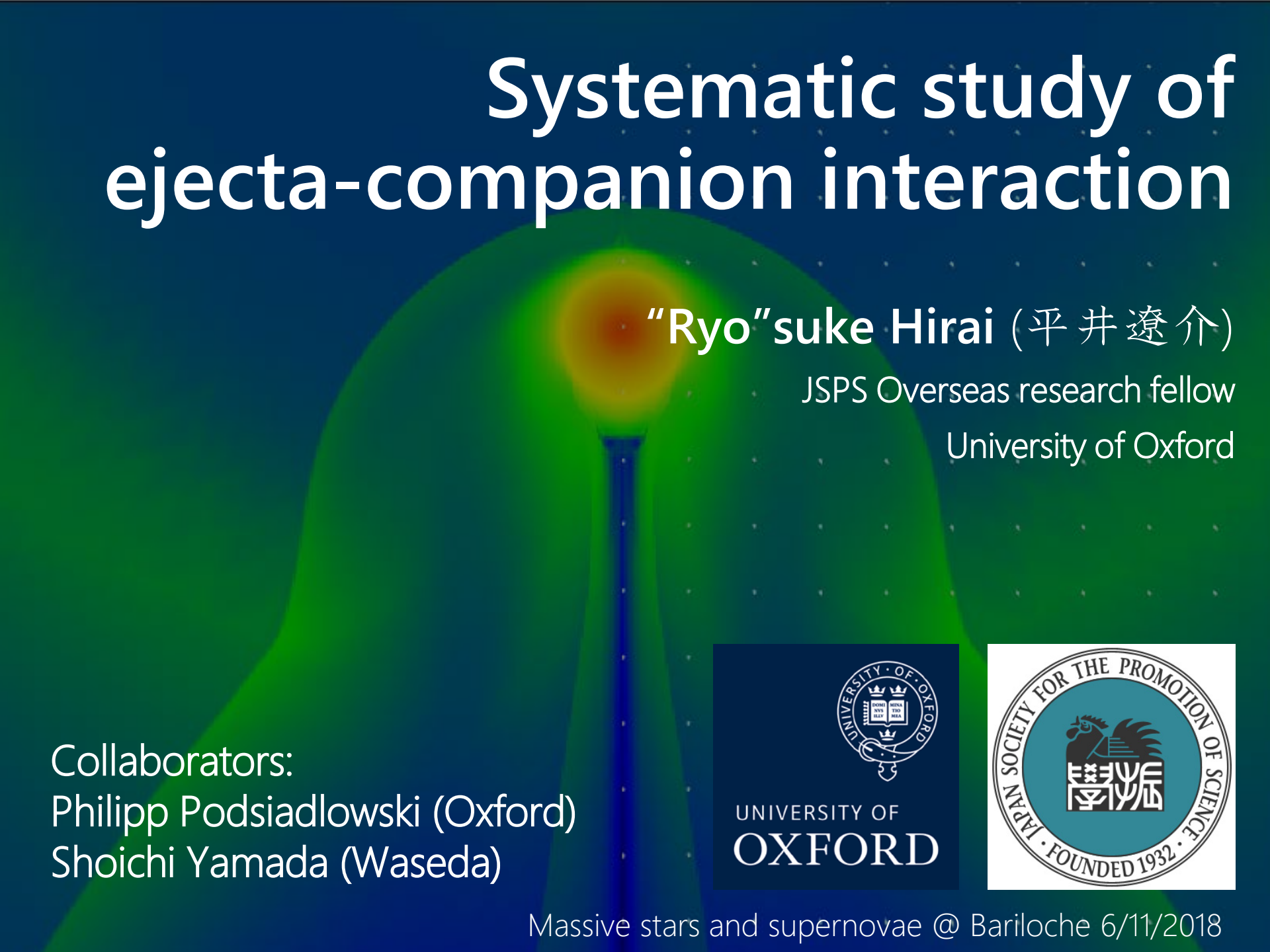
Systematic study of ejecta-companion interaction

"Ryo"suke Hirai (平井遼介)

JSPS Overseas research fellow

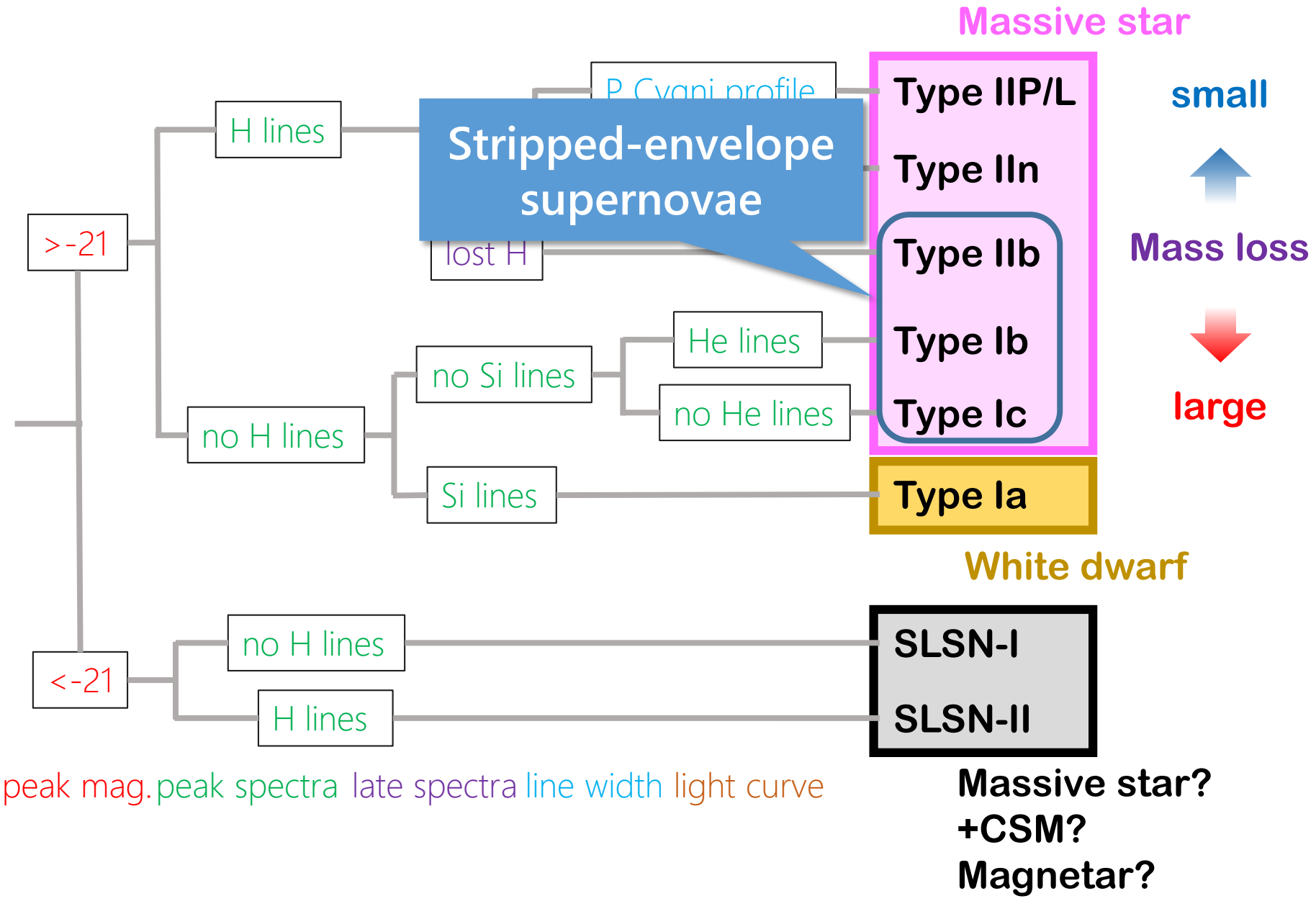
University of Oxford



Collaborators:
Philipp Podsiadlowski (Oxford)
Shoichi Yamada (Waseda)

