

# The origin of merging black holes: the B-POP code

*May 7th, 2026*

*Manuel Arca Sedda*



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## Who am I?

Manuel Arca Sedda (GSSI)  
Associate Professor  
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*I study the formation and evolution of gravitational wave sources in star clusters and galactic nuclei*

## What will we learn today?

- How the population-synthesis code B-POP works
- How to interpret, analyse, and post-process B-POP outputs

## Resources?

- Main Paper: <https://ui.adsabs.harvard.edu/abs/2026arXiv260320430A/abstract>
- Github repo: <https://github.com/marcasedda/BPOP>
- Simulated data: <https://zenodo.org/records/19115567>
- Catalogue of stellar BHs:  
<https://drive.google.com/drive/folders/1FmVfXwF1aYHNBpzDcdeyufyV3lzvbOqr?usp=sharing>

## What's B-POP?

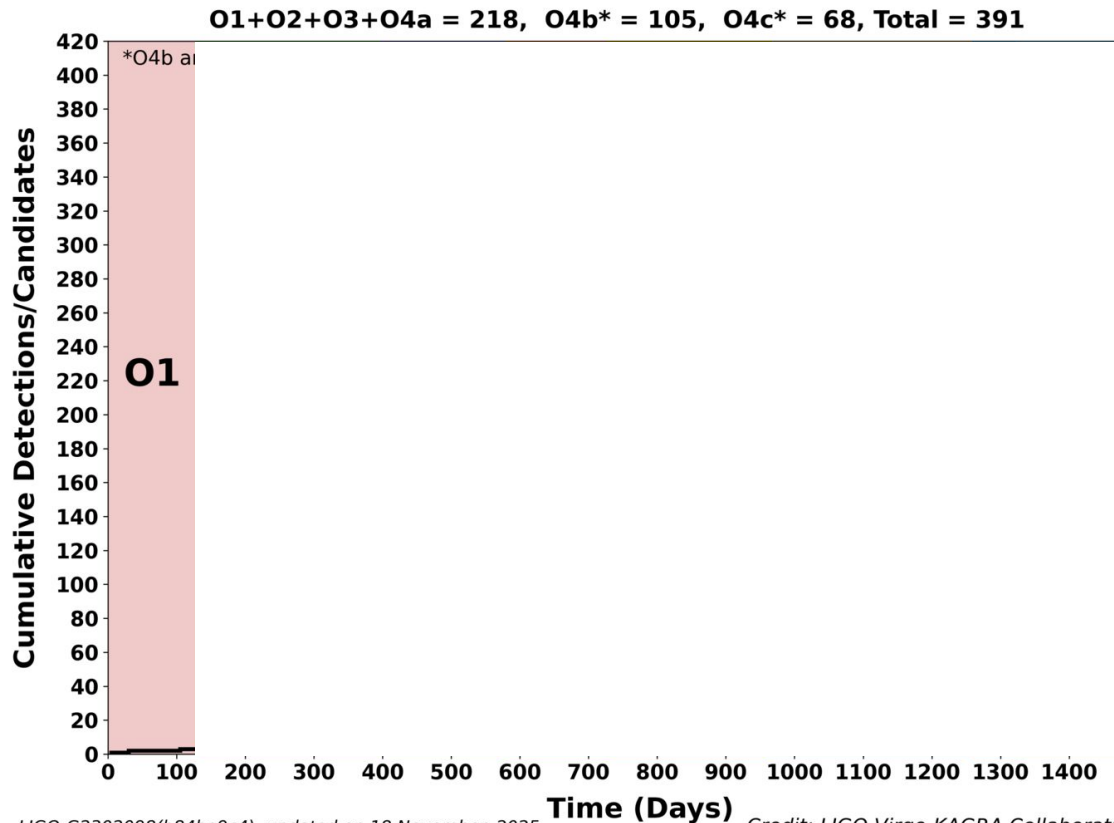
Arca Sedda & Benacquista (2019), arXiv:1806.01285

Arca Sedda et al (2020), arXiv:2003.07409

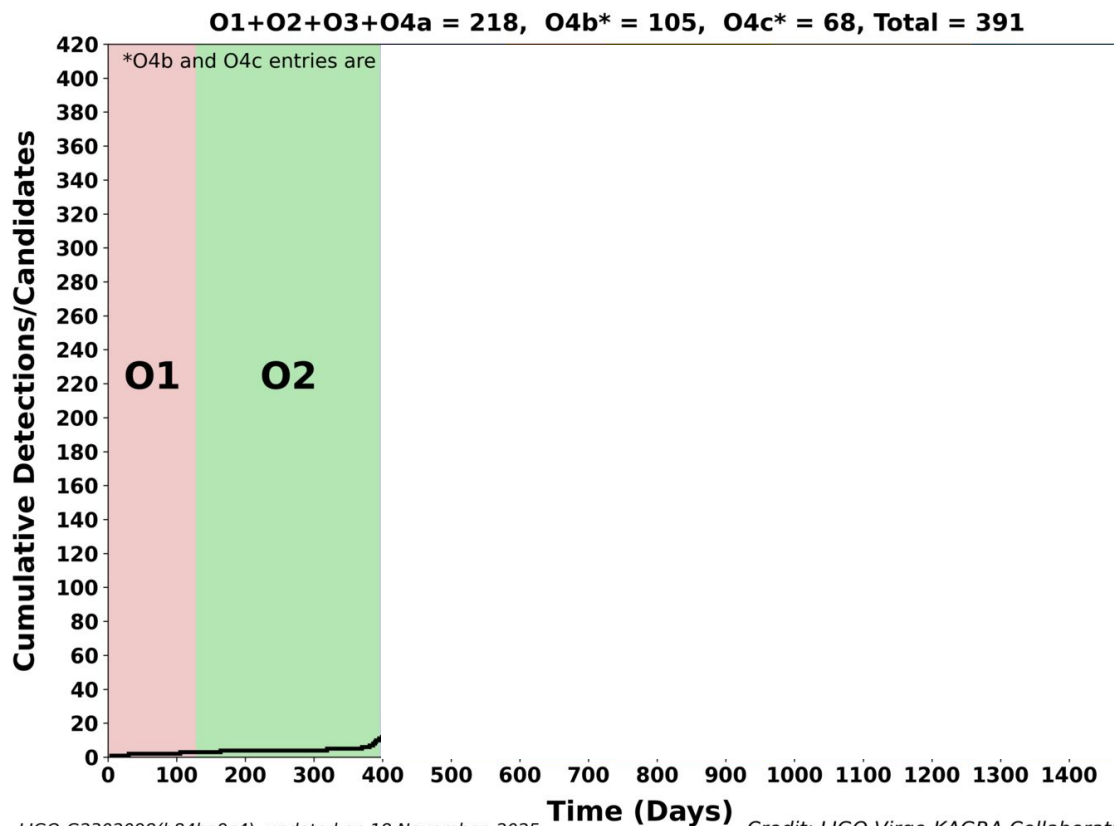
Arca Sedda et al (2023), arXiv:2109.12119

Arca Sedda et al (2026) arXiv:2603.20430

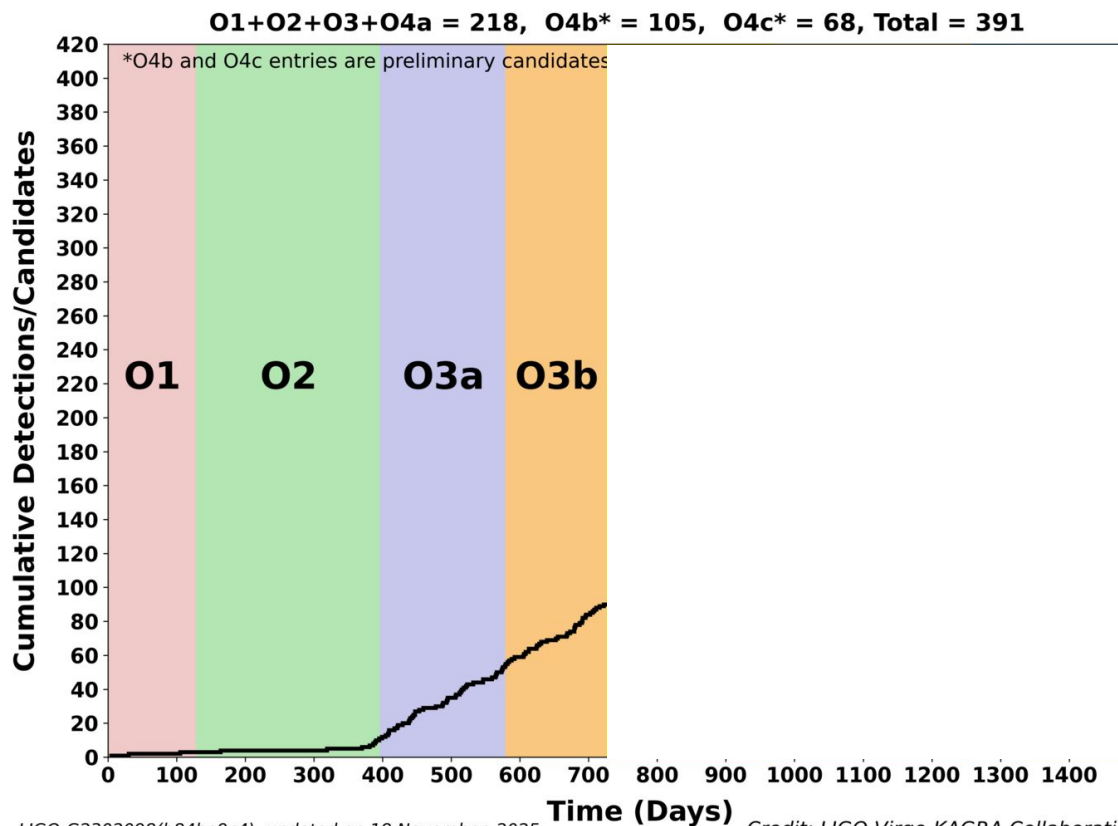
# Black hole binaries and gravitational waves: a myth that became ~ routine



## Black hole binaries and gravitational waves: a myth that became ~ routine



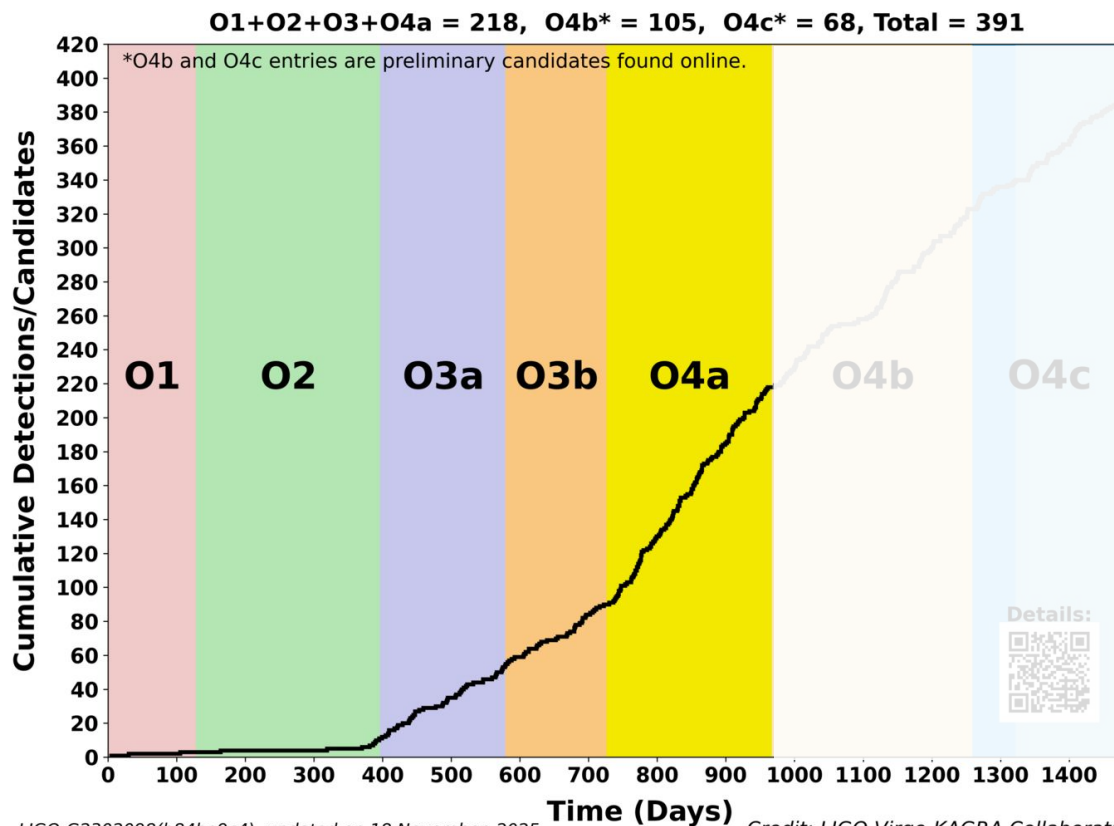
## Black hole binaries and gravitational waves: a myth that became ~ routine



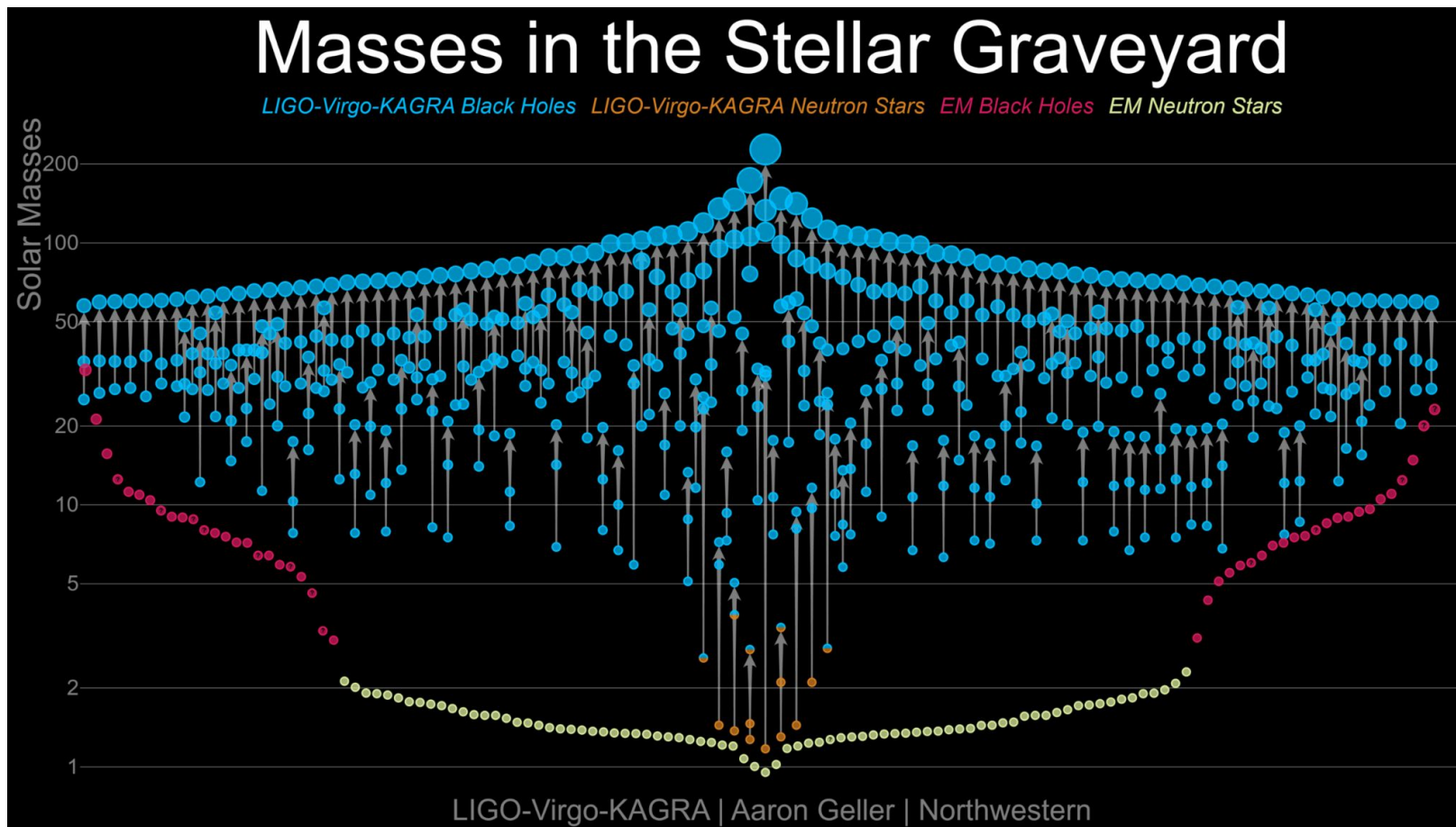
LIGO-G2302098(b84be9c4), updated on 18 November, 2025

Credit: LIGO-Virgo-KAGRA Collaboration

## Black hole binaries and gravitational waves: a myth that became ~ routine

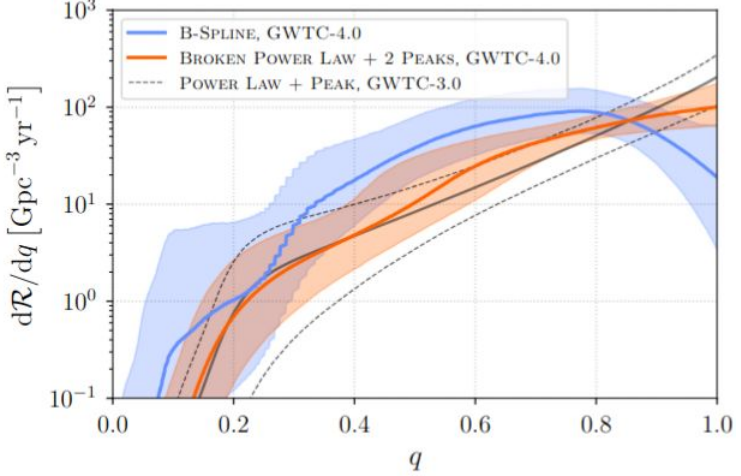
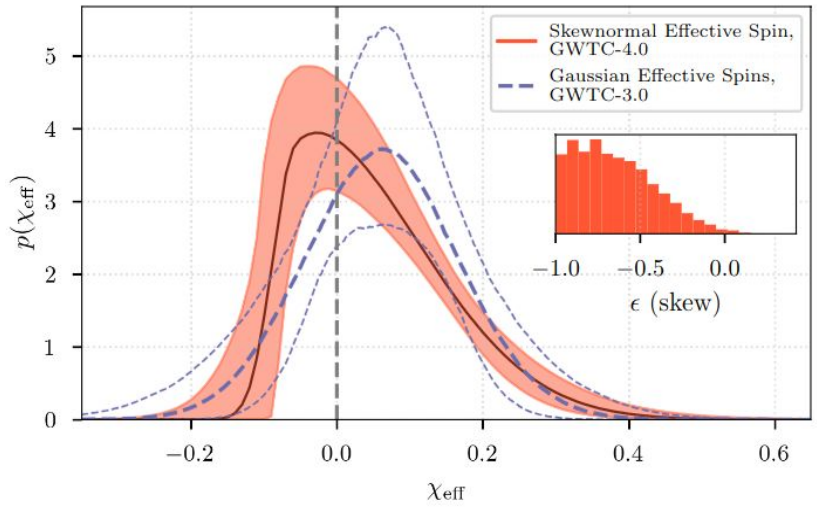
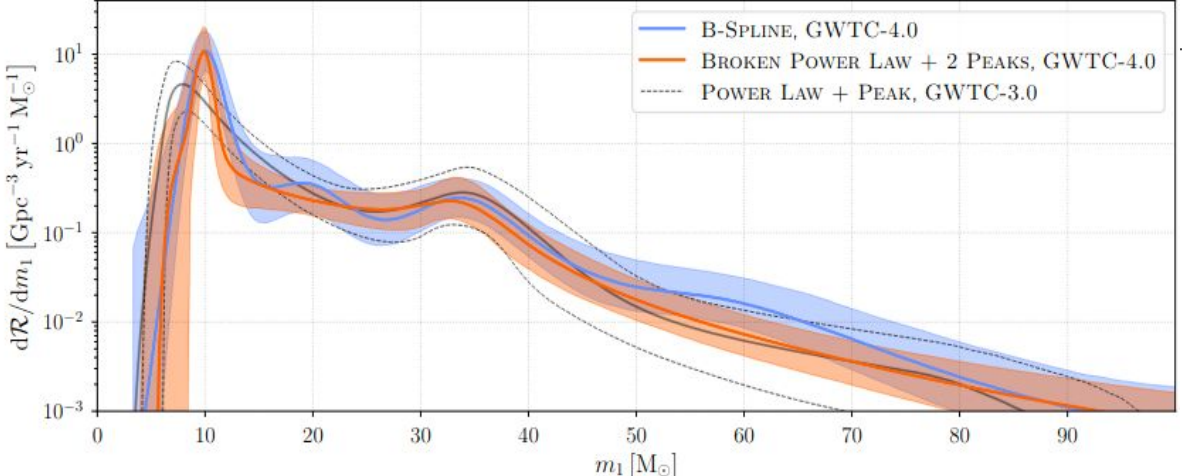


