The Spin Evolution of Binary Black Holes Progenitors in open cluster

arXiv:2102.09323

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Challenging and Innovation in Computational Astrophysics 2021
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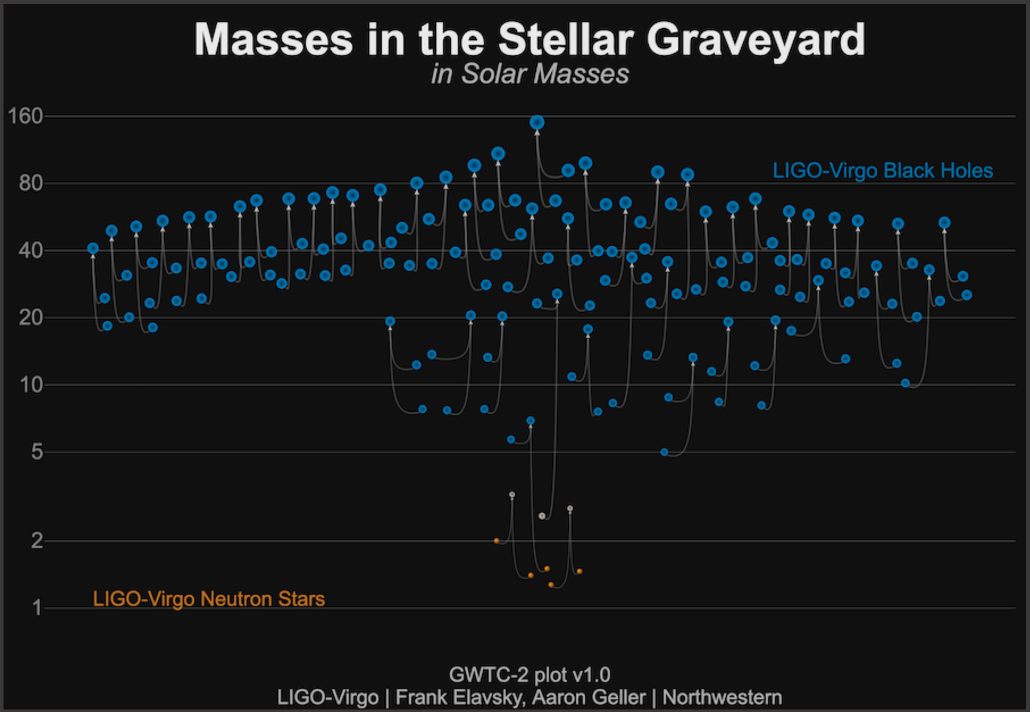
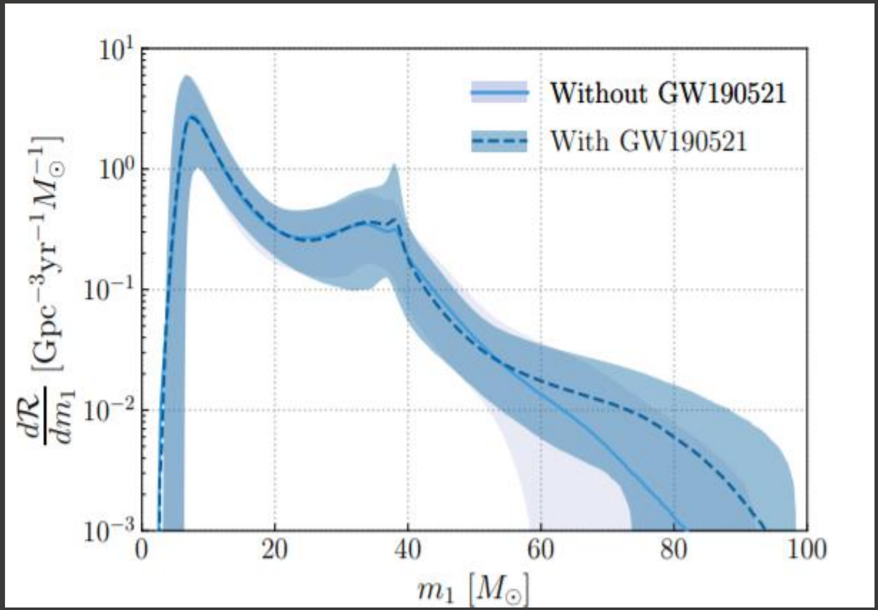
INTRODUCTION



