Title: The Gravitational Wave Bias Parameter from Angular Power Spectra: Bridging Between Galaxies and Binary Black Holes

Speakers: Amirhossein Dehghanizadeh

Collection/Series: Training Programs (TEOSP)

Subject: Other

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Abstract:

This study presents the modeling of the gravitational wave (GW) bias parameter by bridging a connection between simulated GW sources and galaxies in low redshift galaxy surveys 2MPZ and WISExSCOS (WISC). We study this connection by creating a mock GW catalog, populating galaxy surveys with binary black holes (BBHs) for different scenarios of the GW host-galaxy probability as a function of the galaxy stellar mass. We probe the observable consequences of this connection by exploring the spatial clustering of the GW sources in terms of the GW bias parameter. We consider a phenomenological broken power law model for the host-galaxy probability function, with a potential turnover M_K at high stellar mass (10^{11} solar mass in the fiducial model) where the star formation efficiency begins to drop. We vary the parameters of the GW host-galaxy probability function and find that generically the GW bias increases as M_K increases (and gets suppressed as M_K decreases). The change in the GW bias parameter shows a maximum change of about 30% for different scenarios explored in this work in comparison to the galaxy bias. Future measurements of the GW bias can help constrain M_K and the slopes of the host-galaxy probability function and thus offer insights into the underlying astrophysical processes.

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The Gravitational Wave Bias Parameter Bridging Between Galaxies and Binary Black Holes

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Feb 2025

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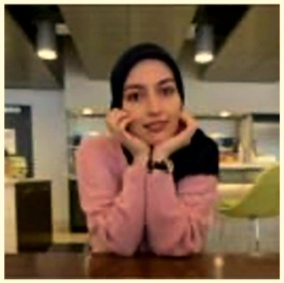

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arXiv:2411.11965

Outline

- Goal: What we learn from spatial clustering of the gravitational waves (GW) source?
- What is GW bias parameter?
- Connection between GW sources and galaxies.

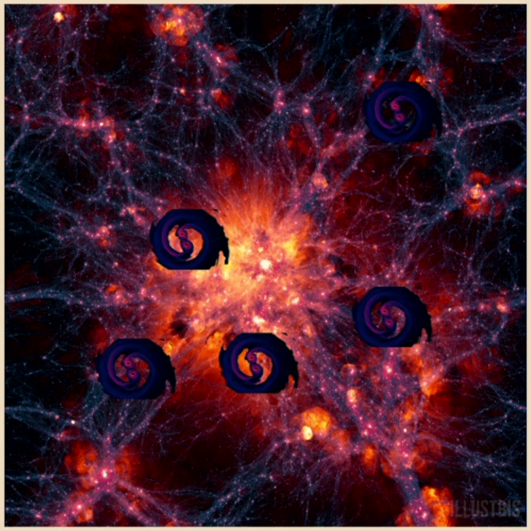
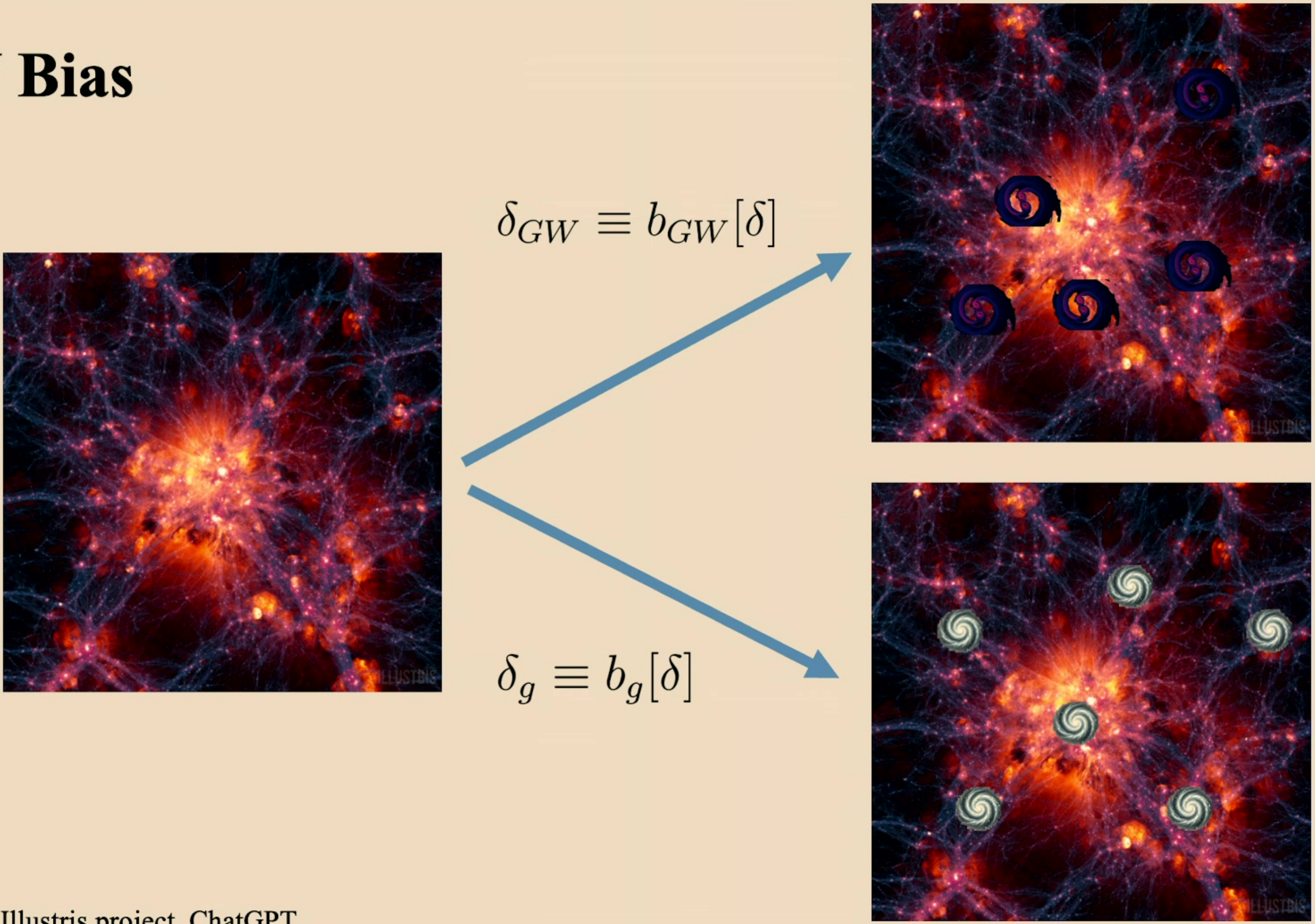


Photo credits: Illustris project, ChatGPT.

GW Bias



$$\delta_{GW} \equiv b_{GW}[\delta]$$

$$\delta_g \equiv b_g[\delta]$$

Photo credits: Illustris project, ChatGPT.

- Halo-galaxy connection.
- Galaxies are formed with mainly three characteristics:

  - Mass (M_*)
  - Metallicity (Z)
  - Star-formation rate (SFR).

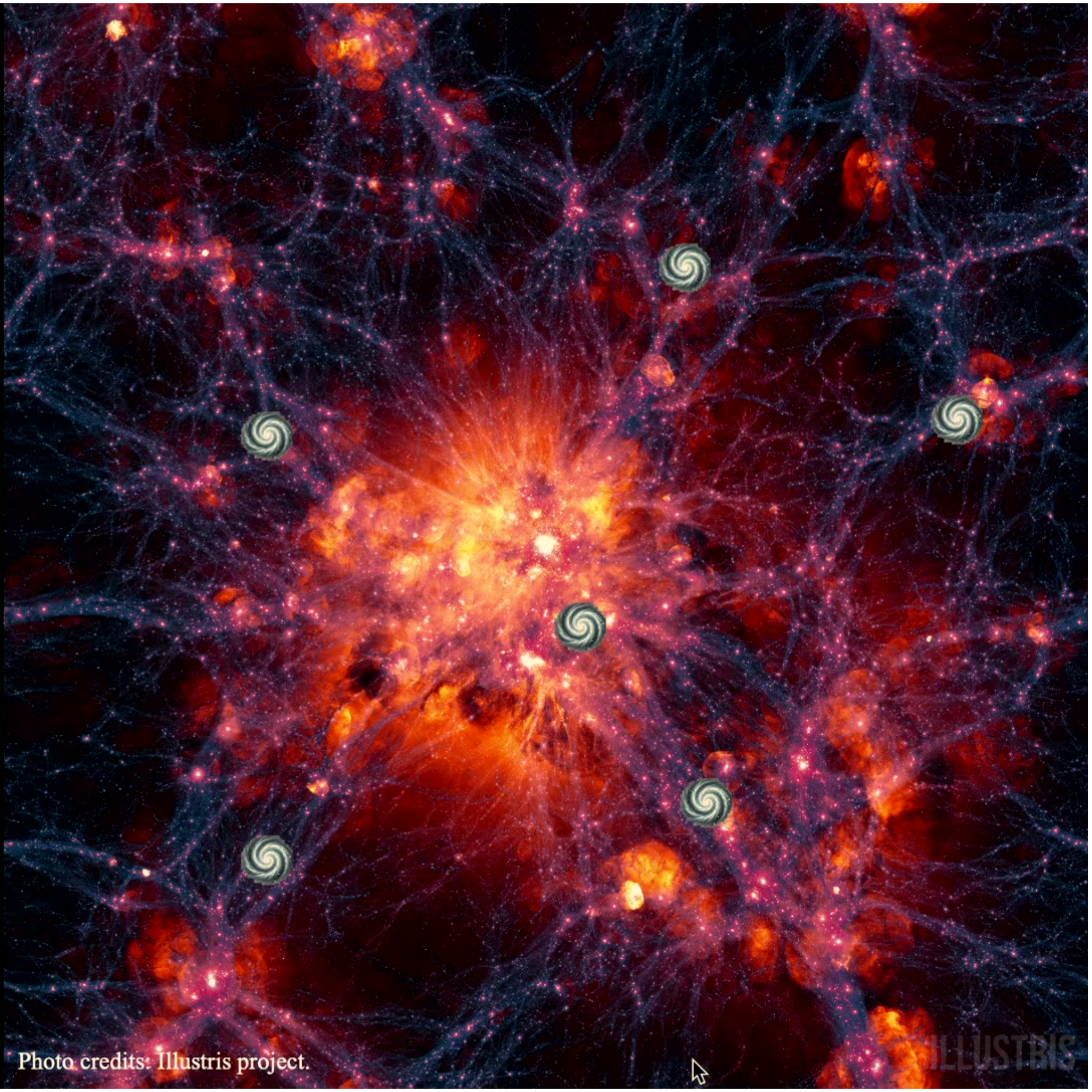


Photo credits: Illustris project.

