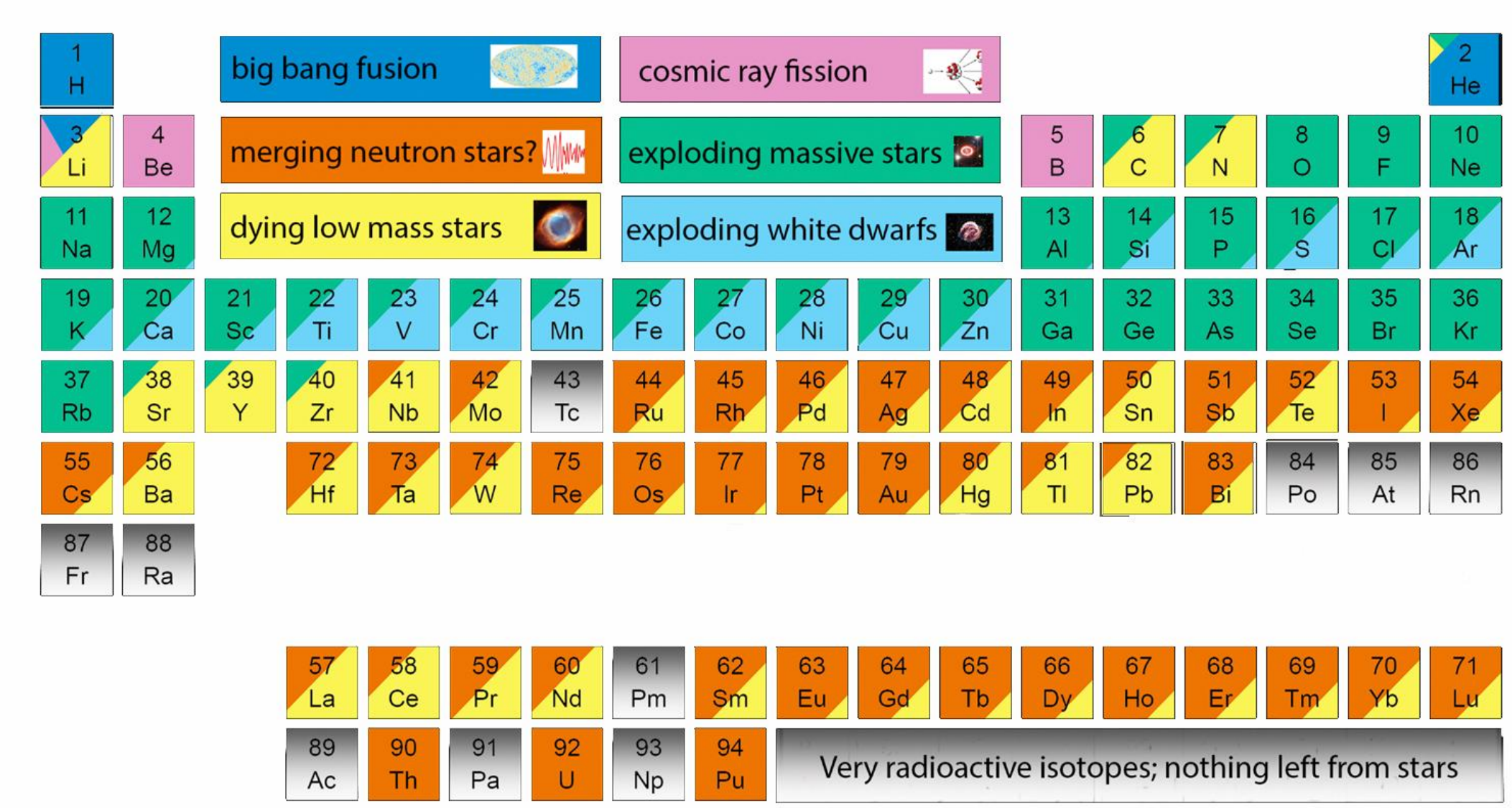
Credit: Caltech/MIT/LIGO Lab

GW170817 – collision of two neutron stars



Credit: NASA/Goddard Space Flight Center/CI Lab

Importance of binary star: origin of chemical elements



https://www.astronomy.ohio-state.edu/johnson.3064/nucleo, ESA/NASAS/AASNova

Theoretical description of binary stars - equations of fluid dynamics

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = \text{sources of mass}$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) + \nabla P = \text{sources of momentum}$$

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho E \mathbf{u} + P \mathbf{u}) = \text{sources of energy}$$

Complications due to physics

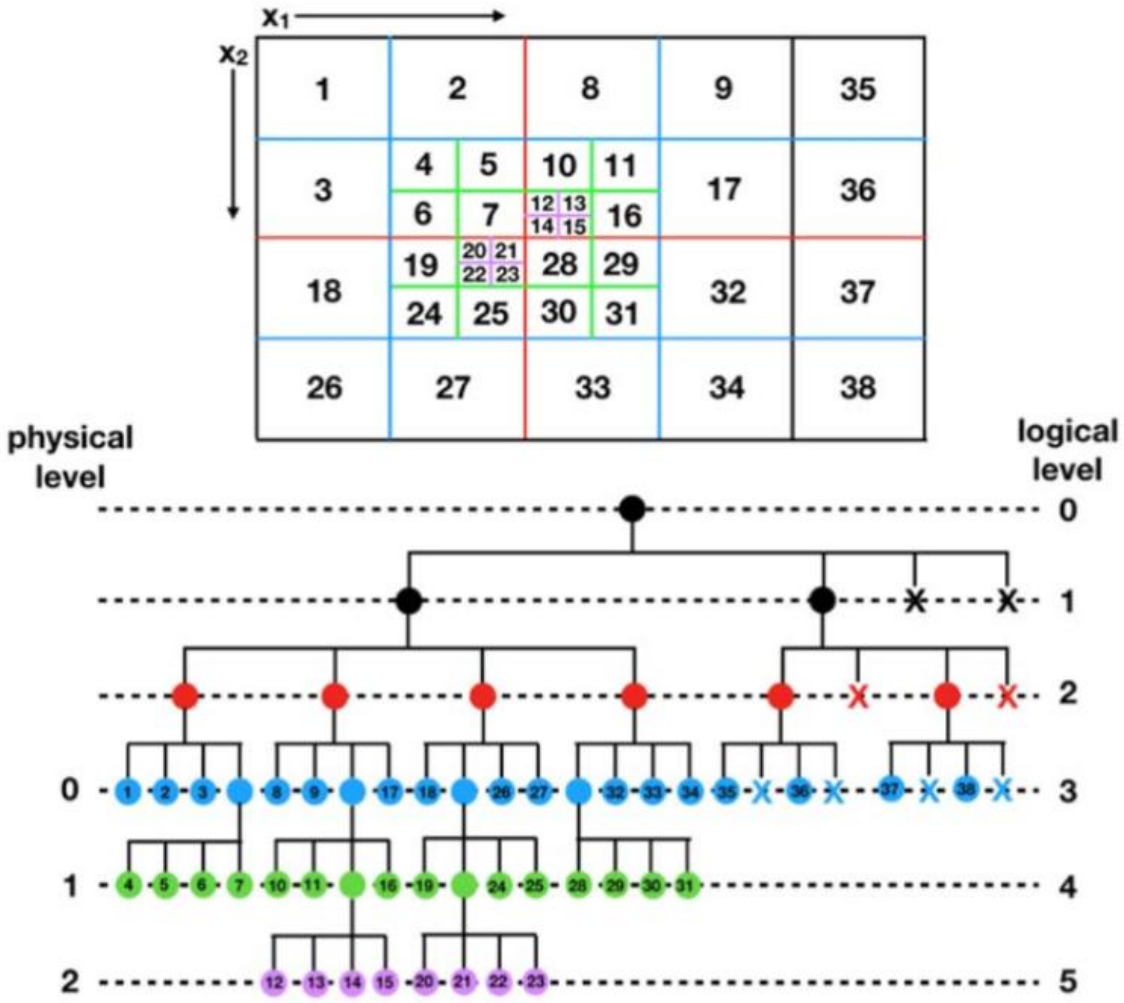
- Gravity (self- and GR)
- Magnetic fields
- Equation of state (ionization, recombination, …)
- Effective viscosity
- Transport of momentum and energy due to radiation or neutrinos
- Changes of chemical composition (nuclear or chemical reactions)
- Multiple components (gas, dust, rocks, …)
- Phenomena not captured by Euler equations of fluid dynamics

