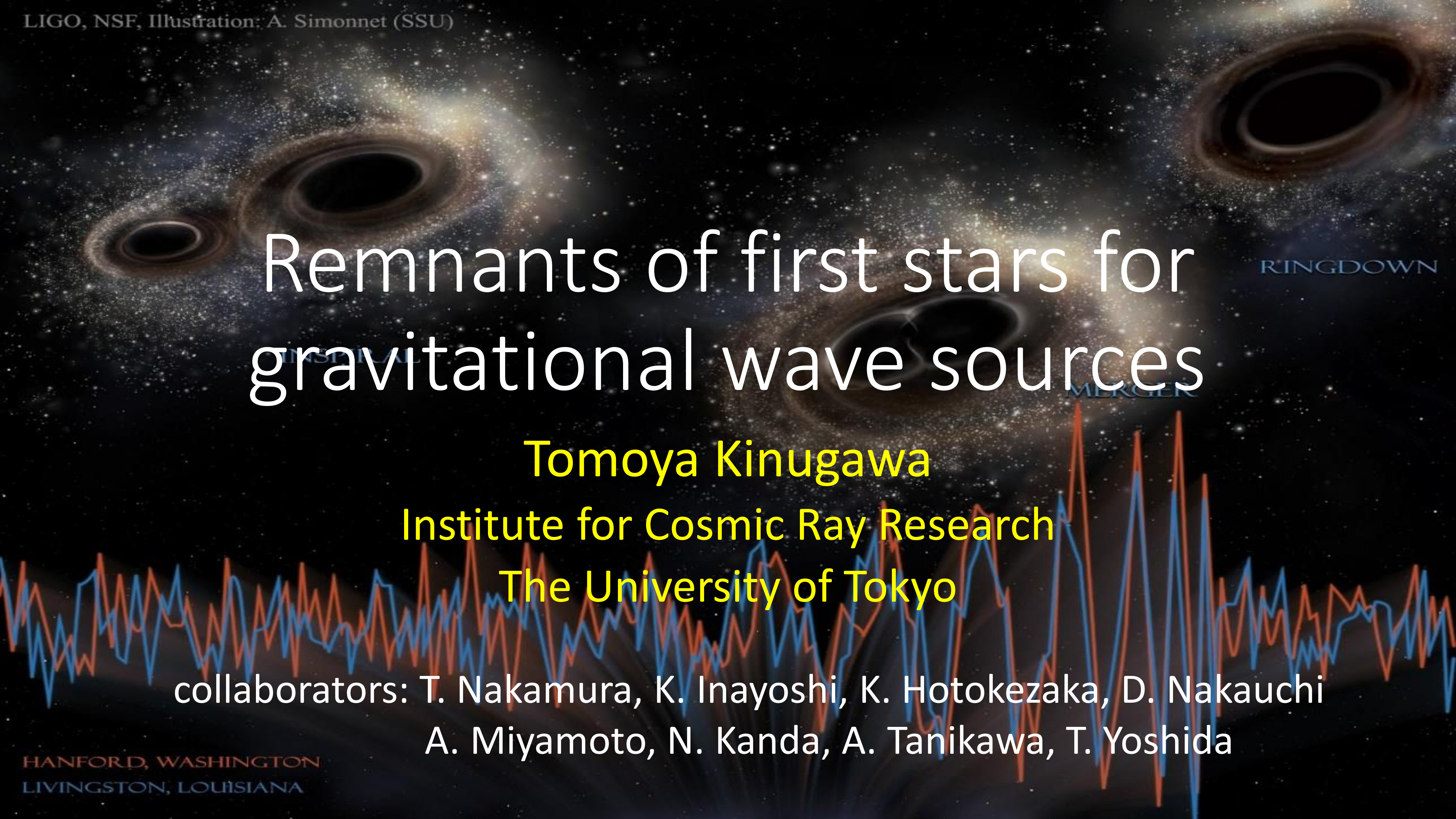

Remnants of first stars for gravitational wave sources

Tomoya Kinugawa
Institute for Cosmic Ray Research
The University of Tokyo

collaborators: T. Nakamura, K. Inayoshi, K. Hotokezaka, D. Nakauchi
A. Miyamoto, N. Kanda, A. Tanikawa, T. Yoshida

The beginning of Gravitational wave astronomy

- Gravitational wave detectors

KAGRA

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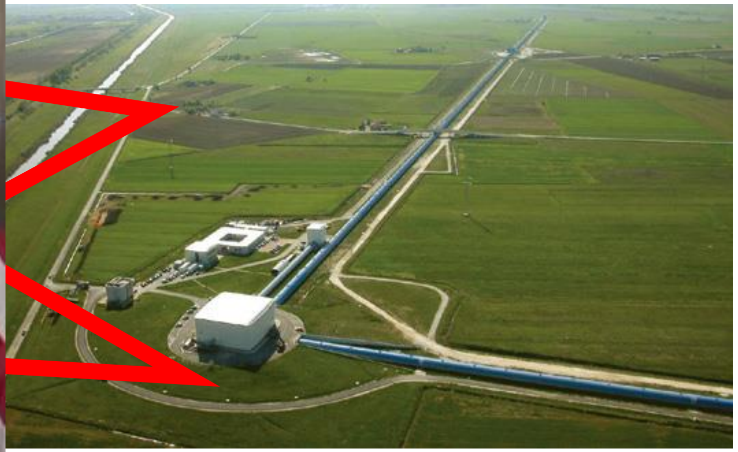
Advanced VIRGO



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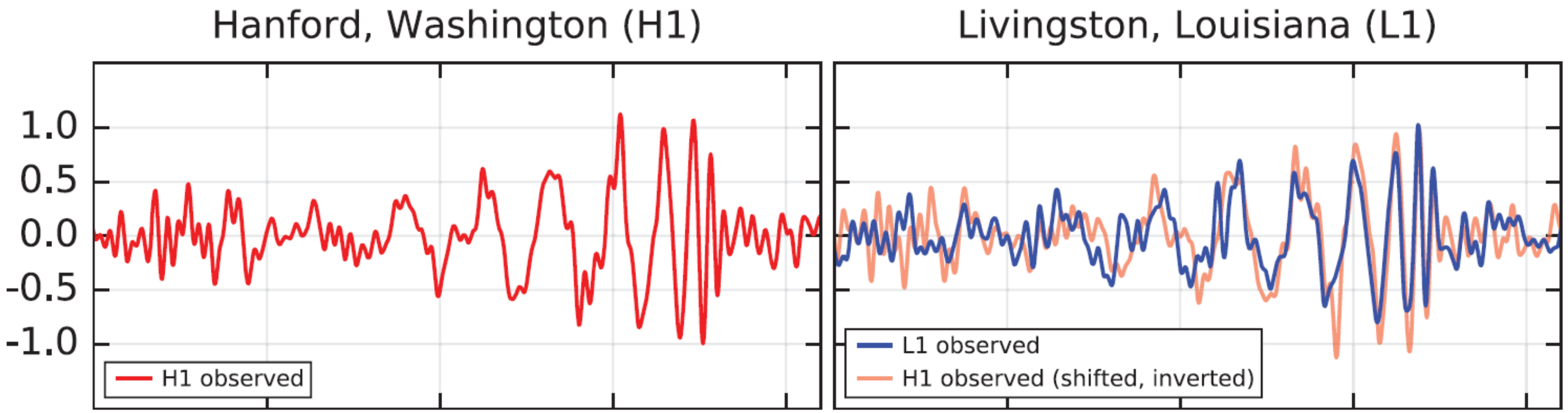
Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.



Masses of GW events

- GW events show that there are many massive BHs (≳30 Msun).
- 7/10 BBHs are massive BBHs

- On the other hand, the typical mass of BHs in X-ray binaries is ~10 Msun.

Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$

The LIGO scientific collaboration 2018

Origin of massive BBHs

7/10 GW BBHs are massive BBHs

In order to explain the origin of such massive BBHs

Many theories exist such as

- 1)Pop II BBH
- 2)Pop III BBH **No metal field binaries**
- 3)Primordial Binary BH
- 4)N body origin from Globular Cluster
- ………………………

Pop III binary population synthesis

We simulate 10^6 Pop III-binary evolutions and estimate how many binaries become compact binary which merges within Hubble time.
×84 models (*Kinugawa et al.2014, 2016*)

Initial stellar parameters are decided by Monte Carlo method with initial distribution functions

- Initial parameter (M1,M2,a,e) distribution in our standard model

  M1 : Flat ($10\,M_{\odot}<M<100\,M_{\odot}$)

  q=M2/M1 : P(q)=const. ($0<q<1$)

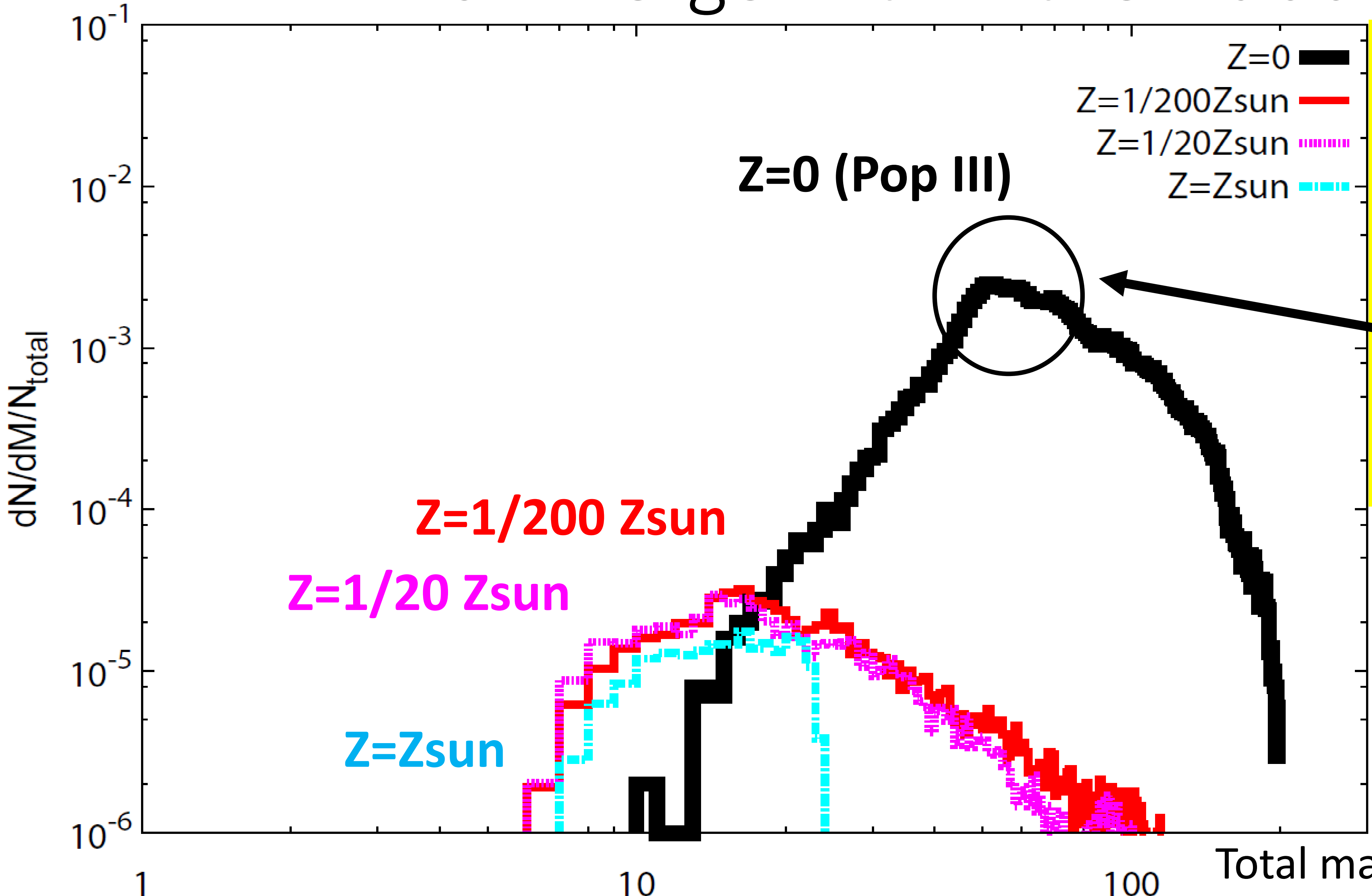
  a : $P(a)\propto 1/a$ ($a_{min}<a<10^6 R_{\odot}$)

  e : $P(e)\propto e$ ($0<e<1$)

