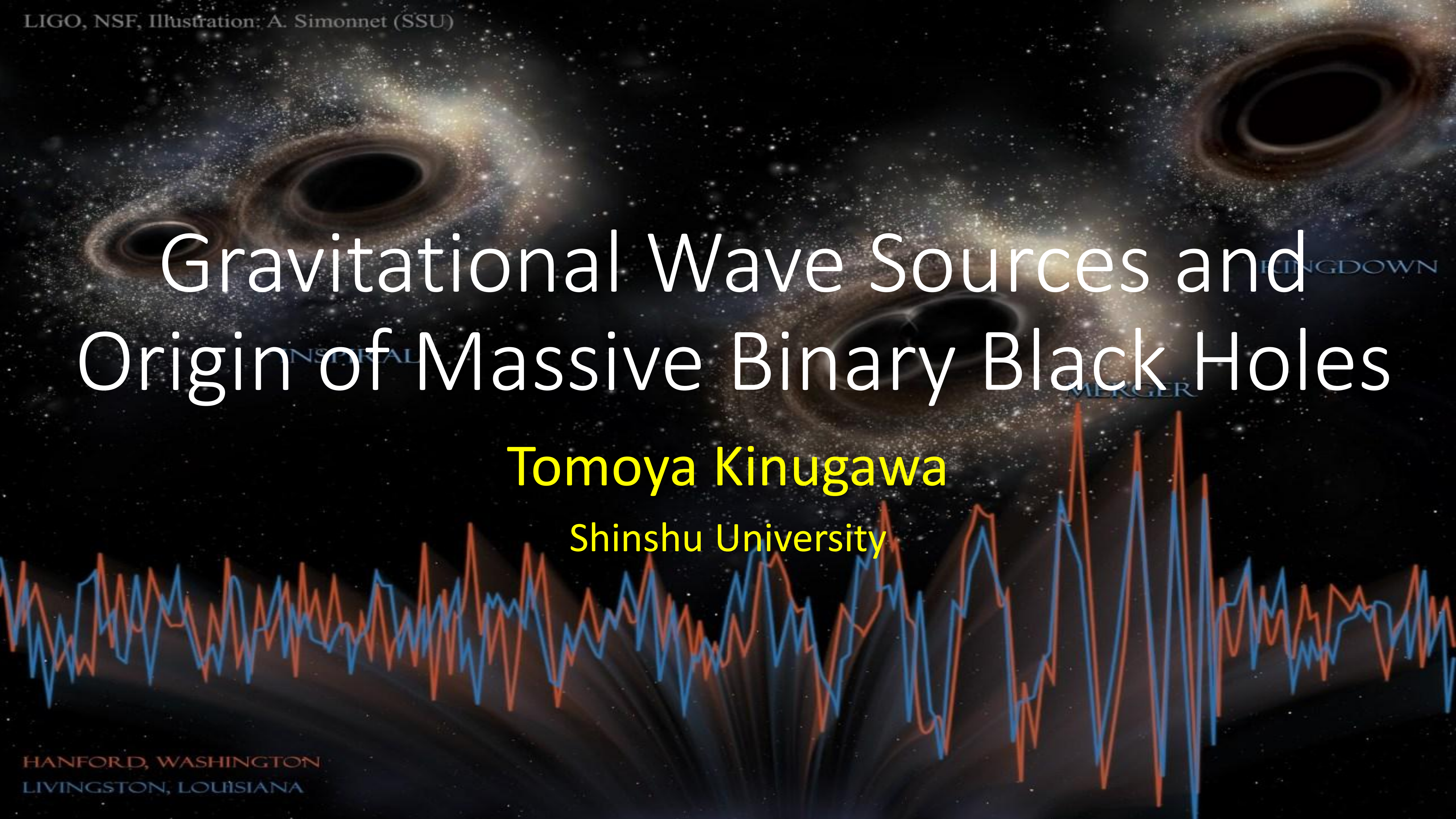
Gravitational Wave Sources and Origin of Massive Binary Black Holes

Tomoya Kinugawa

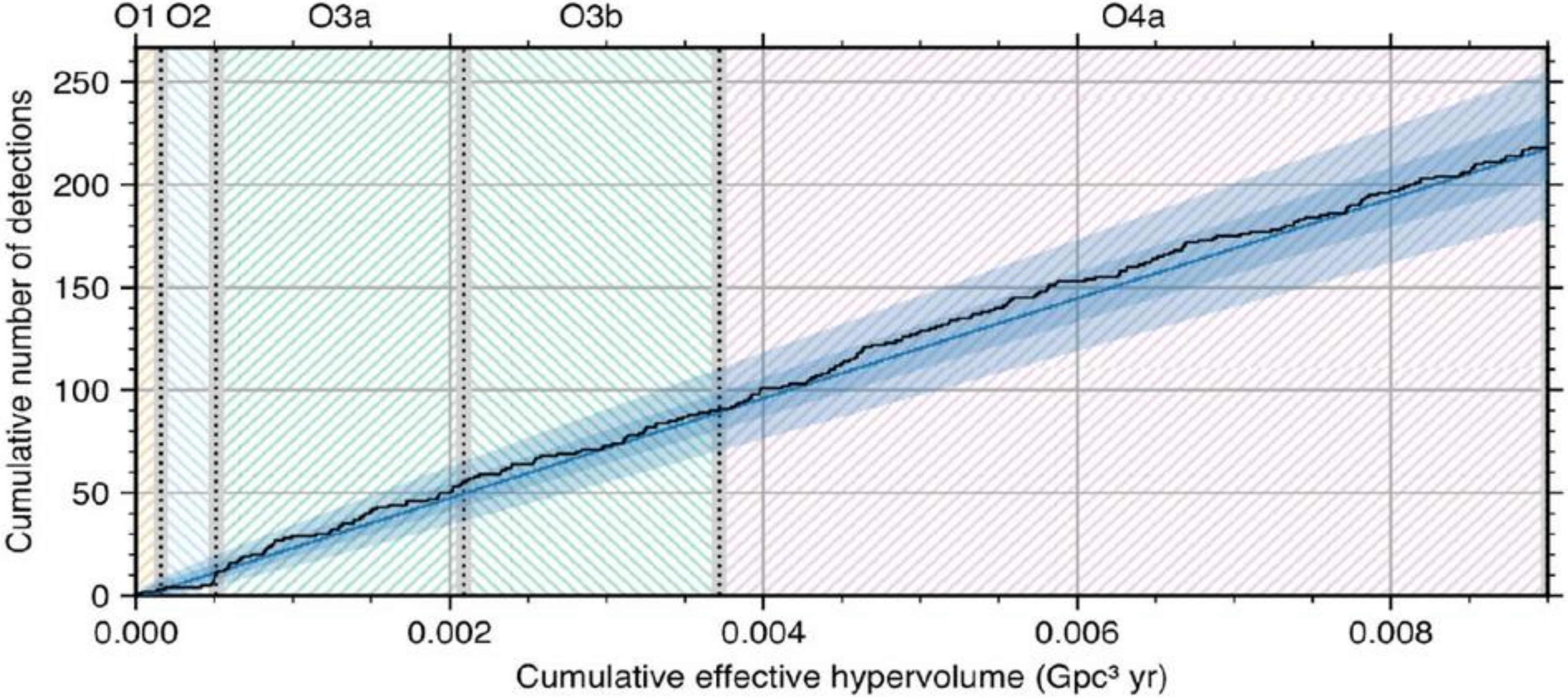
Shinshu University



GW observatories

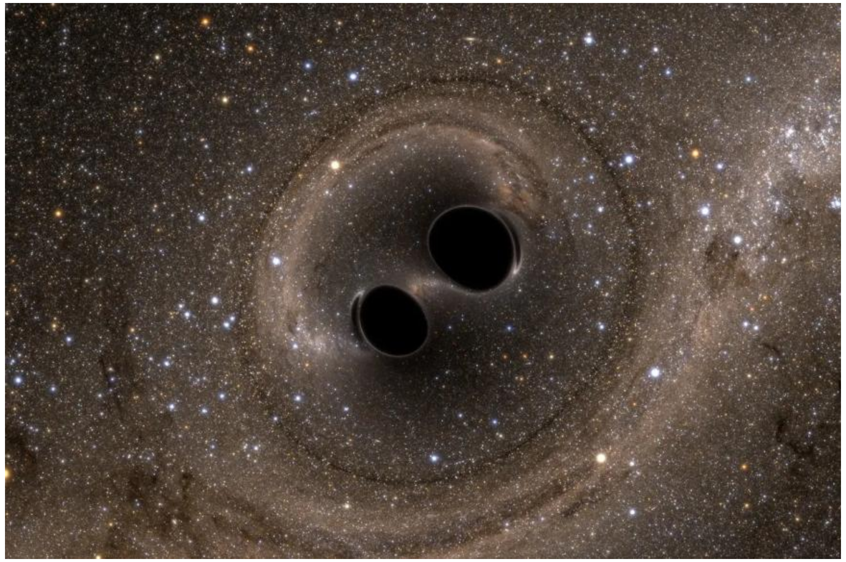
©LIGO

detections



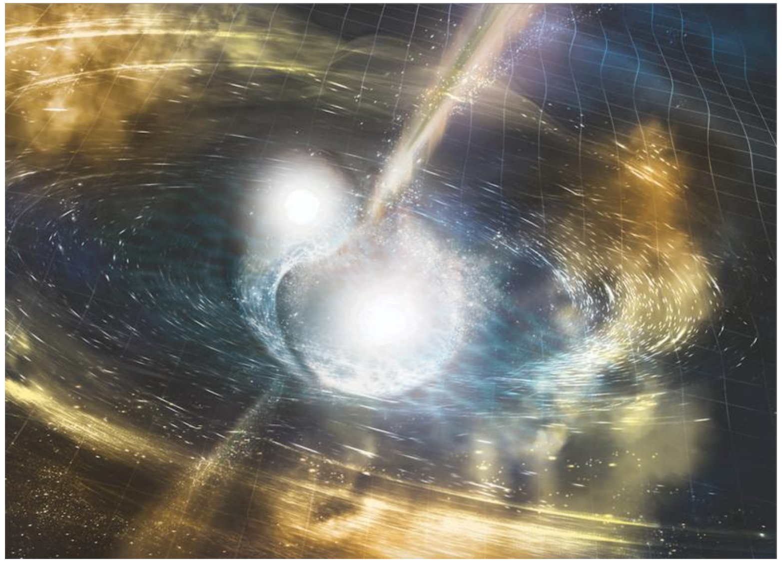
The cumulative number of detections (candidates found with a probability of being astrophysical greater than 50%) against the approximate space-time hypervolume surveyed by the detectors (source: LVK consortium).

GW sources



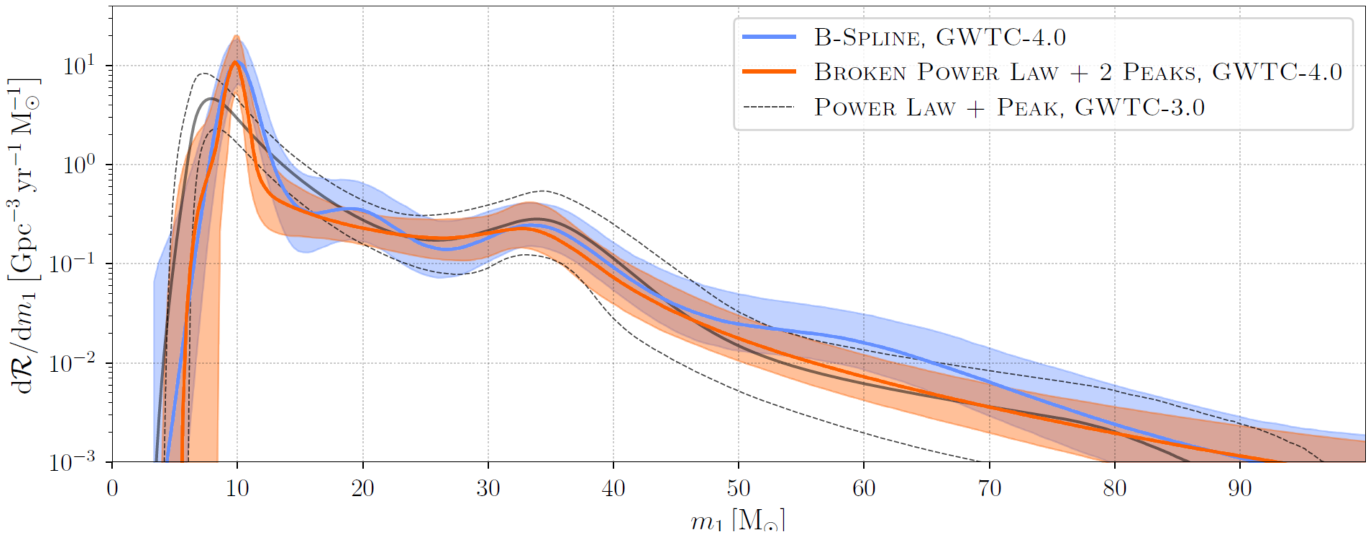
Binary Black Hole

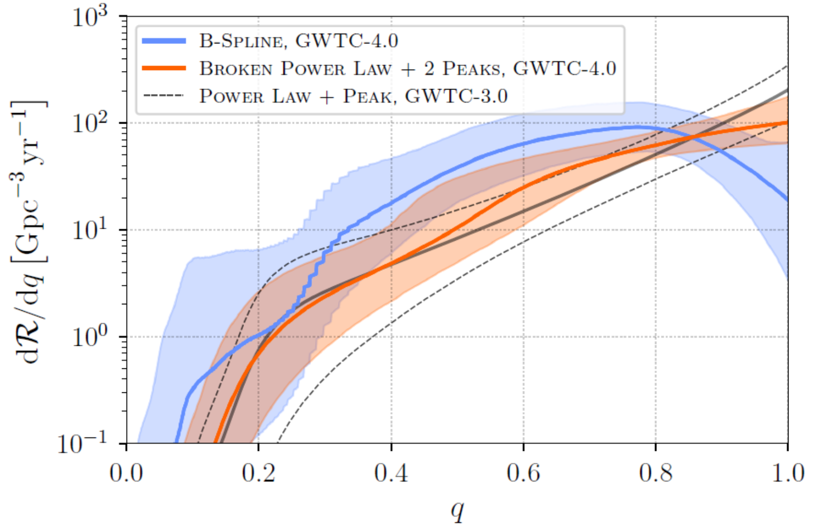
Neutron Star Black Hole Binary

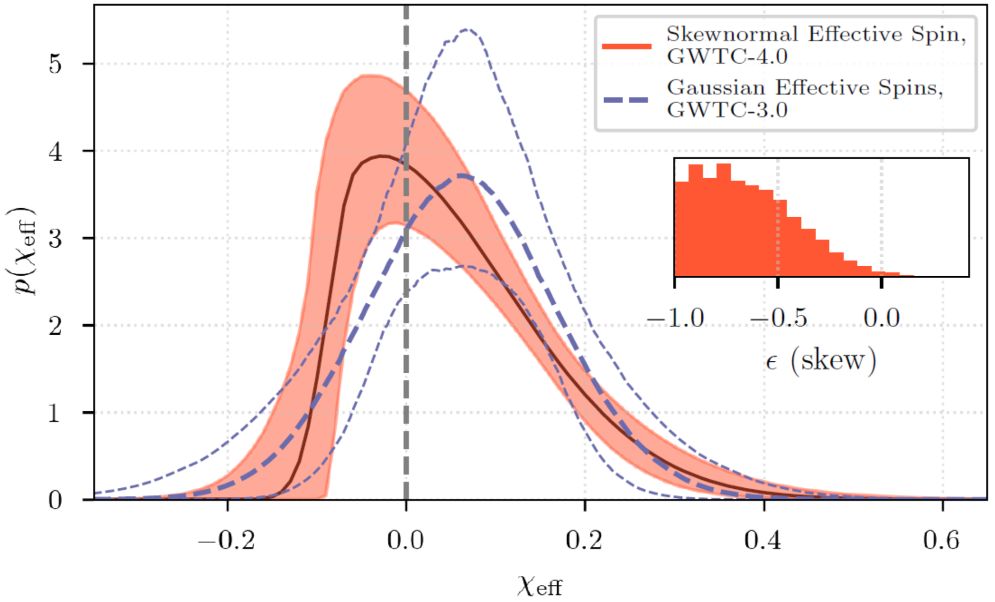


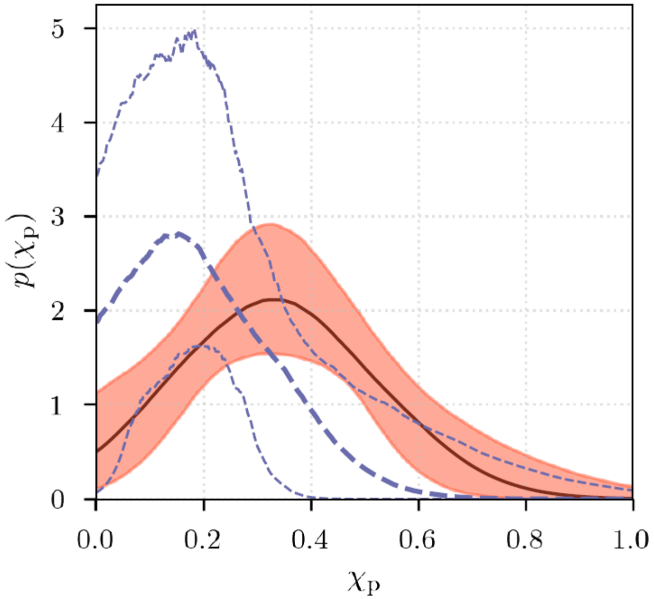
Binary Neutron Star

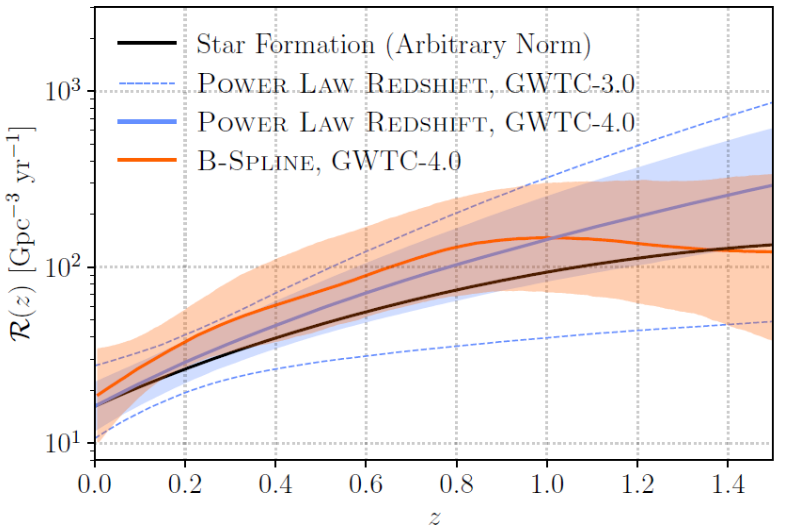
BBH merger profile





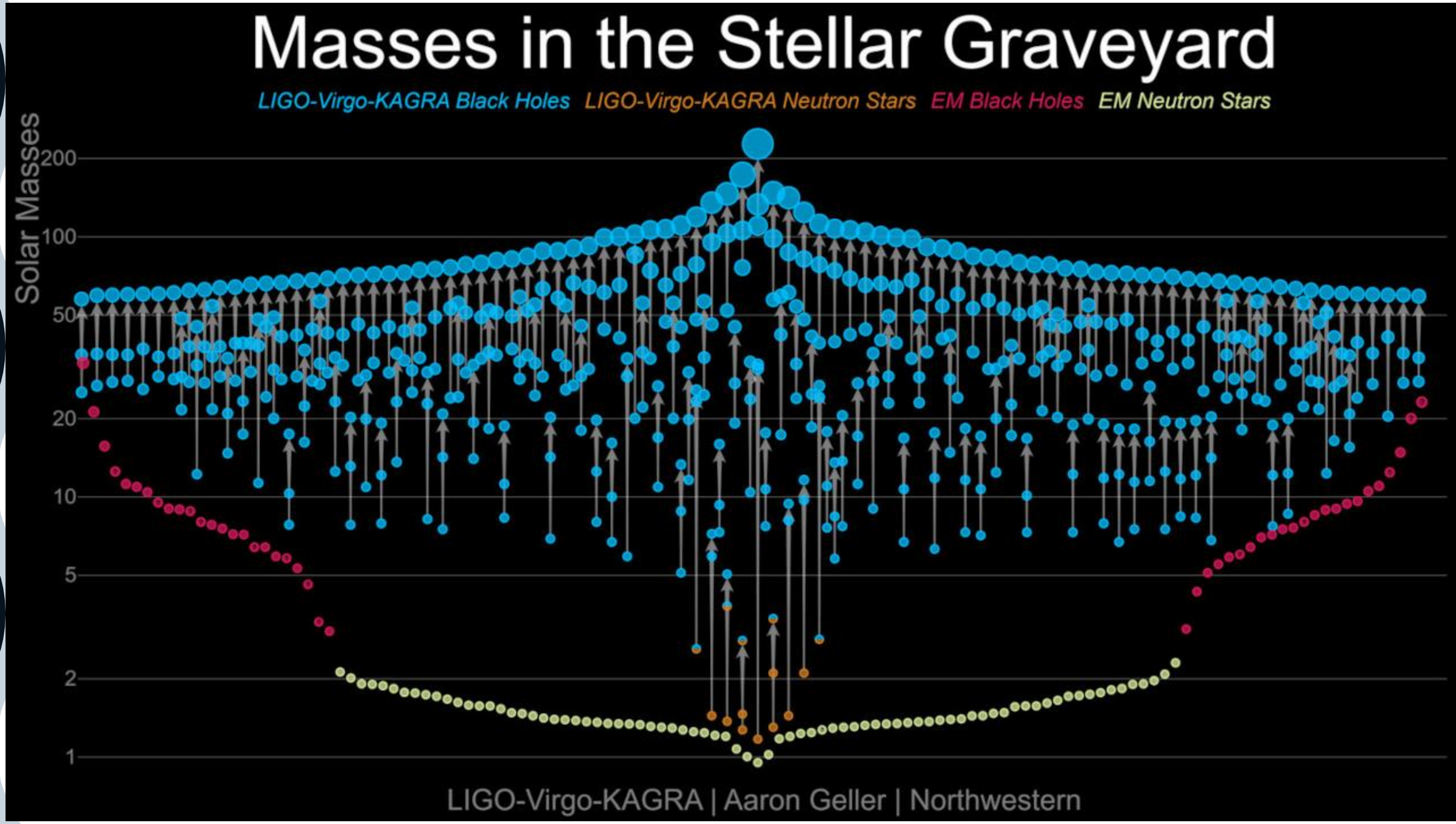






Mistery of GW events

- GW events show that there are many massive BHs (≳30 Msun).
- On the other hand, the typical mass of BHs in X-ray binaries is ~10 Msun.



Origin of massive BBHs

In order to explain the origin of such massive BBHs
Many theories exist such as

- 1) Pop I and Pop II BBH (present day and low metal stars)
- 2) Pop III BBH (First stars)
- 3) Dynamical formation (Dence stellar environment)
- 4) AGN disk
- 5) Primordial BBH
- ……………………..

