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THE EVOLUTION OF STELLAR INTERIORS IN MASSIVE BINARY SYSTEMS

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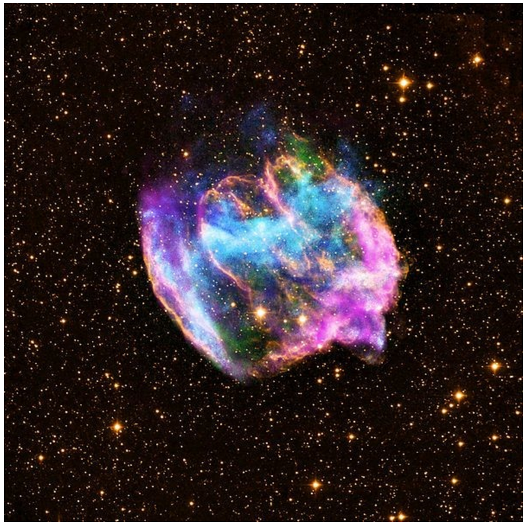
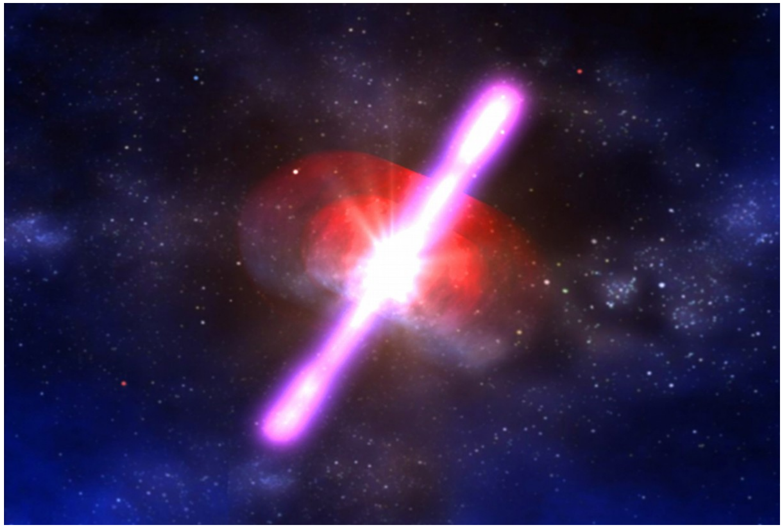
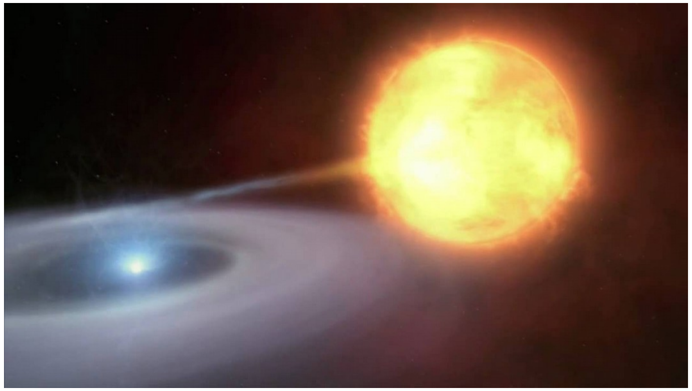
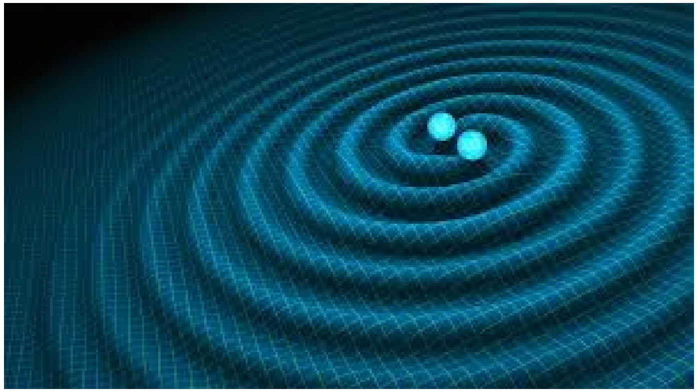
Massive binary systems are connected with many interesting phenomena:

- -Wolf Rayet stars
- -Ib/Ic supernova explosions
- -x ray emission
- -gamma ray bursts / Collapsars
- -gravitational waves







