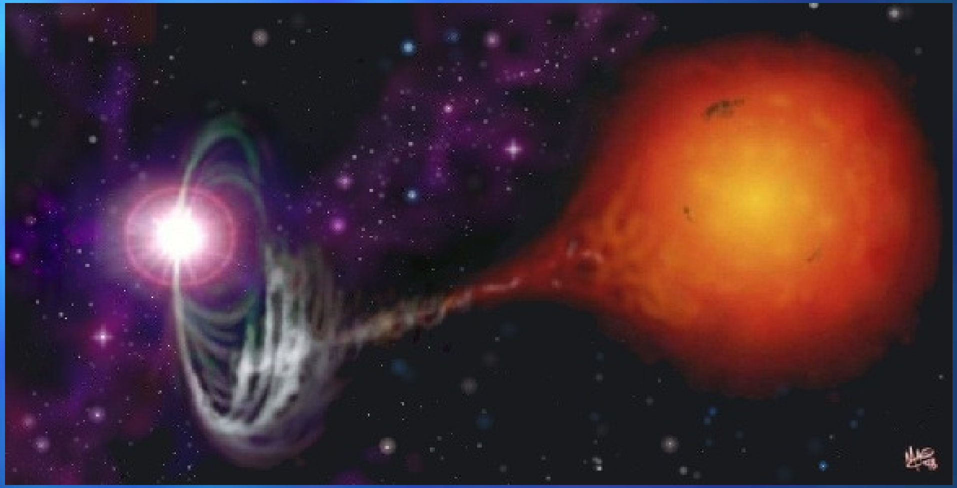
Formation and Evolution of Compact Binaries

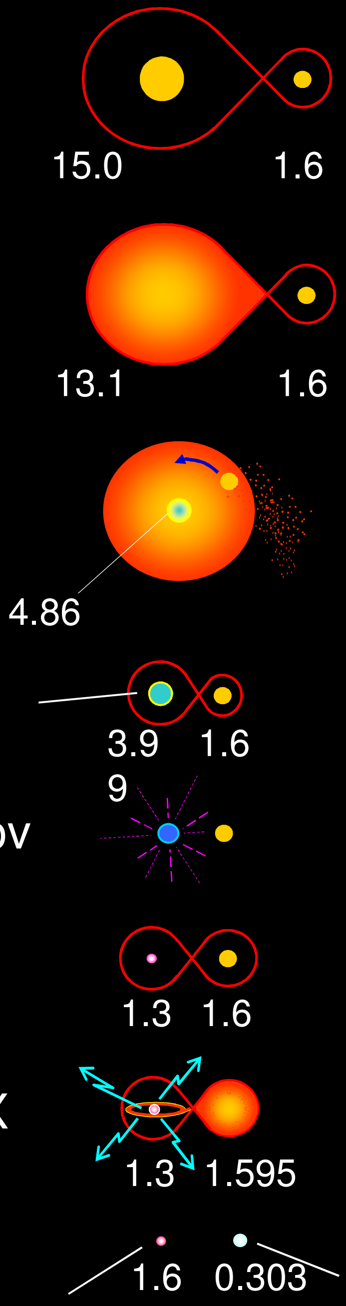


Niels Bohr International Academy Summer School 2009

Thomas Tauris

Lecture topics:

- HMXBs and LMXBs – a cartoon overview
- Roche-lobe overflow (RLO): case A, case B, case C
- Stability criteria for mass transfer / stellar evolution
- The orbital angular momentum balance equation
- Common envelope + spiral-in
- Formation of millisecond pulsars
  - Detailed evolution of LMXBs



	Porb	age	
ZAMS	1200 days	0.0 Myr	eccentricity: 0.0
Roche-lobe overflow	1538 days	13.87 Myr	
common envelope + spiral-in	0.83 days	13.87 Myr	
helium star	1.10 days	14.95 Myr	
supernova	80.75 days	15 Myr	eccentricity: 0.93
neutron star	4.11 days	2.29 Gyr	eccentricity: 0.0
LMXB	58 days	2.39 Gyr	

millisecond pulsar

white dwarf

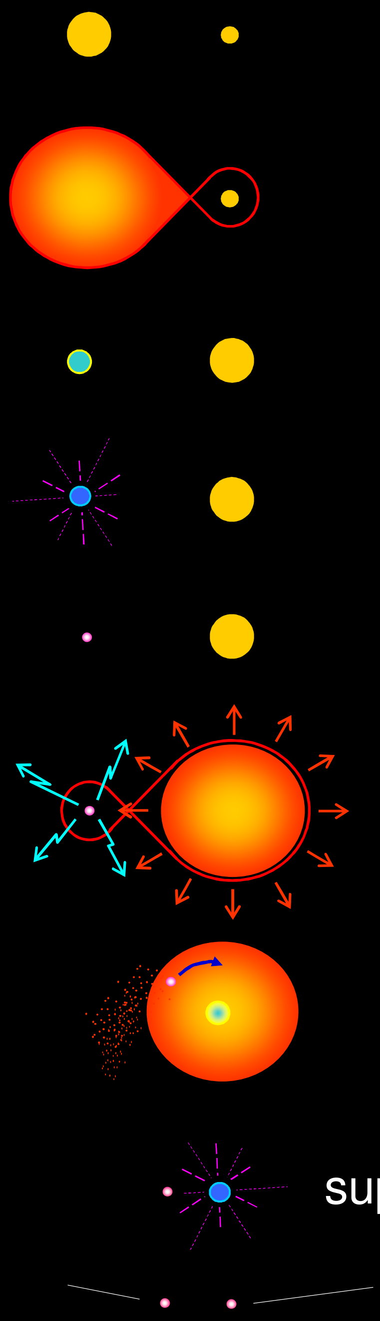
How to make a double pulsar

Perfect playground for:

- population synthesis
- Monte Carlo simulations

Things you need to consider:

- stellar evolution (incl. He-star evoution)
- various binary interactions
  (mass transfer, accretion, CE
  tidal interactions, GWR)
- asymmetric supernovae



ZAMS

Roche-lobe overflow

helium star

supernova

neutron star

HMXB

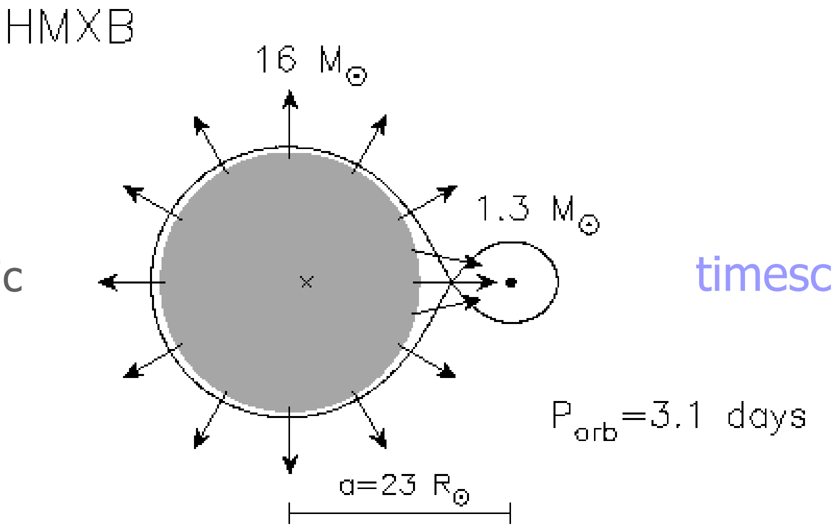
common envelope + spiral-in

supernova

recycled pulsar

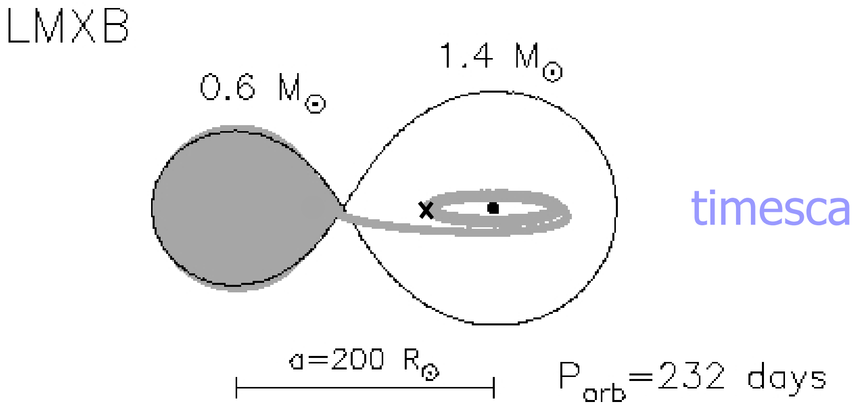
young pulsar