  } The same distribution functions adopted for Pop I population synthesis

- de Souza SFR

Total mass distribution of BBH which merge within the Hubble time



Typical total mass

M～60 $M_\odot$

(30 $M_\odot$ +30 $M_\odot$)

TK et al. 2014,2016

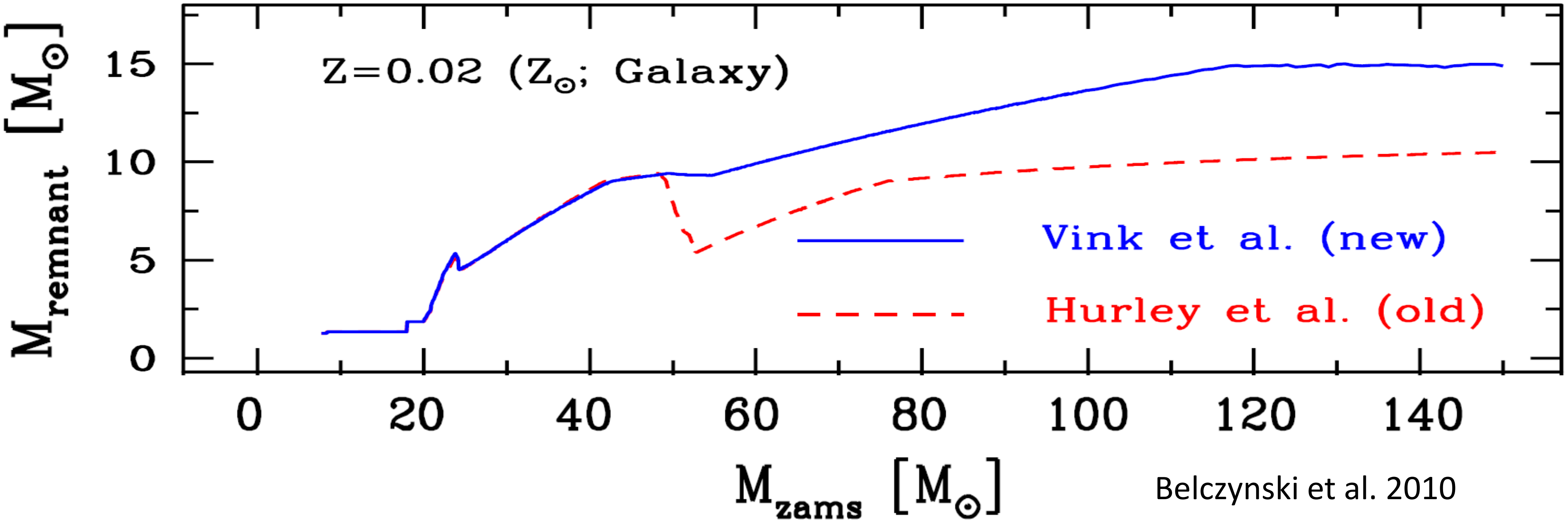
IMF:Flat

(10M<M<140M)

e.g. Pop I, Pop II
(Z=0.02,0.001,0.0001)
IMF:Salpeter
(1Msun<M<140Msun)
Typical mass ～10 $M_\odot$

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

- The orbit become wide due to stellar wind mass loss

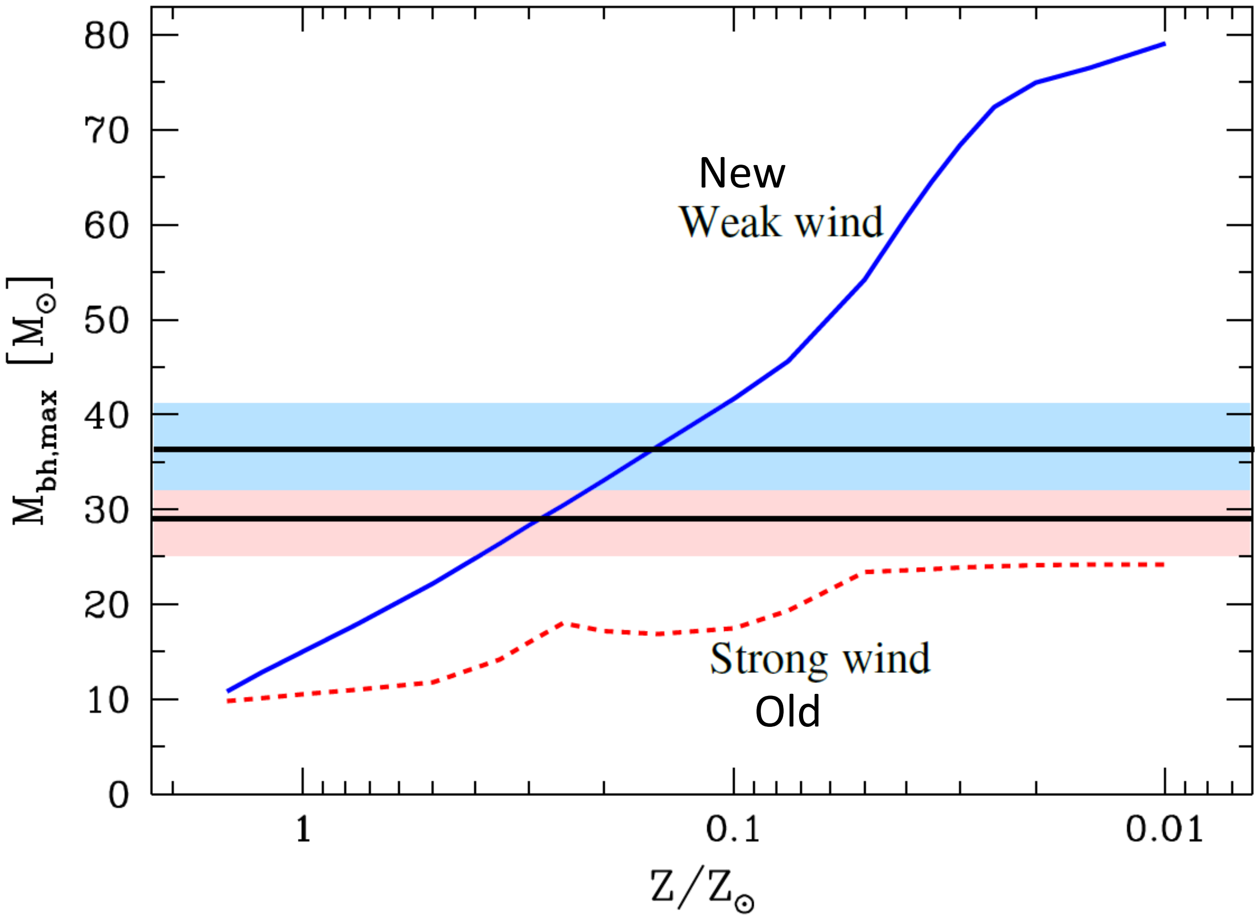
Wind mass loss & IMF

- If the progenitor is low metal,

- Pop II (Metal<0.1SolarMetal)

  Typical mass is same as Pop I

  But, week wind mass loss



Minitial: 8Msun<M<150Msun
Single stellar evolution
with 2 stellar wind models.
(Belczynski et al.2010,
Abbot et al.2016)

- Pop III (No metal)

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

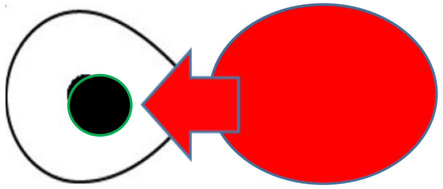
  Typical mass is more massive than Pop I, II

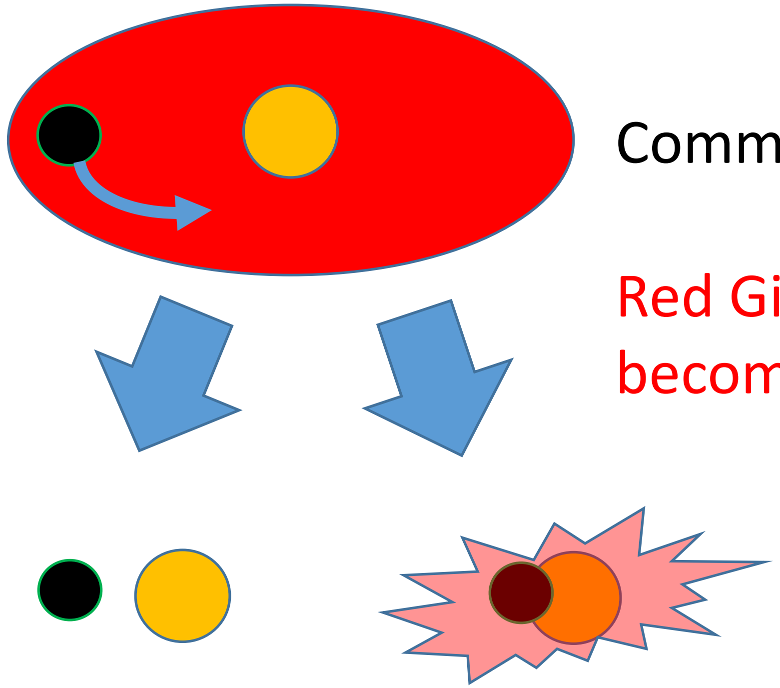
  MpopIII~10-100Msun

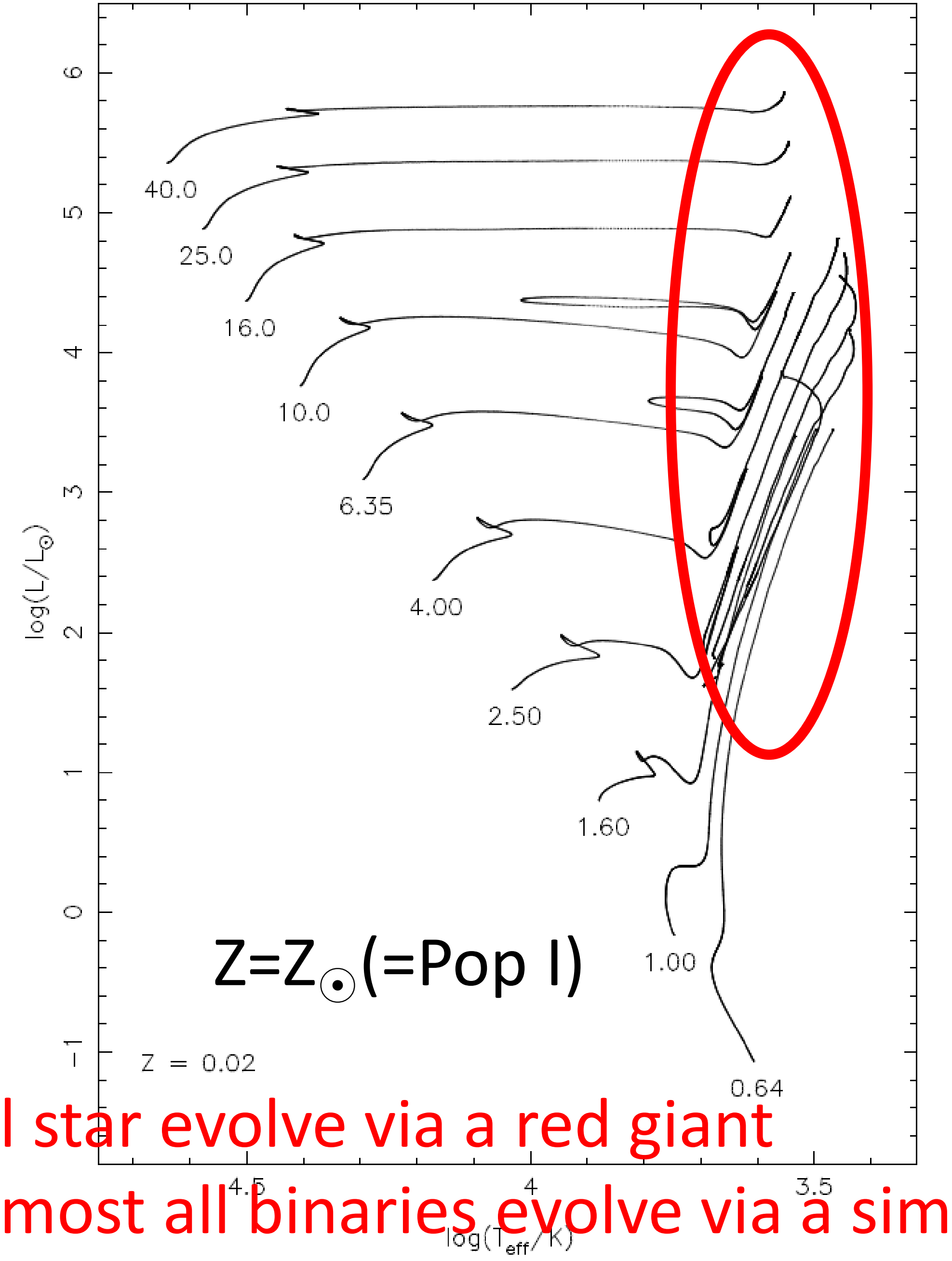
  No wind mass loss due to no metal.