differential merger rate density for m_1



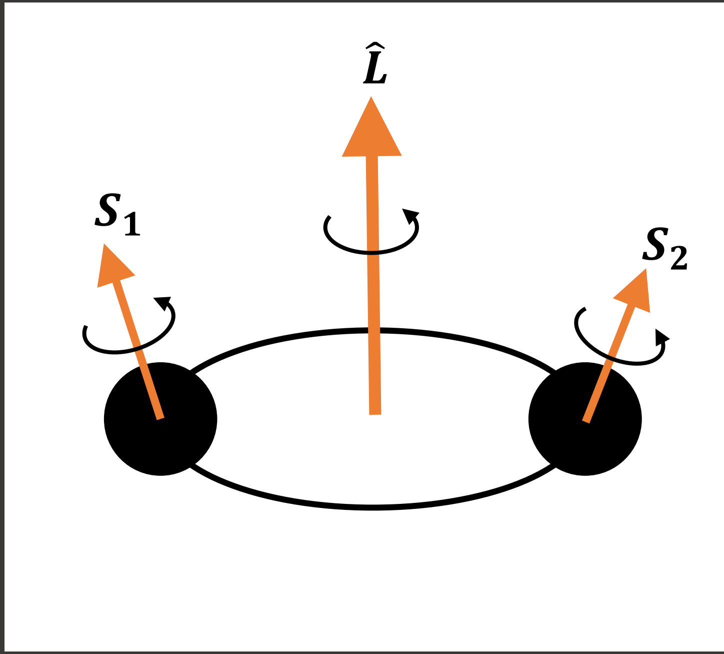
LIGO/Virgo O1-O3a (arXiv 2010.14533)

Formation scenarios for these binary black holes

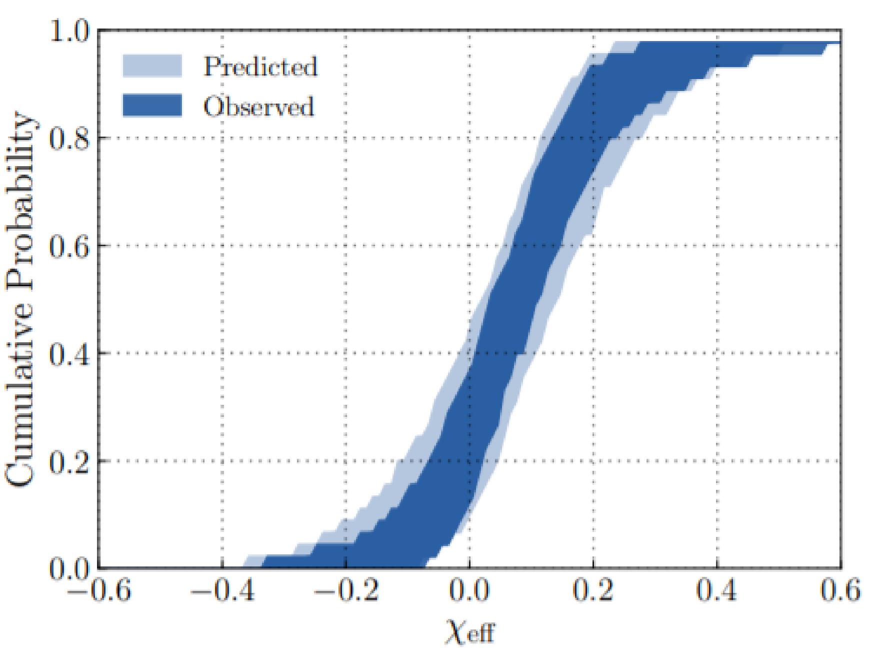
1. isolated field binary (common envelope, mass transfer)
2. dynamical formation in the dens star region

Spin parameter : χ_{eff}

$$\chi_{1,2} = \frac{c}{G m_{1,2}^2} S_{1,2} \cdot \hat{L}. \qquad \chi_{\rm eff} = \frac{m_1\chi_1 + m_2\chi_2}{M},$$

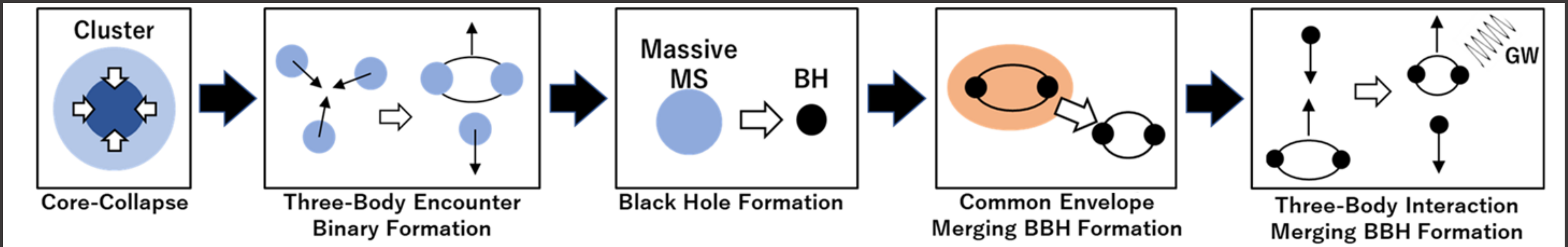


O1-O3a (arXiv 2010.14533)



previous our results

1) BBH formation in open cluster (Kumamoto+2019)