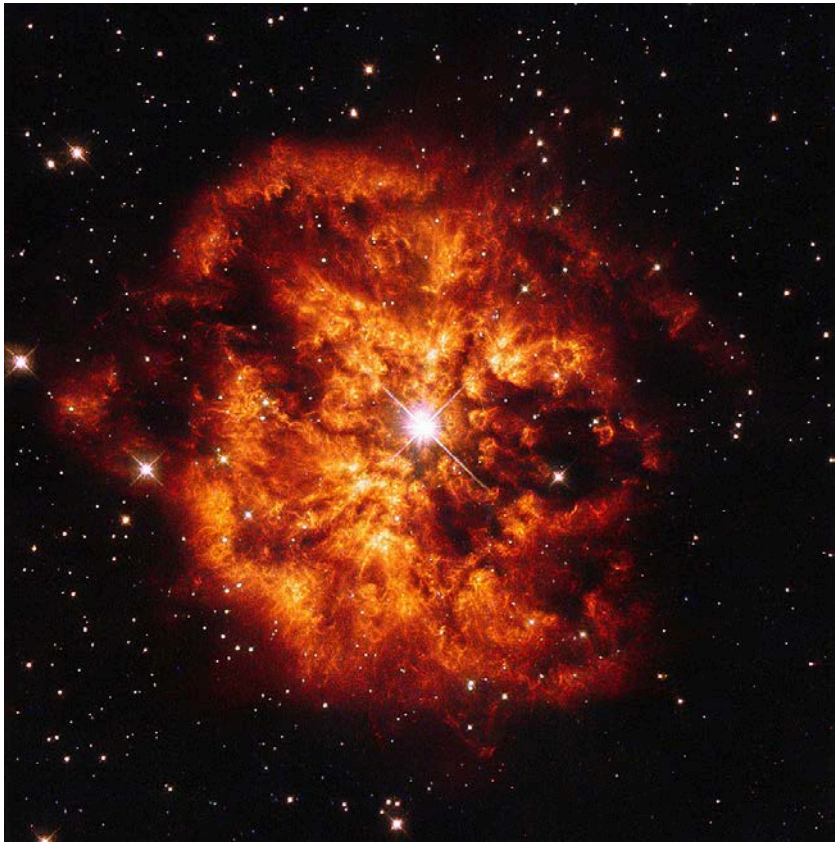
Massive stars and supernovae @ Bariloche 6/11/2018

Supernova classification

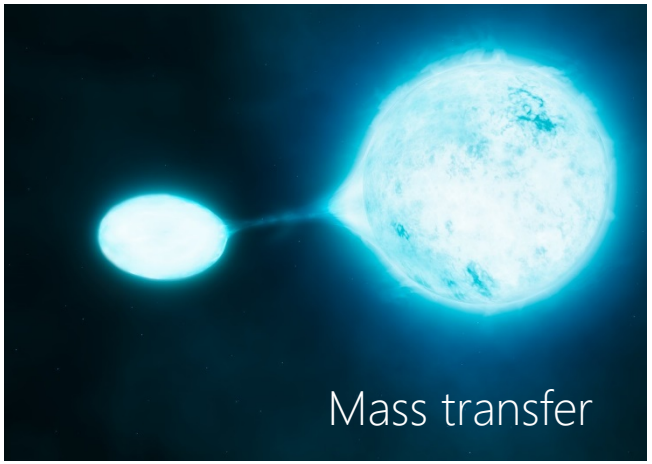


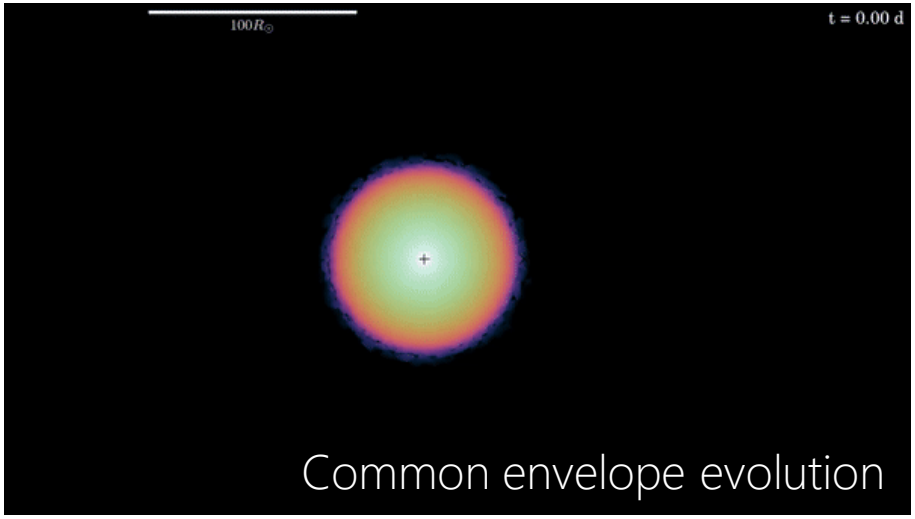
Mass loss mechanism

Single star wind mass-loss or Binary interaction?



Wolf-Rayet star WR124

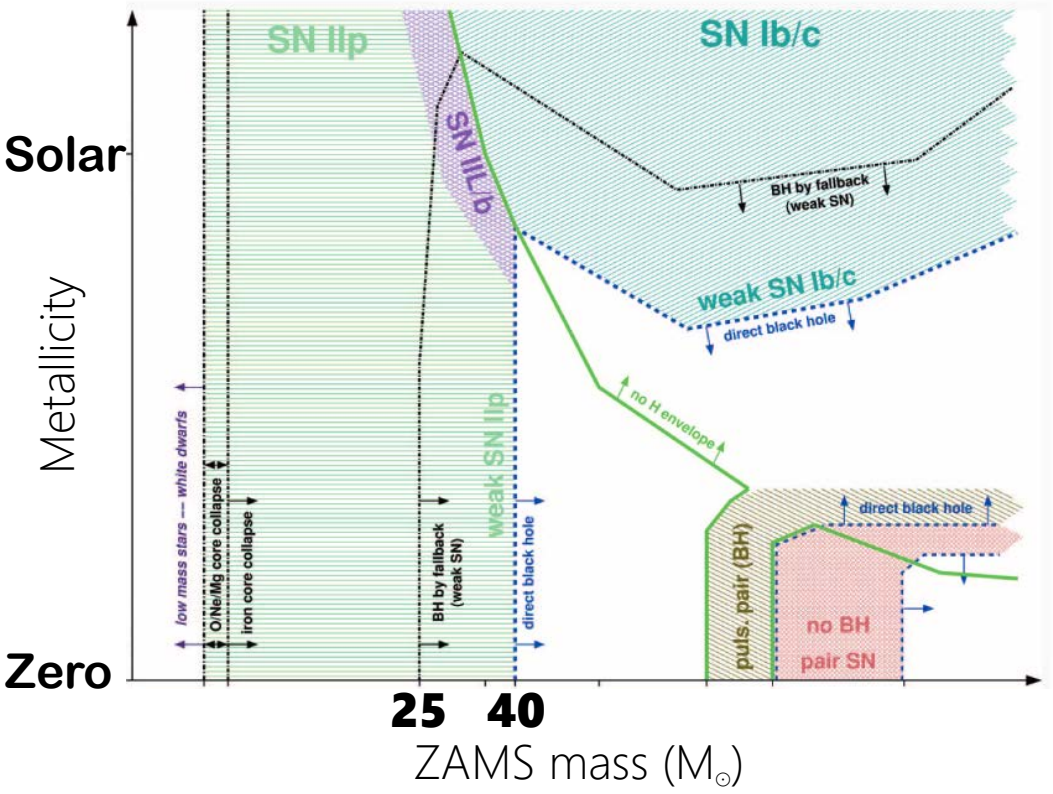




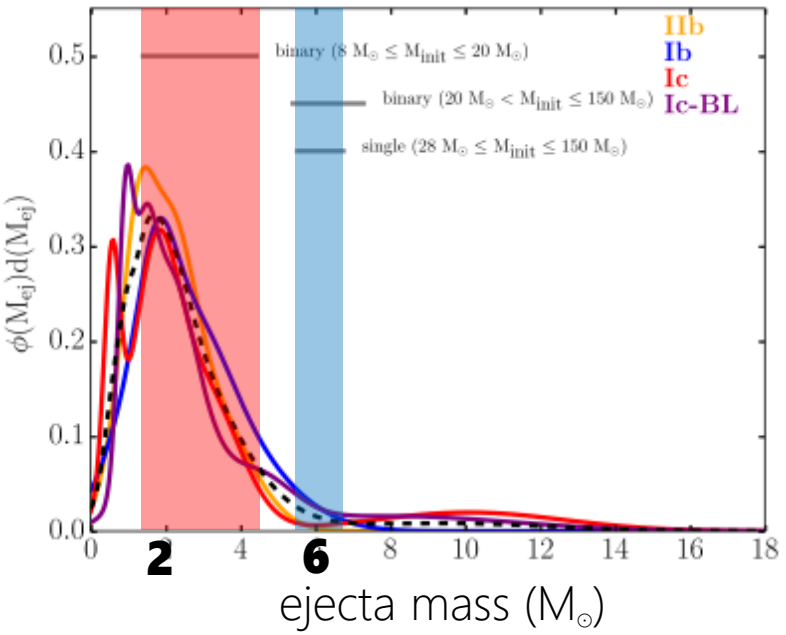
Mass loss mechanism

Single star wind mass-loss or Binary interaction?

