Using merged BHs final spins and final masses to infer the formation history of their progenitors

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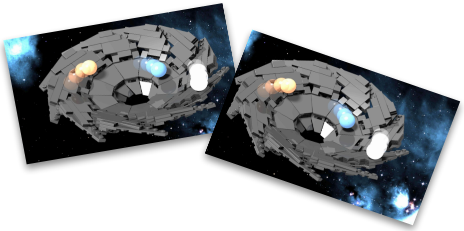
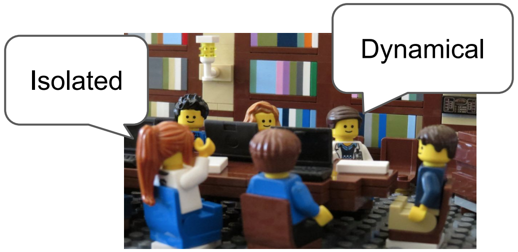
Outline



- The discovery of gravitational waves emitted by black hole binary mergers

- Black hole binaries formation channels

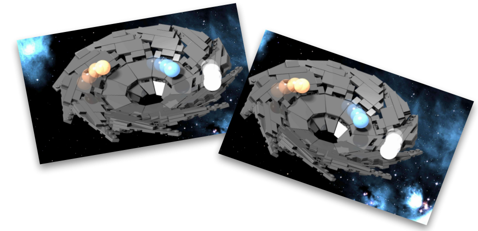


- A link between the remnant black hole and its progenitors: masses and spins
    - Isolated black hole binary mergers
    - Dynamical black hole binary mergers

- Constraining the formation channel of the observed population of merged black hole binaries

- Conclusions

The discovery of gravitational waves emitted by black hole binary mergers

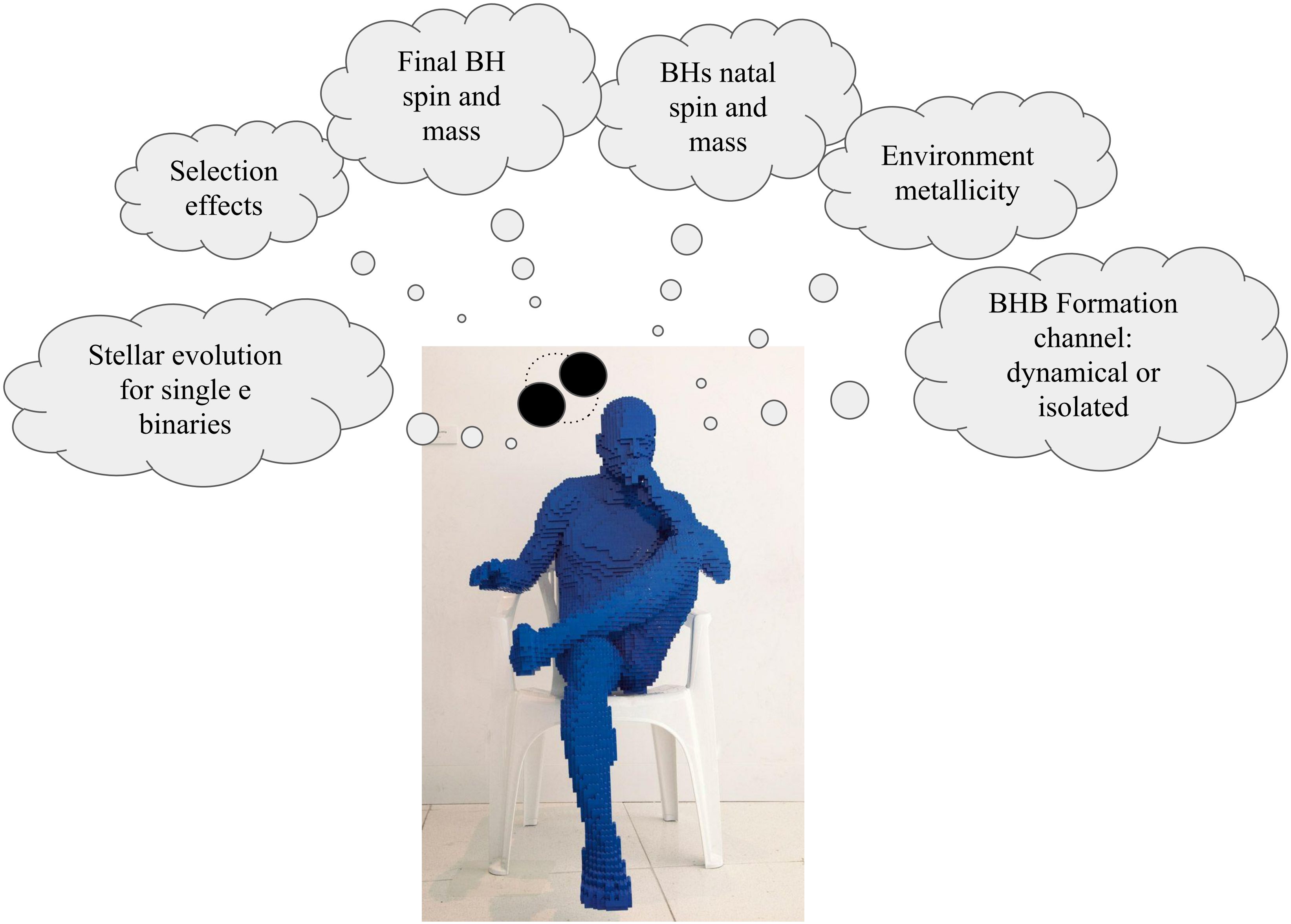


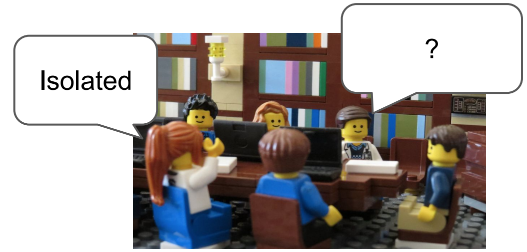
On 23rd May 2018, if you search on ADS
"2016-2018"+"LIGO" + "Gravitational waves" + "Abbott" (evidently the luckiest physicist ever):
72 *papers with* **6462** *citations*

What did we learn?

1. **Black holes do exist**
2. **Black hole binaries do exist**
3. **Black holes heavier than 30 solar masses do exist**
4. **Black hole binaries heavier than 30 solar masses do exist**

Where are they from?


