Gravitational Wave Detection of Massive Stellar BH Binaries
Outline

• Rates and volumes of GW detection
• Dynamics: three-body encounters
• Dynamics: Kozai-Lidov resonances in triples
Maximum Rate per Volume

- IMF reaches to $>500 \, M_{\text{sun}}$
- Wind losses are not severe
- Pair instability SNe do not dominate
- Kicks are not too high
Possible Detection Rates

- $5 \times 10^{-9}$ Mpc$^{-3}$ yr$^{-1}$, few $10^{-3}$ yr
- Rate could be much lower, but point is that efficiency need not be high to get few yr$^{-1}$
- But if MBH binaries form (no PISN), they may all be wide (no CE); how will they merge?

Belczynski et al. 2014

"Spin" means $a/M = 0.6$
Binary-Single Interactions

- In dense stellar environment, third objects can interact with binary.
- Binary is hardened.
- Binary eccentricity tends to increase; three equal masses $\Rightarrow P(e) = 2e$, but smaller interlopers mean $e$ driven higher.
- Reduces merger time.

Diagram:

A

B

C
Some Equations and Numbers

\[ T_{\text{shrink}} \approx 6 \times 10^8 \text{ yr} \ \rho_3^{-1} \left( \frac{a}{10 \ \text{AU}} \right)^{-1} \left( \frac{v_\infty}{3 \ \text{km s}^{-1}} \right) \]

\[ T_{\text{GW}} = 2.9 \times 10^{15} \text{ yr} \left( \frac{\eta}{0.25} \right)^{-1} \left( \frac{M}{200 \ M_\odot} \right)^{-3} \left( \frac{a}{10 \ \text{AU}} \right)^4 (1 - e^2)^{7/2} \]
Total Time For This Path

Using formulae of Quinlan (1996), a 100M sun⁻¹00M sun binary will go from \( e=0.7 \) to \( e=0.99 \) in \( 2.4 \times 10^{-5} \) foldings (\( \sim 1 \) Gyr), and to \( e=0.999 \) in \( 3.4 \times 10^{-5} \) foldings.

Thus \( \sim 1 \) Gyr is typical; spins typically not aligned at merger.

Note: R136 has \( \rho_c \sim 1.5 \times 10^4 \) M sun pc⁻³, and Arches and others even denser.
Kozai-Lidov Resonance

• Three-body system; relevant because ~10% (?) of massive stars are in triple or higher-order systems
• Inner binary exchanges inclination, eccentricity
• Can get to high e, but can be limited by pericenter precession (prob. not here) (Miller and Hamilton 2002)
• Increasing e decreases $T_{GW}$ dramatically: $\sim (1-e^2)^{7/2}$

(Miller and Hamilton 2002)
Simplified Equations, Numbers

\[ T_{\text{Kozai}} \approx 2 \times 10^5 \text{ yr} \left( \frac{0.01M}{m} \right) \left( \frac{0.1b}{a} \right)^3 \left( \frac{M}{200 \, M_{\odot}} \right)^{-1/2} \left( \frac{a}{10 \, \text{AU}} \right)^{3/2} \]

\[ e_{\text{max}} \approx \left[ 1 - \frac{5}{3} \cos^2 i_0 \right]^{1/2} \]

e.g., \( e_{\text{max}} = 0.97 \) for \( i_0 = 80^\circ \)
Open Questions

• Many!
• Numbers for massive stars in binaries that evolve to MBH, fraction in triples, orientations of triples, mass ratios, ...
• Also, of MBH, what fraction are in clusters that last long enough (~1 Gyr) for three-body interactions?
Conclusions

• We don't know if ~100 $M_{\odot}$ BH evolve from single stars, and what fraction are in binaries with similarly massive BH.

• But they are visible over a huge volume, so efficiency need not be large for GW detection.

• Even if newly-formed binary MBH have long inspiral time, 3-body and Kozai processes are promising for merger.