Complications due to (binary) stars

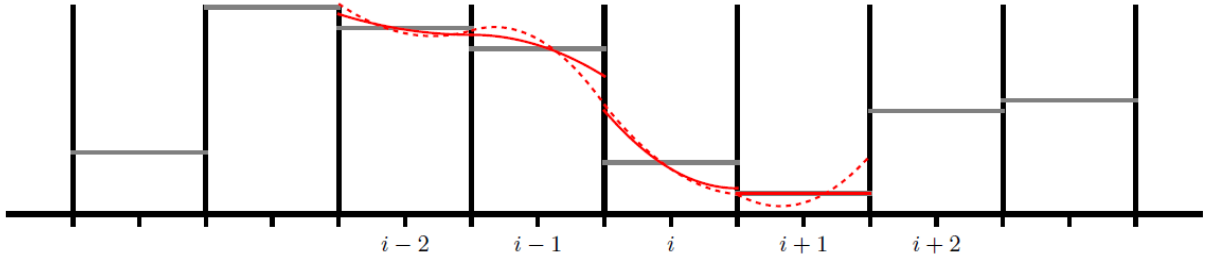
- Disparate length scales
  (from cm to AU)
- Disparate time scales
  (from ms to millenia)
- Disparate velocities
  (fluid velocity, sound speed, speed of light)

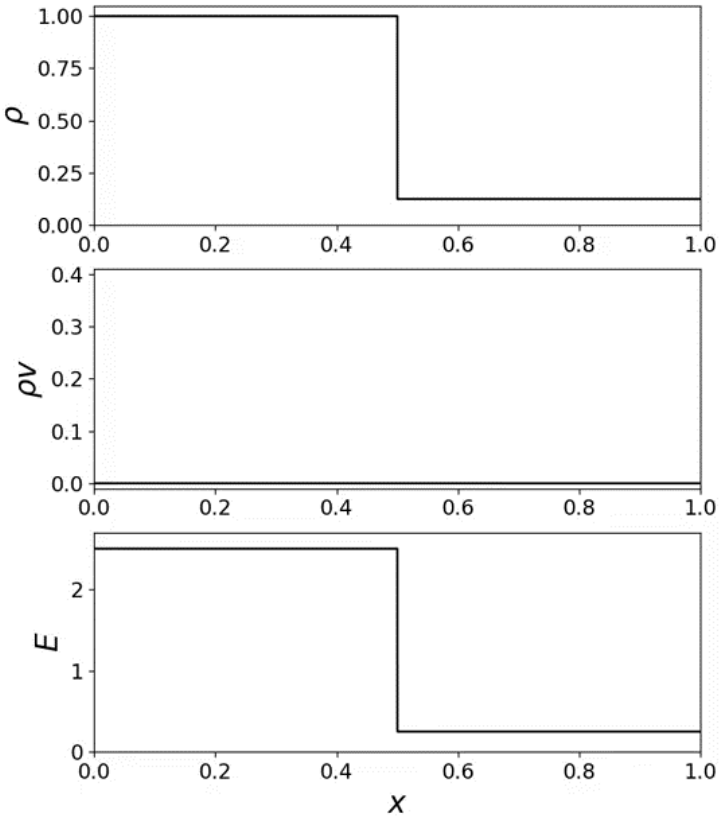
Practical solution: finite volume method

Adaptive mesh refinement



Reconstruction of solution

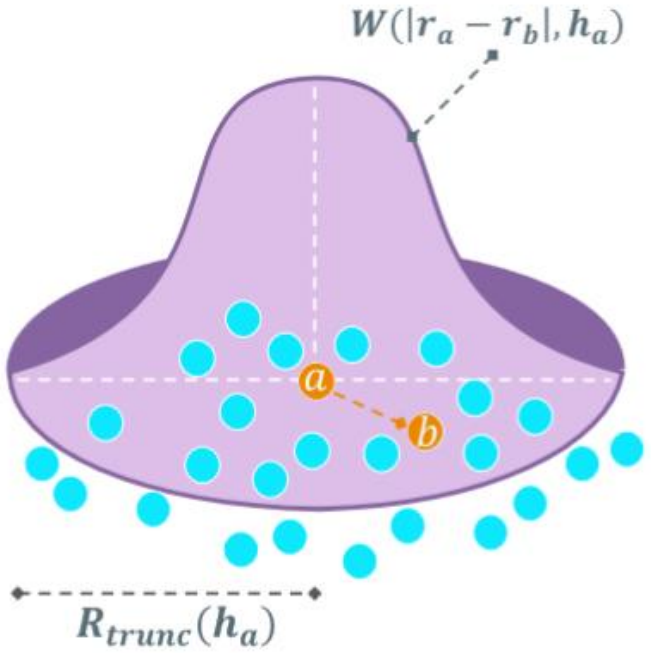




Riemann solver for fluxes

Stone et al. (2020), Zingale (2024)

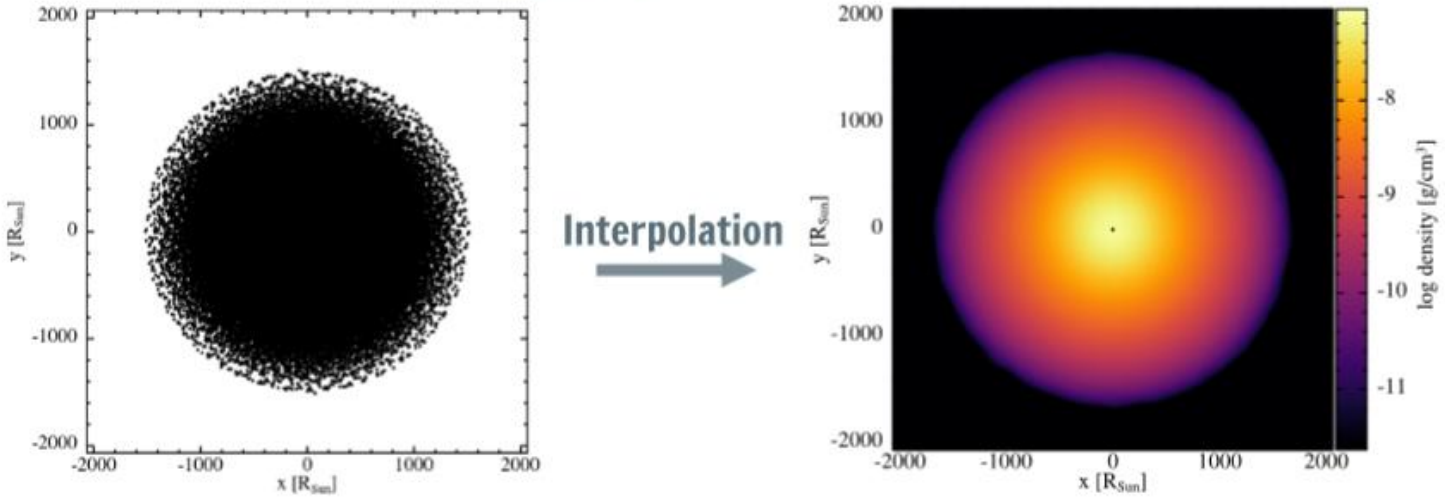
Practical solution: smoothed particle hydrodynamics



$$\rho_a = \sum_b m_b W\left(\vec{r}_a - \vec{r}_b, h_a\right); \quad h = h(\rho),$$

$$\frac{\mathrm{d}\vec{v}_a}{\mathrm{d}t} = -\sum_b m_b \left[\frac{P_a}{\Omega_a \rho_a^2}\nabla_a W_{ab}\left(h_a\right) + \frac{P_b}{\Omega_b \rho_b^2}\nabla_a W_{ab}\left(h_b\right)\right],$$

$$\frac{\mathrm{d}u_a}{\mathrm{d}t} = \frac{P_a}{\Omega_a \rho_a^2}\sum_b m_b \left(\vec{v}_a - \vec{v}_b\right)\cdot\nabla_a W_{ab}\left(h_a\right),$$

