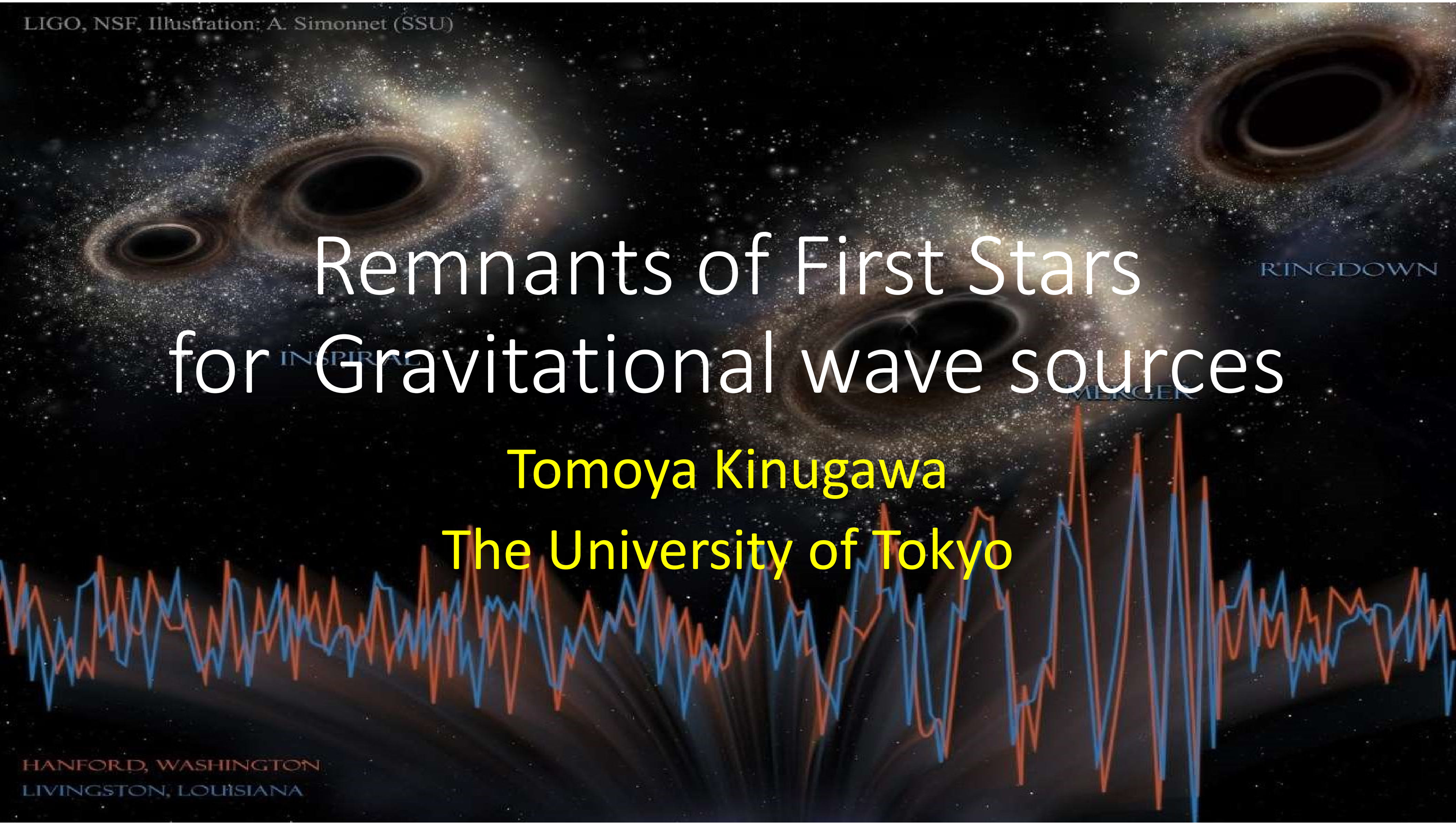
Remnants of First Stars for Gravitational wave sources

Tomoya Kinugawa

The University of Tokyo



GW150914

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.

- $36M_\odot + 29M_\odot$

Masses 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.

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

Many theories exist such as

- 1)Pop II BBH
- 2)Pop III BBH

Low metal field binaries

- 3)Primordial Binary BH (PBBH)
- 4)N body origin from Globular Cluster
- ……………………..

Why field binaries?

- There are many massive close binaries

  Example

  Milky way young open clusters

  71 O stars   fbinary=69+/-9% (P<3200days)

  Sana et al. 2012

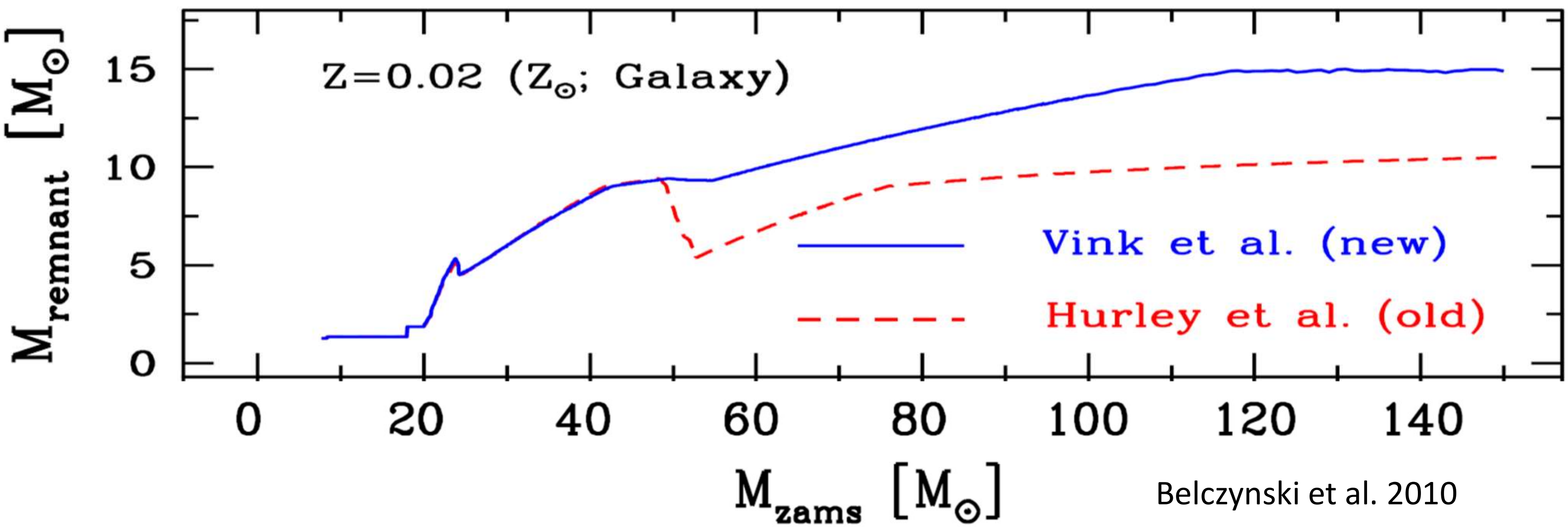
  30 Doradus (Tarantula Nebula)

  362 O stars fbinary=51+/-4%(P<3200days)

  Sana et al. 2013

Why low metal?

- 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

Why low metal?