Heger et al. 2003



Lyman et al. 2016



Looks like binary interaction is more likely

Progenitor/Companion detections

>30 supernovae have progenitor detections so far

Progenitor

SN2013df (IIb)

SN2016gkg (IIb)

SN2017ein (Ic)

Companion

SN1993J (IIb)

SN2011dh (IIb)

SN2006jc (Ibn)

SN2001ig (IIb)

Constraint on companion

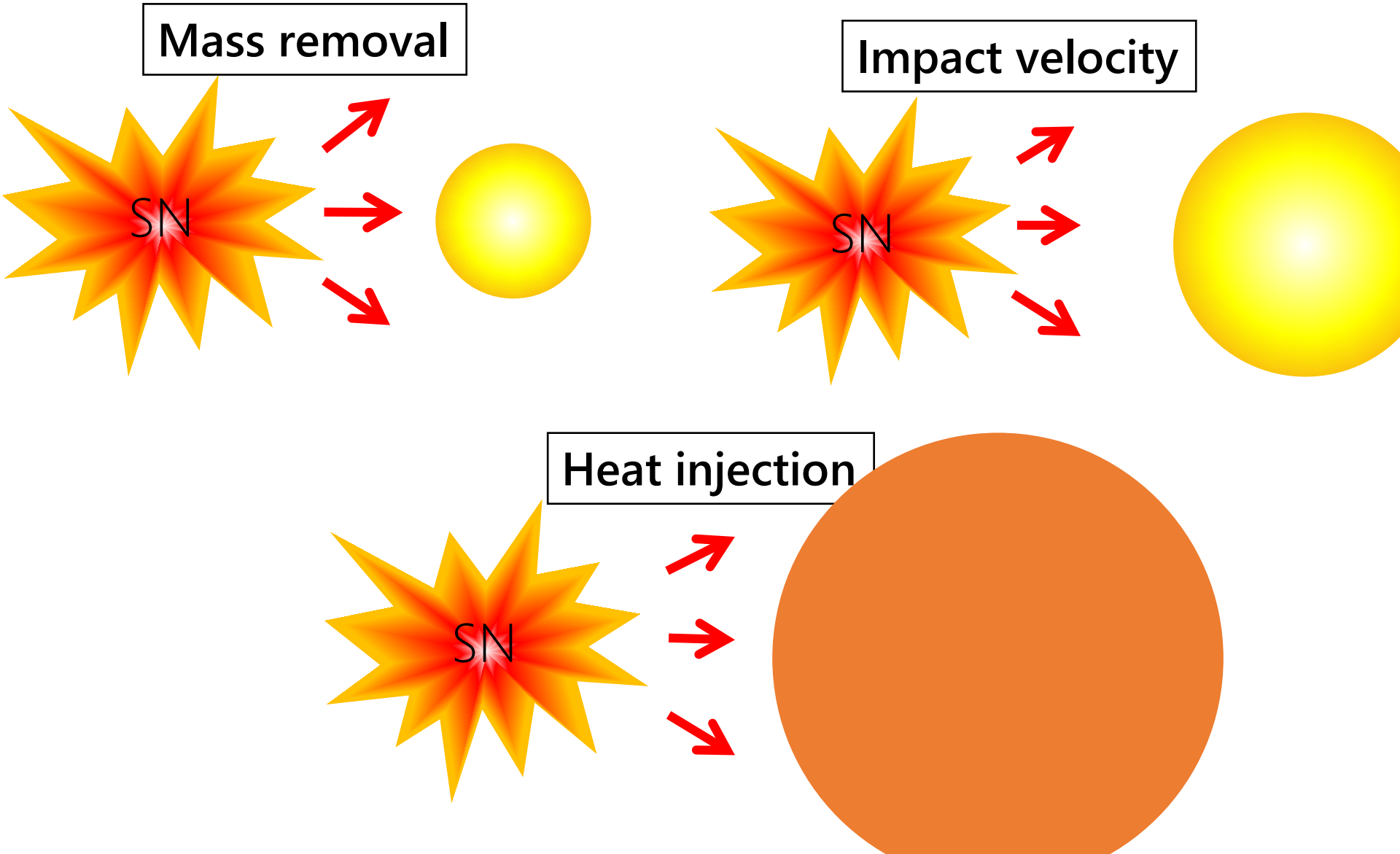
iPTF13bvn (Ib)

SN2008ax (IIb)

SN1994I (Ic)

Complete list of progenitor/companion non-/detections of stripped-envelope supernovae

