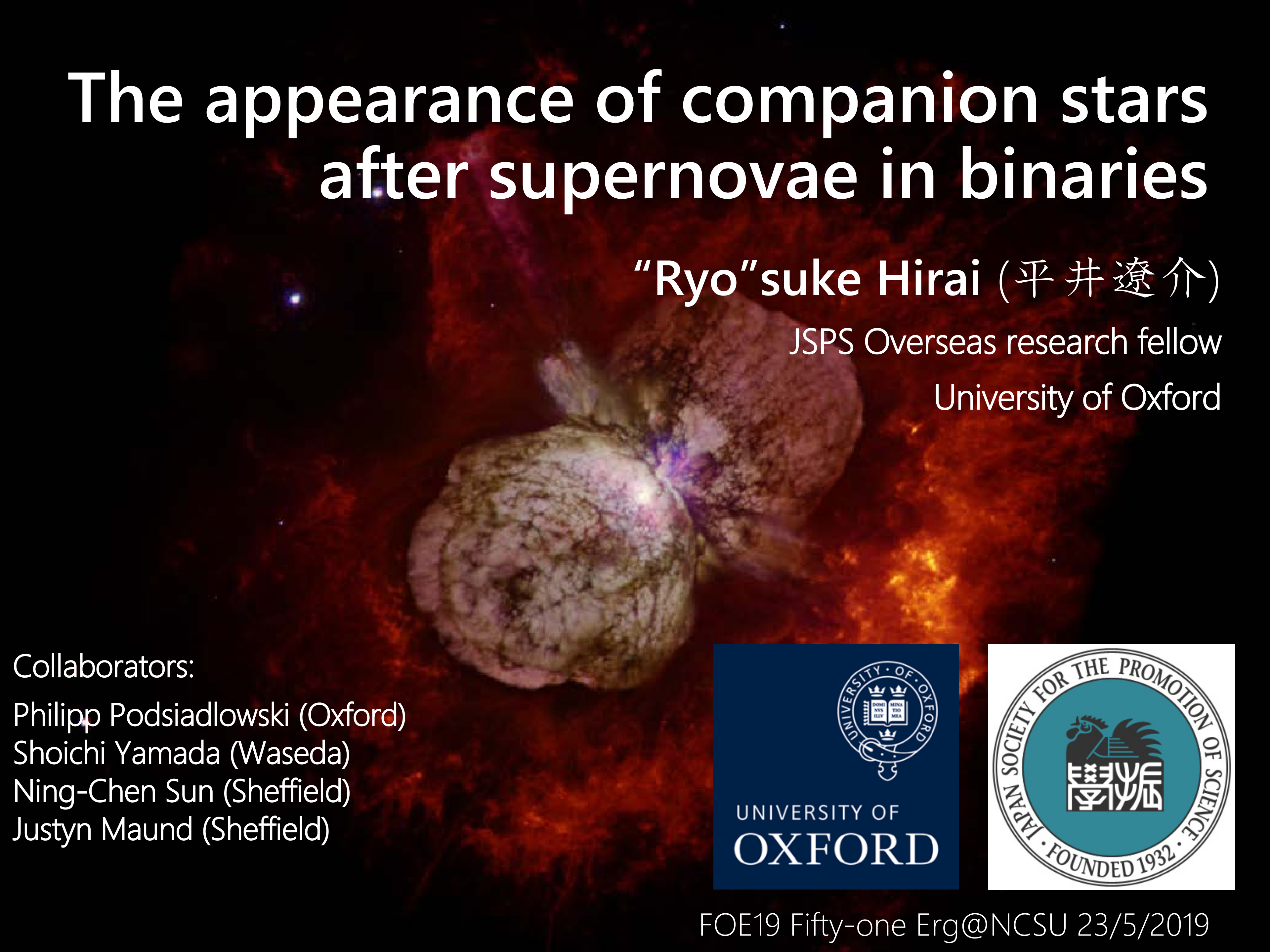

The appearance of companion stars after supernovae in binaries

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University of Oxford

Collaborators:

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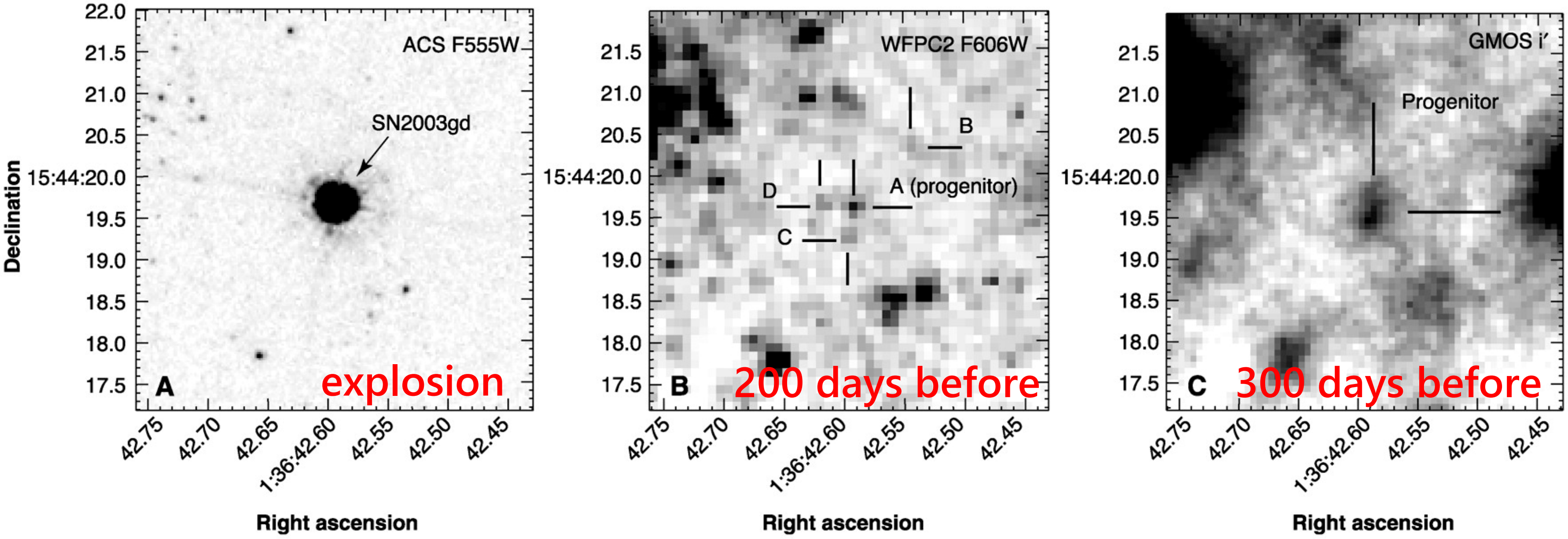
Shoichi Yamada (Waseda)
Ning-Chen Sun (Sheffield)
Justyn Maund (Sheffield)

FOE19 Fifty-one Erg@NCSU 23/5/2019

Progenitor detections

Smartt et al. 2004



explosion

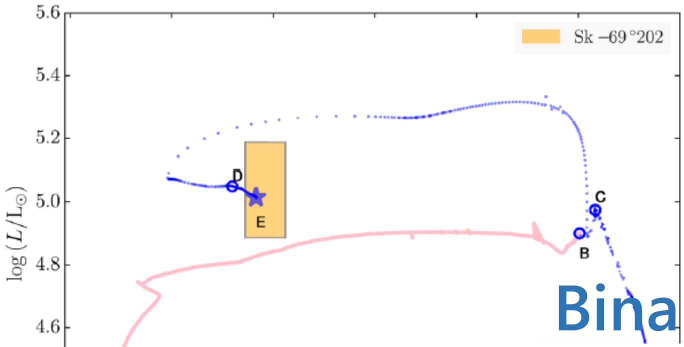
200 days before

300 days before

What can it tell us?

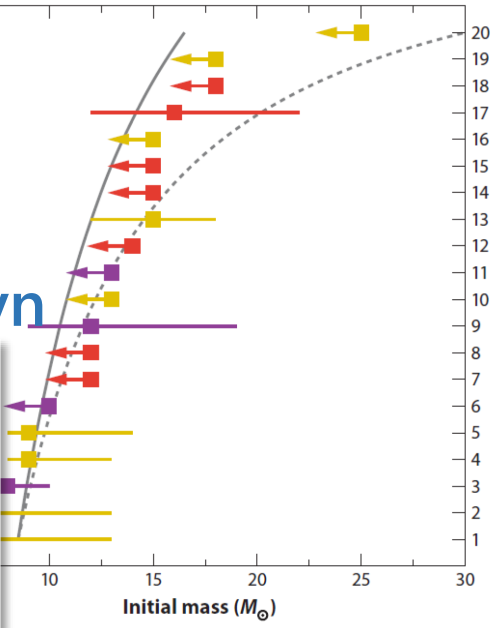
Direct progenitor detections are crucial for understanding CCSN progenitors

Merger model for SN1987A



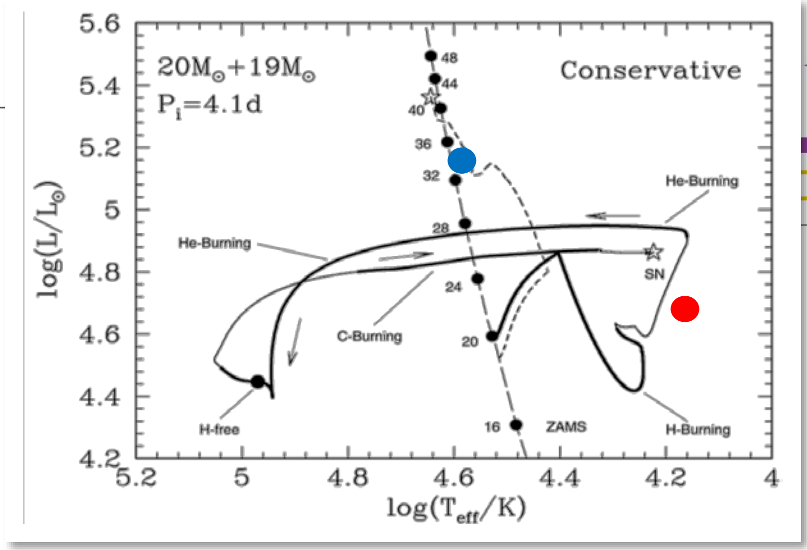
Podsiadlowski 1990
Menon & Heger 2017 etc