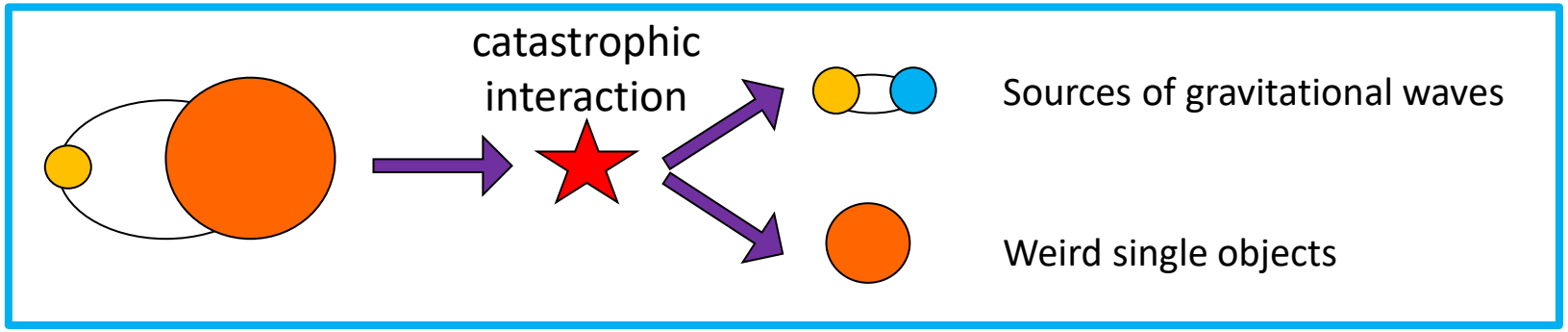


Landri (2024, PhD thesis)

What is the physics of catastrophic binary interactions?



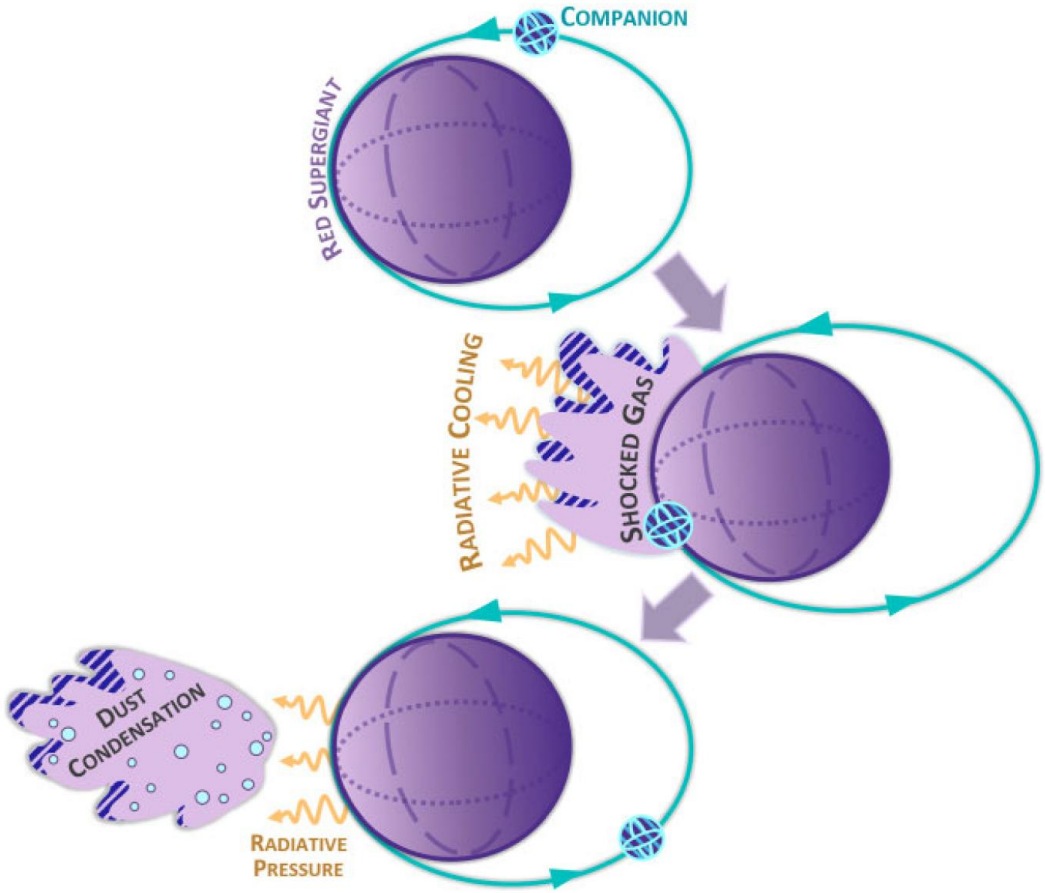
Cat-In-hAT



What happens to the **orbital energy** of the binary star?
What is the **physics** of the brightening?
How are **magnetic fields** amplified?

How do binaries interact: eccentric inspiral

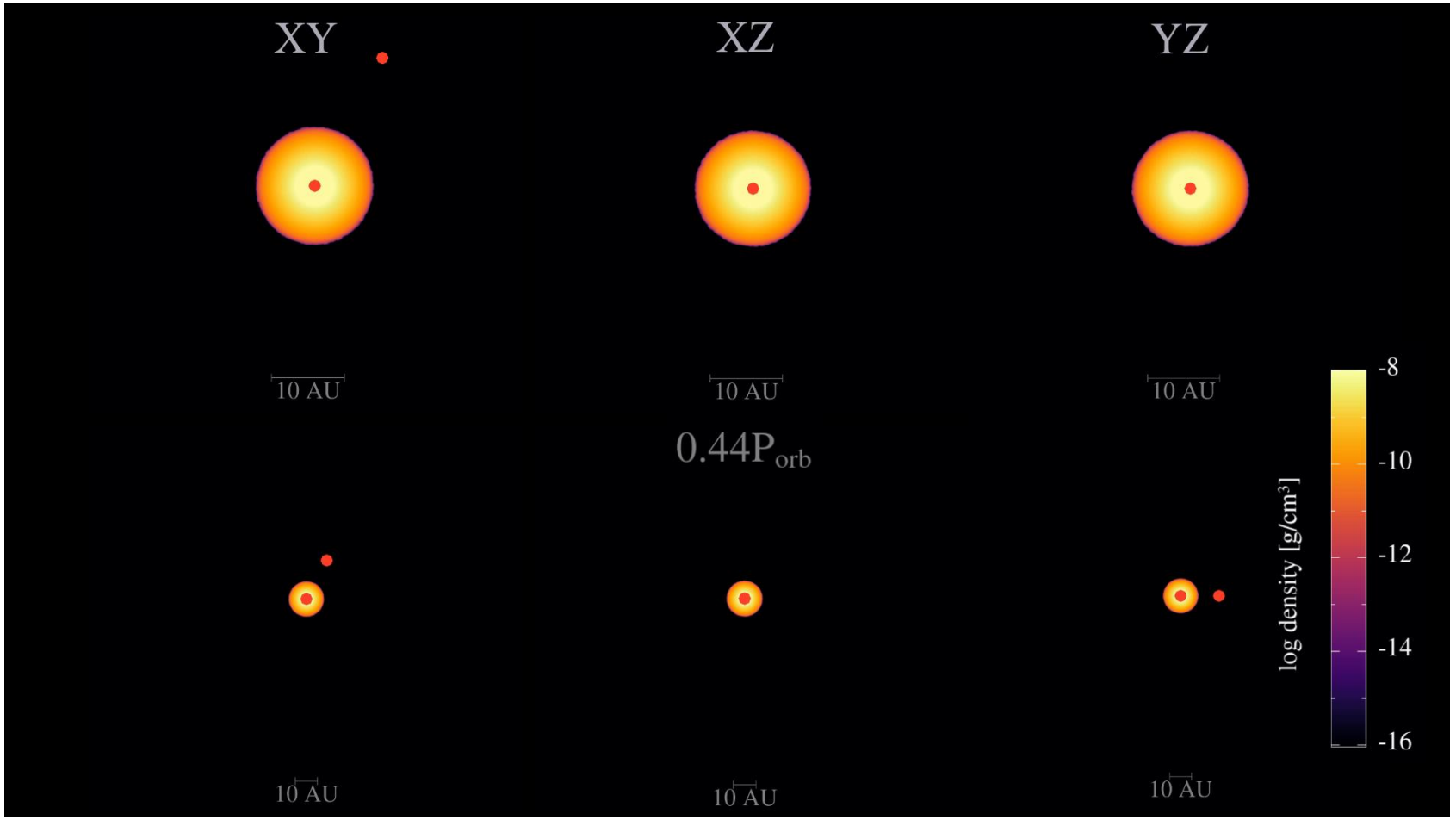
- New model: 3D simulations with radiative cooling+pressure and dust
- Method: smoothed particle hydrodynamics
- Result: Asymmetric mass ejection