Origin of massive BBHs

In order to explain the origin of such massive BBHs
Many theories exist such as

Stellar origin BH

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Non-stellar origin BH

- ………………………

Origin of massive BBHs

In order to explain the origin of such massive BBHs
Many theories exist such as **Isolated Binary**

- 1) Pop I and Pop II BBH (present day and low metal stars)
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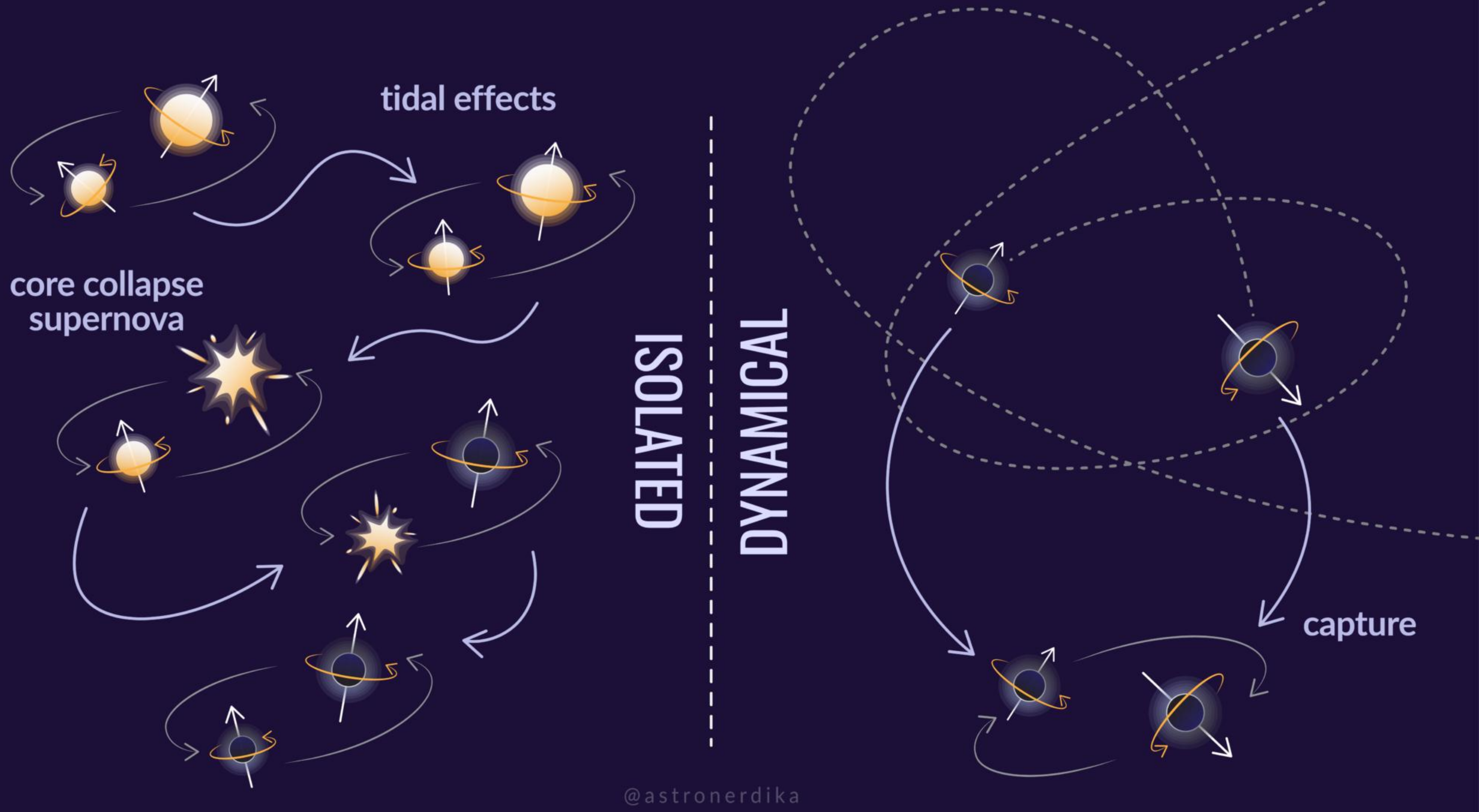
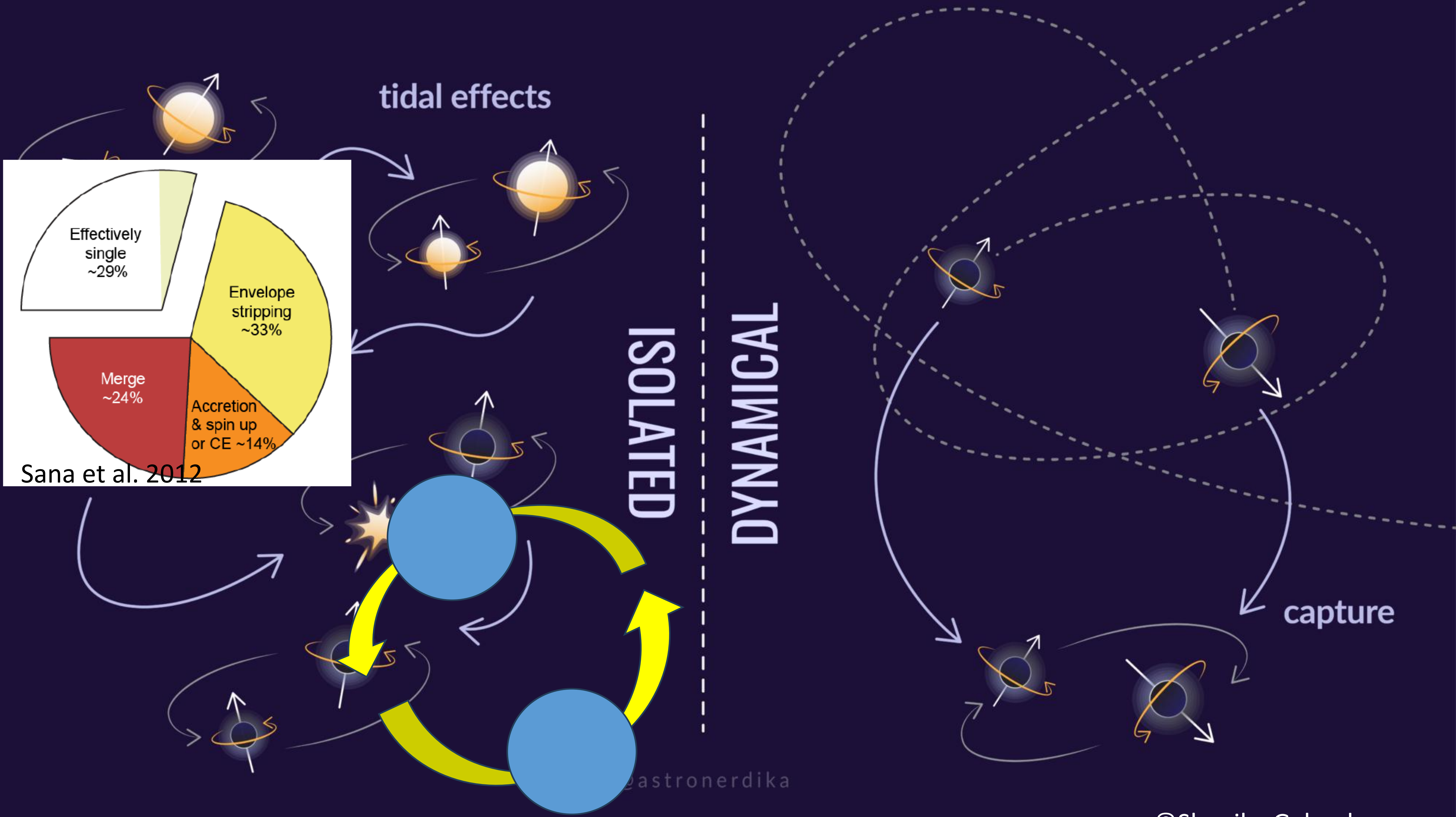
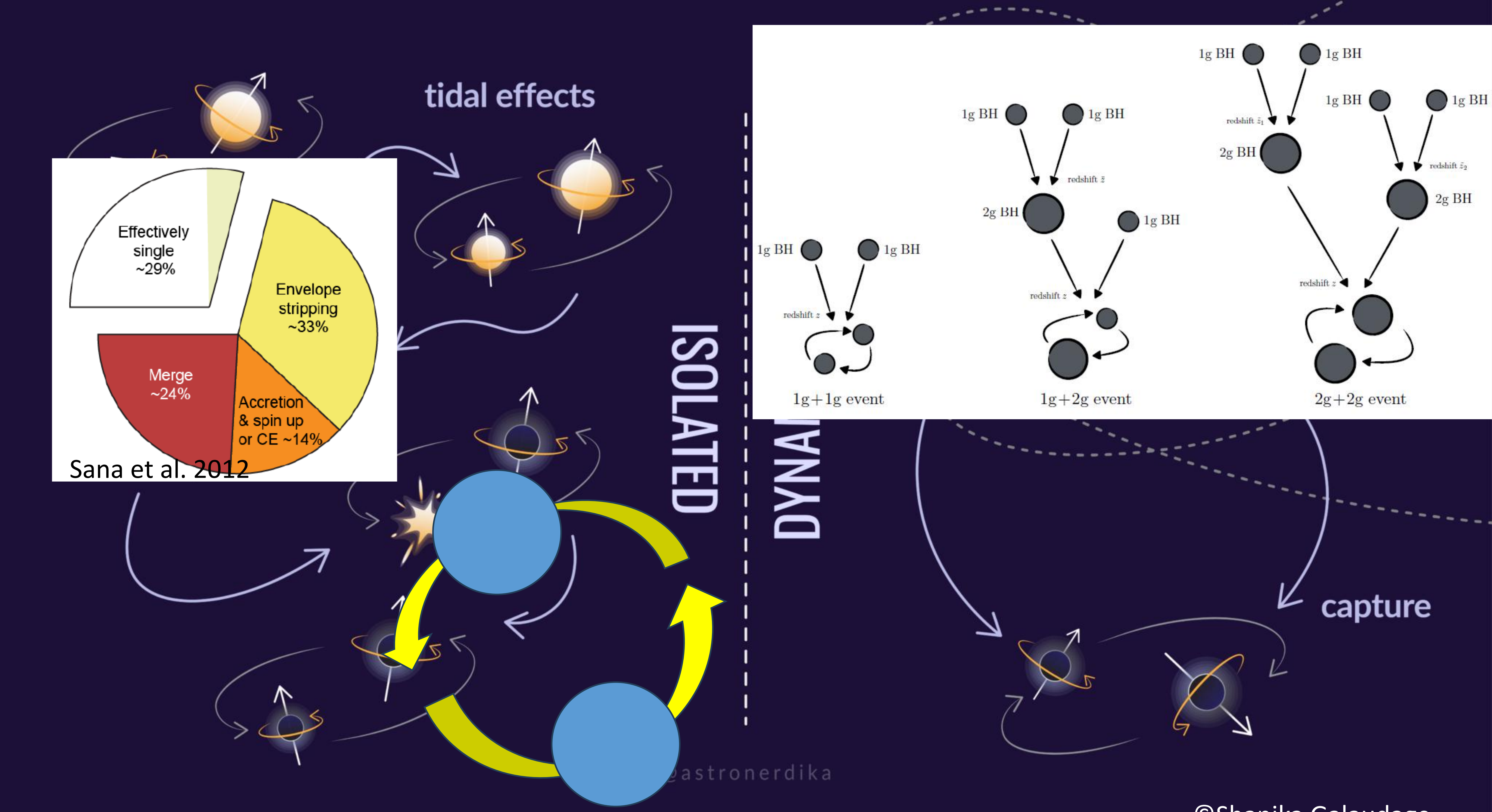
Dynamical

- ……………………….


tidal effects
core collapse supernova
ISOLATED
DYNAMICAL
capture
@astronerdika



tidal effects
Effectively single ~29%
Envelope stripping ~33%
Merge ~24%
Accretion & spin up or CE ~14%
Sana et al. 2012
ISOLATED
DYNAMICAL
capture
@astronerdika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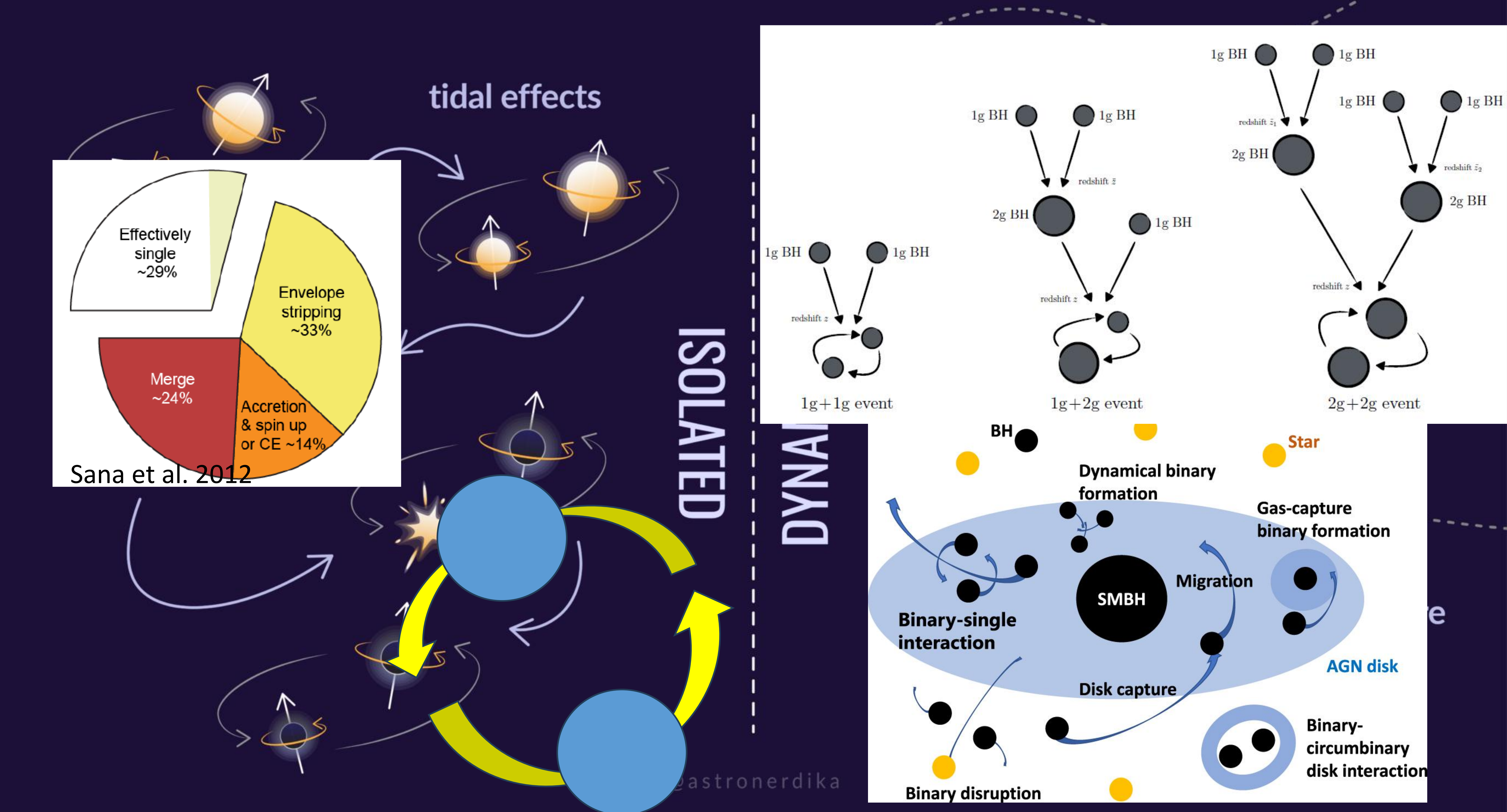
ISOLATED
DYNAM
1g BH
2g BH
redshift z
1g+1g event
1g+2g event
2g+2g event
capture
@astronerdika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1g BH
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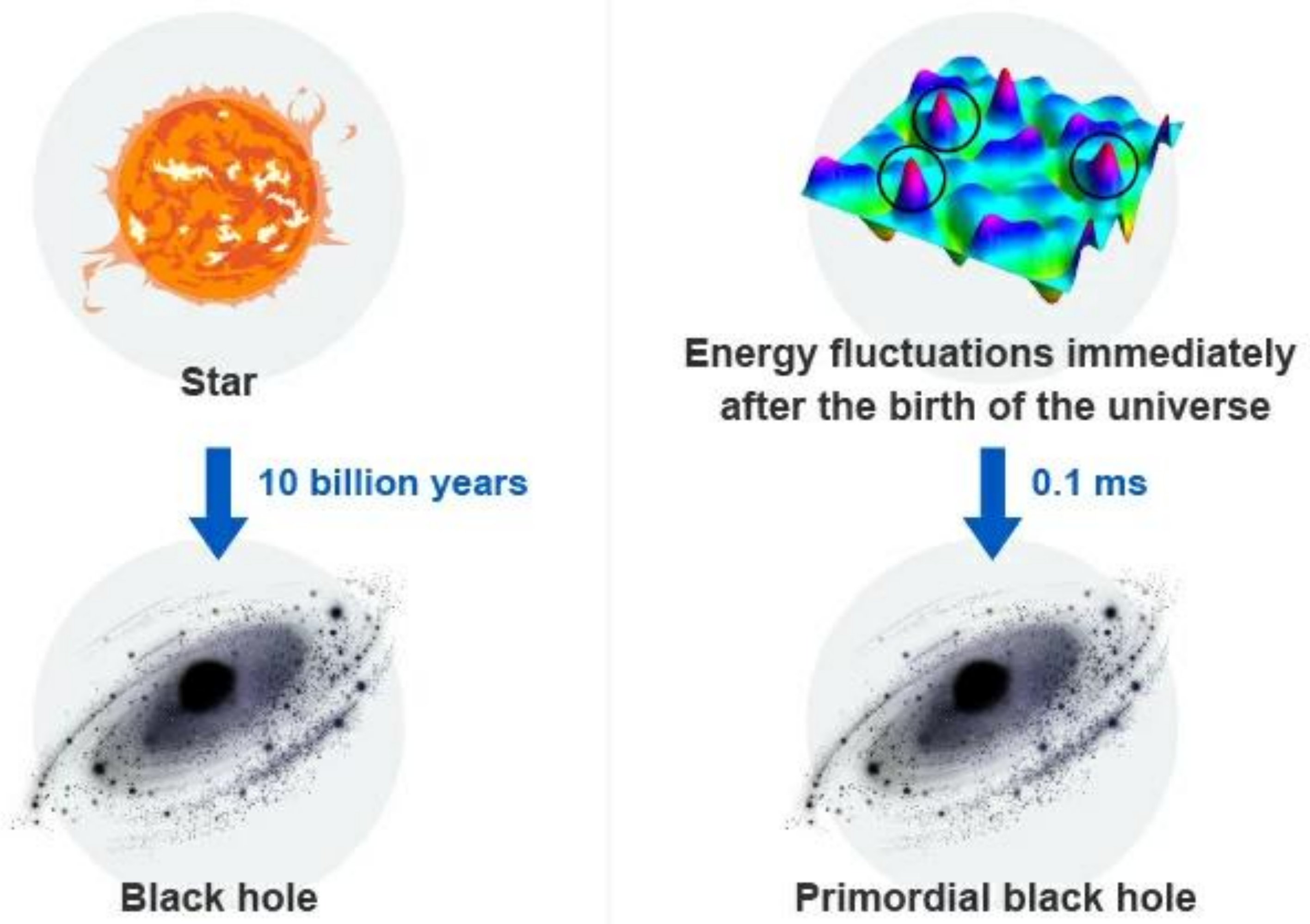
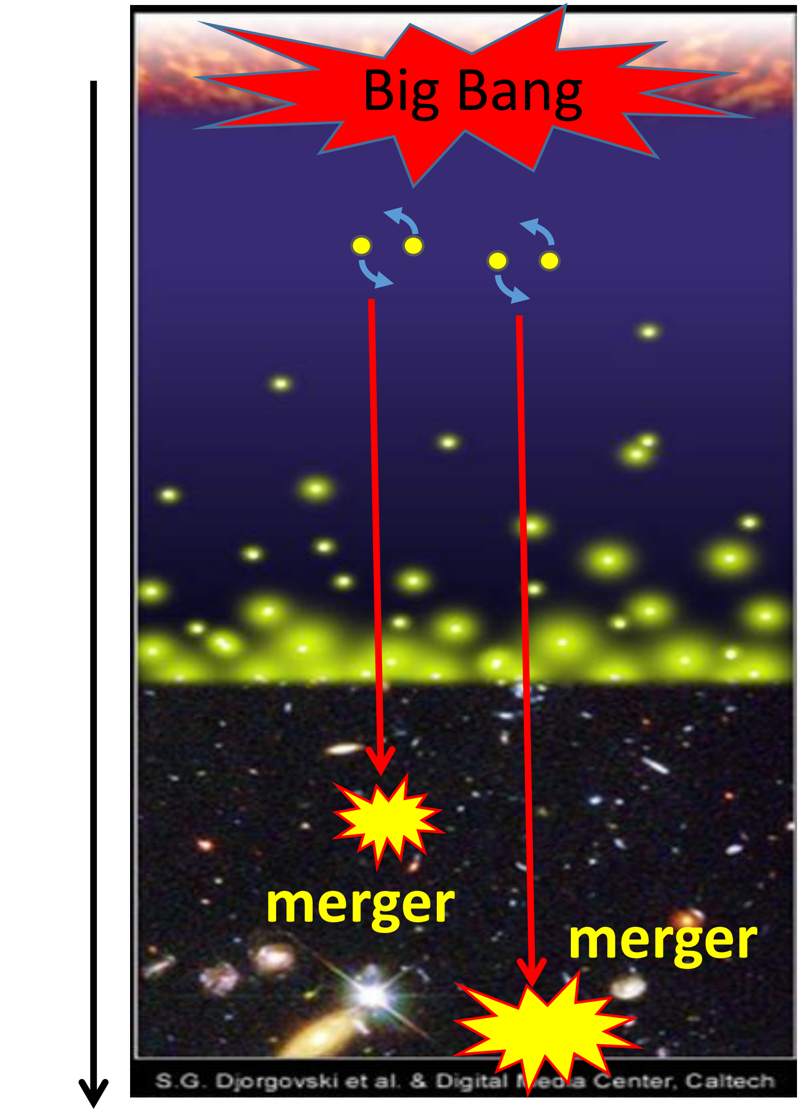
2g BH
redshift $\bar{z}$
redshift $\bar{z}_1$
redshift $\bar{z}_2$
1g+1g event
1g+2g event
2g+2g event
BH
Star
Dynamical binary formation
Gas-capture binary formation
Migration
SMBH
Binary-single interaction
AGN disk
Disk capture
Binary-circumbinary disk interaction
Binary disruption
astronerdika

Primordial Black Hole





Djorgovski et al.&Degital Media Center

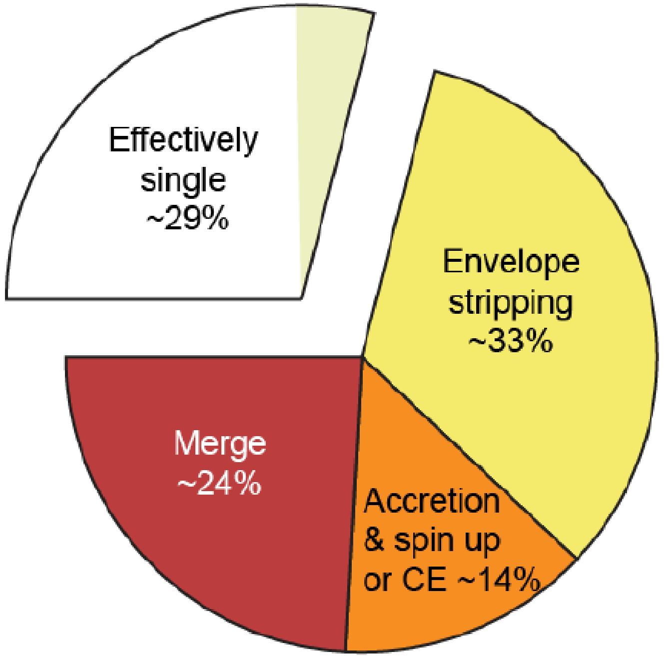
Origin of massive BBHs

In order to explain the origin of such massive BBHs
Many theories exist such as **Isolated Binary**

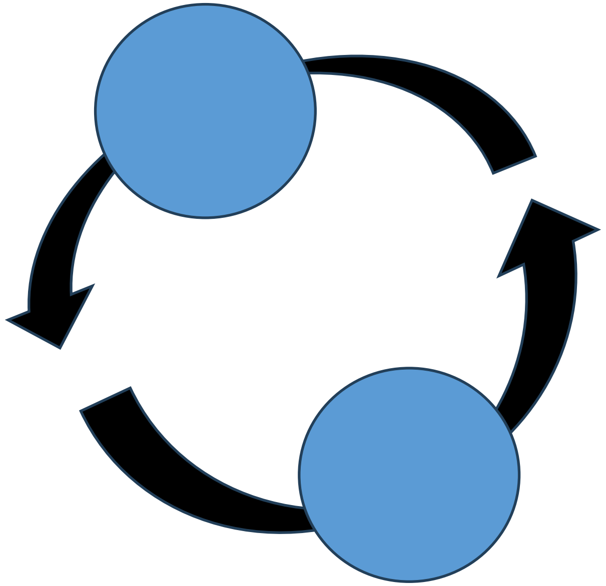
- 1) Pop I and Pop II BBH (present day and low metal stars)
- 2) Pop III BBH (First stars)
- 3) Dynamical formation (Dence stellar enviroment)
- 4) AGN disk
- 5) Primordial BBH
- ……………………..

Why is isolated binary important for BBH?

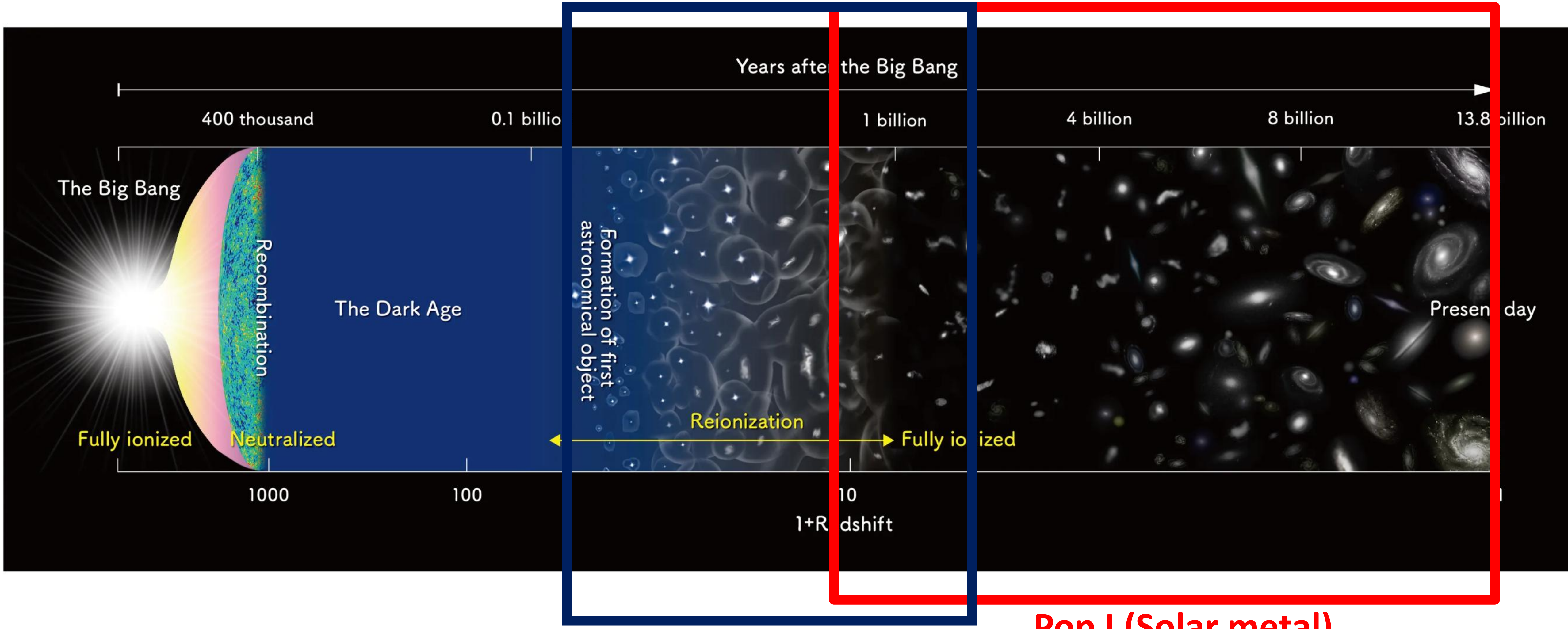
- Binary fraction of massive stars is high (~70% e.g. Sana et al. 2012)
- Almost BH progenitors might evolve in binary systems



Sana et al. 2012



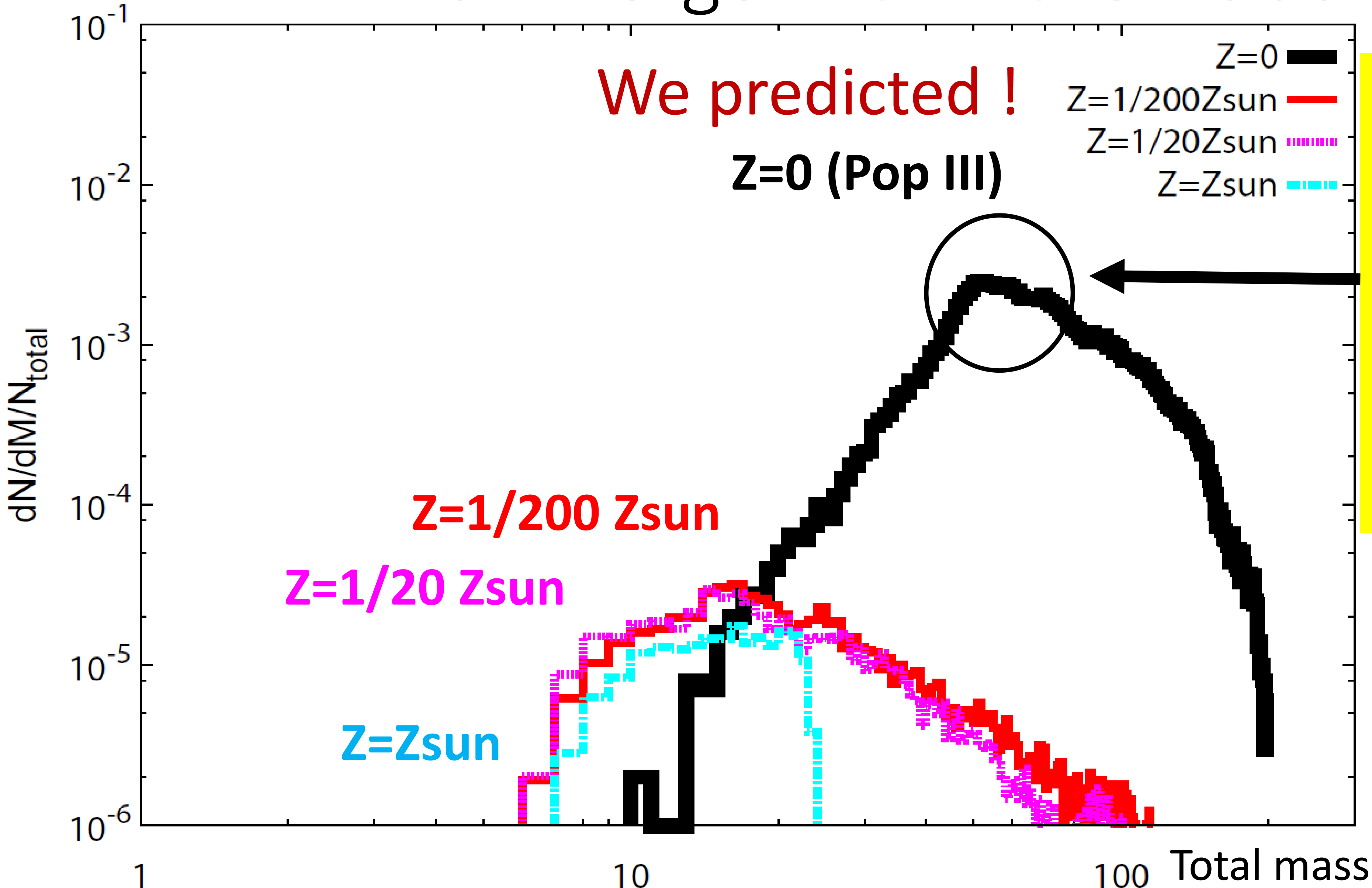
Isolated Binary scenarios



Pop III formation (First stars)

Pop I (Solar metal)
and Pop II (low metal) formation

Formation fraction of BBH which merge within the Hubble time



Typical total mass

M～60 M⊙

(30 M⊙ +30 M⊙)

TK et al.

