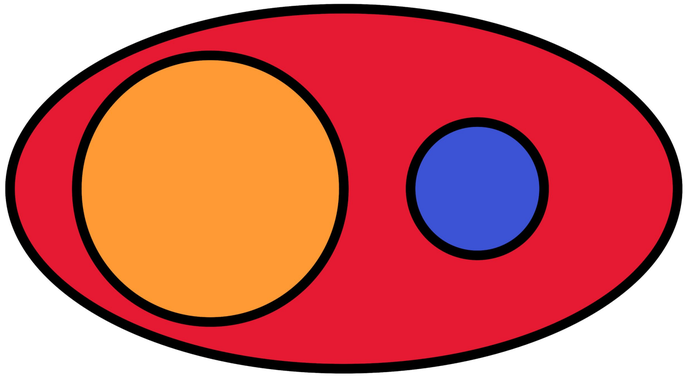
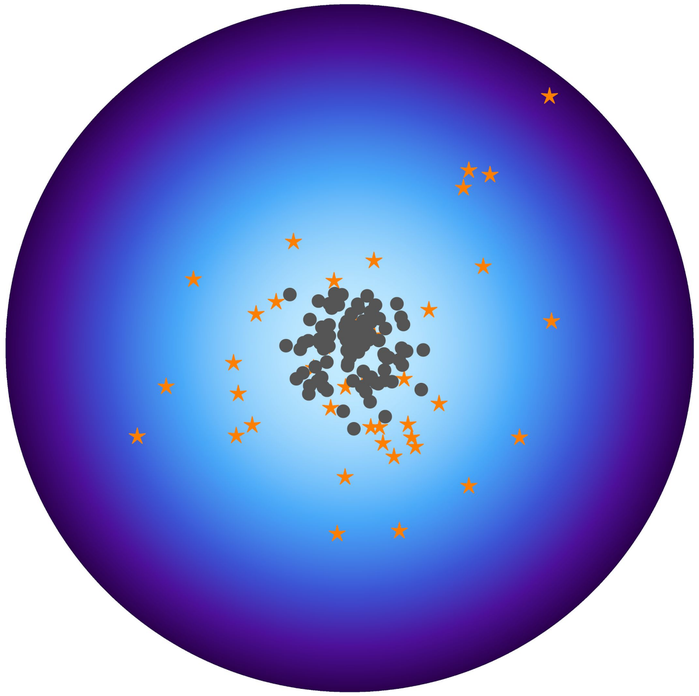
The parents of LIGO black holes and their hometown

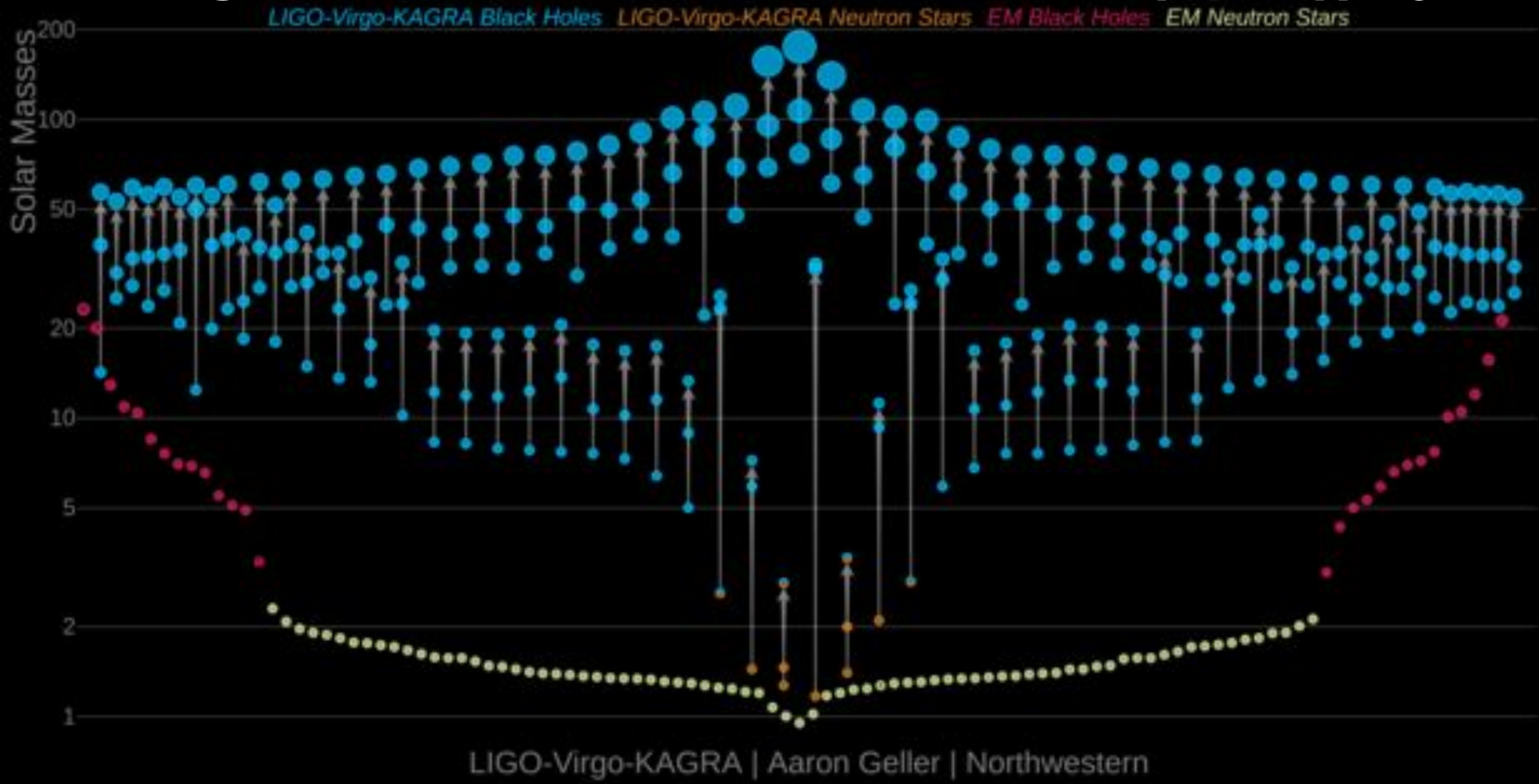


VS

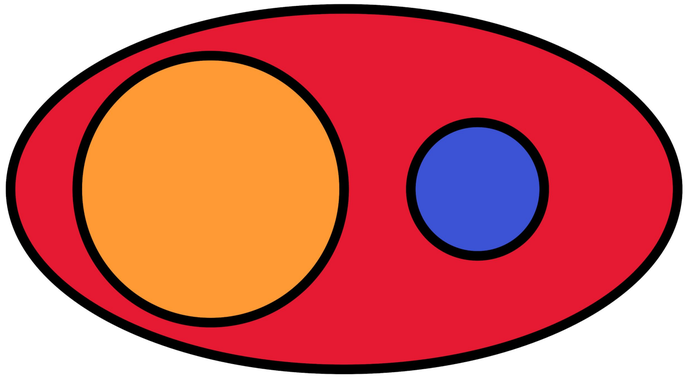


Vishal Baibhav
CIERA, Northwestern University

Exciting times for a Gravitational wave (astro)physicist

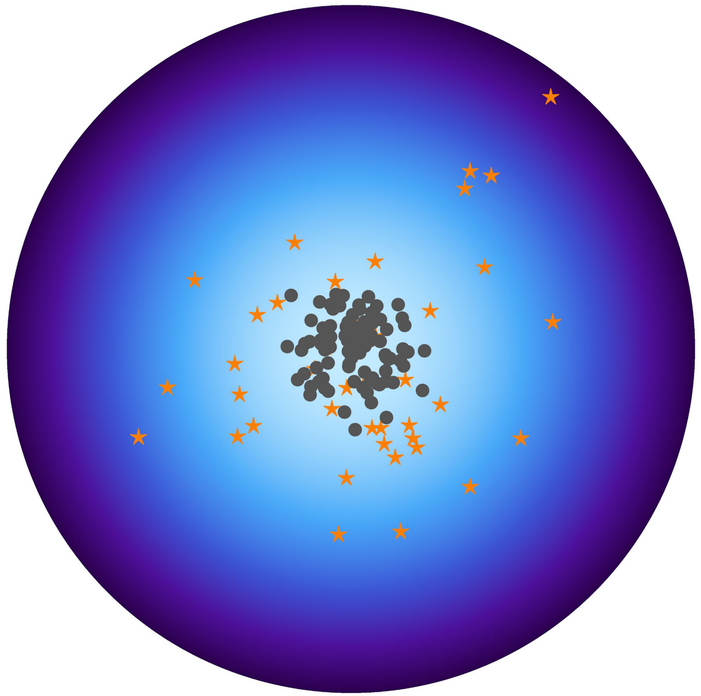


Where, when, how were LIGO BHs born?



Isolated

Common envelope, Chemically homogeneous evolution, Triples



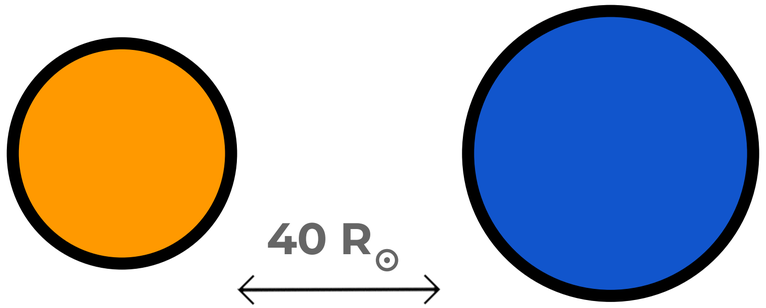
Dynamical

Globular clusters, Nuclear star clusters, Young star cluster, Active galactic nuclei

Black binary formation through field binaries

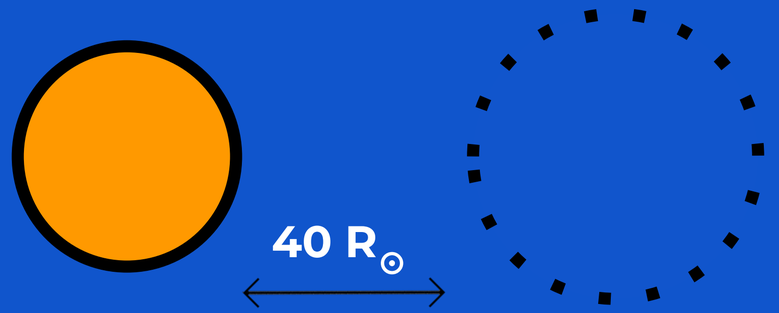
The ‘separation problem’

$$t_{\mathrm{merger}} = 13.6\,\mathrm{Gyr}\left(\frac{a}{46R_{\odot}}\right)^{4}$$



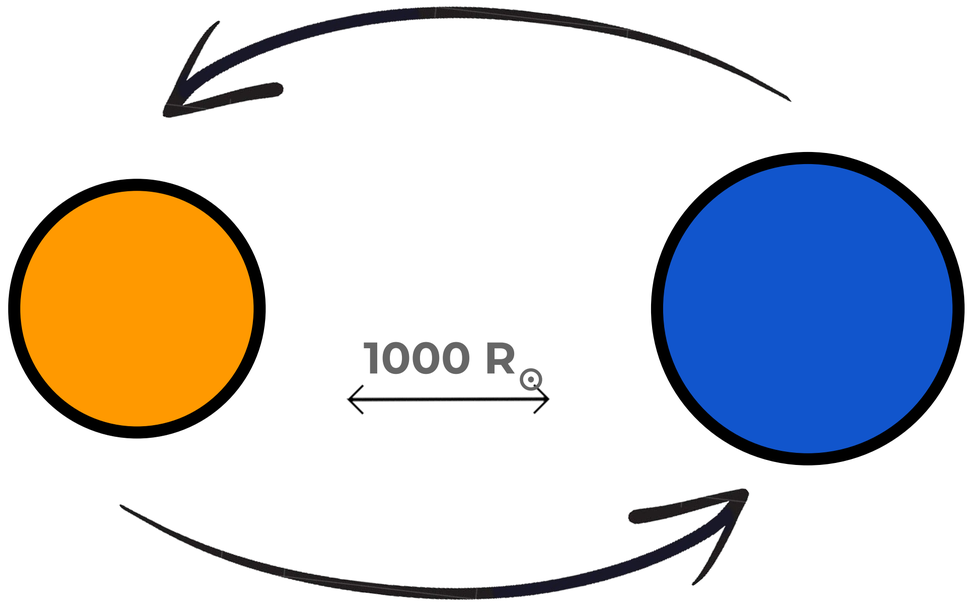
The ‘separation problem’

~1000 $R_\odot$



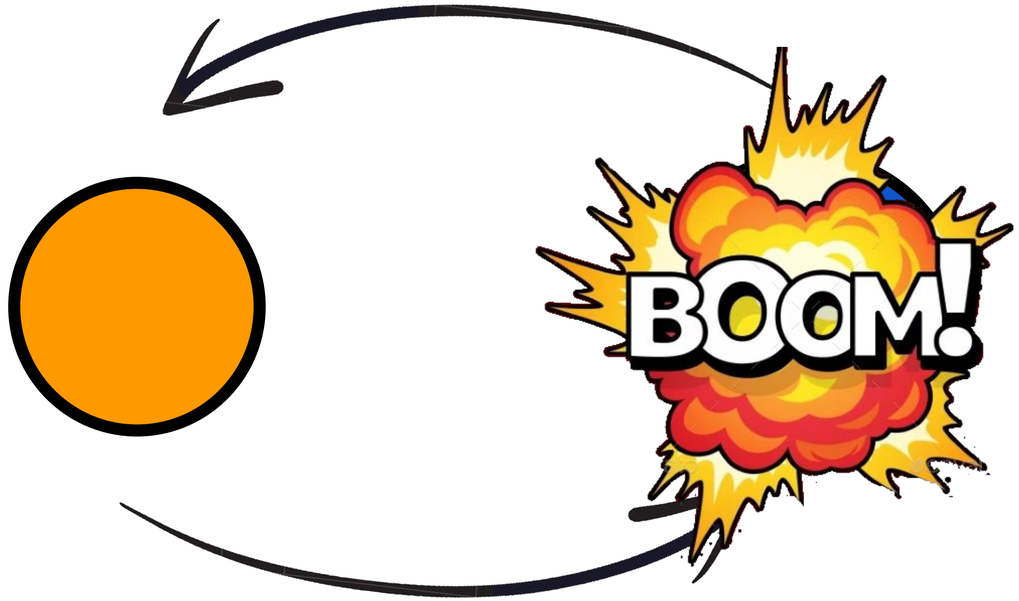
The ‘separation problem’

Solution: common envelope



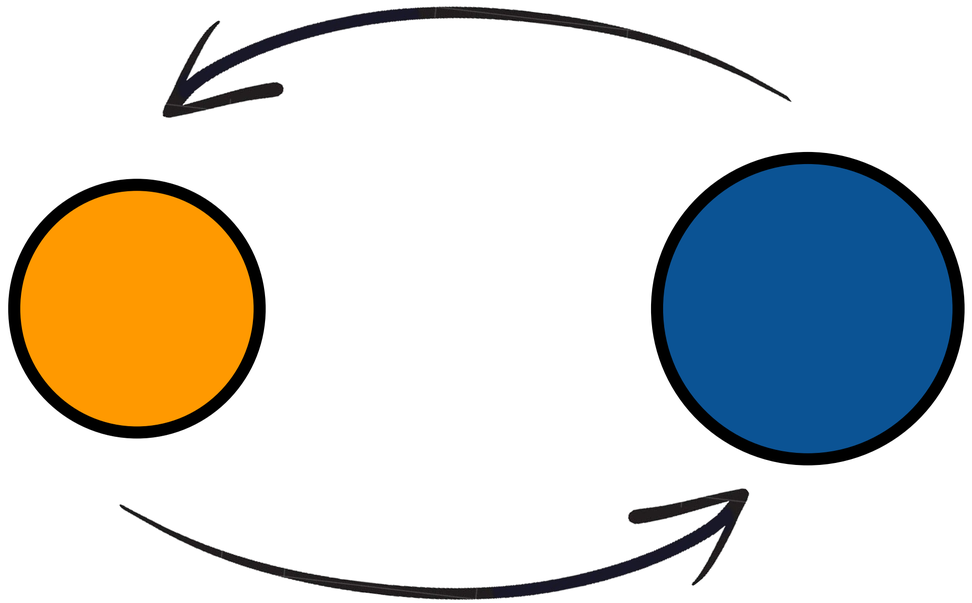
The ‘separation problem’

Solution: common envelope



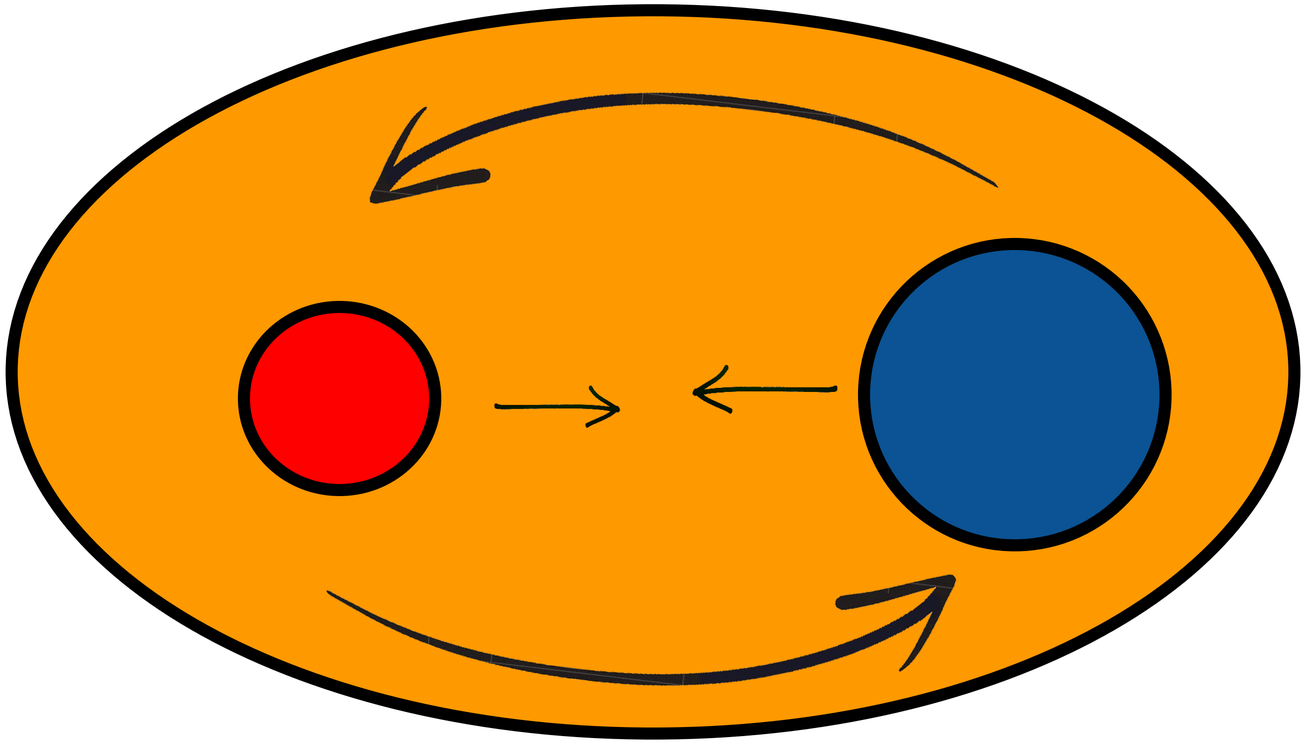
The ‘separation problem’