- A population of stars at their birth (depending on Mass M_* Z, SFR of the parent galaxy).
- Some are in binary systems (f_{bi}).

Photo credits: Hubble, Pinwheel Galaxy.

- Stellar-evolution formulation from birth to the final remnants (BH, NS, WD). (Metallicity plays a role)
- A distribution for mass and orbital geometry parameters of binaries.
- Mass and momentum loss due to stellar winds.
- Mass transfer events (Common envelope physics).
- Supernova physics.
- Dynamical effects of supernovas on binary orbits (Natal kicks).
- Gravitational radiation after formation of compact objects until merger.

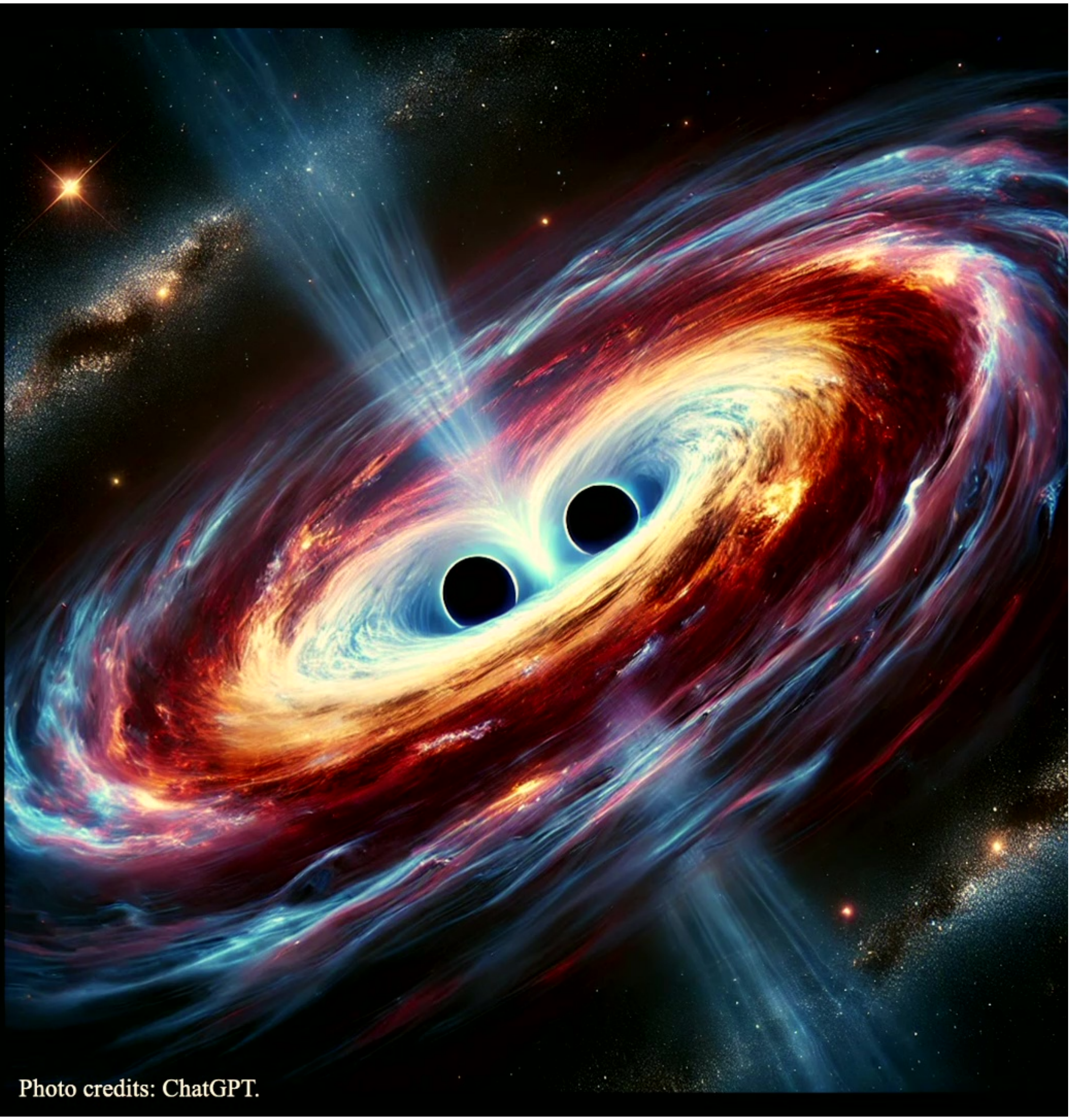


Photo credits: ChatGPT.

- [Belczynski, et al., 2002]
  21 formation channels for compact object binaries.

  - 14 for NS-NS
  - 4 for NS-BH
  - 3 for BH-BH

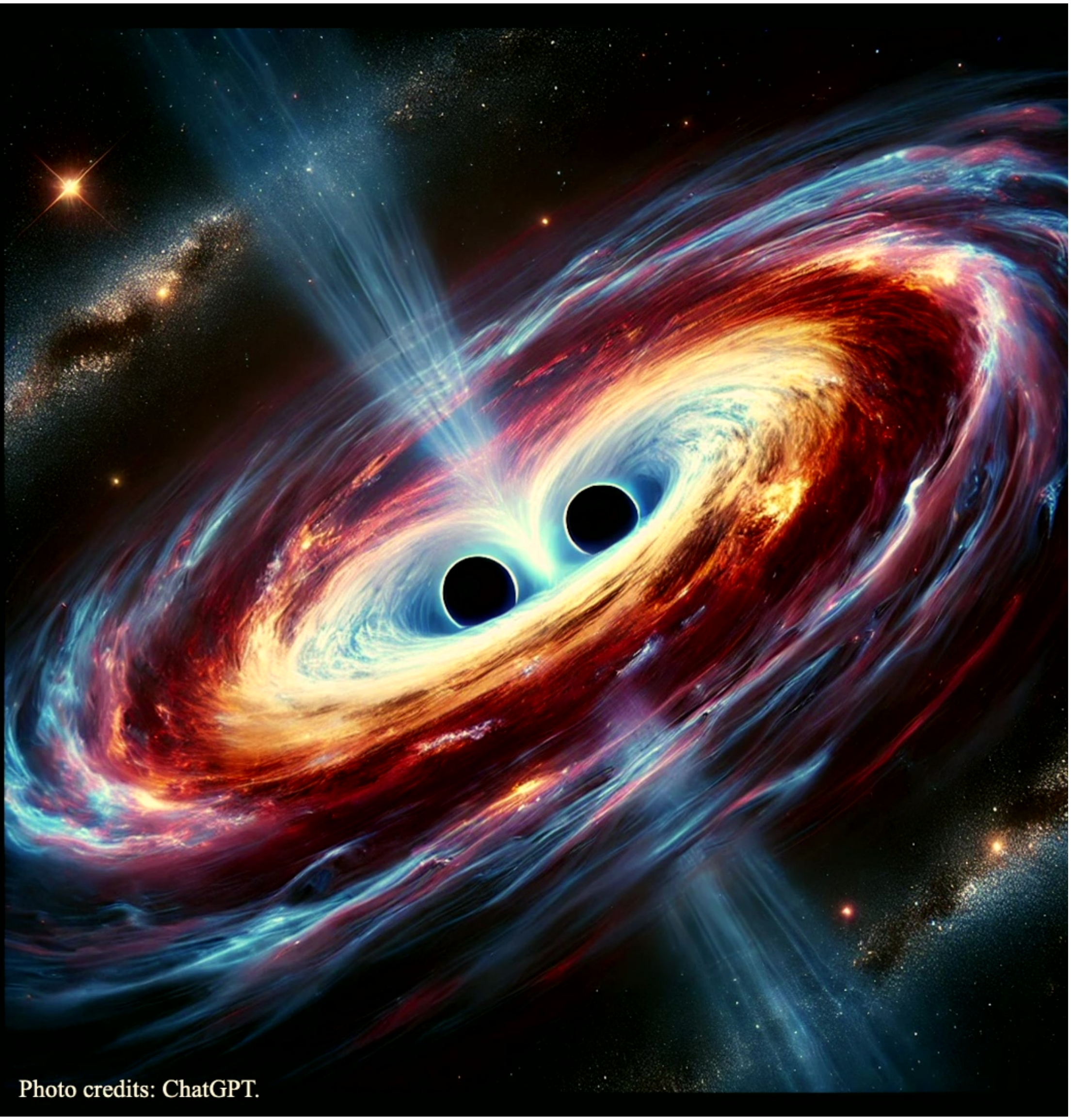
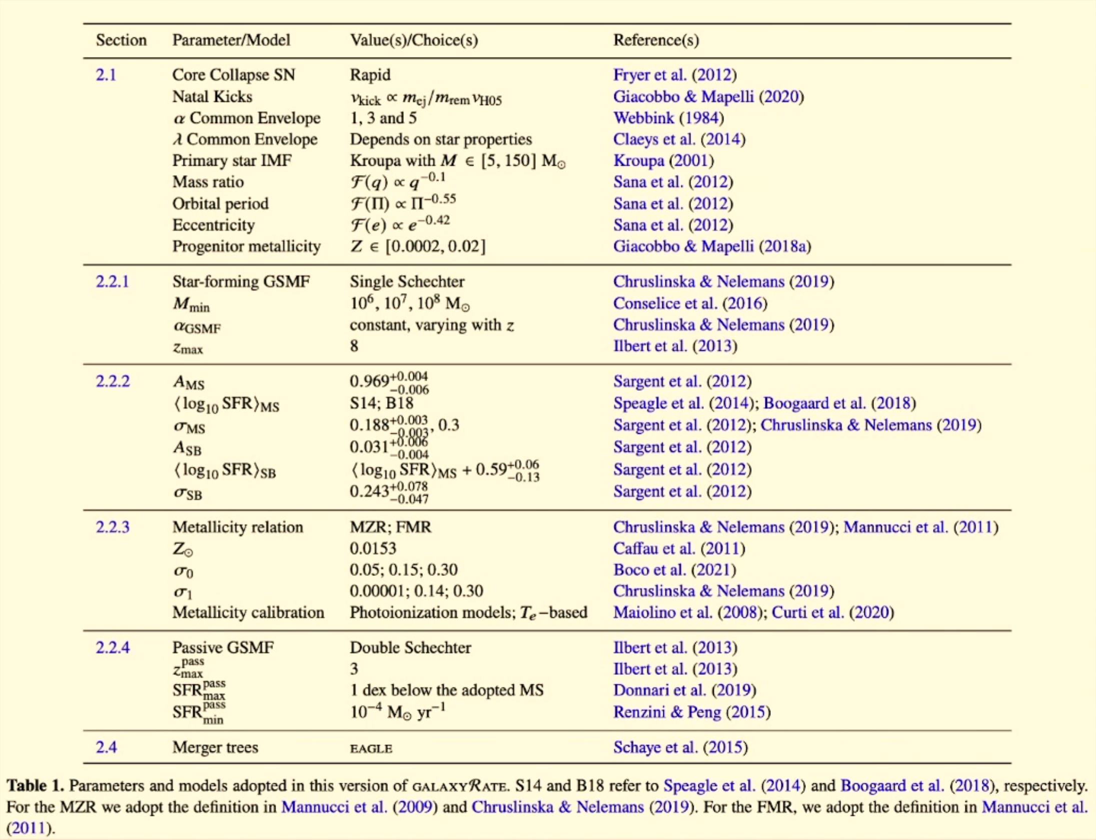