Landri & Pejcha (2024)

How do binaries interact: eccentric inspiral

- New model: 3D simulations with radiative cooling+pressure and dust
- Method: smoothed particle hydrodynamics
- Result: Asymmetric mass ejection



(performed on Barbora)

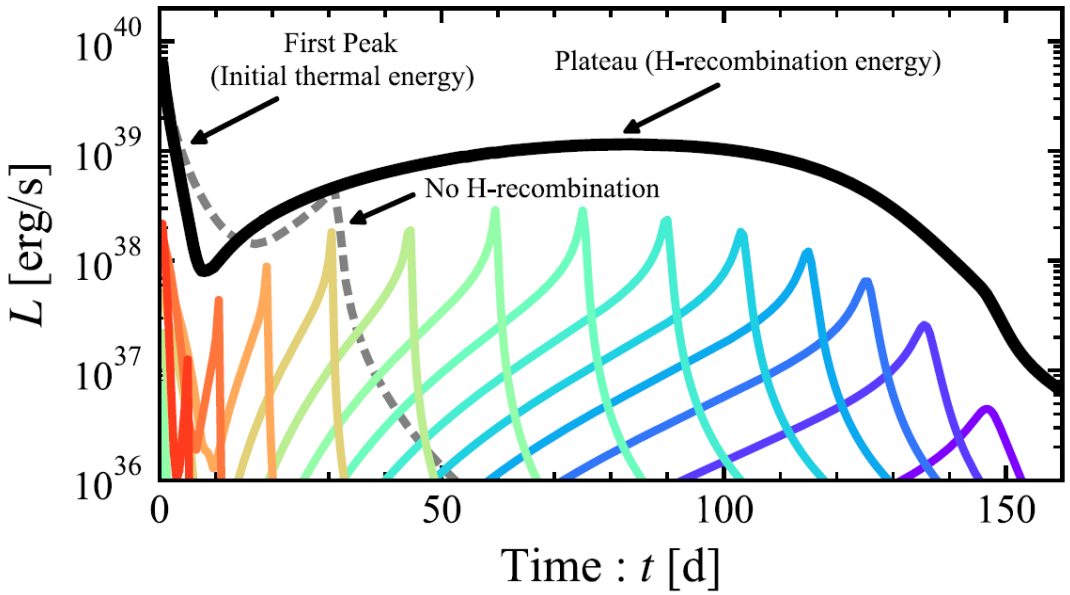
Landri & Pejcha (2024)

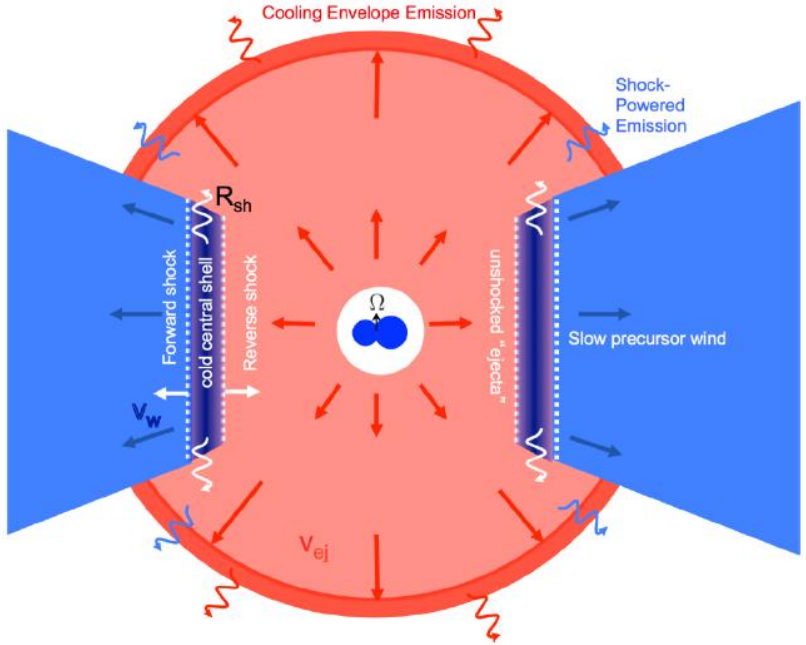
How to interpret observations of binary brightenings?

H & He recombination

vs.

Shock power



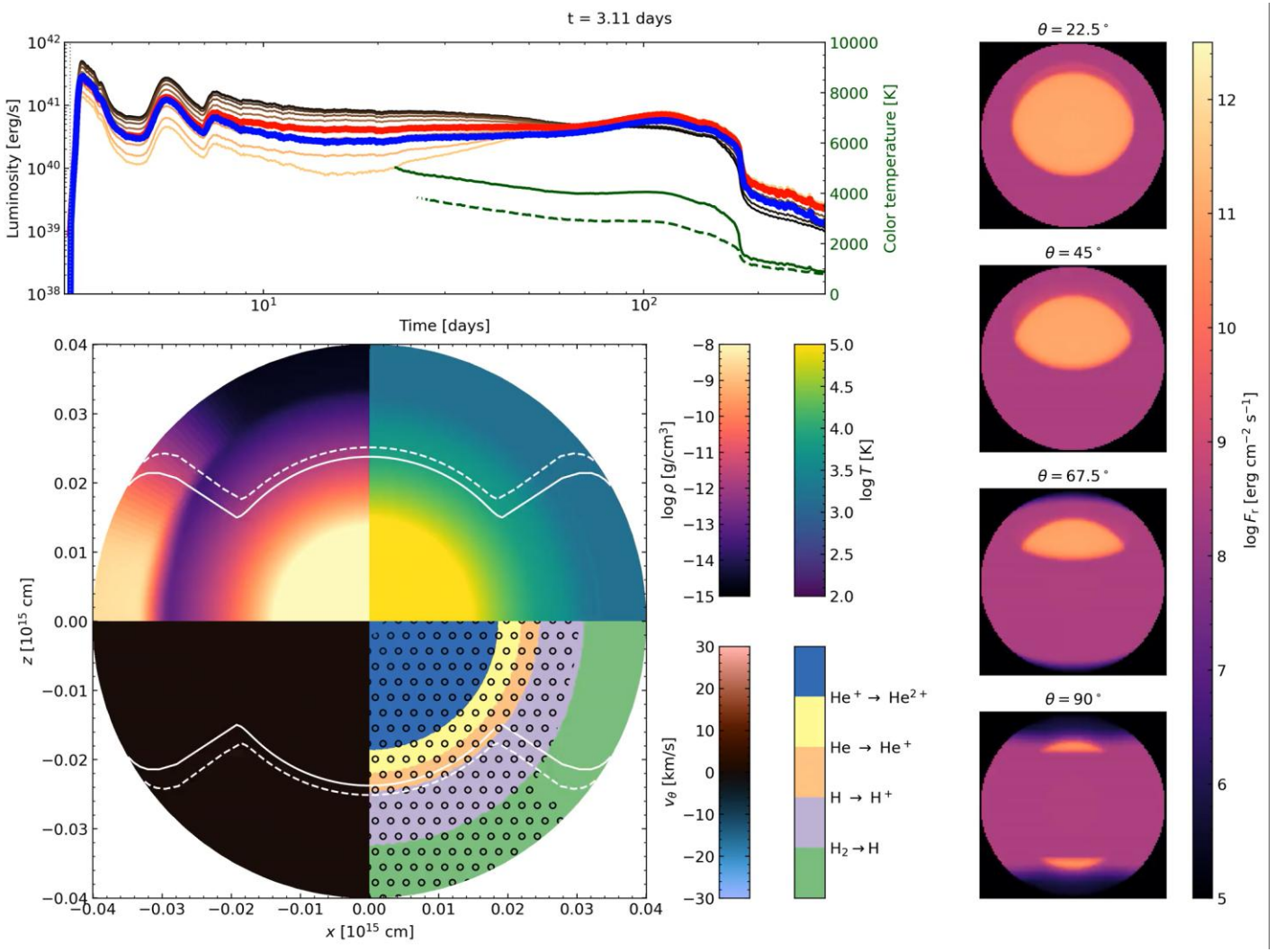


Ivanova et al. (2013), Matsumoto & Metzger (2022)