Solution: common envelope



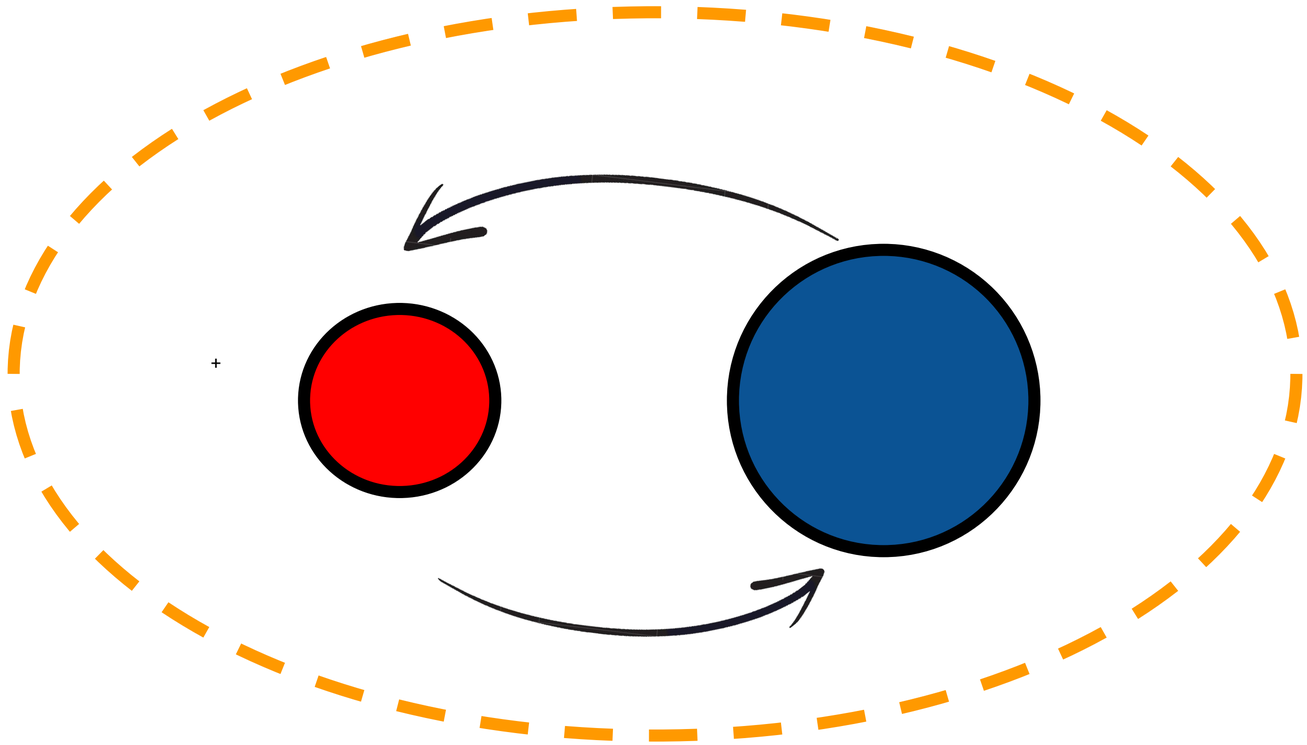
The ‘separation problem’

Solution: common envelope



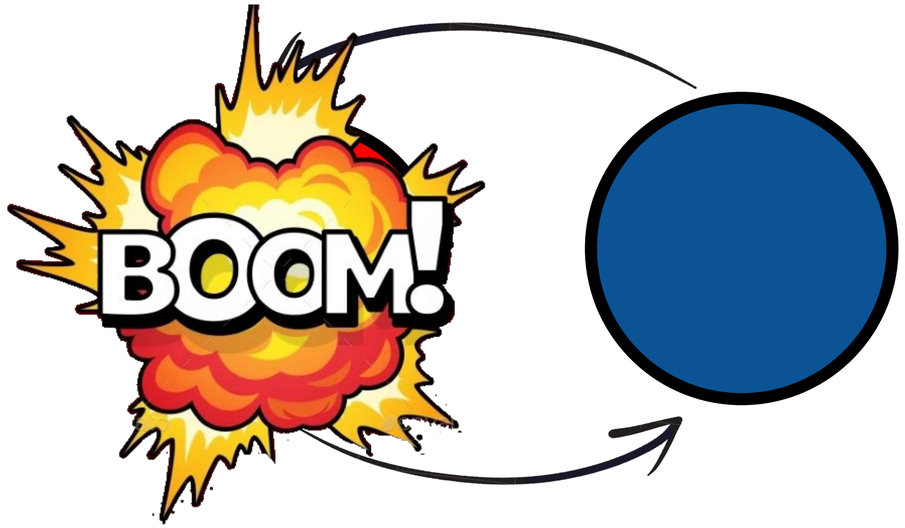
The ‘separation problem’

Solution: common envelope



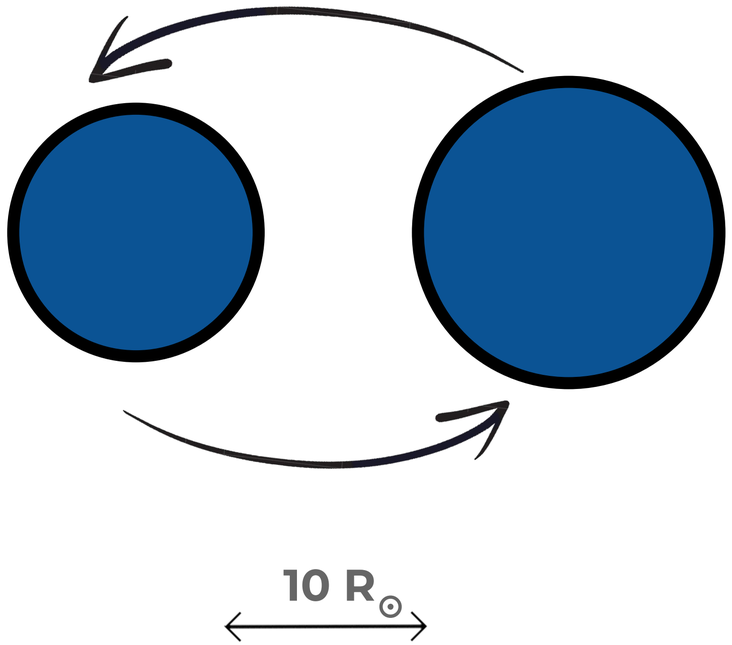
The ‘separation problem’

Solution: common envelope



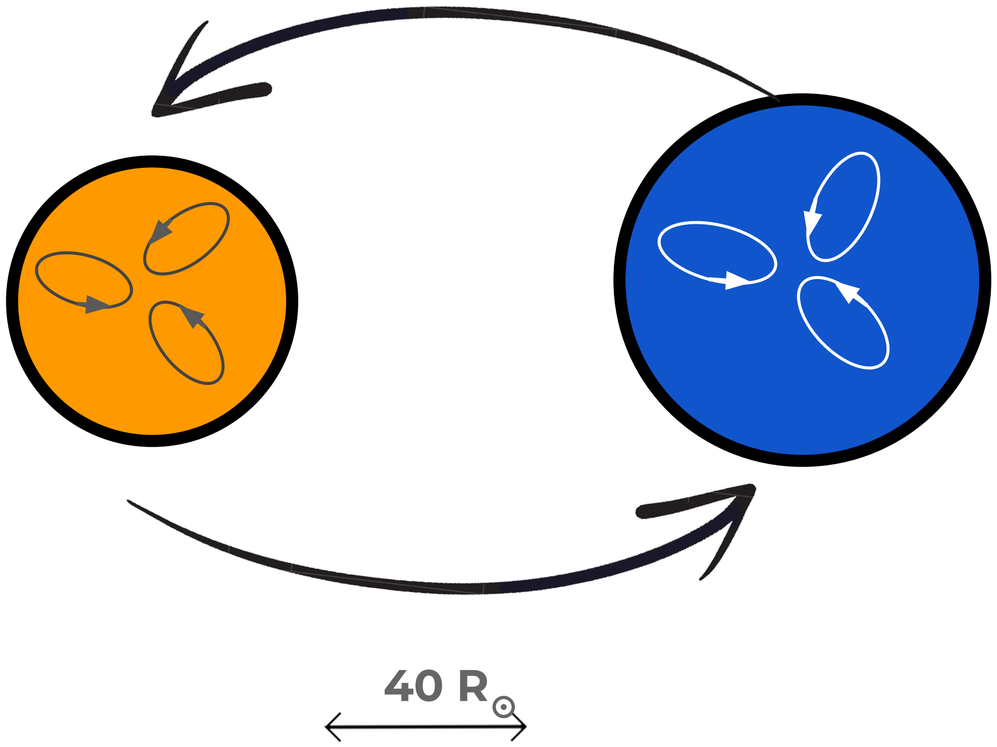
The ‘separation problem’

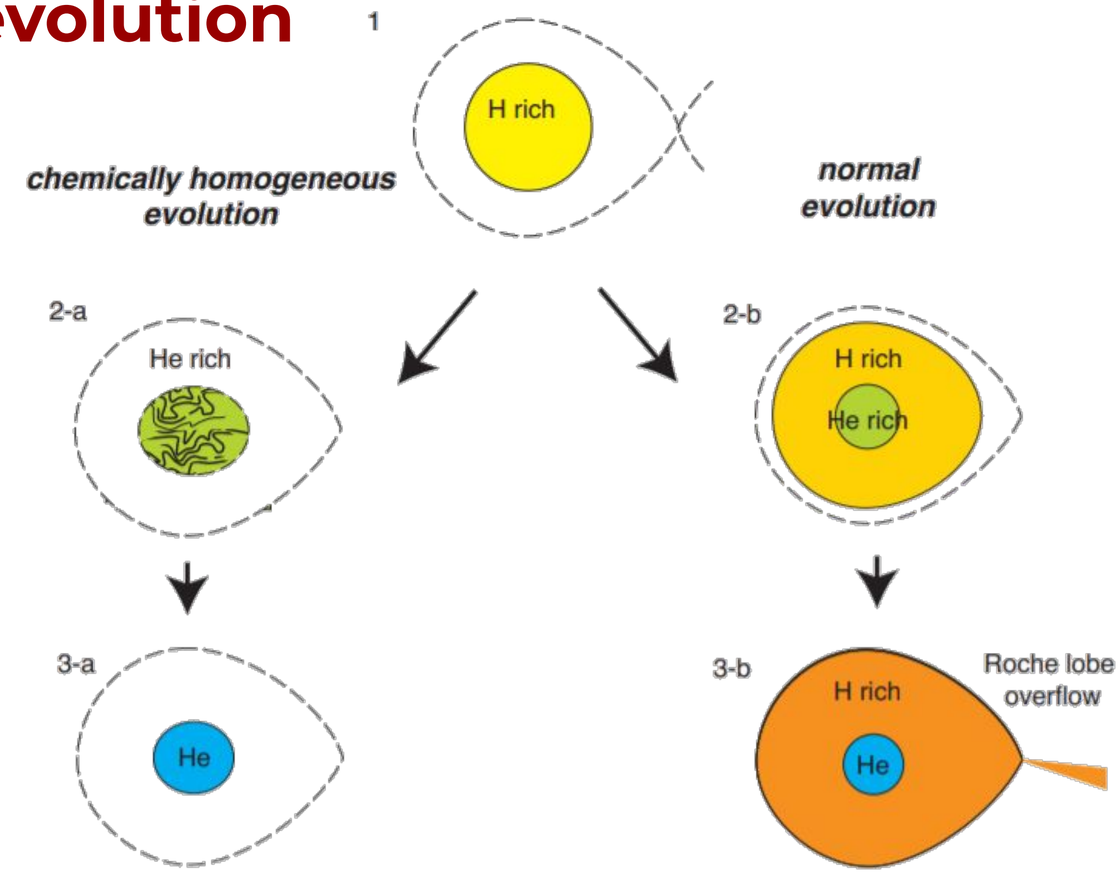
Solution: common envelope



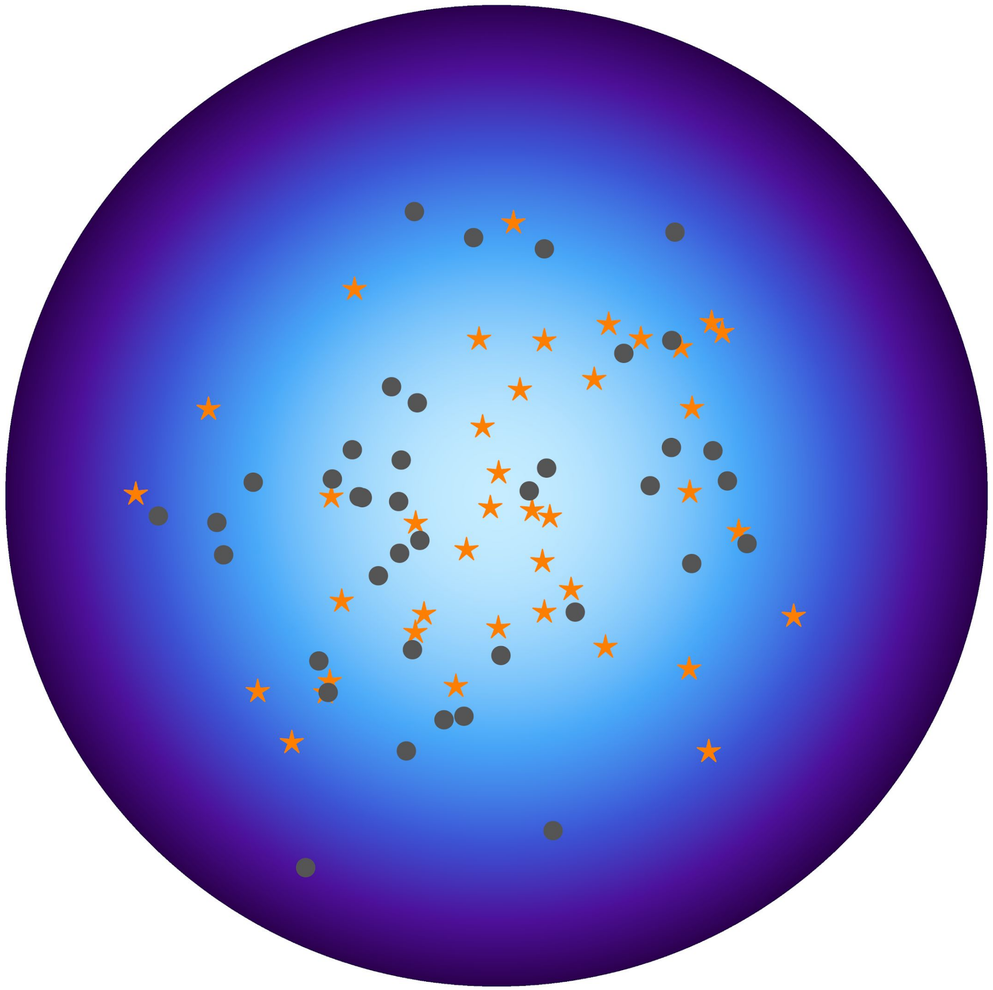
The ‘separation problem’