Photo credits: ChatGPT.

Santoliquido, et al., 2022.

- GalaxyRate
  code for estimation of the merger rate density.

- Estimating the properties of their host galaxies
  based on observational scaling relations (FMR, MZR).

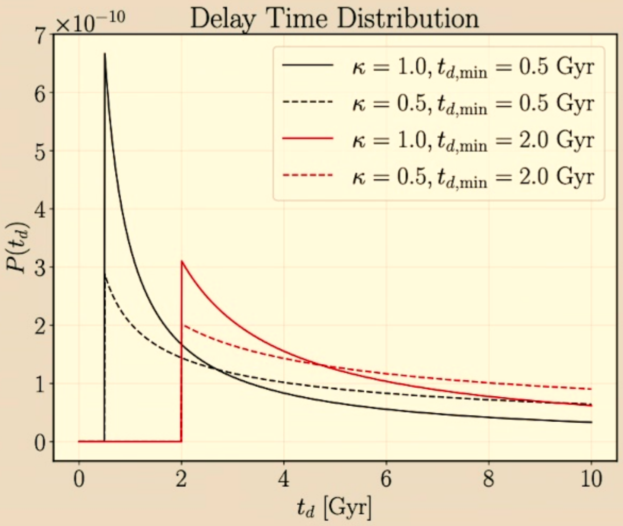


Section	Parameter/Model	Value(s)/Choice(s)	Reference(s)
2.1	Core Collapse SN	Rapid	Fryer et al. (2012)
	Natal Kicks	$v_{\rm kick} \propto m_{\rm ej}/m_{\rm rem}\, v_{\rm H05}$	Giacobbo & Mapelli (2020)
	α Common Envelope	1, 3 and 5	Webbink (1984)
	λ Common Envelope	Depends on star properties	Claeys et al. (2014)
	Primary star IMF	Kroupa with $M \in [5, 150]$ M$_\odot$	Kroupa (2001)
	Mass ratio	$\mathcal{F}(q) \propto q^{-0.1}$	Sana et al. (2012)
	Orbital period	$\mathcal{F}(\Pi) \propto \Pi^{-0.55}$	Sana et al. (2012)
	Eccentricity	$\mathcal{F}(e) \propto e^{-0.42}$	Sana et al. (2012)
	Progenitor metallicity	$Z \in [0.0002, 0.02]$	Giacobbo & Mapelli (2018a)
2.2.1	Star-forming GSMF	Single Schechter	Chruslinska & Nelemans (2019)
	$M_{\rm min}$	$10^6, 10^7, 10^8$ M$_\odot$	Conselice et al. (2016)
	$\alpha_{\rm GSMF}$	constant, varying with z	Chruslinska & Nelemans (2019)
	$z_{\rm max}$	8	Ilbert et al. (2013)
2.2.2	$A_{\rm MS}$	$0.969^{+0.004}_{-0.006}$	Sargent et al. (2012)
	$\langle \log_{10} {\rm SFR} \rangle_{\rm MS}$	S14; B18	Speagle et al. (2014); Boogaard et al. (2018)
	$\sigma_{\rm MS}$	$0.188^{+0.003}_{-0.003}$, 0.3	Sargent et al. (2012); Chruslinska & Nelemans (2019)
	$A_{\rm SB}$	$0.031^{+0.006}_{-0.004}$	Sargent et al. (2012)
	$\langle \log_{10} {\rm SFR} \rangle_{\rm SB}$	$\langle \log_{10} {\rm SFR} \rangle_{\rm MS} + 0.59^{+0.06}_{-0.13}$	Sargent et al. (2012)
	$\sigma_{\rm SB}$	$0.243^{+0.078}_{-0.047}$	Sargent et al. (2012)
2.2.3	Metallicity relation	MZR; FMR	Chruslinska & Nelemans (2019); Mannucci et al. (2011)
	$Z_\odot$	0.0153	Caffau et al. (2011)
	σ_0	0.05; 0.15; 0.30	Boco et al. (2021)
	σ_1	0.00001; 0.14; 0.30	Chruslinska & Nelemans (2019)
	Metallicity calibration	Photoionization models; T_e−based	Maiolino et al. (2008); Curti et al. (2020)
2.2.4	Passive GSMF	Double Schechter	Ilbert et al. (2013)
	$z_{\rm max}^{\rm pass}$	3	Ilbert et al. (2013)
	${\rm SFR}_{\rm max}^{\rm pass}$	1 dex below the adopted MS	Donnari et al. (2019)
	${\rm SFR}_{\rm min}^{\rm pass}$	10^{-4} M$_\odot$ yr^{-1}	Renzini & Peng (2015)
2.4	Merger trees	EAGLE	Schaye et al. (2015)

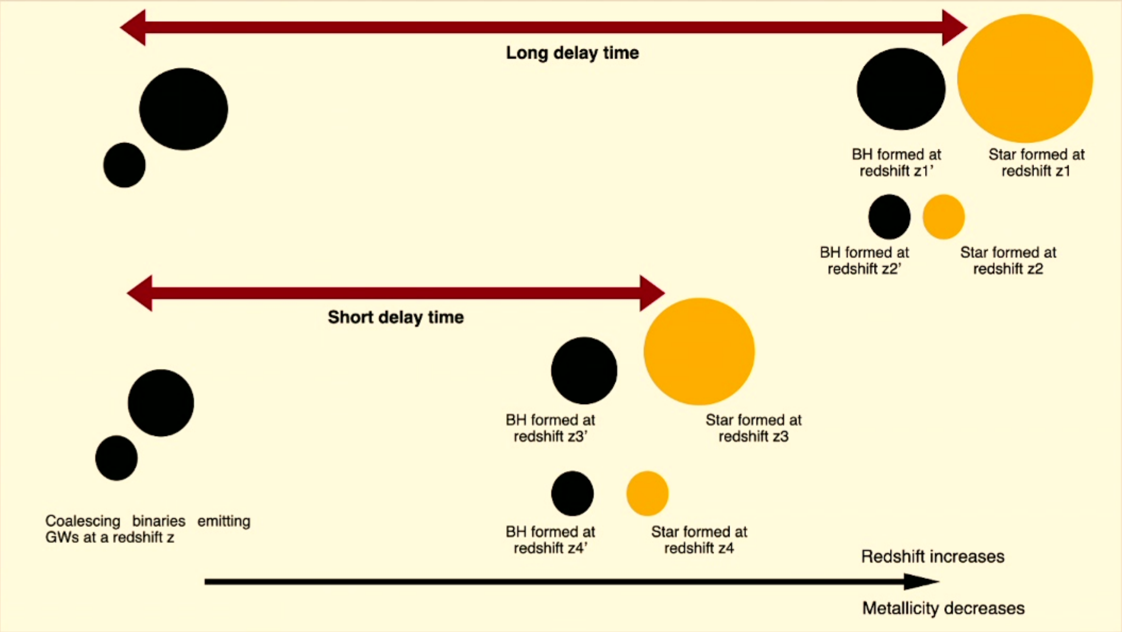
Table 1. Parameters and models adopted in this version of GALAXY$\mathcal{R}$ATE. S14 and B18 refer to Speagle et al. (2014) and Boogaard et al. (2018), respectively. For the MZR we adopt the definition in Mannucci et al. (2009) and Chruslinska & Nelemans (2019). For the FMR, we adopt the definition in Mannucci et al. (2011).