## Black hole binaries and gravitational waves: a myth that became ~ routine

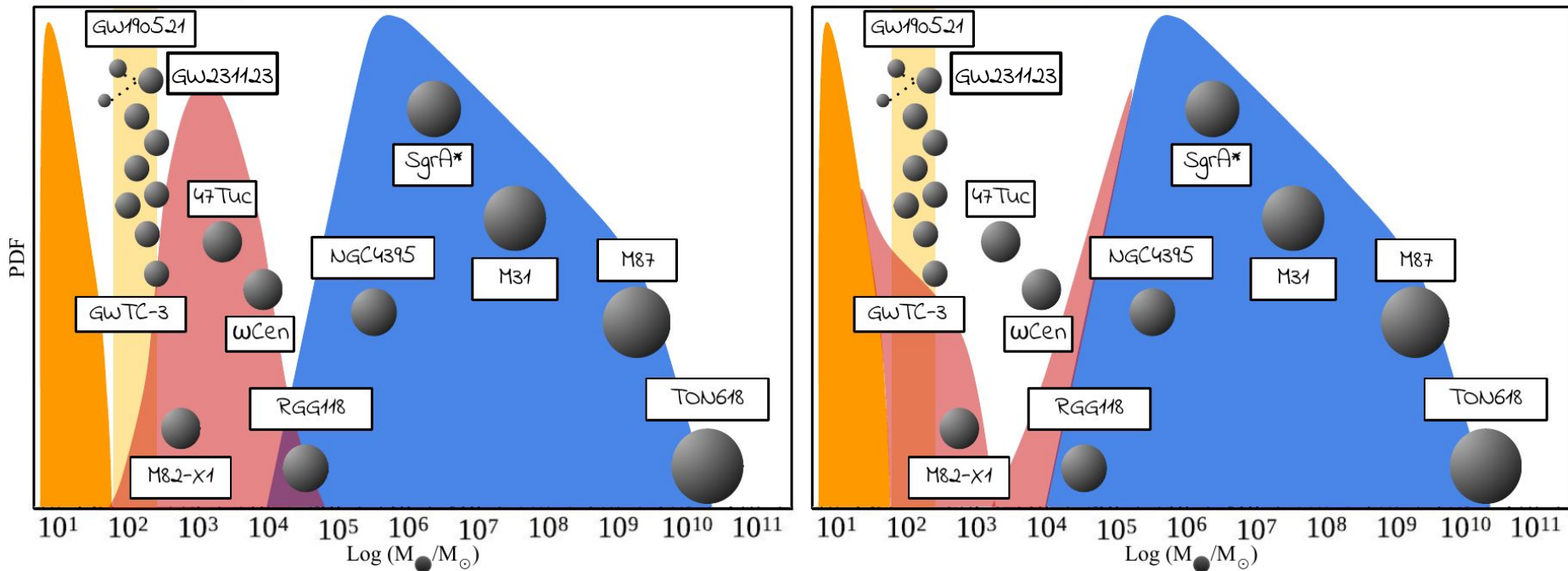


### Properties of black hole binary mergers inferred from GW observations

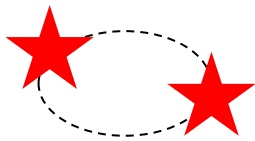
- Features in the primary mass ( $m_1 > m_2$ )
  - Effective spin distribution
- $$\chi_{\text{eff}} = \frac{(m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2) \vec{L}}{m_1 + m_2}$$
- Mass ratio ( $q < 1$ )



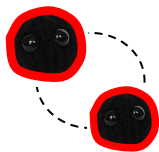
## Black hole binaries: how do they form and how do they relate to other BH classes?



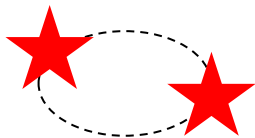
## Where do black hole binary mergers come from?



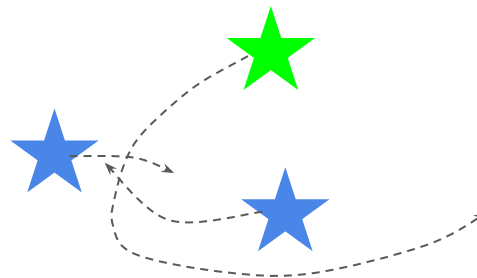
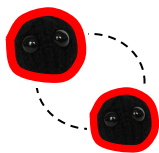
*Some originate from stars  
paired at birth  
(primordial/original binaries)*



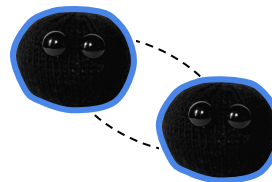
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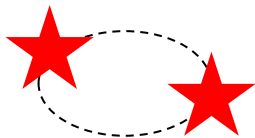
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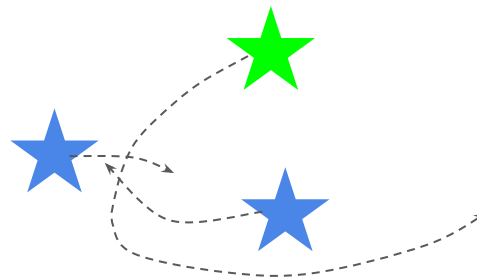
*Some originate from stars that find  
themselves in star clusters  
(dynamical binaries)*



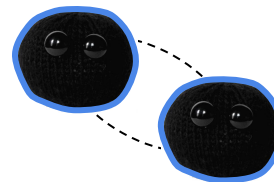
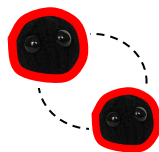
## Where do black hole binary mergers come from?



**Isolated Channel**



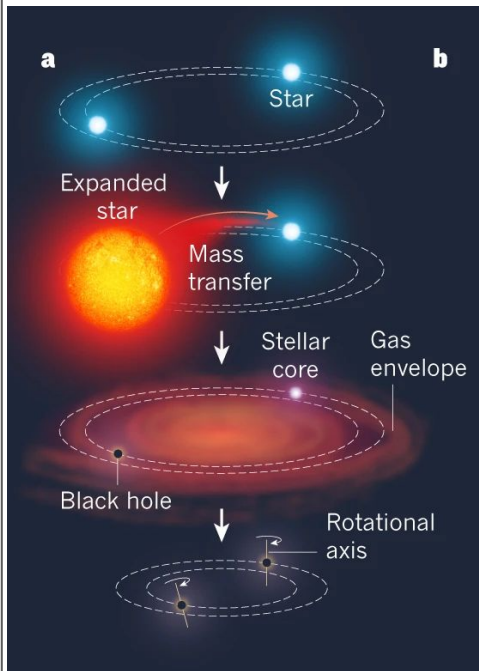
**Dynamical Channel**



# Where do black hole binary mergers come from?

## isolated channel

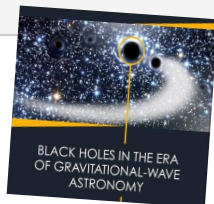
(Dominik+12,Belczynski+12,+16,Giacobbo&Mapelli18,Eldridge+19,Spera+19, Broekgaarden+20,Breivik+20,Bavera+20, VanSon+22,Iorio+23 ...)



Mandel & Farmer 2017

### Alternative channels

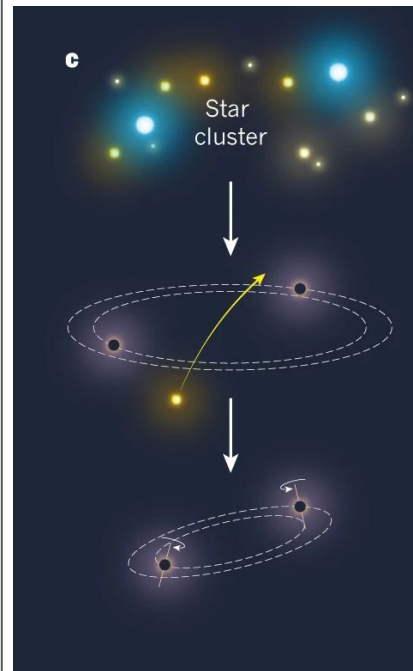
- Pop III stars (Tanikawa20, Santoliquido+23)
- Chemically homogenous evolution (de Mink&Mandel16, Marchant+16)
- Interacting and non-interacting isolated triples (e.g. Thompson&Silsbee16, Toonen20)



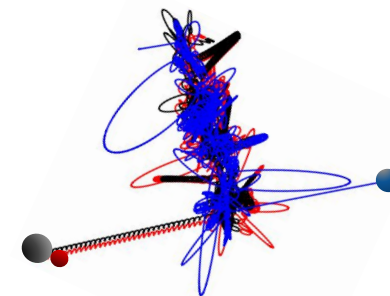
(see also arxiv:2311.15778)

## dynamical channel

(Miller&Hamilton02,Miller&Lauburg05,O'Leary06,09,Downing+09,Banerjee+10,20, Ziosi+14,Rodriguez+16,19,Antonini&Rasio16,Antonini+19,20,DiCarlo+19,20,Zevin+20 Rastello+21,ArcaSedda20, ArcaSedda+20,23,24,Torniamenti+23,24, Arca Sedda+26 ...)



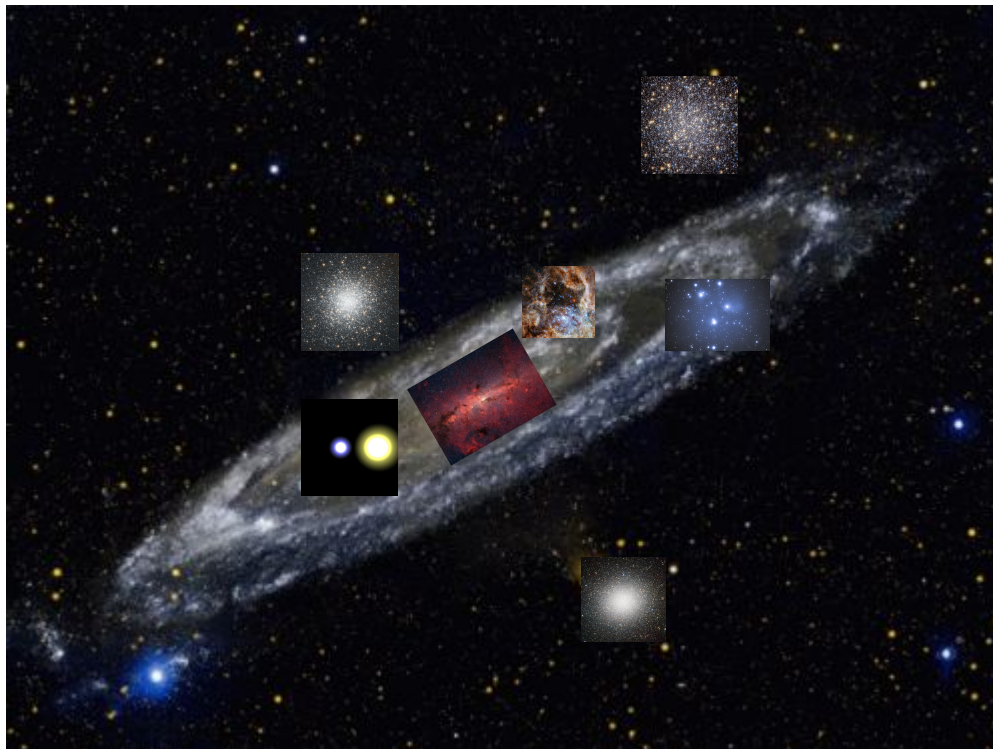
Mandel & Farmer 2017



### Alternative channels

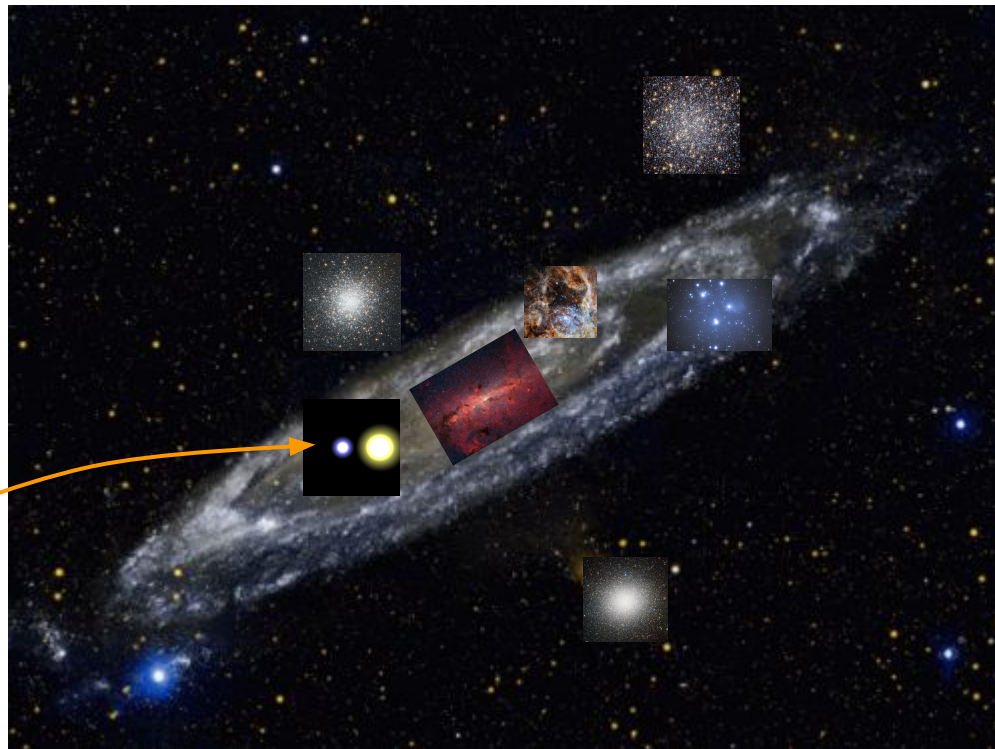
- Triples (Antonini&Perets12, Fragione+19,ArcaSedda+21)
- AGN (McKernan+12, Tanikawa+20, Vaccaro+23)
- Pop III (Mesticelli+24)
- GW captures (O'Leary+06, Bartos+20)

# Why B-POP?

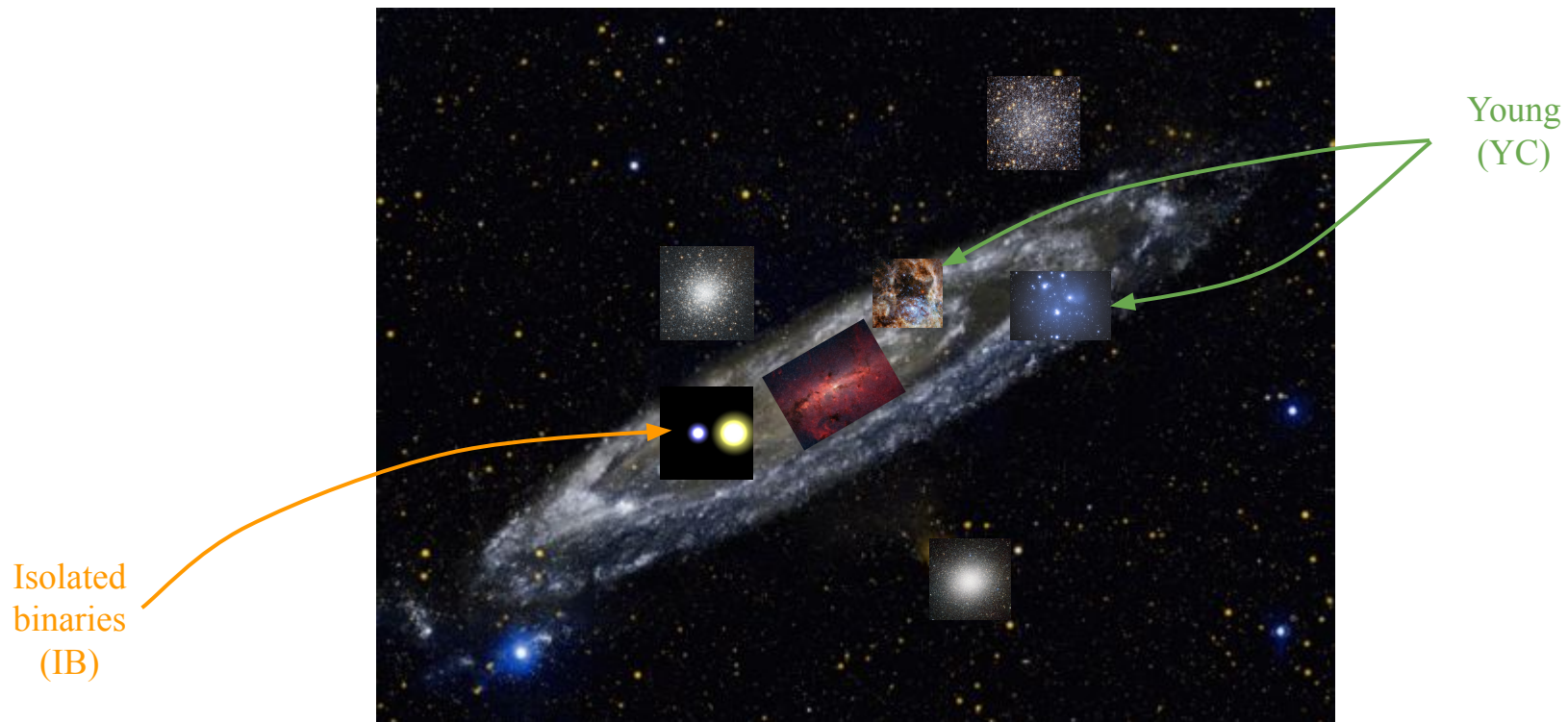


# Why B-POP?

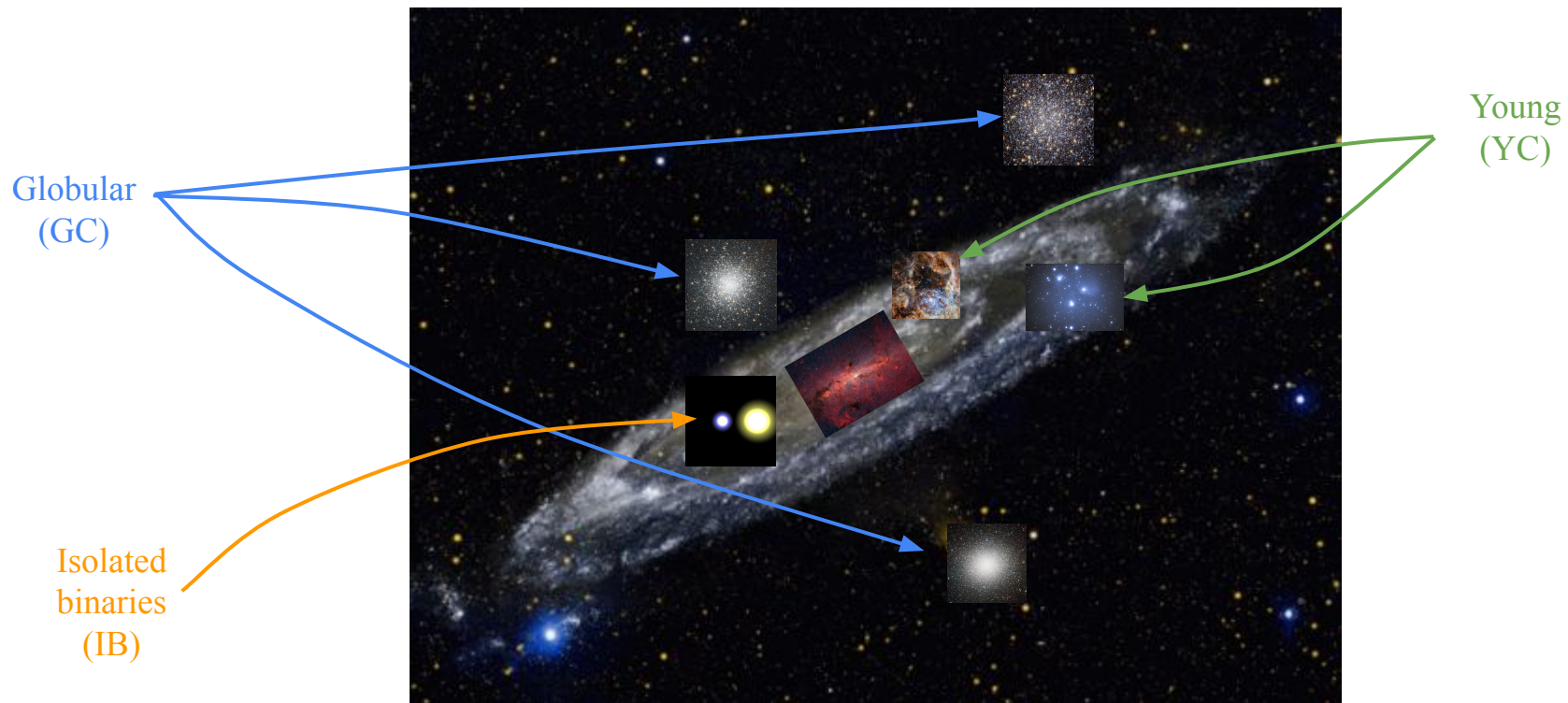
Isolated  
binaries  
(IB)



