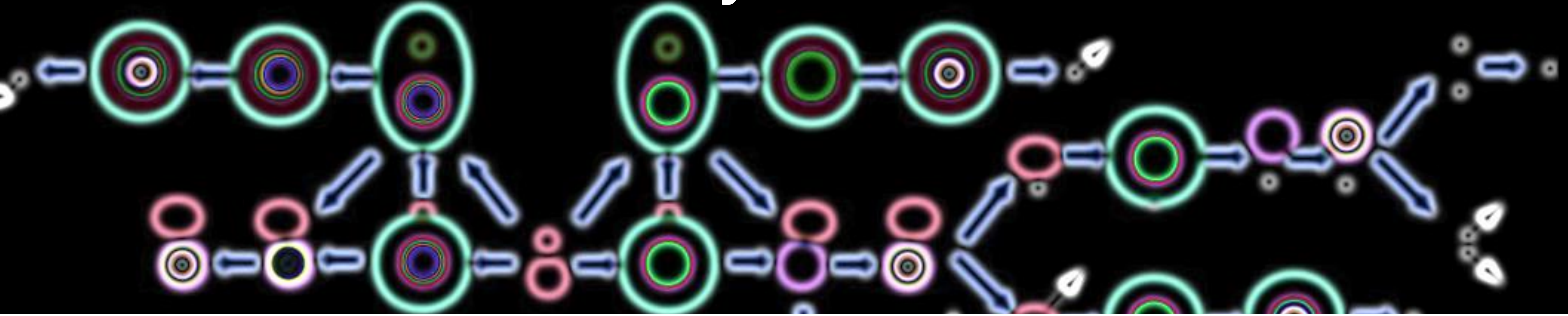
Understanding the stars that make ripples in spacetime.

Jan J. Eldridge,

Elizabeth Stanway and the BPASS team



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NEW ZEALAND

WARWICK
THE UNIVERSITY OF WARWICK

Who am I?

A. Prof. JJ/Jan Eldridge

She/her/they pronouns.

Astro**physicist.**

UoA Physics **HoD**.

"I study **exploding binary stars** while exploding the **myth of a gender binary**."

Work on **stars, galaxies, supernovae**....

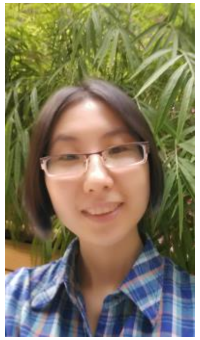
Twitter: **@astro_jje**

The BPASS team…!

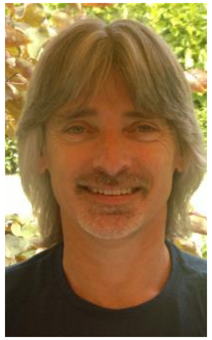
Jan Eldridge

Elizabeth Stanway

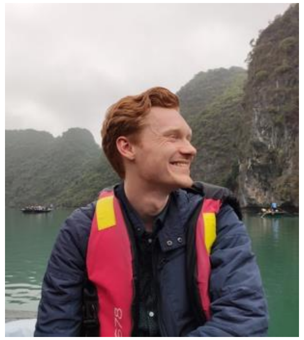
Heloise Stevance



Lin Xiao



John Bray



Max Briel

Emma Chittenden

Petra Tang

Wouter Van Zeist

Sohan Ghodla

Sean Richards

Gleb Geinke

Adib Mowaz

Louis Newton

and previously…

Sirius Sun
Celina Emma
Amanda Lee
Ashley Chrimes
Liam McClelland
Georgie Taylor
Mason Ng
Lillian Guo
Nicole Rodrigues
Lucas Ostrowski
Itwinder Singh

binary population and spectral synthesis

Developed by Elizabeth Stanway and JJ Eldridge to study a broad range of astrophysical systems in the Universe: **stars, supernovae, clusters, galaxies, compact remnant mergers**

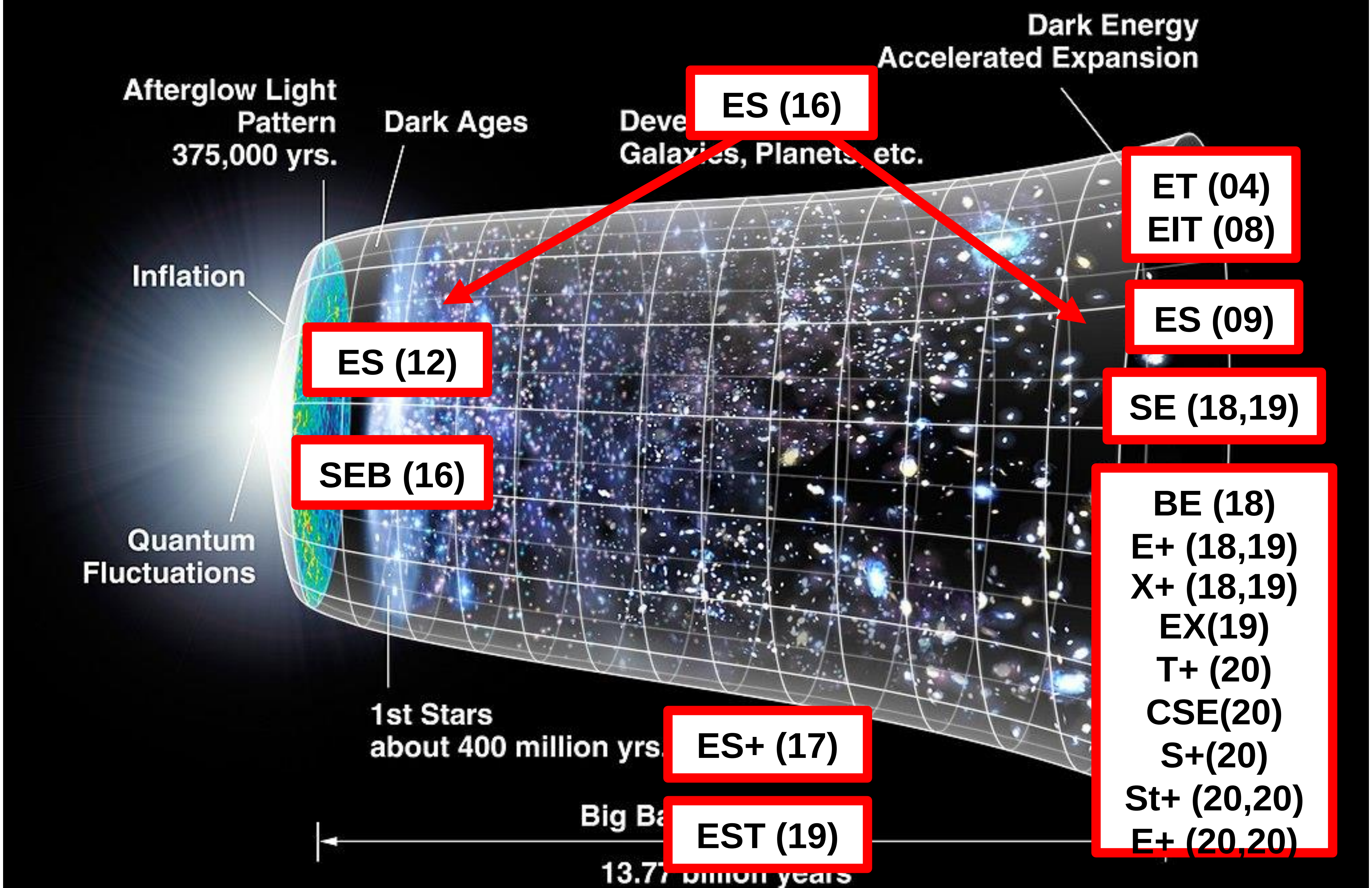
“Be the theoretical equivalent of multi-messenger observations, make one model of stars in the Universe and observe in every way possible”.

BPASS.AUCKLAND.AC.NZ and WARWICK.AC.UK/BPASS

It is now really easy to use thanks to:

Python package for easy use: **HOKI** details and cookbooks at **HELOISE.GITHUB.IO/HOKI/INTRO**.

Have a star or star cluster you want to understand, search for it with BPASS! Email us if you have questions.


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Deve
Galaxies, Planets, etc.
ES (16)
ET (04)
EIT (08)
ES (09)
Inflation
ES (12)
SE (18,19)
SEB (16)
BE (18)
E+ (18,19)
X+ (18,19)
EX(19)
T+ (20)
CSE(20)
S+(20)
St+ (20,20)
E+ (20,20)
Quantum
Fluctuations
1st Stars
about 400 million yrs.
ES+ (17)
Big Ba
EST (19)
13.77 billion years

binary population and spectral synthesis

The main papers:

- Stanway, Eldridge & Becker (16) – Reionization **v2.0**
- Eldridge & Stanway (16) – GW events
- Bray & Eldridge (16,18) – Supernova kicks
- **Eldridge, Stanway et al. (17)** – Instrument paper ***v2.1 Kiwi***
- Xiao, Stanway & Eldridge (18,19) – HII regions
- **Stanway & Eldridge (18)** – Old populations ***v2.2 Tuatara***
- Eldridge, Stanway & Tang (19) – GW & EM transients
- Eldridge, Tang, Bray & Stanway (18) – Chirp mass distribution of GW events
- Eldridge, Xiao et al. (18) – CURVEPOPS 1
- Stanway & Eldridge (19) – IMF and ionizing photons
- Eldridge & Xiao (19) – NGC 6946 distance & progenitors
- Eldridge, Guo, Rodriguez et al. (19) – CURVEPOPS 2
- Tang, Eldridge, Stanway & Bray (2020) - SFH & GW events
- **Stevance et al. (2020) – Hoki**
- Stevance et al. (2020) – HII region ages - **AgeWizard**
- Chrimes et al. (2020) – Tides in BPASS and long-GRBs
- Stanway et al. (2020) – Changing initial binary parameters effects
- Eldridge, Beasor & Britzvskiy (2020) – Using RSGs to estimate star cluster ages
- Eldridge et al. (2020) – LB1 doesn’t contain a 70Msun black hole
- Stanway et al. (2020) – Binary fractions, stellar populations and supernova rates.
- Coming soon: X-ray binaries and more... I need more time....

What is Hoki?

Note

NEW FEATURES: Check out AgeWizard - A pipeline to systematically age any resolved stellar population!

Bridging the gap between theory and observations

Historically, theoretical models have been released to the community with the expectation that users would create their own data handling scripts as they perform the analysis. This was in line with a research culture where most people had their own code, resulting in a duplication of effort and creating the potential for a reproducibility crisis, as most personal scripts are not shared with the community.

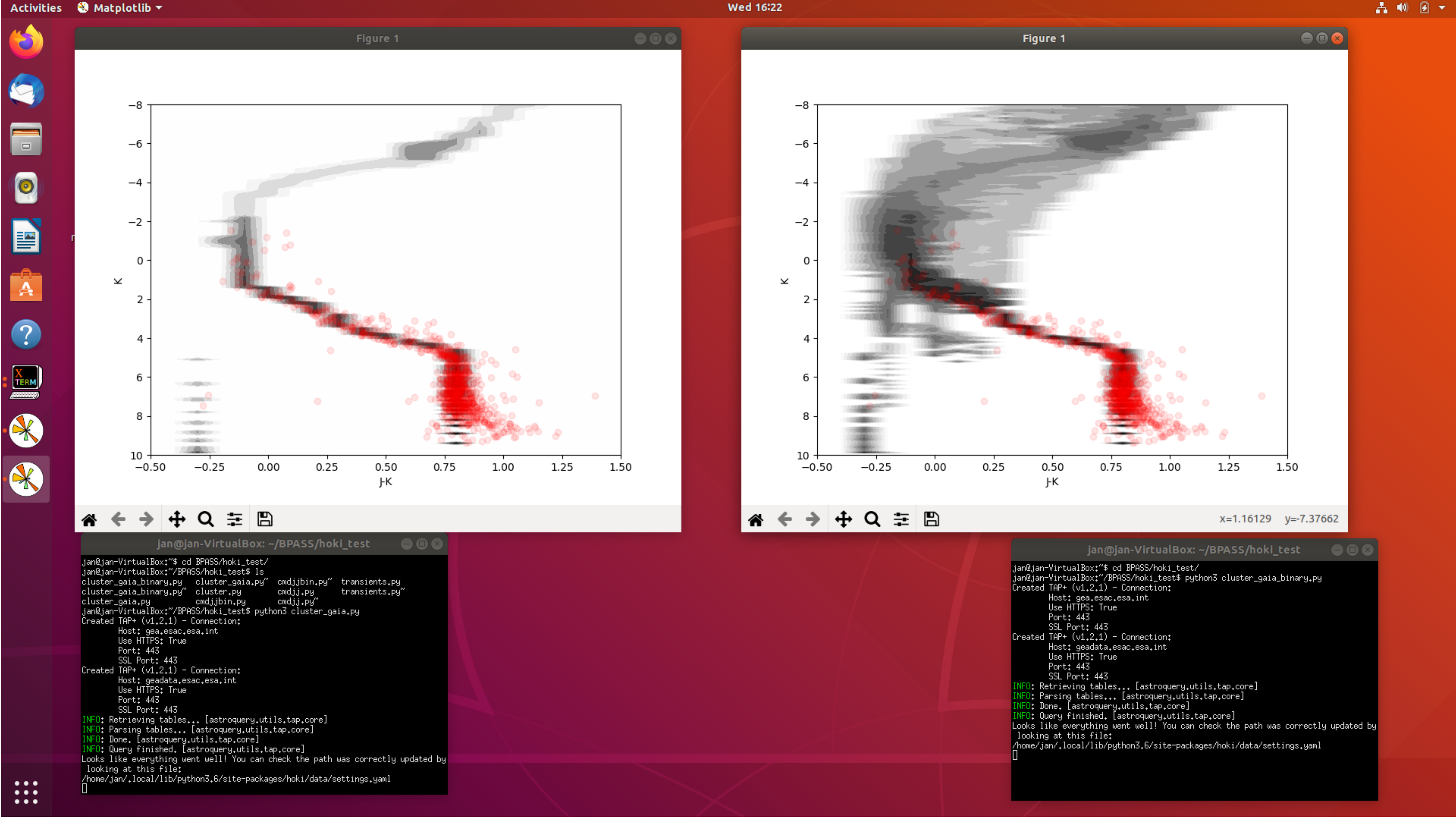
In order to facilitate the application of BPASS to a wide range of scientific investigations, we have developped the tools necessary for observers to take full advantage of our models in a stream-lined, intuitive manner.

