LUNDS UNIVERSITET

Cosmic explosions from compact binaries

Ross Church
Department of Astronomy and Theoretical Physics
Lund University

Collaborators include: Melvyn B. Davies (Lund), Andrew Levan (Warwick), Nial Tanvir (Leicester), Chris Tout (Cambridge)

Overview

Single star evolution

Physical processes in binary evolution

Explosions from compact binaries:

- Short-duration gamma-ray bursts

  Church et al. (2011) *MNRAS* **413** 204

- Long-duration gamma-ray bursts

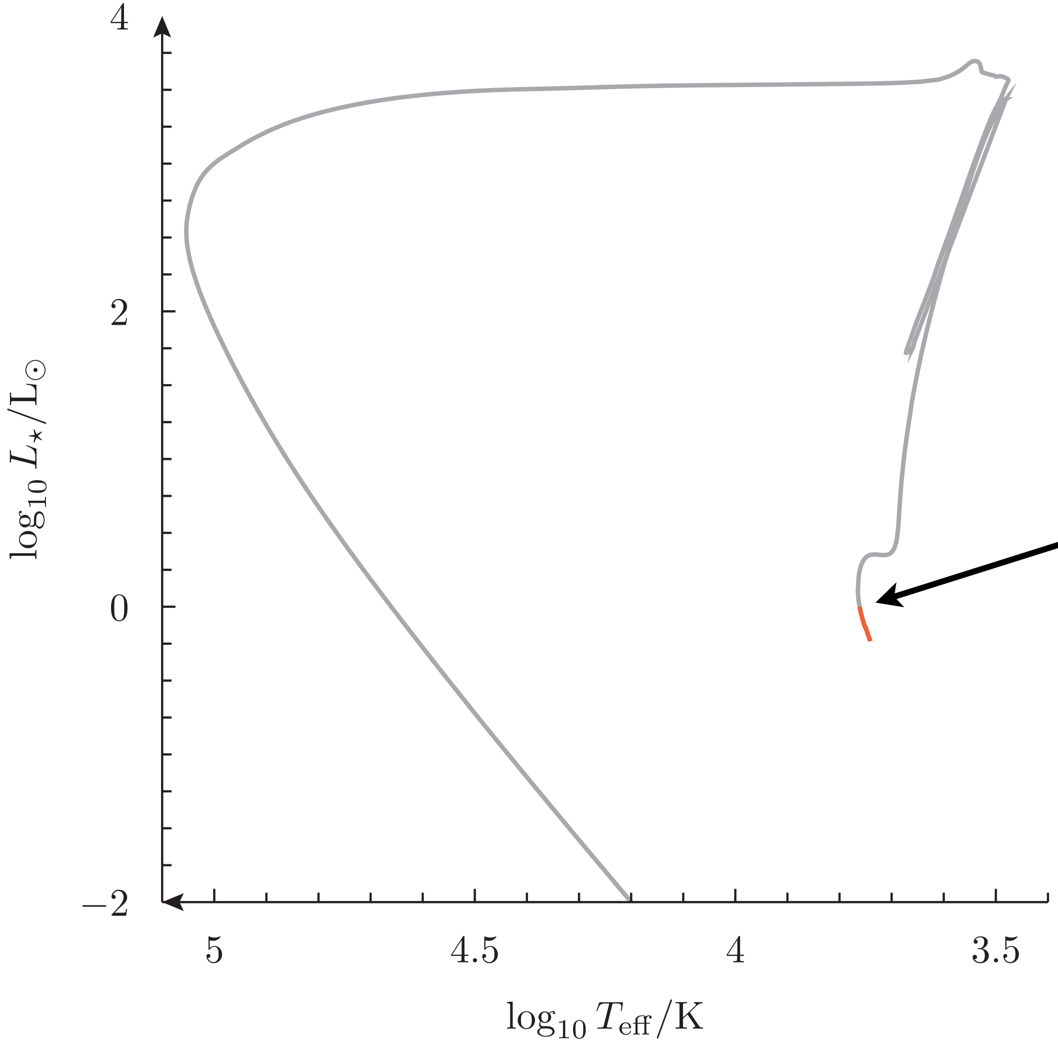
  Church et al. (2012) *MNRAS* **425** 470

- Calcium-rich optical transients

  Church et al. in prep.

Evolution of single, low-mass stars

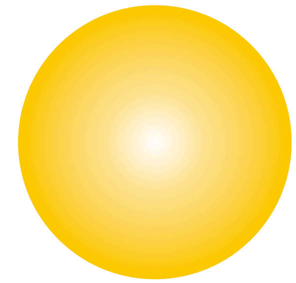
E.g. the Sun



Today:

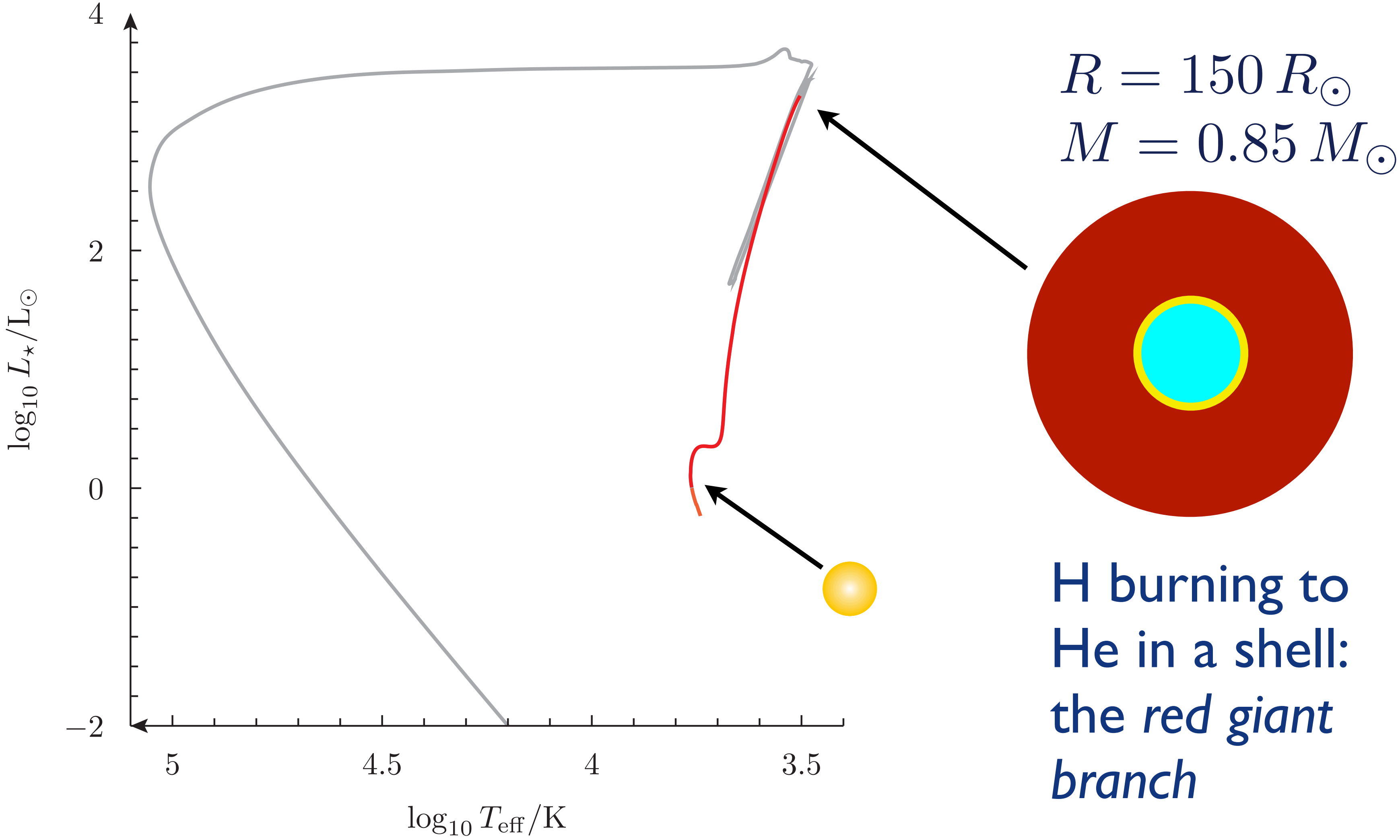
$R = R_\odot$

$M = M_\odot$



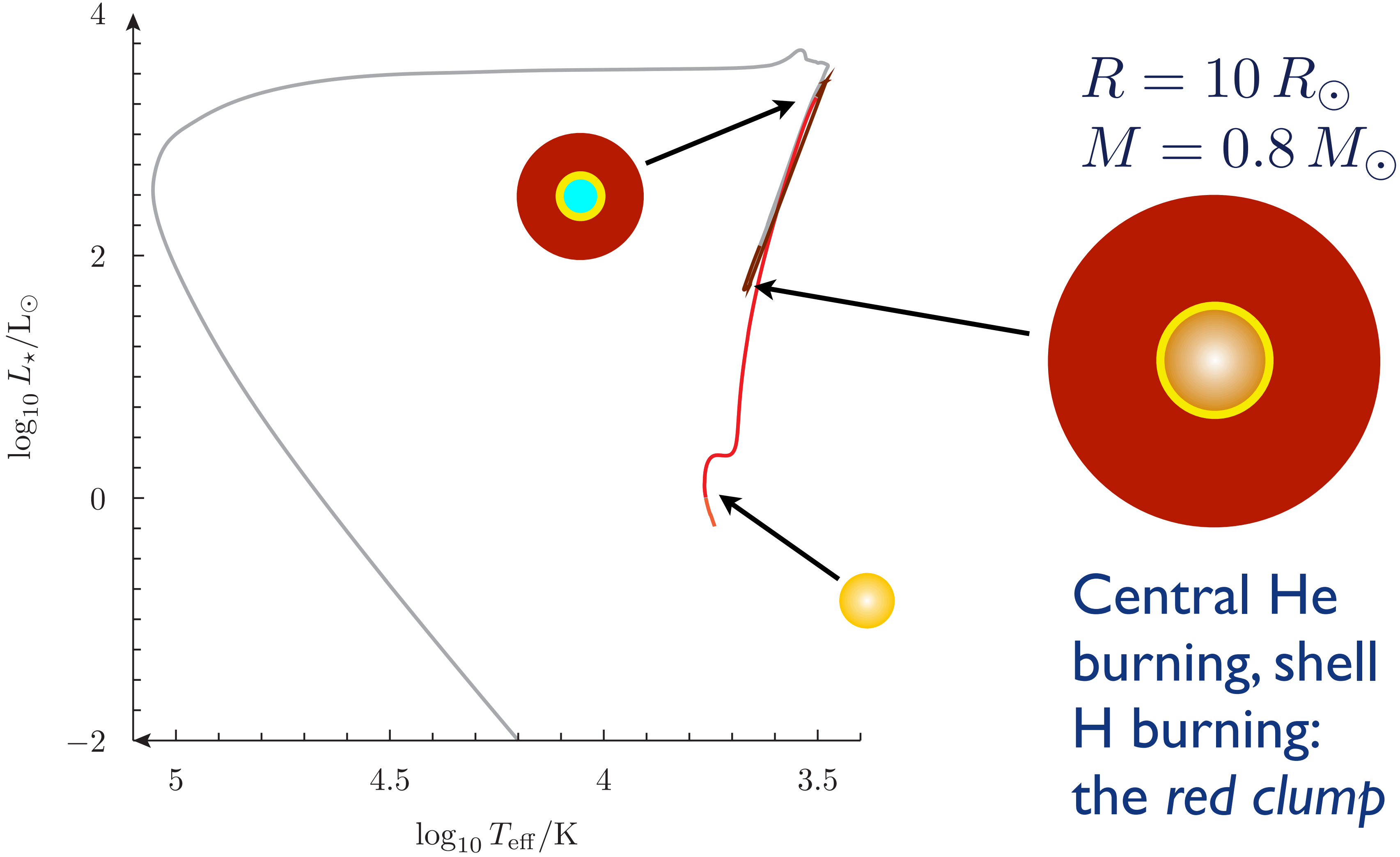
H burning to He at the centre: the *main sequence*

