Gravitational Waves
from
Merging Intermediate-Mass Black Holes

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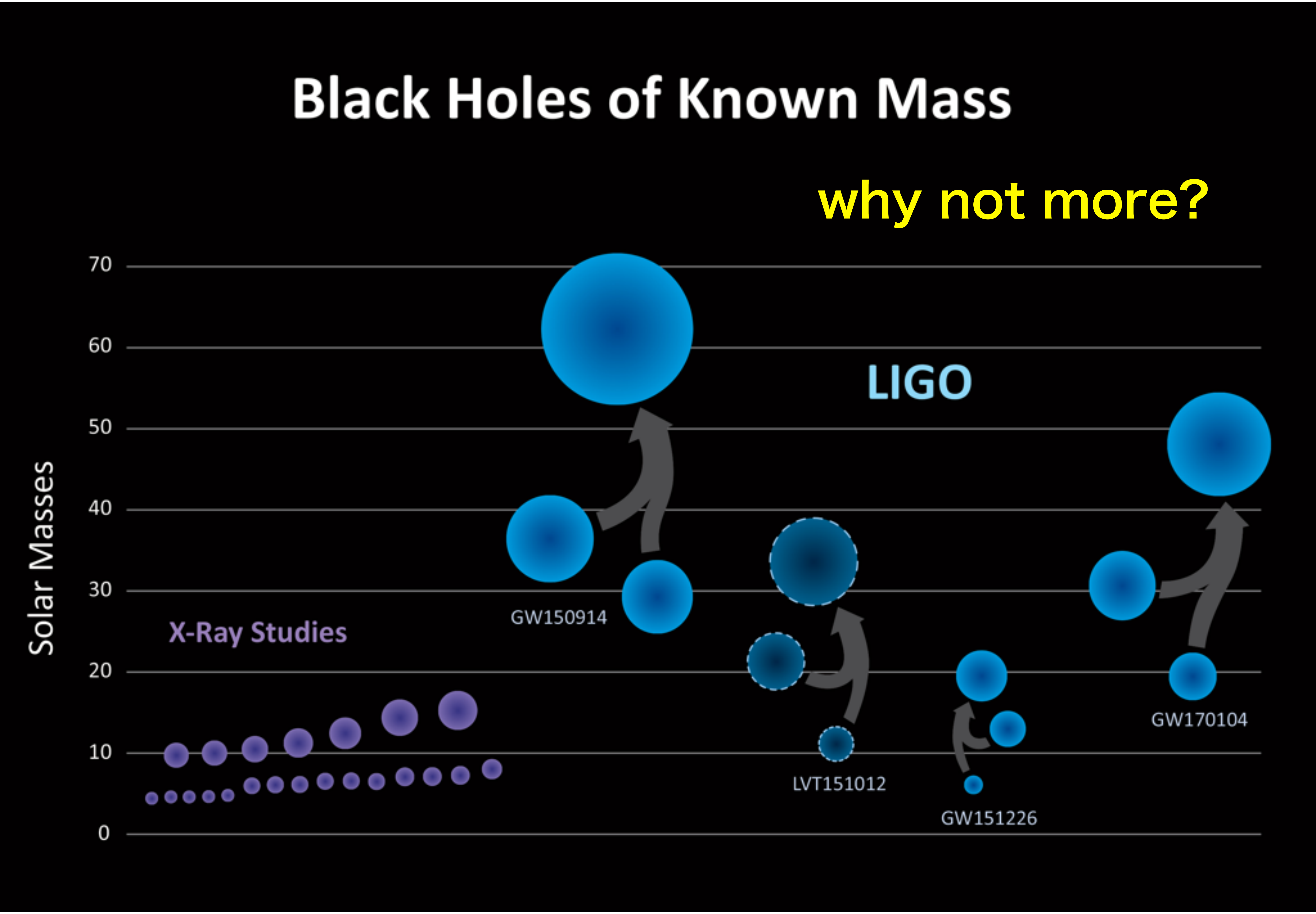
Counting BHs

- How many BHs in a galaxy?
- How many galaxies in the Universe?
- How many BH mergers in the Universe?

Event Rates at aLIGO/KAGRA/DECIGO/LISA

Ref: HS, Kanda & Ebisuzaki, ApJ, 835 (2017) 276 [arXiv:1610.09505]

2017/7/4 The 13th International Conference on Gravitation, Astrophysics, & Cosmology (ICGAC-XIII)
@ Seoul, Korea



http://ligo.org/detections/GW170104.php

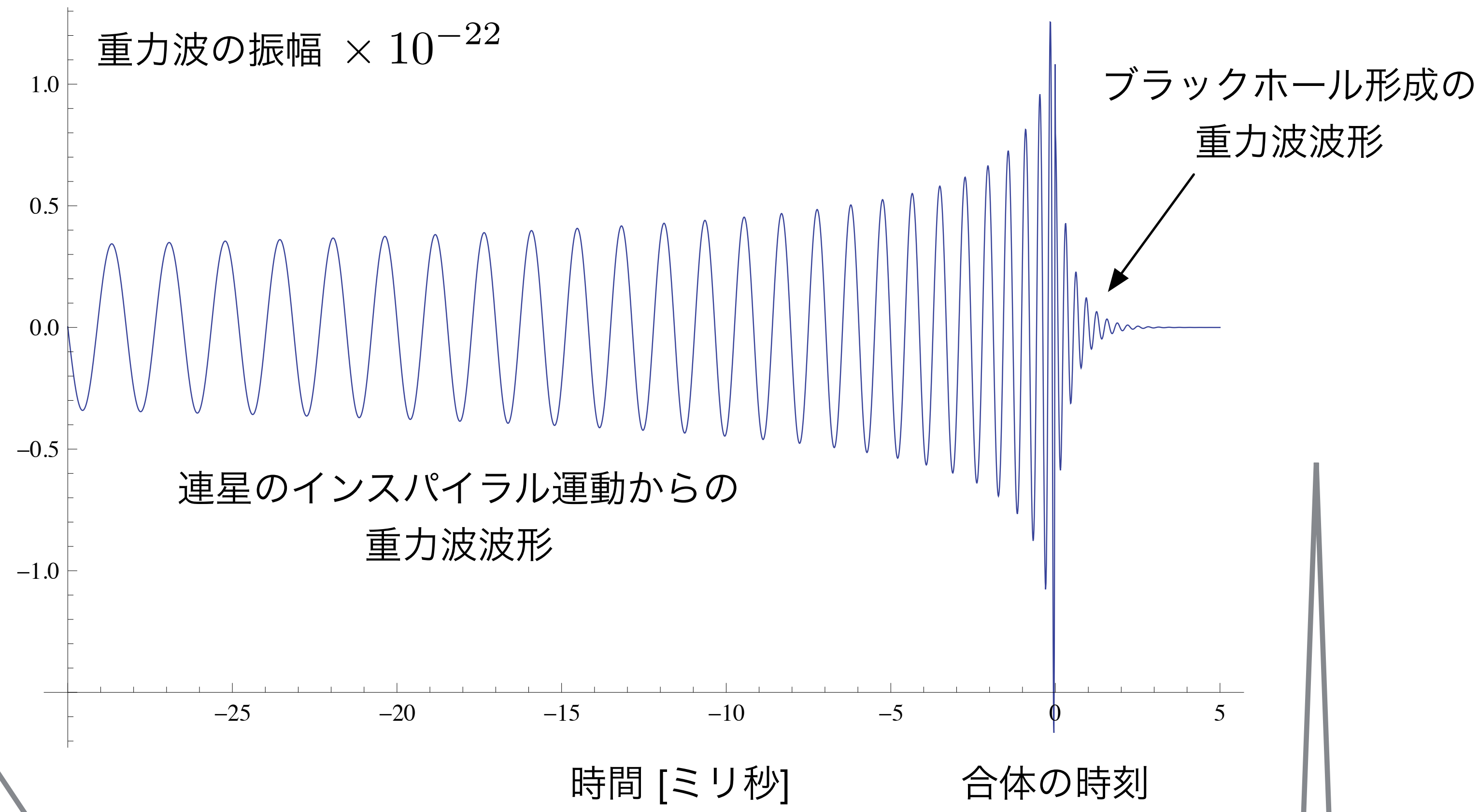
List of Detected GW events

		M1+M2=Mf, Mdiff/Mtotal a_final	Mpc z	SNR	deg^2
GW150914	PRL116, 061102 (2016/2/11)	36.2+29.1=62.3+3.0 **4.59%** 0.68	410Mpc 0.09	23.7	600
LVT151012	(2016/2/11)	23+13=35+1.5 **2.78%** 0.66	1000Mpc 0.20	9.7	
GW151226	PRL116, 241103 (2016/6/15)	14.2+7.5=20.8+0.9 **4.15%** 0.74	440Mpc 0.09	13.0	850
GW170104	PRL118, 221101 (2017/6/1)	31.2+19.4=48.7+1.9 **3.75%** 0.64	880Mpc 0.18	13.0	1300

https://losc.ligo.org/events/GW150914/
https://losc.ligo.org/events/LVT151012/
https://losc.ligo.org/events/GW151226/
https://losc.ligo.org/events/GW170104/