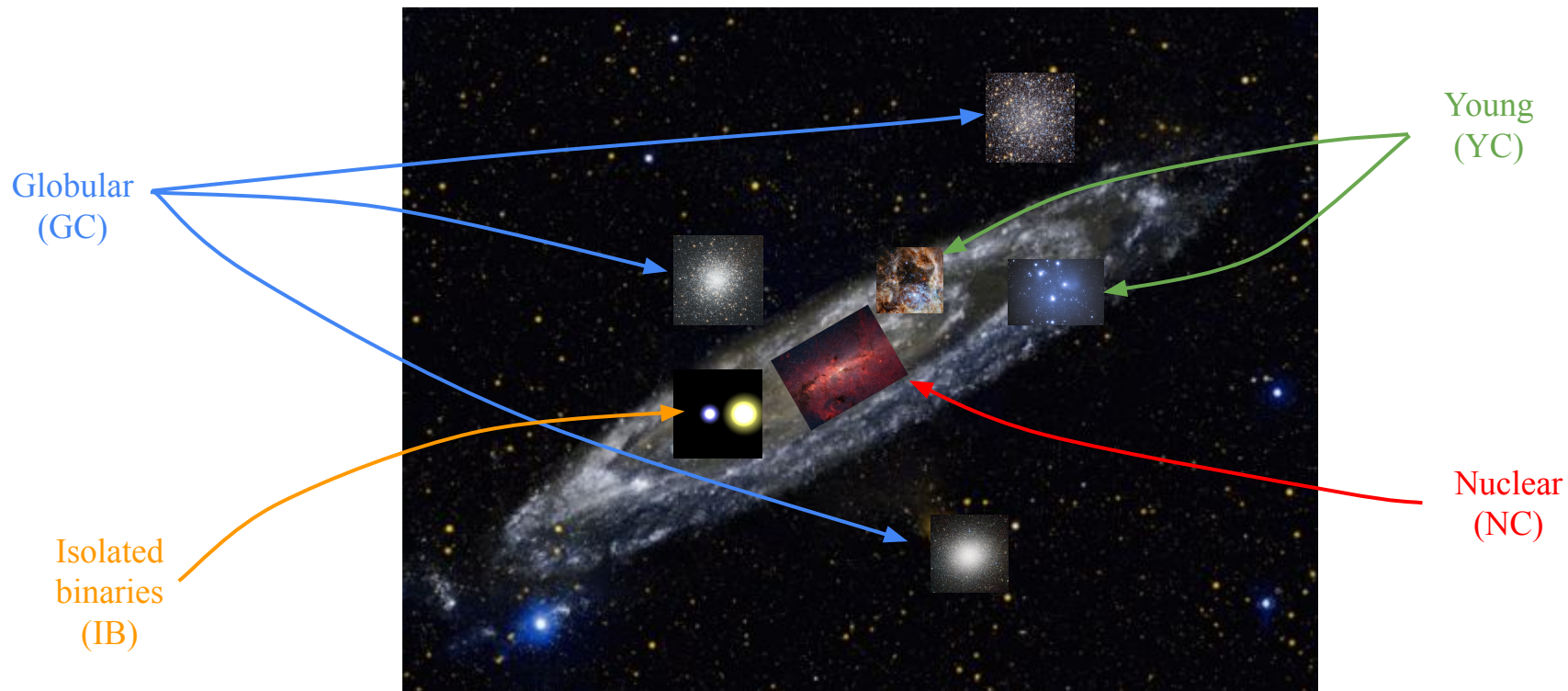
# Why B-POP?



# Why B-POP?

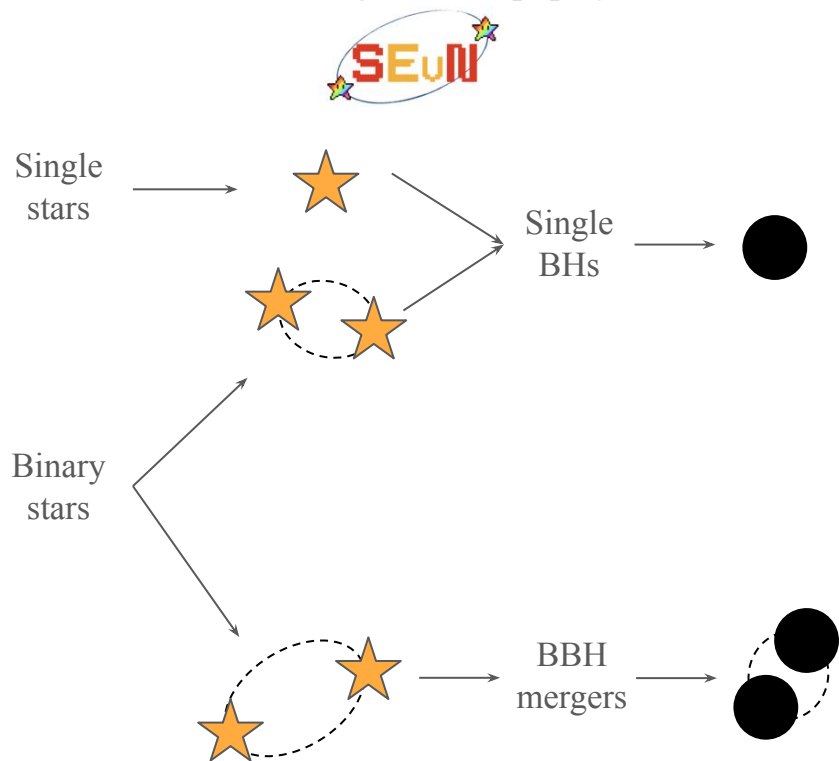


# Why B-POP?





## BH catalogues from pop-synth

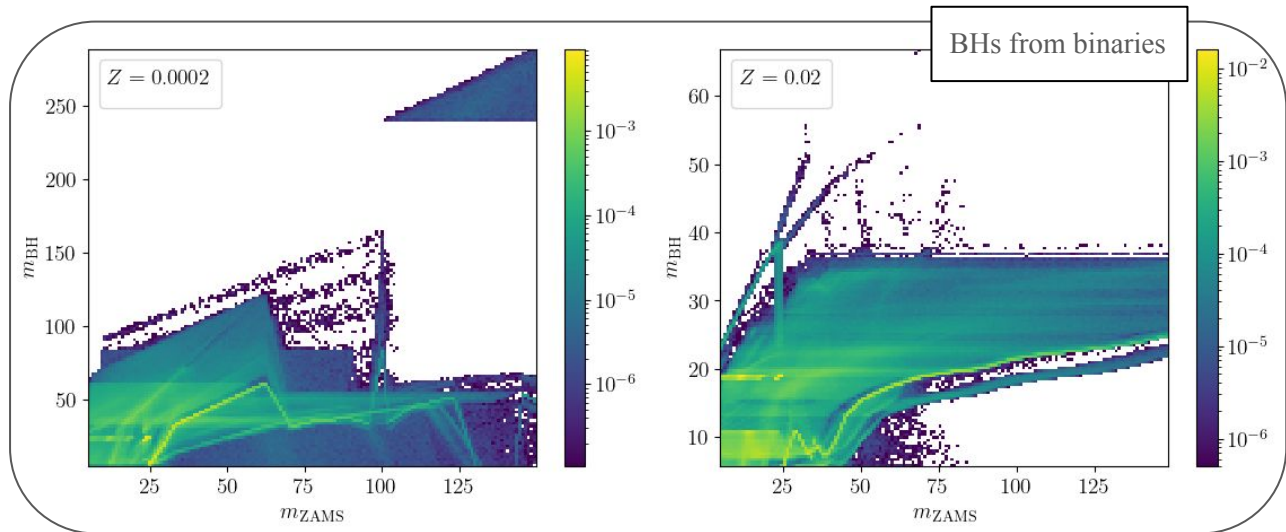
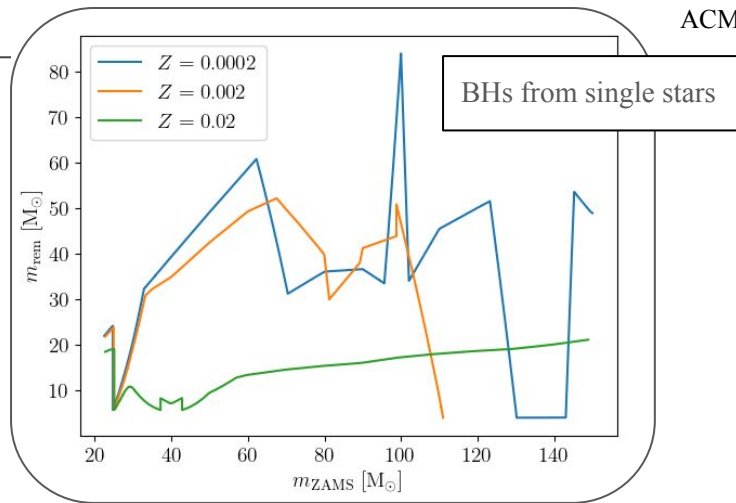
BBH mergers from  
isolated and dynamical channelsRate and cosmic  
BBH population

# BH catalogues from pop-synth:



Fiducial model from Iorio+(2023)

- 13 values of metallicities.  
 $Z = 0.0002 - 0.03$
- Rapid SNe (Fryer+2012)
- PISNe (Woosley2007)
- Natal kick (Mapelli+2020)
- Fallback prescription
- Orbits: Moe&Di Stefano (2017) + Sana+(2012)
- Kroupa IMF (single and primary stars)



## Dynamical mergers

### Types of clusters

#### Young Clusters

- Portegies-Zwart et al (2012)

#### Globular Clusters

- Harris (1996,2010)

#### Nuclear Clusters

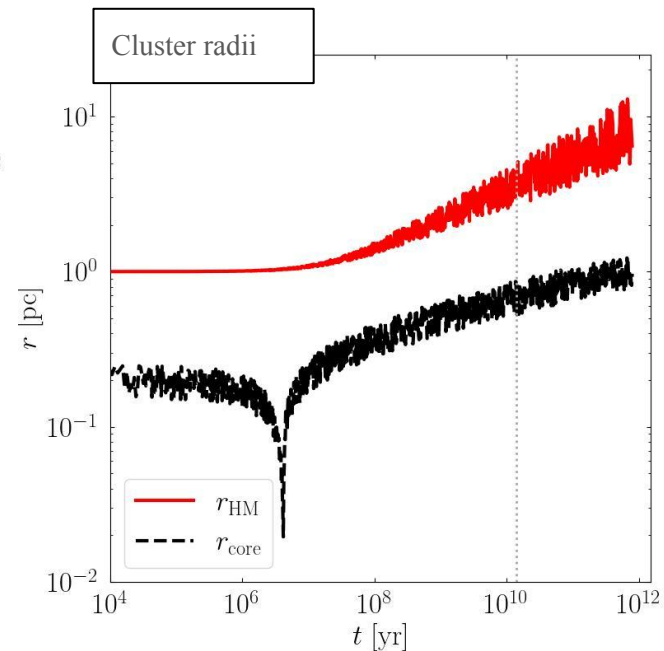
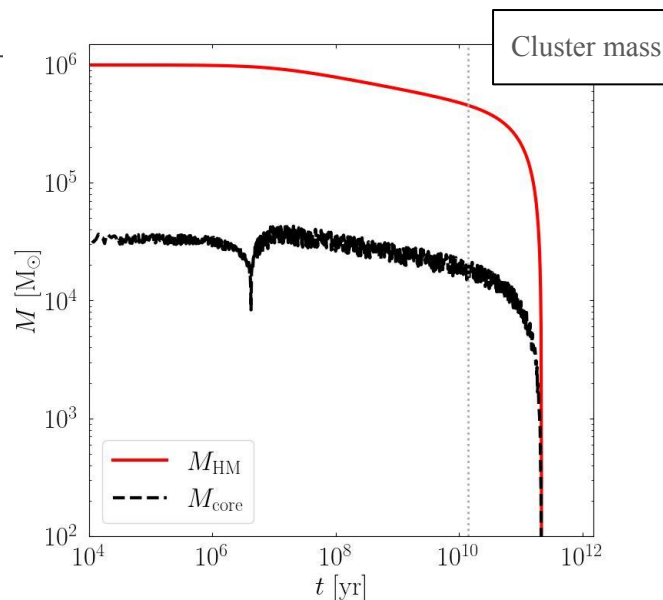
- Georgiev+(2016), Neumayer+(2020)

### Cluster evolution

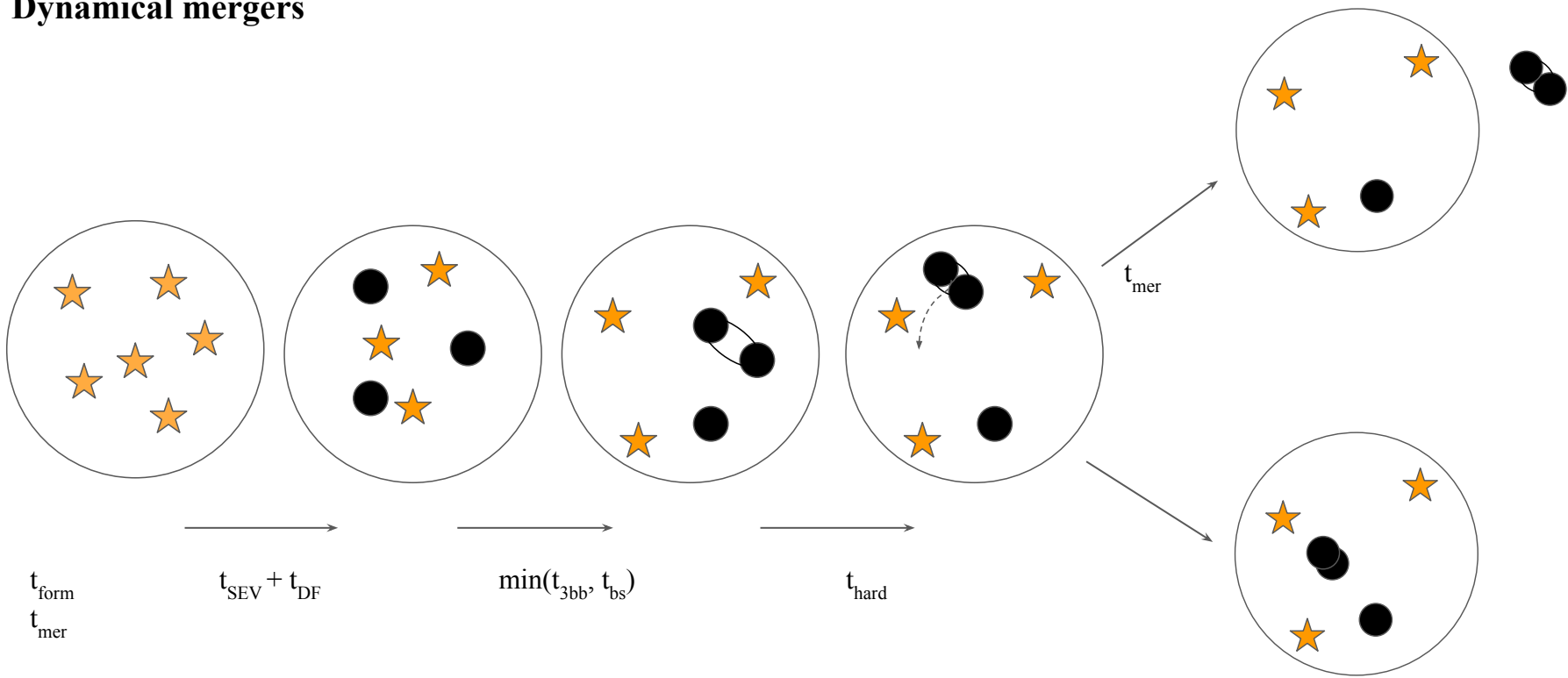
Contraction + core-collapse + relaxation

### Cluster dynamics

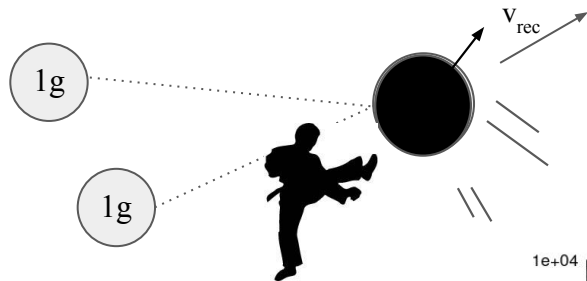
Formation	$t_{\text{form}}$
Stellar evolution	$t_{\text{SEV}}$
Dynamical friction	$t_{\text{DF}}$
Three-body and binary-single	$t_{3\text{bb}} + t_{\text{bs}}$
Hardening	$t_{\text{hard}}$
Ejection/in-cluster merger	$t_{\text{mer}}$
Hierarchical mergers	$t_{\text{repeat}}$



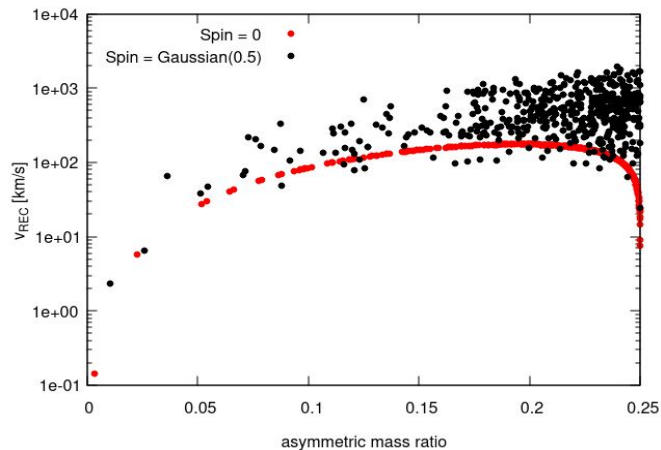
# Dynamical mergers



# Dynamical mergers: hierarchical BH mergers



$$t = t_{\text{form}} + t_{\text{SEV}} + t_{\text{DF}} + t_{\text{3bb}} + t_{\text{bs}} + t_{\text{mer}}$$