Evolution of the Sun



H burning to He in a shell: the *red giant branch*

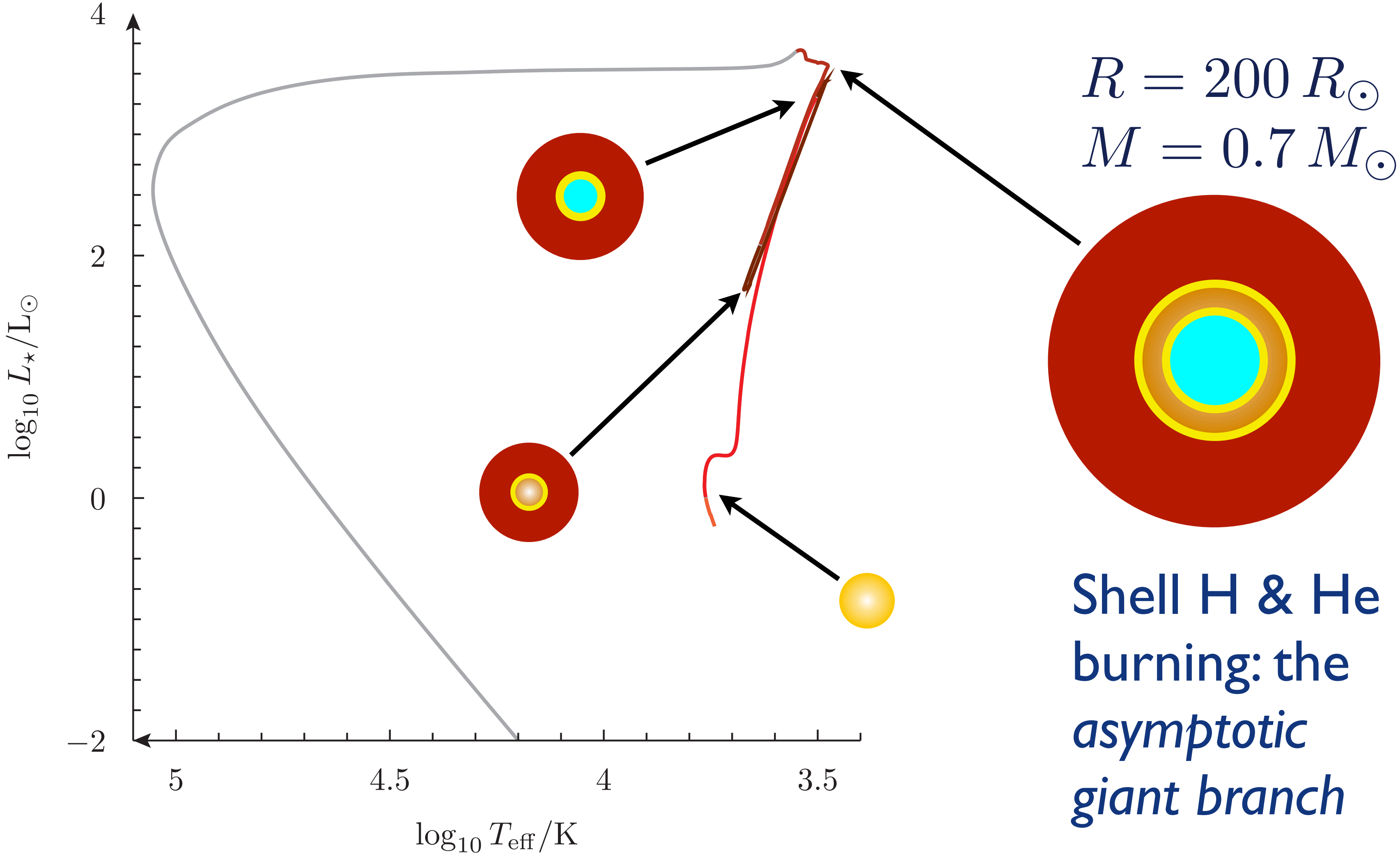
Evolution of the Sun



$R = 10\,R_\odot$
$M = 0.8\,M_\odot$

Central He burning, shell H burning: the *red clump*

Evolution of the Sun

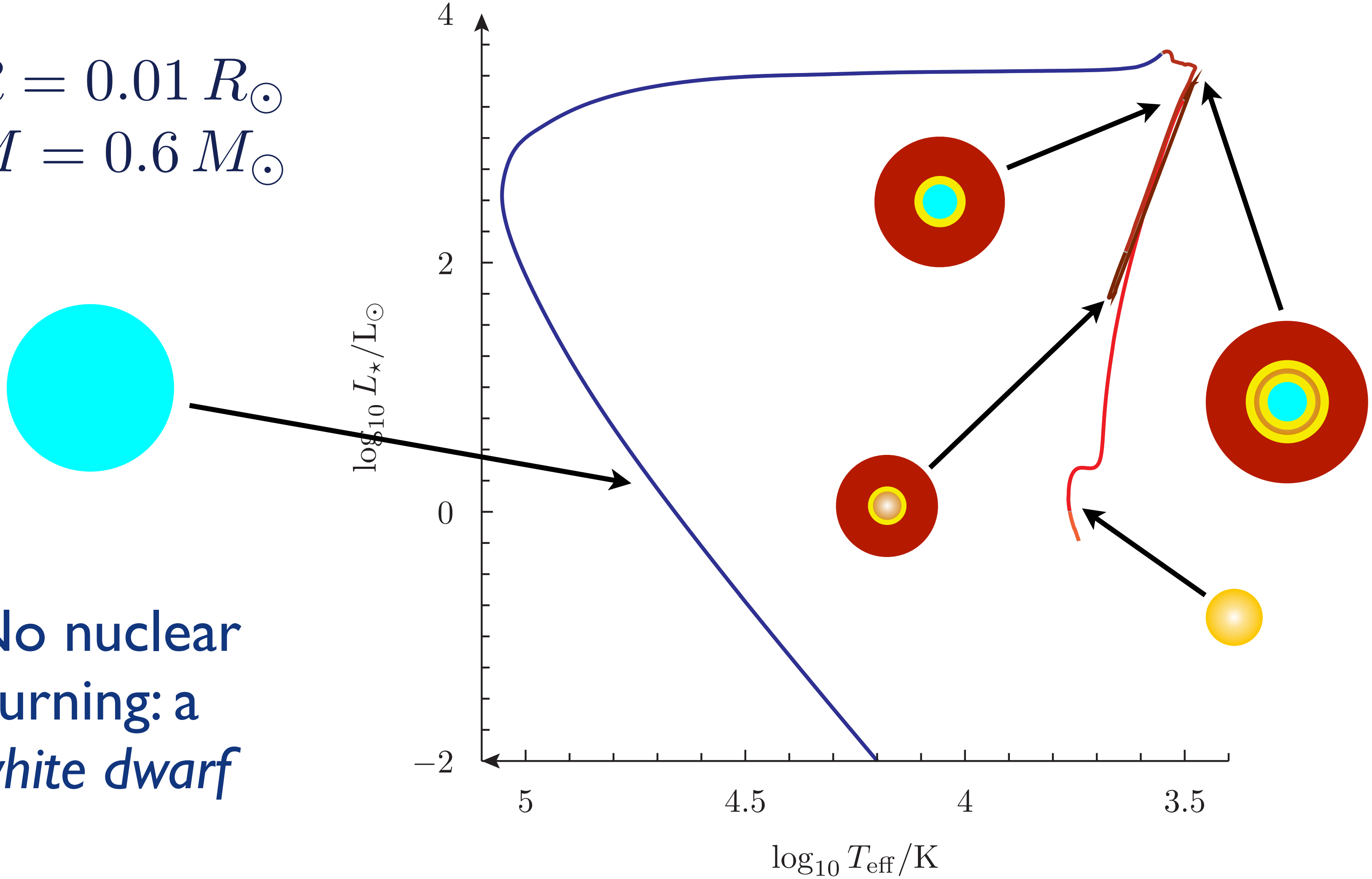


$R = 200\, R_\odot$
$M = 0.7\, M_\odot$

Shell H & He burning: the *asymptotic giant branch*

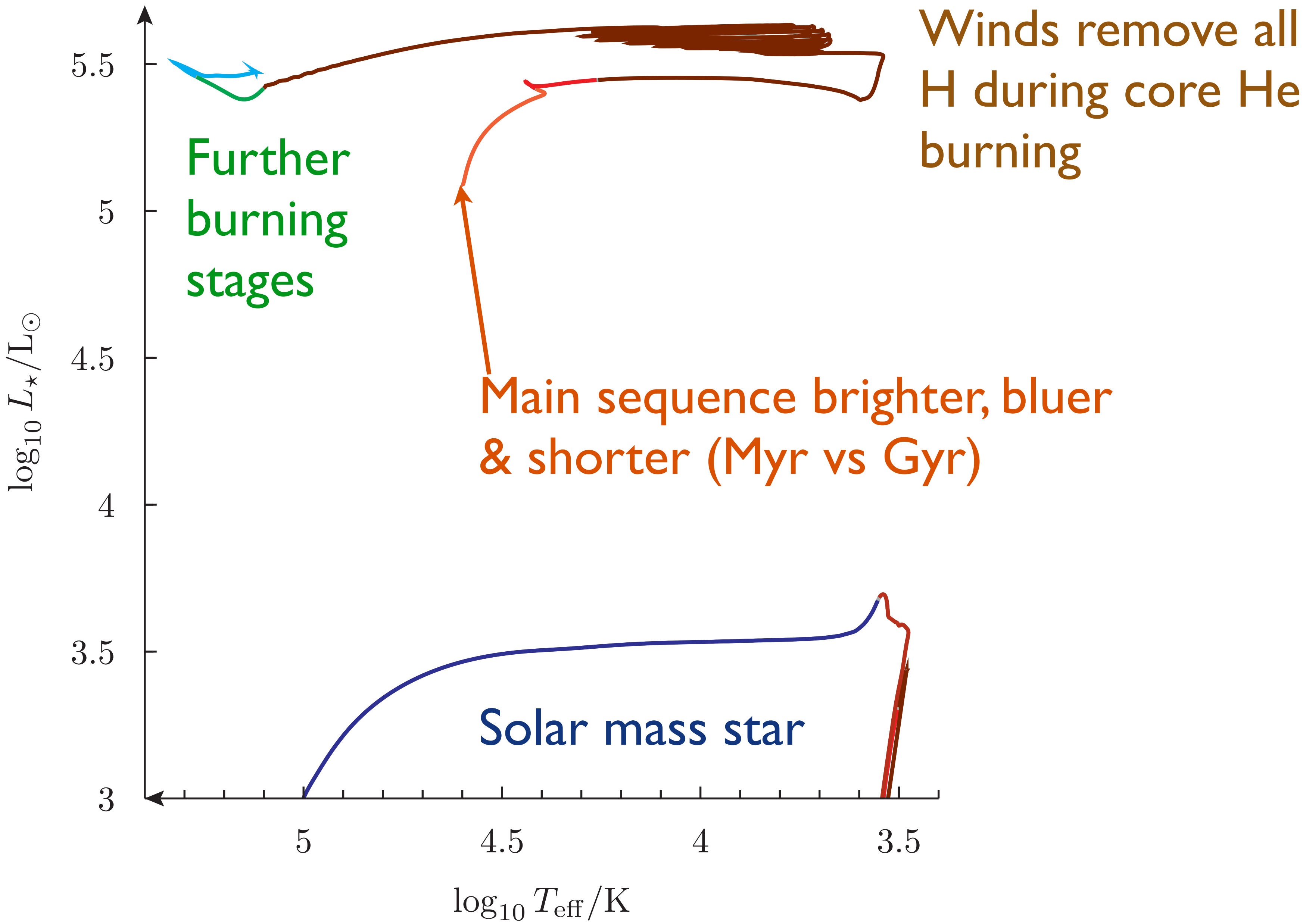
Evolution of the Sun

$R = 0.01\, R_\odot$
$M = 0.6\, M_\odot$

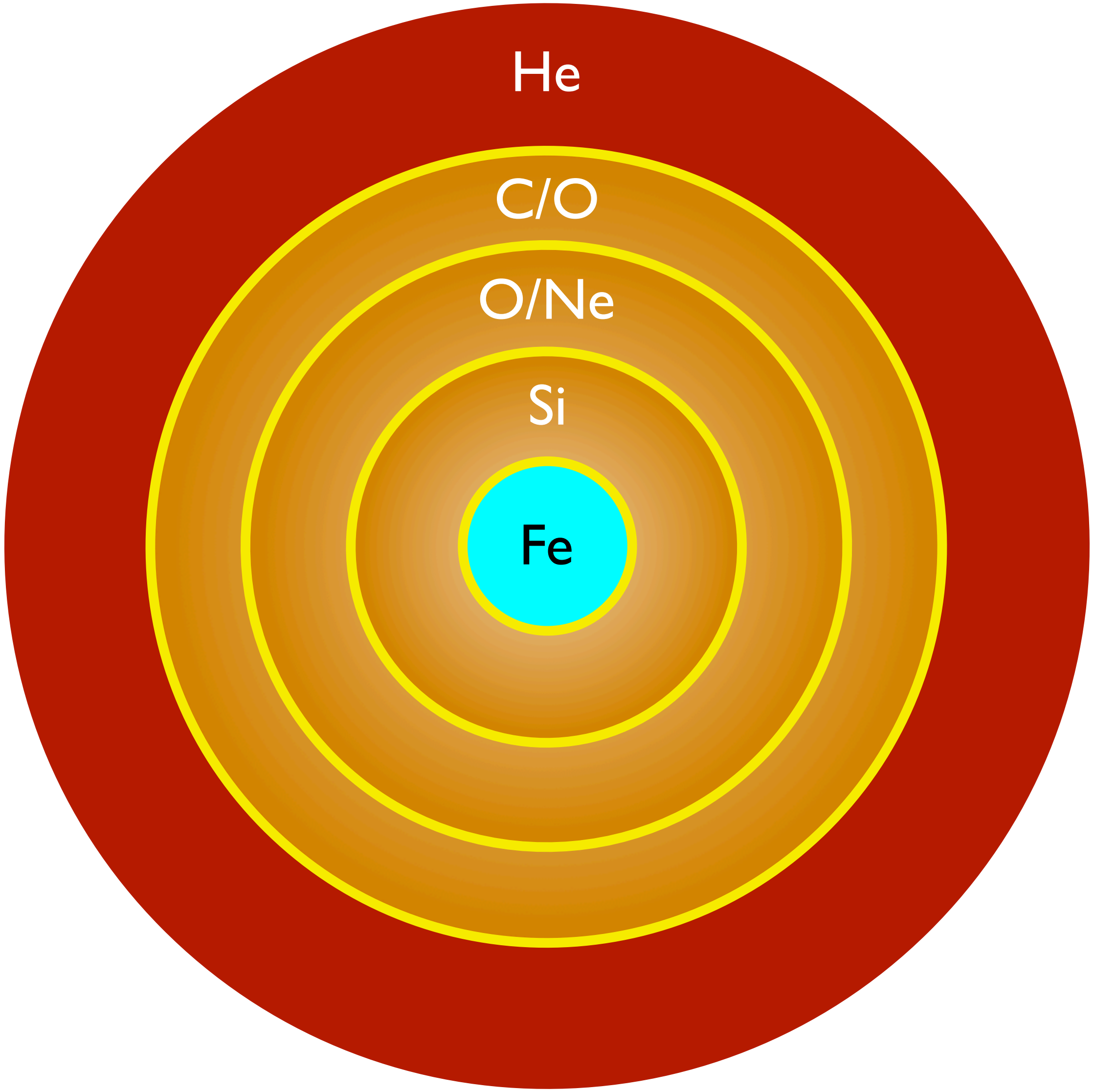


No nuclear burning: a *white dwarf*

Evolution of a massive star



The end of a massive star

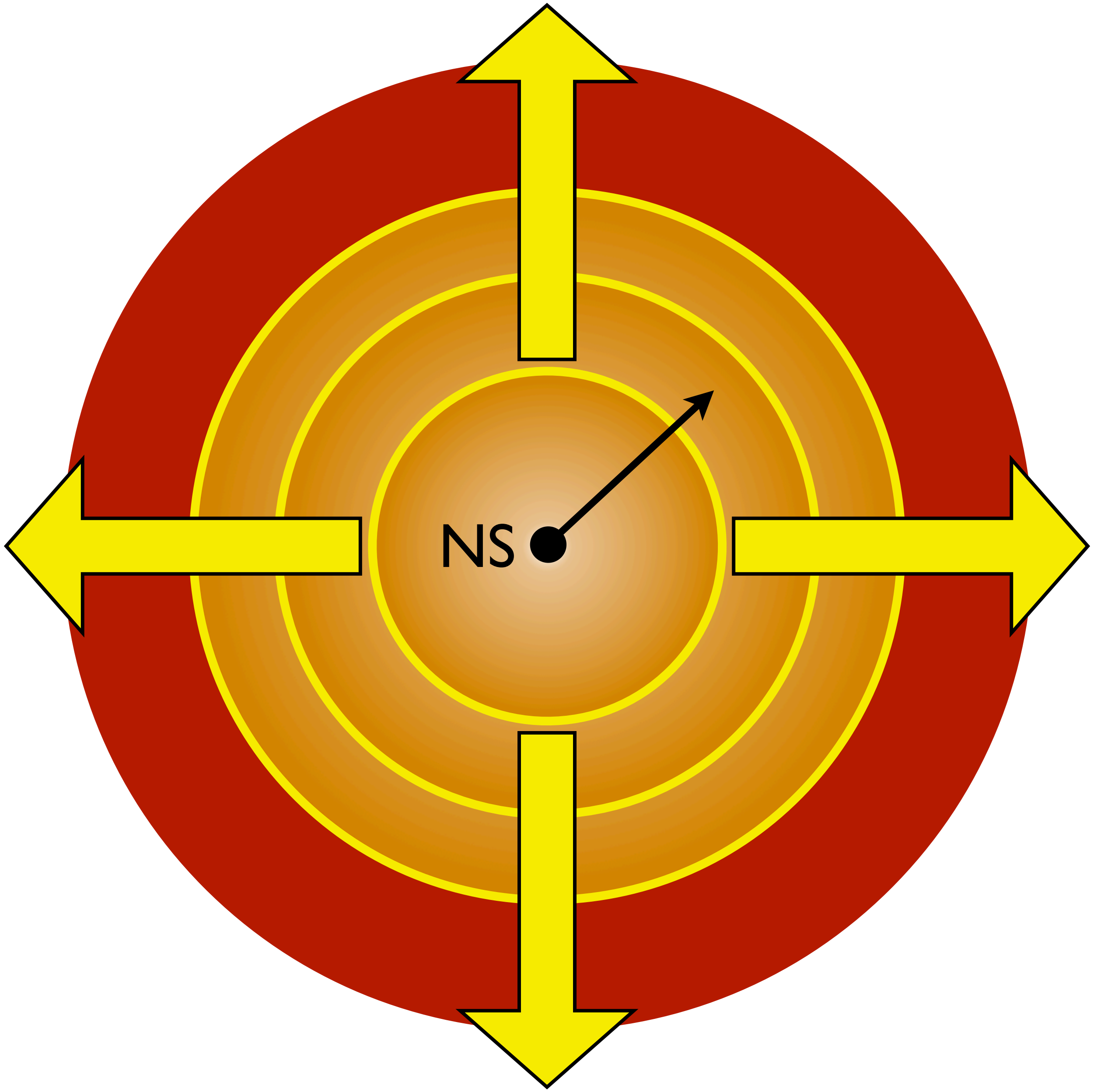


Nuclear reactions ultimately produce iron at the centre.

Once 1.44 solar masses of iron has accumulated the core collapses into a neutron star.

Some stars - probably the most massive - produce black holes instead of neutron stars.

The end of a massive star