- If the progenitor is low metal,

- Pop II (Metal<0.1SolarMetal)

  Typical mass is same as Pop I

  But, week wind mass loss

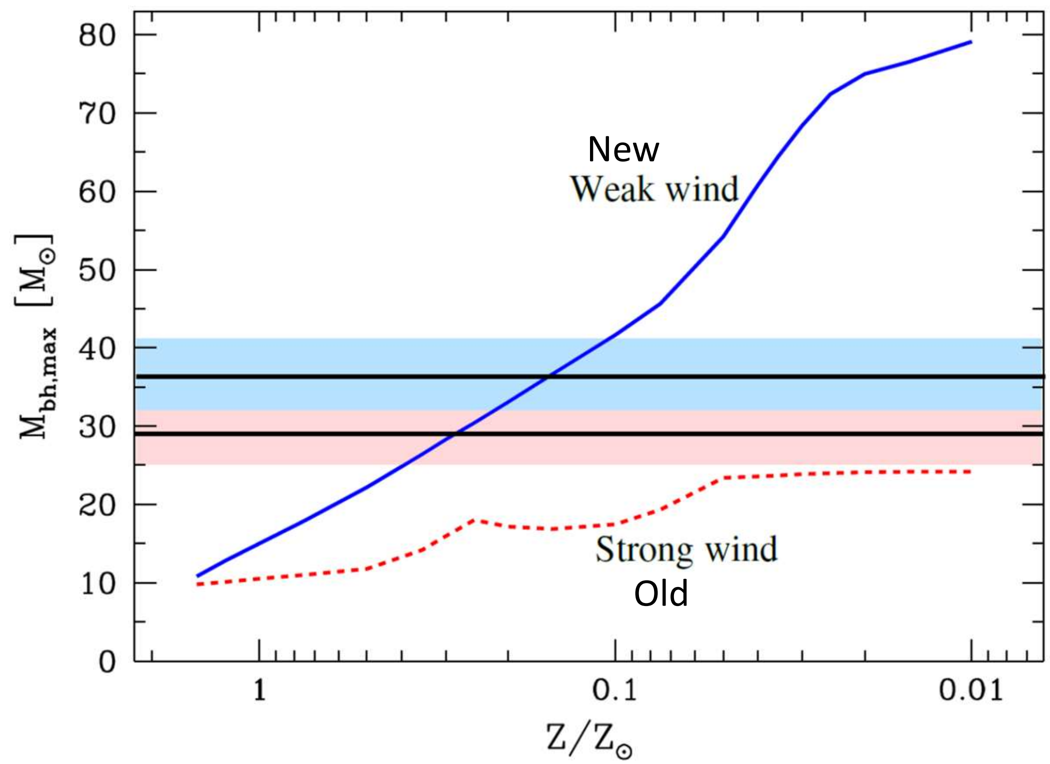
- Pop III (No metal)

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

  Typical mass is more massive than Pop I, II

  MpopIII~10-100Msun

  No wind mass loss due to no metal.



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

Pop III binary population synthesis

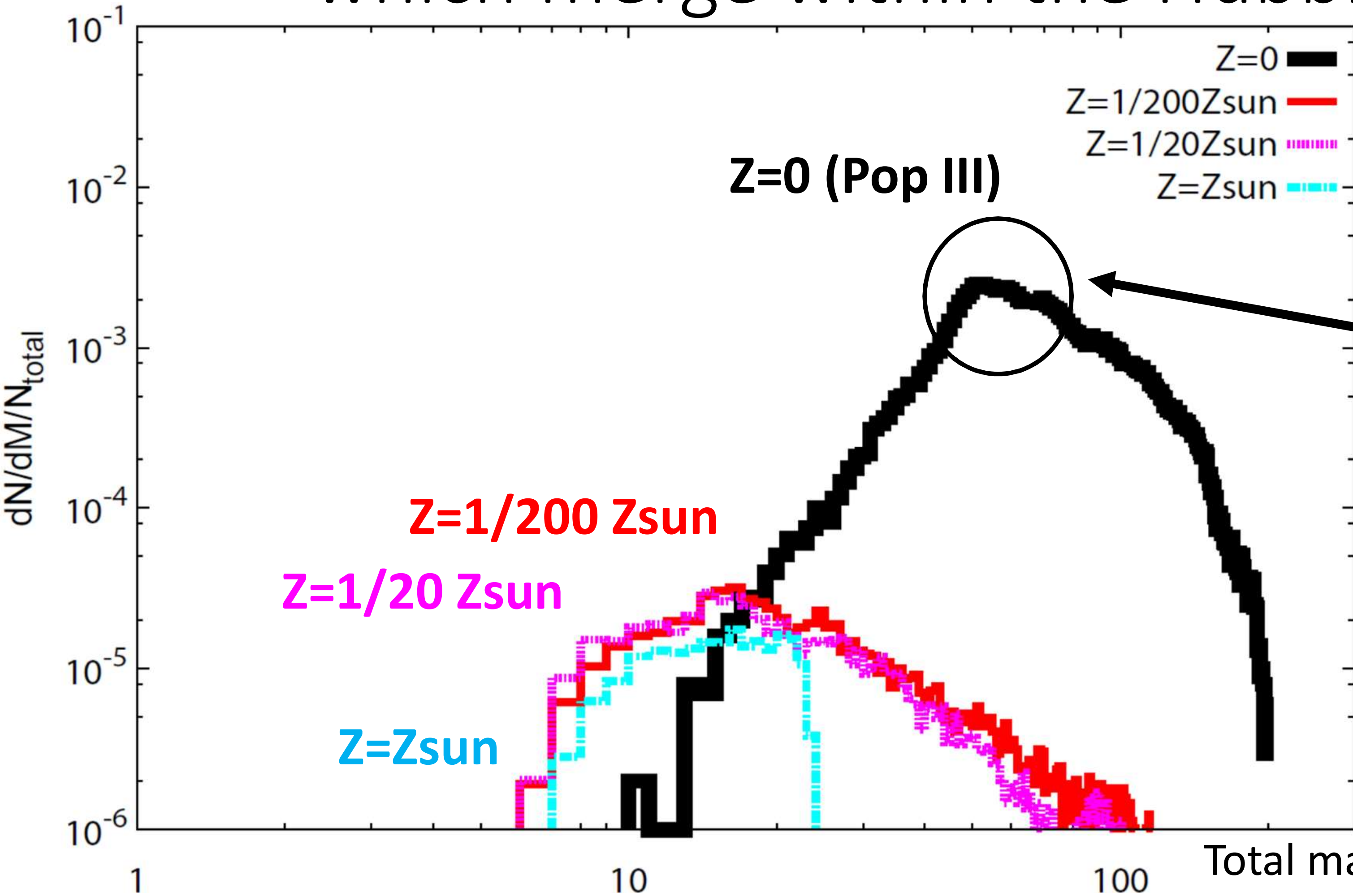
We simulate 10^6 Pop III-binary evolutions and estimate how many binaries become compact binary which merges within Hubble time.
×84 models (**Kinugawa et al.2014, 2016**)
Initial stellar parameters are decided by Monte Carlo method with initial distribution functions

- 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. (10Msun/M1<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

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. <u>2014</u>,2016

IMF:Flat

(10M<M<140M)

e.g. Pop I, Pop II

(Z=0.02,0.001,0.0001)

IMF:Salpeter

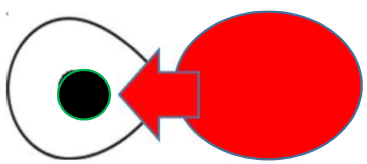
(1Msun<M<140Msun)