Solution: chemically homogeneous evolution

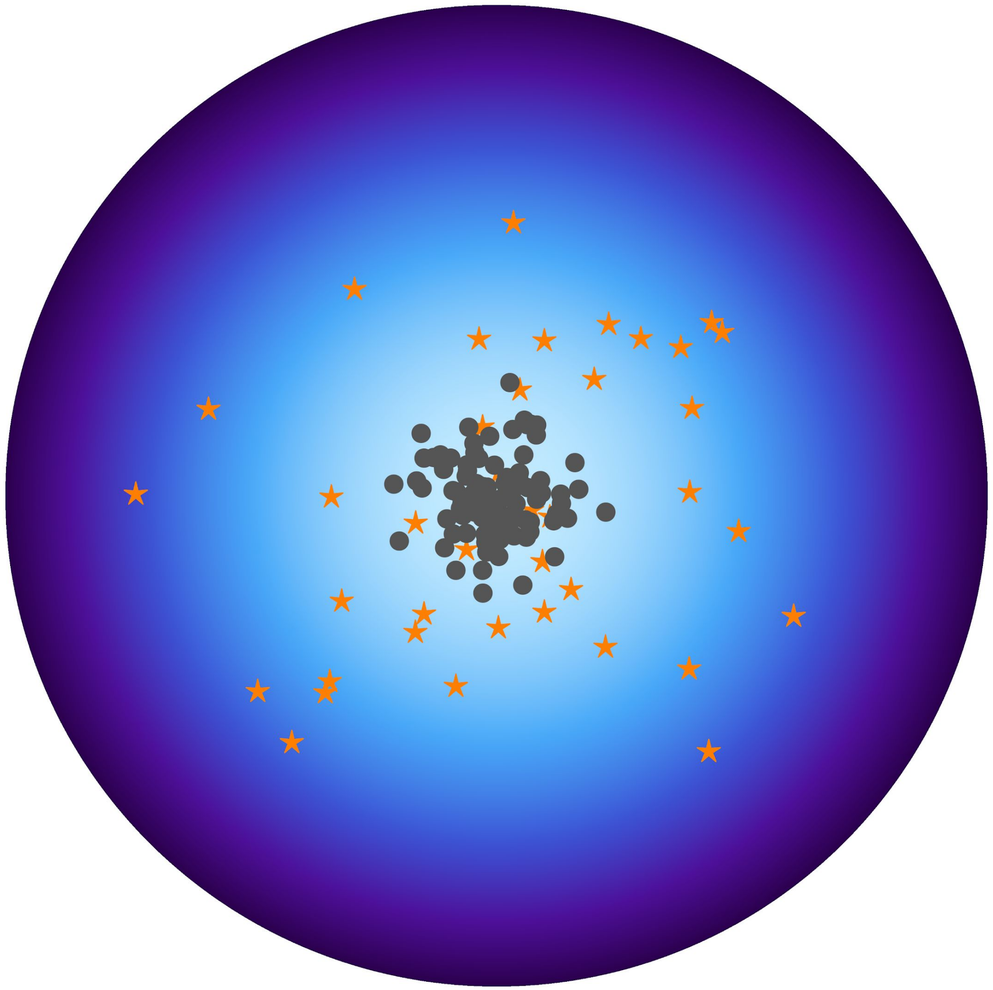




Mandel & deMink 2016

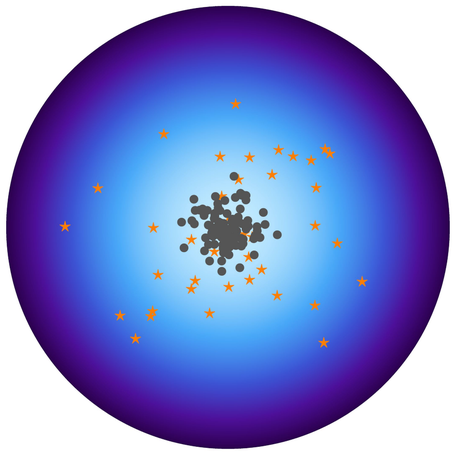


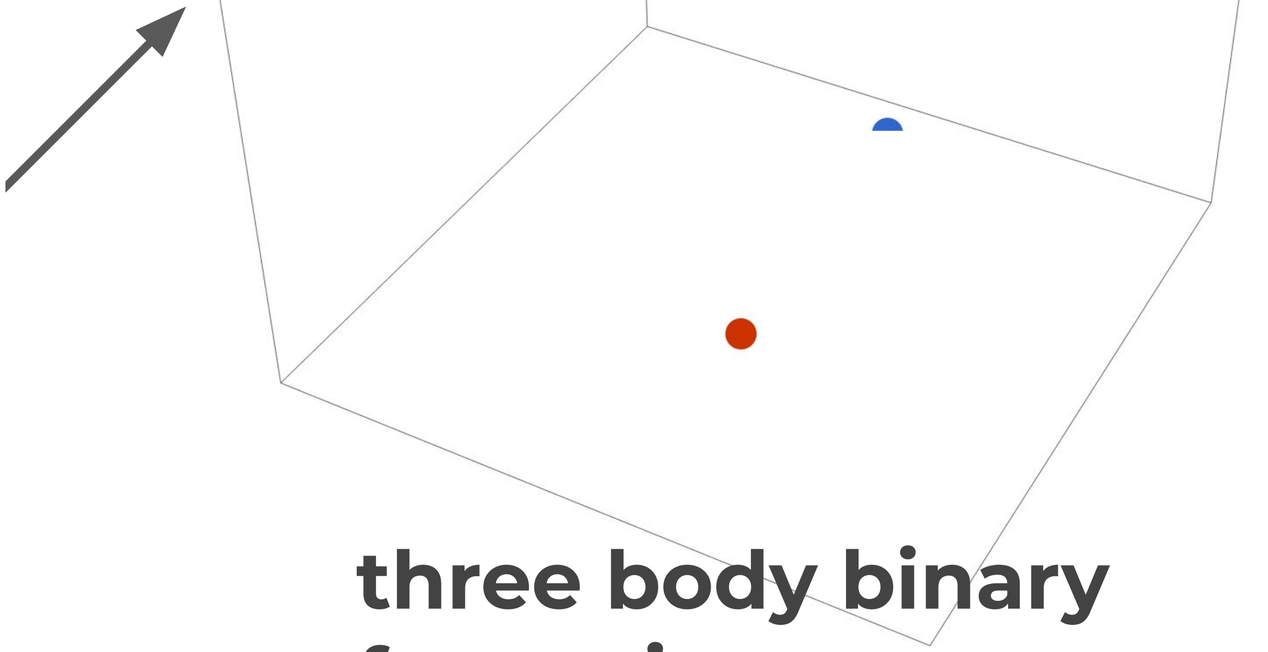
Black binary formation in star clusters



Mass segregation

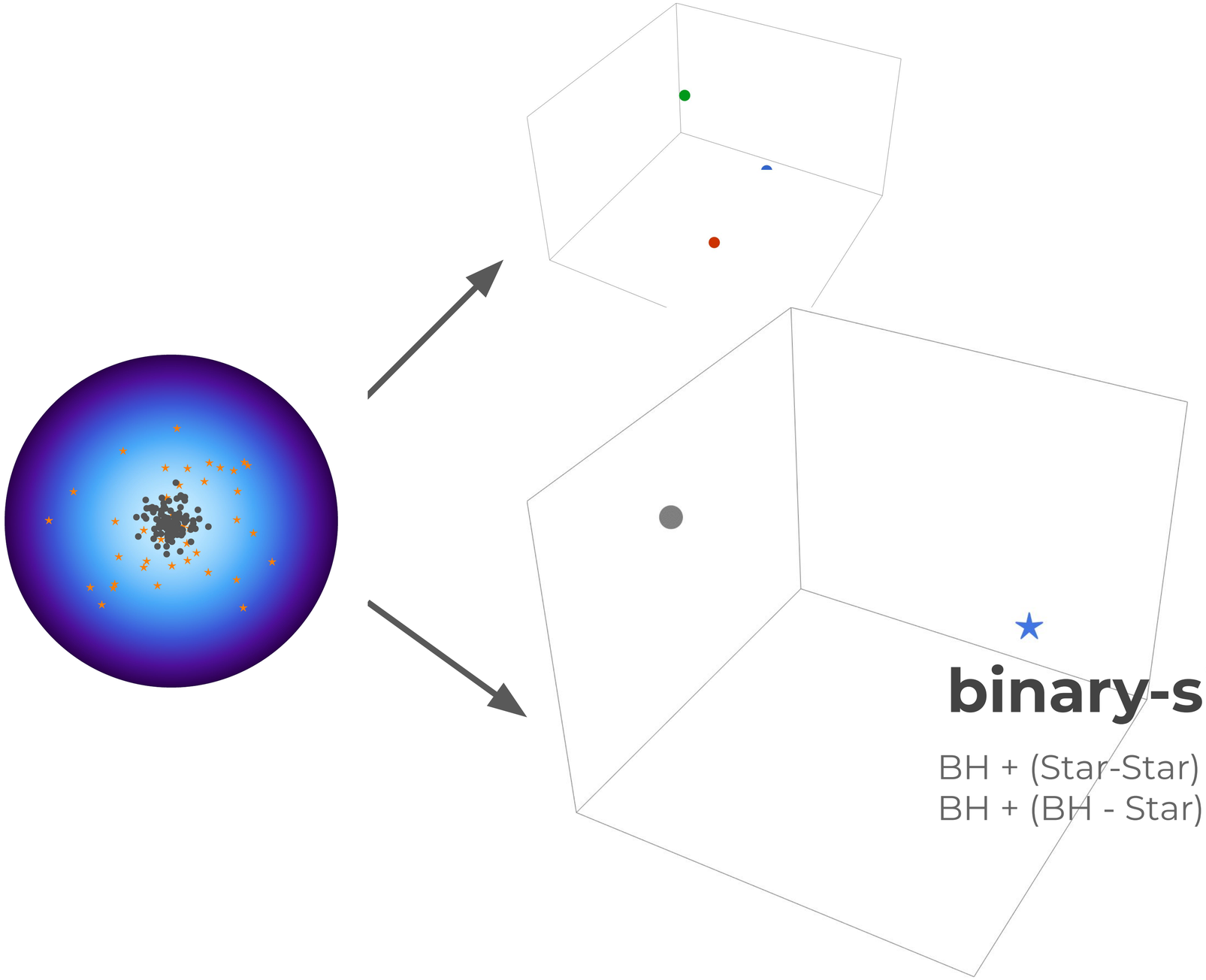
$$t_{\rm MS} \sim 100\,{\rm Myr}\left(\frac{M_{\rm cl}}{10^7\,M_\odot}\right)^{1/2}$$





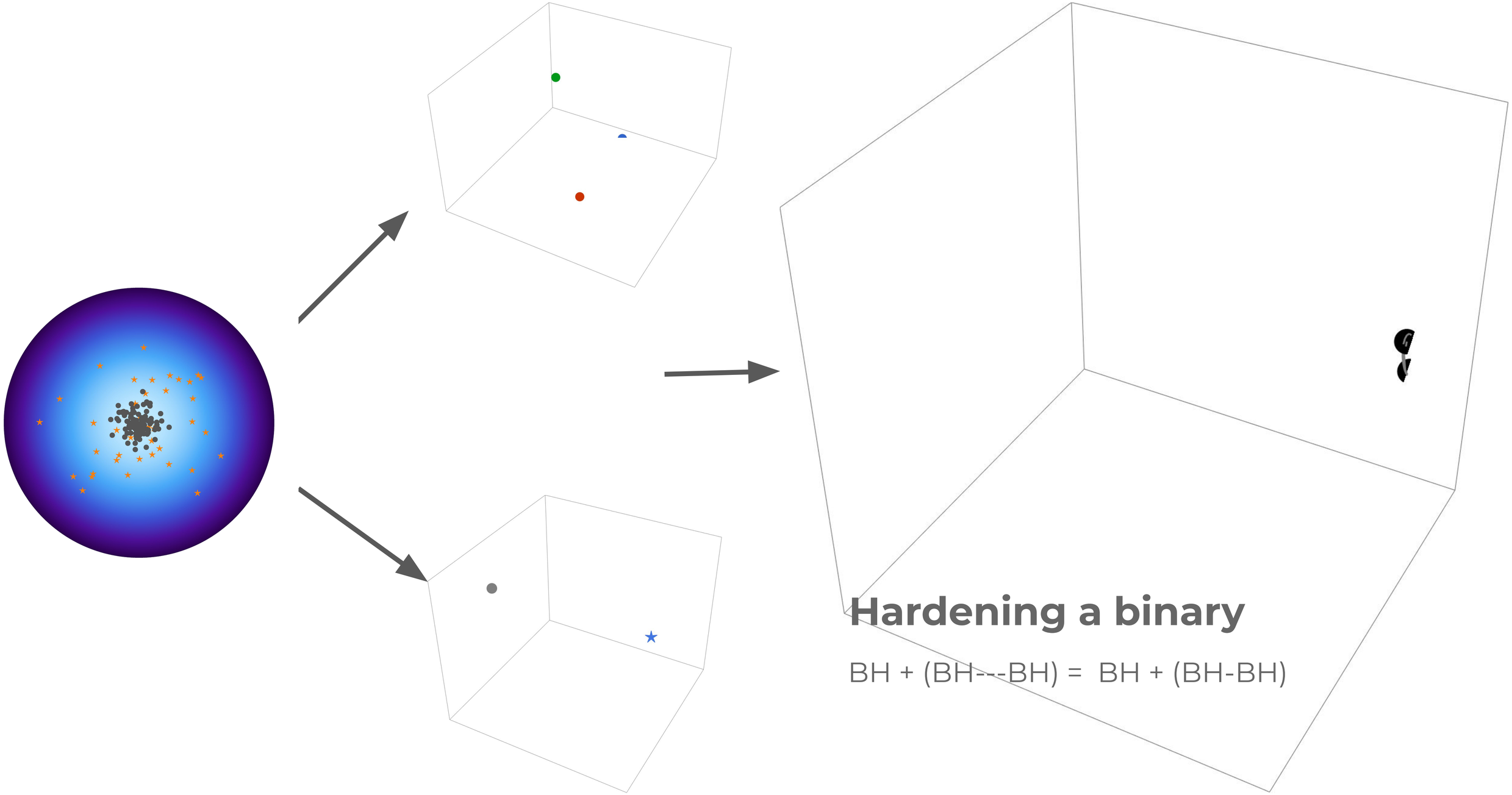
three body binary formation

BH + BH + BH ⟶ (BH-BH) + BH



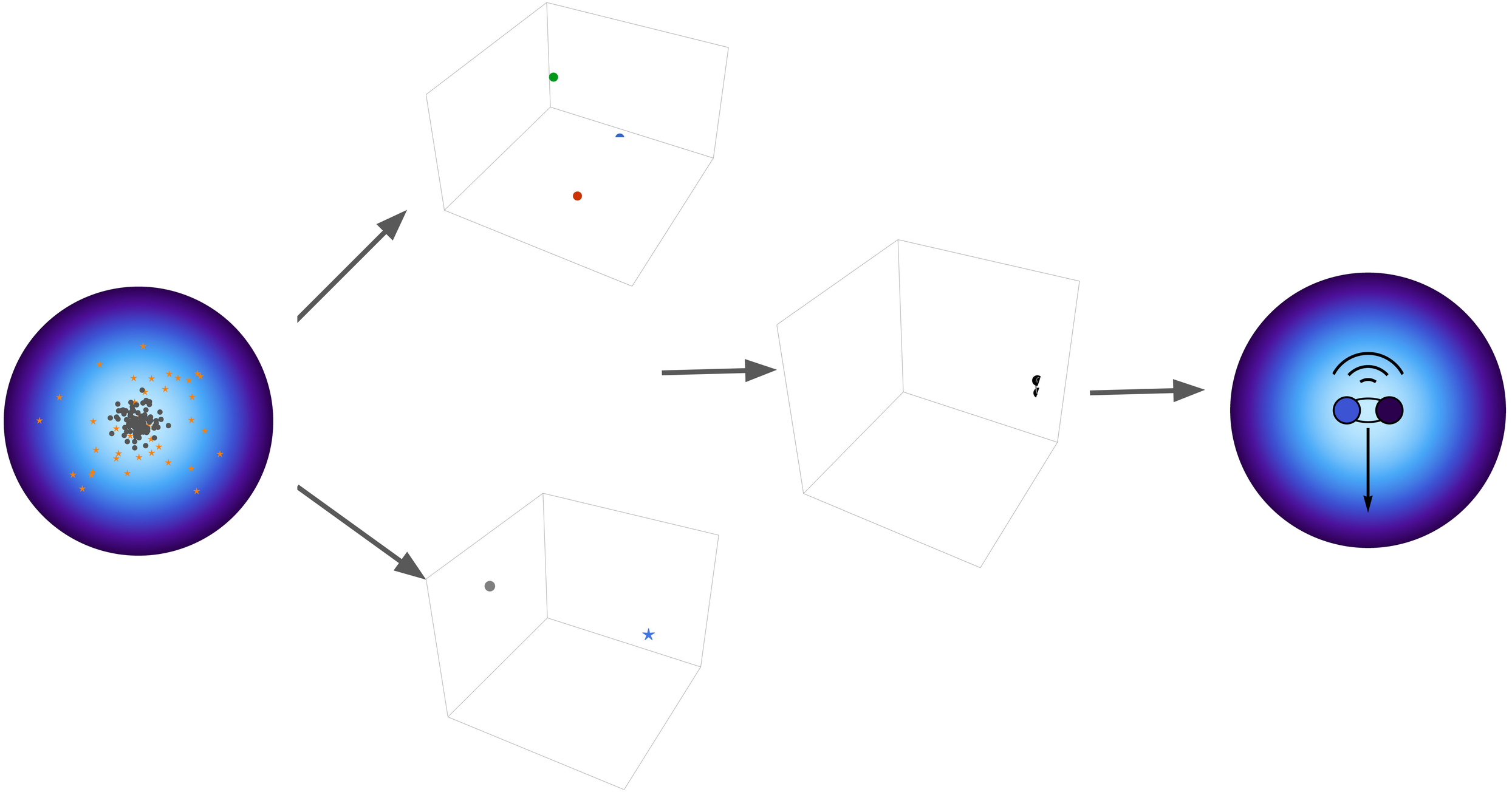
binary-single exchanges

BH + (Star-Star) ⟶ (BH-Star) + Star
BH + (BH - Star) ⟶ (BH-BH) + Star

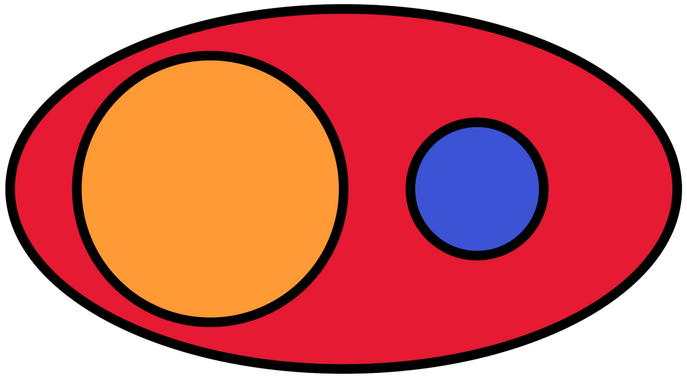


Hardening a binary

BH + (BH---BH) = BH + (BH-BH)

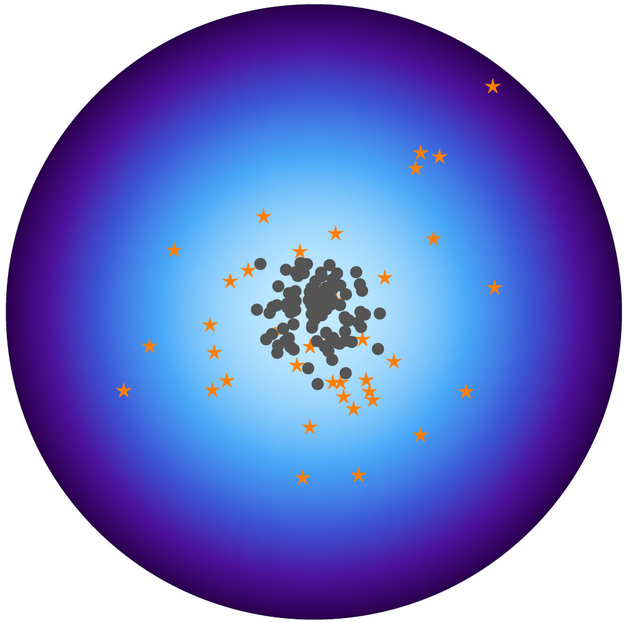


Where/when/how were LIGO BHs born?



Isolated

Common envelope, Chemically homogeneous, Triples



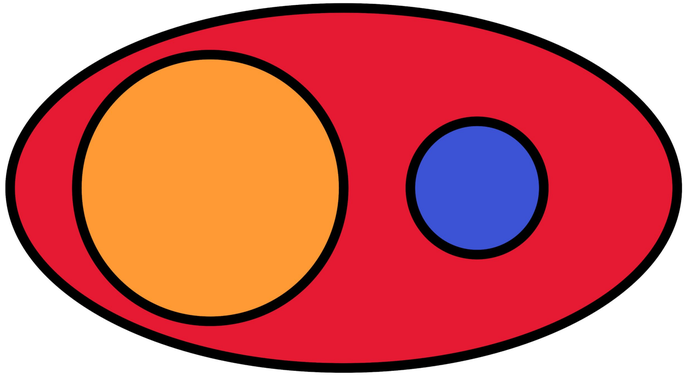
Dynamical

Globular clusters, Nuclear star clusters, Young star cluster, Active galactic nuclei

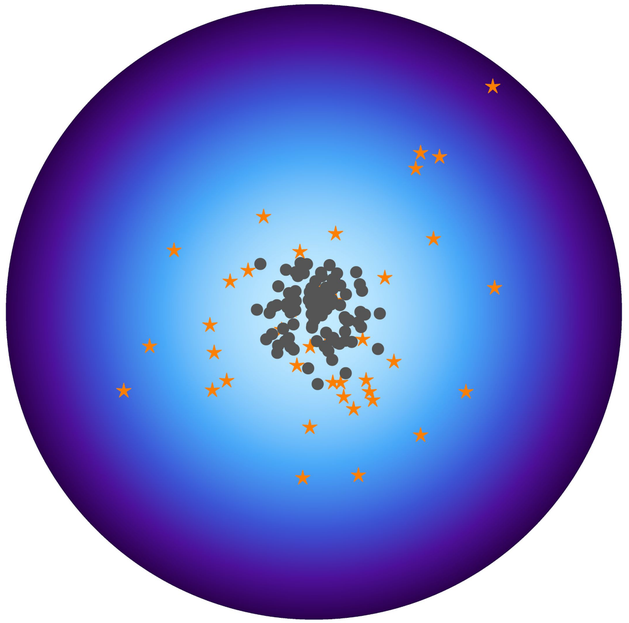
Where/when/how were LIGO BHs born?

What GWs can tell us?

Masses
Spins
Distance



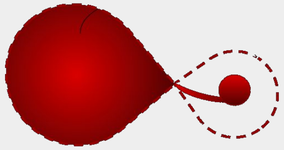
Isolated



Dynamical

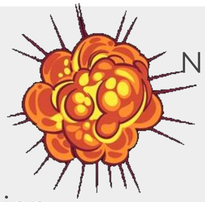
What we don't know?

Mass transfer



Common envelope efficiency

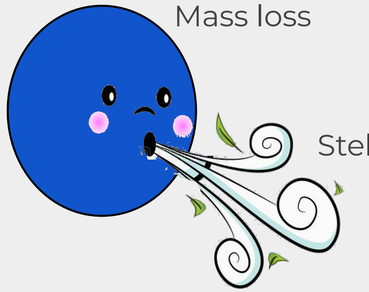
Star formation rate



Natal kicks

Explosion mechanism

Mass loss



Rotational mixing

Metallicity evolution

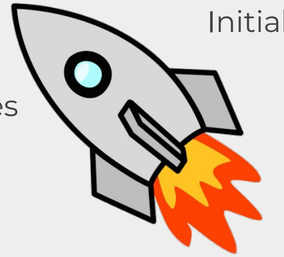
Stellar winds

Nuclear reaction rates

Time delays

Pair instability supernovae

Initial conditions



cluster properties

Initial Mass function

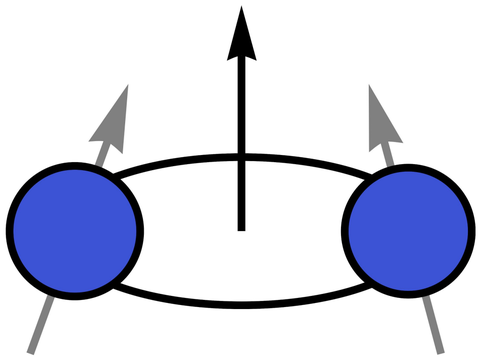
BH birth spins

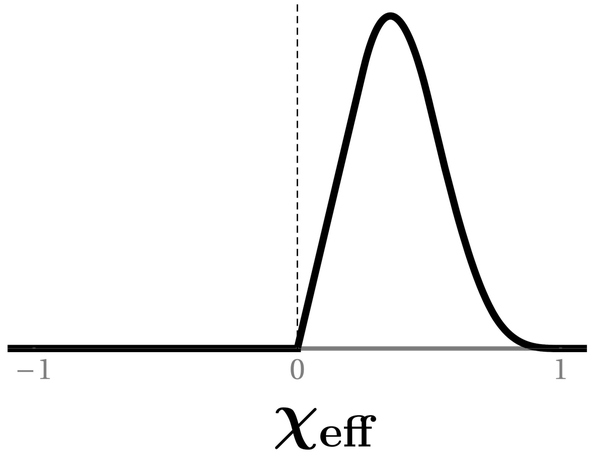
Angular momentum transport

Escape velocities

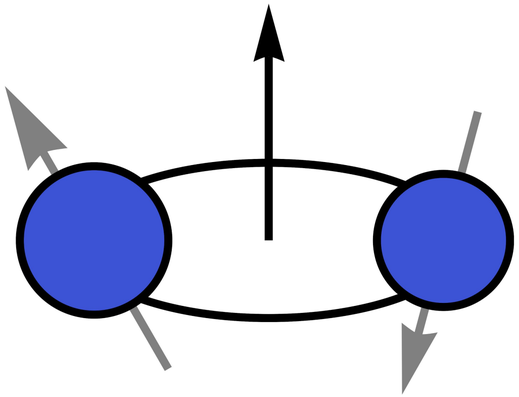
Discovering the homeland of LIGO binaries?