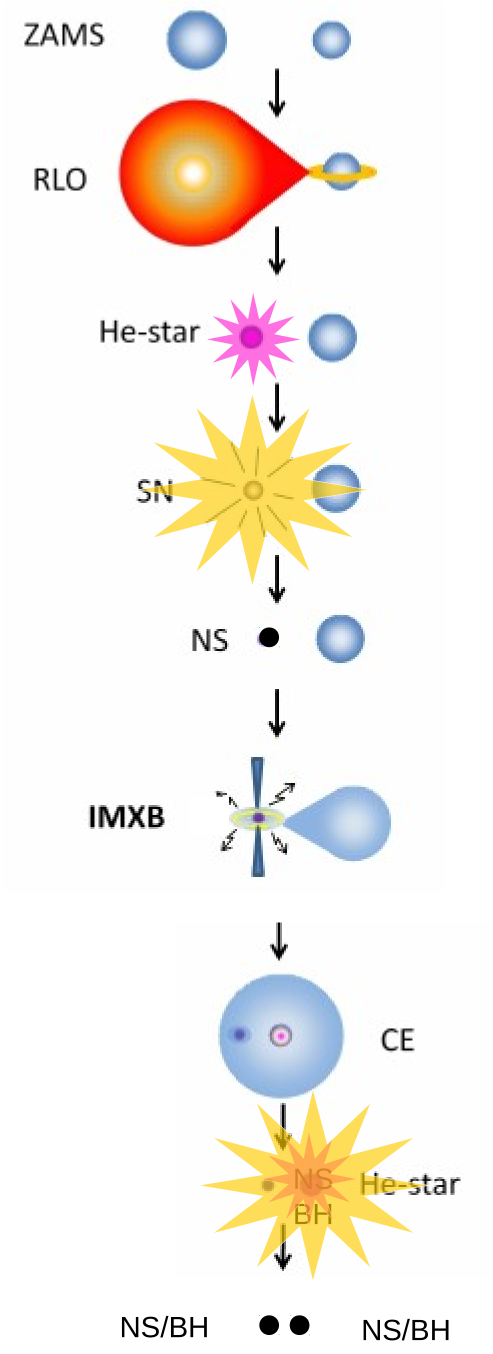


Gravitational Wave events

GW150914	11-02-2016	35.6Ms	30.6Ms
GW151012	15-06-2016	23.3	13.6
GW151226	15-06-2016	13.7	7.7
GW170104	01-06-2017	31.0	20.1
GW170608	16-11-2017	10.9	7.6
GW170729	30-11-2018	50.6	34.3
GW170809	30-11-2018	35.2	23.8

GW170814	27-09-2018	30.7Ms	25.3Ms
GW170817	16-10-2017	**1.46**	**1.27**
GW170818	30-11-2018	35.5	26.8
GW170823	30-11-2018	39.6	29.4
GW190412	17-04-2020	29.7	8.4
GW190425	06-01-2020	**1.60**	**1.46**
GW190814	23-06-2020	?23.2	?2.59

https://www.ligo.org/detections.php



Evolution of binary systems

Depending on an initial period, the primary star fills its Roche lobe during the hydrogen core burning,hydrogen shell burning or after core helium burning phase and mass transfer to the secondary starts: **Case A**, **Case B** or **Case C** respectively

The primary loses most of its hydrogen envelope and becomes **Wolf Rayet** (He) star.

Later it explodes as a **supernova** and leaves a **neutron star** or a **black hole** as a remnant

If the secondary fills its Roche lobe, mass transfer to the compact object starts accompanied by **x-ray emission**

If the secondary star is rotating fast in moment of supernova explosion, a **collapsar** is formed: fast spinning black hole with accretion disk and jets – **gamma-ray burst** can be observed

Common Envelope can develop during any mass transfer phase and lead to a shortening of a period or a merger

Merger of compact objects causes emission of **gravitational waves**

Conservative vs non-conservative stable mass transfer

Initial mass ratio should be close to 1 to avoid contact (Wellstein & Langer, A&A, 2001)

Conservative: all matter lost by one star due to RLOF is accreted by the other star
Non-conservative: certain amount of matter leaves the system

Unknown what processes can expel matter from the binary system and on which parameters and how accretion efficiency depends

Evolutionary calculations of massive binaries with different assumptions of accretion efficiency were done by various authors:
"**Brussels school**": Vanbeveren, de Loore, de Greve.. (Brussels code)
"**Postdam/Utrecht school**": Braun, Langer, Wellstein, Heger, Petrovic, Yoon (STERN code)
"**Oxford school**": Podsiadlowski, Pols, Dewi.. (Eggleton STAR code)

The newest code: Modules for Experiments in Stellar Astrophysics (**MESA**)