standard X-ray binaries



- wind accretion
- beginning atmospheric Roche-lobe overflow

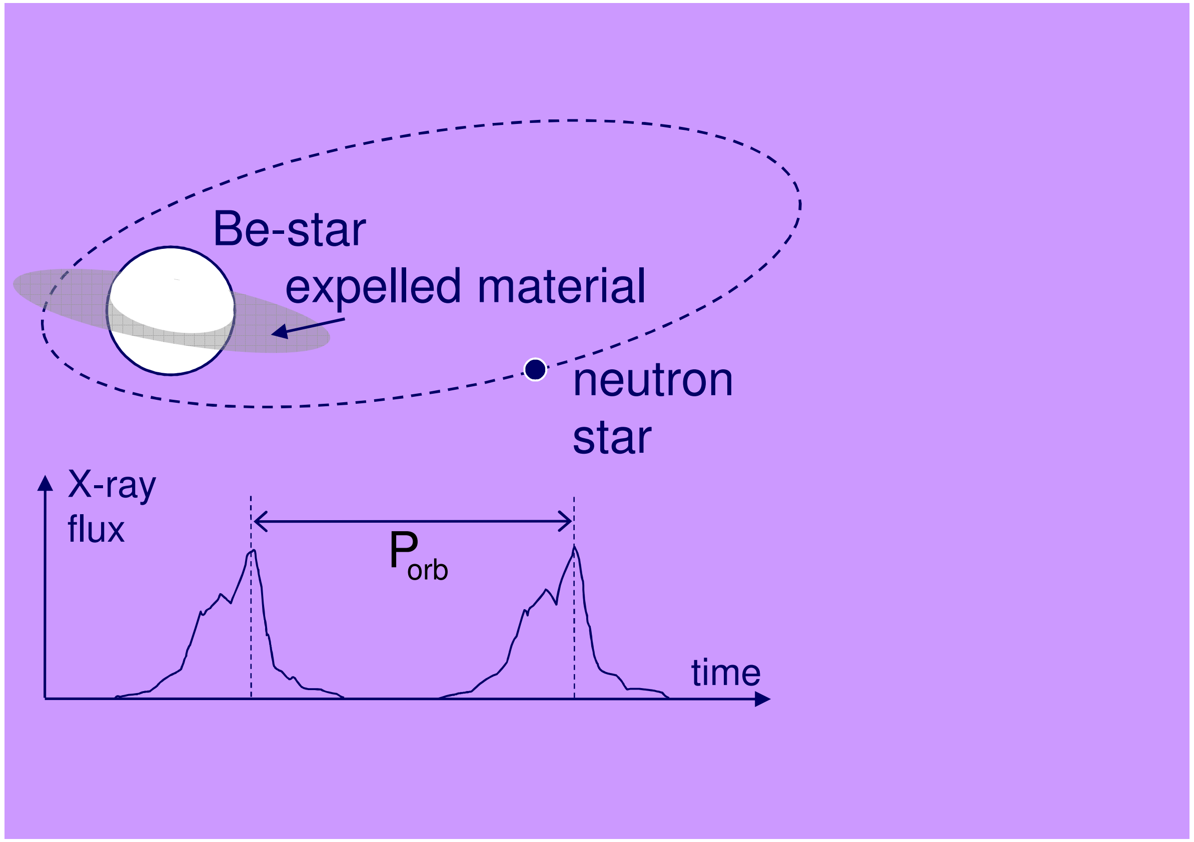
timescale: 10^5– 10^6 yr



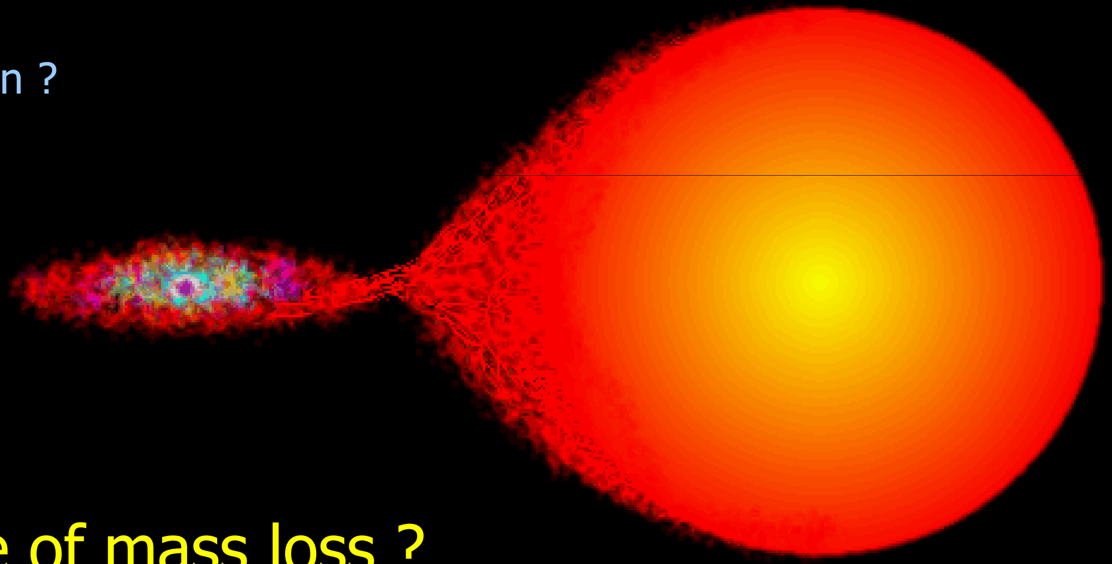
- Roche-lobe overflow

timescale: 10^8– 10^9 yr

Be-star X-ray binary



Aspects of Roche-lobe overflow



Stability ?

response of donor star ?

dynamically stable ?

Accretion ?

super-Eddington ?

jet ?

B-field, spin ?

Mode of mass loss ?

specific orbital angular momentum ?