2014,2016,2020

We predicted ！

e.g. Pop I, Pop II

(Z=0.02,0.001,0.0001)

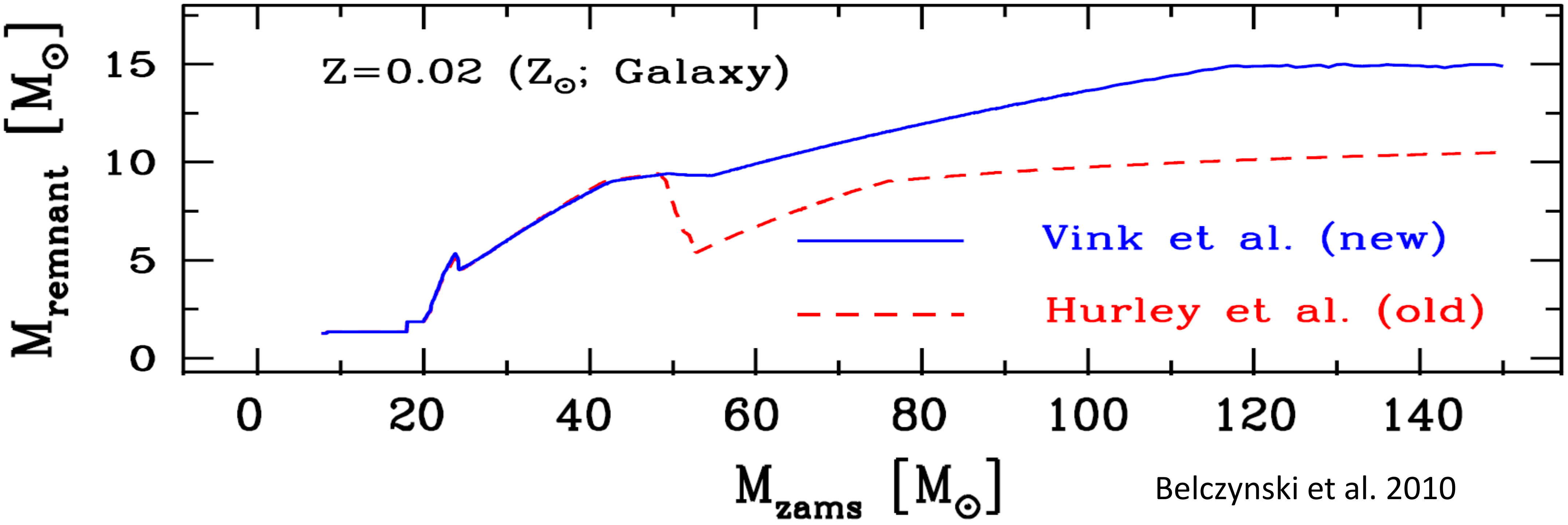
IMF:Salpeter

(1Msun<M<140Msun)

Typical mass ～10 M⊙

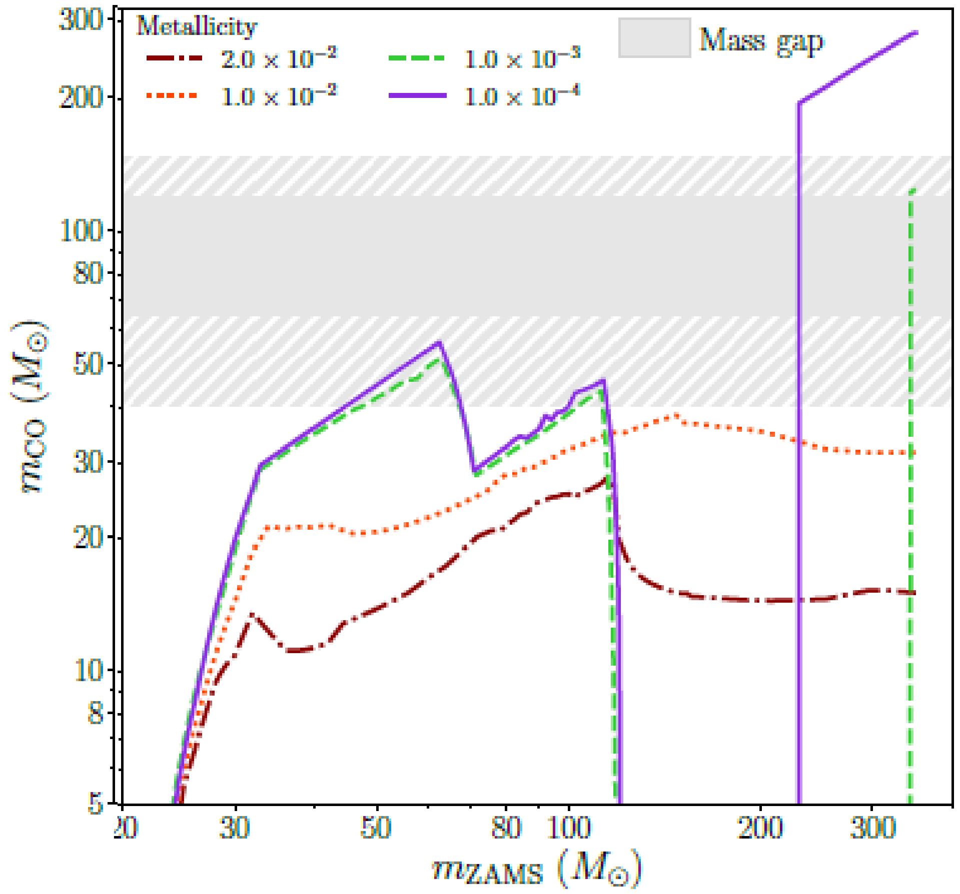
Wind mass loss & IMF

- If the progenitor of BH is Pop I (=Solar metal stars)
- Typical mass is small (IMF$\propto M^{-2.35}$, 0.1Msun<M<100Msun)
- Stars lose a lot of mass due to the strong stellar wind



Belczynski et al. 2010

Wind mass loss & IMF



Abbot et al. 2020

If the progenitor is low metal,

- Pop II (Metal<0.1SolarMetal)

  Typical mass is same as Pop I

  But, week wind mass loss

- Pop III (No metal)

  Pop III stars are ***the first stars*** after the Big Bang.

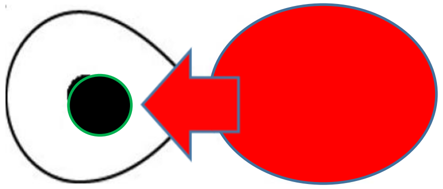
  Typical mass is more massive than Pop I, II

  M_{PopIII}~10-100Msun

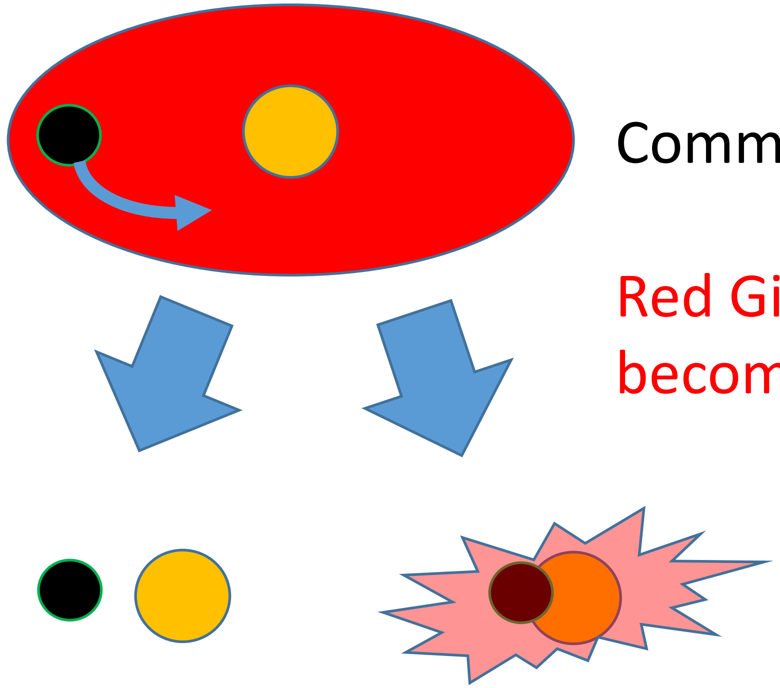
  No wind mass loss due to no metal.

Binary interaction changes progenitor mass

- Mass transfer
- Common envelope



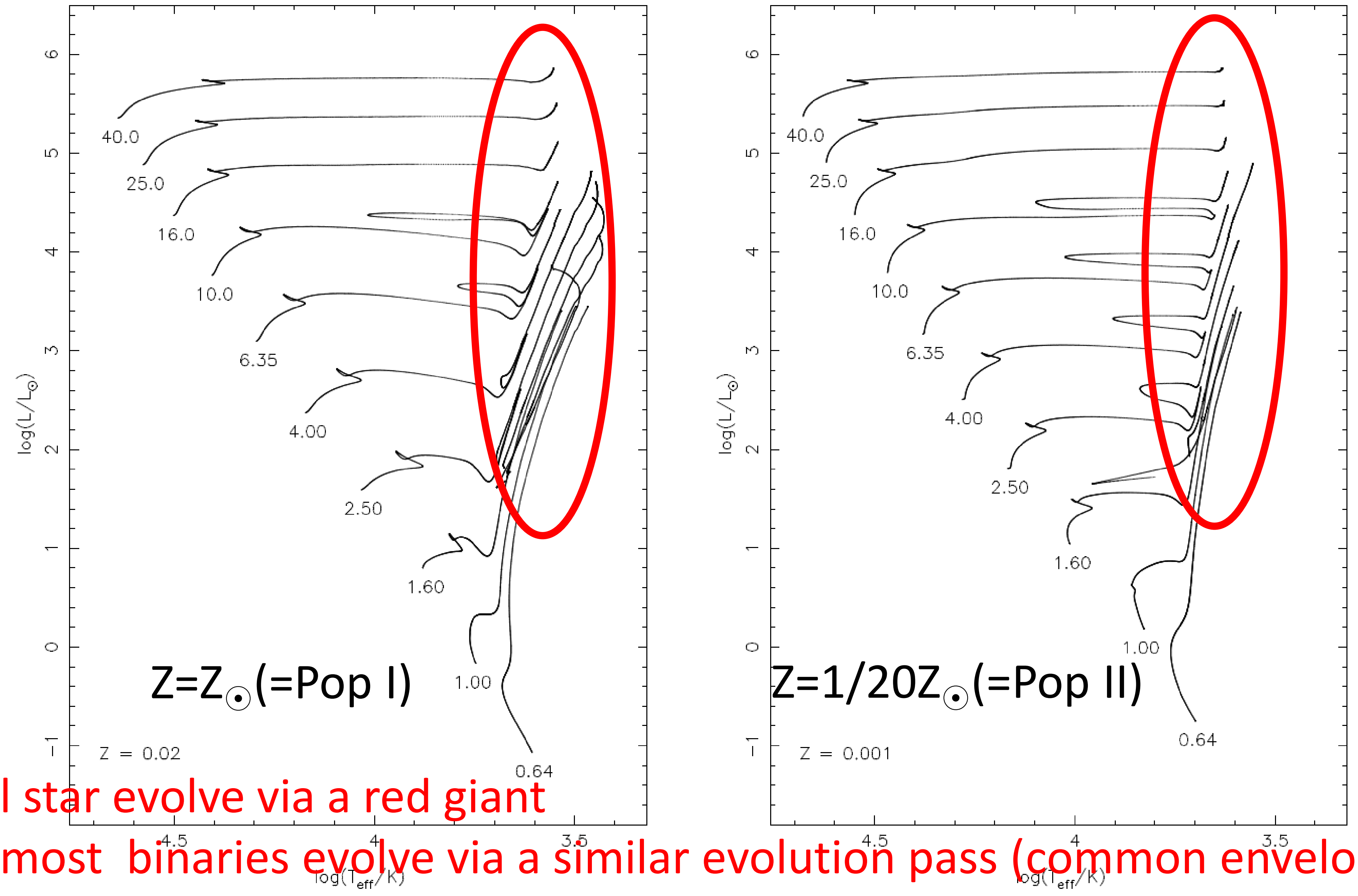
Mass transfer



Common envelope

Red Giants tend to become CE

Close binary or merge

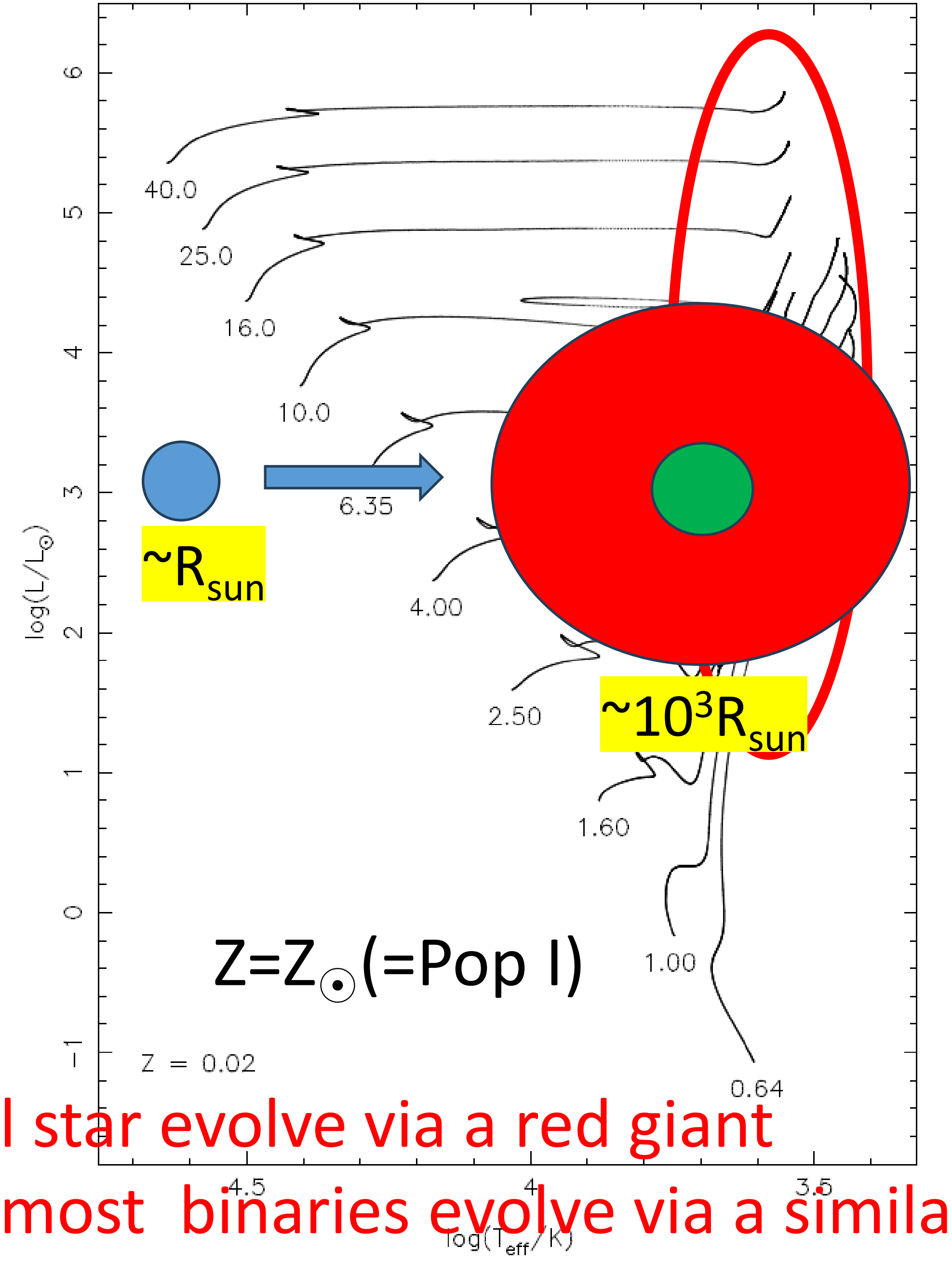


All star evolve via a red giant

Almost binaries evolve via a similar evolution pass (common envelope)

Figure 1. Selected OVS evolution tracks for $Z = 0.02$, for masses 0.64, 1.0, 1.6, 2.5, 4.0, 6.35, 10, 16, 25 and 40 $M_\odot$.

Figure 2. Same as Fig. 1 for $Z = 0.001$. The 1.0 $M_\odot$ post He flash track has been omitted for clarity.



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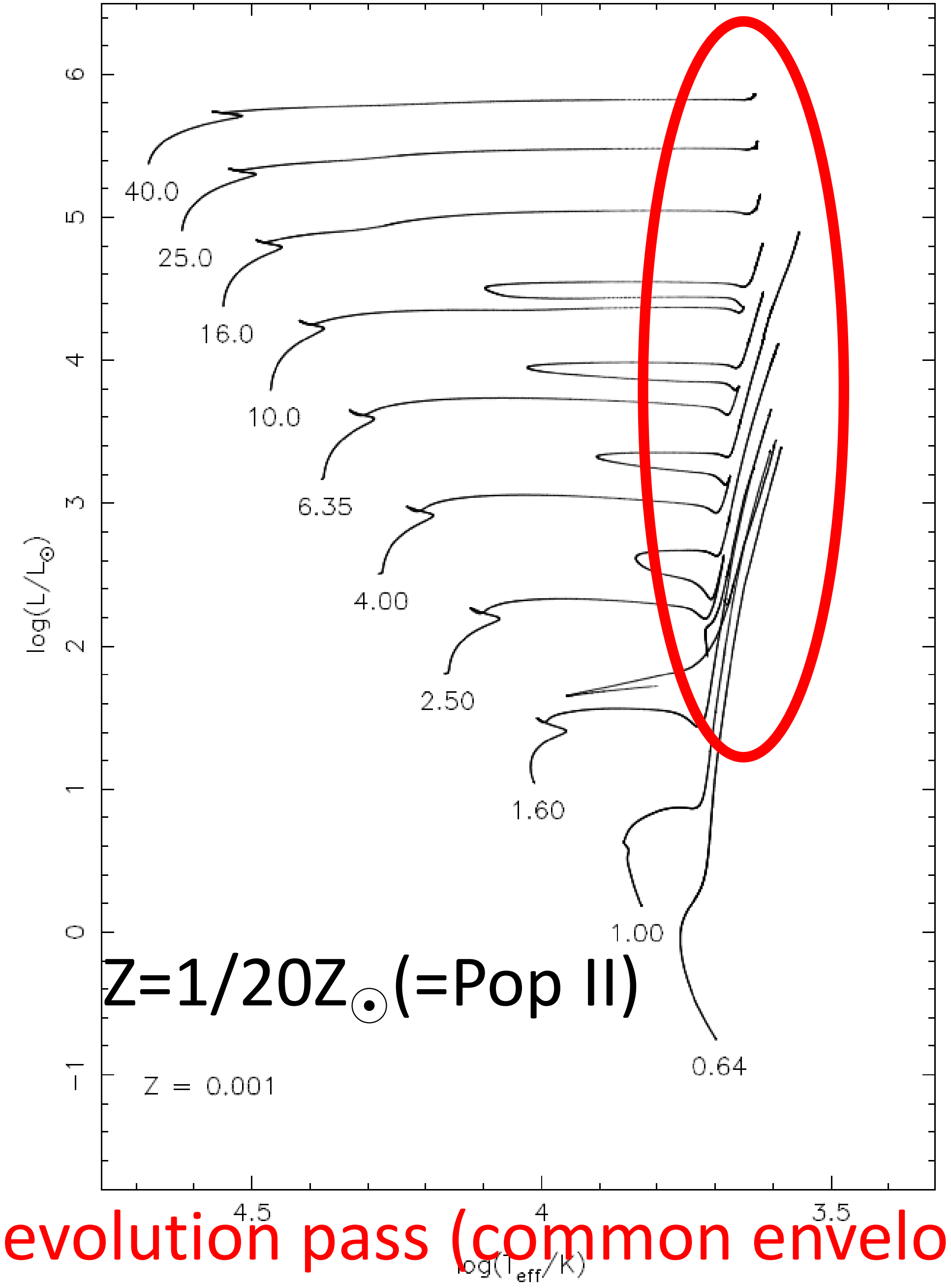

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All star evolve via a red giant