Metzger & Pejcha (2017)

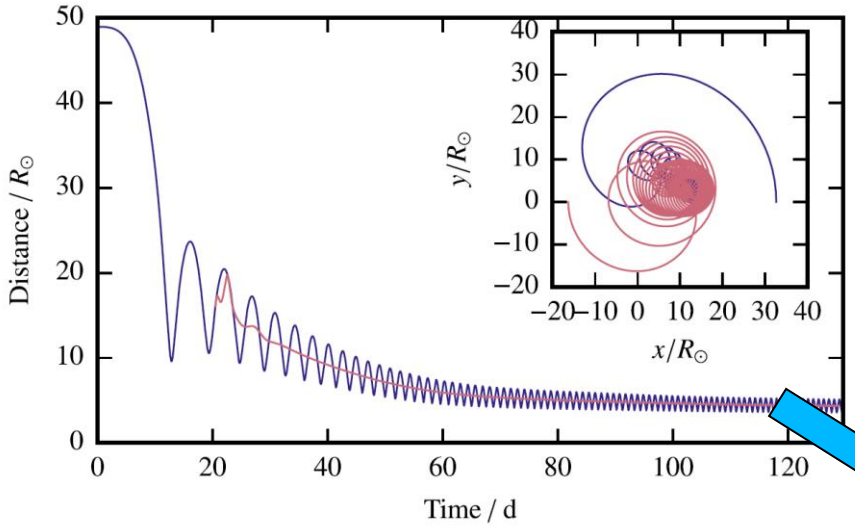
How to interpret observations of binary brightenings?

- Method: 2D radiation finite-volume on moving mesh with realistic microphysics
- Result: shock power explains luminosities and durations



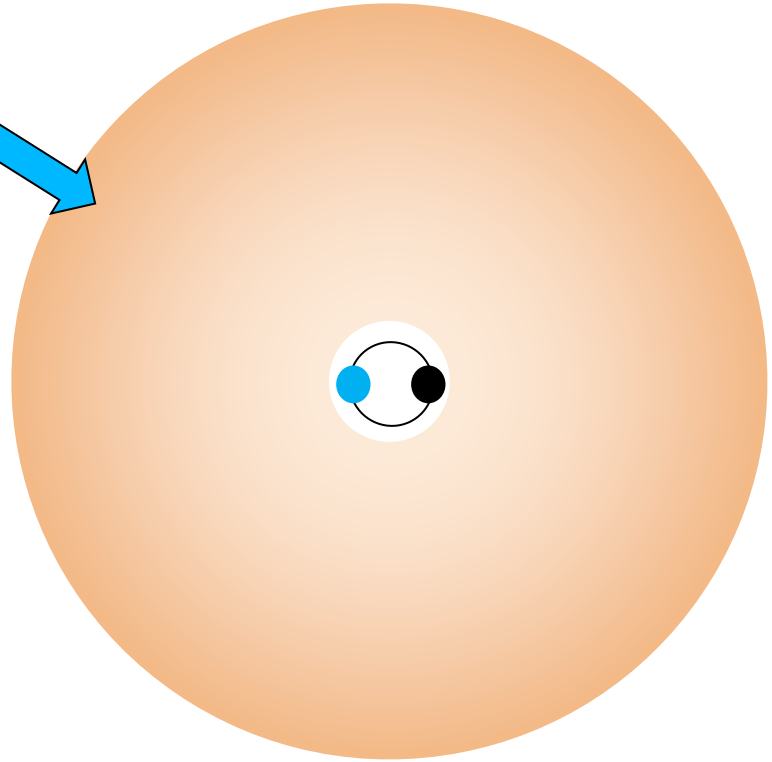
Kirilov, Calderón, Pejcha, Duffell (2025)

How does the binary emerge out of interaction?



Ohlmann et al. (2016)

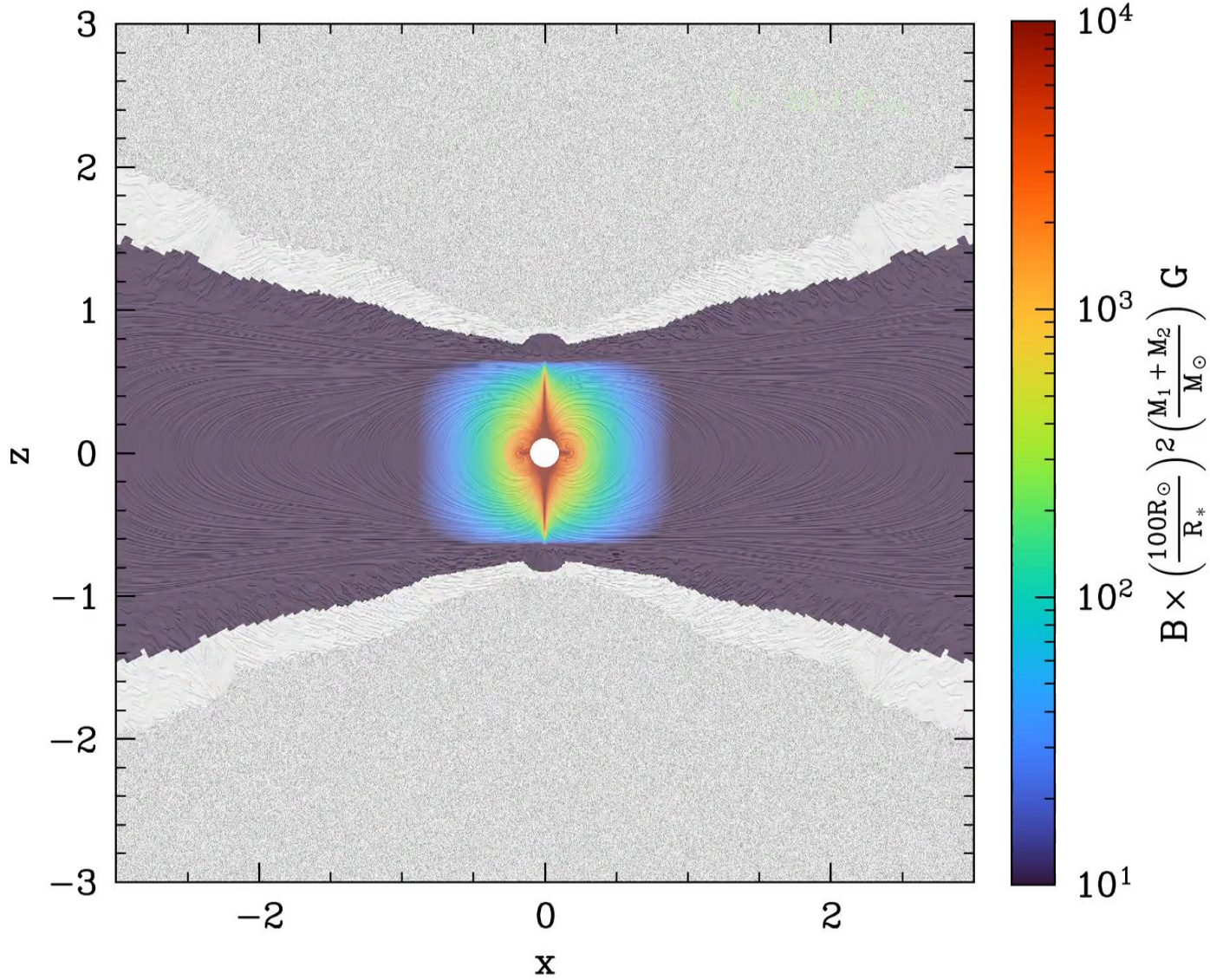
“very thick circumbinary disk”



from Damien Gagnier

How does the binary emerge out of interaction?