Ejecta-Companion interaction

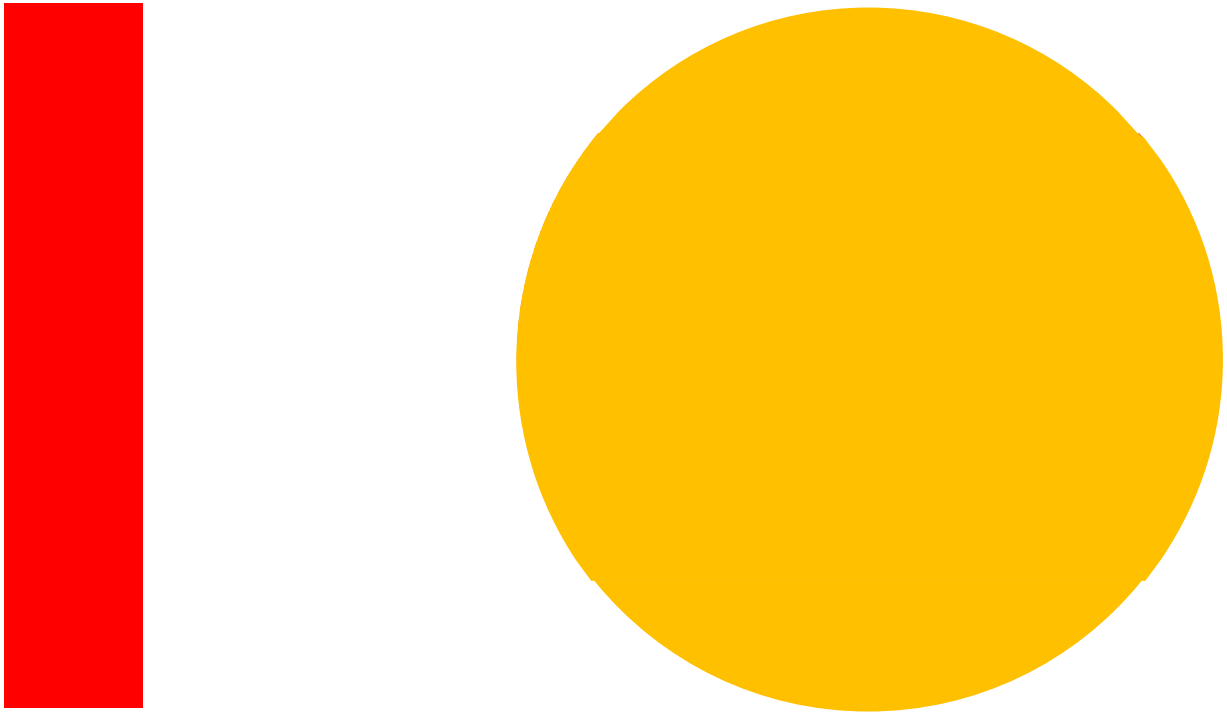


Ejecta-Companion interaction

Wheeler et al. 1975

SN ejecta

Companion

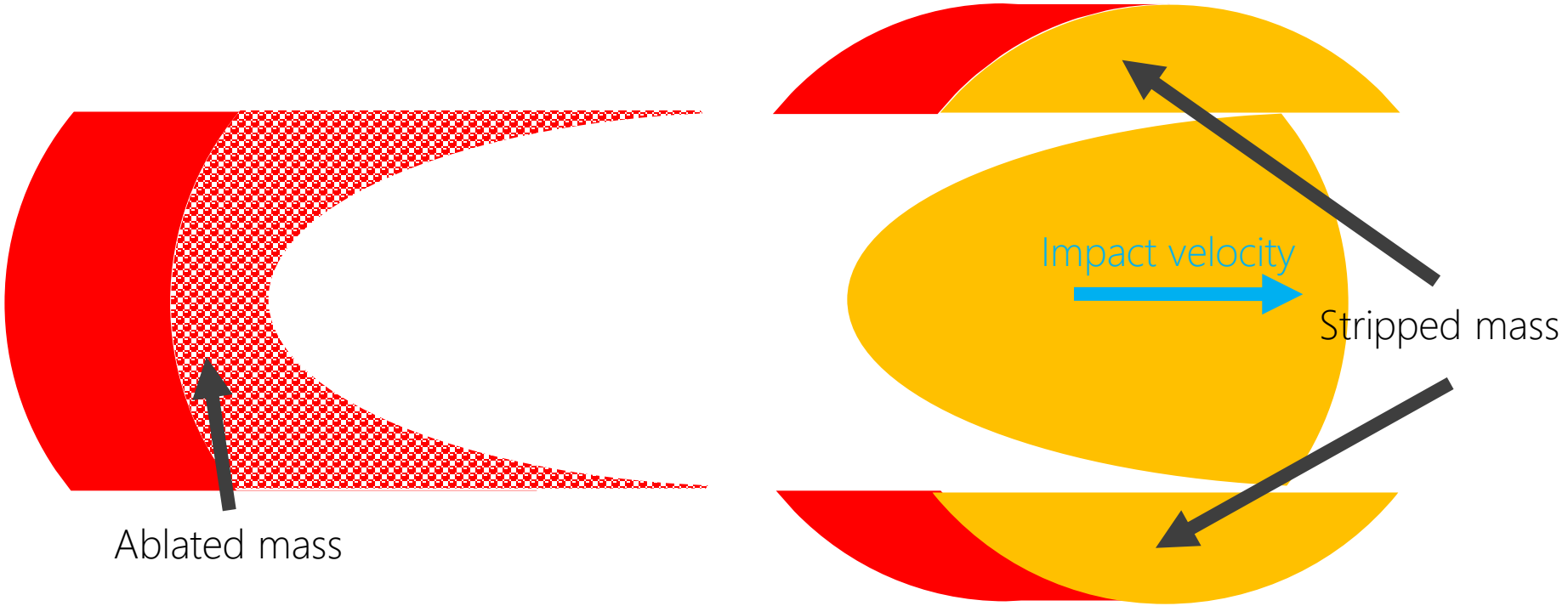


Ejecta-Companion interaction

Wheeler et al. 1975

SN ejecta

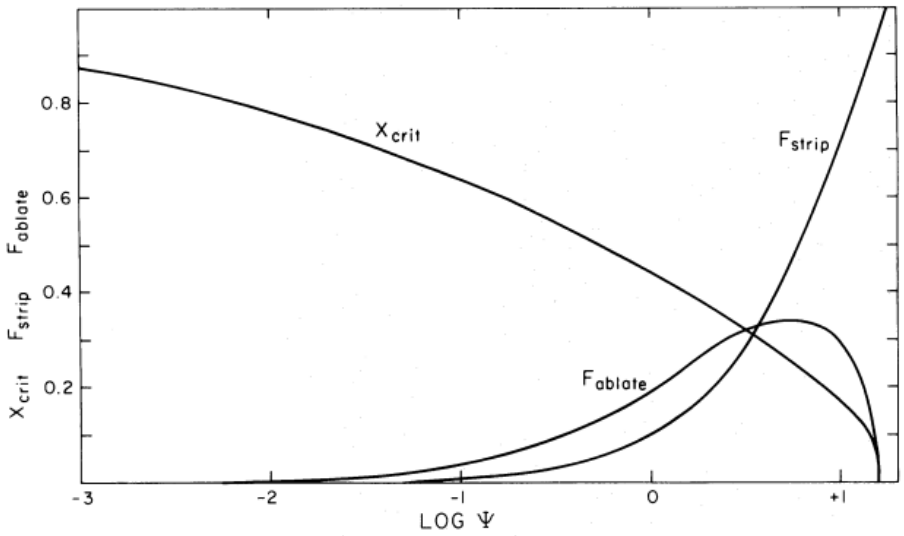
Companion



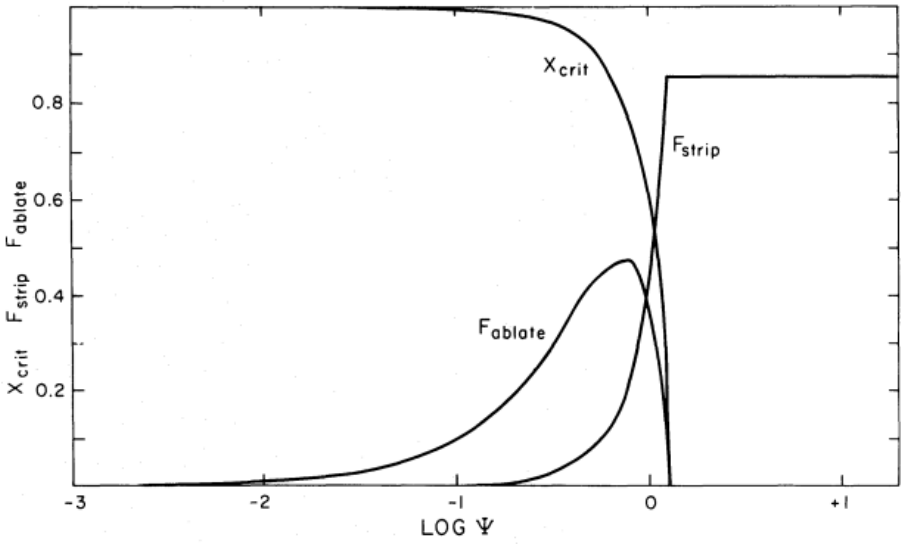
Ejecta-Companion interaction

Wheeler et al. 1975

n=3 polytrope



Red giant



$$\Psi \equiv \frac{1}{4}\frac{M_{SN}}{M_C}\frac{R^2}{{a_0}^2}\left(\frac{v_{SN}}{v_{es}} - 1\right)$$

: Parameter that indicates the capability of mass stripping

Unbound mass strongly depends on stellar structure + this analysis doesn't tell you much more…

ECI simulation

We carried out hydrodynamical simulations of ejecta-companion interaction (ECI)

Code

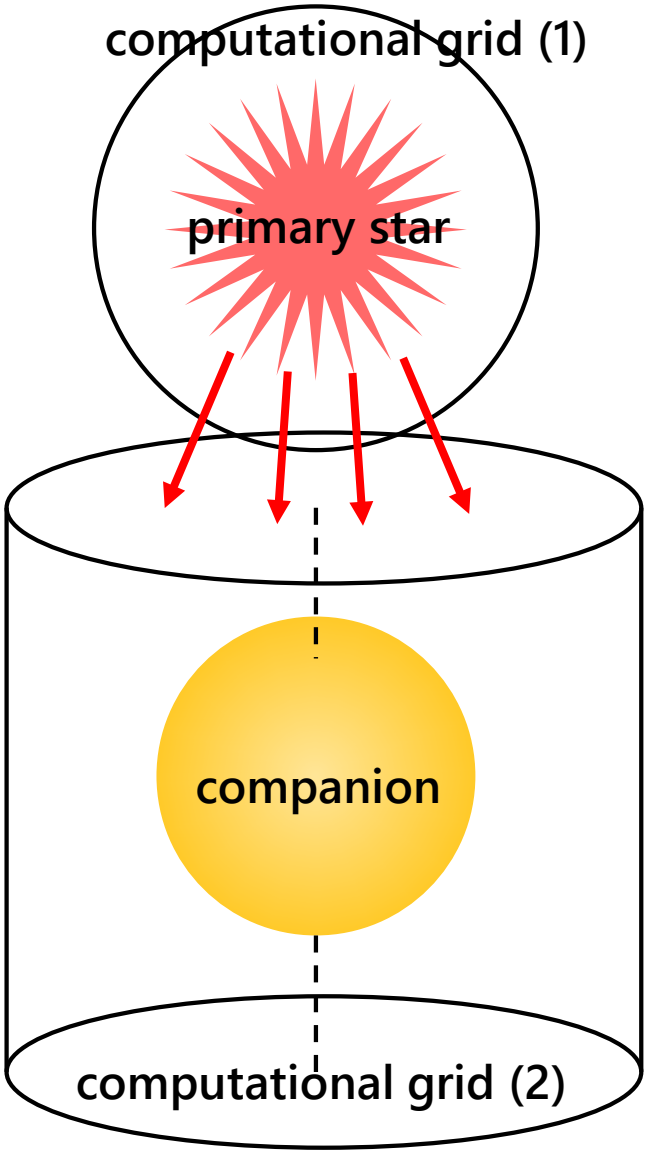
- Eulerian hydrodynamic code
- HLLC approximate Riemann flux
- 2nd order in space, 3rd order in time
- Hyperbolic self-gravity (RH et al. 2016)

Step 1: 1D simulation of explosion

- Spherically symmetrical grid
- Explosion energy: 10^{51}, 10^{52}erg
- Ejecta mass: $3.2M_{\odot}$, $7.1M_{\odot}$
- Progenitors made with MESA
- Explosion with "thermal bomb" method