RSG problem



Smartt et al. 2009

Binary models for iPTF13bvn

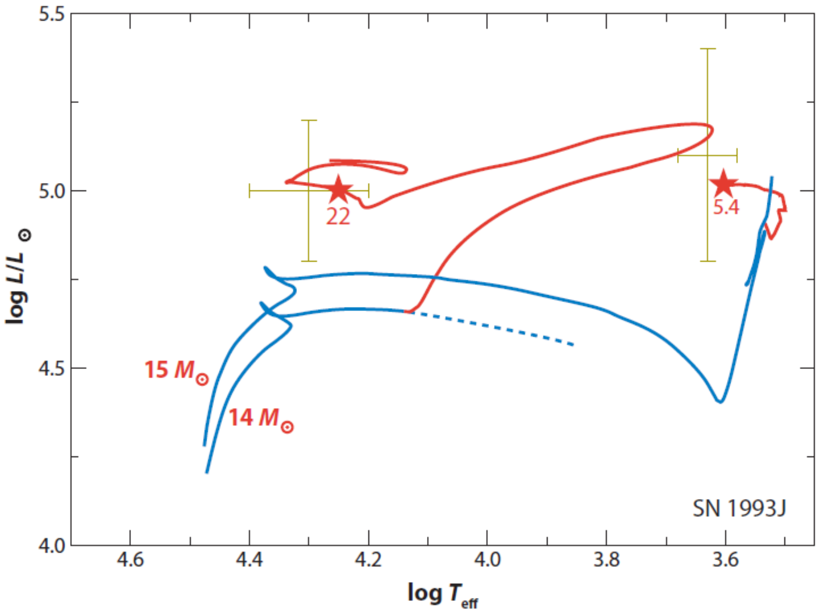


Bersten et al. 2014, Eldridge et al. 2015, RH & Yamada 2015

Companion (non-)detections

Companion detections or non-detections tell us even more

SN1993J



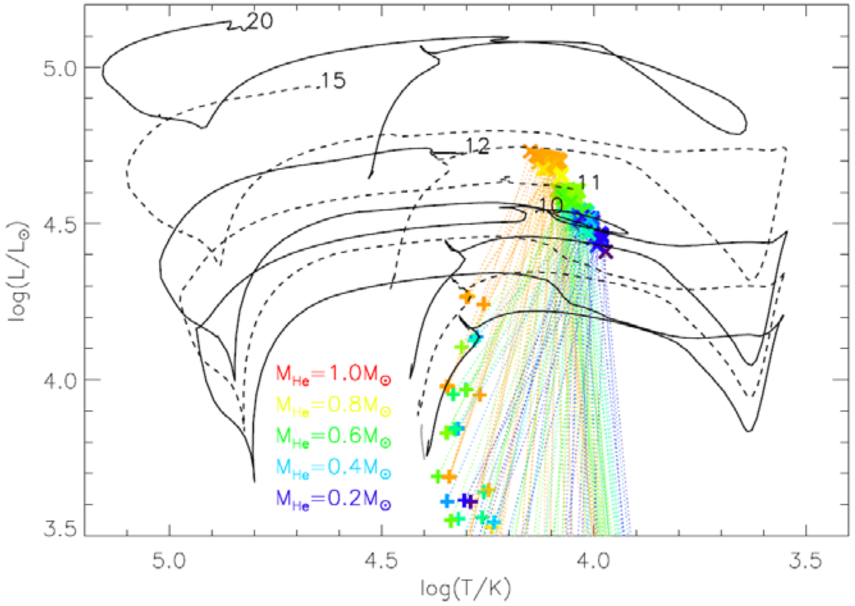
Maund et al. 2004

Progenitor detection

+

companion detection

iPTF13bvn



Folatelli et al. 2016, Eldridge & Maund 2016, RH 2017a,b

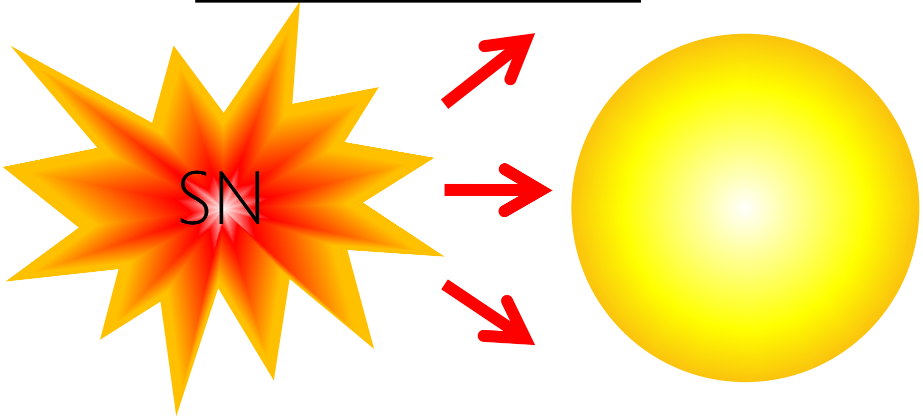
Progenitor detection

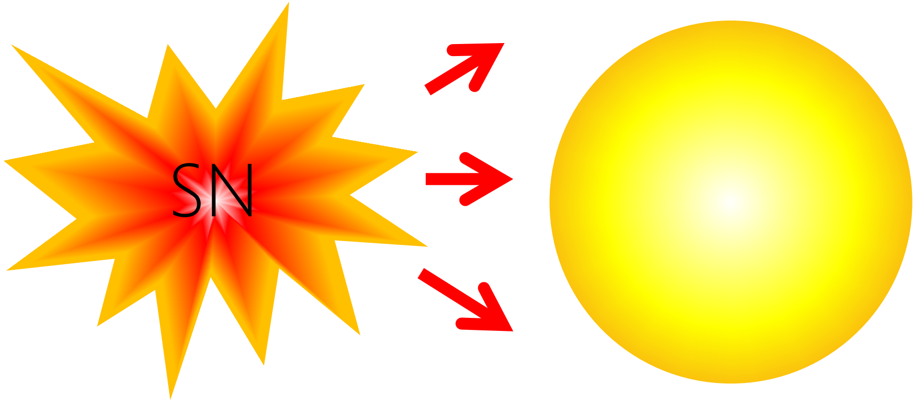
+

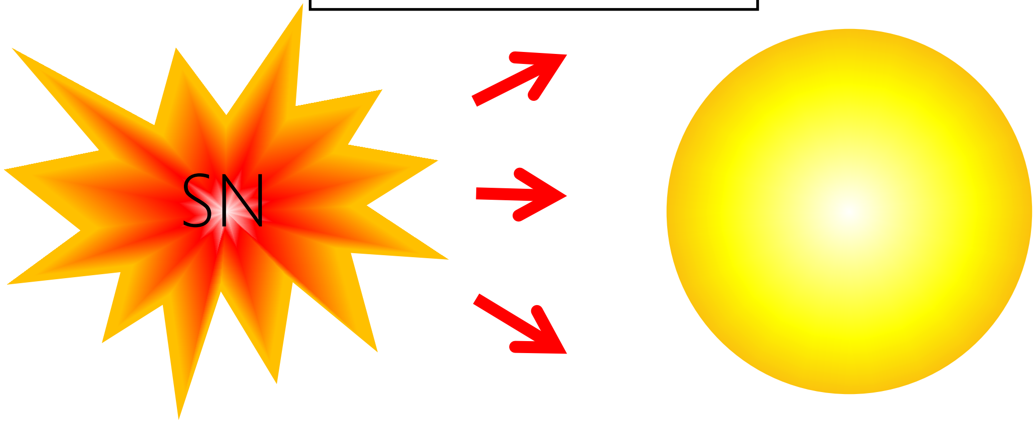
companion non-detection

Do companions look the same after supernova?

Ejecta-Companion interaction


Mass removal


Impact velocity


Heat injection

ECI simulation

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

Code

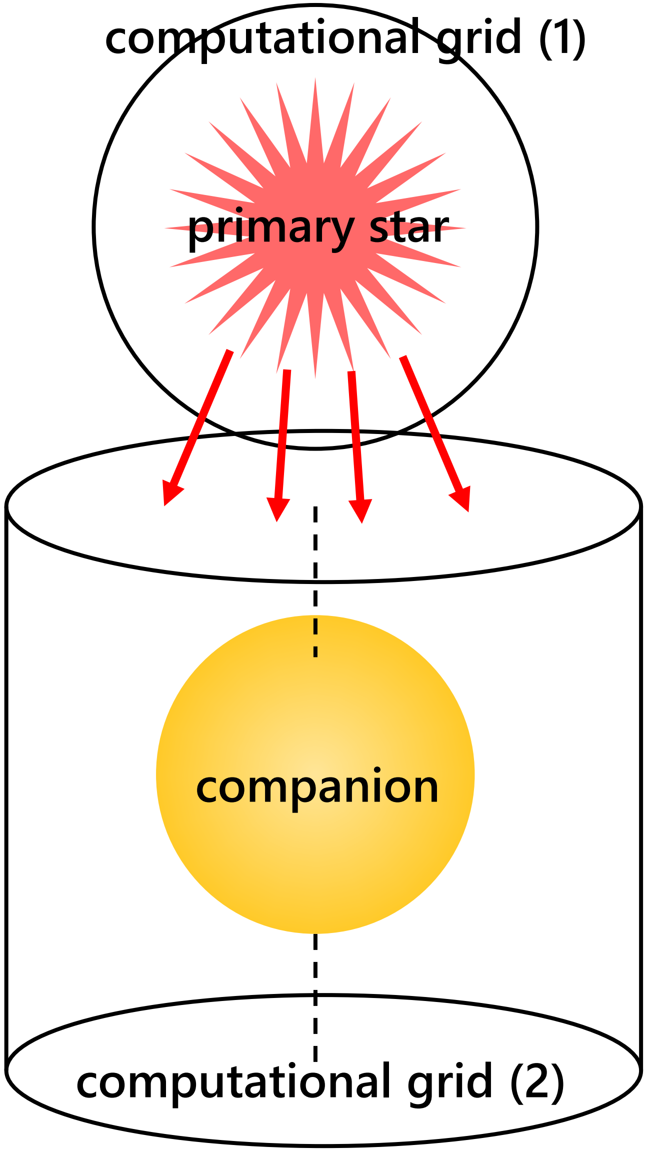
- Eulerian hydrodynamic code
- HLLC approximate Riemann flux
- 2nd order in space, 3rd order in time
- Hyperbolic self-gravity (RH et al. 2016)