Typical mass ～10 $M_{\odot}$

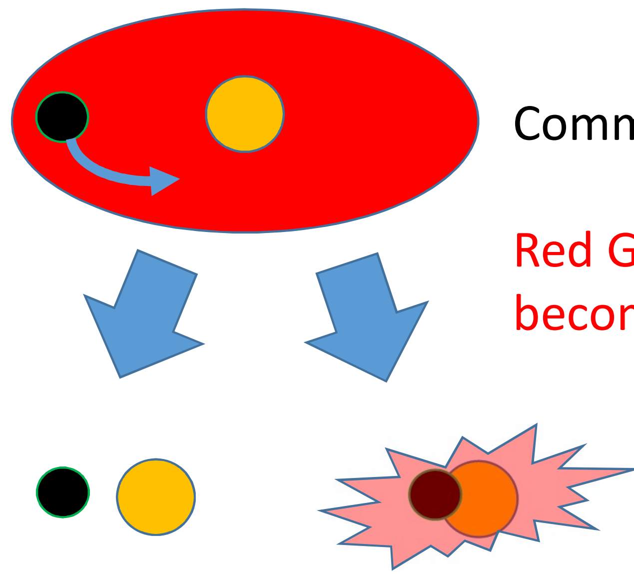
What do determine the BH-BH mass?

- Steller wind mass loss
- Binary interactions

(Mass transfer, Common envelope)



