BH-BH mergers from rotational mixing in tight binaries

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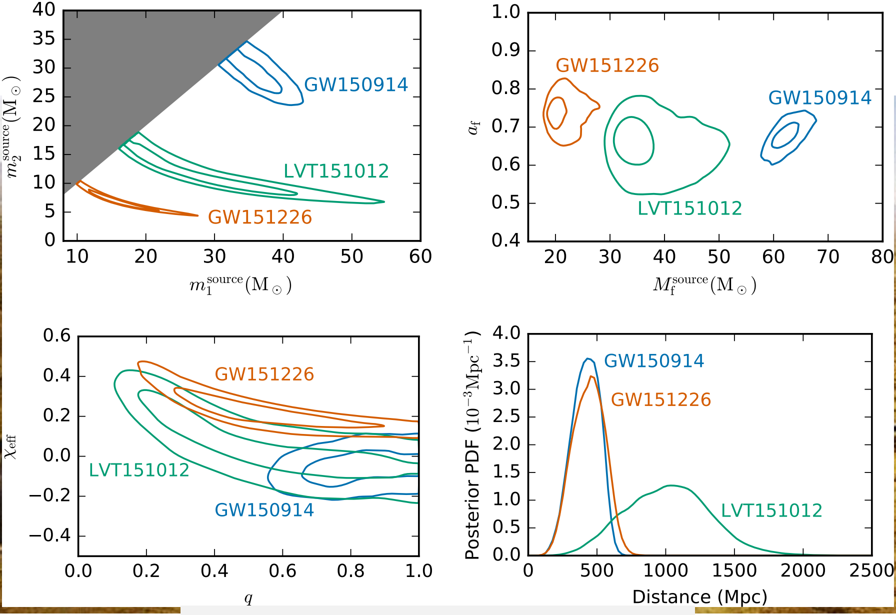

Abbott+ 2016 , astro-ph/1606.04856

Second science run on its way!

Abbott+ 2016
astro-ph/1606.04856

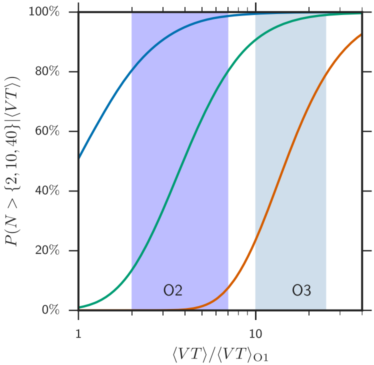

FIG. 13. The probability of observing $N > 2$, $N > 10$, and $N > 40$ highly significant events, as a function of surveyed space-time volume, given the results presented here. The vertical line and bands show, from left to right, the expected sensitive space-time volume for the second (O2) and third (O3) advanced detector observing runs.

- Inferred rate of merging BHs of $9 - 240\ \mathrm{Gpc}^3\ \mathrm{yr}^{-1}$.
- Several detections expected in the upcoming science runs.
- What are the astrophysical implications of these detections?

Proposed formation channels

- Dynamical formation in a cluster (Portegies Zwart & McMillan 2000, Rodriguez+ 2016a,b).
  - Form the black holes through single stellar evolution, bring them together through many body interactions.
- Common-envelope evolution in wide binaries (Tutukov & Yungelson 1993, Belczynski+ 2016).
  - Start from a very wide binary and make it compact through binary interaction.
- Chemically homogeneous evolution in short period binaries (Mandel & de Mink 2016, Marchant+ 2016).
  - Start with a small separation and avoid stellar expansion through efficient mixing.

Paczynski 1976

COMMON ENVELOPE BINARIES

B. PACZYNSKI

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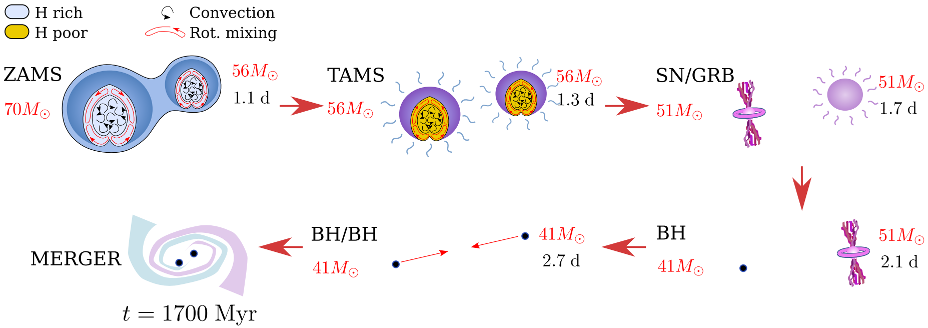
envelope binary. I think this is the most natural way for explaining the origin of cataclysmic binaries, and other suggestions are less realistic.