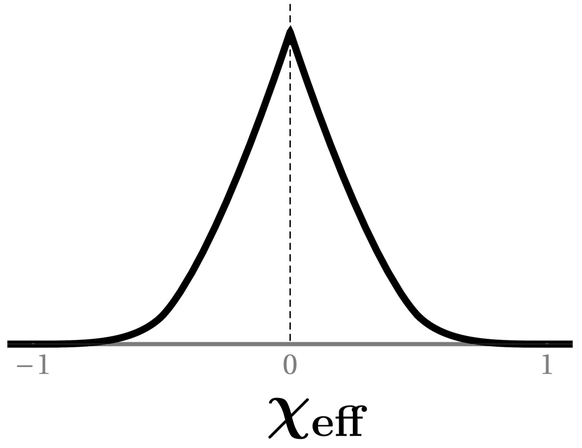
Field



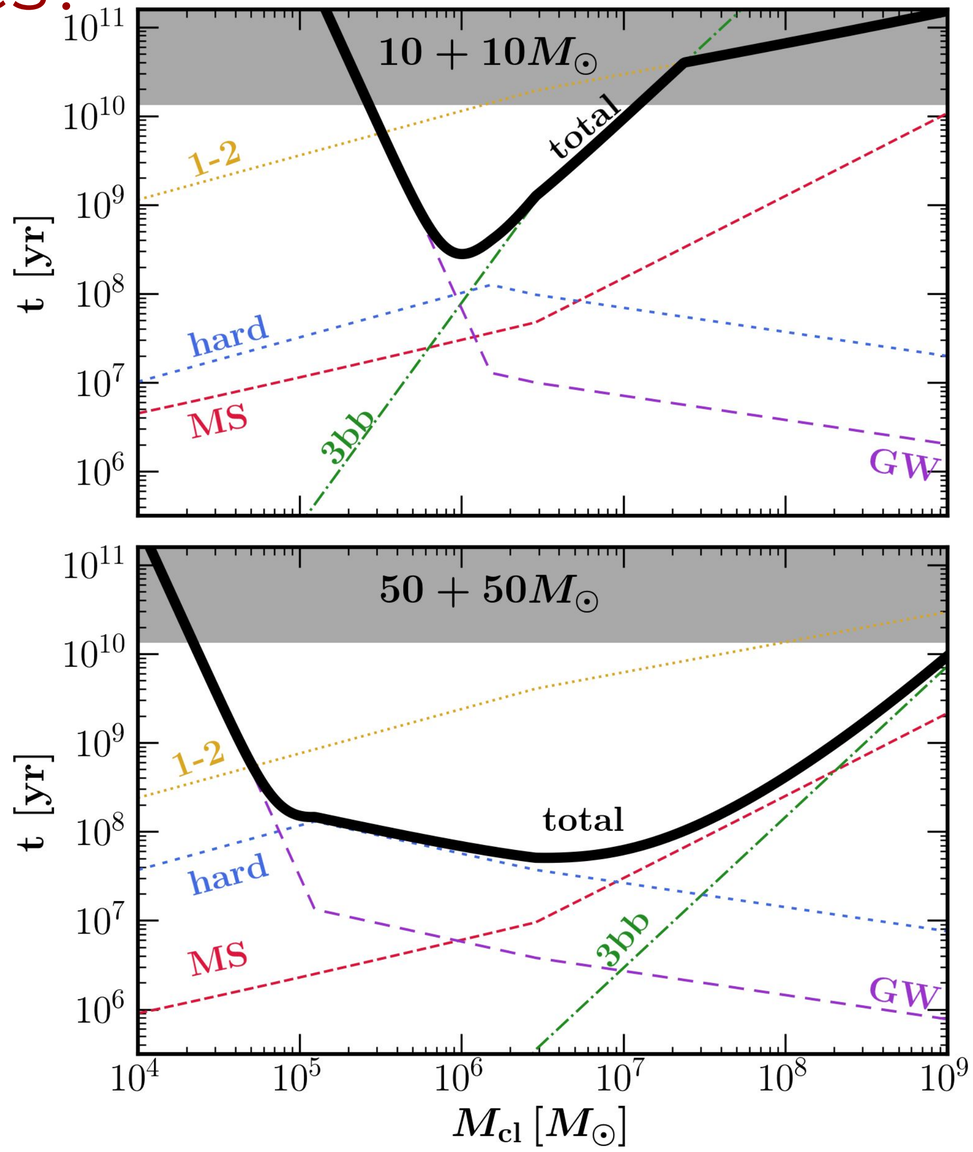


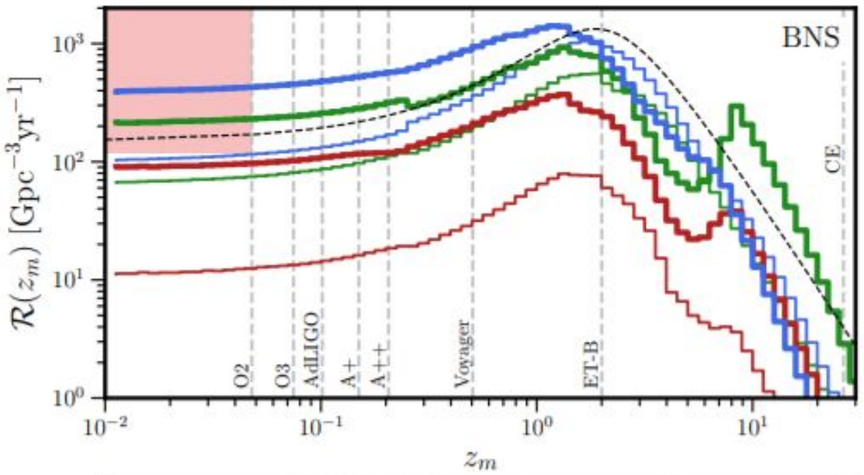
Cluster

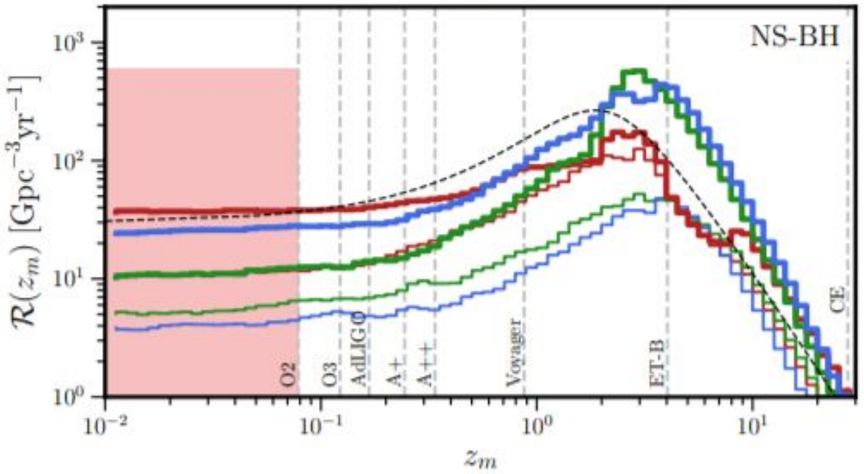


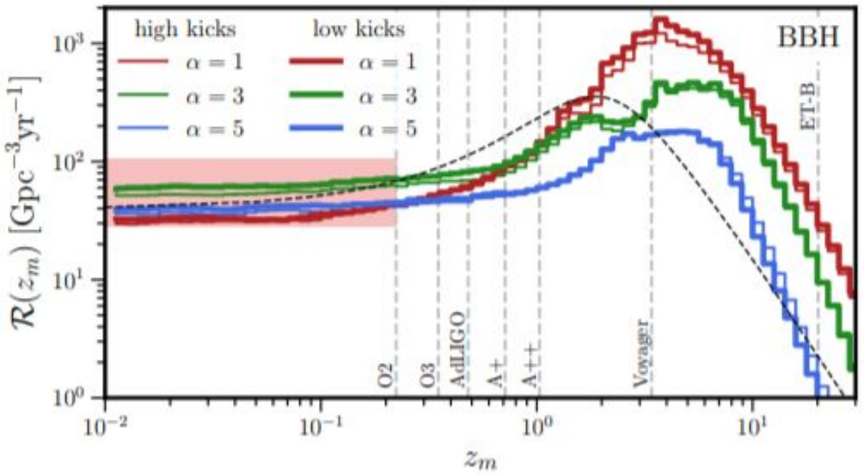


Discovering the homeland of LIGO binaries?

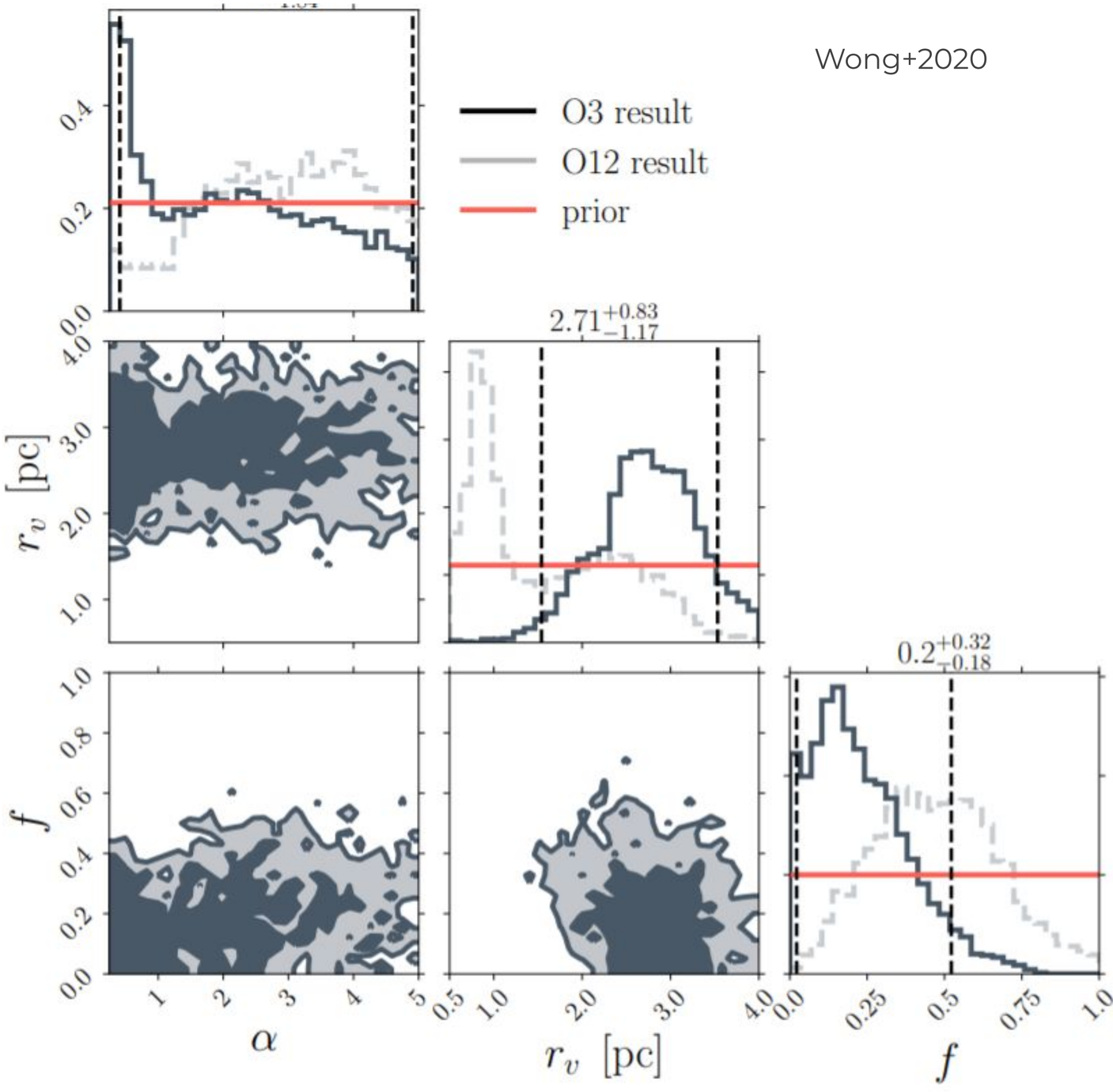








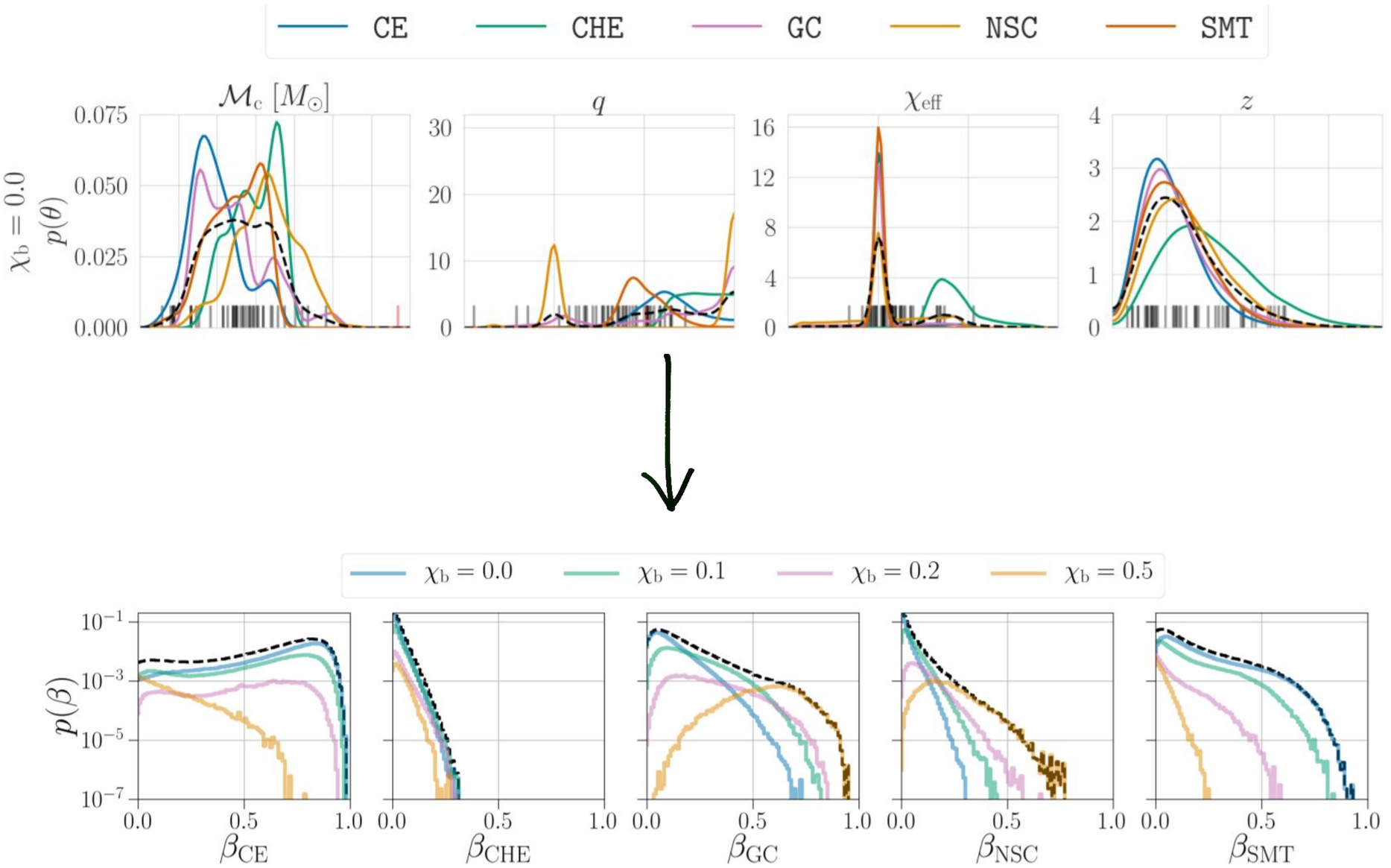
Discovering the homeland of LIGO binaries



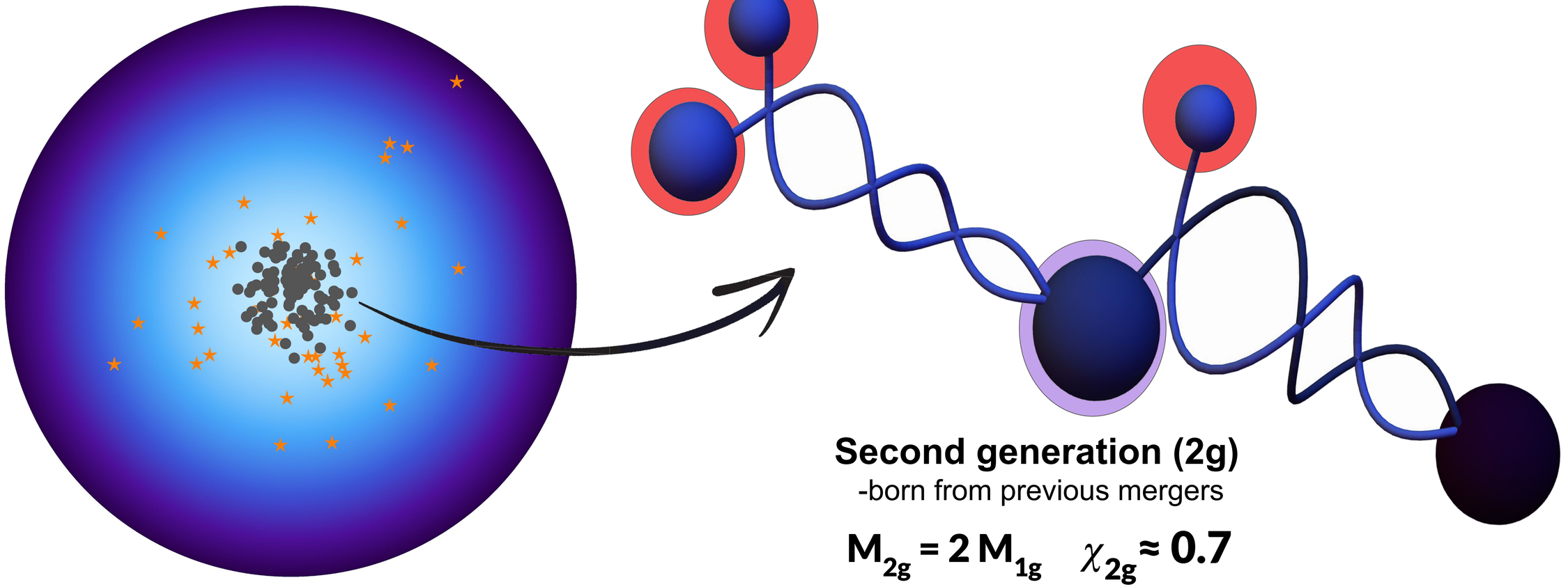
Wong+2020

Discovering the homeland of LIGO binaries?

