The Role of Dense Star Clusters in Gravitational Wave Source Formation

NBI LIGO/Virgo O3a Workshop — November 18, 2020

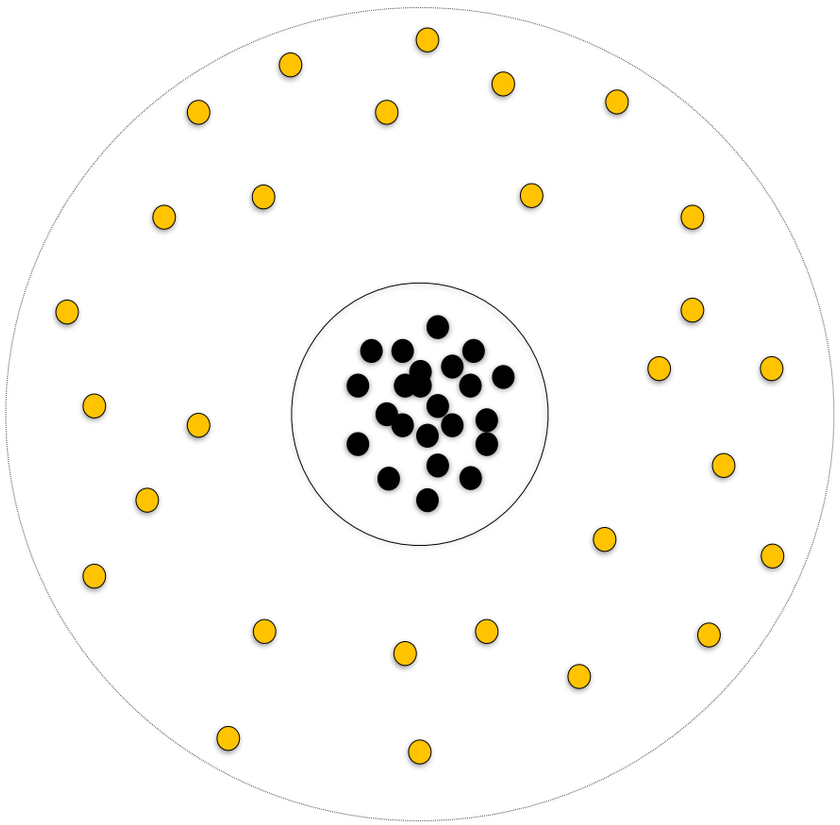
Kyle Kremer

Claire Ye, Nicholas Rui, Newlin Weatherford, Miguel Martinez,
Katie Breivik, Giacomo Fragione, Michael Zevin, Sourav Chatterjee,
Dan D'Orazio, Shane Larson, Carl Rodriguez, Johan Samsing, Mario Spera, Fred Rasio