1. Gravitational Wave >> Expected Amplitude

Inspiral | **Merger** | **Ringdown**



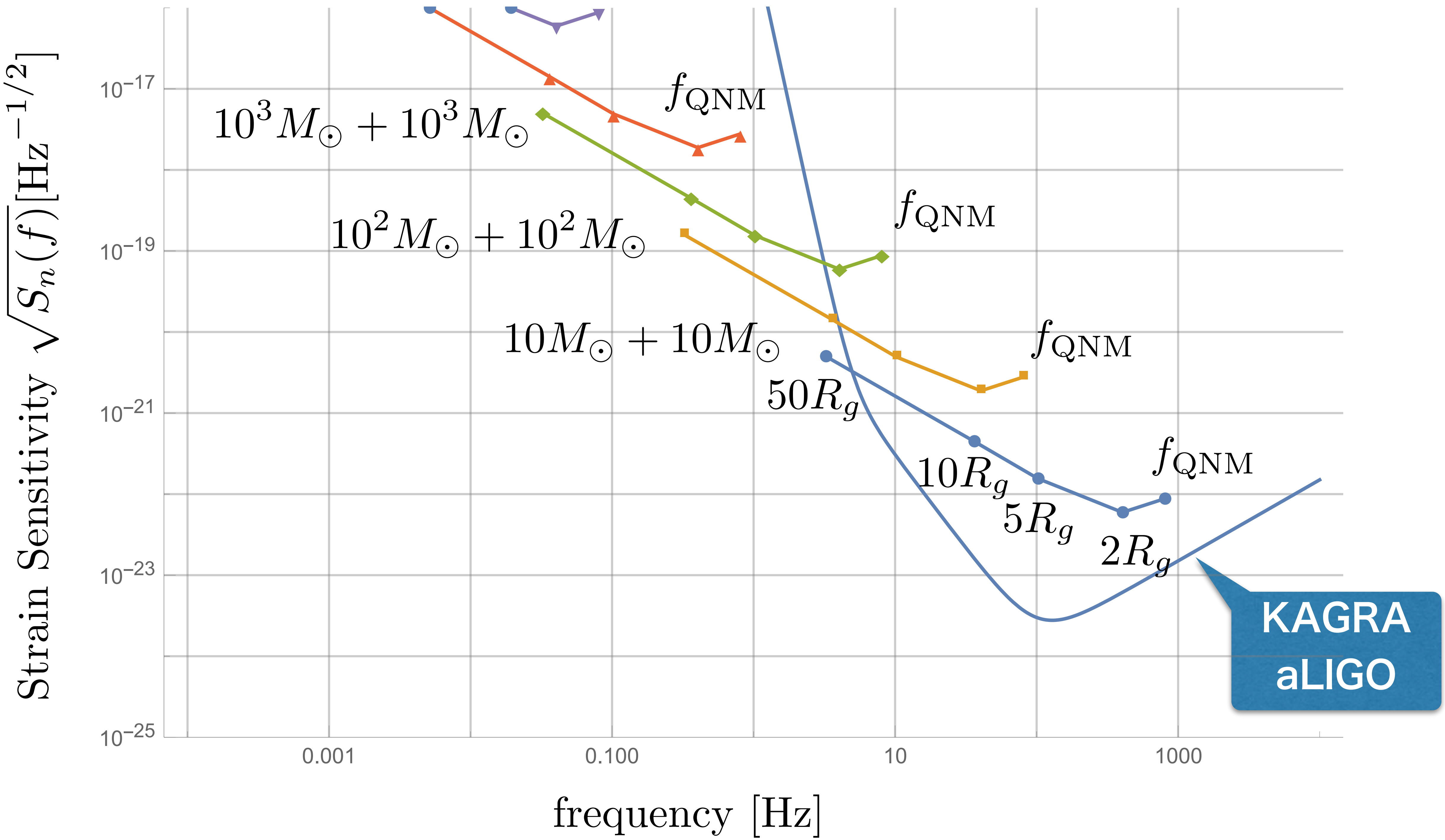
$$f_{\rm insp} = \frac{1}{\pi}\sqrt{\frac{GM_T}{a^3}}$$
$$\approx 11.4\left(\frac{a}{R_{\rm grav}}\right)^{-3/2}\left(\frac{2\times10^3\ M_\odot}{M_T}\right)\ \mathrm{Hz},$$

$$h_{\rm insp} = \sqrt{\frac{32}{5}}\pi^{2/3}G^{5/3}c^{-4}M_1M_2M_T^{-1/3}f^{2/3}R^{-1},$$
$$\approx 1.49\times10^{-21}\left(\frac{M_1}{10^3\ M_\odot}\right)\left(\frac{M_2}{10^3\ M_\odot}\right)$$
$$\times\left(\frac{M_T}{2\times10^3\ M_\odot}\right)^{-1/3}\left(\frac{f}{1\ \mathrm{Hz}}\right)^{2/3}\left(\frac{R}{4\ \mathrm{Gpc}}\right)^{-1}.$$

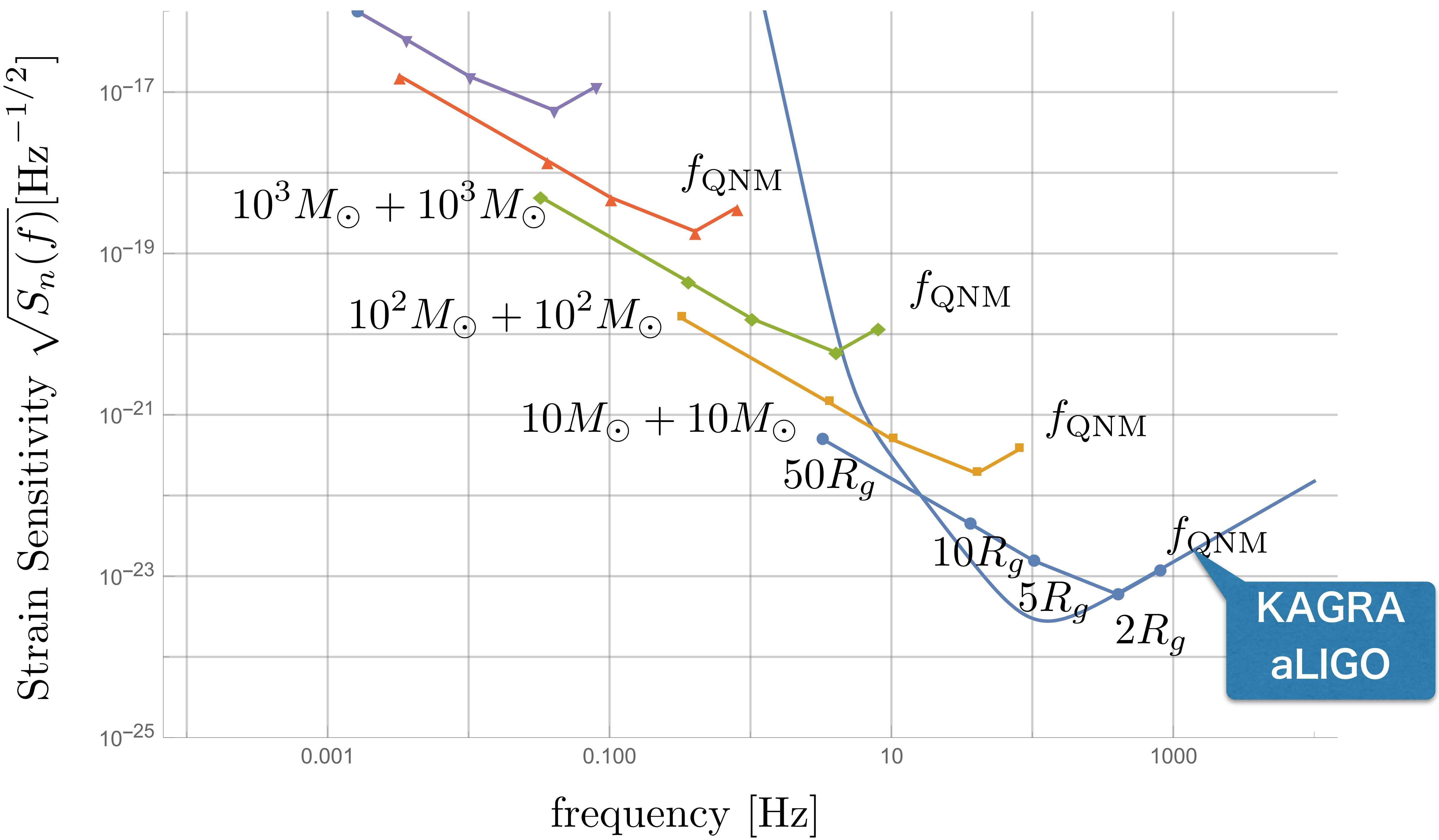
$$f_{\rm QNM} \approx \frac{lc^3}{\sqrt{27}GM_T} \sim 39.1\left(\frac{2\times10^3\ M_\odot}{M_T}\right)\ \mathrm{Hz},$$

$$h_{\rm coal} \approx 5.45\times10^{-21}\left(\frac{\epsilon}{0.01}\right)^{1/2}\left(\frac{4\ \mathrm{Gpc}}{R}\right)\left(\frac{\mu}{\sqrt{2}\times10^3\ M_\odot}\right)$$