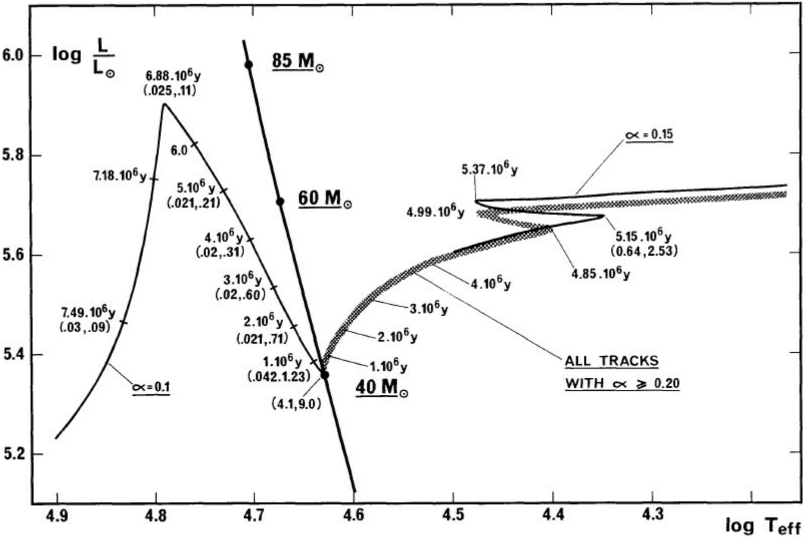
The two most common suggestions for the origin of novae and dwarf novae do not require a common envelope phase of evolution. According to the first hypothesis one of the components of a short period binary was always mixed so well that it evolved as a chemically homogeneous star. It becomes a white dwarf without ever being a red giant. I can see no physical process that could account for the complete mixing of a star. Notice that no binary can be identified as a system evolving according to this hypothesis. It should be emphasized that nuclear evolution lasts much longer if a star is kept homogeneous because it has more fuel to burn. According to a second hypothesis the white

Chemically homogeneous evolution

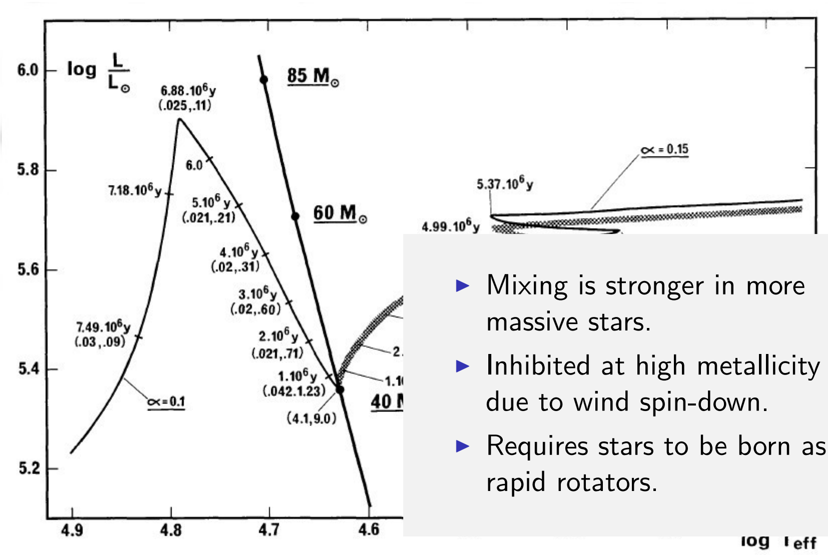


Mandel & de Mink 2016,
Marchant+ 2016

Chemically homogeneous evolution (Maeder 1987)

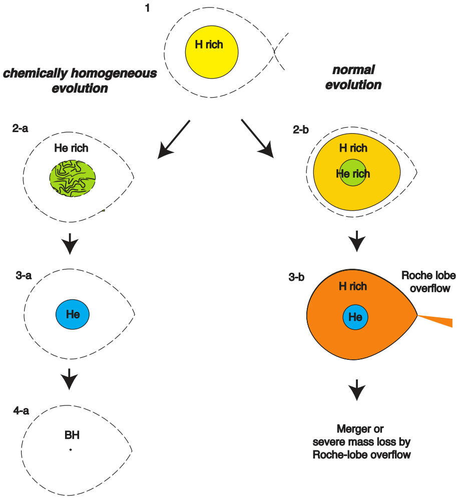


Chemically homogeneous evolution (Maeder 1987)



- Mixing is stronger in more massive stars.
- Inhibited at high metallicity due to wind spin-down.
- Requires stars to be born as rapid rotators.