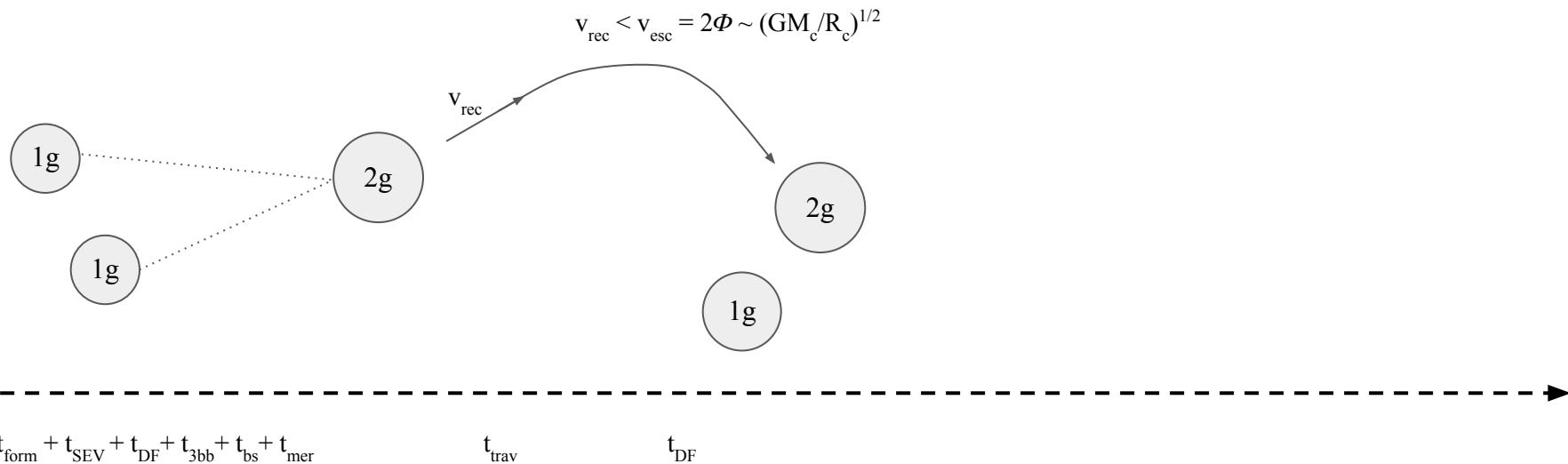
$$\mathbf{v}_k = v_m \hat{e}_{\perp,1} + v_{\perp} (\cos \xi \hat{e}_{\perp,1} + \sin \xi \hat{e}_{\perp,2}) + v_{\parallel} \hat{e}_{\parallel},$$

$$v_m = A\eta^2 \sqrt{1 - 4\eta} (1 + B\eta)$$

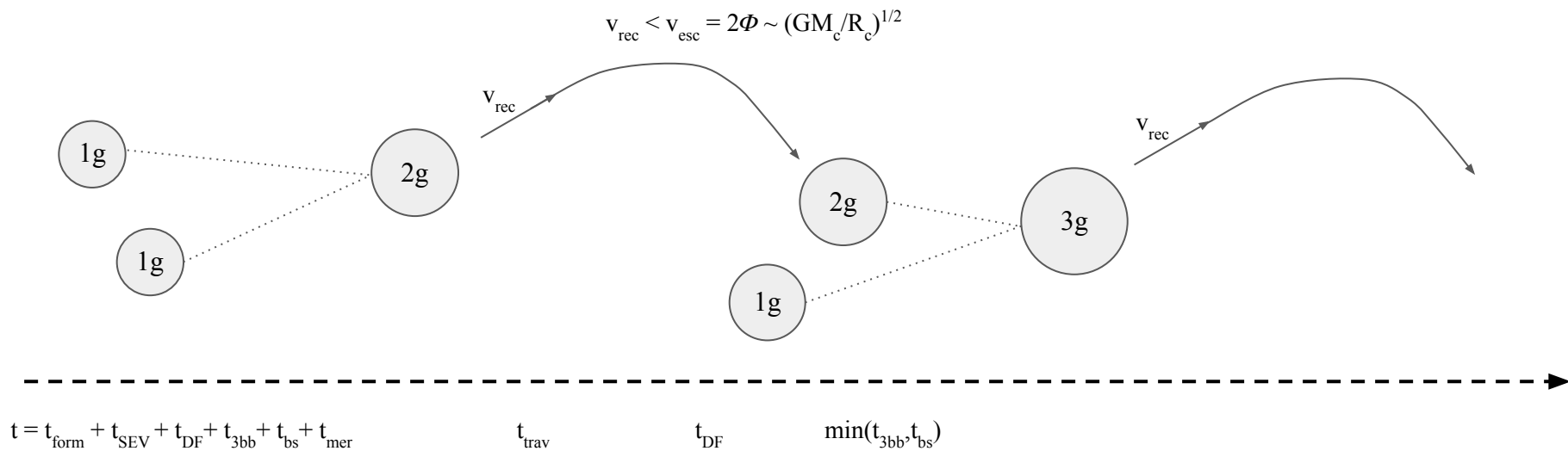
$$v_{\perp} = \frac{H\eta^2}{1 + q_{\text{BBH}}} (a_{2,\parallel} - q_{\text{BBH}} a_{1,\parallel})$$

$$v_{\parallel} = \frac{16\eta^2}{1 + q_{\text{BBH}}} [V_1 + V_A \Xi_{\parallel} + V_B \Xi_{\parallel}^2 + V_C \Xi_{\parallel}^3] \\ \times |a_{2,\perp} - q_{\text{BBH}} a_{1,\perp}| \cos(\phi_{\Delta} - \phi_1).$$

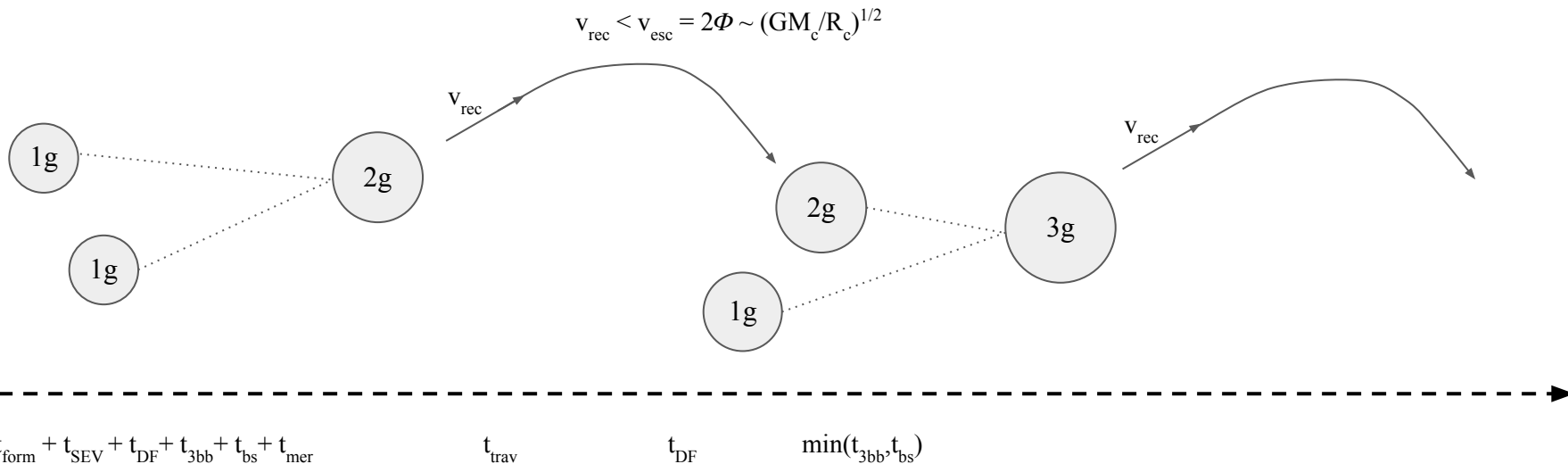
# Dynamical mergers: hierarchical BH mergers



# Dynamical mergers: hierarchical BH mergers



# Dynamical mergers: hierarchical BH mergers



**Dynamical Mergers:**

Natal spins?  
Mass ratios?  
Remnant spin?

BH mass function?  
BH evolution?

Cluster lifetime?  
Cluster evolution?

**Isolated Mergers:**

Galaxy velocity  
curve

2g + 1g  
unlikely

## Using B-POP: quick start

Clone the code

```
git clone github.com/marcasedda/bpop
```

Download BH catalogues here

```
https://drive.google.com/drive/folders/1FmVfXwF1aYHNBpzDcdeyufyV3lzvBOqr?usp=drive\_link
```

The catalogue's size is  $\sim 4.5$ Gb, and the initial conditions are based on the Fiducial model of [Iorio et al \(2023\)](#)

Let's move to the [git repository](#)

## Using B-POP: initial conditions

See example [here](#). The initial condition file consists of different blocks affecting:

- The number of independent chunks to be run in parallel
- The total number of BBHs to be simulated per chunk (not necessarily merging BBHs!)
- The fraction of BBHs from the dynamical channel (and from different cluster types)
- The prescriptions to treat BHs from stellar collisions
- The prescriptions to initialise and evolve star clusters
- The prescriptions to initialise BH natal spins
- The prescriptions to distribute formation redshift and metallicity
- A set of deprecated parameters soon-to-be-removed

In this hands-on session, we adopt the initial condition reproducing the Fiducial model in [Arca Sedda et al \(2026\)](#)

## Using B-POP: initial conditions

```
//input_params.h
```

```
//Guard
```

```
#ifndef PARAMETERS_H
```

```
#define PARAMETERS_H
```

```
#define CHUNKS "yes"
```

Tells B-POP that you will run parallel instances of the code.

B-POP will assign a unique, monotonically increasing, ID to every BBH.

## Using B-POP: initial conditions

```
// DATAFILES (Metal. distri, Single BHs, Binary BHs)
```

```
#define PREDIR "/home/manuel/Scrivania/ACTIVE_PROJECTS/BPOP/"
```

```
#define SINGPTH "../SEVN_Catalog/rapid_M20/"
```

```
#define PATH    "../SEVN_Catalog/rapid_M20/"
```

```
#define SEVN "yes"
```

```
//FILE STRUCTURE
```

```
#define kpar 20
```

```
#define spar 5
```

Directory containing the code

Directories containing the pre-compiled catalogues

“yes” implies 13 values of the metallicity (as done in Iorio+23)

Number of columns in binary BH catalogues

Number of columns in single BH catalogues

## Using B-POP: initial conditions

```
// GLOBAL
#define N      1000000      Number of binaries (per chunk)
#define mmax   150.        Maximum/minimum stellar mass
#define mmin   18.5        Slope of the IMF (already encoded in catalogues though)
#define mslope -2.35       Solar metallicity
#define Zsun   0.019

//DYNAMICAL FRACTIONS
#define Dyn0vTot 0.9       Fraction of dynamical BBH over the total
#define pYC     0.75       Fraction of BBHs from different cluster types over the dynamical (they must sum up to 1)
#define pGC     0.15
#define pNC     0.1

#define mixing  1.0        Fraction of BHs drawn from progenitors originally in binary stars
```

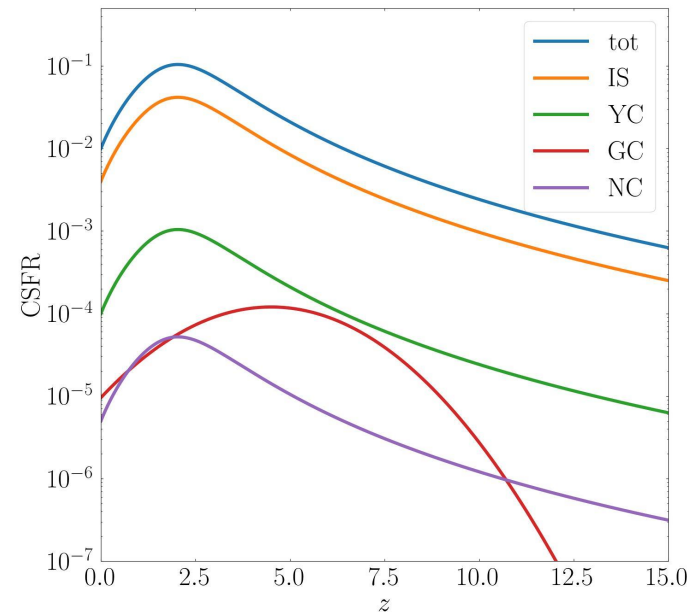
## Using B-POP: initial conditions

```
#define SFRTYPE_ISO "continuous" //"MF17" //"continuous" //"bigbang" // "single"  
#define SFRTYPE_CLU "continuous" //"EB18_MF17" //"KR13" //"EB18_MF17" //"continuous" //"bigbang" //
```

Star formation rate for isolated and YC, and for GC and NC.

Main options:

- Continuous: formation redshift distribution flat between 0 and 15
- MF17: Madau & Fragos 2017
- Bigbang / Burst: fixed formation redshift  $z = 15$  (modifiable in funcGR.cpp)
- Single: fixed formation redshift  $z = 2$
- EB18: El-Badry et al (2019) with correction in Mapelli et al (2022) for NCs & GCs
- MF17\_EB18: uses MF17 for NCs and EB18 for GCs



## Using B-POP: initial conditions

```
#define SFRTYPE_ISO "continuous" //"MF17" //"continuous" //"bigbang" // "single"
#define SFRTYPE_CLU "continuous" //"EB18_MF17" //"KR13" //"EB18_MF17" //"continuous" //"bigbang" //
```

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- EB18: El-Badry et al (2019) with correction in Mapelli et al (2022) for NCs & GCs
- MF17\_EB18: uses MF17 for NCs and EB18 for GCs

```
//METALLICITY SPREAD
```

```
//NOTE: The choice Elbadry19 requires a sigma_metal. Redshift-dependent metallicity relation for isolated and dynamical
```

```
#define sigma_metal_iso 0.2
```

```
#define sigma_distri_iso "Mapelli"
```

```
#define sigma_metal_clu 0.2
```

```
#define sigma_distri_clu "Elbadry19"
```

binaries:

- “Mapelli” refers to Mapelli et al (2022) and refs. Therein
- “Elbadry19” refers to El-Badry et al (2019) and Ma et al (2016)

## Using B-POP: initial conditions

```
//BH SEED
#define f_seed 0.2
#define maxseed 1000.0
#define minseed 100.0
#define seedslope 3.0
#define bhseed "bifrost"
#define bifZ 0.001
#define bhpisn 270.

//HIGH MASS BHs
#define a_gp 2.0
#define uppergap "yes"
#define fupgp 0.15
#define mass_gap 60.0
#define upgtp "dicarlo"

//SPINS
#define spinlb "bavera"
#define obslope 0.0

#define INDEX_ALIGN 8.0
```

## Using B-POP: initial conditions

```
//BH SEED
#define f_seed      0.2
#define maxseed    1000.0
#define minseed    100.0
#define seedslope  3.0
#define bhseed     "bifrost"
#define bifZ       0.001
#define bhpsn     270.
```

Some clusters can undergo repeated stellar collisions that rapidly build-up a very massive star, which eventually can directly collapse to an IMBH

(see e.g. Portegies-Zwart & McMillan 2002, Giersz et al 2015, Mapelli 2016, Arca Sedda 2016, Rizzuto et al 2021, Arca Sedda et al 2021, Gonzalez et al 2021, Arca Sedda et al 2023, Vergara et al 2024, Vergara et al 2025, Rantala et al 2024, 2025, 2026, Mestichelli et al 2026 ...)

B-POP implements several options through the `bhseed` = [ “yes”, “vms”, “bifrost” ]

**bhseed** = “yes”: assuming a formation probability **f\_seed**, B-POP extracts the primary mass from a power-law with slope **seedslopes** within **minseed** and **maxseed** and a spin randomly distributed in the [0,1] range

**bhseed** = “vms”: formation probability **f\_seed**, assumes a conservative scaling according to which the IMBH mass is  $< 10^3 M_{\text{SUN}}$

**bhseed** = “density”: like option “yes” but only for cluster with scale density  $> 3 \times 10^5 M_{\text{SUN}} \text{ pc}^{-3}$

**bhseed** = “bifrost”: formation probability **f\_seed**, minimum mass to form an IMBH from direct collapse and avoid PISN given by **bhpsn**, minimum metallicity to avoid PISN **bifZ**, the mass is extracted according to the results from Rantala et al (2024) only if cluster density exceeds  $10^5 M_{\text{SUN}} \text{ pc}^{-3}$  and cluster mass  $> 5,000 M_{\text{SUN}}$

## Using B-POP: initial conditions

```
//BH SEED
#define f_seed 0.2
#define maxseed 1000.0
#define minseed 100.0
#define seedslope 3.0
#define bhseed "bifrost"
#define bifZ 0.001
#define bhpsn 270.

//HIGH MASS BHs
#define a_gp 2.0
#define uppergap "yes"
#define fupgp 0.15
#define mass_gap 60.0
#define upgtp "dicarlo"
```

If **uppergap** = “yes”, it allows some BHs to have a mass in the upper-mass gap, between **mass\_gap** and  $100 M_{\text{SUN}}$

If:

**upgtp** = “dicarlo”: the probability for a BH mass to be in the gap is metal-dependent following Di Carlo et al (2021) and Arca Sedda et al (2024)

**upgtp** != “dicarlo”: the probability is set by **fupgp**, and the mass of the BHs is extracted according to a power-law with slope **a\_gp** between **mass\_gap** and  $100 M_{\text{SUN}}$

## Using B-POP: initial conditions

```
//SPINS
#define spinlb "bavera"
#define obslope 0.0
```

If **spinlb** = “mixed”: natal spins from a Maxwellian with  $\sigma=0.2$  (GWTC-3) for IBs and a negligible spin for dynamical one (following Fuller and Ma 2019)

If **spinlb** = “mixedhigh”: same as above, but assume a Gaussian with mean = 0.5 for IBs

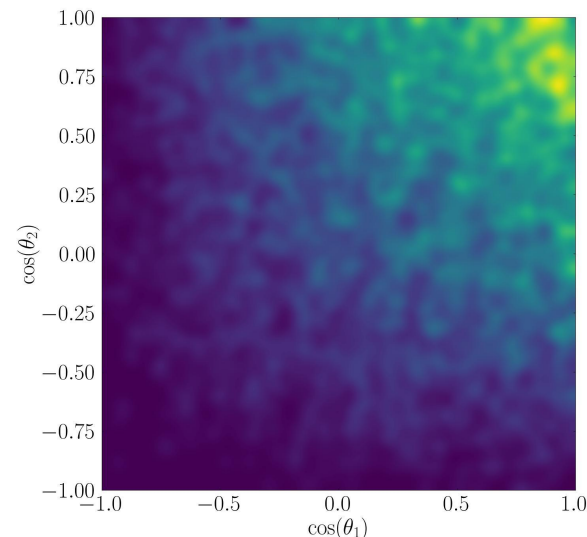
If **spinlb** = “Bavera”: BHs from single stars and first-born BHs in binaries spin negligible, second-born BHs, BHs in the upper mass-gap, and IMBH seeds extracted between 0,1 assuming flat distribution

Further options are available (Maxwellian, Gaussian, zero spin, following Belczynski et al 2016, or Amaro-Seoane and Chen 2016)

```
#define INDEX_ALIGN 8.0
```

Alignment is assumed to be isotropical for dynamical binaries, while for IBs the level of alignment is regulated by **INDEX\_ALIGN** (ndx)

$$P(\theta_i) = \frac{1}{2} (\cos\theta_i + 1)^{ndx+1}$$



## Using B-POP: initial conditions

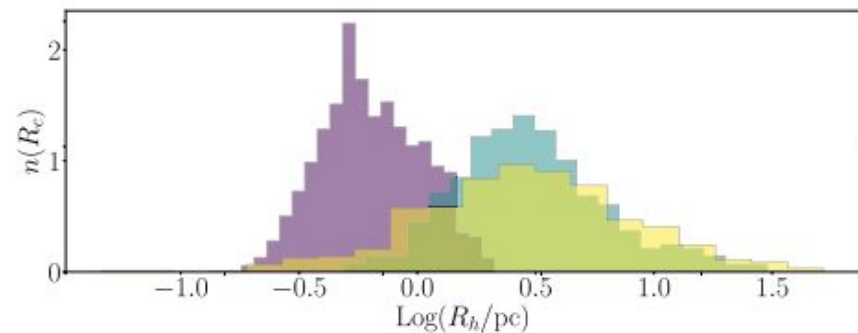
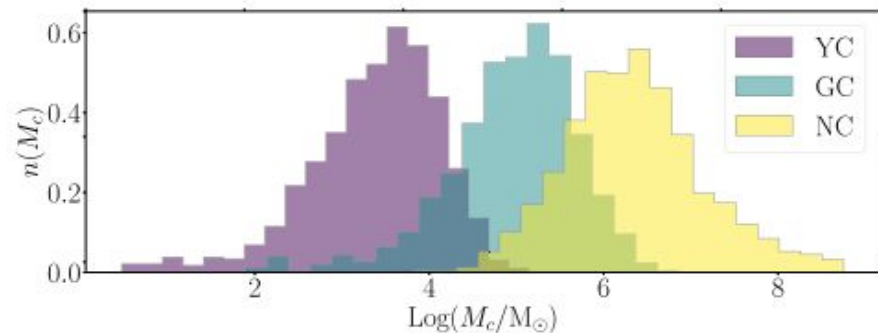
```
//YC mass-size relation  
//Marks12, Rantala24, Mapelli20, AS20, seeds  
//if None, sizes and masses are rescaled from GCs  
#define TagR "AS20"
```

If **TagR** = “AS20”: all masses and radii are taken from observations

If **TagR** = “Mapelli20”: follows Mapelli et al 2020, 2021

If **TagR** = “Marks12”: YCs have a radius according to Marks and Kroupa (2012)

If **TagR** = “Rantala24”: YCs have an initial radius scaled by a factor w.r.t. Marks12



## Using B-POP: first run

- Set “Chunks” to “yes”
- Set “N” to 100
- Open the file “bh\_chunks.sh”
  - Set  $N = 4$  (4 cores of your laptop will be used)

## 2) Compiling and running B-POP

```
make clean && make
```



The executable is saved in /build/BPOP.x

To run the code, copy BPOP.x into the chosen directory and type

```
./BPOP.x > Output.txt &
```



The Output.txt file will contain all printouts of the code. All files with \*.txt and \*.dat files produced by B-POP are ultimately stored in a new directory whose naming summarises some of the main parameters of the simulation.