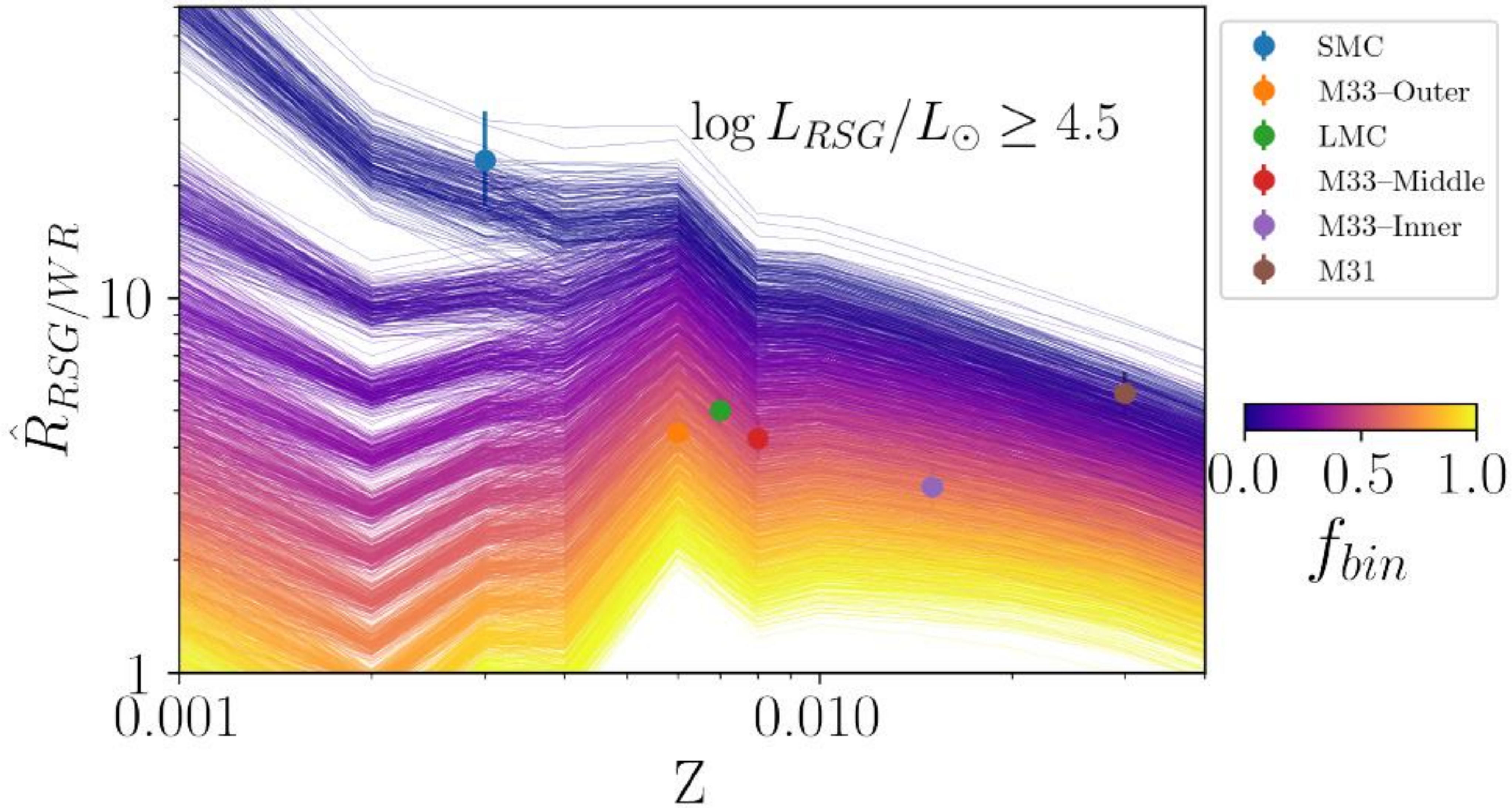
> **Hoki is a dedicated python package designed to provide a user friendly interface to the BPASS models in order to bridge the gap between theory and observations.**

The varsatility of **Hoki** allows you to focus on the science, and worry less about the technical nitty gritty that comes with using the varied outputs of a theoretical code.

What is BPASS?

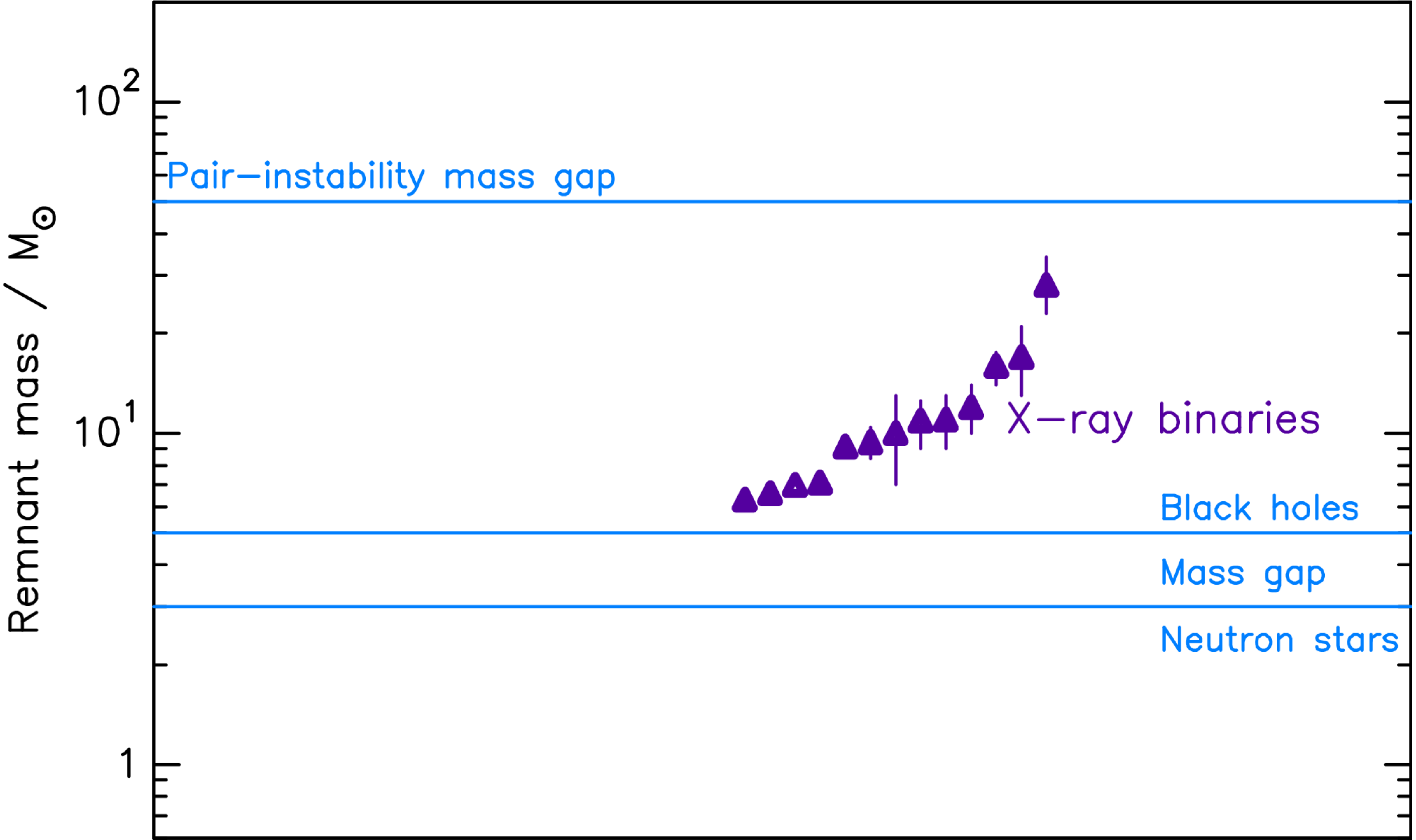
The **Binary Populations And Spectral Synthesis (BPASS)** code simulates stellar populations and follows their evolution until death. Including binary evolution is **crucial to correctly interpreting** astronomical observations. The detailed follow-up of the stellar evolution within the code allows the retreival of important information such as supernova and gravitational wave event rates, giving us the ability to understand the properties of the stellar populations that are the precursors of these events.


Activities
Matplotlib
Wed 16:22
Figure 1
K
J-K
Figure 1
K
J-K
x=1.16129 y=-7.37662
jan@jan-VirtualBox: ~/BPASS/hoki_test
jan@jan-VirtualBox:~$ cd BPASS/hoki_test/
jan@jan-VirtualBox:~/BPASS/hoki_test$ ls
cluster_gaia_binary.py cluster_gaia.py~ cmdjjbin.py~ transients.py
cluster_gaia_binary.py~ cluster.py cmdjj.py transients.py~
cluster_gaia.py cmdjjbin.py cmdjj.py~
jan@jan-VirtualBox:~/BPASS/hoki_test$ python3 cluster_gaia.py
Created TAP+ (v1.2.1) - Connection:
Host: gea.esac.esa.int
Use HTTPS: True
Port: 443
SSL Port: 443
Created TAP+ (v1.2.1) - Connection:
Host: geadata.esac.esa.int
Use HTTPS: True
Port: 443
SSL Port: 443
INFO: Retrieving tables... [astroquery.utils.tap.core]
INFO: Parsing tables... [astroquery.utils.tap.core]
INFO: Done. [astroquery.utils.tap.core]
INFO: Query finished. [astroquery.utils.tap.core]
Looks like everything went well! You can check the path was correctly updated by
looking at this file:
/home/jan/.local/lib/python3.6/site-packages/hoki/data/settings.yaml
jan@jan-VirtualBox: ~/BPASS/hoki_test
jan@jan-VirtualBox:~$ cd BPASS/hoki_test/
jan@jan-VirtualBox:~/BPASS/hoki_test$ python3 cluster_gaia_binary.py
Created TAP+ (v1.2.1) - Connection:
Host: gea.esac.esa.int
Use HTTPS: True
Port: 443
SSL Port: 443
Created TAP+ (v1.2.1) - Connection:
Host: geadata.esac.esa.int
Use HTTPS: True
Port: 443
SSL Port: 443
INFO: Retrieving tables... [astroquery.utils.tap.core]
INFO: Parsing tables... [astroquery.utils.tap.core]
INFO: Done. [astroquery.utils.tap.core]
INFO: Query finished. [astroquery.utils.tap.core]
Looks like everything went well! You can check the path was correctly updated by
looking at this file:
/home/jan/.local/lib/python3.6/site-packages/hoki/data/settings.yaml