Binary interaction changes progenitor mass

- Mass transfer
- Common envelope

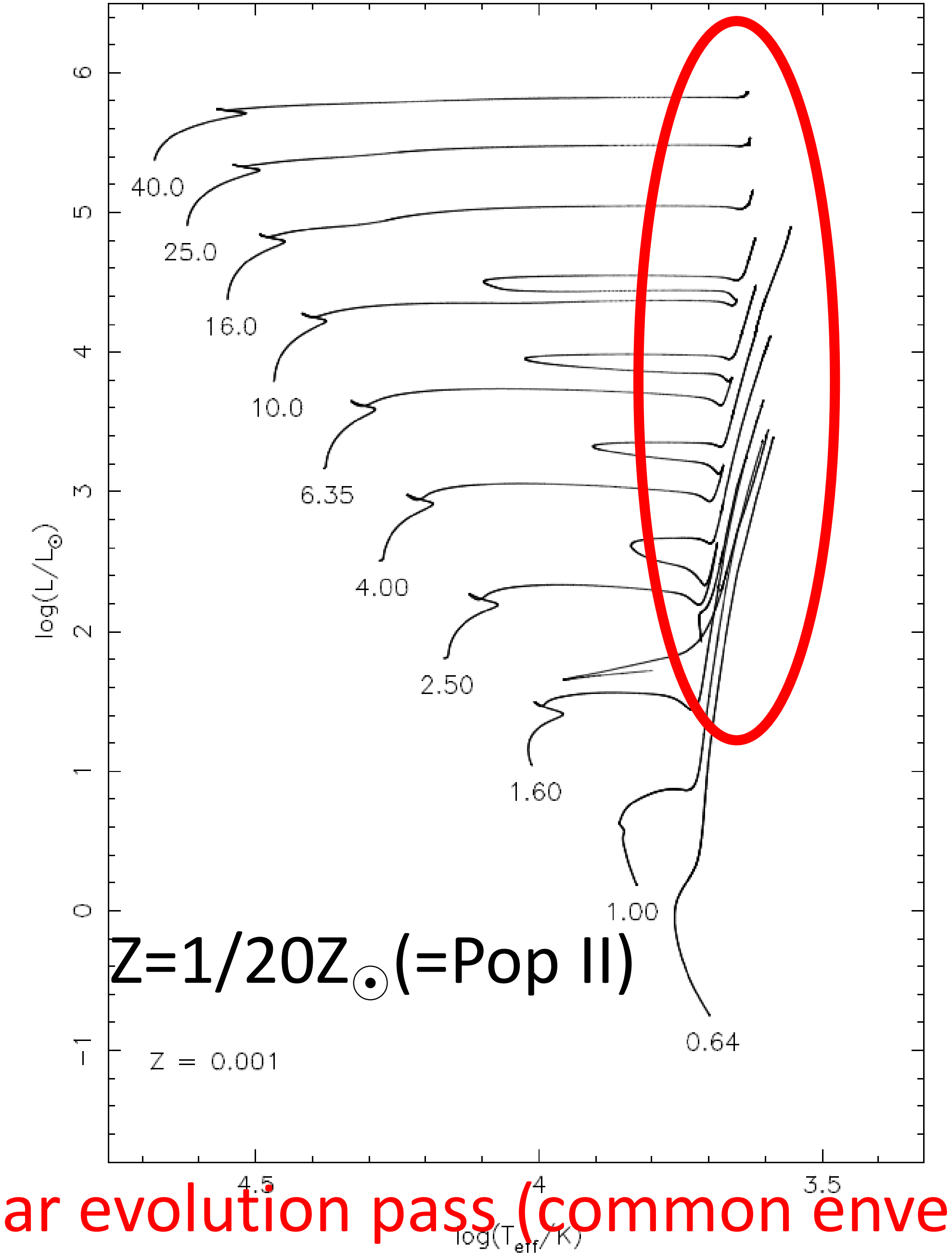






All star evolve via a red giant

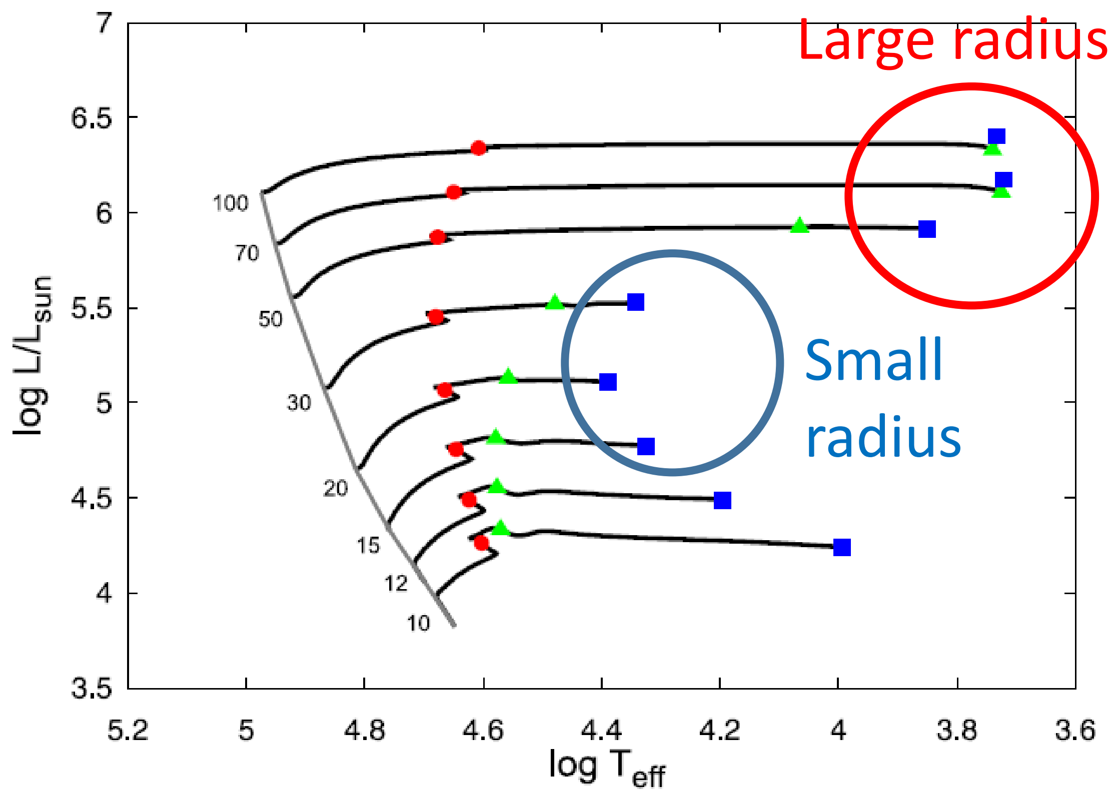
Figure 1. Selected OVS evolution tracks for $Z = 0.02$, for masses 0.64, 1.0, 1.6, 2.5, 4.0, 6.35, 10, 16, 25 and 40 $M_\odot$.



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

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

Why Pop III binaries become 30Msun BH-BH

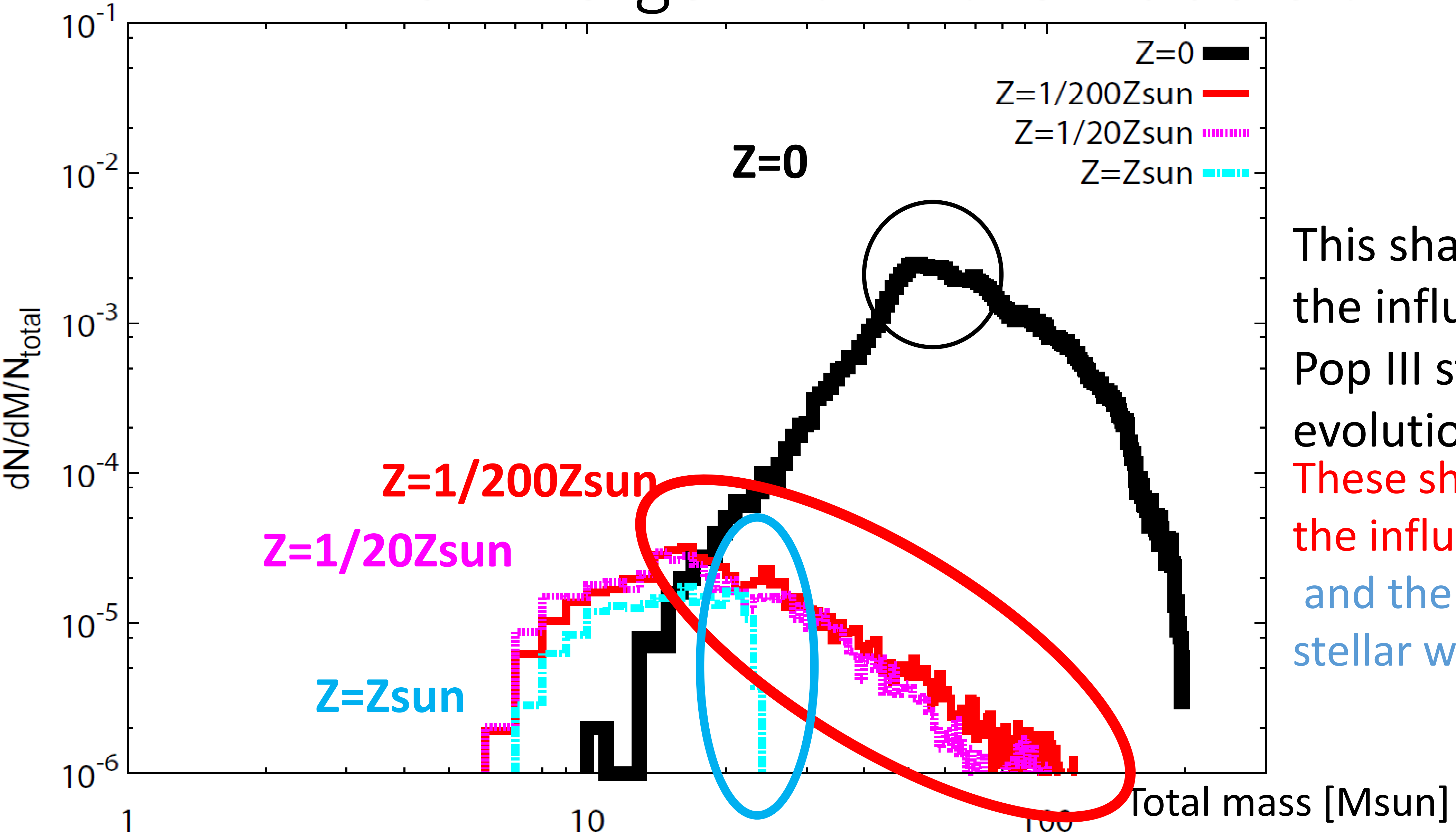


Marigo et al. 2001

- M>50Msun red giant
  →Mass transfer is unstable
  →common envelope
  →1/3~1/2 of initial mass (~25-30Msun)

- M<50Msun blue giant
  →Mass transfer is stable
  →mass loss is not so effective
  →2/3~1 of initial mass (25-30Msun)

