Possible confirmation of the existence of Population III stars by KAGRA

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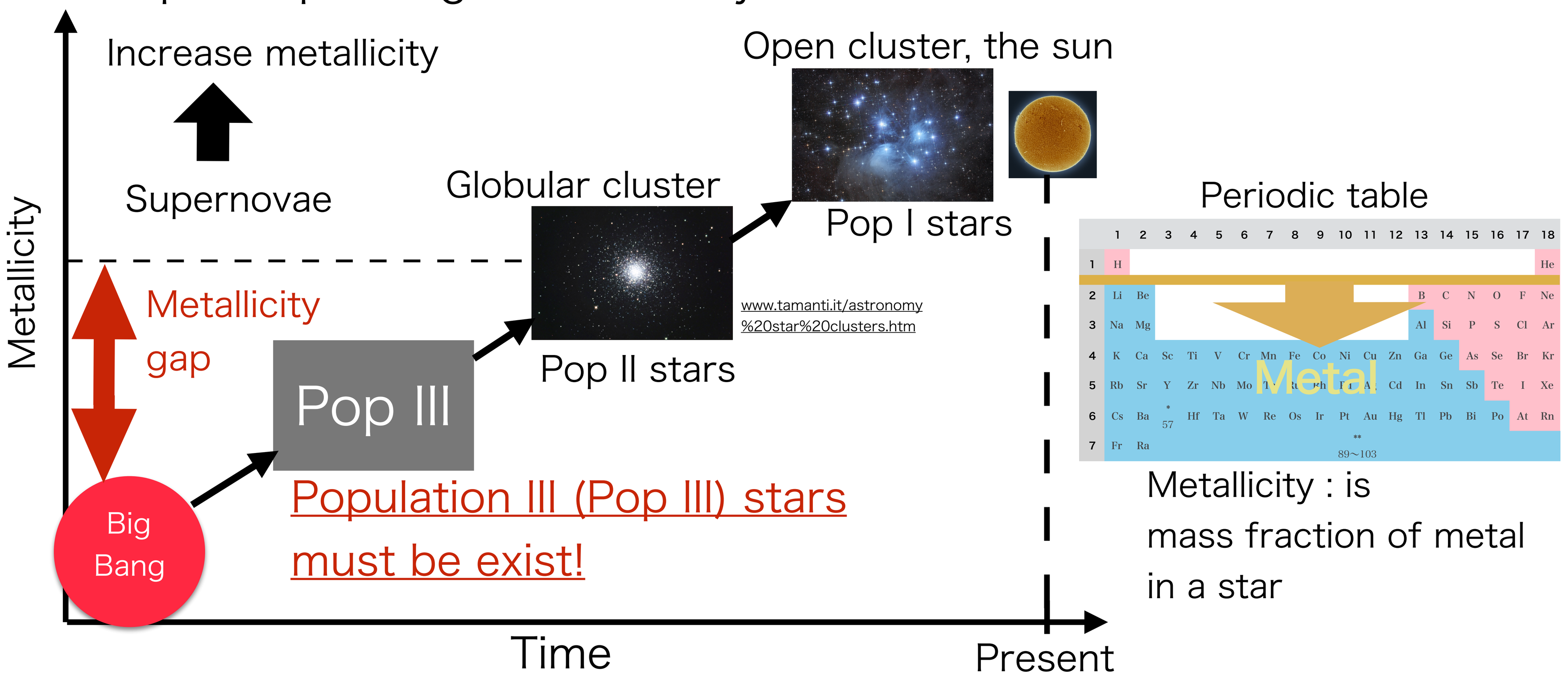
1. Abstract

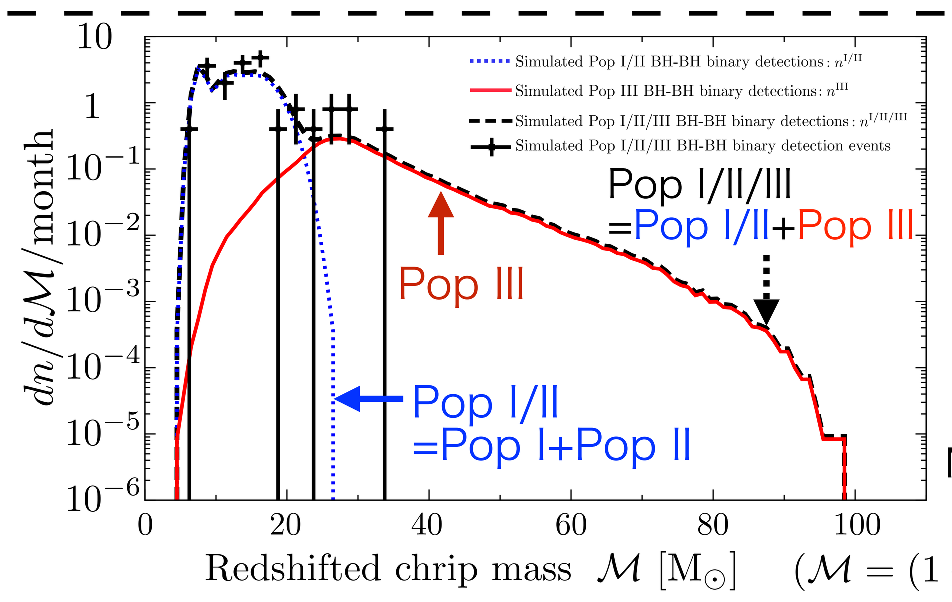
See also Ref. [5], Miyamoto et al., "How to confirm the existence of population III stars by observations of gravitational waves", Phys. Rev. D **96**, 064025

