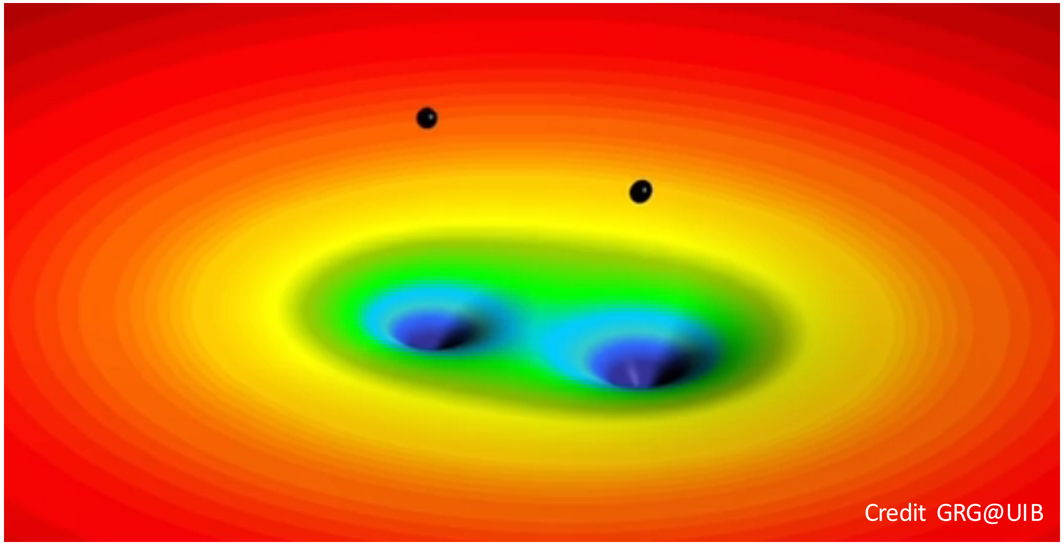
GW150914 in Light of Binary Stellar Evolution Models



THOMAS TAURIS

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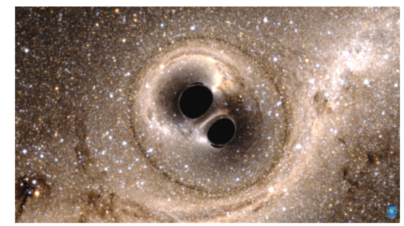
I. Standard formation scenario for producing BH-BH binaries
   – Common envelopes: pitfalls and some optimism

II. New model: massive overcontact binary (MOB) scenario with CHE

III. Momentum kicks and BH-BH binaries



Two new papers led by Bonn PhD-students:

Kruckow, Tauris, Langer, Szecsi, Marchant & Podsiadlowski (2016), in prep.
On the ejectability of common envelopes of massive stars
– Implications for the progenitor of GW150914

Marchant, Langer, Podsiadlowski, Tauris & Moriya (2016), A&A 558, 50
A new route towards merging massive black holes

- **GW150914**: BH-BH merger detected by LIGO

⇨ First lesson: **Rumour waves** travel though **social media** at near the **speed of light**

Well… it's a BH binary and the masses are **crazily big!!**

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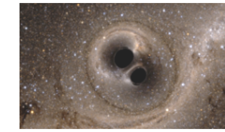
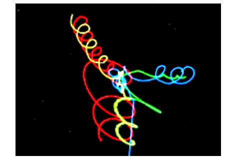
Three scenarios for producing a massive BH-BH merger:



- Dynamical channel in a dense stellar environment

(Sigurdsson & Hernquist 1993; Portegies-Zwart & McMillan 2000; Rodriguez et al. 2016)

Less than 10%



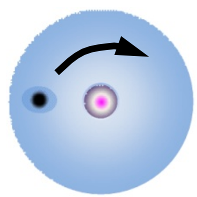
- Standard scenario with common envelope (CE) evolution

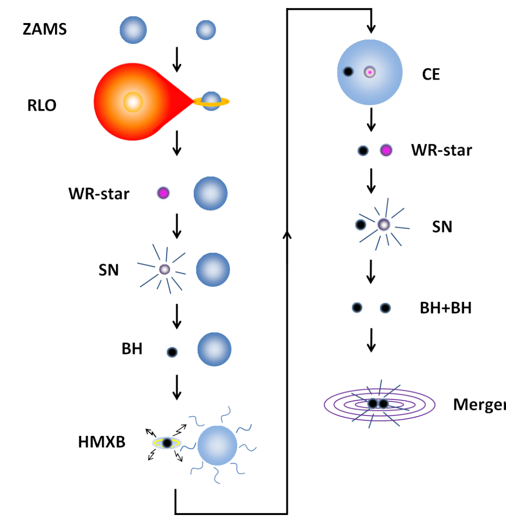
(Voss & Tauris 2003; Belczynski et al. 2002,2008,2016; Mennekens & Vanbeveren 2012)

Population synthesis

Talk by Bulik

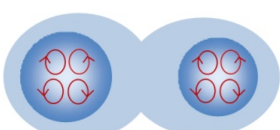
Unknown CE physics





- Chemically homogeneous evolution (CHE) and massive overcontact binaries (MOB)

(de Mink et al. 2009; Mandel & de Mink 2016; de Mink & Mandel 2016; Marchant et al. 2016)



New stellar physics

All three channels may co-exist

Abadie et al. (2010)

TABLE II: Compact binary coalescence rates per Milky Way Equivalent Galaxy per Myr.

Source	$R_{\rm low}$	$R_{\rm re}$	$R_{\rm high}$	$R_{\rm max}$
NS-NS (MWEG^{-1} Myr^{-1})	1 [1][a]	100 [1][b]	1000 [1][c]	4000 [16][d]
NS-BH (MWEG^{-1} Myr^{-1})	0.05 [18][e]	3 [18][f]	100 [18][g]	
BH-BH (MWEG^{-1} Myr^{-1})	0.01 [14][h]	0.4 [14][i]	30 [14][j]	
IMRI into IMBH (GC^{-1} Gyr^{-1})			3 [19][k]	20 [19][l]
IMBH-IMBH (GC^{-1} Gyr^{-1})			0.007 [20][m]	0.07 [20][n]