Selection effects
Final BH spin and mass
BHs natal spin and mass
Environment metallicity
Stellar evolution for single e binaries
BHB Formation channel: dynamical or isolated



Black hole binaries formation channels:

General information

Basic assumption: Kroupa (2001) stellar mass function

$$f(M_*) = \begin{cases} M^{-0.3} & M_* < 0.08\,\mathrm{M}_\odot \\ M^{-1.3} & M_* \in [0.08-0.5]\,\mathrm{M}_\odot \\ M^{-2.3} & M_* > 0.5\,\mathrm{M}_\odot \end{cases} \longrightarrow N_{\rm BH} = 10^{-3} N_* \simeq \begin{cases} 10^7 & \text{Elliptical galaxies} \\ 10^4 & \text{Nuclear clusters} \\ 10^3 & \text{Globular clusters} \end{cases}$$

Total number of BHs:

Our sample: $N_{\rm BBH} = 7000$

Metallicity
(affect the BH natal mass and spin):

$$Z = \begin{cases} 2\times10^{-4} \\ 2\times10^{-3} \\ 2\times10^{-2} \end{cases}$$

2×10^{-4}, 2×10^{-3}: Globular clusters
2×10^{-2}: Solar neighbourhoods

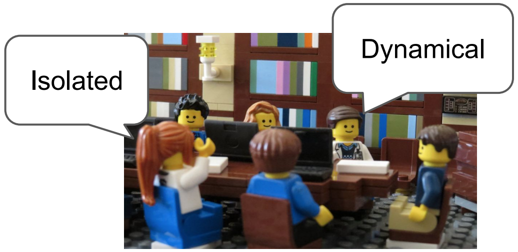
Sensitivity volume
(Fishbach & Holz 17)

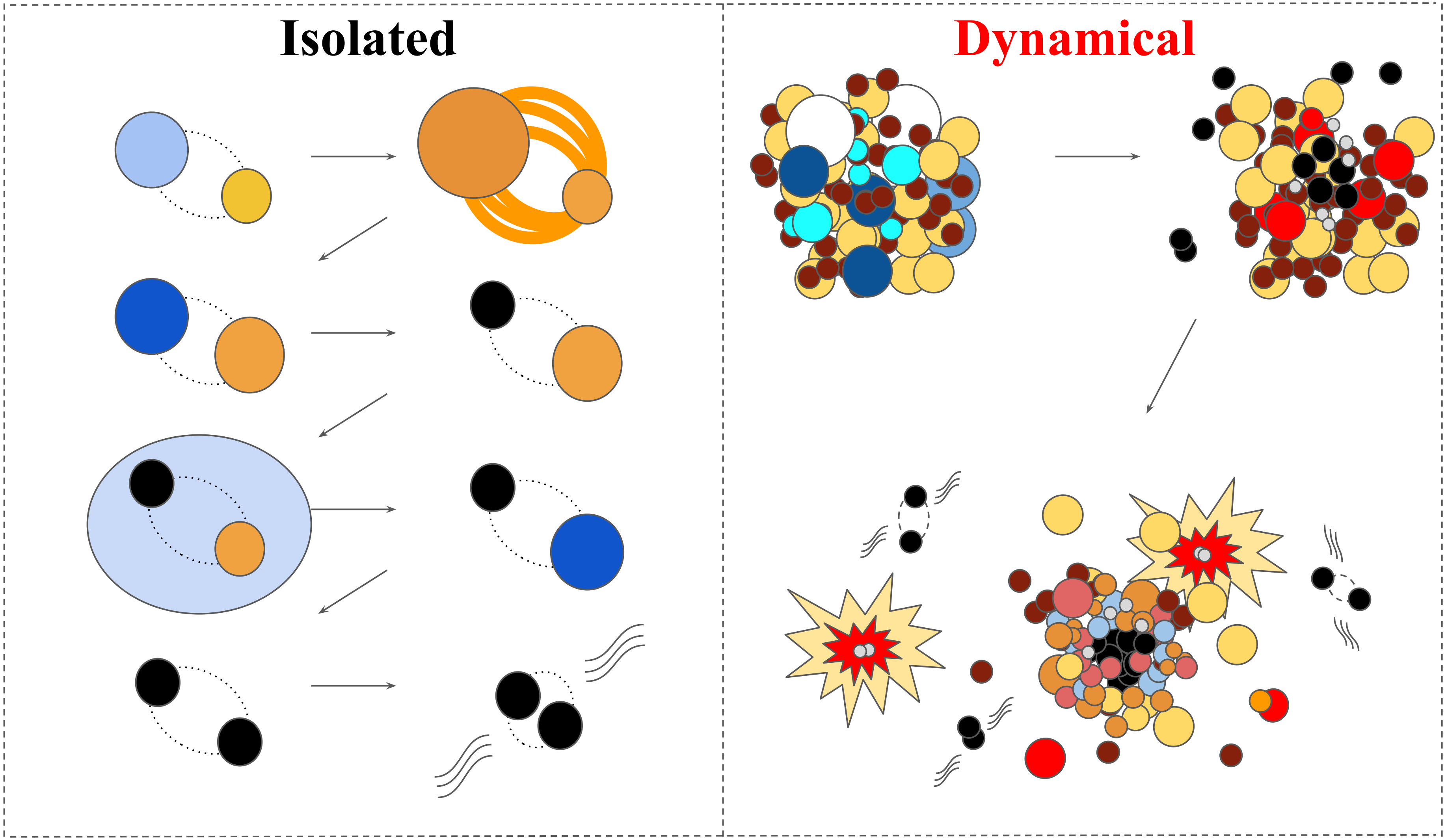
$$V \propto (m_1 + m_2)^{2.2}$$

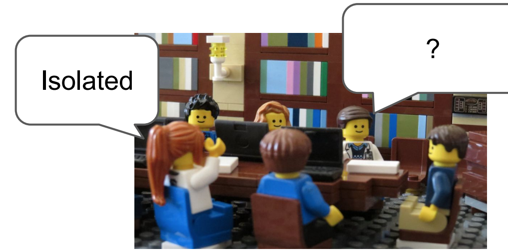
Stellar evolution recipes
(affect the BH natal mass and spin):

SSE (Hurley+00)	SEVN (Spera+15)	BSE (Hurley+02)
Single stellar evolution	Single stellar evolution	Binary stellar evolution
Extracted from the Nbody6 code	Adapted from SEVN through fitting formulae	Extracted from the Nbody6 code
Name: SSE18	**Name: SEVN18**	**Name: BSE18**

Black hole binaries formation channels:







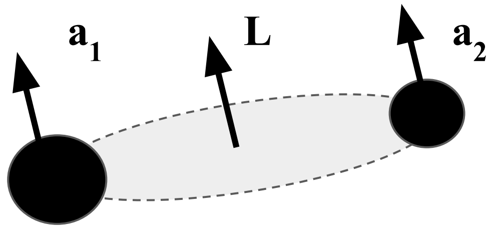
Black hole binaries formation channels:

Isolated: general information

Code used:

SSE18
(Adpt. from Nbody6)