Caltech

Carnegie Science

Black Holes in Globular Clusters



1. Massive stars form BHs (t ~ few - 10s of Myr)

2. Fraction of BHs are ejected promptly from natal kicks

3. BHs mass-segregate through dynamical friction (t < 1 Gyr)

4. Dynamical interactions in dense core lead to binary BH formation, hardening, ejection, and merger. (t ~ 1-12 Gyr)

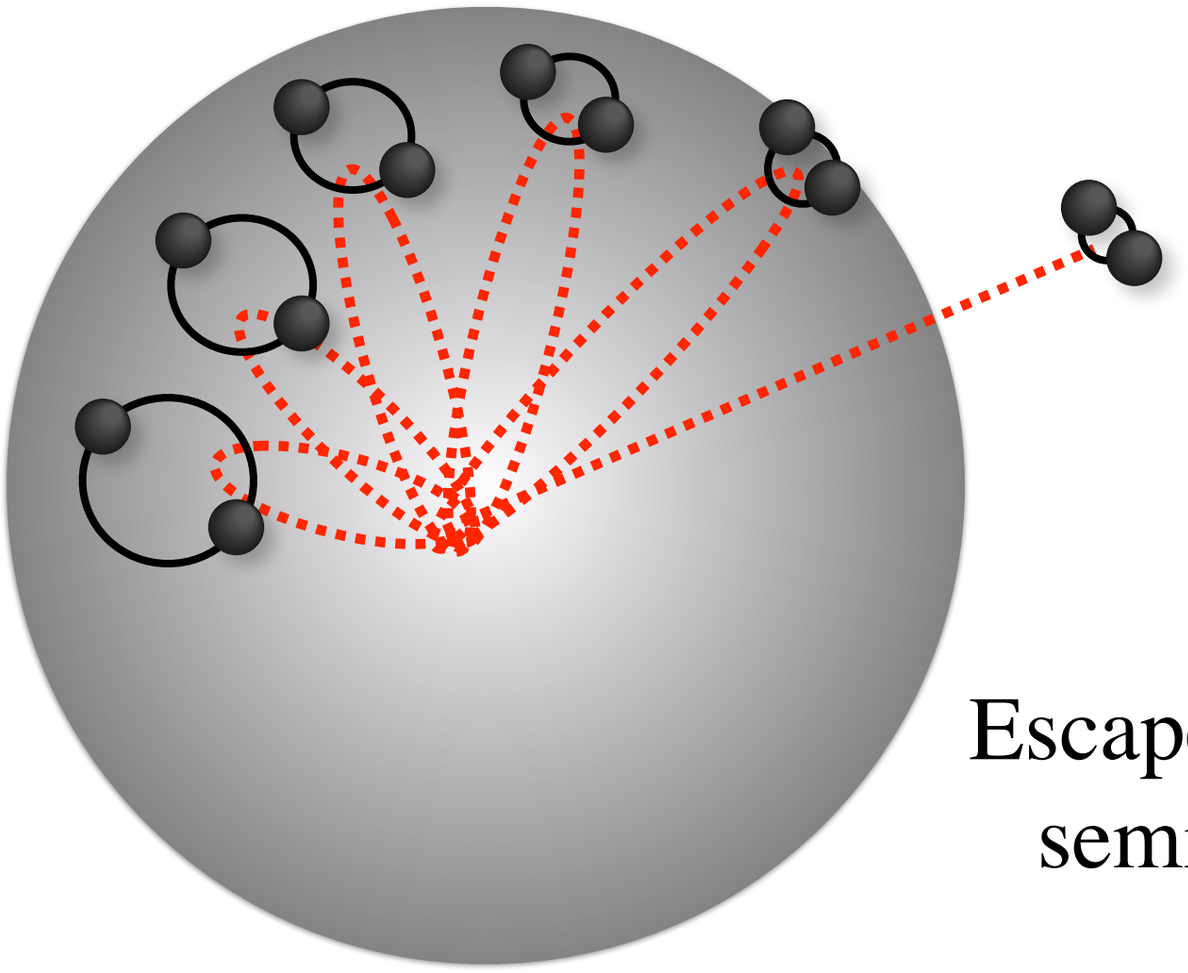
---

e.g., Spitzer 1967, Kulkarni+1993, Sigurdsson & Hernquist 1993, Belczynski+2006, Mackey+2007, 2008, Fryer+2012, Breen & Heggie 2013, Morscher+2015, Heggie & Giersz 2014, Rodriguez+2016, Chatterjee+2017, Arca Sedda+2018, Askar+2018, Banerjee 2018, Antonini & Gieles 2020, Kremer+2019, 2020, Di Carlo+2020, Mapelli+2020

Binary Black Hole Merger Channels

1. **Ejected mergers:** BBH is ejected from host cluster through dynamical recoil. Merges through GW inspiral outside of host cluster. Roughly 50% of all mergers.

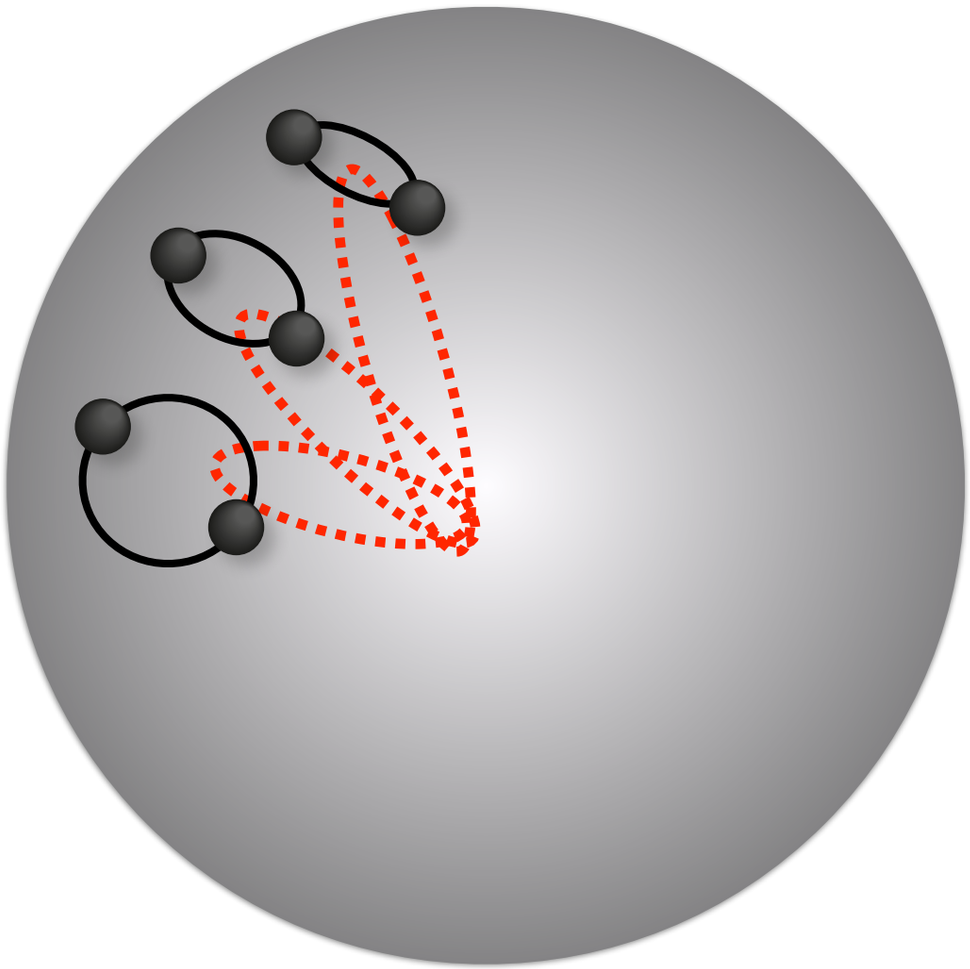
$$v_{\rm recoil} \sim \sqrt{\frac{GM}{a}} \sim v_{\rm orb}$$



