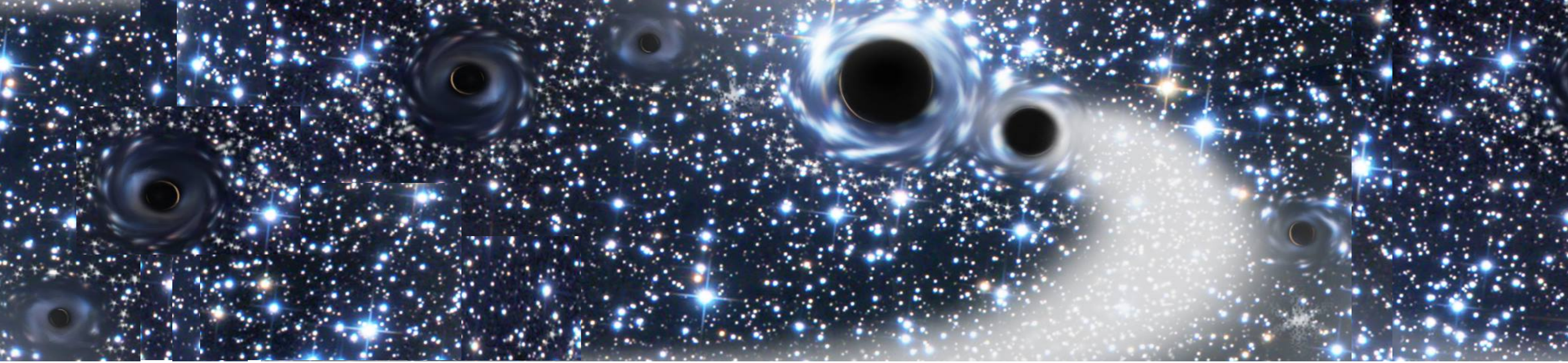


Population synthesis of BBH mergers with B-POP …

Manuel Arca Sedda

2019MNRAS.482.2991A
2020ApJ...894..133A
2021arXiv210912119A

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

UNIVERSITÀ DEGLI STUDI DI PADOVA

Niels Bohr
Dynamics Meeting

02 - 06 - 2022

MARIE CURIE ACTIONS

Marie Curie Fellow @ University of Padova

Rainer Spurzem, Mirek Giersz, Albrecht Kamlah, Agostino Levesque, Thorsten Naab, Francesco Rizzuto, Mario Spera, Matthew Benacquista, Bence Kocsis, Smadar Naoz, Nicola Giacobbo, Tuan Do, Alessia Gualandris, Nadine Neumayer, Roberto Capuzzo-Dolcetta, Abbas Askar, Gongjie Li, Pau Amaro-Seoane, Xian Chen, Alberto Sesana, Matteo Bonetti, Josè Francisco Nuno, Juan Garcia-Bellido, …