SSEVN18
(Adpt. from Spera+15)



Aligned configuration
- maximize the BBH effective spin

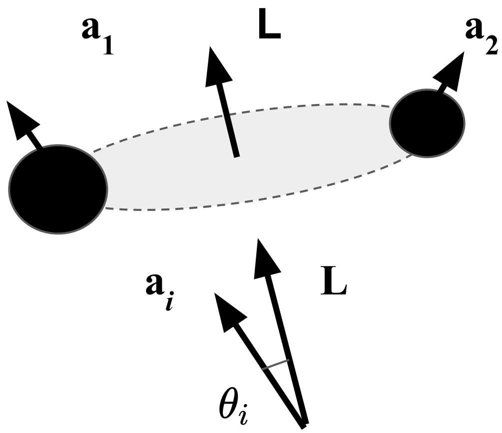
- maximize the BH final spin

Orbital properties

$$P(M_1) \propto M_1^{-}2.3$$

$$P(M_2) \propto M_2^0$$

Basic assumption:
a fraction of the BBH sample merge (no matter what orbital properties the BBH have)



Mildly aligned configuration
- required to get BH final spins below 0.7

$$P(cos\theta_i) = (cos\theta_i + 1)^{n_\theta}$$

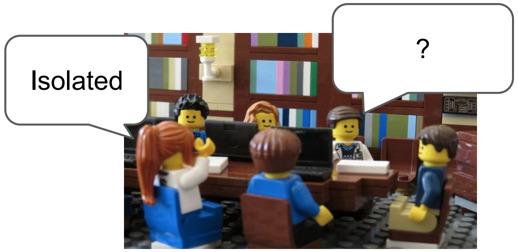
$\theta_i \to \infty$ aligned

$\theta_i \equiv 2$ thermal

$\theta_i \equiv 0$ flat

Fun facts: a zoology of stellar binary evolution tools

BSE/SSE (Hurley+2002) , **StarTrack** (Belczynski+2002,2008...), **MOBSE** (Giacobbo+2016), **MOCCABSE** (Belloni+), **MESA** (Pavloski+16), **MC pop** (Mandel & de Mink 16)



Black hole binaries formation channels:

Isolated: method 2

Code used:

BSE18

(adapted from Nbody6)

Orbital properties

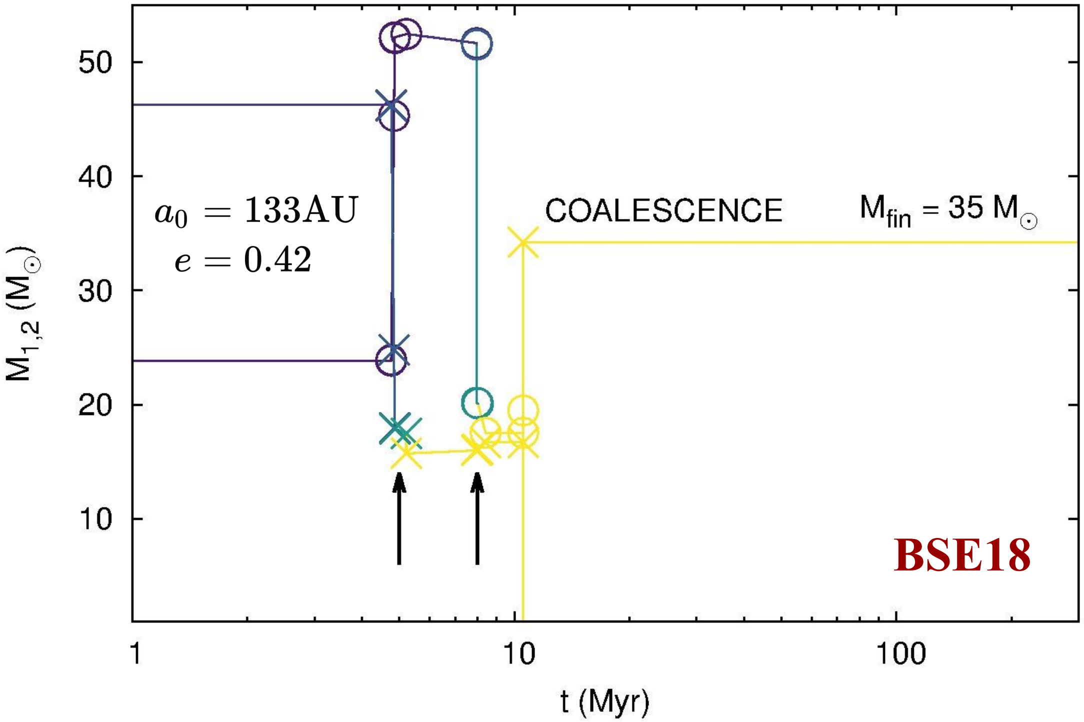
Sana et al. 2012

$P(T_{\rm orb}) \propto T_{\rm orb}^{1/2}$

$P(e) \propto e^{-0.42}$

$P(M_1) \propto M_1^{-}2.3$

$P(M_2) \propto M_2^0$



Fun facts: a zoology of stellar binary evolution tools

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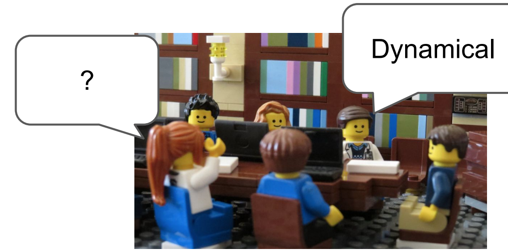


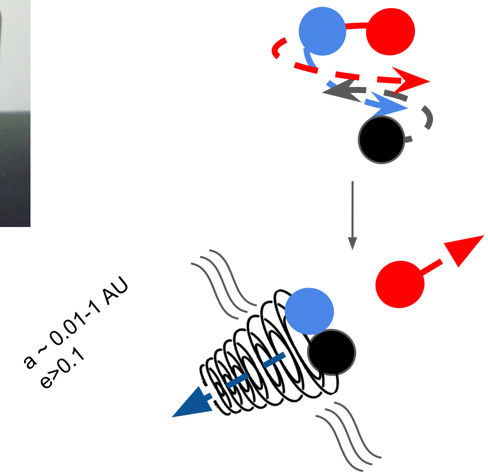
Black hole binaries formation channels:

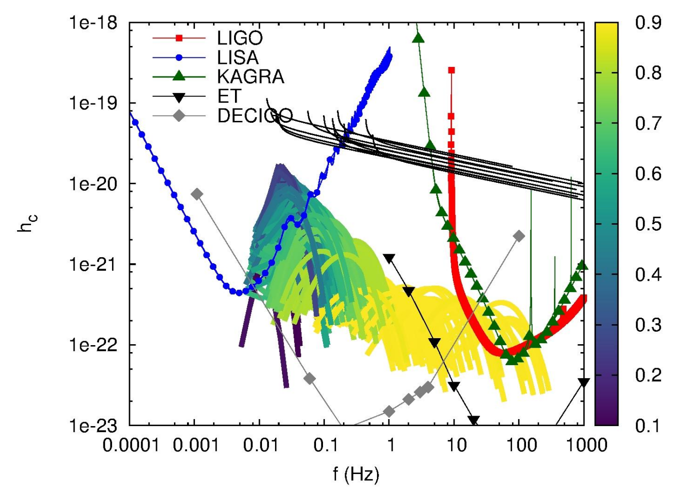
Dynamical

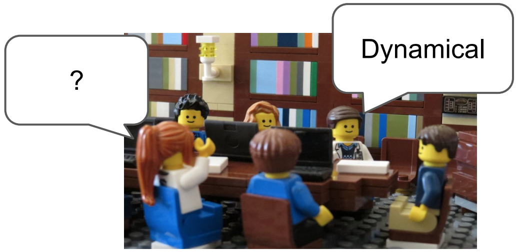
BHB forms mainly through triple interactions

The BHB merges in the cluster due to	The BHB is ejected from the cluster	The BHB breaks up
- Secular effects (like KL resonance)	- Merger due solely to GW emission	- New BHB formation possible
- Non-hierarchical interactions	**- Ejection caused by 3B interactions**	- Possible ejection of one or more BHs

Arca Sedda, Li and Kocsis, 2018, Arxiv: 1805.06458







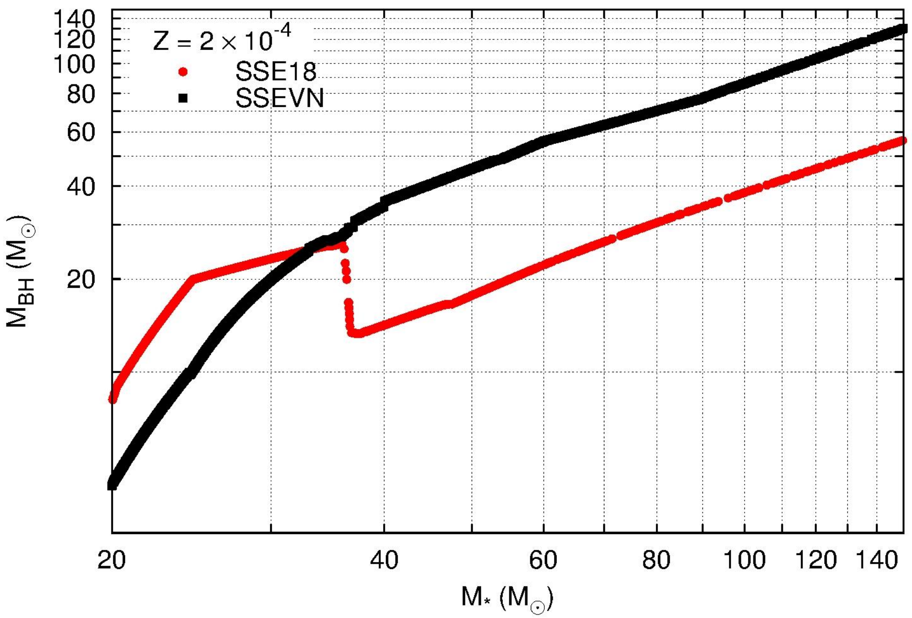
Black hole binaries formation channels:

Dynamical

Code used:

SSE18
(adapted from Nbody6)

SSEVN18
(adapted from Spera+15)



Orbital properties

- Merging BBHs in star clusters have high mass-ratios (Rodriguez+15)
- A fraction of merged BHs undergo a second merger (Rodriguez+18)

Fun facts: simulating a real star system? Take your time

Only 4 one-to-one direct N-body models of a Globular Cluster exists, but old stellar evolution recipes.
Ran on GPU-enabled machine, required ~ **4 months each**, which means **~50 yrs on a normal laptop**

A link between the remnant black hole and its progenitors: masses and spins

Chapter 1: Remnant masses and spins

$$M_{\rm rem} = 1 - \left(b_0 + b_1/(b_2 + \chi)\right)\right) (M_1 + M_2)$$

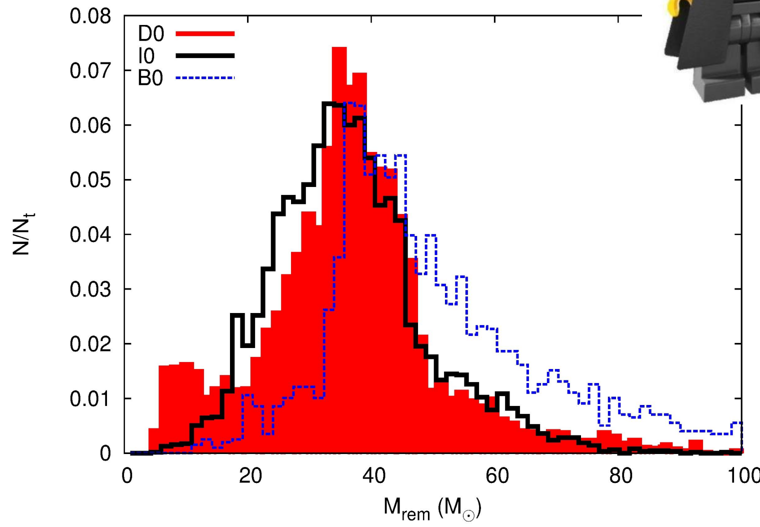
$$a_{\rm rem} = (1+q)^{-2}[a_1^2 + a_2^2 q^4 + 2a_1 a_2 q^2 \cos\alpha + \\ + 2\left(a_1 \cos\beta + a_2 q^2 \cos\gamma\right) lq + l^2 q^2]^{1/2},$$

$$l = 2\sqrt{3} + t_2\nu + t_3\nu^2 + \\ s_4 (1+q^2)^{-2}(a_1^2 + a_2^2 q^2 + 2a_1 a_2 q^2 \cos\alpha) + \\ (s_5\nu + t_0 + 2)(1+q^2)^{-1}(a_1 \cos\beta + a_2 q^2 \cos\gamma).$$

