Formation Scenario of SMBHs and Gravitational Wave

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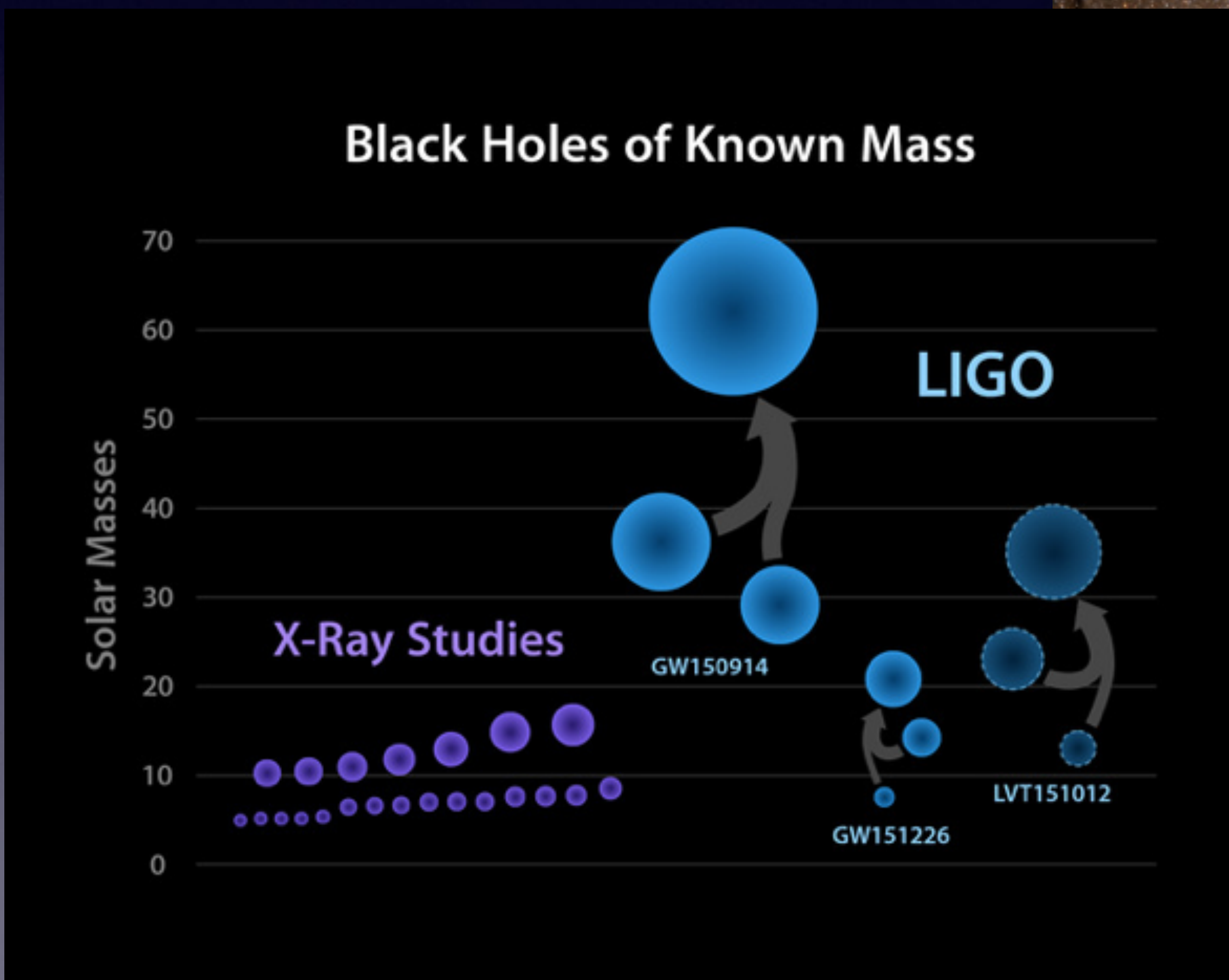
신카이 히사아키

First International Meeting on KAGRA,
@Daejeon, Korea. 2016 June25

BHs!



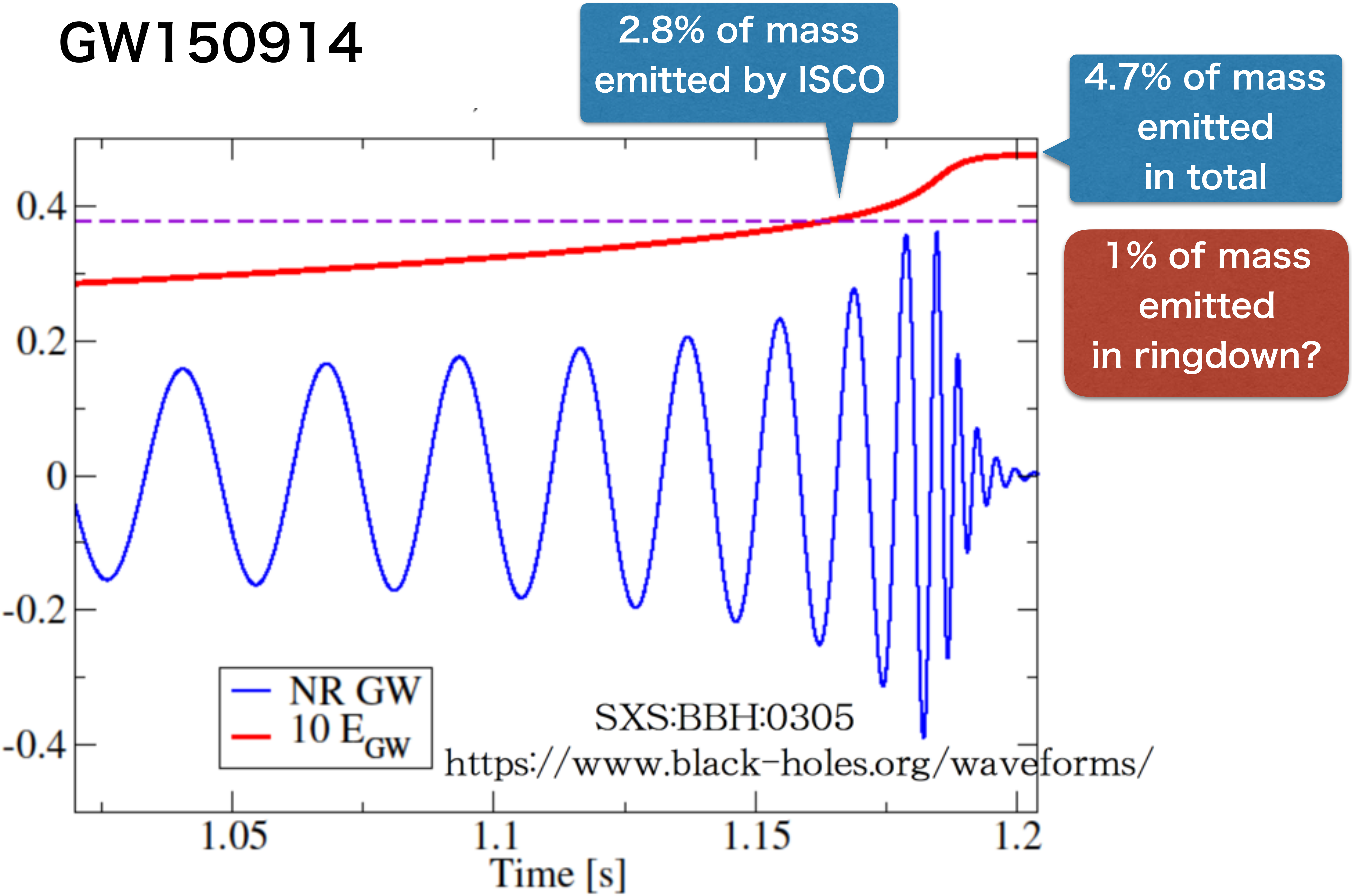
7M+14M=20M

29M+36M=62M

why not more?

https://www.ligo.caltech.edu/system/avm_image_sqls/binaries/57/page/Black_Hole_Mass_Chart.jpg?1465864737

GW150914



Slide copy from Hiroyuki Nakano

BH-BH from Pop III

1505.06962
Kinugawa, Miyamoto, Kanda, Nakamura

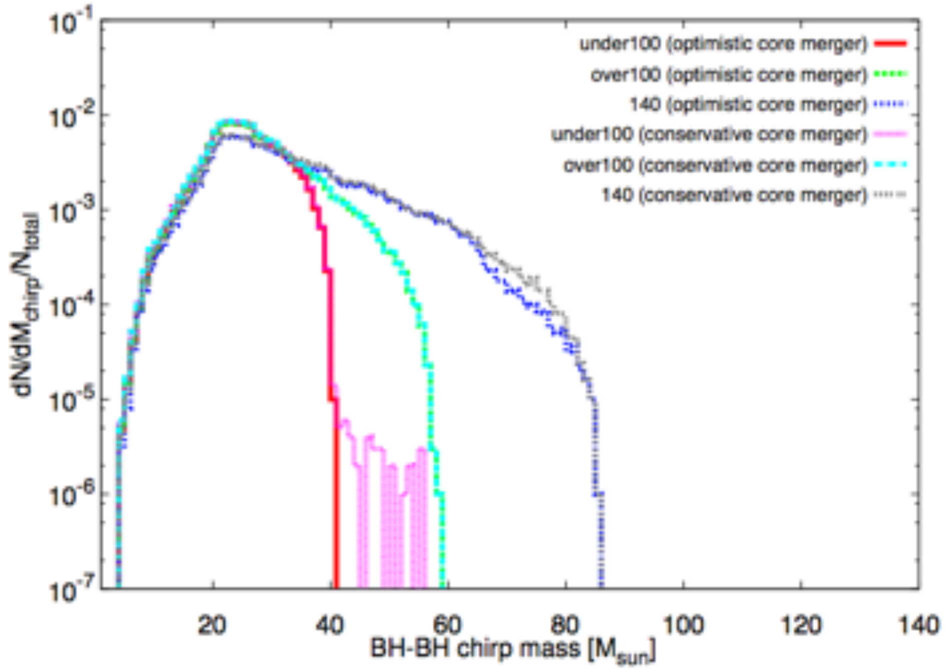


Figure 1. our standard model

Each line is the normalized distribution of the BH-BH chirp mass. The red, green, blue, pink, light blue and grey lines are the under100 case with optimistic core-merger criterion, the over100 case with optimistic core-merger criterion, the 140 case with optimistic core-merger criterion, the under100 case with conservative core-merger criterion, the over100 case with conservative core-merger criterion and the 140 case with conservative core-merger criterion, respectively. $N_{total} = 10^6$ binaries.

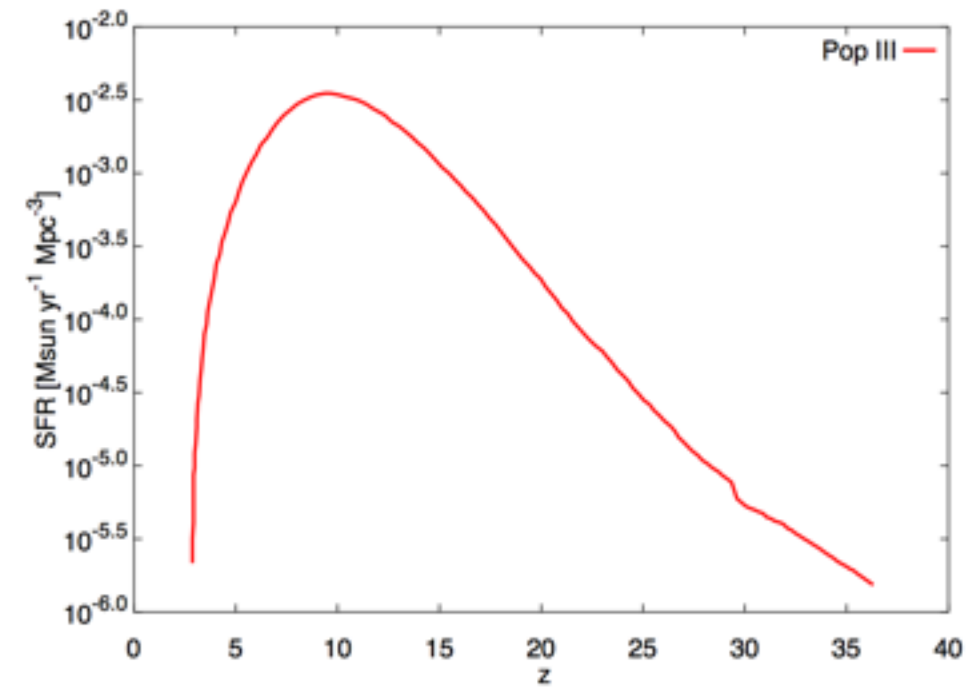


Figure 21. The star formation rate density (comoving) calculated by de Souza et al. (2011). The unit of the rate is $M_\odot$ per comoving volume per proper time. The red line is the the total SFR density of Pop III stars.