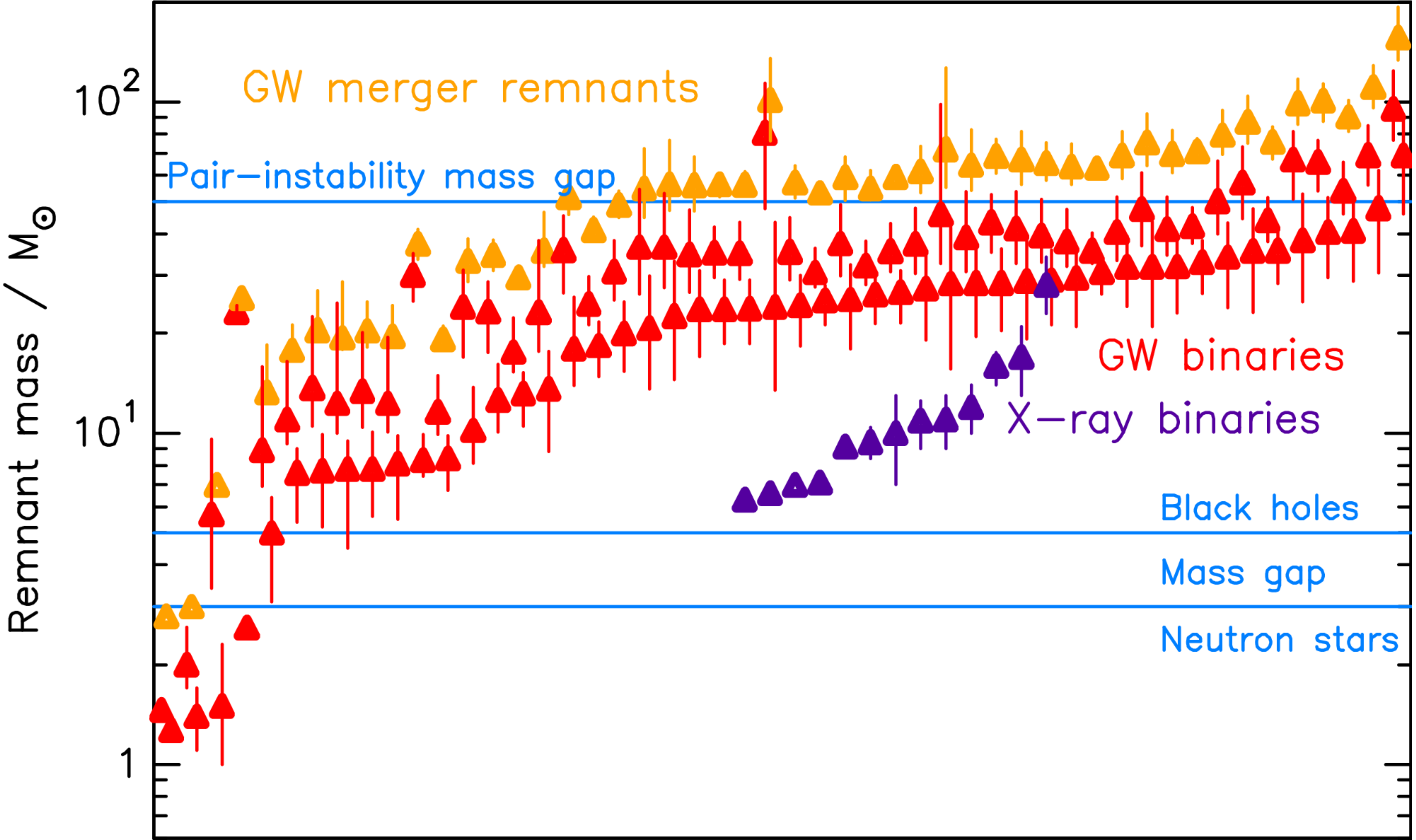


Massey et al. (2021)

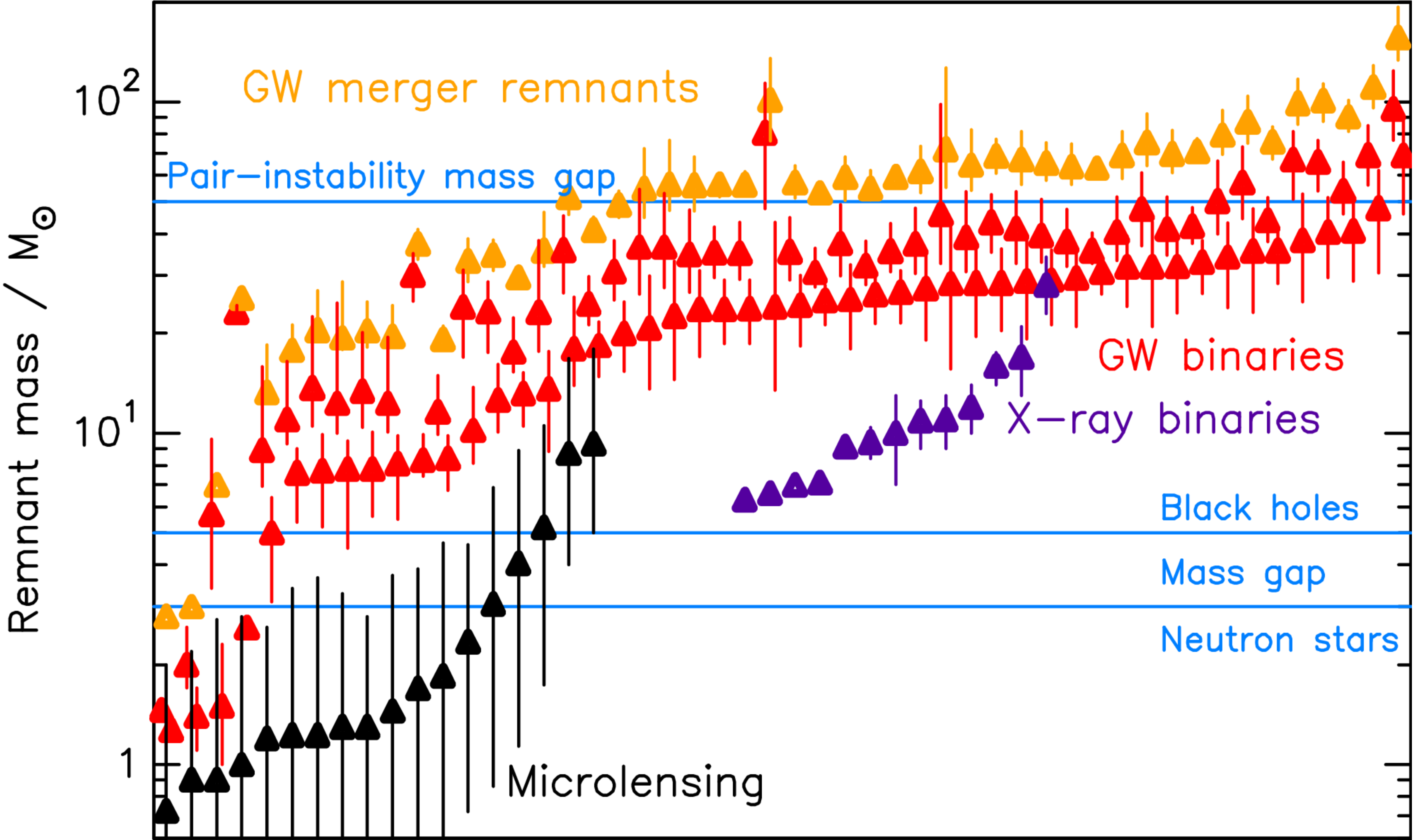
What are the masses of black holes?



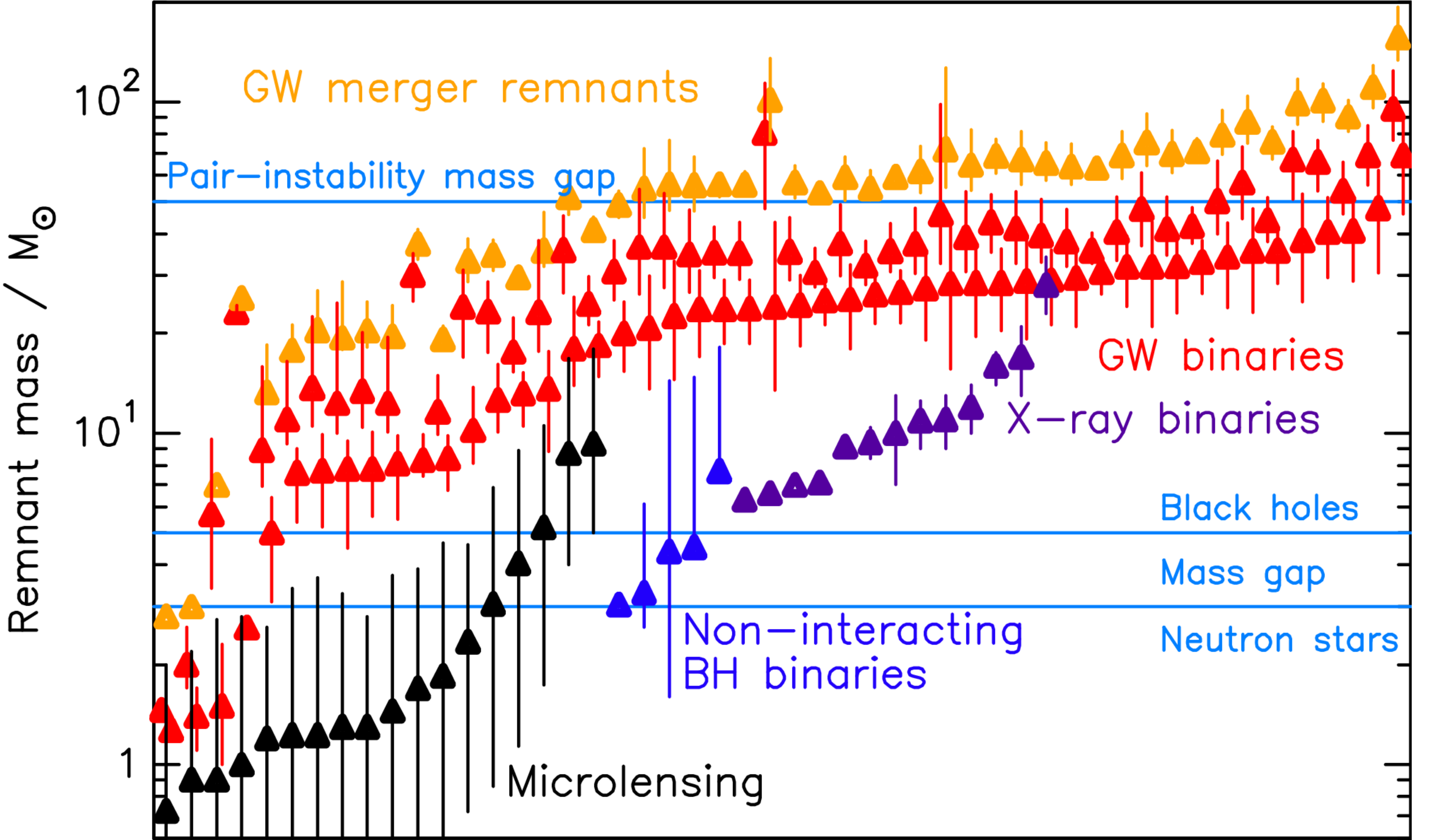
Remnant mass / M⊙
10^2
10^1
1
Pair-instability mass gap
X-ray binaries
Black holes
Mass gap
Neutron stars



GW merger remnants
Pair-instability mass gap
GW binaries
X-ray binaries
Black holes
Mass gap
Neutron stars
Remnant mass / $M_\odot$
10^2
10^1
1