Typical frequency of BH-BH binary merger @ 100Mpc

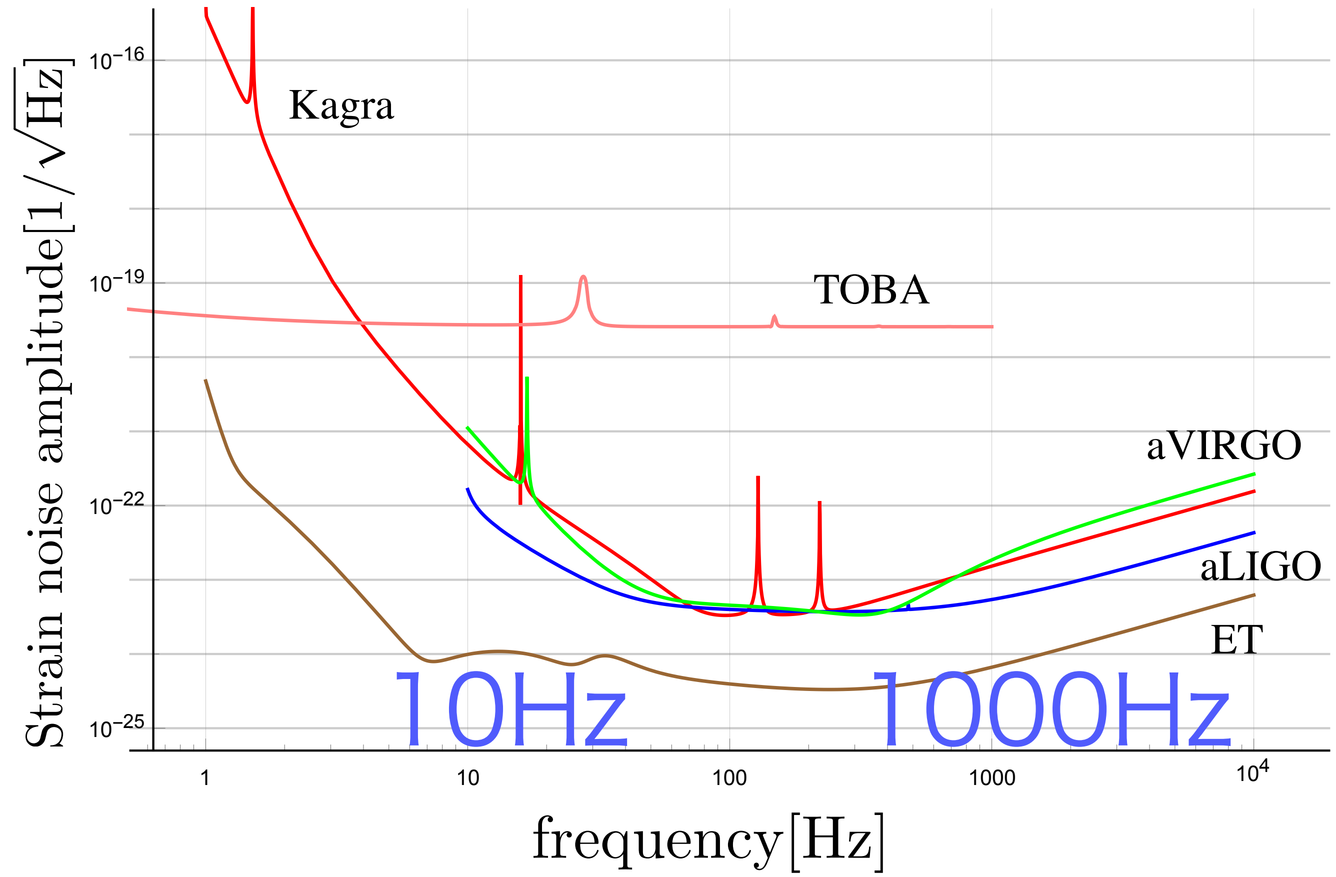


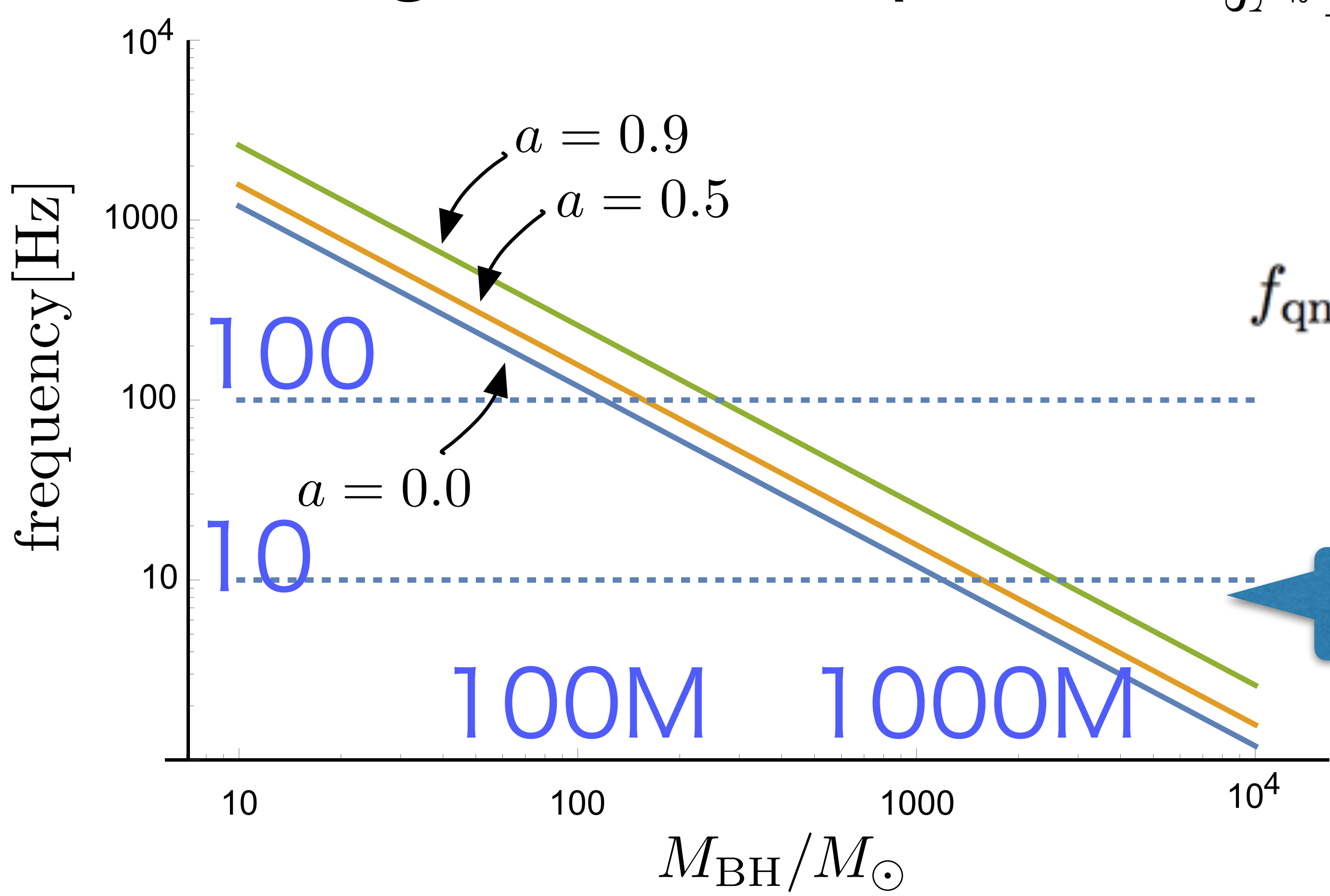
Typical frequency of BH-BH binary merger @ 1000Mpc



IMBH ringdown freq. is detectable at LIGO/KAGRA

BH quasi-normal freq.
(ringdown freq.)