Factor ~1000

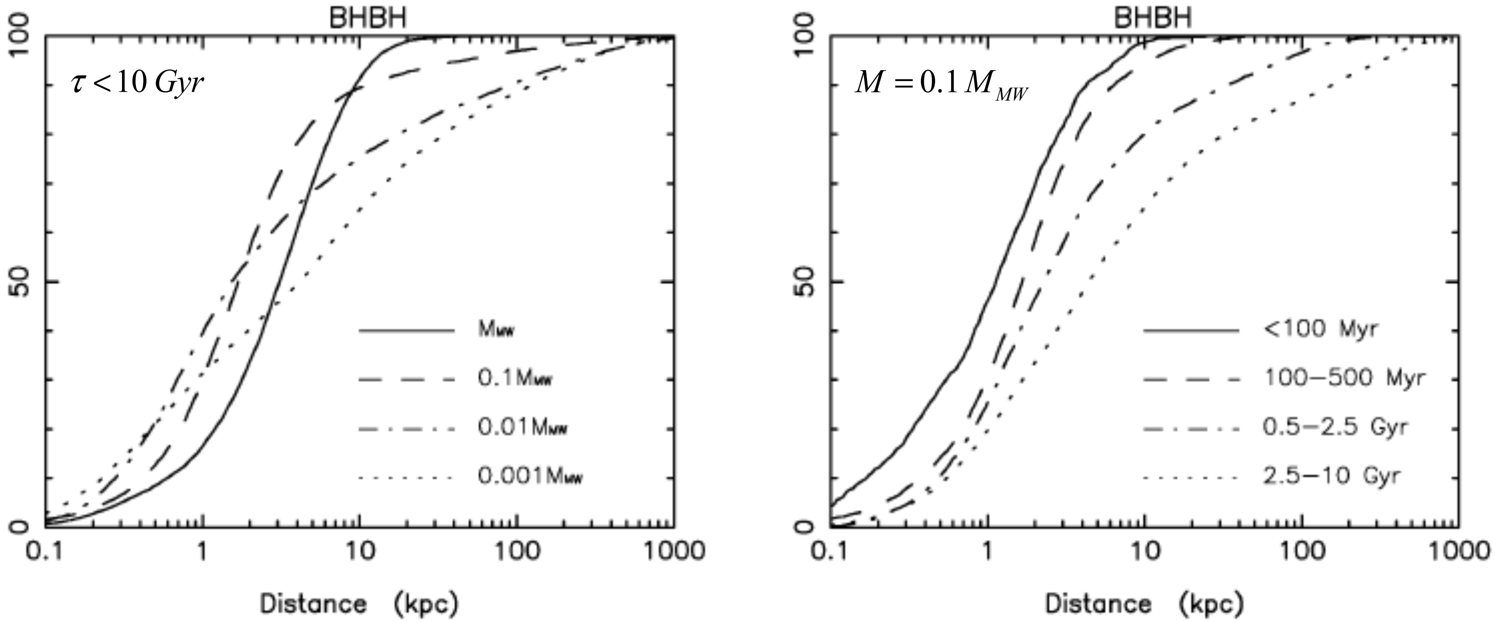
TABLE VIII: Estimates of BH-BH inspiral rates.

Rate model	$R_{\rm low}$	$R_{\rm re}$	$R_{\rm high}$	$R_{\rm max}$
O'Shaughnessy et al. pop. synth. [14][a] (MWEG^{-1} Myr^{-1})	0.01	0.4	30	
Voss & Tauris pop. synth. [34][b] (MWEG^{-1} Myr^{-1})	1.3	9.7	76	
Belczynski et al. pop. synth.: model A of [35][c] (MWEG^{-1} Myr^{-1})		0.02		
Belczynski et al. pop. synth.: model B of [35][c] (MWEG^{-1} Myr^{-1})		0.01		
Belczynski et al. pop. synth.: model C of [35][c] (MWEG^{-1} Myr^{-1})		7.7		
Nelemans pop. synth. [36][d] (MWEG^{-1} Myr^{-1})	0.1	5	250	
"Double-core" scenario: Dewi et al. [37][e] (MWEG^{-1} Myr^{-1})	0.19	19.87		
Globular cluster dynamics [55][f] (Mpc^{-3} Myr^{-1})	10^{-4}	0.05		1
Globular cluster dynamics and pop. synth. [42][g] (GC^{-1} Gyr^{-1})		2.5		
Nuclear cluster w/ MBH [56][h] (NC^{-1} Myr^{-1})	2×10^{-4}	1.3×10^{-3}	0.015	
Nuclear cluster w/out MBH [57][i] (NC^{-1} Myr^{-1})		0.3		

Mon. Not. R. Astron. Soc. **342,** 1169–1184 (2003)

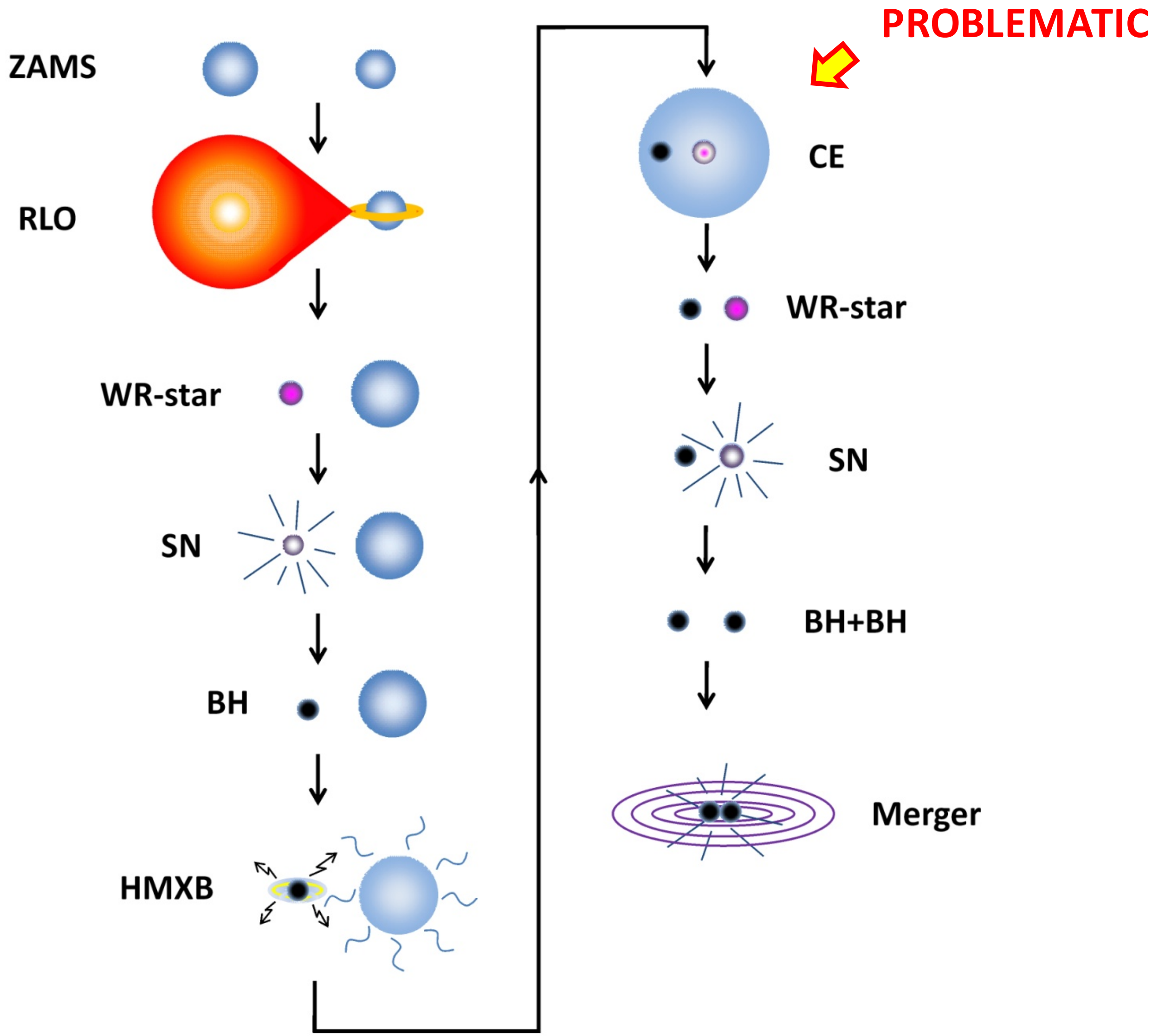
Galactic distribution of merging neutron stars and black holes – prospects for short gamma-ray burst progenitors and LIGO/VIRGO