Zevin+2020



Repeated mergers in clusters

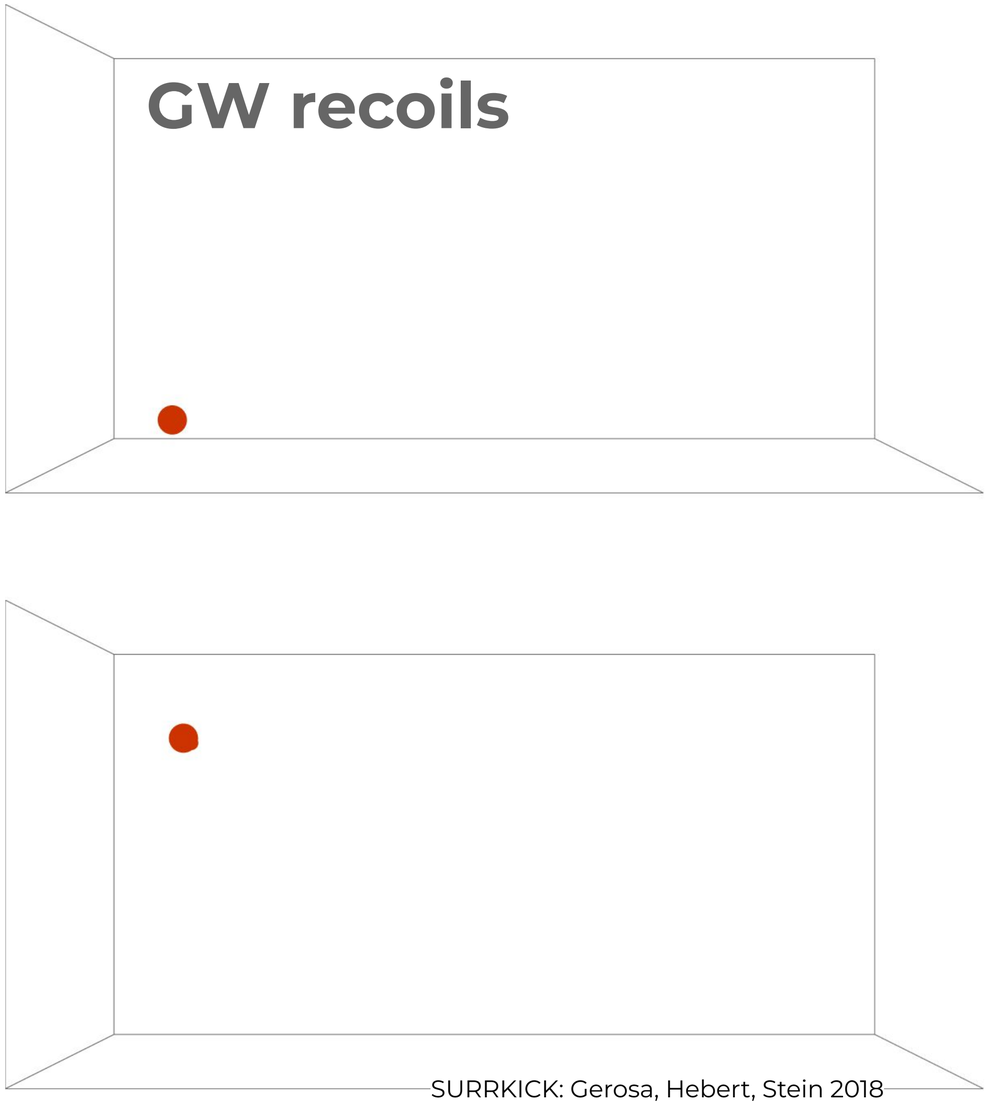


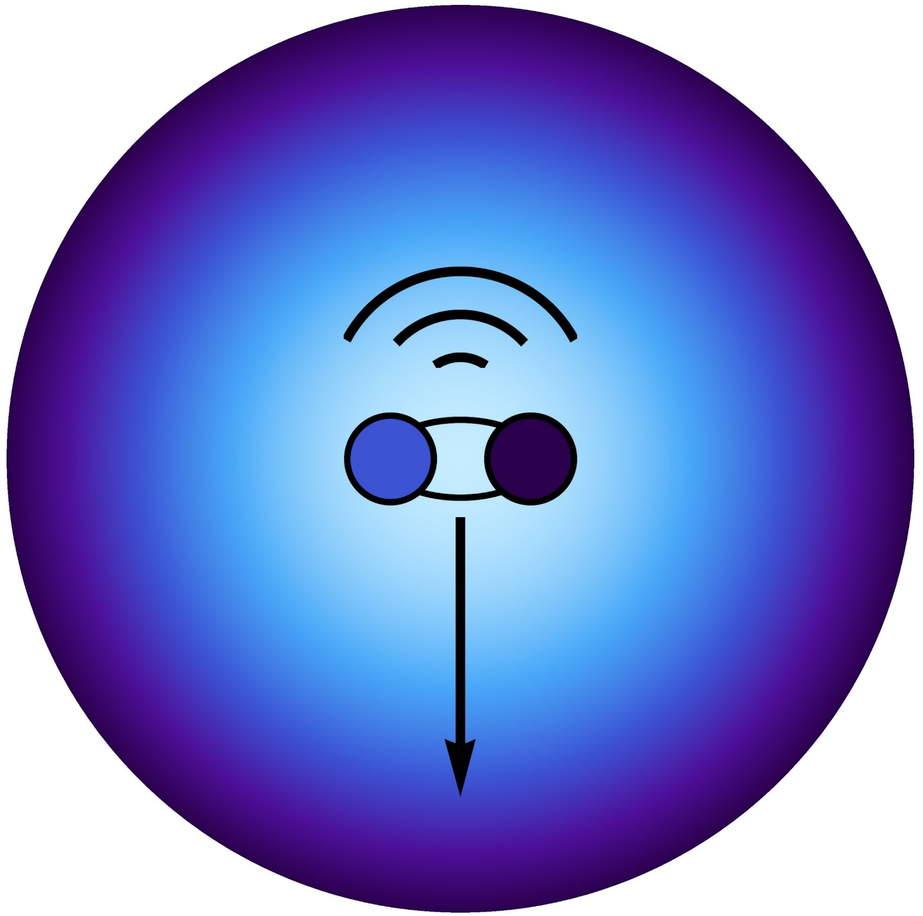
First generation (1g)
-born from stars

Second generation (2g)
-born from previous mergers

$$M_{2g} = 2\,M_{1g} \quad \chi_{2g} \approx 0.7$$

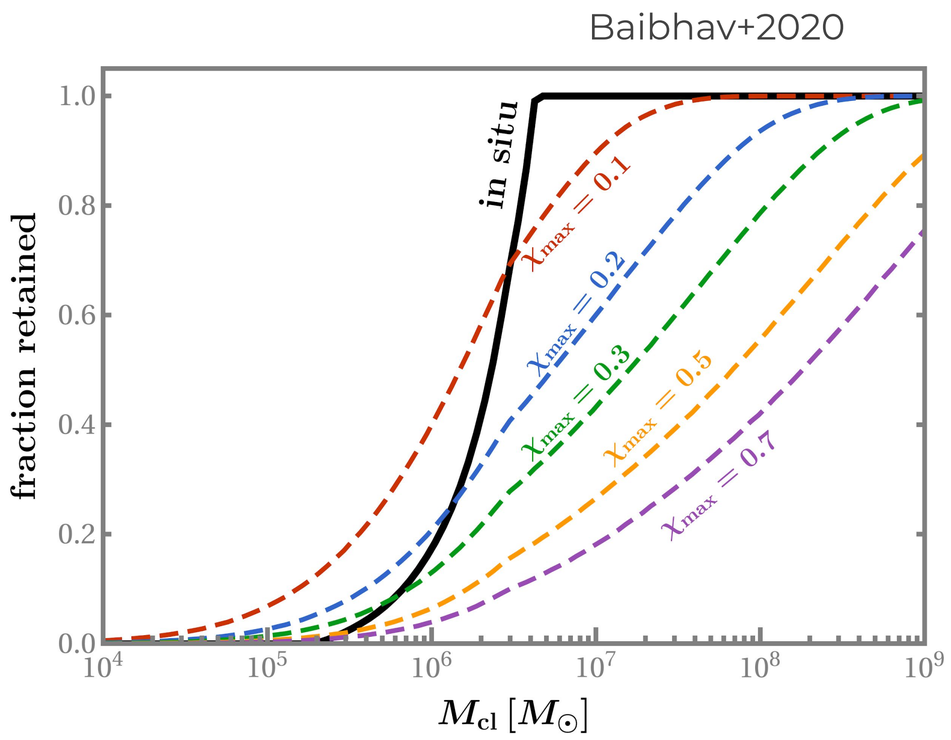
Can clusters retain their BHs?

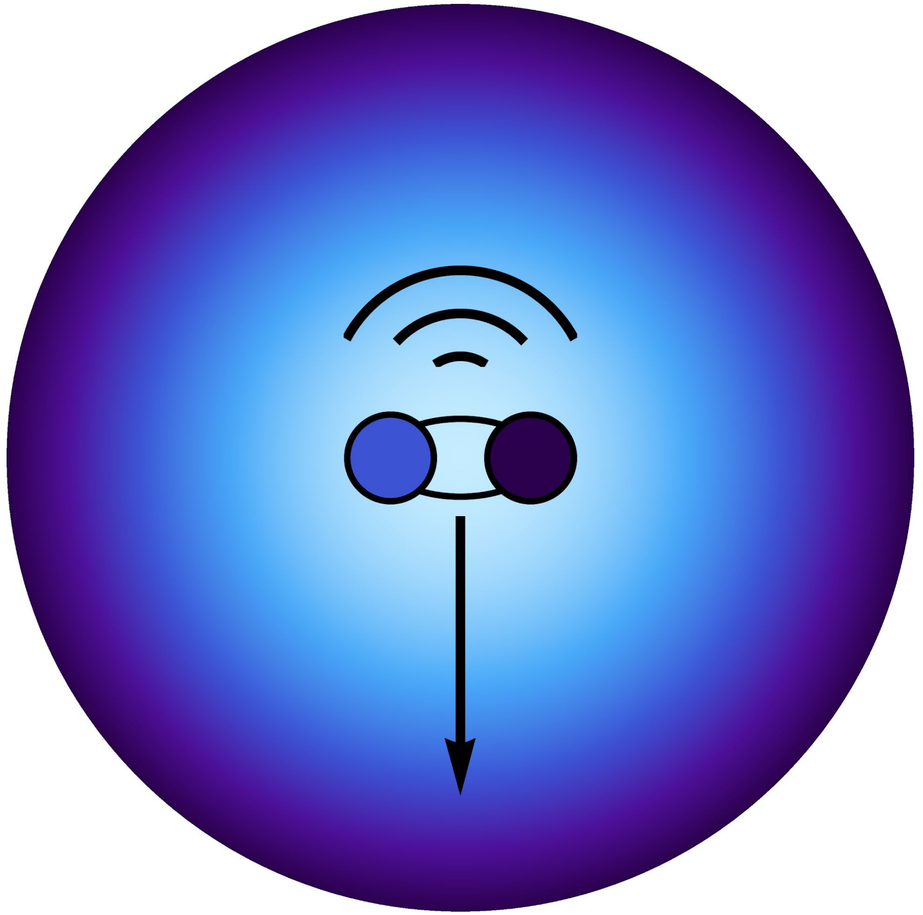




SURRKICK: Gerosa, Hebert, Stein 2018

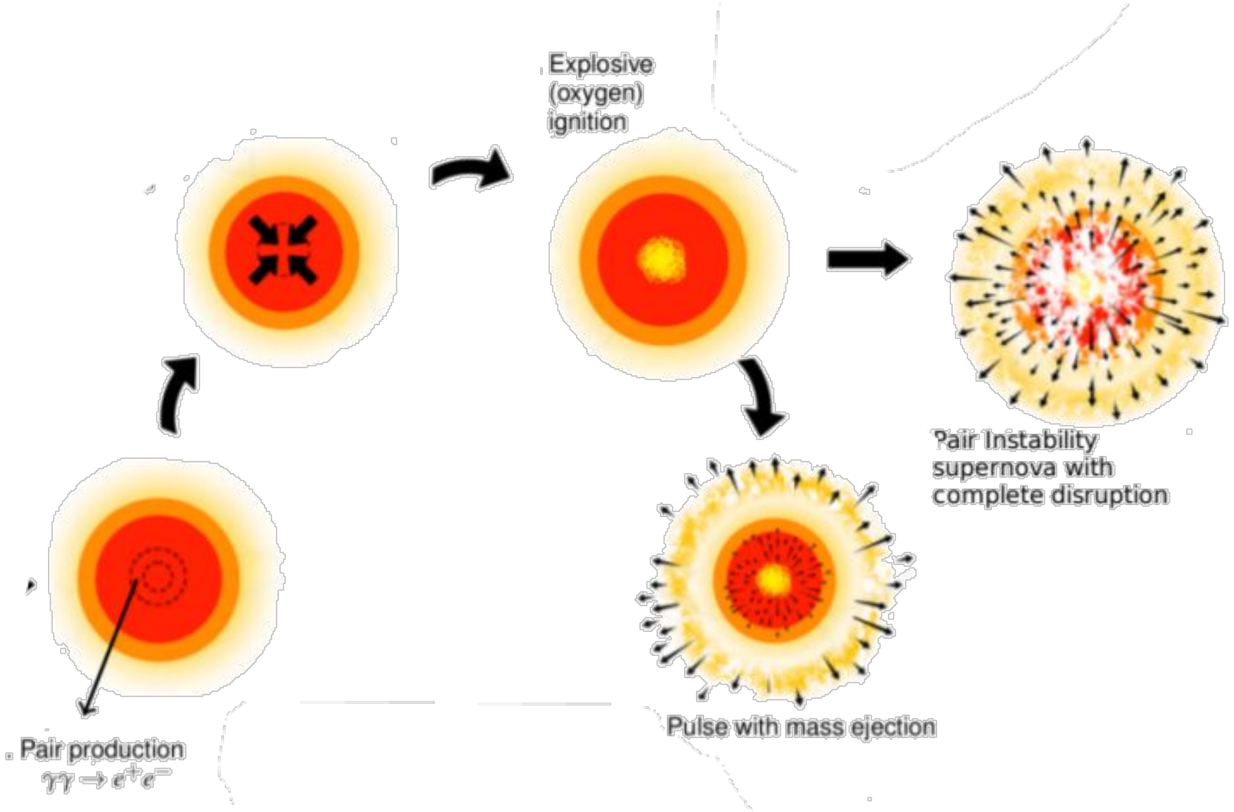
Can clusters retain their BHs?