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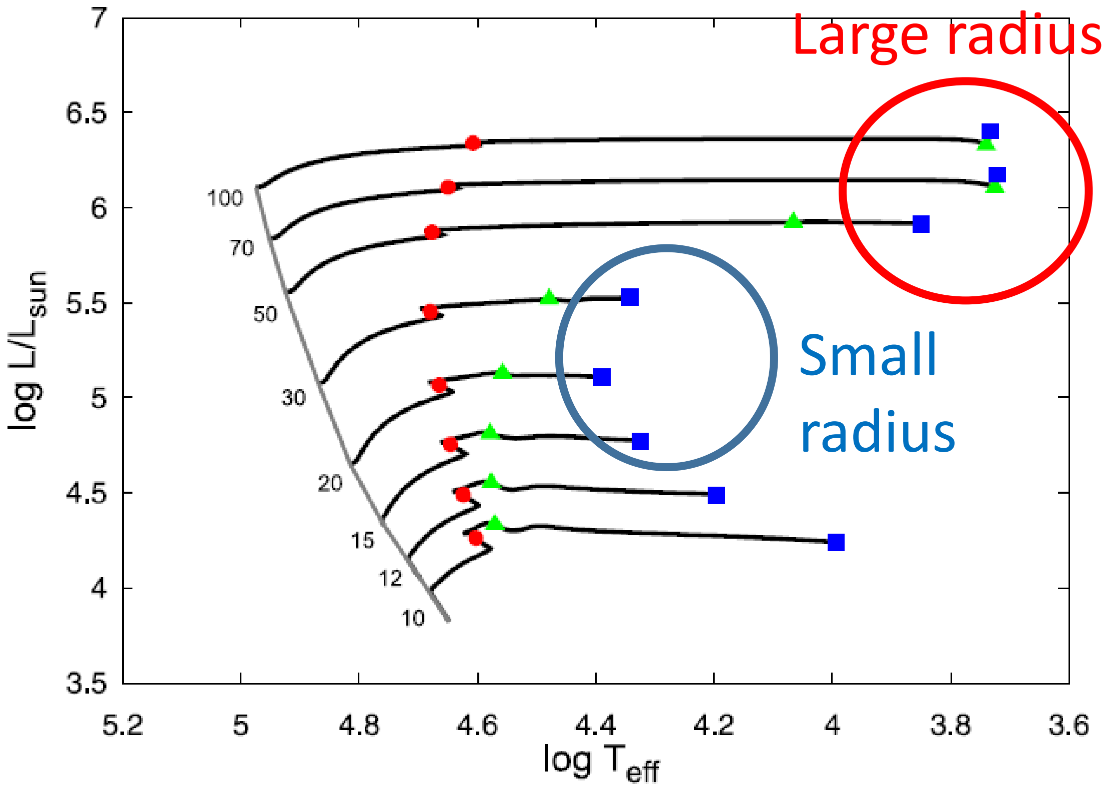
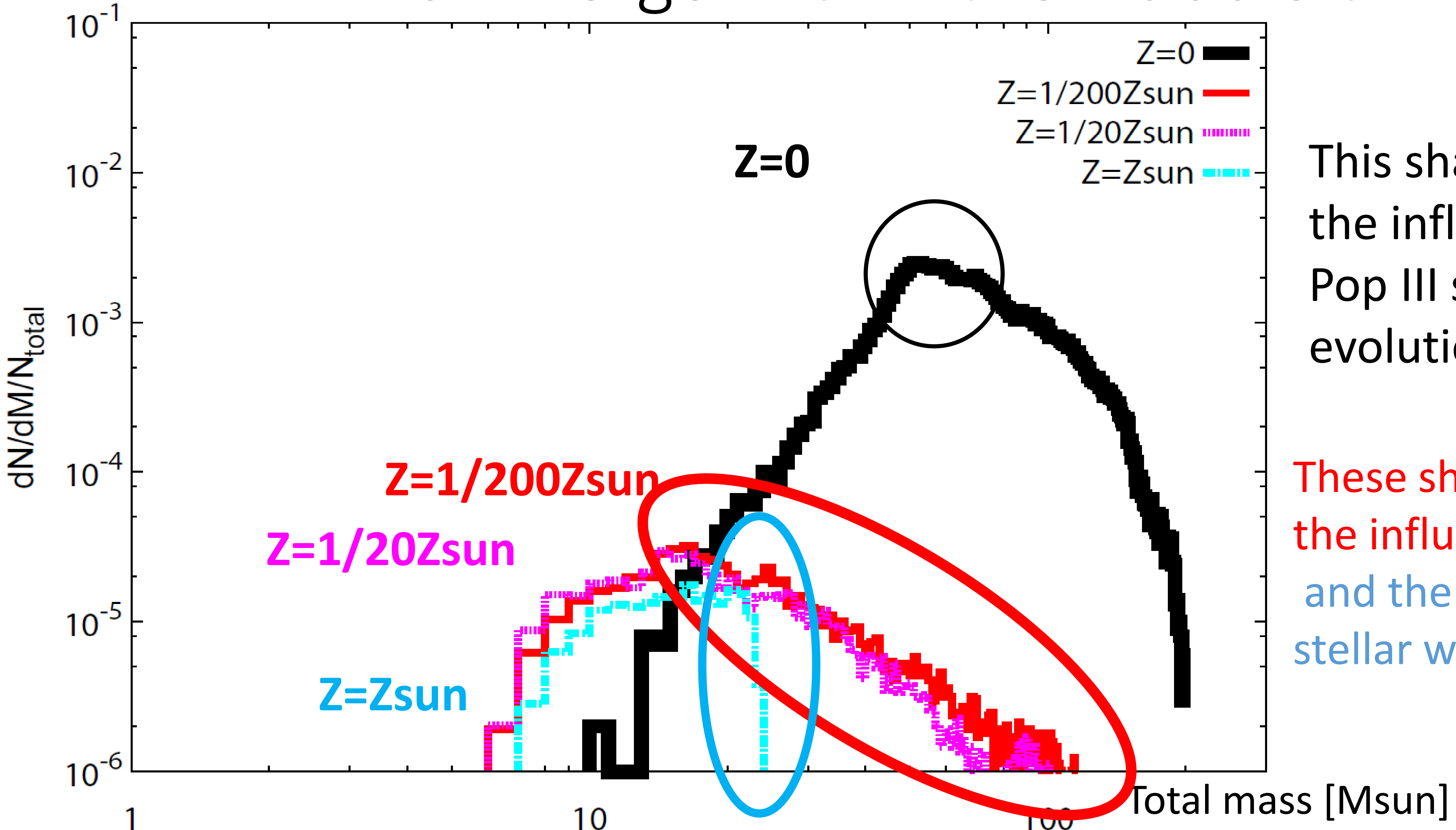
Why Pop III binaries become 30Msun BH-BH



Marigo et al. 2001

- M>50Msun red giant
  - →Mass transfer tend to be unstable
  - →common envelope
  - →1/3~1/2 of initial mass (~30Msun)
- M<50Msun blue giant
  - →Mass transfer tend to be stable
  - →mass loss is not so effective
  - →2/3~1 of initial mass (30Msun)

Formation fraction of BBH which merge within the Hubble time

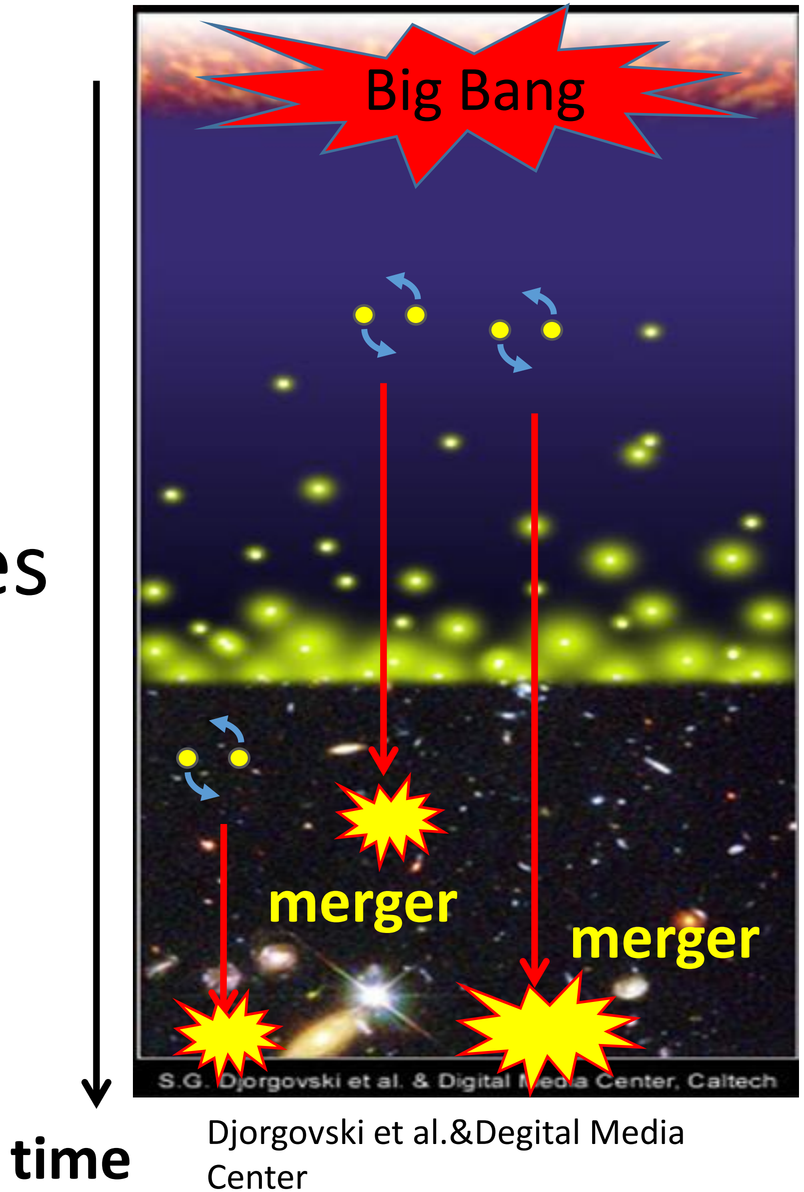


This shape reflects the influence of Pop III stellar evolution

These shapes have the influence of IMF and the influence of stellar wind mass loss

Pop III BBH remnants for gravitational wave

- Pop III stars were born and died at $z \gtrsim 10$.
- The typical merger time of compact binaries $\sim 10^{8\text{-}10}$yr
  $dN/dt \propto t^{-1}$ (Kinugawa et al .2014,2020 Inayoshi et al. 2017)
- We can see Pop III BBH at the present day!



Djorgovski et al.&Degital Media Center

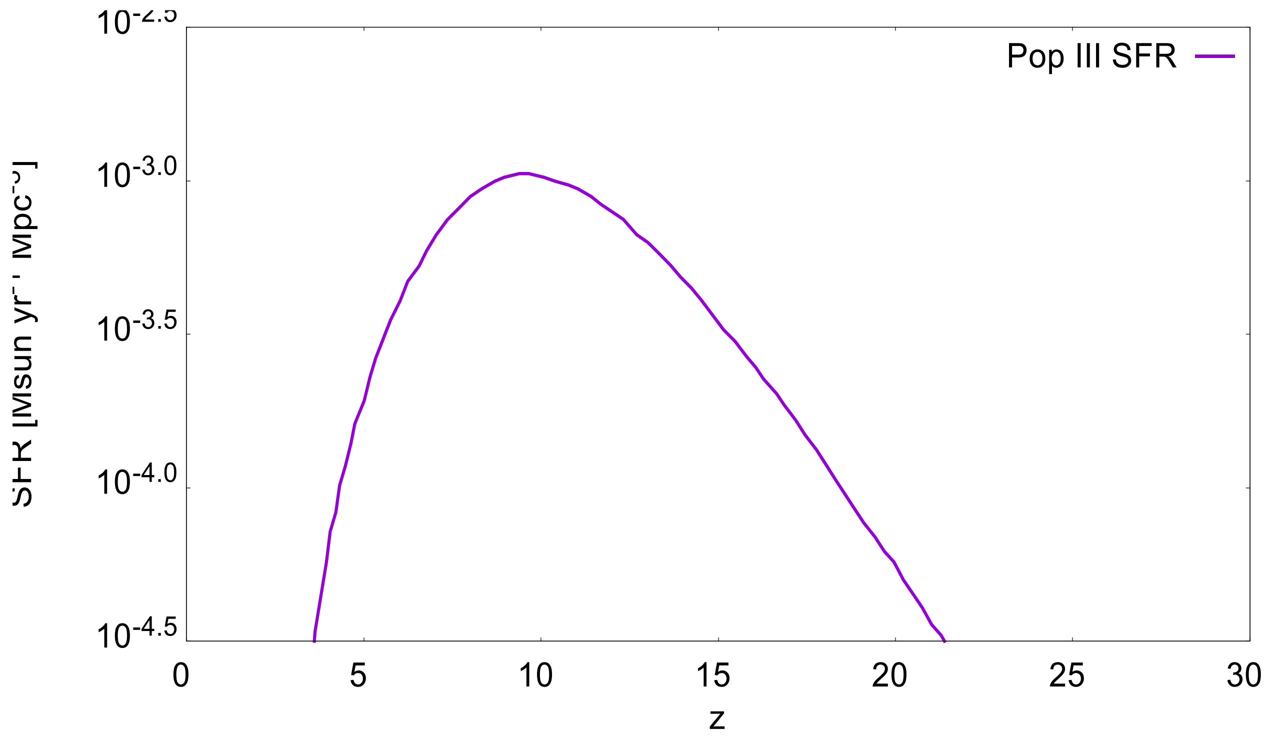
The star formation rate of Pop III

In order to calculate merger rate,

we need to know

- When were Pop III stars born?
- How many were Pop III stars born?

⇒Star formation rate



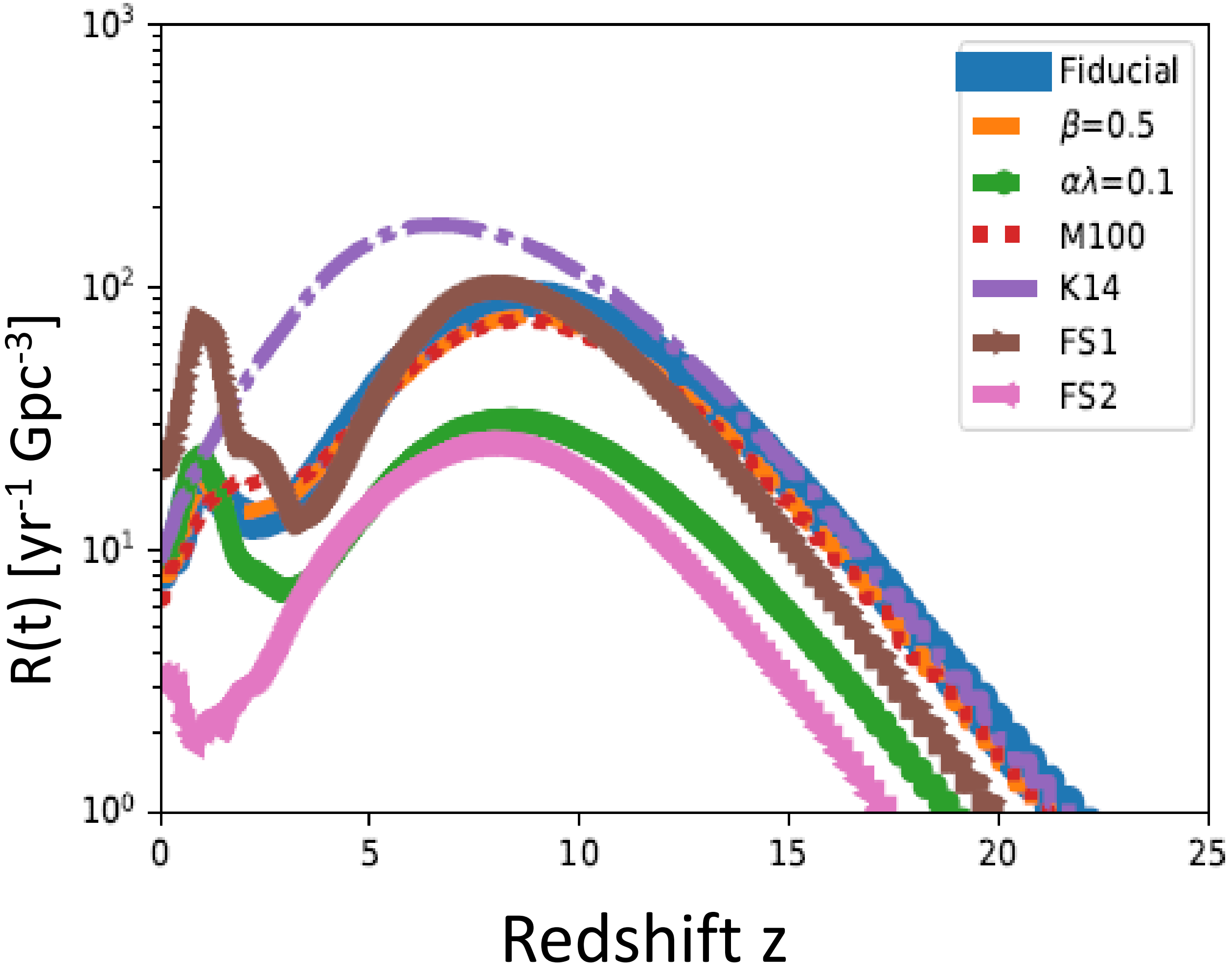
We adopt the total Pop III stellar mass density by Inayoshi et al. 2016

$\rho = 6 \times 10^5$ Msun/Mpc^3

(SFR peak at z=10)

We assume the binary fraction fb=0.5

The Pop III BH-BH merger rate density

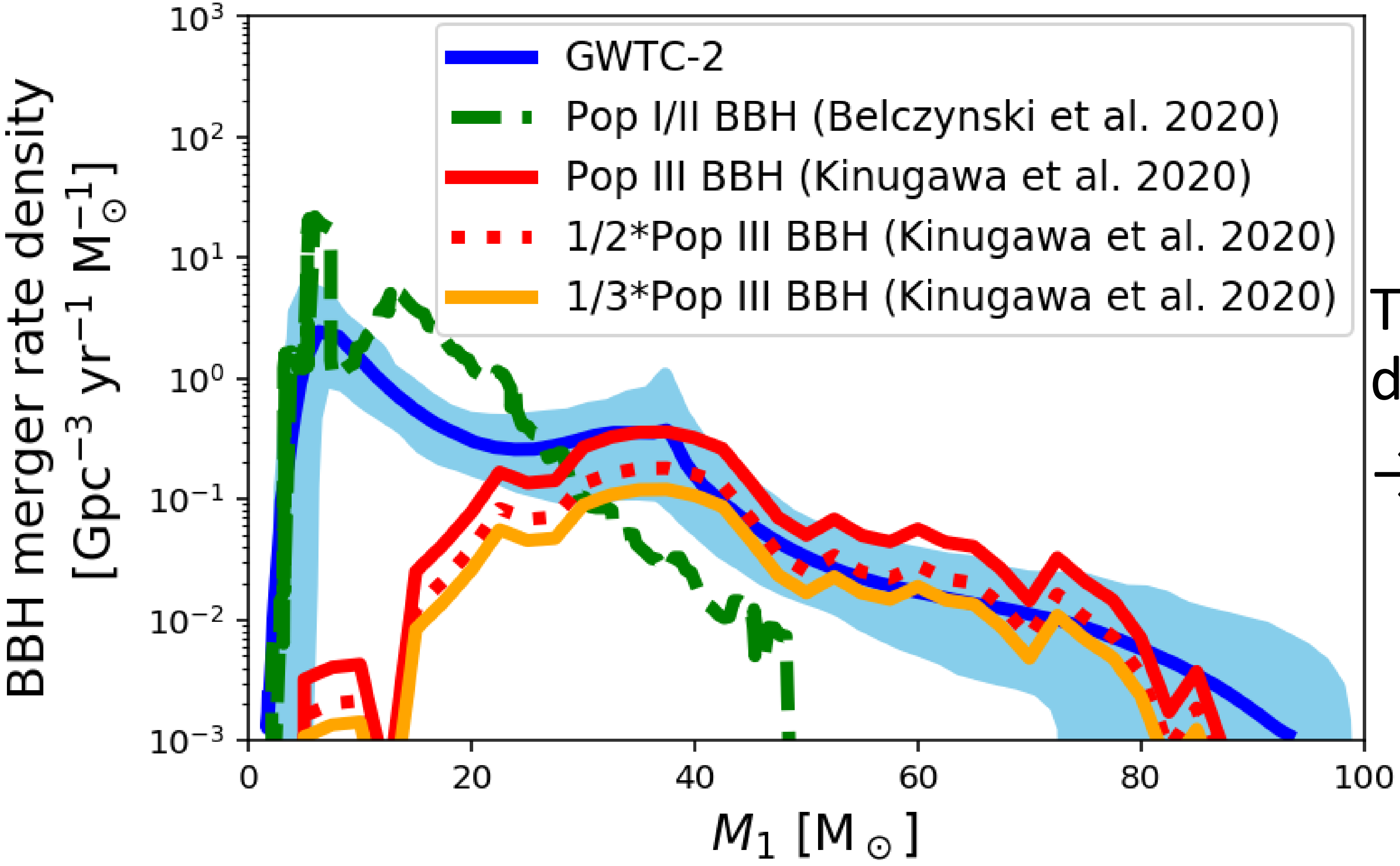


Pop III BHBH merger rate at z=0
In our fiducial model

$$R \sim 10 \left(\frac{\rho_{\mathrm{Pop\ III}}}{6\times10^5 M_\odot/Mpc^3}\right)\left(\frac{f_b/(1+f_b)}{0.33}\right)\ [\mathrm{yr^{-1}\ Gpc^{-3}}]$$

(Kinugawa et al. 2014,2016,2020)

Comparison with mass distributions of observed BBHs



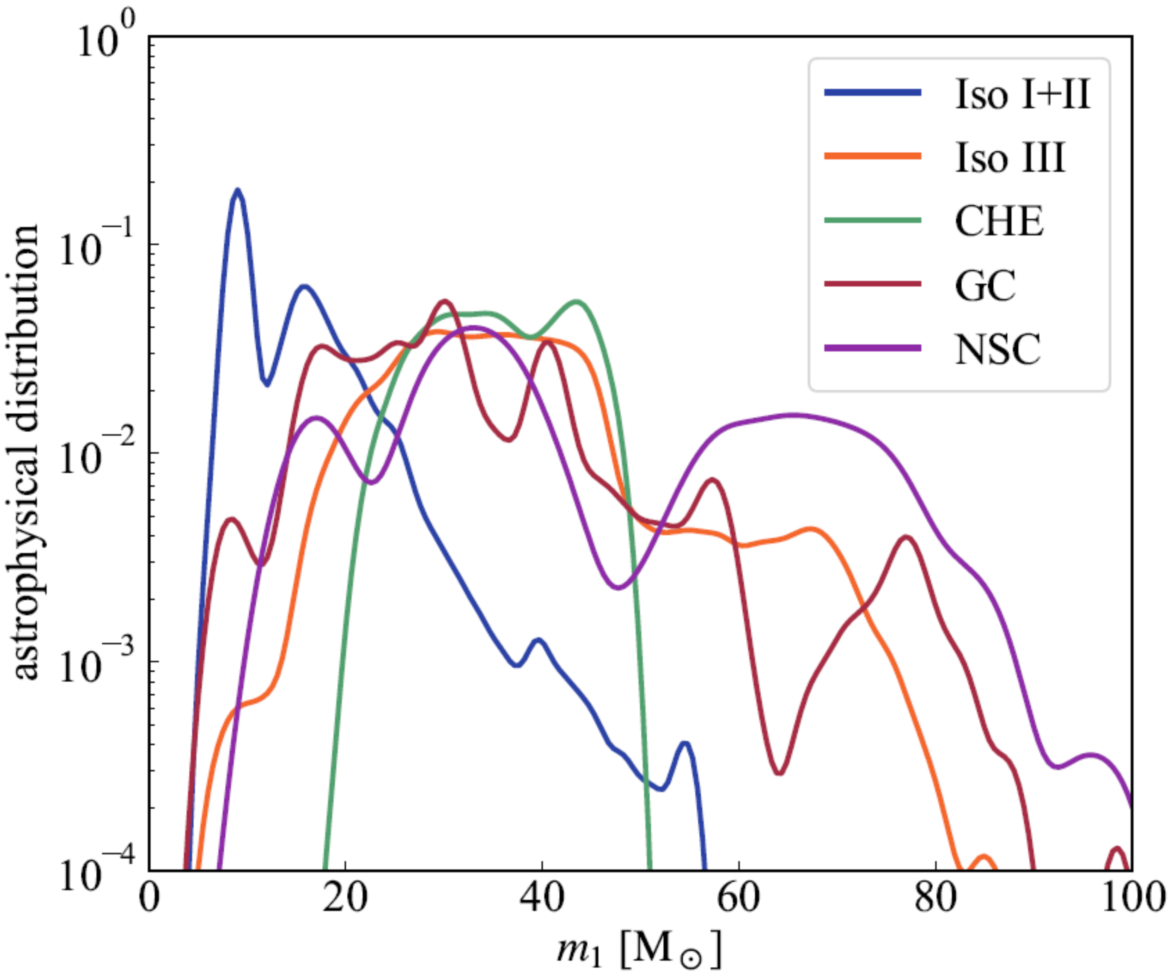
(Kinugawa, Nakamura& Nakano 2021)

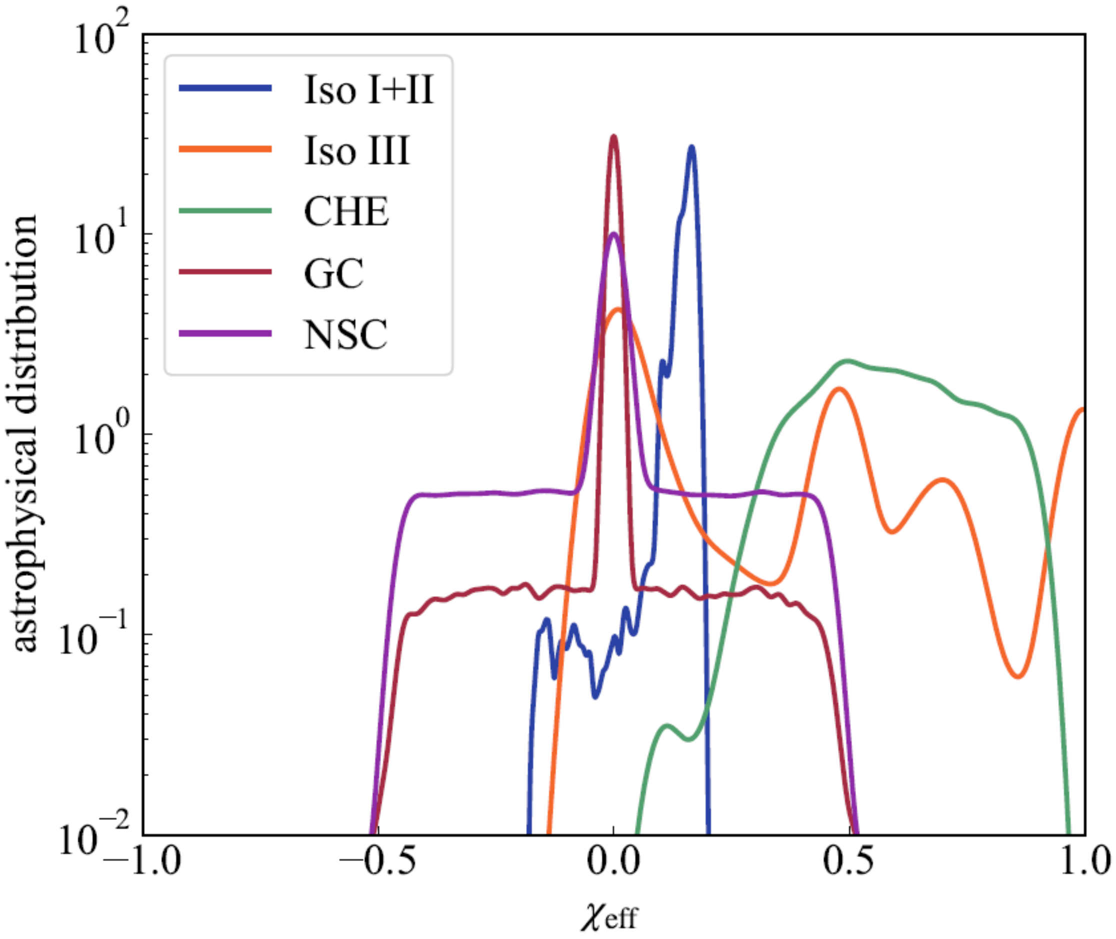
The mass distribution might distinguish Pop III from Pop I/II

→The evidence of Pop III？

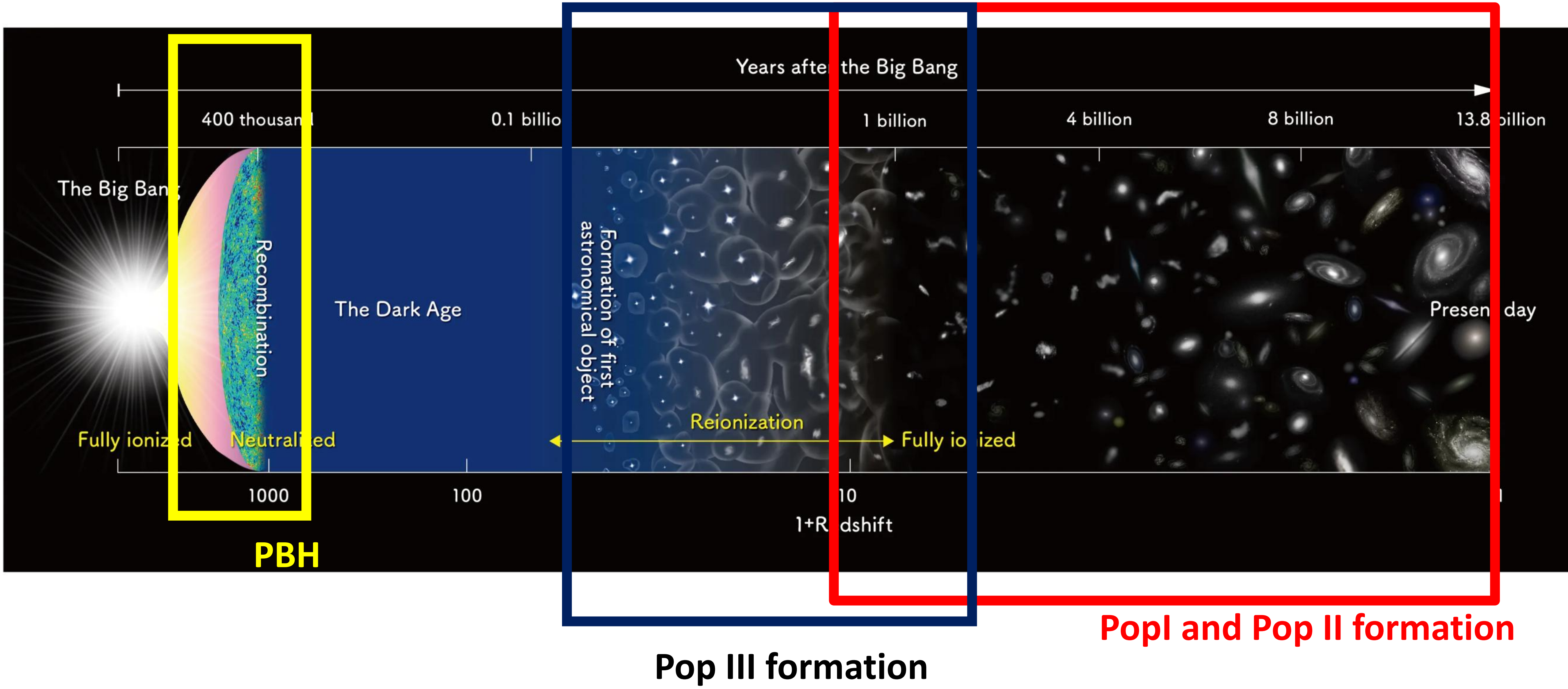
Not yet

Best combination model for GWTC-3 (Iwaya, TK, Tagoshi in prep.)