Escape speed of the cluster determines the semi-major axis of the ejected binaries

Binary Black Hole Merger Channels

1. **Ejected mergers:** BBH is ejected from host cluster through dynamical recoil. Merges through GW inspiral outside of host cluster. Roughly 50% of all mergers.
2. **In-cluster 2-body:** Dynamical encounter creates a compact BBH $\left(a\,(1\text{-}e) \sim 10^{-3}\ \mathrm{AU}\right)$ that mergers inside cluster. Roughly 40% of all mergers.



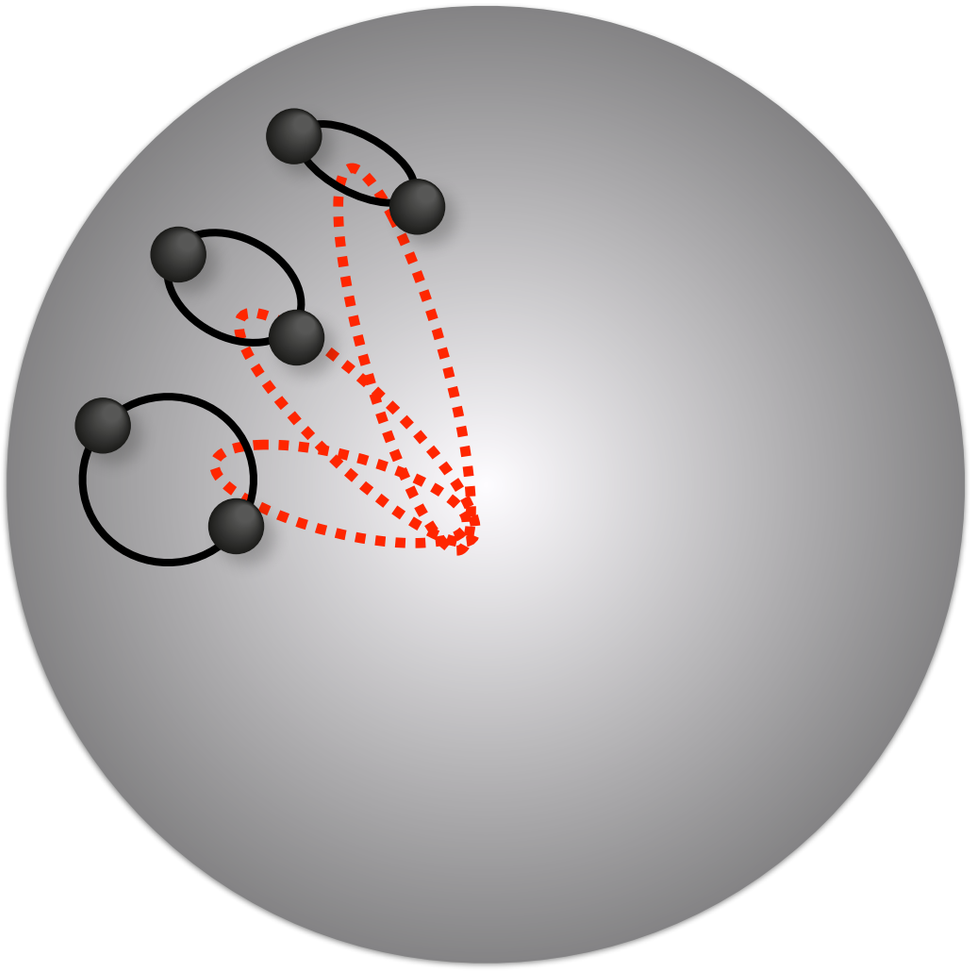
For high eccentricities:

$$t_{\mathrm{insp}} \propto (1-e^2)^{7/2}$$

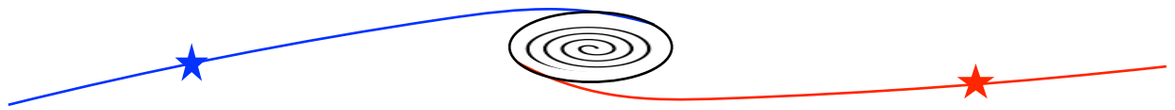
If $t_{\mathrm{insp}} < t_{\mathrm{enc}}$, the BBH mergers in cluster

Binary Black Hole Merger Channels

1. **Ejected mergers:** BBH is ejected from host cluster through dynamical recoil. Merges through GW inspiral outside of host cluster. Roughly 50% of all mergers.
2. **In-cluster 2-body:** Dynamical encounter creates a compact BBH $\left(a\,(1\text{-}e) \sim 10^{-3}\,\mathrm{AU}\right)$ that mergers inside cluster. Roughly 40% of all mergers.
3. **In-cluster GW capture:** Highly eccentric BBH is formed through GW-driven capture during close passage in dynamical encounter. Roughly 10% of all mergers.



Single-single encounters

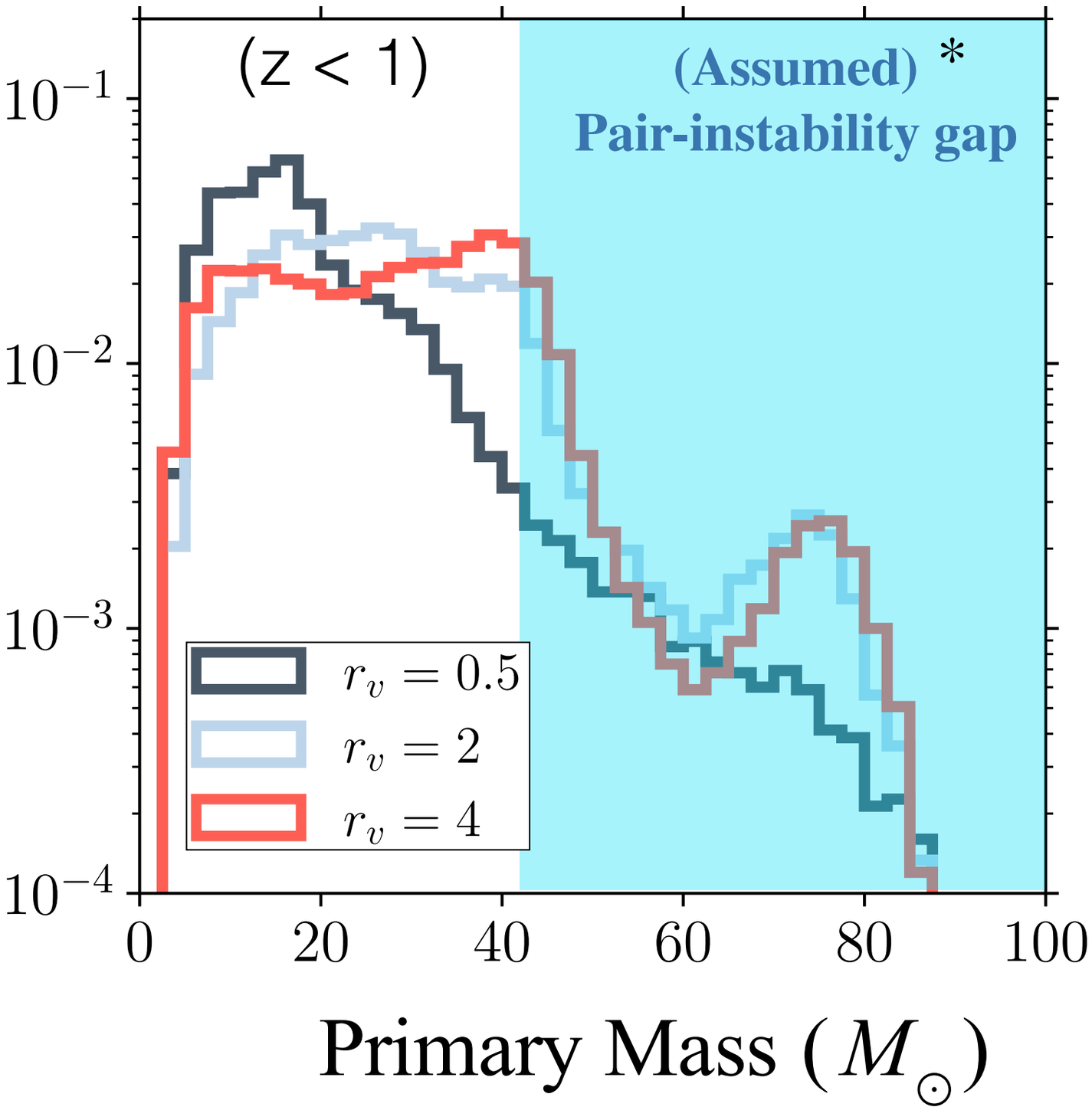