The collapse releases gravitational energy, which expels the star's outer layers.

An asymmetric explosion causes the neutron star (NS) to receive a velocity *kick* of 100-1000 km/s.

Binaries

About 80% of solar-like stars are in a binary (a gravitationally bound pairs of stars orbiting their common centre of mass). Duquennoy & Mayor (1991)

80-100% of massive stars are in binaries.

e.g. Kiminki & Kobulniki (2012)

About 70% of high-mass (O-type) stars interact significantly with their companion. Sana et al. (2013)

Only 50% of low-mass (M-type) stars are in binaries (but low-mass stars are not very interesting).

Marchal et al. (2003)

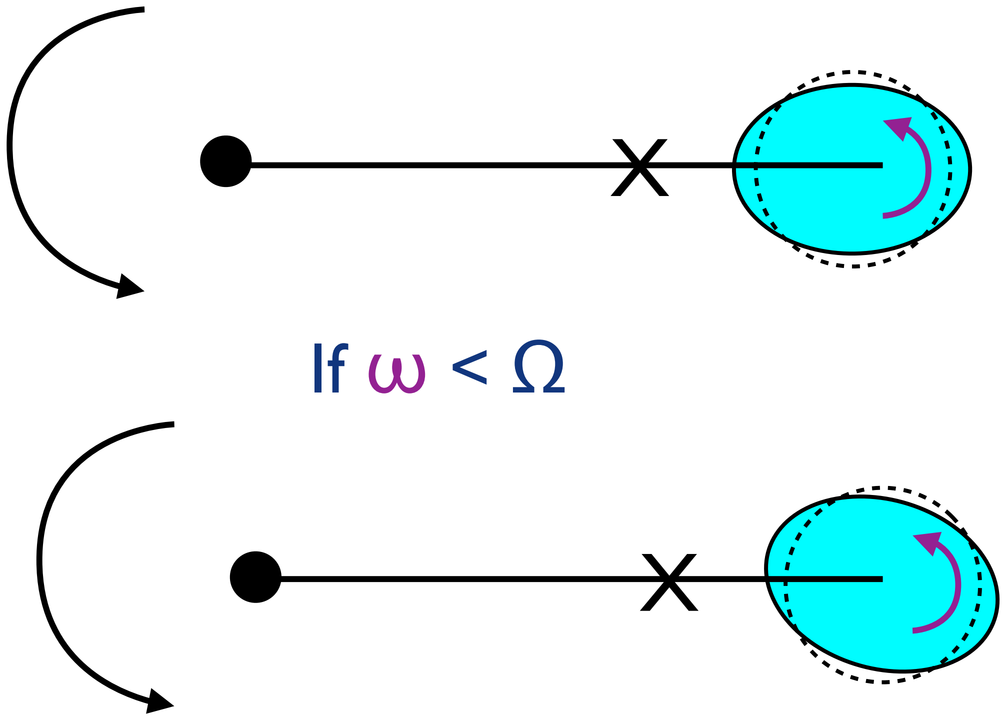
Four additional processes in binaries

1. Tidal interactions
2. Mass transfer
3. Common envelope evolution
4. Gravitational radiation

1. Tidal interactions

In a close binary, tidal forces from one star will raise a bulge on the surface of the other.