Tidal locking in close binaries as a source of rapid rotation



de Mink+ 2009

- Possibility of double-BH formation.
- Königsberger et al. 2014: Double He star system in the SMC
  - $M_1 = 66 M_\odot$, $M_2 = 61 M_\odot$
  - $P = 19.3$ days

Song+ 2016

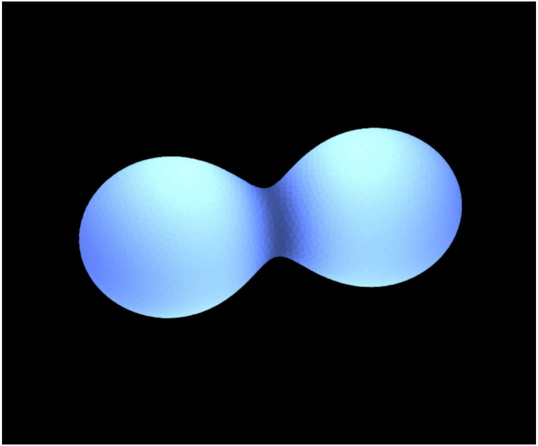
Mandel & de Mink 2016

Marchant+ 2016

de Mink & Mandel 2016

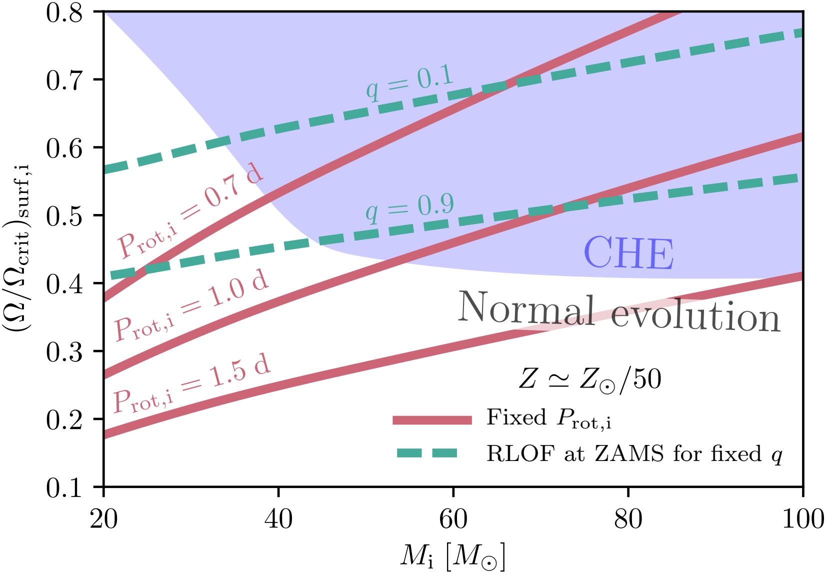
Almeida et al. 2015: Massive overcontact binary

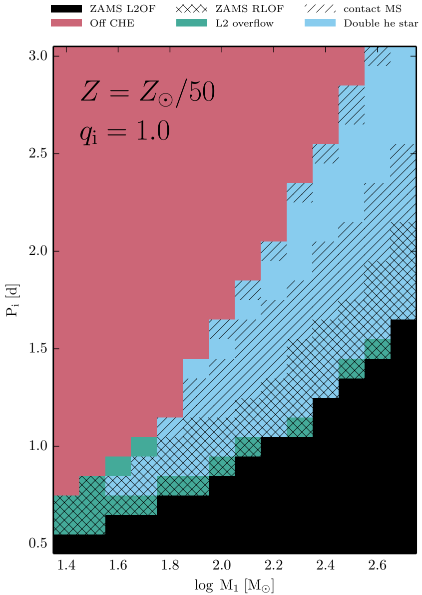
$M_1 \simeq M_2 \simeq 30 M_\odot$, $q = M_1/M_2 = 1.008$, $P_{\rm orb} = 1.12$ [d]



VFTS 352, most massive overcontact binary known.