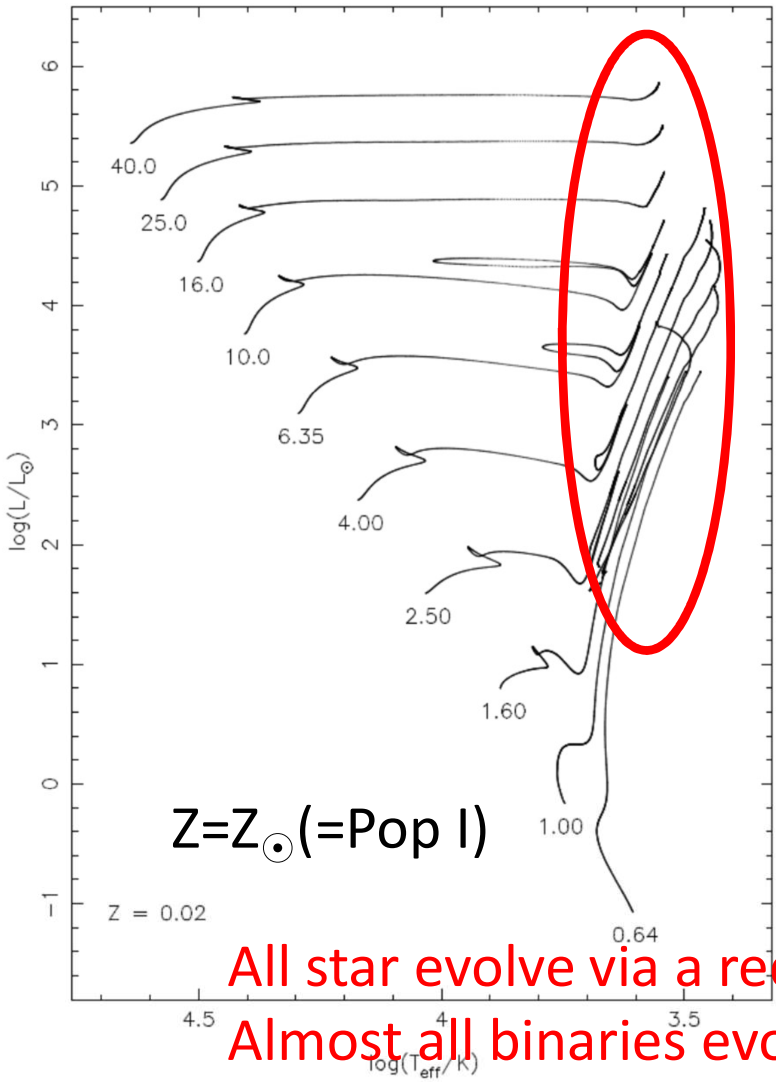
Mass transfer

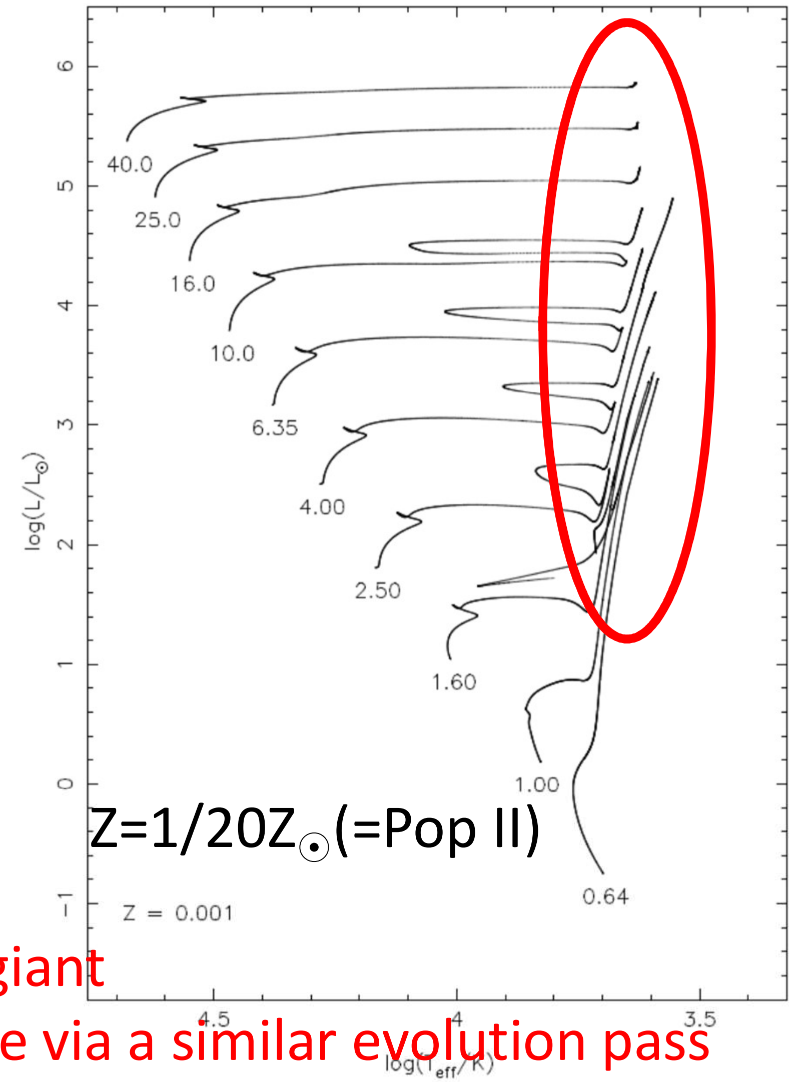


Common envelope

Red Giants tend to become CE

Close binary or merge





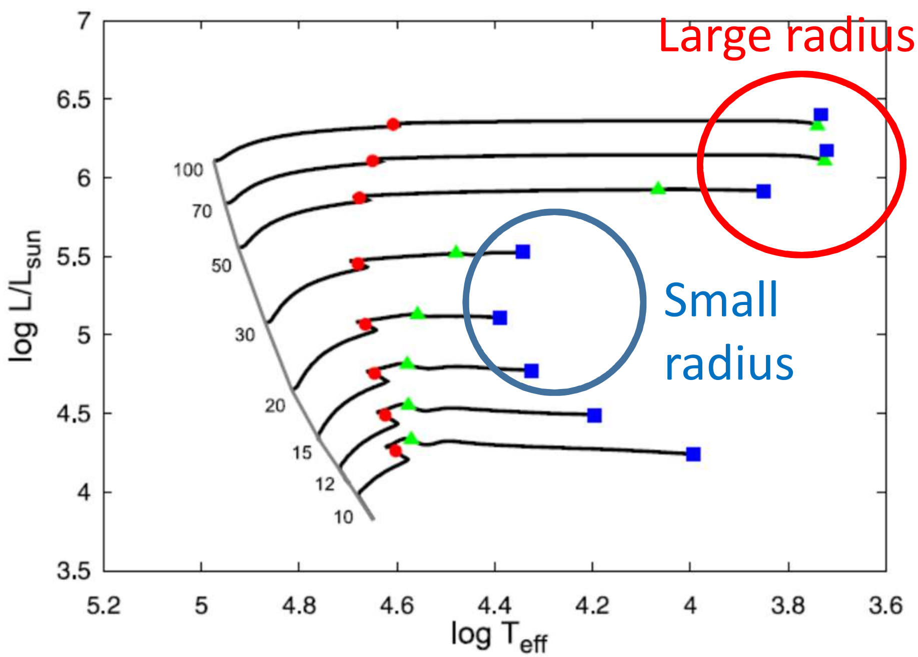
All star evolve via a red giant

Almost all binaries evolve via a similar evolution pass

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.

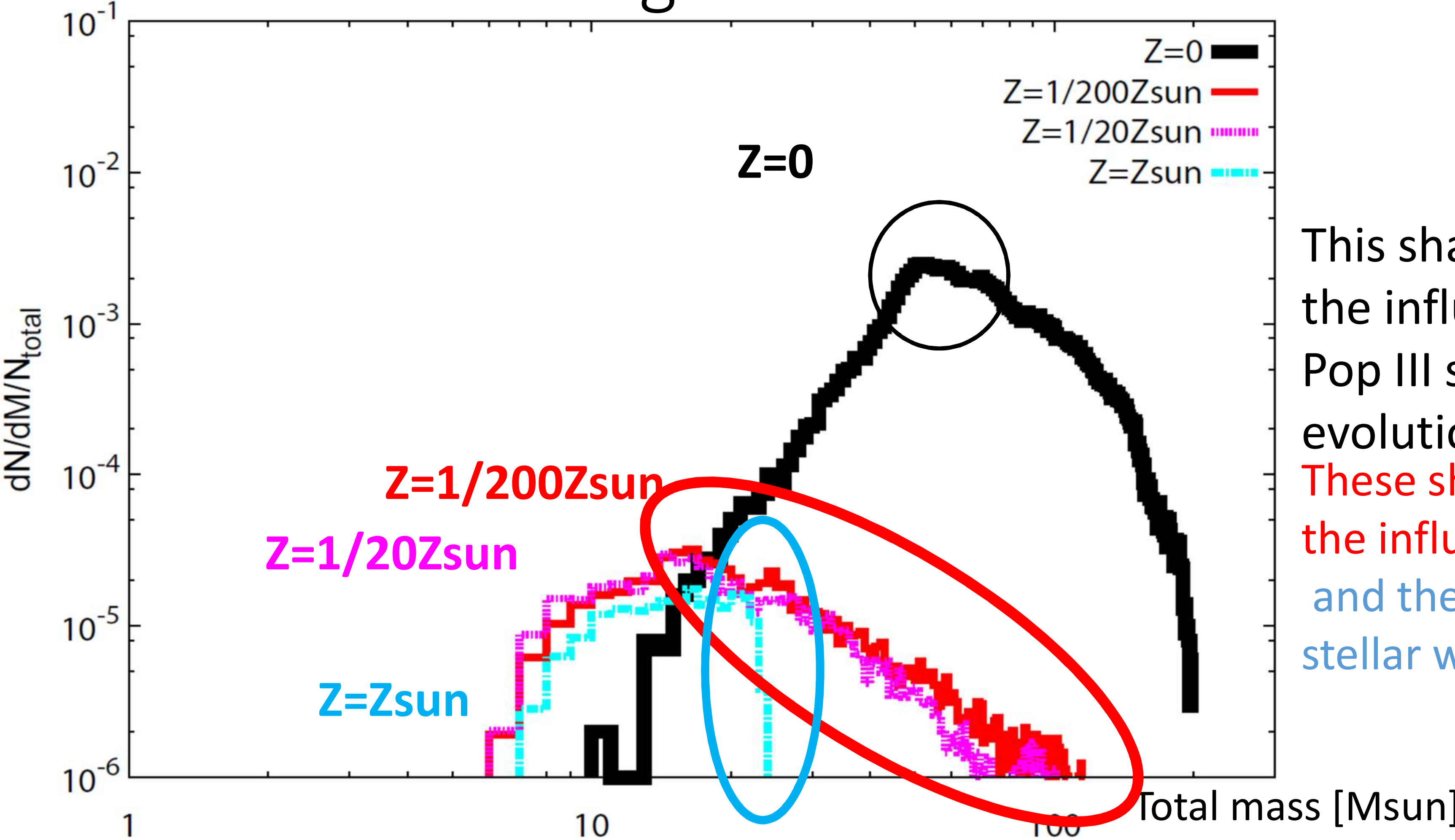
Why Pop III binaries become 30Msun BH-BH