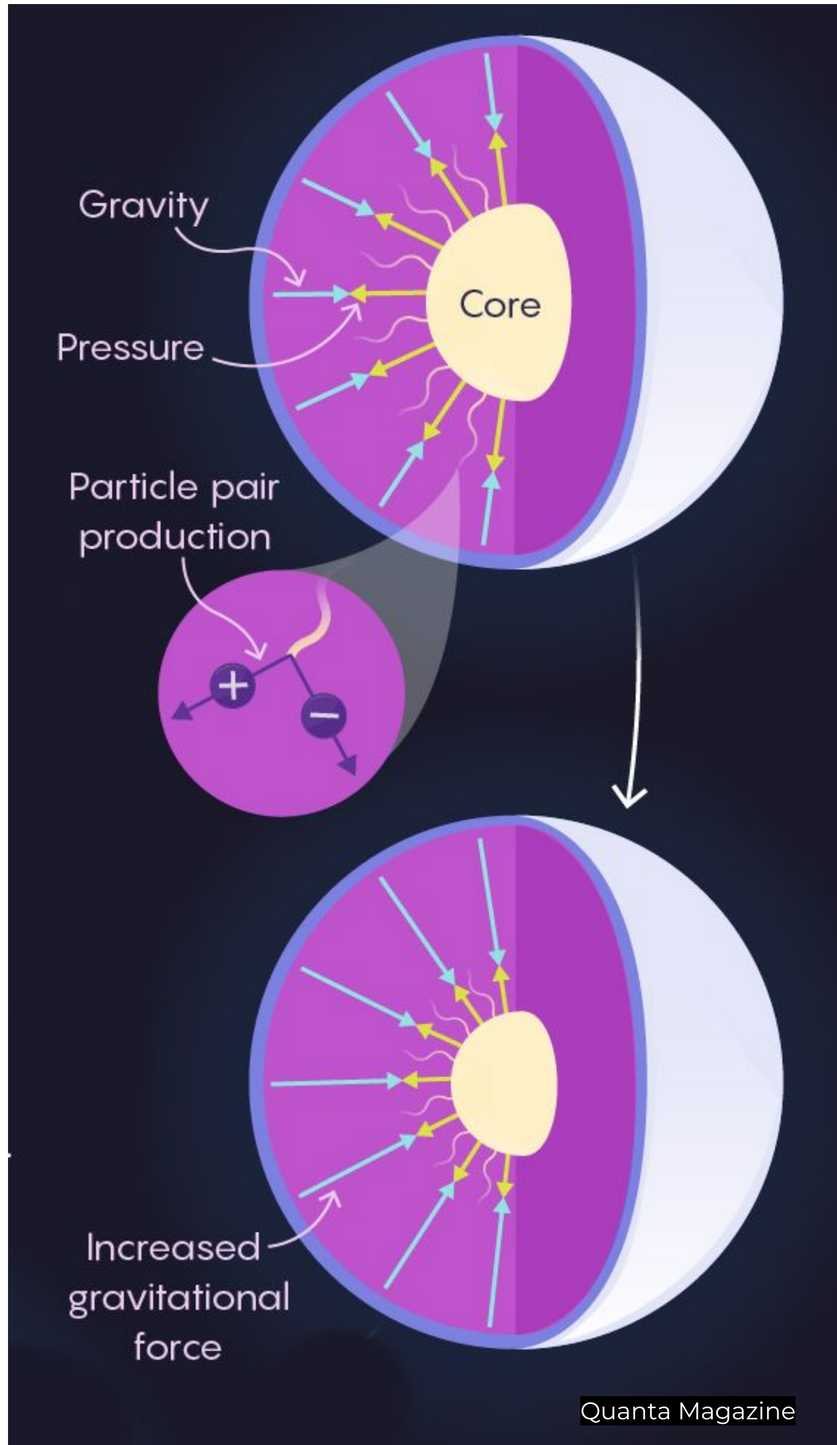


Finding 2g black holes in our midst

The Mass Gap



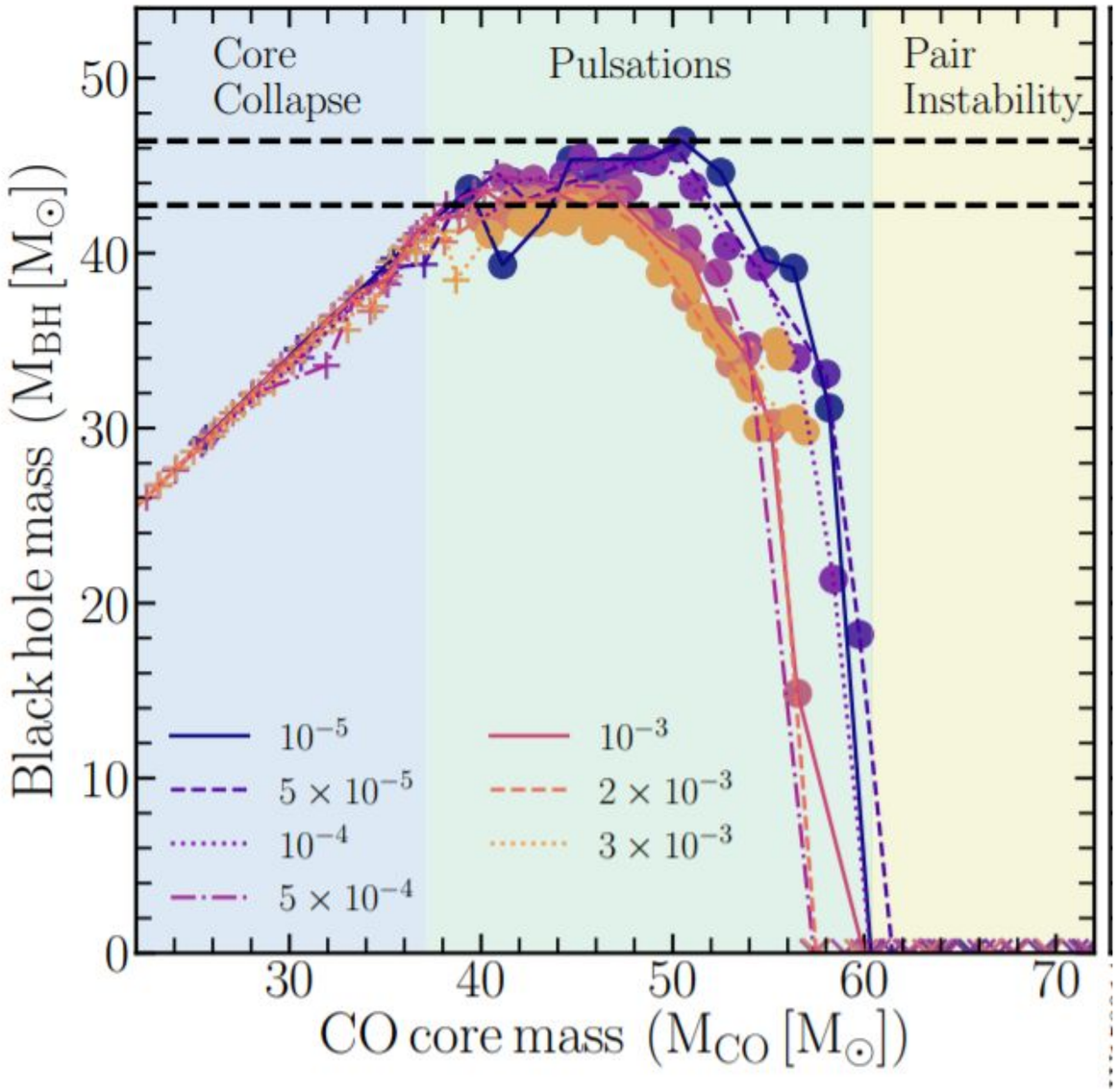
Adapted from Renzo+2020

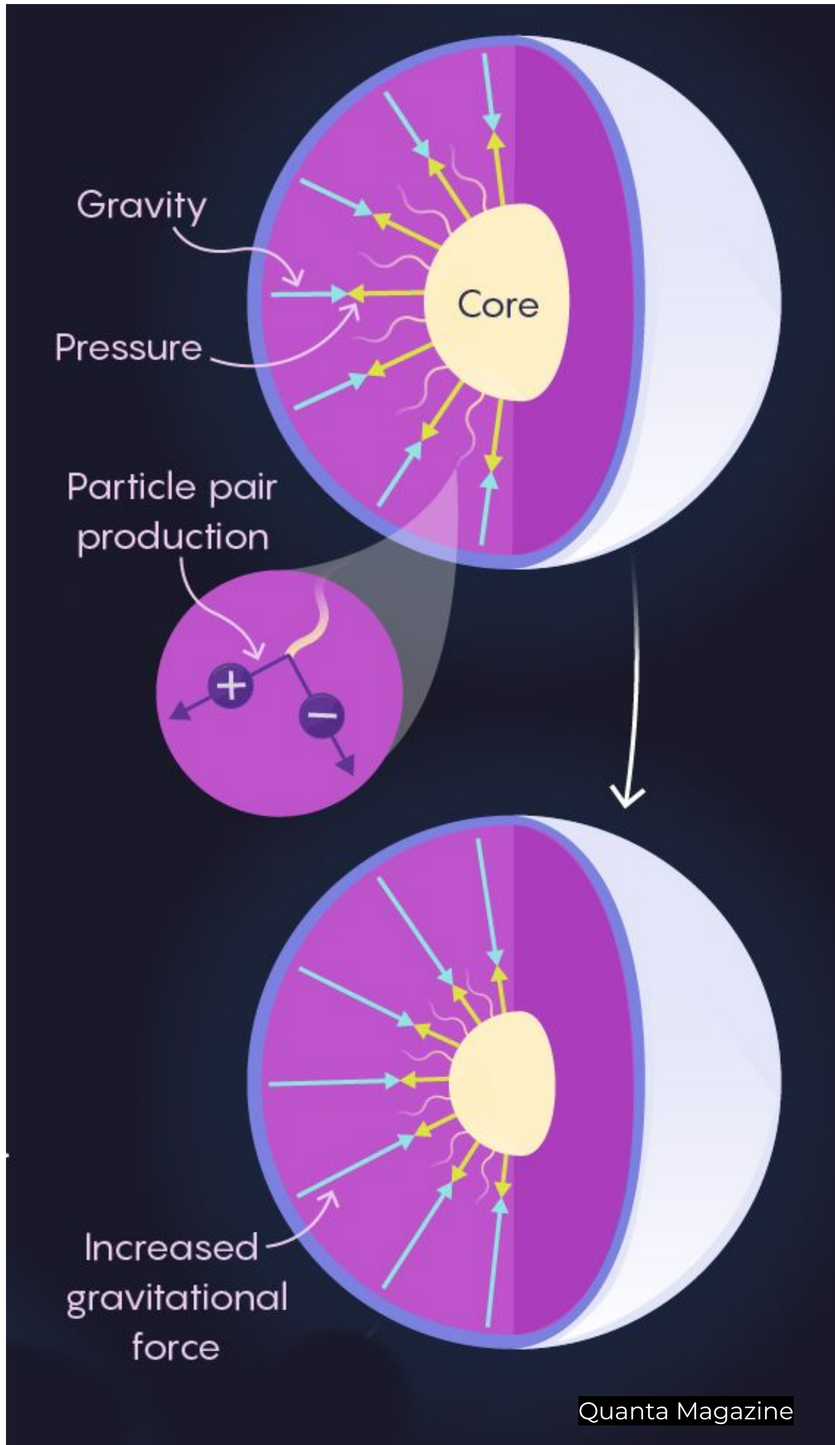


Quanta Magazine

The Mass Gap

Farmer+2019



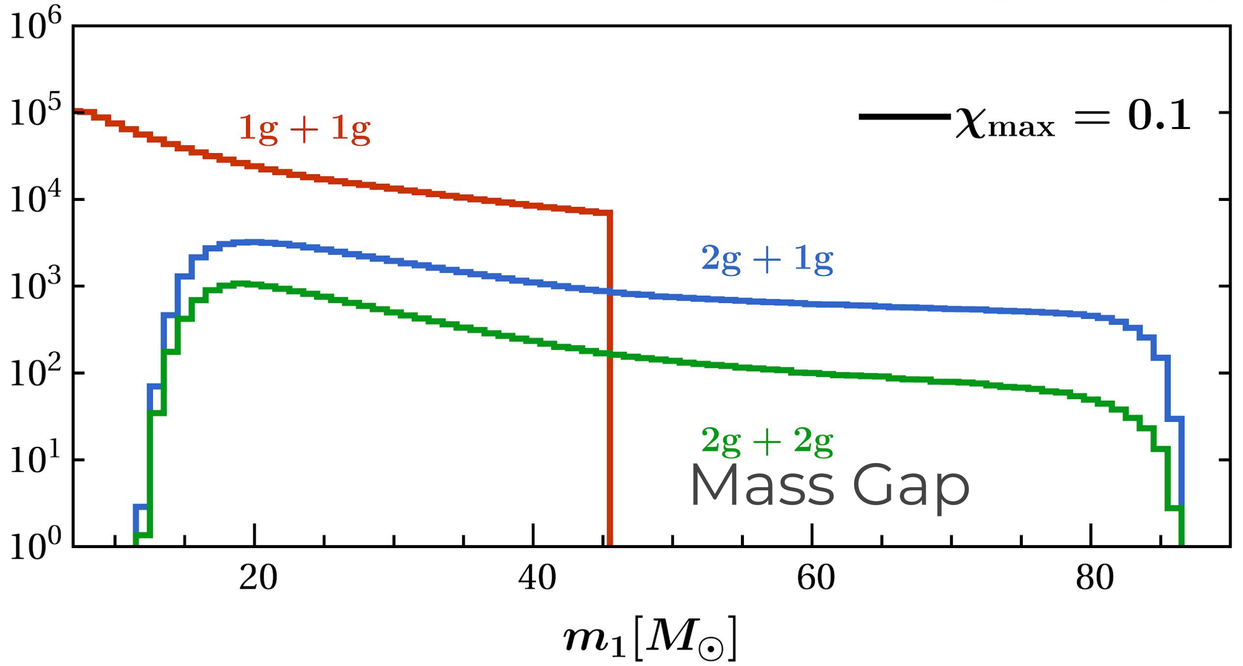


Filling the gap

Mass gap exists due to PISN and PPISN

Second-generation mergers fill the gap

Baibhav+2020



GW190521

$85M_\odot$ $50M_\odot$ $33M_\odot$

GW190521 GW170729 GW150914

Los Angeles Times

Cosmic mash-up reveals a type of black hole scientists have never observed before

THE HINDU

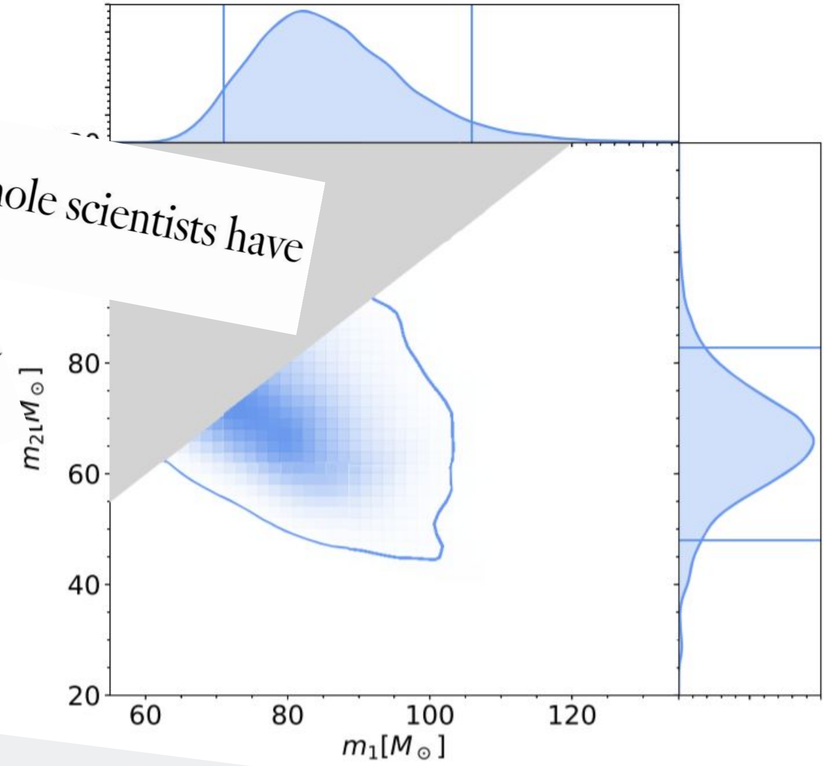
"It is a whole new world": scientists det… mysterious black hole

