Clues on hierarchical binary black hole mergers from kick velocity inferences

Second Chennai Symposium on Gravitation and Cosmology

Parthapratim Mahapatra

February 3, 2022

Chennai Mathematical Institute

Collaborator: Anuradha Gupta, Marc Favata, K. G. Arun, and B. S. Sathyaprakash

Based on *ApJL 918 L31 (2021)*

Introduction

- LVC has reported 90 confident gravitational wave detections, listed in GWTC-3 catalog.
- The origin of binary mergers is still highly uncertain, with several possible scenarios that could potentially account for most of the observed events.
- Several high mass ($\geq 50 M_{\odot}$) black holes are reported in GWTC-3, with some of them exceeding $100 M_{\odot}$. This has led to the speculation of the presence of hierarchical mergers in the LIGO/Virgo data.

Formation channels

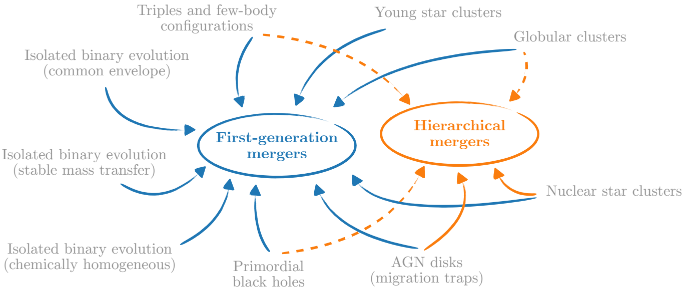


Figure 1: Different proposed formation channels of merging compact binaries (Gerosa+ (2021)).

- Necessary condition for hierarchical mergers: $V_{\mathrm{kick}} < V_{\mathrm{esc}}$.

Gravitational recoil

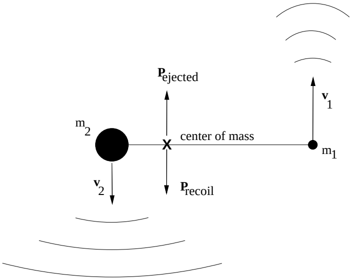
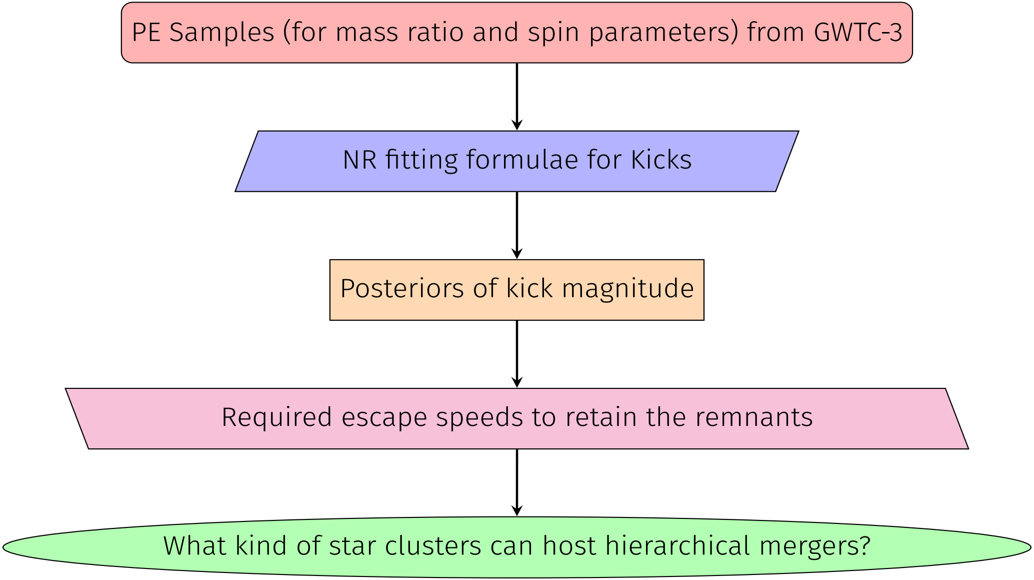


Figure 2: Linear momentum ejection and subsequent recoil of a binary system (Wiseman (1992)).