Population synthesis of BBH mergers with B-POP …

… or how to make a (allegedly) good carbonara

… or how to make a (allegedly) good carbonara









… or how to make a (allegedly) good carbonara

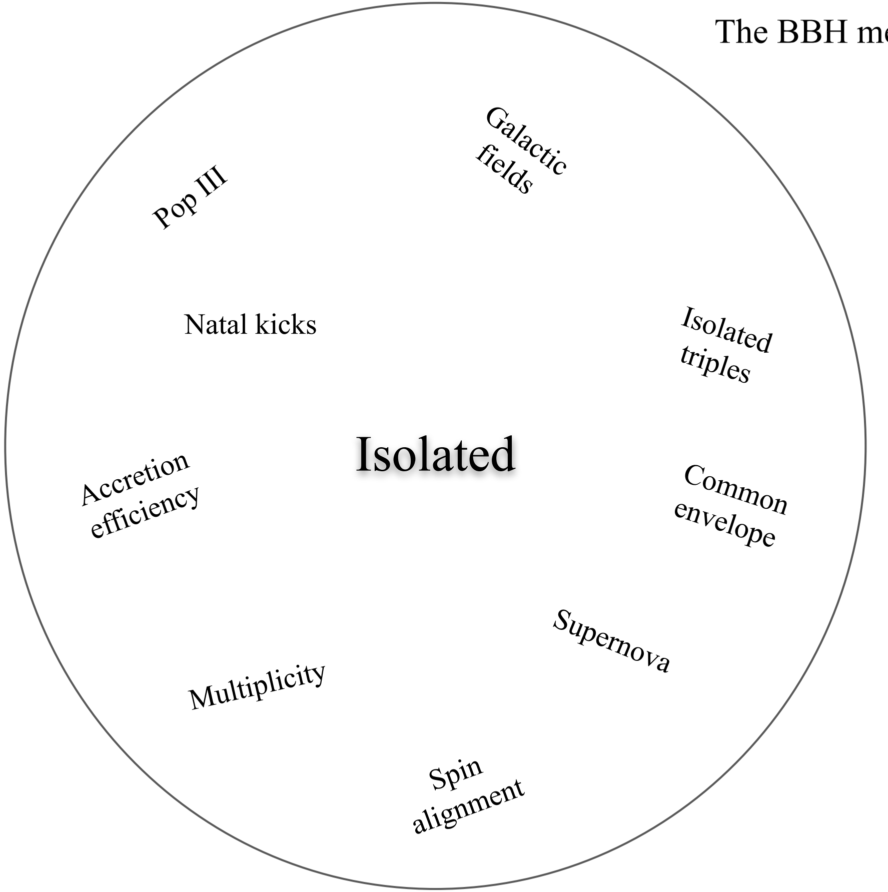


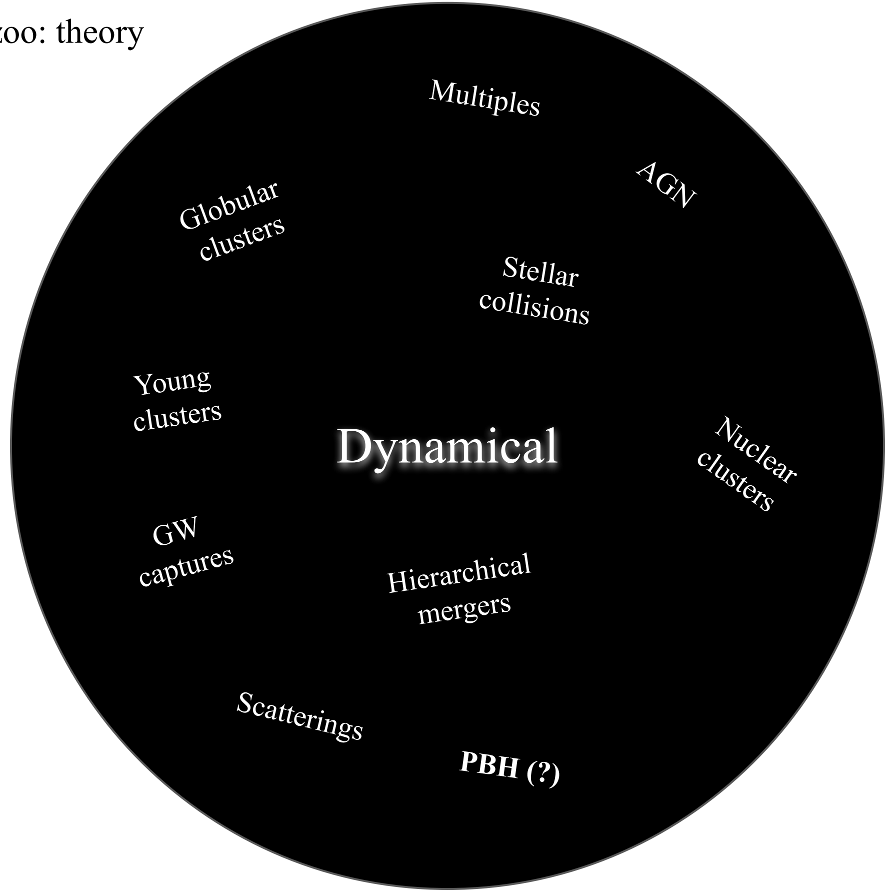




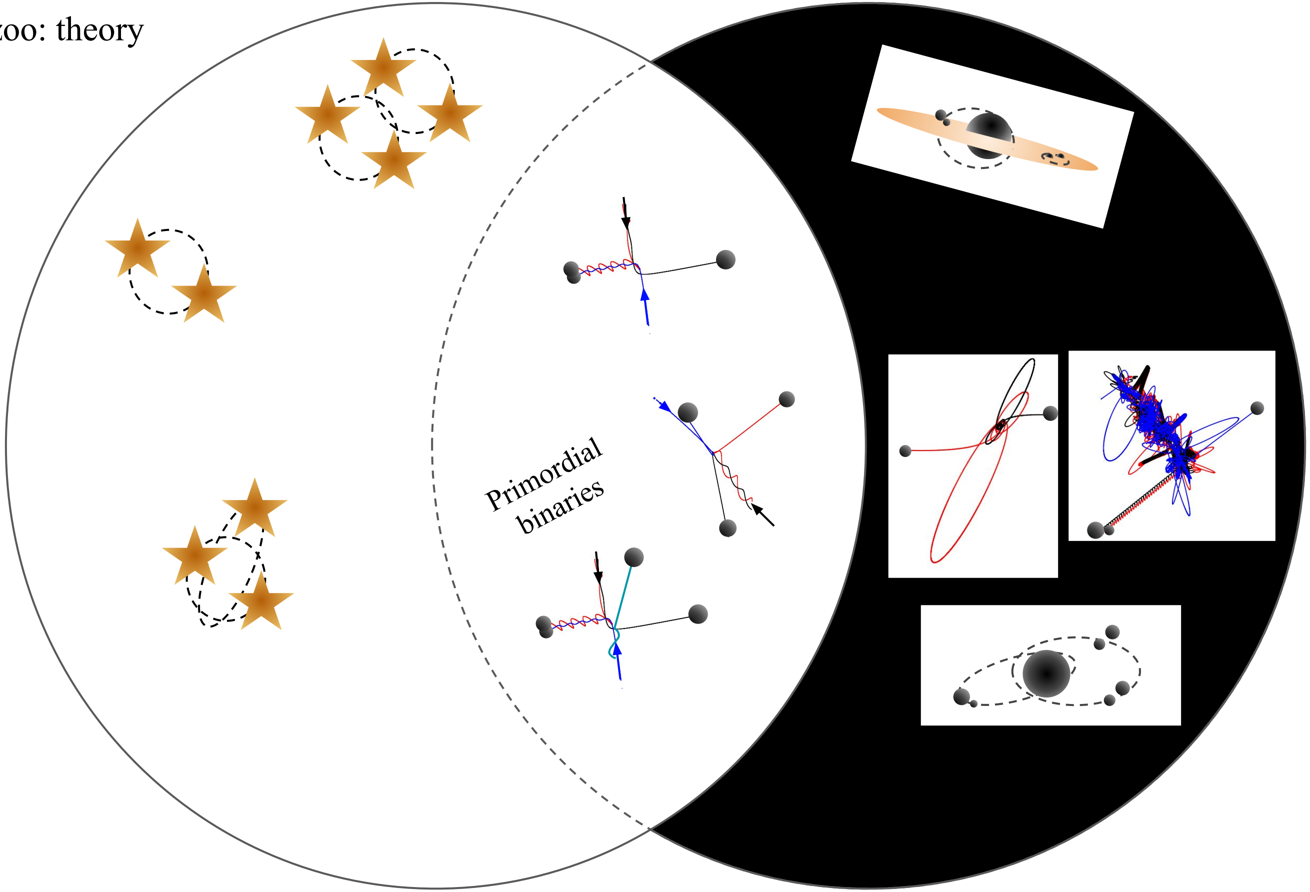


The BBH mergers zoo: theory





The BBH mergers zoo: theory



The BBH mergers zoo: detector perspective

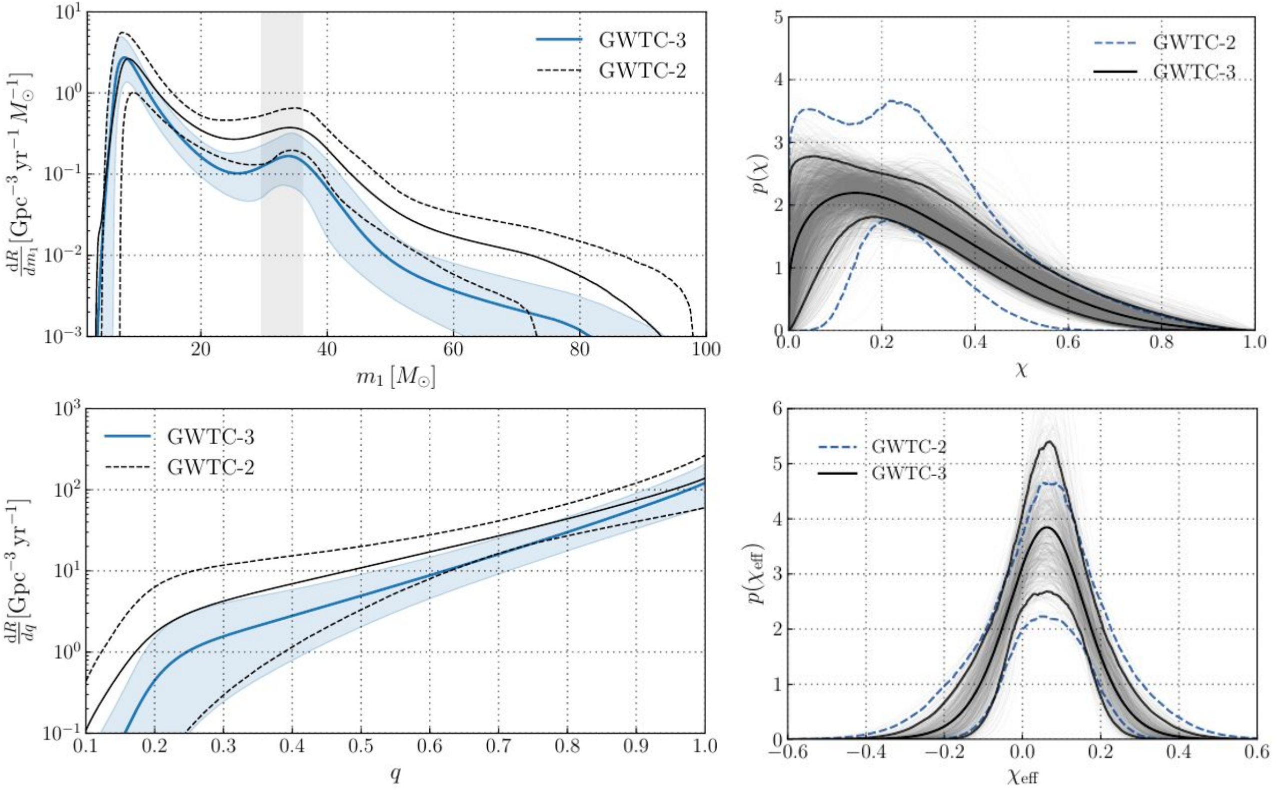
In O1,2,3 LVC identified ~70 BBH mergers:

★ Primary mass distribution
- substructured
- decreasing beyond $50M_{SUN}$

★ Mass ratio
- power-law with slope ~1.1(+1.7-1.3)

★ Spin amplitude
- clustered < 0.4
- correlate with the mass ratio

★ Effective spin parameter
- centered ~ 0.06(+0.04−0.05)
- (slightly) misaligned

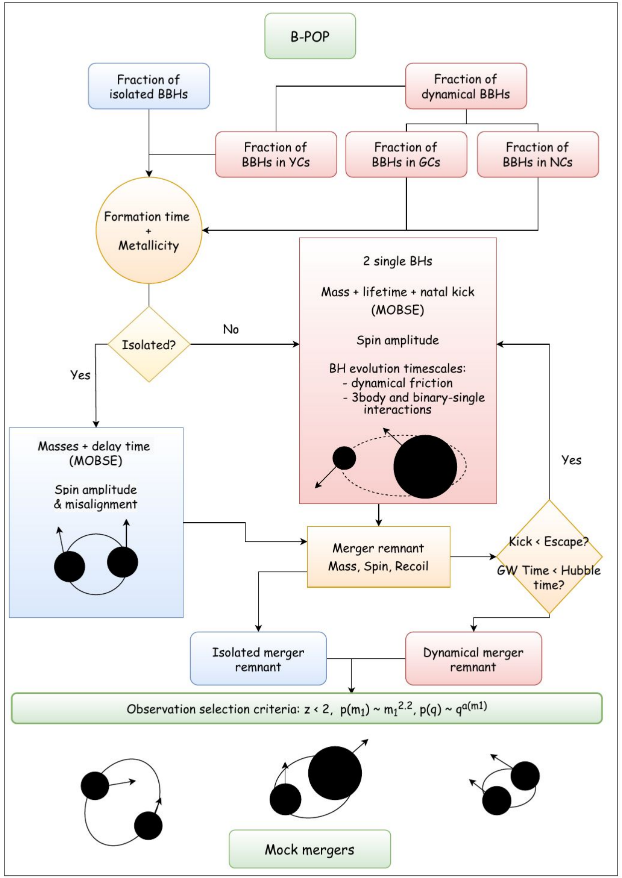


What is B-POP?

★ Population synthesis tool for mixed population of isolated and dynamical binaries (Arca Sedda and Benacquista 2019, Arca Sedda et al 2020, Arca Sedda et al 2021)

★ Main ingredients:

- Two general scenarios: isolated and dynamical (for YCs, GCs, and NCs)
- Metallicity distribution (SDSS + metallicity-redshift dependency)
- Star Formation (Madau & Fragos 2017, Katz & Ricotti 2013)
- Single and binary stars from MOBSE (Giacobbo & Mapelli 2018)
- Dynamical merger model (mass segregation, 3body scattering, binary-single)
- Merger remnant properties (Jimenez-Forteza et al 2017)
- GW recoil kicks (Campanelli et al 2007, Lousto et al 2012, Lousto & Zlochower 2017)
- Hierarchical mergers
- Observational selection criteria based on primary mass and mass ratio



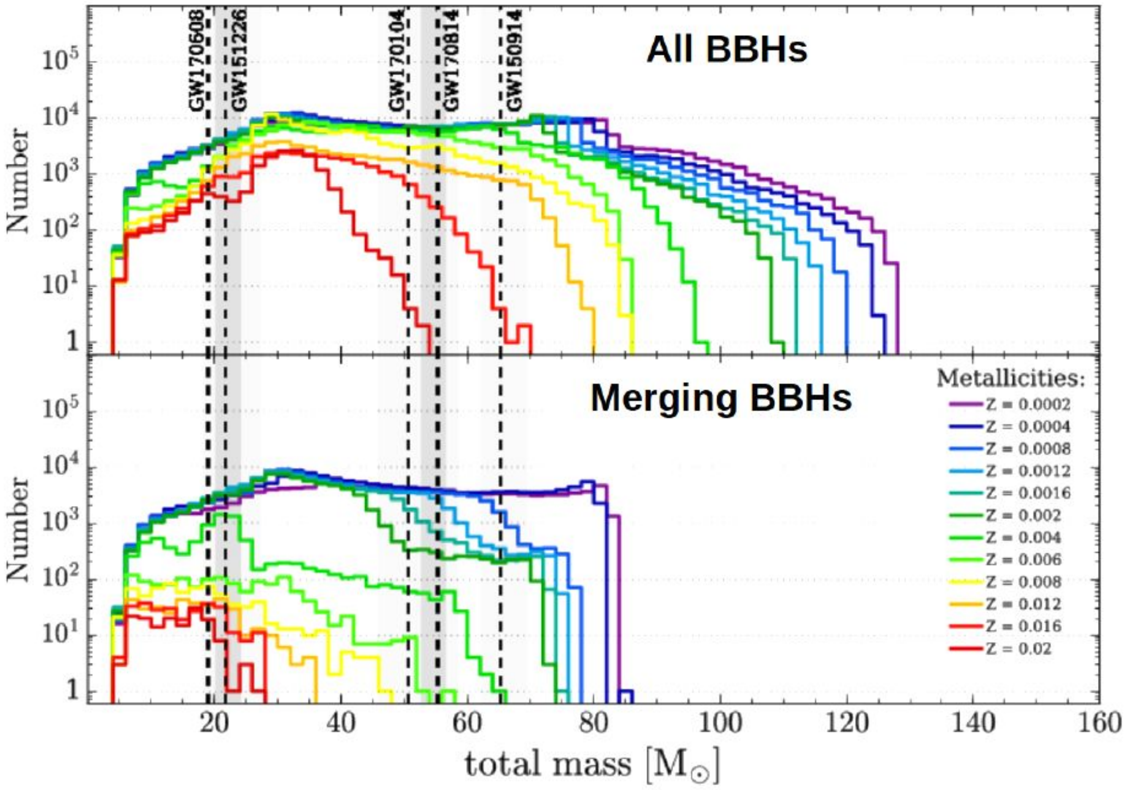
Example 1: isolated BBH mergers

Selection probability

Isolated binaries are a fraction f_{ISO} of the pop.