Method: long 3D (M)HD simulations with finite volume (Athena++)

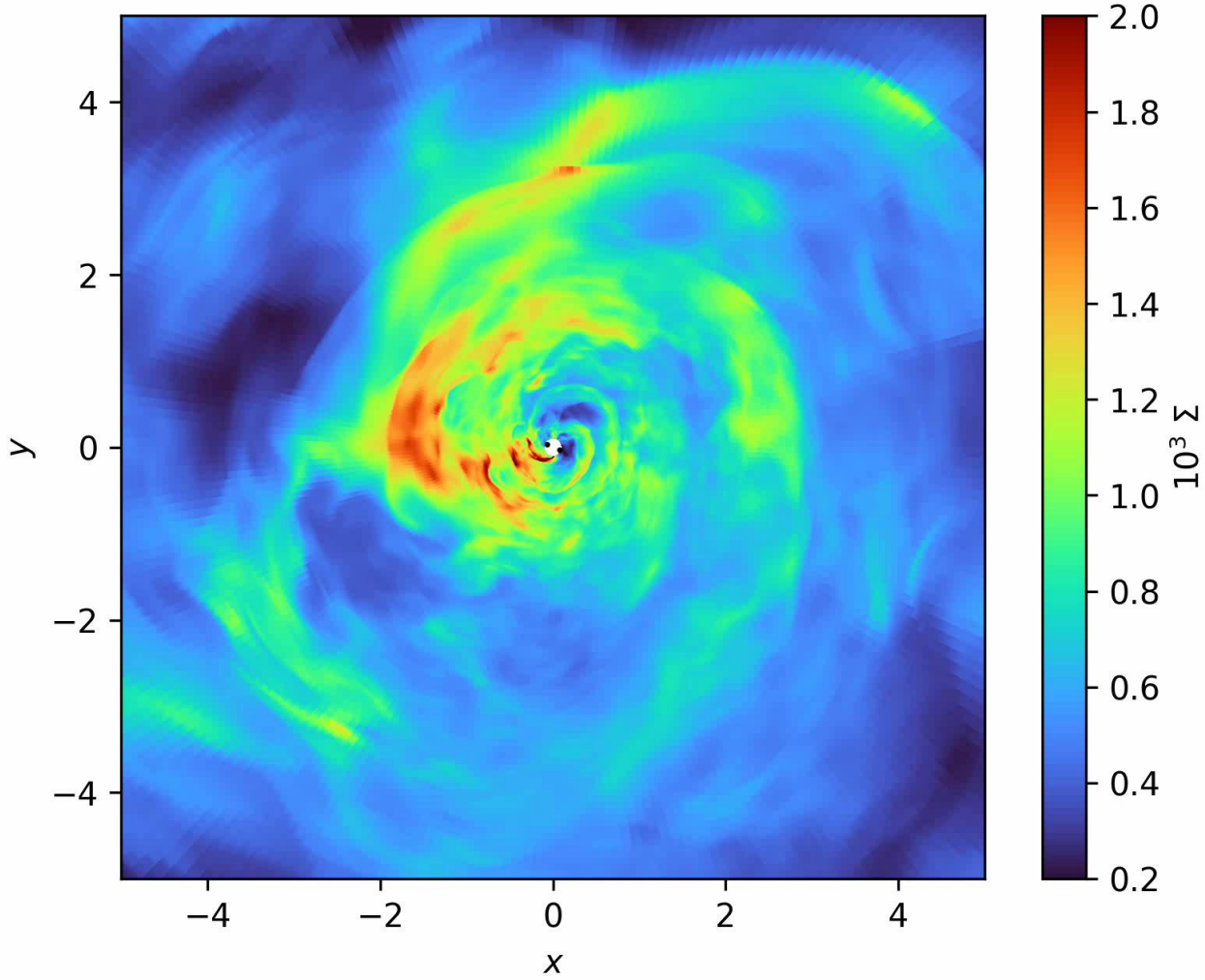


(performed on Karolina)

Gagnier & Pejcha (2023, 2024, 2025)

How does the binary emerge out of interaction?

- Result: very efficient transport of angular momentum → timescale 10^3 – 10^5 orbits
- Result: weak magnetic energy production on large scales → no collimated bipolar outflows from the envelope
- Result: inspiral works very differently than imagined in 1D models

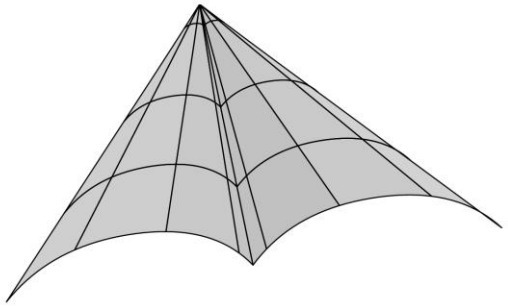


(performed on Karolina)

Gagnier & Pejcha (2023, 2024, 2025)

How can we reach the next level of realism of computer simulations of binary systems?





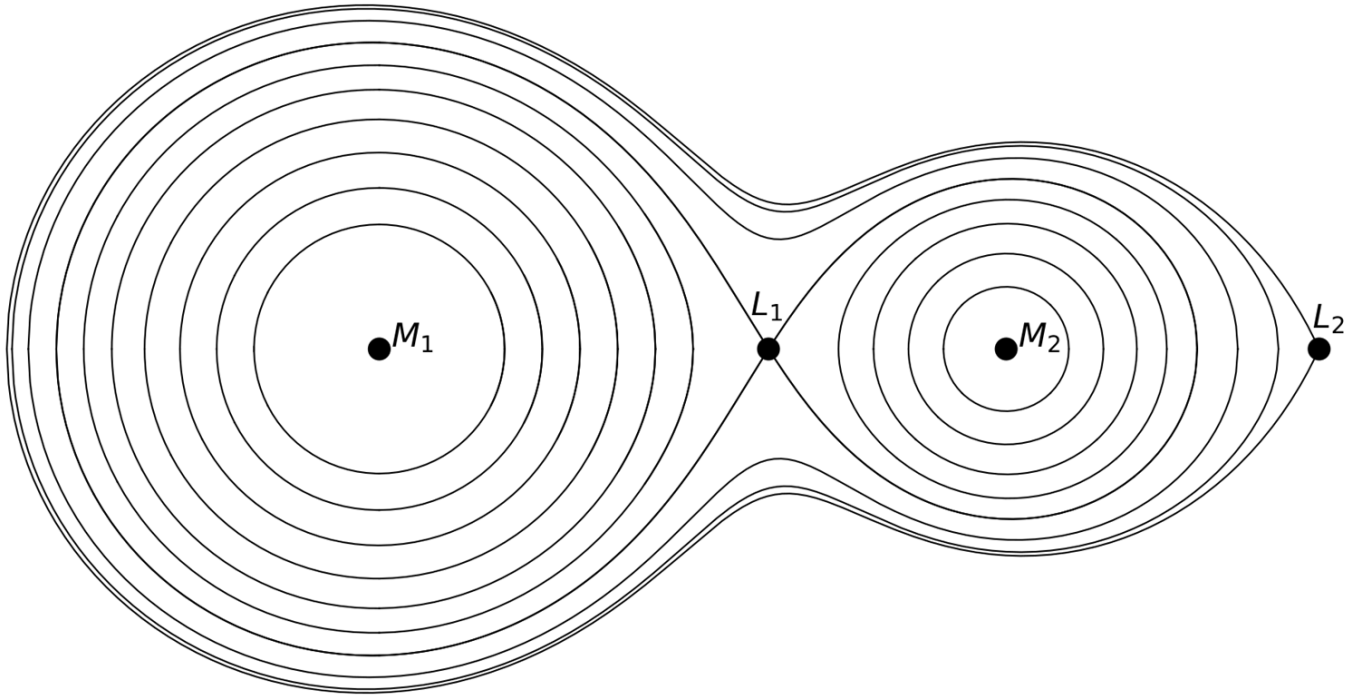
Lack of useful symmetries in binary systems