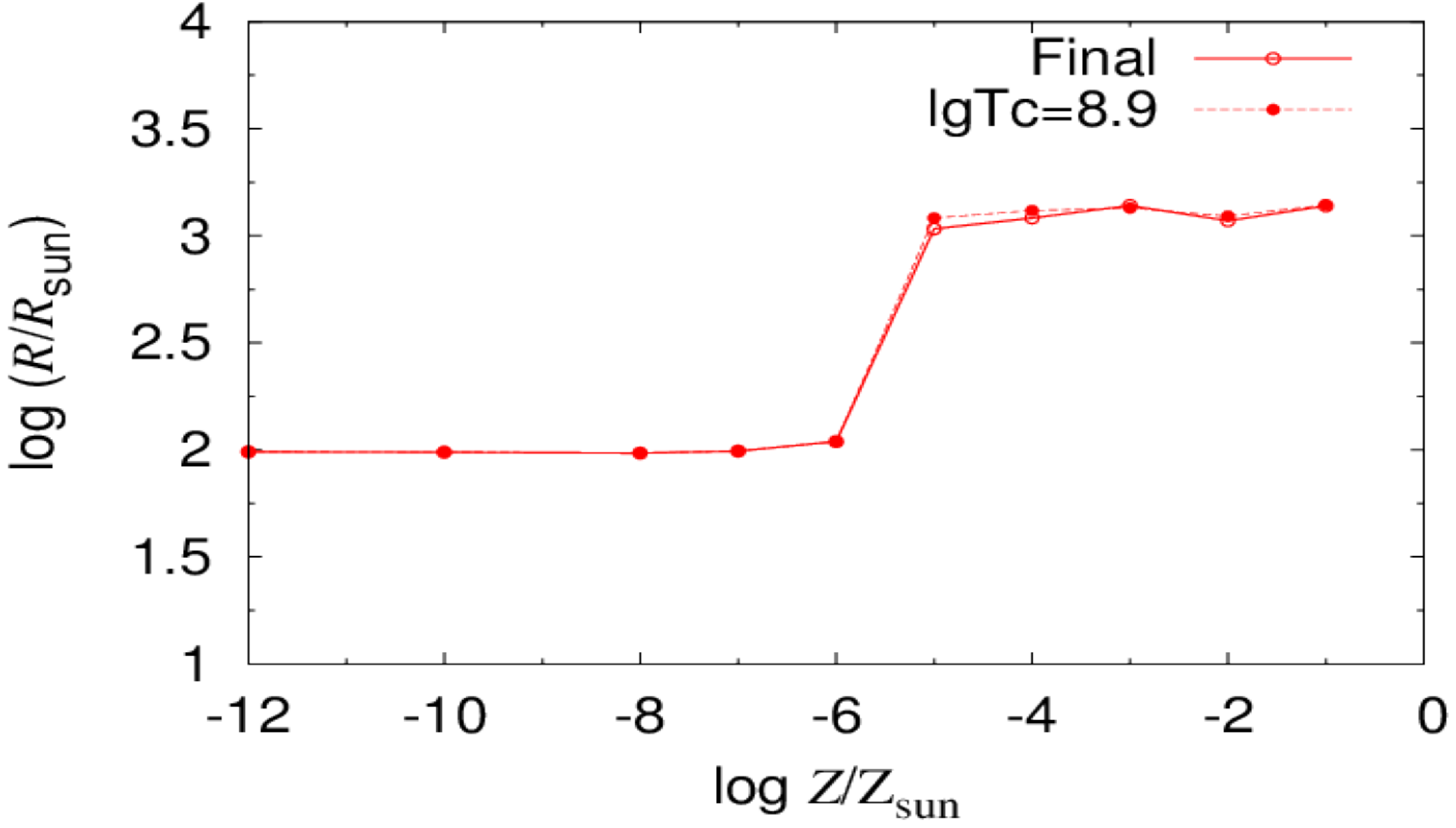
Total mass distribution of BBH which merge within the Hubble time



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

Evolution Transition from Pop III to Pop II

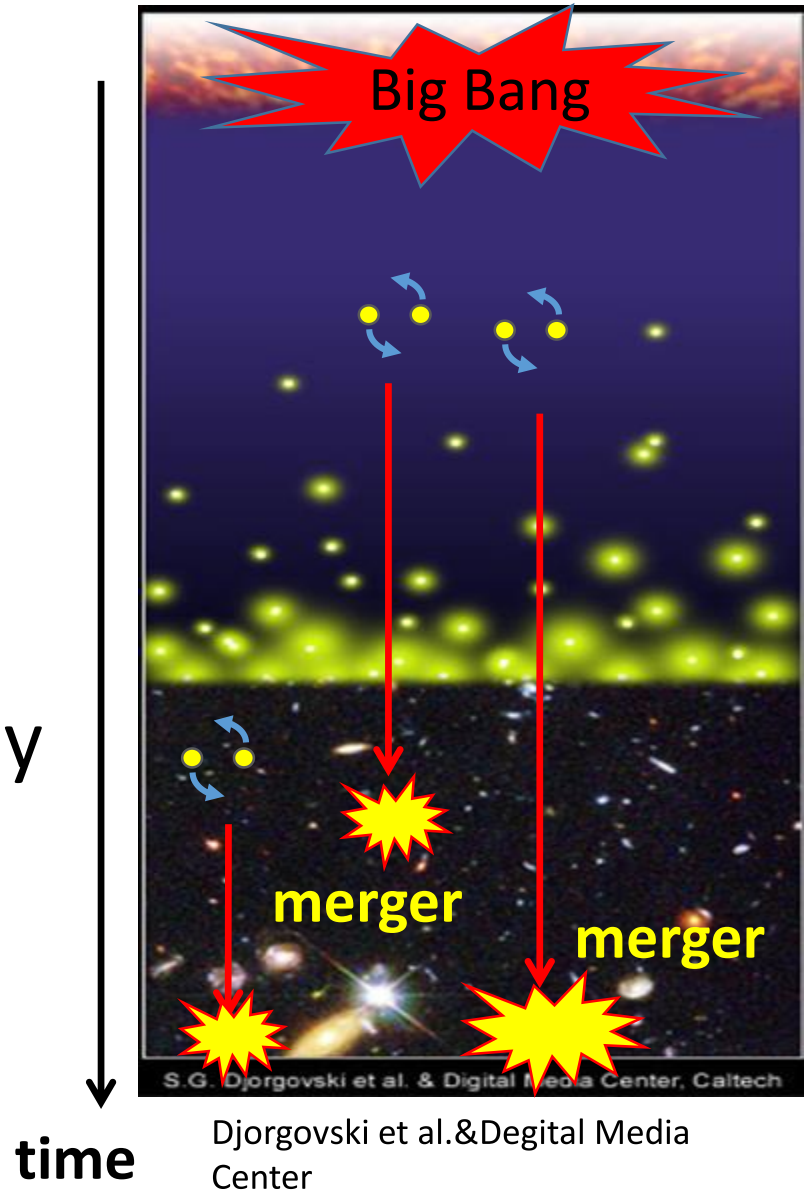


Maximum radius of 30Msun (Tanikawa, Yoshida, TK et al. 2019)

Pop III BBH remnants for gravitational wave

- Pop III stars were born and died
  at z~10 (~13.3Gyrs ago).
- The typical merger time of compact binaries ~$10^{8\text{-}10}$yr
  $dN/dt \propto t^{-1}$ (Kinugawa et al .214, Inayyoshi et al. 2017)
- We might see Pop III BBH at the present day.
- Predicted Pop III merger rate at the present day
  ~30 /yr/Gpc3 (Kinugawa et al. 2014,2016)

  BBH merger rate estimated by LIGO
  9.7-101 [yr^{-1} Gpc^{-3}] (1811.12907)



Djorgovski et al.&Degital Media Center

Pop III BBH?

ASTROPHYSICAL IMP… …ACK-HOLE MERGER GW150914

2014, D…
On th… …t has been proposed
that BB… … the case of stellar
binaries… …II [PopIII] stars; see
Belczyn… …014). The predictions
from the… …in, since we have no
observa… …es of first-generation
stellar … …mass ratios, orbital
separati… …hat the properties of
PopIII … …ifferent from binary
populati… …tedly a considerable
extrapol… …H total masses agree
astonish… …can have sufficiently
long merger times to occur in the nearby universe (Kinugawa
et al. 2014). This is in contrast to the predicted mass properties

However....

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

1.Bad news

~1/3 decreasing expected Pop III SFR

Because of constraints by Planck τe

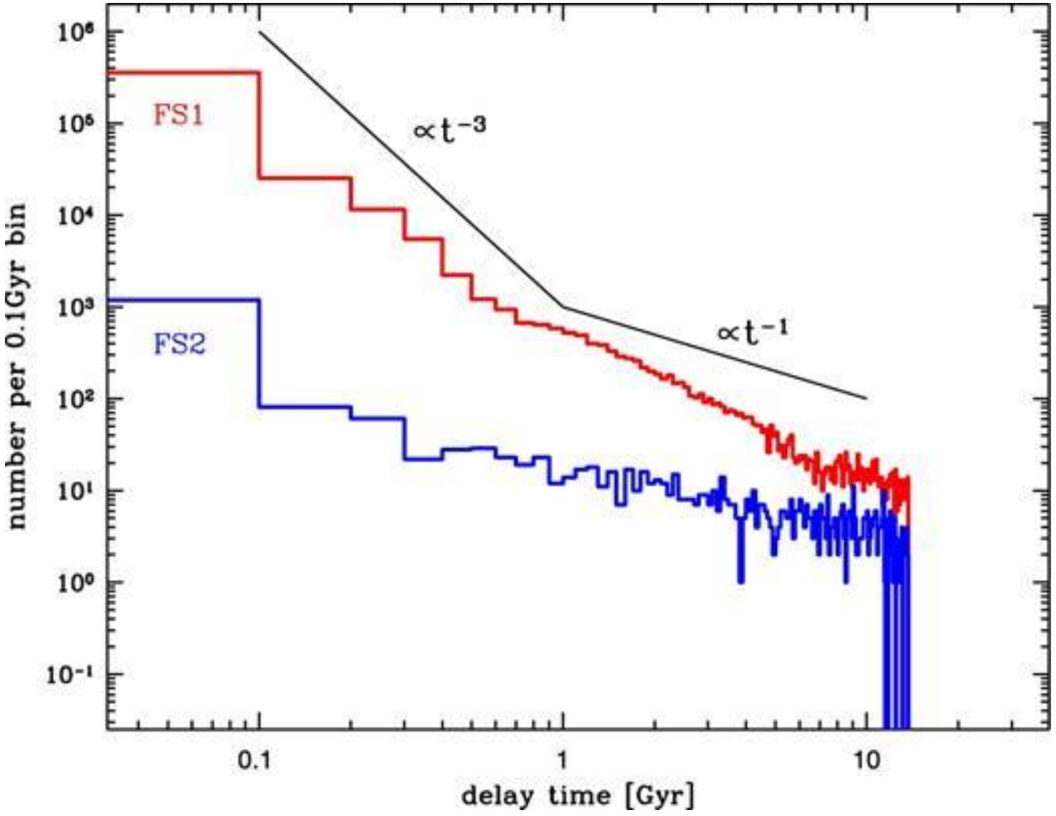
(Visbal et al.2015, Hartwig et al.2016, Inayoshi et al.2016)

2.Objection

Chris Belczynski 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



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?