Stellar evolution: MOBSE CC15α1

Database: 10^7 BBHs in 12 Met. values



Example 1: isolated BBH mergers

Times & Metallicity

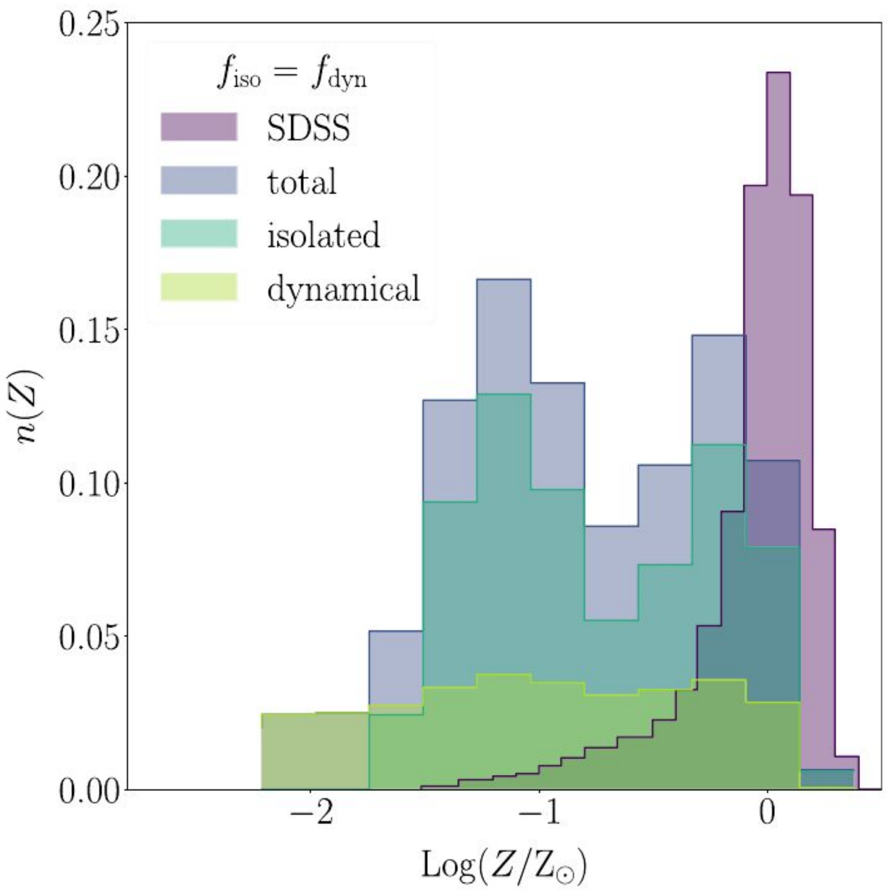
Formation: SFR Madau & Fragos(2017)

Metallicity: SDSS (Gallazzi et al 2006)

Redshift dependent shift (RDS):

Lower Z - higher merger probability: $P(Z) \sim Z^{1.5}$

$$\mathrm{Log}\left(\delta Z/\mathrm{Z}_{\odot}\right) = -0.074 z^{\alpha z}$$



Example 1: isolated BBH mergers

Spin amplitude

Plenty of choices:

Gaussian Large(Small): $x_{mea} = 0.5(0.2)$

Maxwellian: $\sigma_x = 0.2$

→ LVK (?)

Fueller and Ma 2019, FM19: $x = 0.01$ → Isolated Stellar Evolution

Mixed: FM19+MXL, FM19+GSS

In Arca Sedda and Benacquista (2019)
Amaro-Seoane and Chen (2016), Belczynski et al (2017)

Example 1: isolated BBH mergers

Spin misalignment

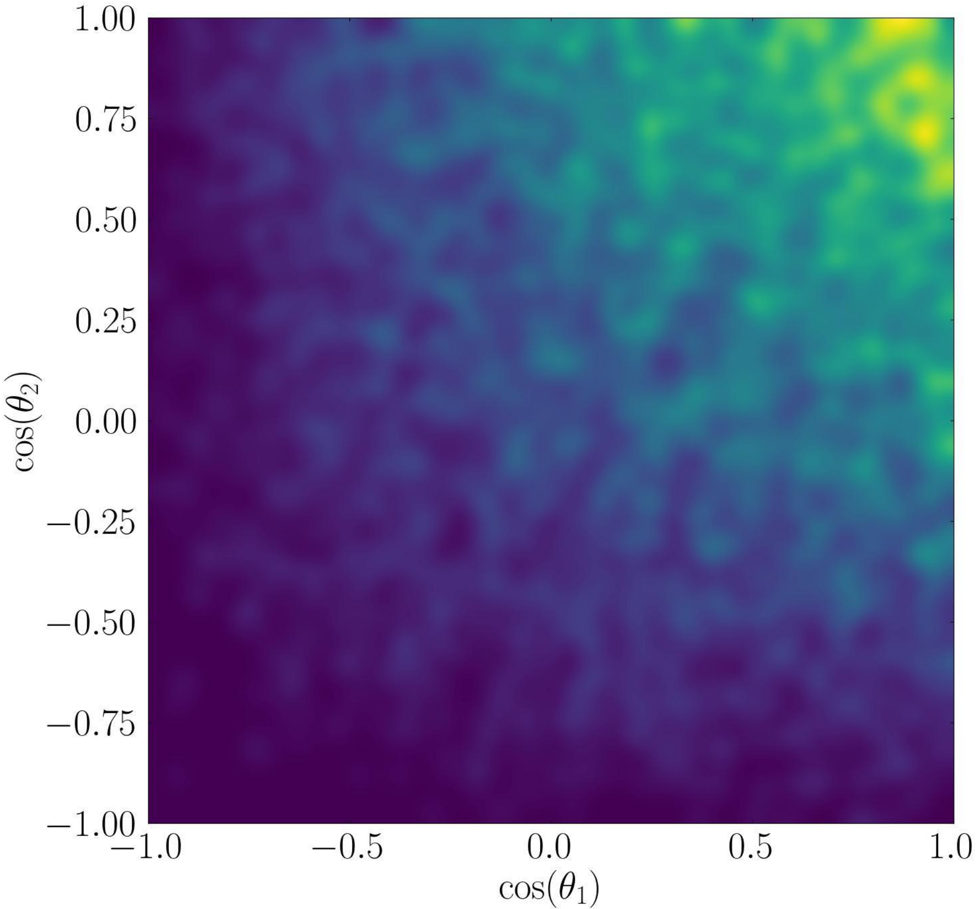
Spin alignment
(θ spin-angular momentum angle):

$$P_\theta = [(\cos\theta + 1)/2]^{n_\theta+1}$$

$n_\theta = 8$ implies:

- 20% BBHs have $\Delta\theta/\theta < 5\%$

- 55% BBHs have $\Delta\theta/\theta < 20\%$



Example 1: isolated BBH mergers

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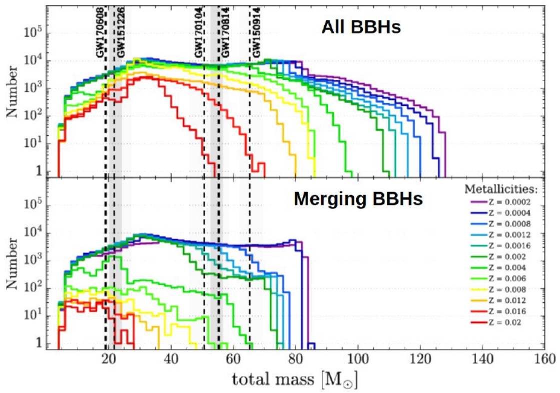
Database: 10Mio BBHs in 12 Met. values



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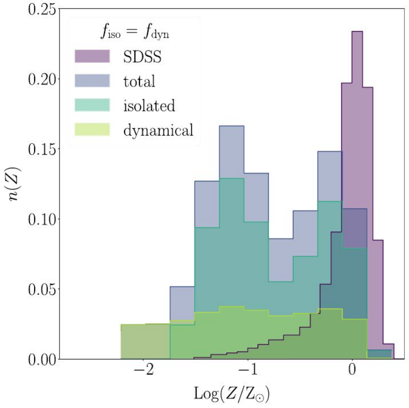
Lower Z - higher merger probability: P(Z) ~ $Z^{1.5}$



Spin amplitude and misalignment

Spin amplitude: plenty of choices:

Gaussian, GSSH(L): $x_{mea} = 0.5(0.2)$

Maxwellian, MXL: $\sigma_x = 0.2$

Fueller and Ma 2019, FM19: $x = 0.01$

Mixed (FM19+MXL)
(FM19+GSS)

Spin alignment
(θ spin-angular momentum angle):