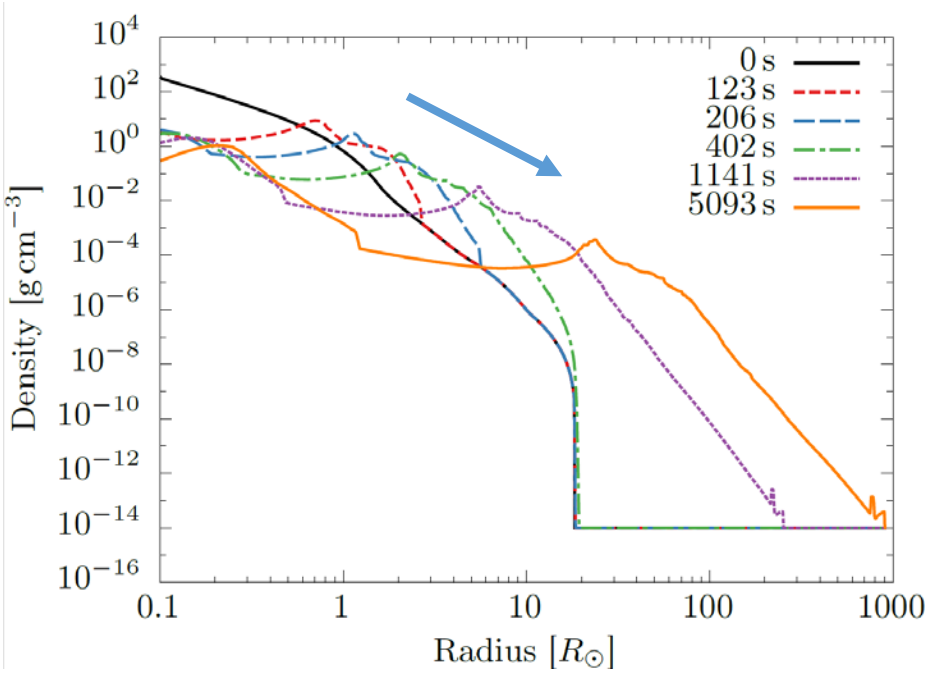
Step 2: 2D simulation of ECI

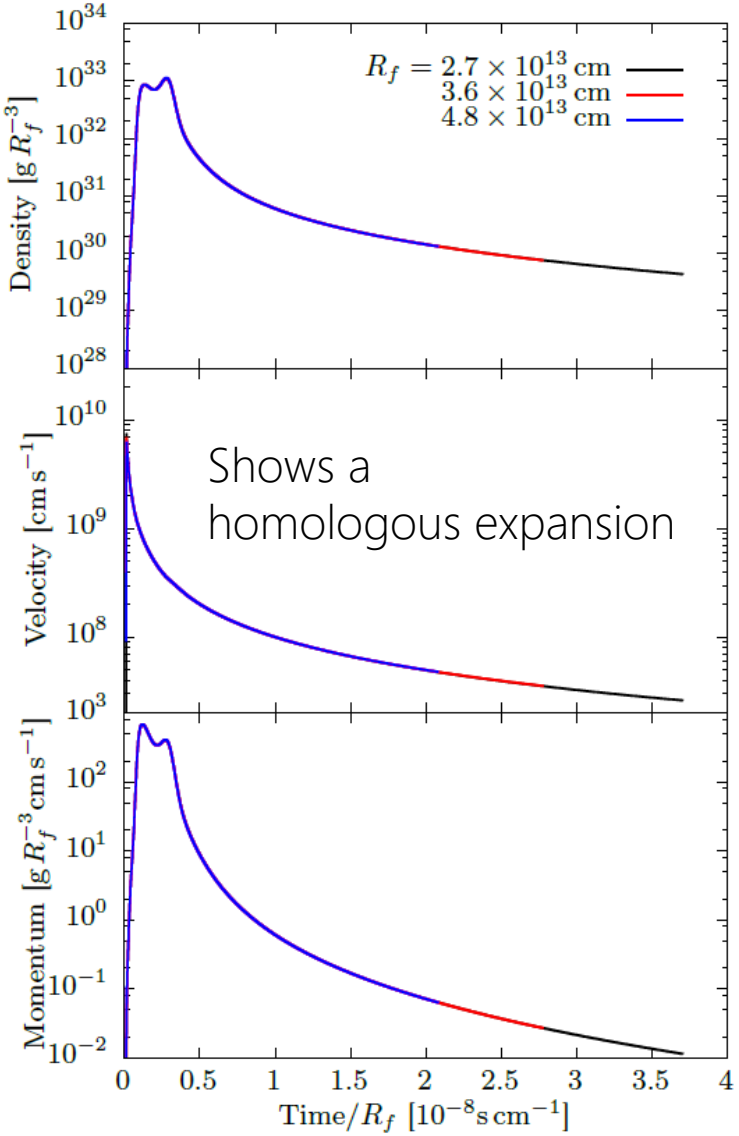
- Cylindrical grid assuming axisymmetry
- Companion mass: 10, 15, $20M_{\odot}$
- Companion radius: 5 – $9R_{\odot}$
- Orbital separation: 20, 30, 40, $60R_{\odot}$