Orbital angular frequency Ω



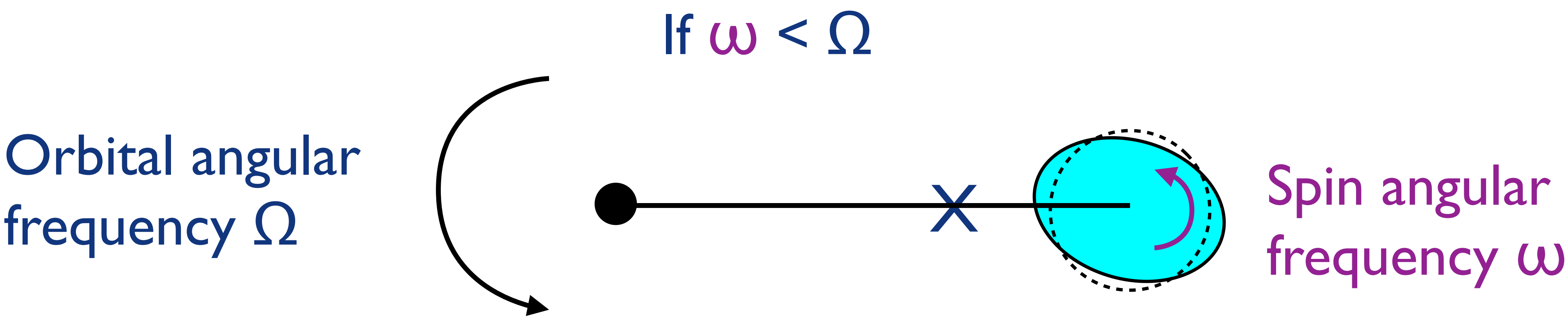
Spin angular frequency ω

If $\omega < \Omega$

The torque on the tidal bulge transfers angular momentum between the orbit and star. This can spin the star up.

1. Tidal interactions

Tides can transfer angular momentum and spin a star up.

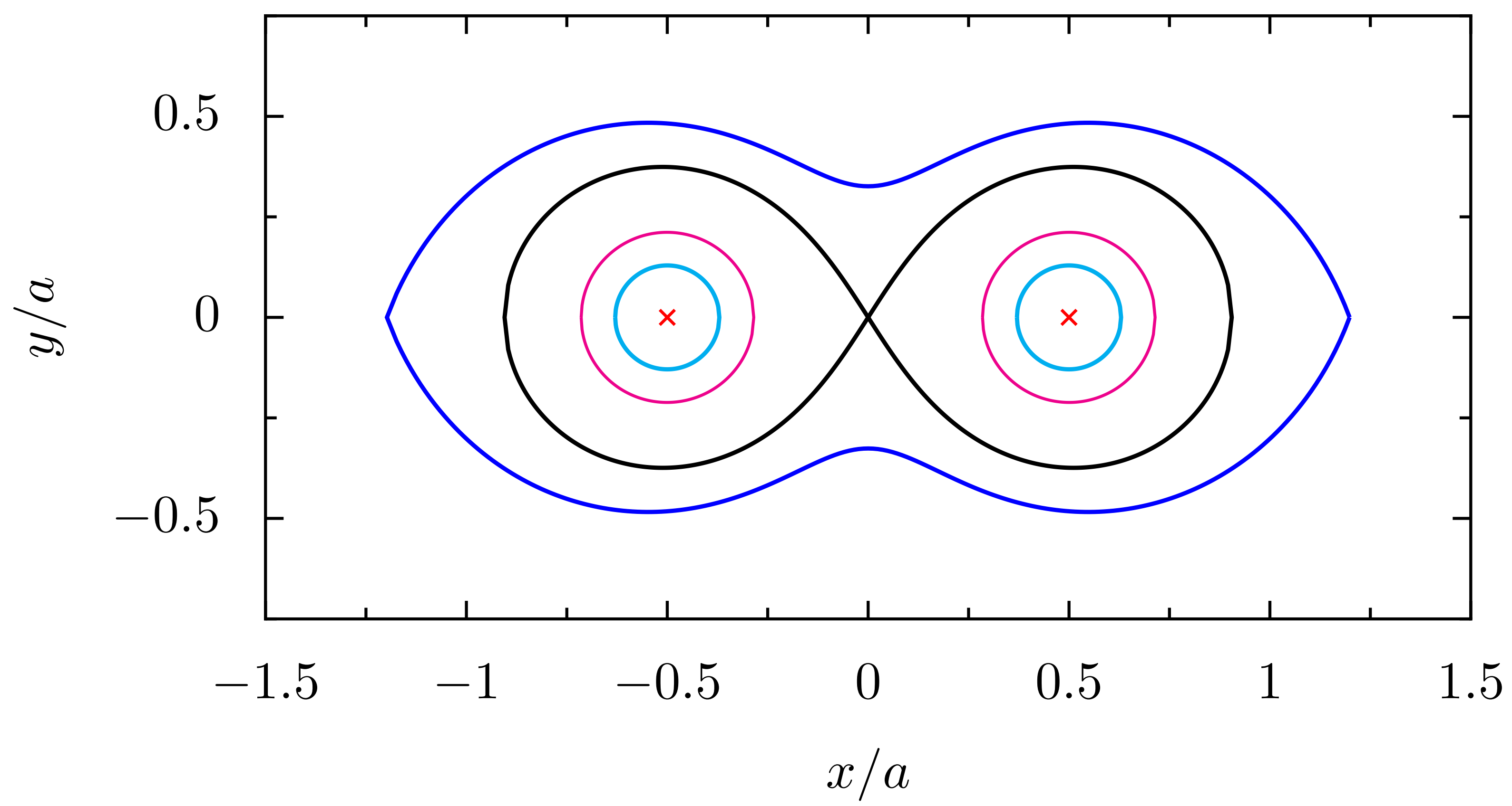


$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = f(\text{structure}, q)\left(\frac{R}{a}\right)^6(\Omega - \omega)$$

Tides are only significant in close binaries.

2. Mass transfer

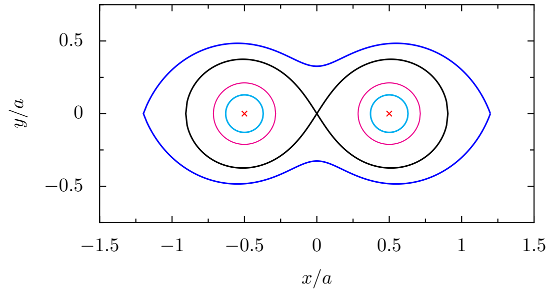
The Roche Lobe is the equipotential surface connecting the two stars in the rotating frame

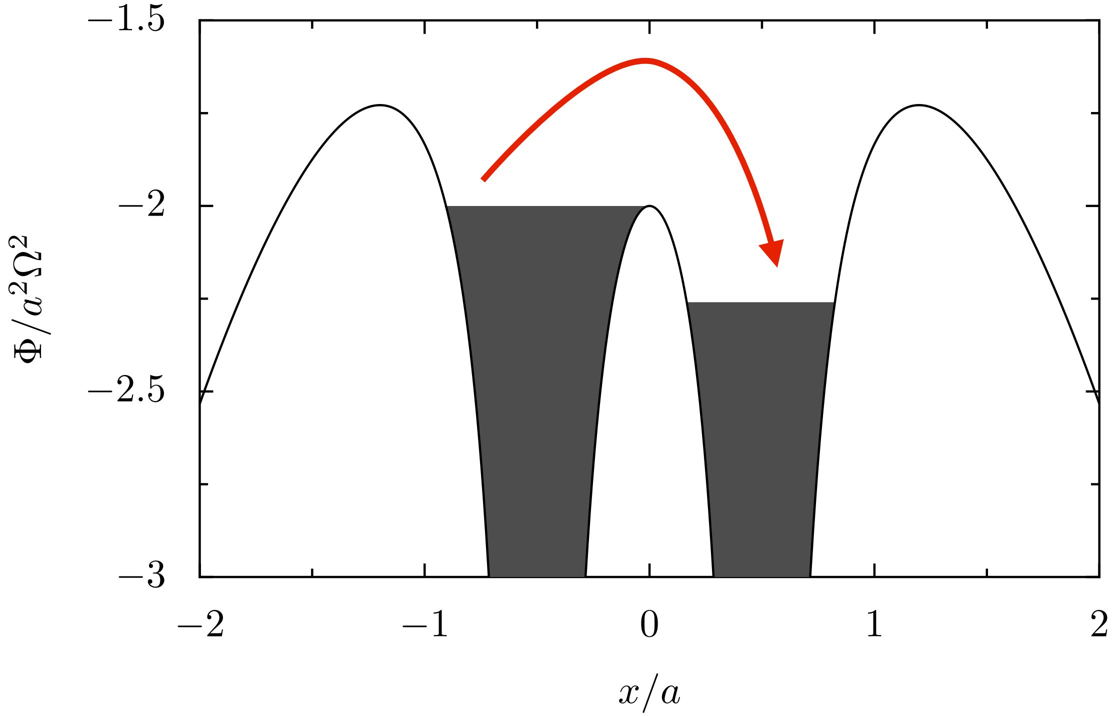


2. Mass transfer

When a star expands to fill its Roche lobe, mass transfers to its companion.