- Kick depends on mass ratio and spin parameters of the binary.
- To avoid prior dominated posteriors on kick we need accurate measurements of spins of the individual BHs in the binary (Varma+ (2020)).

This work


PE Samples (for mass ratio and spin parameters) from GWTC-3
NR fitting formulae for Kicks
Posteriors of kick magnitude
Required escape speeds to retain the remnants
What kind of star clusters can host hierarchical mergers?

Posteriors of kick magnitude

- We use fitting formula for kick from NR (as developed in Campanelli+ (2007), Lousto+ (2008, 2012, 2013) and summarized in Gerosa, Kesden (2016)).

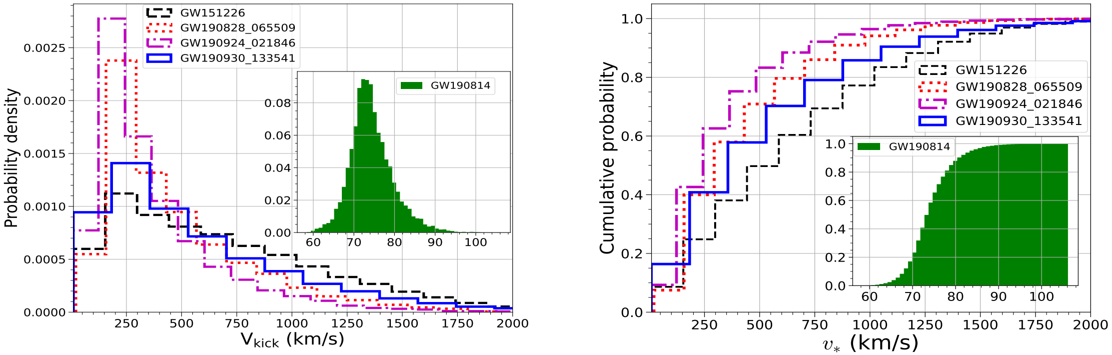


Figure 3: PDF (left) and CDF (right) of kick magnitude for few GW events. CDF, $F(v_*) = \int_0^{v_*} p(V_{kick})\, dV_{kick}$, where $p(V_{kick})$ is the PDF (Mahapatra+ (2021)).

Set up for our inference: with one example

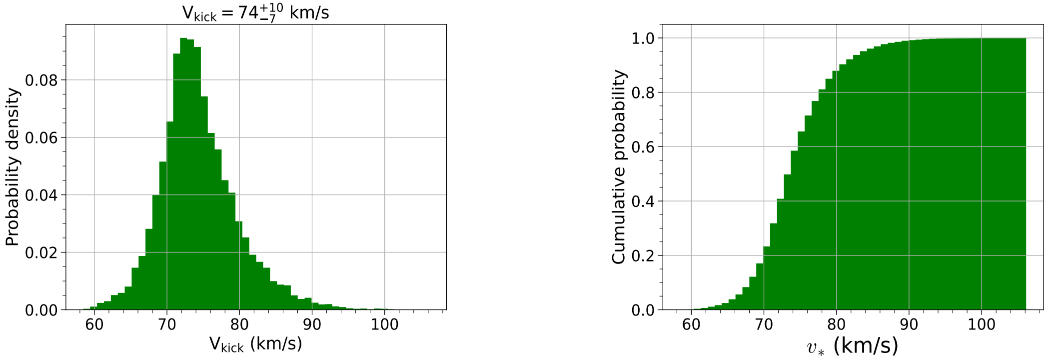


Figure 4: PDF and CDF of recoil velocity for GW190814 LVC posterior samples (Mahapatra+ (2021)).

- From the CDF, cumulative probability 0.9 correspond to recoil velocity $\sim$80 km/s $\Longrightarrow$ A star cluster whose escape speed is 80 km/s, can retain GW190814 remnant with a probability 0.9 and hence can facilitate next generation BBHs (if it is in a suitable environment).