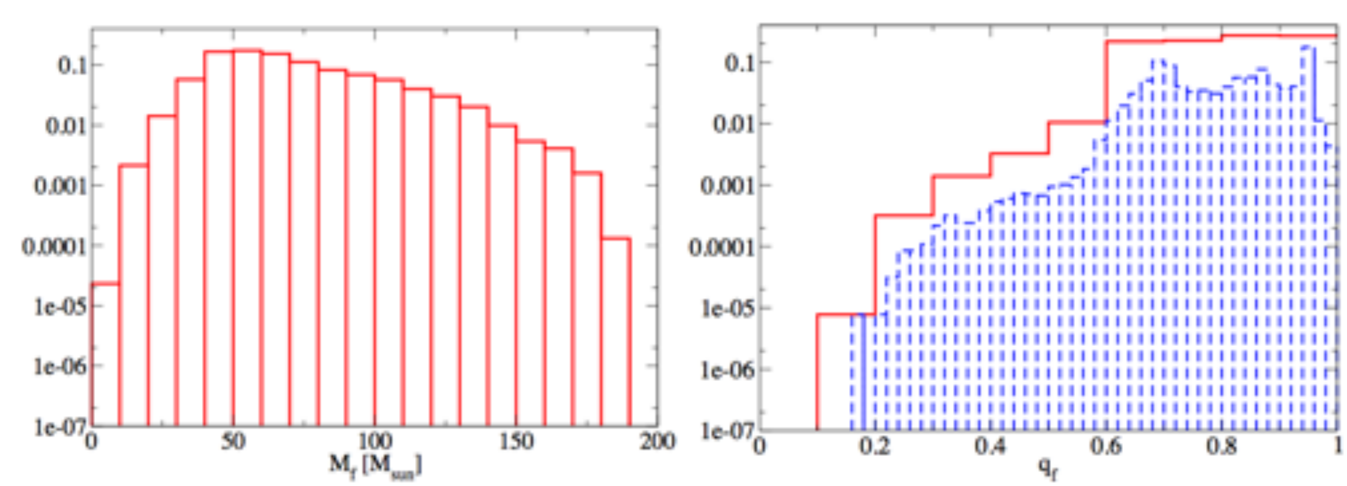
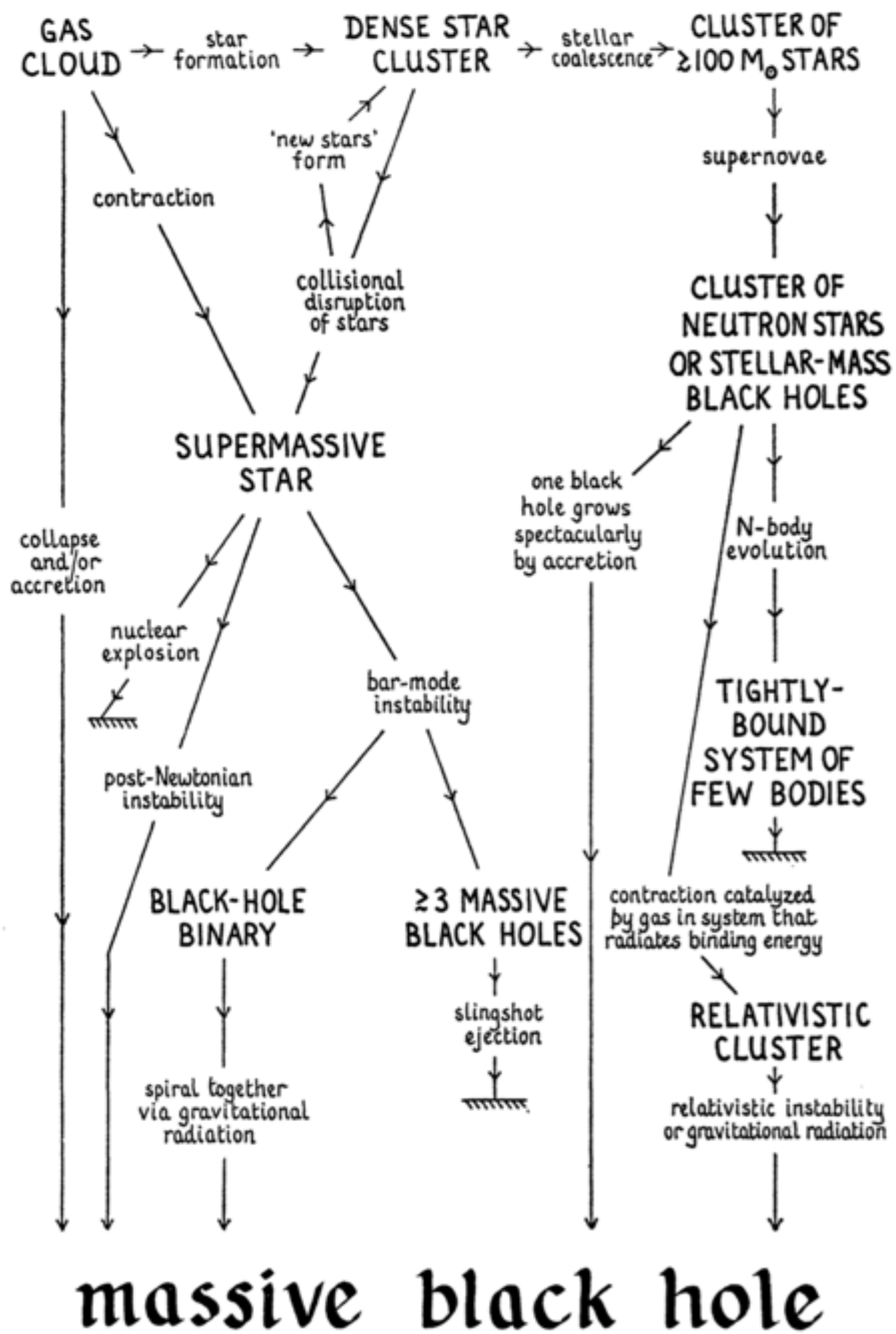
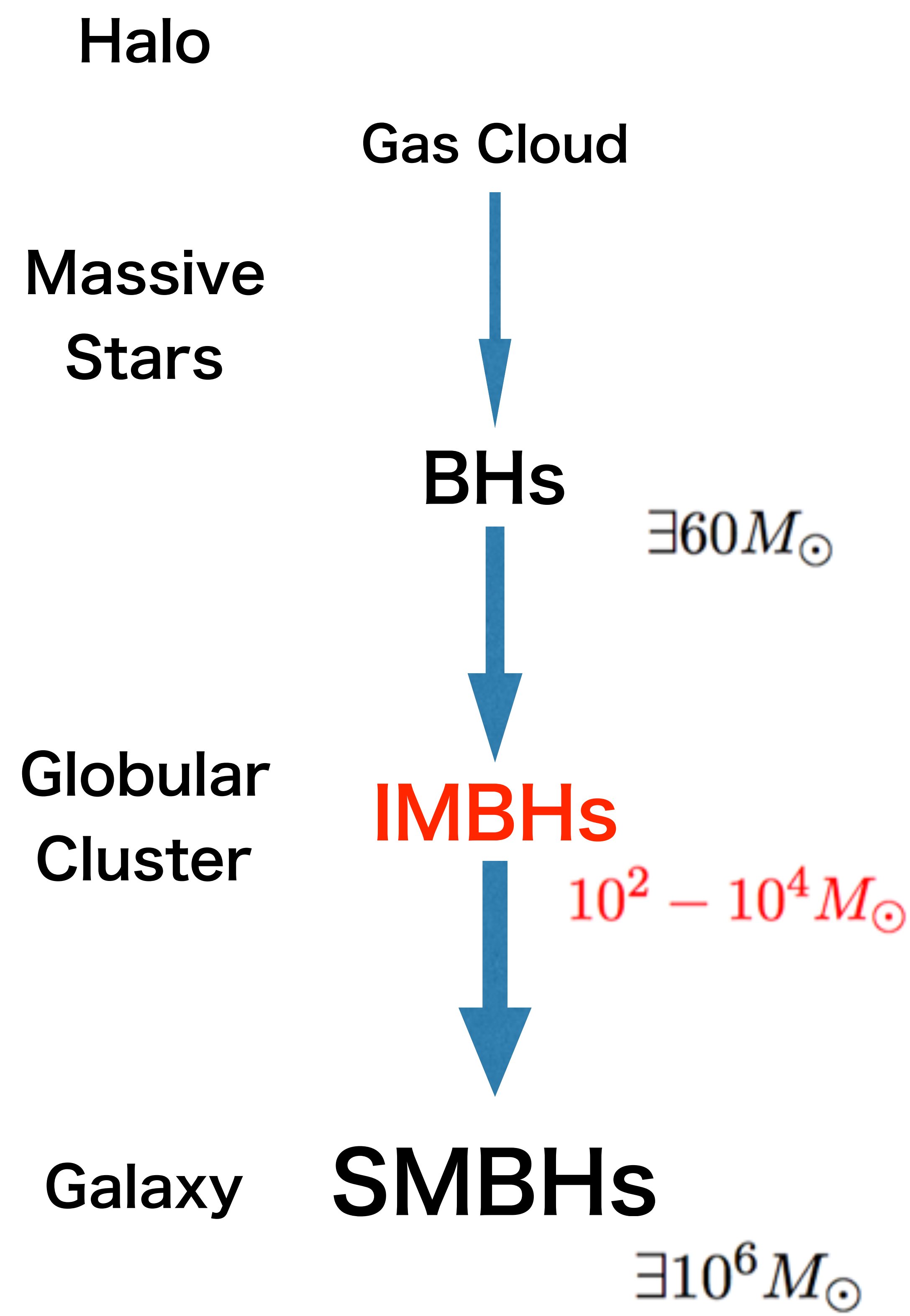


Fig. 4: (Left) The normalized distribution of M_f obtained by binning with $\Delta M_f = 10\,M_\odot$. (Right) The normalized distribution of q_f. The solid red and dashed blue lines are obtained by binning with $\Delta q_f = 0.1$ and 0.02, respectively.

1601.07217
Kinugawa, Nakano, Nakamura



Rees, M.J. 1978. Observatory 98: 210



Starburst galaxy M82 has 1000M BH

Matsushita+, ApJ, 545, L107 (2000)
Matsumoto+, ApJ, 547, L25 (2001)

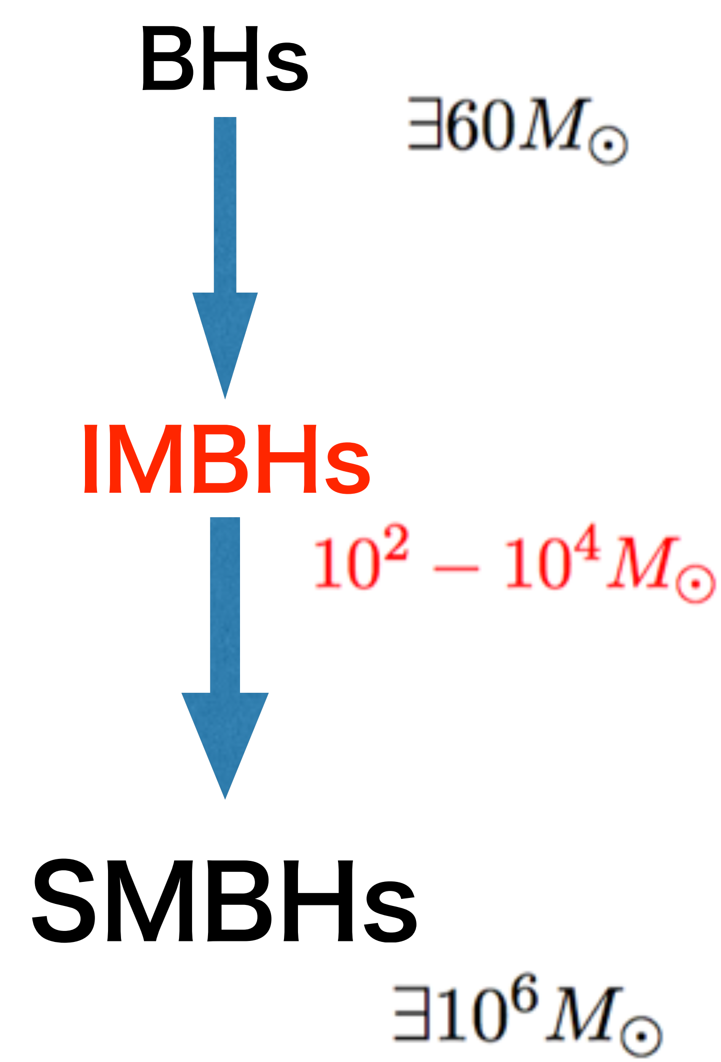
HLX-1 has 20,000M BH!

http://hubblesite.org/newscenter/archive/releases/2012/2012/11/full/

Table 2. The distances and velocity dispersions of galactic globular clusters. Possible masses of IMBHs, if they exit, are obtained from $M-\sigma$ relation [112].

NGC No.	distance (kpc) [63]	vel. disp. σ (km/s) [111]	BH mass ($M_\odot$)
104	4.5	10.0	794.7
362	8.5	6.2	116.3
1851	12.1	11.3	1299
1904	12.9	3.9	18.04
5272	10.4	4.8	41.57
5286	11.0	8.6	433.4
5694	34.7	6.1	108.9
5824	32.0	11.1	1209
5904	7.5	6.5	140.6
5946	10.6	4.0	19.97
6093	10.0	14.5	3539
6266	6.9	15.4	4508
6284	15.3	6.8	168.6
6293	8.8	8.2	357.9
6325	8.0	6.4	132.4
6342	8.6	5.2	57.35
6441	11.7	19.5	11645
6522	7.8	7.3	224.3
6558	7.4	3.5	11.68
6681	9.0	10.0	794.7
7099	8.0	5.8	88.96

Yagi, CQG 29 075005 (2012)
[arXiv:1202.3512]



'Missing link' founded

Ebisuzaki +, ApJ, 562, L19 (2001)

(1)formation of IMBHs by runaway mergers of massive stars in dense star clusters,

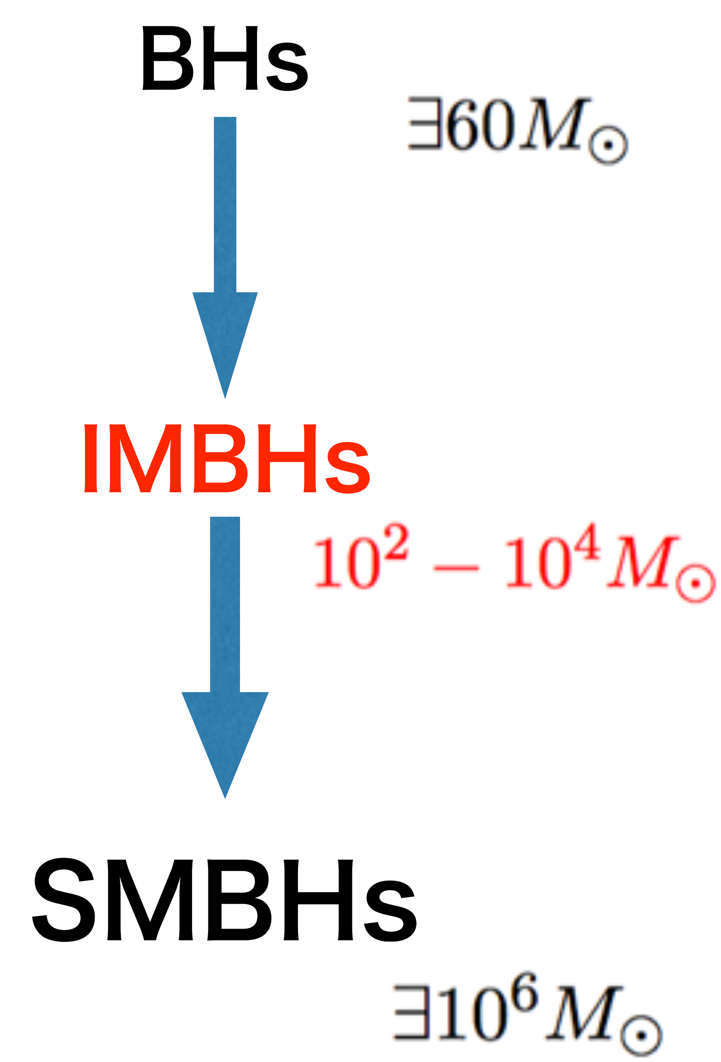
Marchant & Shapiro 1980; Portegies Zwart et al. 1999;
Portegies Zwart & McMillan 2002;
Portegies Zwart et al. 2004;
Holger & Makino 2003

(2) accumulations of IMBHs at the center region of a galaxy due to sinkages of clusters by dynamical friction

Matsubayashi et al. 2007

(3) mergings of IMBHs by multi-body interactions and gravitational radiation.