The main files produced by a single run are:

- ["Catalogue.txt"](#) This file contains all BBH mergers. It consists of 36 columns which represent:
- ["Catalogue\\_multiple\\_dyn.txt"](#) This file contains the merger trees of all multiple mergers.
- ["Larger\\_than\\_tH.txt"](#) contains info about binaries that do not merge within a Hubble time
- ["retention\\_Z0\\_#.dat"](#) contains the cumulative distribution of natal kicks of BHs from single and binary stars. The distribution is calculated for different values of the metallicity

## Using B-POP: main outputs

### Catalogue.txt

#### Header:

```
#ID Metal Nrec EnvType lab m1[Msun] m2[Msun] a1 a2 Mfin[Msun] afin xeff vGW[km/s] tfor[yr] tlast_mer[yr] Mclu_t0[Ms] Rclu_t0[pc] Vesc[km/s]  
BinaryStatus aeje[AU] aGW[AU] nBHs Mcore_th[Ms] rcore_th[pc] redshift_merger redshift_formation tSMBH[yr] redshiftSMBH mprog[Ms] eccentricity  
semimajoraxis[AU] acrit[AU] tmerger[yr] cos(angle_s1s2) cos(angle_s1L) cos(angle_s2L)
```

### Catalogue\_multiple\_dyn.txt

#### Header:

```
# m1[Msun] m2[Msun] a1 a2 acrit[AU] aeje[AU] aGW[AU] tfor[yr] tSNe[yr] t12capt[yr] t3bb[yr] tdf[yr] t12[yr] tbbh[yr] tmer[yr] time[yr] Nrec  
Mcore_t[Ms] Rcore_t[pc] Mclu_t0[Ms] Rclu_t0[pc] tcc[yr] name BinaryStatus EnvType Mfin[Msun] afin xeff vGW[km/s] Vesc[km/s] ID-1 eccentricity
```

### Larger\_than\_tH.txt

#### Header:

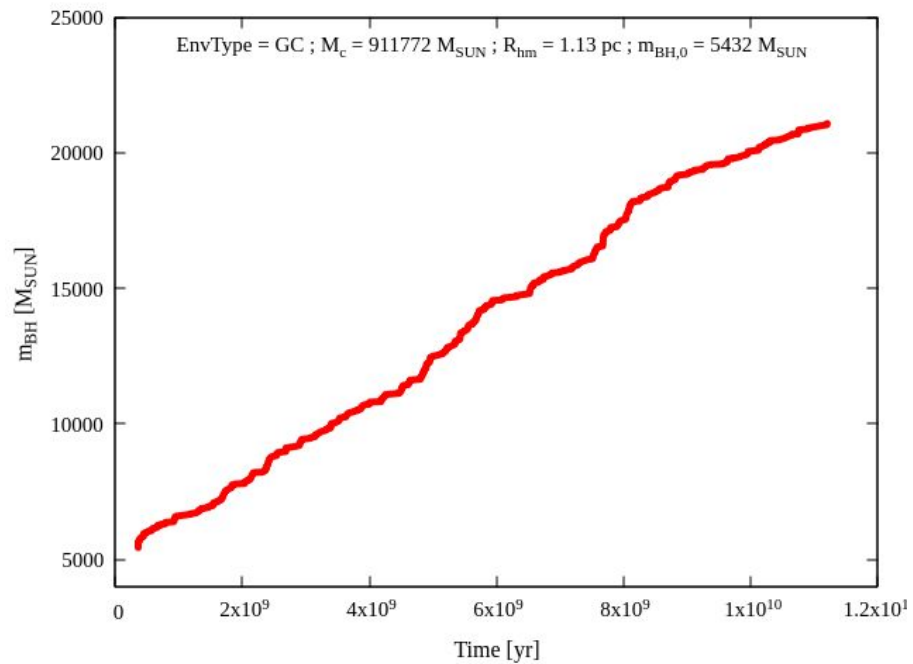
```
# ID-1 Mclu_t0[Ms] Rclu_t0[pc] Mcore/Mcore0 Rcore/Rcore0 trelax_0[yr] Vesc[km/s] sigma[km/s] tdf[yr] tbbh[yr] t12[yr] tmer[yr] Ncalls Metallicity  
EnvType m1[Msun] m2[Msun] a1 a2 eccentricity semimajoraxis[AU] acrit[AU] time[yr] tfor[yr]
```

### Retention\_Z#.dat

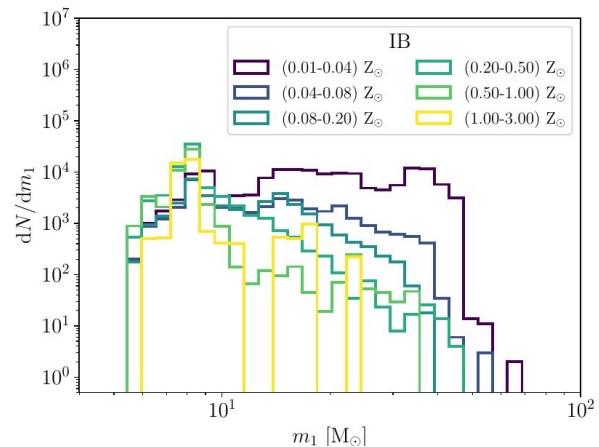
#### Header:

```
# Vesc[km/s] fret_single[km/s] fret_mix[km/s]
```

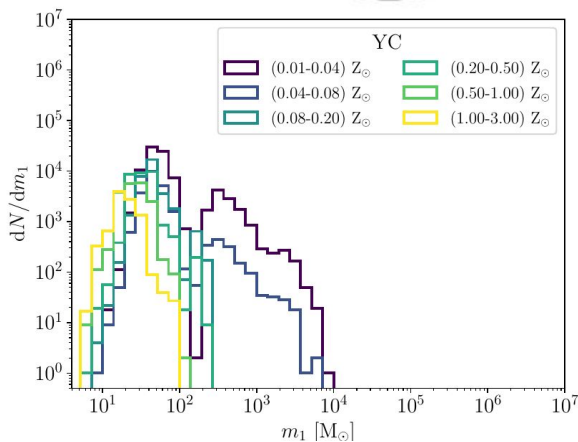
## Using B-POP: track BH growth



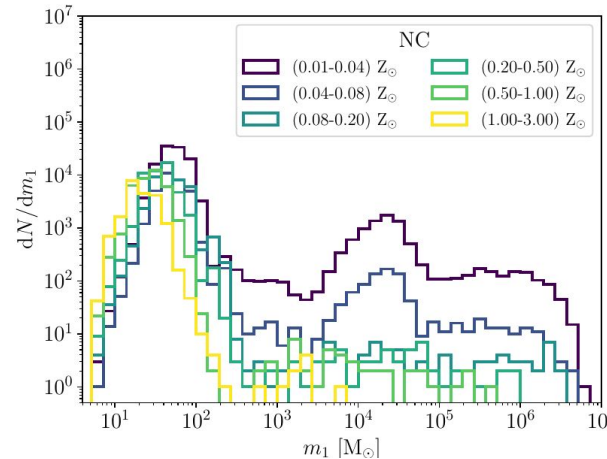
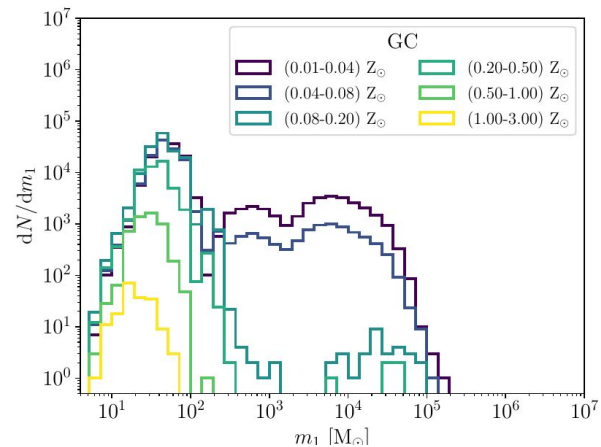
# BBH mergers from isolated and dynamical channels



ISOLATED



DYNAMICAL



## From BBH catalogues to merger rate densities

With B-POP alone, we can create BBHs from different channels varying

- Mass distribution of different cluster types
- Half-mass radii
- Redshift distribution
- Metallicity distribution
- Fraction of BHs forming from single or binary stars
- Fraction of BHs forming from stellar collisions

## From BBH catalogues to merger rate densities

With B-POP alone, we can create BBHs from different channels varying

- Mass distribution of different cluster types
- Half-mass radii
- Redshift distribution
- Metallicity distribution
- Fraction of BHs forming from single or binary stars
- Fraction of BHs forming from stellar collisions

**Is this enough to obtain a “mock” population of BBH mergers?**

## From BBH catalogues to merger rate densities

With B-POP alone, we can create BBHs from different channels varying

- Mass distribution of different cluster types
- Half-mass radii
- Redshift distribution
- Metallicity distribution
- Fraction of BHs forming from single or binary stars
- Fraction of BHs forming from stellar collisions

**NOPE**

## From BBH catalogues to merger rate densities

There are additional quantities to be included in the game:

### 1) metallicity-dependent merger efficiency.

How many BBH mergers form per simulated solar mass?

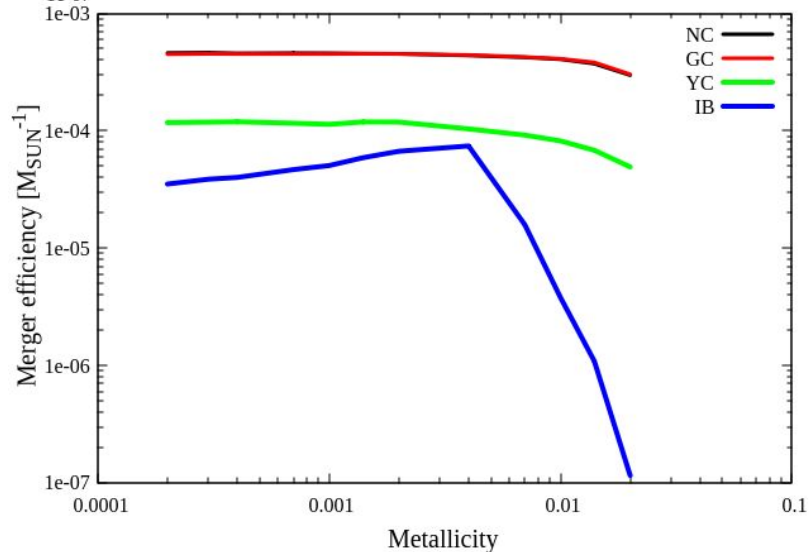
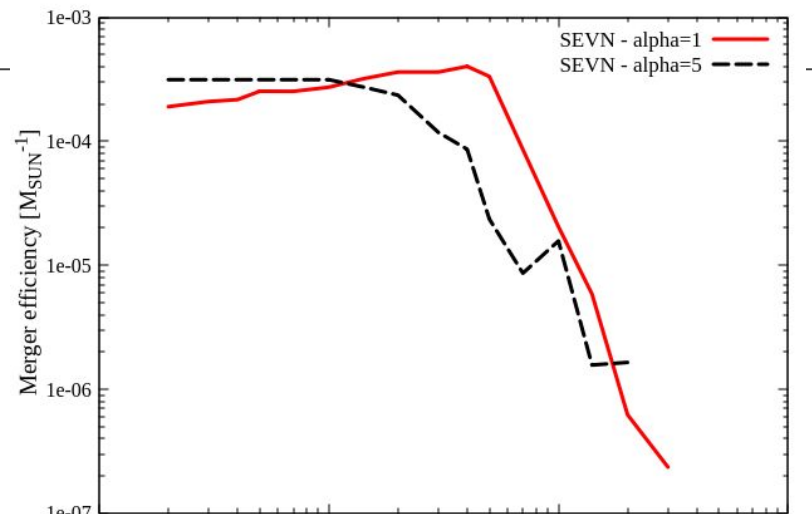
For IB, this quantity is simply given by the

$$\eta_{\text{iso}} = f_{\text{IMF}} \frac{N_{\text{merge}}}{M_{\text{sim}}}$$

For dynamical mergers, we need to quantify a posteriori

- Use B-POP to simulate, e.g., GCs
- Check how many BBH merge (beware of GC mass distribution)
- Take into account binary fraction and fraction of BHs in the population

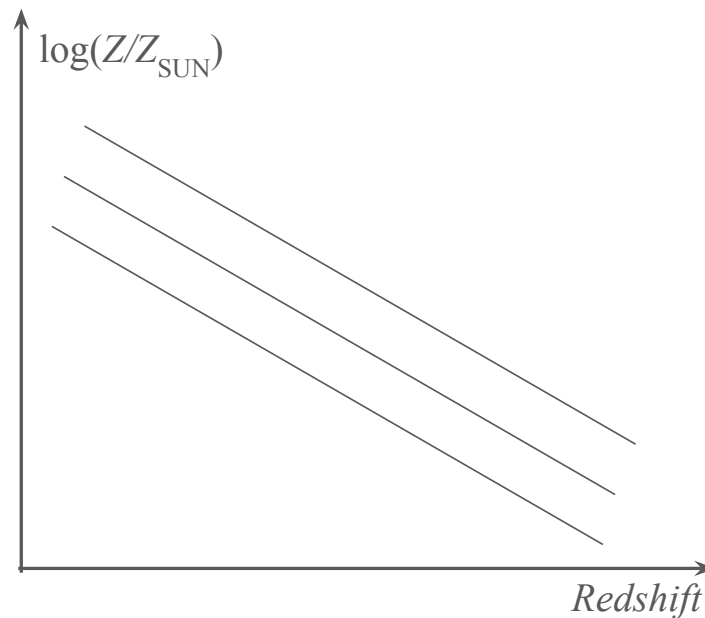
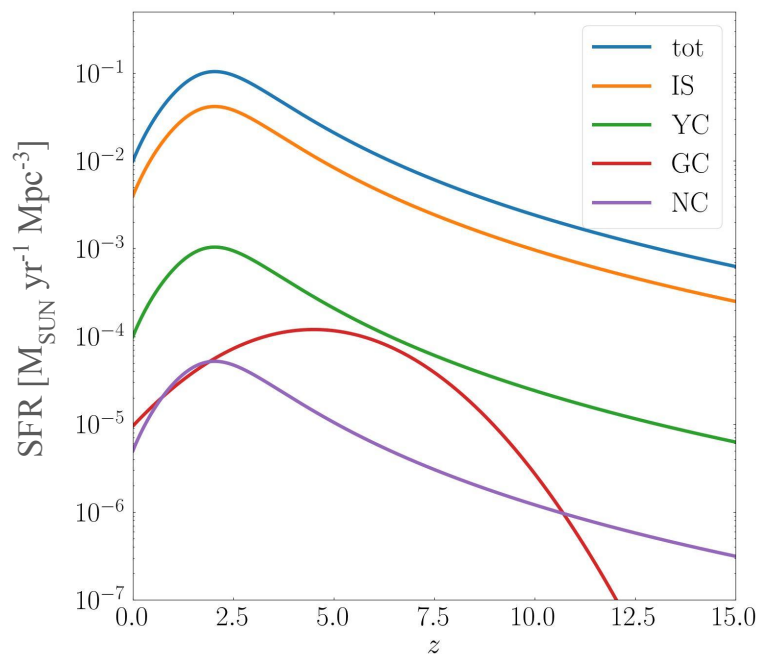
$$\eta_{\text{dyn}} = f_{\text{bin}} \frac{f_{\text{BH}}}{\langle m_* \rangle} \frac{N_{\text{merge}}}{N_{\text{tot}}} \frac{\sum_i f_{\text{ret},i} M_{\text{cl},i}}{\sum_i M_{\text{cl},i}}$$



## From BBH catalogues to merger rate densities

There are additional quantities to be included in the game:

2) **volume and star formation rate scaling.** How much stellar material forms in different channels, redshift bins, and metallicity bins?