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

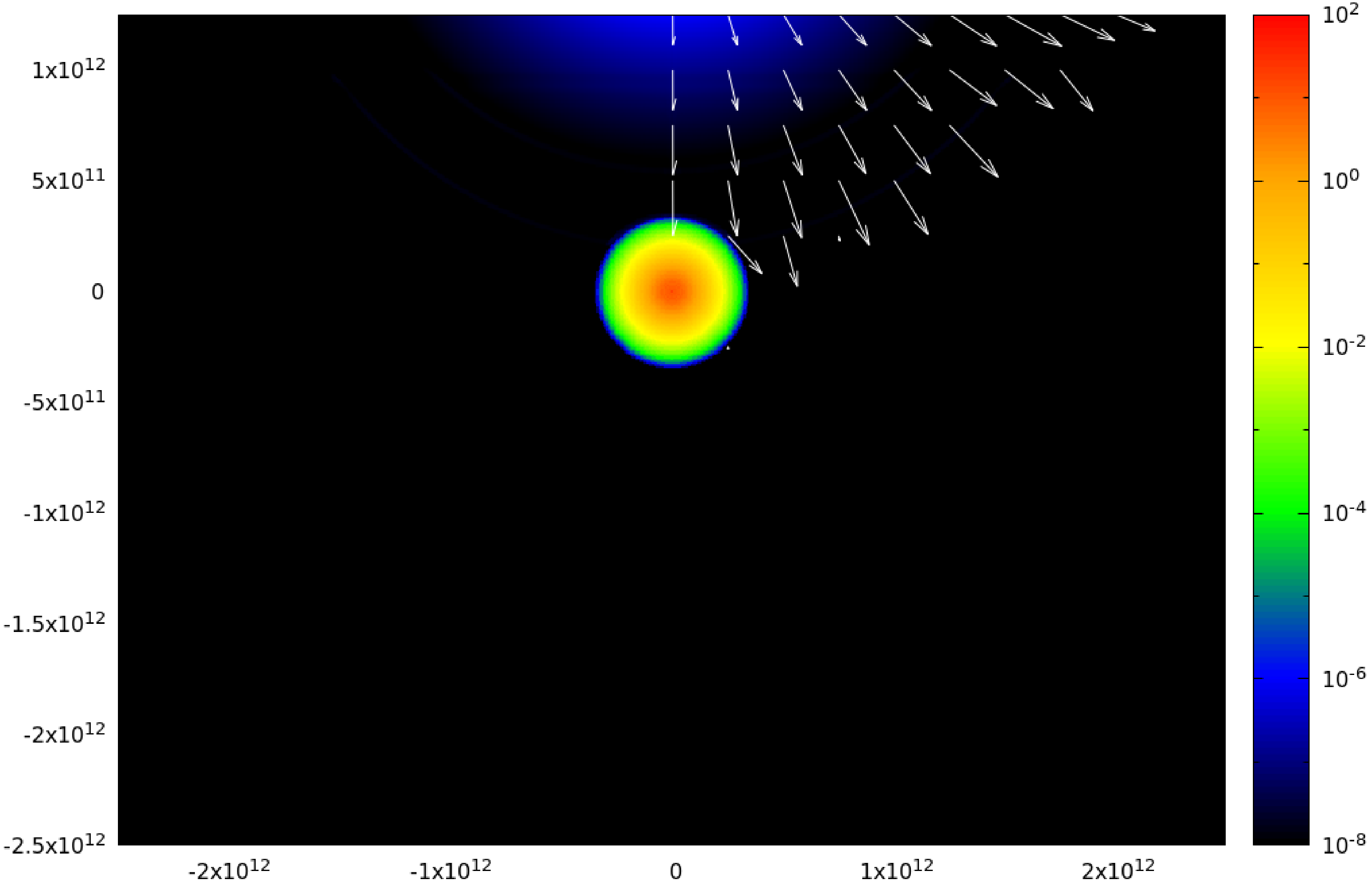
- Cylindrical grid assuming axisymmetry
- Companion mass: 10, 15, $20M_\odot$
- Companion radius: 5 – $9R_\odot$
- Orbital separation: 20, 30, 40, $60R_\odot$



ECI simulation

Step 2: 2D simulation of ECI

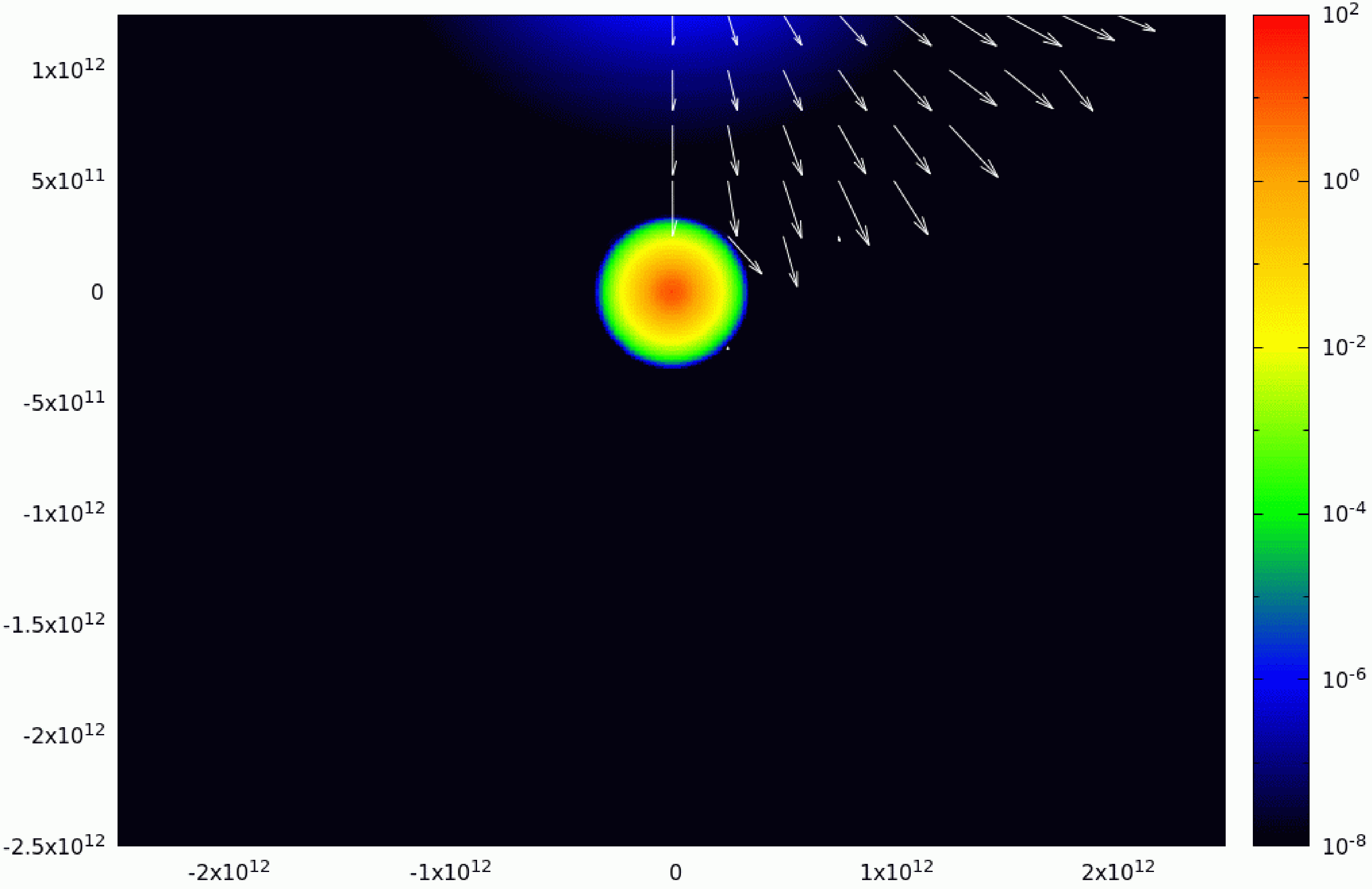
$M_2 = 10M_\odot, R_2 = 5R_\odot, a = 30R_\odot$