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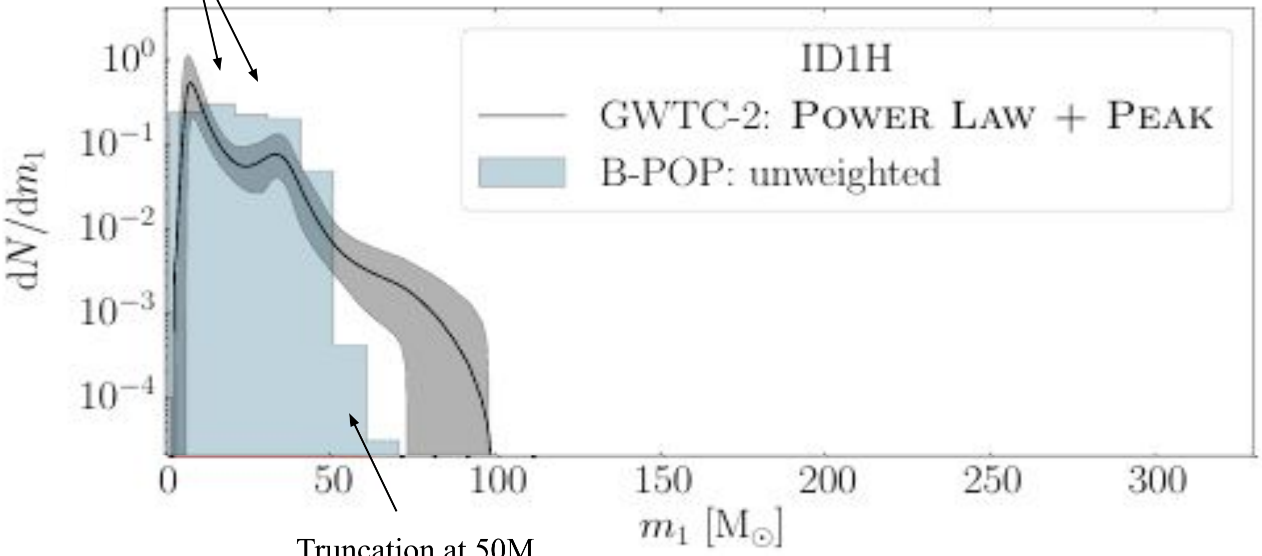
Example 1: isolated BBH mergers

Complex structure



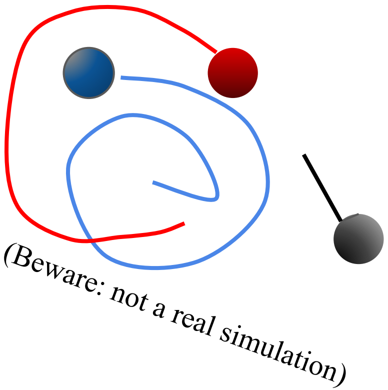
Truncation at $50M_{SUN}$
metallicity-redshift + stellar evolution

Example 2: dynamical BBH mergers

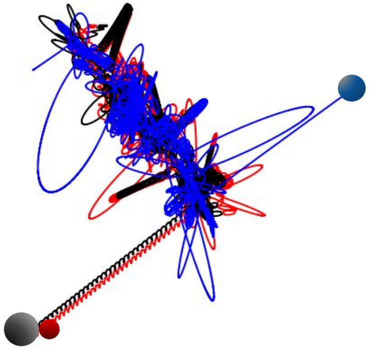
Dynamics in B-POP

t_{FOR} $+t_{BIR}$ $+t_{DF}$ $+\min(t_{3b}, t_{bs})$ $+t_{2\text{-}1}$ $+t_{GW,GW3}$

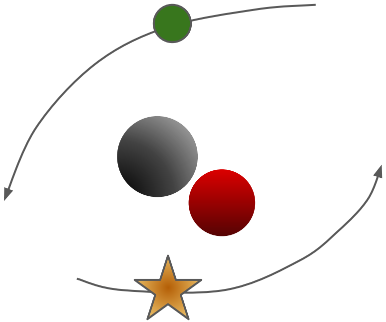
Step 0:
Stellar progenitors form according to the adopted SFR (formation time t_{FOR}) and turn into BHs (birth time t_{BIR}).



Step 1:
BHs reach the cluster centre in a Dynamical Friction time (t_{DF}, Binney and Tremaine 2008) and start interacting



Step 2:
A hard BBH forms over a 3body (Lee 1995) or binary-single capture (Miller and Lauburg 2009).

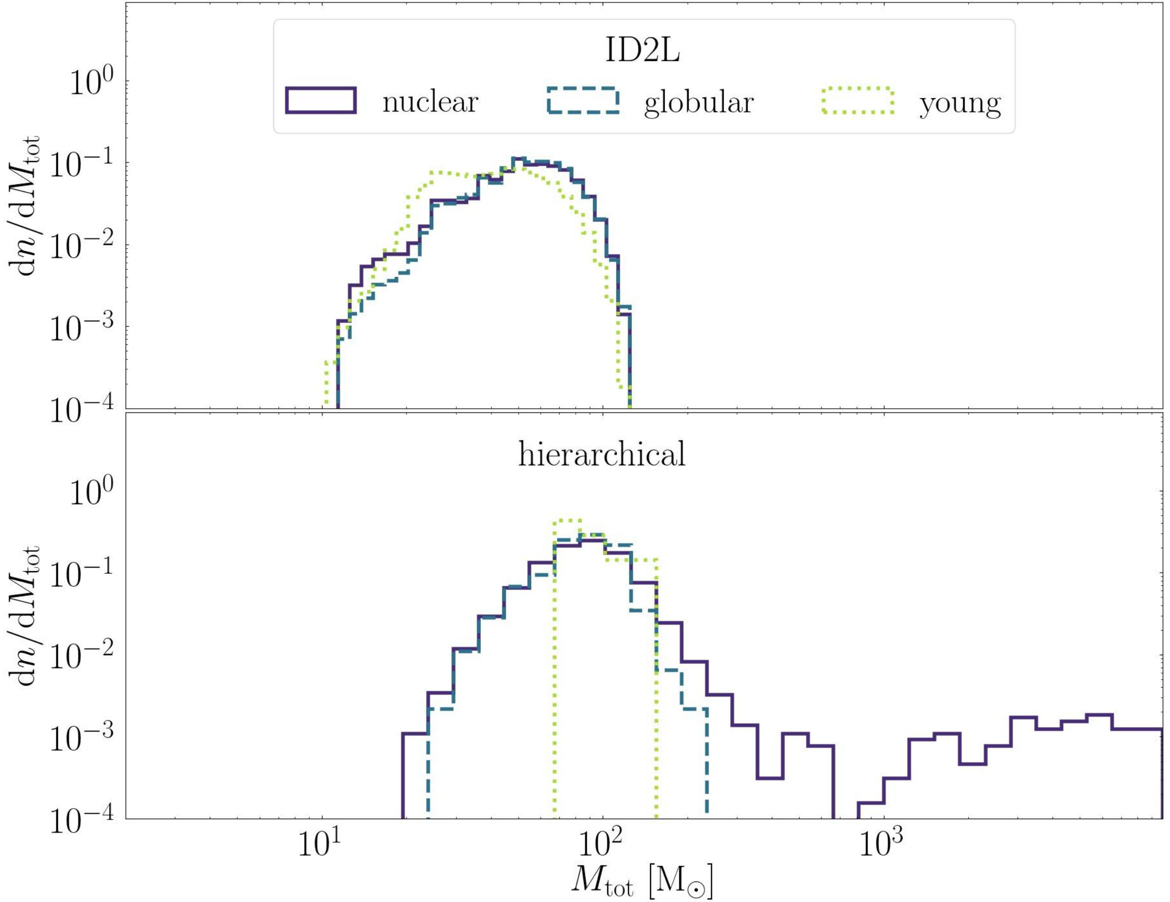


Step 3:
BBH undergoes binary-single scatterings ($t_{2\text{-}1}$): ejected (and merge in t_{GW}) or merge in t_{GW3} (Miller and Hamilton 2002)

Example 2: dynamical BBH mergers

Dynamics in B-POP: hierarchical mergers

Step 4:
BH remnant is kicked;
- $v_{MAX} > v_{ESC}$ that's it…
- $v_{MAX} < v_{ESC}$ the BH reaches r_{MAX} and come back within t_{DF}

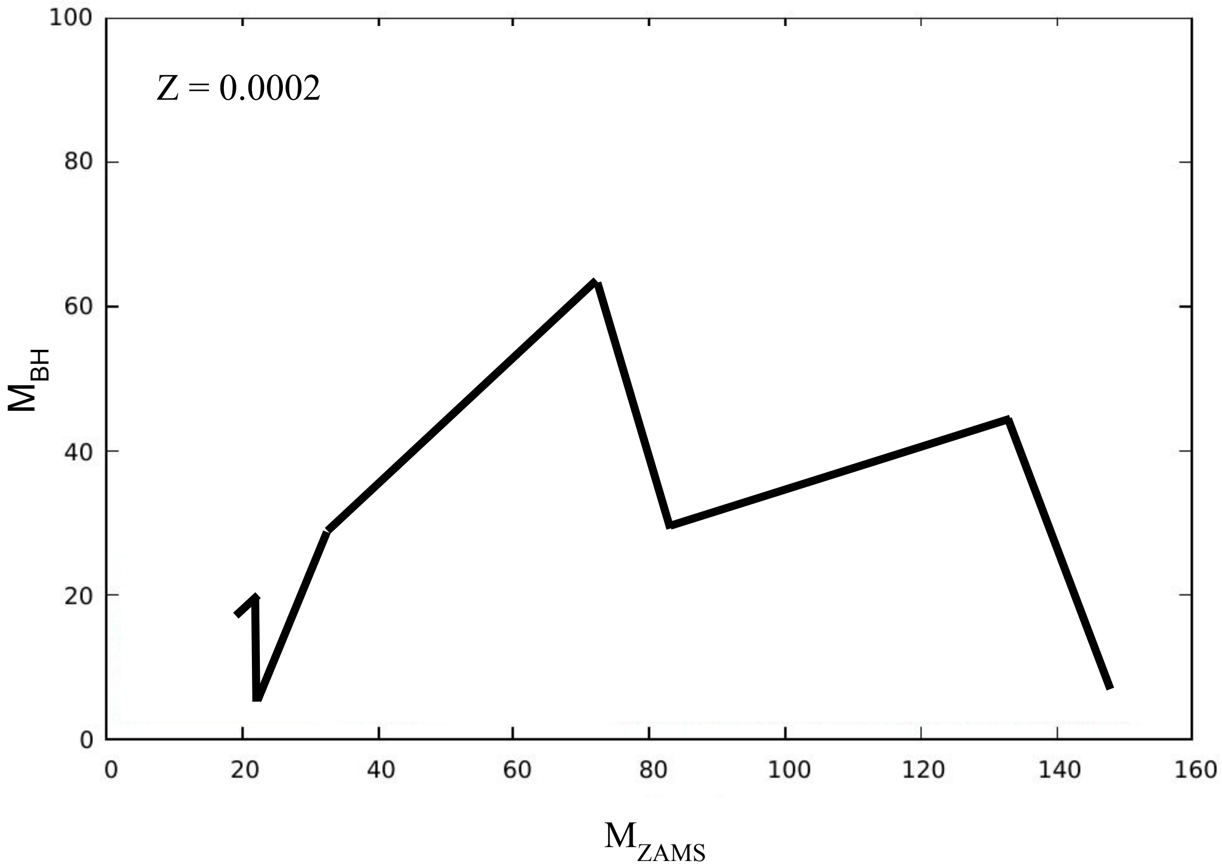


Example 2: dynamical BBH mergers

Mass spectrum

Single BHs:

- from a single star:
Single Stellar BH (SSBH) spectrum



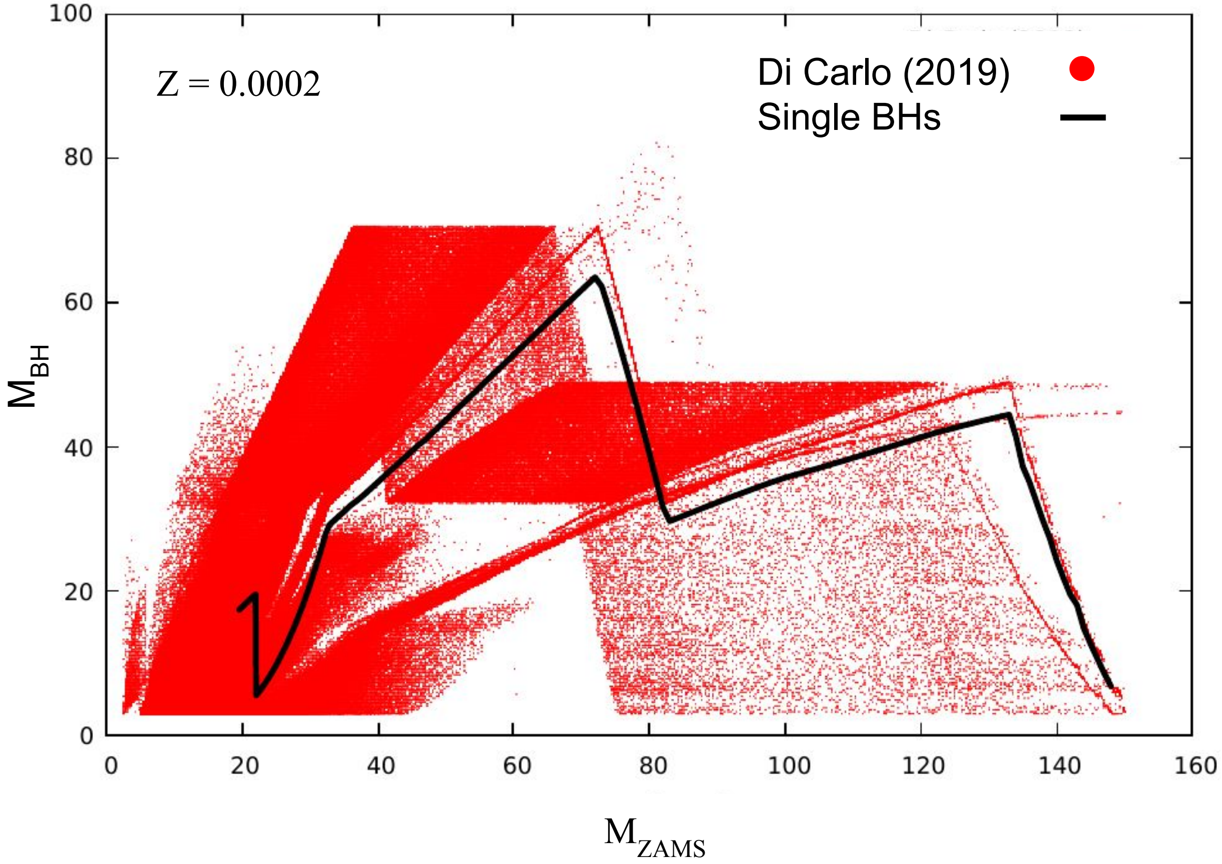
Example 2: dynamical BBH mergers

Mass spectrum

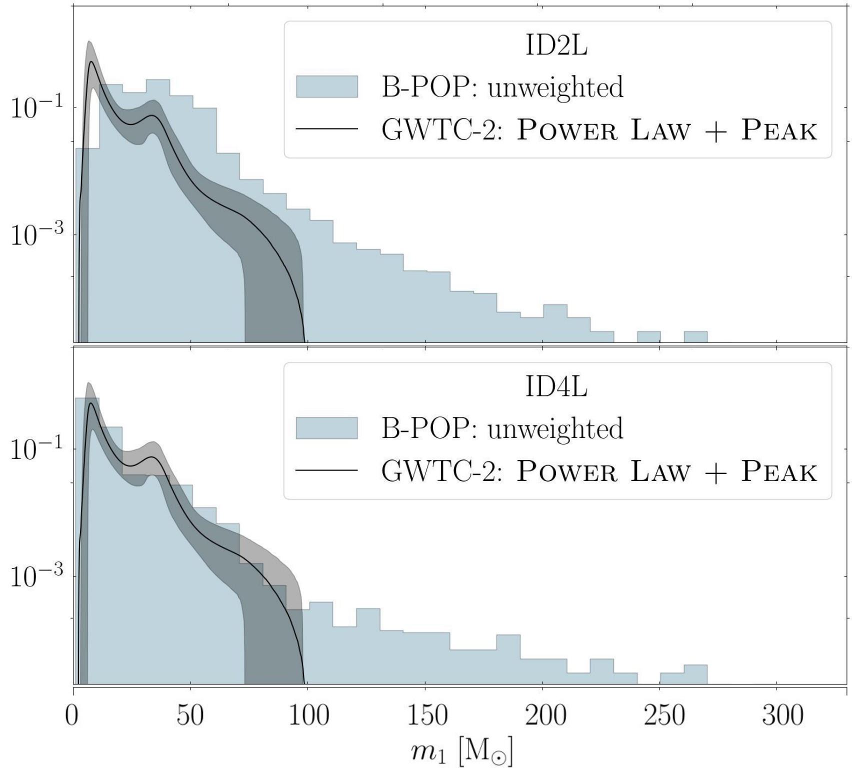
Single BHs:

- from a single star:
Single Stellar BH (SSBH) spectrum

- from binary evolution
Mixed Stellar BH (MSBH) spectrum



Example 2: dynamical BBH mergers



Single Stellar BH (SSBH)
no stellar binaries (not even on the fly …)

characteristic feature:
1. A bump in 20-50 M_{SUN}

2. Long tail >100 M_{SUN} dominated by hierarchical mergers

Mixed Stellar BH (MSBH)
(100% of "die hard" primordial binaries)

characteristic features:
1. A dominant population at 3-20 M_{SUN}

2. Smaller chance for M_1 > 100 M_{SUN}

Example 3: Carbonara

ID	Channel		Dynamics			Metallicity		Spins		BHMF		
	$f_{\rm iso}$	$f_{\rm dyn}$	$f_{\rm GC}$	$f_{\rm NC}$	$f_{\rm YC}$	iso+YC	GC+NC	$P(a_1)$	n_θ	SSBH	MSBH	HS[illegible]H
0(H/L)	0.5	0.5	0.33	0.33	0.33	SDSS	LOG	GSS(H/L)	8	0.5	0.5	[illegible] ?

Example 3: Carbonara(+detector?)

ID	Channel		Dynamics			Metallicity		OBS		Spins		BHMF		
	f_{iso}	f_{dyn}	f_{GC}	f_{NC}	f_{YC}	iso+YC	GC+NC	α_{M_1}	α_q	$P(a_1)$	n_θ	SSBH	MSBH	HSBH
0(H/L)	0.5	0.5	0.33	0.33	0.33	SDSS	LOG	2.2	0.4-0.7	GSS(H/L)	8	0.5	0.5	[illegible]

Comparing with LVC data: weighted and unweighted samples

The Volume scales with the:

primary mass
$P(m_1) \sim m_1^{2.2}$ ($10 < m_1/M_{SUN} < 100$)
(Fishbach & Holz 2017)