Steady mass transfer rate keeps the star just inside its Roche Lobe

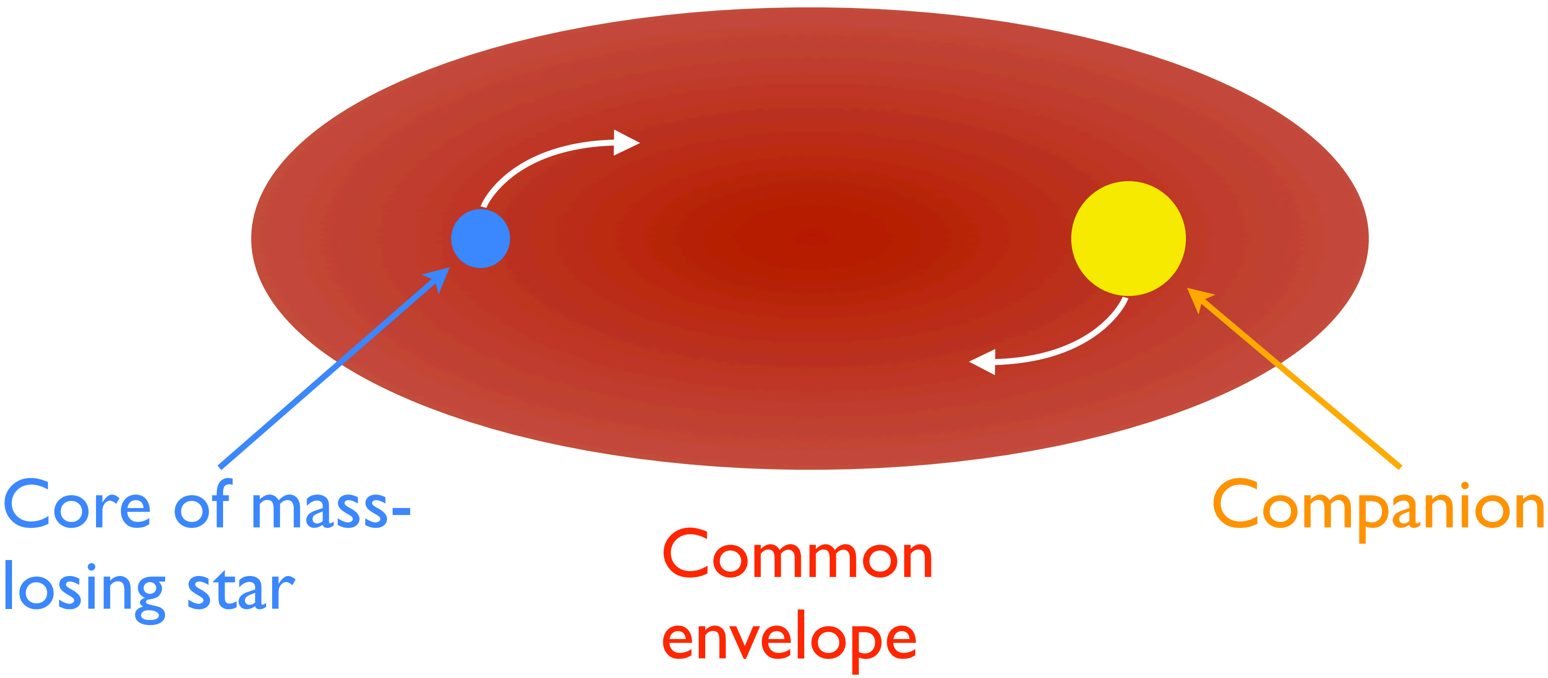




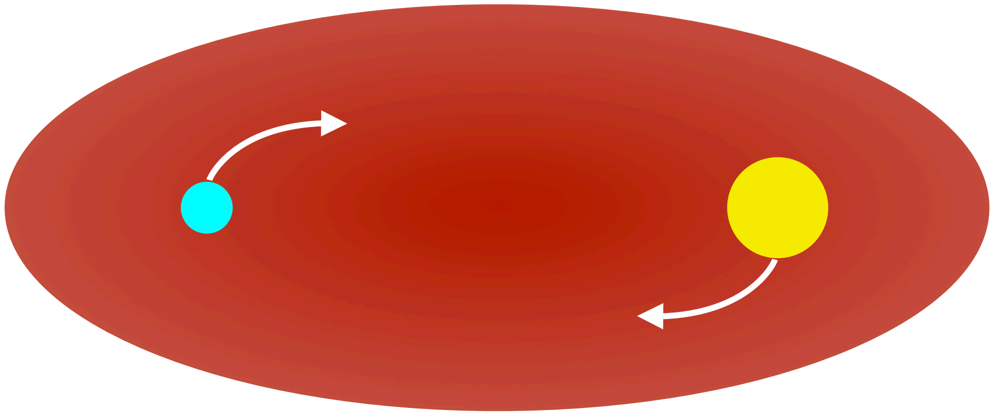
3. Common envelope evolution

If the star expands as it loses mass, the mass transfer accelerates and runs away.

The envelope of the mass-losing star is shredded and surrounds both stars (the common envelope).



3. Common envelope evolution

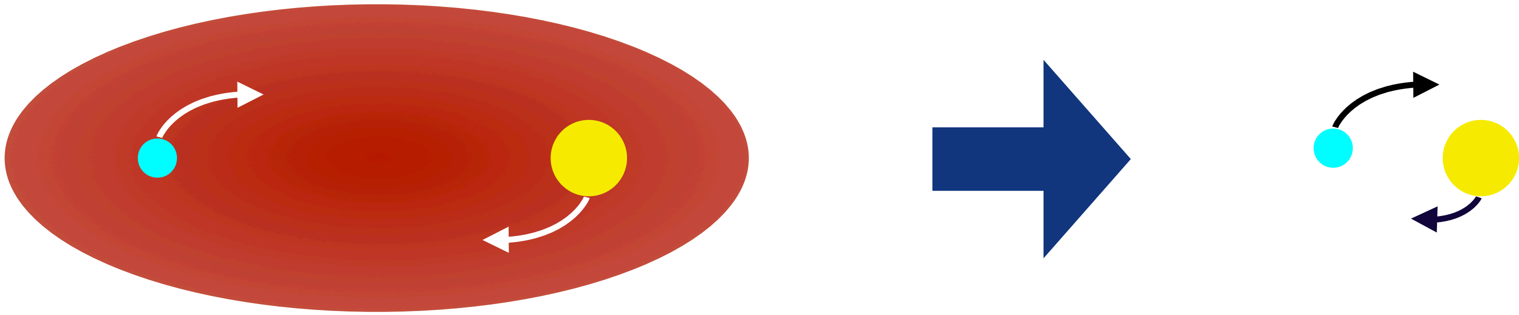


The stars spiral together, driving the envelope off.

A close binary of the mass-losing star's core and the companion is left.

The resulting binary is (much) smaller than the giant star was originally.

3. Common envelope evolution



The existence of common envelope evolution is implied by the observed compact binaries.

All the evidence for this process is indirect: the relationship between initial and final orbits is uncertain.

All close, evolved binaries must have undergone some form of interaction.

4. Gravitational radiation

Stars orbiting one another emit gravitational radiation.

This carries angular momentum away and ultimately the stars merge.

$$\tau_{\rm merge} = 150\,{\rm Myr} \left(\frac{a}{R_\odot}\right)^4 \left(\frac{M_{\rm tot}}{M_\odot}\right)^{-2} \frac{M_\odot}{\mu} (1-e^2)^{7/2}$$

Gravitational radiation is only significant for close binaries.

Gamma-ray bursts

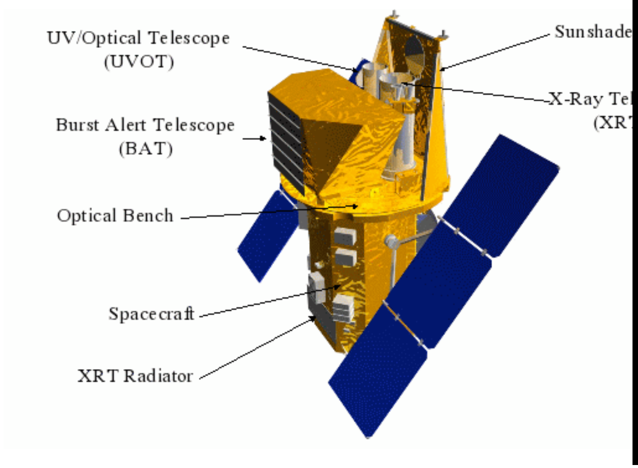
"GRBs"

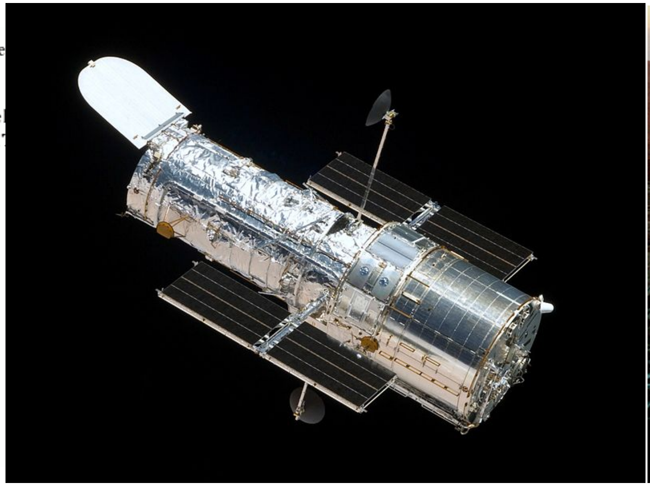
Gamma-ray bursts

Observation: a bright flash of gamma-rays, lasting for typically a few seconds, detected by space telescopes.

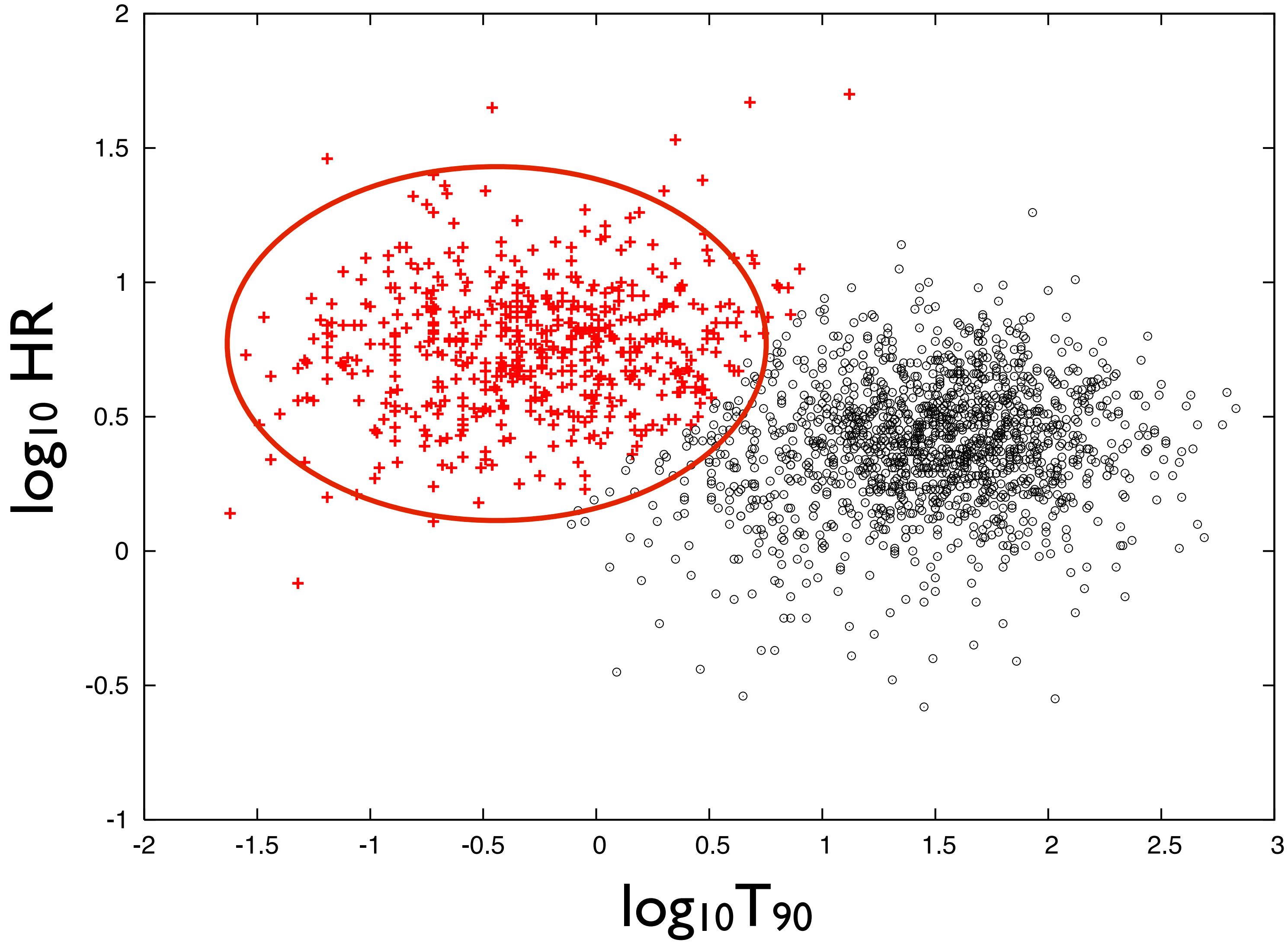
Followed by: an afterglow, which fades and reddens through X-rays, visible & IR to radio. Need to detect rapidly in X-rays and follow up from ground and space.

Energetics suggest that we are seeing the birth of an accreting, rapidly-rotating black hole.