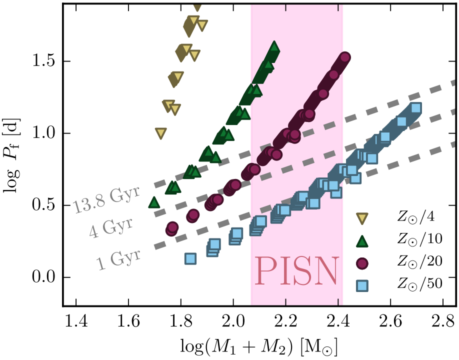
CHE is more likely to happen in very massive stars



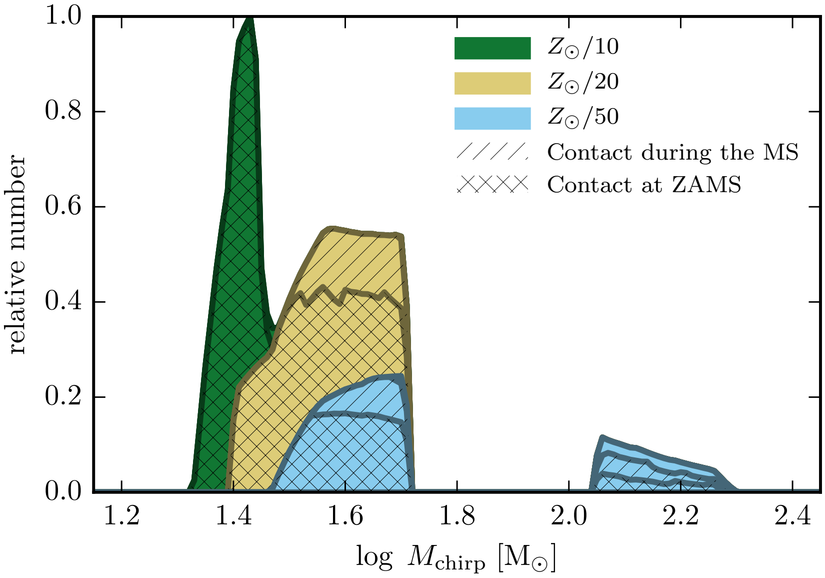


Marchant+ 2016

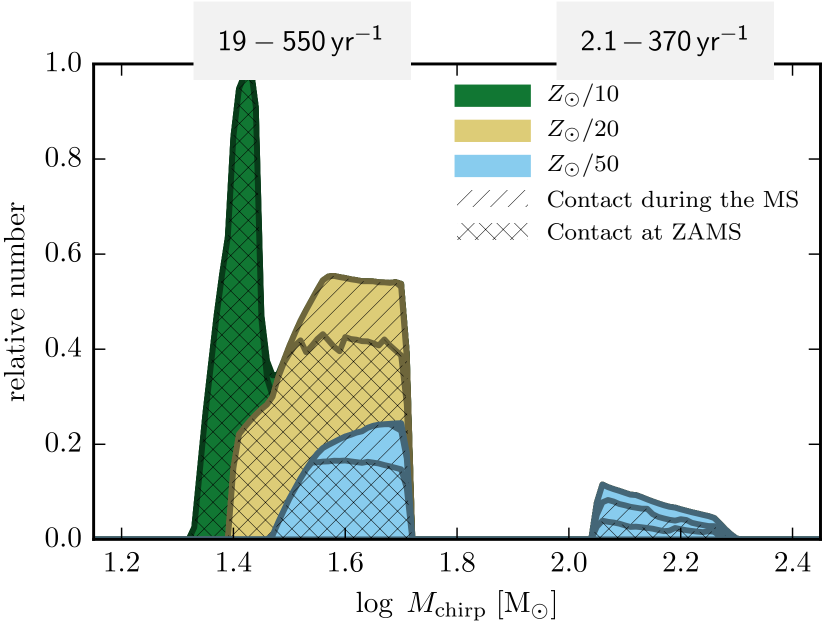
- Black hole mergers with mass ratio very close to 1
- Gap in chirp masses due to PISNe
- For $Z < Z_\odot/20$ LGRBs could be produced