## Star Formation Rate and Metallicity evolution

Merger rate density  
(number of mergers per  
units of time and  
cosmological volume)

$$\mathcal{R}_i(z) = \int_{Z_{\min}}^{Z_{\max}} \int_z^{z_{\max}} dZ dz' \frac{dt_{\text{lb}}(z')}{dz'} \psi_i(z') p(z', Z) \eta(Z) \dot{\mathcal{F}}(z', z, Z)$$

Lookback time element

Star formation rate

Fraction of stars  
formed at  $z'$  with  
metallicity  $Z$

Merger efficiency  
at metallicity  $Z$

Rate of mergers for BBH born  
with metallicity  $Z$  at  $z'$  and  
merging at redshift  $z$

## Star Formation Rate and Metallicity evolution

$$dz' \frac{dt_{1b}(z')}{dz'} \psi_i(z')$$

Stellar mass density produced at  $z'$

$$dz' \frac{dt_{1b}(z')}{dz'} \psi_i(z') p(z', Z)$$

Stellar mass density with metallicity  $Z$  produced at  $z'$

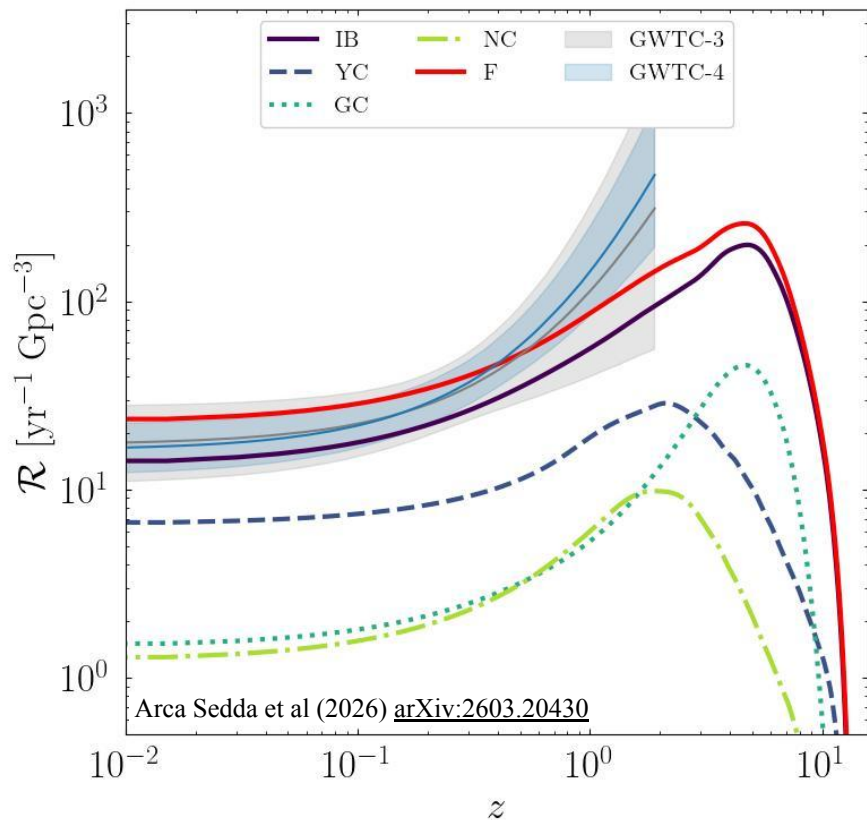
$$dz' \frac{dt_{1b}(z')}{dz'} \psi_i(z') p(z', Z) \eta(Z)$$

Stellar mass density of mergers with metallicity  $Z$  produced at  $z'$

$$dz' \frac{dt_{1b}(z')}{dz'} \psi_i(z') p(z', Z) \eta(Z) \dot{\mathcal{F}}(z', z, Z)$$

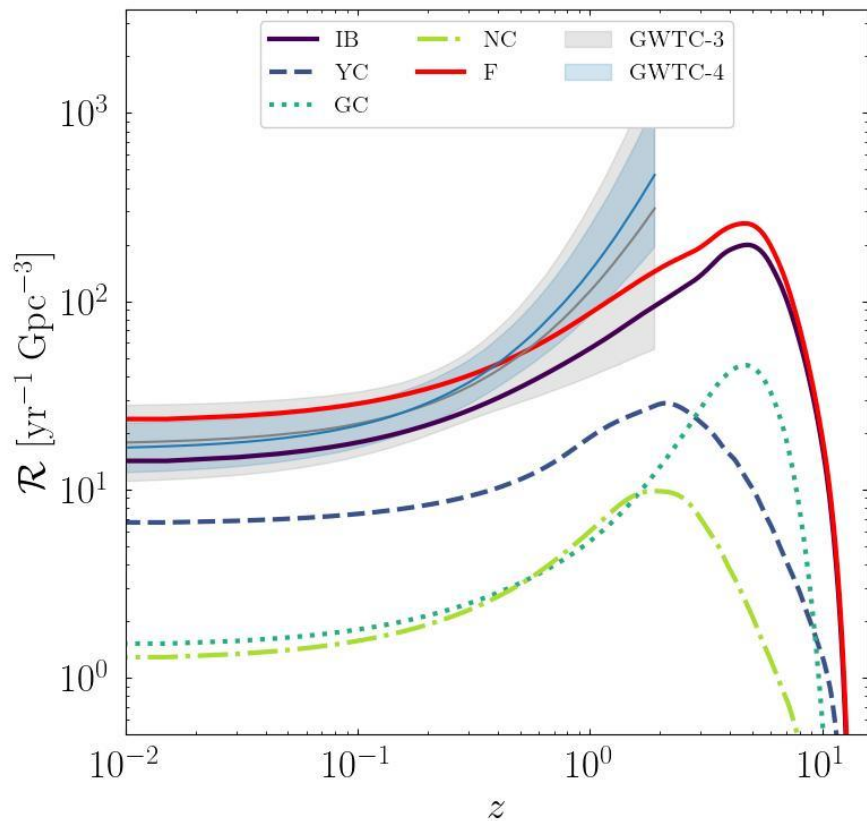
Rate of mergers with metallicity  $Z$  produced at  $z'$  that merge at  $z$

## Star Formation Rate and Metallicity evolution



$$\mathcal{R}_i(z) = \int_{Z_{\min}}^{Z_{\max}} \int_z^{z_{\max}} dZ dz' \frac{dt_{\text{lb}}(z')}{dz'} \psi_i(z') p(z', Z) \eta(Z) \dot{\mathcal{F}}(z', z, Z)$$

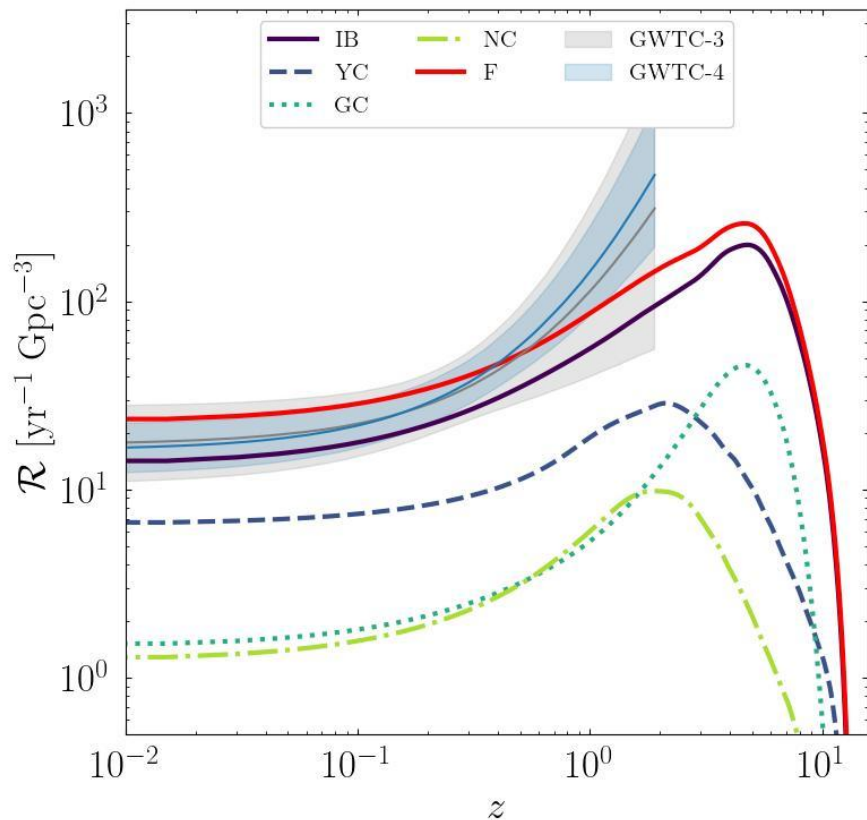
## Star Formation Rate and Metallicity evolution



$$\mathcal{R}_i(z) = \int_{Z_{\min}}^{Z_{\max}} \int_z^{z_{\max}} dZ dz' \frac{dt_{\text{lb}}(z')}{dz'} \psi_i(z') p(z', Z) \eta(Z) \dot{\mathcal{F}}(z', z, Z)$$

$$d\Gamma_i(z, Z) = \int_{z_i}^{z_{i+1}} \mathcal{R}_i(z', Z) \frac{dV(z')}{(1+z')} dz'$$

## Star Formation Rate and Metallicity evolution



$$\mathcal{R}_i(z) = \int_{Z_{\min}}^{Z_{\max}} \int_z^{z_{\max}} dZ dz' \frac{dt_{\text{lb}}(z')}{dz'} \psi_i(z') p(z', Z) \eta(Z) \dot{\mathcal{F}}(z', z, Z)$$

$$d\Gamma_i(z, Z) = \int_{z_i}^{z_{i+1}} \mathcal{R}_i(z', Z) \frac{dV(z')}{(1+z')} dz'$$

### Fiducial:

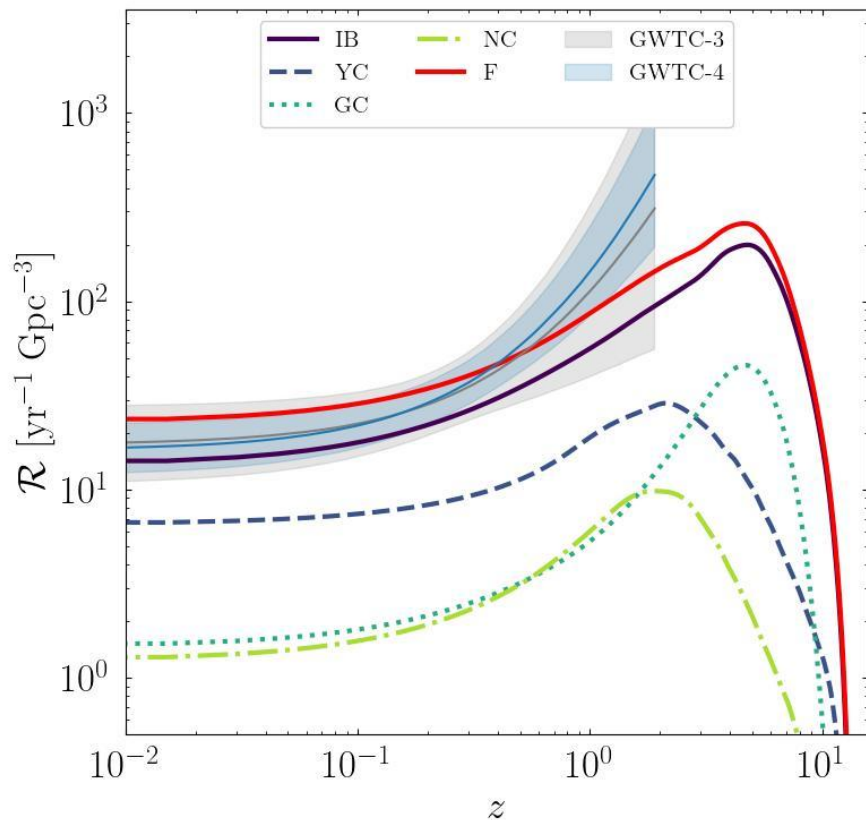
$$N_{\text{BBH}} = \Gamma T \sim 10^5 \text{ events } (T = 1 \text{ yr})$$

### BBH Origin:

~ 70% from the isolated channel

~ 30% from the dynamical channel

## Star Formation Rate and Metallicity evolution



$$\mathcal{R}_i(z) = \int_{Z_{\min}}^{Z_{\max}} \int_z^{z_{\max}} dZ dz' \frac{dt_{\text{lb}}(z')}{dz'} \psi_i(z') p(z', Z) \eta(Z) \dot{\mathcal{F}}(z', z, Z)$$

$$d\Gamma_i(z, Z) = \int_{z_i}^{z_{i+1}} \mathcal{R}_i(z', Z) \frac{dV(z')}{(1+z')} dz'$$

*This is currently done by*

***BPOPRate***

See [utils/BPOP\\_MERGER\\_RATE/BPOPRate\\_v2025.py](#)

## From simulations to mock sources

With *BPOPRate* you can both calculate the MRD and retrieve a catalogue of sources for given years of events  
In the main script, there are some parameters to initialise:

```
IDmod = 2           # Fraction of dynamical BHs from single/binary stars (must be equal to B-POP choice)
a = "a"            # Model name
name_file = "../"  # Where B-POP catalogue is stored
IBfrac = 0.4       # Fraction of isolated binaries
fysc_mw = 0.01     # Fraction of stars in bound YCs
f_NCoc = 1.0       # Scaling factor for NCs (test)
f_GCsc = 1.0       # Scaling factor for GCs (test)
Tobs = 10.0        # Observation time

sigma_Z = 0.2      # Metallicity dispersion (must be equal to B-POP choice)

maxz = 15          # Maximum redshift (must be equal to B-POP choice)

...
```

## From simulations to mock sources

With *BPOPRate* you can both calculate the MRD and retrieve a catalogue of sources for given years of events  
In the main script, there are some parameters to initialise:

```
...  
  
pre = "SEVN"  
aCE = ""  
IBonly=False  
  
...  
  
if(pre=="MOBSE"):  
    IBcorr = 0.285  
elif(pre=="SEVN" or pre=="SEVN_all"):  
    IBcorr = 0.185  
elif(pre=="IORIO"):  
    IBcorr = 0.255  
else:  
    print("please select SEVN or MOBSE and retry")  
    exit()  
  
...
```

## From simulations to mock sources

With *BPOPRate* you can both calculate the MRD and retrieve a catalogue of sources for given years of events  
In the main script, there are some parameters to initialise:

```
...  
  
fmix = -1  
if(IDmod < 5):  
    fmix = (1.0 * IDmod)/4.  
elif(IDmod == 5):  
    fmix = (1.0 * IDmod)/10.  
elif(IDmod < 0):  
    fmix = 0  
else:  
    print("Unknown type of model, check fmix")  
    exit()  
  
mstar = 1.0  
fbh = 0.0026  
fbin_is = 1.0  
fbin_yc = 0.6  
fbin_gc = 0.2  
fbin_nc = 0.2
```

## From simulations to mock sources

With *BPOPRate* you can both calculate the MRD and retrieve a catalogue of sources for given years of events  
Some pre-loaded models are available in the library [/utils/BPOP\\_LIBPY/lib\\_BPOPRate.py](#)

Example: model "a" for NC, GC, YC, IB

Star Formation Rate: ["mf17", "eb19", "mf17", "mf17"] (Madau & Fragos 2017, El-Badry et al 2019)

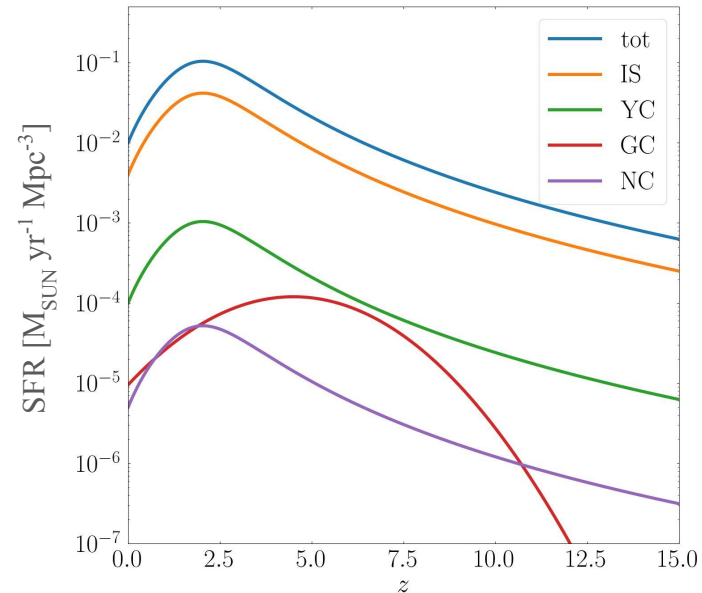
Metallicity distribution: ["bavera20", "elbadry19a", "bavera20", "bavera20"] (Bavera et al 2020)

Scaling for NC SFR: 3.E7 / 6.E10 (mass of MW NC and stellar mass)

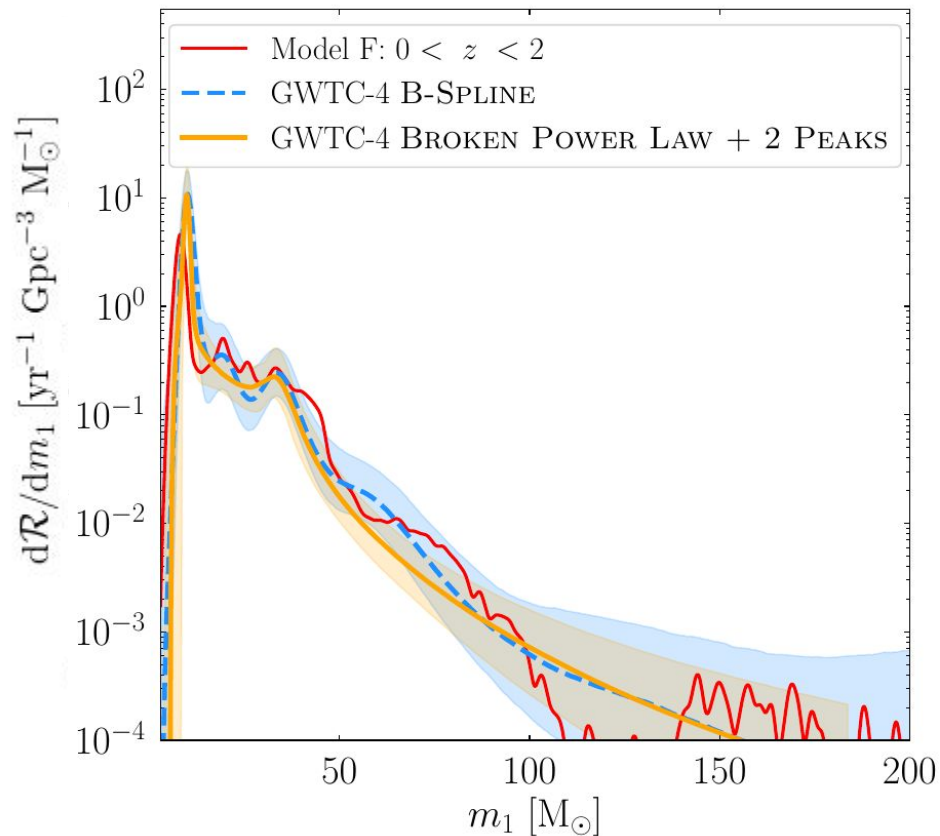
GC SFR: 1.2E-4 (from El-Badry et al 2019)

Mean Red: 4.5

Sigma Red: 2.0



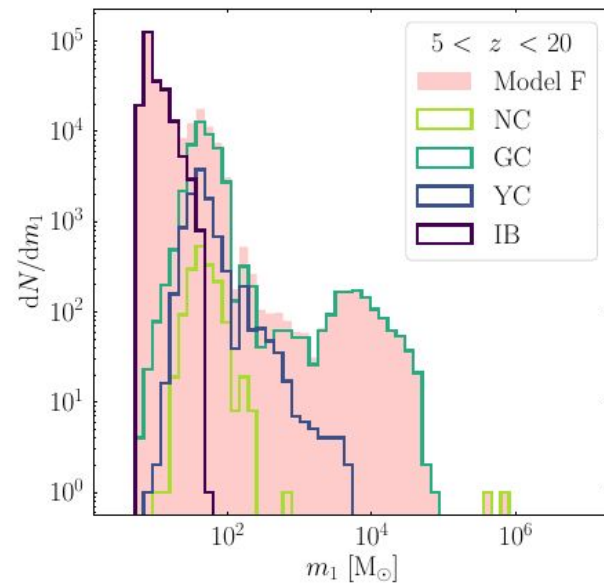
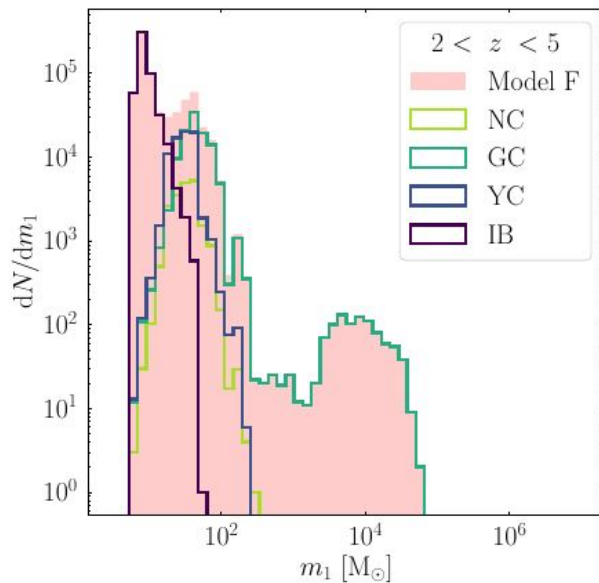
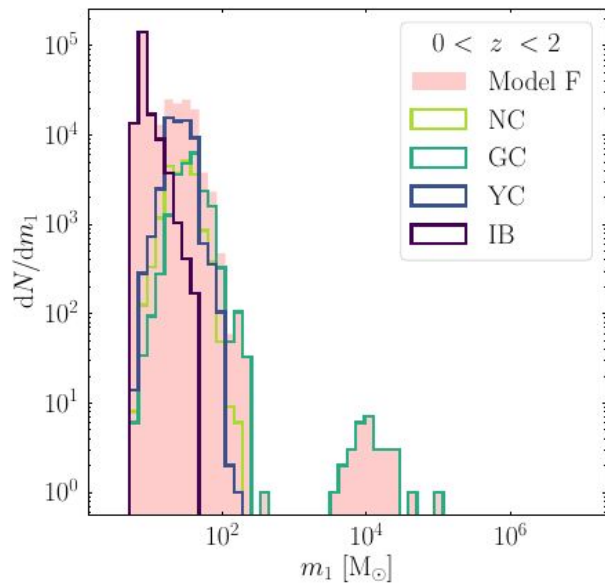
## Cosmic evolution of B-POP mergers: primary mass distribution