Delay Time

- Current observational constraints on the delay time distribution are weak.
- The minimum delay time seems to be less than 5 Gyrs.
- Some population synthesis simulations prefer longer delay times.



$$P(t_d) \propto \Theta(t_d - t_{d,\mathrm{min}}) t_d^{-\kappa}$$



Long delay time

BH formed at redshift z1'

Star formed at redshift z1

BH formed at redshift z2'

Star formed at redshift z2

Short delay time

BH formed at redshift z3'

Star formed at redshift z3

Coalescing binaries emitting GWs at a redshift z

BH formed at redshift z4'

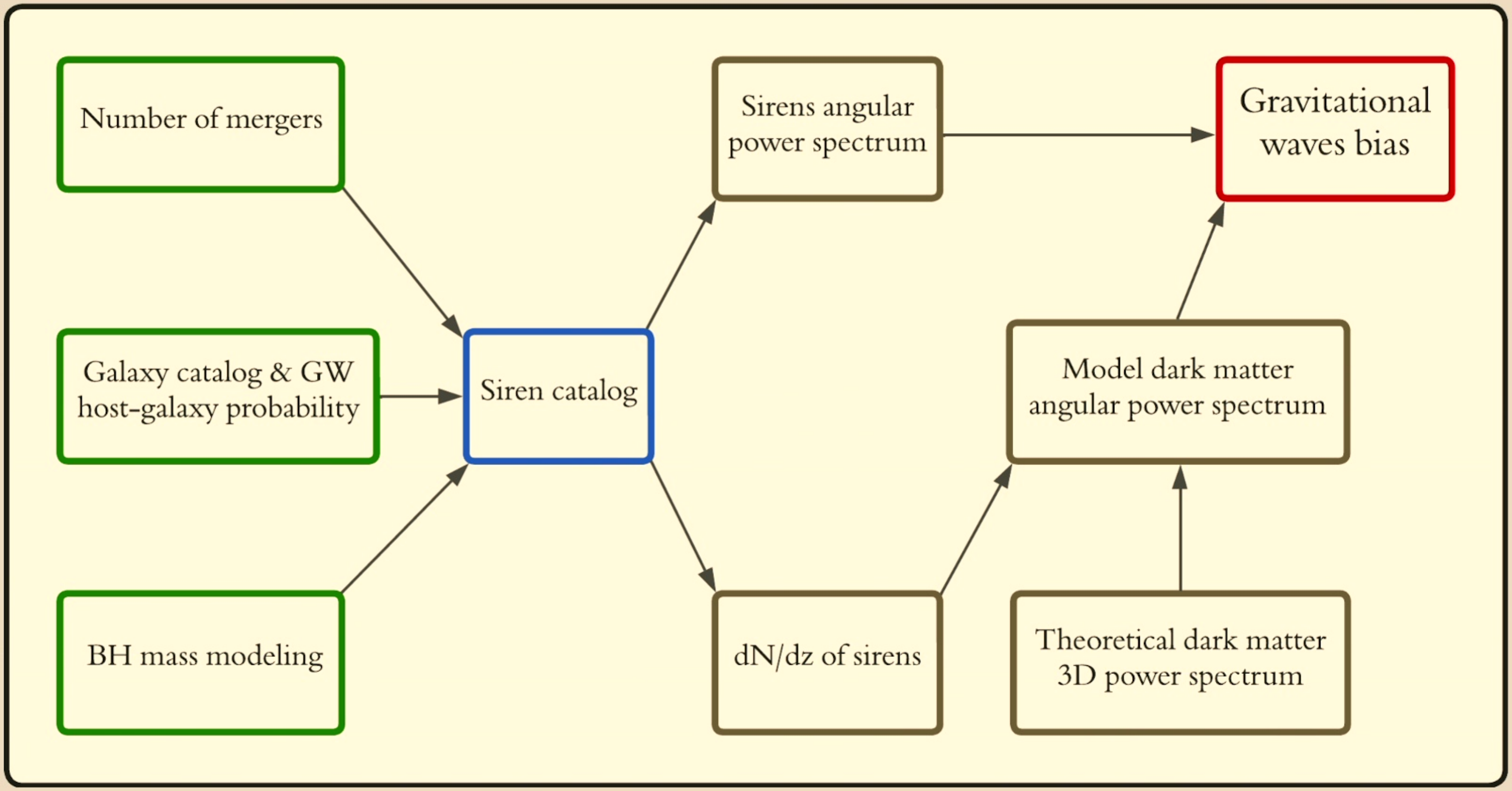
Star formed at redshift z4

Redshift increases

Metallicity decreases

Mukherjee, 2022.

Our proposal



Number of mergers

Galaxy catalog & GW host-galaxy probability

BH mass modeling

Siren catalog

Sirens angular power spectrum

dN/dz of sirens

Model dark matter angular power spectrum

Theoretical dark matter 3D power spectrum

Gravitational waves bias

GW bias definition

- Photometric galaxy survey ≡ Angular power spectrum

$$\delta_{GW}(\ell, z) = b_{GW}(\ell, z)\delta(\ell, z)$$

$$\hat{C}_\ell^{GWGW} = b_{GW}^2 C_\ell^{\text{Mod}}$$

- The expected theoretical angular power spectrum:
  Autocorrelation for a sample of the same number of sources if they were unbiased tracers of the dark matter distribution.

$$C_\ell^{\text{Mod}} = 4\pi \int d(\ln k)\ \mathcal{P}_{\mathcal{R}}(k)\left(\Delta_\ell(k)\right)^2$$

$$\Delta_\ell(k) = \int dz\,\frac{dN}{dz} T_\delta(k, z) j_\ell(k\chi(z))$$

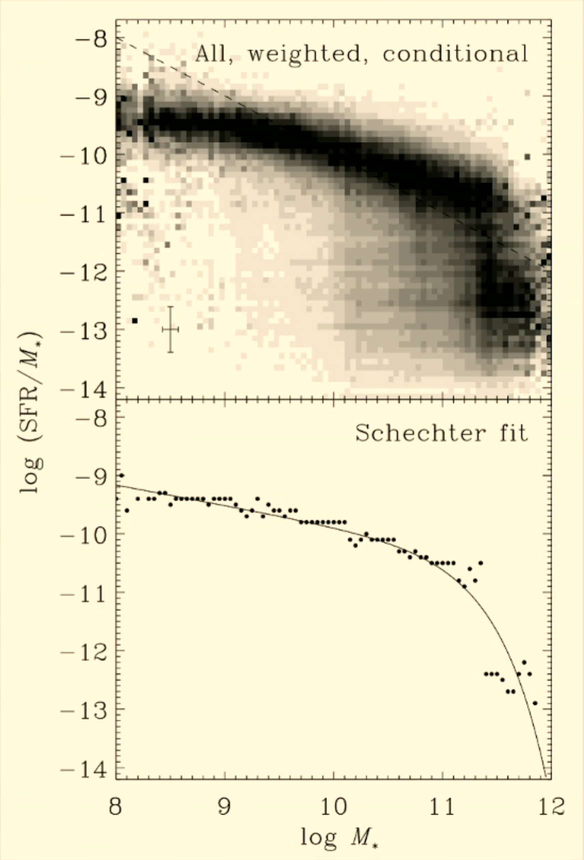
Host-galaxy probability, $P(GW|M_*)$

- $P(GW|M_*)$ can depend on stellar mass, metallicity, and SFR.
- 2MPZ and WISC only provide the mass.
- $P(GW|M_*)$ encapsulates the physics from the formation to the merger of BBHs, manifested in terms of the stellar mass of the host galaxy.
- The stellar mass at merger time is influenced by other astrophysical properties at earlier times, such as the initial stellar mass, star formation history, and merger history of the galaxies.

M_*-SFR relation

- Based on SDSS

- ***Quenching time scale:***
  The time it takes for a galaxy to transition from being actively star-forming to a quenched (non-star-forming) state.



- S. Salim, et al., 2007

Host-galaxy probability, $P(GW|M_*)$

- Merger rate per galaxy is positively correlated with the SFR.
- Consequently, merger rate per galaxy is expected to be positively correlated with the stellar mass up to a particular mass scale.
- High mass galaxies form stars rapidly at early times before their star formation is quenched.
- $P(GW|M_*)$ depends on the two timescales in the problem, the delay time and the quenching time.
- Delay time shorter than the quenching timescale = Suppression in the number of BBHs at high stellar mass.
- Longer delay times = No suppression

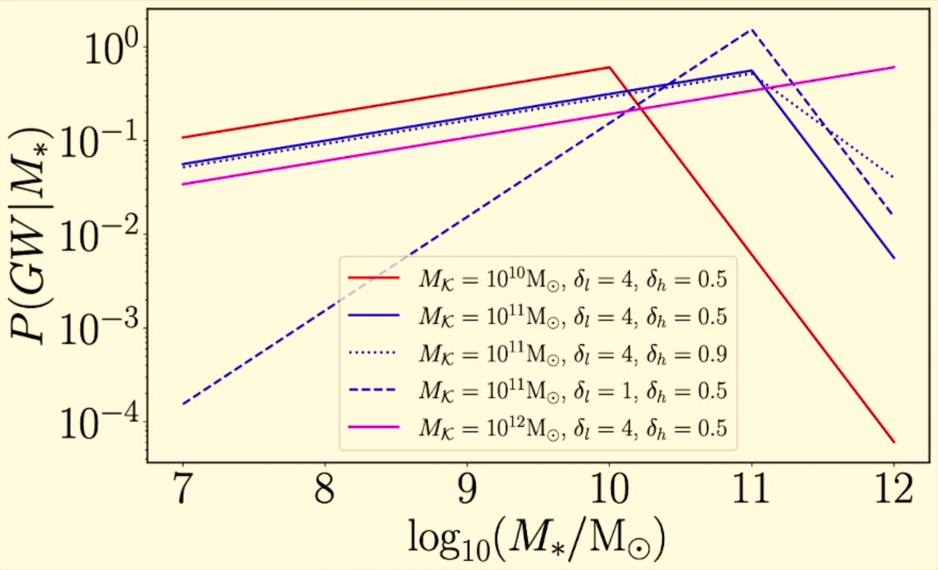
Host-galaxy probability, $P(GW|M_*)$

$$P_{\rm host}(\mathrm{GW}|\mathrm{M}_*) \propto \begin{cases} (M_*/M_{\mathcal{K}})^{1/\delta_l} & M_* \leq M_{\mathcal{K}}, \\ (M_*/M_{\mathcal{K}})^{1/\delta_h} & M_* \geq M_{\mathcal{K}}, \end{cases}$$