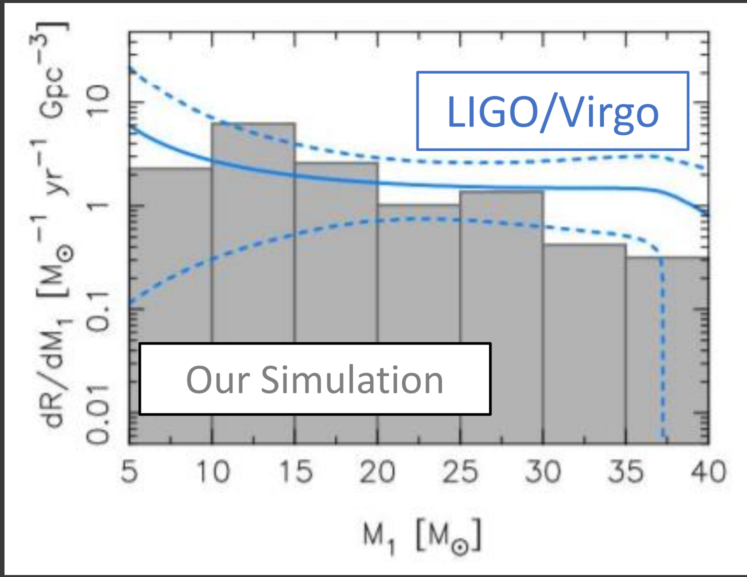
2) merger rate density of BBHs formation in open cluster (Kumamoto+2020)

$$R_{OC} \sim 70\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$$

c.f. BBH merger rate density estimated from 10 BBHs observed O1 and O2;

$$R = 53.2^{+58.5}_{-28.8}\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$$

(Abbott + 2019)



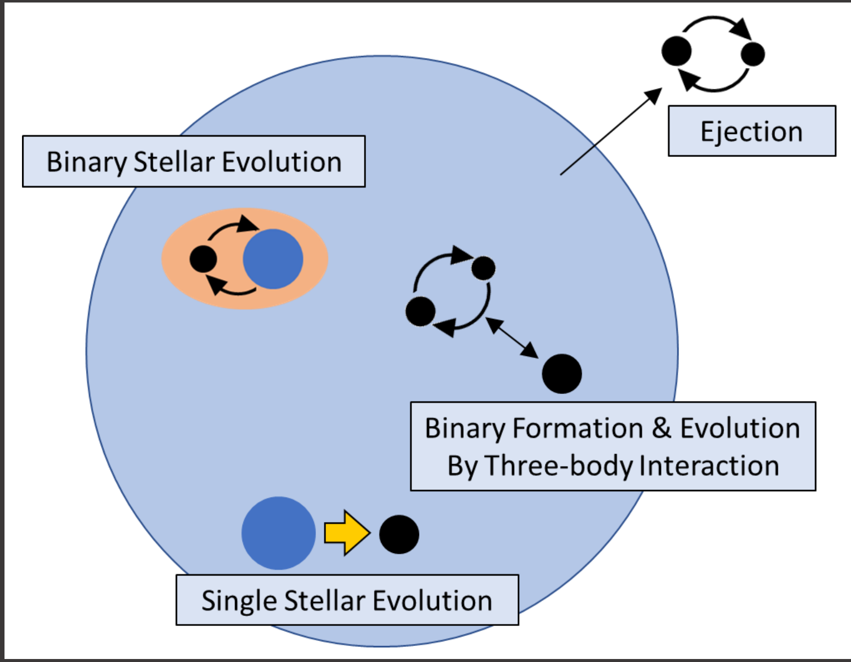
N-body simulation – Methods and Models

We performed N-body simulations of open clusters with four different metallicities to estimate a local merger rate density of BBHs from open clusters.