Equipotential surfaces

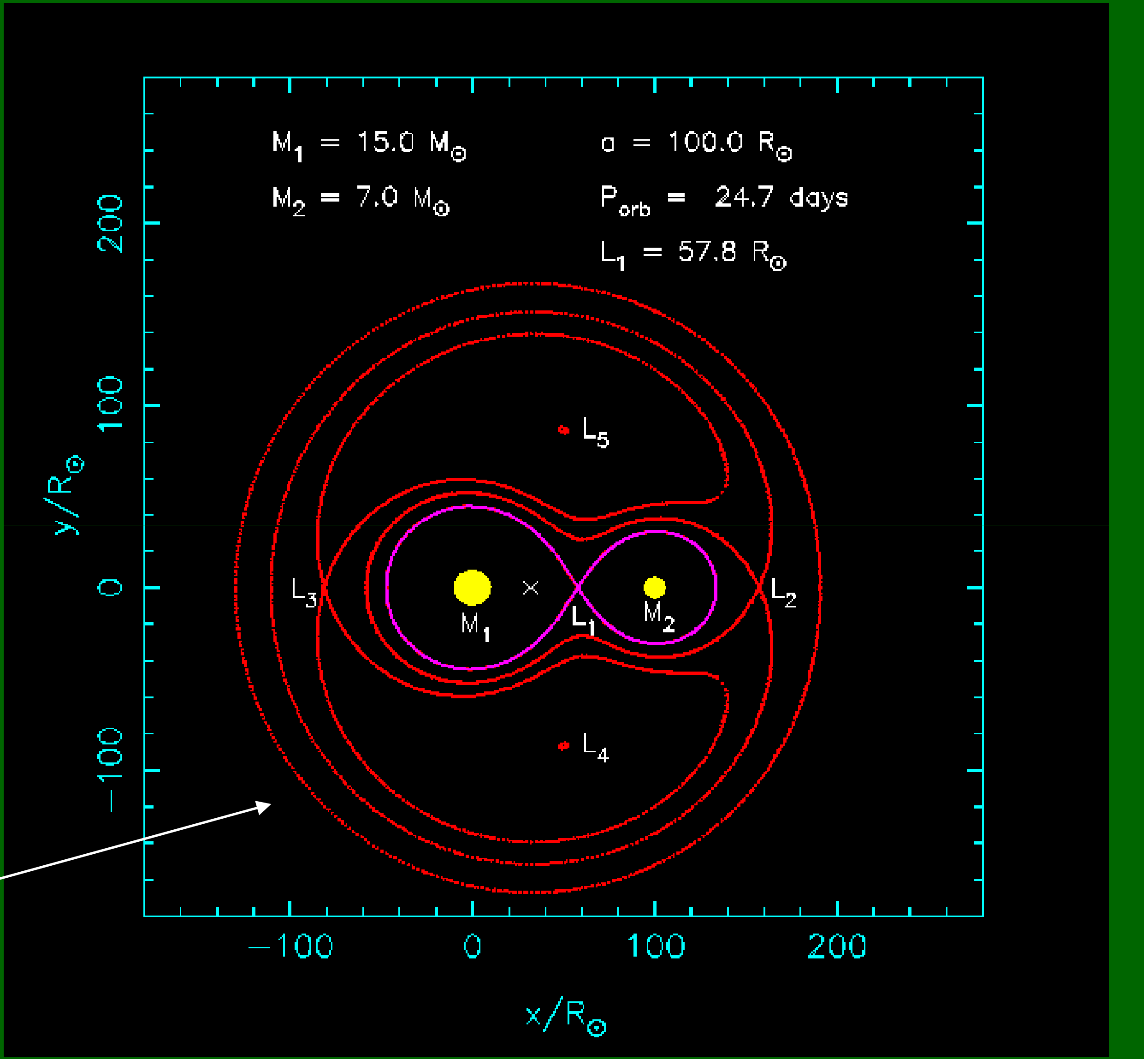
effective gravitational potential:

$$\Phi = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \frac{\Omega^2 r_3^2}{2}$$

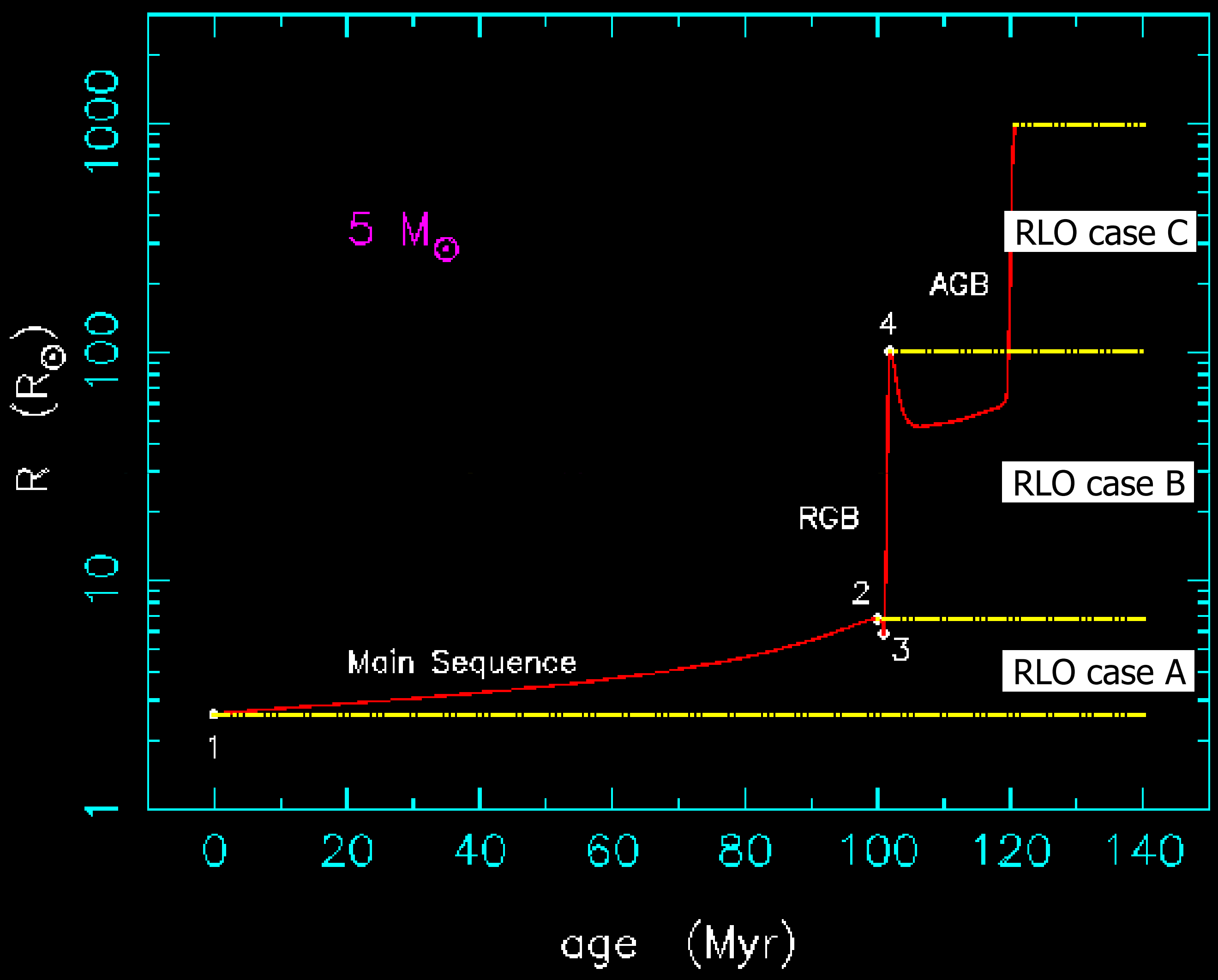
Roche-lobe radius:

$$\frac{R_L}{a} = \frac{0.49\, q^{2/3}}{0.6\, q^{2/3} + \ln\left(1 + q^{1/3}\right)}$$

co-moving frame

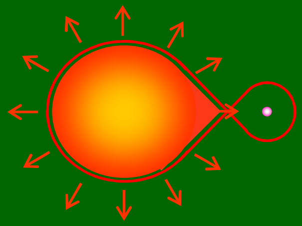


Stellar evolution



Stability criteria for mass transfer

exponents of radius to mass: $R \propto M^{\zeta}$



$$\zeta_{donor} \equiv \frac{\partial \ln R_2}{\partial \ln M_2} \quad \wedge \quad \zeta_L \equiv \frac{\partial \ln R_L}{\partial \ln M_2}$$

adiabatic or thermal response of the donor star to mass loss

initial stability criteria: $\zeta_L \leq \zeta_{donor}$

$$\dot{R}_2 = \frac{\partial R_2}{\partial t}\bigg|_{M_2} + R_2\,\zeta_{donor}\,\frac{\dot{M}_2}{M_2}$$

$$\dot{R}_L = \frac{\partial R_L}{\partial t}\bigg|_{M_2} + R_L\,\zeta_L\,\frac{\dot{M}_2}{M_2}$$

nuclear burning

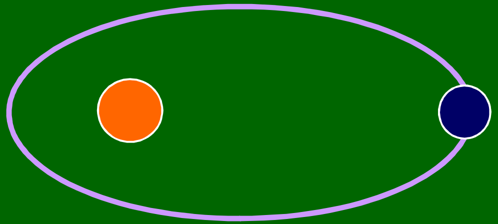
tidal spin-orbit couplings
gravitational wave radiation

$\dot{R}_2 = \dot{R}_L$ yields mass loss rate!

The Orbital Angular Momentum Balance Equation

$$J_{orb} = \frac{M_1 M_2}{M} \, \Omega \, a^2 \sqrt{1-e^2}$$

orbital angular momentum



logarithmic differentiation

$\Downarrow$ (e=0, tidal circularization)

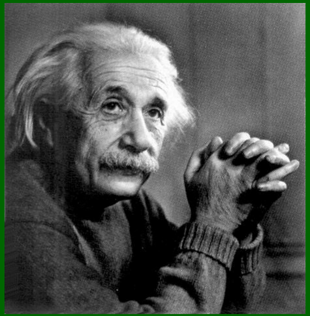
$$\frac{\dot{a}}{a} = 2\frac{\dot{J}_{orb}}{J_{orb}} - 2\frac{\dot{M}_1}{M_1} - 2\frac{\dot{M}_2}{M_2} + \frac{\dot{M}_1 + \dot{M}_2}{M}$$

$$J_{orb} = |\vec{r} \times \vec{p}|$$

$$\frac{\dot{J}_{orb}}{J_{orb}} = \frac{\dot{J}_{gwr}}{J_{orb}} + \frac{\dot{J}_{mb}}{J_{orb}} + \frac{\dot{J}_{ls}}{J_{orb}} + \frac{\dot{J}_{ml}}{J_{orb}}$$

Gravitational wave radiation:

$$\frac{\dot{J}_{gwr}}{J_{orb}} = -\frac{32}{5}\frac{G^3}{c^5}\frac{M_1 M_2 M}{a^4} \qquad s^{-1}$$



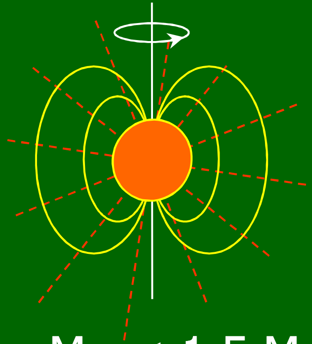
Magnetic braking:

$$\frac{\dot{J}_{mb}}{J_{orb}} \propto -\frac{k^2 R^4}{a^5}\frac{G M^3}{M_1 M_2}$$

(uncertain)