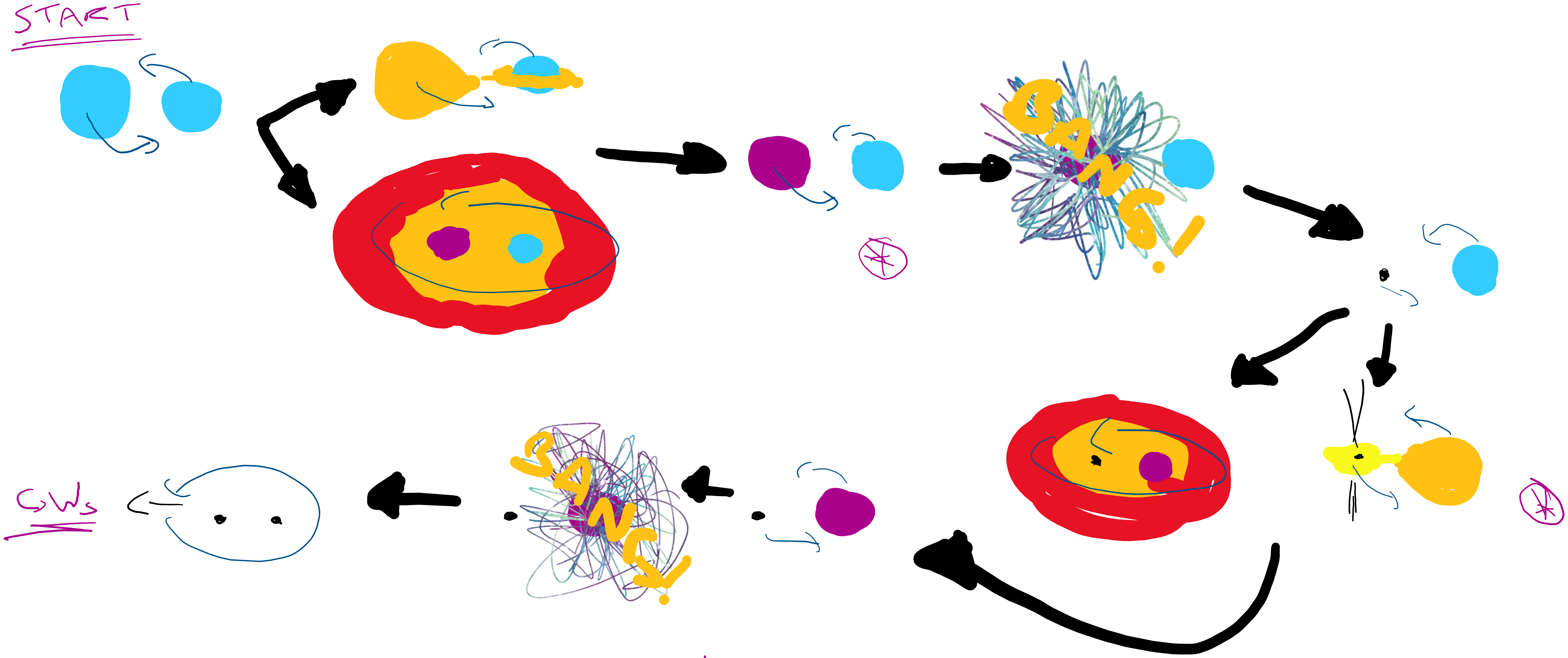


GW merger remnants
Pair-instability mass gap
GW binaries
X-ray binaries
Black holes
Mass gap
Neutron stars
Microlensing
Remnant mass / $M_\odot$
10^2
10^1
1



GW merger remnants
Pair−instability mass gap
GW binaries
X−ray binaries
Black holes
Mass gap
Neutron stars
Non−interacting
BH binaries
Microlensing
10^2
10^1
1
Remnant mass / $M_\odot$

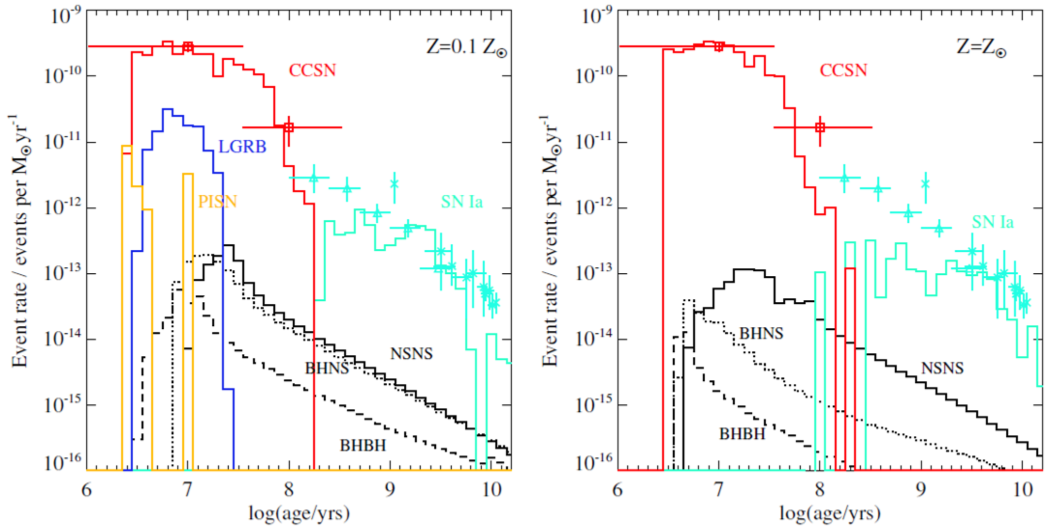
Which stars make ripples in spacetime?



(*) - Typically BH forms first, unless mass transfer is efficient.
So BH forms 2nd, note in BPASS also causes QHE.
In BPASS would mean no XRB!

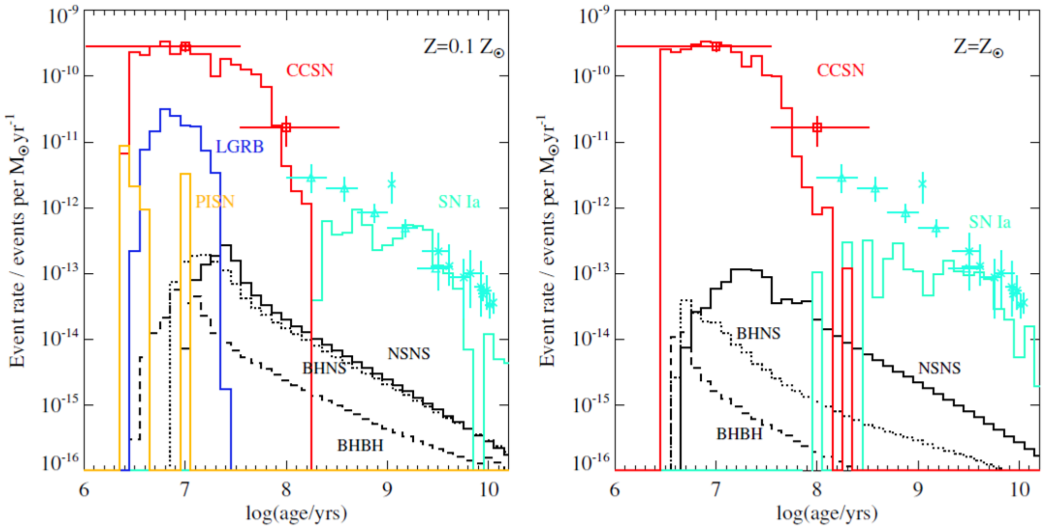
How we **model** the GW transients?