What is the smoking gun of the origin of BBHs?



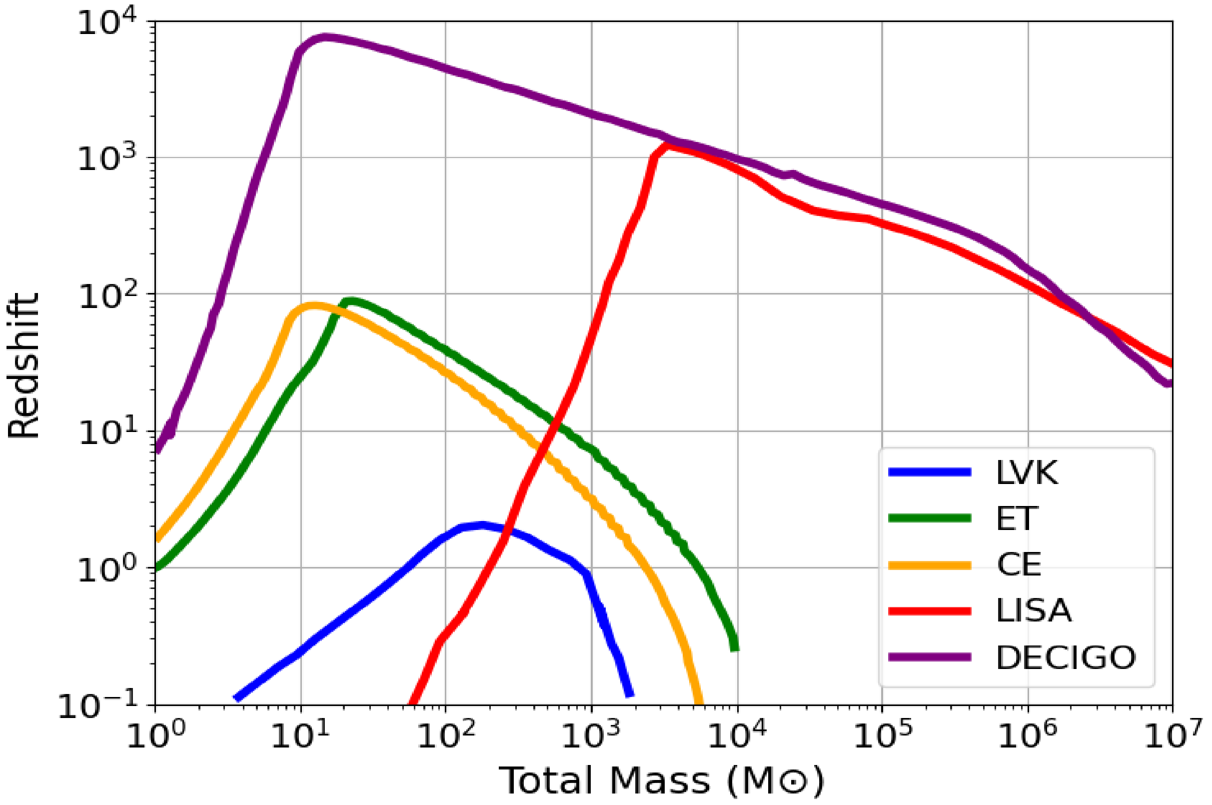
Future plan of GW observer : ET, CE, B-DECIGO and DECIGO

- Einstein telescope (ET): the next generation GW observatory of Europe
- Cosmic explorer (CE) : the next generation GW observatory of US.
- DECIGO: Japanese space gravitational wave observatory project

We can see Pop III BH-BHs

when Pop III stars were born (z>10)!

(Nakamura, Ando, Kinugawa et al. 2016)

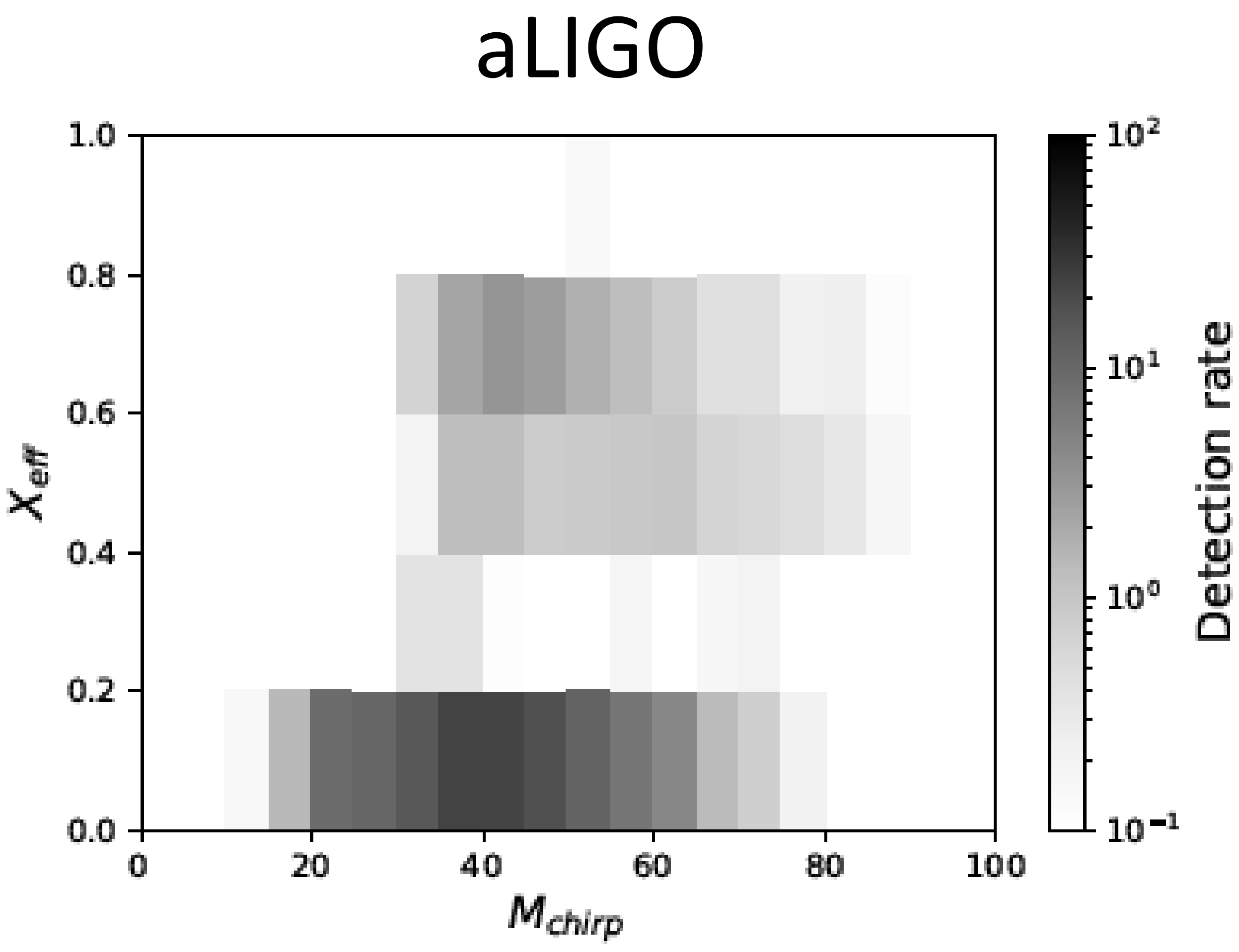


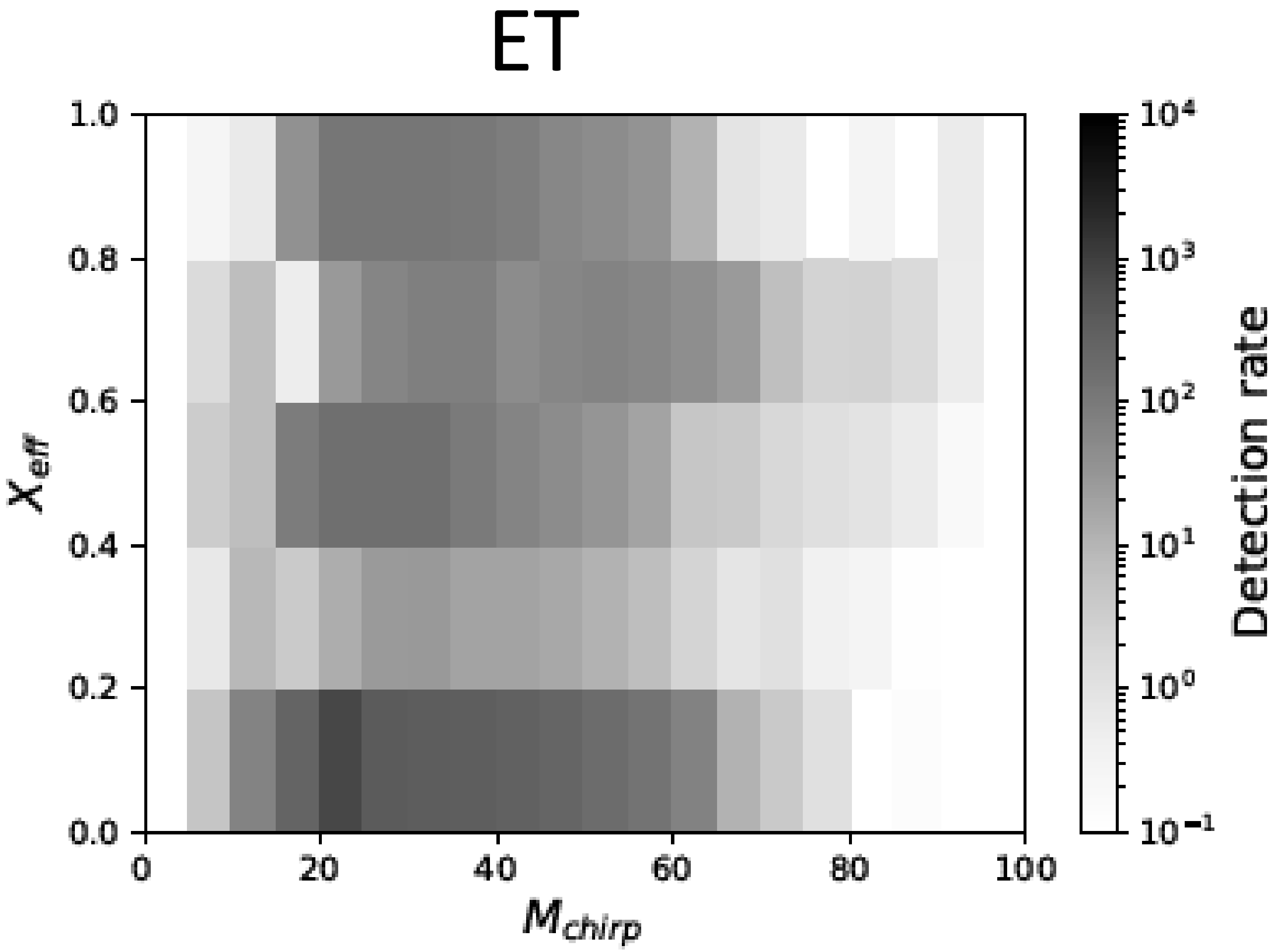
Merger time dependence of Pop III BBH spin

	a1/M1<0.1 a2/M2<0.1	a1/M1<0.1 a2/M2>0.9	a1/M1>0.9 a2/M2<0.1	a1/M1>0.9 a2/M2>0.9
Merger time <1Gyr	25%	36%	0%	23%
Merger time >10Gyr	70%	0.3%	4%	0%

- If the origin of massive BBHs is Pop III,
  high spin BBHs are easier to be detected at high redshift

Detection rate of Pop III BBH for ET and aLIGO design sensitivity





(Kinugawa et al.2020)

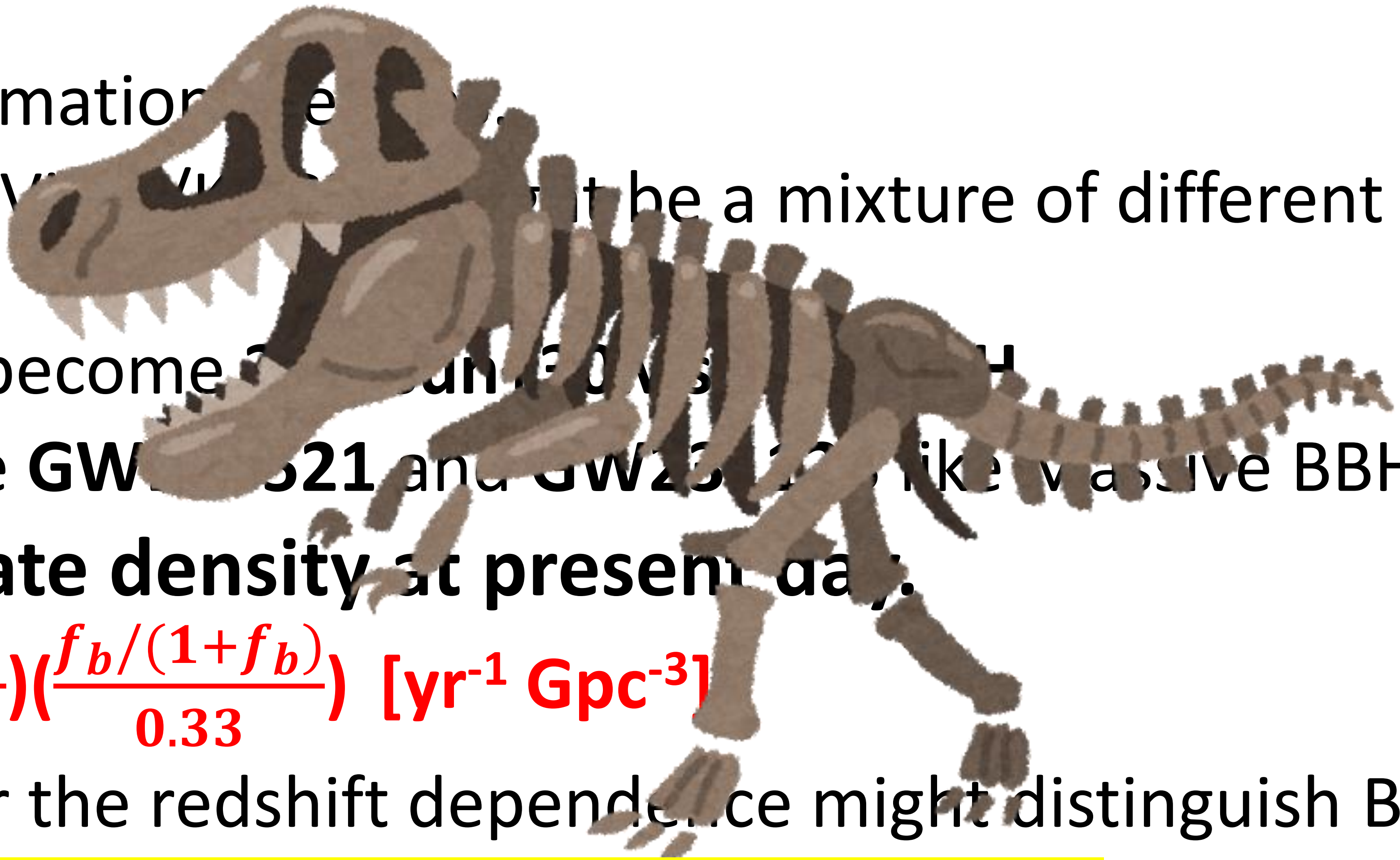
Summary

- There are many BBH formation theories.
- BBHs detected by LIGO/Virgo/KAGRA might be a mixture of different origins.
- Pop III binaries tend to become **30Msun+30Msun BH-BH**
- Pop III might explain the **GW190521** and **GW231123** like massive BBHs
- **Pop III BBH merger rate density at present day.**

$$R \sim 10 \left(\frac{\rho_{\mathrm{Pop\ III}}}{6\times10^{5} M_{\odot}/Mpc^{3}}\right)\left(\frac{f_b/(1+f_b)}{0.33}\right)\ [\mathrm{yr^{-1}\ Gpc^{-3}}]$$

- The mass distribution or the redshift dependence might distinguish BH origins.

Summary



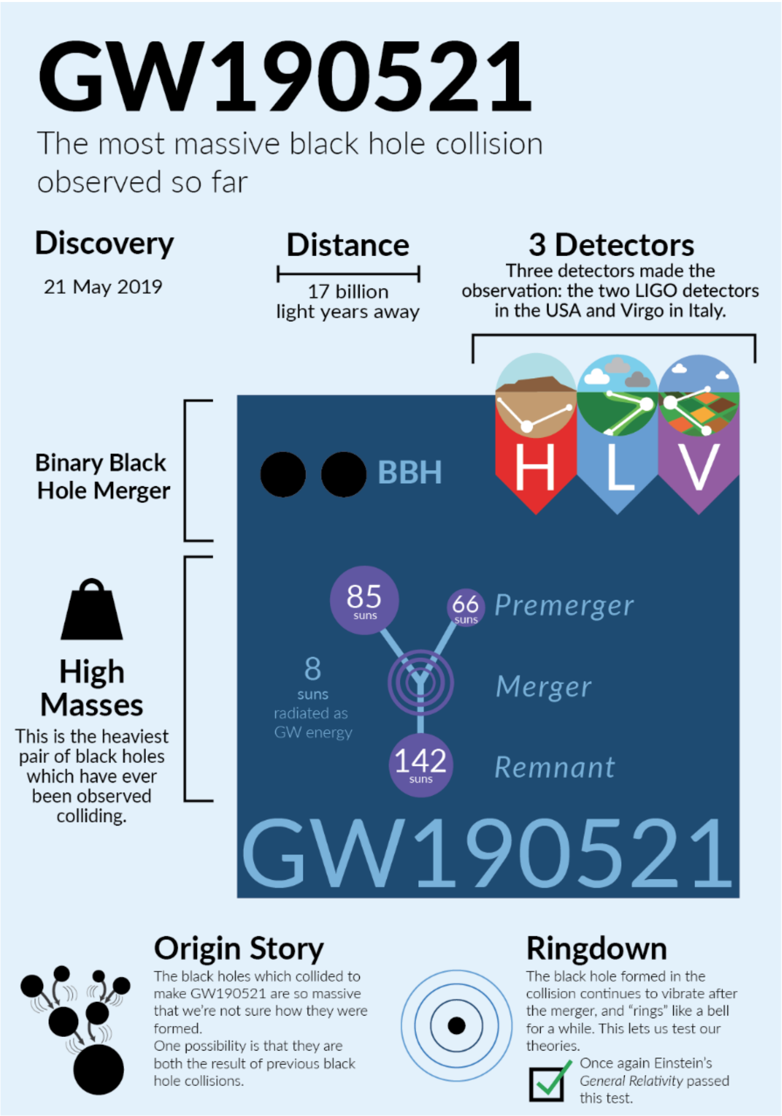
- Ther … rmation … e …
- BBHs … /V … /I … t be a mixture of different origi…
- Pop … become …
- Pop … e **GW… 521** an… **GW2…** …ike … BBHs
- **Pop … rate density … present da…**

$$R\sim \ldots \,)\left(\frac{f_b/(1+f_b)}{0.33}\right)\ [\mathrm{yr^{-1}\ Gpc^{-3}}]$$

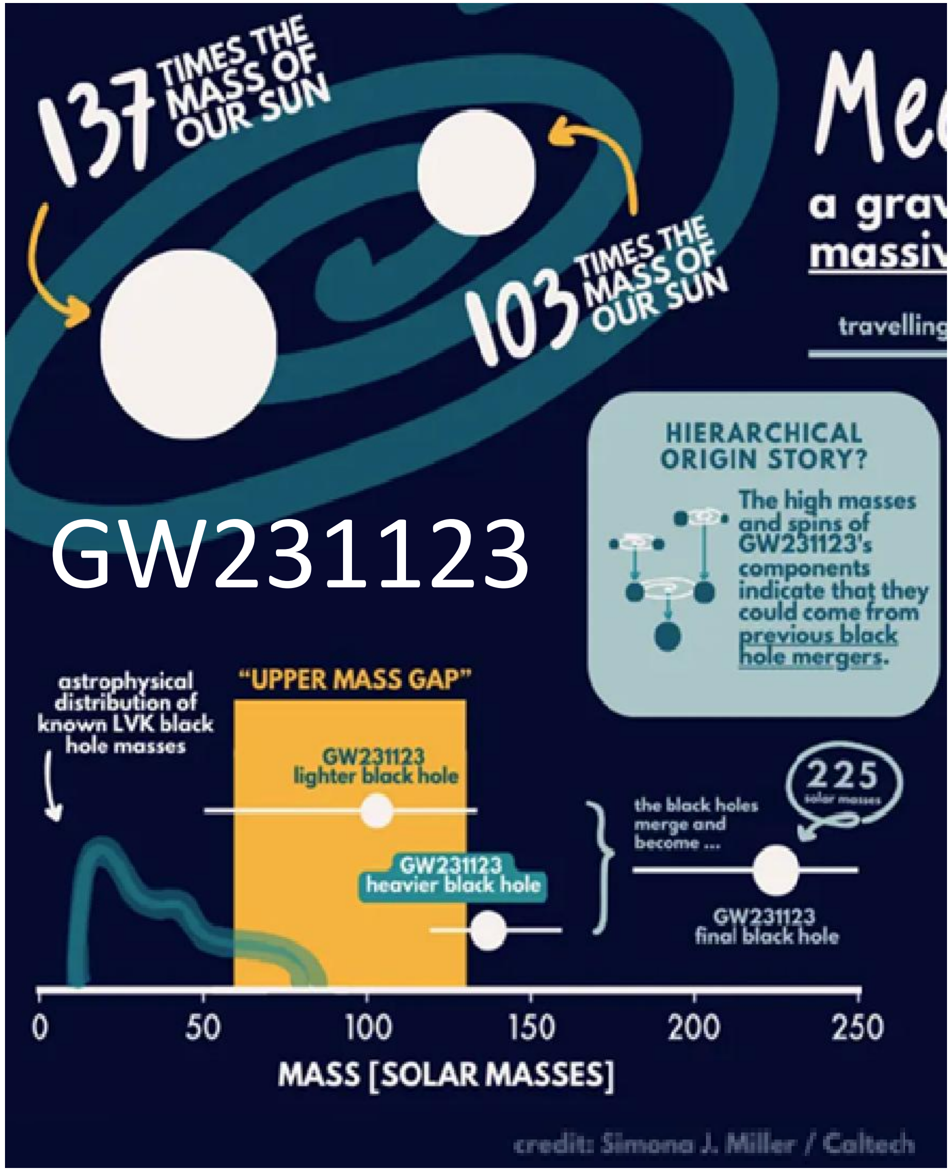
- The mass distribution or the redshift depende…ce might distinguish BH origins.

Massive BBHs = the fossil of ancient BH?

Can Pop III explain "Mass gap" BBH mergers?