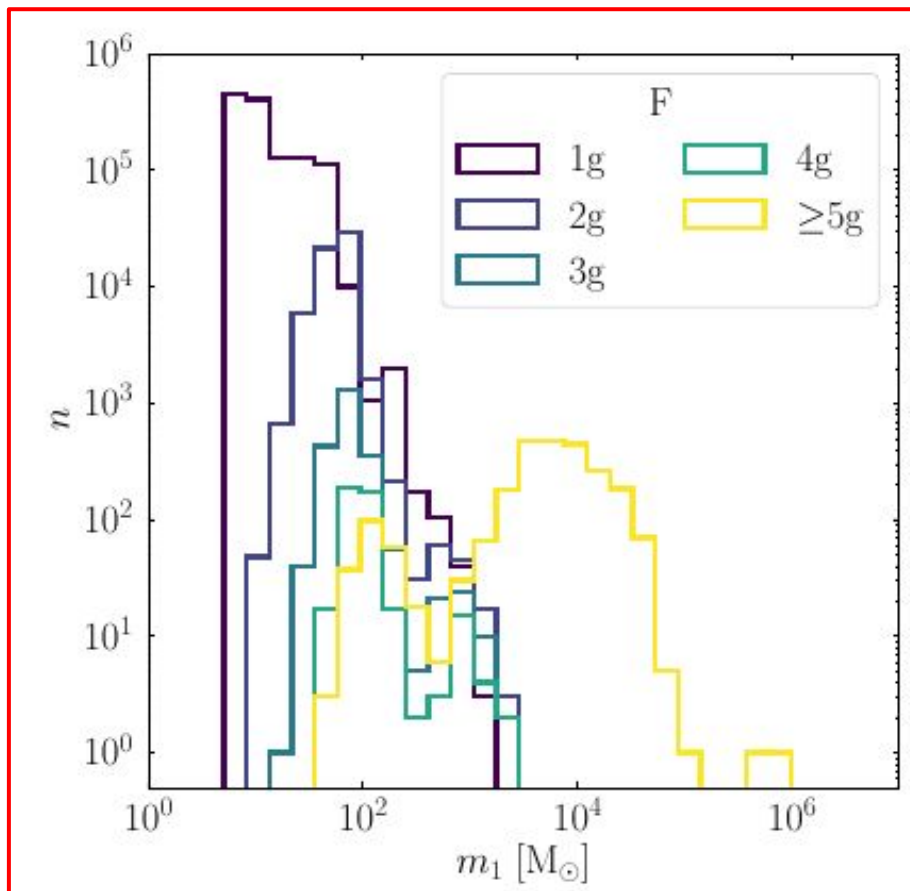
### Primary mass distribution

- Isolated binaries:
  - Dominate at  $m_1 < 15 M_{\text{SUN}}$
  - Peak  $\sim 8.6 M_{\text{SUN}}$
  - Median BBH mass  $\sim$  constant up to  $z \sim 8$
- Dynamical binaries
  - Dominate at  $m_1 > 15 M_{\text{SUN}}$
  - Multiple peaks 20, 25, 35  $M_{\text{SUN}}$
  - High-end tail out to 200  $M_{\text{SUN}}$  (and beyond..)
  - Median BBH mass steadily increases with  $z$

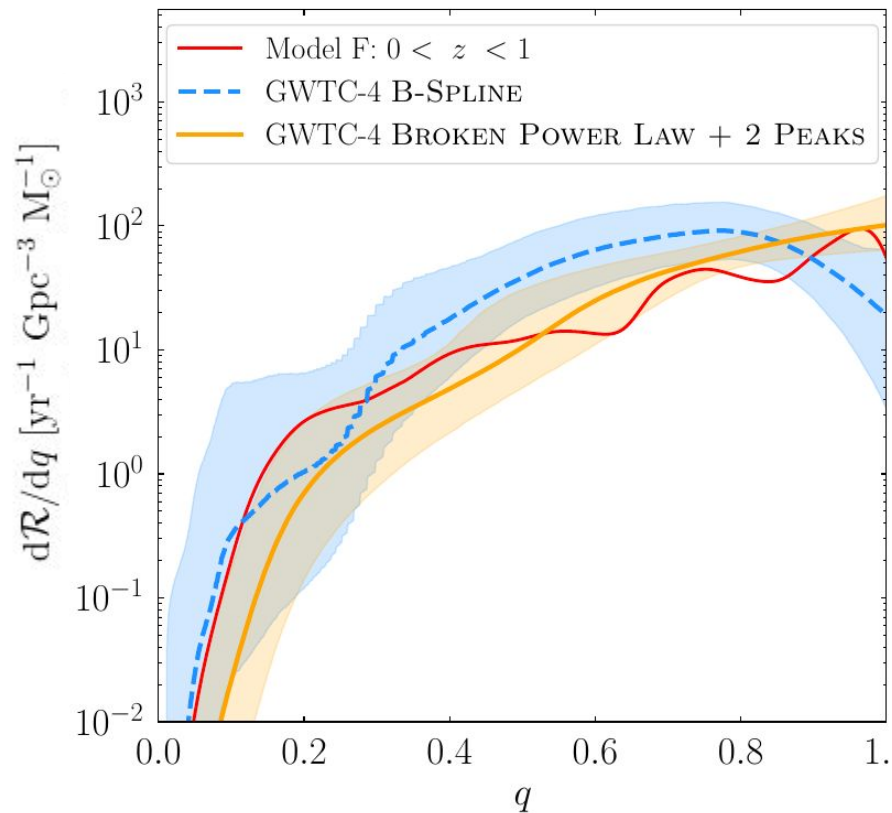
## Cosmic evolution of B-POP mergers: primary mass distribution



## Cosmic evolution of B-POP mergers: primary mass distribution



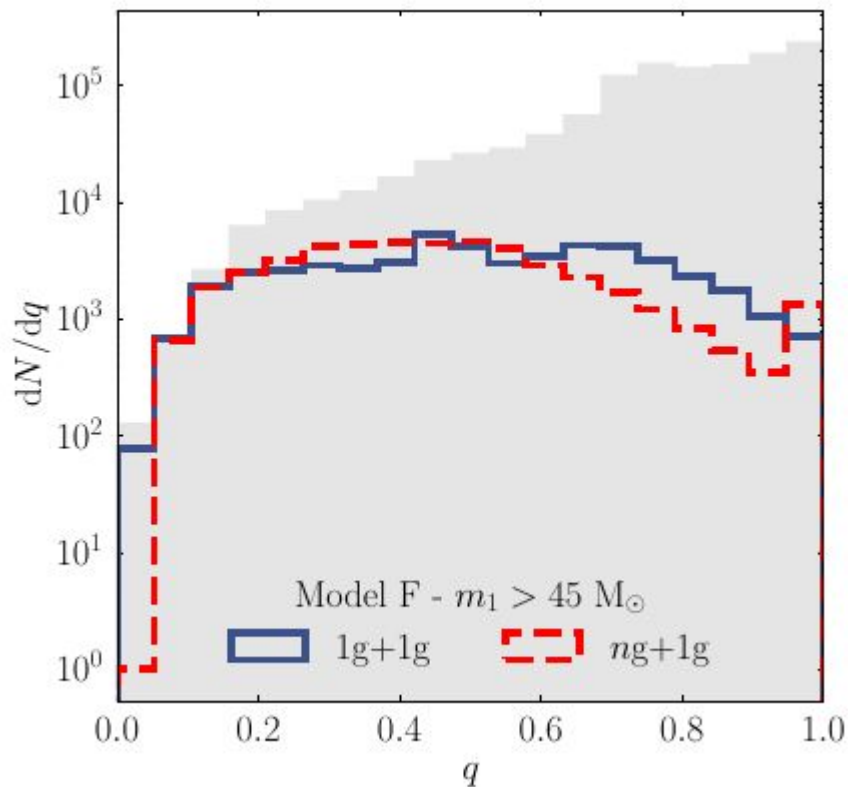
## Cosmic evolution of B-POP mergers: mass ratio



### Mass-ratio distribution

- Multiple peaks with cut-off at low  $q$
- Isolated binaries:
  - 83% of population with  $q > 0.6$
- Dynamical binaries:
  - 90% of population with  $q < 0.6$

## Cosmic evolution of B-POP mergers: mass ratio

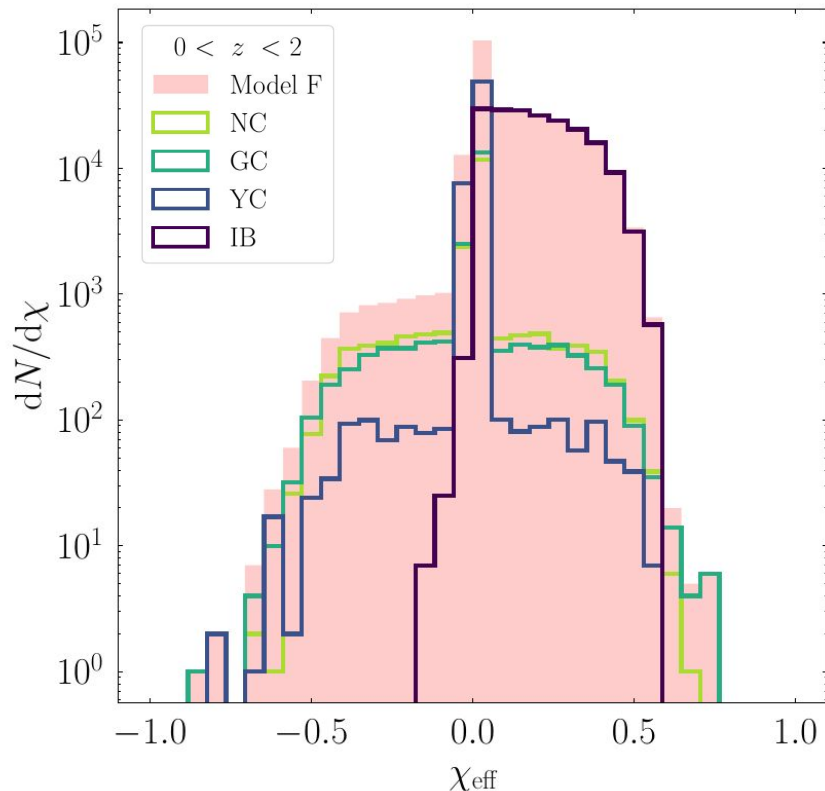


Mass-ratio distribution of massive BBHs ( $m_1 > 45 M_{\text{SUN}}$ )

Distribution  $\sim$  flat, dominated by dynamical mergers

- First generation mergers (1g+1g)
- High-generation mergers ( $ng + 1g$ )

## Cosmic evolution of B-POP mergers: spins



### Spins

#### Prescription:

- BHs from single stars  $\sim$  zero spin
- First-born BHs  $\sim$  zero spin
- Second-born BHs =  $[0,1]$  uniform
- BHs in the upper gap =  $[0,1]$  uniform

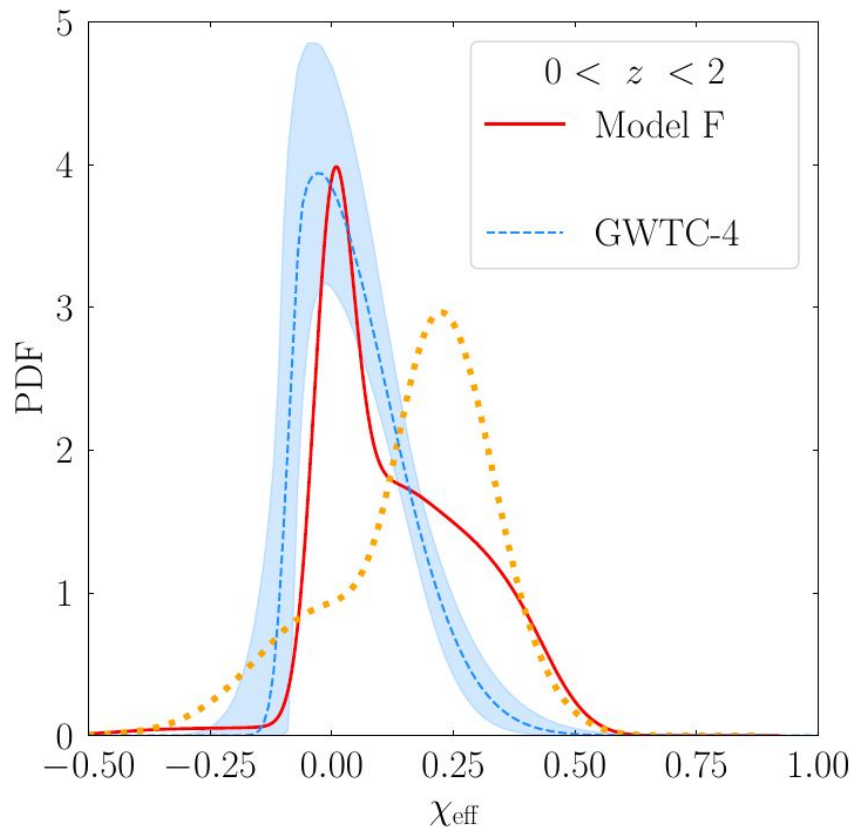
#### Isolated binaries

- Mildly aligned (Arca Sedda & Benacquista 2019)
- Dominate  $\chi_{\text{eff}} > 0$

#### Dynamical binaries

- Isotropic spin distribution
- Dominate  $\chi_{\text{eff}} < 0$

## Cosmic evolution of B-POP mergers: spins



### Spins

#### Prescription 1:

- BHs from single stars  $\sim$  zero spin
- First-born BHs  $\sim$  zero spin
- Second-born BHs =  $[0,1]$  uniform
- BHs in the upper gap =  $[0,1]$  uniform

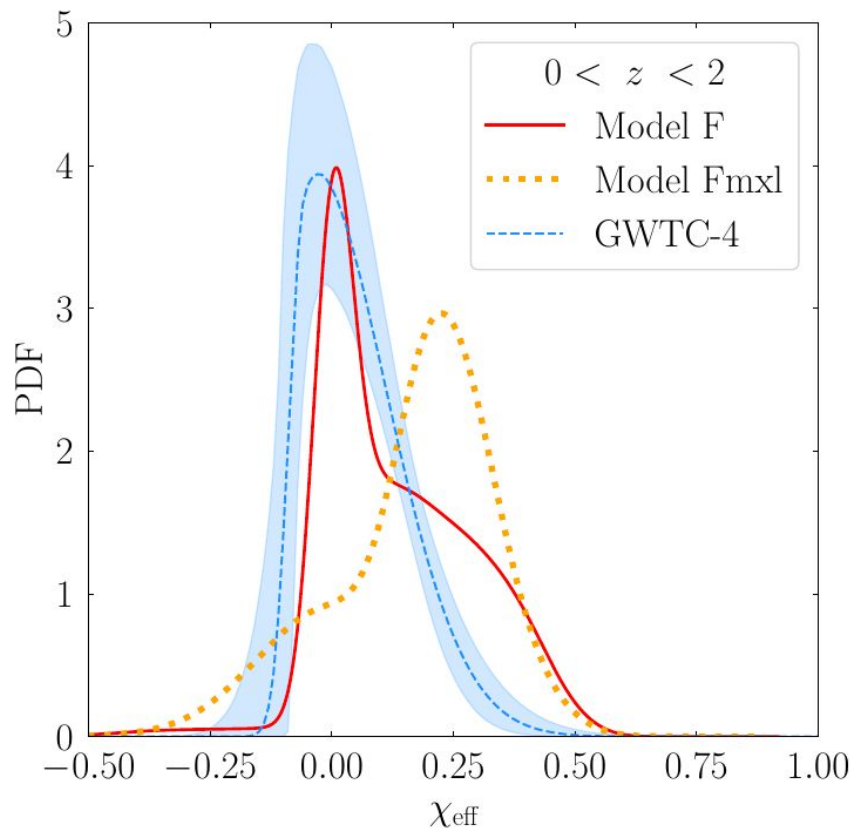
#### Isolated binaries

- Mildly aligned (Arca Sedda & Benacquista 2019)

#### Dynamical binaries

- Isotropic spin distribution

## Cosmic evolution of B-POP mergers: spins



### Spins

#### Prescription 1:

- BHs from single stars  $\sim$  zero spin
- First-born BHs  $\sim$  zero spin
- Second-born BHs = [0,1] uniform
- BHs in the upper gap = [0,1] uniform

#### Prescription 2:

- Maxwellian with dispersion = 0.2

#### Isolated binaries

- Mildly aligned (Arca Sedda & Benacquista 2019)

#### Dynamical binaries

- Isotropic spin distribution

## **Supplemental material**

## Cosmic evolution of B-POP mergers: models variations

- Common envelope parameter
- Fraction of BHs in clusters with progenitors in binary stars
- Treatment for dynamical BHs in the upper-mass gap
- Treatment for IMBH seeds from stellar collisions
- Treatment for natal spins
- Cosmic SFR for isolated and dynamical BBHs

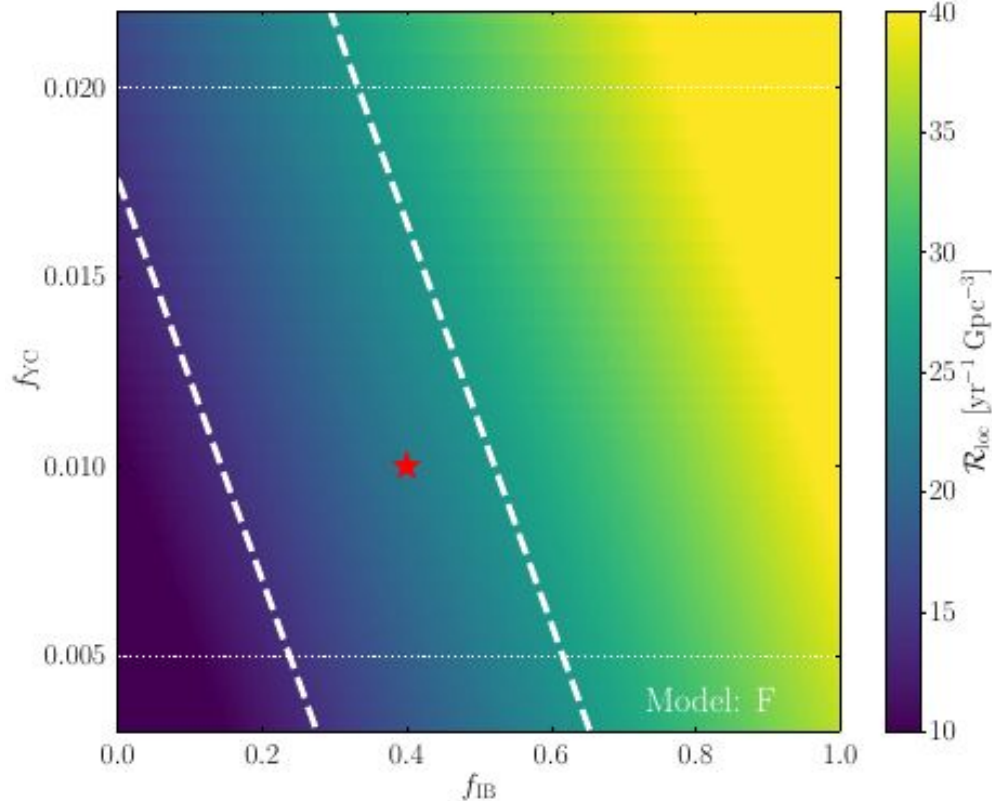
Model name	$\alpha_{CE}$	$f_{IB}$	$f_{YC}$	$f_{mix}$	Upper mass gap	IMBH seeds	Spin	$\psi_{IB}$	$\psi_{YC}$	$\psi_{NC}$	$\psi_{GC}$
<b>Fiducial</b>											
F	1	0.4	0.01	0.5	DC19	R24	B20	MF17	MF17	MF17	EB19
<b>Primordial binary fraction</b>											
Fb0	1	0.4	0.01	0	DC19	R24	B20	MF17	MF17	MF17	EB19
Fb1	1	0.4	0.01	1	DC19	R24	B20	MF17	MF17	MF17	EB19
<b>Common Envelope</b>											
F5	5	0.4	0.01	0.5	DC19	R24	B20	MF17	MF17	MF17	EB19
<b>Star formation history</b>											
Fe	1	0.4	0.01	0.5	DC19	R24	B20	MF17	MF17	MF17	M20
Fb	1	0.4	0.01	0.5	DC19	R24	B20	MF17	MF17	EB19	EB19
<b>BH natal spins</b>											
Fmxl	1	0.4	0.01	0.5	DC19	R24	LVK	MF17	MF17	MF17	EB19
<b>Seeds</b>											
Fgp	1	0.4	0.01	0.5	DC19	-	B20	MF17	MF17	MF17	EB19
Fst	1	0.4	0.01	0.5	-	-	B20	MF17	MF17	MF17	EB19