Delay-time distribution

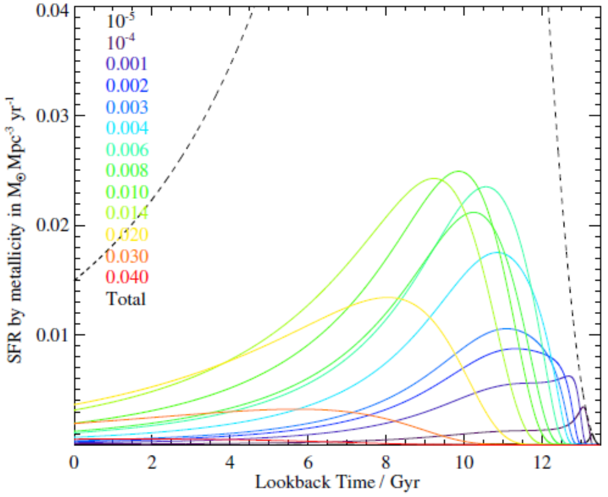


BPASSv2.2

Delay-time distribution

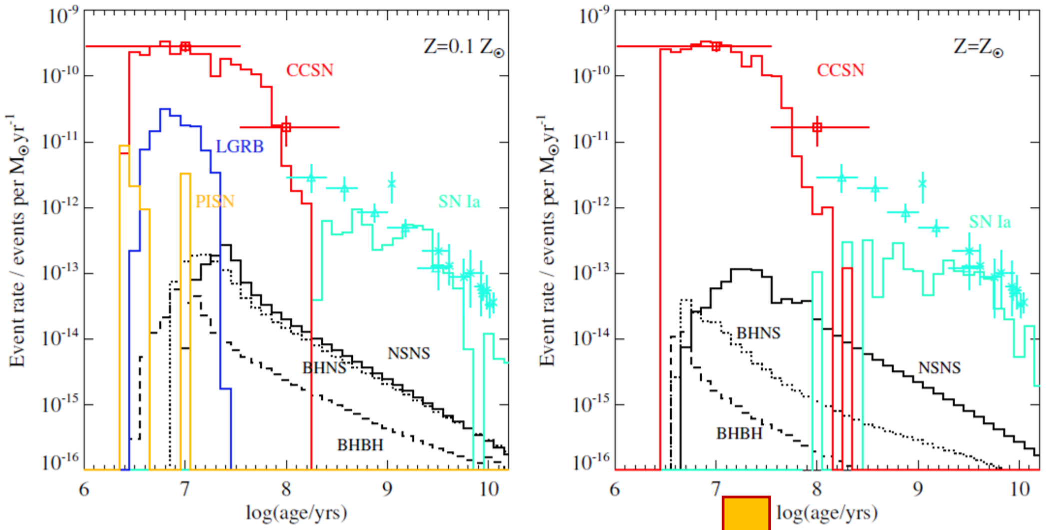


Cosmic star formation history

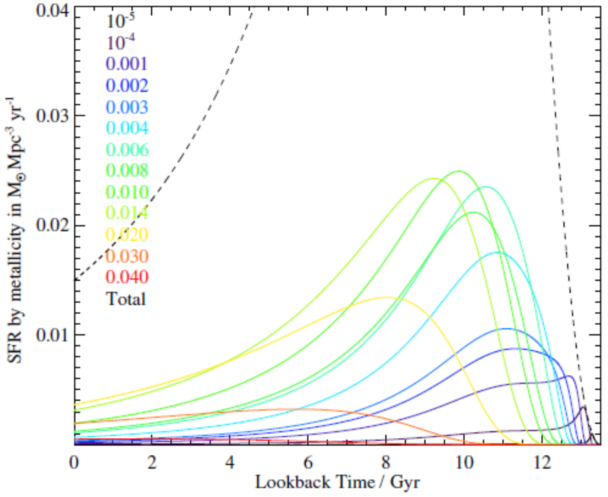


BPASSv2.2

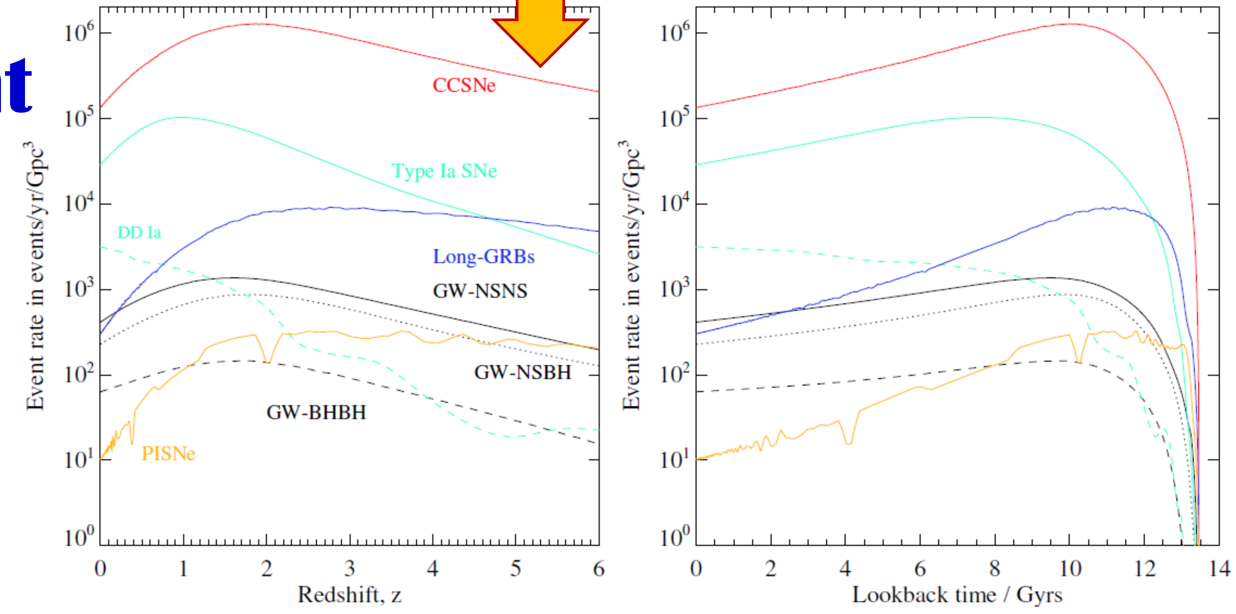
Delay-time distribution



Cosmic star formation history

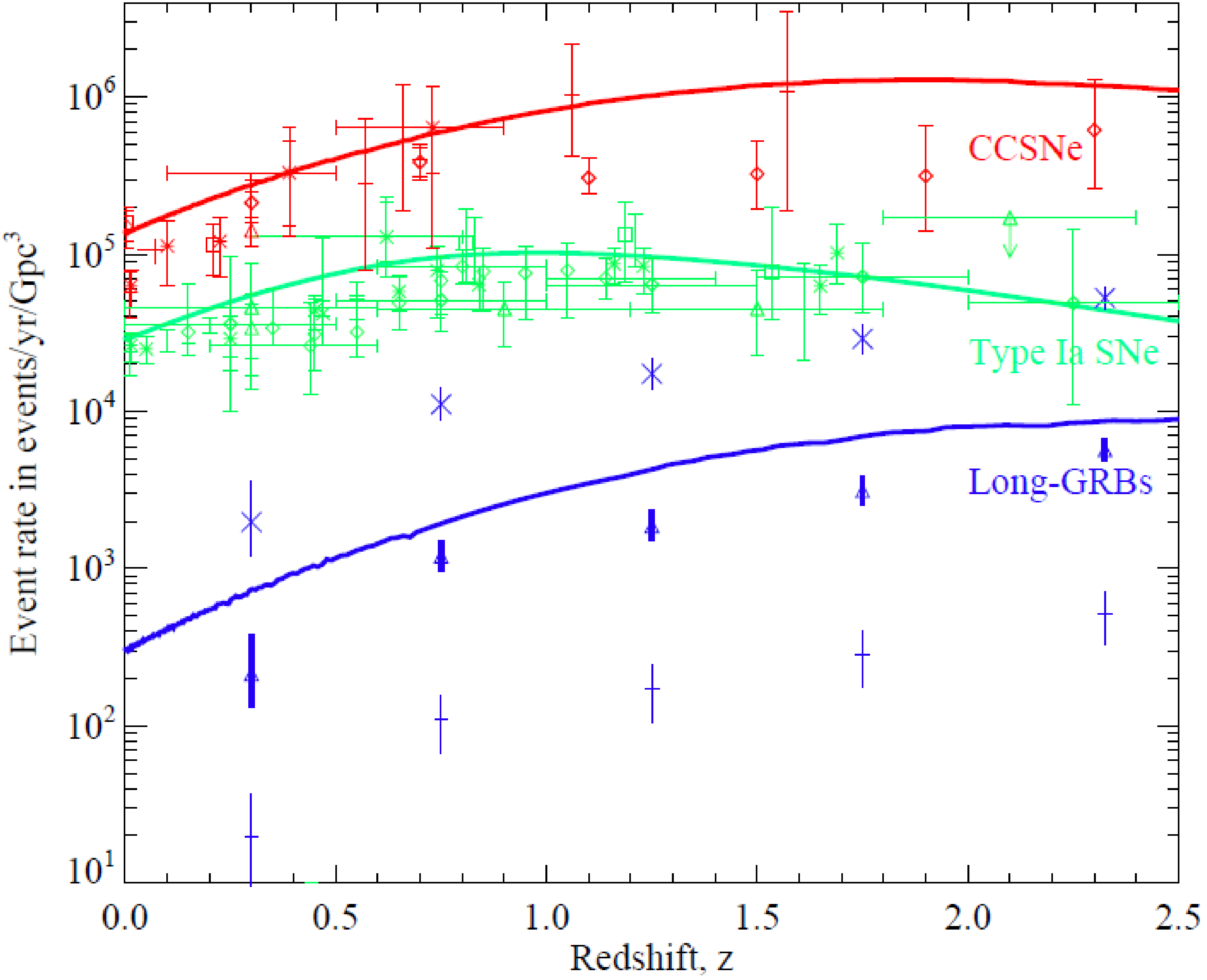


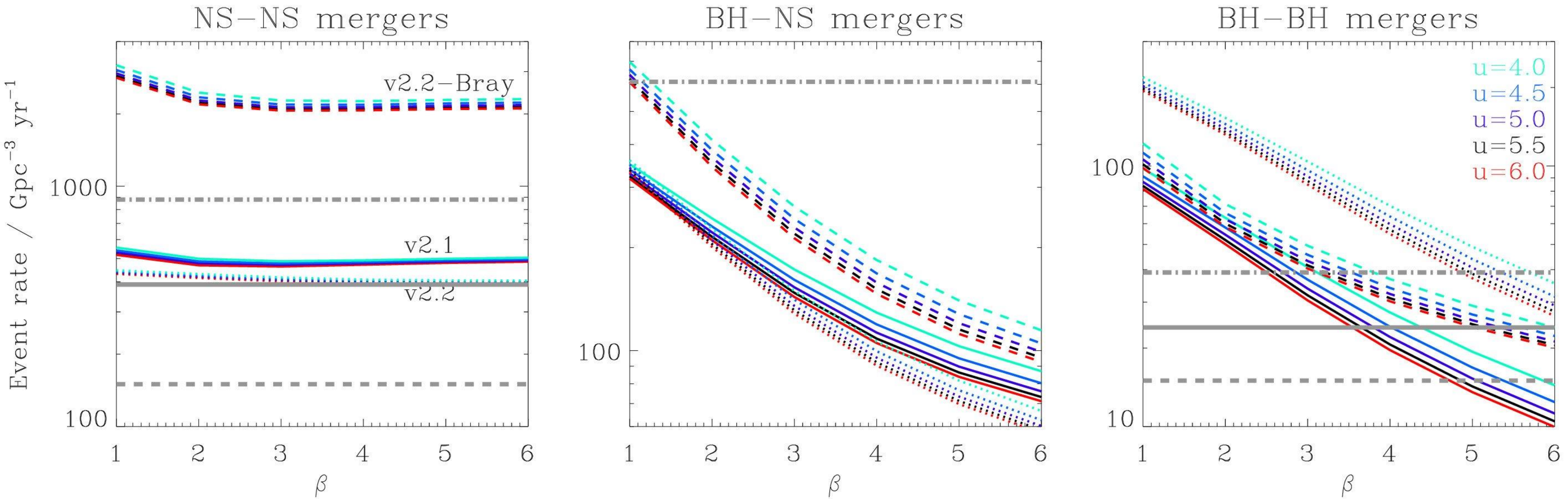
Transient cosmic history



BPASSv2.2

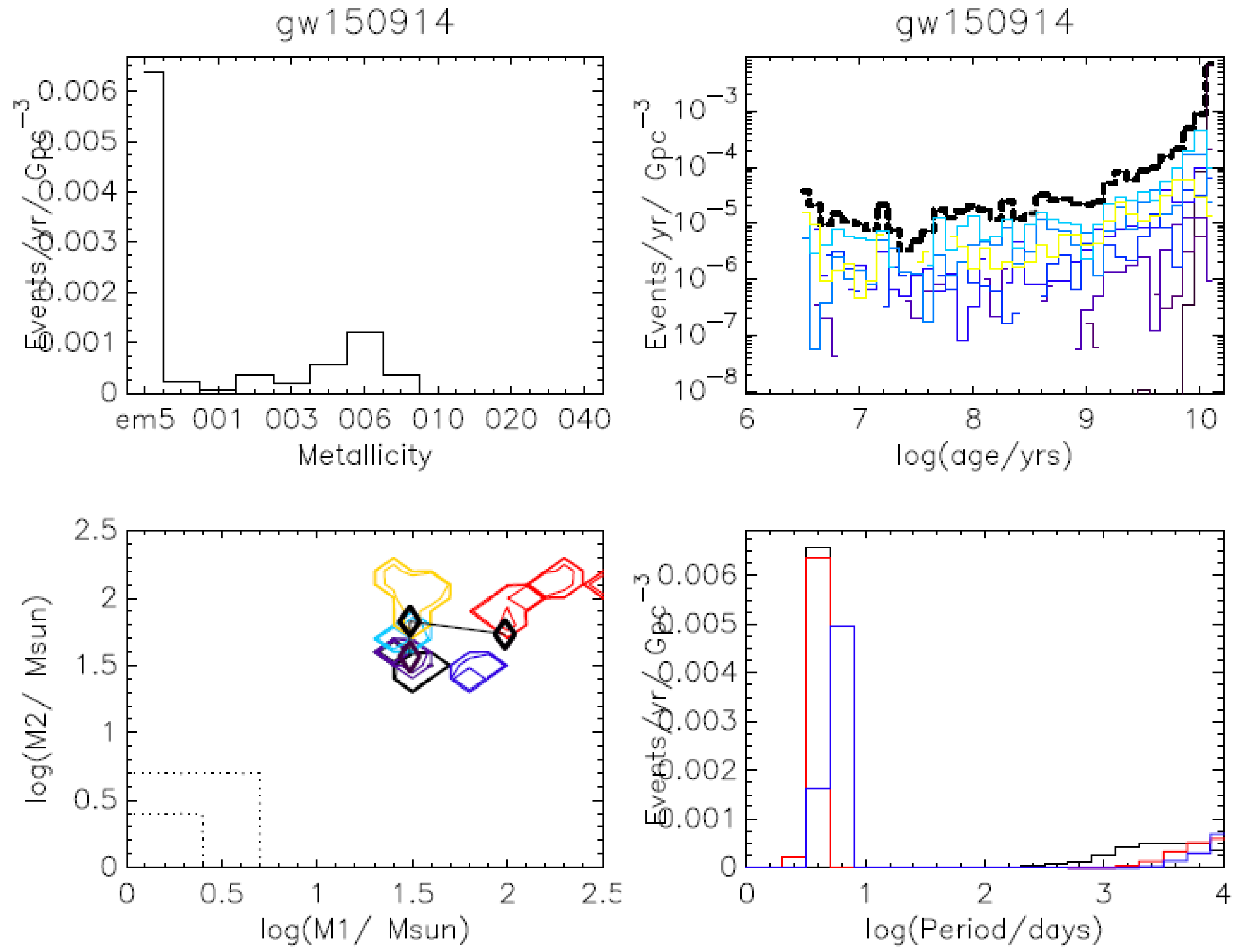
EM event rates (supernovae)





BPASS v2.1 and v2.2

Tang et al. (2020).



35.6000 30.6000

gw150914 0 QHE(no/yes/event rate): 29.709429 70.290571 0.0093831510

log(Age/yrs): 9.9452195± 0.51822353

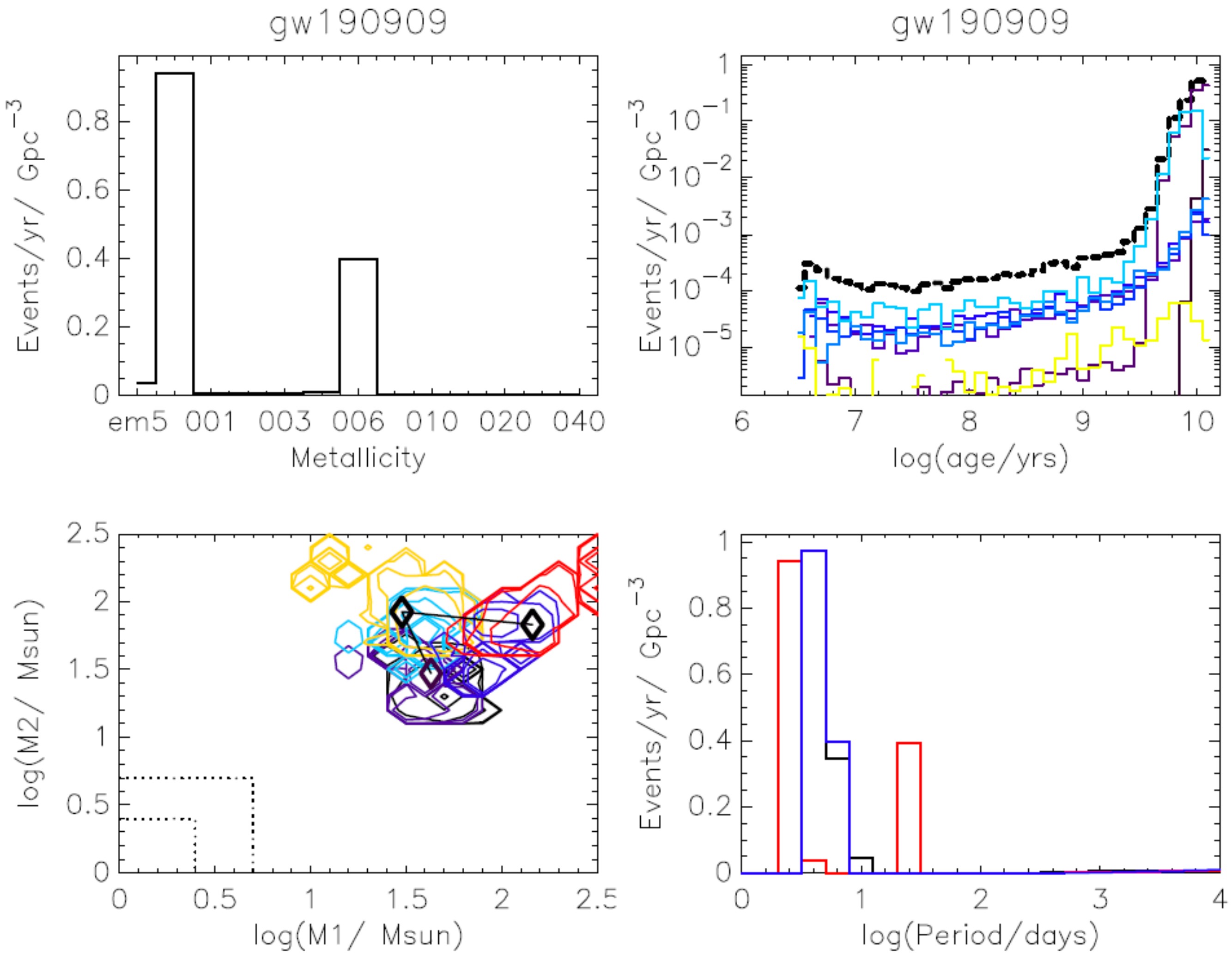
Metallicity: -4.1888073± 1.2129101

Initial M1/M2/log P 96.779306± 51.563700 53.983659± 41.034063 1.4480440± 1.3205082