$\delta_l \in [0.5, 10]$

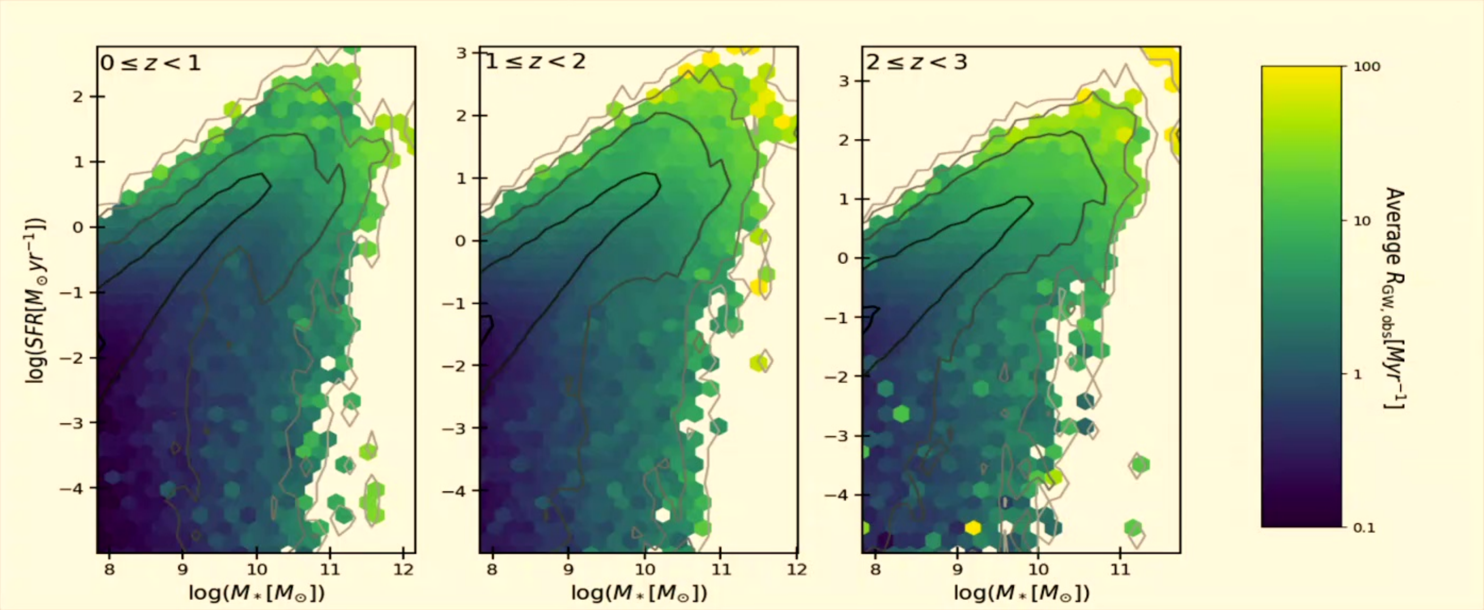
$\delta_h \in [0.1, 5]$

$M_{\mathcal{K}} \in [10^9\mathrm{M}_\odot, 10^{12}\mathrm{M}_\odot]$



Host-galaxy probability, $P(GW|M_*)$

- Connection between GW merger rates of BBH and galaxy properties.
- By generating populations of stars using the binary population synthesis code COMPAS.
- Evolving them in galaxies from the semi-analytic galaxy formation model Shark.



Rauf, et al., 2023.

Host-galaxy probability, $P(GW|M_*)$

- **GalaxyRate**
  code for estimation of the merger rate density.
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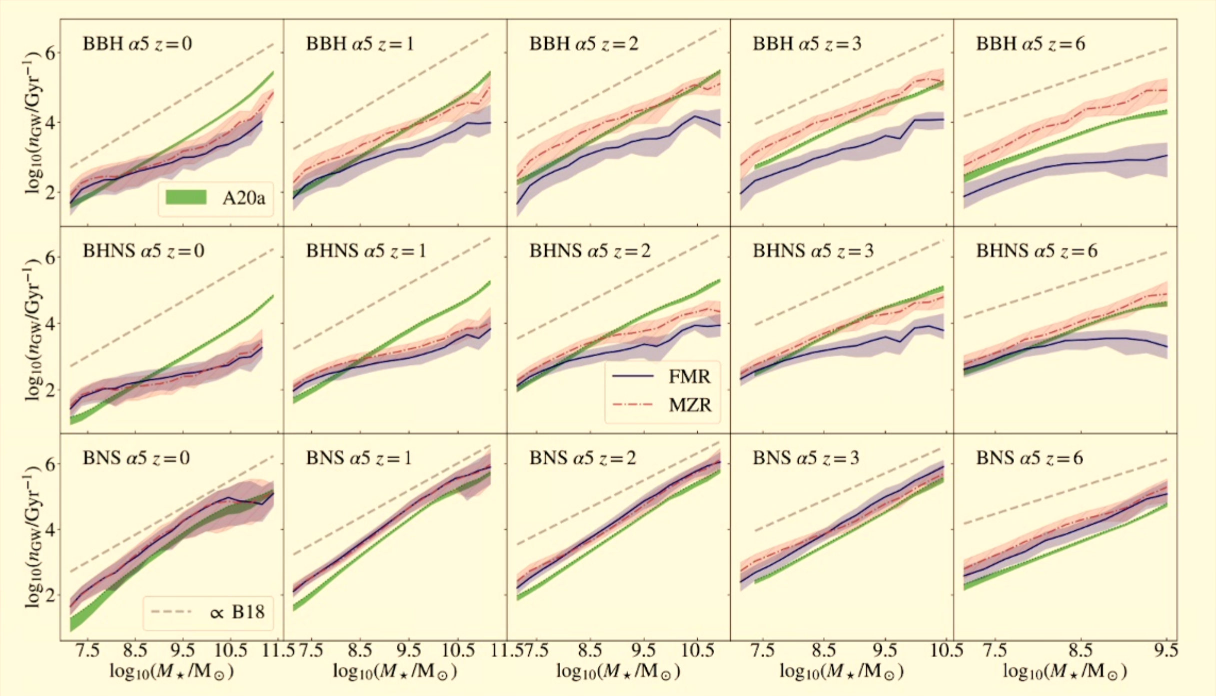
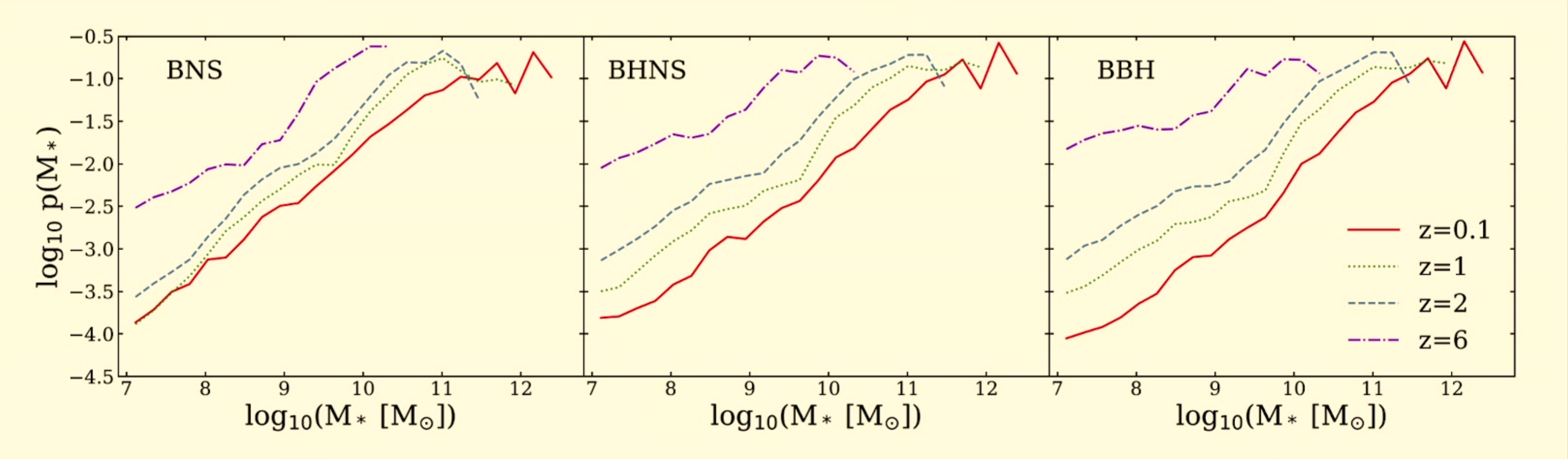


Santoliquido, et al., 2022.