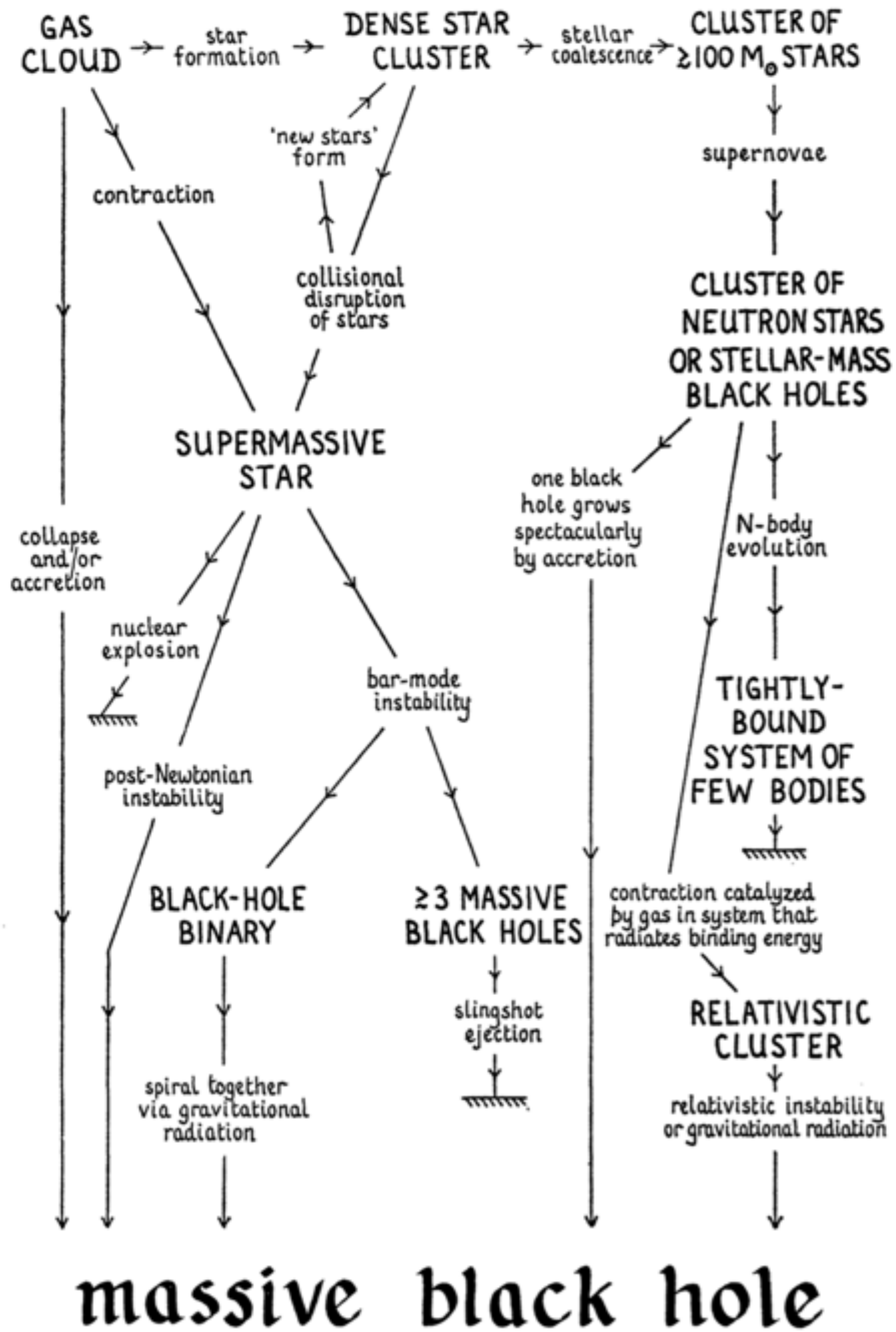


$$f_{\mathrm{qnm}}[\mathrm{Hz}] = \frac{c^3}{2\pi G M} f_R$$

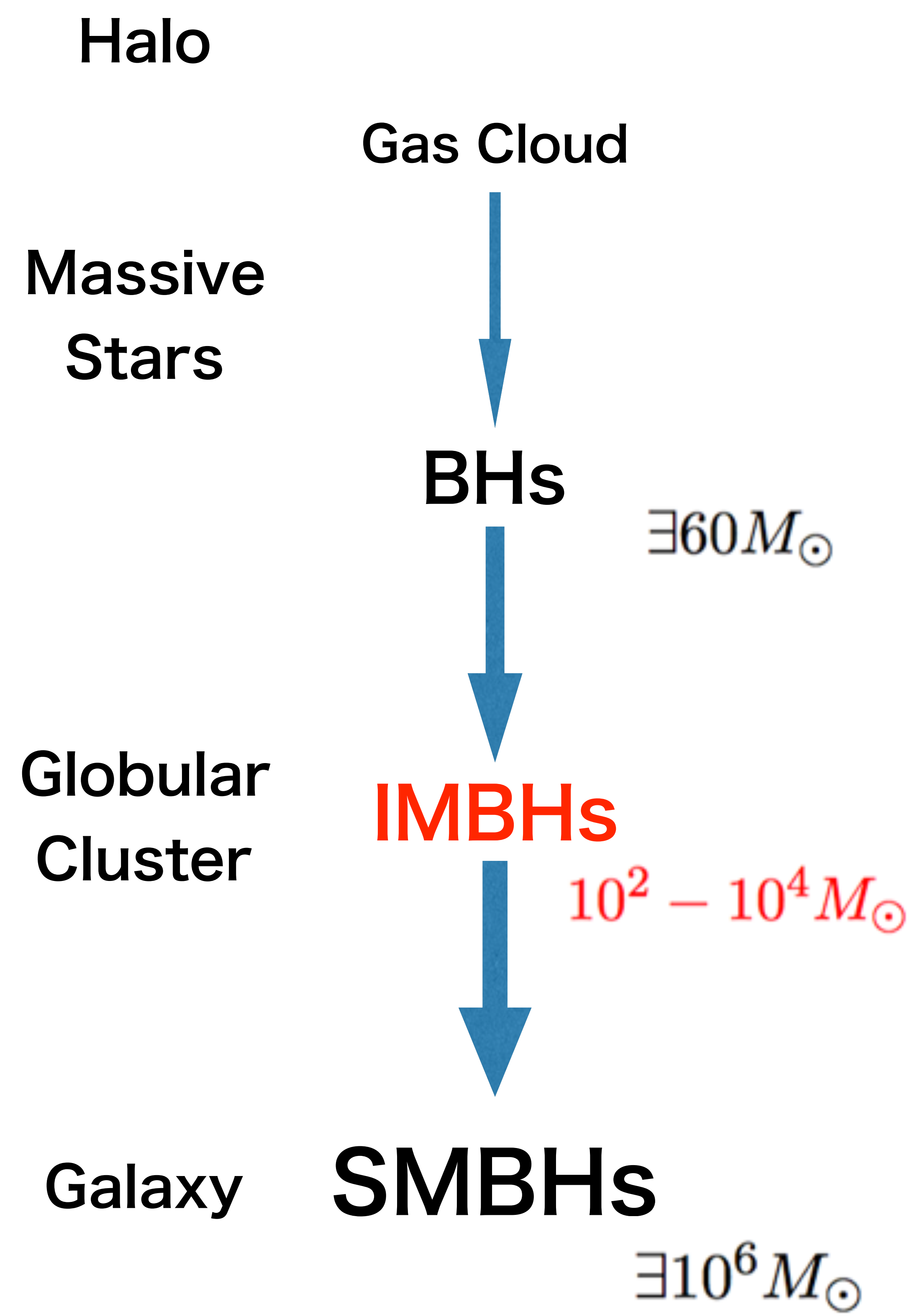
$$f_R = f_1 + f_2(1-a)^{f_3}$$

BH < 2000Msun can be a target

2. Models of SMBH



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



Ebisuzaki +, ApJ, 562, L19 (2001)

Starburst galaxy M82 has 1000M BH

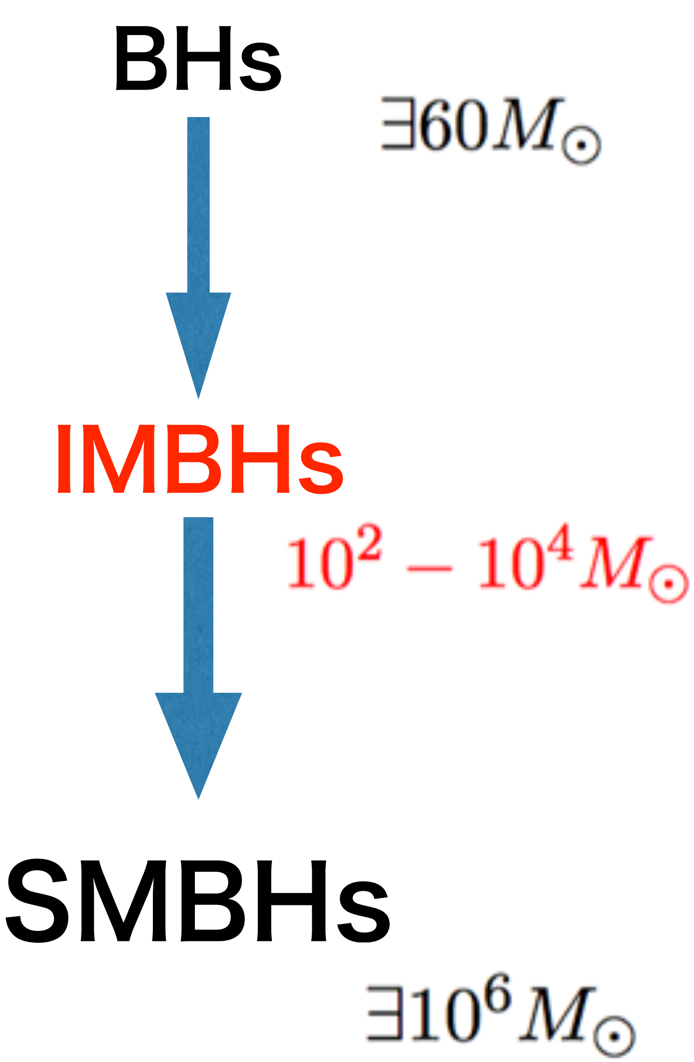
Matsushita+, ApJ, 545, L107 (2000)
Matsumoto+, ApJ, 547, L25 (2001)

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]

Ebisuzaki +, ApJ, 562, L19 (2001)

'Missing link' founded

Ebisuzaki +, ApJ, 562, L19 (2001)