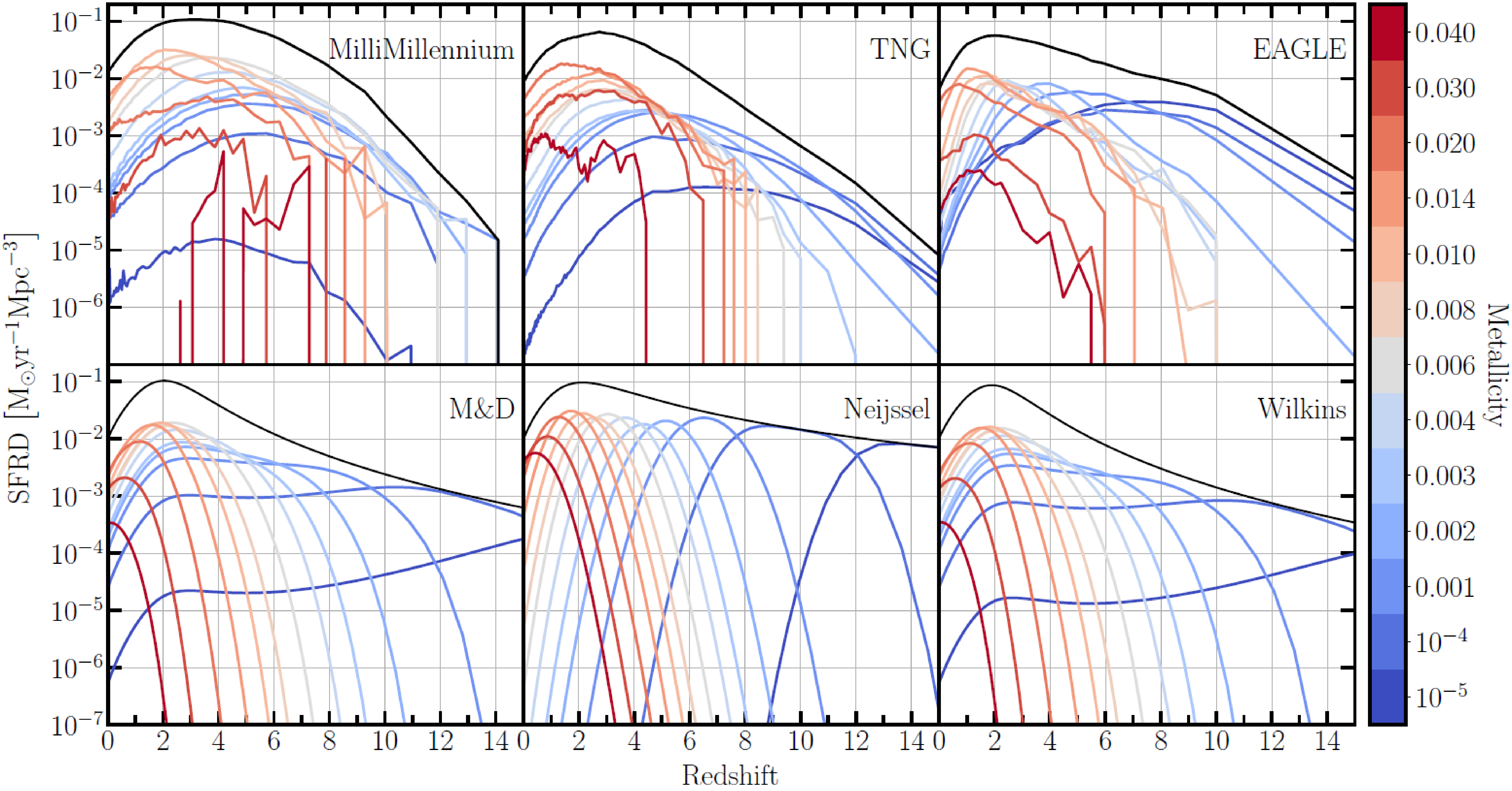
Mid M1/M2/log P 30.641268± 4.0934832 67.092021± 33.137719 1.6272418± 1.6064710

Final M1/M2/log P 30.641985± 4.0929878 36.771791± 4.4885287 1.7358112± 1.5892736

Final ecc 0.36039429± 0.41577658



43.2000 27.6000
gw190909 44 QHE(no/yes/event rate): 30.474819 69.525181 1.4084592
log(Age/yrs): 9.9873419± 0.16778509
Metallicity: -3.4910520± 0.83919300
Initial M1/M2/log P 144.90882± 97.298297 67.651401± 62.778929 0.73857184± 0.45607872
Mid M1/M2/log P 30.022269± 11.903313 84.157577± 53.766057 0.77837125± 0.68747058
Final M1/M2/log P 42.622961± 10.244162 29.520210± 5.7068095 0.76394293± 0.52250215
Final ecc 0.13880094± 0.14909127



Briel et al. (in prep).

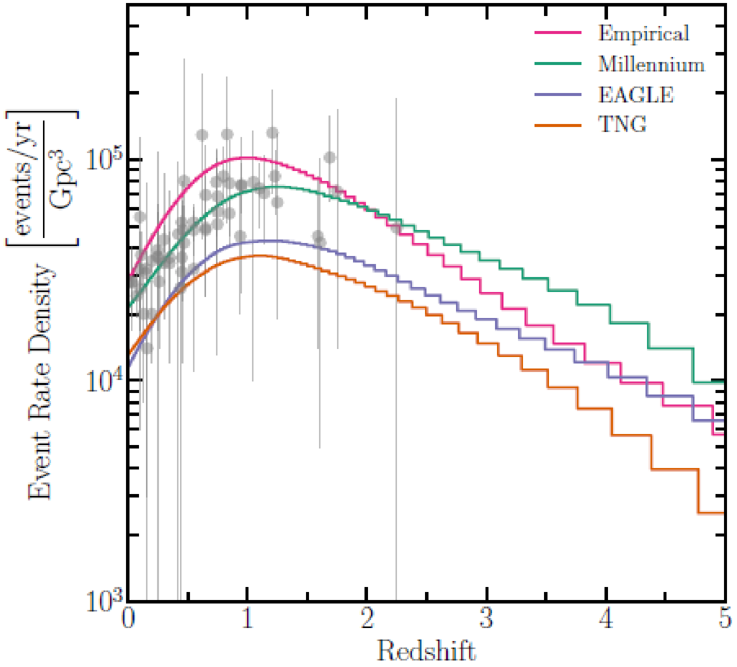


Figure 6. Type Ia SN rate from the four stellar formation histories with observations from several surveys.

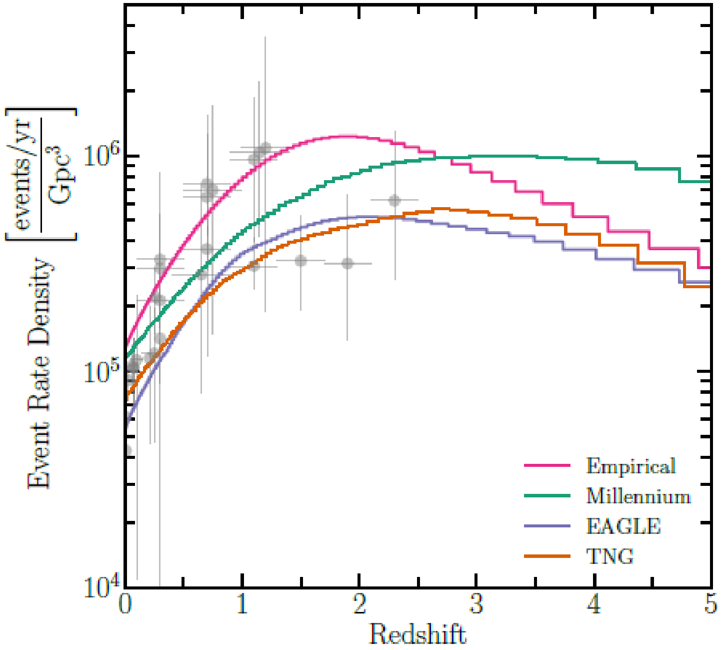


Figure 7. Predicted Core-Collapse Supernova rates with observations in grey for comparison.

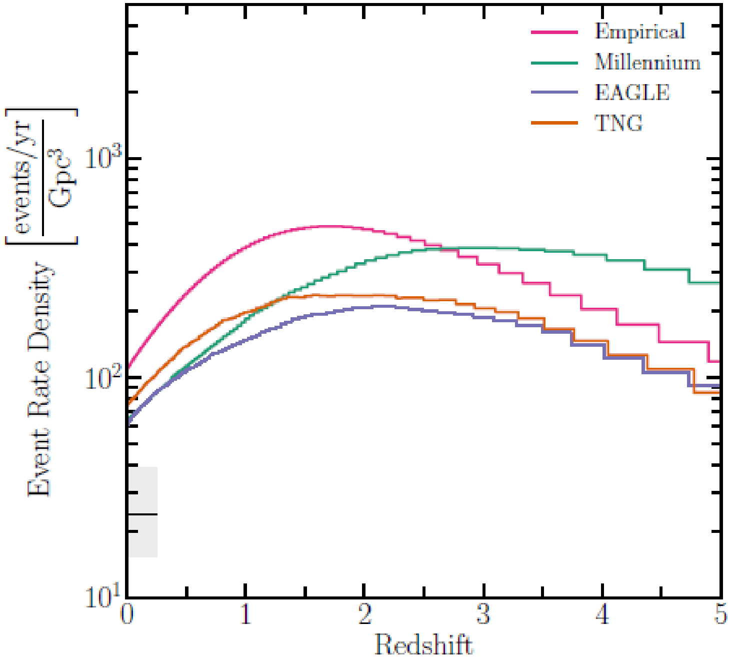
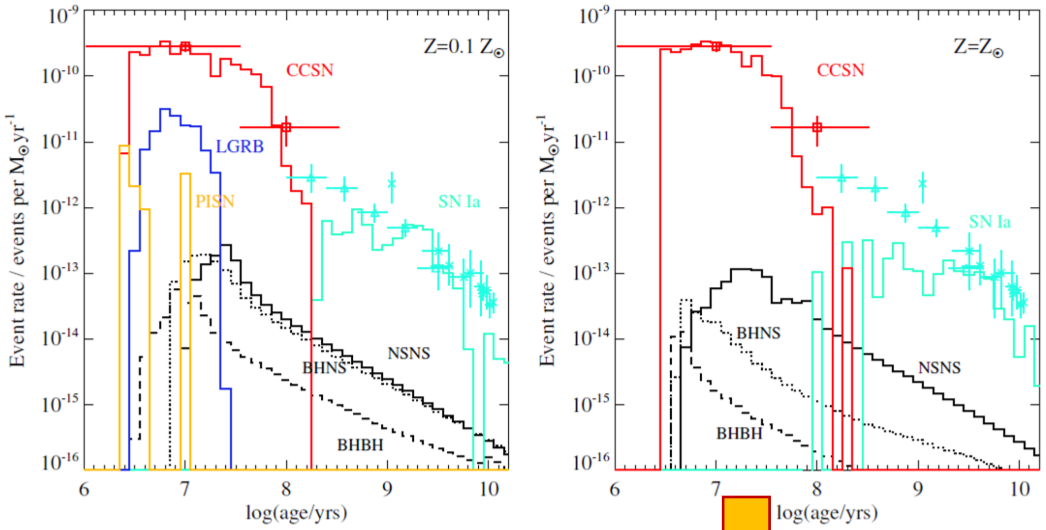


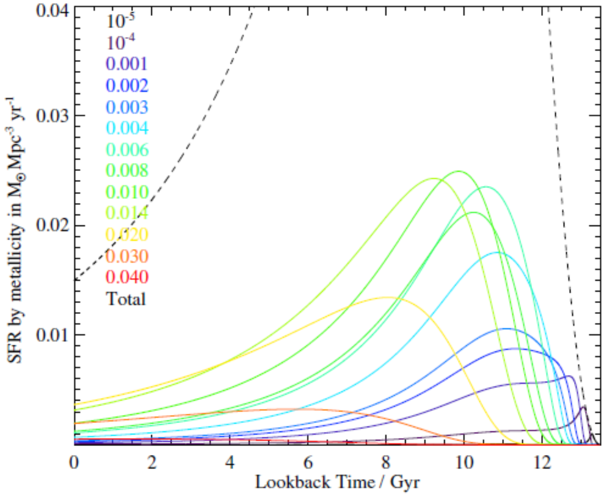
Figure 18. BHBH merger rate with the observed rate from Collaboration et al. (2020).