ECI simulation

Step 1: 1D simulation of explosion



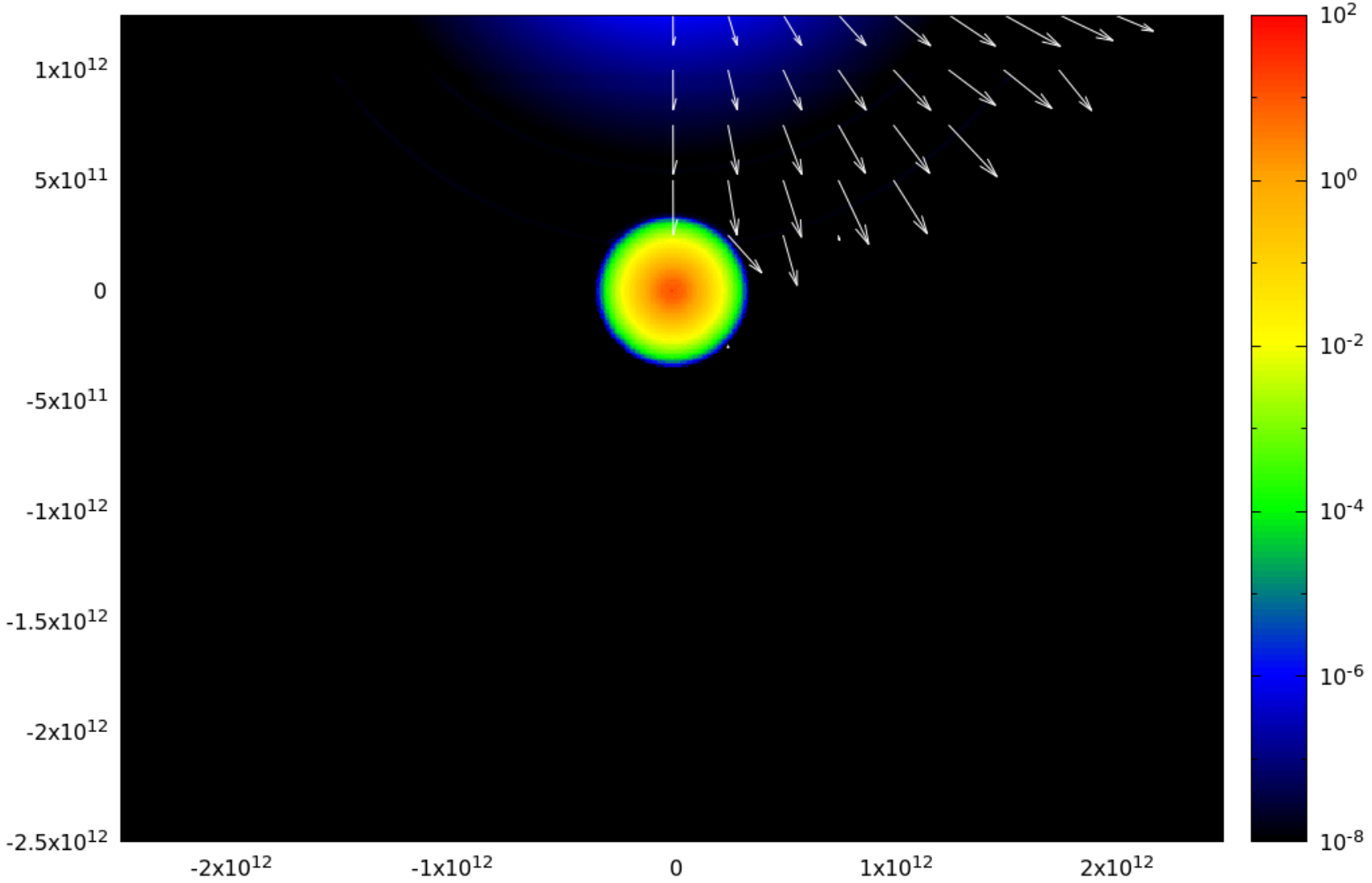


→Ejecta profiles used for step 2

ECI simulation

Step 2: 2D simulation of ECI

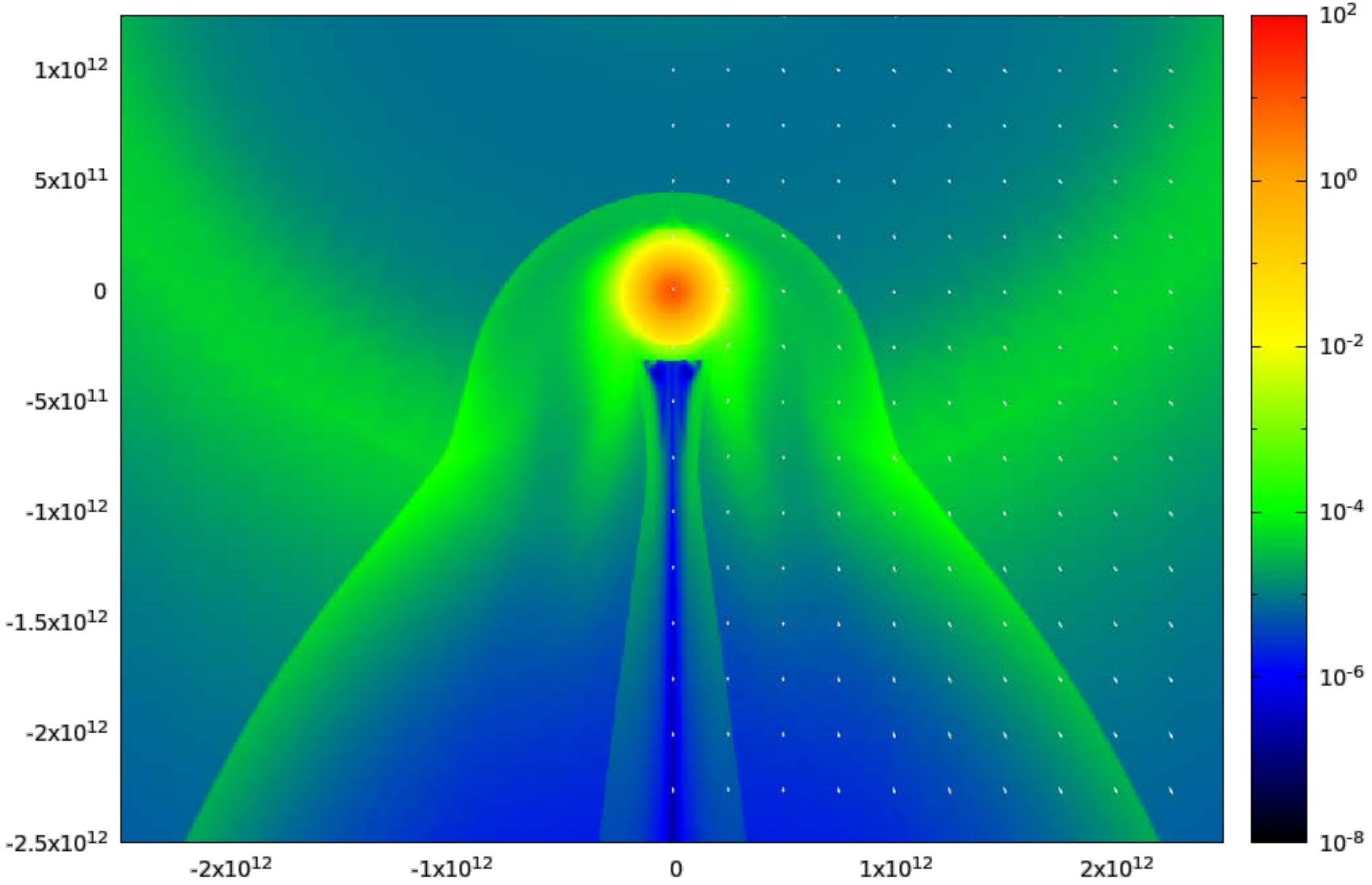
$M_2 = 10M_\odot, R_2 = 5R_\odot, a = 30R_\odot$

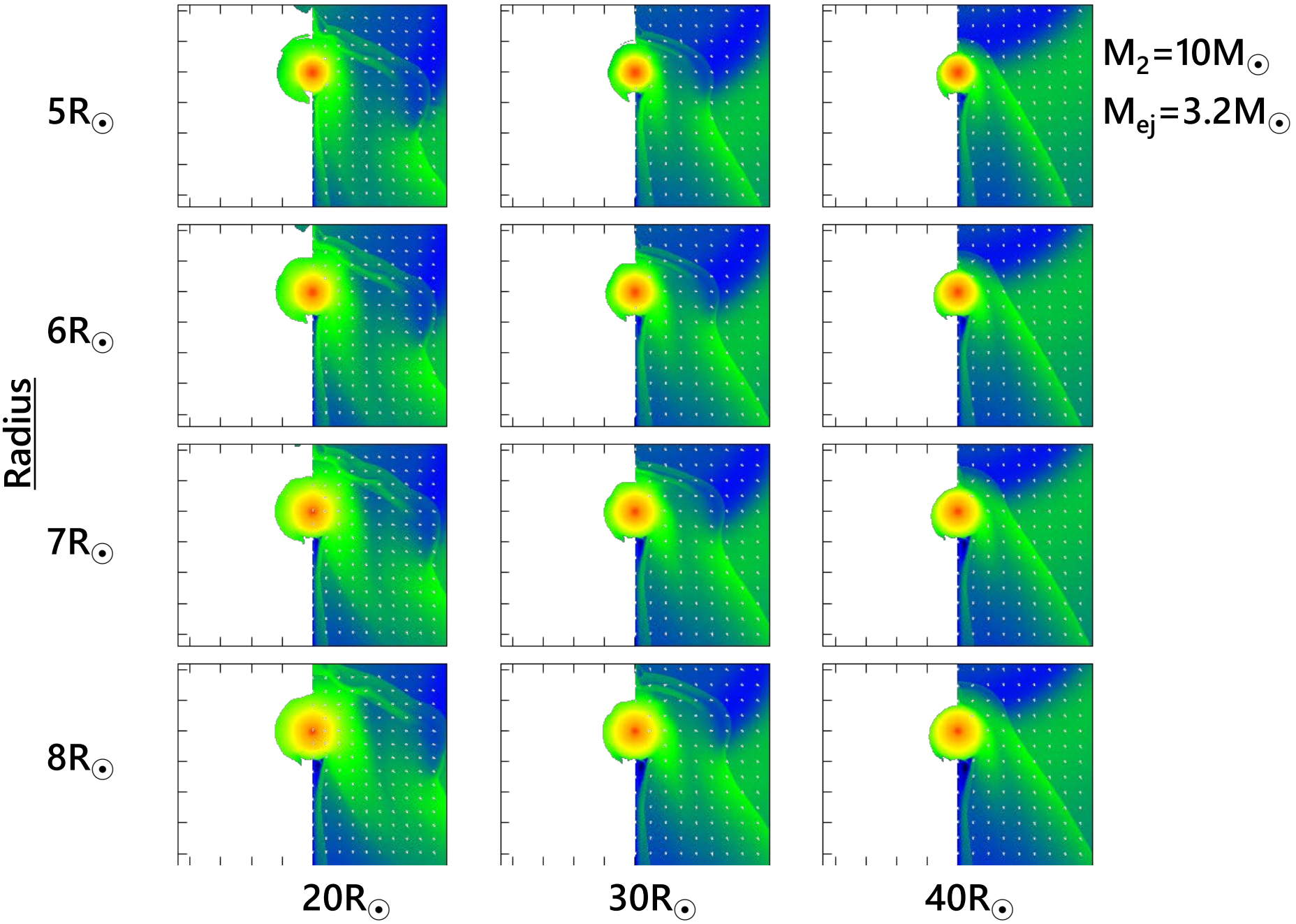


ECI simulation

Step 2: 2D simulation of ECI

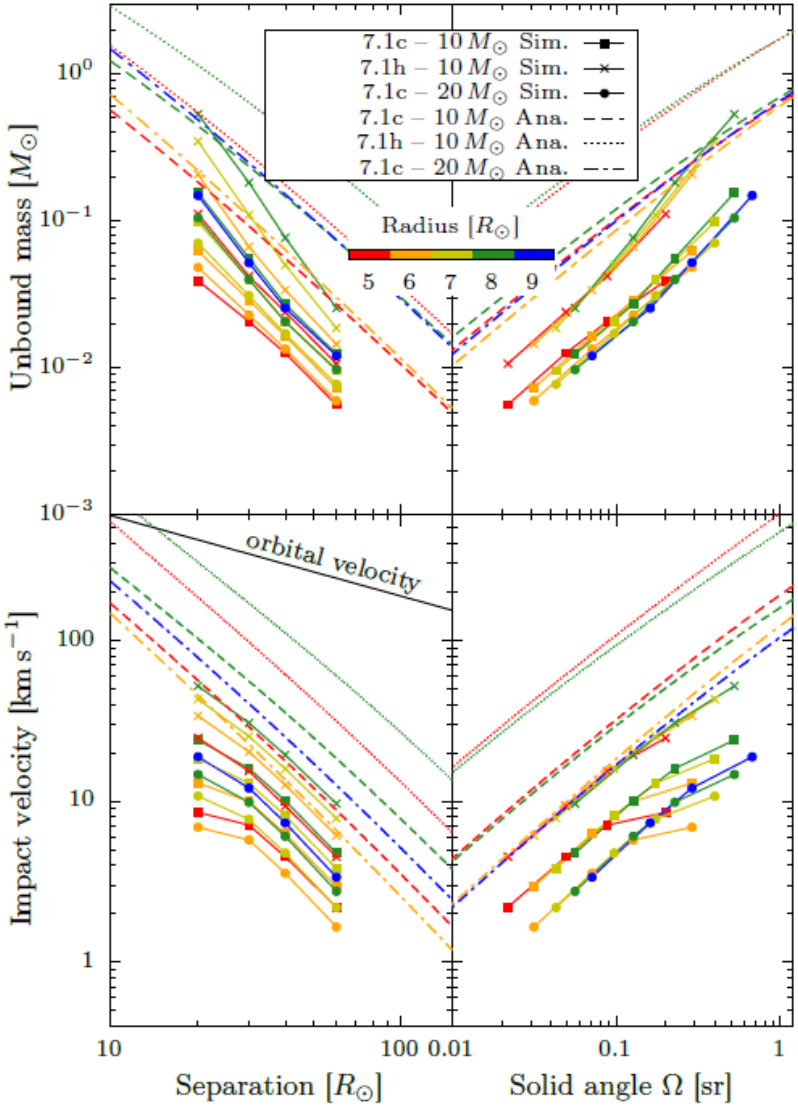
$M_2 = 10M_\odot, R_2 = 5R_\odot, a = 30R_\odot$