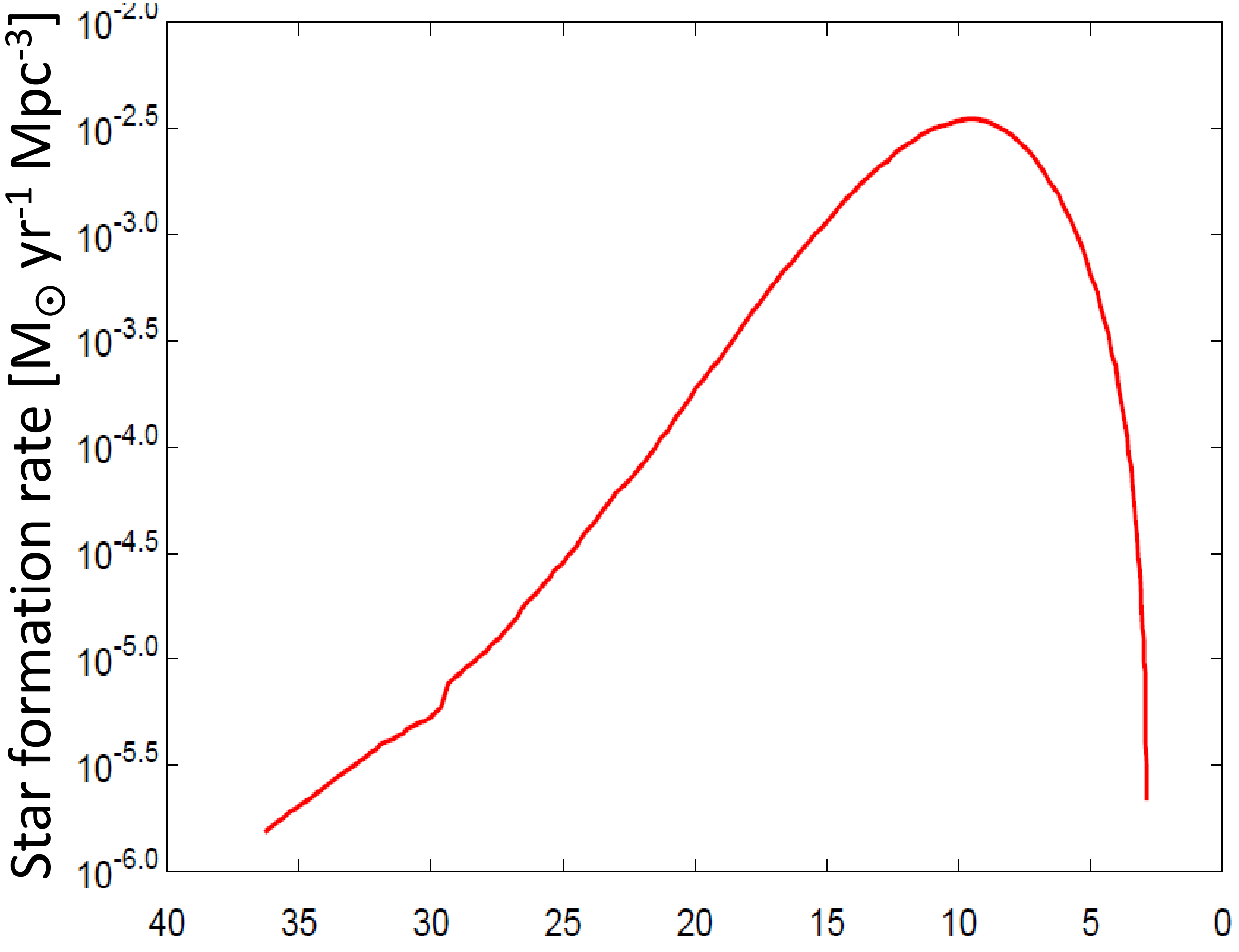
⇒Star formation rate

We adopt the Pop III SFR

by de Souza et al. 2011

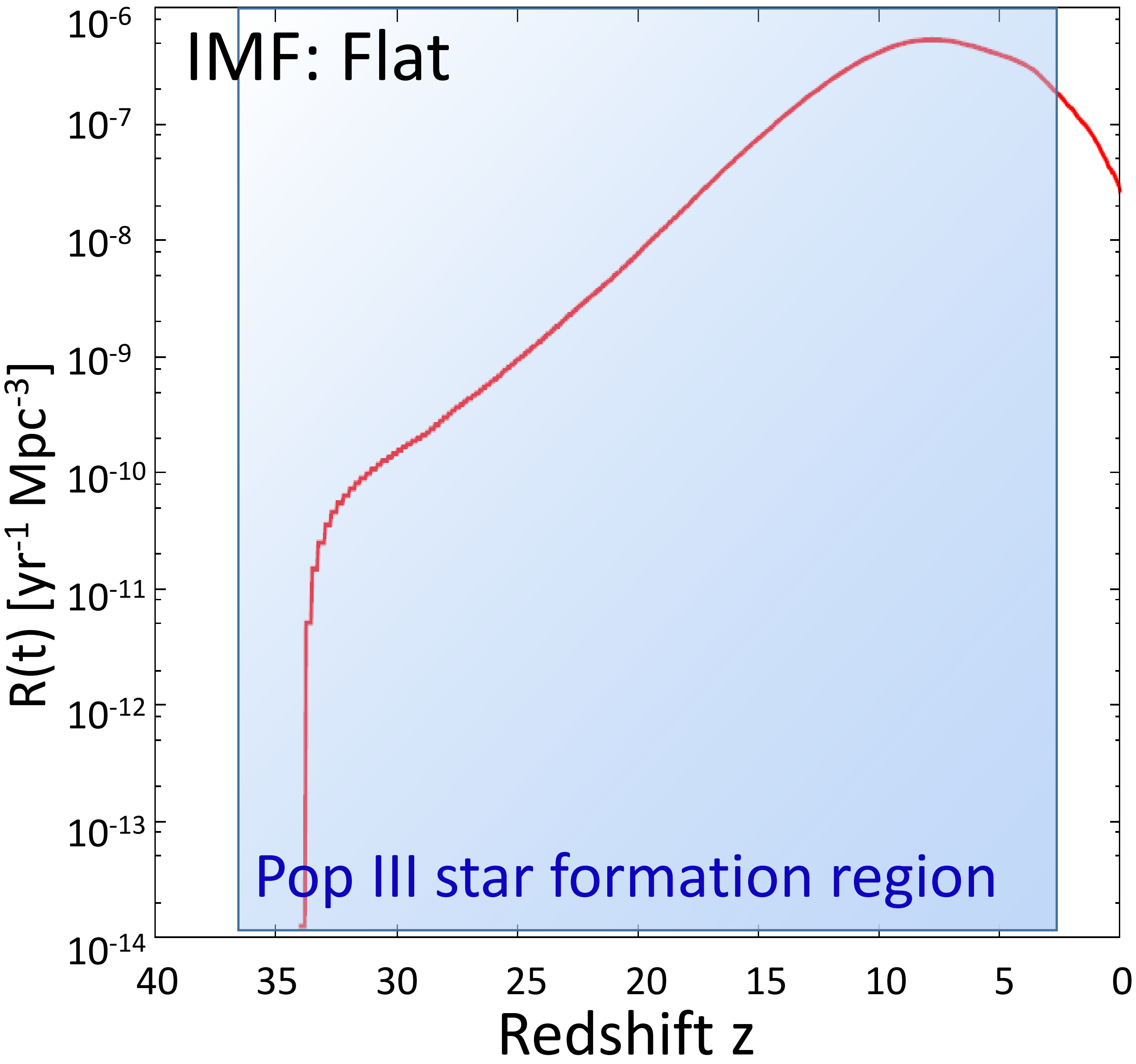
$$SFR_{peak} \sim 10^{-2.5}\ [M_\odot\ yr^{-1}\ Mpc^{-3}]$$

$$\rightarrow 10^{-3}$$



(de Souza et al. 2011)

The Pop III BH-BH merger rate density



Pop III BHBH merger rate at the present day
In our standard model
(Kinugawa et al. 2014,2016)

R～30 [yr^{-1} Gpc^{-3}]

(Kinugawa et al. 2014,2016)

SFR decreased factor 1/3

→～10 [$yr^{-1}$$Gpc^{-3}$]

BBH merger rate estimated by LIGO

R=9.7-101 [yr^{-1} Gpc^{-3}] (1811.12907)

Merger rate of massive BBH (~30Msun)

R～several [yr^{-1} Gpc^{-3}] (1811.12940)

However....

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

1.Bad news

$\lesssim$1/3 decreasing expected Pop III SFR

Because of constraints by Planck τe

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

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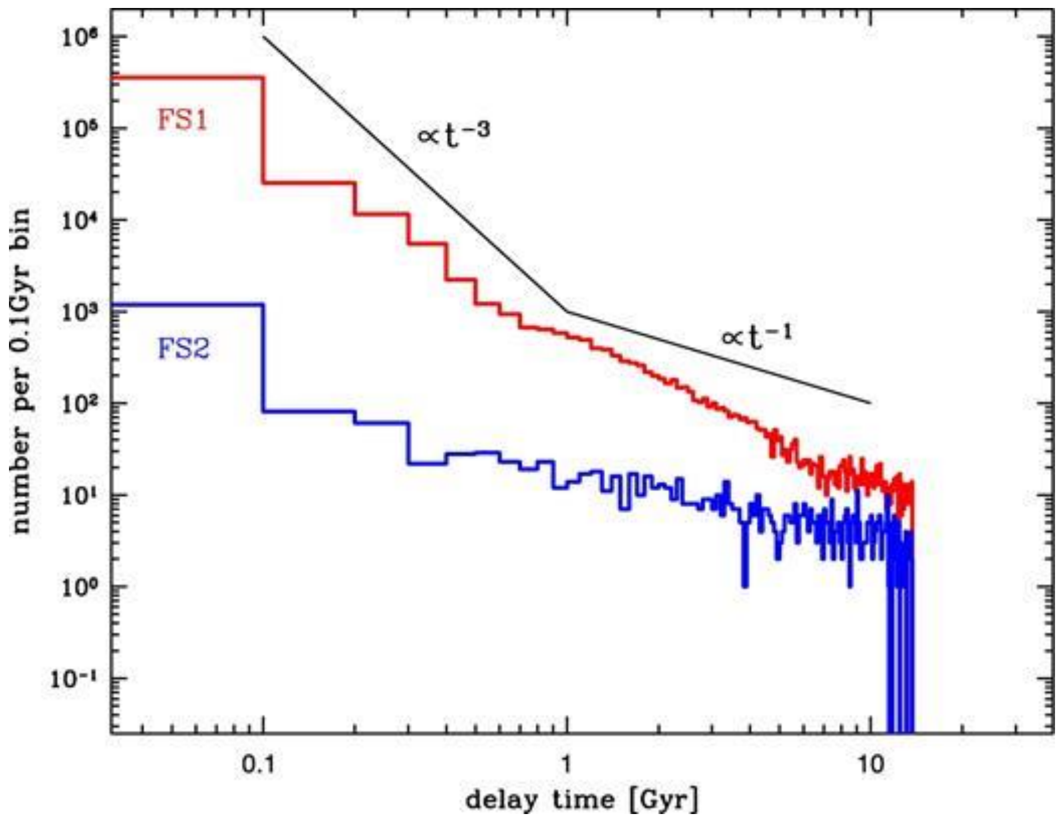
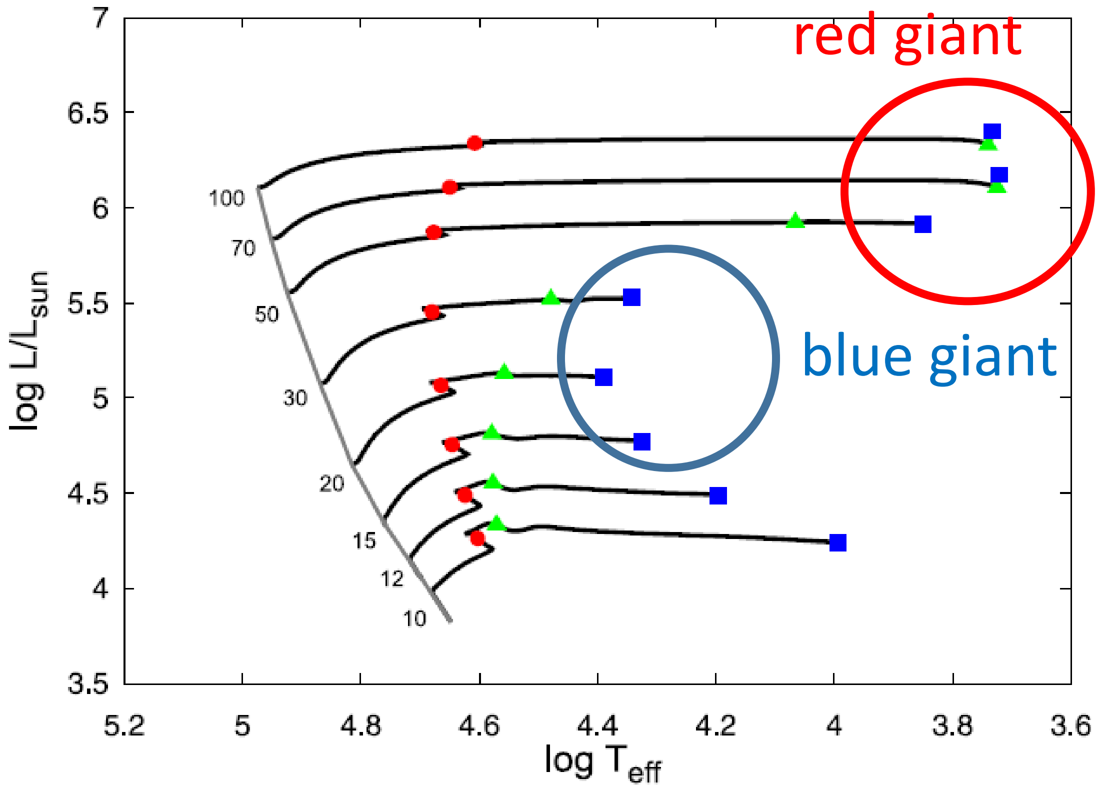
Belczynski et al. 2017

