Gravitational Wave Detection of Massive Stellar BH Binaries

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Outline

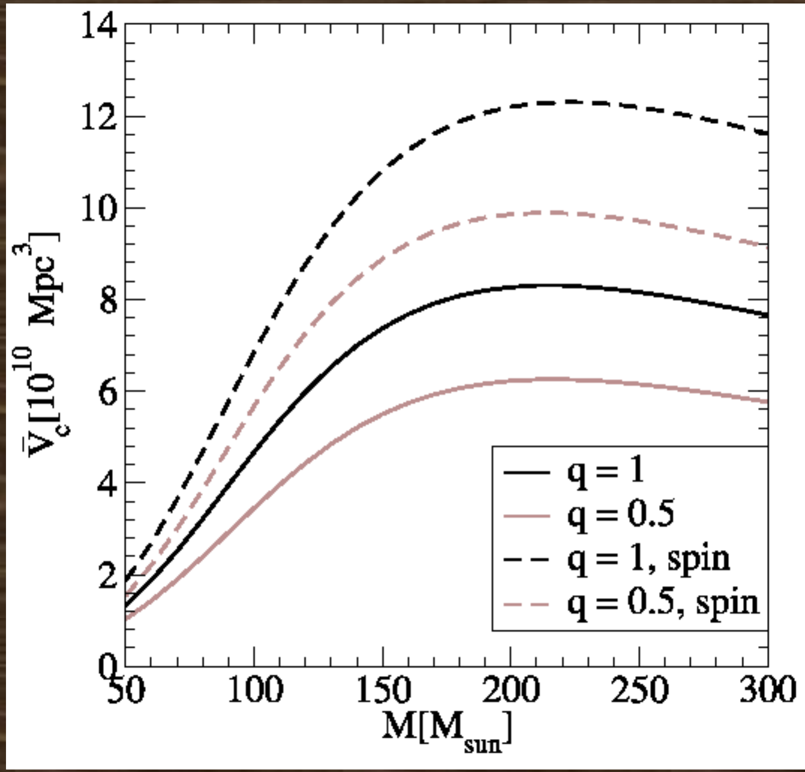
- Rates and volumes of GW detection
- Dynamics: three-body encounters
- Dynamics: Kozai-Lidov resonances in triples

Maximum Rate per Volume

- A key point from Chris' talk is that the formation rate of ~100 M_{sun} BH binaries could be as high as 5×10^{-9} Mpc^{-3} yr^{-1} if:
  IMF reaches to >500 M_{sun}
  Wind losses are not severe
  Pair instability SNe do not dominate
  Kicks are not too high
- What does this imply about the possible aLIGO/Virgo/KAGRA rates?

Possible Detection Rates

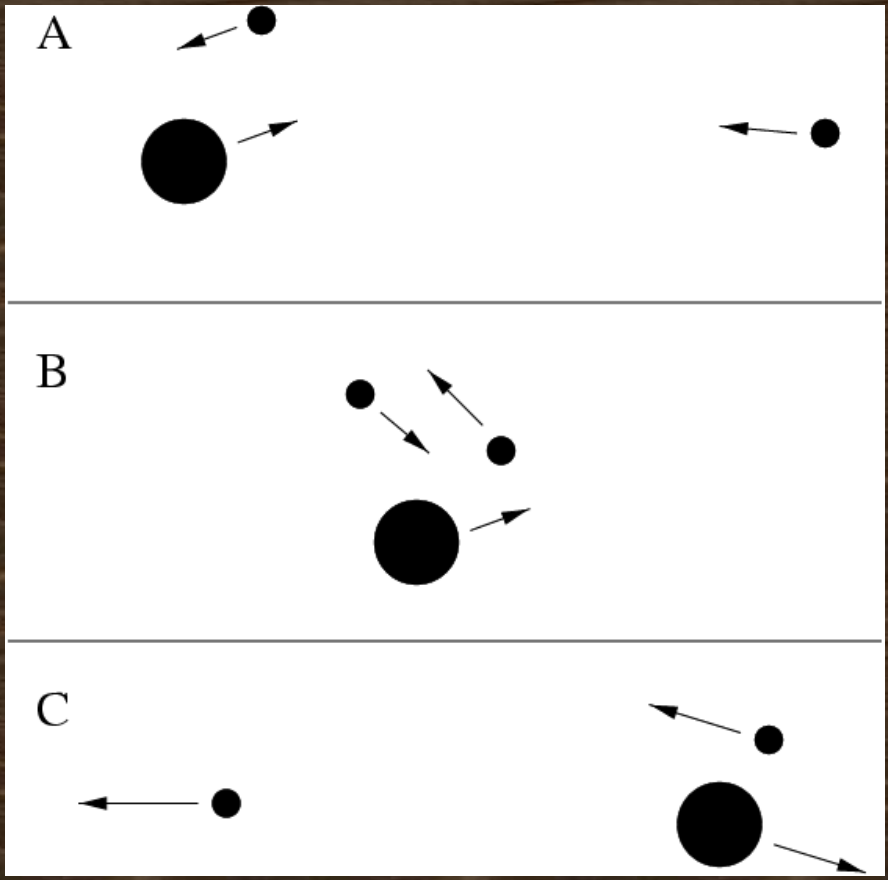
- 5×10^{-9} Mpc^{-3} yr^{-1}, few x 10^{10} Mpc^{3}: max few x 10^{2} yr^{-1}
- Rate could be much lower (0!), but point is that efficiency need not be high to get few yr^{-1}
- But (KB) if MBH binaries form (no PISN), they may all be wide (no CE); how will they merge?