e.g., Samsing+2019

“Few”-body encounters

e.g., Samsing+2014, Rodriguez+2018, Zevin+2019, Kremer+2020

Black Hole Masses



Repeated BH mergers ("second generation")

e.g., Miller & Hamilton 2002, McKernan+2012, Rodriguez+2019, Antonini+2019, Gerosa & Berti 2019, Kimball+2020, Fragione+2020, Mapelli+2020

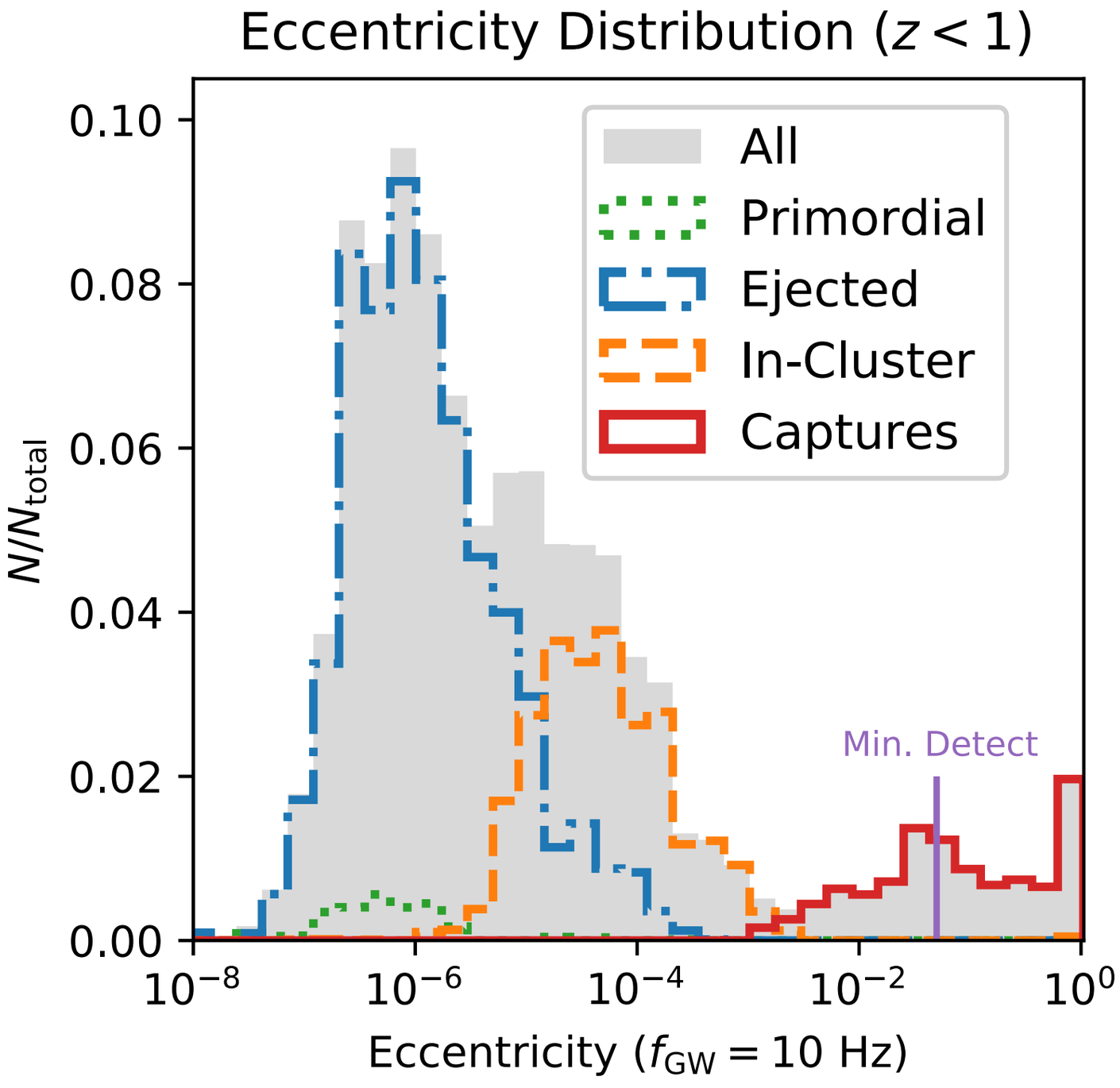
Repeated stellar mergers

Spera+2019, Di Carlo+2019, 2020, Banerjee 2020, Kremer+2020

Roughly a few-10% of cluster mergers have one component in mass gap

***Exact boundary of mass gap are highly uncertain:** e.g., Belczynski+2016, Woosley 2017, Spera & Mapelli 2017, Giacobbo+2018, Limongi & Chieffi 2018, Marchant+2019, Mapelli+2019, Stevenson+2019, Farmer+2019, Belczynski+2020, Renzo+2020