Example model of WR+O progenitor systems

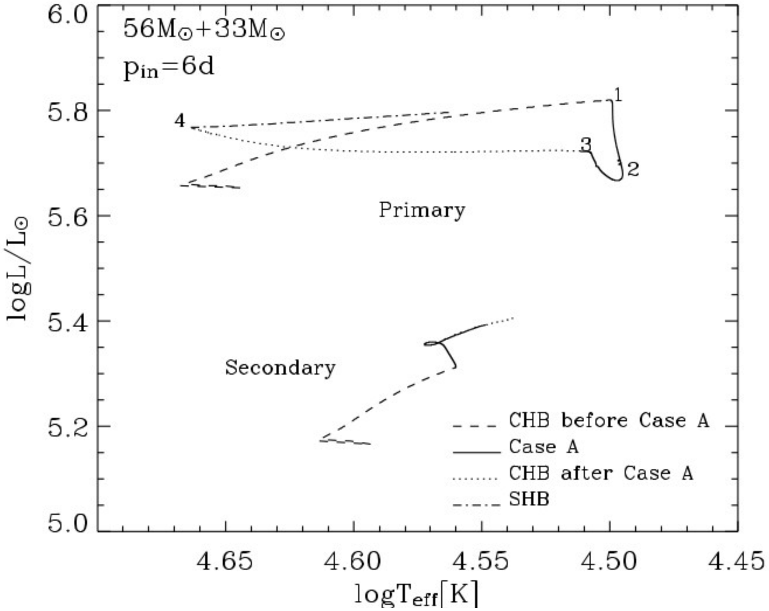


Fig. 3. HR diagram of the initial system $M_{1,\rm in} = 56\,M_\odot$, $M_{2,\rm in} = 33\,M_\odot$, $p_{\rm in} = 6$ days. Both stars are core hydrogen burning (dashed line) until Case A mass transfer starts (solid line). The primary is losing mass and its luminosity and effective temperature decrease. At the same time the secondary is accreting matter and expanding, becoming more luminous and cooler. After Case A mass transfer is finished, the primary is losing mass by stellar wind and contracting at the end of core hydrogen burning (dotted line). After this the primary starts with shell hydrogen burning and expands (dash-dotted line).

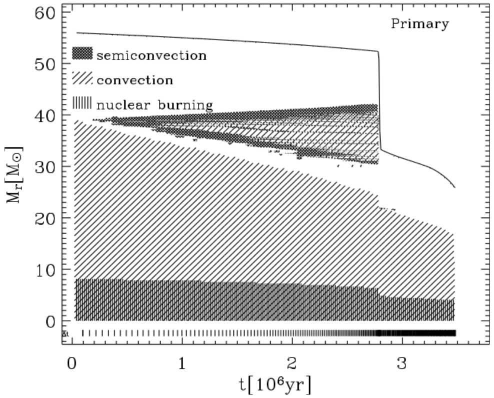


Fig. 4. The evolution of the internal structure of the 56 $M_\odot$ primary during the core hydrogen burning. Convection is indicated with diagonal hatching and semiconvection with crossed hatching. The hatched area at the bottom indicates nuclear burning. The topmost solid line corresponds to the surface of the star.

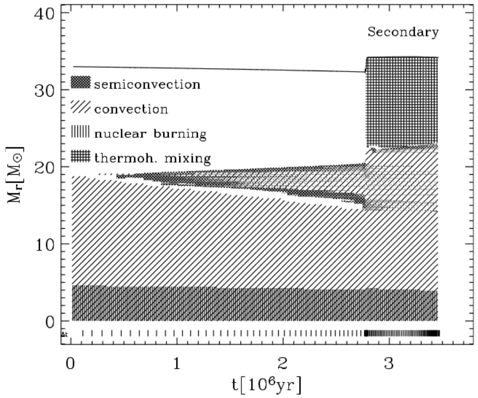


Fig. 5. The evolution of the internal structure of the 33 $M_\odot$ secondary during core hydrogen burning of the primary. Convection is indicated with diagonal hatching, semiconvection with crossed hatching and thermohaline mixing with straight crossed hatching. The hatched area at the bottom indicates nuclear burning. The topmost solid line corresponds to the surface of the star.

Accretion efficiency of only 10% reproduces observations the best!