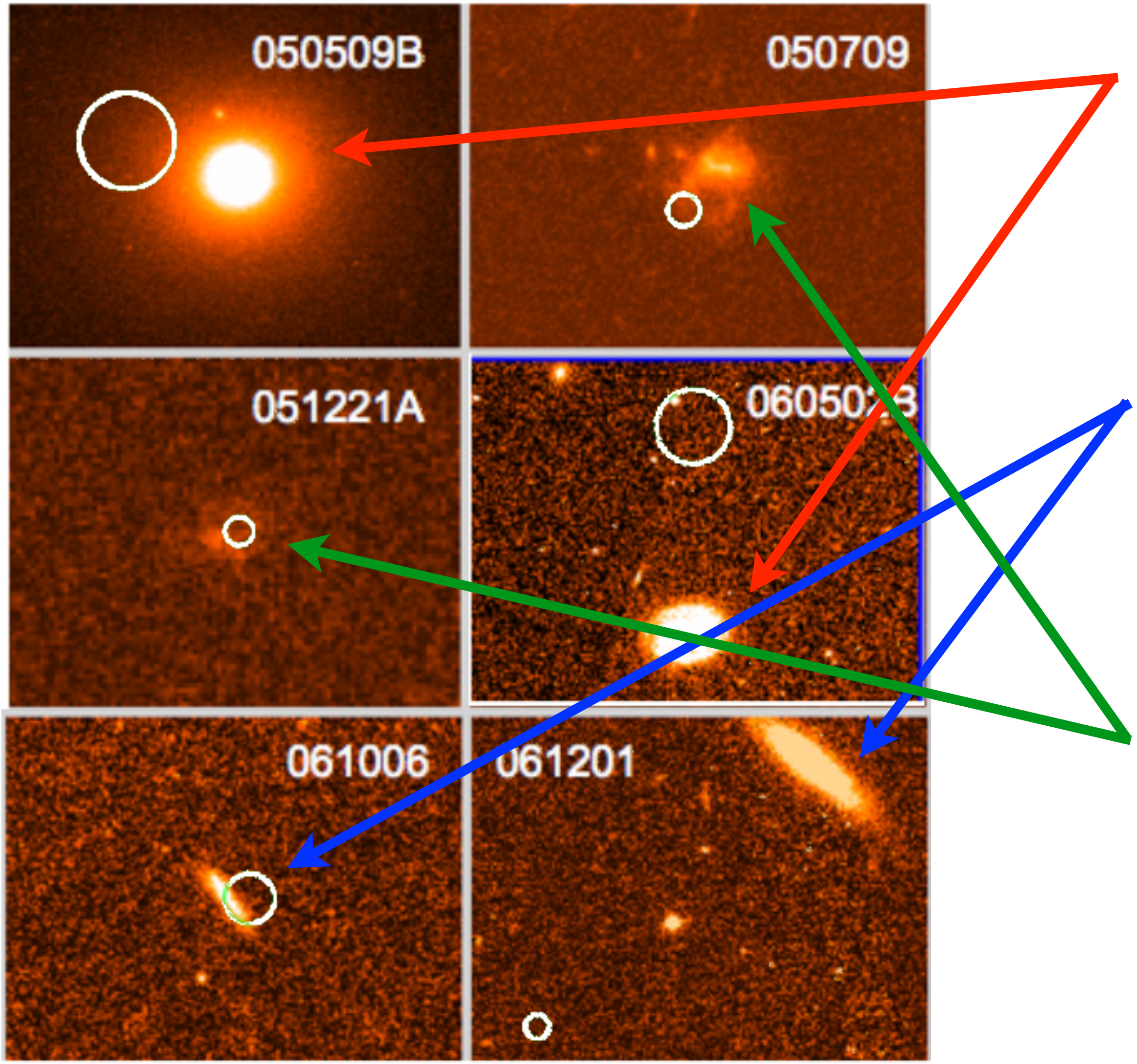


Short vs. long bursts



(Kouveliotou et al. 1993; figure adapted from Horváth et al. 2006)

Short burst environments



Elliptical galaxies

Spiral galaxies

Irregular galaxies

Localisations from the Swift satellite

See Fong et al. (2013) for a recent compilation

Host galaxies constrain progenitors

Bursts seen associated with elliptical galaxies

⇒ progenitor can be old (not a massive star)

Bursts seen outside galaxies (not correlated with light)

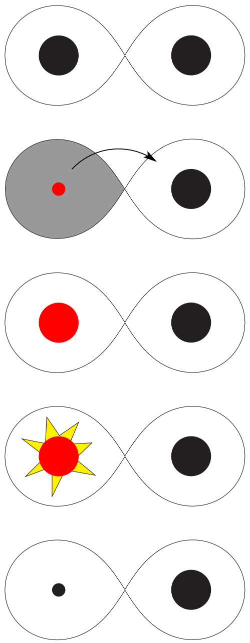
⇒ progenitor moves significantly from birthplace

Bursts are short and hard (high-energy photons)

⇒ progenitor is relatively compact

This evidence points to an origin in a compact binary merger

Typical evolutionary pathway



Initial main sequence–main sequence binary

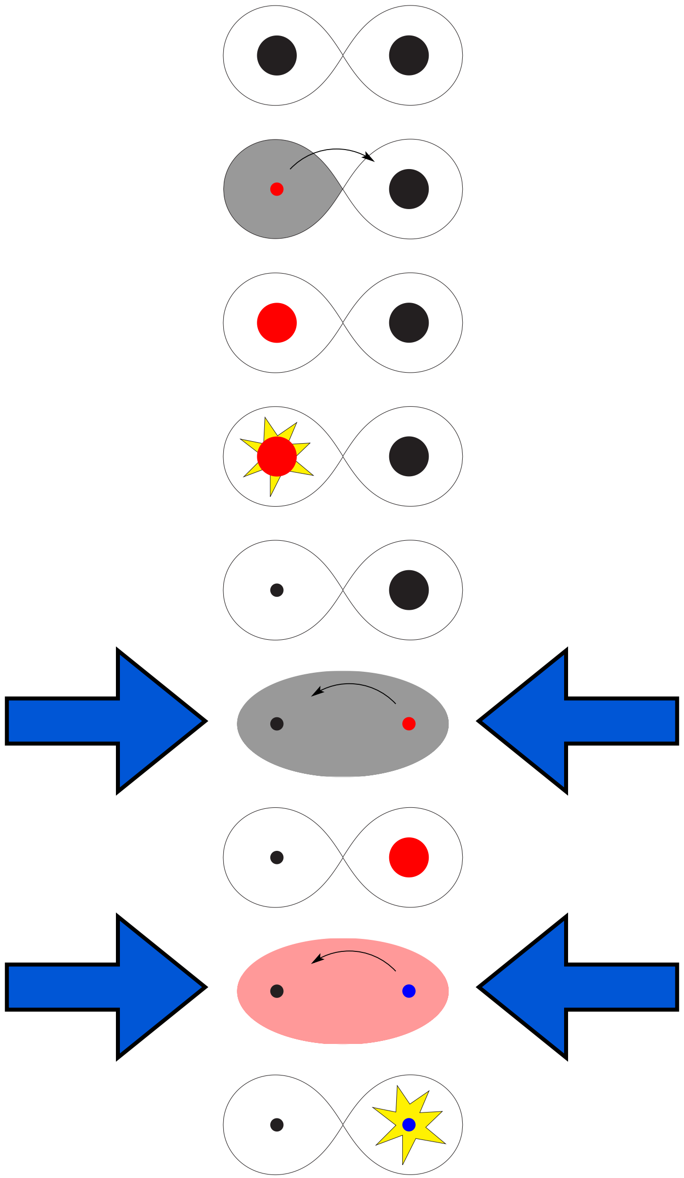
Stable mass transfer from primary

Helium star–main sequence star binary

First supernova

Neutron star–main sequence star binary

Typical evolutionary pathway



Initial main sequence–main sequence binary

Stable mass transfer from primary

Helium star–main sequence star binary

First supernova

Neutron star–main sequence star binary

Common envelope evolution

Close neutron star–helium star binary

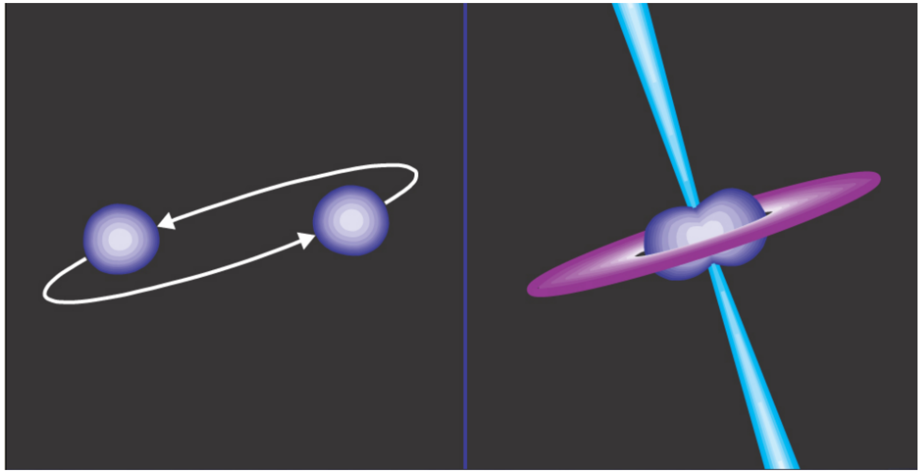
Common envelope evolution (round 2)

Final supernova

Compact binary model for GRBs

The stars evolve into a close double neutron star binary.

The binary emits gravitational waves. This drives the neutron stars together until they merge.



Observed properties:

Old: gravitational wave inspiral can be very slow

Offsets: the supernovae produce a kick

Compact: the neutron stars are small (~20 km)

See Church et al. (2011) *MNRAS* **413** 204 for more details

Long-duration gamma-ray bursts

Long gamma-ray bursts: observations

Longer-lasting emission, softer spectrum, higher fluence

Found in star-forming regions out to very high redshift

Many bursts show co-incident Type Ib/Ic supernova

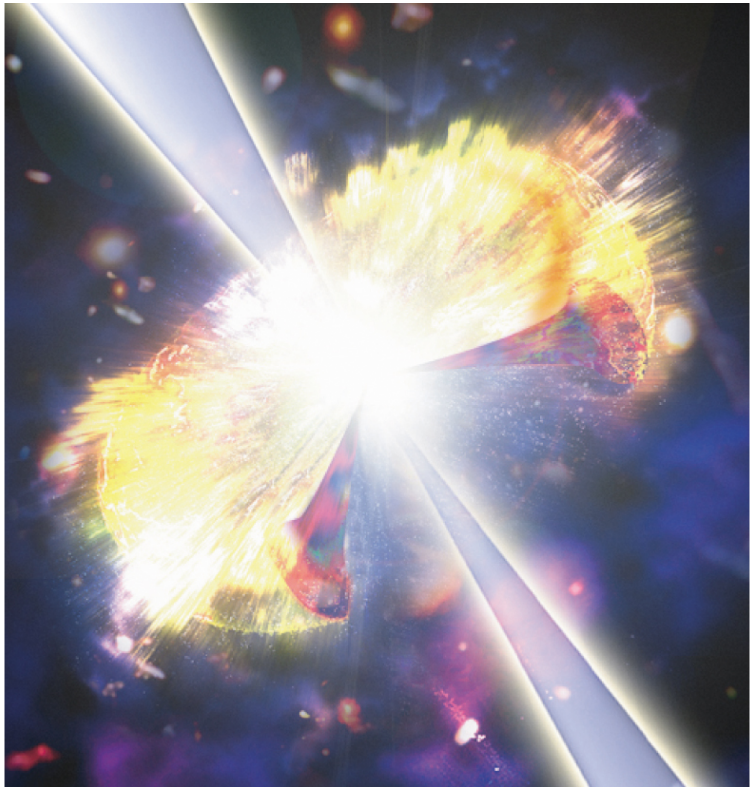
- Type Ibc supernovae show neither H nor Si lines
- Thought to be the outcome of core collapse of massive stars (>40ish solar masses)
- Winds during the stars' lifetimes remove the hydrogen envelopes (and He in the case of Ic)

See Hjorth & Bloom, arXiv 1104.2274, for a review

Long gamma-ray bursts: standard model

A black hole forms from a massive star in a supernova.