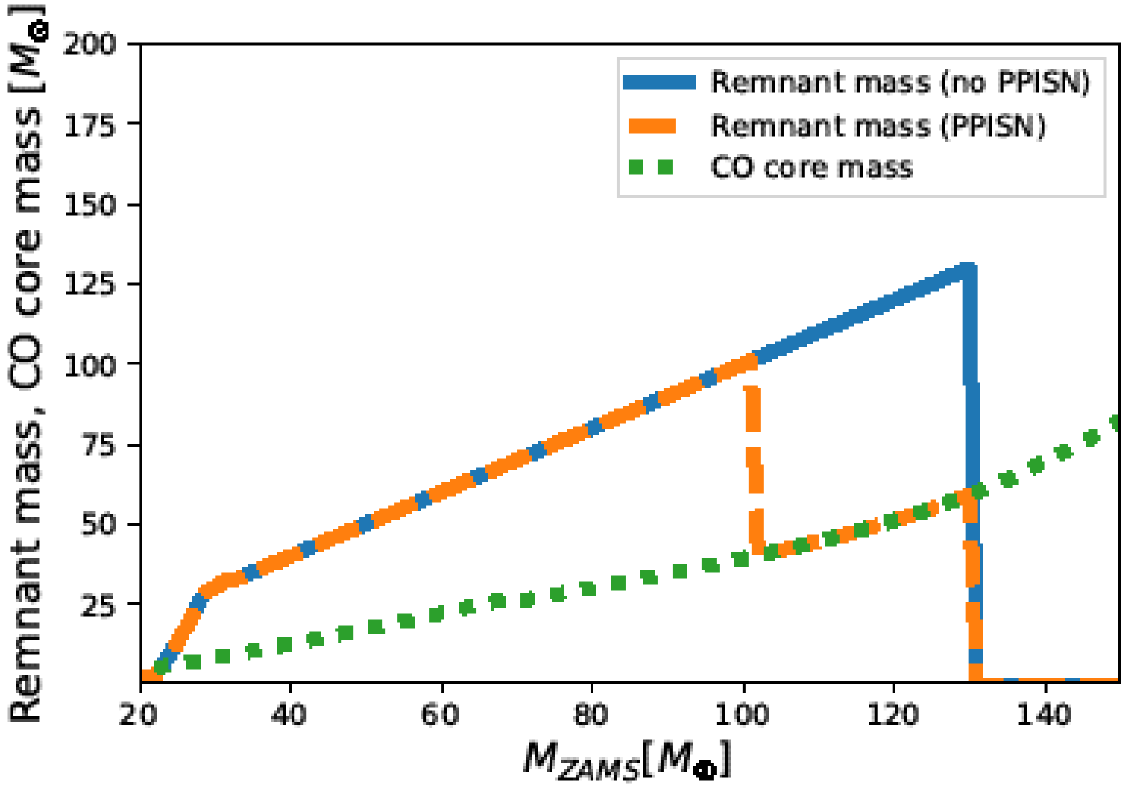


Credit: LVC/Daniel Williams



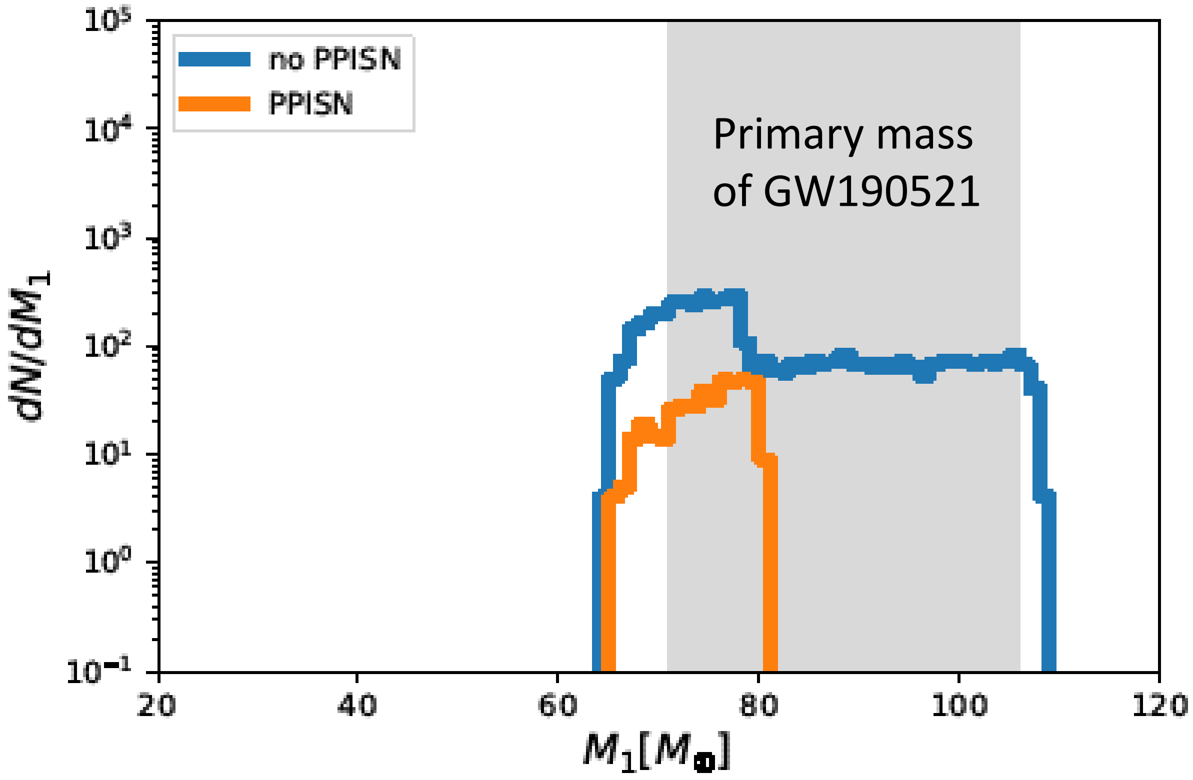
GW190521

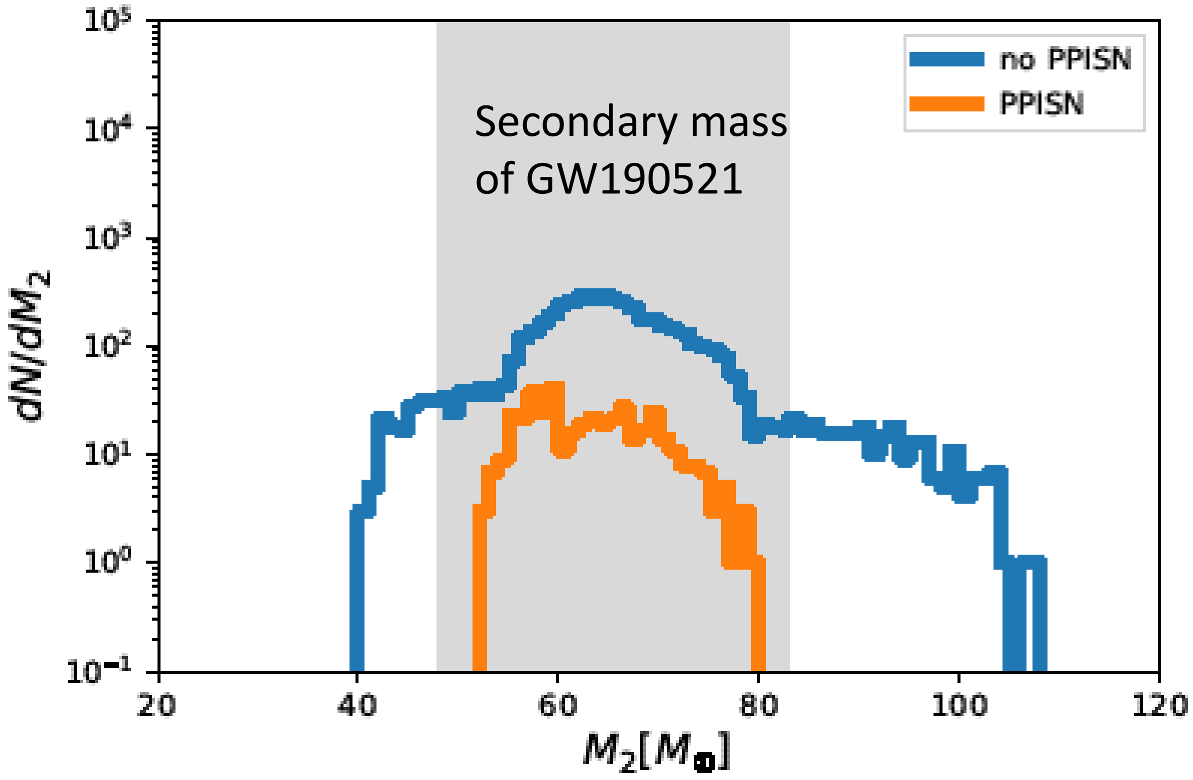
- Pop III can make GW190521 like BBH!
  (Kinugawa et al. 2020, Farrell et al. 2020, Tanikawa et al. 2020)



Kinugawa et al. 2021

GW190521



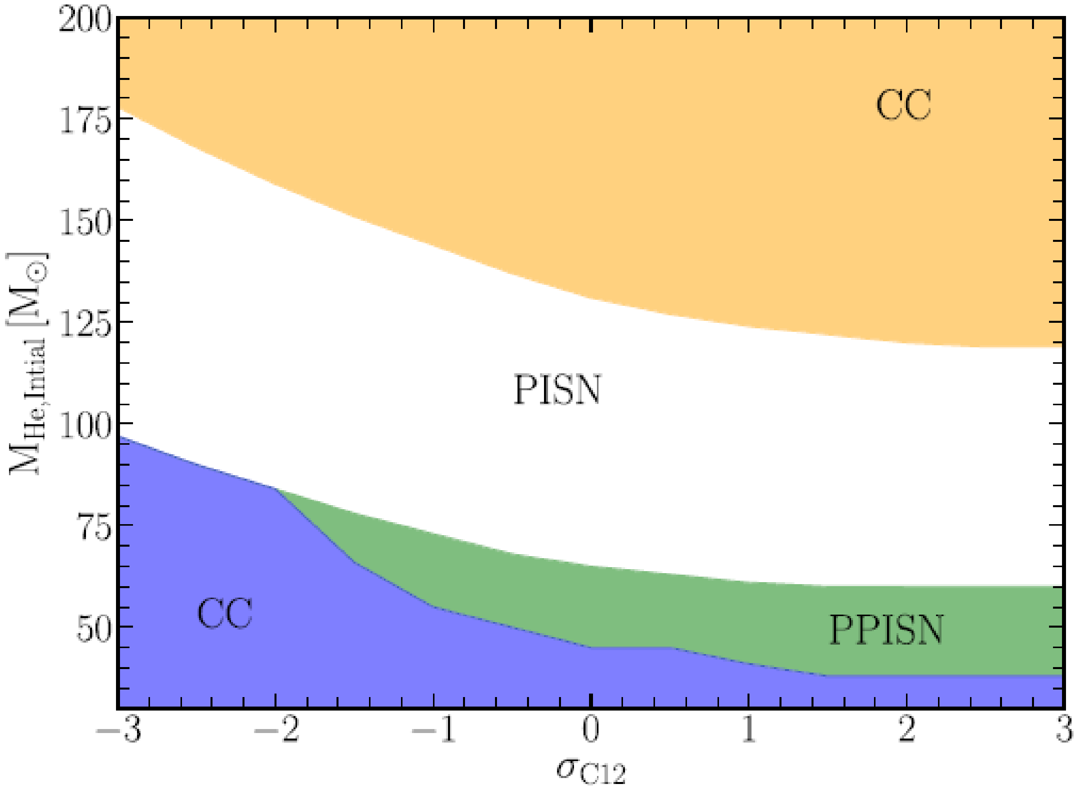


Kinugawa et al. 2021

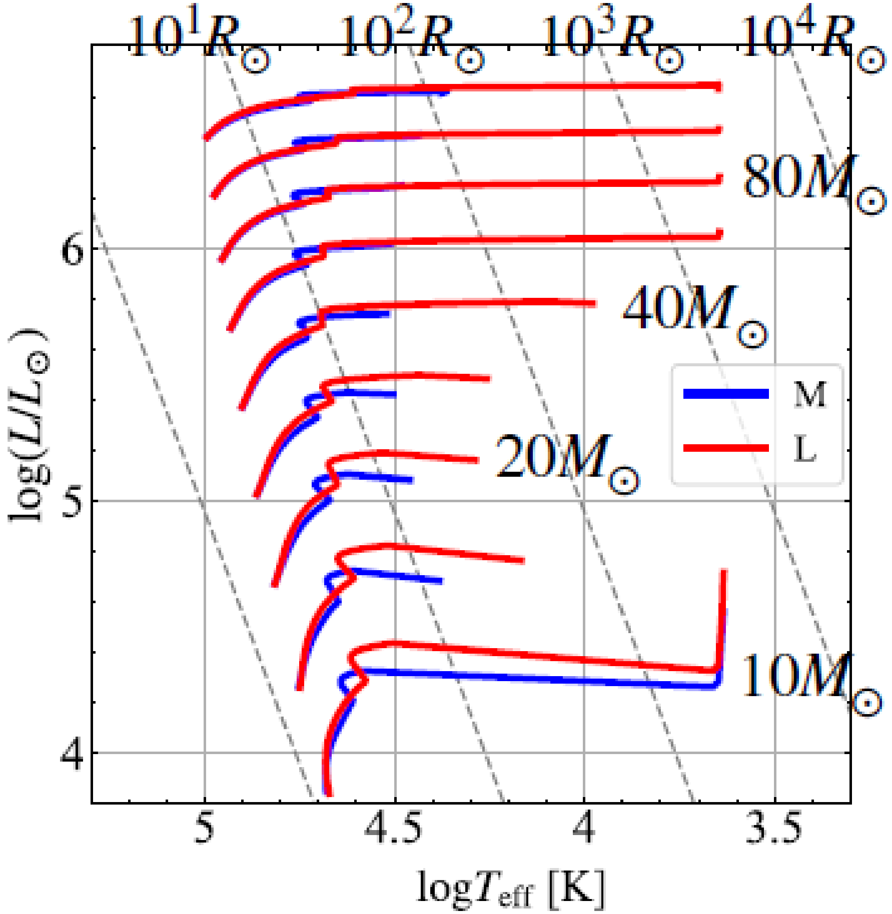
GW231123

- 100Msun BH is very difficult,

But it might be explained by uncertainty of $^{12}C(\alpha,\gamma)^{16}O$ and overshooting parameter (Tanikawa et al. 2025)

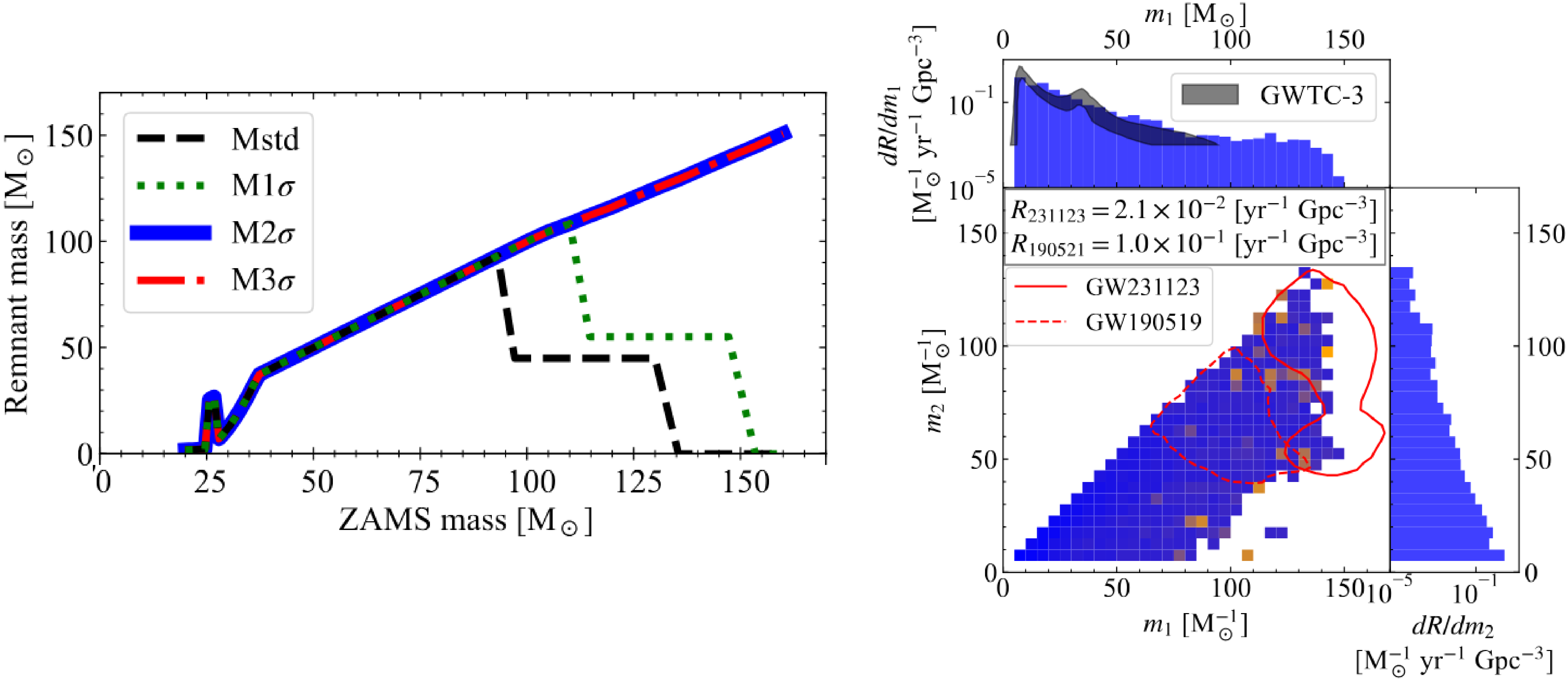


Farmer et al. 2020



Tanikawa et al. 2020

GW231123



Tanikawa et al. 2025

Can Pop III BBH explain massive BBHs?

30Msun BBHs	✔
GW190521	✔
GW231123	❓ Small $^{12}C(\alpha,\gamma)^{16}O$ reaction rate and small overshooting parameter needed

Uncertainty in Pop. III model

- No massive Pop. III stars discovered so far
- Extrapolation from nearby stars to Pop. III stars
- Nearby star models

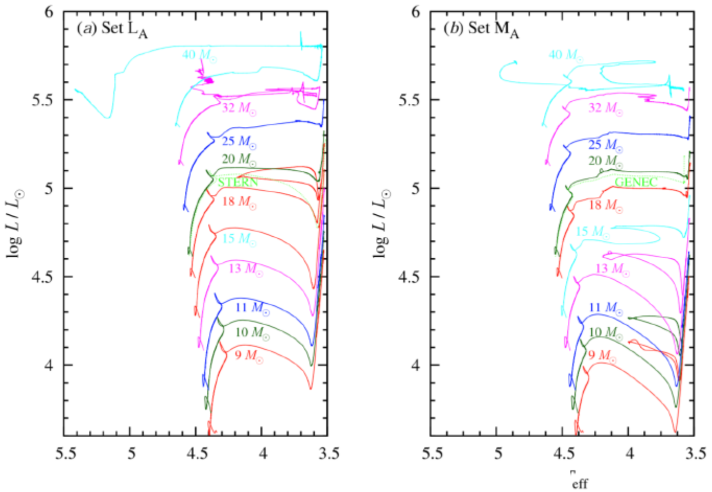
M model

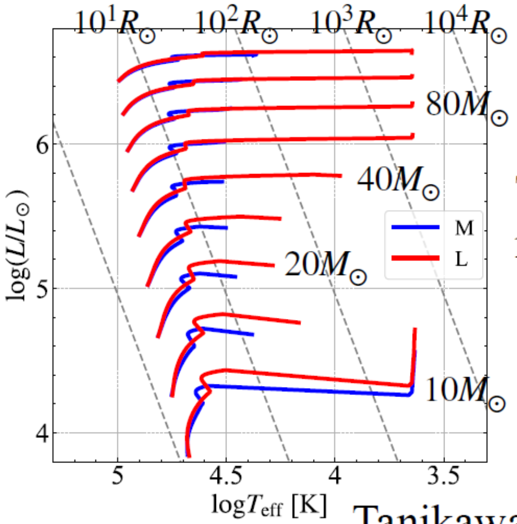
  - AB-type stars in MW open clusters, GENEC(Ekstrom et al. 2012), adopted by Farrell et al. (2020)
  - Early B-type stars in LMC, Stern (Brott et al. 2011)

L model

- The maximums radius of a $80M_\odot$ star
  - M model: $\sim 40R_\odot$, similar to Farrell et al. (2020)
  - L model: $\sim 3\times10^3 R_\odot$, similar to Yoon et al. (2012)

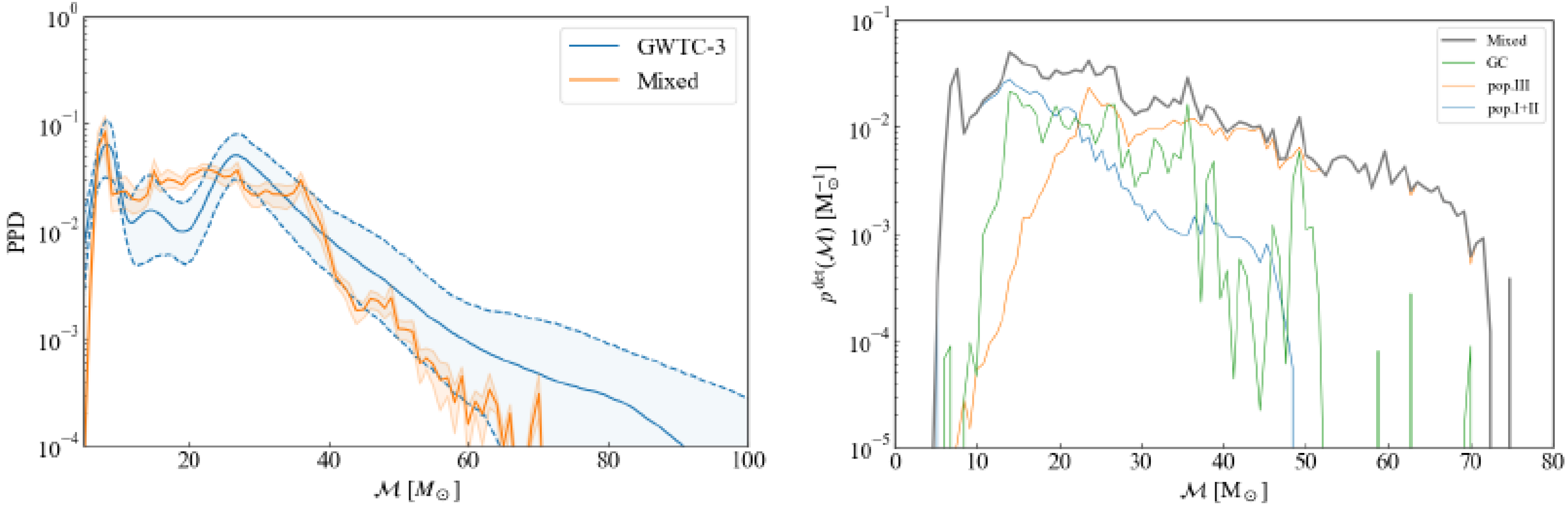
Yoshida et al. (2019)





Two Pop. III models

Tanikawa et al. (2020c)



GWTC-3
Mixed
PPD
$\mathcal{M}$ [$M_\odot$]
Mixed
GC
pop.III
pop.I+II
$p^{\rm det}(\mathcal{M})$ [M$_\odot^{-1}$]
$\mathcal{M}$ [M$_\odot$]

Table 1. Parameter sets and merger rate density of GW231123- and GW190521-like events in each set.

Name	Single star model (Overshoot efficiency)	PPISN/PISN model ($^{12}C(\alpha,\gamma)^{16}O$ rate)	GW231123-like event [yr^{-1} Gpc^{-3}]	GW190521-like event [yr^{-1} Gpc^{-3}]
Mstd	M (inefficient)	Standard	0	4.9×10^{-2}
M1σ	M (inefficient)	1σ lower	0	1.0×10^{-1}
M2σ	M (inefficient)	2σ lower	2.1×10^{-2}	1.0×10^{-1}
M3σ	M (inefficient)	3σ lower	2.1×10^{-2}	1.0×10^{-1}
Lstd	L (efficient)	Standard	0	0
L3σ	L (efficient)	3σ lower	0	8.6×10^{-2}

NOTE—The Mstd and L3σ sets are the same as the fiducial and L-3σ sets in A. Tanikawa et al. (2022).

Tanikawa et al .2025

Merger rate (GWTC-3)

13-1900 /yr/Gpc^3
(NS-NS)

7.4-320 /yr/Gpc^3
(NS-BH)

17.3-45 /yr/Gpc^3
(BH-BH)

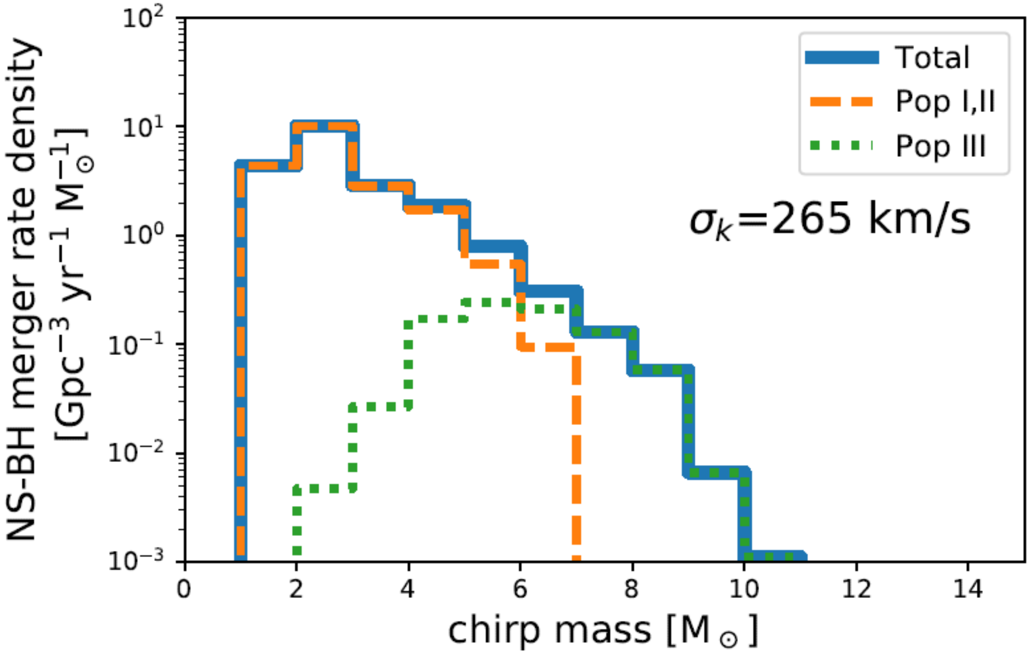
NS-BH formation (Kinugawa et al. 2017)

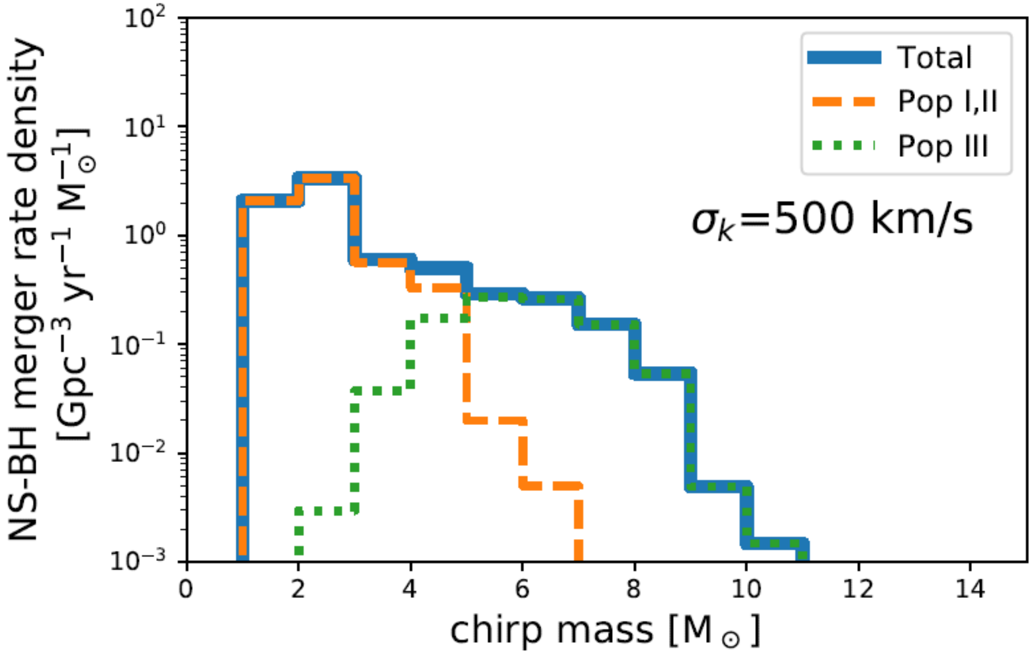
- Pop I/II
- Pop III

Table 2: The number of NS-BH formations and the number of NS-BHs which merge within 15 Gyrs for each metallicity for the initial 10^6 binaries. The numbers are for the $\sigma_k = 265$ km/s models, while the numbers in the parenthesis are for the $\sigma_k = 500$ km/s models.