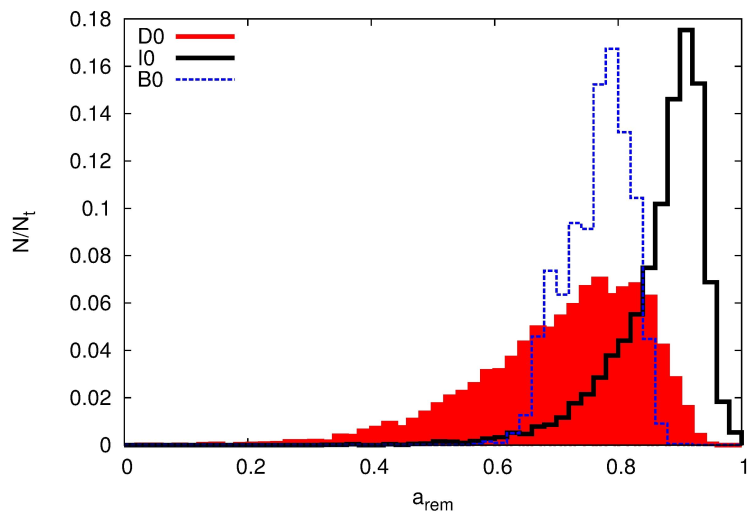
Barausse+12, Hofmann+16

Constraining the formation channel of the observed population of merged black hole binaries

- Dynamical binaries (D0): evidence for low-mass BHs, narrow peak at ~35-40 Msun
- Isolated binaries (I0, method 1): broad mass distribution, cut-off at BH masses below 20 Msun
- Isolated binaries (B0, method 2): cut-off at BH masses 30 Msun, long high-end tail.



- Dynamical binaries: broad distribution, cut-off above 0.82, shallow rise in the range 0-0.8
- Isolated binaries (aligned, method 1): narrow peak at 0.9, tiny fraction of BHs with spin below 0.6
- Isolated binaries (aligned, method 2): broad distribution limited in between 0.6 and 0.85

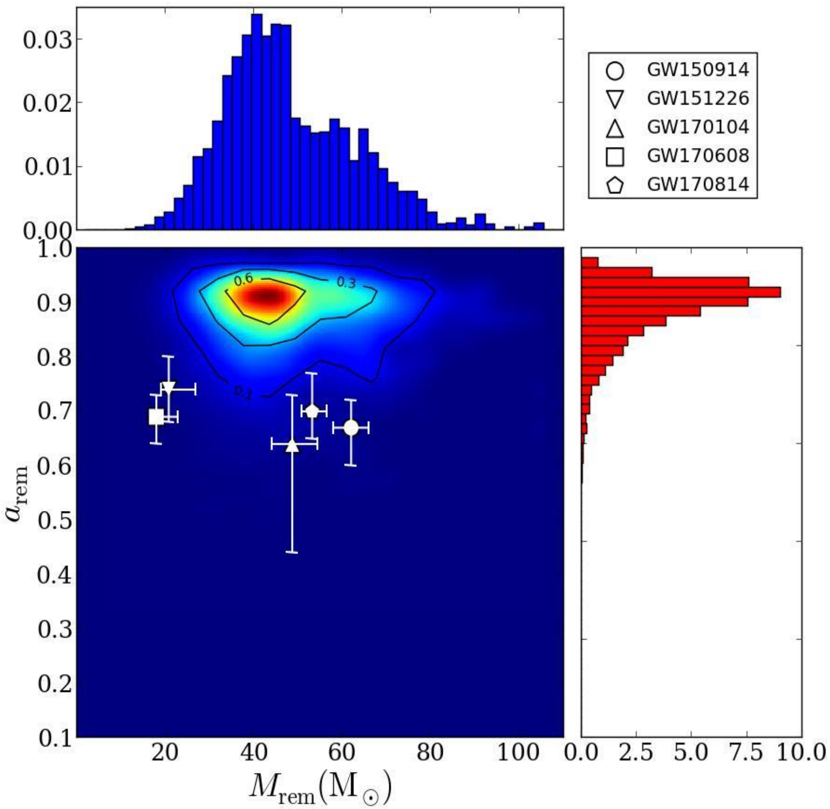


Constraining the formation channel of the observed population of merged black hole binaries

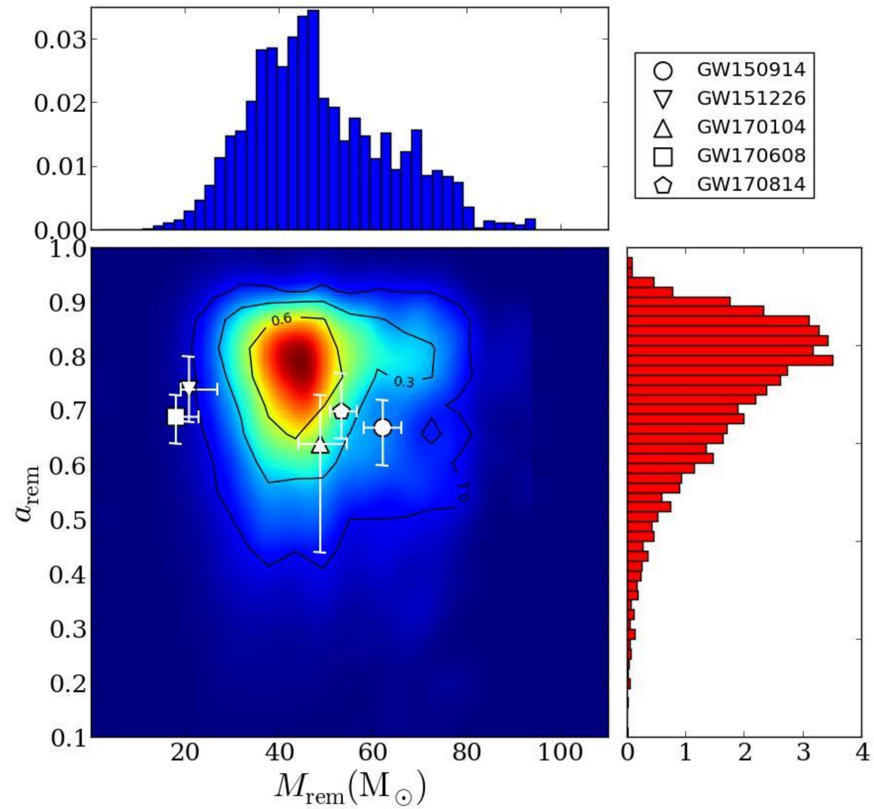
Isolated: method 1 (approximated)