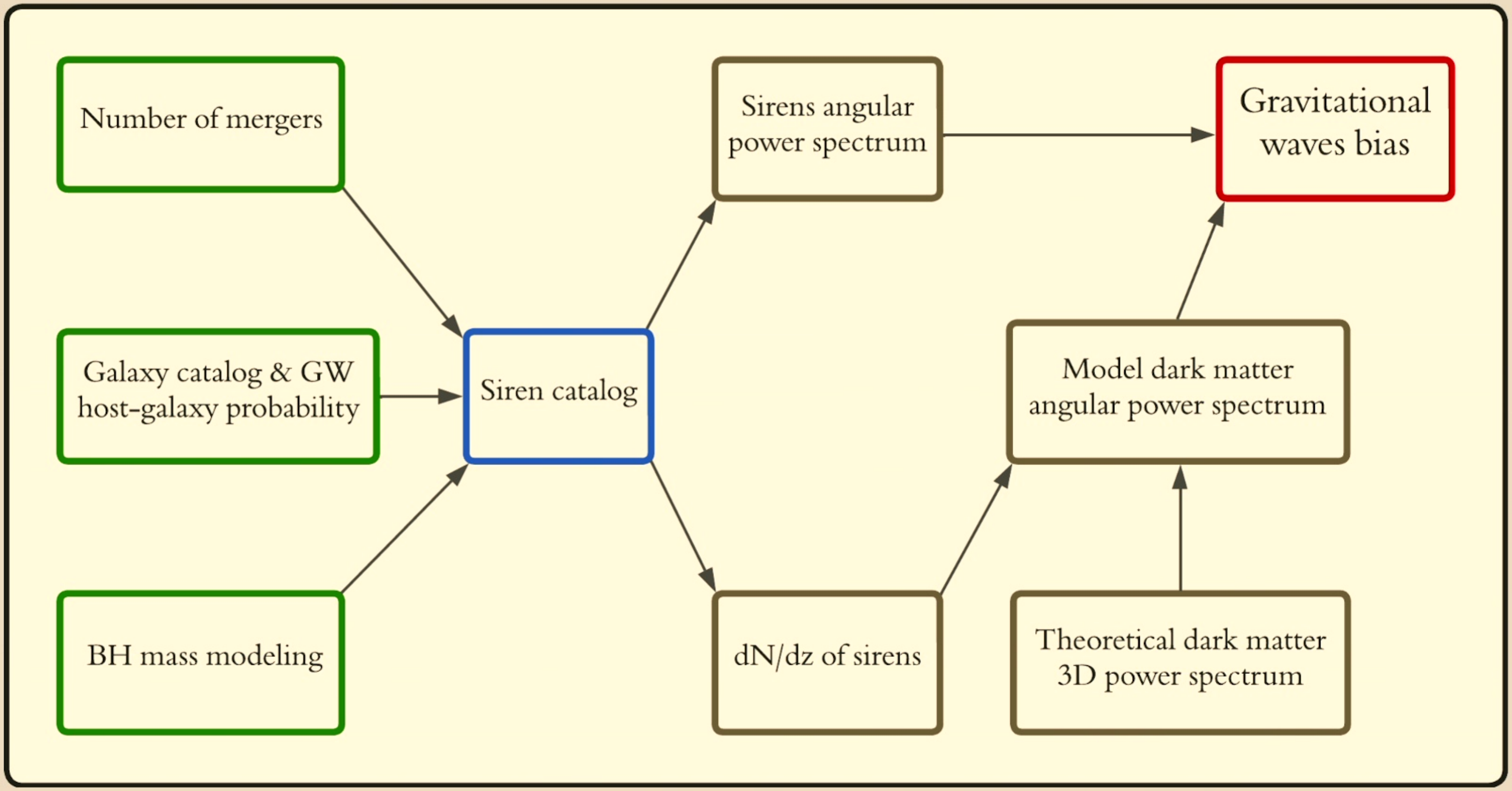
Host-galaxy probability, $P(GW|M_*)$

- Investigating the properties of the host galaxies of CBOs.
- By means of population-synthesis simulations (MOBSE).
- Combined with galaxy catalogues from the eagle suite (simulation).



M. C, Artale, et al., 2020.

Our proposal



Number of mergers

Galaxy catalog & GW host-galaxy probability

BH mass modeling

Siren catalog

Sirens angular power spectrum

dN/dz of sirens

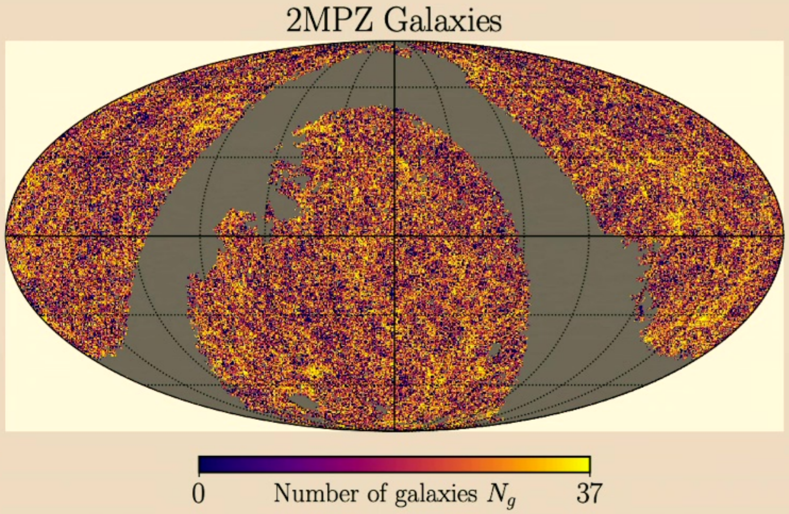
Gravitational waves bias

Model dark matter angular power spectrum

Theoretical dark matter 3D power spectrum

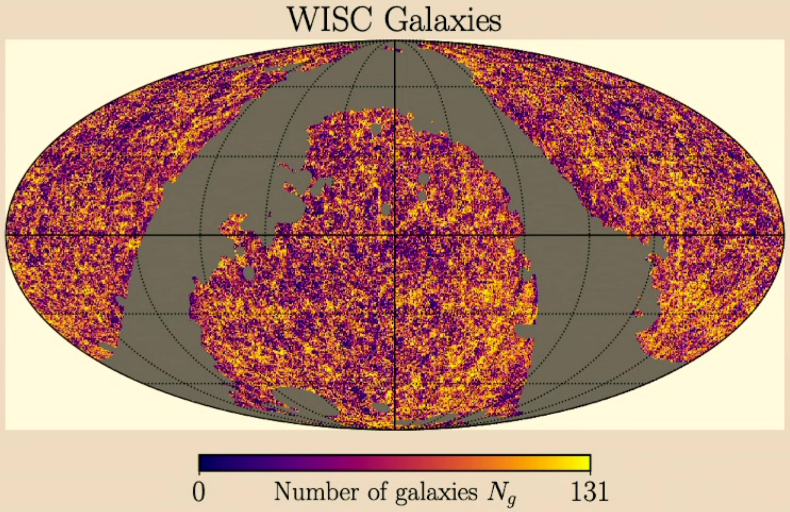
Photometric Redshift Galaxy Catalogs

- 1 million galaxies, with a median z = 0.07.



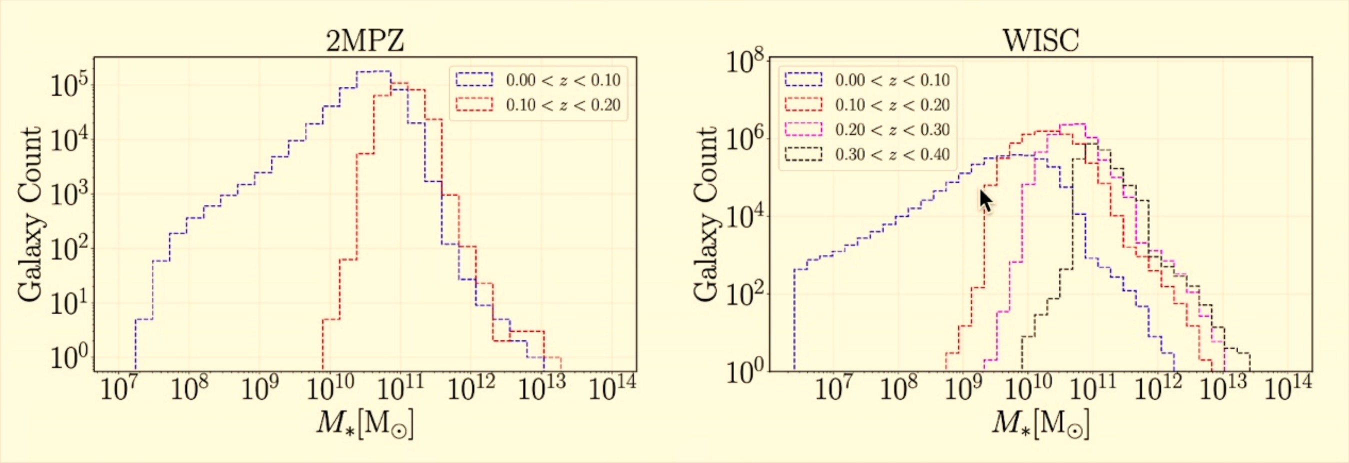
Built by cross-matching the 2 Micron All-Sky Survey Extended Source Catalog (2MASS XSC), the All-Sky data release of the Wide-field Infrared Survey Explorer (WISE), and SuperCOSMOS.