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

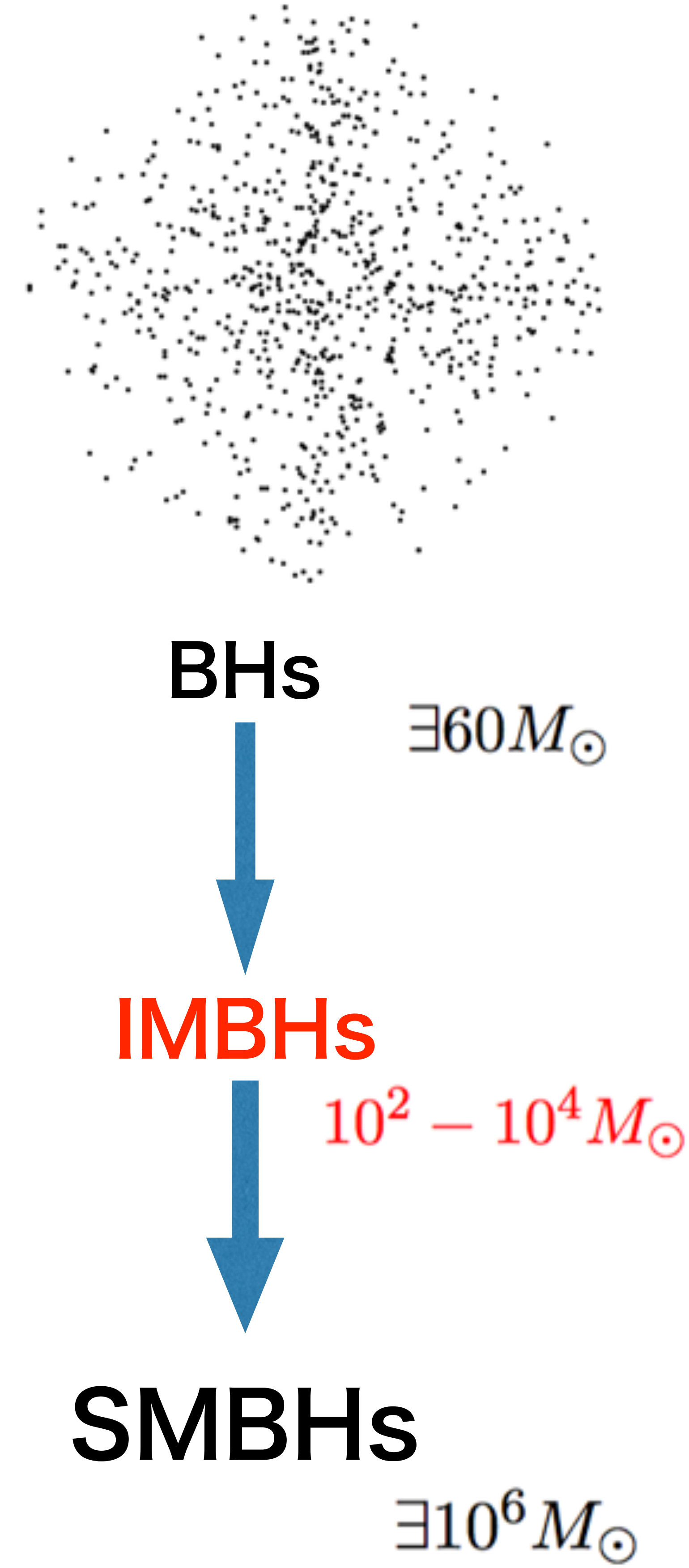
Marchant & Shapiro 1980; Portegies Zwart et al. 1999;
Portegies Zwart & McMillan 2002;
Portegies Zwart et al. 2004;
Holger & Makino 2003

(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



IMBH-IMBH mergers produce low freq. GW

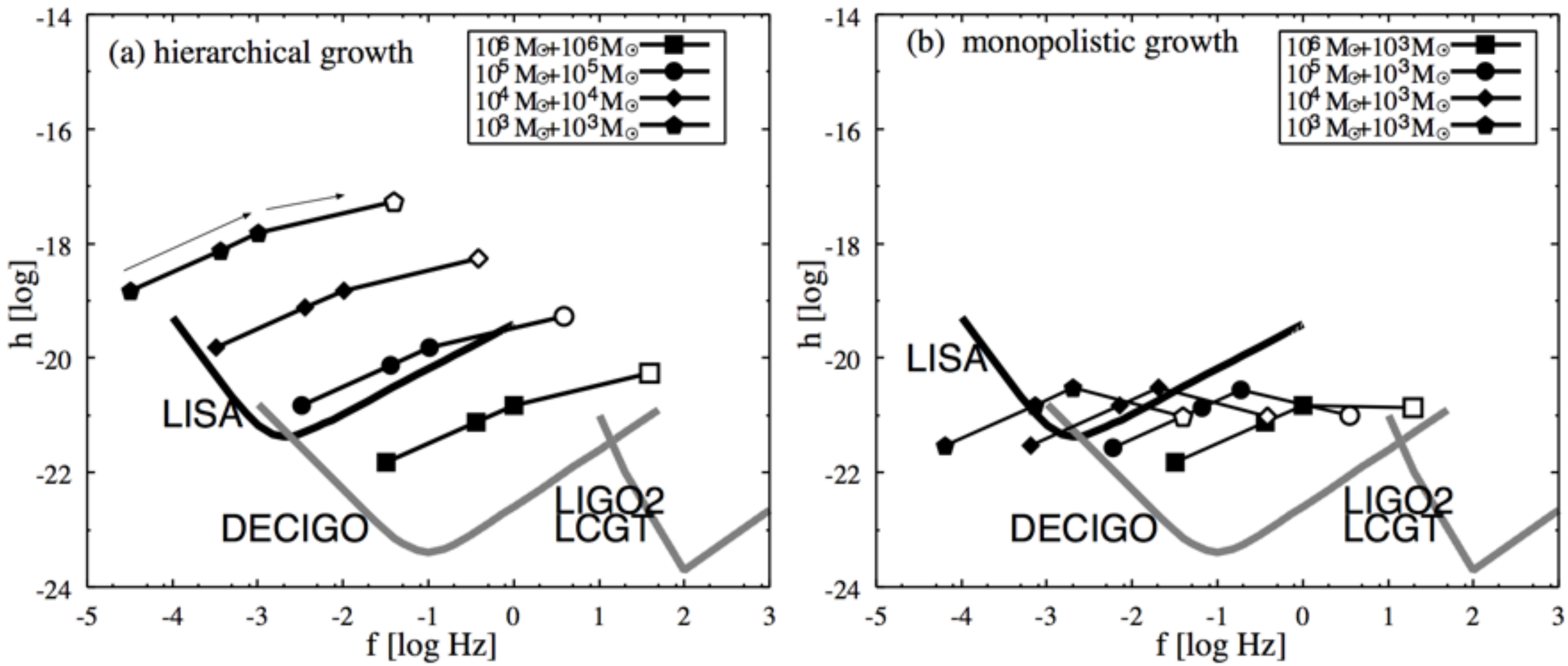
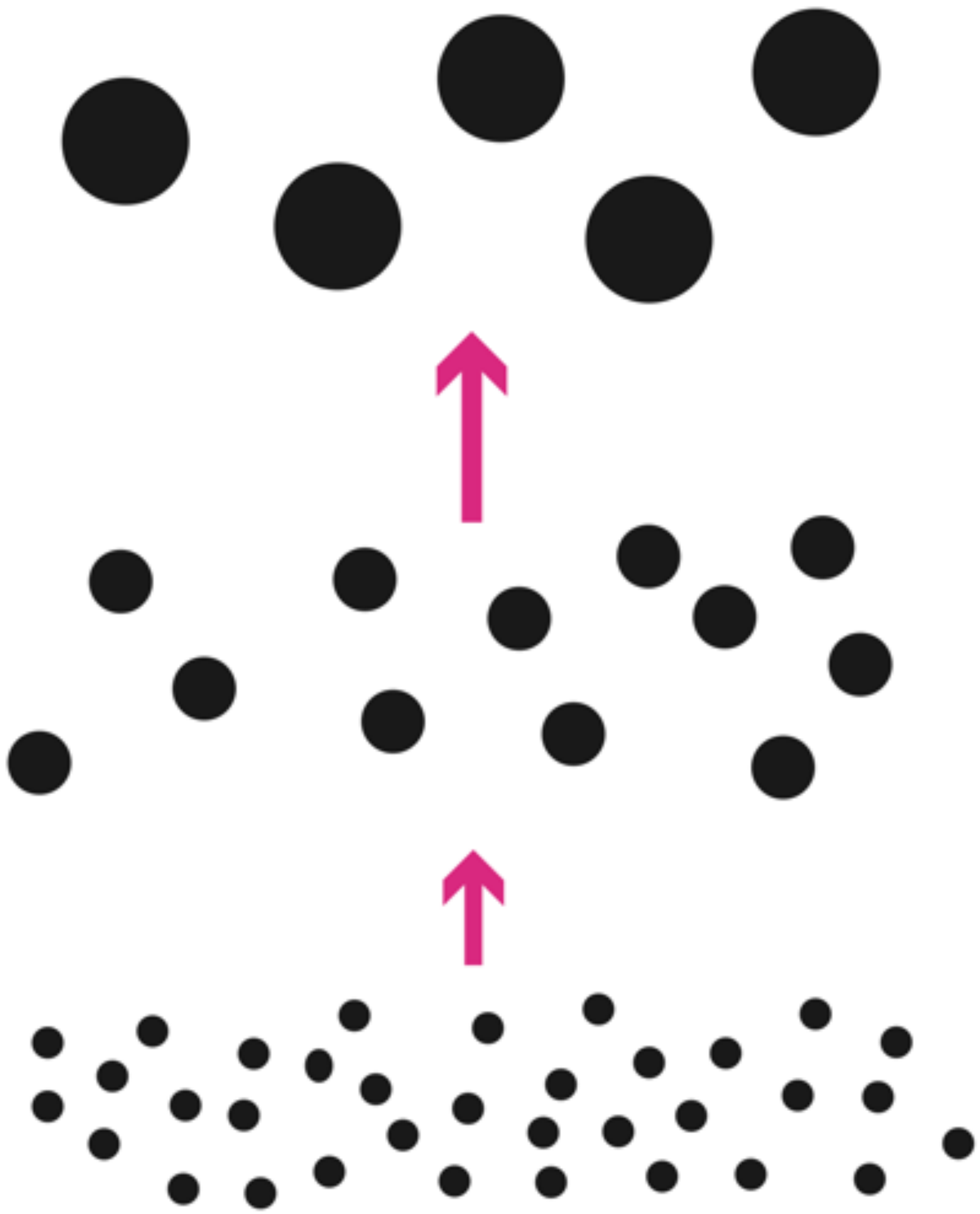