- 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

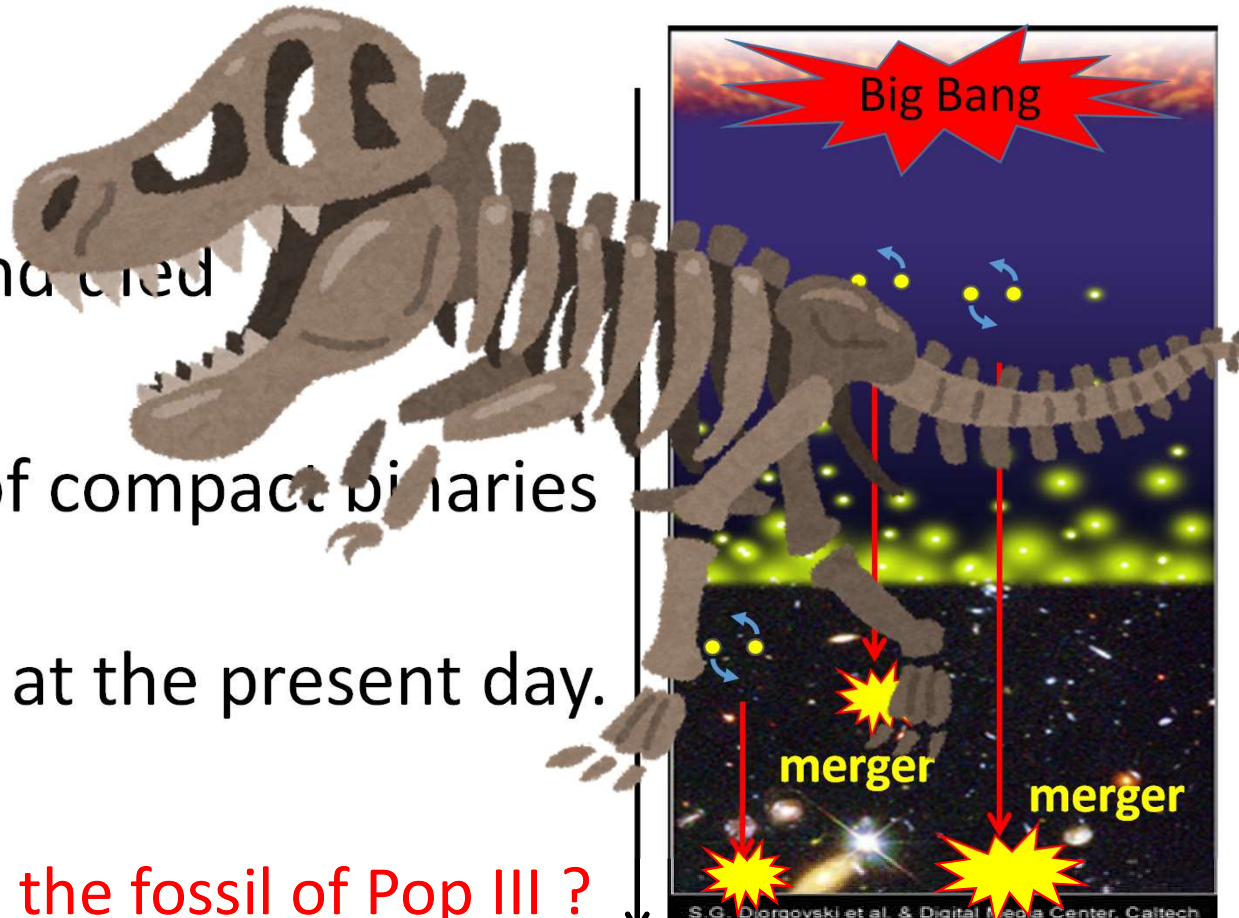


This shape reflects the influence of Pop III stellar evolution

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

Pop III BBH remnants for gravitational wave

- Pop III n and died at z≳
- The ty e of compact binaries ~10^8-1
- We mi BH at the present day.



Djorgovski et al.&Degital Media Center

Massive BBHs = the fossil of Pop III ?

Pop III BBH?

ASTROPHYSICAL IMPLICATIONS OF THE BINARY BLACK-HOLE MERGER GW150914

ApJL Abbot. et al 2016

2014; Dominik et al. 2015).

On the extreme low-metallicity end, it has been proposed that BBH formation is also possible in the case of stellar binaries at zero metallicity (Population III [PopIII] stars; see Belczynski et al. 2004; Kinugawa et al. 2014). The predictions from these studies are even more uncertain, since we have no observational constraints on the properties of first-generation stellar binaries (e.g., mass function, mass ratios, orbital separations). However, if one assumes that the properties of PopIII massive binaries are not very different from binary populations in the local universe (admittedly a considerable extrapolation), then recently predicted BBH total masses agree astonishingly well with GW150914 and 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

Results

The numbers of the compact binaries which merge within Hubble time for 10^6 binaries (Kinugawa et al. 2014,2016)

BHBH
115056

Our standard model

- A lot of Pop III BH-BH binaries form and merge within Hubble time

The star formation rate of Pop III

In order to calculate merger rate,

we need to know

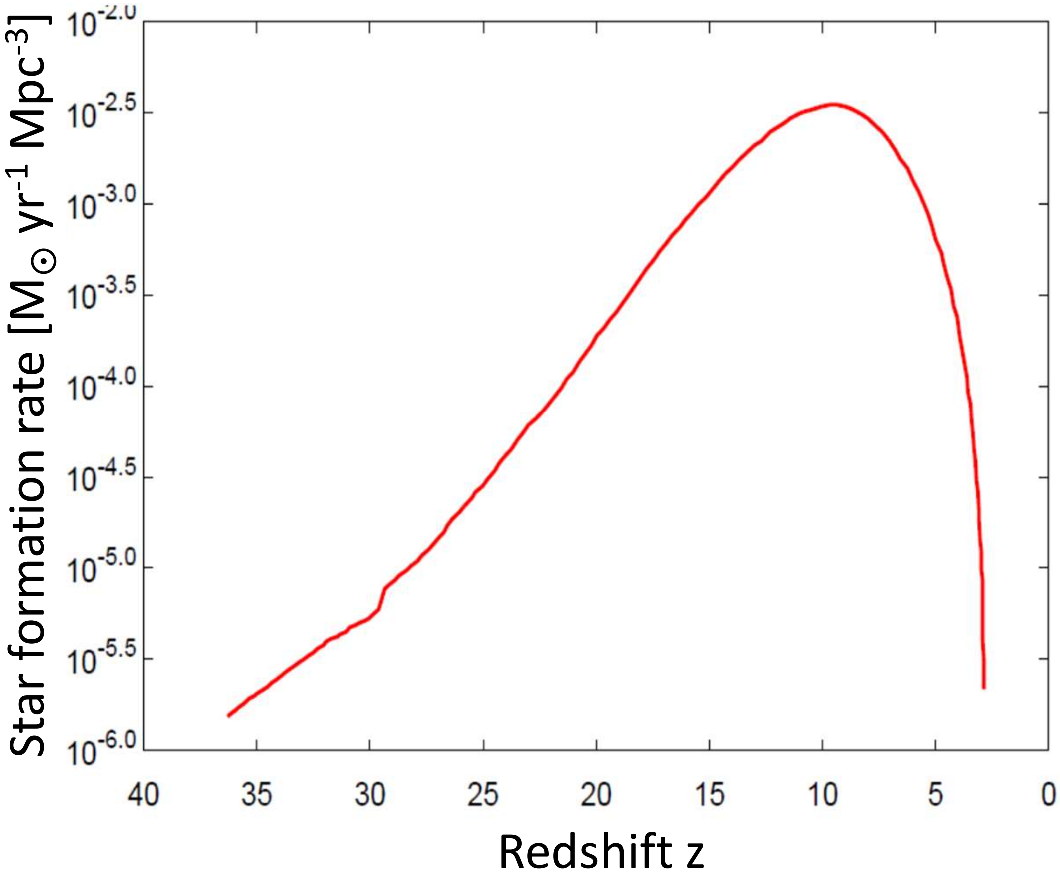
- When were Pop III stars born?
- How many were Pop III stars born?