Briel et al. (in prep).

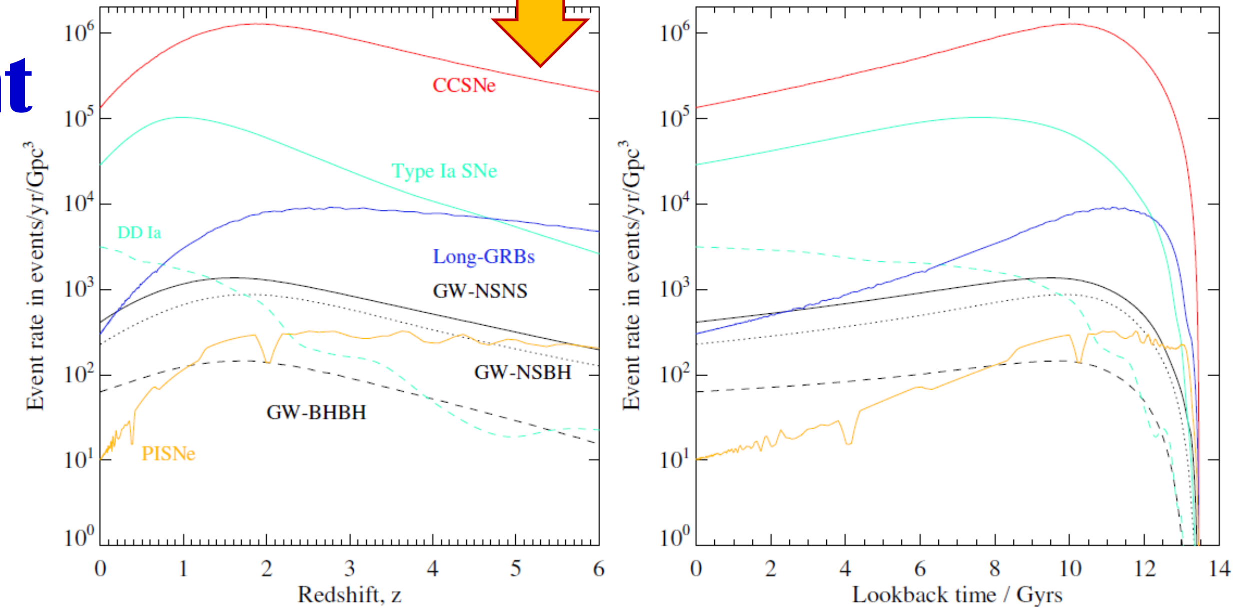
Delay-time distribution



Cosmic star formation history

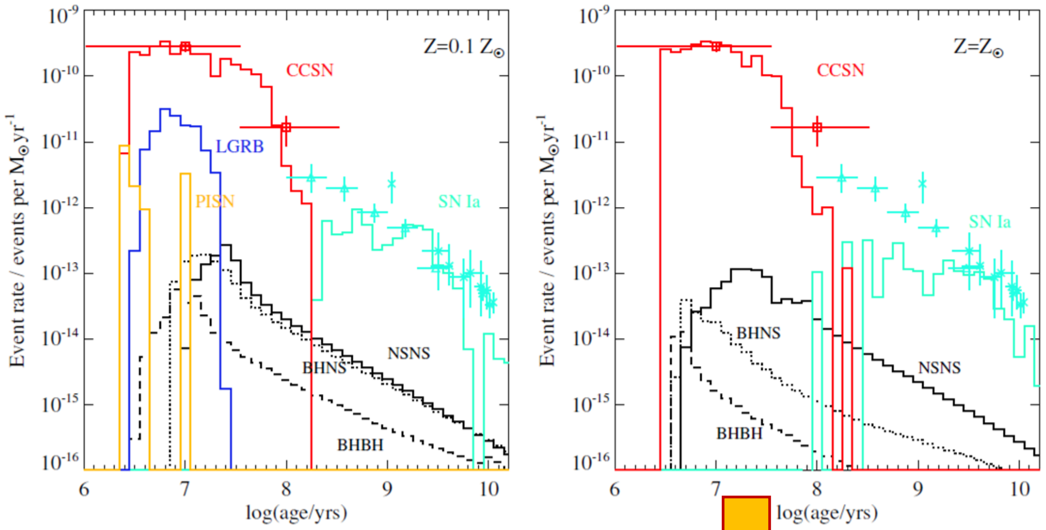


Transient cosmic history

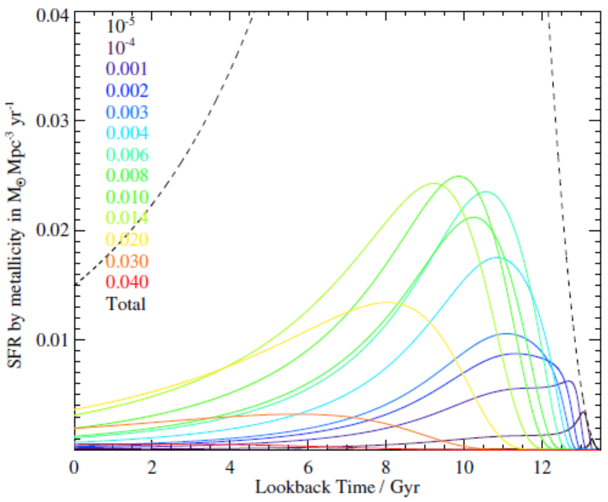


BPASSv2.2

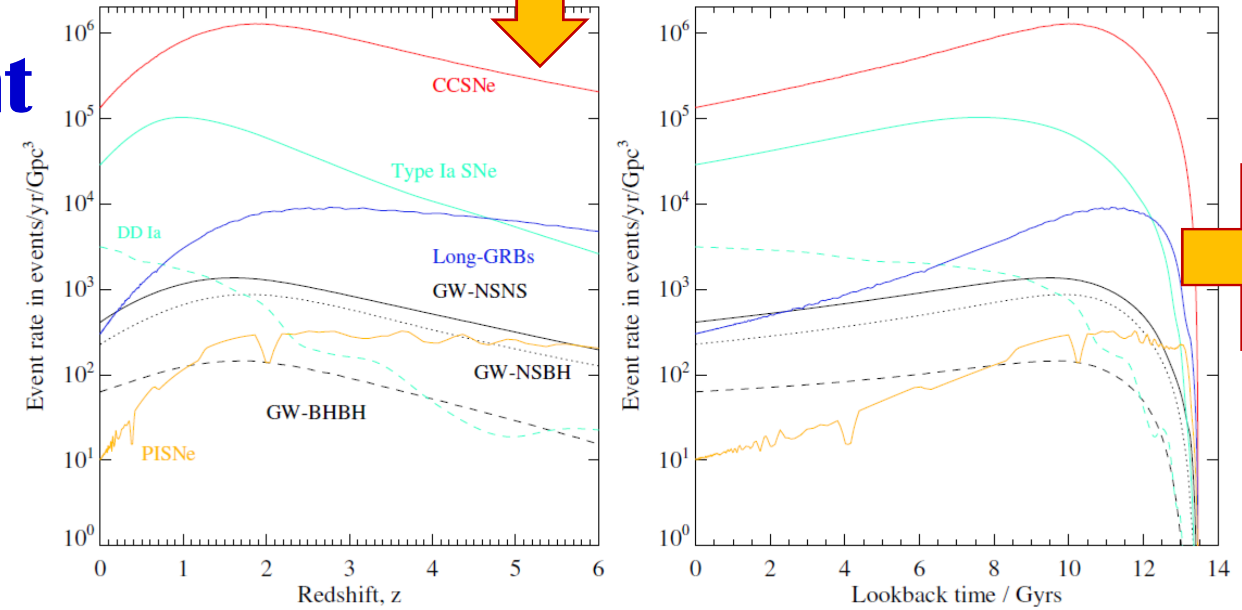
Delay-time distribution



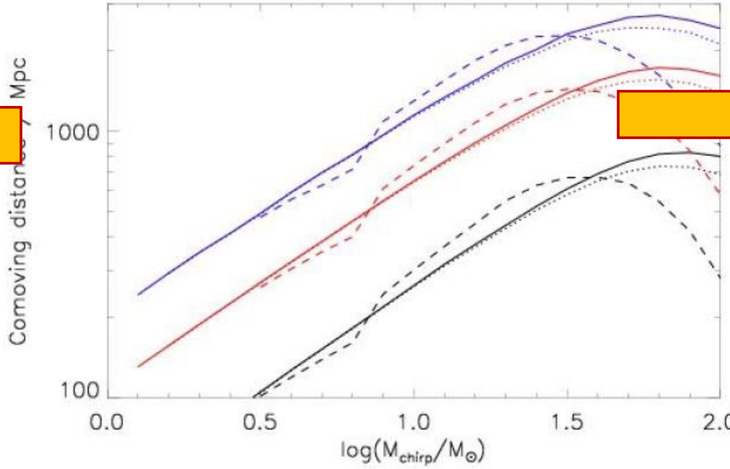
Cosmic star formation history



Transient cosmic history



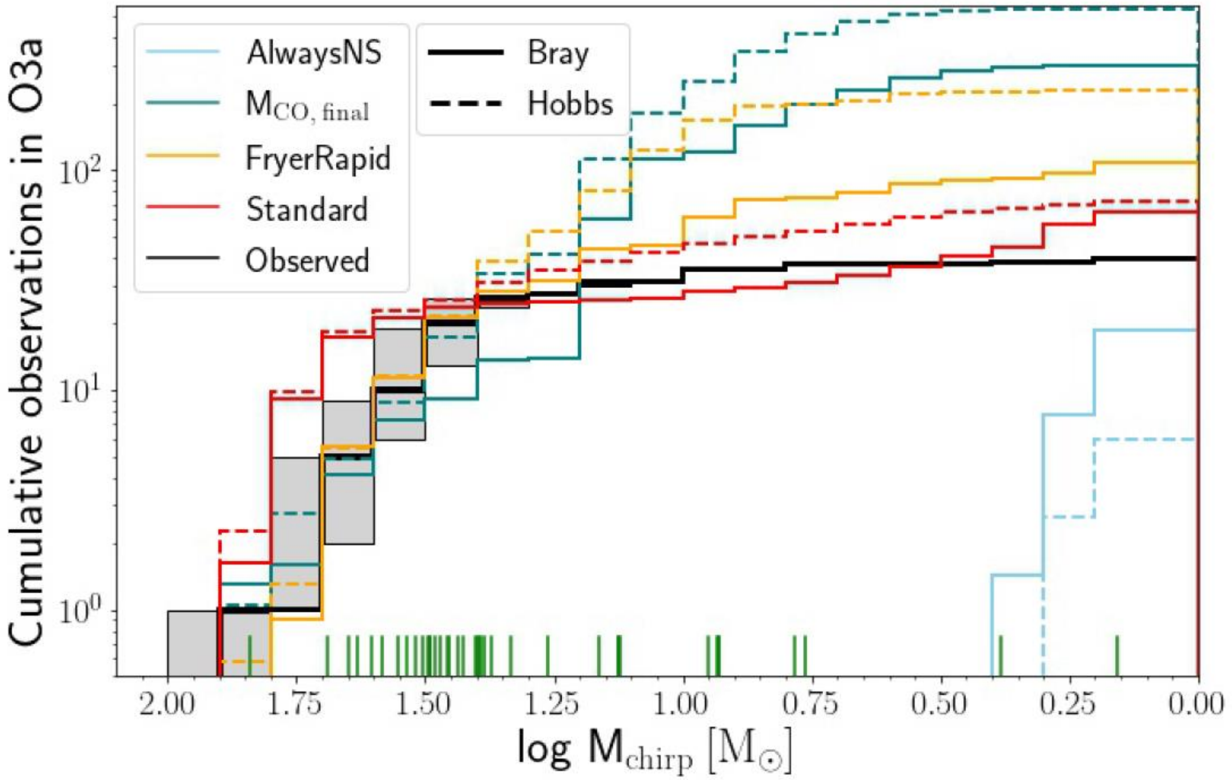
Selection effects



BPASSv2.2

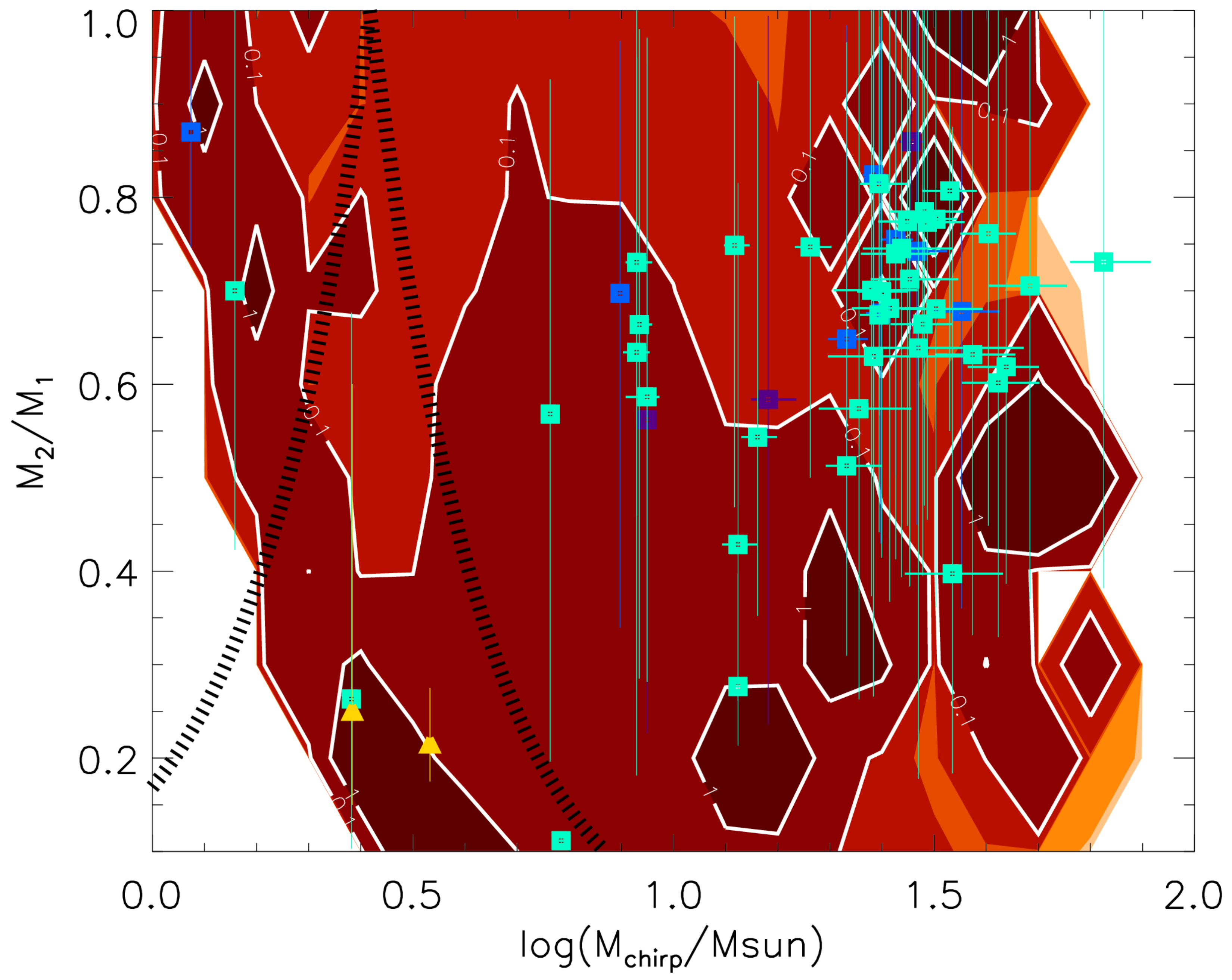
	NS-NS	BH-NS	BH-BH
Observed	**1±1**	**2±1.4**	**36±6**
BPASS	**2.7**	**7**	**25**
Inferred density	80—810 $Gpc^{-3}yr^{-1}$	12—242 $Gpc^{-3}yr^{-1}$	15.3—38.2 $Gpc^{-3}yr^{-1}$
BPASS density	208 $Gpc^{-3}yr^{-1}$	131 $Gpc^{-3}yr^{-1}$	31 $Gpc^{-3}yr^{-1}$

Ghodla et al. (2021)
and
van Zeist et al. (2021)