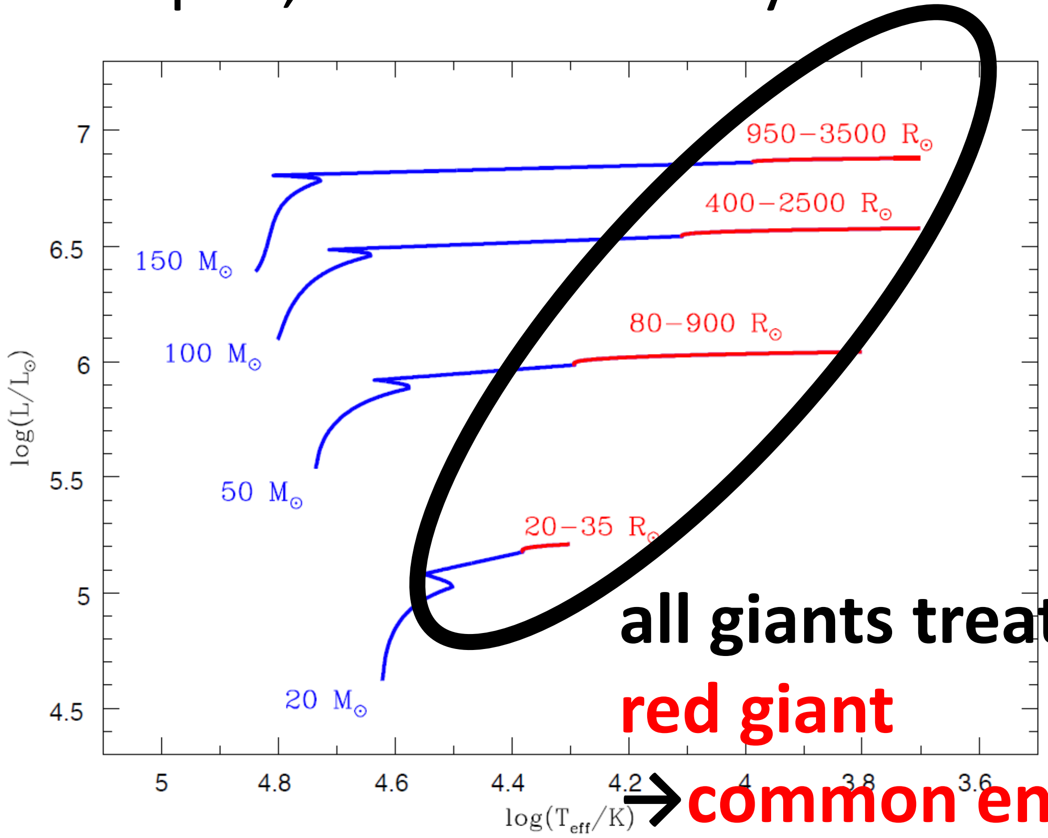


Difference between K14 and Belczynski's Pop III calc.

- 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

However....

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

1.Bad news

$\lesssim$1/3 decreasing expected Pop III SFR

Because of constraints by Planck τe

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

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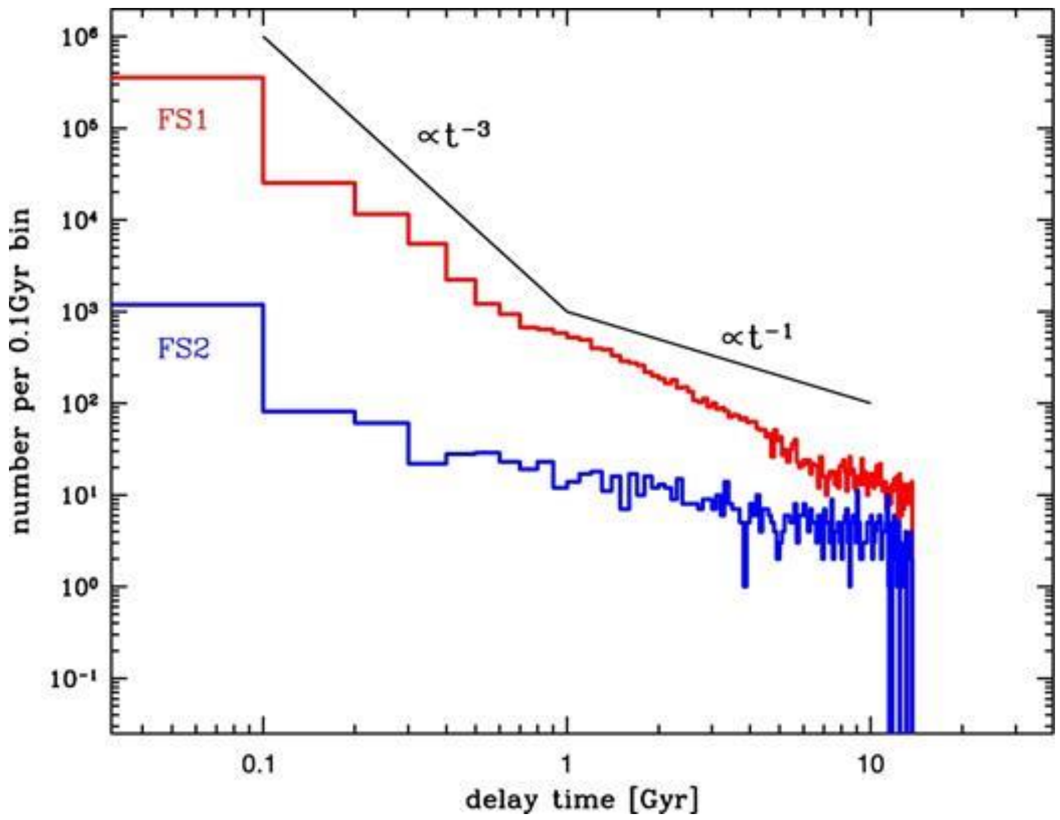
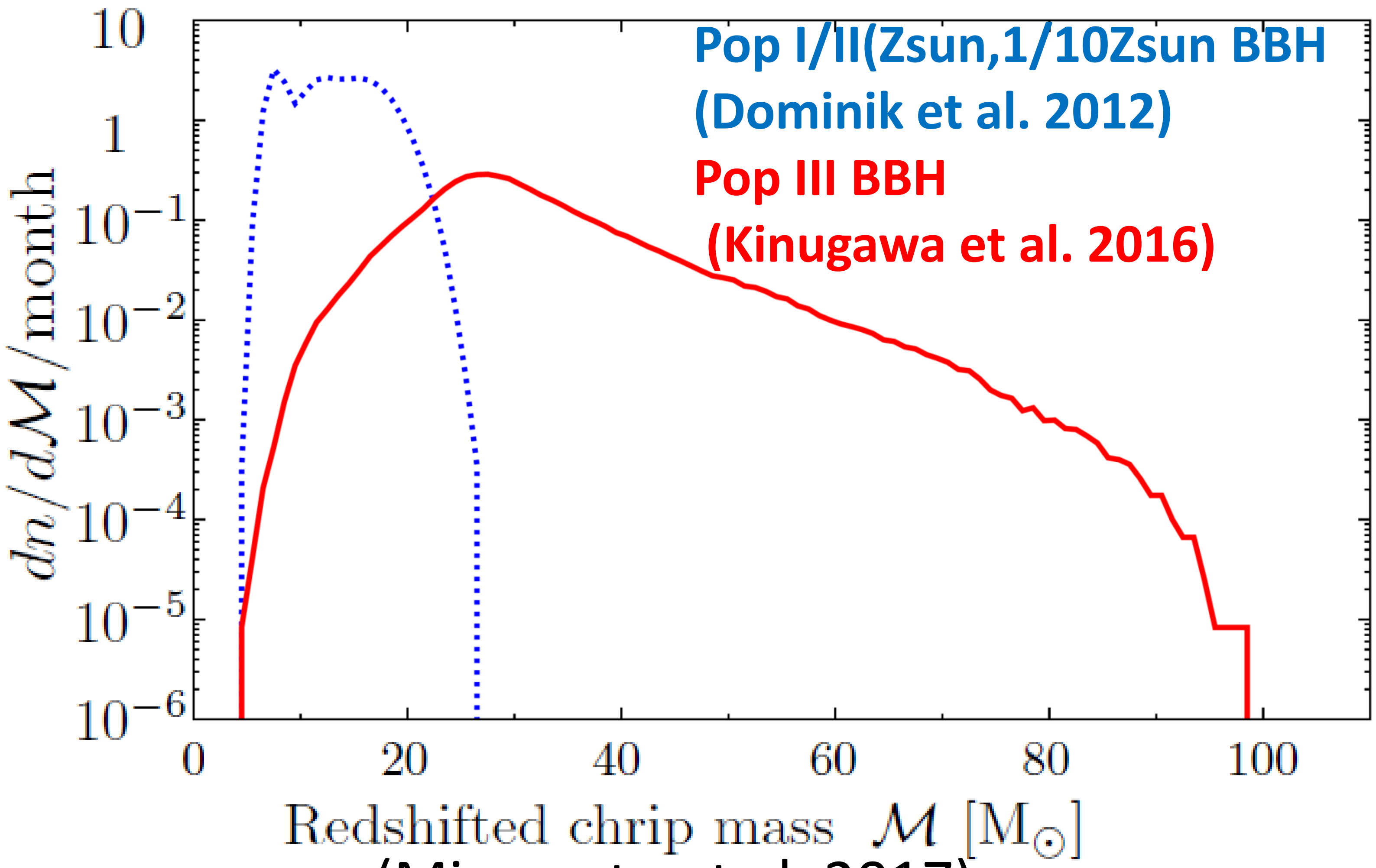


Mass distributions of observable BBHs (KAGRA)



(Miyamoto et al. 2017)

$$\mathcal{M} = (1+z)\frac{(M_1\ M_2\ )^{3/5}}{(M_1\ + M_2\ )^{1/5}}$$

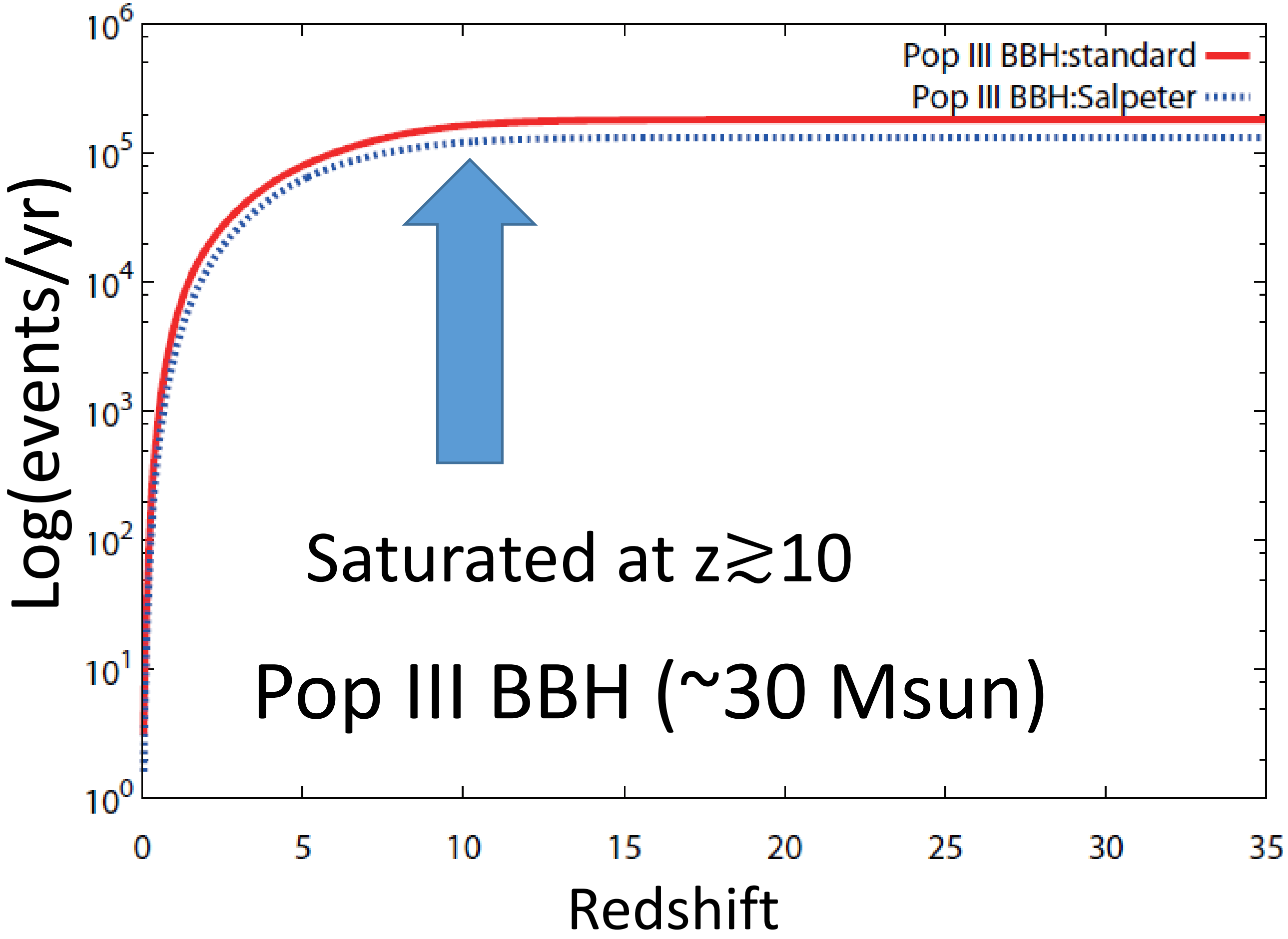
- The mass distribution might distinguish Pop III from Pop I, Pop II