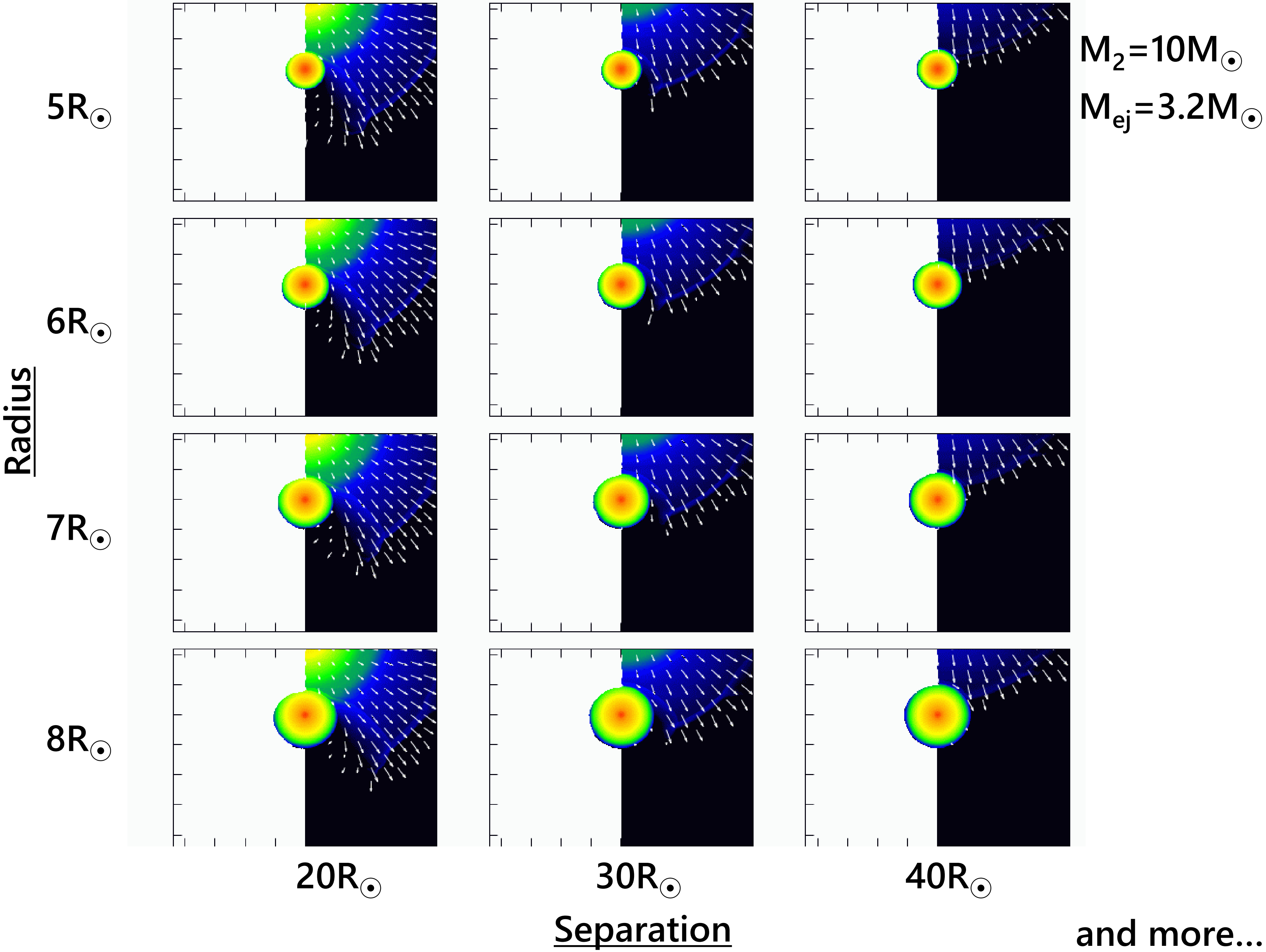


ECI simulation

Step 2: 2D simulation of ECI

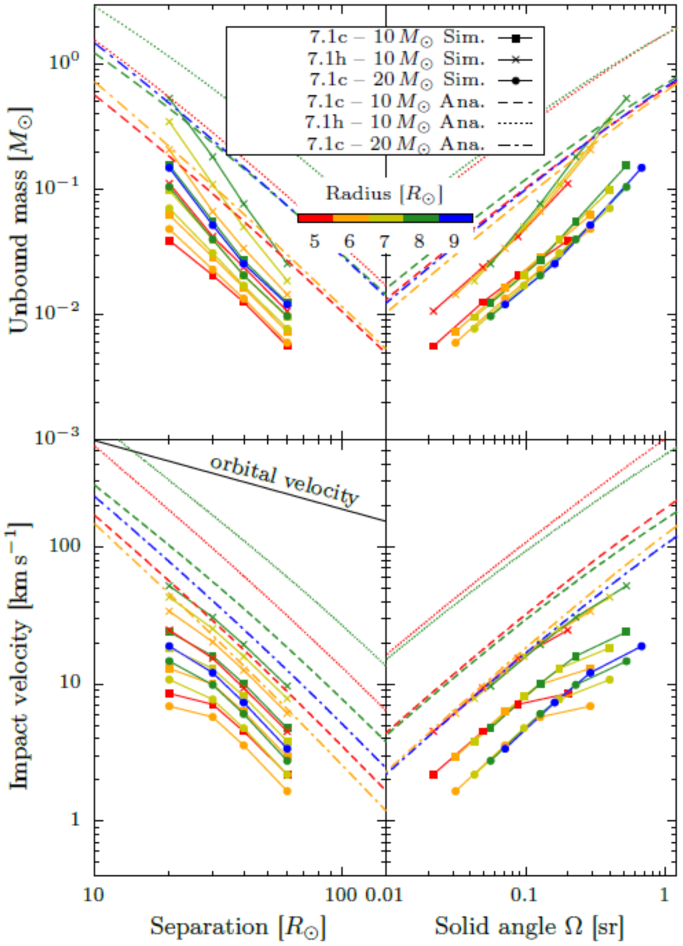
$M_2 = 10M_\odot, R_2 = 5R_\odot, a = 30R_\odot$



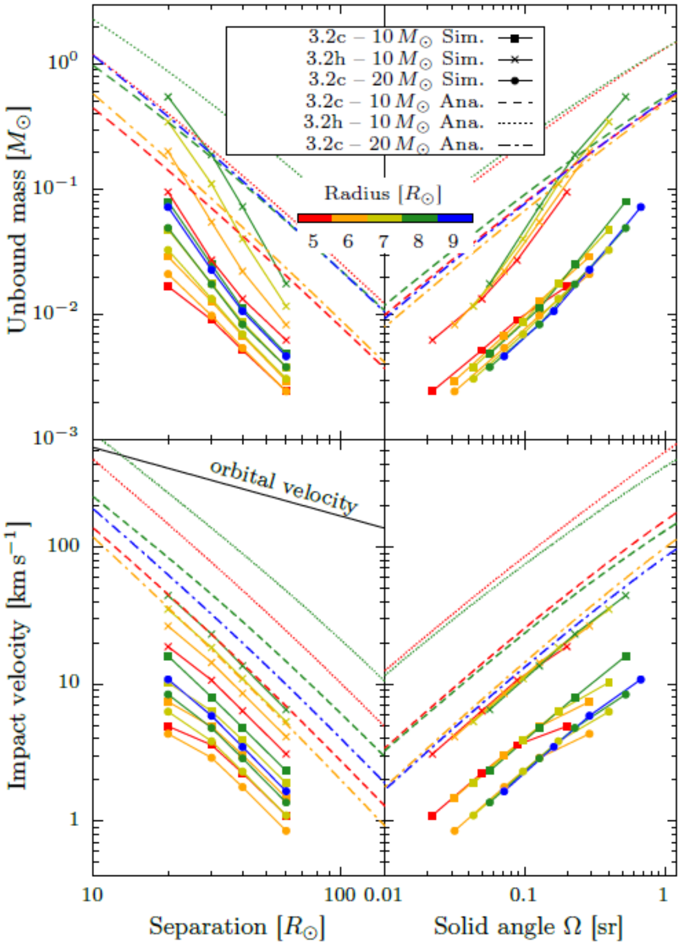

$M_2=10M_\odot$
$M_{ej}=3.2M_\odot$
Radius
$5R_\odot$
$6R_\odot$
$7R_\odot$
$8R_\odot$
$20R_\odot$
$30R_\odot$
$40R_\odot$
Separation
and more...