Petrovic, Langer & van der Hucht. A&A, 435, 1013, 2005

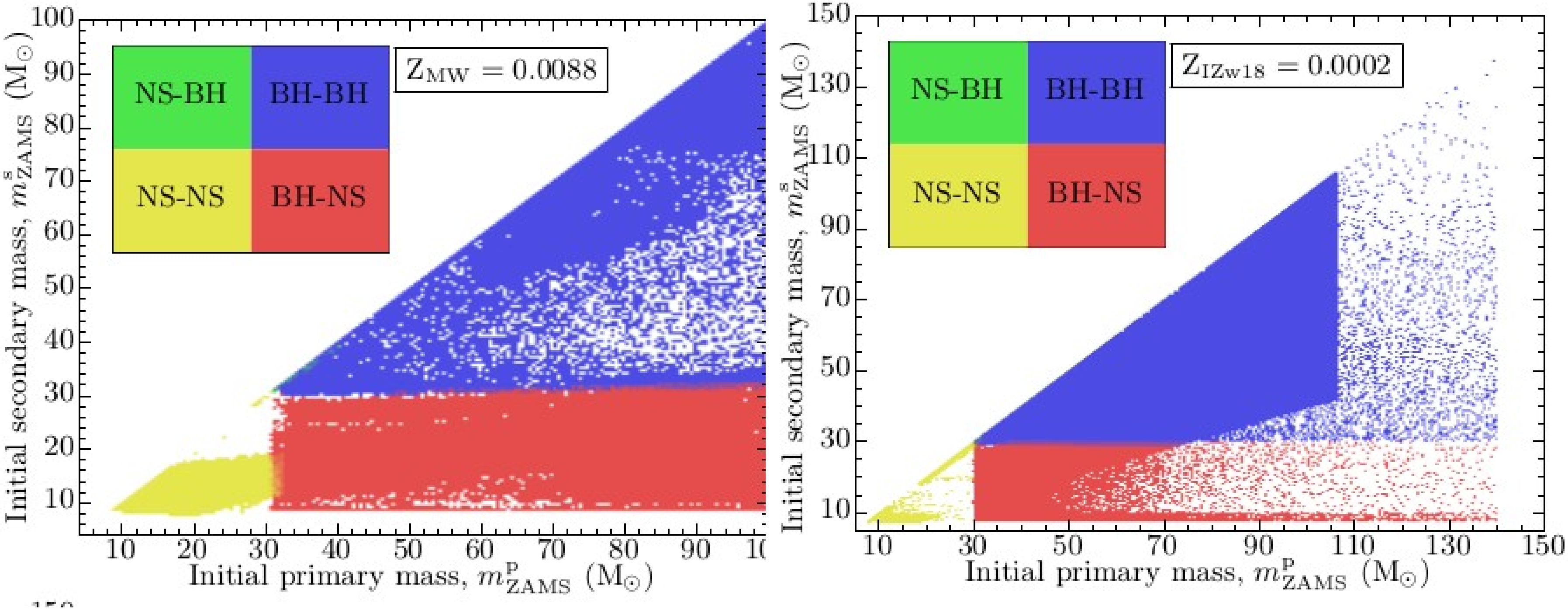
MESA - Modules for Experiments in Stellar Astrophysics

Hydrodynamic stellar evolution code - calculates simultaneously evolution of both stellar components in a circular orbit and the mass transfer (Paxton et al. 2011, 2013, 2015, 2018)

-Nuclear reaction library includes more than 300 rates for elements up to nickel (Caughlan & Fowler 1988, Augulo et al. 1999)
-Includes convection, overshooting, semiconvection and thermohaline mixing
-Opacity tables (Cassisi et al. 2007)
-Stellar wind mass loss included (various option depending on stellar mass and phase: De Jager, Nieuwhuizen & van der Hucht 1988 for MS, Kudritzki 1989 for massive MS stars, Vink et al 2001 for O and B stars, "Dutch" all authors for massive stars, Reimers 1975 for red giants, Blocker 1995 for AGB stars...)
-Rotation is derived from STERN (Heger, Langer & Woosley 2000, Heger, Woosley & Spruit, application in binaries Petrovic et al. 2005; Yoon & Langer, 2005)
-Spruit-Tayler dynamo in MESA is based on STERN (Petrovic et al. 2005) and KEPLER (Heger et al. 2005)
-Mass transfer rate through the first Langrangian point as in STERN (Ritter 1988)
-Accretion efficiency control (Tauris & van der Heuvel 2006)
-Evolution of Orbital angular momentum: mass loss, magnetic braking, spin-orbit coupling (for rotating models) and gravitational waves
-Mass lost in a stellar wind has the specific orbital angular momentum of its star (Sobberman et al. 1997)