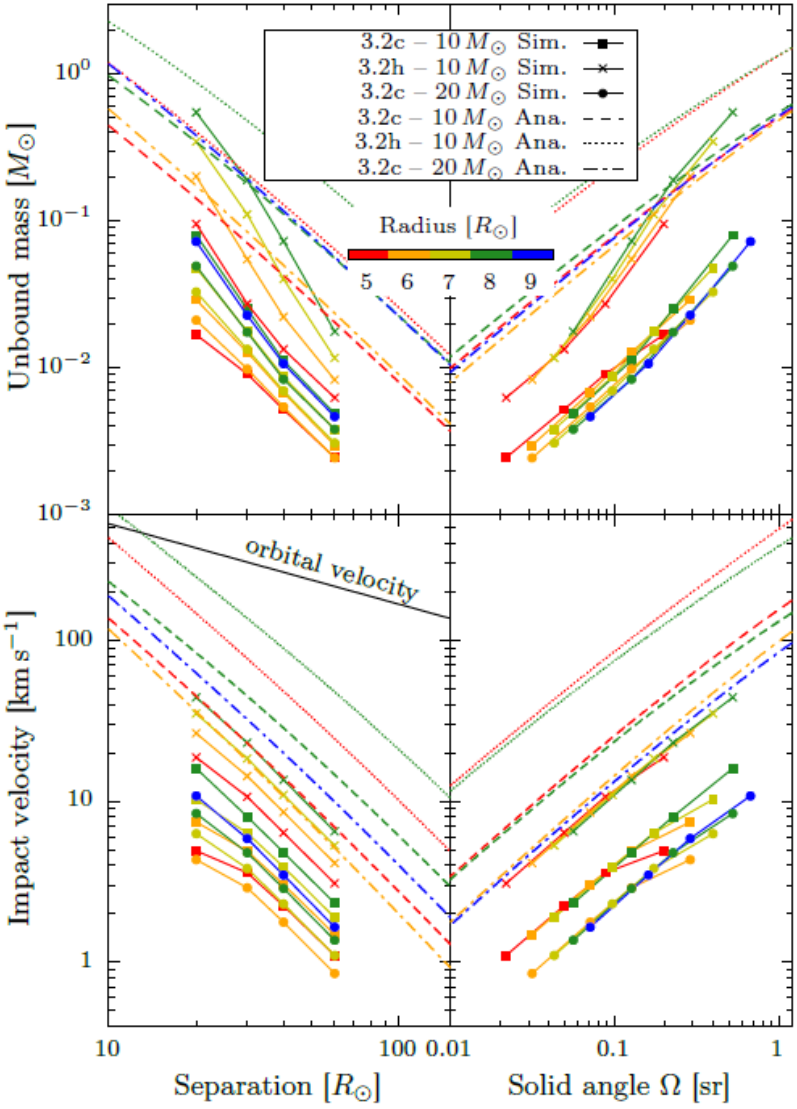

5R⊙
6R⊙
7R⊙
8R⊙
Radius
20R⊙
30R⊙
40R⊙
Separation
M2=10M⊙
Mej=3.2M⊙
and more...