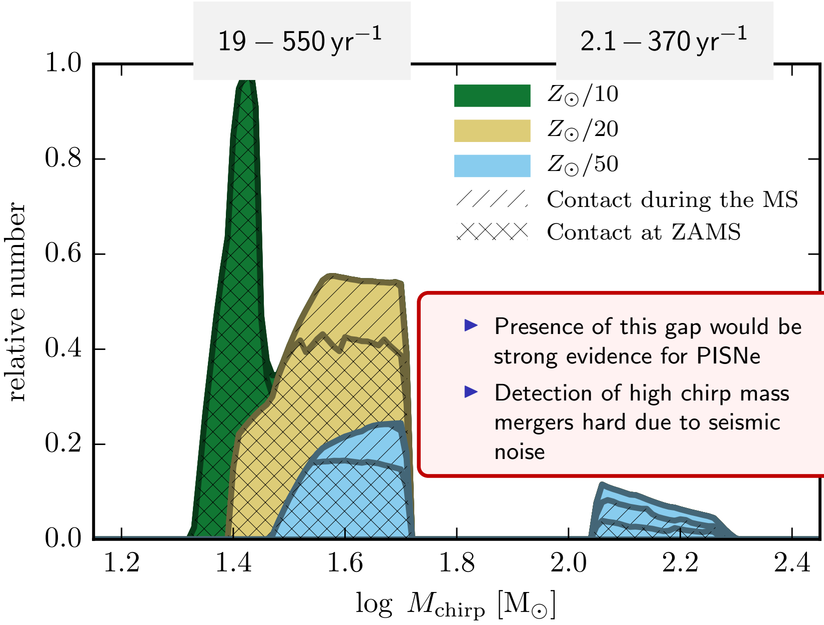
Chirp mass distribution



Chirp mass distribution

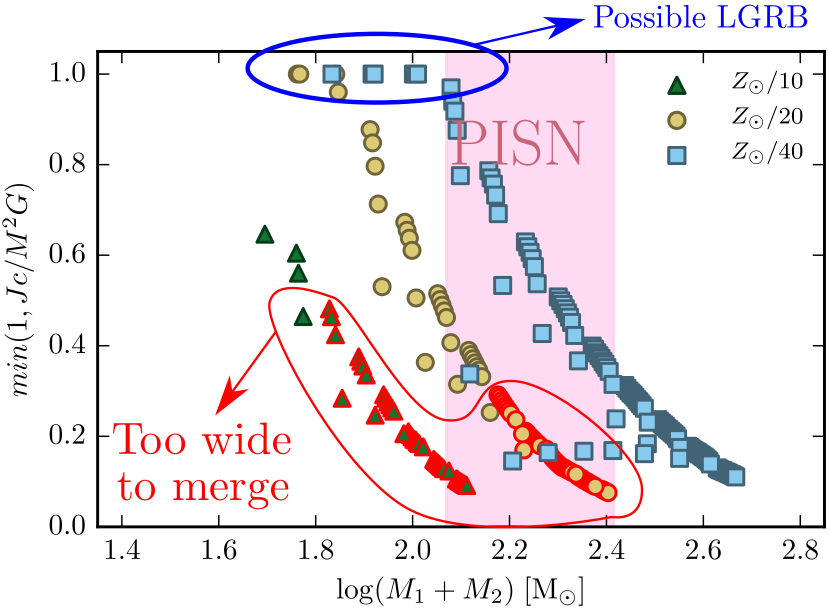


Chirp mass distribution



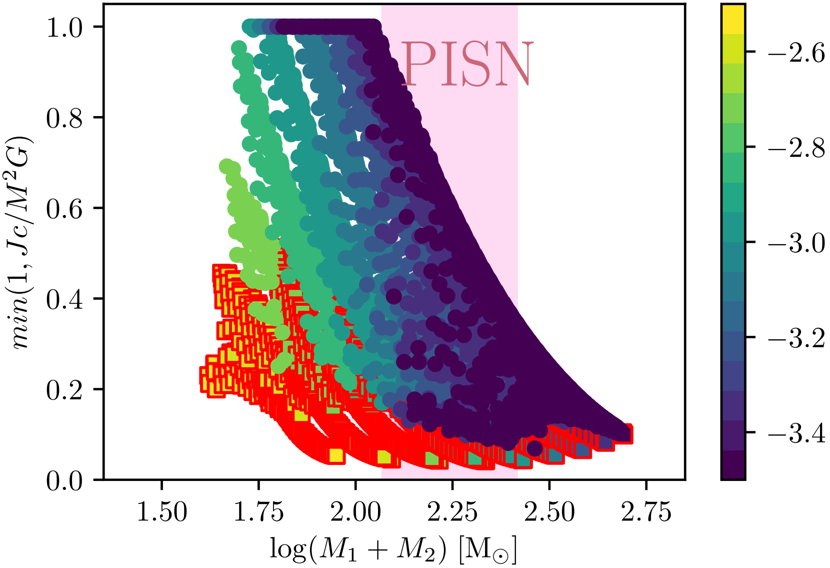
- Presence of this gap would be strong evidence for PISNe
- Detection of high chirp mass mergers hard due to seismic noise

High spins!



Possible LGRB
PISN
$Z_\odot/10$
$Z_\odot/20$
$Z_\odot/40$
Too wide
to merge
$min(1, Jc/M^2G)$
$\log(M_1 + M_2)$ [$M_\odot$]
1.0
0.8
0.6
0.4
0.2
0.0
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8

High spins!