Rapid rotation causes some material to fall back into a disc around the newly-formed black hole.



Same mechanism as for short-duration bursts, except for the presence of the star.

Woosley (1993) *ApJ* **405** 273

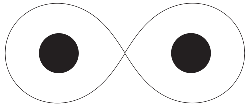
Problem

Strong winds carry off angular momentum
$\Rightarrow$ spins star down

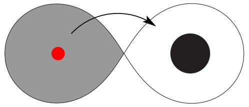
Potential solution

Can a binary companion prevent spin-down?

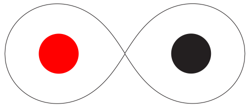
The evolutionary pathway, revisited



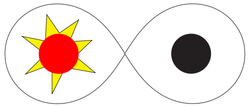
Initial main sequence–main sequence binary



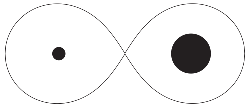
Stable mass transfer from primary



Helium star–main sequence star binary

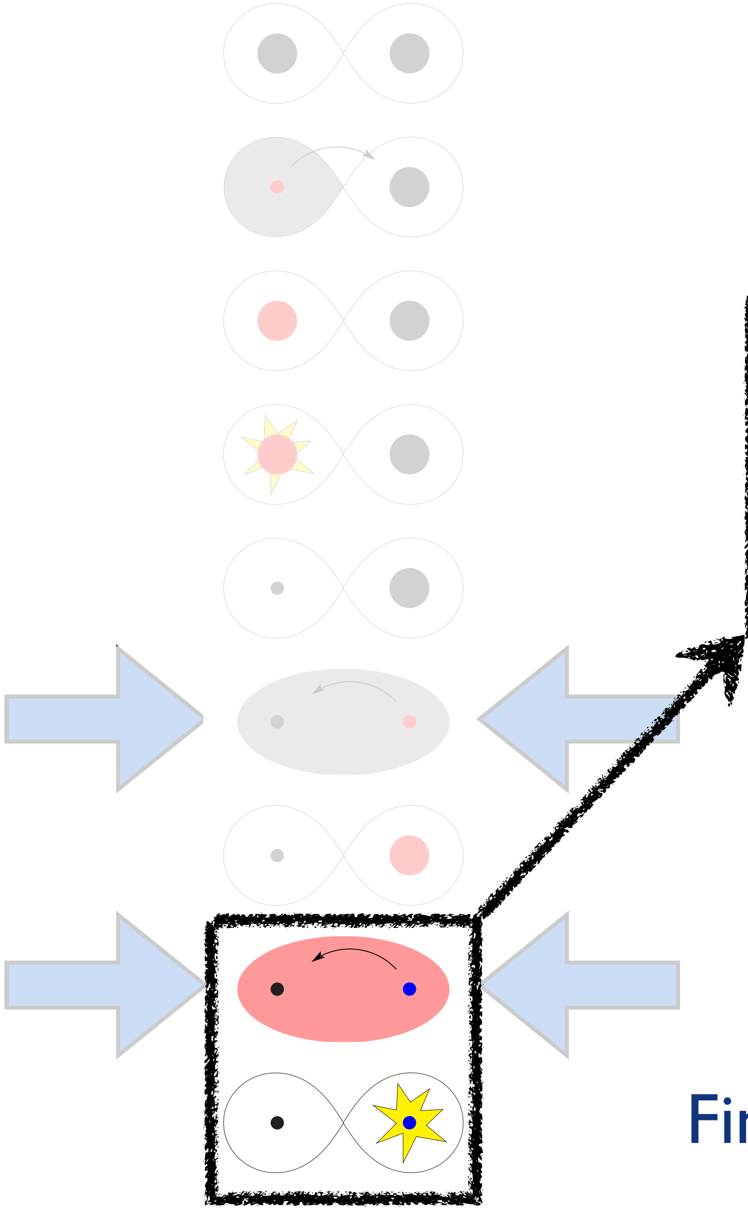


First supernova



Black hole–main sequence star binary

The evolutionary pathway, revisited

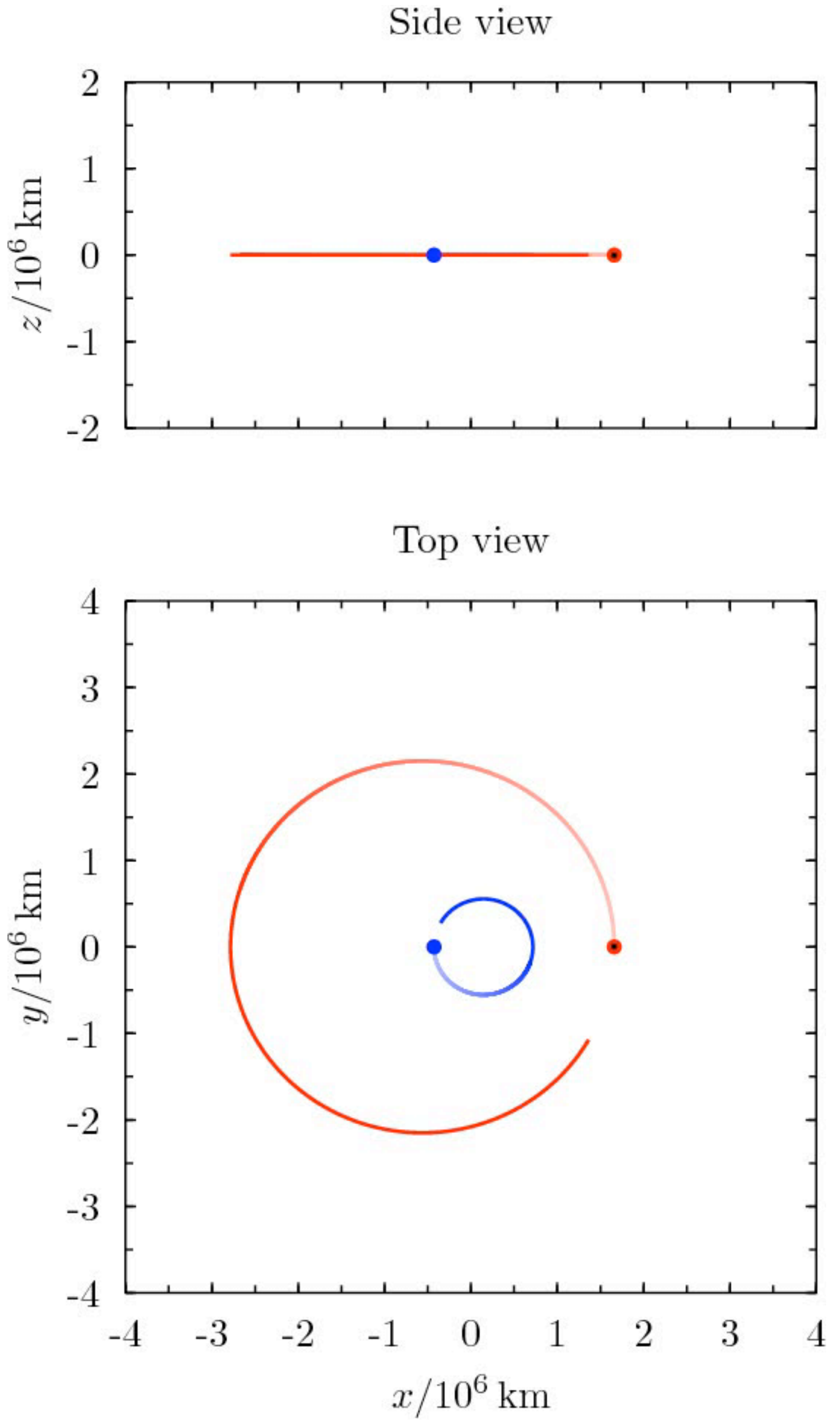


Binary is closest at the end
⇒ Tides can spin the star up before the final supernova

Common envelope evolution (round 2)

Final supernova

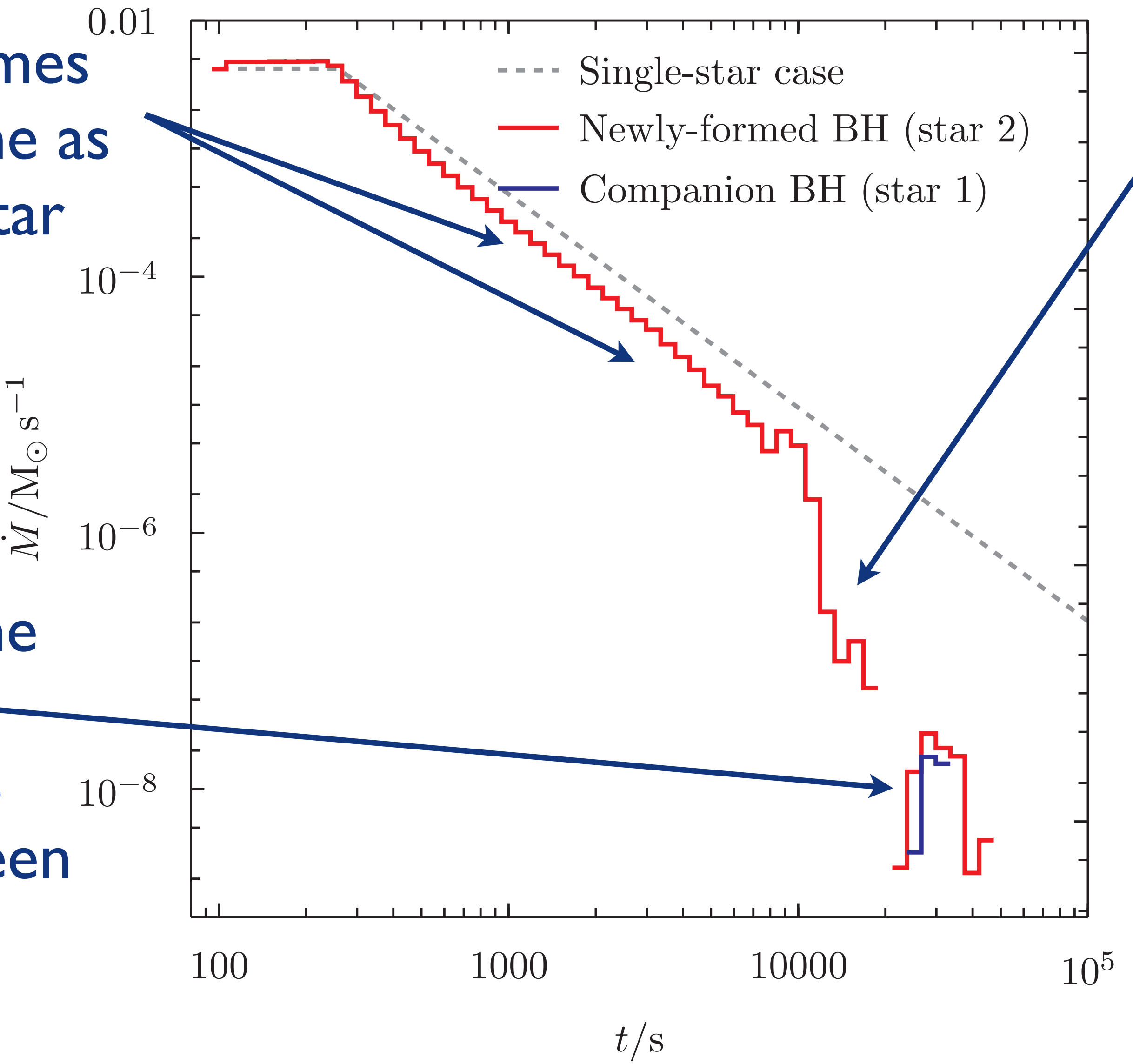
What effect does the companion have?