- code：NBODY6++GPU
- Cluster Mass：$\sim 2500 M_\odot$
- Number of Particles：4266
- Initial Mass Function：Kroupa 2001

  $0.08 M_\odot < M_{star} < 150 M_\odot$
- Density Profile：Plummer Model
- Half Mass Density：

  $\rho_{\rm hm,ini} = 10^4\ M_\odot \mathrm{pc}^{-3}$
- No primordial binary
- No natal kick
- Metallicity：$Z/Z_\odot = 0.1, 0.25, 0.5, 1$
- Stellar Evolution (Hurley+2000)
  - Evolution of stellar mass, radius and luminosity
  - Common envelope
  - Mass transfer



Kumamoto et.al. 2019
Kumamoto et.al. 2020

RESULTS – ejected BBHs from cluster

Number of binaries black holes formed in cluster

Model	metallicity Z	$N_{cluster}$	N_{BBH}	$N_{BBH}(t_{GW} < 14\text{Gyr})$
Z0002	0.002	360	338	37
Z0005	0.005	500	487	17
Z001	0.01	1000	988	32
Z002	0.02	1000	877	7

We calculate the merger time of binary black holes escaped from the cluster.

merger time：

$$t_{GW} \sim 1.2 \left[\frac{M_1}{30M_\odot}\right]^{-3} \left[\frac{a}{0.1\text{AU}}\right]^4 \frac{\text{g}(e)}{q(1+q)} \text{Gyr},$$

$$\text{g}(e) \equiv \frac{(1-e^2)^{3.5}}{1+\frac{73}{24}e^2+\frac{37}{96}e^4}$$

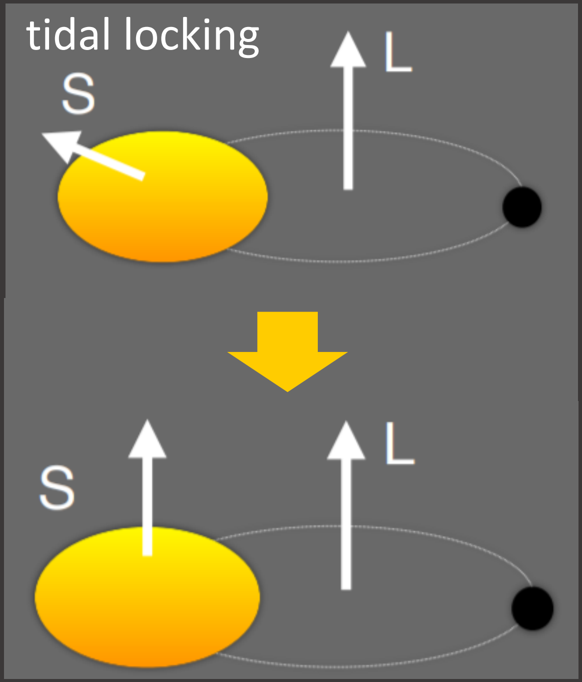
Spin-up by tidal locking

Time scale of synchronization by tidal locking:

$$t_{syn} \approx 10\ \mathrm{Myr}\ q^{-1/8} \left(\frac{1+q}{2q}\right)^{31/24} \left(\frac{t_c}{1\mathrm{Gyr}}\right)^{17/8}$$

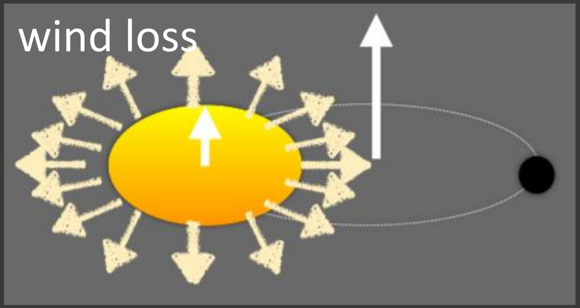
Fully synchronized spin parameter:

$$\chi_{syn} \approx 0.5\ q^{1/4} \left(\frac{1+q}{2}\right)^{1/8} \left(\frac{\epsilon}{0.075}\right) \left(\frac{R_2}{2R_\odot}\right)^{2} \left(\frac{m_2}{30M_\odot}\right)^{-13/8} \left(\frac{t_c}{1\mathrm{Gyr}}\right)^{-3/8},$$



Time scale of spin-loss by wind mass loss:

$$t_w = \frac{\chi_*(t)}{\dot{\chi}_*(t)} = \frac{M(t)}{\dot{M}(t)} \propto Z^{-0.86}$$



Spin Evolution

Time evolution of stellar spin parameter (Piran & Piran 2020):

$$\frac{d\chi_*}{dt} = \frac{(\chi_{syn} - \chi_*)^{8/3}}{t_{syn}(t_c)} - \frac{\chi_*}{t_w} ,$$