R. Voss★ and T. M. Tauris★
★*Astronomical Observatory, Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen Ø, Denmark*



The BH-BH formation rate is extremely sensitive to a few key parameters

The standard formation scenario



$$\left(\frac{dE_{orb}}{dt}\right) = -\frac{GM_{donor}M_X}{2a^2}\frac{da}{dt} = \xi(\mu)\pi R_{acc}^2 \rho_{donor} v^3$$

Dissipation of E_{orb} by drag force (Bondi & Hoyle 1944)

Energy budget (α, λ)-formalism:

Webbink (1984), de Kool (1990)

Han et al. (1994), Dewi & Tauris (2000)

$$E_{env} \equiv \alpha\,\Delta E_{orb}$$

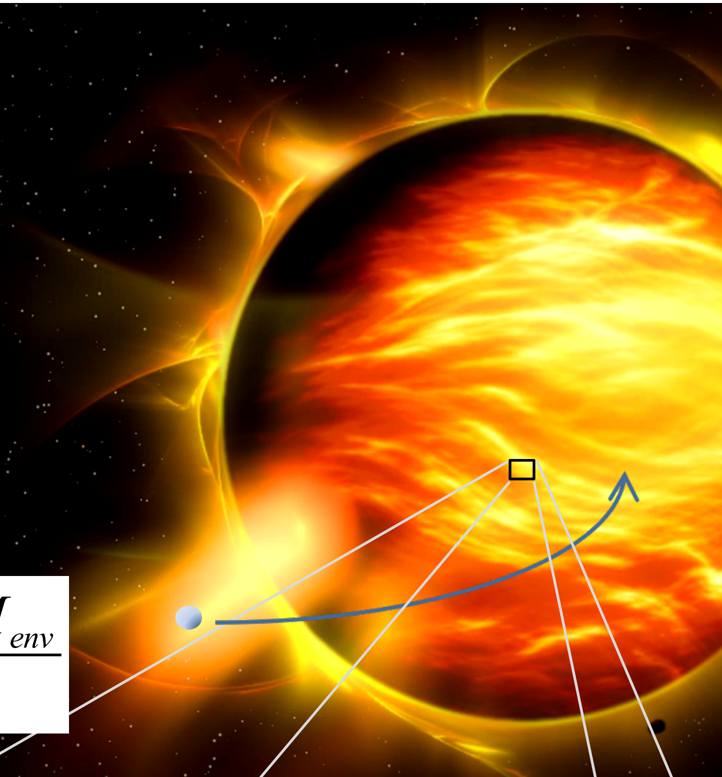
$$E_{env} = \int_{M_{core}}^{M_{donor}} \left(-\frac{GM(r)}{r} + \eta_{th}\,U\right) dm \equiv -\frac{GM_{donor}M_{env}}{\lambda\,R_{donor}}$$

gravitational binding energy

internal thermodynamic energy

- thermal energy
- energy of radiation
- recombination energy

Review by Ivanova et al. (2013)



1

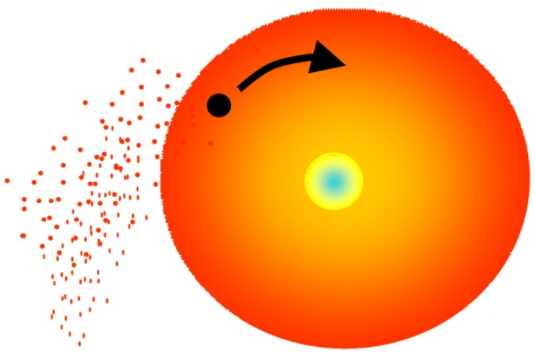
On the ejectability of common envelopes of massive stars

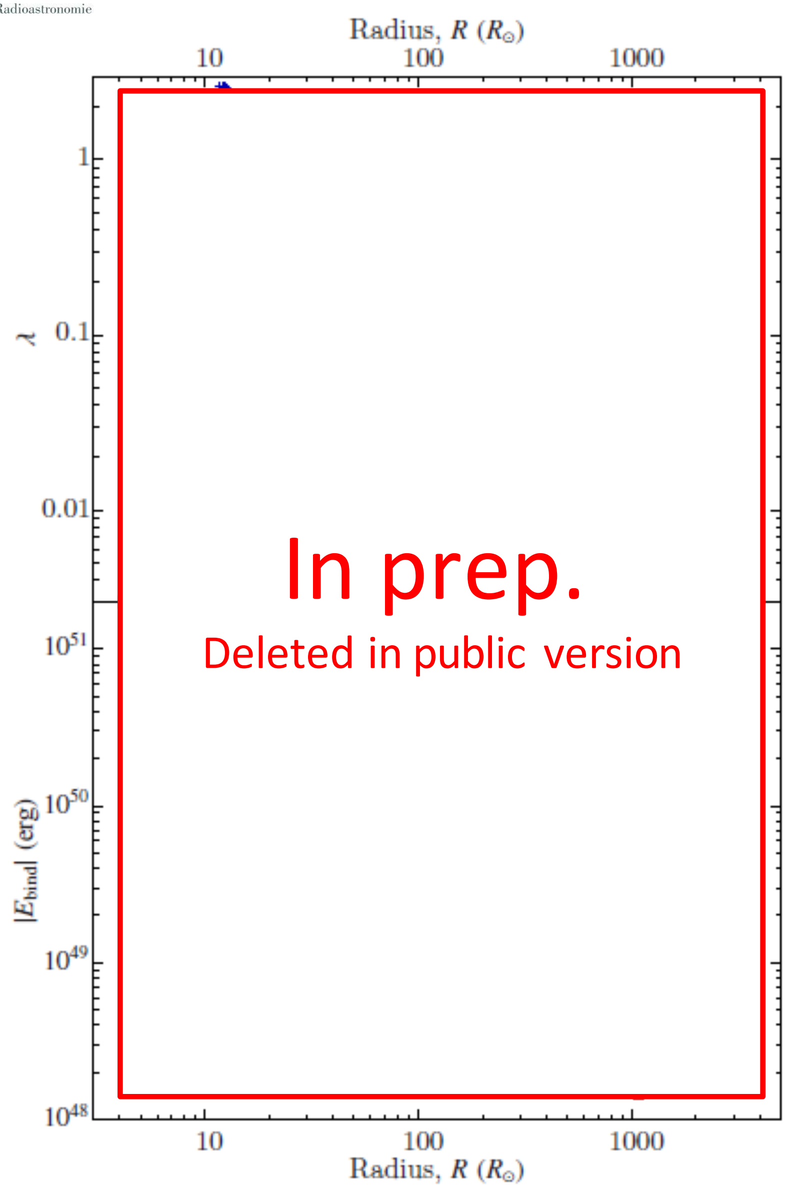
Implications for the progenitor of GW150914

in prep.

M. U. Kruckow[1,⋆], T. M. Tauris[2,1], N. Langer[1], D. Szécsi[1], P. Marchant[1] and Ph. Podsiadlowski[3,1]

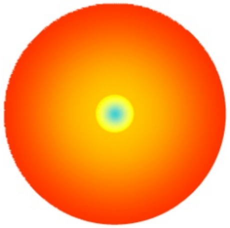
Can an in-spiralling BH eject the envelope of a massive star?





Kruckow et al. (2016), in prep.