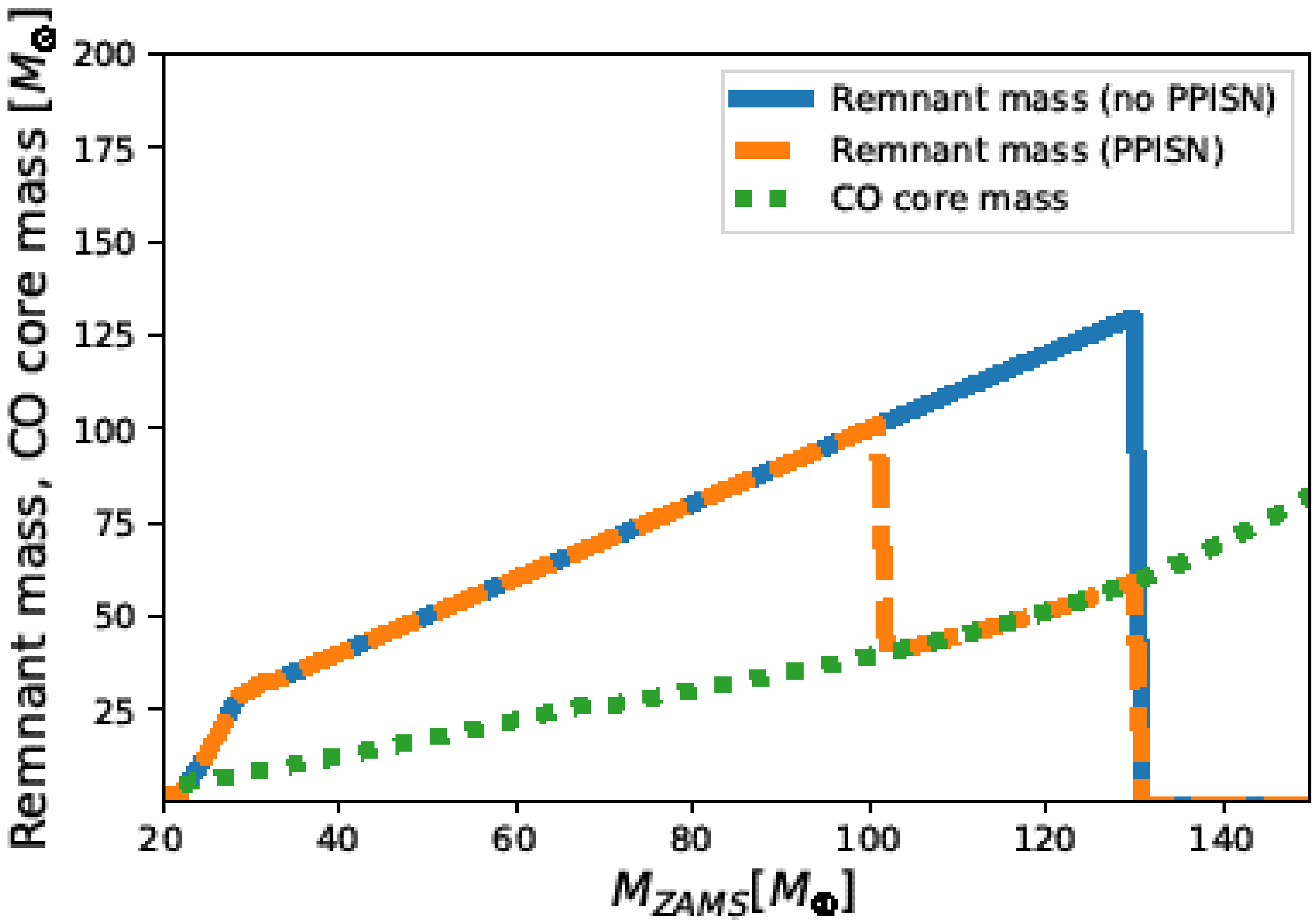
Z	$Z_\odot$	$10^{-0.5} Z_\odot$	$10^{-1} Z_\odot$	$10^{-1.5} Z_\odot$	$10^{-2} Z_\odot$	0
NS-BH	148 (32)	598 (169)	1296 (416)	1686 (576)	1896 (617)	22638 (11192)
merging NS-BH	15 (2)	191 (67)	525 (213)	755 (377)	862 (401)	9089 (5856)

Chirp mass distribution of observable NS-BH

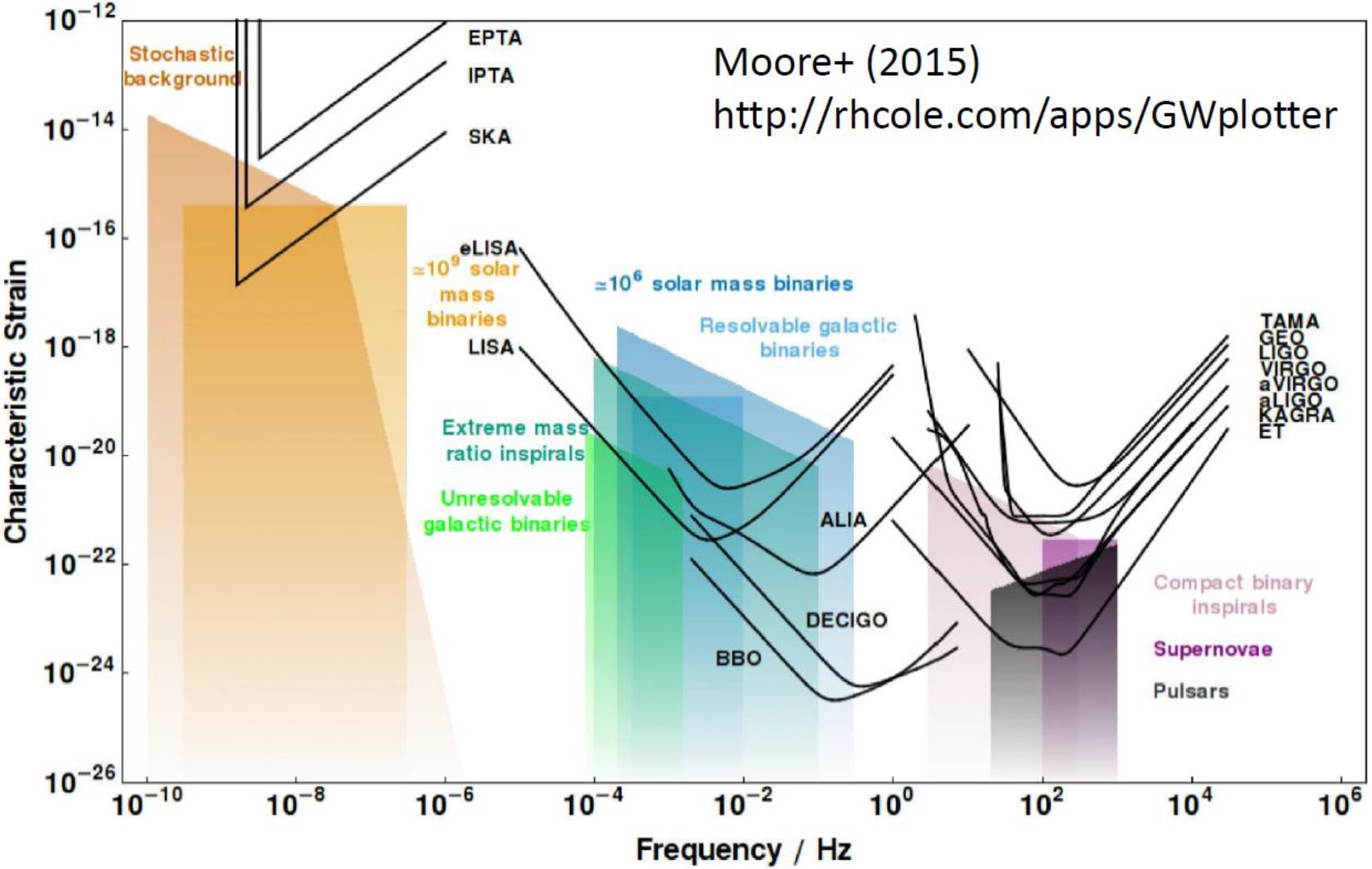




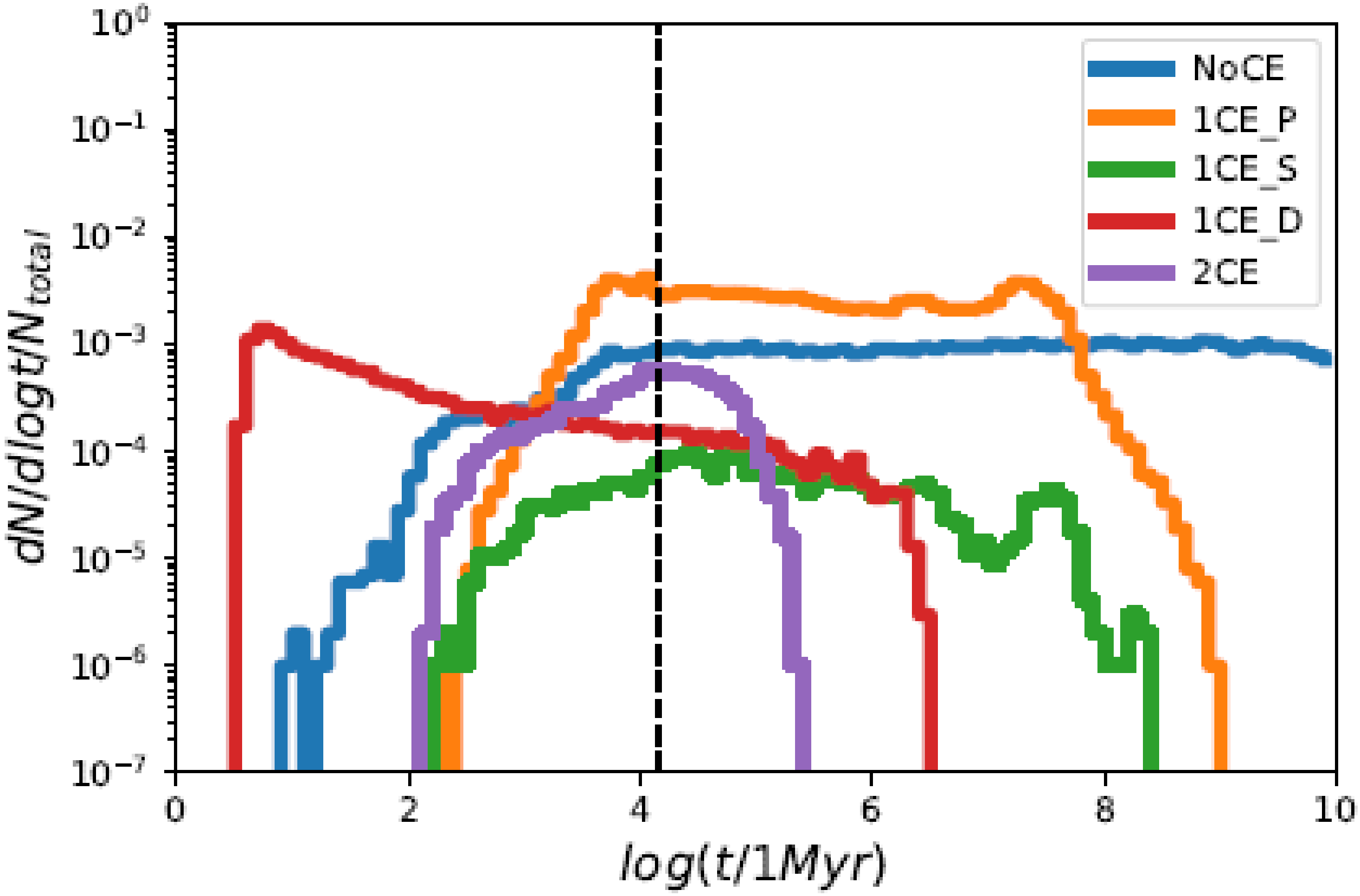
Pop III remnant mass for single star case



- We assume M_{He}=40-60Msun →PPISN



Moore+ (2015)
http://rhcole.com/apps/GWplotter
Characteristic Strain
Frequency / Hz
Stochastic background
EPTA
IPTA
SKA
≃10^9 solar mass binaries
eLISA
LISA
≃10^6 solar mass binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
ALIA
DECIGO
BBO
TAMA
GEO
LIGO
VIRGO
aVIRGO
aLIGO
KAGRA
ET
Compact binary inspirals
Supernovae
Pulsars



(a) fiducial model

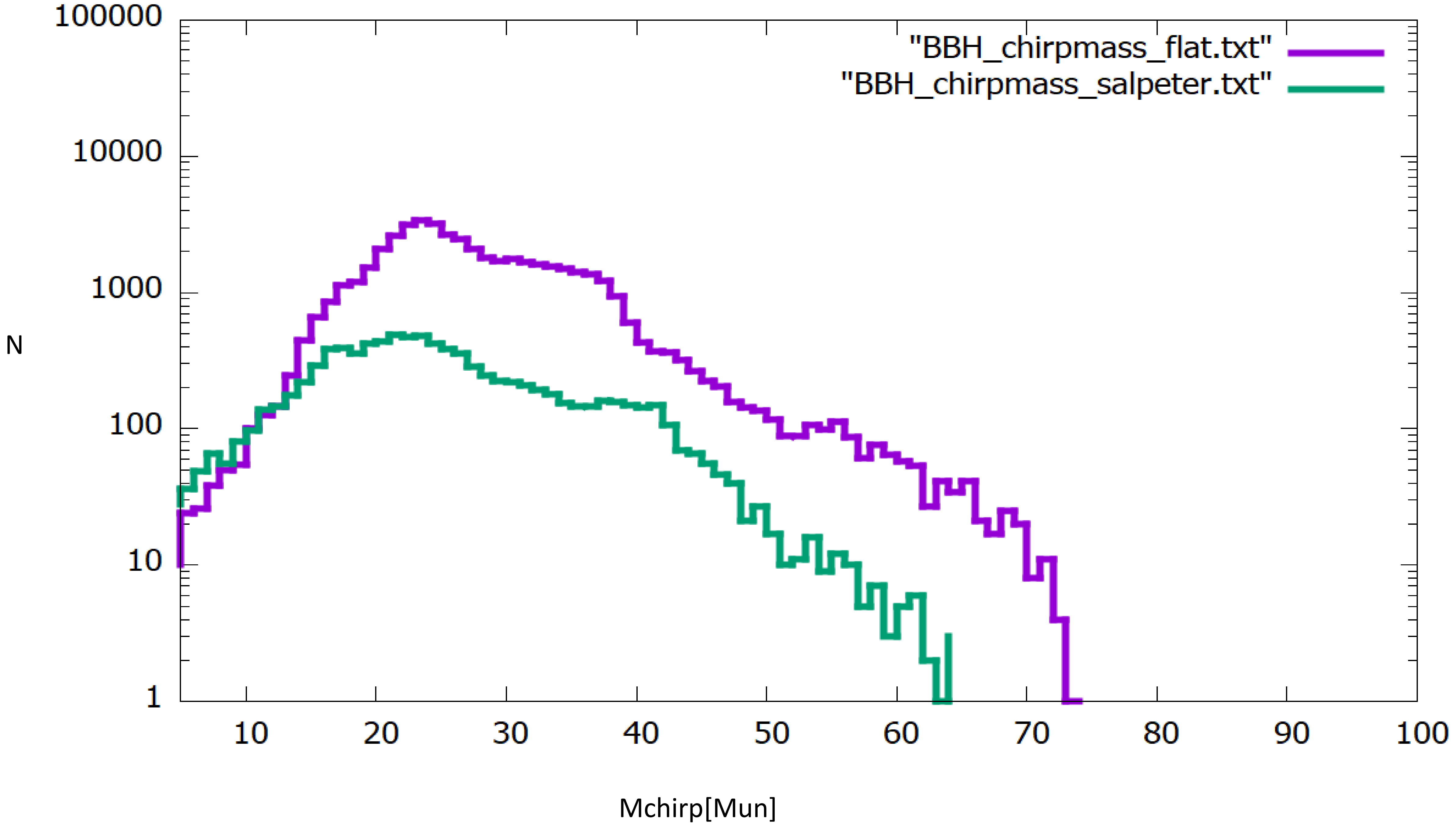
Event rate of GW190521 like BH-BH mergers

Pop III GW190521 like BBH merger rates at the present day

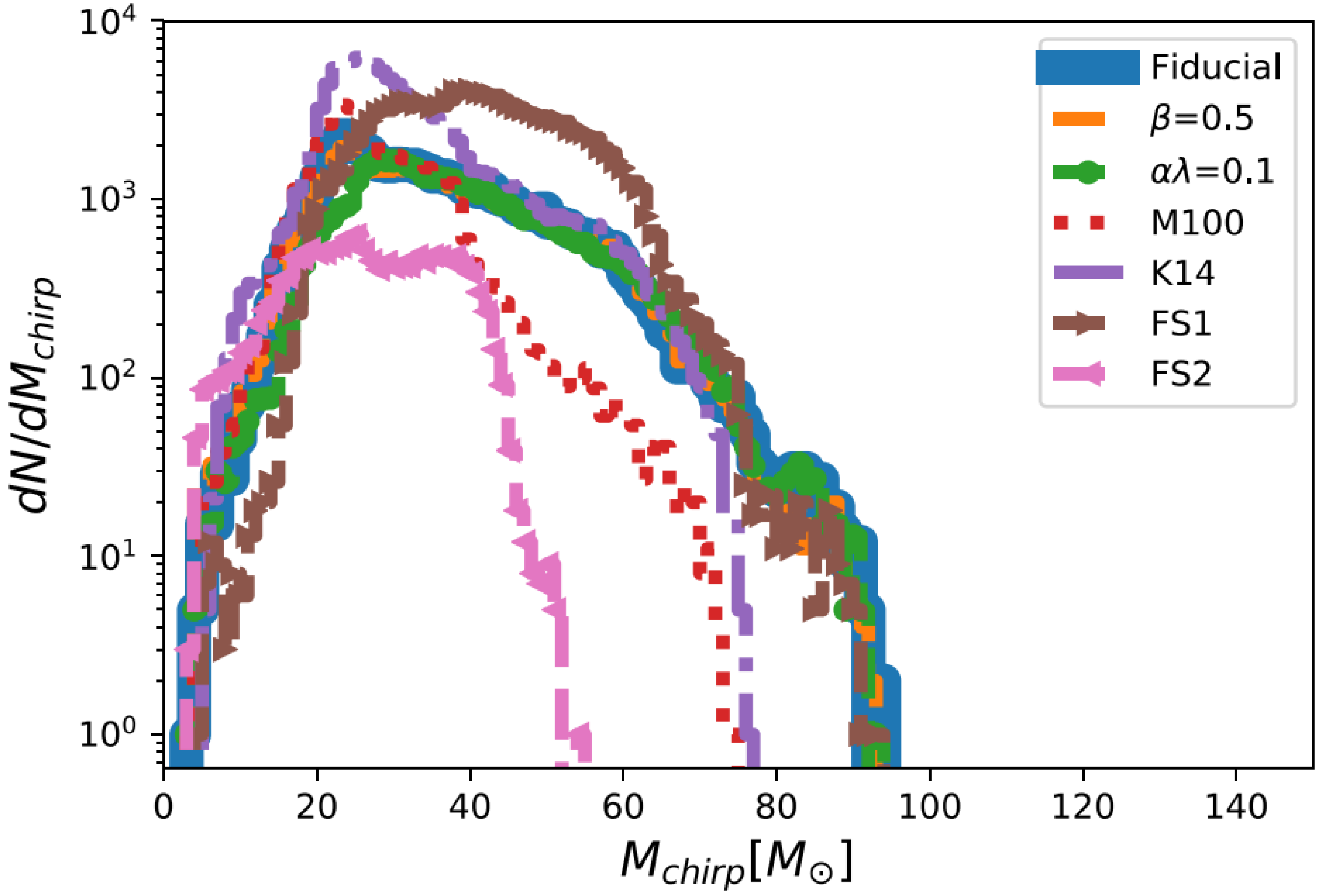
- 0.13 $/yr/Gpc^3$ for PPISN model
- 0.66 $/yr/Gpc^3$ for no PPISN model

Rate of GW190521 by LIGO is

0.02-0.43 $/yr/Gpc^3$



"BBH_chirpmass_flat.txt"
"BBH_chirpmass_salpeter.txt"
N
100000
10000
1000
100
10
1
10
20
30
40
50
60
70
80
90
100
Mchirp[Mun]



Fiducial
β=0.5
αλ=0.1
M100
K14
FS1
FS2
10^4
10^3
10^2
10^1
10^0
0
20
40
60
80
100
120
140
dN/dM_{chirp}
$M_{chirp}[M_\odot]$

However....

After GW150914, there are 1 bad news and 1 objection for Pop III BBH scenario

1.Bad news

~ decreasing expected Pop III SFR

Because of constraints by Planck τe

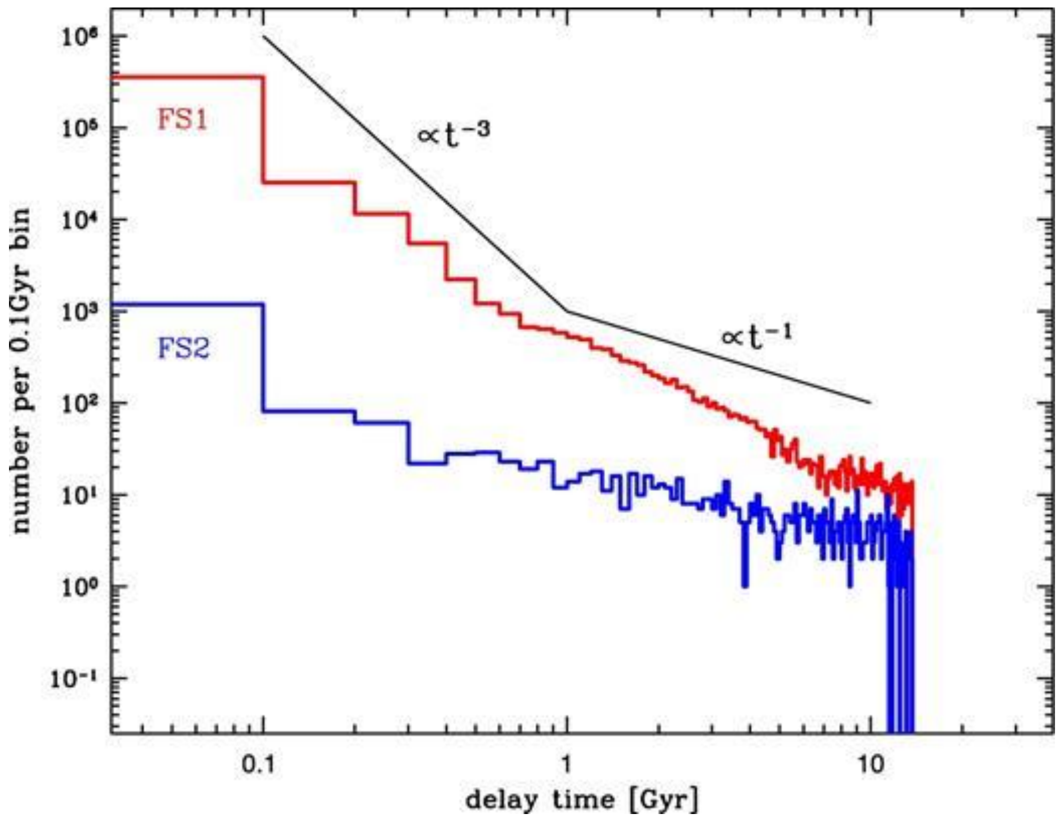
(Visbal et al.2015, Hartwig et al.2016, Inayoshi et al.2016)

2.Objection

Chris Belczynski also tried to calculate Pop III BBH merger rate.

In his calculation, almost all Pop III BBHs ***merge at the early universe***

Belczynski et al. 2017



Pop III star formation constraint by Planck

- The optical depth of the universe to electron scattering was inferred from CMB anisotropies by the *Planck*
- It is lower than previous estimates from *WMAP*
- This makes tight constraints on the star formation history of Pop III

- Before *Planck*

  $\rho=2\times10^{6}$ Msun/Mpc^{3} (de Souza et al. 2011)

- After *Planck*

  Optimistic constraint $\rho\leqq6\times10^{5}$ Msun/Mpc^{3} ← our model uses this value

  (Inayoshi et al. 2016)

  Conservative constraint $\rho\leqq2\times10^{5}$ Msun/Mpc^{3}

  (Visval et al. 2015, Inayoshi et al. 2021)

However….