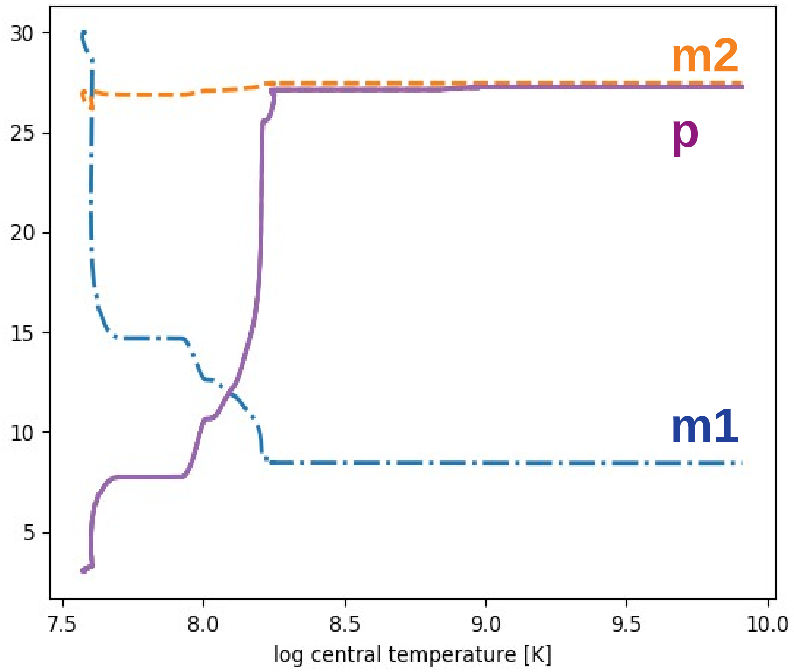
http://mesa.sourceforge.net/

Population synthesis models of GW



Kruckow et al. 2018

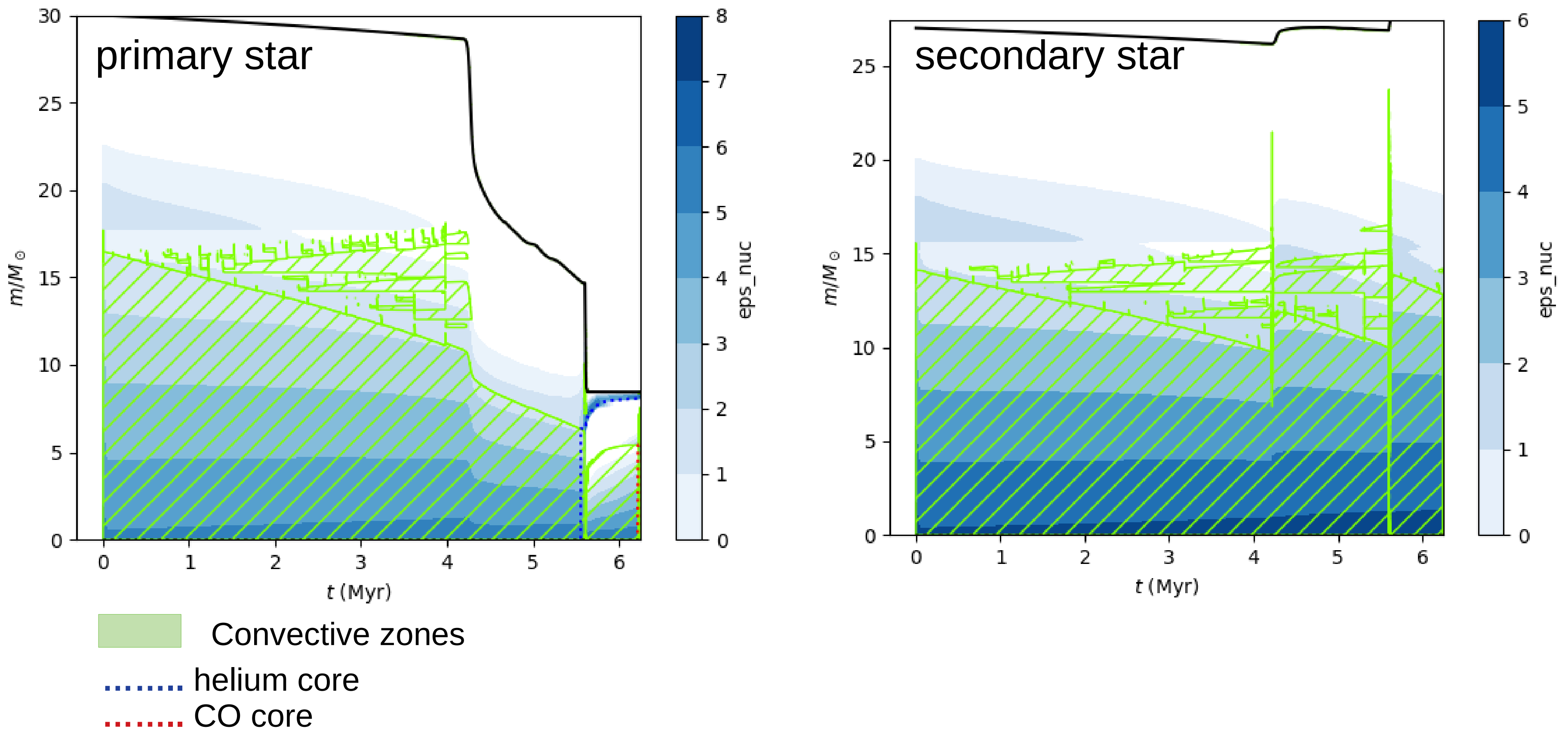
Evolutionary progenitor MESA models of double compact binaries