Investigated the stellar structure of 4 – 115 M_{sun} stars at $Z=Z_{sun}/2$ (Milky Way) and $Z=Z_{sun}/50$ (IZw18).



$$E_{env} = \int_{M_{core}}^{M_{donor}} \left(-\frac{GM(r)}{r} + \eta_{th}\, U \right) dm$$

$$\equiv -\frac{GM_{donor} M_{env}}{\lambda R_{donor}}$$

Minimum mass of in-spiralling star to successfully eject the envelope?

$$\Delta E_{orb} \approx -\frac{G M_{core} M_X}{2\,a_{final}}$$

Kruckow et al. (2016), in prep.

In prep.

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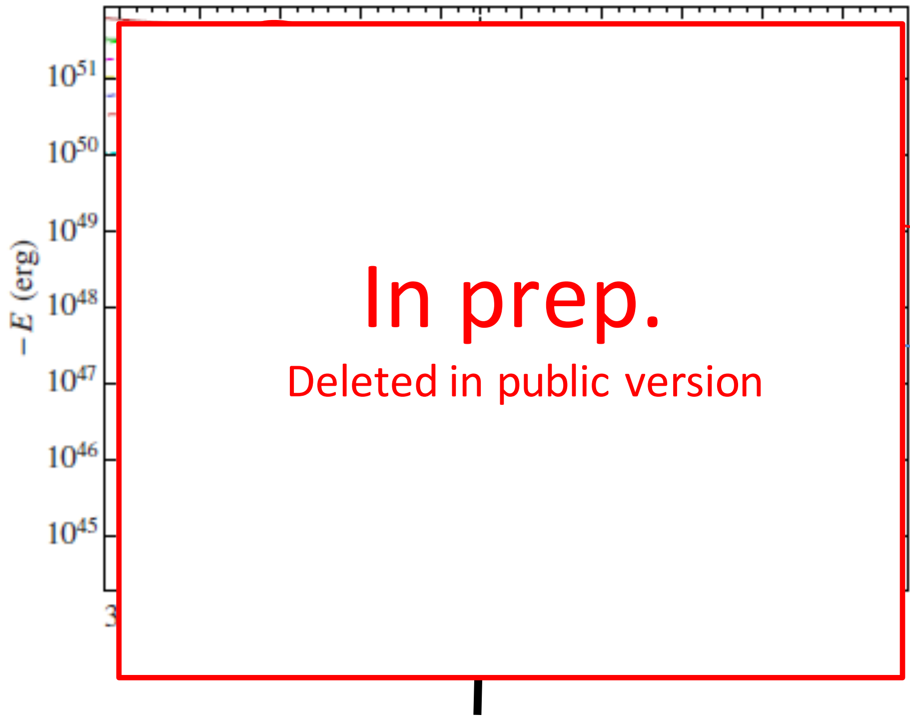
Where does the envelope ejection terminate?

Kruckow et al. (2016), in prep.

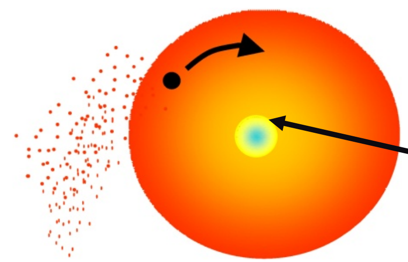


Core boundary: X_H=0.10
(close to local max. sonic velocity)

$88\ M_{sun}$ star @ $Z=Z_{sun}/50$
$R = 3530\ R_{sun}$

Point of no return

Minimum in-spiral

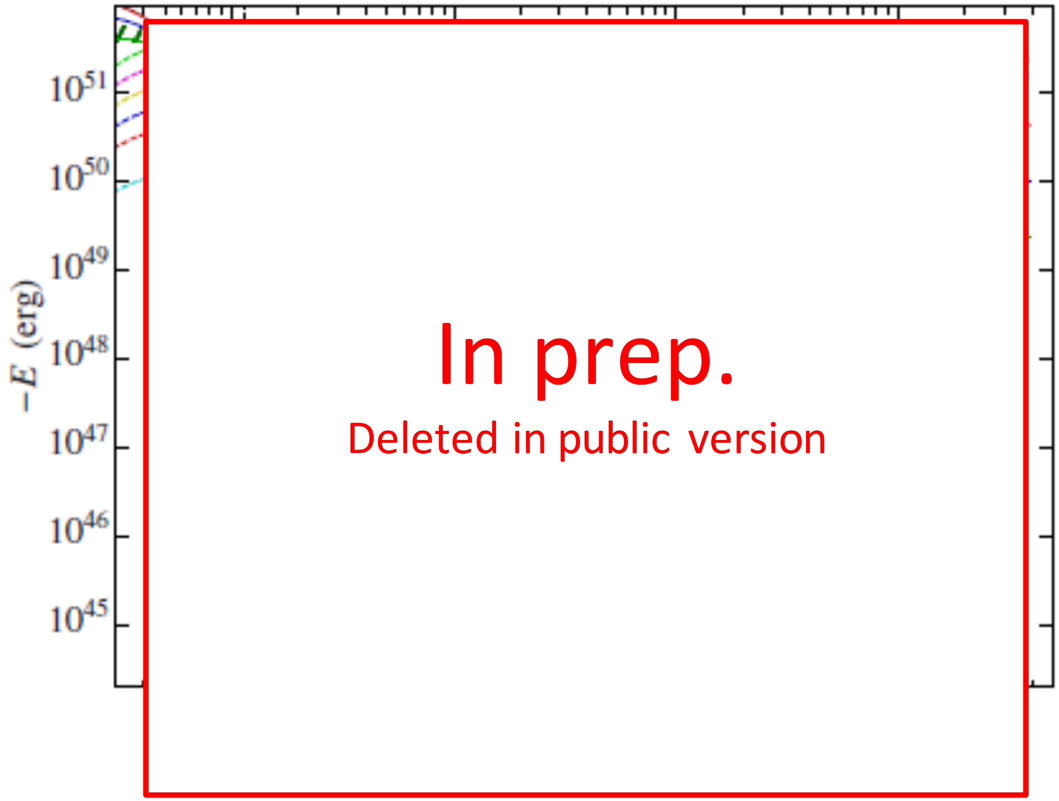


Bifurcation point?
Tauris & Dewi (2001)
Ivanova (2011)

Response of star to mass loss?

- Convective or radiative layer
  (Hjelming & Webbink 1987)
- Remaining amount of hydrogen

Kruckow et al. (2016), in prep.



Difference in mass coordinate of about 4 M_{sun} corresponds to a radius difference by a factor 500! Extremely important for the final orbital separation.

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Massive overcontact binary (MOB) and chemically homogeneous evolution (CHE) channel

CHE: (Talk by Mandel)
Maeder (1987), Langer (1992)
Heger & Langer (2000)
de Mink+(2009)
Mandel & de Mink (2016)
de Mink & Mandel (2016)

2

A new route towards merging massive black holes

Astronomy & Astrophysics
A&A 588, 50 (2016)

Pablo Marchant[1], Norbert Langer[1], Philipp Podsiadlowski[2,1], Thomas M. Tauris[1,3], and Takashi J. Moriya[1]

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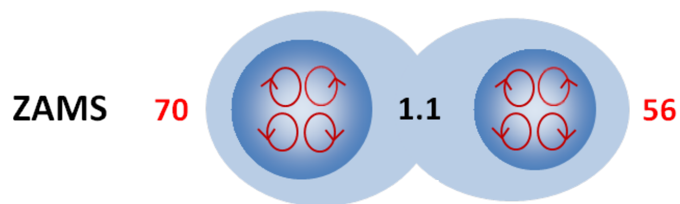

Requires:
- massive stars (high radiation pressure helps mixing)
- low-metallicity (small stellar winds):
  - removes little spin.ang.mom.
  - prevents orbital widening

NEW:
- first binary CHE calculations to core collapse
- MOB (avoid merger if no mass loss from L_2)

tight binary
↓ tidal forces
rapid rotation
↓ meridional currents
effective mixing
↓ no composition gradients
star remains compact
↓
no common envelope!