$$Z = 2 \times 10^{-4} = 0.01 Z_{\odot}$$

Fully aligned



Misaligned spins

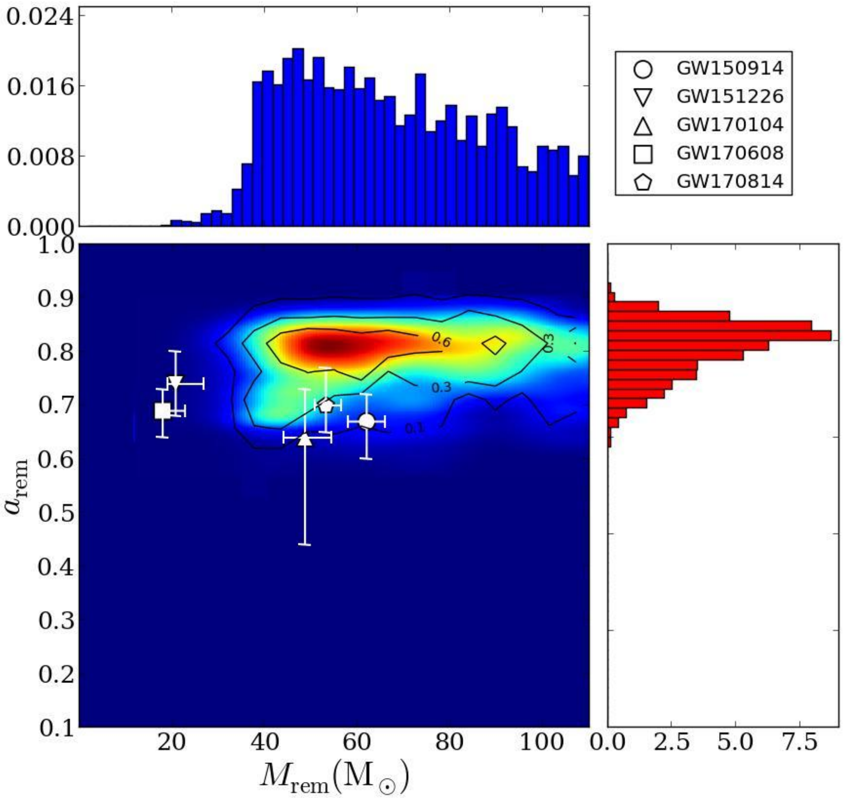


Constraining the formation channel of the observed population of merged black hole binaries

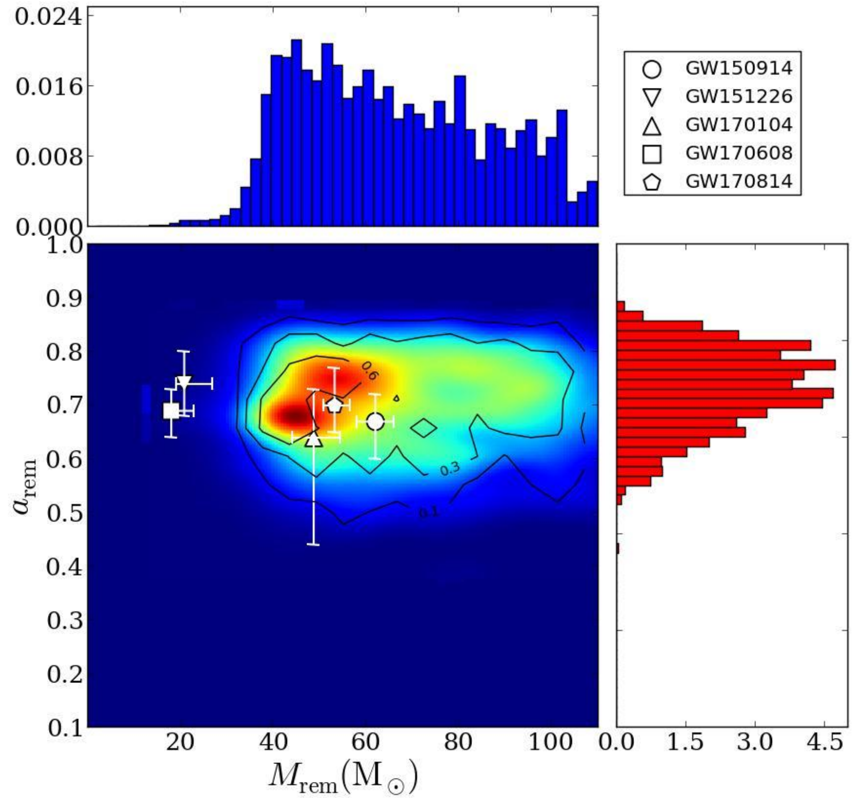
Isolated: method 2 (self consistent)

$$Z = 2 \times 10^{-4} = 0.01 Z_{\odot}$$

Fully aligned



Misaligned spins

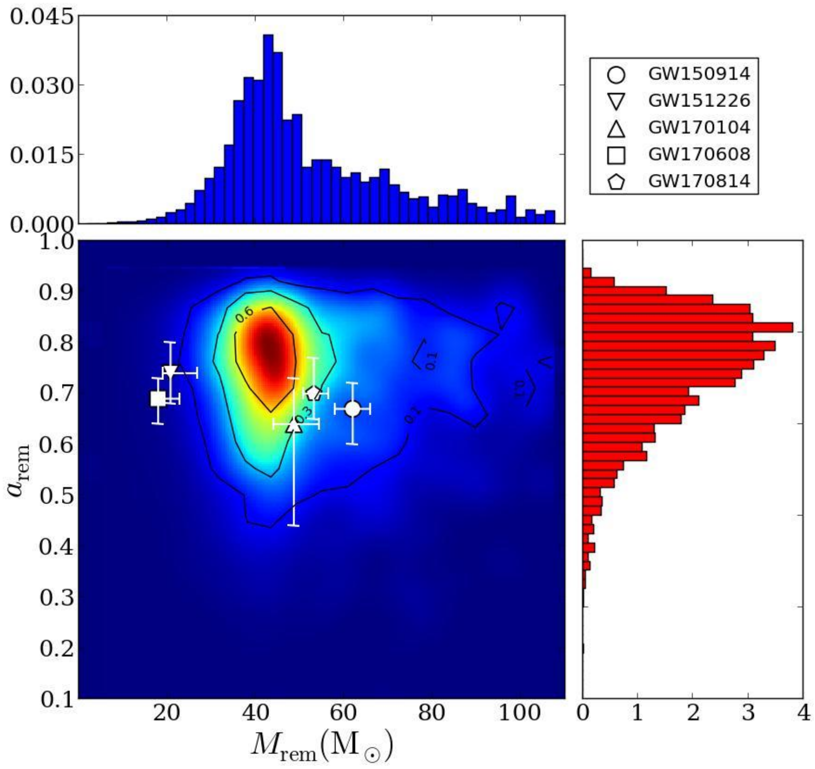


Constraining the formation channel of the observed population of merged black hole binaries