Roche potential

$$\ddot{\mathbf{r}} = -\nabla\phi_R(\mathbf{r}) - 2\boldsymbol{\omega}\times\dot{\mathbf{r}},$$

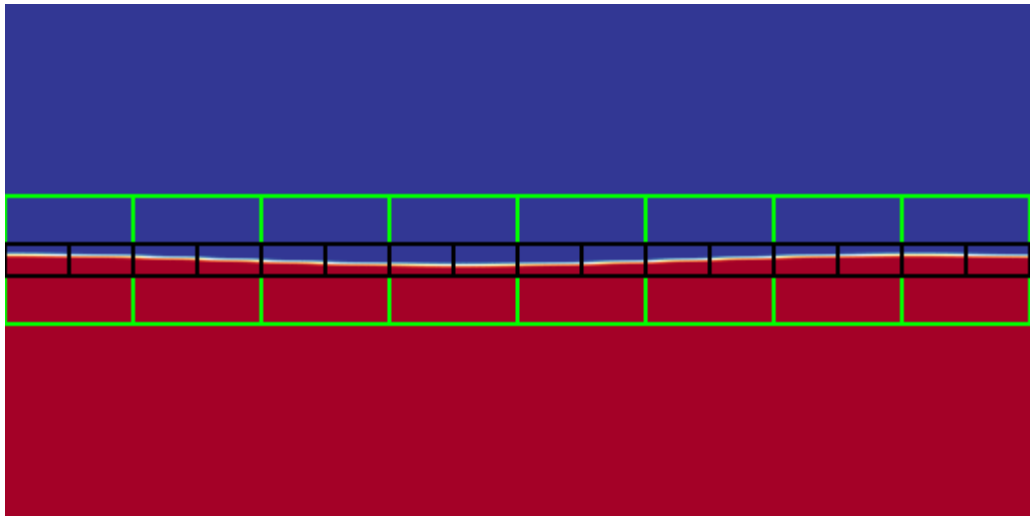
$$\phi_R(\mathbf{r}) = -\frac{GM_1}{|\mathbf{r}-\mathbf{r_1}|} - \frac{GM_2}{|\mathbf{r}-\mathbf{r_2}|} + \frac{1}{2}|\boldsymbol{\omega}\times\mathbf{r}|^2$$

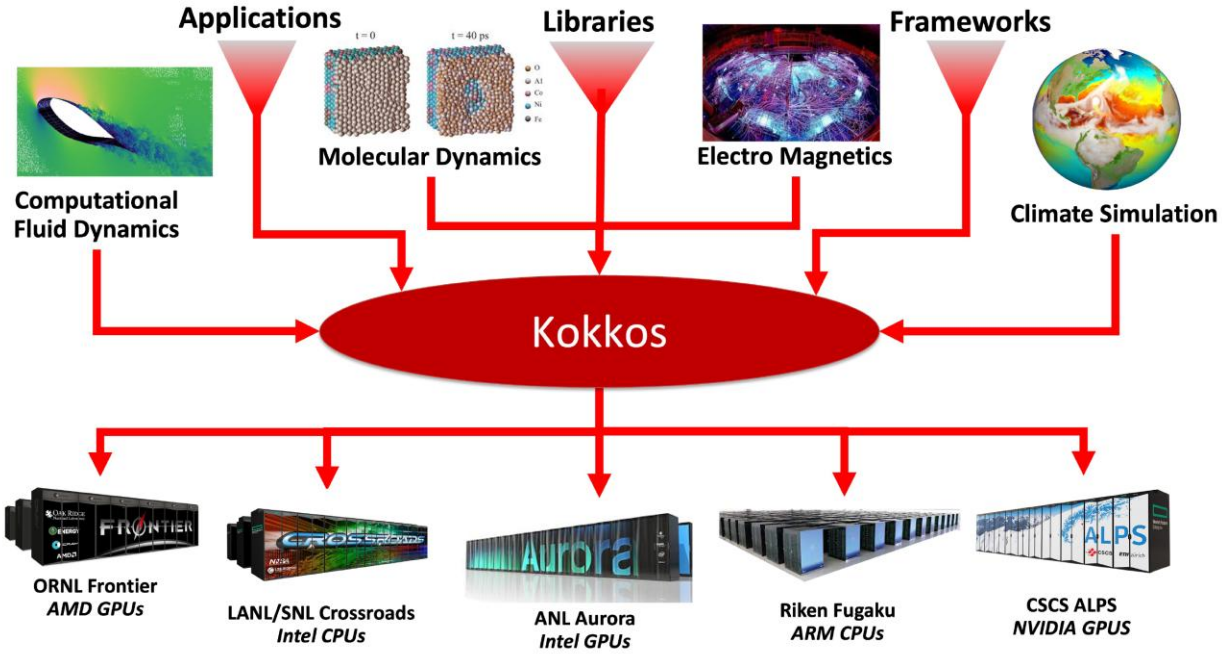
$$\phi_R(x,y,z) = -\frac{\mu}{\sqrt{(x-1+\mu)^2+y^2+z^2}} - \frac{1-\mu}{\sqrt{(x+\mu)^2+y^2+z^2}} - \frac{1}{2}\left(x^2+y^2\right) \qquad \mu = \frac{M_2}{M_1+M_2}$$



Advancements in CPU and GPU computation

AMReX
performance-portable framework for building massively parallel adaptive mesh refinement applications across CPUs, GPUs, and advanced HPC systems

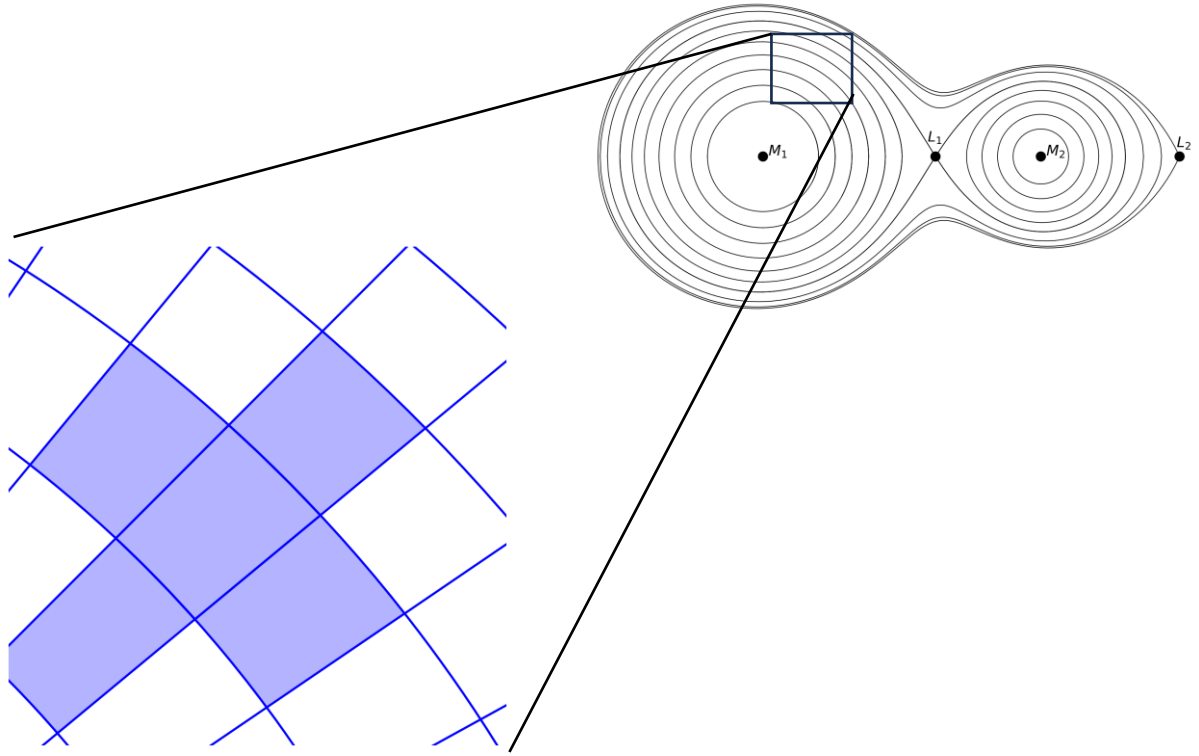




"AthenaK shows excellent performance and weak scaling, achieving over 1 billion cell updates per second for hydrodynamics in three dimensions on a single NVIDIA Grace Hopper processor. It does this with a typical parallel efficiency of 80% on 65,536 AMD GPUs on the OLCF Frontier system." (Stone et al. 2026)