Eccentricities



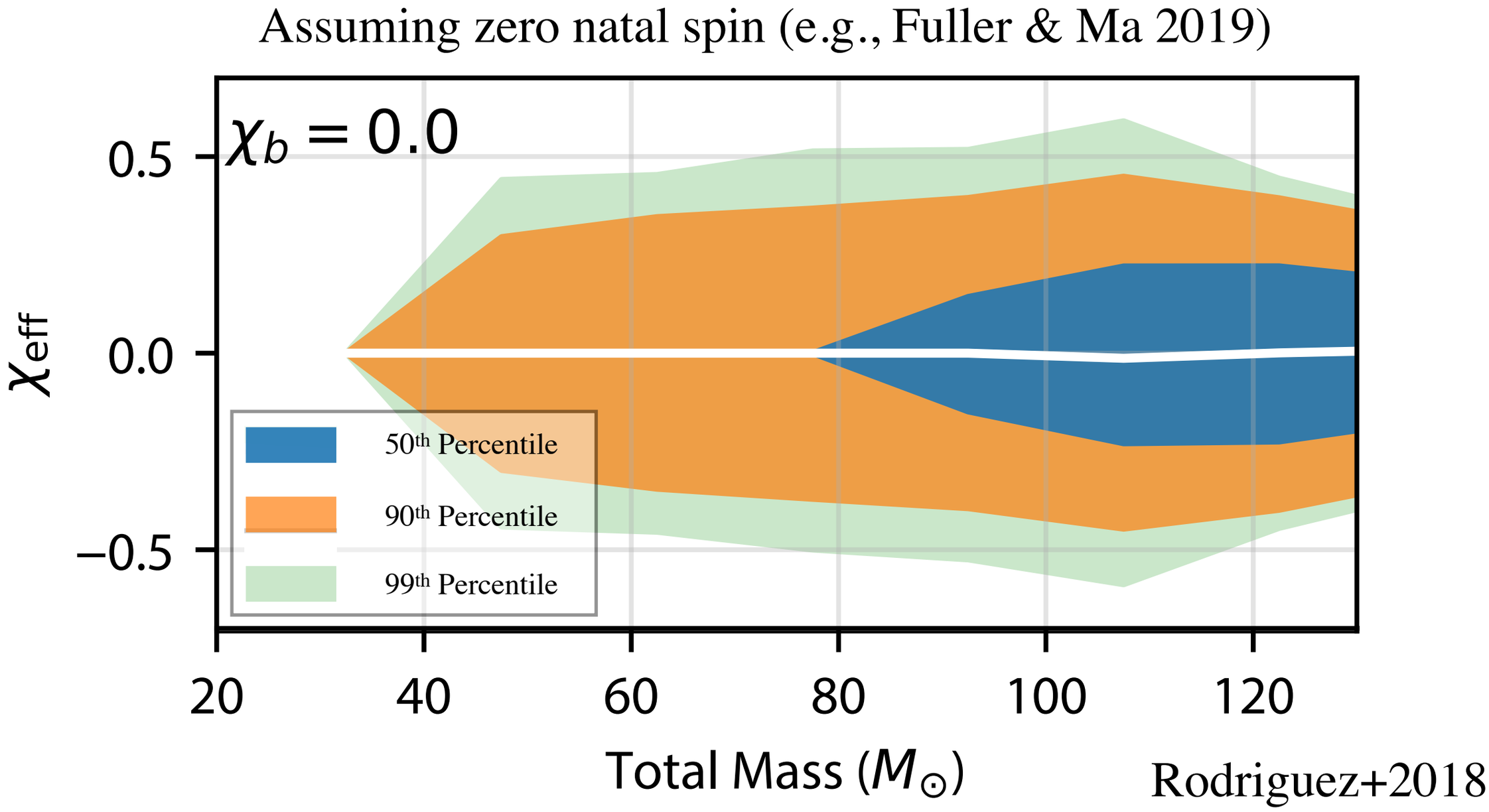
Rodriguez+2019

Is GW190521 eccentric?
Romero-Shaw+2020

Note: LISA may be ideal for eccentricity measurements