Side view
2
1
0
-1
-2
$z/10^6$ km
Top view
4
3
2
1
0
-1
-2
-3
-4
$y/10^6$ km
-4
-3
-2
-1
0
1
2
3
4
$x/10^6$ km

Typical accretion curve

Early times the same as single star case

Late-time flare matches those seen in GRBs



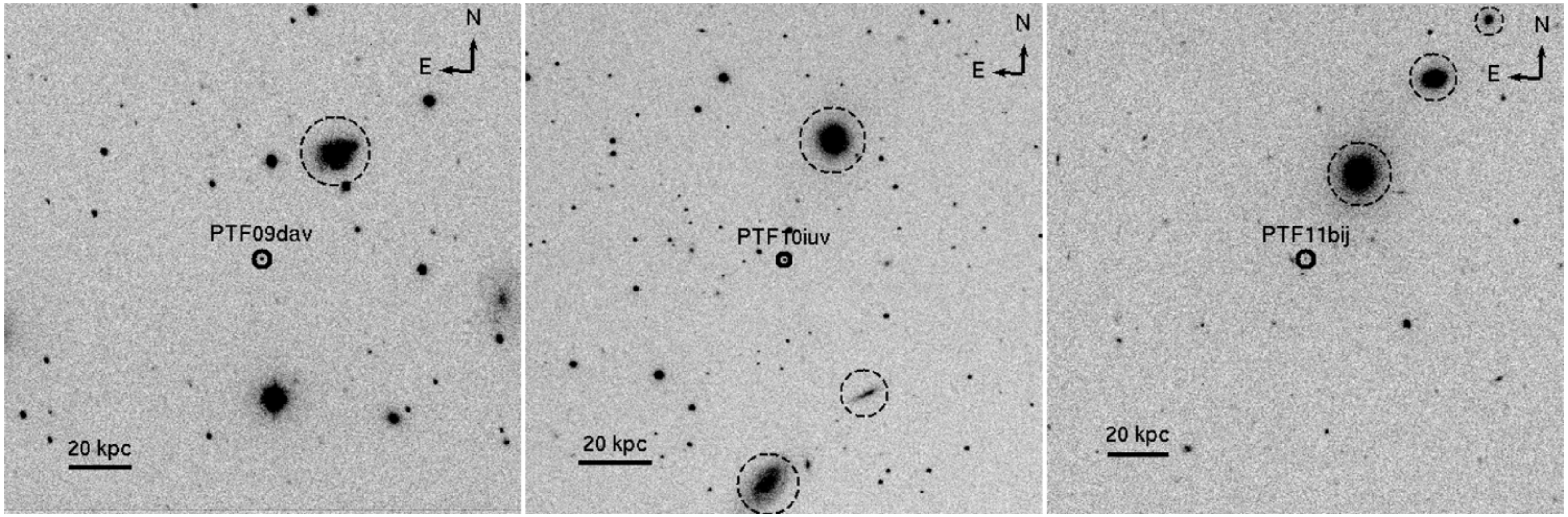
Sharp break from Roche Lobe truncation

Church et al. (2012) *MNRAS* **425** 470

Calcium-rich optical transients

AKA "gap transients"

Gap transients



Luminosities between those of novae and supernovae.

Spectra dominated by calcium.

Offset from the host galaxies.

Kasliwal et al. (2012) *ApJ* **755** 161

Disrupted white dwarf progenitor?

If the mass transfer from a white dwarf to a neutron star is unstable, the white dwarf will be tidally disrupted and form an accretion disc around the neutron star.

Nuclear burning in the accretion disc can produce the observed calcium (Metzger 2012, *MNRAS* **419** 827).

These binaries contain a neutron star. Hence the supernova kick could be responsible for the offset.

Evolutionary pathway

Stars initially of similar mass

White dwarf forms from initially more massive star

Late-time mass transfer shrinks the orbit

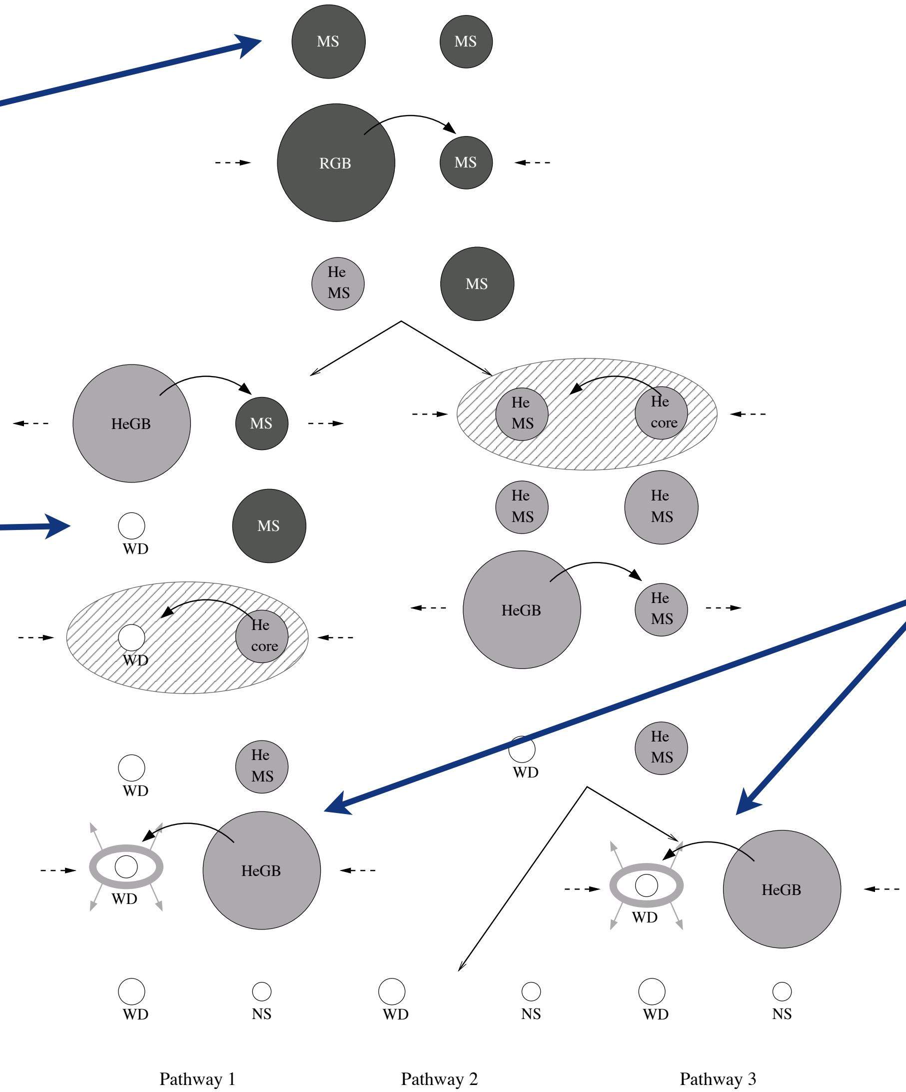
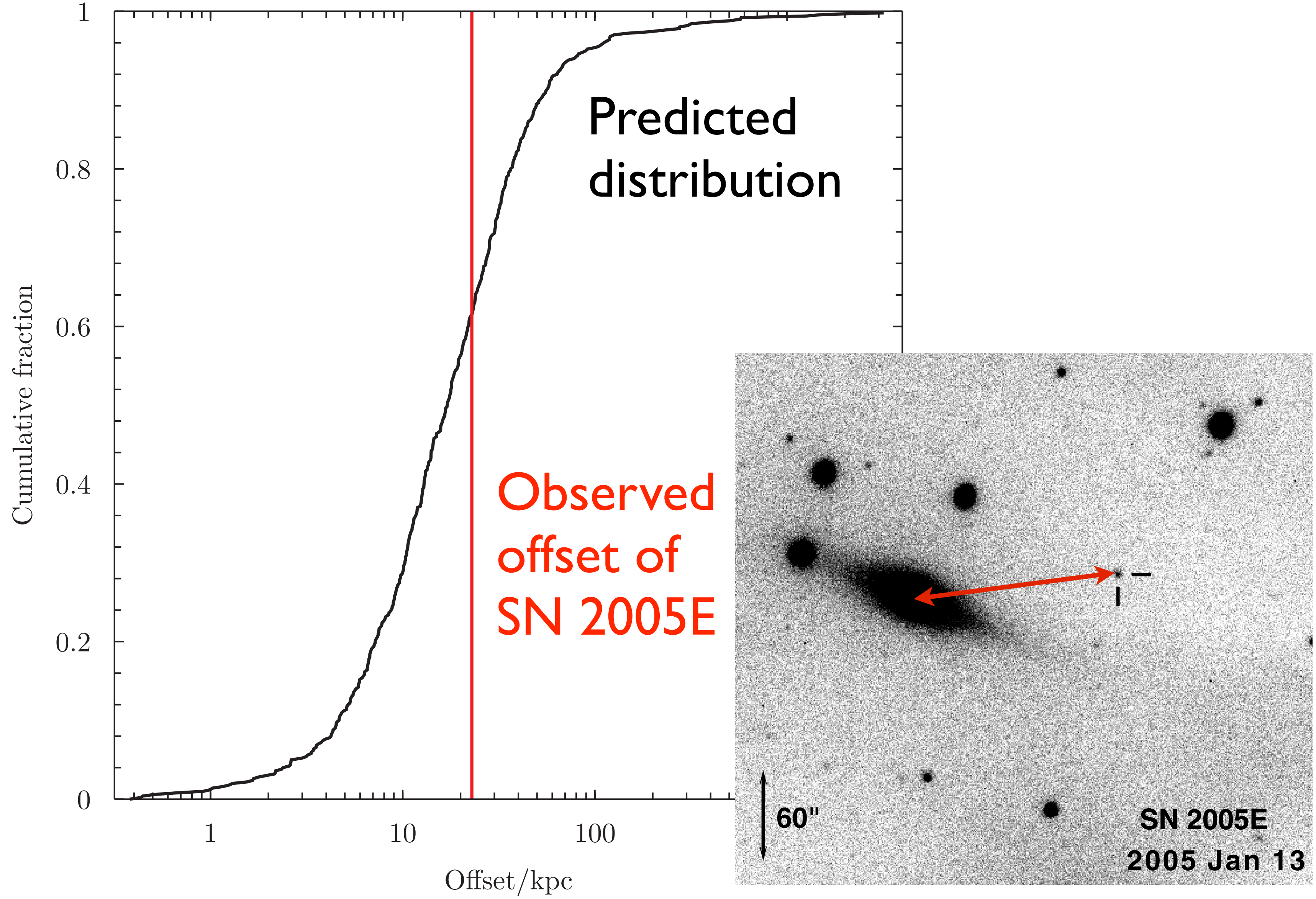


Figure from Church et al. (2006) *MNRAS* **372** 715; see also Davies et al. (2002)

Predicted offsets (provisional!)



Summary

Most solar-mass and massive stars are in binaries.

The presence of a companion can significantly change a star's evolution, by tides, mass transfer, common-envelope evolution and emission of gravitational waves.

Short gamma-ray bursts probably come from merging binaries of two neutron stars.

Some long gamma-ray bursts may come from binaries that form two black holes.

Calcium-rich "gap transients" may come from merging white dwarf - neutron star binaries.