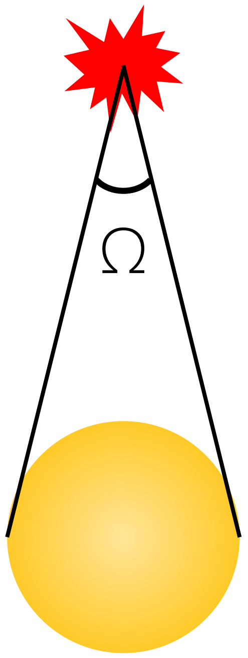
Stripped mass/Impact velocity

7.1$M_\odot$ ejecta model



3.2$M_\odot$ ejecta model



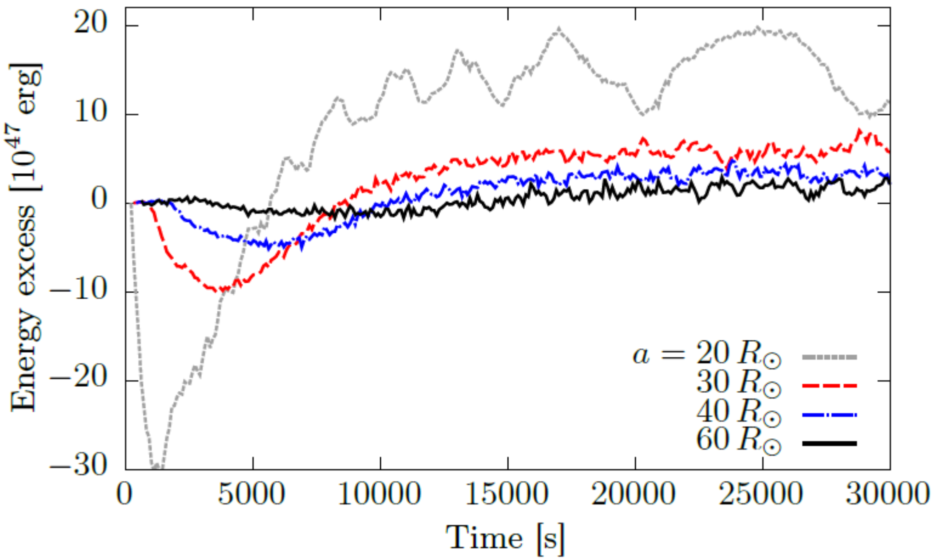


Mass removal is very minor and won’t affect its appearance

Heat injection

The companion star had some energy excess after the simulation

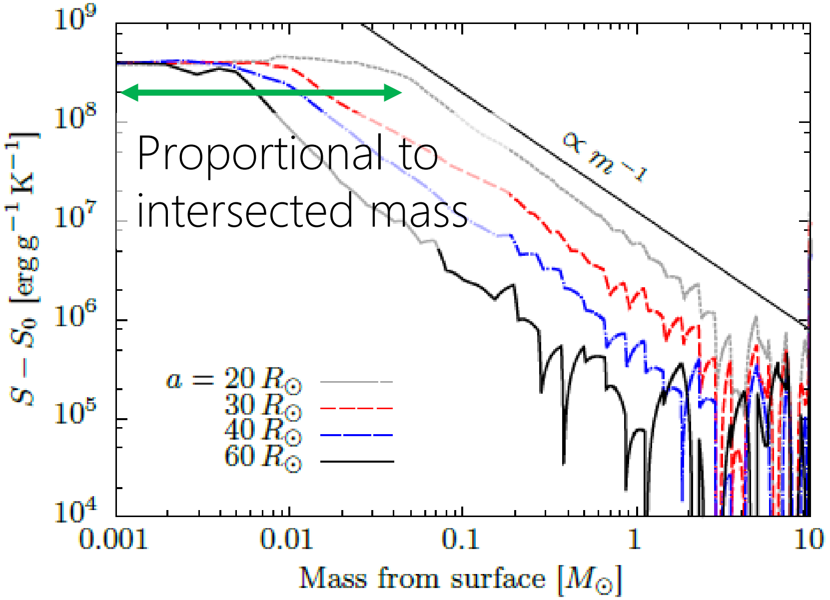
Post-ECI excess energy



Heat injection efficiency was ~8-12% of intersected energy

Differs depending on stellar structure and separation

Excess energy distribution



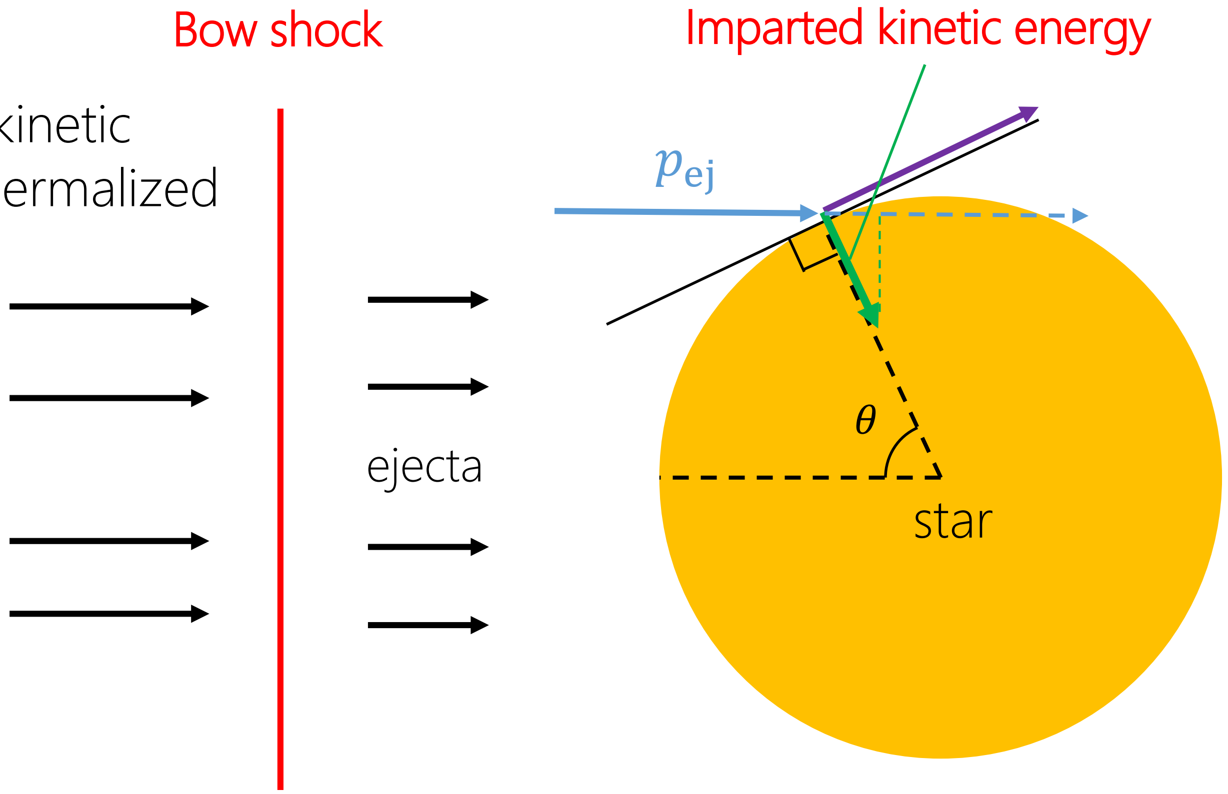
Proportional to intersected mass

Most of the excess energy is distributed around the surface, and declines as it goes deeper into the star

Model for heat injection

Energy transfer efficiency on a solid surface

Part of the kinetic energy is thermalized



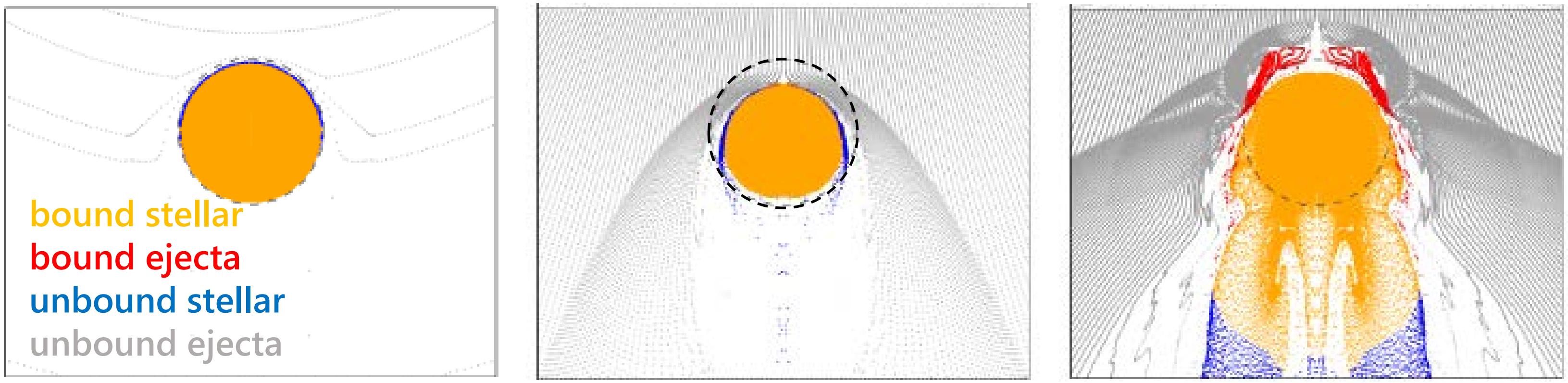
Rankine Hugoniot condition

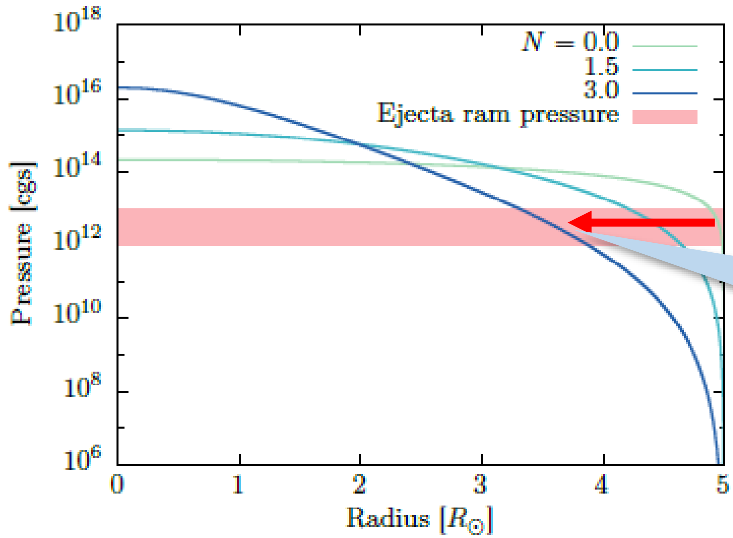
$$\eta_{\mathrm{ideal}} = \frac{\int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}} \sin\theta \cos^3\theta d\theta}{\int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}} \sin\theta \cos\theta d\theta} = \frac{1}{2}$$