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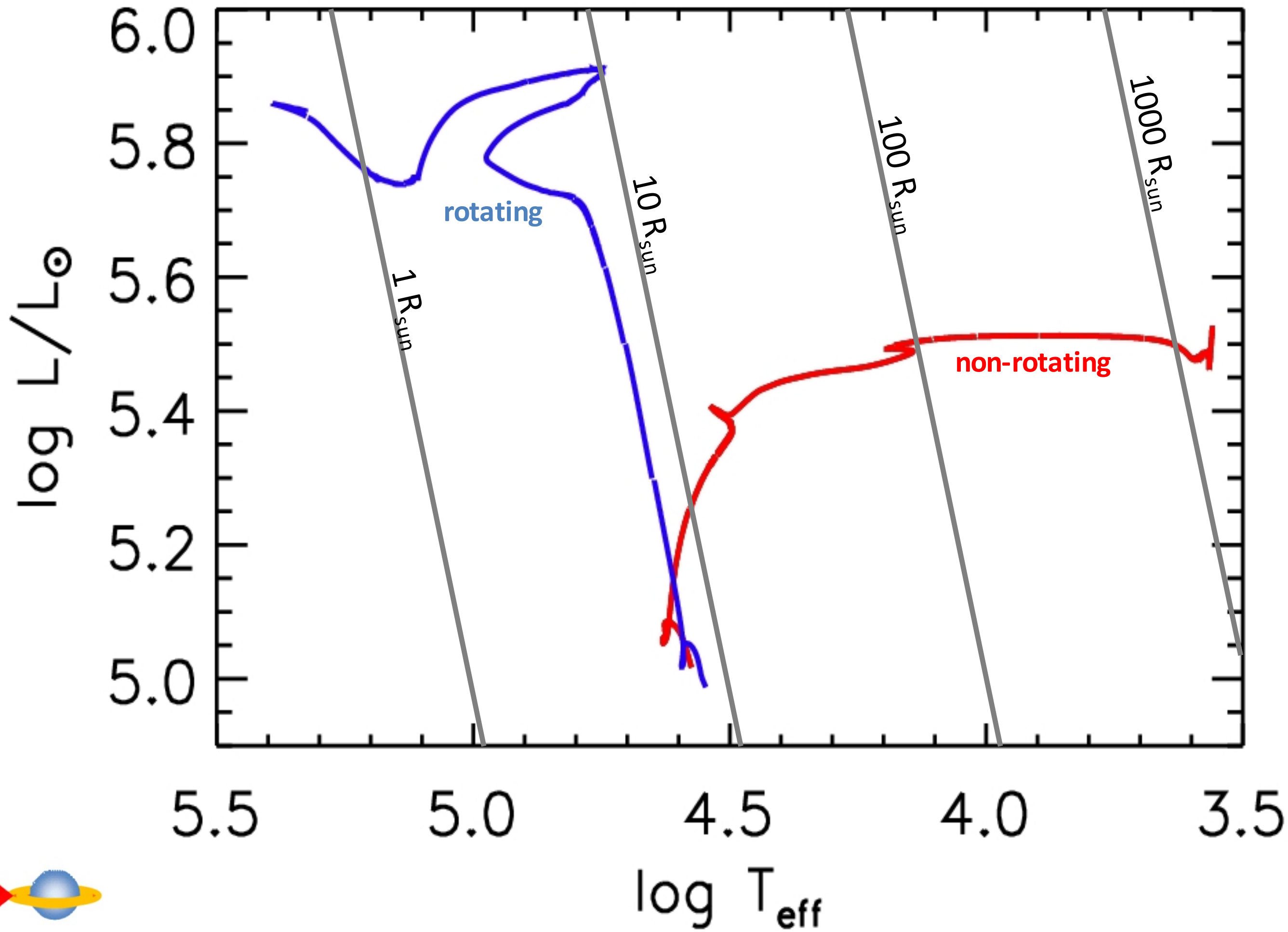
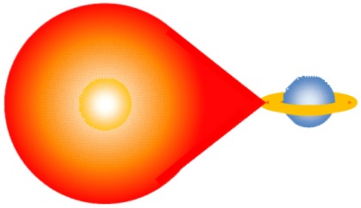
Chemically Homogeneous Evolution of a 30 M_{sun} star with Z=0.002

These rapidly **rotating stars** remain blue and compact, and often avoid RLO/CE

Yoon, Langer & Norman (2006)