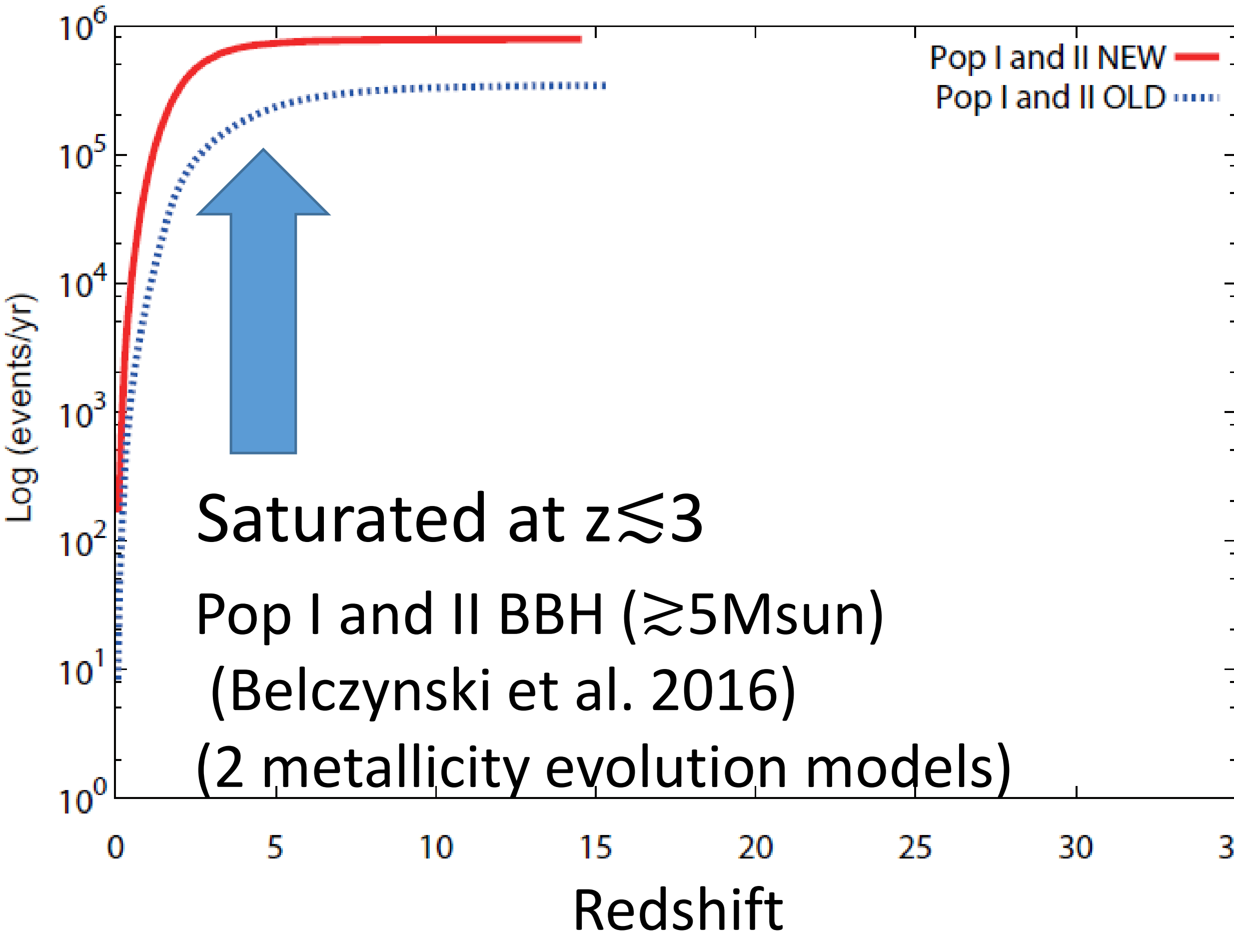
→The evidence of Pop III

Even if Mass dist. cannot distinguish

→redshift dependence

Cumulative BBH merger rate





Merger time dependence of Pop III BBH spin

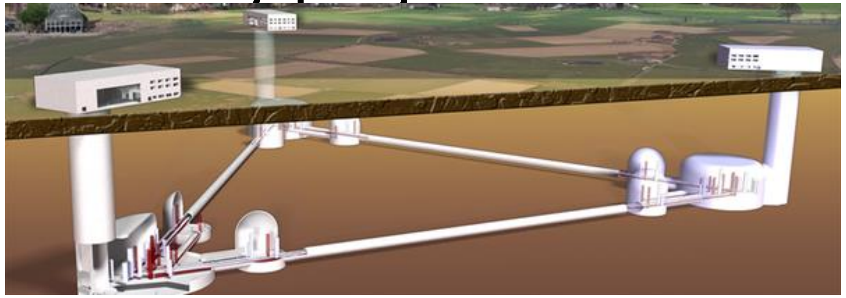
Preliminary results

	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

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
- B-DECIGO: test version of DECIGO

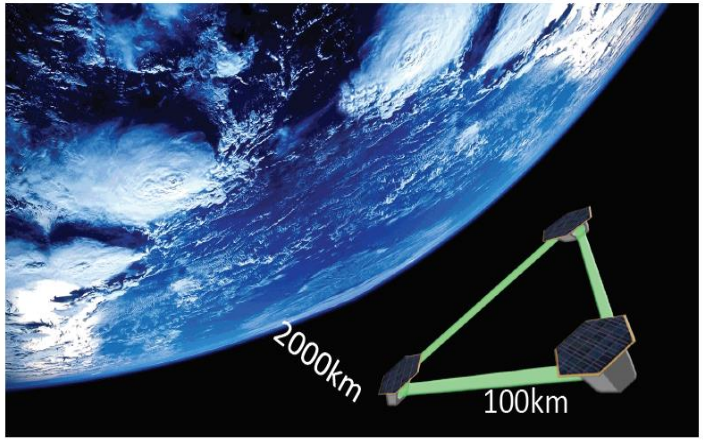


ET, CE, B-DECIGO : z~10 (30 Msun BH-BH)

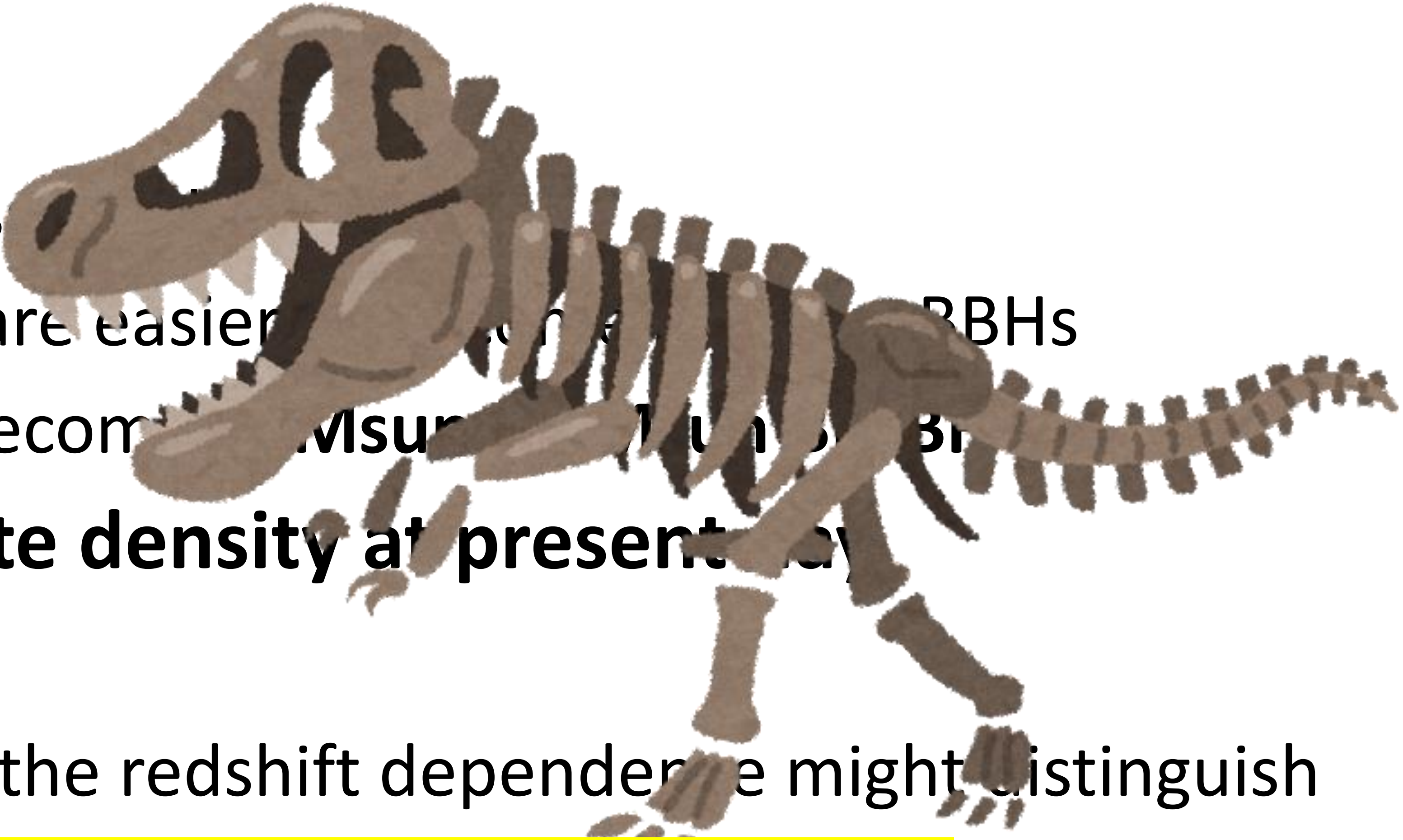
DECIGO can see Pop III BH-BHs

when Pop III stars were born (z~20)!

(Nakamura, Ando, Kinugawa et al. 2016)



PopIII BH-BH



- 7 ou … has
- Low … es are easier … BBHs
- Pop … becom … Msun …
- **Pop … rate density at present …**

R …]

- The … or the redshift dependence might distinguish Pop III fro…

Massive BBHs = the fossil of Pop III ?