PISN
$min(1, Jc/M^2G)$
$\log(M_1 + M_2)$ [$M_\odot$]
$\log Z$
0.0
0.2
0.4
0.6
0.8
1.0
1.50
1.75
2.00
2.25
2.50
2.75
−2.6
−2.8
−3.0
−3.2
−3.4

Expected properties of formed BHs

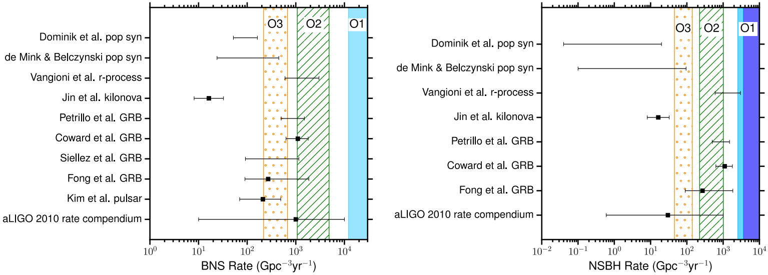
Within uncertainties, all channels fall within the expected rates.

- Dynamical:
  - Mass ratios close to unity.
  - Randomly oriented spins.
  - High eccentricity.
- Common envelope:
  - Mass ratios close to unity.
  - Aligned spins.
- Chemically homogeneous evolution:
  - Mass ratios extremely close to unity.
  - Aligned, and high spins.
  - Gap in chirp masses.
  - Hard to produce masses below $15M_\odot$ (GW151226).

Very hard to find a smoking gun in an individual observation (see `http://gwaves-m16.wikispaces.com/Reference+Material` for a discussion).

Mergers with a neutron star

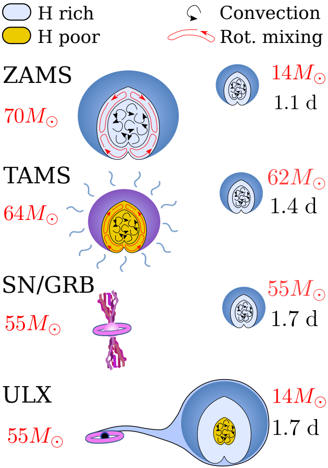
- The prospect of detection of binary mergers with an electromagnetic counterpart can provide further constraints.

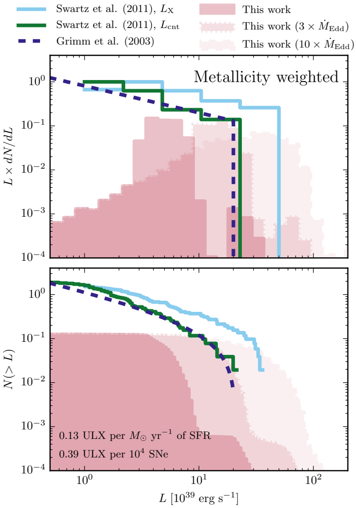


Abbott+ 2016 (astro-ph:1607.07456)

- NS-NS and NS-BH mergers expected from common envelope. NS-BH expected from chemically homogeneous evolution.

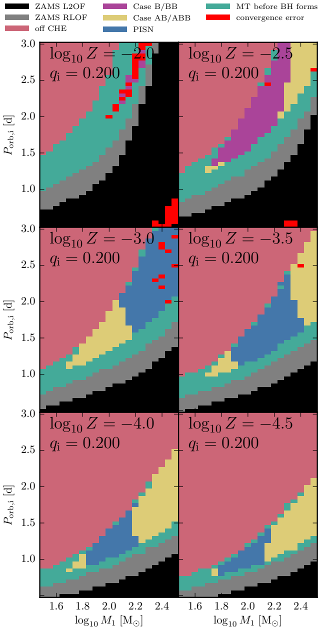
Formation of ULXs through CHE





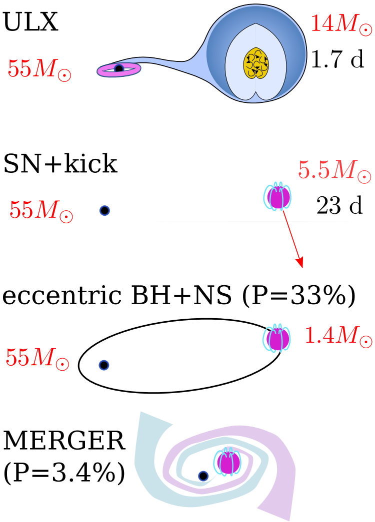
Marchant+, submitted

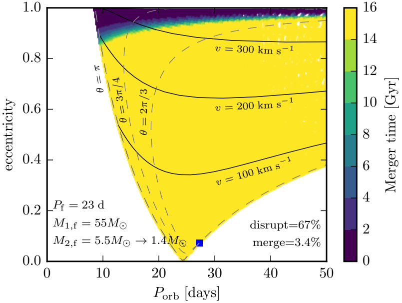
∼ 120 000 MESA models



- Strong metallicity dependence due to mass loss.
- Few sources below $Z = 10^{-2}$
- At $Z = 10^{-3}$, PISNe produce mass cutoff below $M_{\rm BH} = 60 M_\odot$
- At a metallicity of $Z = 10^{-3.5}$, BHs above the PISNe gap could be formed.
- Possible gap in ULX luminosities!