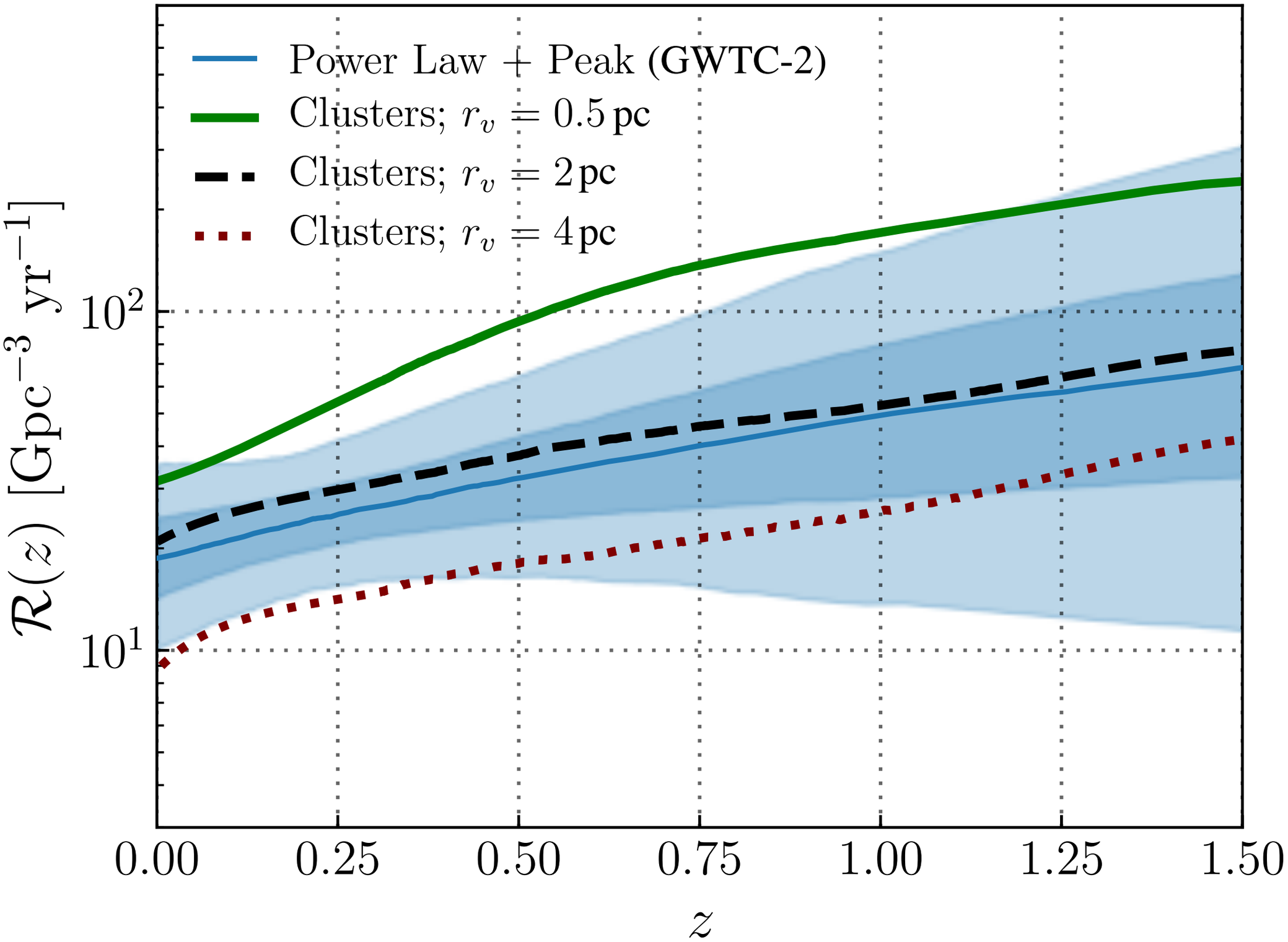
See also work by Samsing+2014, Breivik+2016, D'Orazio & Samsing 2018, Hoang+2018, Zevin+2019, Banerjee 2020, Martinez+2020