Iwasawa et. al. 2010



THE ASTROPHYSICAL JOURNAL, 722:1197–1206, 2010 October 20 doi:10.1088/0004-637X/722/2/1197

DETECTION OF IMBHs WITH GROUND-BASED GRAVITATIONAL WAVE OBSERVATORIES: A BIOGRAPHY OF A BINARY OF BLACK HOLES, FROM BIRTH TO DEATH

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Received 2009 January 10; accepted 2010 August 16; published 2010 September 28

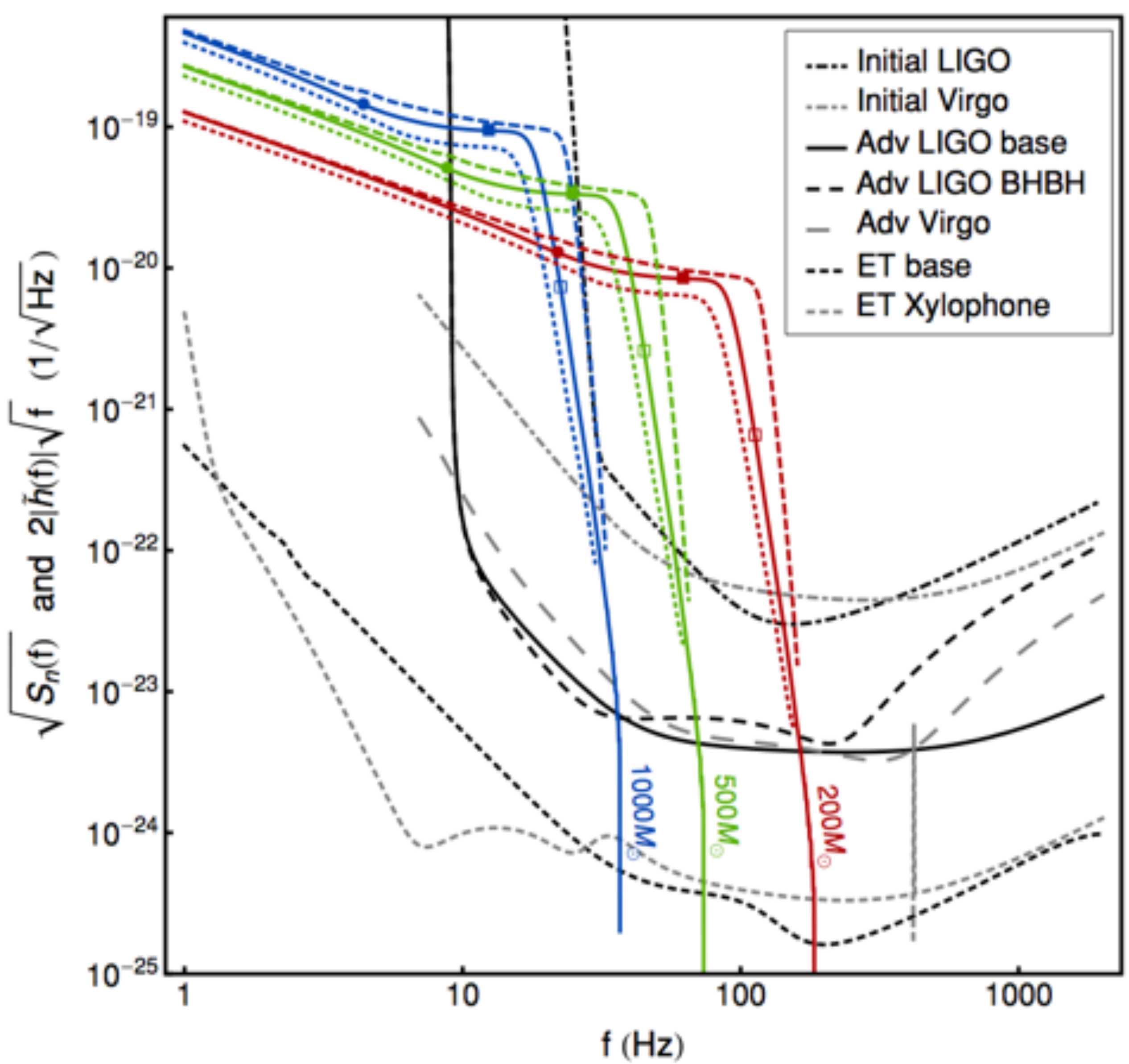
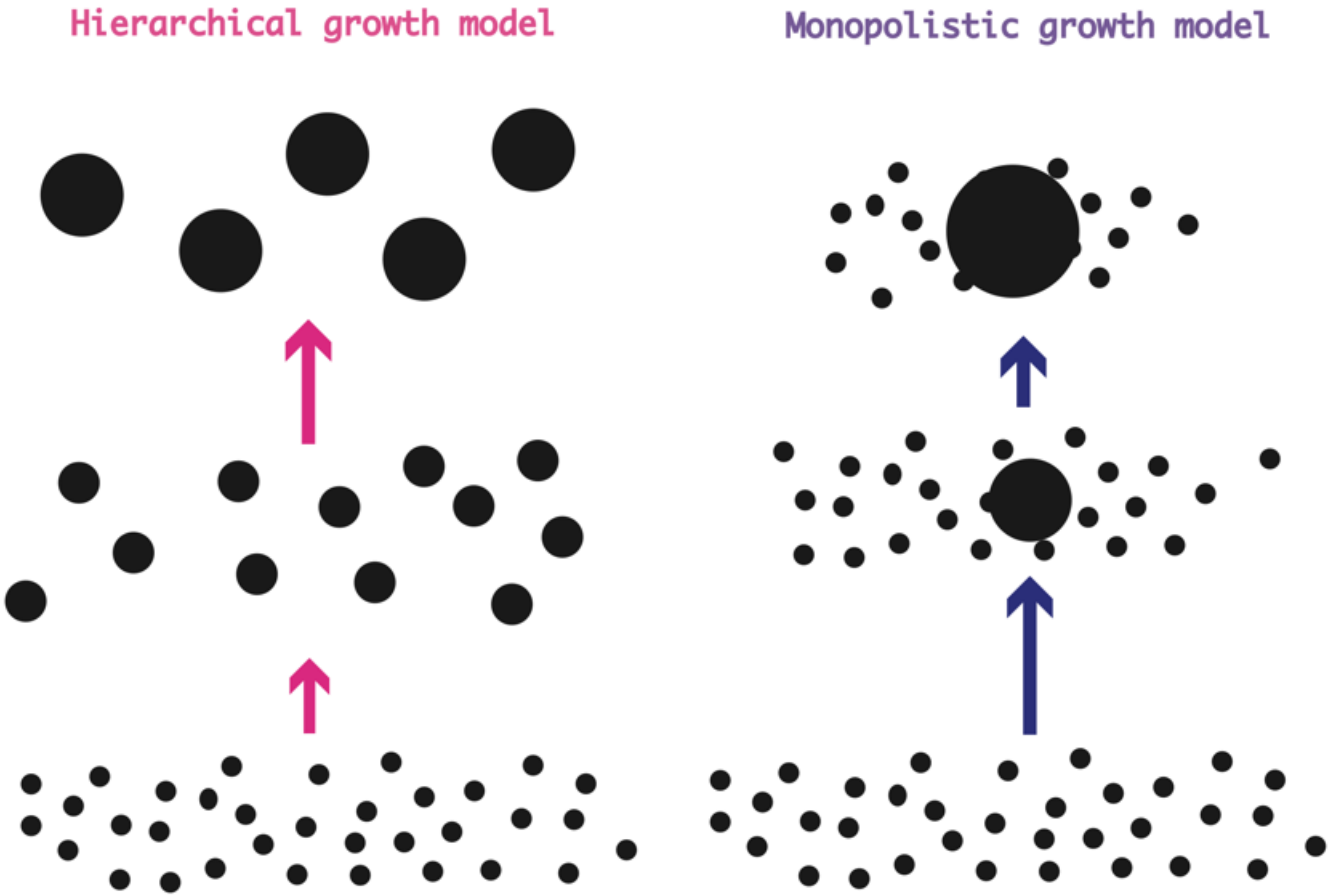


Figure 6. Hybrid waveform for three BBH configurations scaled to various IMBH masses. From top to bottom, we show BBH systems with total mass 1000, 500, and 200 $M_\odot$ in blue, green, and red, respectively. Solid lines correspond to the equal-mass, non-spinning configuration (1), dashed lines to the equal-mass, $\chi = 0.75$ configuration (2), and dotted lines to the non-spinning, $q = 3$ configuration (3). The sources are optimally oriented and placed at 100 Mpc of the detectors. The symbols on top of configuration (1) mark various stages of the BBH evolution: solid circles represent the ISCO frequency, squares the light ring frequency, and open squares the Lorentzian ringdown frequency (corresponding to 1.2 times the fundamental ringdown frequency f_{FRD}), when the BBH system has merged and the final BH is ringing down. Currently operating and planned ground-based detectors are drawn as well: plotted are the sensitivity curves of initial LIGO and Virgo, two possible configurations for Advanced LIGO (zero detuning and 30–30 $M_\odot$ BBH optimized), Advanced Virgo, and the proposed ET in both its broadband and xylophone configurations.


Hierarchical growth model
Monopolistic growth model

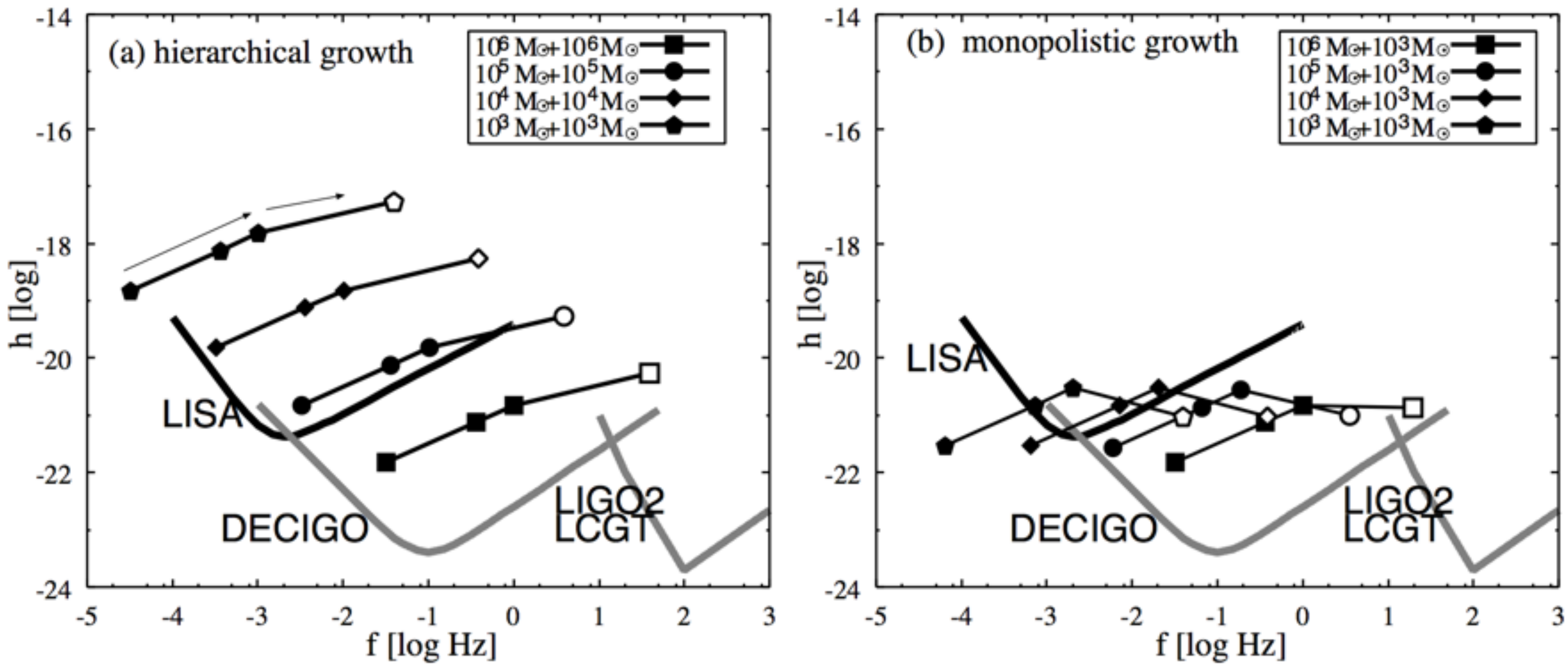


Fig. 1.— Expected gravitational radiation amplitude from merging IMBHs of (a) hierarchical growth model, and (b) monopolistic growth model. We plotted both the inspiral phase ($f_{\rm insp}, h_{\rm insp}$), [eqs. (2) and (3)], and the ringdown phase ($f_{\rm QNM}, h_{\rm coal}$), [eqs. (4) and (6)], for various mass combinations. The open and closed circle and square in the inspiral phase are of $a = 50, 10$ and $5\ R_{grav}$. The final burst frequency, $f_{\rm QNM}$, depends on the efficiency, ϵ, which we fix $\epsilon \simeq 10^{-2}$ for plots. Lines are the sensitivity of the future detectors; LISA, DECIGO, LIGO 2, and LCGT, taken from Fig. 1 in Seto et al. (2001). The data are evaluated at the distance $R = 4$ Gpc.