Possibility of forming NS+BH mergers

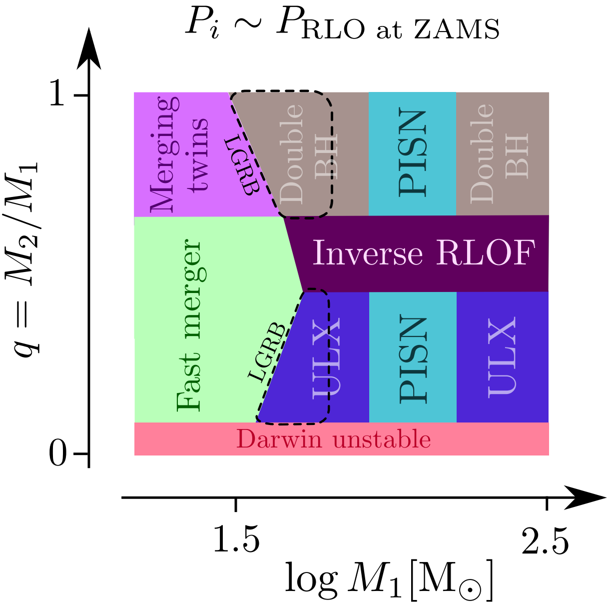




Rate $< 0.2\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ No

EM counterpart expected (see Foucart 2012)

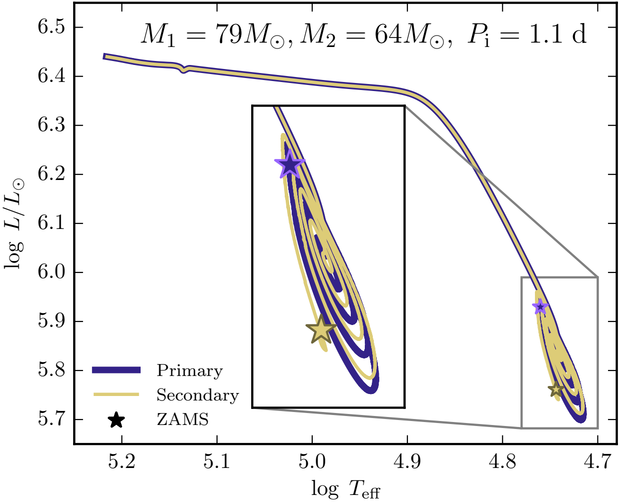
Evolutionary channels of VMS stars in compact orbits



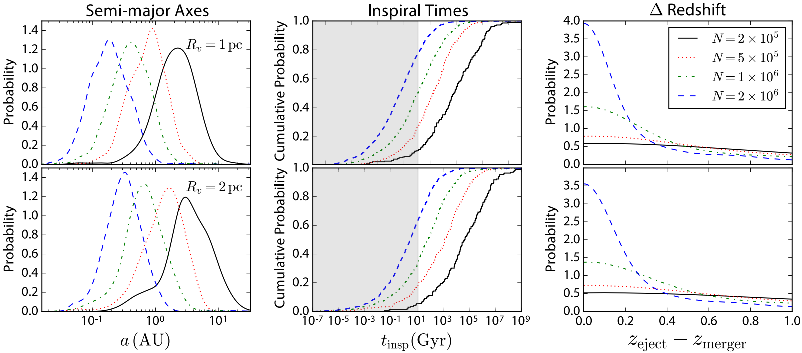
Conclusions

- Chemically homogeneous evolution is expected to produce binary BHs that can merge in less than a Hubble time, which can be detected by aLIGO.
- The observation of a gap in BH masses in the range $\sim 60 - 130 M_{\odot}$ would give strong evidence for the existence of PISNe.
- Binary BHs with masses similar to GW150914 and low effective spins can also be produced, but would require enhanced loss of orbital angular momentum to result in a merger.
- Systems where only one component evolves chemically homogeneous are expected to produce ULXs, resulting in a gap in X-ray luminosity distributions.
- After a ULX phase, there is a small probability of forming a BH-NS binary compact ennough to result in a merger, with a formation rate $< 0.2\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$.