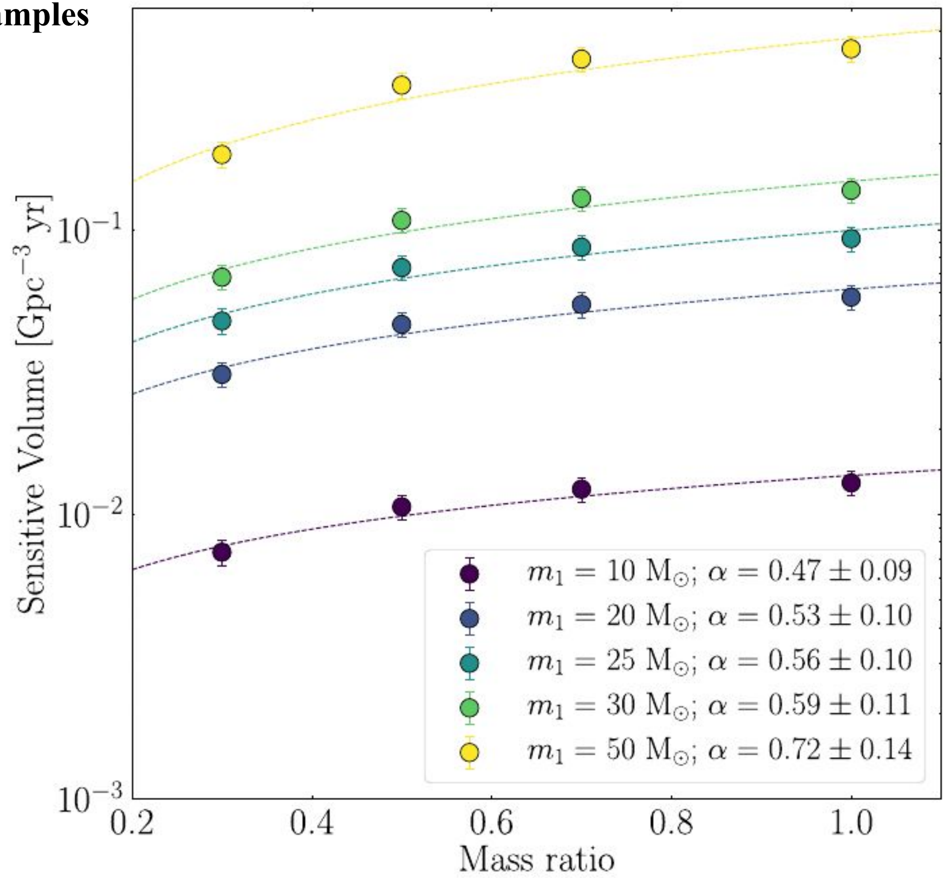
mass ratio
$P(q) \sim q^{\alpha(m1)}$
$\alpha(m_1) \sim 0.47\text{-}0.72$ ($10 < m_1/M_{SUN} < 50$)
(Arca Sedda 2021)

The volume is larger for:
more massive BBHs with similar components

To create a "mock" catalogue we:

- weight the BBH population with the selection functions $P(m_1)$ and $P(q)$

- limit the sample to mergers happening at z<2



Results: the reference model

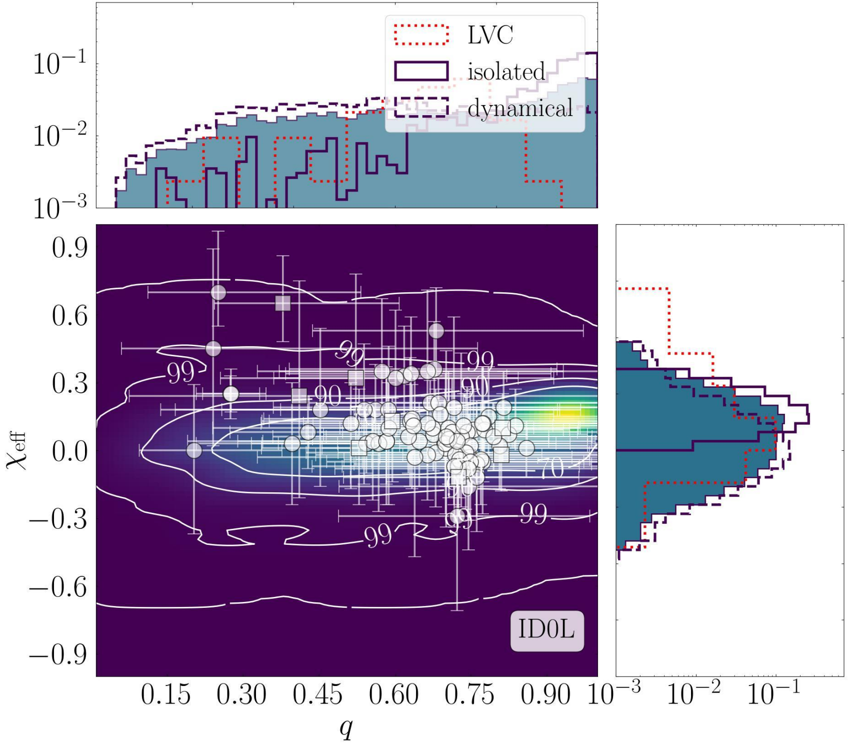
"Universal"
Isolated BBH: 50%

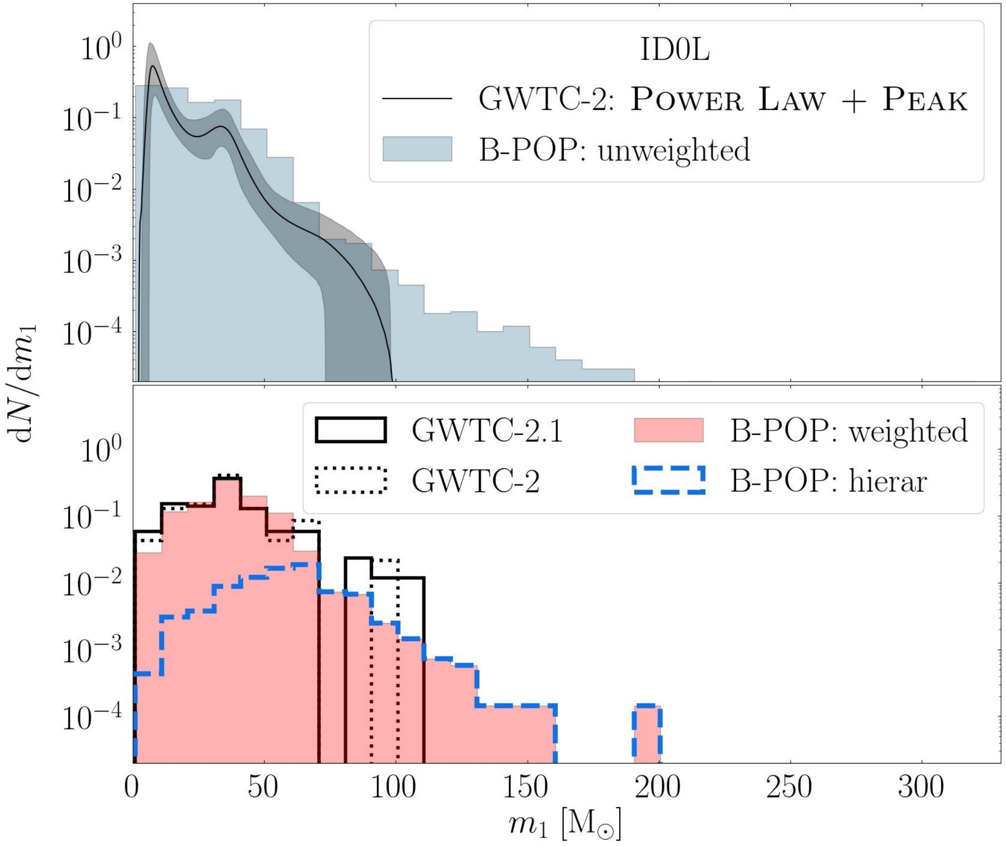
Dynamical BBHs: 50%
YC: 33.3%
GC: 33.3%
NC: 33.3%

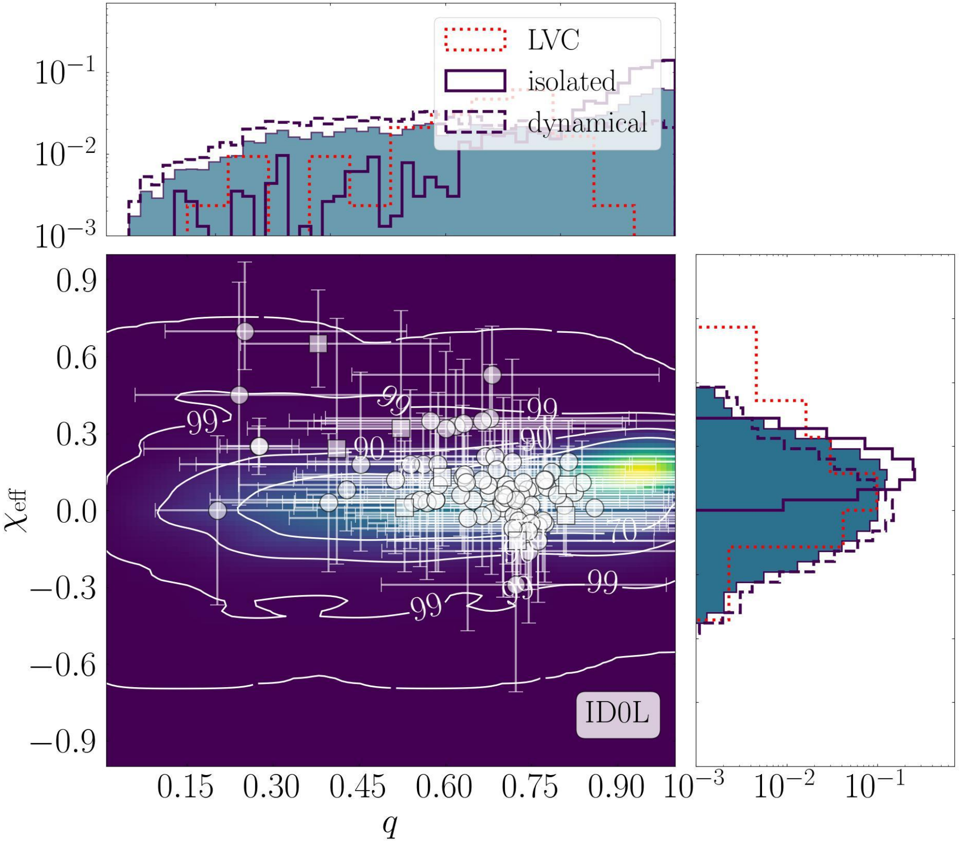
Results: the reference model

"Universal"	"Mock"
Isolated BBH: 50%	Isolated BBH: 34%
Dynamical BBHs: 50%	Dynamical BBHs: 66%
YC: 33.3%	YC: 29%
GC: 33.3%	GC: 53%
NC: 33.3%	NC: 18%