Low-mass stars: magnetic wind!
⇒ loss of spin angular momentum

In tight binaries the system
is tidally locked (synchronized)
and spin-orbit couplings operate
⇒ loss of orbital angular momentum



$M_2 < 1.5\ M_{\odot}$

$P_{orb} < 2$ days

Spin-orbit couplings:

$$\frac{\dot{J}_{ls}}{J_{orb}}$$

- fx . change in stellar moment of inertia

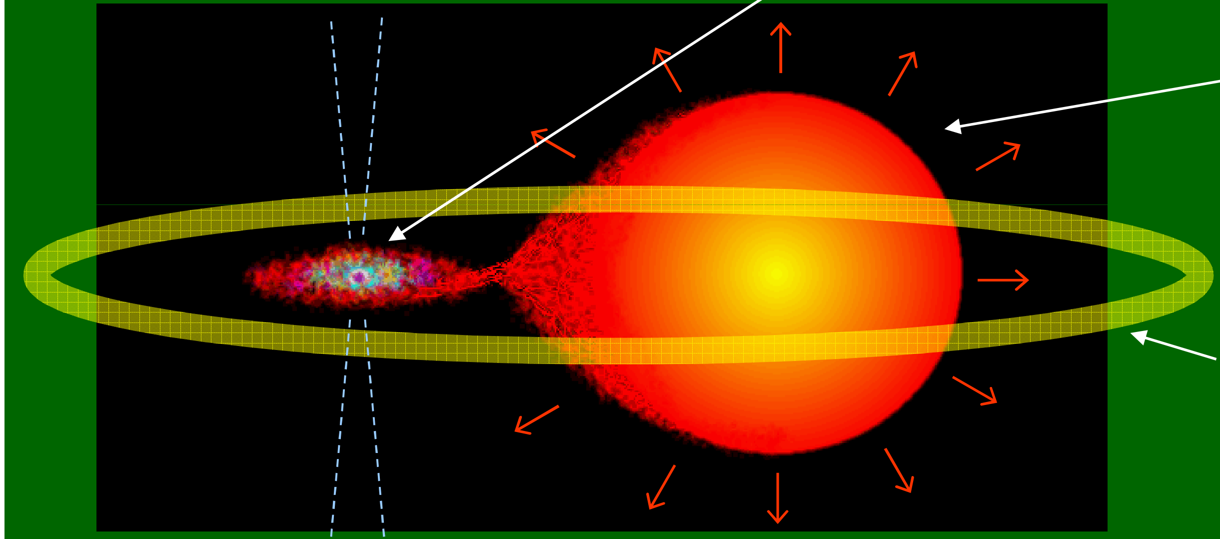
(as a result of nuclear burning or mass loss)

Mass loss:

$$\frac{\dot{J}_{ml}}{J_{orb}} = \frac{\alpha + \beta q^2 + \delta\gamma(1+q)^2}{1+q} \frac{\dot{M}_2}{M_2}$$

$$\beta = \max\left(\frac{|\dot{M}_2| - \dot{M}_{Edd}}{|\dot{M}_2|}, 0\right)$$

β: mass ejected from accretor
- fx. in a relativistic jet
(isotropic re-emission)



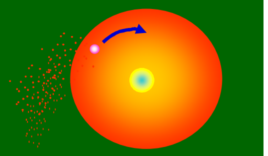
α: direct fast wind

δ: mass loss via circumbinary
coplanar toroid with
radius: $\gamma^2 a$

accretion efficiency: $\varepsilon = 1 - \alpha - \beta - \delta$ $\quad (\partial M_{NS} = -\varepsilon\, \partial M_2)$

Common envelope + spiral-in evolution

dynamically unstable mass transfer:



- deep convective envelope of donor star
  (rapid expasion in response to mass loss)
- $M_{donor} > M_{accretor}$
  (orbit shrinks in response to mass loss)

}

Run-away process!!

⇓

common envelope

drag force → dissipation of orb. ang. mom. + deposition of E_{orb} in the envelope

outcome:

- huge reduction of orbital separation

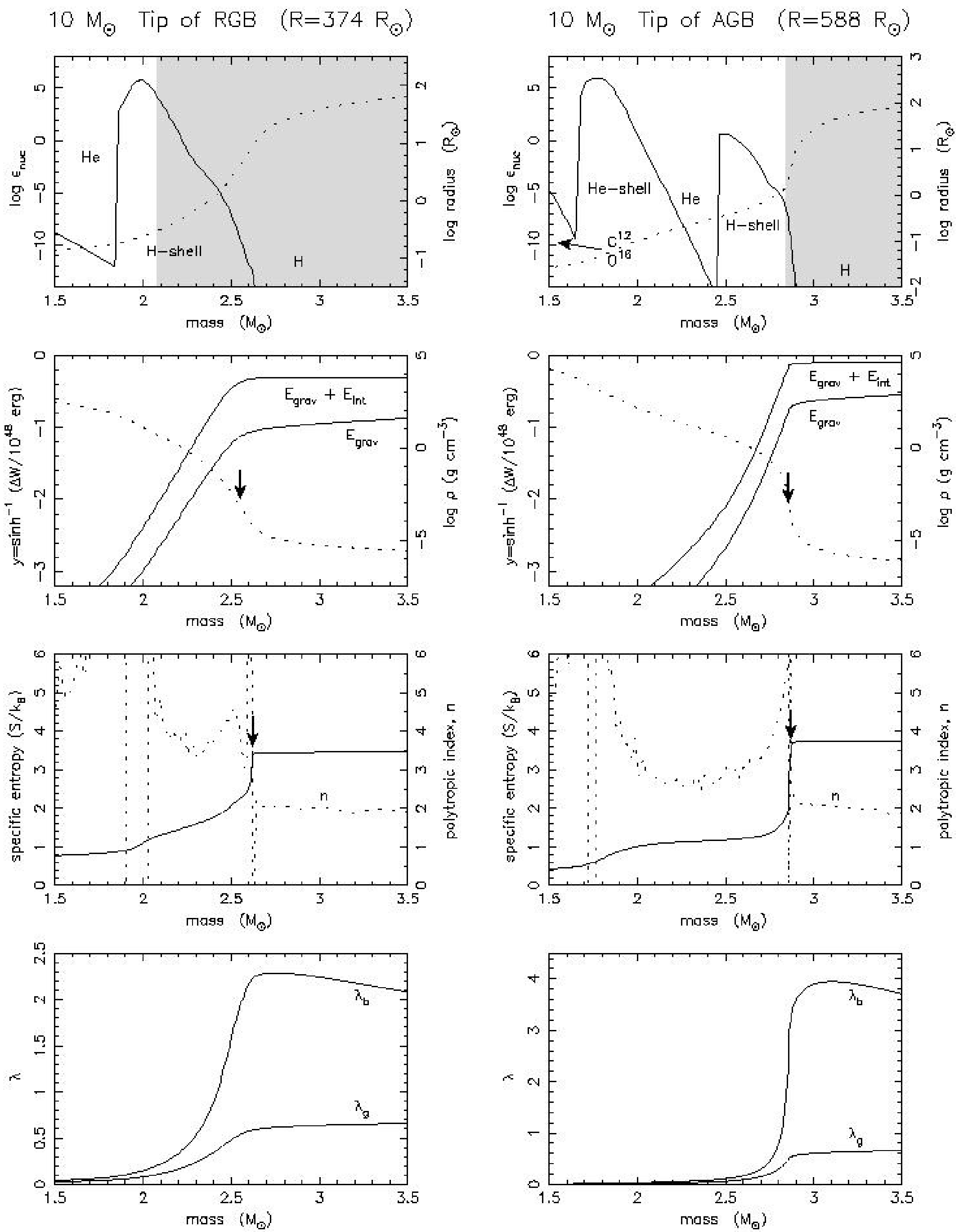
→ rejection of stellar envelope
(NS orbiting a naked helium star)

→ merging of NS + core
(Thorne-Zytkow object / black hole)

Needed to explain observed tight systems!!

How to define M_{core} ?

- quite important!



Tauris & Dewi (2001)

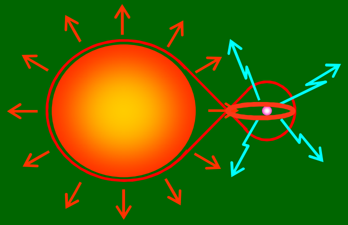
Intermediate Mass X-ray Binaries

Why are so few IMXBs observed ?

HMXB: wind accretion (beginning atmospheric RLO)

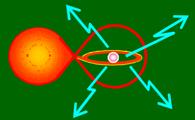
RLO is dynamically unstable and a CE forms

$$M_2 > 10\,M_\odot$$



LMXB: stable RLO

$$M_2 \leq 1.5\,M_\odot$$



IMXB: wind accretion is too weak, and

RLO is often unstable (or very short)

Formation of millisecond pulsars (MSPs)

First pulsar discovered in 1967 (today ~1800 pulsars are known)

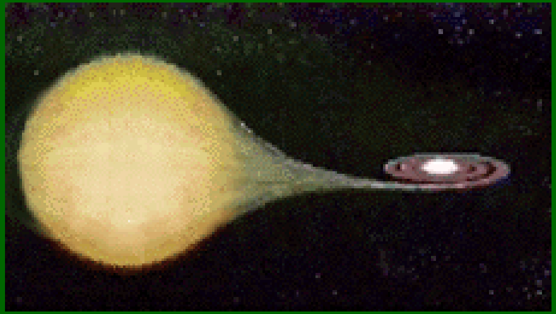
First binary pulsar discovered in 1974: PSR 1913+16 (today ~50 systems are known)

First millisecond pulsar discovered in 1982: PSR 1937+21 (P=1.5 msec)

Millisecond pulsar characteristics: P-Pdot diagram

- high incidence of binaries among millisecond pulsars
- rapid spin (P < 20 msec)
- relatively weak magnetic fields ($B=10^8 - 10^9$ G)

old neutron stars which have been "recycled" via accretion of mass and angular momentum