The New York Times

These Black Holes Shouldn't Exist, but There They Are

CHIRP, CHIRP, BANG, BANG —

Meet GW190521—a black-hole merger for the record books

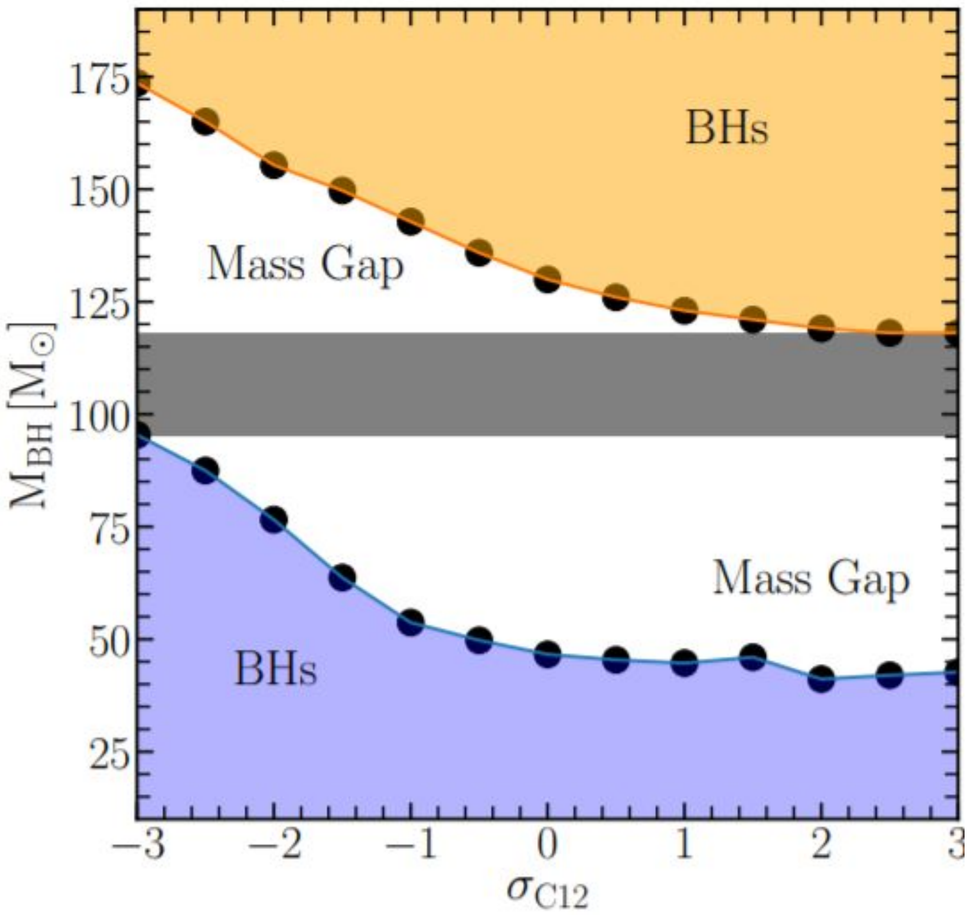


Filling the gap

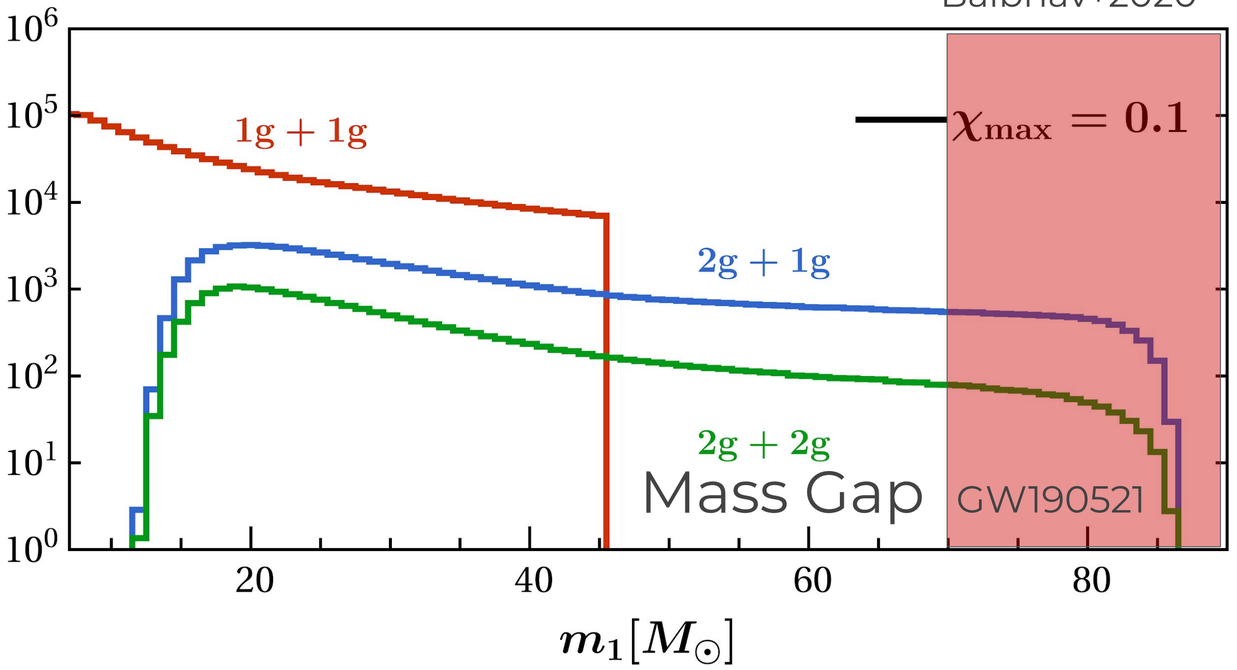
Mass gap exists due to PISN and PPISN

Second-generation mergers fill the gap

Shifting the gap — Farmer+2020



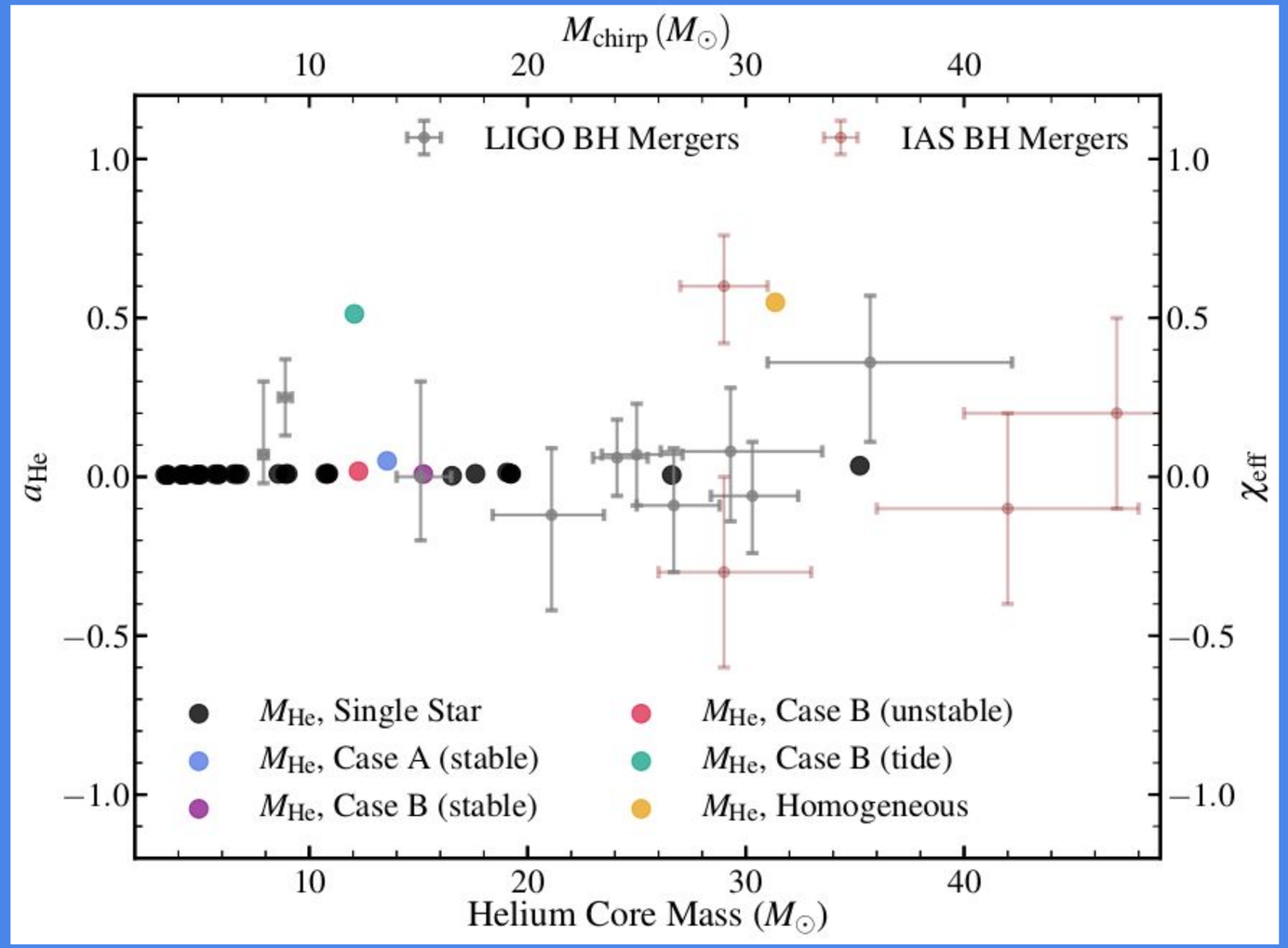
Baibhav+2020



GW190521 lies in the gap → **a 2g merger**

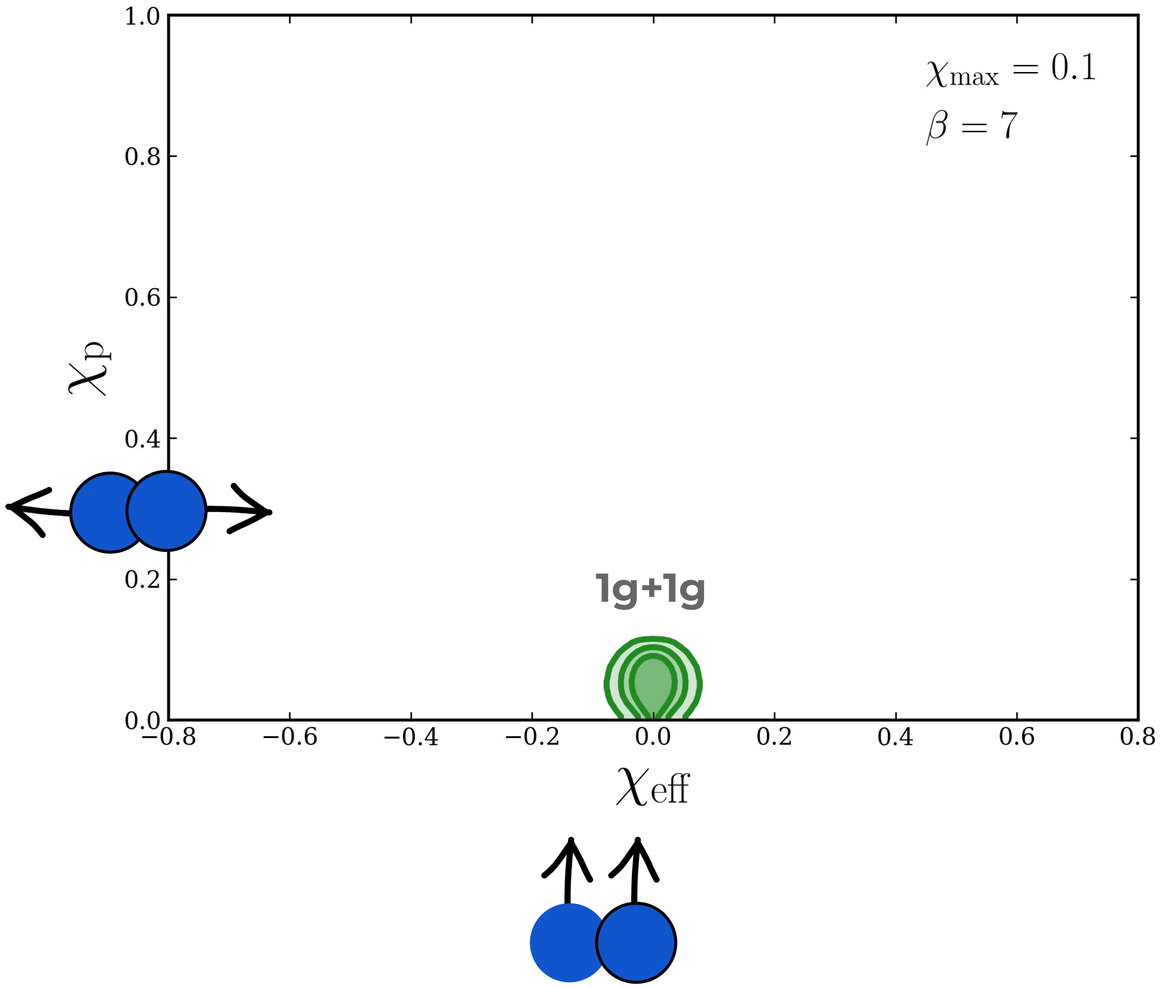
The Spin Gap

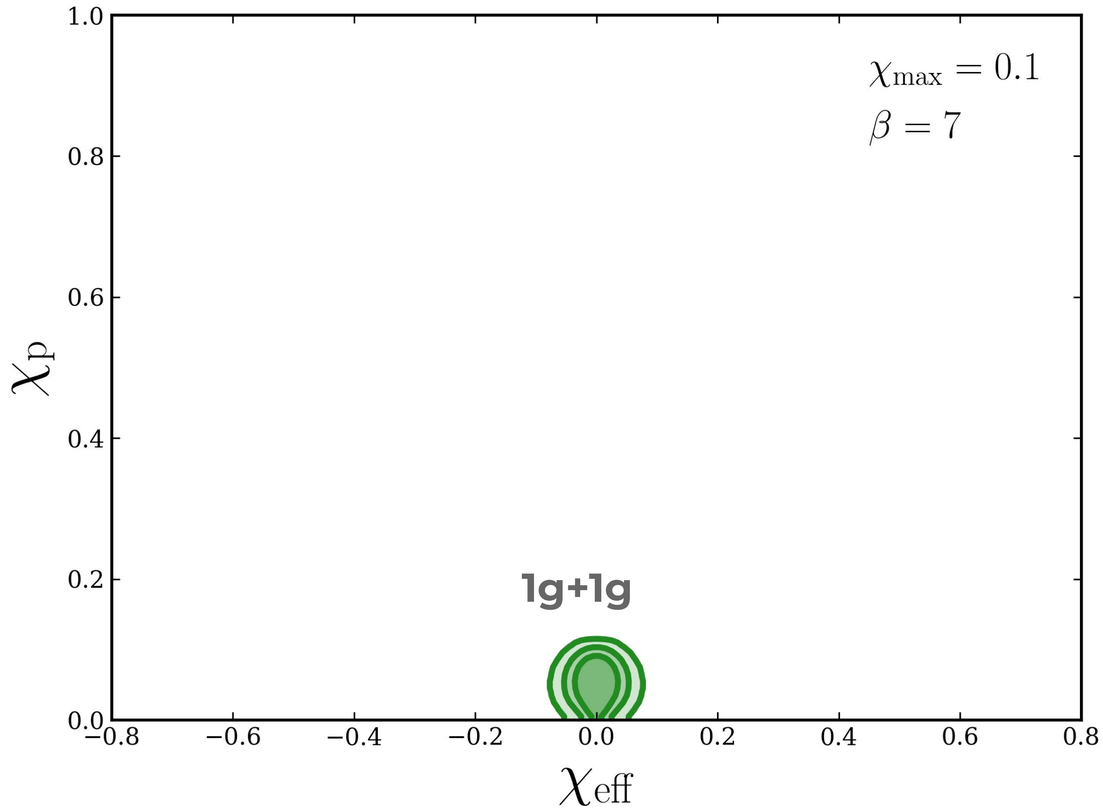
$$a \sim 10^{-2}$$



Fuller, Ma 2019

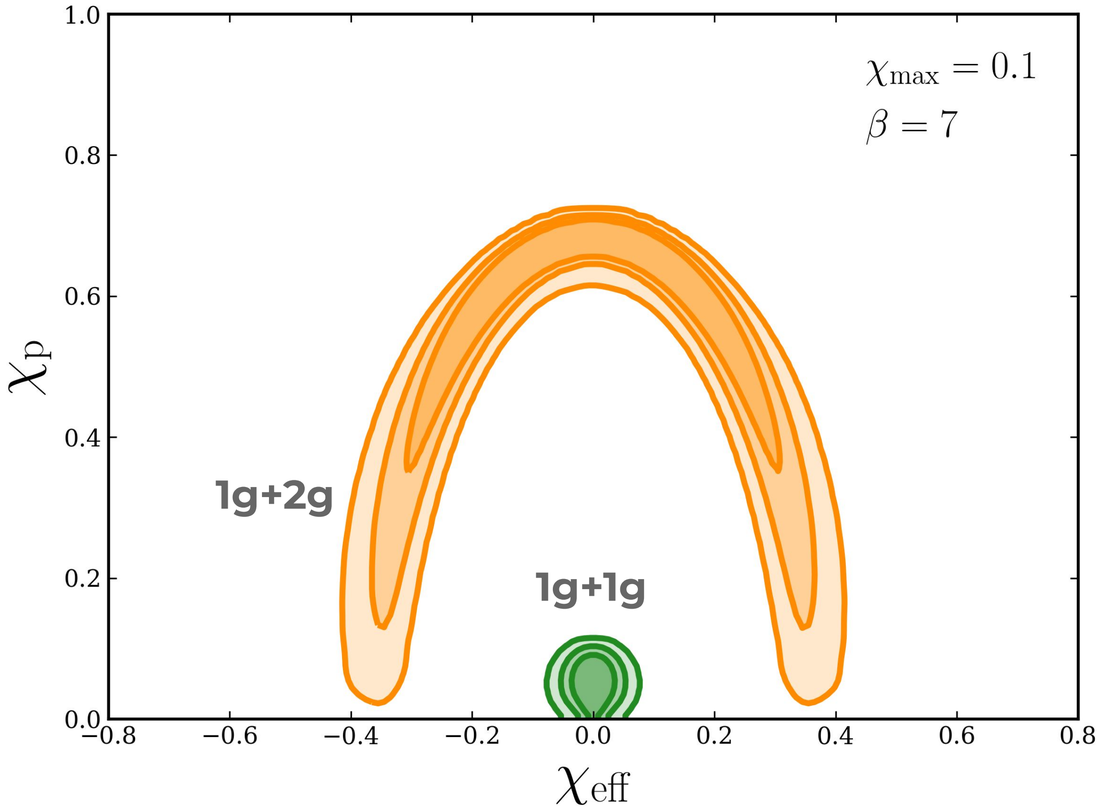
Repeated Mergers can fill the SPIN GAP



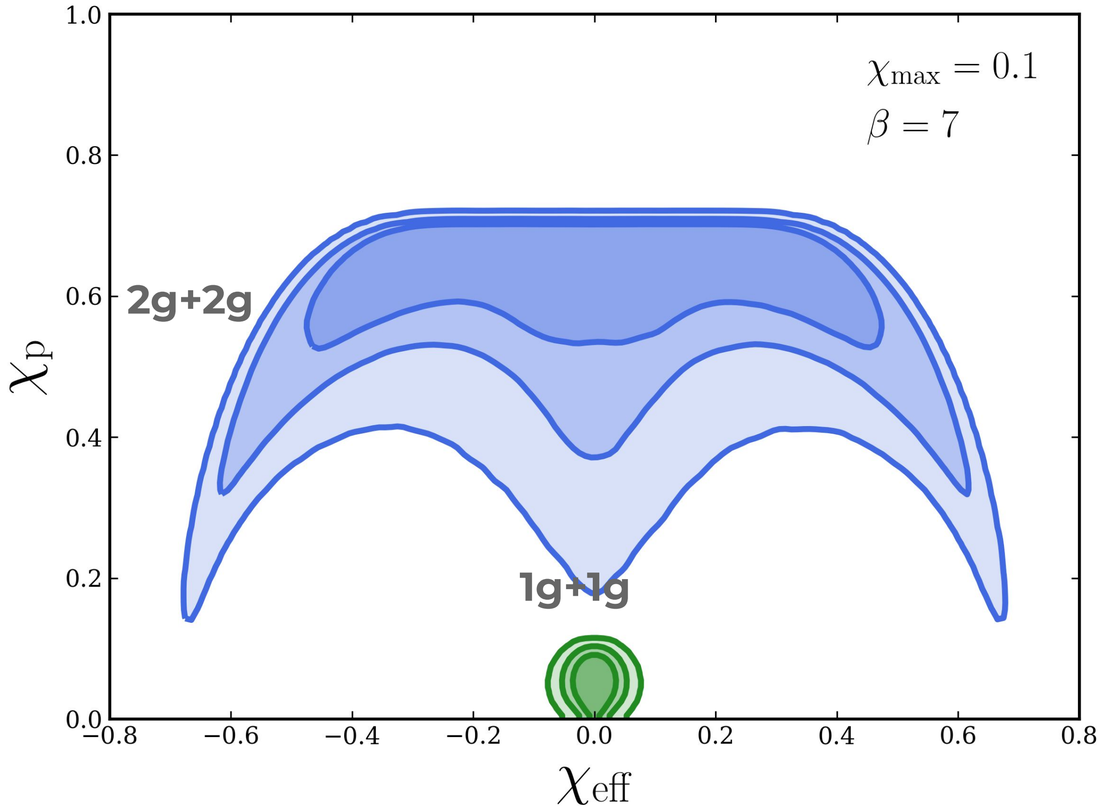


Baibhav+ 2021

Repeated Mergers can fill the SPIN GAP



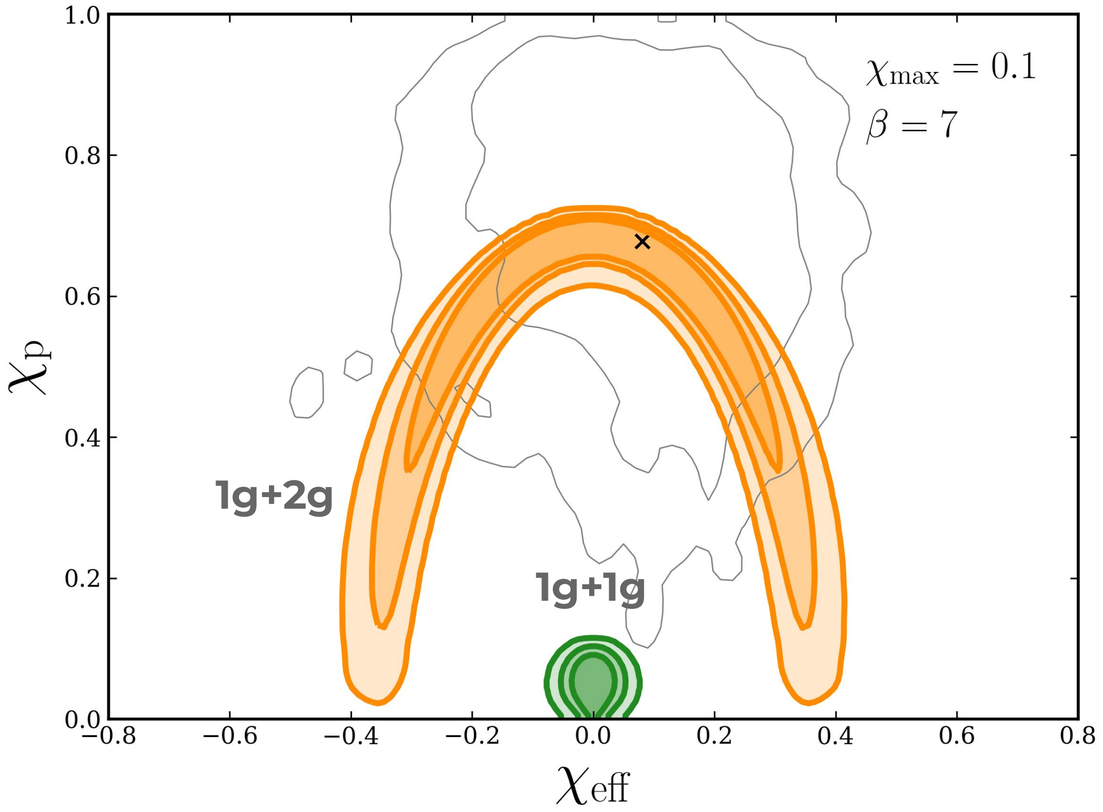
1g+2g



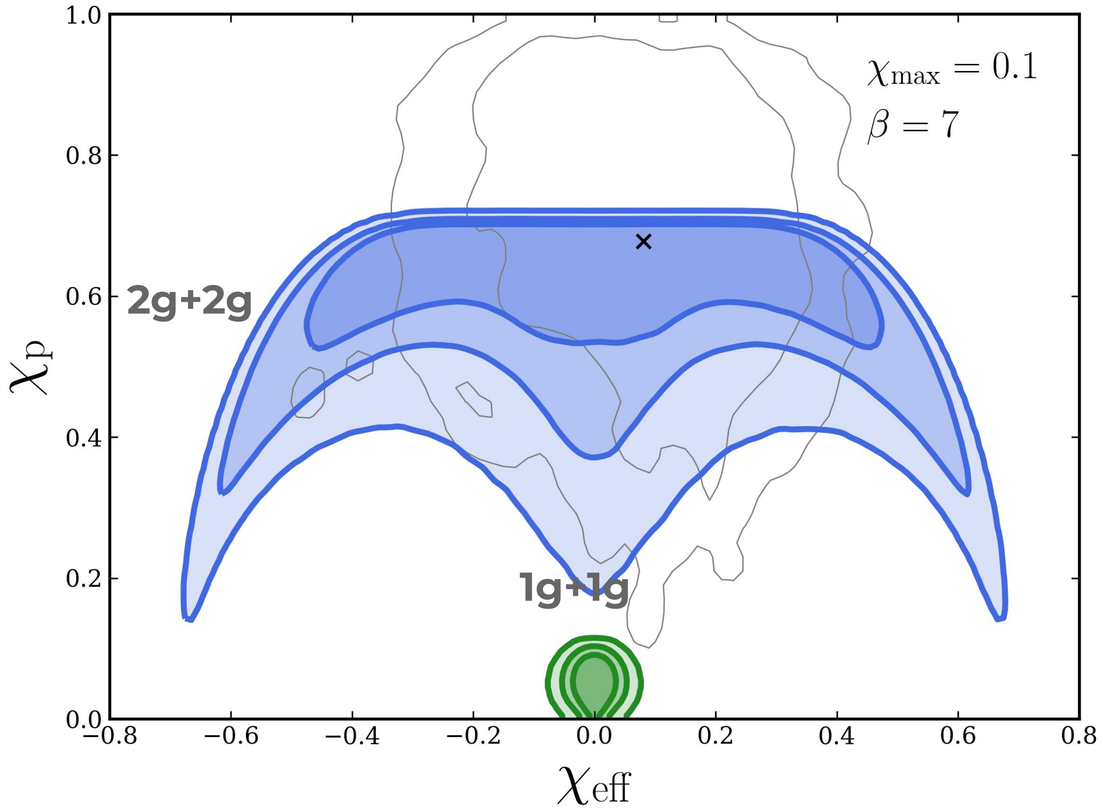
2g+2g

Baibhav+ 2021

Repeated Mergers can fill the SPIN GAP



1g+2g

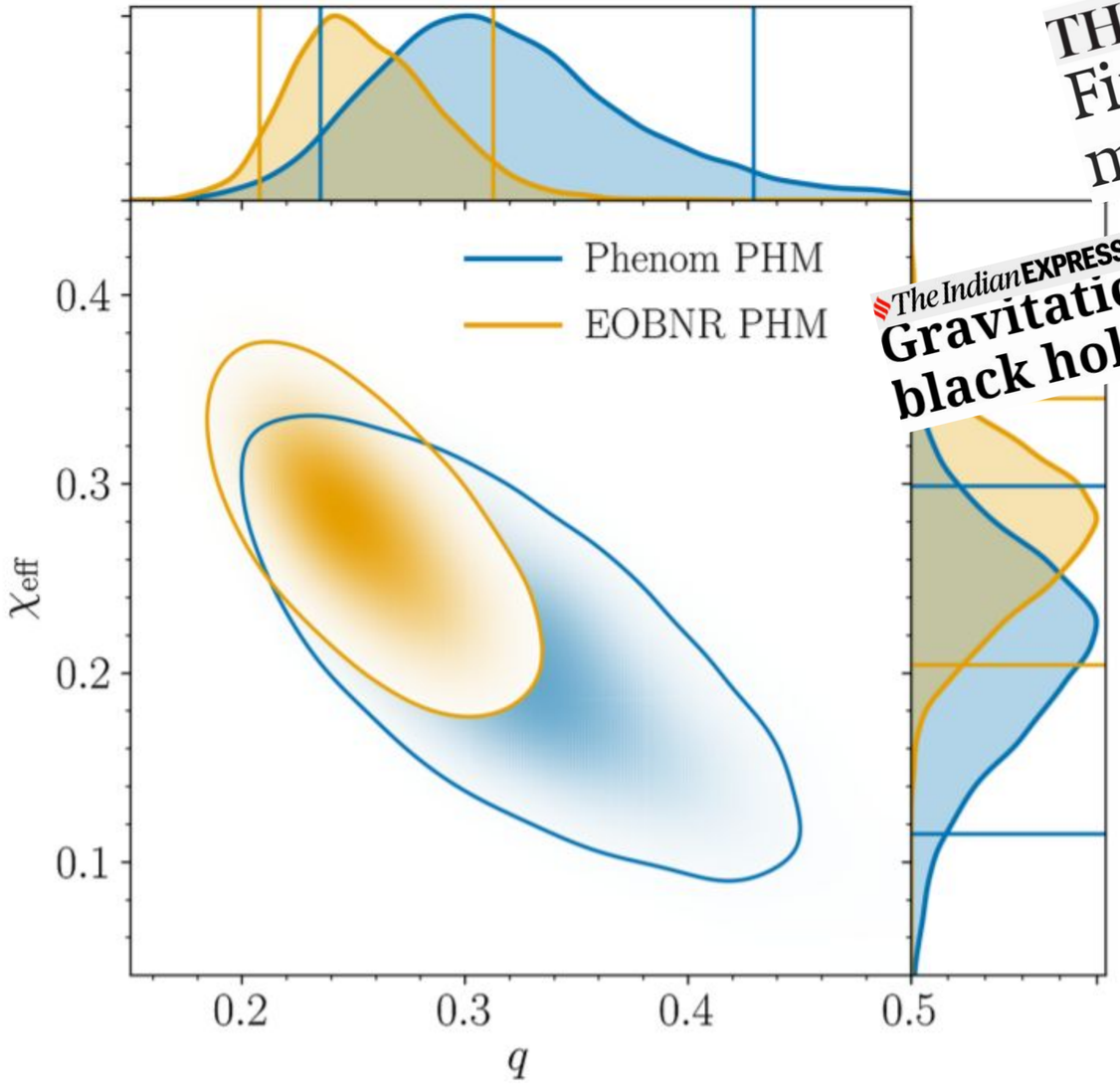


2g+2g

Baibhav+ 2021

Parents
of second-generation
black holes

GW190412

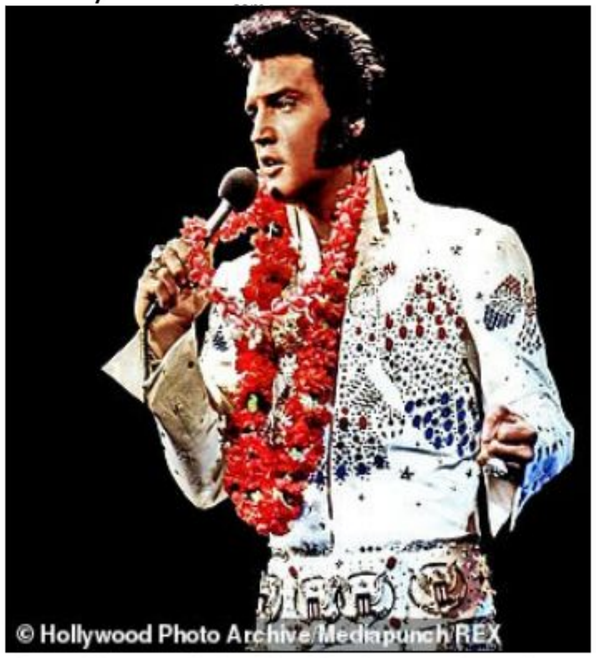


THE HINDU
First merger of two black holes with unequal masses detected

The Indian EXPRESS
Gravitational waves from unequal mass black holes detected

ScienceAlert
Astronomers Find First-Ever Collision of Black Holes With a Strange Mass Discrepancy