Stripped mass/Impact velocity

7.1$M_\odot$ ejecta model



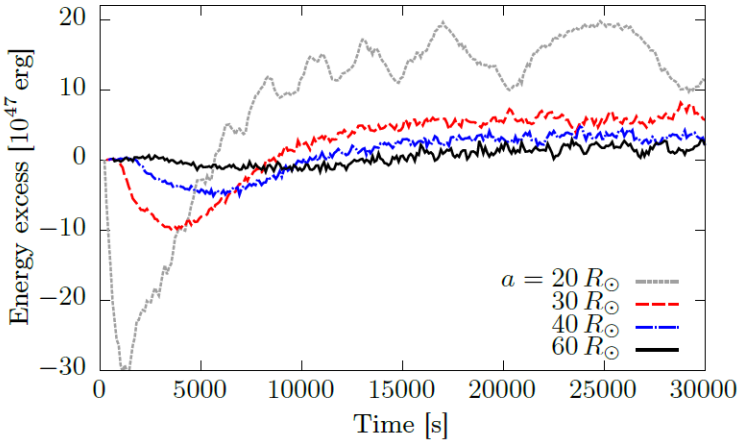
3.2$M_\odot$ ejecta model

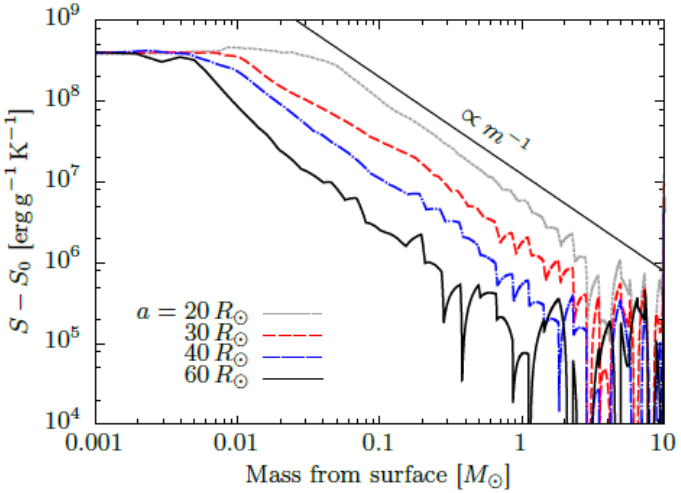


Heat injection

The companion star had some energy excess after the simulation

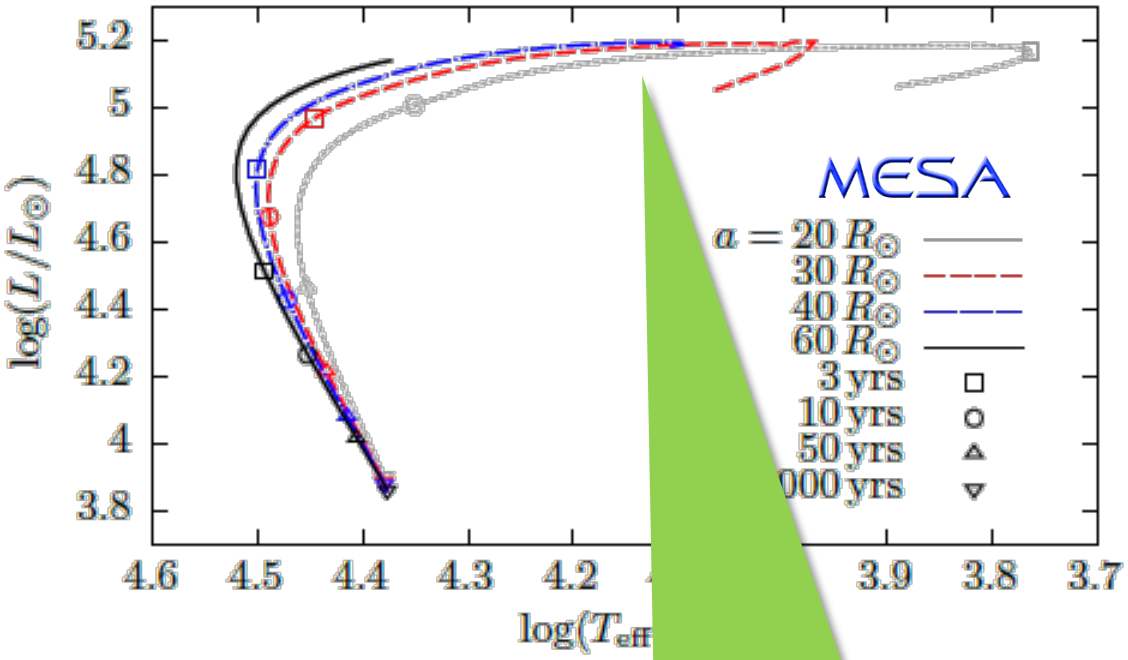
Post-ECI excess energy





Heat injection efficiency was ~8% of intersected energy

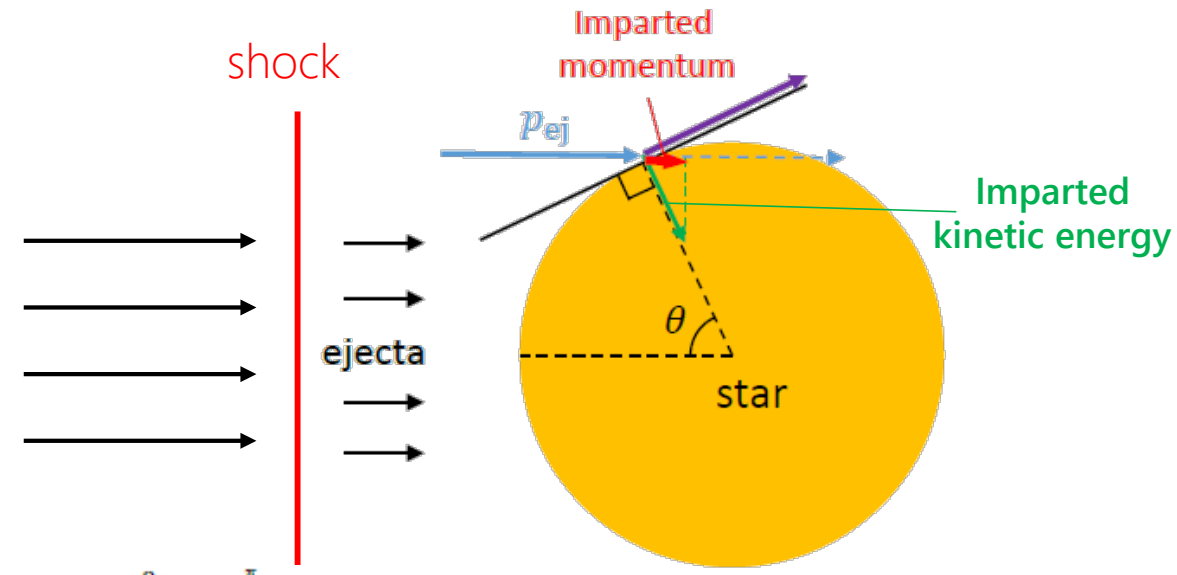
Post-ECI evolution



The companion can become quite puffed-up due to the heat excess injected by the ejecta

Model for energy injection

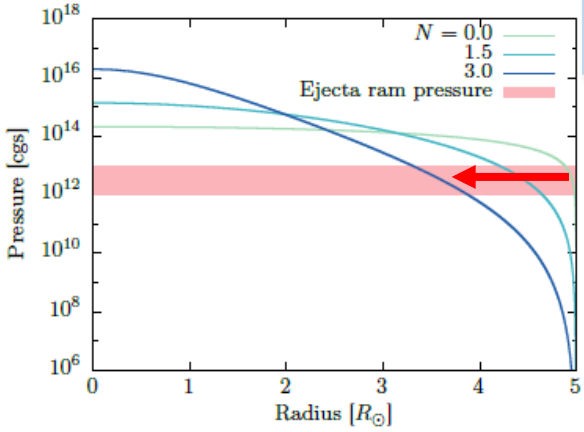
Energy transfer efficiency on a solid surface



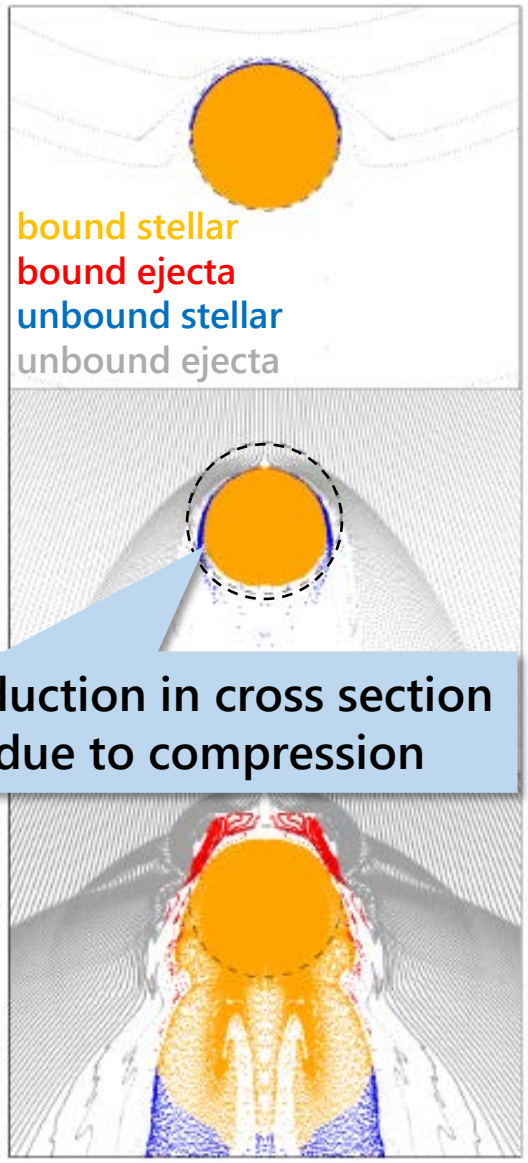
$$\eta_{\rm ideal} = \frac{\int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}} \sin\theta \cos^3\theta d\theta}{\int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}} \sin\theta \cos\theta d\theta} = \frac{1}{2}$$

$$\vartheta = \frac{1}{2}\frac{\gamma-1}{\gamma+1}\left(\frac{r_{p=p_{\rm ej}(a)}}{R_2}\right)^2$$

In good agreement with simulated results!



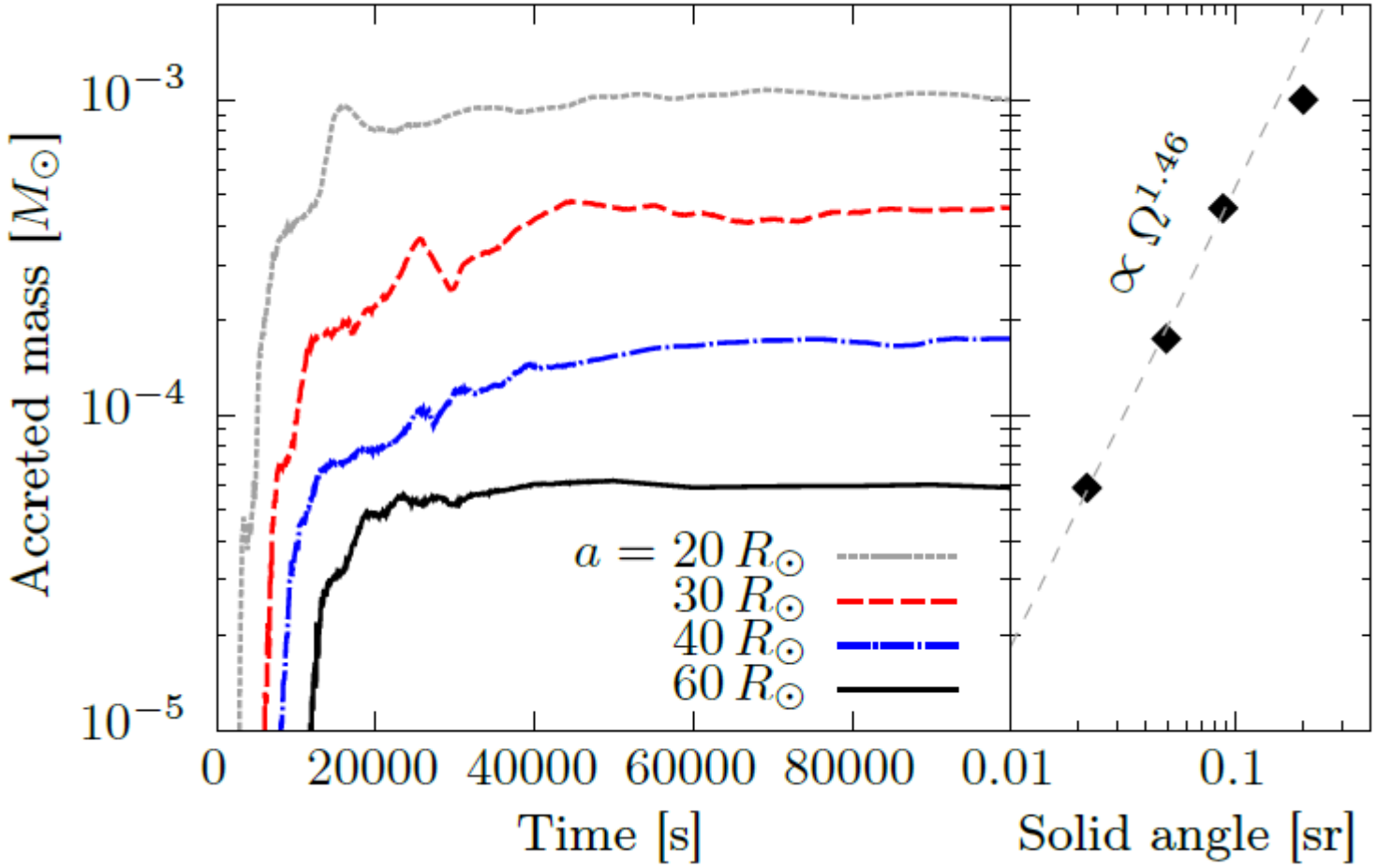
Tracer particles



Reduction in cross section due to compression

Surface pollution

Amount of ejecta tracer particles accreted onto the companion



Summary

- Stripped-envelope supernovae should arise from progenitors which have experienced binary interactions.
- Ejecta-companion interaction would not be important even for the most closest binaries in terms of mass removal and impact velocity.
- Energy injection by the ejecta can puff up the remaining companion and may be useful to constrain pre-SN binary parameters

Ongoing work

- Hydrodynamical modelling of the homunculus nebula of Eta Carinae
- Based on the merger scenario