Retention probability

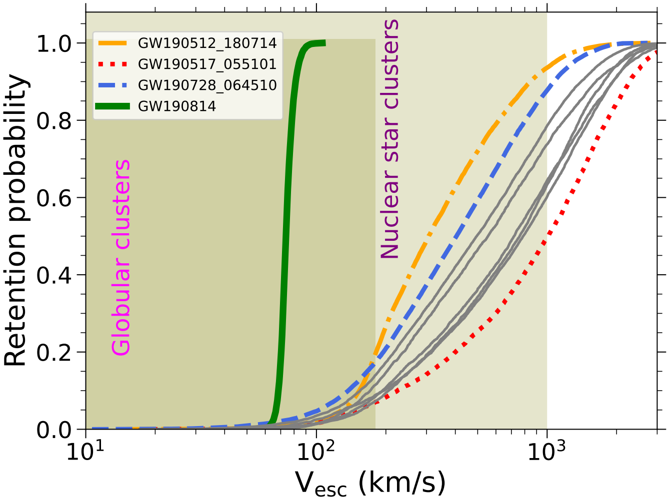


Figure 5: Retention probability as a function of escape speed for a few selected events from GWTC-2 in different star clusters (Mahapatra+ (2021)). Grey curves correspond to five of the six events reported by Kimball+ (2020) to be of hierarchical origin.

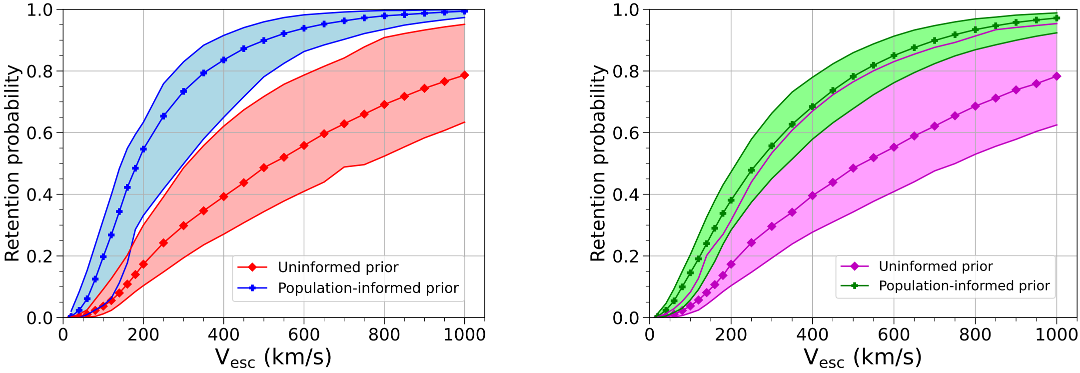


Figure 6: Distribution of retention probability as a function of escape speed for different star clusters (Mahapatra+ (2021)). (GWTC-2 -Left, GWTC-3 -Right)

- Clusters with escape speeds of 300 km/s can retain $56^{+10}_{-10}\%$ of the informative GWTC-3 population.
- Clusters with $V_{esc} \lesssim 80-180$ km/s, have median retention probabilities $\lesssim 34\%$.

Retention probabilities of GWTC-3 events by GCs and NSCs

$$P^{k}_{\mathrm{ret},j} = \int_0^{V_{\max}} p_j(V_{\mathrm{kick}})[1 - F_k(V_{\mathrm{kick}})]\, dV_{\mathrm{kick}}\,. \qquad (j - \text{events}, k - \text{GC/NSC}) \qquad (1)$$

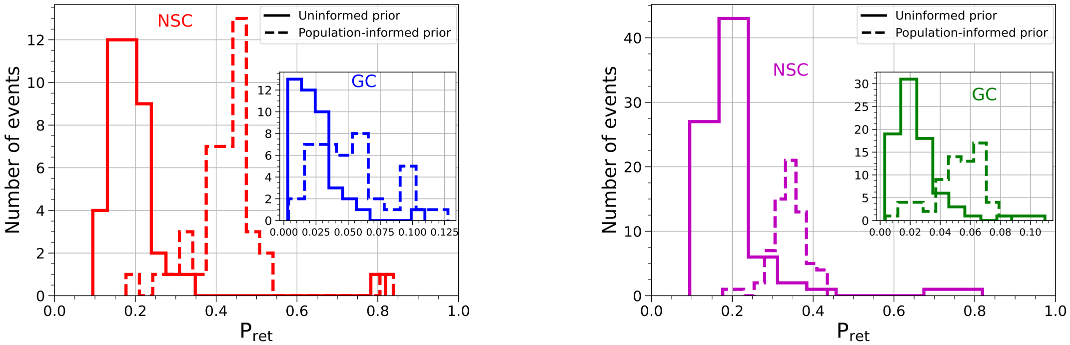


Figure 7: Distribution of retention probabilities for nuclear star clusters and globular clusters (inset) (using escape speed distribution for GC,NSC from Antonini and Rasio (2016)) (Mahapatra+ (2021)). (GWTC-2 -Left, GWTC-3 -Right)

- 90% of the events have retention probability between 0.271-0.408 (0.019-0.071) for NSC(GC).
- ∼24 (∼4) events in GWTC-3 could participate in further mergers if those events happened in NSCs (GCs).