tidal locking   wind

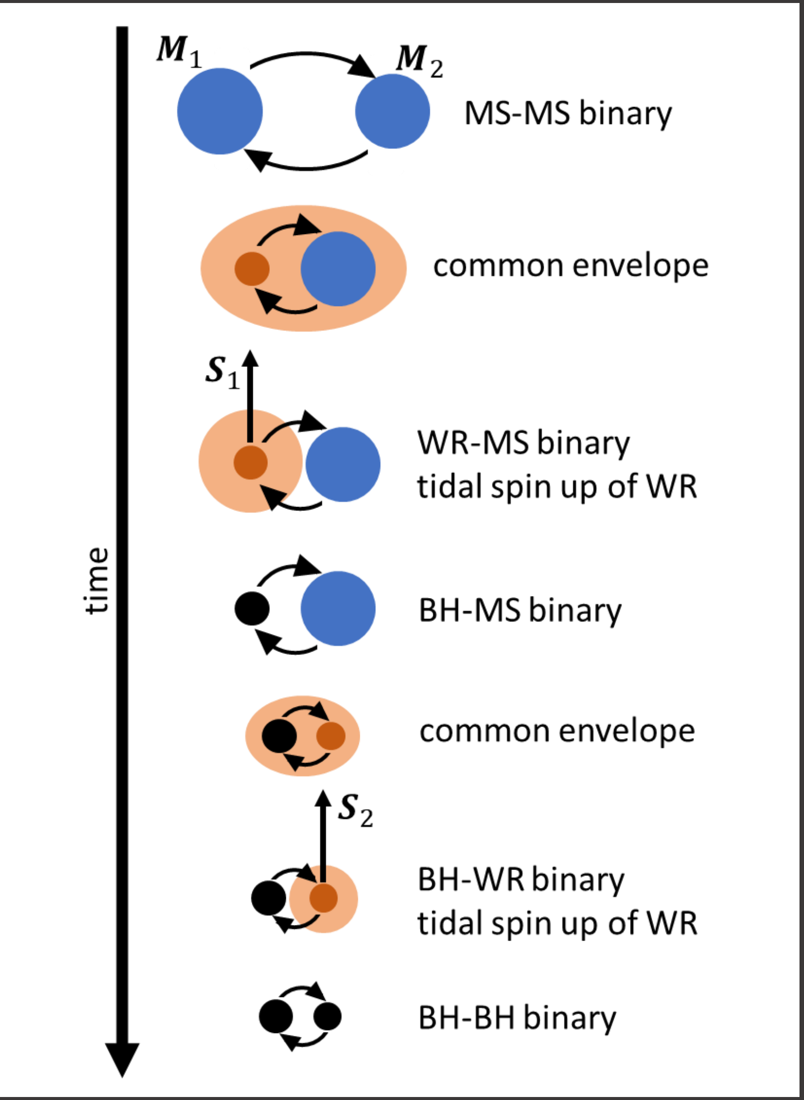
We assumed the initial spin distribution just after the common envelope $S_{1,2}(0)$.

Modal 1:

$S_{1,2}(0) = 0$

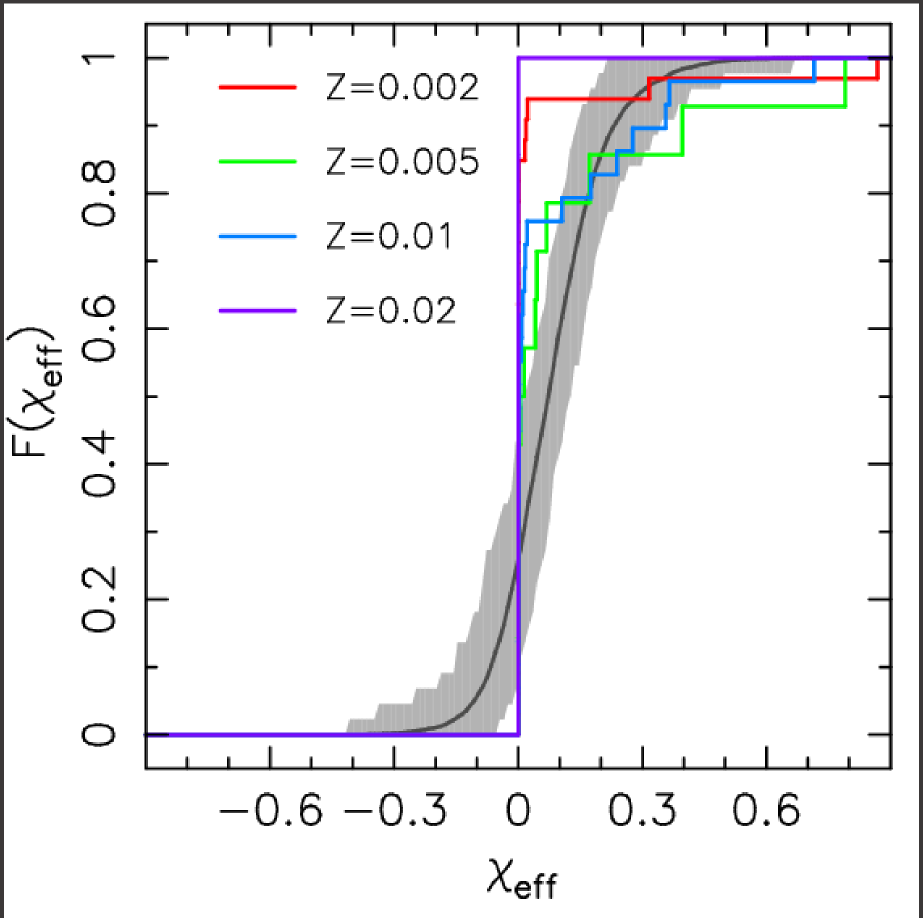
Model 2:

$0 \leq S_{1,2}(0) \leq 1$ randomly flat distribution, direction of $S_{1,2}$ is isotropic

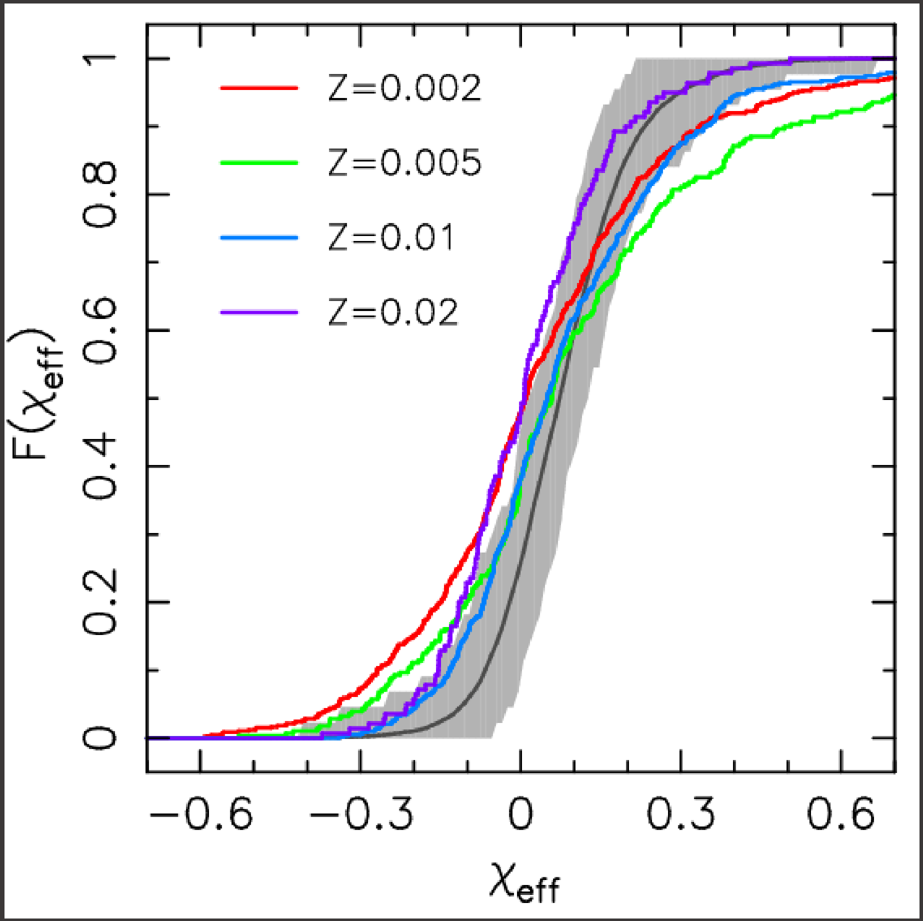


Spin distribution

Modal 1
$S_{1,2}(0) = 0$

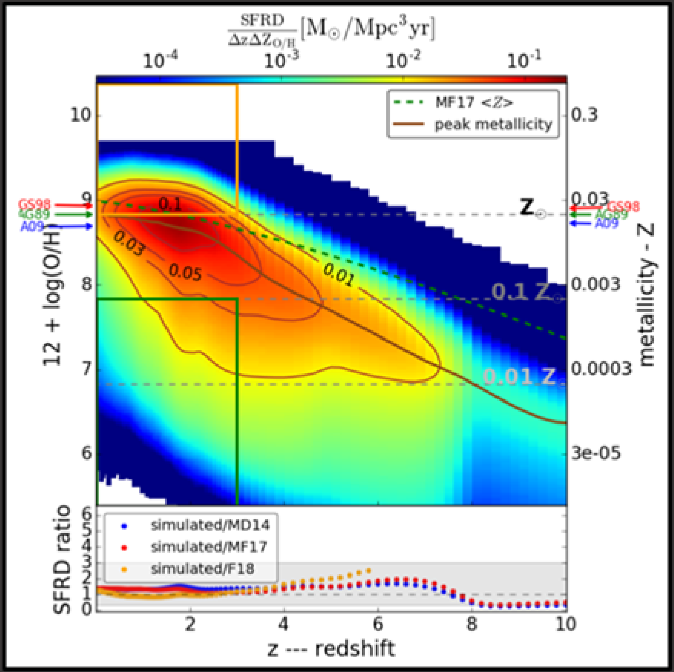


Modal 2
$S_{1,2}(0)$: flat isotropic



Star formation history for each metallicity star

SFR(Z,z)