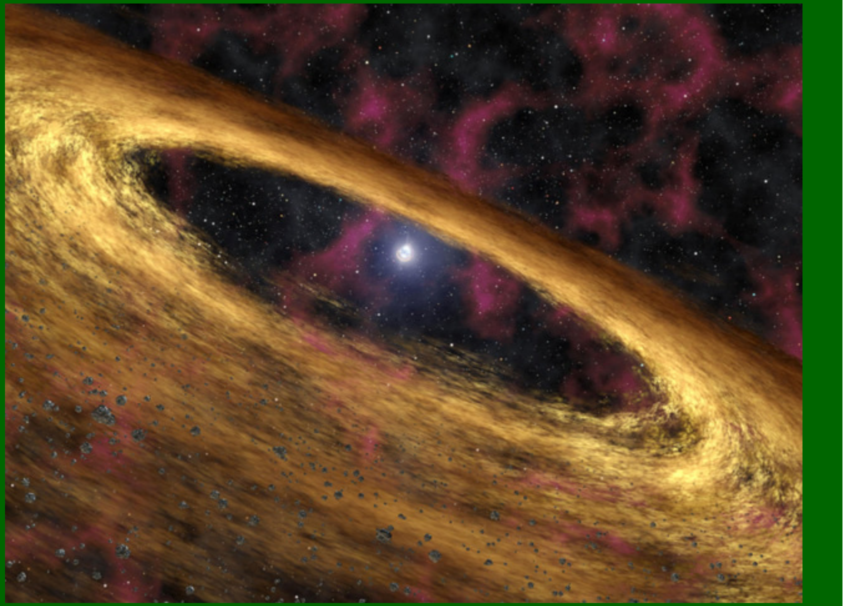
Single millisecond pulsars

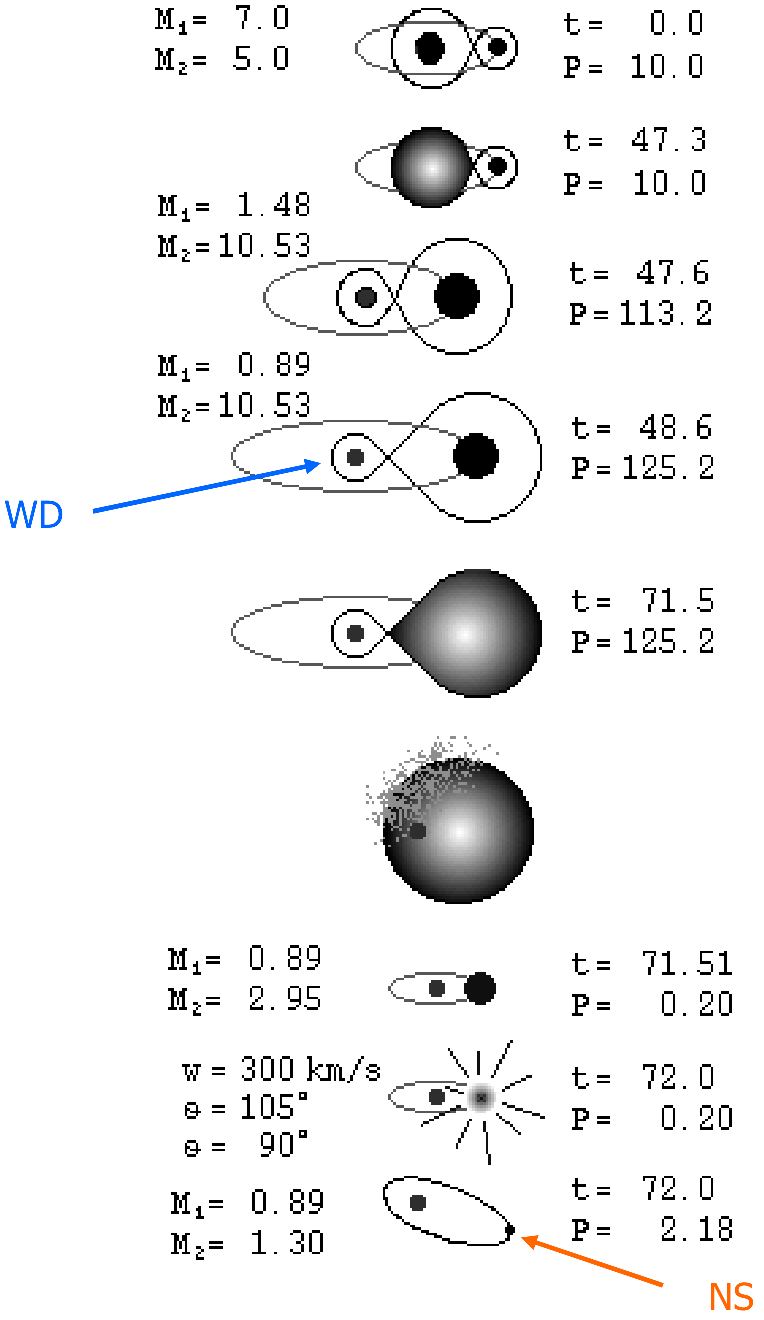
All single millisecond pulsars are born in a binary system.

Once a recycled millisecond pulsar turns on its emission of ultra-relativistic particles, it is often able to completely evaporate its companion and thus end up as an isolated millisecond pulsar.

Observational evidence:

- ✓ eclipsing MSPs with 0.02 $M_\odot$ companions
- ✓ the ”planetary pulsar”, PSR 1257+12





Tauris & Sennels (1999)

Summary:

- To study the formation and evolution of compact binaries one must have a detailed knowledge stellar evolution and binary interactions
- Millisecond pulsars are old ”rejuvenated” pulsars
- Common envelope + spiral-in explain very narrow orbits
- HMXBs and LMXBs are wellknown b/c they are detected
  – IMXBs are not detected
- Perfect scenario for Monte Carlo simulations