Matsubayashi, HS, Ebisuzaki, ApJ 614 (2004) 864

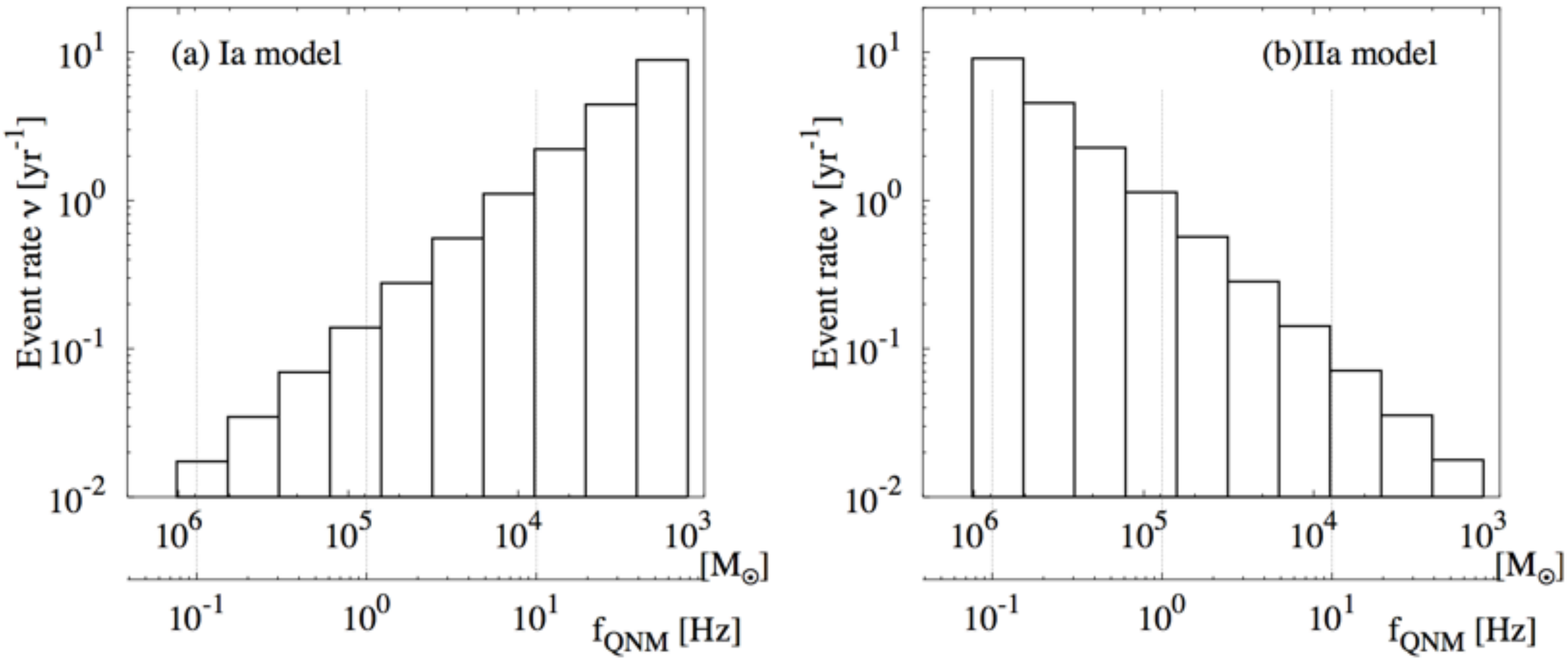


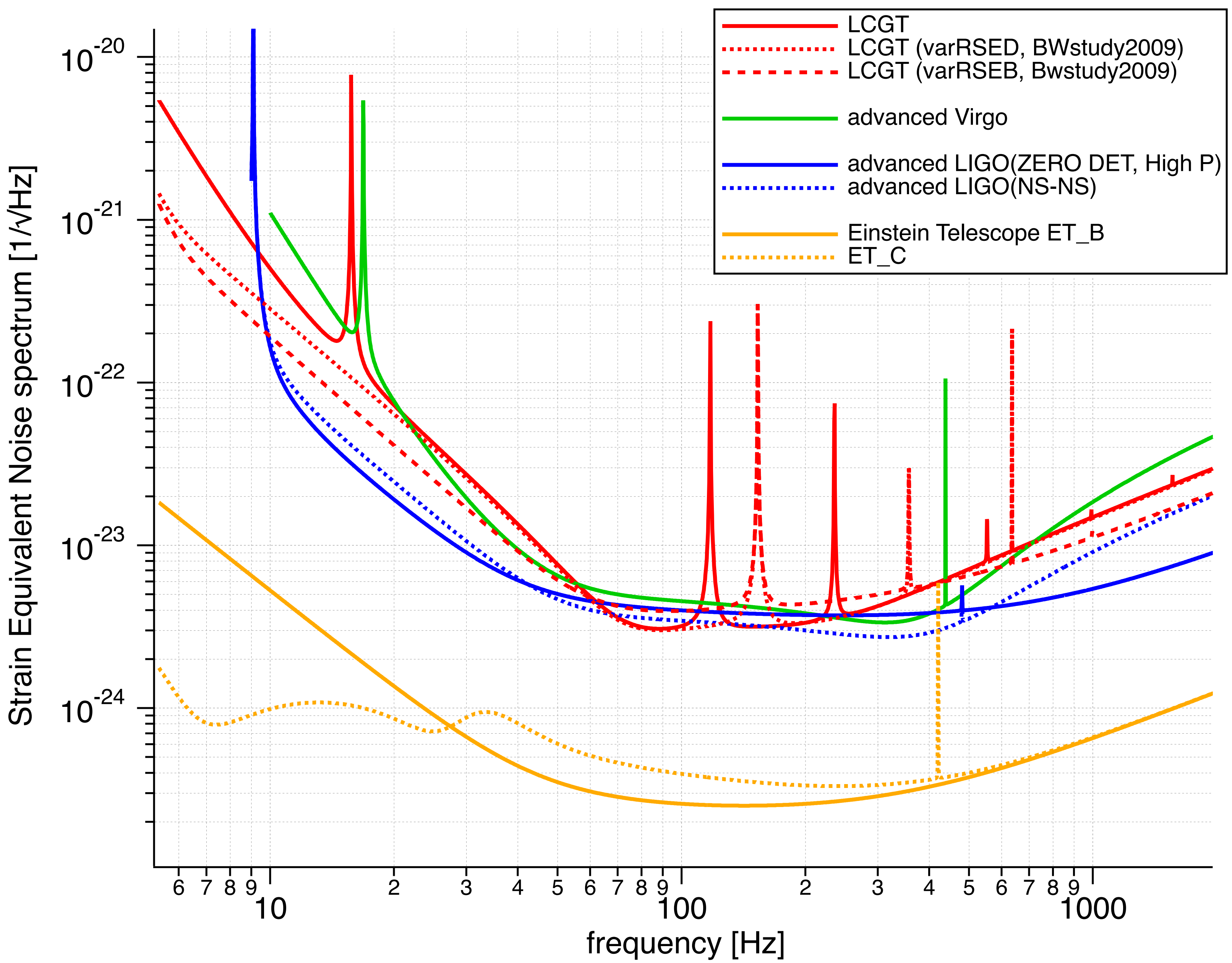
Fig. 2.— Event numbers of mergers starting from a thousand of $10^3 M_\odot$ IMBHs. The vertical axis is the event rate $\nu[\mathrm{yr}^{-1}]$, eqs. (12) and (14). The horizontal axis is the mass of the post-merger BH, M_T, which is also interpreted in the final gravitational radiation frequency $f_{\rm QNM}$. Fig. (a) and (b) are for the hierarchical growth model and for the monopolistic growth model, respectively. Both plots are for the homogeneous distribution model, while we just multiply three for each event rate for the thin-shell galaxy distribution model. If a SMBH grows up hierarchically, then the bursts of gravitational radiation appear in higher frequency region. In the monopolistic model, the bursts appear in lower frequency region. We fix the increasing-mass rate, α, as unity for the plots.

Matsubayashi, HS, Ebisuzaki, ApJ 614 (2004) 864

BH quasi-normal ringing frequency (spin=0)

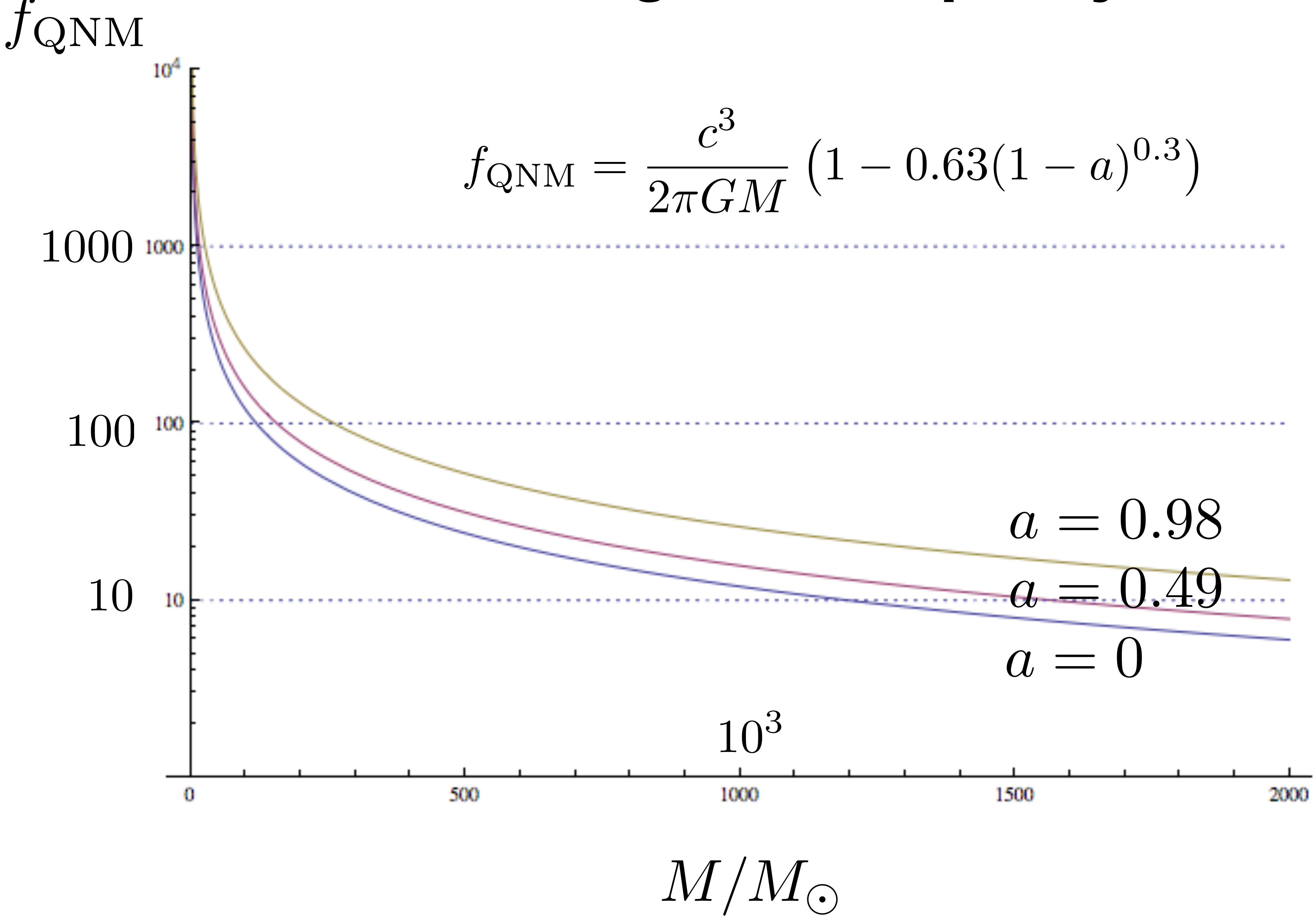
$$f_{\rm QNM} \approx \frac{lc^3}{\sqrt{27}GM_T} \sim 39.1 \left(\frac{2\times10^3\ M_\odot}{M_T} \right)\ {\rm Hz}, \qquad (4)$$

Mtotal	f_QNM
1	78200 Hz
10	7820 Hz
100	782 Hz
1000	78.2 Hz
10000	7.82 Hz



Kagra(LCGT) designed strain (2013/3)