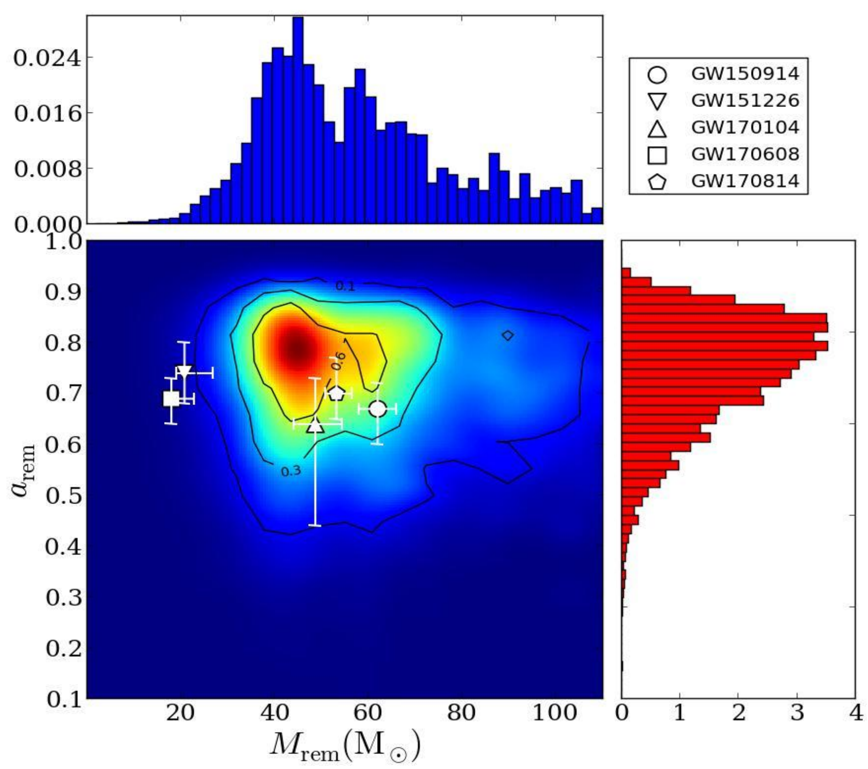
Dynamical

$Z = 2 \times 10^{-4} = 0.01 Z_{\odot}$

$q_{\rm min} = 0.5 \;\; f_{\rm recy} = 0.0$



$q_{\rm min} = 0.0 \;\; f_{\rm recy} = 0.1$



Constraining the formation channel of the observed population of merged black hole binaries

Much more possibilities

Metallicity: $Z = (0.1 - 1)Z_\odot$

Disalignment level: $P(\cos\theta_i) = (\cos\theta_i + 1)^{n_\theta}; \;\; n_\theta = 2$

BHs natal spin: $a_{\rm BH} \neq a_{\rm BH}(M_{\rm BH}); \; a_{\rm BH} = a_{\rm BH}(M_{\rm CO})$

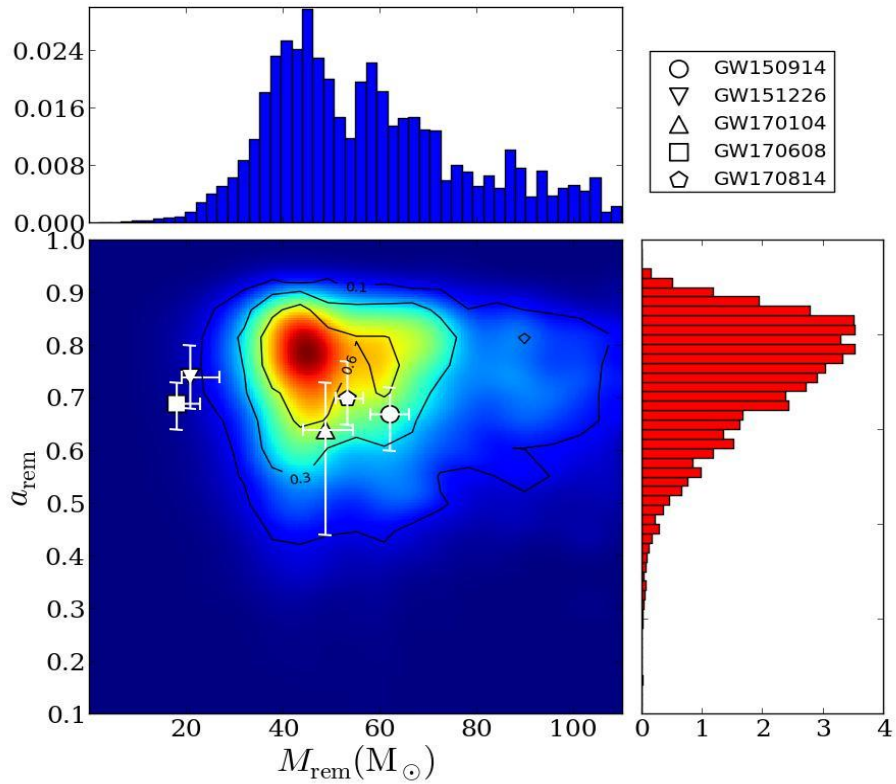
$\mathbf{V - M_{\rm BBH}}$ **Relation :** $V \propto M_{\rm BBH}^k; \; k = 1.0, 1.5, 2.5$

Constraining the formation channel of the observed population of merged black hole binaries

GW150914 - GW170104 - GW170814

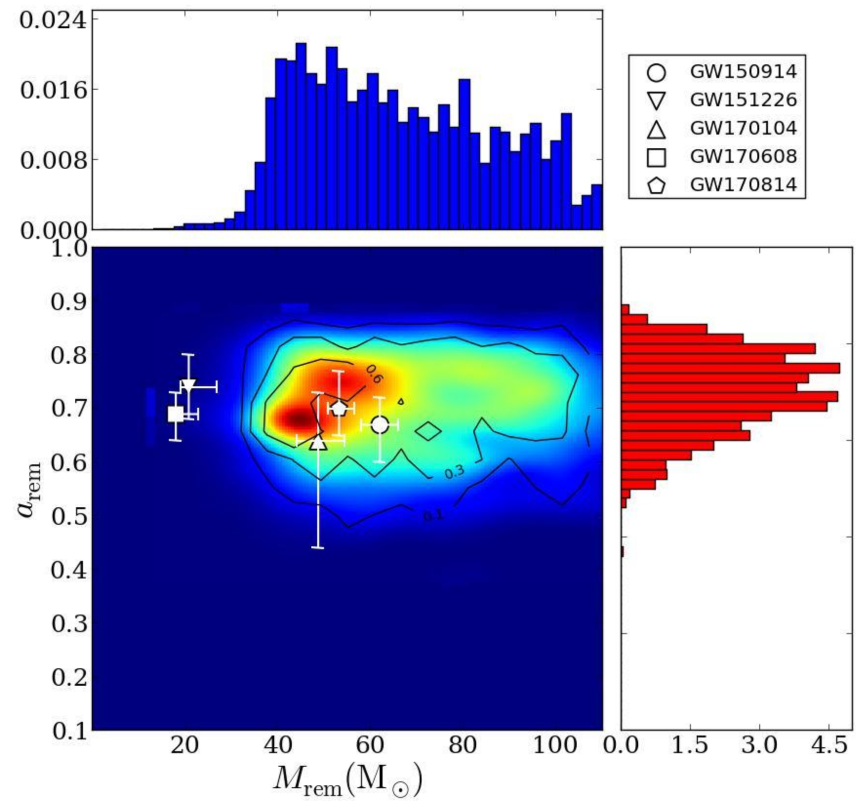
$$Z = 2 \times 10^{-4} = 0.01 Z_{\odot}$$