Spins



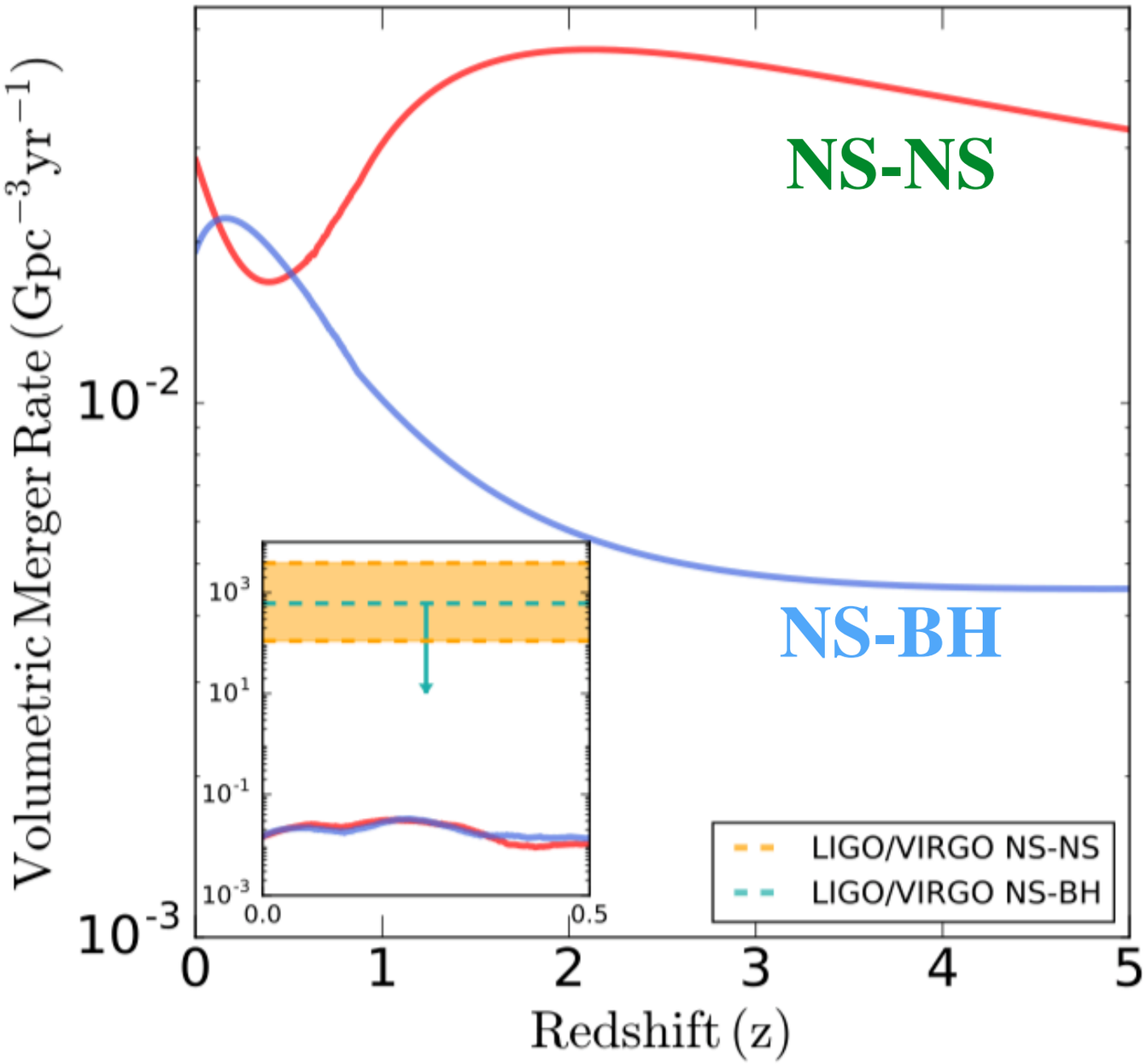
Clear evidence against an isotropic distribution would disfavor dynamical formation in star clusters

Black Hole Merger Rate



Cluster rates from Kremer +2020

Globular clusters *do not* contribute significantly to neutron star merger rate



Local universe rate of ~0.01-0.07 Gpc $^{-3}$ yr $^{-1}$ for both NS-NS and NS-BH

Claire Ye et al. 2020

Key Uncertainties

BH natal spins

- Determines retention of BH merger products + 2G merger rate
- $a = 0$ is typical assumption (Fuller & Ma 2019)

Young cluster properties

- Initial Radii? $r_v = 0.5$ - 4 pc reproduces Milky Way clusters
  (Bastian+2005, Scheepmaker+2007, Portegies Zwart+2010, Kremer+2020)
- What fraction of stars are born in clusters?
  (e.g., Lada & Lada 2003, Di Carlo+2020, Rastello+2020)
- What fraction of clusters survive to present day?
  (e.g., Fragione & Kocsis 2018, Rodriguez & Loeb 2018, Choksi+2019)
- Birth times? Connected to star formation? Reionization?

Present-day cluster properties are excellent constraints

- Current models reproduce observed masses, core/half light radii, density profiles, pulsar/X-ray binary populations, etc.
  (e.g., Mackey+2007, Morscher+2015, Ye+2018, Askar+2018, Arca Sedda+2018, Kremer+2020, Weatherford+2020)