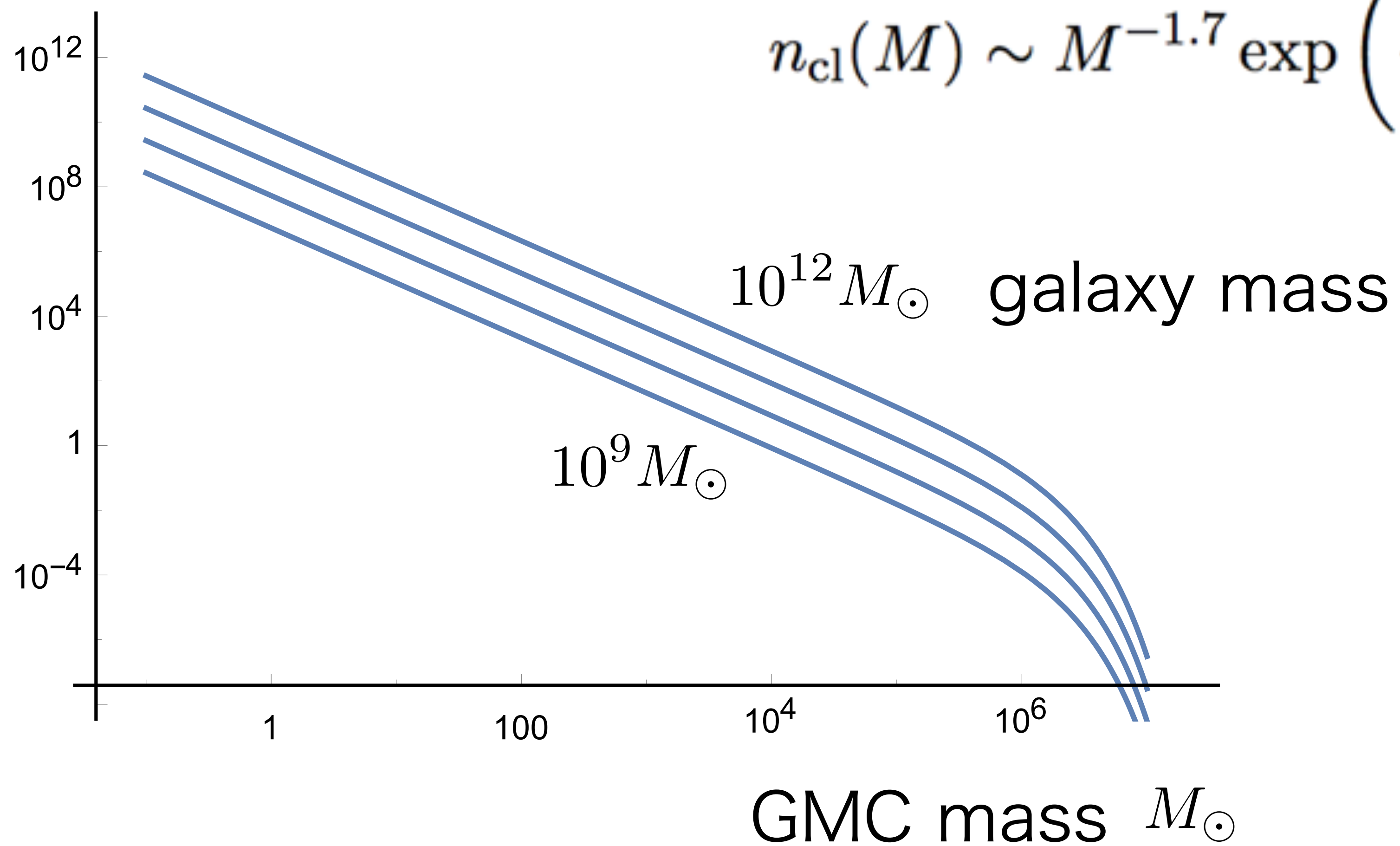
Black-Hole Ringdown frequency



How many BHs in a Galaxy?

Mass Function of Giant Molecular Clouds

$$n_{\rm cl}(M) \sim M^{-1.7} \exp\left(-\frac{M}{M_{\rm cut}}\right), \qquad M_{\rm cut} = 10^6 M_\odot$$



The Formation and Destruction of Molecular Clouds and Galactic Star Formation

An Origin for The Cloud Mass Function and Star Formation Efficiency

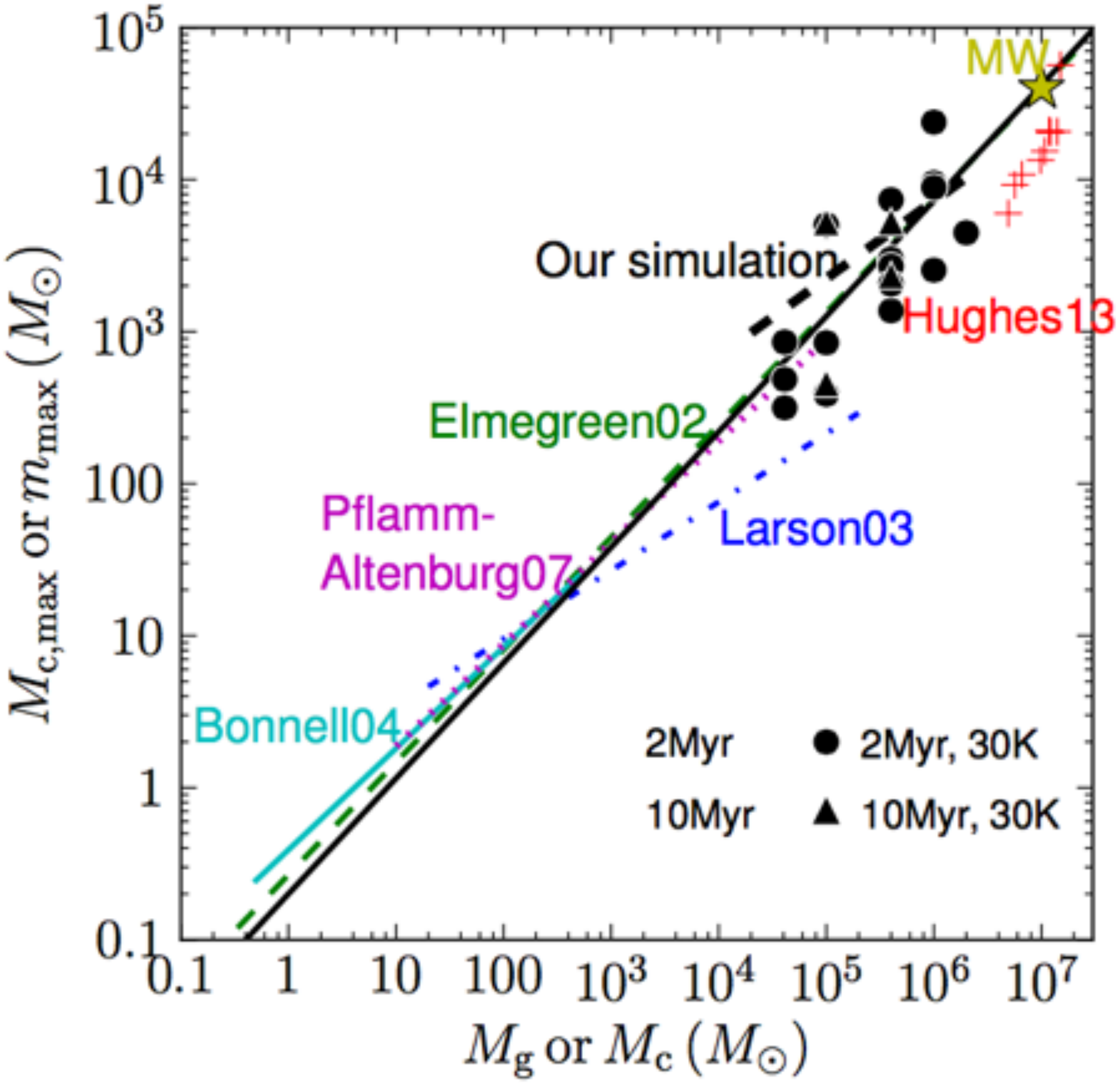
Shu-ichiro Inutsuka[1], Tsuyoshi Inoue,[2], Kazunari Iwasaki[1,3], and Takashi Hosokawa[4]

A&A 580, A49 (2015) [arXiv:1505.04696]

How many BHs in a Galaxy?

Molecular Clouds

Maximum Core



The initial mass function of star clusters that form in turbulent molecular clouds

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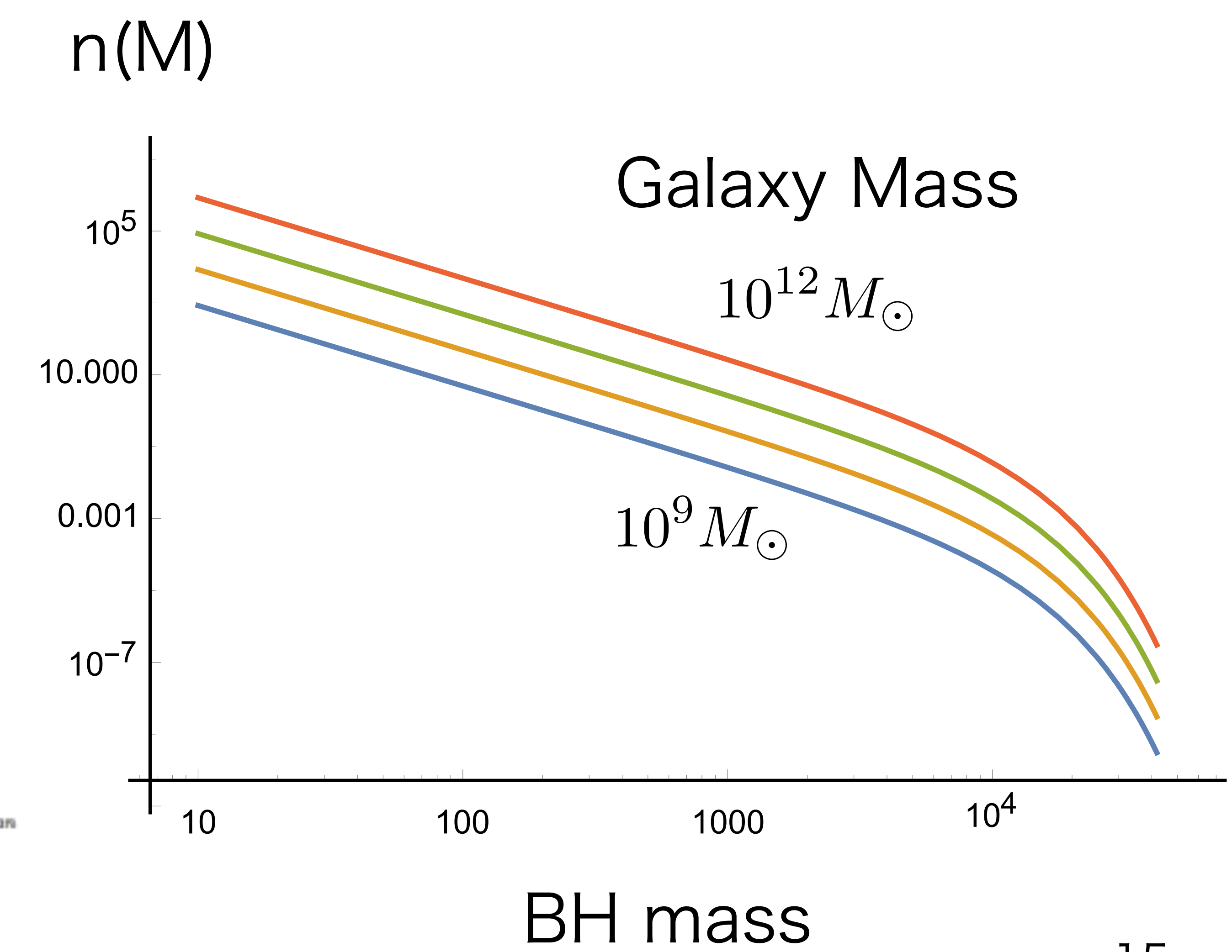
[2] Leiden Observatory, Leiden University, NL-2300RA Leiden, The Netherlands

1309.1223v3

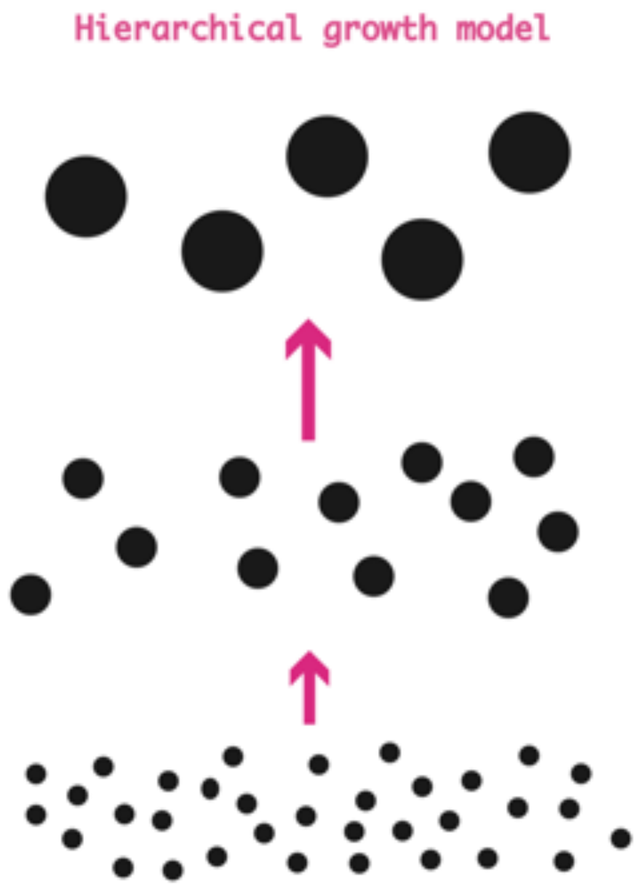
$$M_{c,\max} = 0.20 M_c^{0.76}$$

Building Block BH

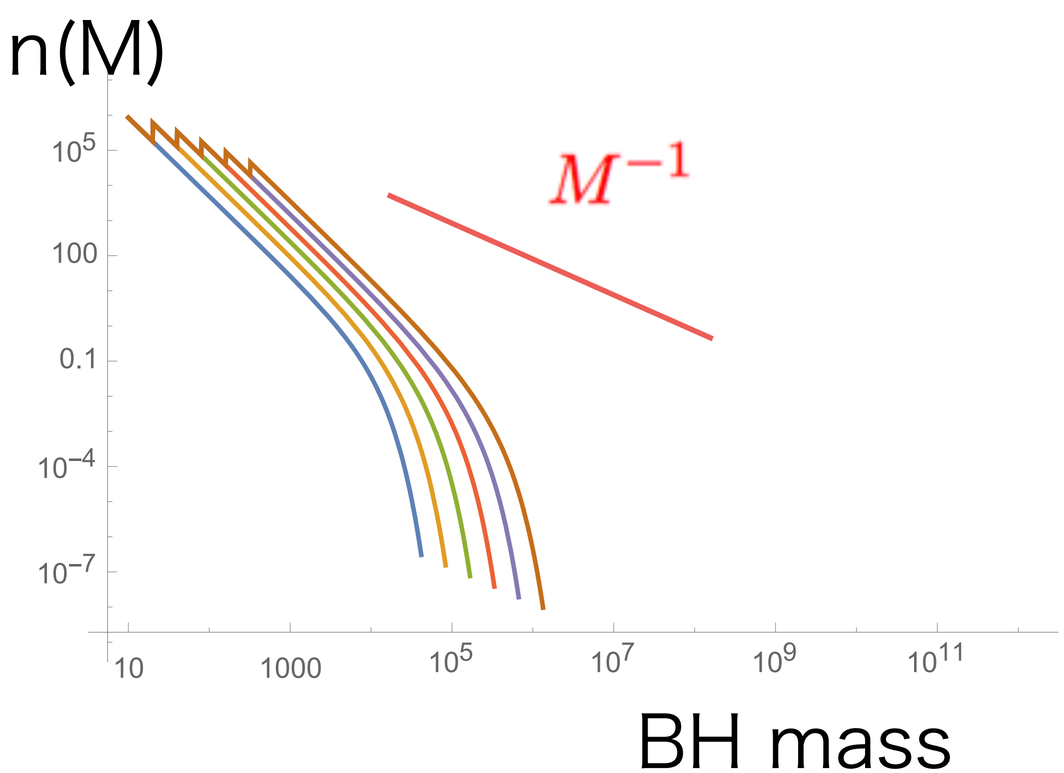


How many BHs in a Galaxy?