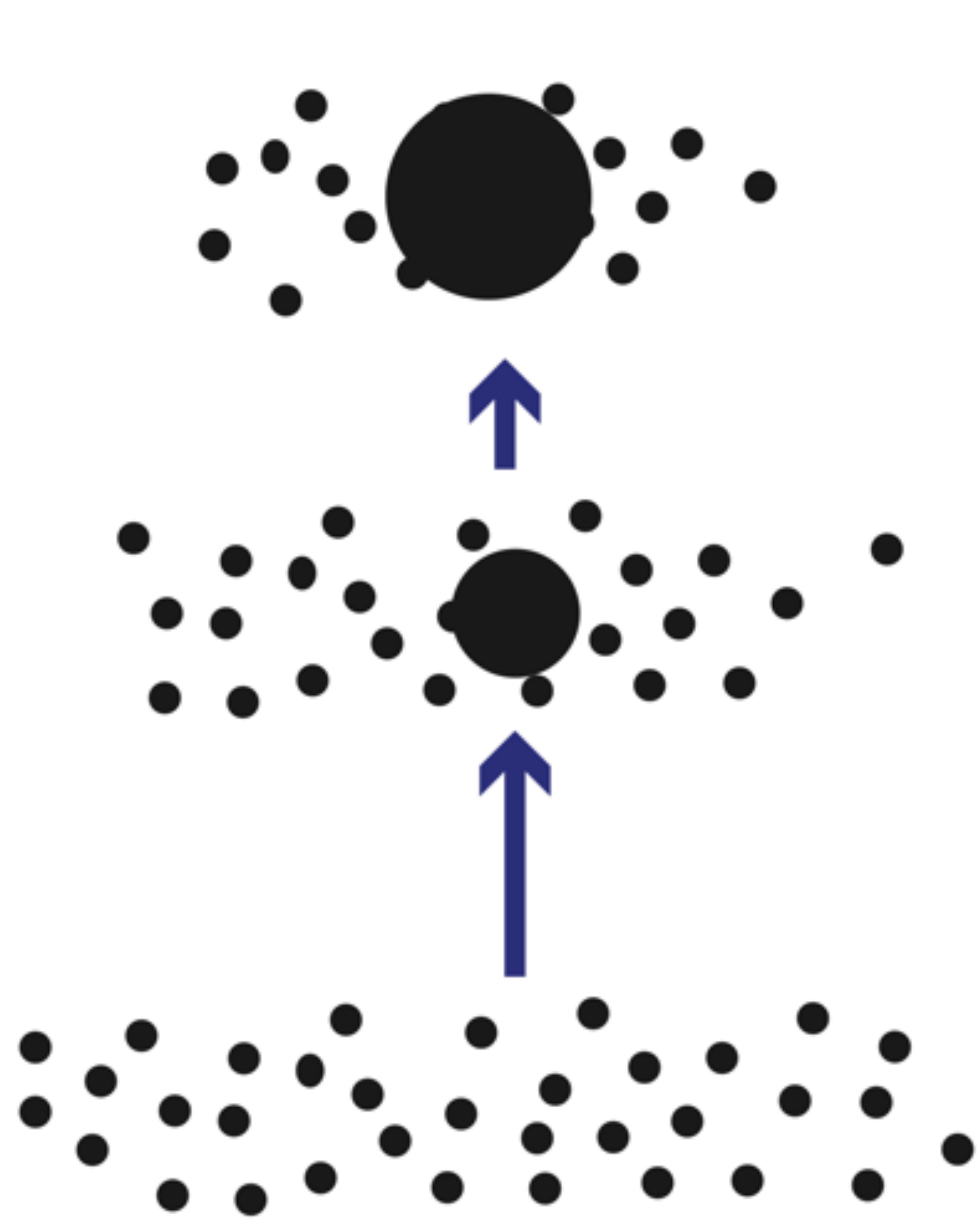
Fig. 1.— Expected gravitational radiation amplitude from merging IMBHs of (a) hierarchical growth model, and (b) monopolistic growth model. We plotted both the inspiral phase ($f_{\rm insp}, h_{\rm insp}$), [eqs. (2) and (3)], and the ringdown phase ($f_{\rm QNM}, h_{\rm coal}$), [eqs. (4) and (6)], 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

Hierarchical growth model



Monopolistic growth model



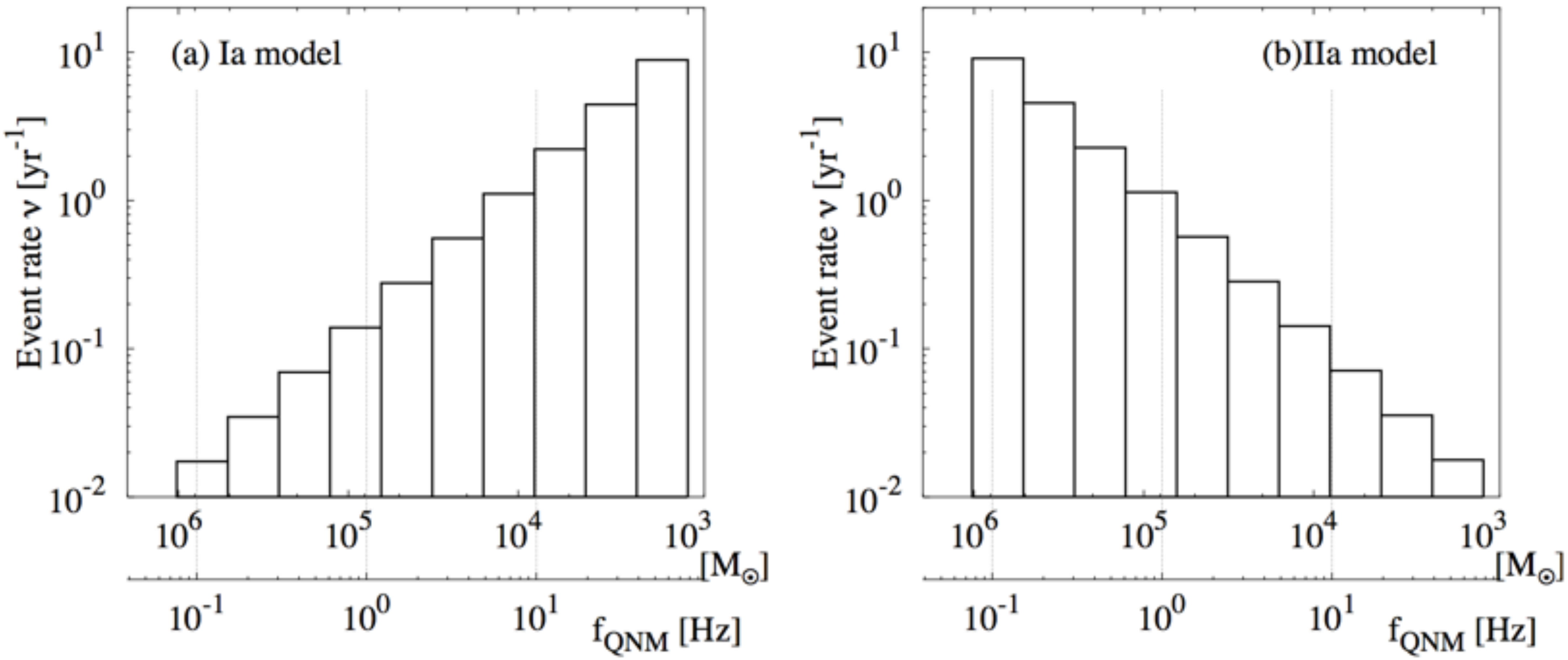
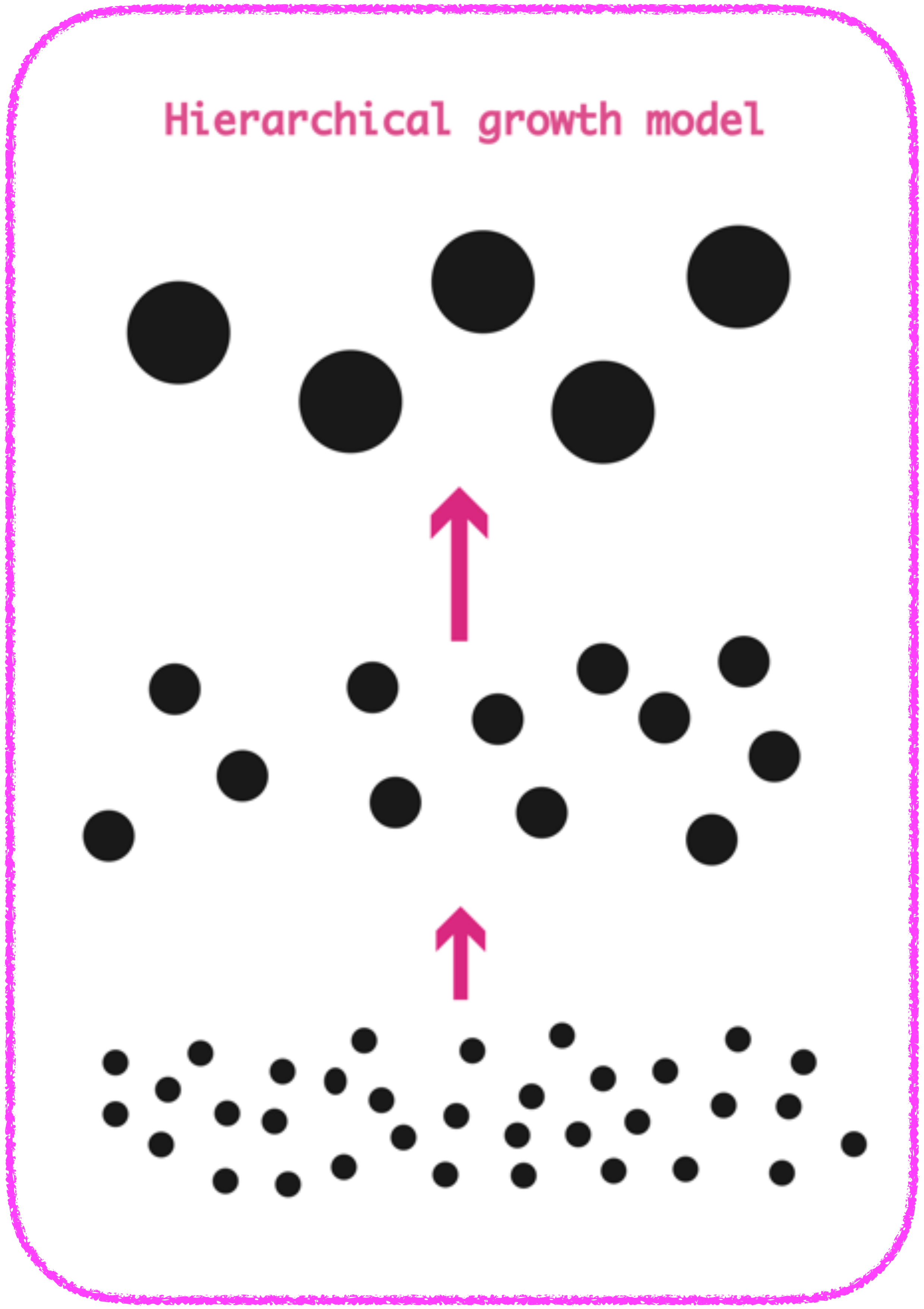