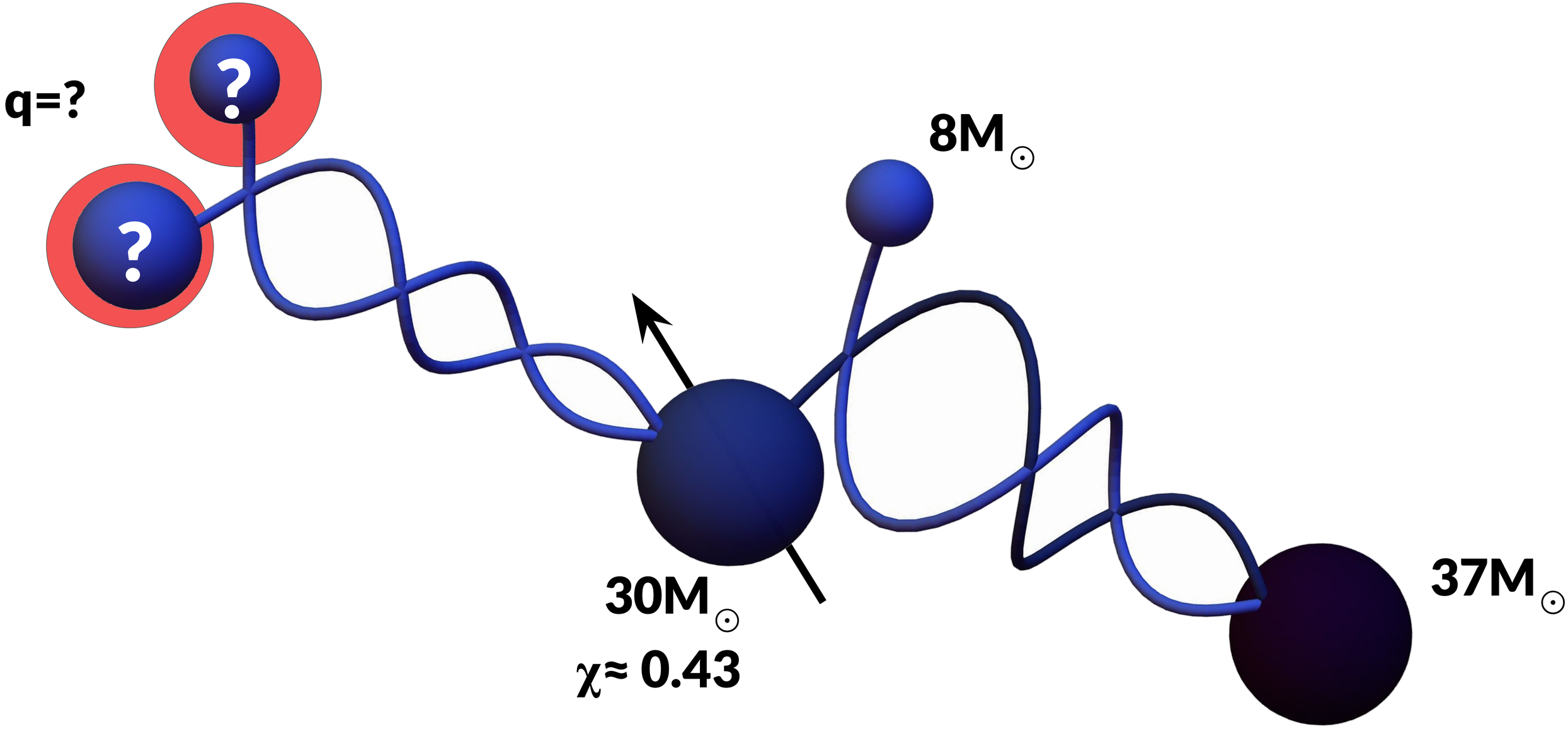
Daily Mail



The collision of the black holes produced sounds similar to Elvis Presley's (pictured) hit song 'I Can't Help Falling in Love with You'

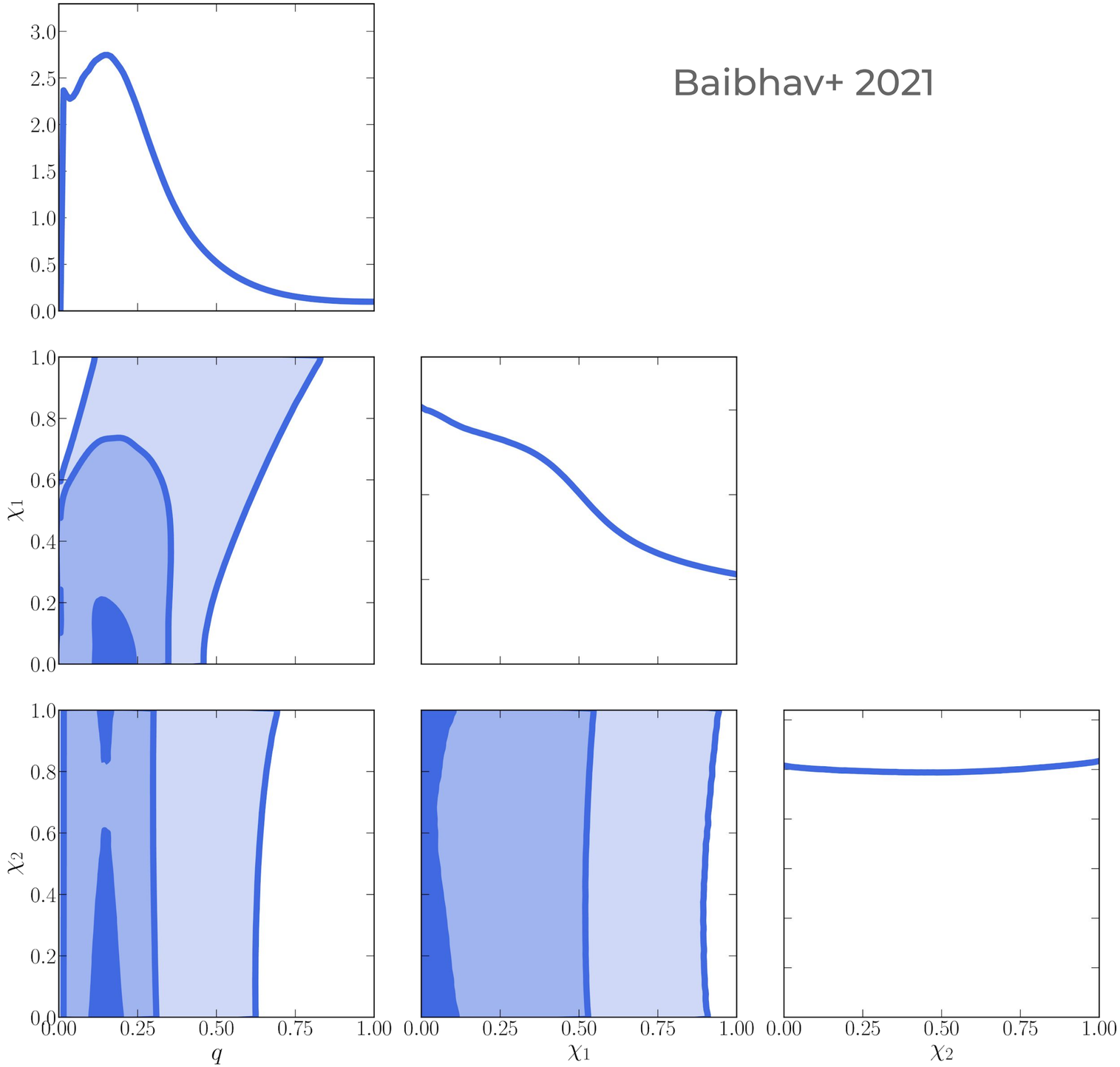
Parents of GW190412

Gerosa, Vitale, Berti 2020 (PRL)
Rodriguez et al 2020 (ApJL)



Parents of GW190412

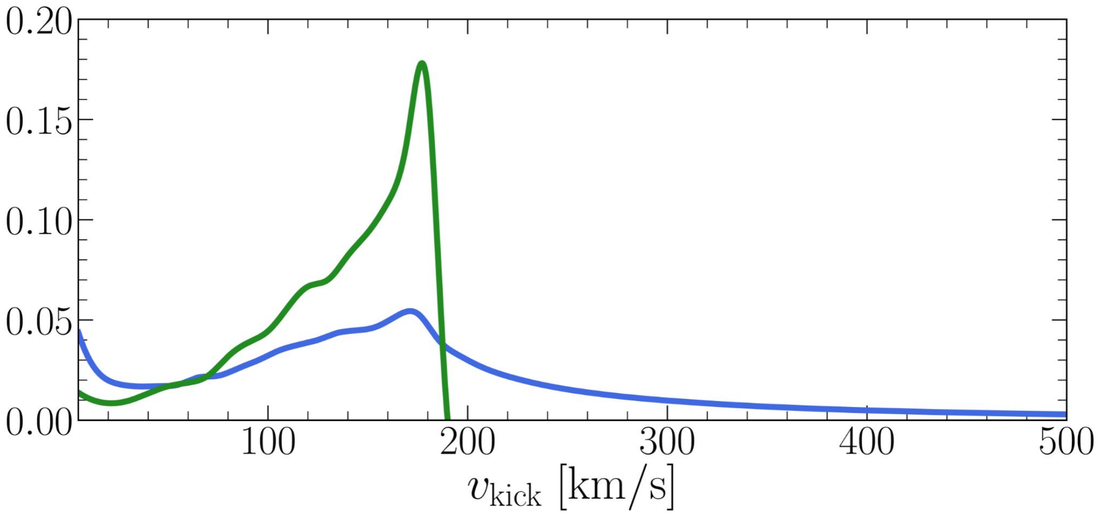
Parents of GW190412 likely had asymmetric masses, q=0.2 and near-zero spins

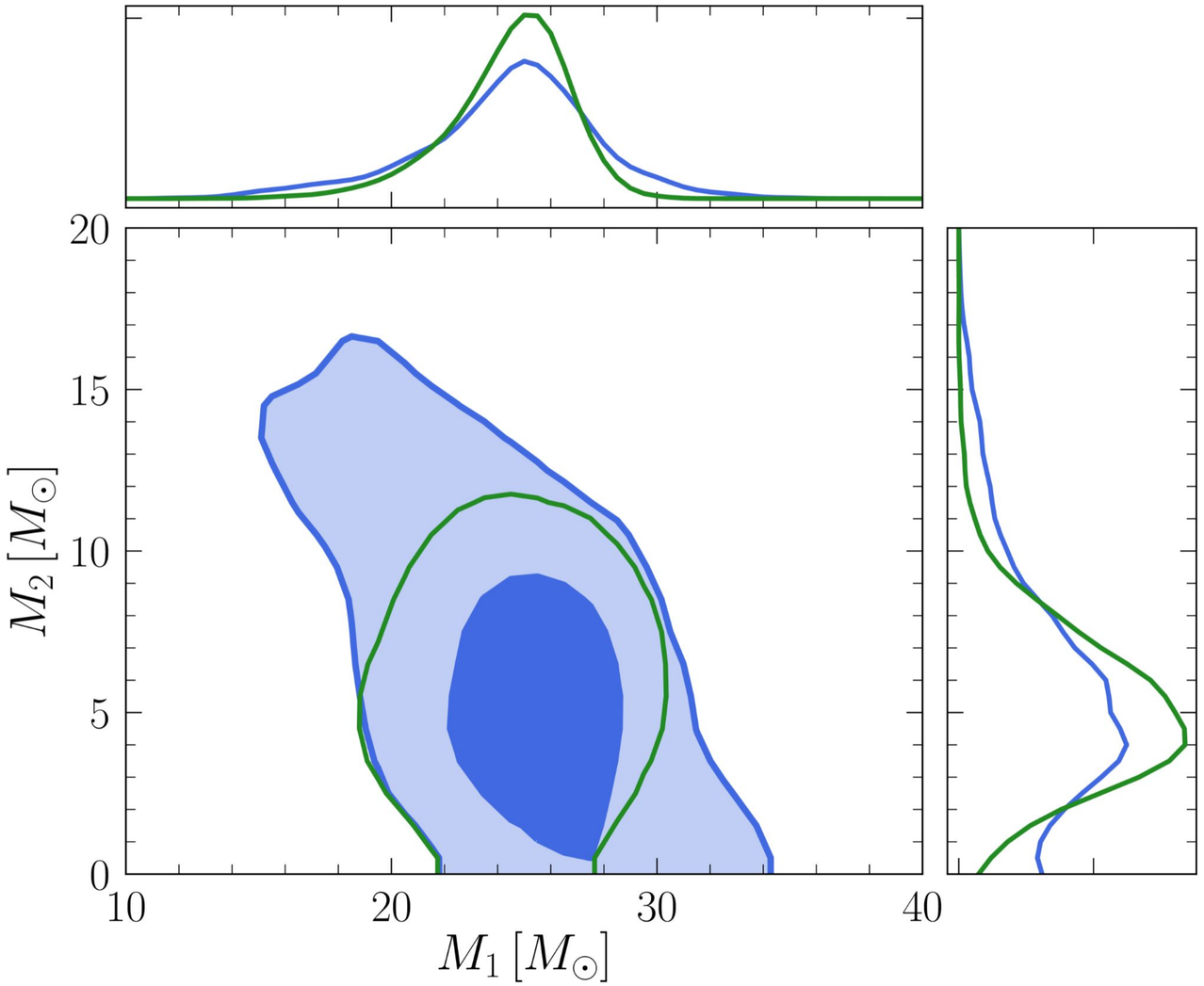


Baibhav+ 2021

Parents of GW190412 and their Hometown

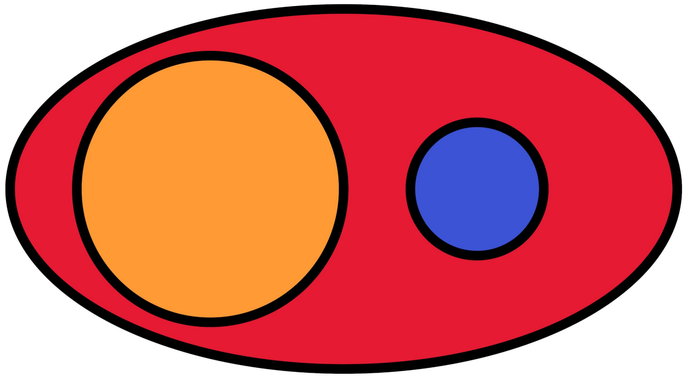
Baibhav+ 2021



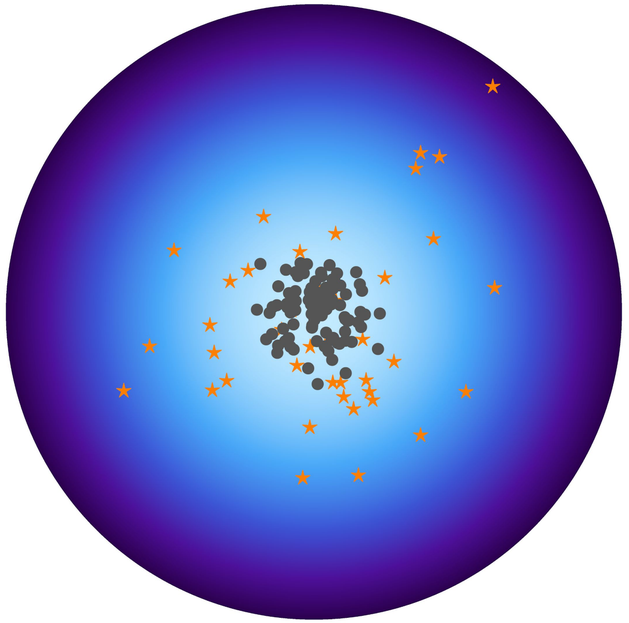


What GWs can tell us?

Masses
Spins
Distance



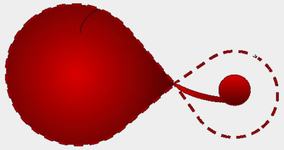
Isolated



Dynamical

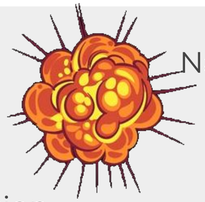
What we don't know?

Mass transfer



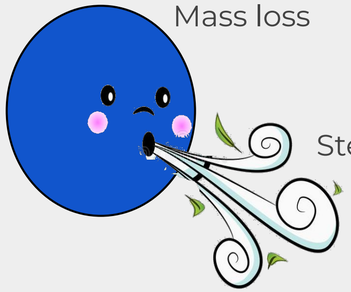
Common envelope efficiency

Star formation rate



Natal kicks

Mass loss



Explosion mechanism

Rotational mixing

Metallicity evolution

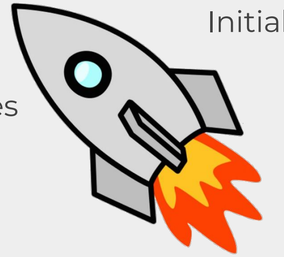
Stellar winds

Nuclear reaction rates

Time delays

Pair instability supernovae

Initial conditions



cluster properties

Initial Mass function

BH birth spins

Angular momentum transport

Escape velocities

A promise ...

Baibhav + 2019