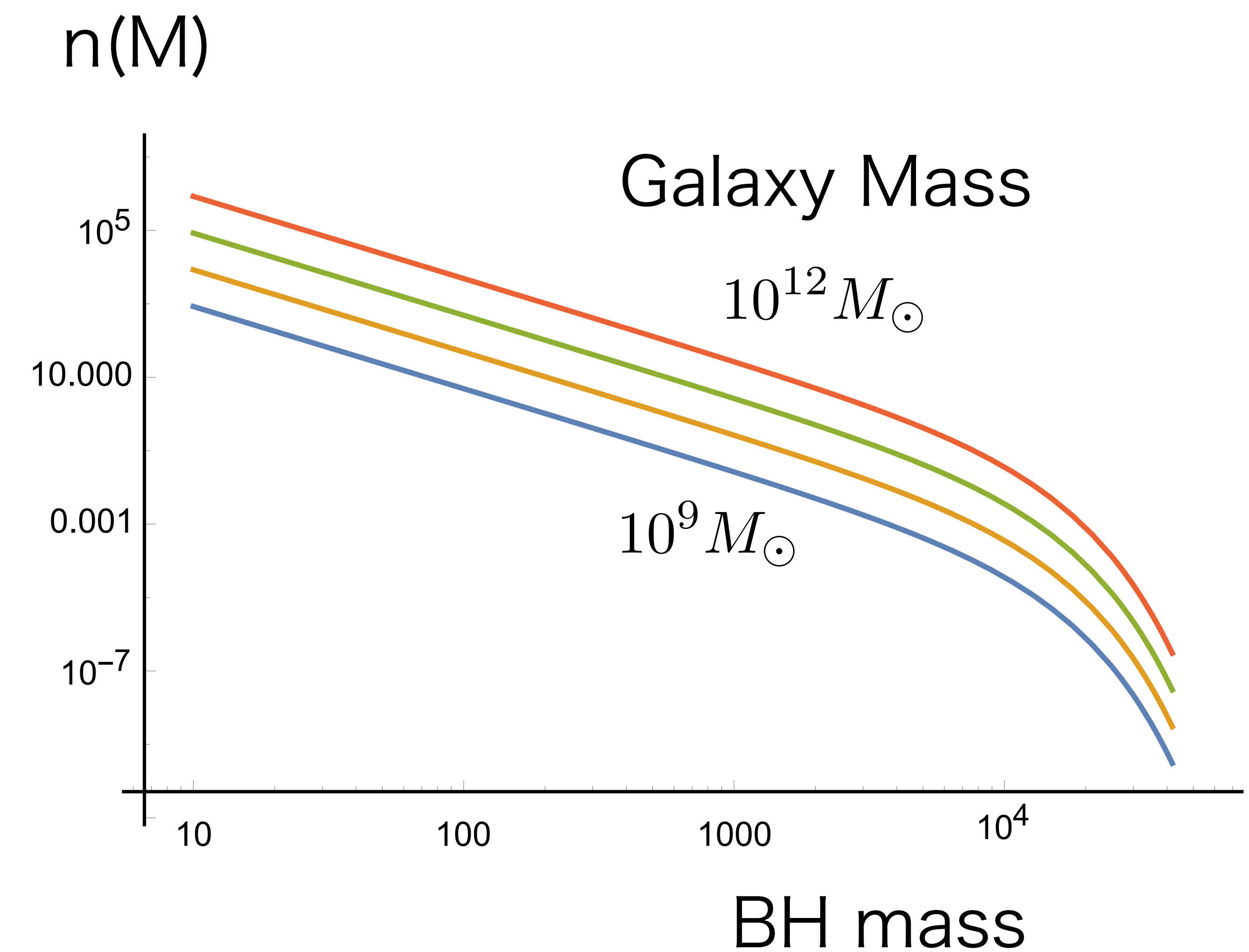
Count BHs to form a SMBH



$$
\begin{aligned}
M_{k+1} &= 2M_k \\
N_{k+1} &= N_k/2
\end{aligned}
$$



Building Block BH



How many Galaxies in the Universe?

Count BHs to form a SMBH

$$M_{\rm SMBH} = 2\times10^{-4} M_{\rm galaxy} = 10^{-3} M_{\rm bulge}$$

(sub-)Galaxy
from Halo model

Mon. Not. R. Astron. Soc. 371, 1173–1187 (2006) doi:10

The non-parametric model for linking galaxy luminosity with halo/subhalo mass

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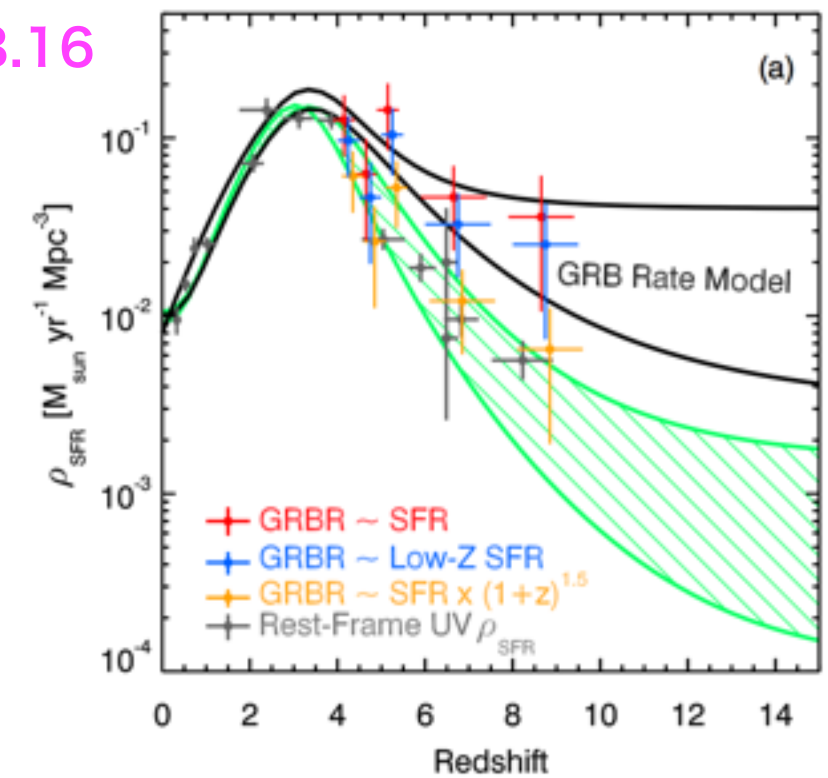
[2] Princeton University Observatory, Princeton University, Princeton, NJ 08544, USA

Star Formation Rate

peak z=3.16



The Astrophysical Journal, 744:95 (13pp), 2012 January 10 doi:10.1088/0004-637X/744/2/95

CONNECTING THE GAMMA RAY BURST RATE AND THE COSMIC STAR FORMATION HISTORY: IMPLICATIONS FOR REIONIZATION AND GALAXY EVOLUTION

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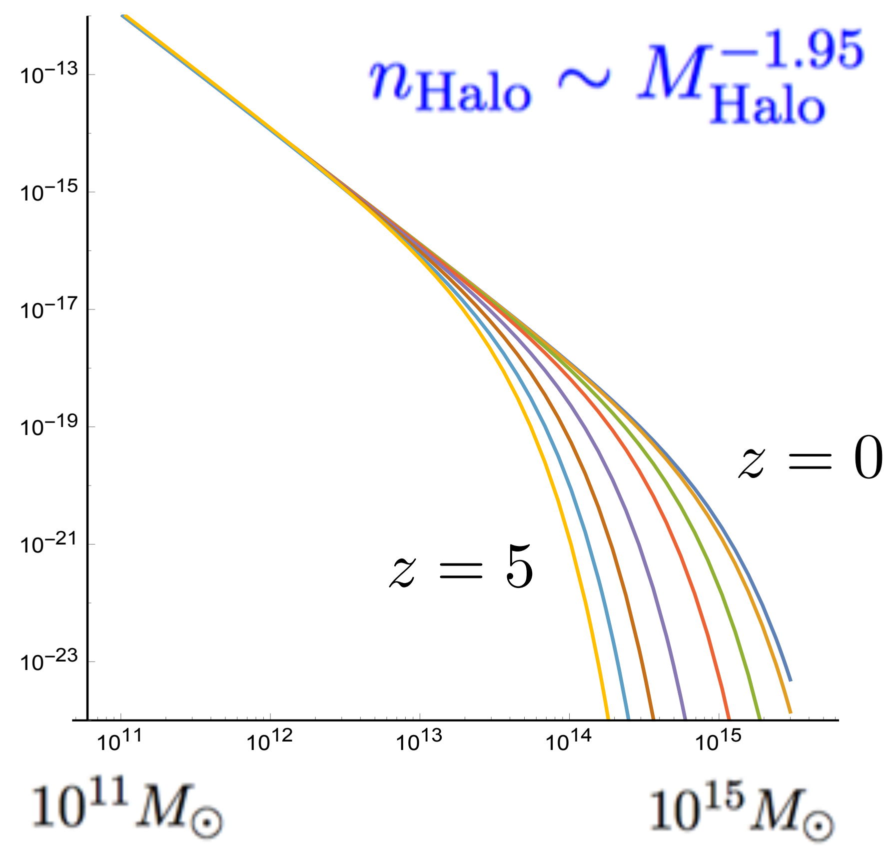
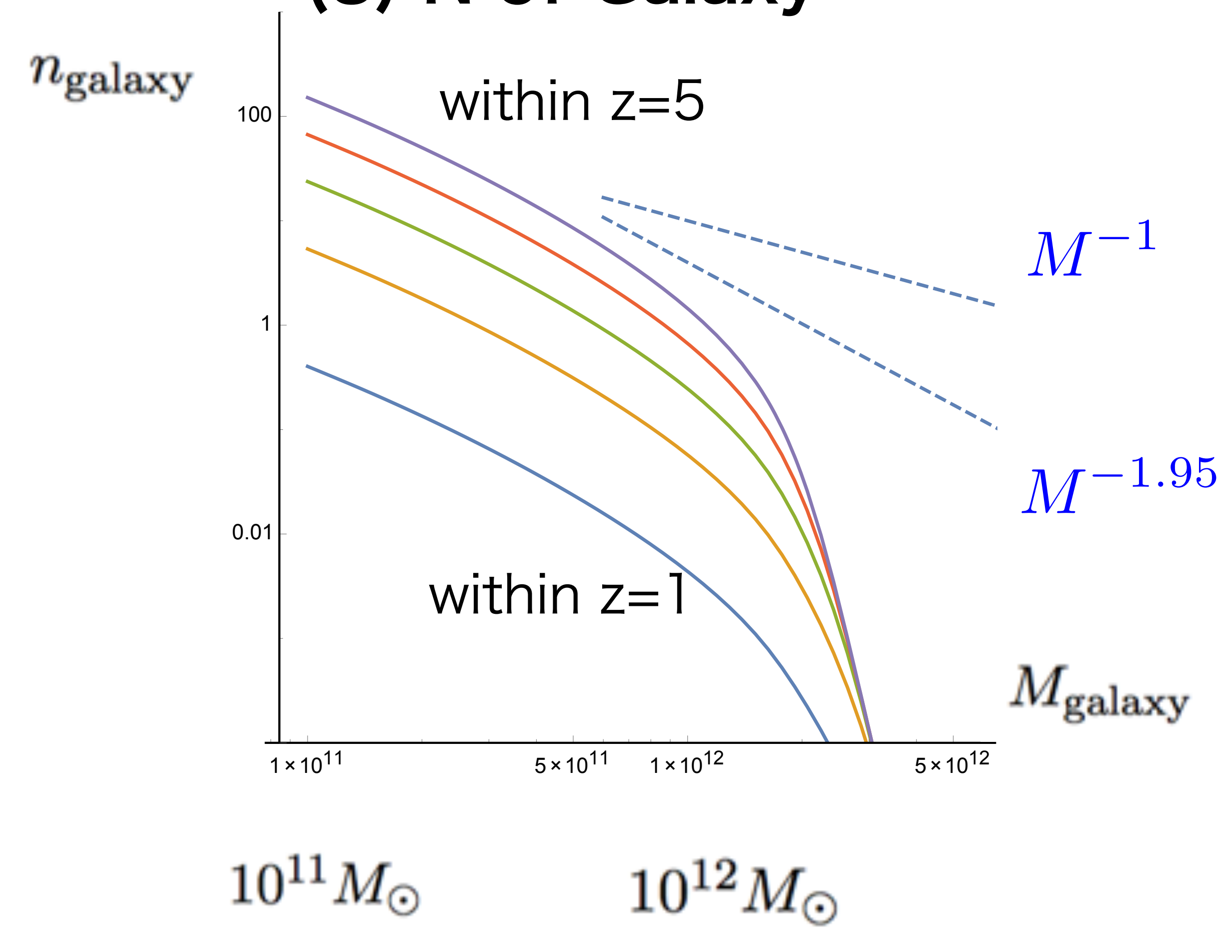
Received 2011 September 5; accepted 2011 November 18; published 2011 December 19

How many Galaxies in the Universe?