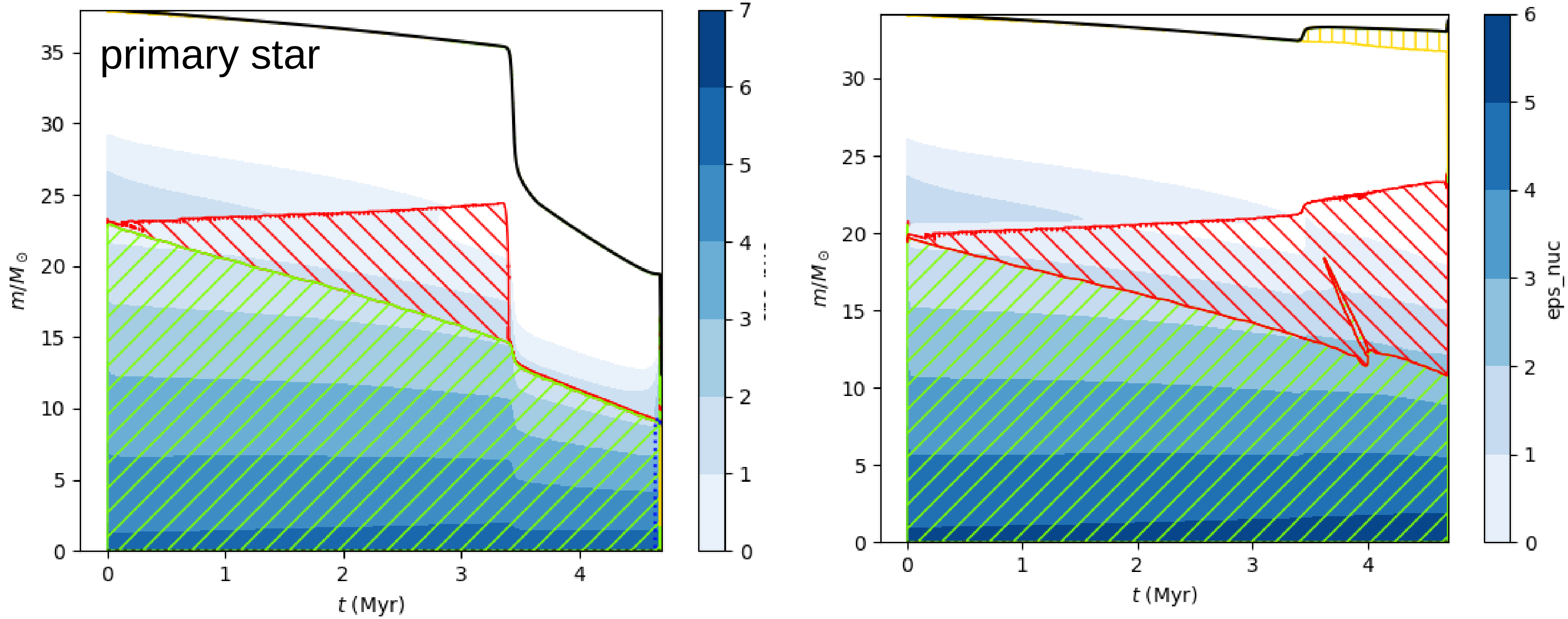
Initial masses: 30Ms and 27Ms
Initial mass ratio 0.9
Initial orbital period 3 days

Case A mass transfer: starts during core hydrogen burning of the binary (X = 0.29)
Accretion efficiency 10% (Petrovic et al. 2005)

Convective – Kippenhahn plots: internal structure evolution: 30Ms + 27Ms example



Evolutionary progenitor MESA models of double compact binaries: 38Ms + 34.2Ms example