⇒Star formation rate

We adopt the Pop III SFR

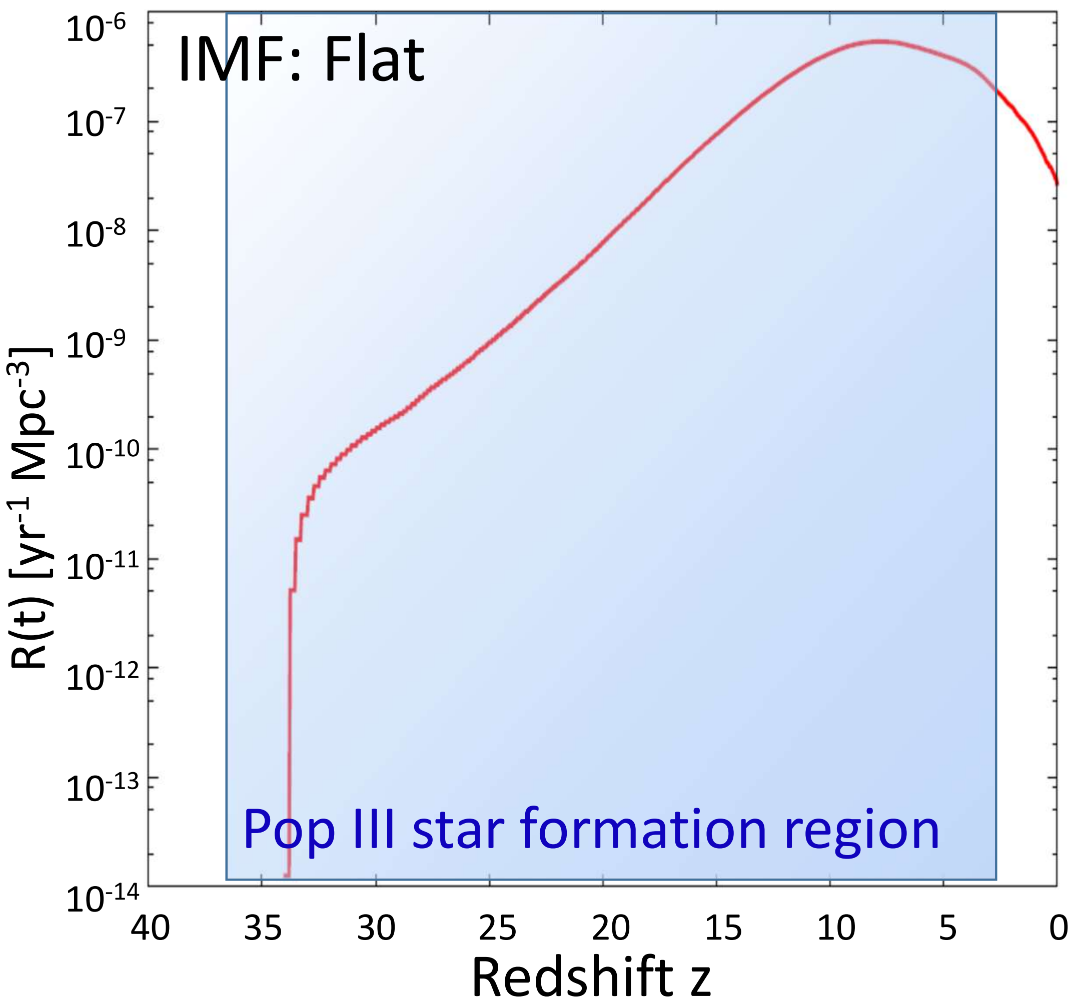
by de Souza et al. 2011

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



(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

$$\mathbf{R \sim 25 \left(\frac{SFR_{peak}}{10^{-2.5}}\right)\left(\frac{f_b/(1+f_b)}{0.33}\right) Err_{sys}\ [yr^{-1}\ Gpc^{-3}]}$$

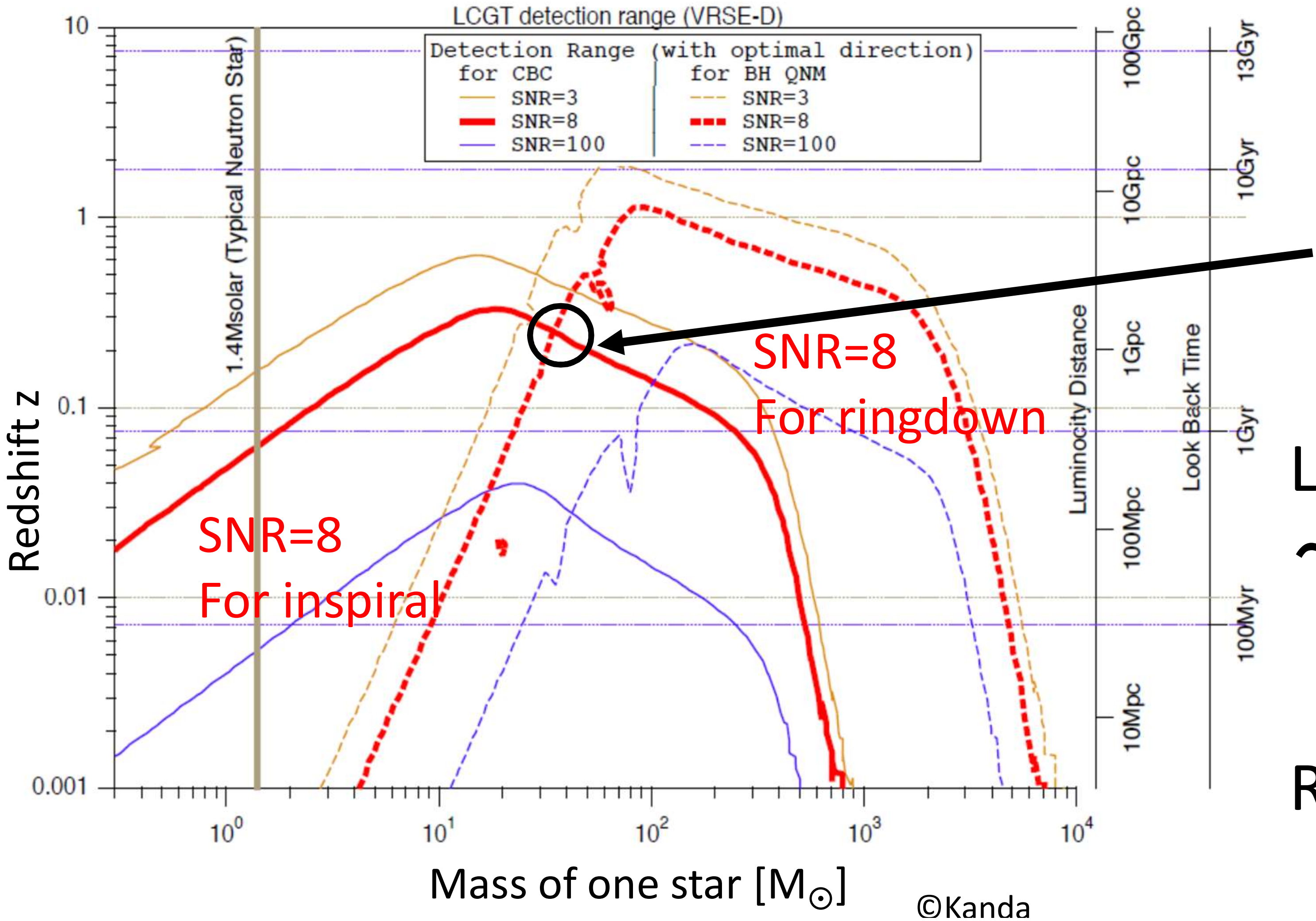
(Kinugawa et al. 2014,2016)

BBH merger rate estimated by LIGO

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

(1811.12907)

Detection range of KAGRA and Adv. LIGO



M_{BH} ～ $30M_\odot$

SNR=8

Luminocity distance

～1.5 Gpc

Redshift z～0.28

Detection rate of Pop III BH-BH

- **Detection rate of Pop III BBH (GW150914 like BBH) in our standard model (aLIGO design sensitivity)**

  $\mathbf{R \sim 180 \left(\frac{SFR_{peak}}{10^{-2.5}}\right) \left(\frac{f_b/(1+f_b)}{0.33}\right) Err_{sys}\ [yr^{-1}]}$ (S/N>8)

  (Kinugawa et al. 2014,2016)