$q_{\mathrm{min}} = 0.0 \quad f_{\mathrm{recy}} = 0.1$



Dense globular clusters
Nuclear star clusters

Misaligned spins



Old elliptical galaxy

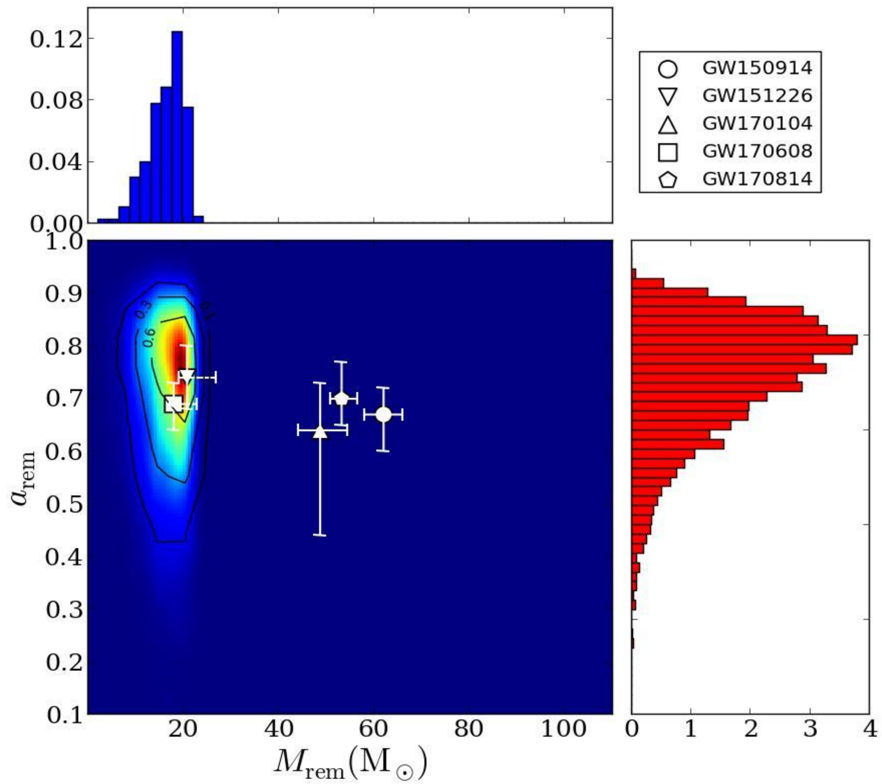
Constraining the formation channel of the observed population of merged black hole binaries

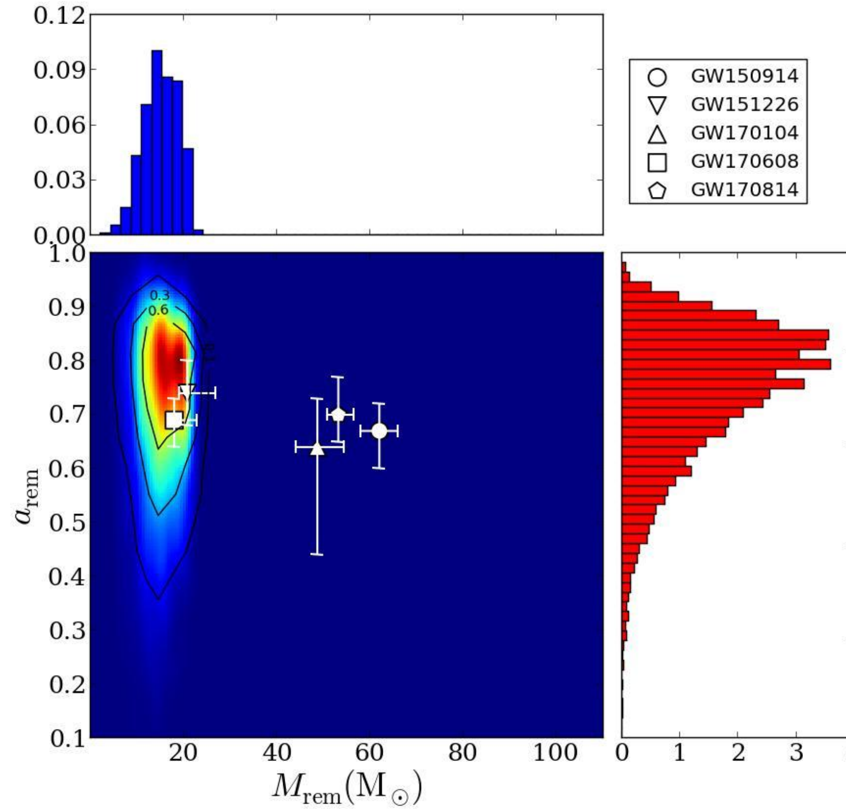
GW151226 - GW170608

$$Z = 2 \times 10^{-2} = 1 Z_\odot$$

$q_{\rm min} = 0.5 \quad f_{\rm recy} = 0.0$

Misaligned spins





Open clusters **Metal rich galaxy**

Conclusions

Arca Sedda and Benacquista, MNRAS res., on ArXiv tomorrow

I. Final mass and spin of remnant BHs can be used to infer the formation history of their progenitor BBHs

II. Many parameters can affect the calculations

- **A. Stellar evolution for single stars → BH natal spin and mass**
- **B. Stellar evolution for binaries**

  Stellar evolution modelists

- **C. Global properties of dynamically formed BBHs**

  Star clusters modelists

- **D. Remnant mass and spin**

  GR modelists

III. Under reliable assumptions

GW150914	**Dense Nuclear Cluster (Galaxy nucleus)**	**Old elliptical Galaxy**
GW151226	**Open Cluster (young, metal rich)**	**Metal rich galaxy (spiral?starburst?)**
GW170114	**Globular Cluster (old, metal poor)**	**Elliptical Galaxy**
GW170608	**Young massive cluster**	**Starburst environment**
GW170814	**Dense Nuclear Cluster (Galaxy nucleus)**	**Old elliptical Galaxy**