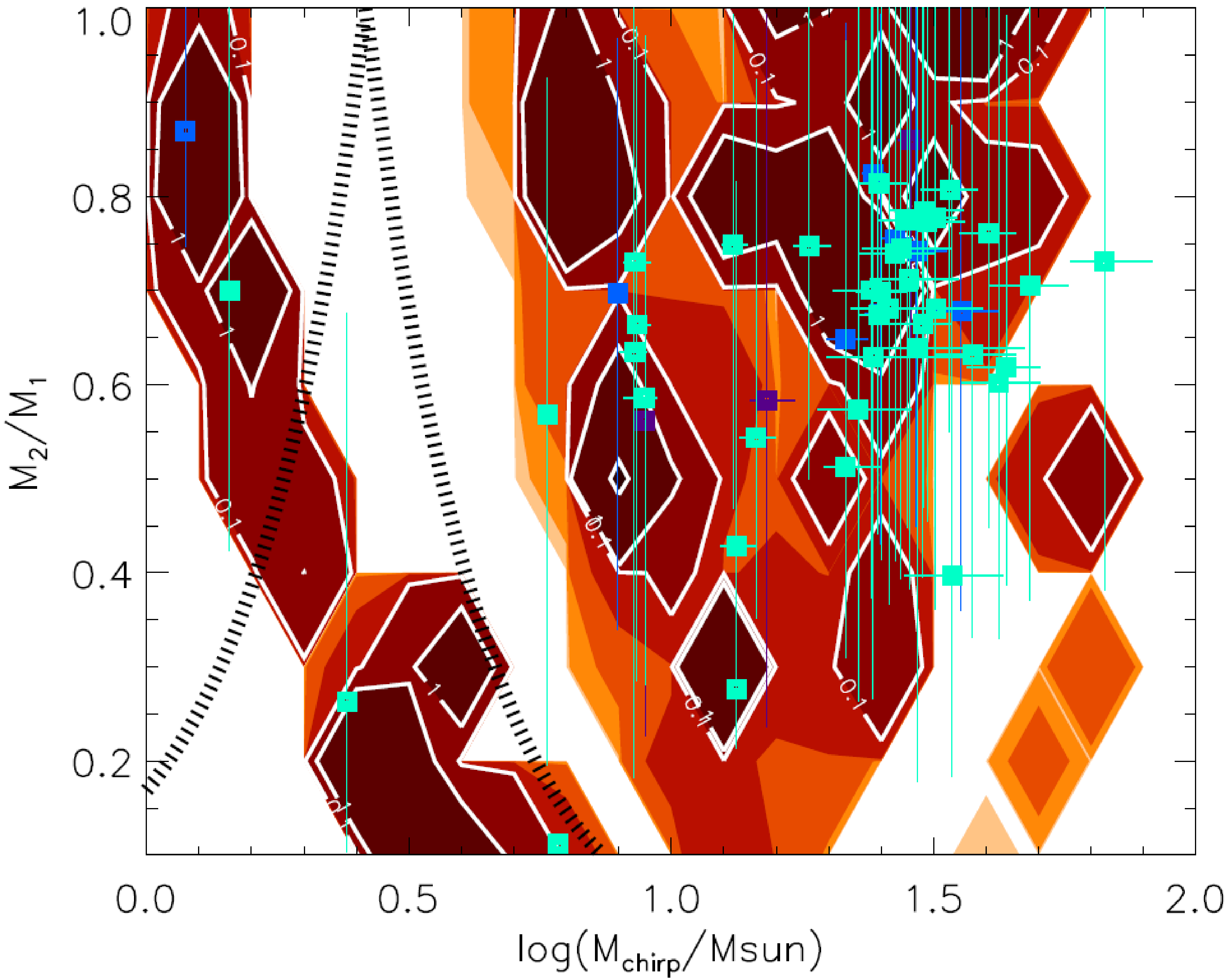
Kick	Remnant	NSNS	BHNS	BHBH
Hobbs	Standard	2.7 (208)	7.0 (131)	25 (31)
Hobbs	$M_{CO, final}$	0.86 (43)	26 (417)	233 (873)
Hobbs	FryerRapid	2.1 (176)	15 (208)	95 (169)
Hobbs	AlwaysNS	2.7 (223)	0.21 (8.7)	0.0
Bray	Standard	9.5 (745)	7.4 (180)	15 (13)
Bray	$M_{CO, final}$	3.1 (179)	24 (498)	118 (569)
Bray	FryerRapid	7.6 (677)	8.9 (157)	36 (70)
Bray	AlwaysNS	8.0 (708)	1.1 (48)	0.0
LVC O3a		1±1	2±1.4	36±6
Intrinsic [Gpc^{-3} yr^{-1}]		(320^{+490}_{-240})	(≤610)	($23.9^{+14.3}_{-8.6}$)

Ghodla et al. (2021)
and
van Zeist et al. (2021)

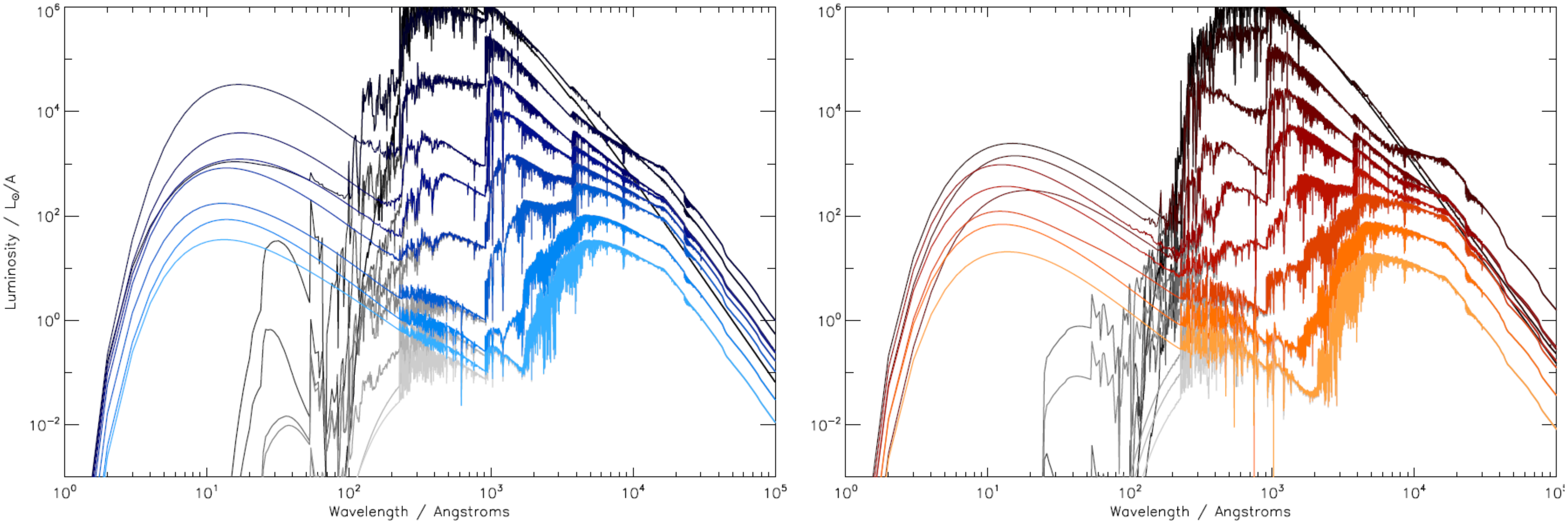


Darker red indicates more GW events expected.

Ghodla et al. (2021).
and
van Zeist et al. (2021)



Ghodla et al. (2021)
and
van Zeist et al. (2021)



Eldridge et al. (in prep).

We are also working on ages of....