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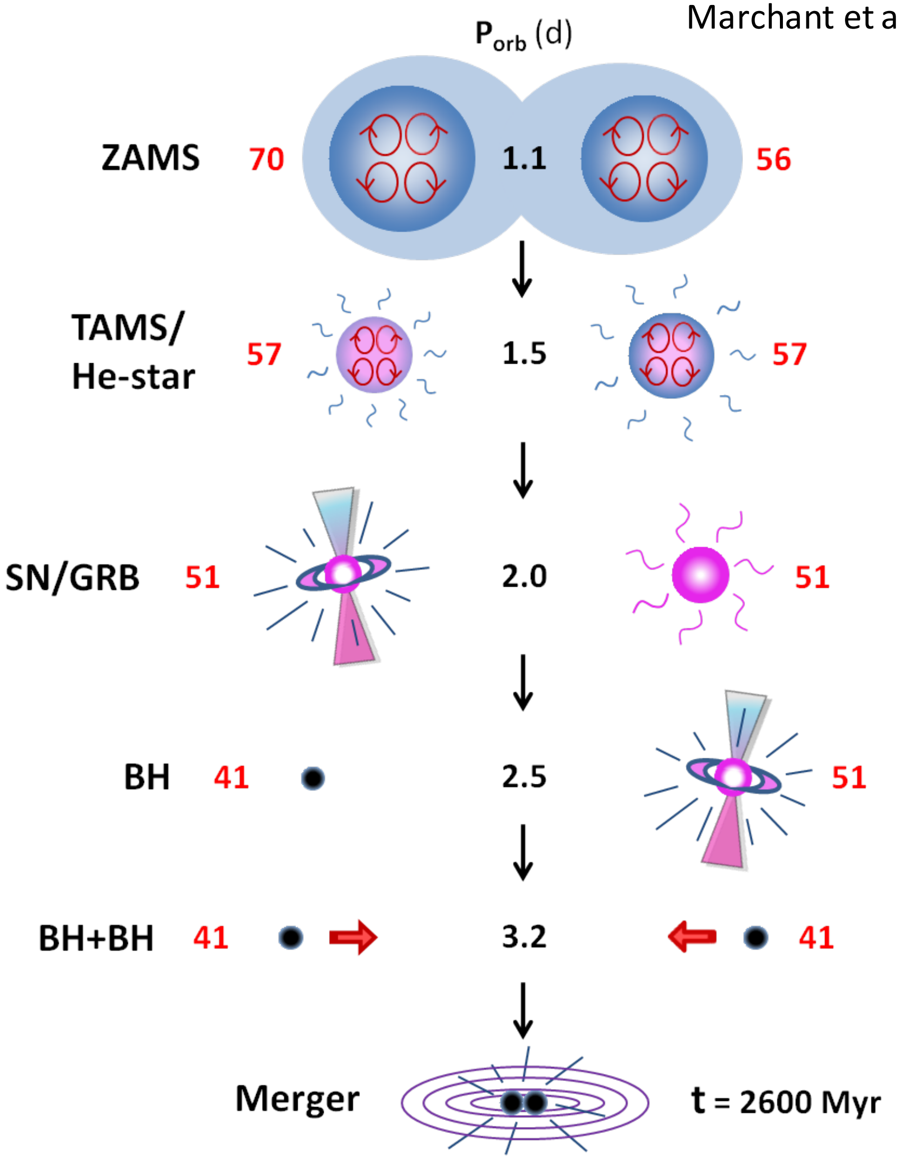
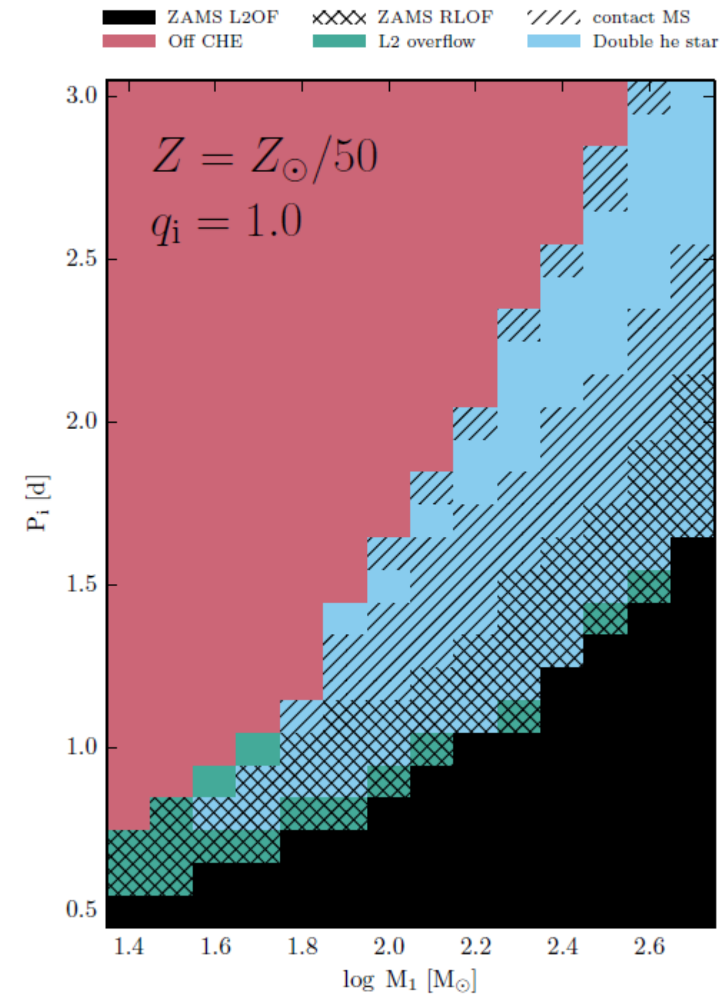
Marchant et al. (2016)

MODEL





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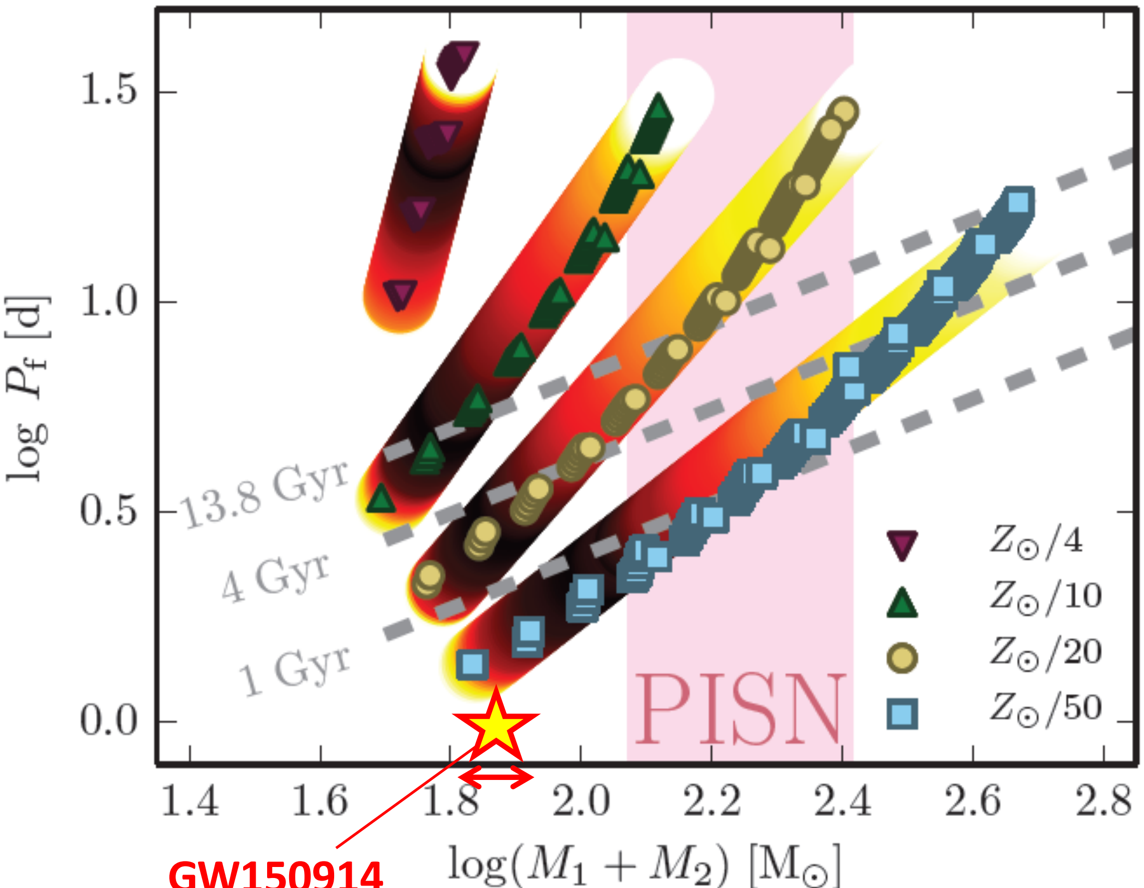
RESULTS

Marchant et al. (2016)



Strong dependence on **metallicity** (stellar winds)

Pair-instability SN gap

Heger & Woosley (2002)

Chatzopoulos & Wheeler (2012)

M_{BH} = 25-60 M_{sun}

M_{BH} > 130 M_{sun}

Can be **detected** by **LIGO** **if** the **seismic-wall cut** can be moved to **lower** frequencies.

Masses of collapsing cores!