Conclusions

- Star clusters with escape speeds of 250 km/s can retain about 50% of the GWTC-3 events.
- Globular clusters are unlikely to seed hierarchical growth of black holes whereas nuclear clusters are the likely hubs for this intriguing phenomenon.
- Remarkably, nuclear star clusters have a high probability of retaining five out of six events in the catalog that are thought to contain at least one companion resulting from prior mergers.
- We find that $\sim$24 (4) events in GWTC-3 could participate in further mergers if events happened in nuclear (globular) clusters.

Back up slides

Fitting formula for kick from NR (as developed in Campanelli+ (2007), Lousto+ (2008, 2012, 2013) and summarized in Gerosa, Kesden (2016))

$$\vec{V}_{\rm kick} = V_m\,\hat{e}_1 + V_{s\perp}\,(\cos\xi\,\hat{e}_1 + \sin\xi\,\hat{e}_2) + V_{s\parallel}\,\hat{\mathsf{L}} \qquad (\hat{\mathsf{L}} = \hat{e}_z). \tag{2}$$

$$\boldsymbol{\Delta} = \frac{\chi_1\hat{\mathsf{S}}_1 - q\chi_2\hat{\mathsf{S}}_2}{1+q}, \qquad \widetilde{\boldsymbol{\chi}} = \frac{q^2\chi_2\hat{\mathsf{S}}_2 + \chi_1\hat{\mathsf{S}}_1}{(1+q)^2}. \tag{3}$$

$$V_m = A\eta^2\frac{1-q}{1+q}(1+B\eta), \qquad V_{s\perp} = H\eta^2\Delta_{\parallel}; \tag{4}$$

$$\begin{aligned} V_{s\parallel} = 16\eta^2[\Delta_{\perp}(V_{11} + 2V_A\widetilde{\chi}_{\parallel} + 4V_B\widetilde{\chi}_{\parallel}^2 + 8V_C\widetilde{\chi}_{\parallel}^3) + \\ 2\widetilde{\chi}_{\perp}\nabla_{\parallel}(C_2 + 2C_3\widetilde{\chi}_{\parallel})]\cos\Theta; \end{aligned} \tag{5}$$

$A = 1.2\times10^4$ km/s, $B = -0.93$, $H = (6.9\pm0.5)\times10^3$ km/s, $V_{11} = 3677.76\pm15.17$ km/s, $V_A = 2481.21\pm67.09$ km/s, $V_B = 1792.45\pm92.98$ km/s, $V_C = 1506.52\pm286.61$ km/s, $C_2 = 1140\pm125$ km/s, $C_3 = 2481\pm434$ km/s, $\xi = 145°$.

Application of the method to six GWTC-2 events

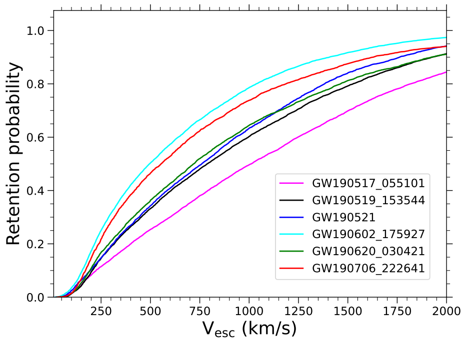


Figure 8: Application of our method to the six events of GWTC-2 found to be most likely to consist of two second-generation black holes or, mixed-generation progenitor in Ref. Kimball+ (2020).

- The rentention probability is the highest for GW190602_175927 and lowest for GW190517_055101.
- Dense star clusters with escape speed 600 km/s will be able to retain GW190521 with probability $\sim$0.45.