Ongoing and future work and team

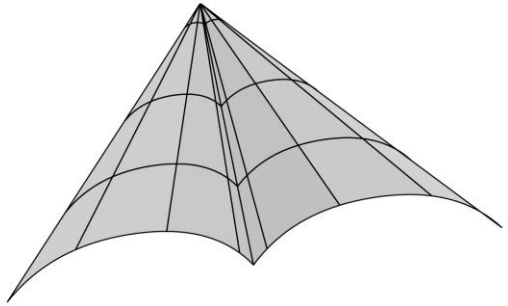
- Develop meshes adapted to binary systems
  - ➢ Curved and accurate
- Implement Discontinuous Galerkin
  - ➢ High order, small stencil
- Study many physical processes in binaries
  - ➢ Mass transfer and loss, accretion, explosions, pulsations, turbulence, mixing



order = arbitrary

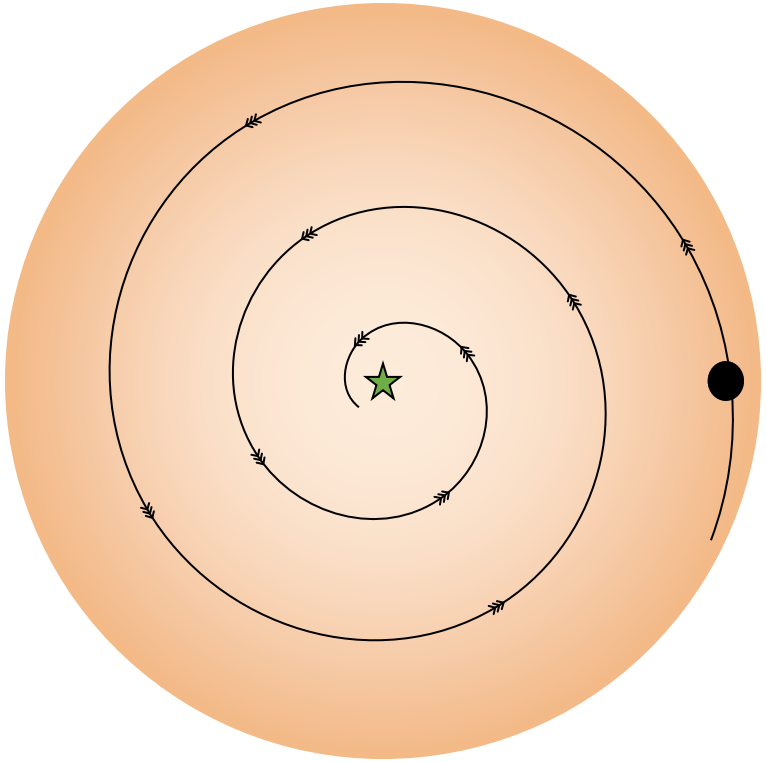
- Amelia Cordwell (postdoc 2026/10-, from Cambridge University)
- Marco Laversveiler (PhD 2025/10-, from Federal University of Rio de Janeiro)
- Mara Čutura (PhD 2026/10-, from University of Geneva)
- Cheuk Nam Chong (PhD 2026/10-, from Chinese University of Hong Kong)
- 1 more PhD
- Master and Bachelor students

erc European Research Council



Simple view of common envelope evolution

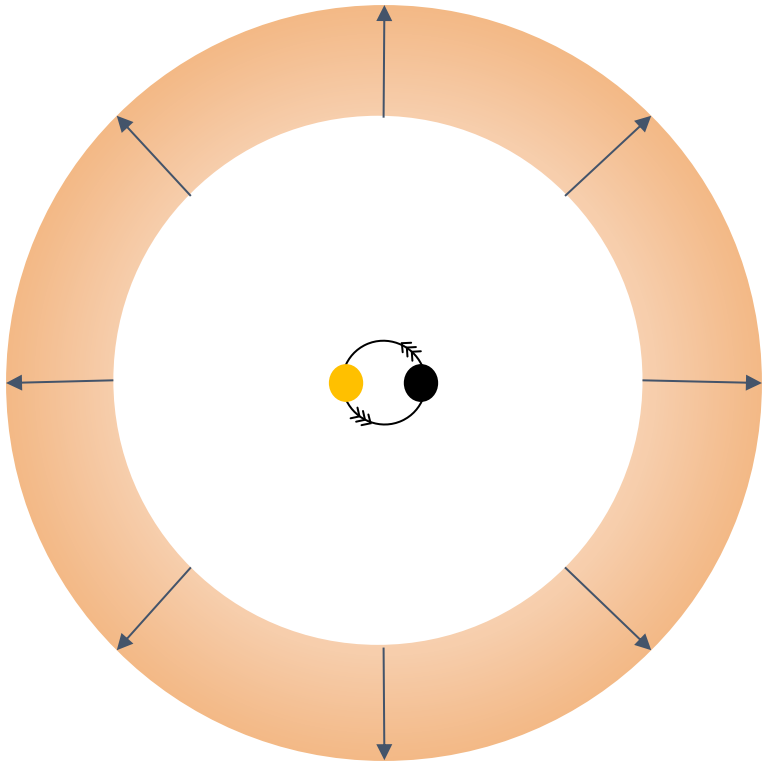
Need to simultaneously resolve neutron star (~10^6 cm) and red giant (>10^{13} cm)



(from Damien Gagnier)

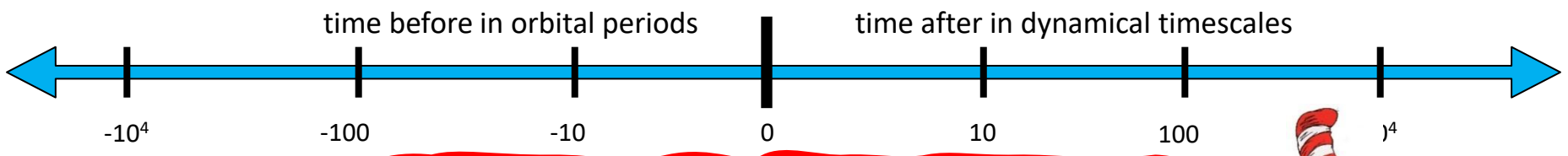
Simple view of common envelope evolution

$$E_{\rm env} = \alpha_{\rm CE}\left(-\frac{GM_{\rm d}M_2}{2a_i} + \frac{GM_{\rm core}M_2}{2a_f}\right)$$



(from Damien Gagnier)

Stages of common envelope evolution





Stages
(Ivanova et al. 2013)

normal binary star | loss of corotation | plunge-in | self-regulated inspiral | post-CE evolution

How do binaries enter CEE?
- **eccentric inspiral**

Theoretical tools

How does the binary emerge out of CEE?
- **(M)HD of post-dynamical inspiral**

1D stellar evolution | ? | multi-D fluid dynamics | ? | 1D stellar evolution

How to interpret observations of brightenings?
- **radiation-hydro simulations**

binary star | **observable brightening! (Luminous red nova)** | **remnant** | binary or single star