Fig. 2.— Event numbers of mergers starting from a thousand of $10^3 M_\odot$ IMBHs. The vertical axis is the event rate $\nu[\mathrm{yr}^{-1}]$, eqs. (12) and (14). The horizontal axis is the mass of the post-merger BH, M_T, which is also interpreted in the final gravitational radiation frequency $f_{\rm QNM}$. 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



How many BHs in a galaxy?
How many galaxies in the Universe?

How many BH mergers in the Universe?

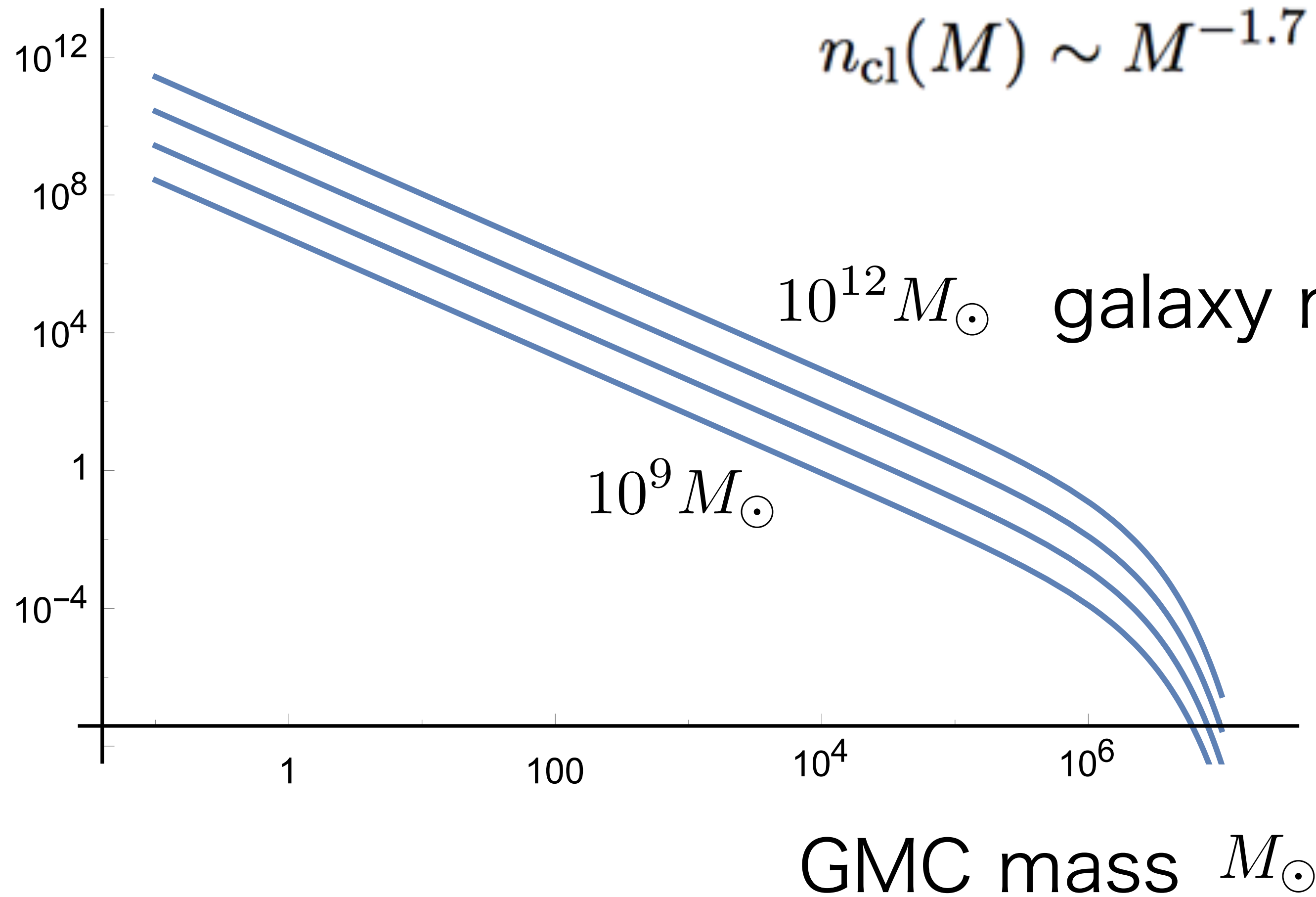
How many BH mergers we observe in a year?

Detectable Distance ?
KAGRA/aLIGO/aVIRGO

Cosmological model?
BH spin? Signal-to-Noise?

Mass Function of Giant Molecular Clouds

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



$$\frac{\partial n_{\rm cl}}{\partial t} + \frac{\partial}{\partial M}\left(n_{\rm cl}\frac{dM}{dt}\right) = -\frac{n_{\rm cl}}{T_{\rm d}},$$

The Formation and Destruction of Molecular Clouds and Galactic Star Formation

An Origin for The Cloud Mass Function and Star Formation Efficiency

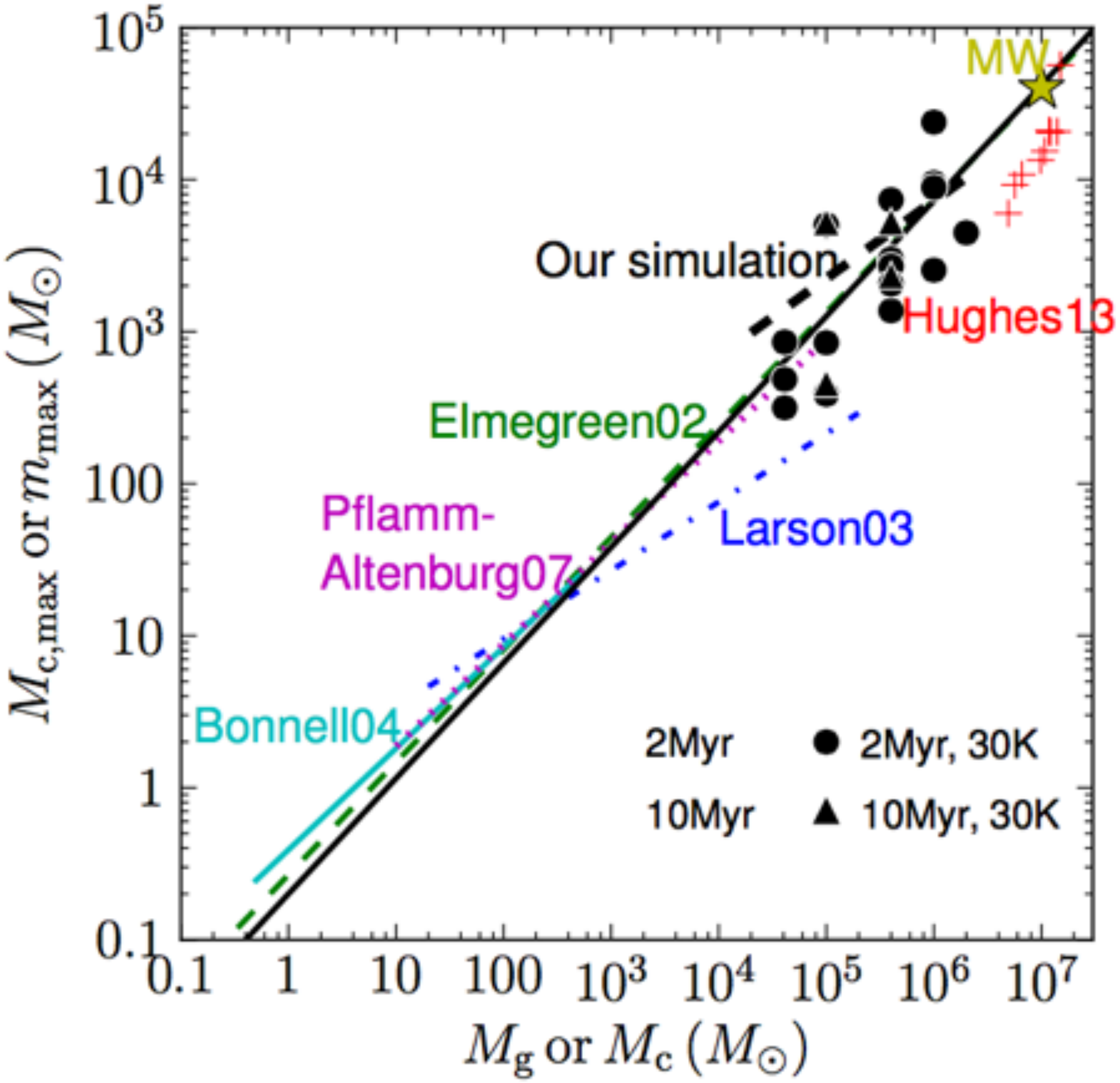
Shu-ichiro Inutsuka[1], Tsuyoshi Inoue,[2], Kazunari Iwasaki[1,3], and Takashi Hosokawa[4]

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

How many BHs in a Galaxy?