Model for heat injection

Reduction of cross section

Tracer particles



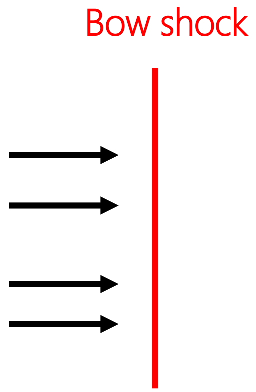


The companion gets compressed by ejecta ram pressure

Ejecta ram pressure ≒ Pressure inside star

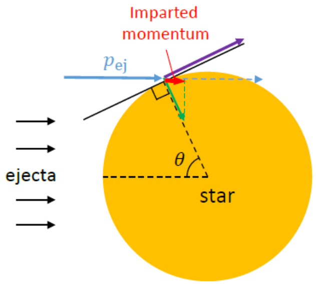
New model for heat injection

Thermalisation



×

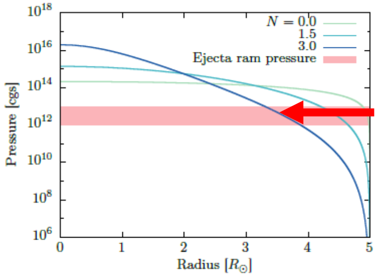
Solid surface



$$\frac{1}{2}$$

×

Compression

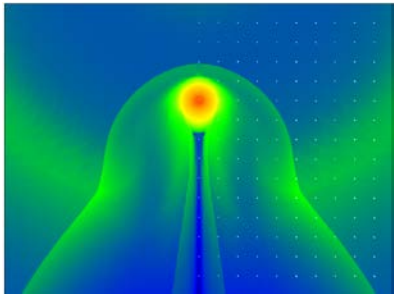


$$\left(\frac{r_{p=p_{\rm ej}(a)}}{R_2}\right)^2$$

Structure dependence is contained here

=

Total



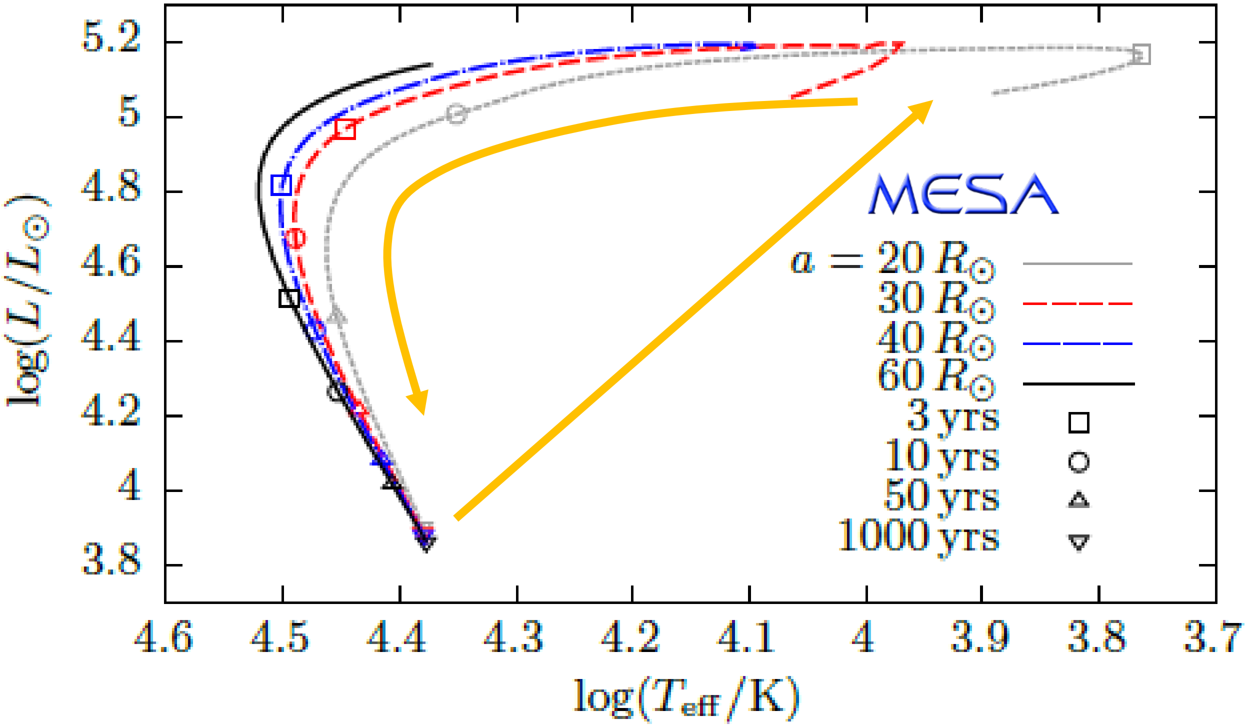
~8-12%

Matches simulated results very well!!

Post-ECI evolution

The companion star can significantly change its appearance after ECI

Post-ECI evolution



Total energy excess

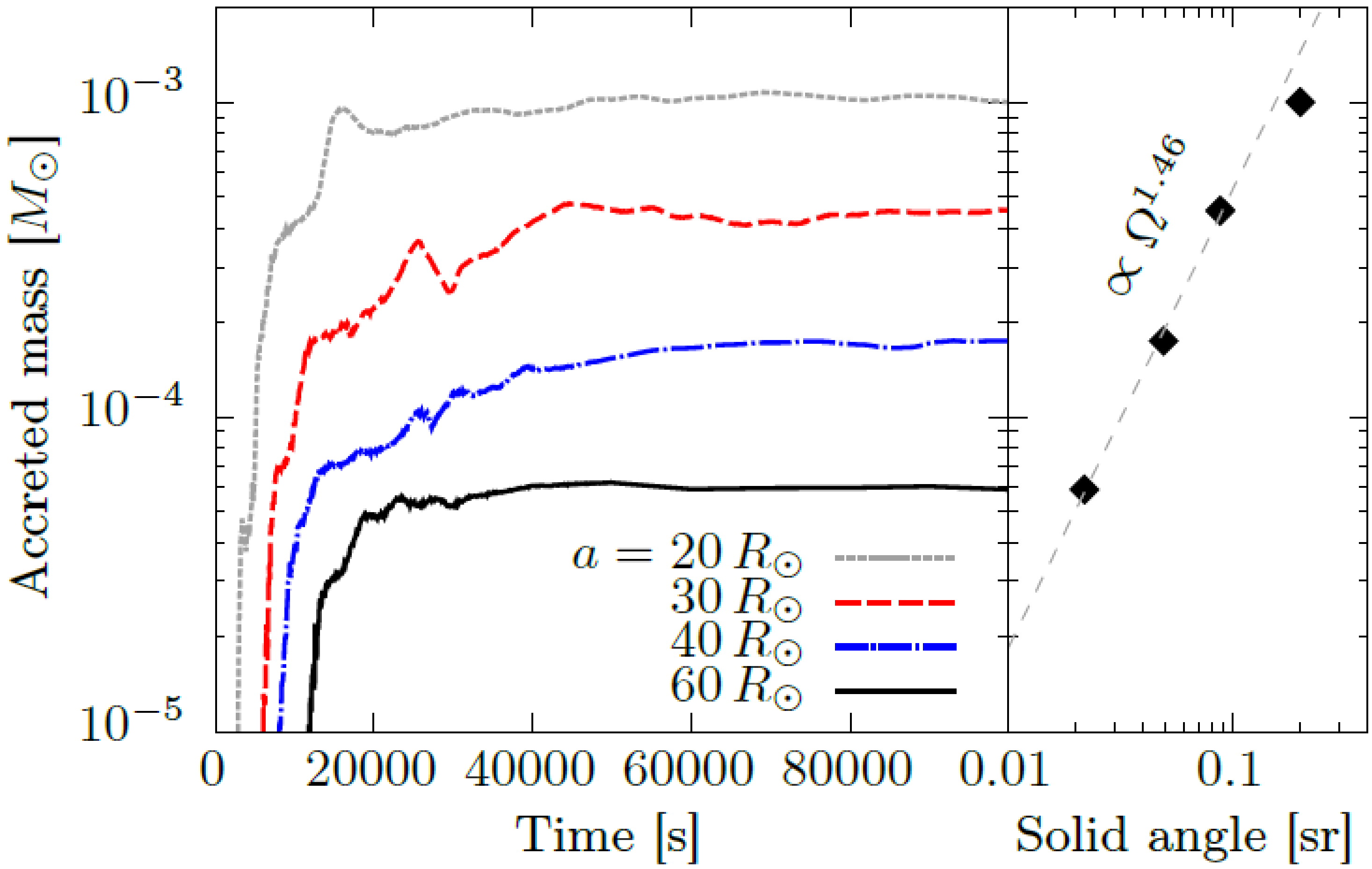
$$\vartheta = \frac{1}{2}\frac{\gamma-1}{\gamma+1}\left(\frac{r_{p=p_\mathrm{ej}(a)}}{R_2}\right)^2$$

Heat distribution

$$\dot{\epsilon}(m) = \frac{E_h}{\tau_h m_h} \cdot \frac{\min(1, m_h/m)}{1 + \ln(M_{2,\mathrm{rem}}/m_h)},$$

Surface pollution

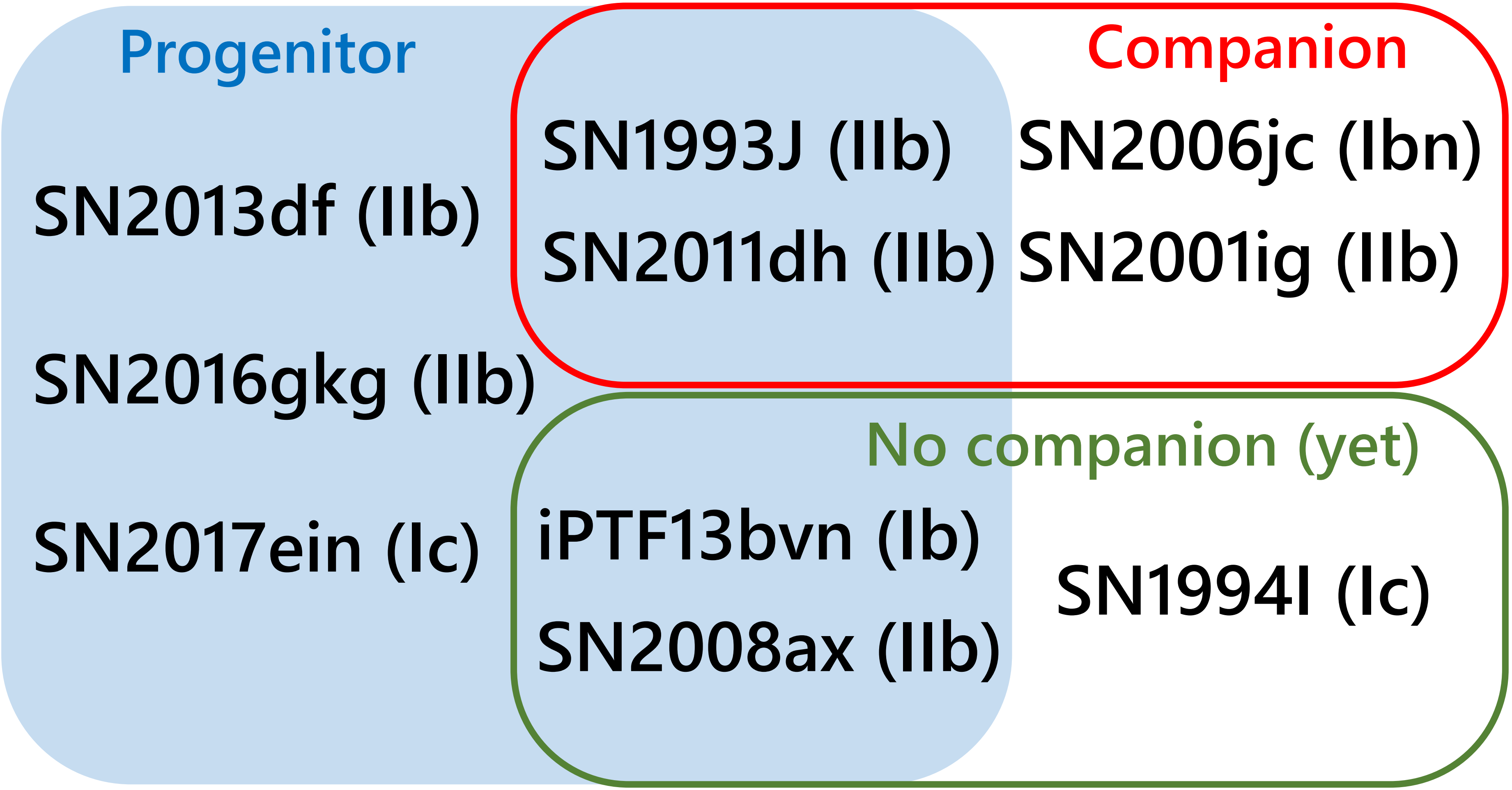
Later slower ejecta material can be accreted onto the companion