- DECIGO can see Pop III BH-BH mergers when they were born

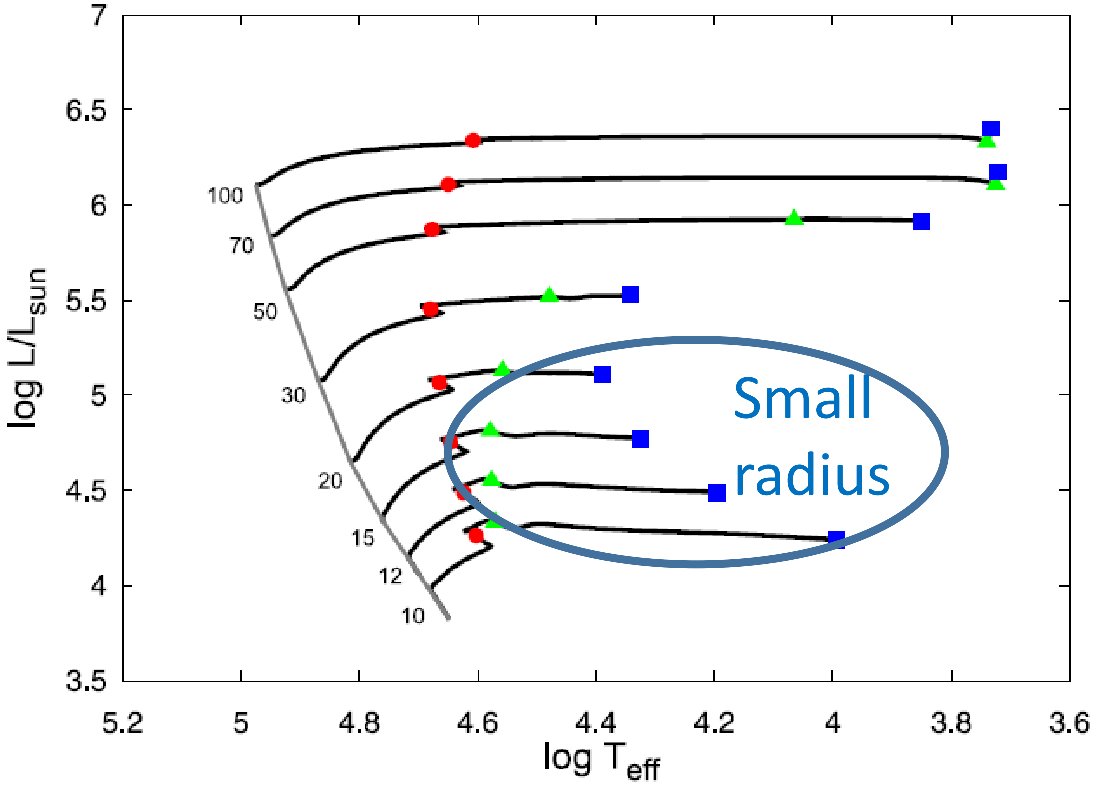
Other Pop III compact binaries cases

- Pop III NSNS

  Almost all binary NS (maybe) disrupt

- Pop III NSBH

Pop III NS progenitor evolution



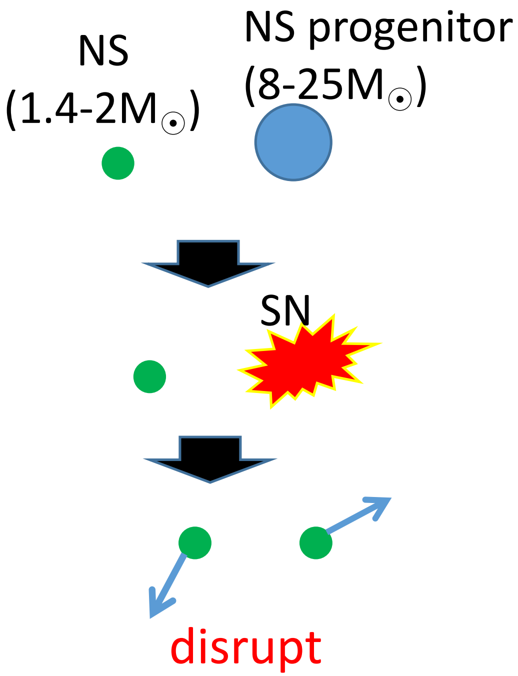
- blue giant

→Mass transfer is stable

→mass loss is not so effective before supernova

Pop III NS-NS disrupt

For example, we consider NS and NS progenitor binary.

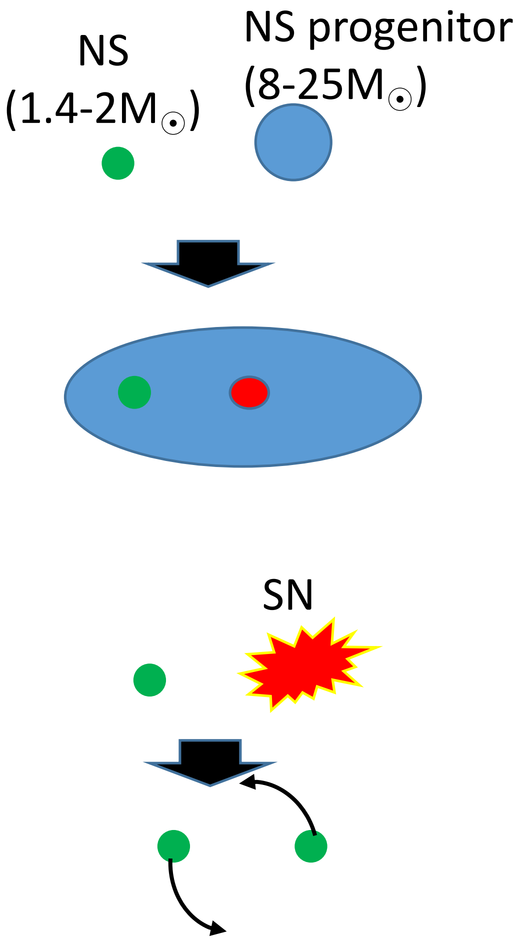


In the case of Pop III NS progenitor, wind mass loss and the mass loss due to binary interaction is not effective.
When NS progenitor becomes supernova, NS progenitor suddenly loses mass and becomes NS.
Then, due to instant mass loss the binding energy of binary decreases and binary NS disrupts.

Binary NS cannot survive!

Pop I and II NS-NS

For example, we consider NS and NS progenitor binary.



In the case of Pop I and II NS progenitor, wind mass loss and the mass loss due to binary interaction is effective.

NS progenitor can loses mass before SN.

⇨ Binary NS can survive!

Other Pop III compact binaries cases

- Pop III NSNS

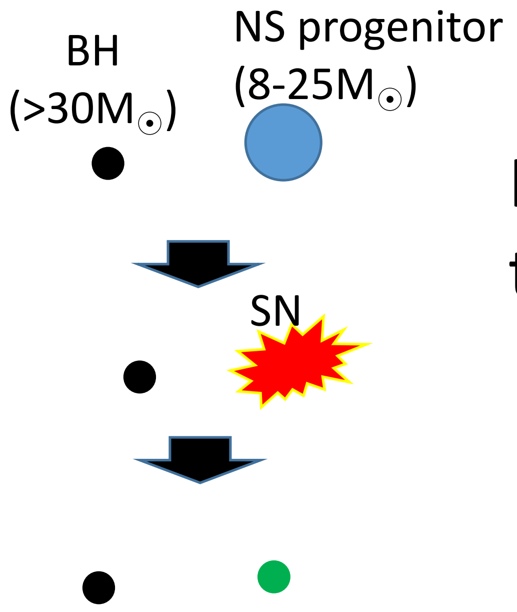
  Almost all binary NS (maybe) disrupt

- Pop III NSBH

  NSBH do not disrupt

Pop III NS-BH do not disrupt

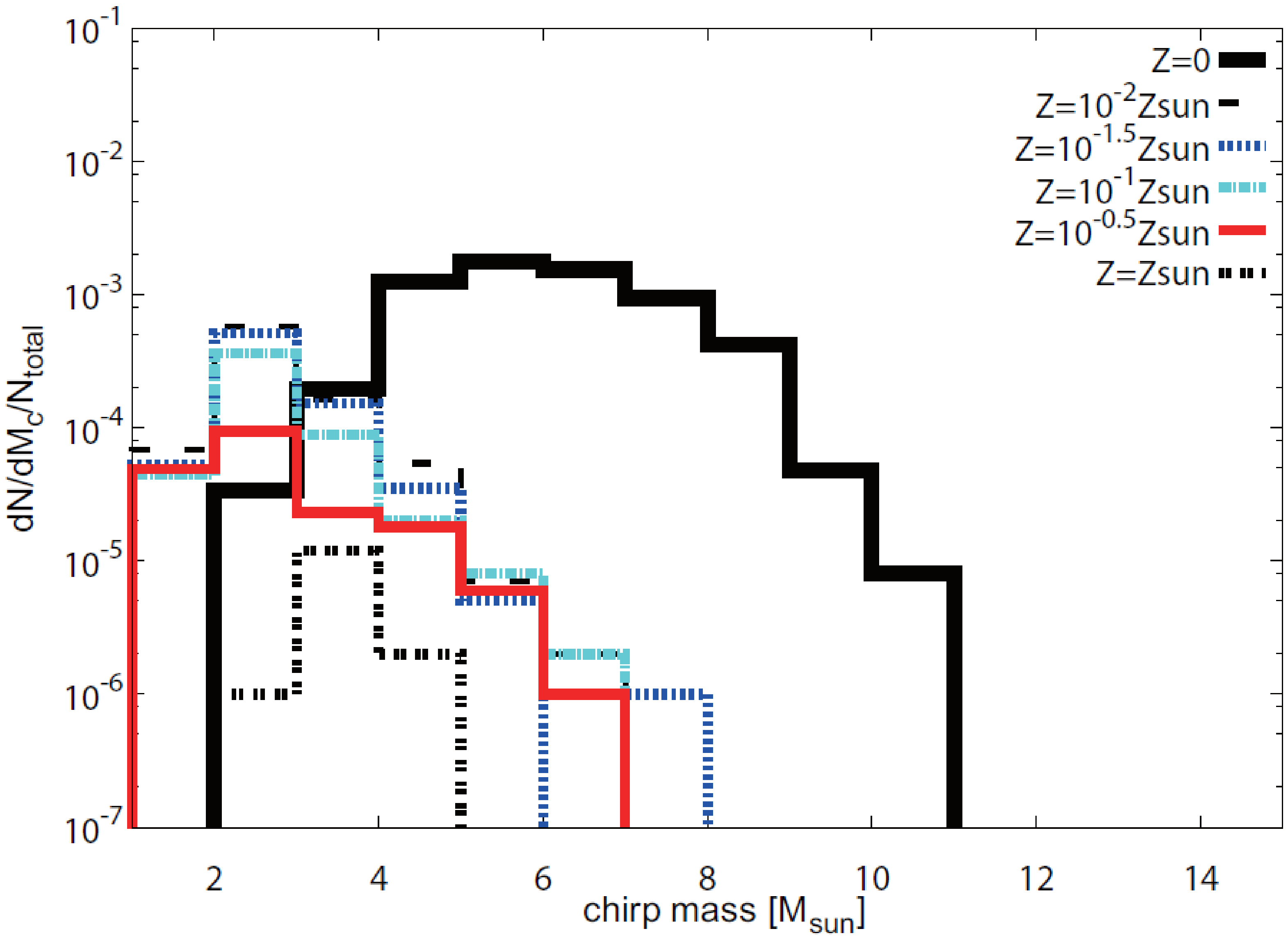
For example, we consider BH and NS progenitor binary.



In the case of Pop III NS progenitor, wind mass loss and the mass loss due to binary interaction is not effective.
When NS progenitor becomes supernova, NS progenitor suddenly loses mass and becomes NS.
But, due to massive BH, NS do not disrupts.

⇨ NS BH can survive!

Merging NSBH chirp mass distribution



NSBH detection rate

	Merger rate [/yr/Gpc^3]	aLIGO (design sensitivity) detection rate [/yr]
Pop I+II	28.8 (Belczynski et al. 2016)	~10
Pop III	1.25	5.24(*)

*For simplicity, as the assumption of the chirp mass of Pop III NSBH, we fixed Mc = $6M_{\odot}$ (Kinugawa et al.2016)

Pop III GW summary

- **Merger rate of Pop III BBH at z~0 (GW150914 like massive BBH)**

  $R \sim 10$ [yr^{-1} Gpc^{-3}]

- Typical chirp mass

  $M \sim 30\ M_{\odot}$

  We might detect (detected?) Pop III BBHs by GW

- **Detection rate of Pop III NSBH for aLIGO designed sensitivity**

  $R \sim 5$ [yr^{-1}]

- **Typical chirp mass**

  $M \sim 6\ M_{\odot}$ (1.4Msun NS +50Msun BH)