Chruslinska & Nelemans 2019

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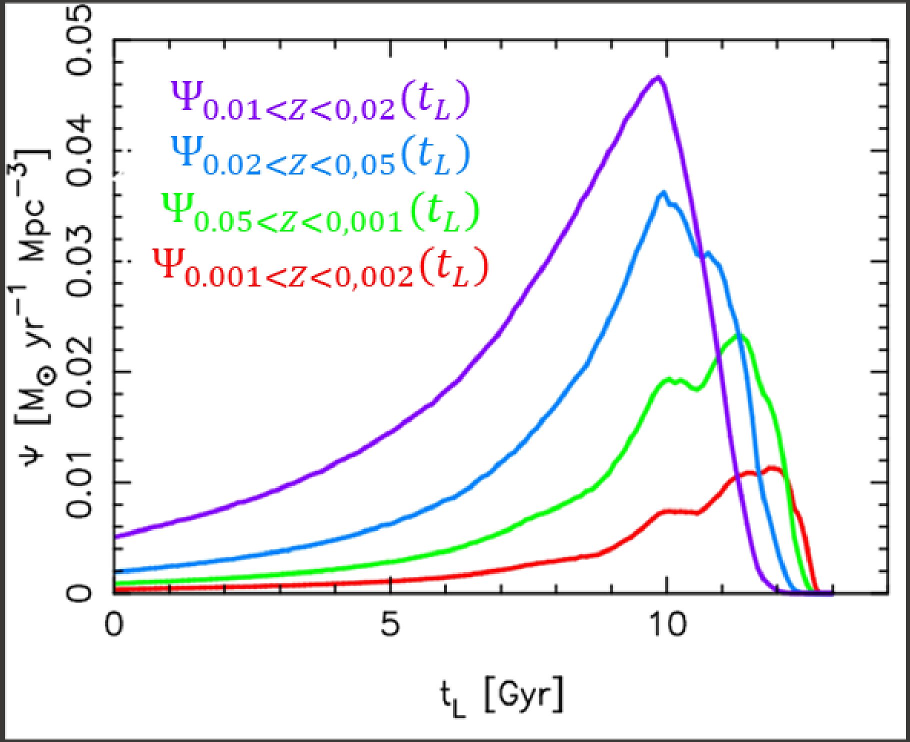
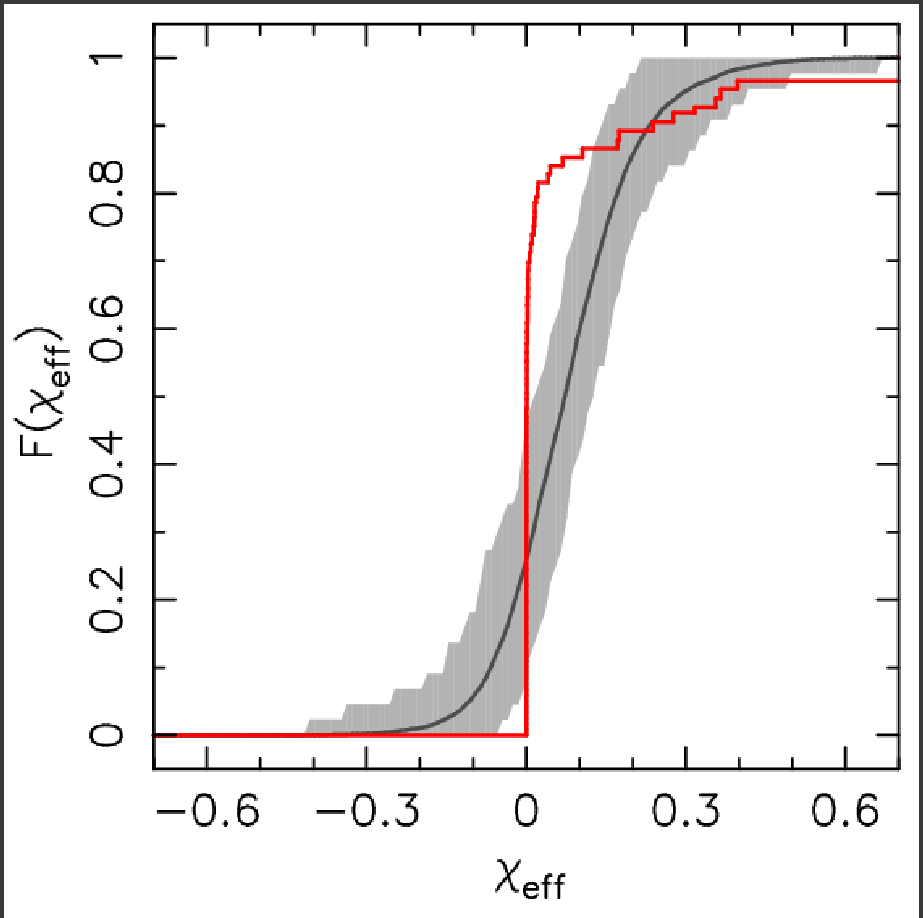