Results: the reference model







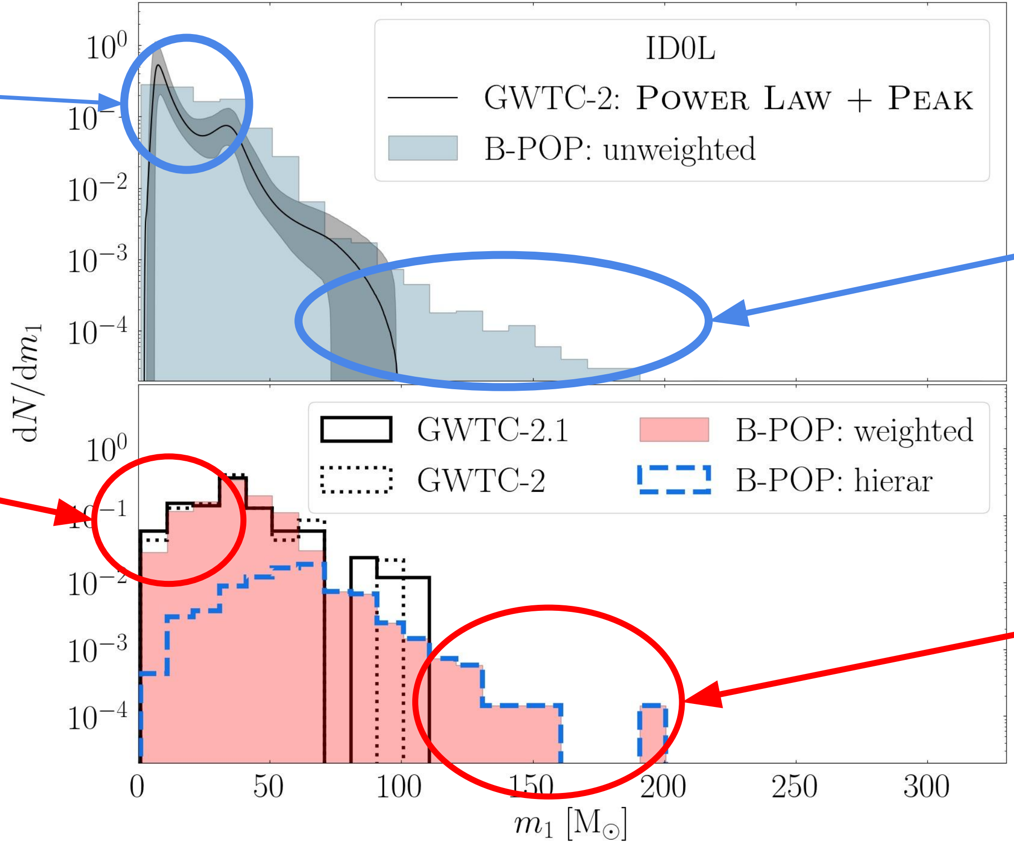
"Mock"

Isolated BBH:
61% of mergers with q>0.9
*X*eff strongly peak 0.2

Dynamical BBHs:
~ flat q distribution
*X*eff ~ 0

Results: the reference model

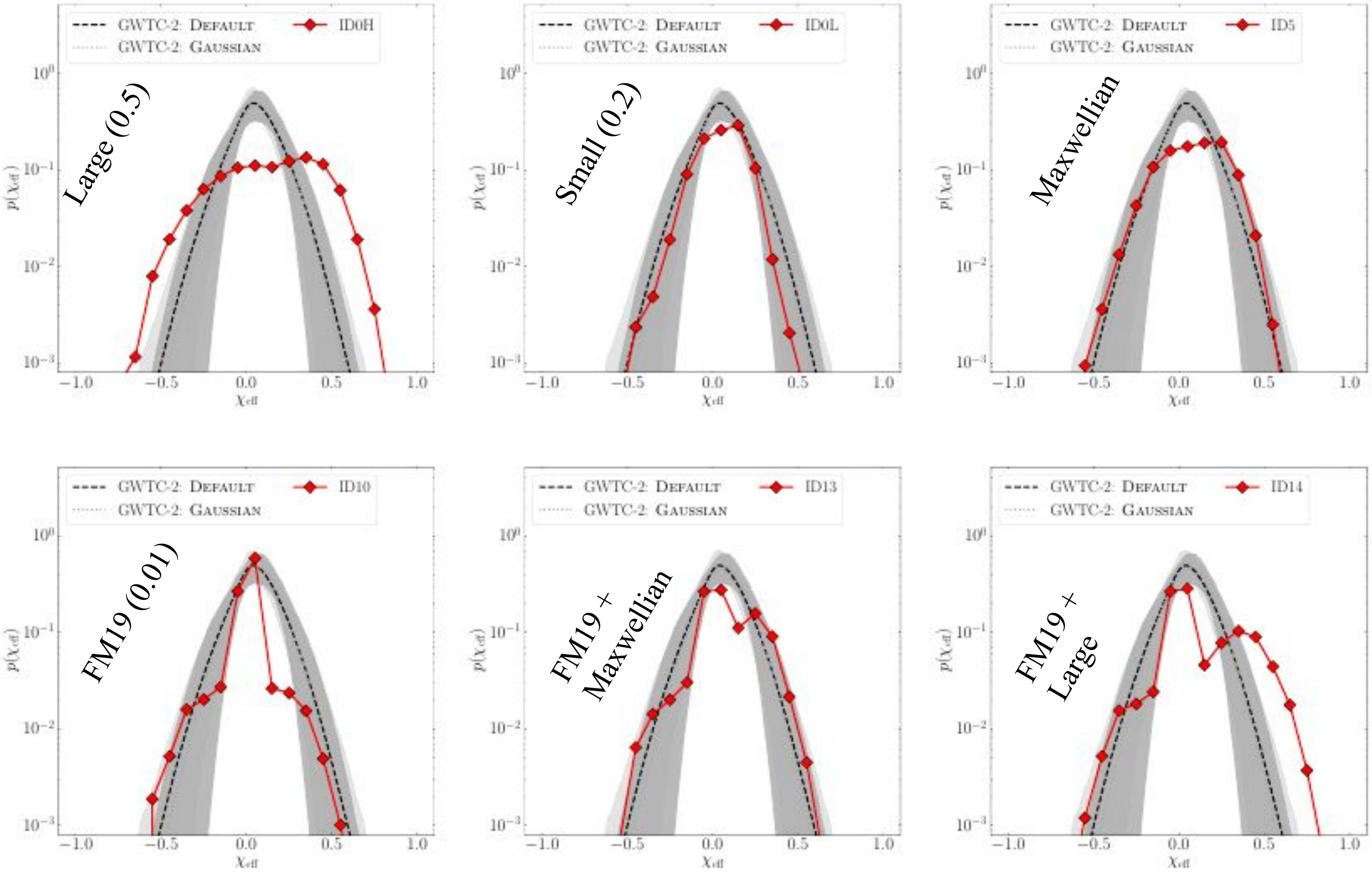
Low-end tail: isolated + YC + MSBH spectrum



High-end tail: dynamical and hierarchical BBH

Primary mass depletion

Mass-ratio depletion


GWTC-2: Default
GWTC-2: Gaussian
ID0H
Large (0.5)
ID0L
Small (0.2)
ID5
Maxwellian
ID10
FM19 (0.01)
ID13
FM19 + Maxwellian
ID14
FM19 + Large
$p(\chi_{\rm eff})$
$\chi_{\rm eff}$