🟩 convective zones

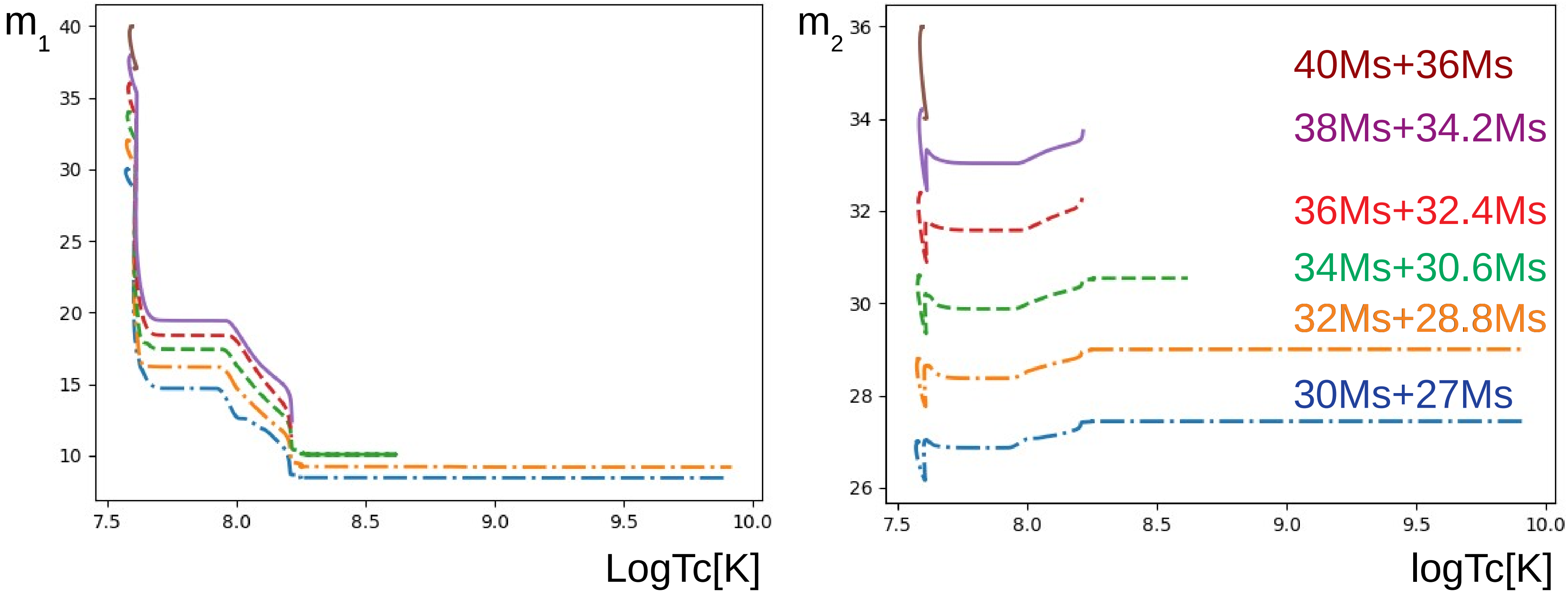
🟥 semiconvection zones

······· helium core

🟨 thermohaline mixing

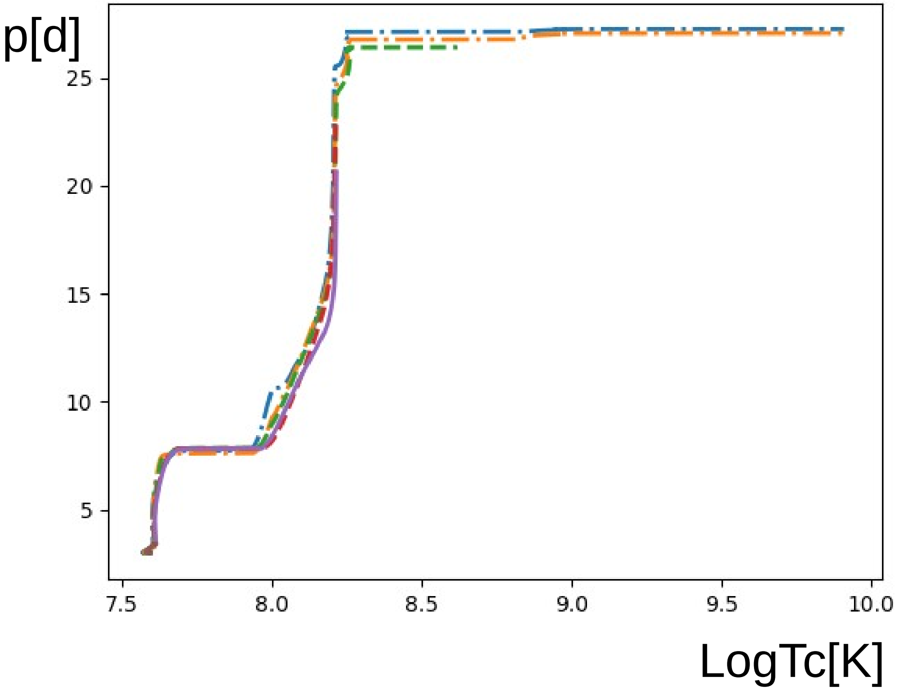
······· CO core

Evolutionary progenitor MESA models of double compact binaries – primary and secondary mass