Belczynski et al. 2014
"Spin" means a/M=0.6

Binary-Single Interactions

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



Hardening interaction

Some Equations and Numbers

- Time to shrink semimajor axis by factor ~3:

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

- Gravitational wave coalescence time:

$$T_{\rm GW} = 2.9 \times 10^{15}\ {\rm yr}\ \left(\frac{\eta}{0.25}\right)^{-1} \left(\frac{M}{200\ M_\odot}\right)^{-3} \left(\frac{a}{10\ {\rm AU}}\right)^{4} (1-e^2)^{7/2}$$

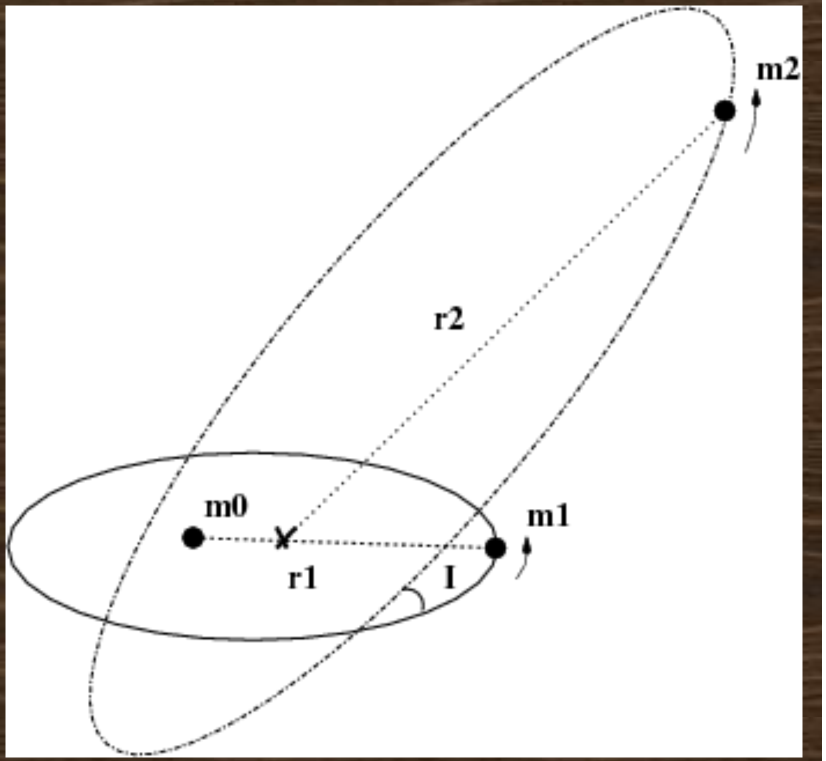
- Here $\eta = M_1 M_2/(M_1+M_2)^2$, $\rho = \rho_3 10^3\ M_{sun}\ pc^{-3}$, a=semimajor axis, M=total mass

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 e-foldings (~1 Gyr), and to e=0.999 in 3.4 e-foldings
- Thus ~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: $\sim(1-e^2)^{7/2}$



L. Wen, 2002

Simplified Equations, Numbers

- Time for Kozai-Lidov cycle:

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

- Maximum eccentricity (standard Kozai)

$$e_{\rm max} \approx \left[1-(5/3)\cos^2 i_0\right]^{1/2}$$

$$\text{e.g., } e_{\rm max} = 0.97 \text{ for } i_0 = 80^\circ$$

- Here b=semiminor axis of tertiary m
- $T_{\rm Kozai}$<interaction time; not disturbed
- 10s of % of triples have right orientation

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_{sun} 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