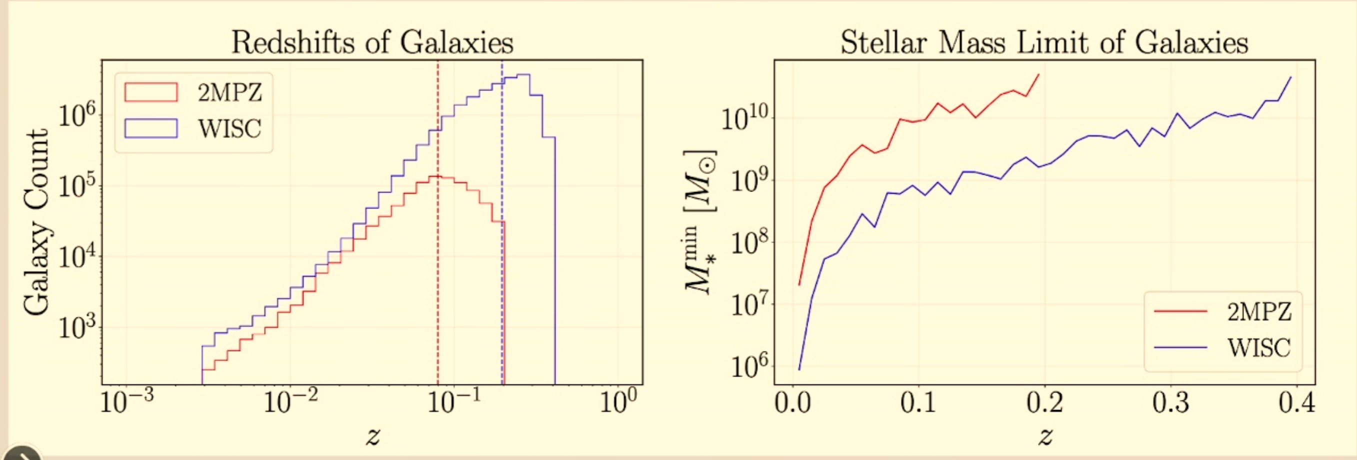
- 18.5 million galaxies with a median of z = 0.2.



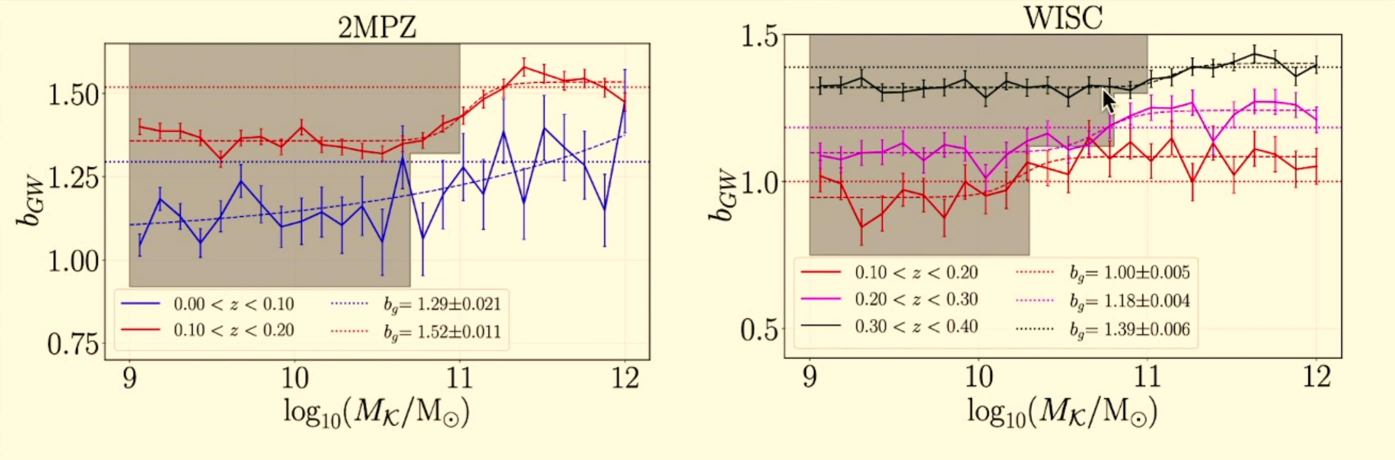
WISExSCOS Photometric Redshift catalog (WISExS- COSPZ, or WISC for short).