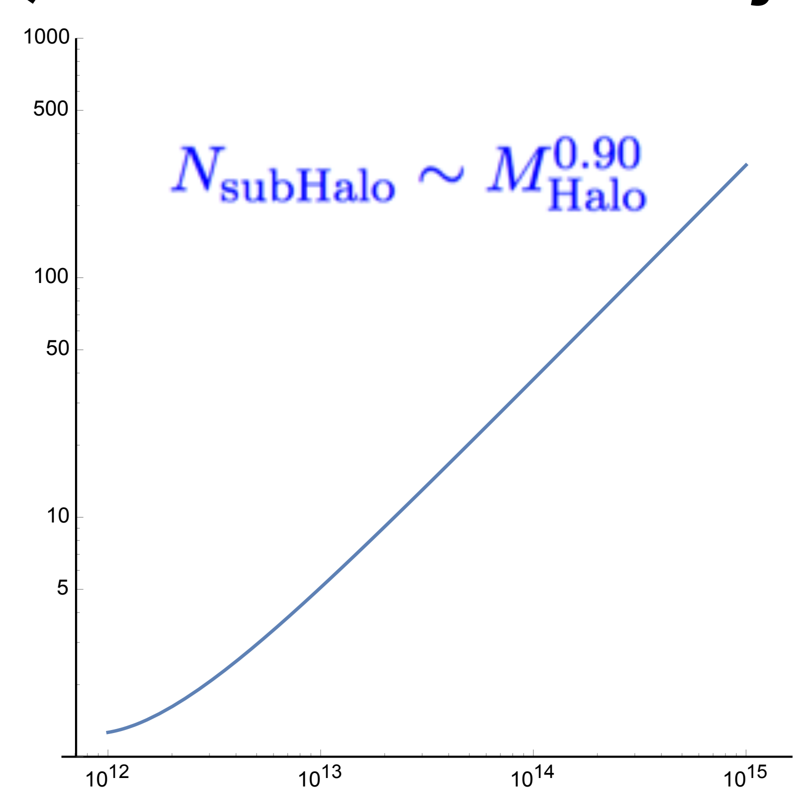
(1) Halo number density

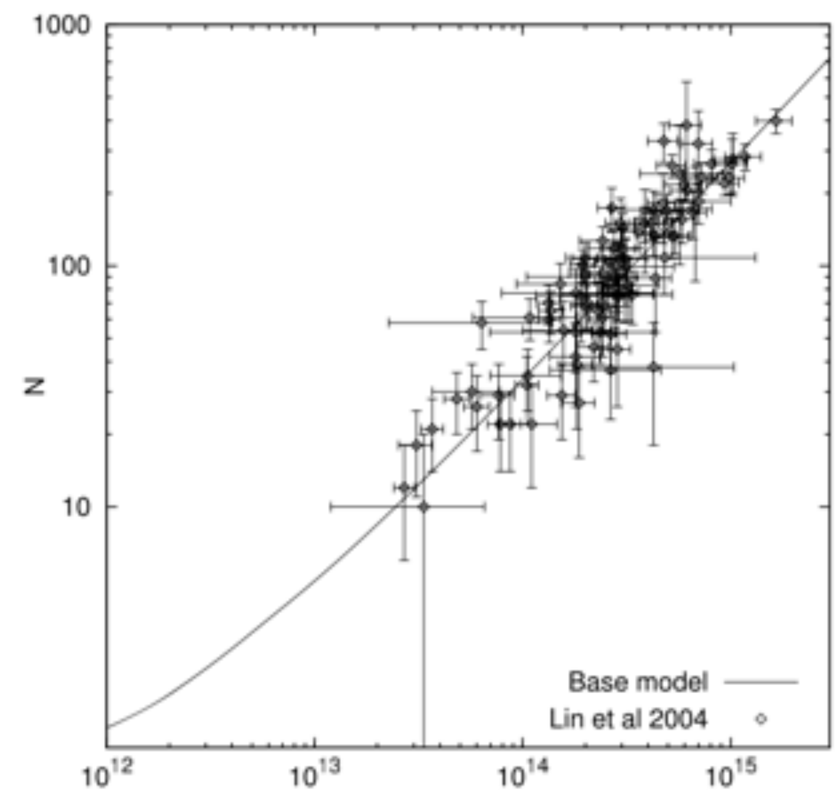


(3) N of Galaxy



(2) N of seeds of Galaxy (subHalo)





Mon. Not. R. Astron. Soc. 371, 1173–1187 (2006)

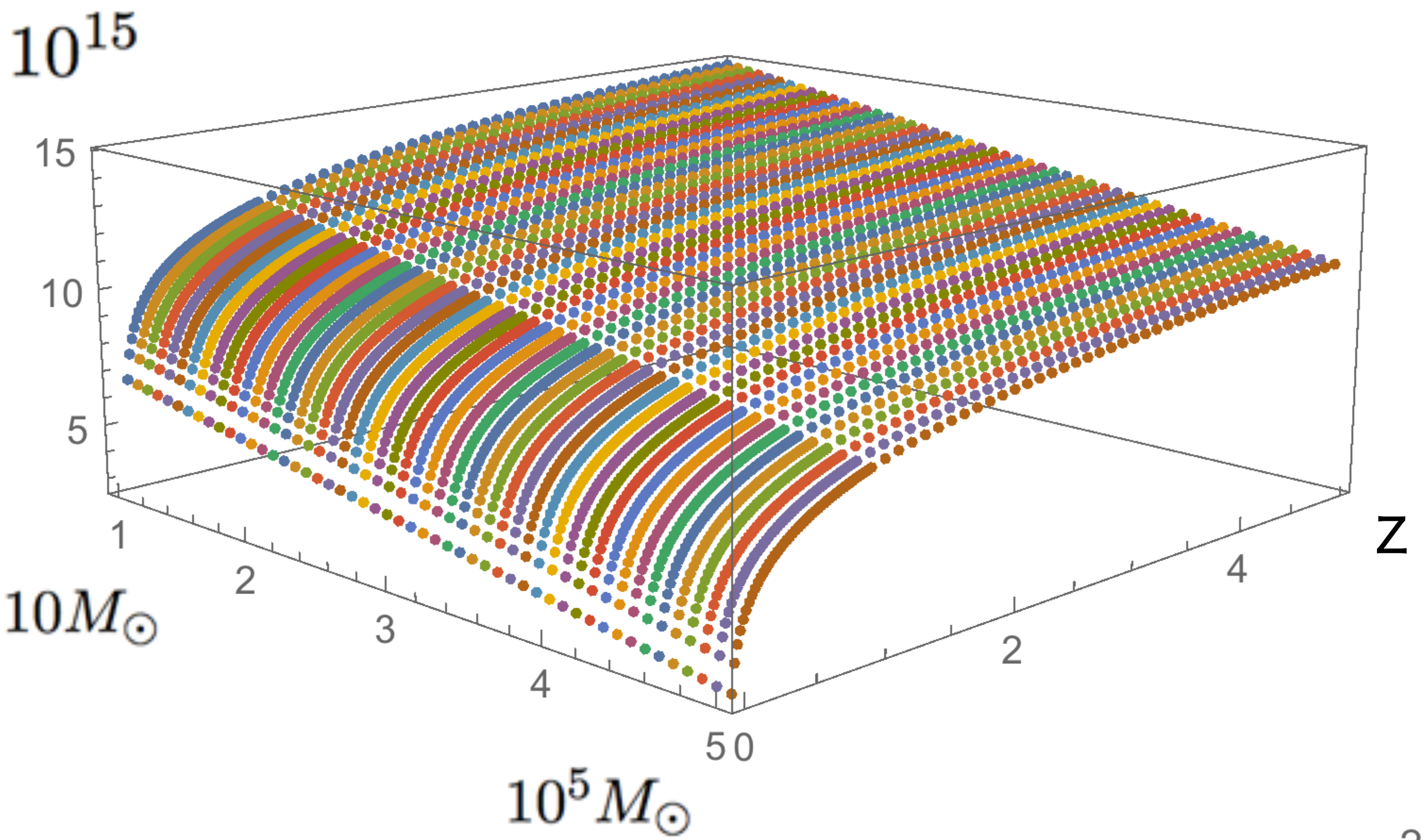
The non-parametric model for li
with halo/subhalo mass

A. Vale[1★] and J. P. Ostriker[1,2]
[1]Institute of Astronomy, University of Cambridge, Madingley Road, C
[2]Princeton University Observatory, Princeton University, Princeton,

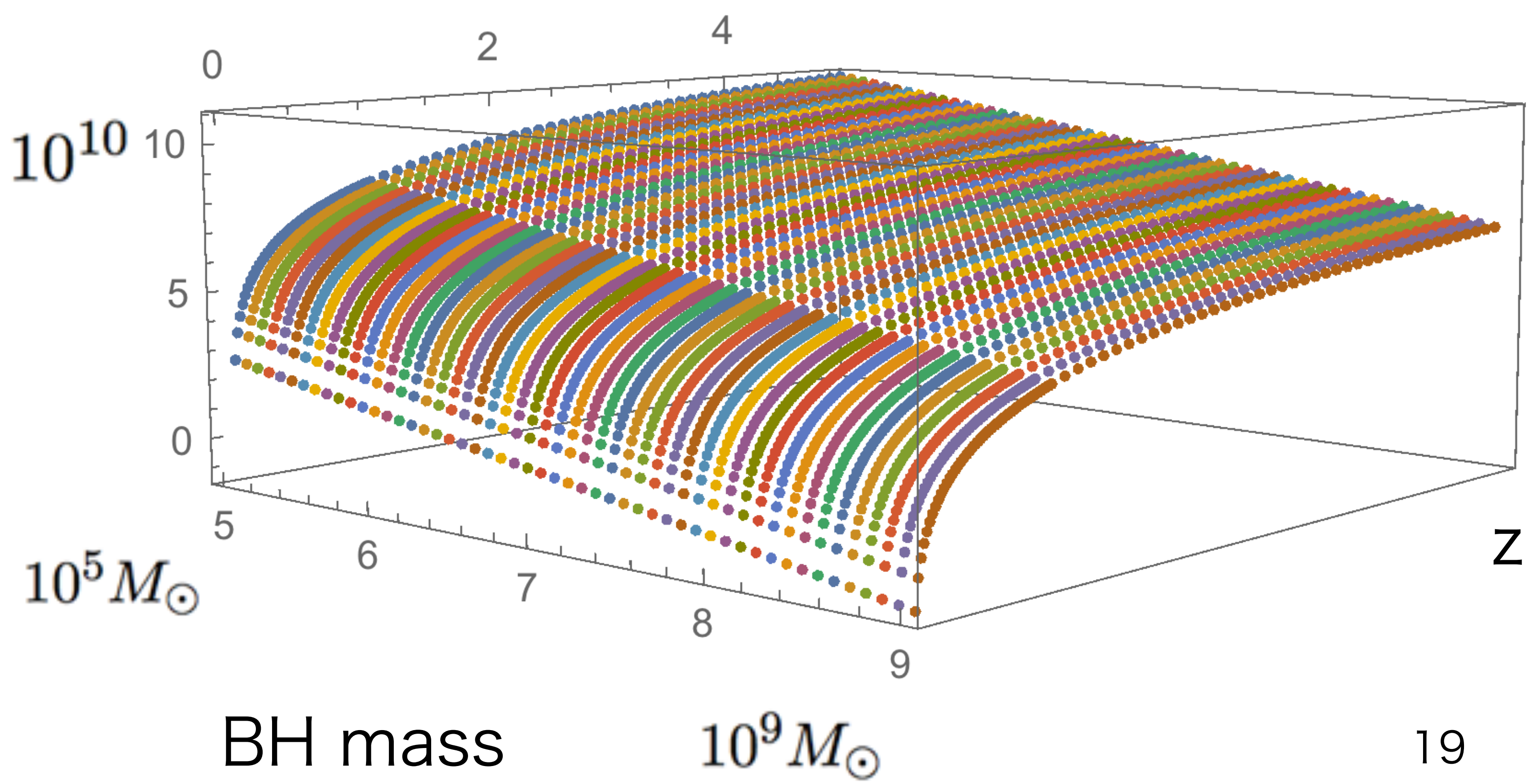
How many BH mergers in the Universe?

in Standard Cosmology

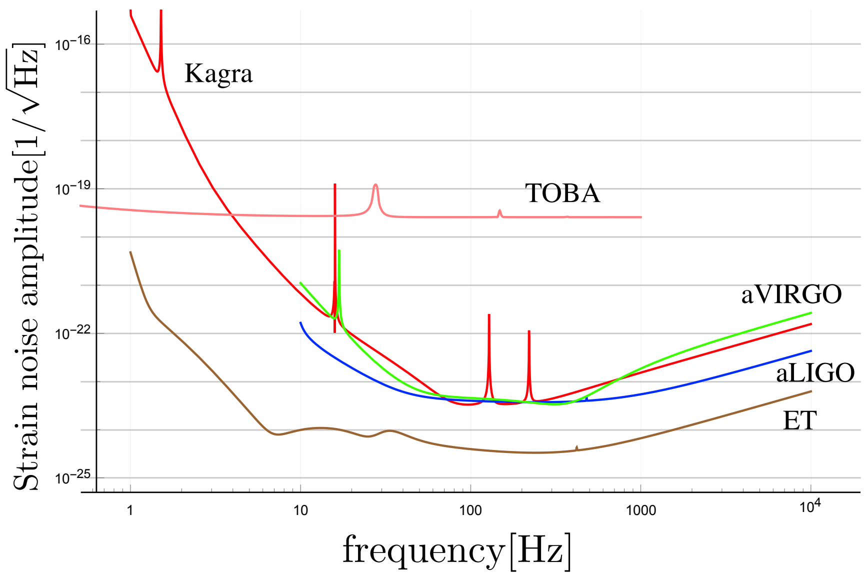
$$N_{\rm merger}(z)/{\rm Vol}(z) = {\rm Event\ Rate}[1/{\rm yr}]$$