After GW150914, there are 1 bad news and 1 objection for Pop III BBH scenario

1.Bad news

decreasing expected Pop III SFR

Because of constraints by Planck τe

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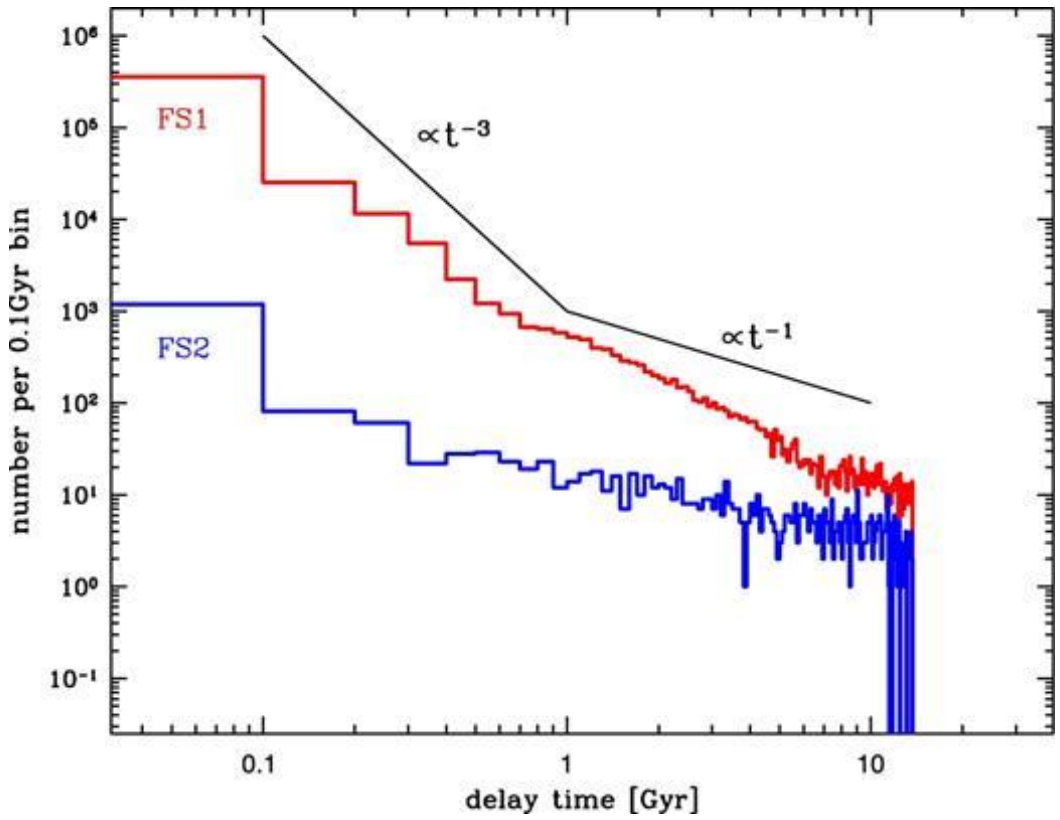
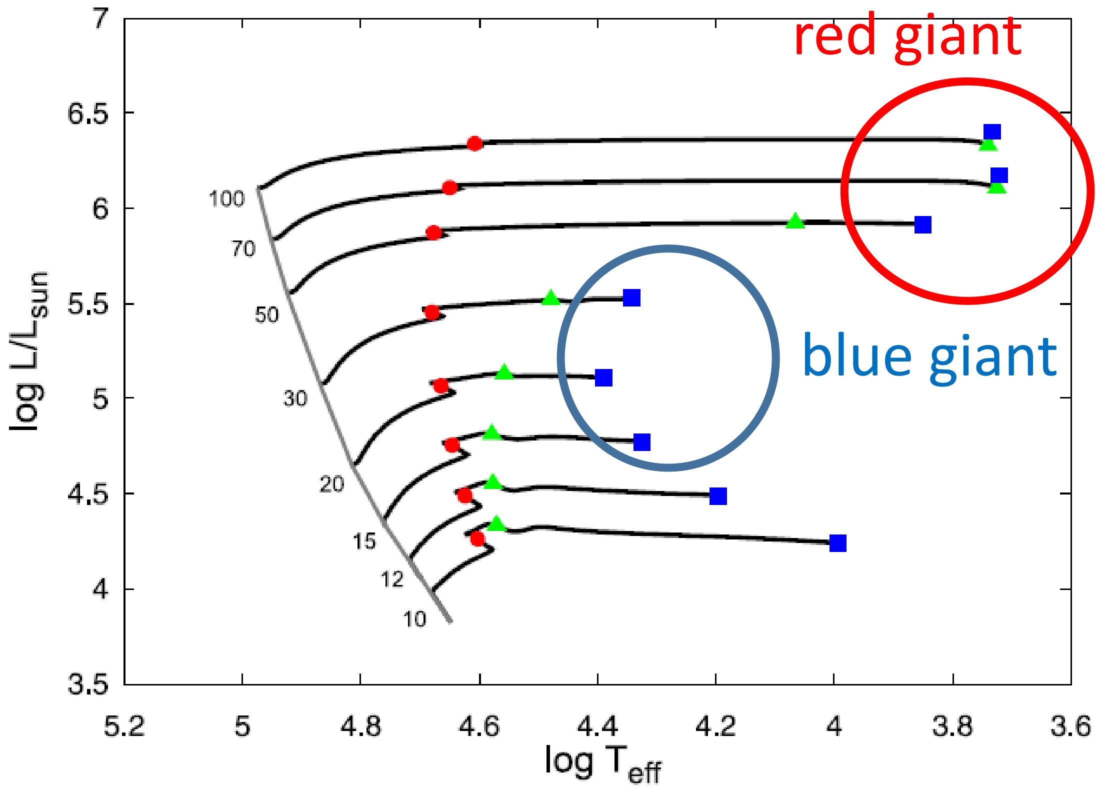
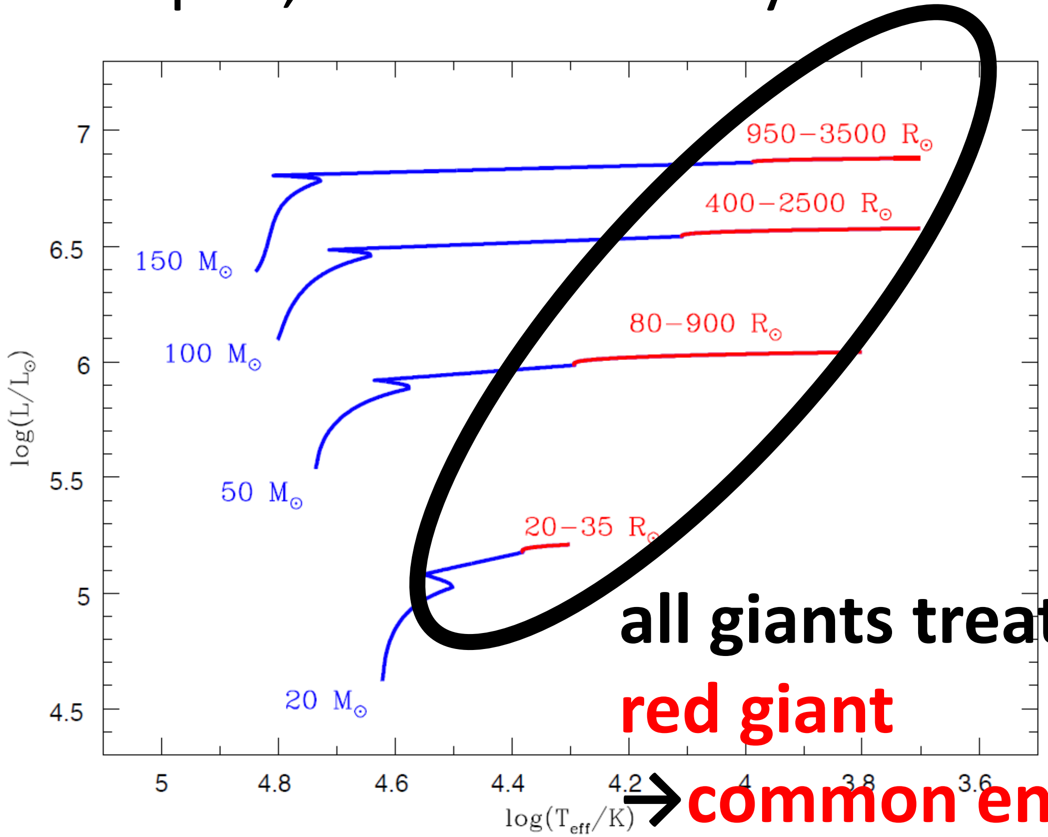


Difference between K14 and Belczynski's Pop III calc.

- Kinugawa 2014: use Pop III stellar evolution model (Marigo et al.2001)
- Belczynski 2017: use modified Z=0.005Zsun model.

(HR and radius evolution is changed like Pop III, but MT stability is not changed)

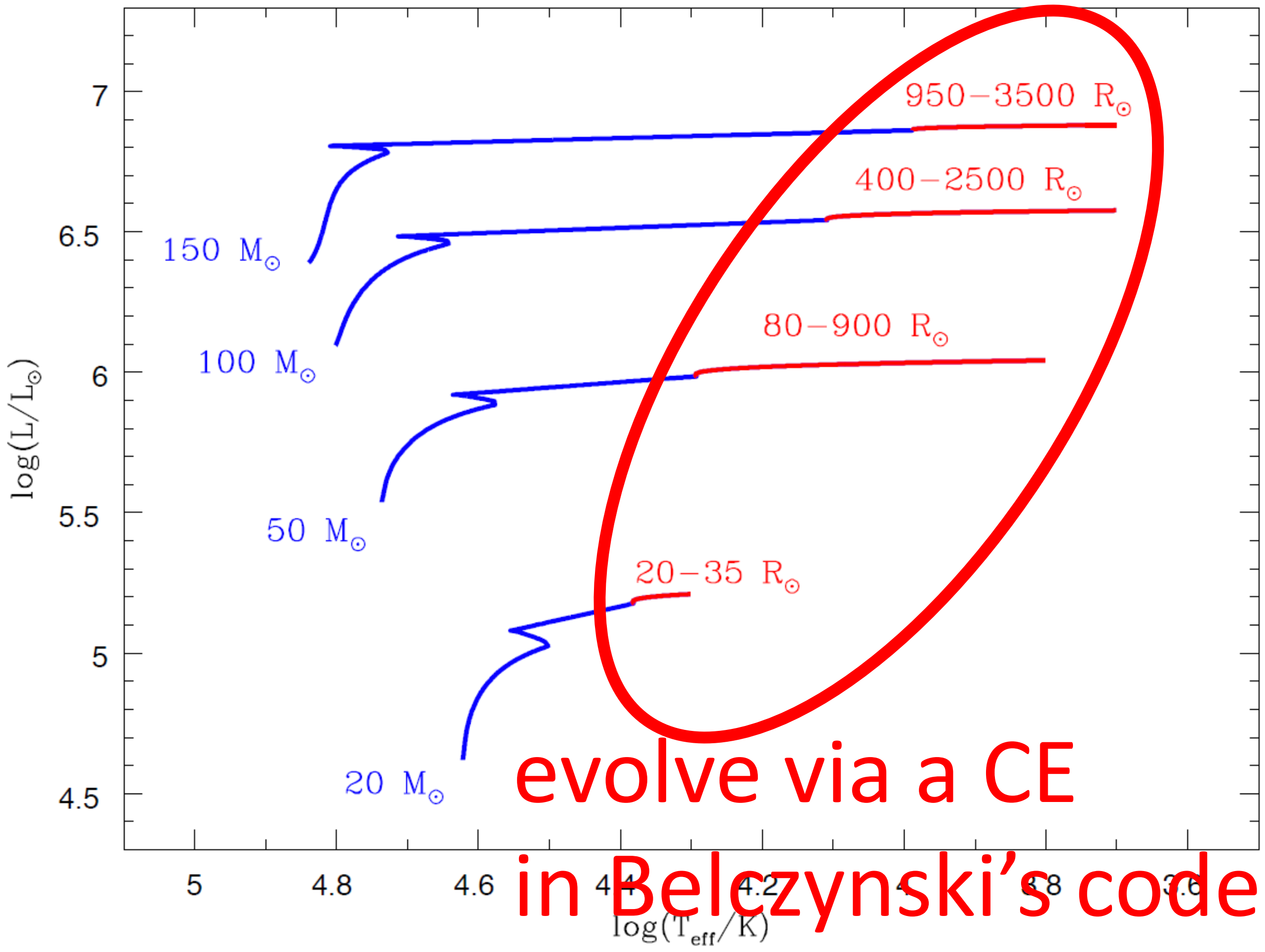




all giants treat as the **red giant**

→ **common envelope**

Difference between our code and Belczynski's Pop III



evolve via a CE
in Belczynski's code

Belczynski's code

- Modified Pop II ($Z=10^{-4}$) evolution
- The radius evolution is likely.
- But, the mass transfer treatment is same as Pop II

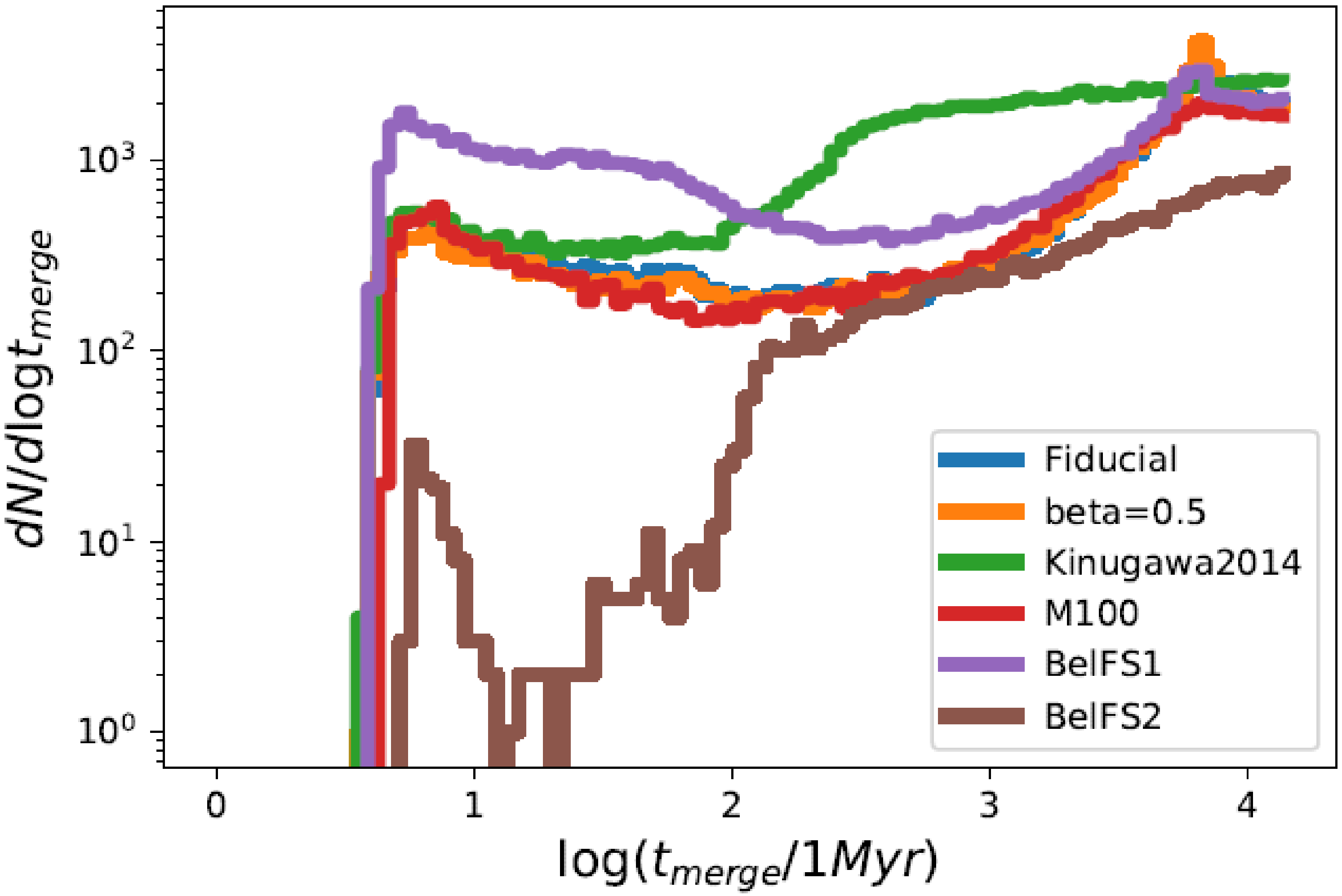
→ all BBH evolved via
a common envelope (CE)

many binaries merge during a CE

Merger Rate of Pop III BBH decrease

and dN/dt change

Merger time distribution of Pop III BBH



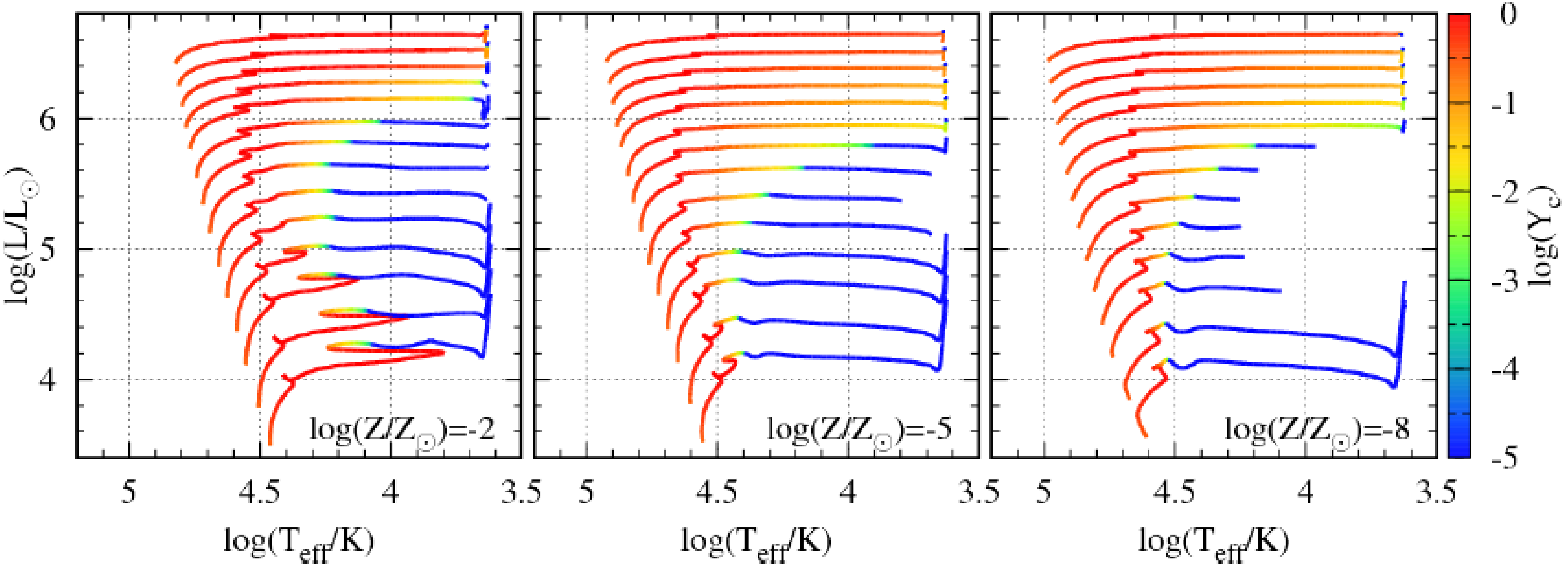


Figure 1. HR diagrams for stellar models with $\log(Z/Z_\odot) = -2, -5$, and -8. In each panel, curves indicate stellar evolutions with $M/M_\odot = 8, 10, 13, 16, 20, 25, 32, 40, 50, 65, 80, 100, 125$, and 160 from bottom to top. Colors are coded by the helium mass fractions in the stellar cores.

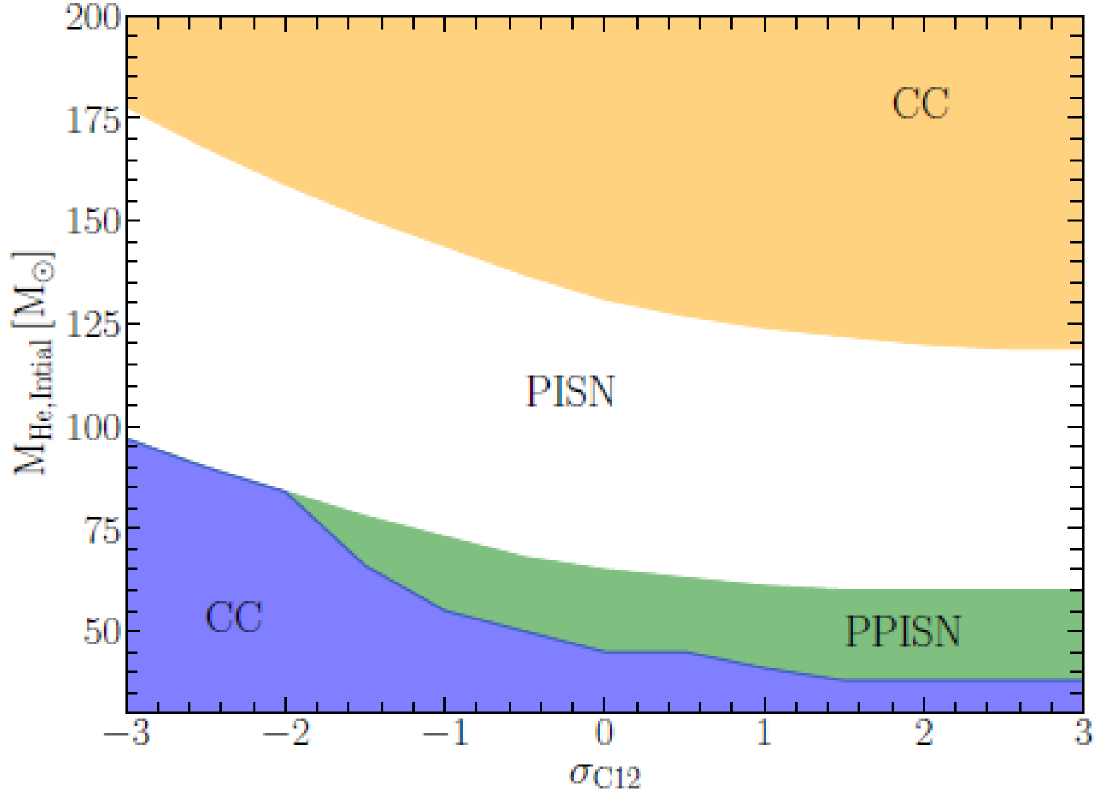
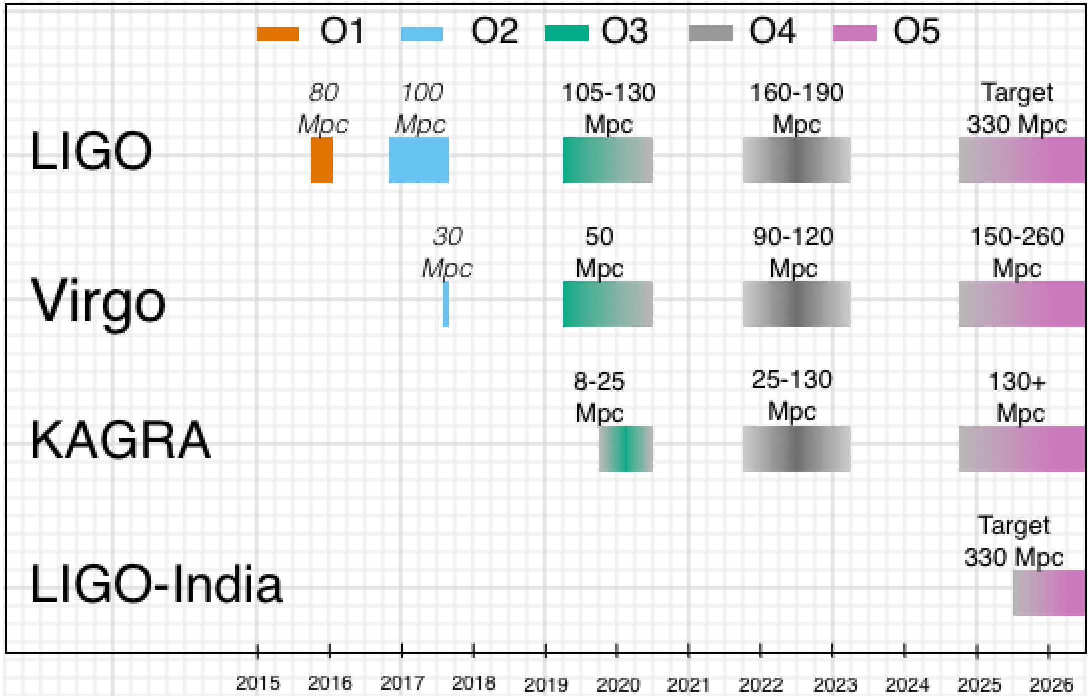


Figure 1. Final fate of a star as function of the initial helium core mass and $^{12}C\,(\alpha,\gamma)^{16}O$ rate. σ_{C12} denotes how far the $^{12}C\,(\alpha,\gamma)^{16}O$ is from the median `STARLIB` rate, measured in standard deviations. Blue regions indicate stars which undergo core collapse (CC) below the pair instability supernovae (PISN) mass gap, green regions form black holes after a pulsational pair instability supernovae (PPISN), while white regions are completely disrupted in a PISN, and models in the orange region form black holes from core collapse for stars above the PISN mass gap. There are 2210 models, in the grid spaced by $1\,M_\odot$ and $0.5\sigma_{C12}$.


O1
O2
O3
O4
O5
LIGO
Virgo
KAGRA
LIGO-India
80 Mpc
100 Mpc
105-130 Mpc
160-190 Mpc
Target 330 Mpc
30 Mpc
50 Mpc
90-120 Mpc
150-260 Mpc
8-25 Mpc
25-130 Mpc
130+ Mpc
Target 330 Mpc
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026

Other Pop III SFRs

- simulation

  e.g. Johnson et al. 2013

  SFR_p~ 10^{-3}-10^{-4} Msun/yr/Mpc^3

- Constraints by Planck τ_e

  e.g. Visbal et al.2015, Hartwig et al.2016,

  Inayoshi et al.2016

  →The merger rate might decrease to 1/3-1/10 ?