Evolution towards $q = 1$ in contact systems.



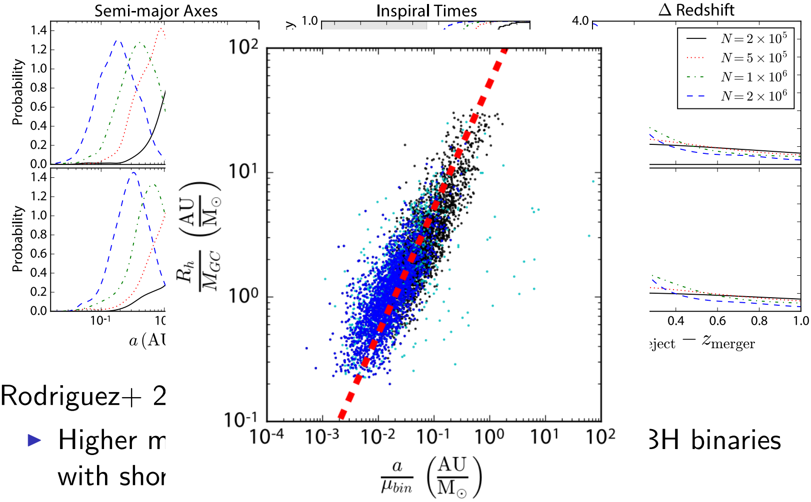
Dynamical formation in a globular cluster



Rodriguez+ 2016a

- Higher mass clusters with smaller radii produce BH binaries with shorter periods.

Dynamical formation in a globular cluster

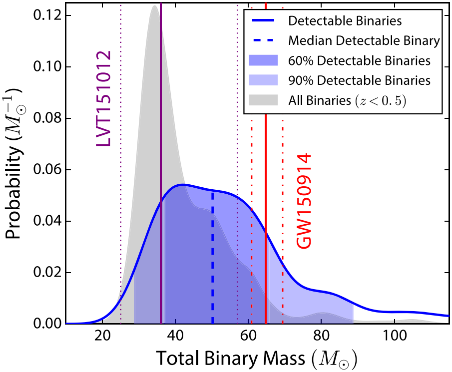


Rodriguez+ 2

- Higher m … 3H binaries
  with shor

Dynamical formation in a globular cluster

- Predicted merger rate at $z \sim 0.1$ of $2 - 20\ Gpc^{-3} yr^{-1}$ (Rodriguez+ 2016b).



- GW151226 can be formed in globular clusters with metallicities $Z > Z_\odot/2$ (Chatterjee+ 2016).

Common envelope evolution

- First discussed in the context of cataclysmic variables by Paczsynski 1976 and van den Heuvel 1976. Classical energy criterion considers the binding energy of the hydrogen rich envelope $E_{\rm bind}$, and estimates the final separation using the change in orbital energy due to the inspiral,

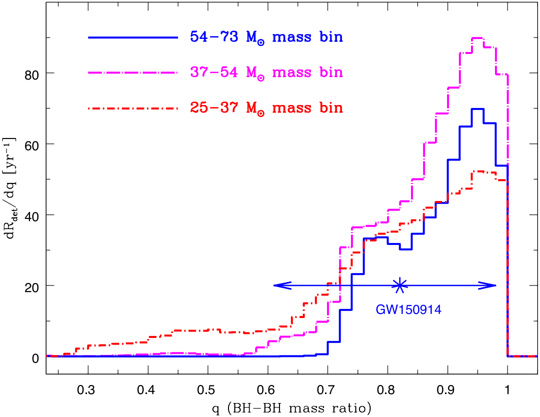
$$\Delta E_{\rm orb} = \alpha \left(-\frac{G M_{1,\rm core} M_2}{2 a_{\rm f}} + \frac{G M_{1,\rm i} M_2}{2 a_{\rm i}} \right) \simeq -\frac{\alpha G M_{1,\rm f} M_2}{2 a_{\rm f}}.$$

$$\Delta E_{\rm orb} = E_{\rm bind} \rightarrow a_{\rm f} = -\frac{\alpha G M_{1,\rm f} M_2}{2 E_{\rm bind}}$$

- Very uncertain process, fundamental to the formation of multiple close binary systems (see Ivanova+ 2013 for a review).

Common envelope evolution

- Expected mass ratios close to unity (Belczynski+ 2016).



Common envelope evolution

- Can produce mass holes covering the range of masses for the three GW detections(Belczynski+ 2016).