We propose a method for confirmation of the existence of Population III (Pop III) stars with massive black hole (BH) binaries in gravitational wave (GW) observation. The first GW event, GW150914, is the binary BH whose masses are 36 solar mass and 29 solar mass. To explain the existence of such massive BHs, there are some BH formation scenarios. One of the possible origins of GW150914 is the Pop III stars, i.e. the zero metal stars. We discussed a method for confirmation of the existence of the Pop III stars using likelihood analysis of mass distributions of binary BH mergers. In typical cases, our analysis can distinguish "Pop I/II/III model" from "Pop I/II model" with 90% probability by 22 GW signals from binary BH mergers.

2. Population I/II stars and Population III stars

Star is classified as one of Population I (Pop I), Population II (Pop II), and Pop III depending on metallicity.





Typical redshifted chirp mass of binary BH of

: **Pop I/II** is $\sim 10M_\odot$

: **Pop III** is $\sim 30M_\odot$

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$(\mathcal{M} = (1+z)(M_1M_2)^{3/5}/(M_1+M_2)^{1/5})$

Fig.1 Average distributions of redshifted chirp mass M of simulated binary BH detections for a 1-month period, and a simulated observation result for a 1-month period of GW detection simulation in KAGRA.

3. Simulation of GW detections

In order to simulate the GW events from the binary BH mergers, we use the results of the binary population synthesis. For an example of population synthesis model of **Pop I/II** and **Pop III**, we employ **Dominik's standard model** [1,2] and **Kinugawa's standard model** [3,4], respectively. For details of these models, see our paper [5].

Inspiral GW waveform can be predicted. So, we can use matched filter analysis for Inspiral GWs in signal to noise ratio (S/N) calculation. We can estimate redshifted chirp mass $\mathcal{M}$ of binary by Inspiral GW detection.

$$(\mathrm{S/N})^2 = 4\int_{f_{\min}}^{f_{\max}} df \frac{|\tilde{h}(f)|^2}{S_n(f)} = \frac{5}{6}\frac{\pi^{-4/3}c^2\,\mathrm{T}_\odot^{5/3}}{d_L^2}\left(\frac{\mathcal{M}}{\mathrm{M}_\odot}\right)^{5/3} I\,\beta$$

$$I = \int_{f_{\min}}^{f_{\max}} df \frac{f^{-7/3}}{S_n(f)},$$

$$\beta = \left(\frac{1+\cos^2\iota}{2}\right)^2 F_+^2 + \cos^2\iota\, F_\times^2$$

Detector : KAGRA
High frequency cutoff $f_{\max} = f_{\mathrm{ISCO}}$
Low frequency cutoff $f_{\min}$
GW frequency at innermost stable circular orbit : f_{ISCO}
Detector antenna patterns : $F_+, F_\times$
$\mathrm{T}_\odot = \frac{GM_\odot}{c^3}$

Detection threshold (S/Nth) is defined 8

4. Evaluate the probability of identifying the existence of Pop III stars

Redshifted chirp mass distribution is the key to distinguish Pop III from Pop I/II. We performed likelihood analysis using redshifted chirp mass.

Detection events from redshifted chirp mass : $\vec{\mathcal{M}}(n) = \{\mathcal{M}_1, \mathcal{M}_2, \ldots, \mathcal{M}_n\}$

n : the number of detections

Which model is closer?

Pop I/II (without PopIII) $\theta^{\mathrm{I/II}}$ | Pop I/II/III (with PopIII) $\theta^{\mathrm{I/II/III}}$

Likelihood $L(\vec{\mathcal{M}}(n)|\theta^{\mathrm{I/II}}) = \prod_{i=1}^{n} p^{\mathrm{I/II}}(\mathcal{M}_i)$, $L(\vec{\mathcal{M}}(n)|\theta^{\mathrm{I/II/III}}) = \prod_{i=1}^{n} p^{\mathrm{I/II/III}}(\mathcal{M}_i)$

Log-likelihood ratio $\ln\Lambda(\vec{\mathcal{M}}(n)) = \ln\left[\frac{L(\vec{\mathcal{M}}(n)|\theta^{\mathrm{I/II/III}})}{L(\vec{\mathcal{M}}(n)|\theta^{\mathrm{I/II}})}\right]$

We determine a log-likelihood ratio threshold $\ln\Lambda_{\mathrm{th}}$ as defined below by 1% false probability by log-likelihood ratio distribution from Pop I/II models.

If a data set satisfies $\ln\Lambda(\vec{\mathcal{M}}(n)) > \ln\Lambda_{\mathrm{th}}$ the Pop I/II model and Pop I/II/III model are distinguished with 1% false probability.