BH masses might be smaller by 0-30%

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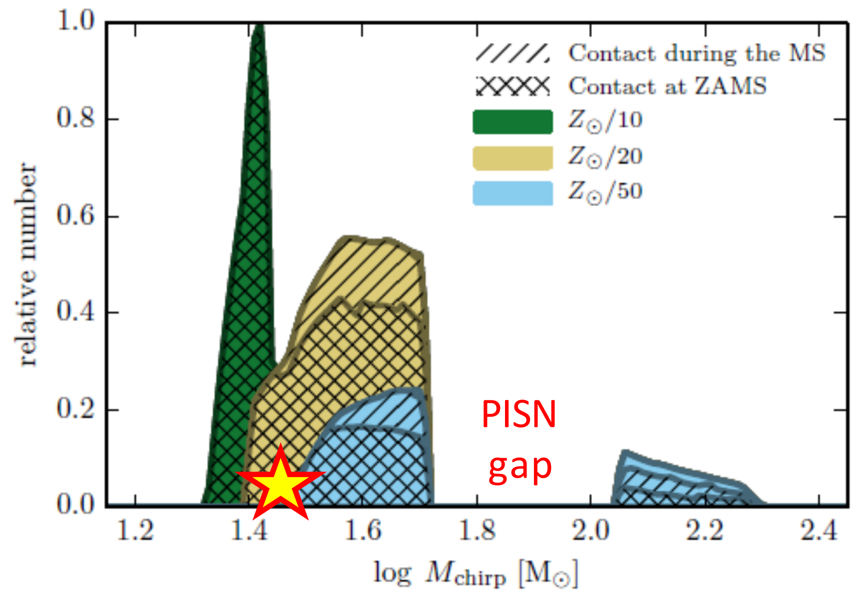
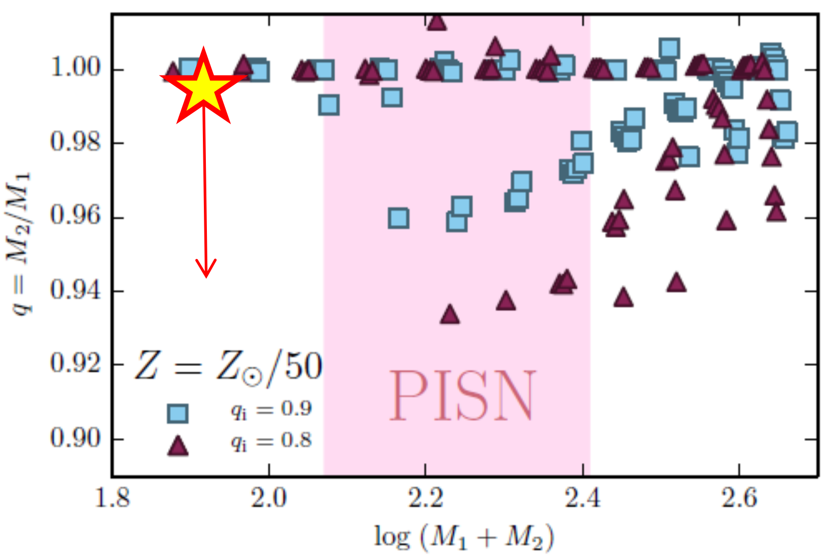
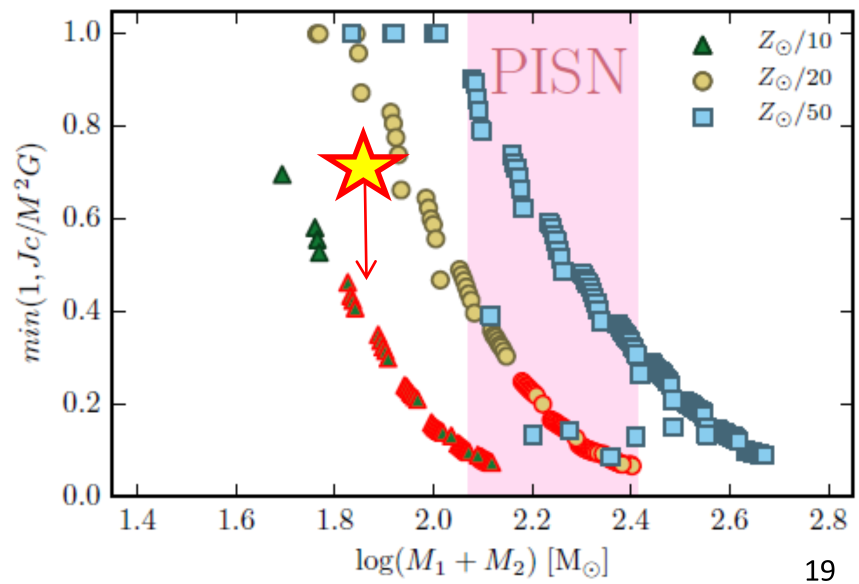
FURTHER RESULTS PREDICTIONS

- BH-BH mergers with q ~ 1
- PISN gap should be detected by LIGO
- Spins of BHs: a > 0.4 $(\vec{s_1} \neq \vec{s_2} \neq \vec{L}\,?)$
- Metallicities < $Z_{sun}/8$

Marchant et al. (2016)







aLIGO detection rates

Marchant et al. (2016)

Metallicity $\longrightarrow$	$Z_\odot/50$	$Z_\odot/20$	$Z_\odot/10$	$Z_\odot/4$	Integrated Z
$N_{\rm BHBH}/N_{\rm SN}$ below PISN gap	6.7×10^{-4}	1.3×10^{-3}	3.4×10^{-4}	0	$(0.69-13)\times10^{-5}$
$N_{\rm BHBH}/N_{\rm SN}$ above PISN gap	2.7×10^{-4}	0	0	0	$(0.011-1.8)\times10^{-5}$
aLIGO rate ($\rm yr^{-1}$) below PISN gap	3539	5151	501	0	19–550
aLIGO rate ($\rm yr^{-1}$) above PISN gap	5431	0	0	0	2.1–370

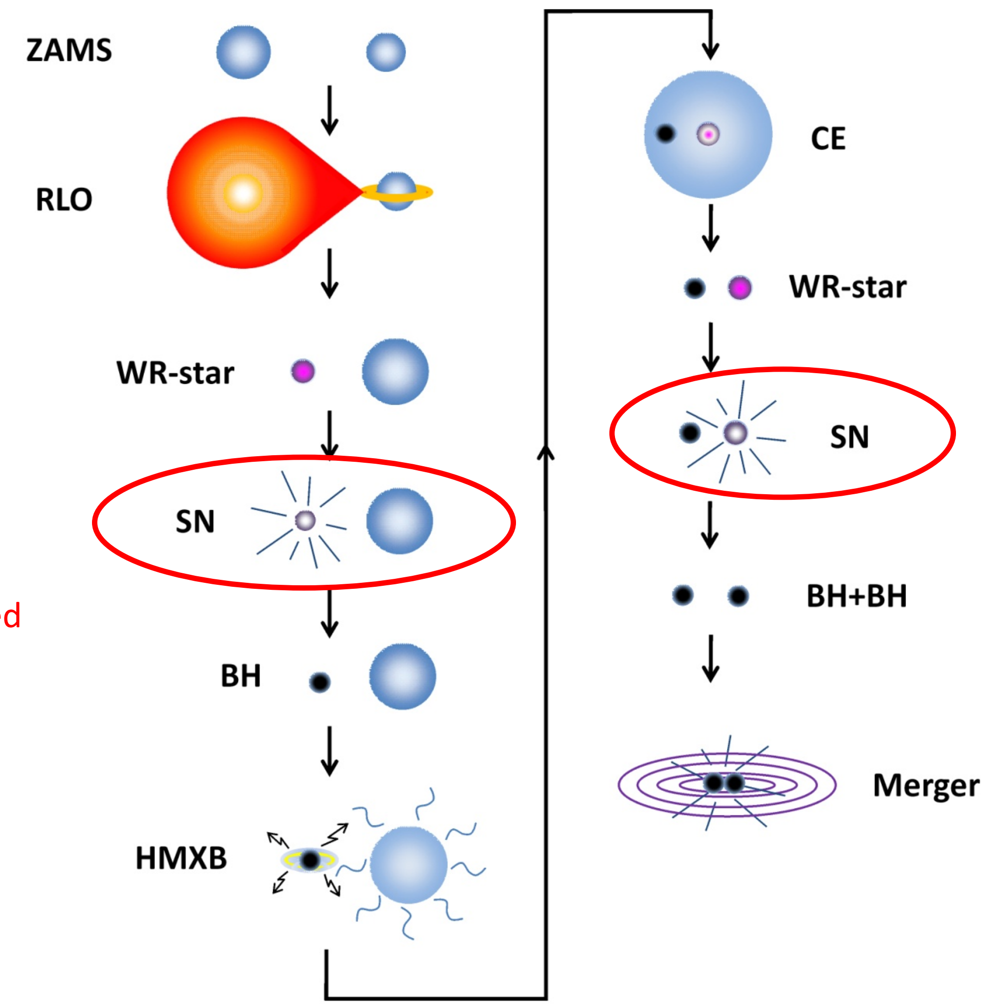
Uncertainties due to mapping of galactic **metallicity distribution** throughout the **Universe** *
Caveat: low f_{ISCO} above PISN gap + redshift