- Typical mass

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

Other Pop III SFRs

- simulation

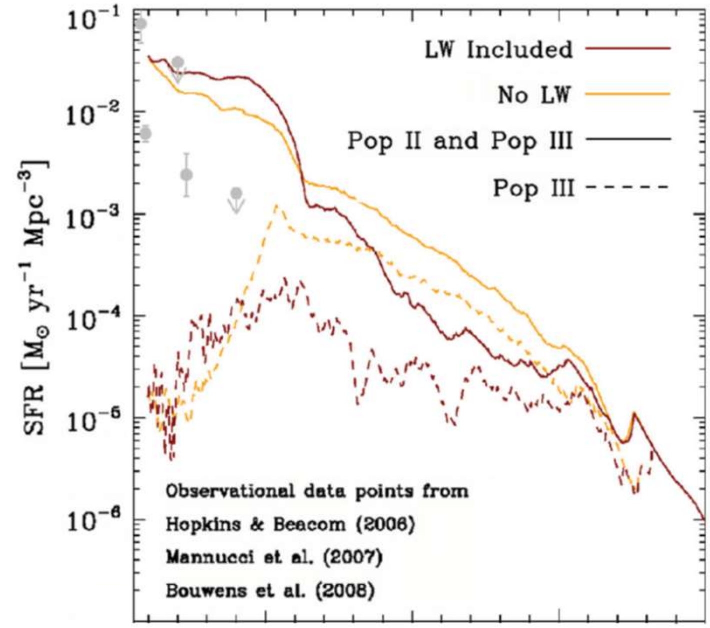
  e.g. Johnson et al. 2013

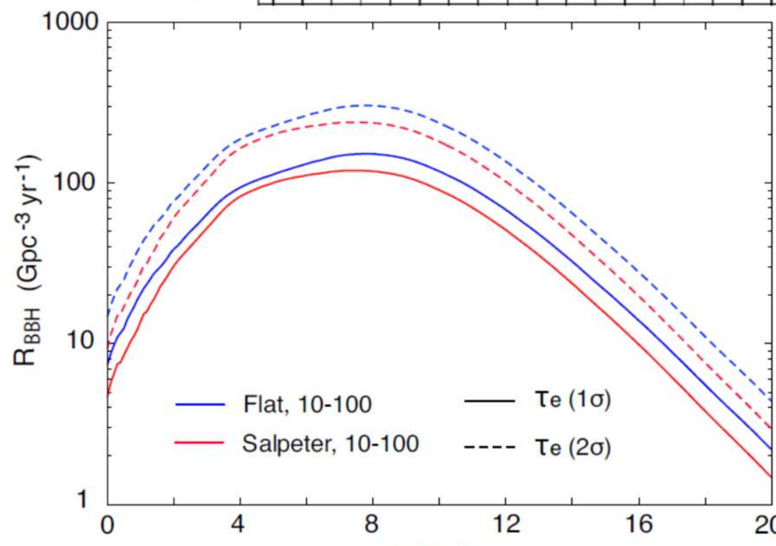
  $SFR_p \sim 10^{-3}$-10^{-4} Msun/yr/Mpc^3
- Constraints by Planck τ_e

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

  Inayoshi et al.2016

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



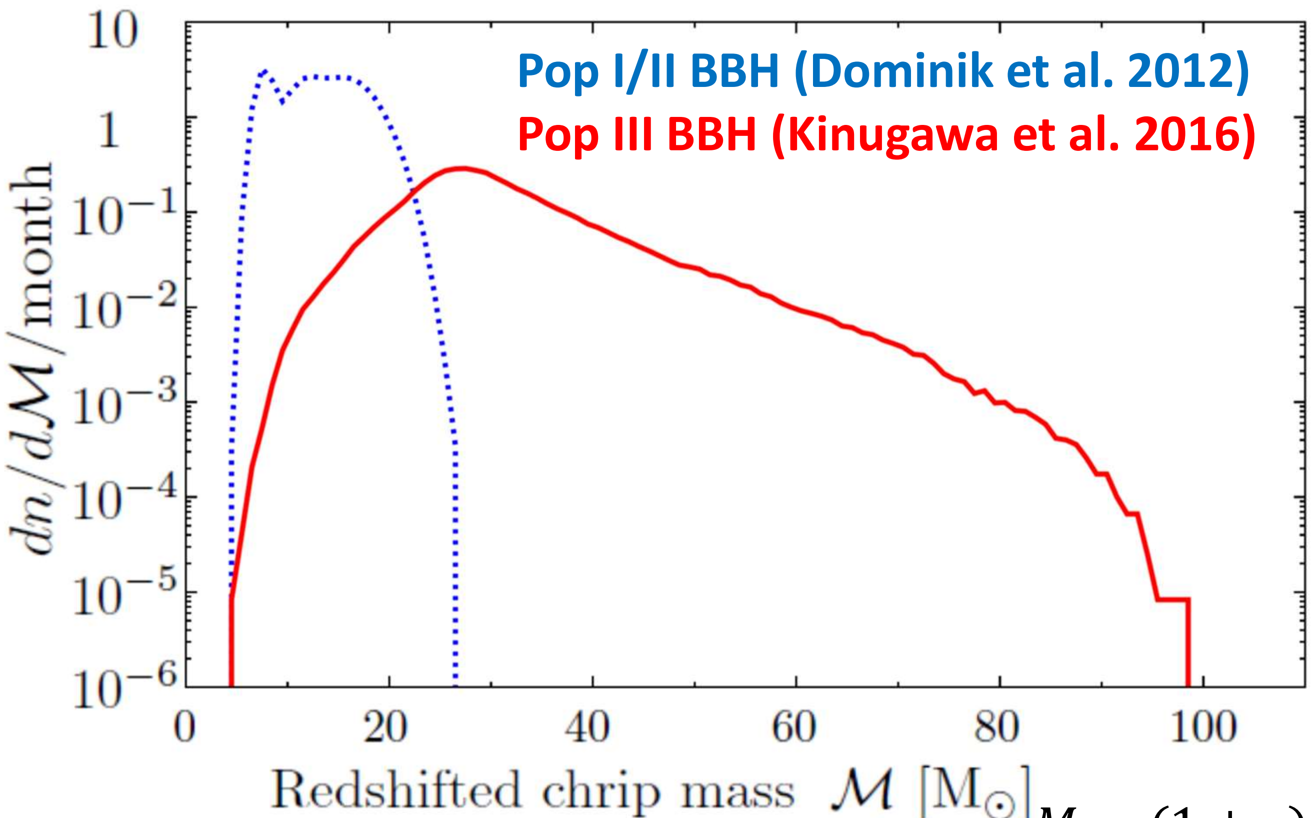


Errsys (Example)

	Errsys
Standard	1 (180 /yr)
Mass range: ($10\ M_\odot < M <$ $100\ M_\odot$ or $140\ M_\odot$)	1~3.4
IMF: Flat, M^{-1}, Salpeter	0.42~1
IEF: $f(e) \propto e$, const., $e^{-0.5}$	0.94~1
BH natal kick: σ_V=0,100,300 km/s	0.2~1
CE: $\alpha\lambda$=0.01,0.1,1,10	0.21~1
Mass transfer (mass loss fraction): β=0, 0.5, 1	0.67~1.3

- The typical mass is **not changed** (**~30 Msun**).