The probability of identifying the existence of Pop III stars P

P = (# of data sets satisfies $\ln\Lambda(\vec{\mathcal{M}}(n)) > \ln\Lambda_{\mathrm{th}}$)/(# of simulated data sets=10^7)

5. Results and discussion

We simulated GW detections of binary black holes assuming KAGRA. The **detection rates** with typical population synthesis models are ~30 events/month (Pop I/II), ~5 events/month (Pop III).

Log-likelihood ratio distributions

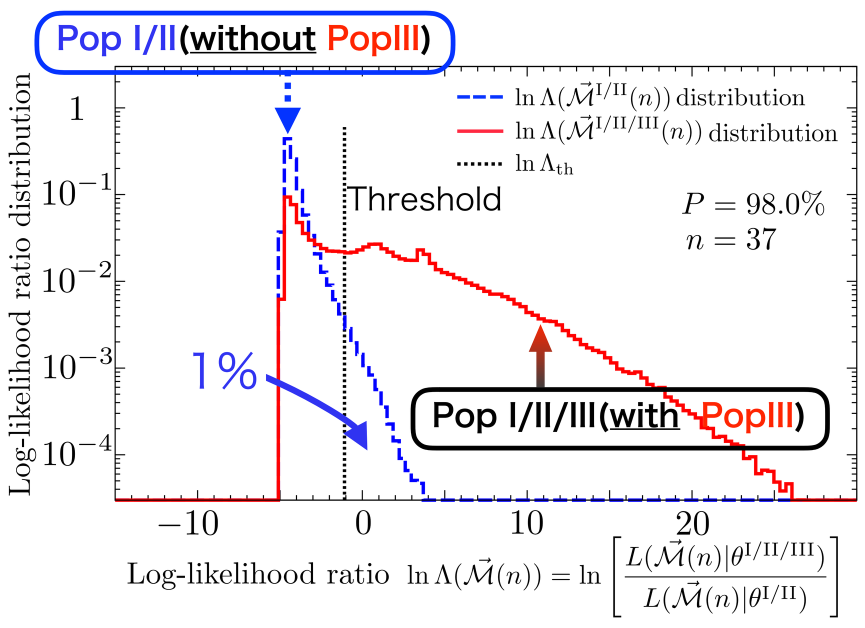

Fig.2 Distributions of the log likelihood ratio for equivalent a 1-month period of observation. The probability of identifying the existence of Pop III stars is estimated to be 98.0% at 37 events.

Probability of identifying the existence of Pop III stars *P*

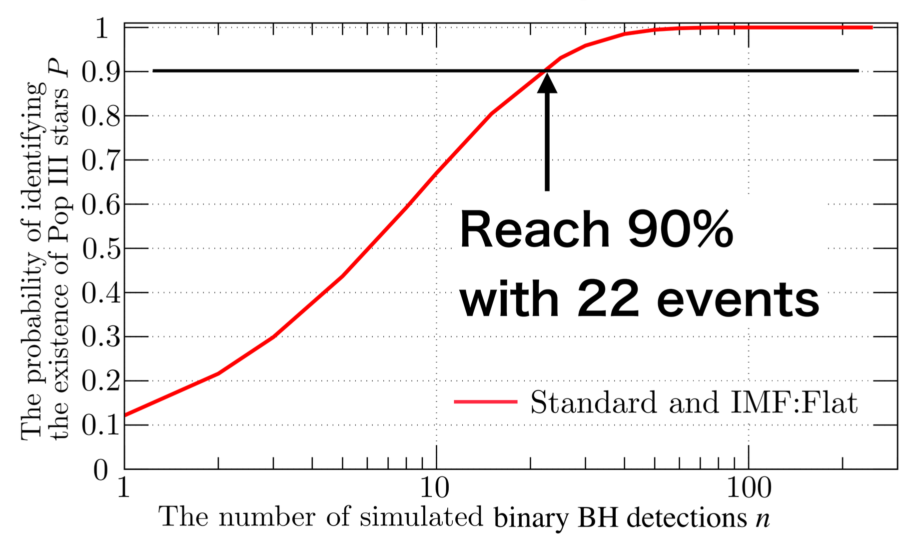

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Fig.3 The probability of identifying the existence of Pop III stars P as a function of the number of simulated binary BH detections n.

Our results depend on merger rates and chirp mass distributions of Pop I/II model and Pop III model. The merger rate depends heavily on *the star formation rate*, *the common envelope parameters*. The chirp mass distribution depends on *the initial mass function*, *binary parameters* and *the metallicity* of stars. In our paper [5], we also performed our simulations using more two examples of Pop I/II models and more two examples of Pop III models. In those models, **the probability is also >90% with O(10) events.**

6. Summary and Acknowledgement

Detection rates of binary BH mergers in KAGRA are calculated as ~30 [/month] for Pop I/II model, and ~5 [/month] for Pop III model.
We calculated the probability of identifying the existence of Pop III binary black holes by likelihood analysis with the redshifted chirp mass distribution from population synthesis.
The probability of identifying the existence of Pop III stars reaches 90% or more with O(10) events.

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