Hierarchical Mergers and IMBHs

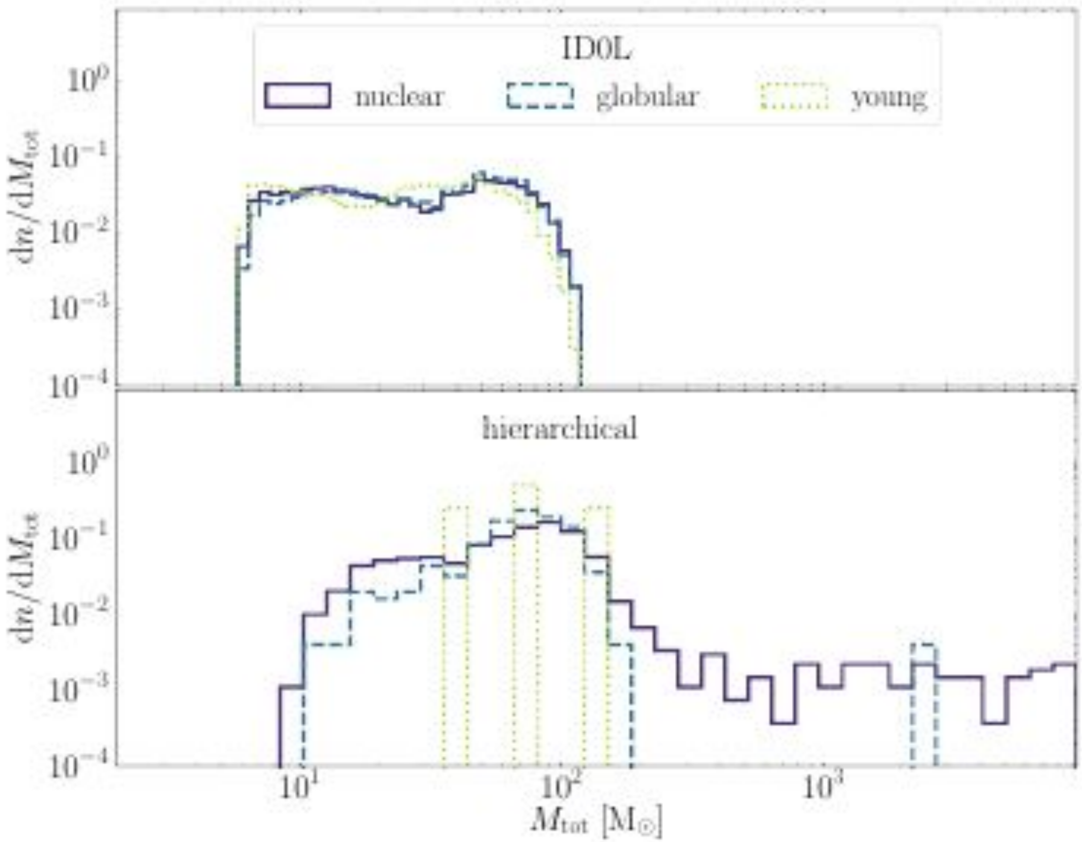
★ ~ 3.7-5% of "mock" mergers

★ BBH total mass

- peak ~ 100 M_{SUN}
- decline > 300 M_{SUN}

★ A tiny fraction (< 0.05%) undergo a

merger avalanche
that leads to > 10^4 M_{SUN}

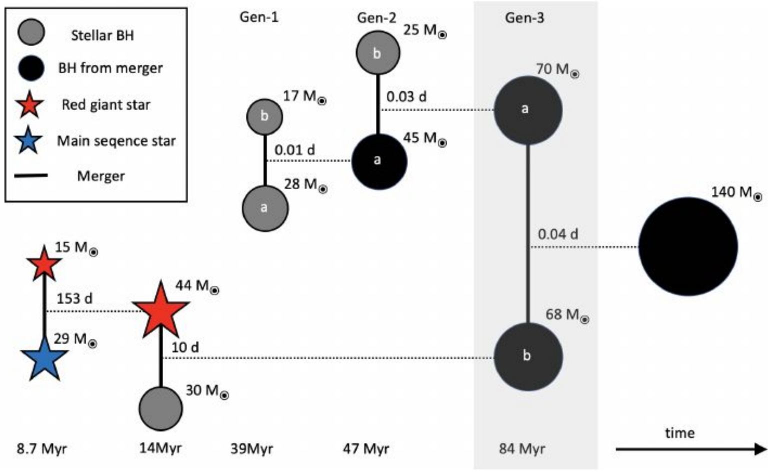


The impact of IMBH seeds onto the population of BBH mergers

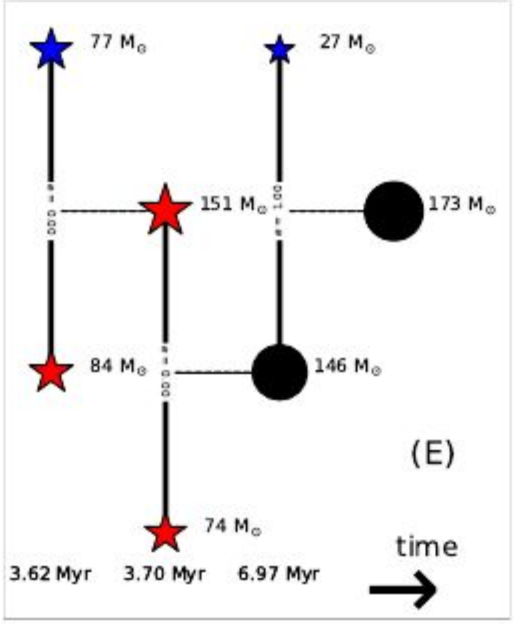
IMBH (>100M_{SUN}) in N-body and Monte Carlo simulations
(Portegies-Zwart et al 2004, Gurkan et al 2009, Giersz et al 2015, Arca Sedda et al 2019, Di Carlo et al 2019, Gonzalez et al 2021, Rizzuto et al 2020,2021 …):

- dense star clusters
- stellar collisions
- stellar-BH accretion
- multiple BH mergers

Arca Sedda et al 2021



Rizzuto et al (AS) 2021



The impact of IMBH seeds onto the population of BBH mergers

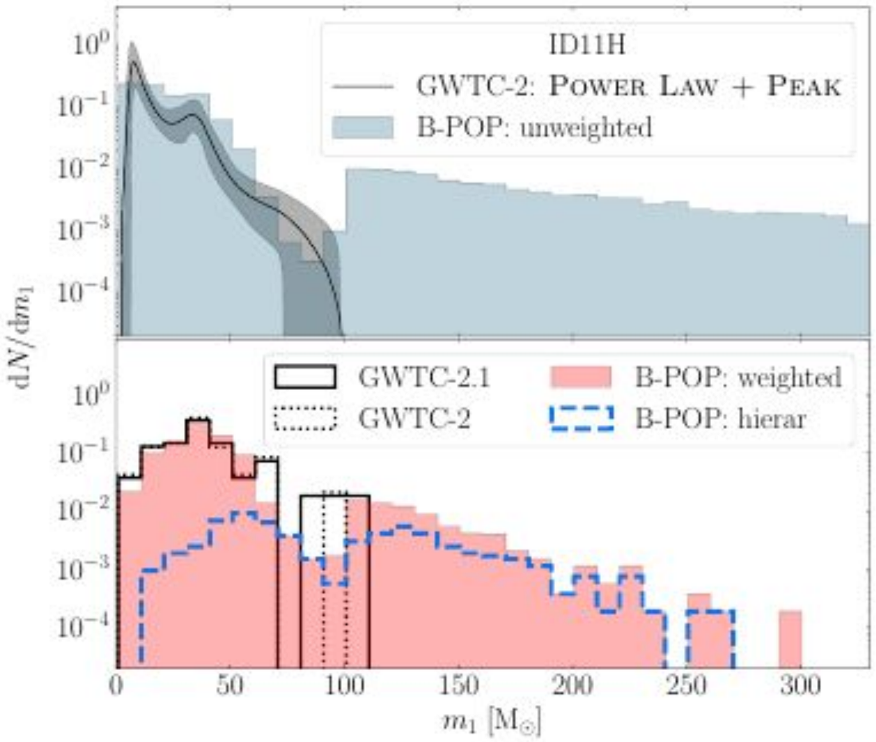
IMBH with $M_{IMBH} = 100 - 500\ M_{SUN}$

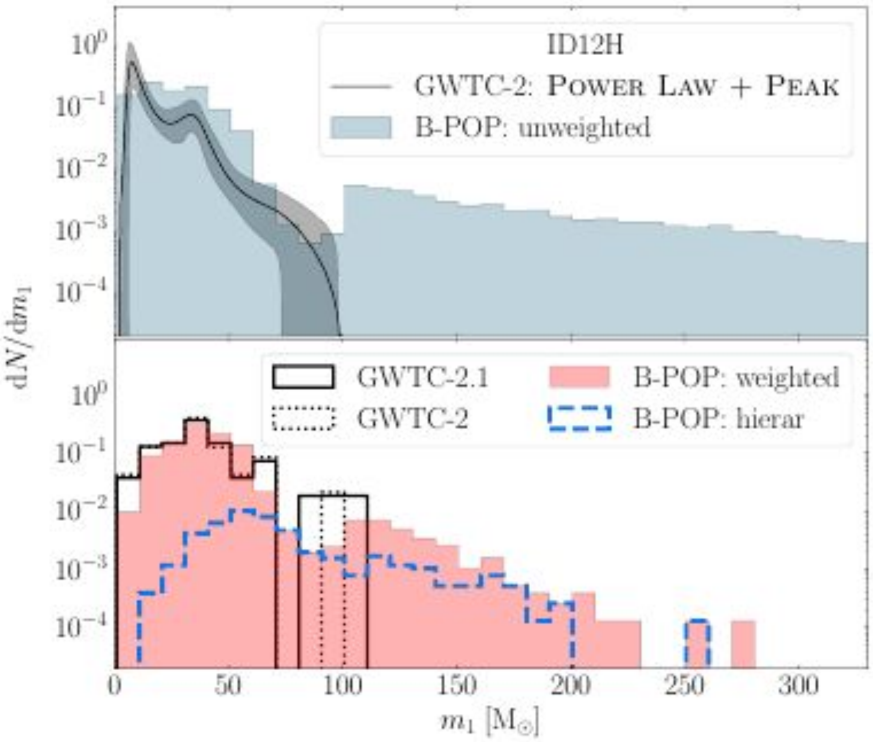
$F(M_{IMBH}) \sim M^{-2}$ (like for star cluster masses …)

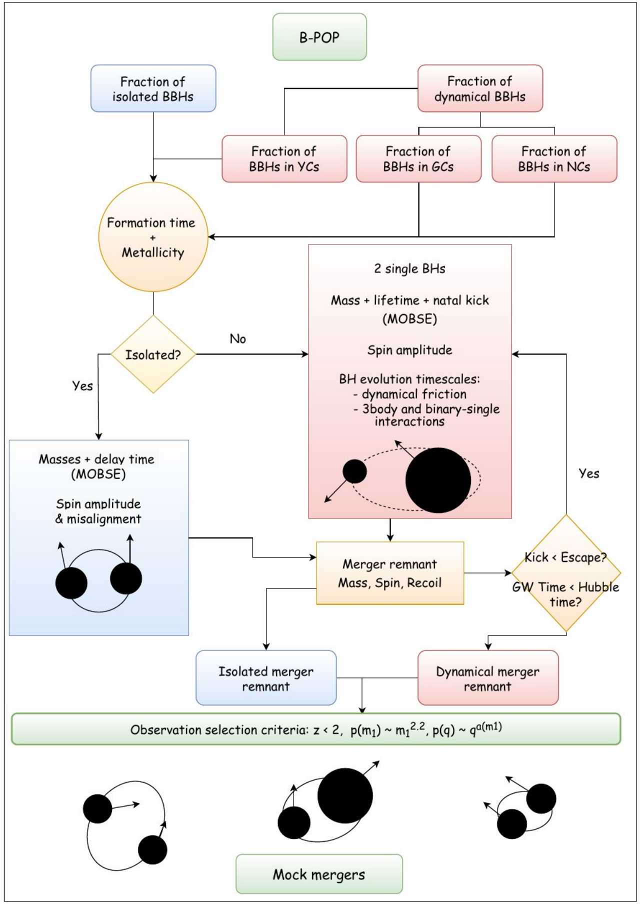
Now we have:

Single (SSBH)	Mixed (MSBH)	Heavy (HSBH)
40%	40%	20%
85%	5%	10%

The impact of IMBH seeds onto the population of BBH mergers







? =

Triples? PBH? AGN? Captures?

Eccentricity?

...?

Selection? Binary-Binary?

Cluster evolution? Stellar evolution? KL effects? Wide Binaries?