BH mass



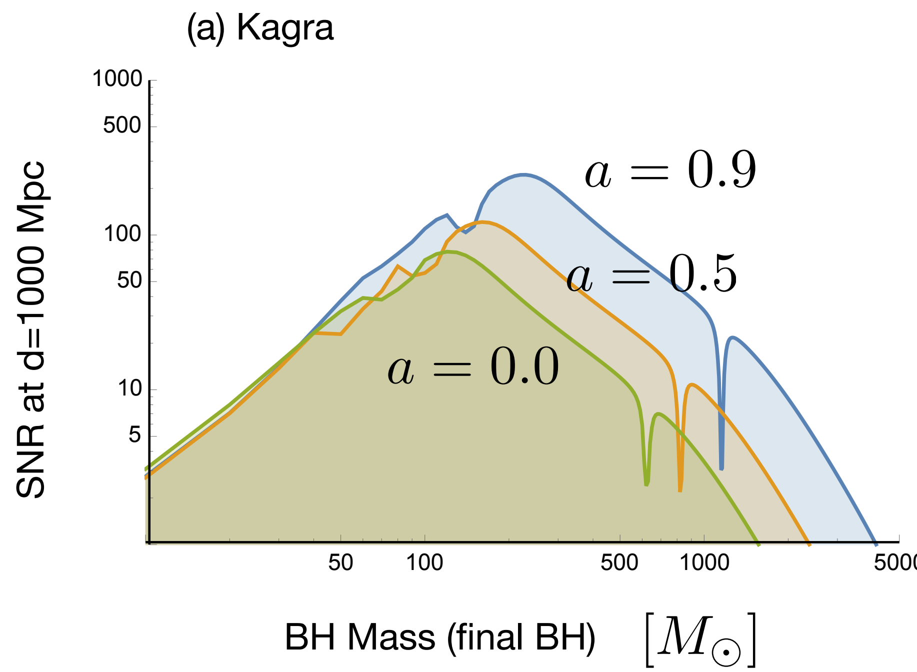
Detectable Distances at bKAGRA



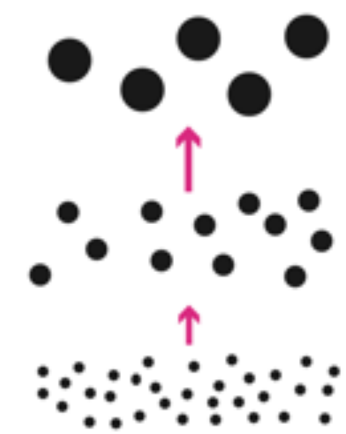
(1) mass distribution

(2) $$\langle \rho^2 \rangle = \left(\frac{S}{N}\right)^2 = \frac{1}{20\pi^2} \frac{(1+z)Q\mathcal{A}^2}{f_{\rm qnr} S_h[f_{\rm qnr}/(1+z)]} \left[\frac{(1+z)M}{D(z)}\right]^2 \left[\frac{4\mu}{M}\right]^2$$

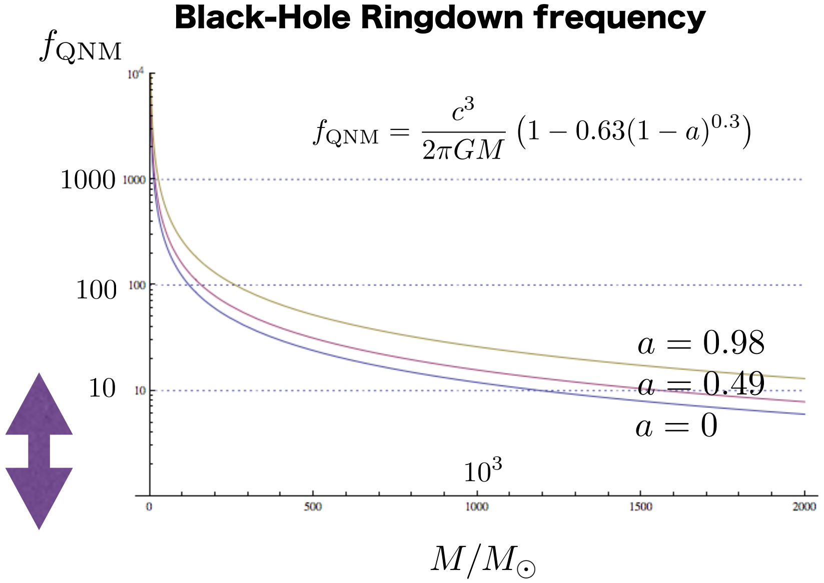
(3) Ringdown only : 1% of total mass emission

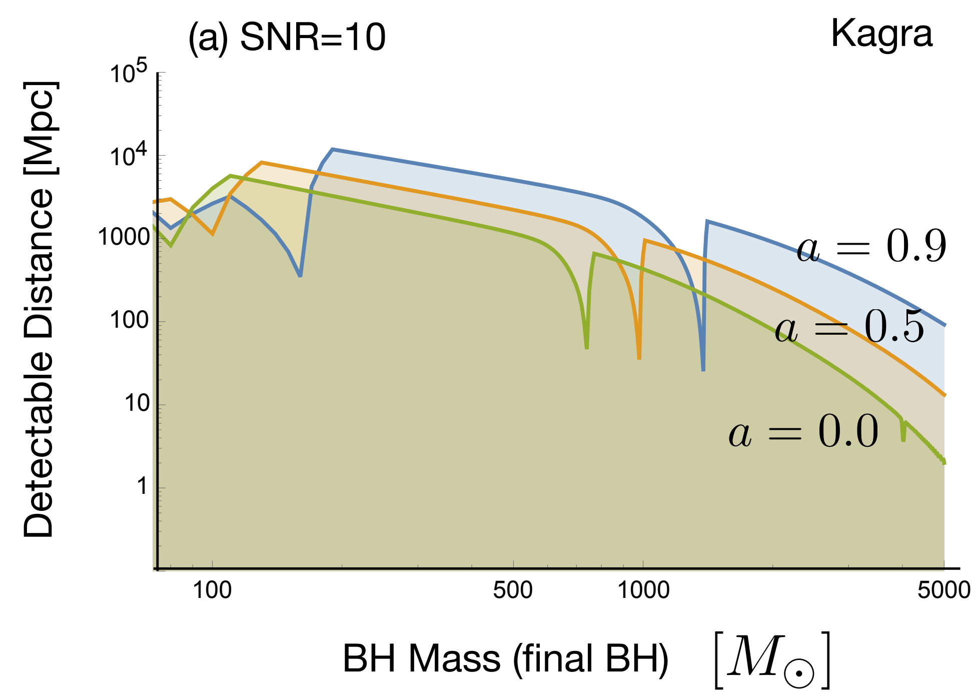


Hierarchical Growth

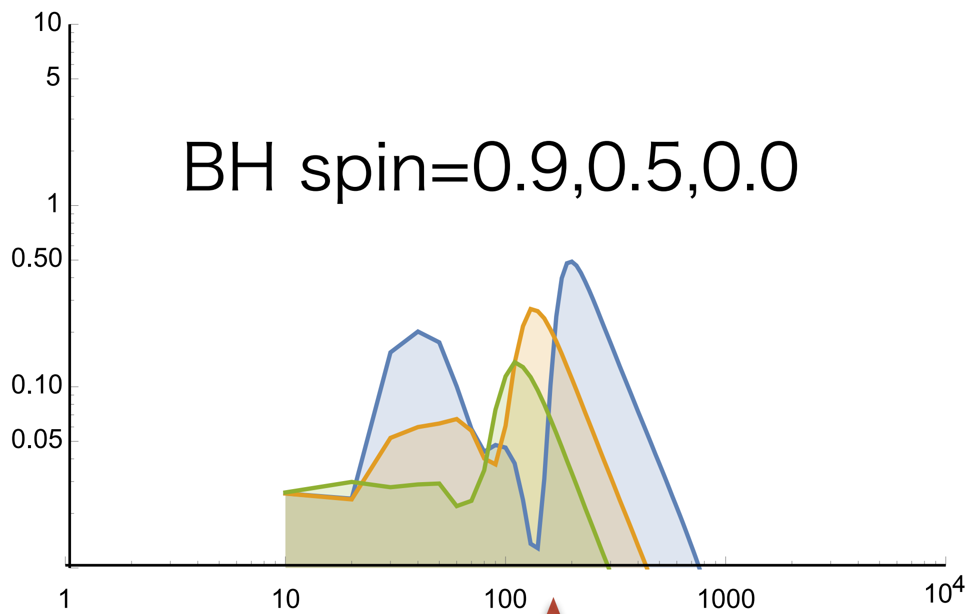


Black-Hole Ringdown frequency





Event Rates at bKAGRA

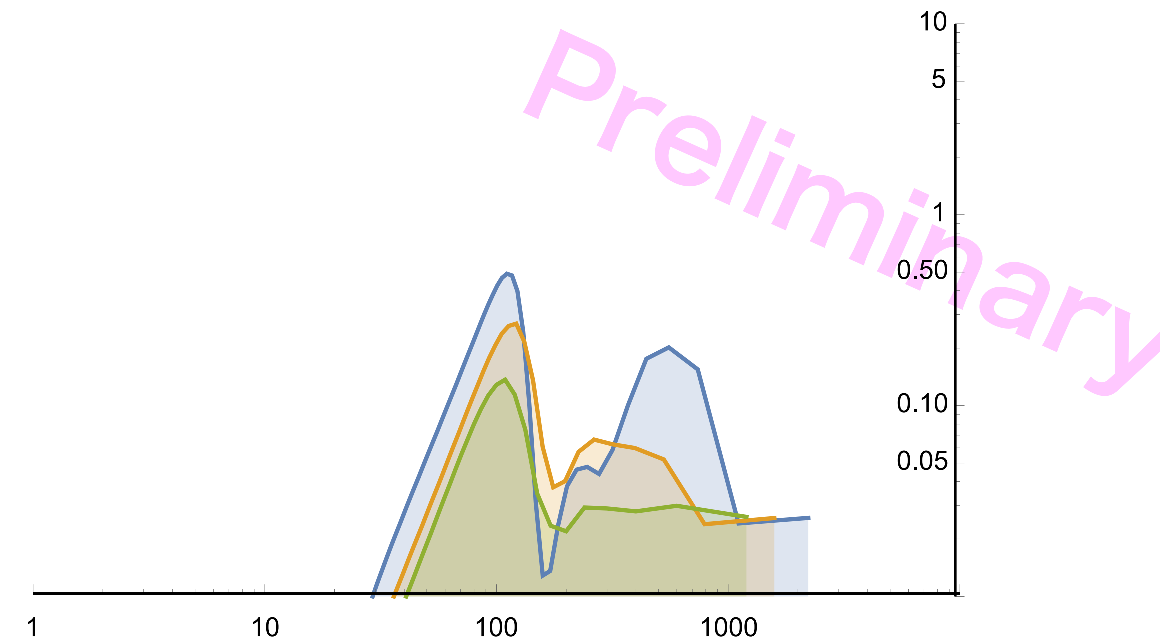


BH spin=0.9,0.5,0.0

peak at 100-200M

BH Mass

different from PopIII model



Frequency

1-10 events/yr

Summary

By accumulating data, we can discuss astrophysics: formation scenario of SMBH, number counts of galaxies, …(and later) cosmological models/gravitational theories.

Preliminary

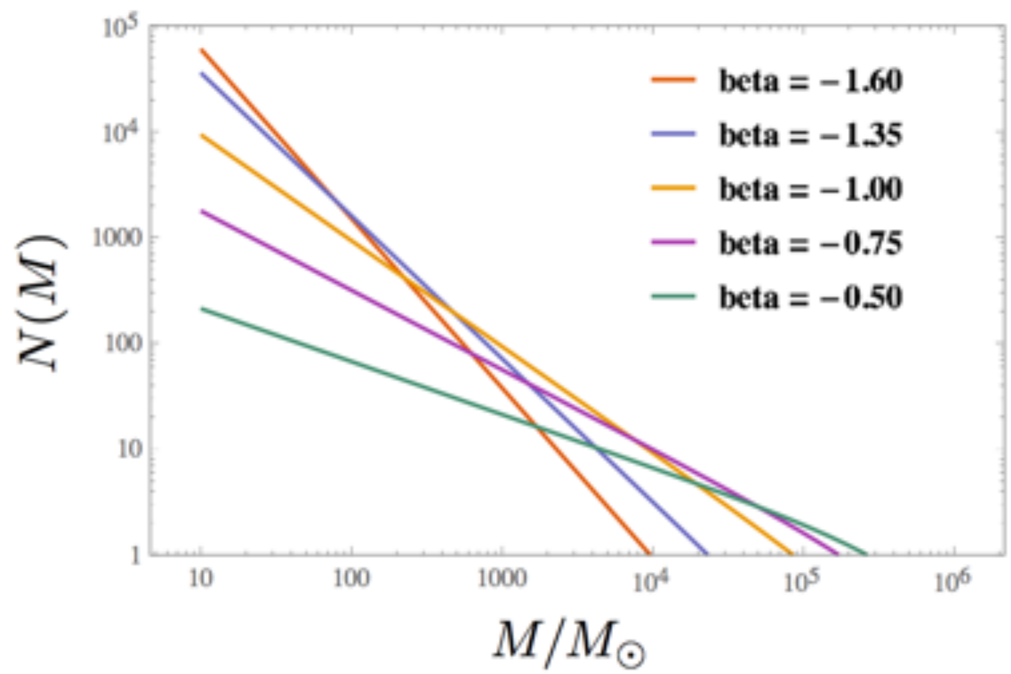


Fig. 3.— The mass distribution models of BHs, eq. (2) for $\beta = -1.60, -1.35, -1.00, -0.75$ and -0.50. We fix the total mass is $10^9 M_\odot$ with minimum mass $10 M_\odot$, and the cut-off mass (also the bulge mass) is $10^6 M_\odot$.

Table 2: Results of required events for distinguishing model parameter β (say β_1 and β_2) for BHs of $a = 0.5$. The cases of Kagra with signal-to-noise ratio $\rho = 10, 30$, and 100 are shown. N_{10} and N_5 are of the number of events for significant level 10% and 5%.

ρ	β_1	β_2	N_{10}	N_5
100	−1.6	−1.35	80	110
	−1.6	−1.00	75	105
	−1.6	−0.75	70	95
30	−1.6	−1.00	780	1110
	−1.6	−0.75	600	850
	−1.6	−0.50	480	670
10	−1.6	−0.75	2120	3010
	−1.6	−0.50	1690	2400

$$N(M) \sim \alpha M^{\beta} \exp\left(-\frac{M}{M_{\rm cut}}\right)$$

Hierarchical distribution
== (beta=1)