## Cosmic evolution of B-POP mergers: models variations

- Common envelope parameter
- Fraction of BHs in clusters with progenitors in binary stars
- Treatment for dynamical BHs in the upper-mass gap
- Treatment for IMBH seeds from stellar collisions
- Treatment for natal spins
- Cosmic SFR for isolated and dynamical BBHs

Model	$\mathcal{R}_{\text{loc}} (\text{yr}^{-1} \text{Gpc}^{-3})$			$p_{\text{IB}}$	$p_{\text{YC}}$	$p_{\text{GC}}$	$p_{\text{NC}}$
name	lg	$n_{\text{g}}$	IMBH				
F	22.13	0.95	0.0082	0.726	0.109	0.134	0.032
Fb0	22.0	1.01	0.00089	0.728	0.107	0.135	0.030
Fb1	23.1	0.88	0.021	0.717	0.118	0.132	0.033
F5	17.5	0.06	0.013	0.376	0.248	0.304	0.072
Fe	24.1	0.063	0.016	0.685	0.103	0.182	0.030
Fb	21.3	0.039	0.0081	0.718	0.108	0.132	0.042
Fmxl	22.4	0.005	0.0055	0.726	0.111	0.129	0.034
Fgp	21.9	0.043	0.0073	0.730	0.101	0.138	0.032
Fst	21.9	0.045	0.0081	0.732	0.099	0.137	0.031

## Cosmic evolution of B-POP mergers: isolated binary fraction and bound young clusters in the Universe



The MRD

$$\mathcal{R}_i(z) = \int_{Z_{\min}}^{Z_{\max}} \int_z^{z_{\max}} dZ dz' \frac{dt_{1b}(z')}{dz'} \psi_i(z') p(z', Z) \eta(Z) \dot{\mathcal{F}}(z', z, Z)$$

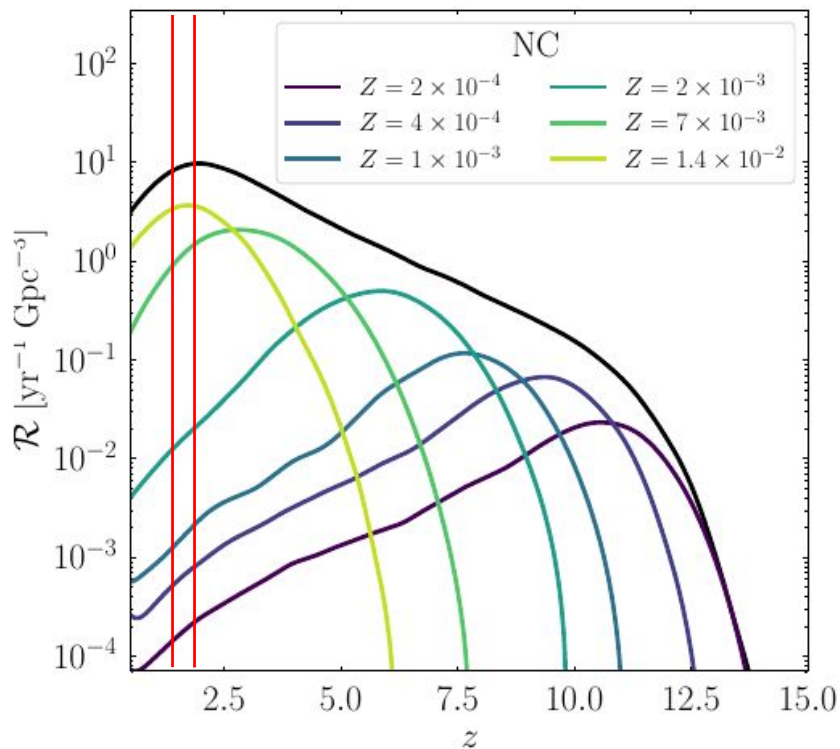
Is given by the sum of rate from different channels

Each contribution scales linearly with

- binary fraction in galactic fields
- fraction of stars born in bound young clusters

LVK can help assessing the impact of these quantities

## Creating the catalogue



### Merger Rate Density

$$\mathcal{R}_i(z) = \int_{Z_{\min}}^{Z_{\max}} \int_z^{z_{\max}} dZ dz' \frac{dt_{\text{lb}}(z')}{dz'} \psi_i(z') p(z', Z) \eta(Z) \dot{\mathcal{F}}(z', z, Z)$$

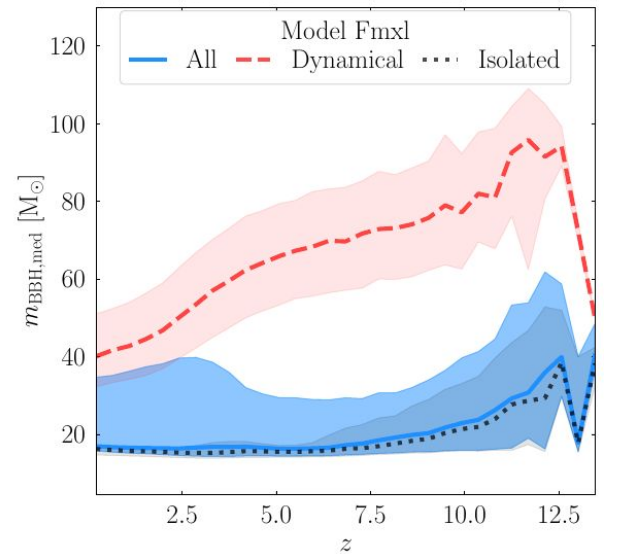
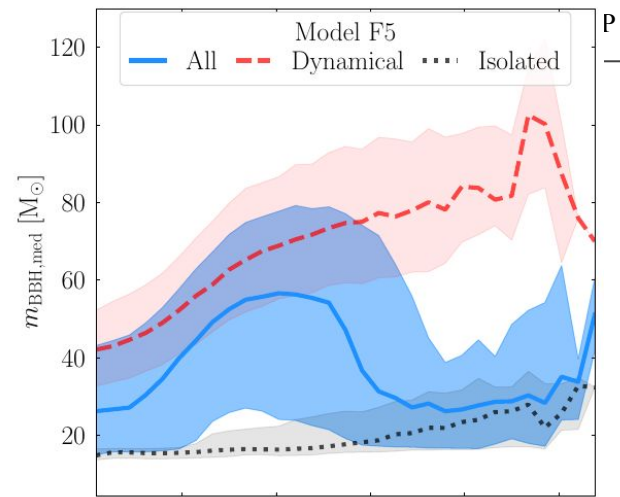
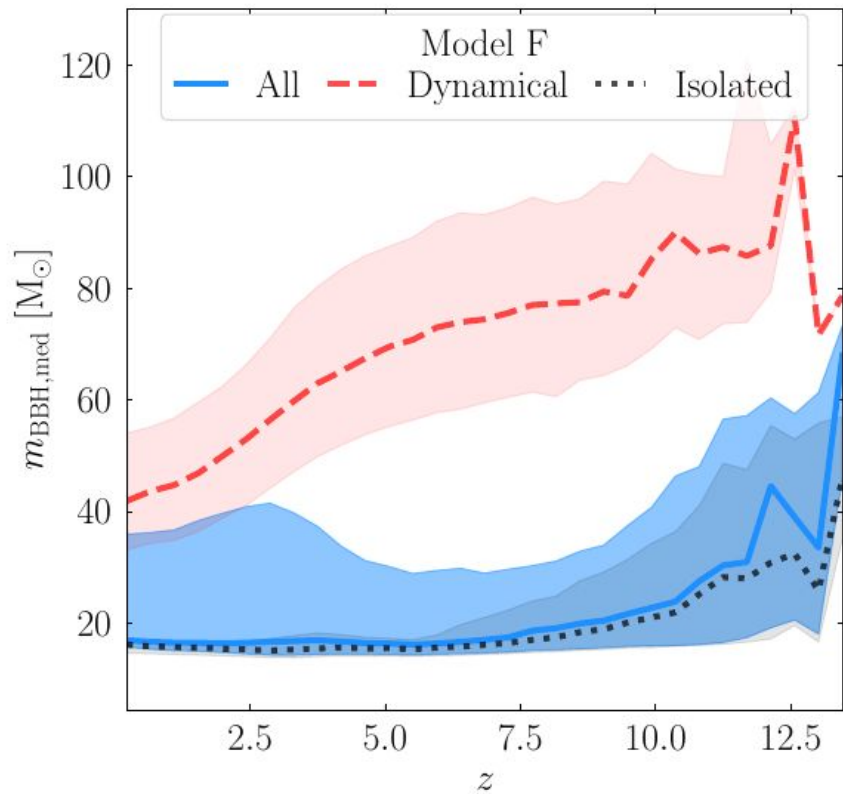
### Events rate

$$d\Gamma_i(z, Z) = \int_{z_i}^{z_{i+1}} \mathcal{R}_i(z', Z) \frac{dV(z')}{(1+z') dz'} dz'$$

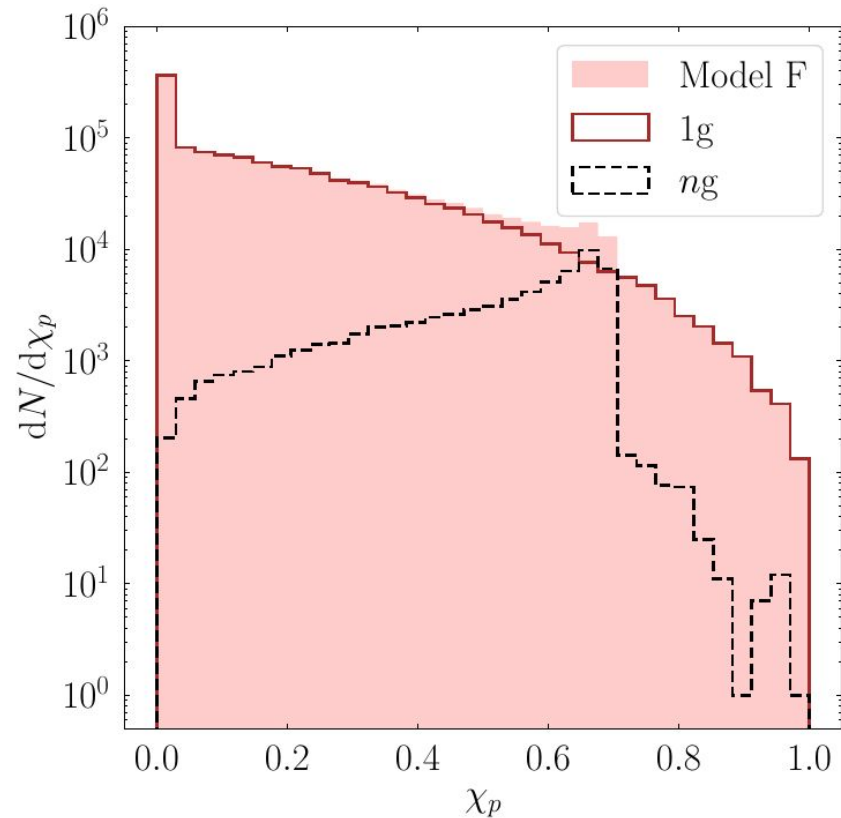
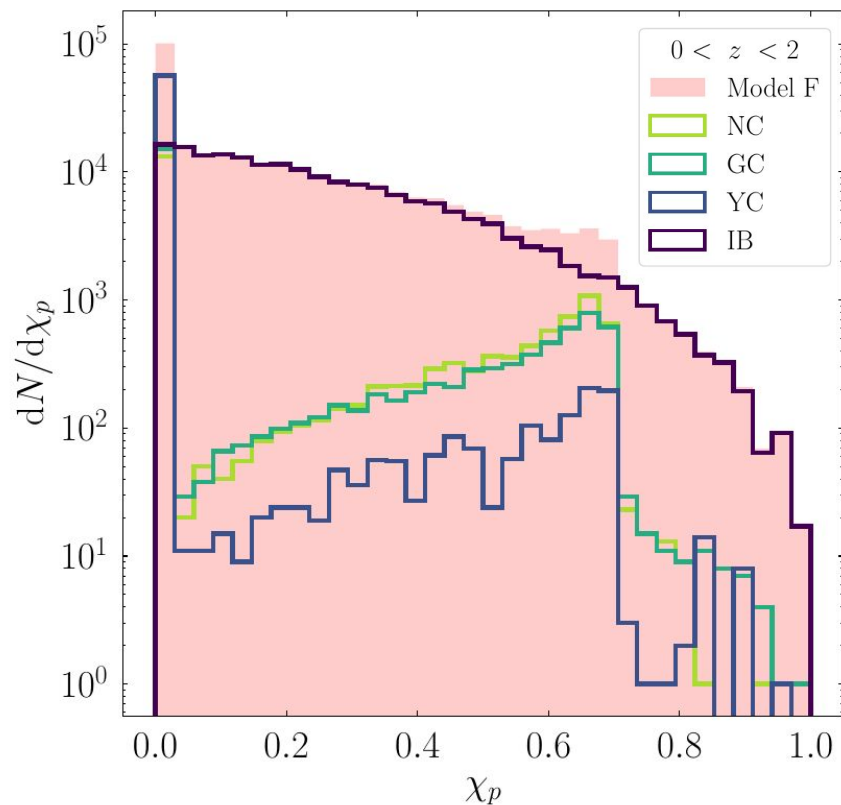
### Number of events in a time T

$$N_{\text{gw},i}(z, Z) = d\Gamma_i(z, Z) T$$

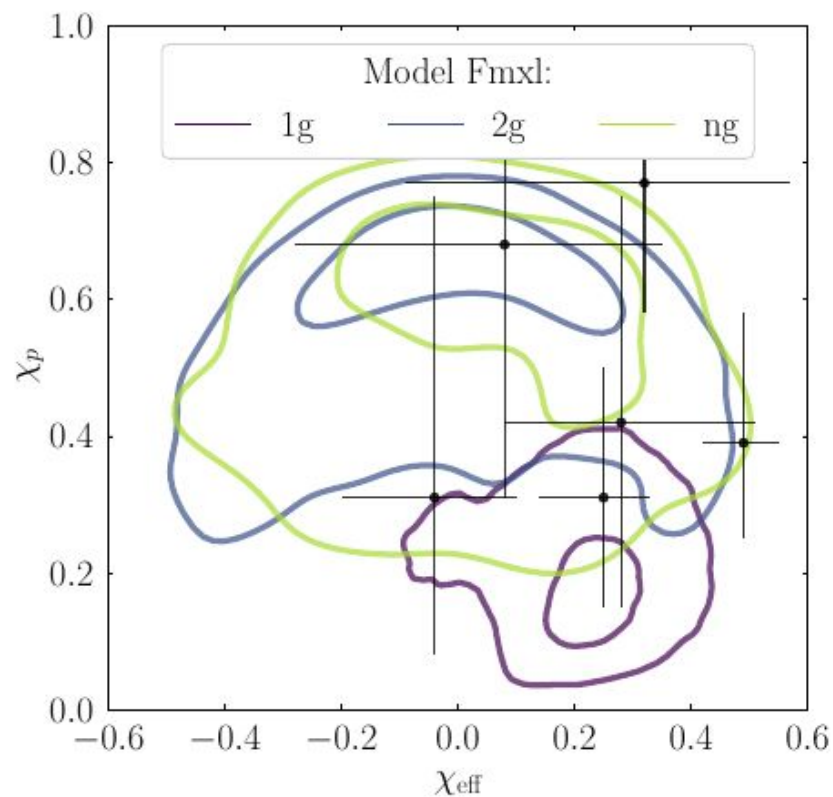
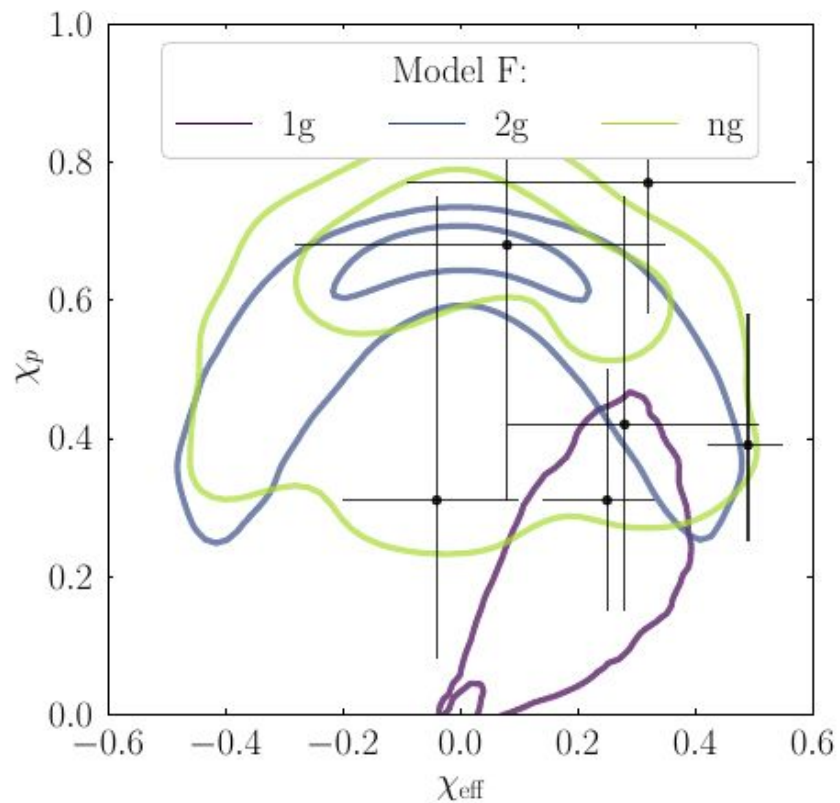
## Cosmic evolution of B-POP mergers: does the mass evolve with redshift?



## Spin precession parameter



## Spins



## Cosmic evolution of B-POP mergers: combined parameters

**Fiducial**

Model F				
	$q < 0.6$		$q > 0.6$	
	Dyn	Iso	Dyn	Iso
$\chi_{\text{eff}} < 0$	0.998	0.002	0.962	0.038
$\chi_{\text{eff}} > 0$	0.757	0.243	0.045	0.955

## Cosmic evolution of B-POP mergers: combined parameters

<b>Model F</b>					
		$q < 0.6$		$q > 0.6$	
<b>Fiducial</b>		Dyn	Iso	Dyn	Iso
$\chi_{\text{eff}} < 0$		0.998	0.002	0.962	0.038
$\chi_{\text{eff}} > 0$		0.757	0.243	0.045	0.955
<b>Model Fmxl</b>					
		$q < 0.6$		$q > 0.6$	
<b>Maxwellian natal spins</b>					
$\chi_{\text{eff}} < 0$		1	0	0.999	0.001
$\chi_{\text{eff}} > 0$		0.851	0.149	0.148	0.852

## Cosmic evolution of B-POP mergers: combined parameters

<b>Model F</b>					
		$q < 0.6$		$q > 0.6$	
		Dyn	Iso	Dyn	Iso
<b>Fiducial</b>	$\chi_{\text{eff}} < 0$	0.998	0.002	0.962	0.038
	$\chi_{\text{eff}} > 0$	0.757	0.243	0.045	0.955
<b>Model Fmxi</b>					
		$q < 0.6$		$q > 0.6$	
		Dyn	Iso	Dyn	Iso
<b>Maxwellian natal spins</b>	$\chi_{\text{eff}} < 0$	1	0	0.999	0.001
	$\chi_{\text{eff}} > 0$	0.851	0.149	0.148	0.852