Companion could be slightly enriched with heavy elements on the surface

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)

No companion (yet)

iPTF13bvn (Ib)

SN2008ax (IIb)

SN1994I (Ic)

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

About SN2006jc

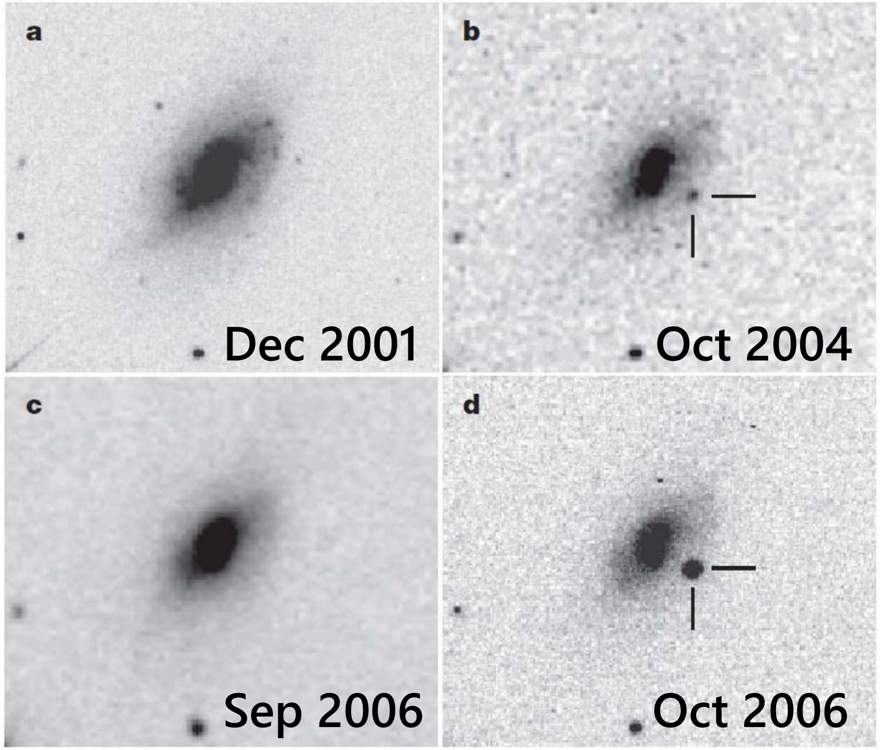
- Prototype Type Ibn
  - Type Ib supernova with narrow He I emission lines
  - ~30 discovered so far

- Pre-SN outburst observed in 2004

- Host galaxy: UGC 4904
  - Distance: 27.8 ± 1.9Mpc

- Slight bit of hydrogen at later times

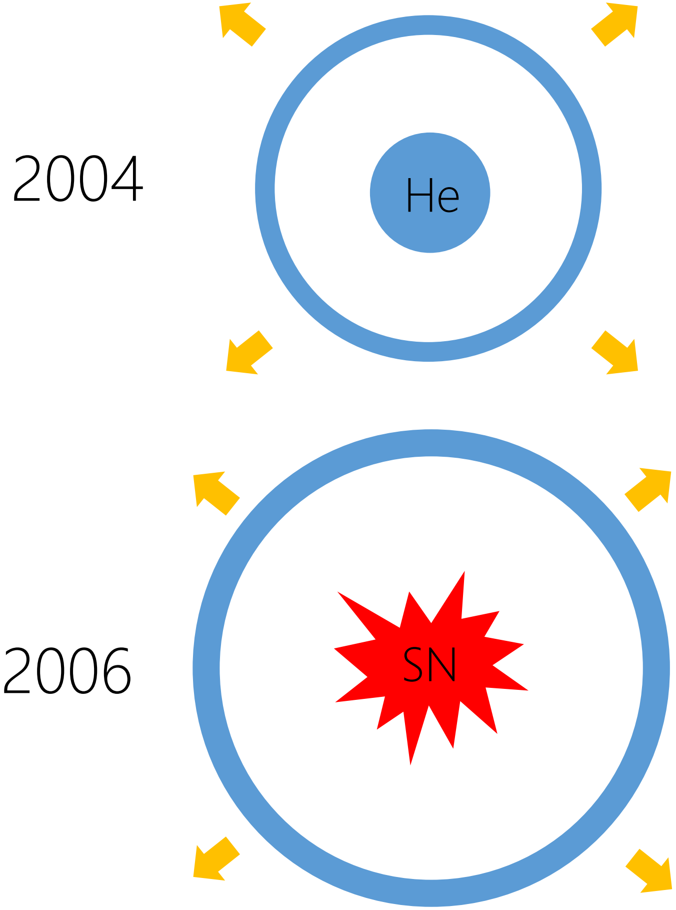
Pastorello et al. 2007



Origin of type Ibn supernovae

① Single star scenario

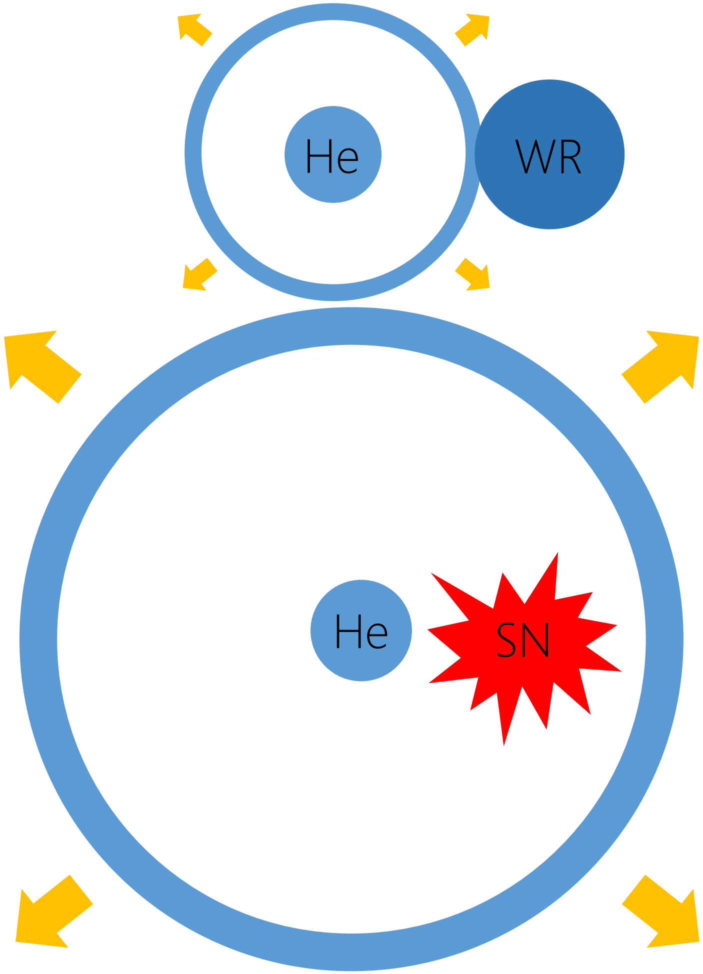
(Foley+07, Pastorello+07, Tominaga+08)



③ Chance alignment

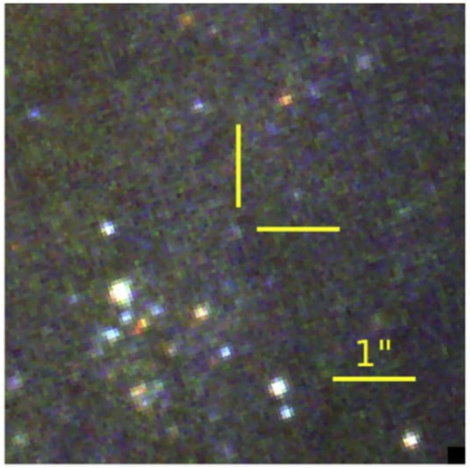
② Binary system scenario

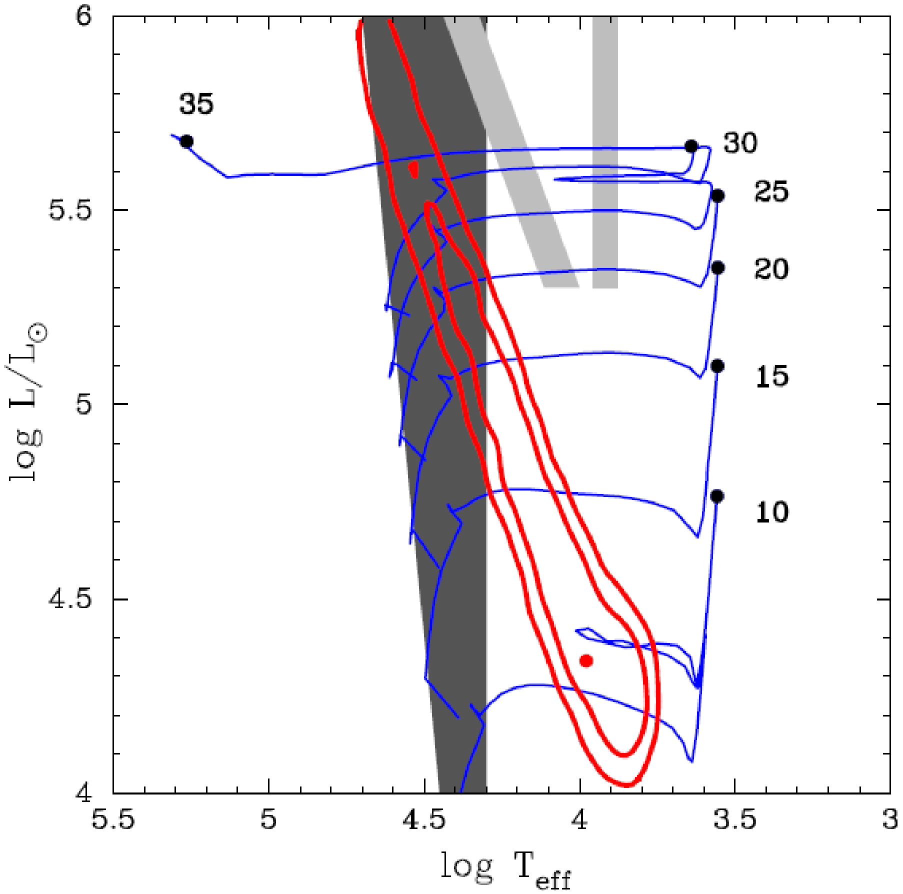
(Foley+07)