*Work in progress: chemical evolution and cosmology, improved LIGO sensitivities

BH kicks in std. scenario

Brandt et al. (1995)
Nelemans et al. (1999)
Repetto et al. (2012)
Janka (2013)
Mandel (2016)

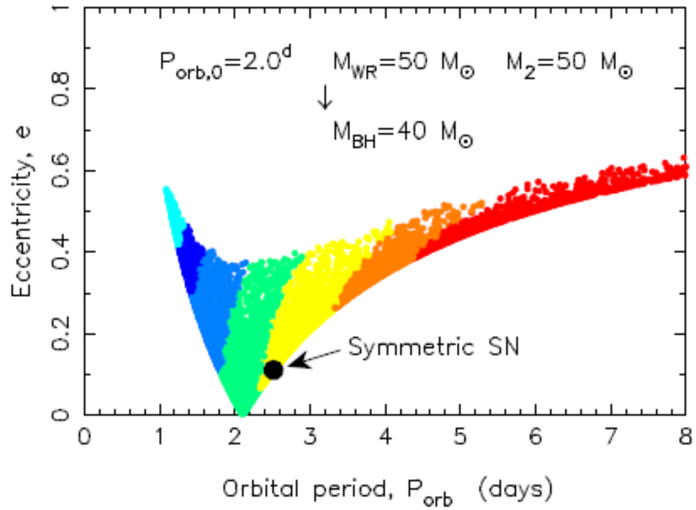
small kicks
because wide
orbit is required
for CE ejection

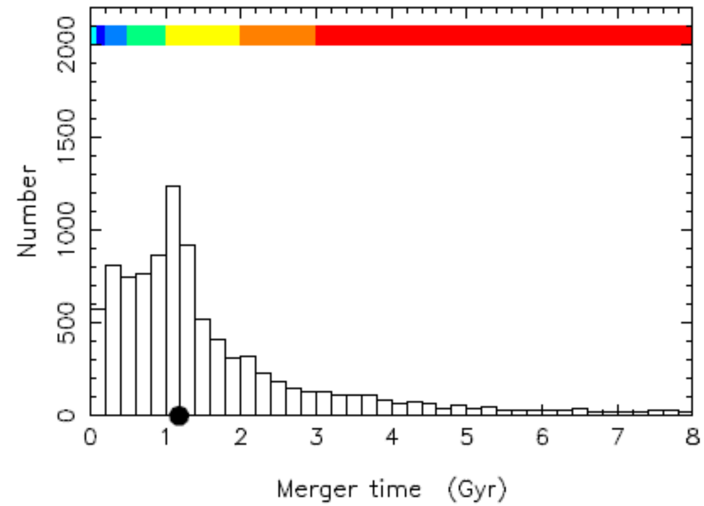


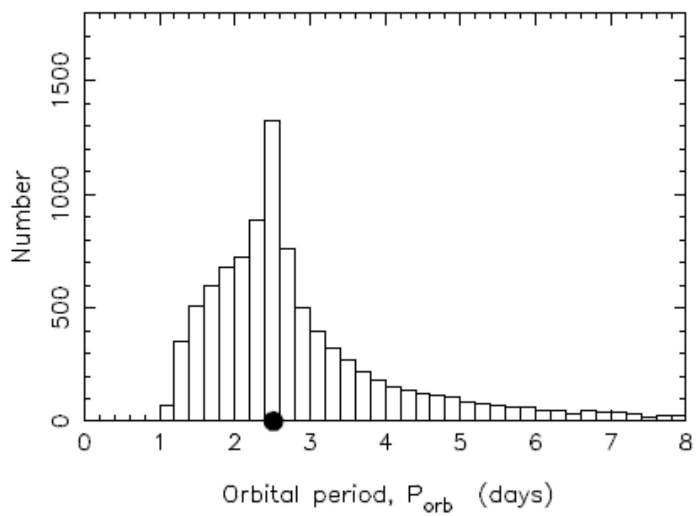
large kick ok

Effect of BH kicks

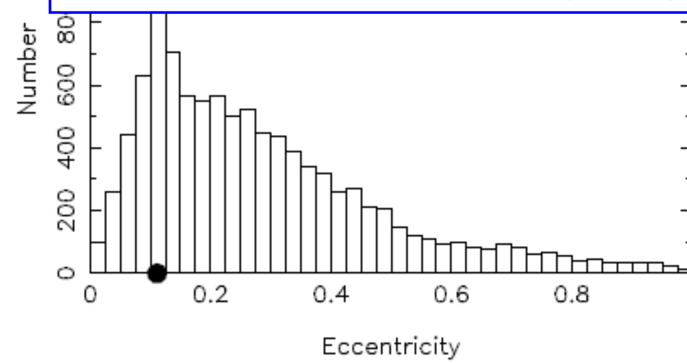
Marchant et al. (2016)







$$L_{gwr} \cong \frac{32}{5}\frac{G^4}{c^5}\frac{M^3\mu^2}{a^5}\frac{1+(73/24)e^2+(37/96)e^4}{\left(1-e^2\right)^{7/2}}$$



Conclusions

- Massive stars up to, at least, 115 M_{sun} (for a wide range of metallicities) are **likely** to shed their envelopes and **survive CE evolution** (Kruckow et al. 2016, in prep.)

  $\rightarrow$ The standard formation channel can possibly produce **GW150914** progenitors

- **MOB** (**massive overcontact binary**) with **CHE** (chemical homogeneous evolution) is a **new formation channel** for massive BH-BH binaries (Marchant et al. 2016)

  $\rightarrow$ **Avoid** the controversial **common envelope** phase

- **Predictions** for LIGO from the **MOB scenario**:

  $\rightarrow$ BH **mass ratios** close to 1 (not required in the standard scenario)

  $\rightarrow$ **Spins** of merging BHs: a > 0.4 $(\vec{s_1} \neq \vec{s_2} \neq \vec{L}\,?)$

  $\rightarrow$ Pair-instability SN **gap** should be **detected** in ref. frame of binaries

- **Future LIGO** BH-BH merger detections will be able to **distinguish** formation models

THANK YOU!