Models are calculated with primary stars between 30Ms and 40Ms with the initial orbital period of 3 days and mass ratio of 0.9

Orbital period evolution

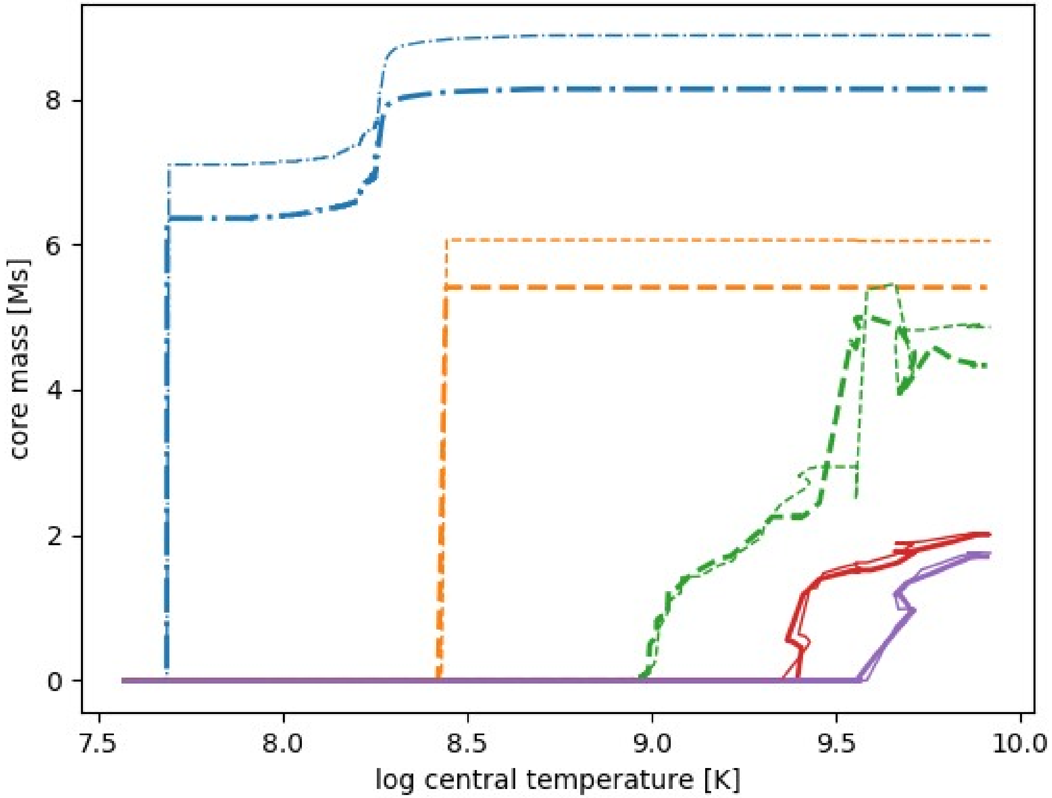


system	WR + O phase	P [d] WR + O phase
30+27Ms	8.4+27.4	27.1
32+28.8Ms	9.2+29.0	26.8
34+30.6Ms	10.7+30.5	22.6*
36+32.4Ms	11.3+32.3	23.0*
38+34.2Ms	12.4+33.7	20.6*
40+36Ms	-	-

* Case A not finished

Models are calculated with primary stars between 30Ms and 40Ms with the initial orbital period of 3 days and mass ratio of 0.9

Evolution to the formation of Si-Fe core in the primary



	30+27Ms	32+28.8Ms
He core	8.138	8.874
C core	5.408	6.044
O core	4.332	4.860
Si core	2.007	2.006
Fe core	1.704	1.755

*core masses given in Solar units

Fe core burning is using energy → Supernova explosion

m_{core} ~2Ms → Neutron star

Summary

Models of close massive binary systems in mass range 30-40Ms were calculated, evolving into double neutron star systems

Initial orbital period 3 days, initial mass ratio 0.9 (to avoid contact during the first mass transfer)

Accretion efficiency 10% is assumed

O + O → (Case A) → WR + O → (SN) → NS + O → (CE, SN) →
NS + NS → (merger) → GW emission

Orbital period is calculated with MESA until the first SN explosion,
further SN kick and common envelope evolution estimates have to be used