Spin distribution

Modal 1

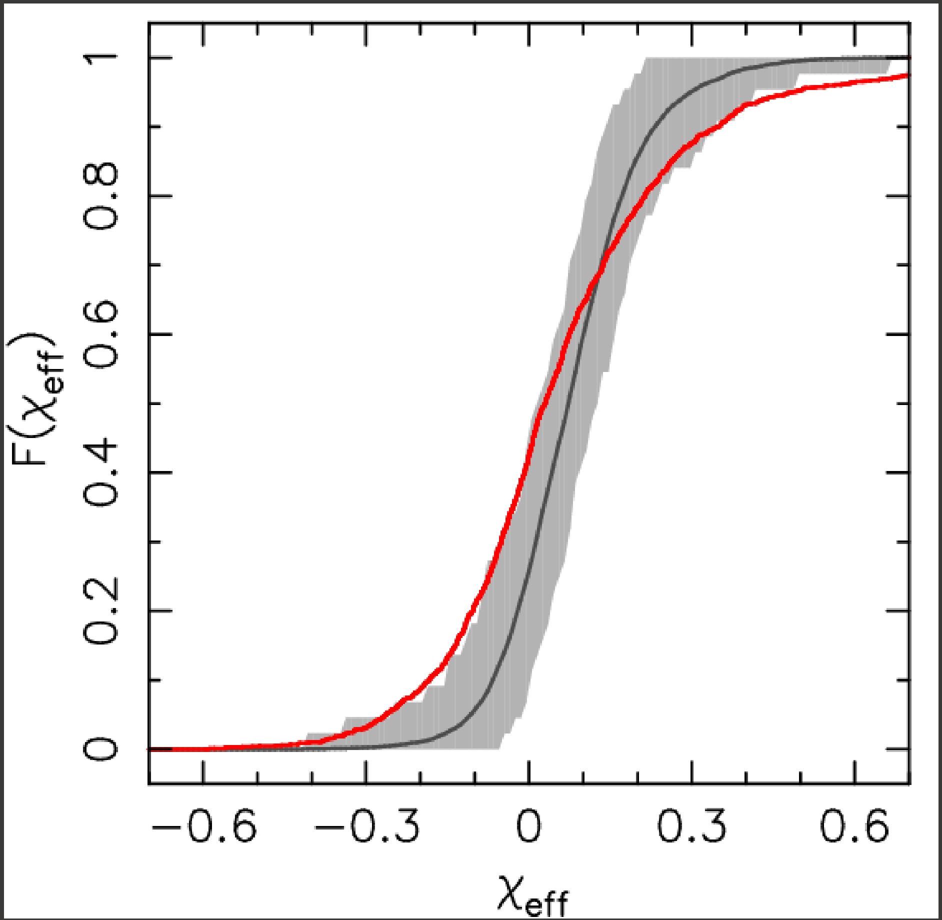
$S_{1,2}(0) = 0$



$R_{\chi_{eff}>0.1} \sim 11\ yr^{-1} Gpc^{-3}$

Modal 2

$S_{1,2}(0)$: flat isotropic



$R_{\chi_{eff}>0.1} \sim 25\ yr^{-1} Gpc^{-3}$

Summary

- We perform N-body simulations with a open cluster model and estimate the evolution of the spin parameters of the binary black holes formed in the simulation.
- By considering binary black hole mergers originating from open clusters, we can reproduce the spin parameter distribution as suggested by observations.
- The merger rate density of binary black holes with an effective spin parameter above 0.1 is

$$\mathrm{R}_{\chi_{\mathrm{eff}}>0.1} \sim 11\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}\ (\chi_*(0) = 0 \text{ model})$$

$$\mathrm{R}_{\chi_{\mathrm{eff}}>0.1} \sim 25\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}\ (\text{flat isolated model})$$