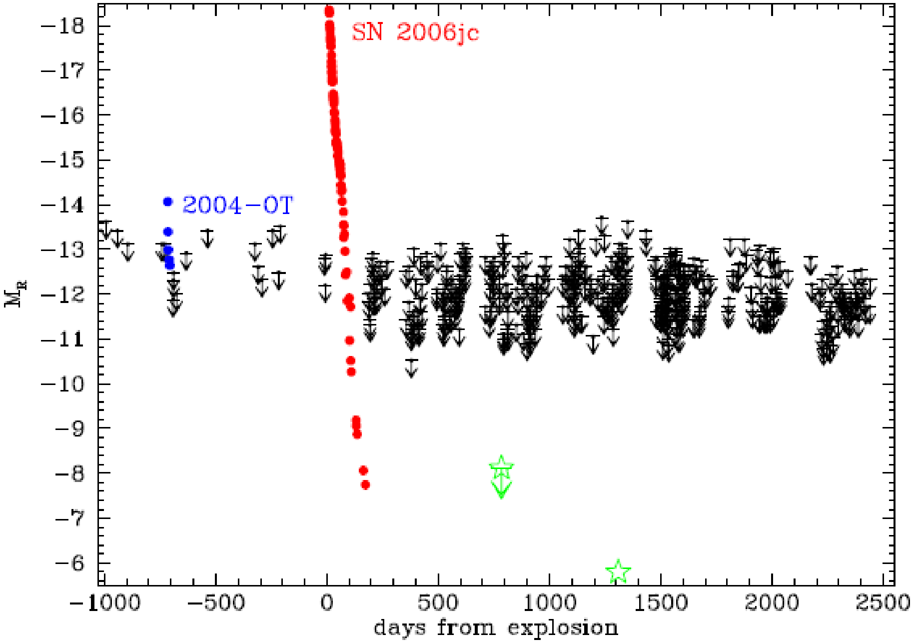


Discovery of a companion

Maund et al. 2016

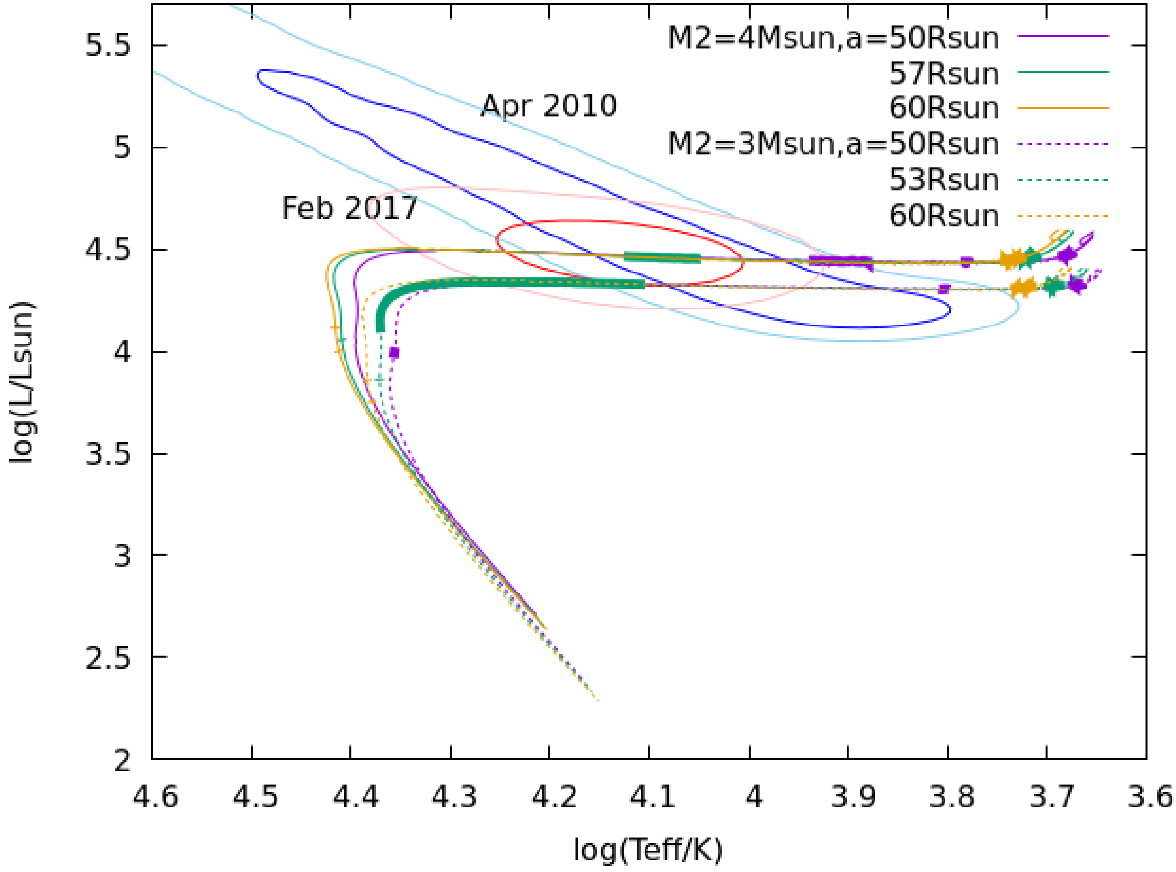






A companion was detected ~4 years after explosion

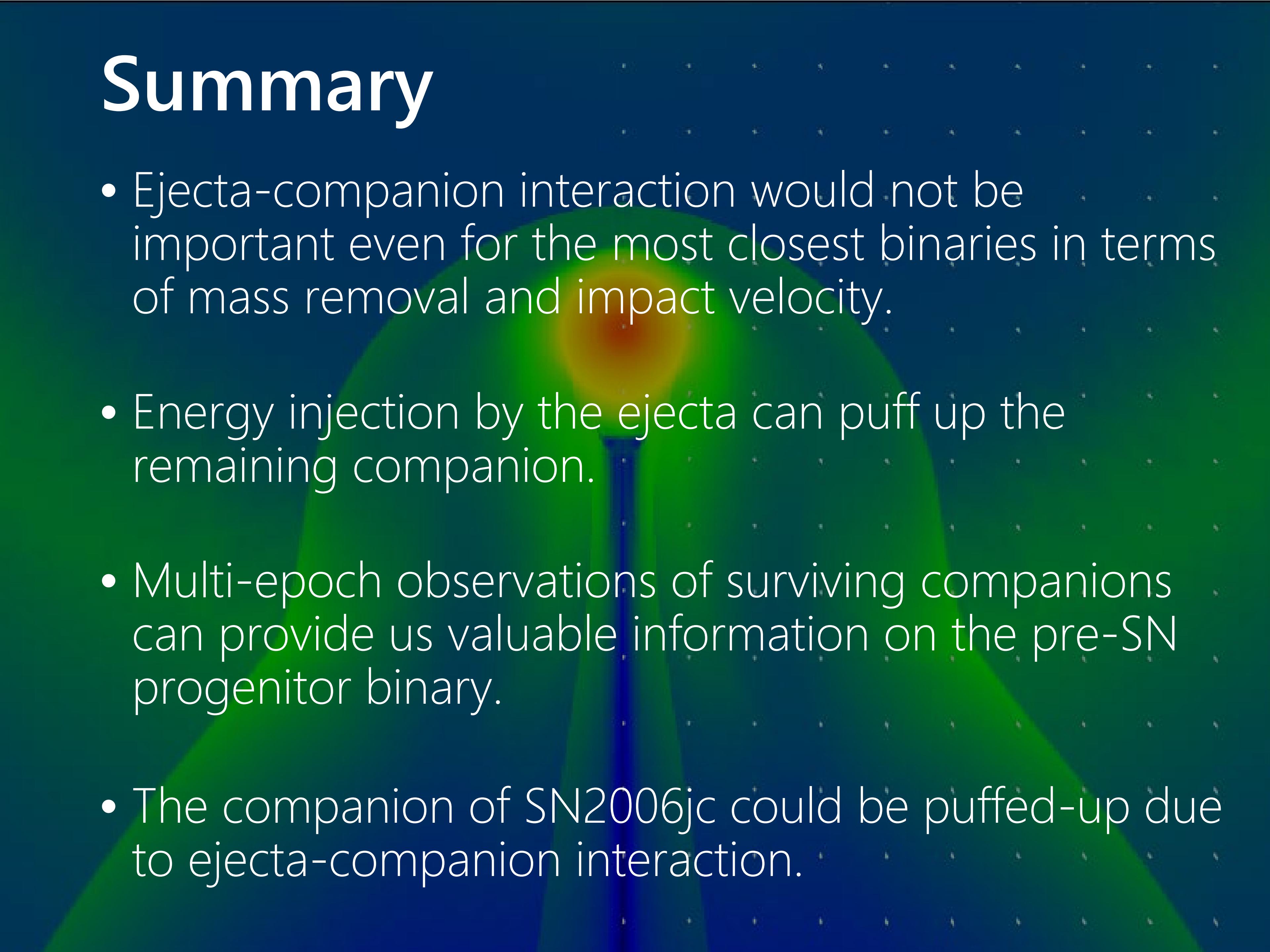
Can ECI explain the weird companion?



Explosion energy: 10^{52} erg
Ejecta mass: 5 Msun
→taken from Tominaga et al. 2008

Multi-epoch observations can strongly constrain pre-SN binary parameters

Summary



- 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.
- Multi-epoch observations of surviving companions can provide us valuable information on the pre-SN progenitor binary.
- The companion of SN2006jc could be puffed-up due to ejecta-companion interaction.