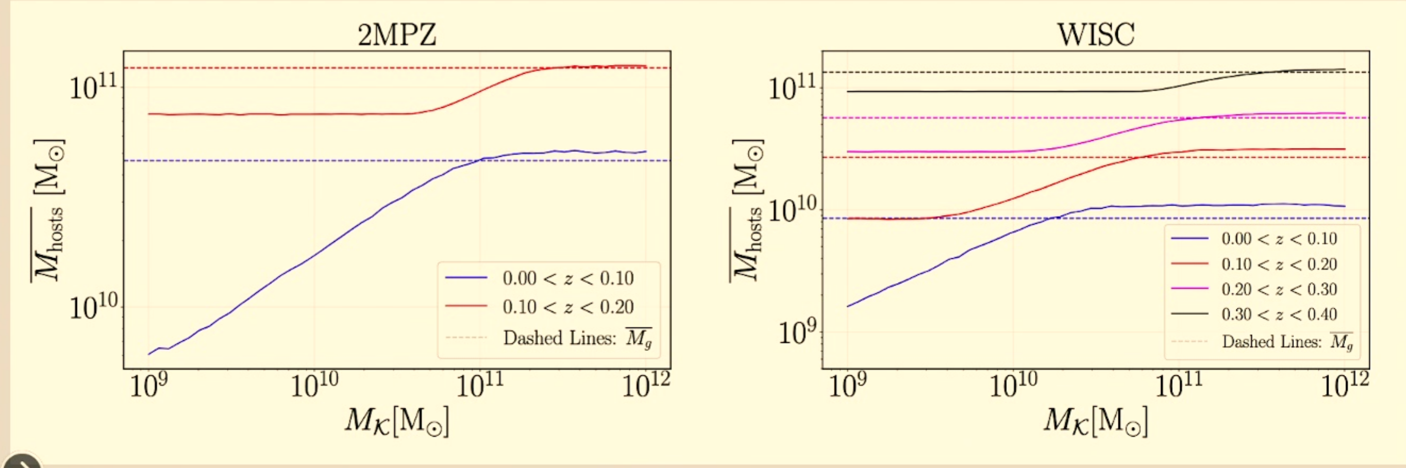
Galaxy Catalogs



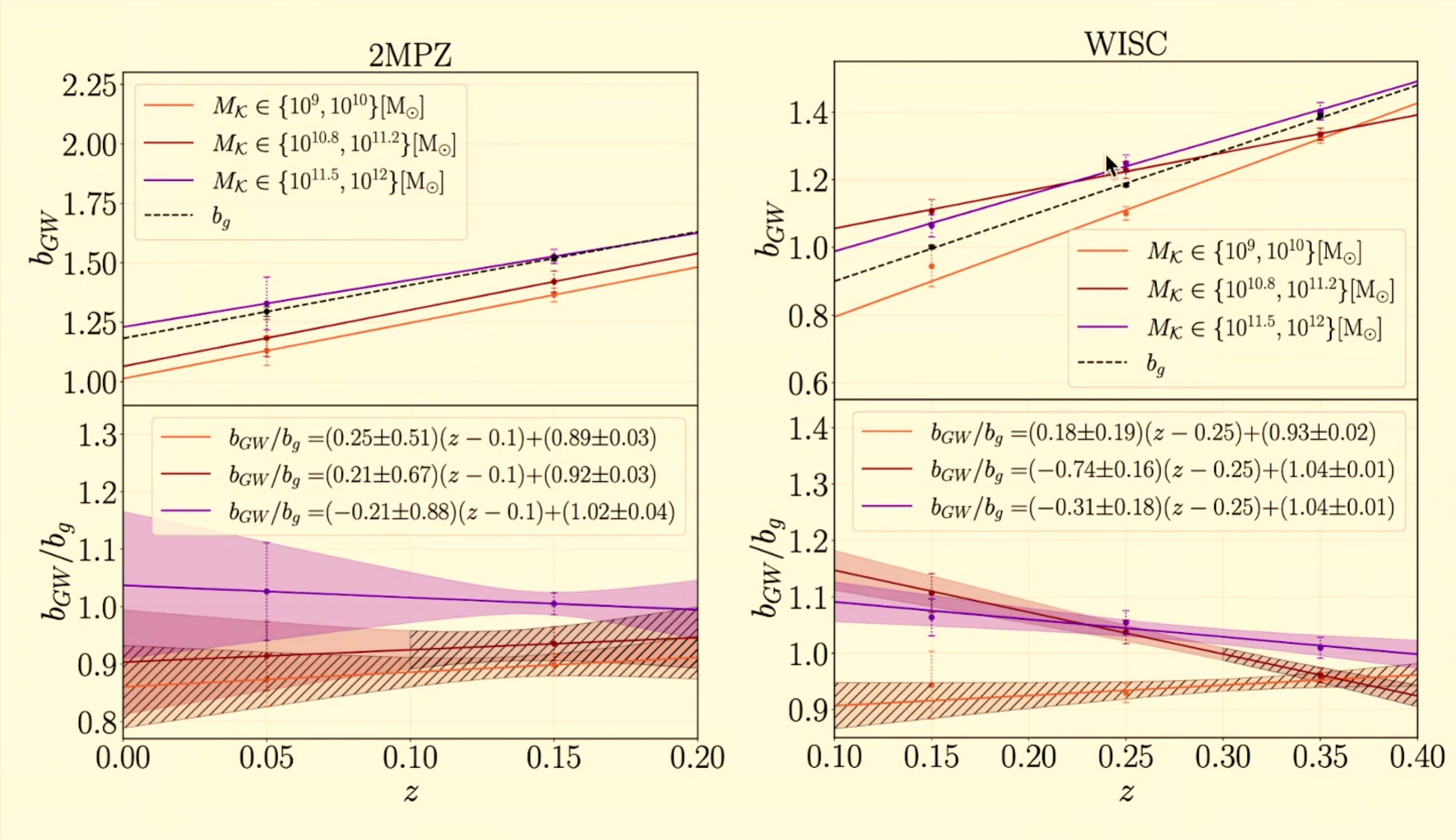


Results

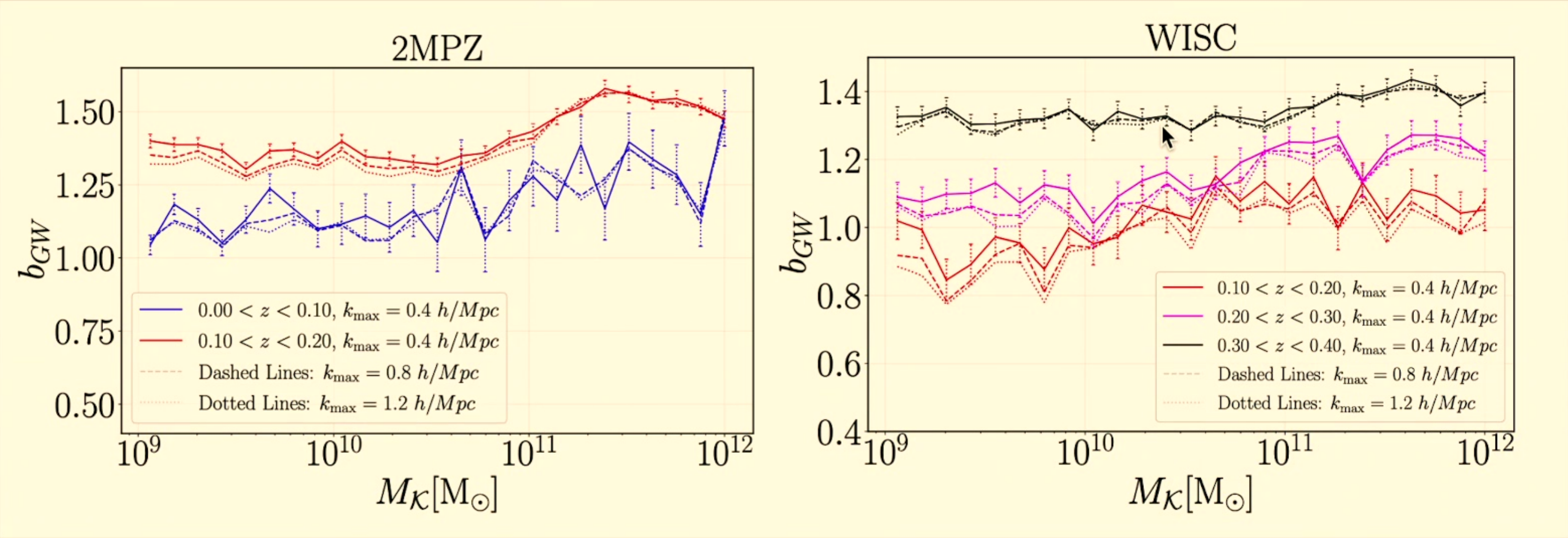

2MPZ
WISC
b_{GW}
1.50
1.25
1.00
0.75
1.5
1.0
0.5
9
10
11
12
$\log_{10}(M_\mathcal{K}/\mathrm{M}_\odot)$
$0.00 < z < 0.10$
$0.10 < z < 0.20$
$b_g = 1.29 \pm 0.021$
$b_g = 1.52 \pm 0.011$
$0.10 < z < 0.20$
$0.20 < z < 0.30$
$0.30 < z < 0.40$
$b_g = 1.00 \pm 0.005$
$b_g = 1.18 \pm 0.004$
$b_g = 1.39 \pm 0.006$


2MPZ
WISC
$\overline{M_{\mathrm{hosts}}}\,[\mathrm{M}_\odot]$
10^{11}
10^{10}
10^{9}
10^{9}
10^{10}
10^{11}
10^{12}
$M_\mathcal{K}[\mathrm{M}_\odot]$
$0.00 < z < 0.10$
$0.10 < z < 0.20$
$0.20 < z < 0.30$
$0.30 < z < 0.40$
Dashed Lines: $\overline{M_g}$

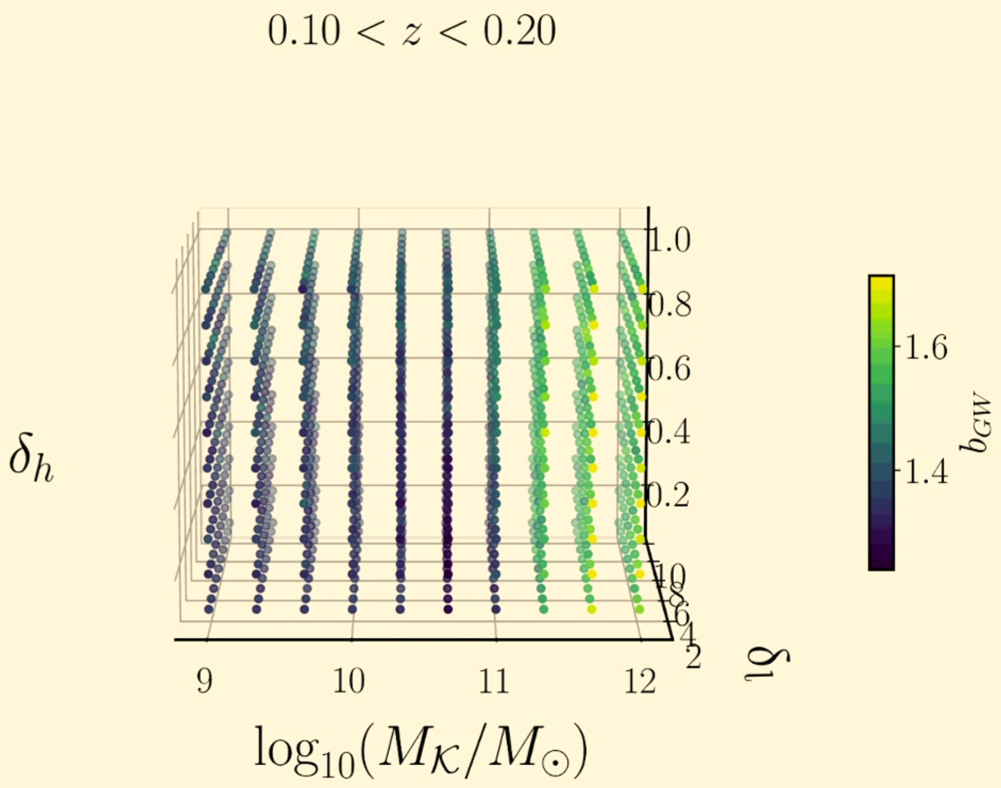
Results


2MPZ
WISC
$M_K \in \{10^9, 10^{10}\}[\mathrm{M}_\odot]$
$M_K \in \{10^{10.8}, 10^{11.2}\}[\mathrm{M}_\odot]$
$M_K \in \{10^{11.5}, 10^{12}\}[\mathrm{M}_\odot]$
b_g
b_{GW}
b_{GW}/b_g
$b_{GW}/b_g = (0.25\pm0.51)(z-0.1)+(0.89\pm0.03)$
$b_{GW}/b_g = (0.21\pm0.67)(z-0.1)+(0.92\pm0.03)$
$b_{GW}/b_g = (-0.21\pm0.88)(z-0.1)+(1.02\pm0.04)$
$b_{GW}/b_g = (0.18\pm0.19)(z-0.25)+(0.93\pm0.02)$
$b_{GW}/b_g = (-0.74\pm0.16)(z-0.25)+(1.04\pm0.01)$
$b_{GW}/b_g = (-0.31\pm0.18)(z-0.25)+(1.04\pm0.01)$
2.25
2.00
1.75
1.50
1.25
1.00
1.3
1.2
1.1
1.0
0.9
0.8
0.00
0.05
0.10
0.15
0.20
1.4
1.2
1.0
0.8
0.6
1.4
1.3
1.2
1.1
1.0
0.9
0.10
0.15
0.20
0.25
0.30
0.35
0.40
z
z

Results


2MPZ
1.50
1.25
1.00
0.75
0.50
b_{GW}
10^9
10^{10}
10^{11}
10^{12}
$M_{\mathcal{K}}[\mathrm{M}_\odot]$
$0.00 < z < 0.10$, $k_{\max} = 0.4\ h/Mpc$
$0.10 < z < 0.20$, $k_{\max} = 0.4\ h/Mpc$
Dashed Lines: $k_{\max} = 0.8\ h/Mpc$
Dotted Lines: $k_{\max} = 1.2\ h/Mpc$
WISC
1.4
1.2
1.0
0.8
0.6
0.4
b_{GW}
10^9
10^{10}
10^{11}
10^{12}
$M_{\mathcal{K}}[\mathrm{M}_\odot]$
$0.10 < z < 0.20$, $k_{\max} = 0.4\ h/Mpc$
$0.20 < z < 0.30$, $k_{\max} = 0.4\ h/Mpc$
$0.30 < z < 0.40$, $k_{\max} = 0.4\ h/Mpc$
Dashed Lines: $k_{\max} = 0.8\ h/Mpc$
Dotted Lines: $k_{\max} = 1.2\ h/Mpc$

Cool Plots


$0.10 < z < 0.20$
δ_h
1.0
0.8
0.6
0.4
0.2
10
8
6
4
2
δ_l
9
10
11
12
$\log_{10}(M_{\mathcal{K}}/M_\odot)$
1.6
1.4
b_{GW}

Summary

- We have studied the dependence of the GW bias parameter for BBHs on the GW host-galaxy probability using observed galaxy catalogs.

- This method allows
  - More flexibility for the host-galaxy probability.
  - Probing a larger volume than simulations.
  - Avoiding dependence on uncertain galaxy formation physics.

- The GW host-galaxy probability is characterized by a broken power law in stellar mass that rises at low mass and falls at high mass.

- The presence of a turnover point in the selection function, M_K, is motivated by the two timescales in the problem, the delay time and the quenching time.

Summary

- Longer delay time ≡ Higher M_K ≡ Higher GW bias.
- For the fiducial values of the slopes (mild increase rate, and strong suppression rate), GW bias is 5-10% more than galaxy bias depending on the value of M_K.
- Assuming stronger positive slope, the GW bias can surpass galaxy bias by 10-30% depending on the value of M_K.
- Stay tuned for the next paper (coming soon) where we use spectroscopic surveys (hence 3D power spectrum) with metallicity and SFR also measured.

Thank you!