Mass distributions of observable BBHs (KAGRA)



(Miyamoto et al. 2017)

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

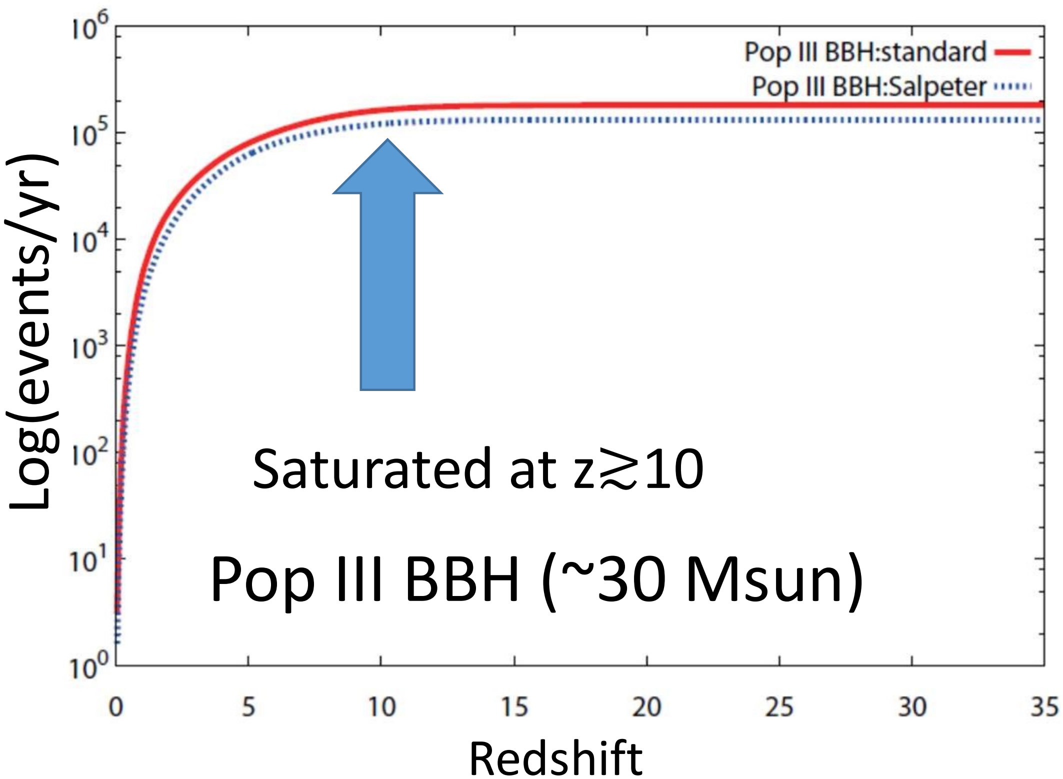
→The evidence of Pop III

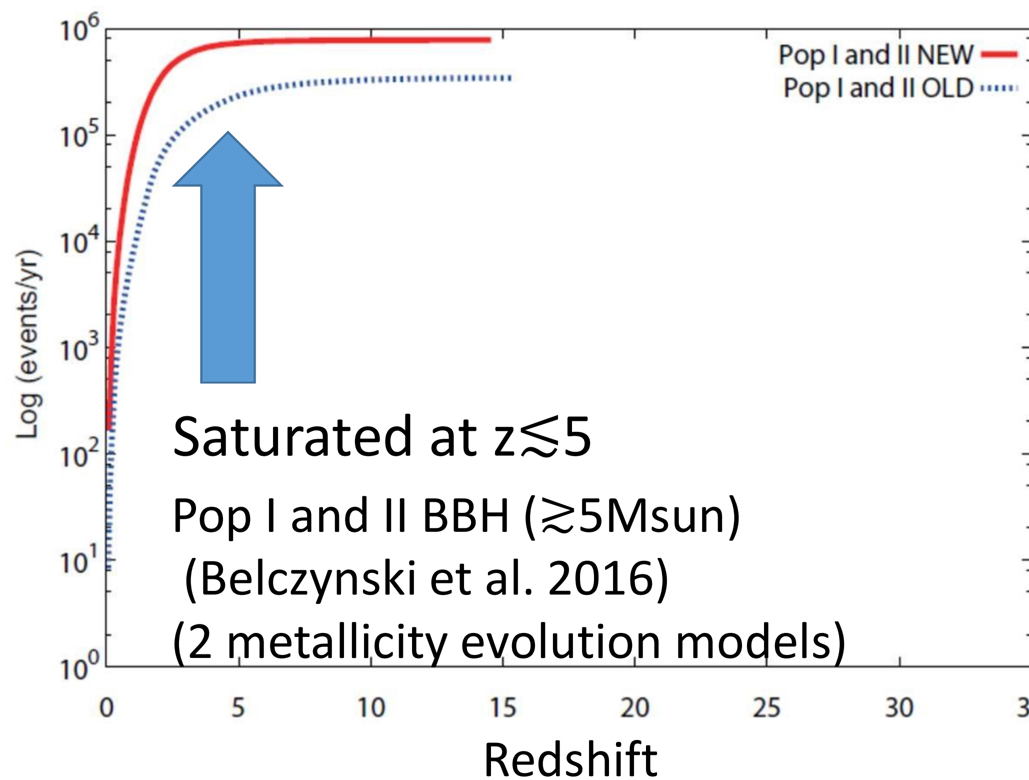
If it cannot distinguish

→redshift dependence

$M = (1+z)\frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}$ if 30+30 BBH →M~26

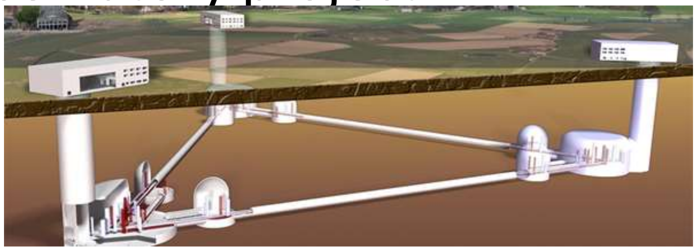
Cumulative BBH merger rate





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



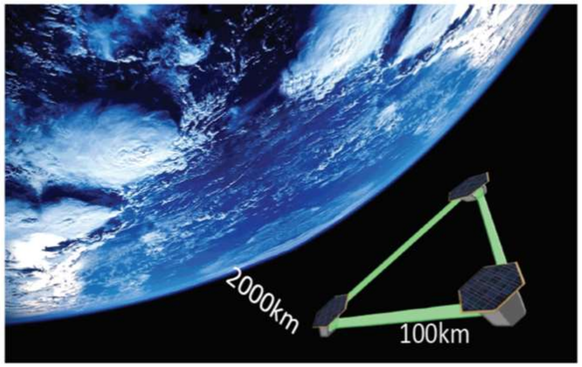
ET, CE, B-DECIGO : z~10 (30 Msun BH-BH)

$\sim 10^5$ events/yr

DECIGO can see Pop III BH-BHs

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

(Nakamura, Ando, Kinugawa et al. 2016)



Summary

- Pop III binaries tend to become **30Msun+30Msun BH-BH**
- **Pop III BBH detection rate of aLIGO in our standard model**

  R～180 $\left(\frac{SFR_{peak}}{10^{-2.5}}\right)\left(\frac{f_b/(1+f_b)}{0.33}\right)$ Errsys [yr^{-1}](S/N>8)
- The mass distribution or the redshift dependence might distinguish Pop III from Pop I,II.
- DECIGO can see Pop III BH-BH merger when they were born