Molecular Clouds
Maximum Core

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

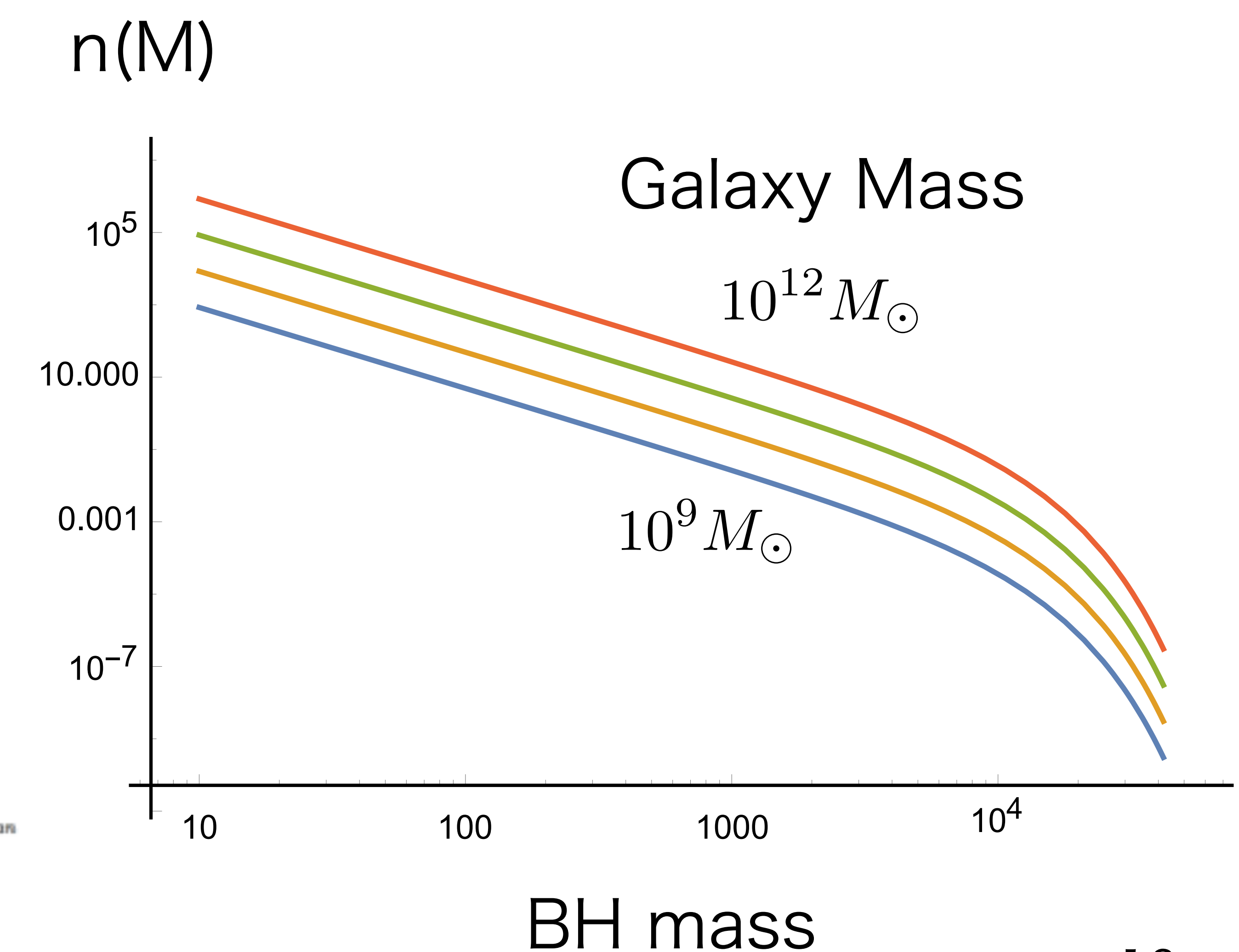


The initial mass function of star clusters that form in turbulent molecular clouds

M. S. Fujii[1] * and S. Portegies Zwart[2]*
[1] Division of Theoretical Astronomy, National Astronomical Observatory of Japan 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[2] Leiden Observatory, Leiden University, NL-2300RA Leiden, The Netherlands

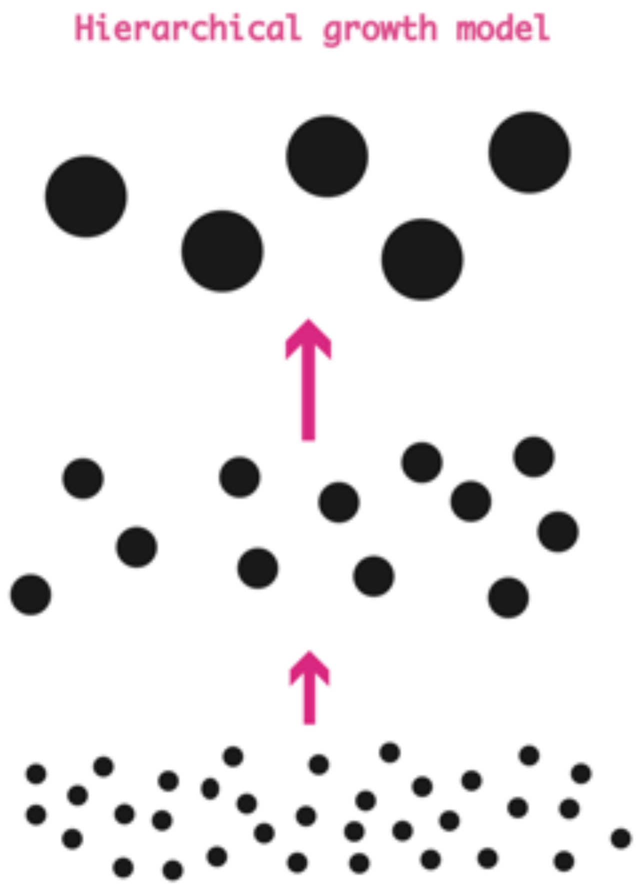
1309.1223v3

Building Block BH

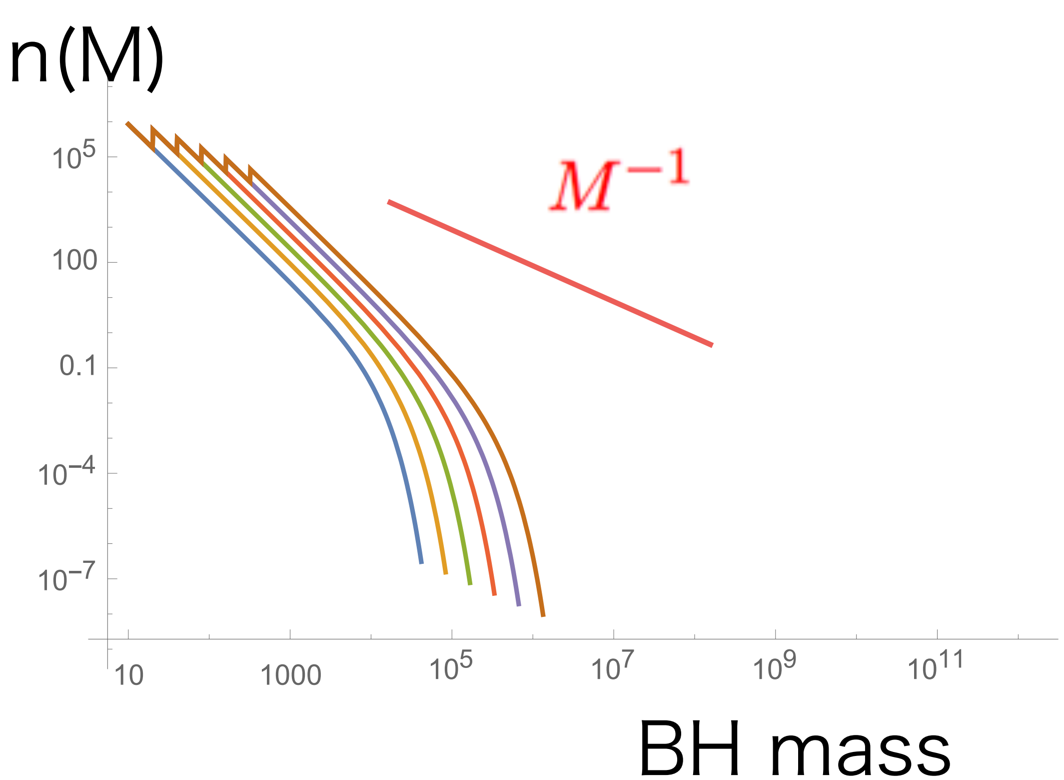


How many BHs in a Galaxy?

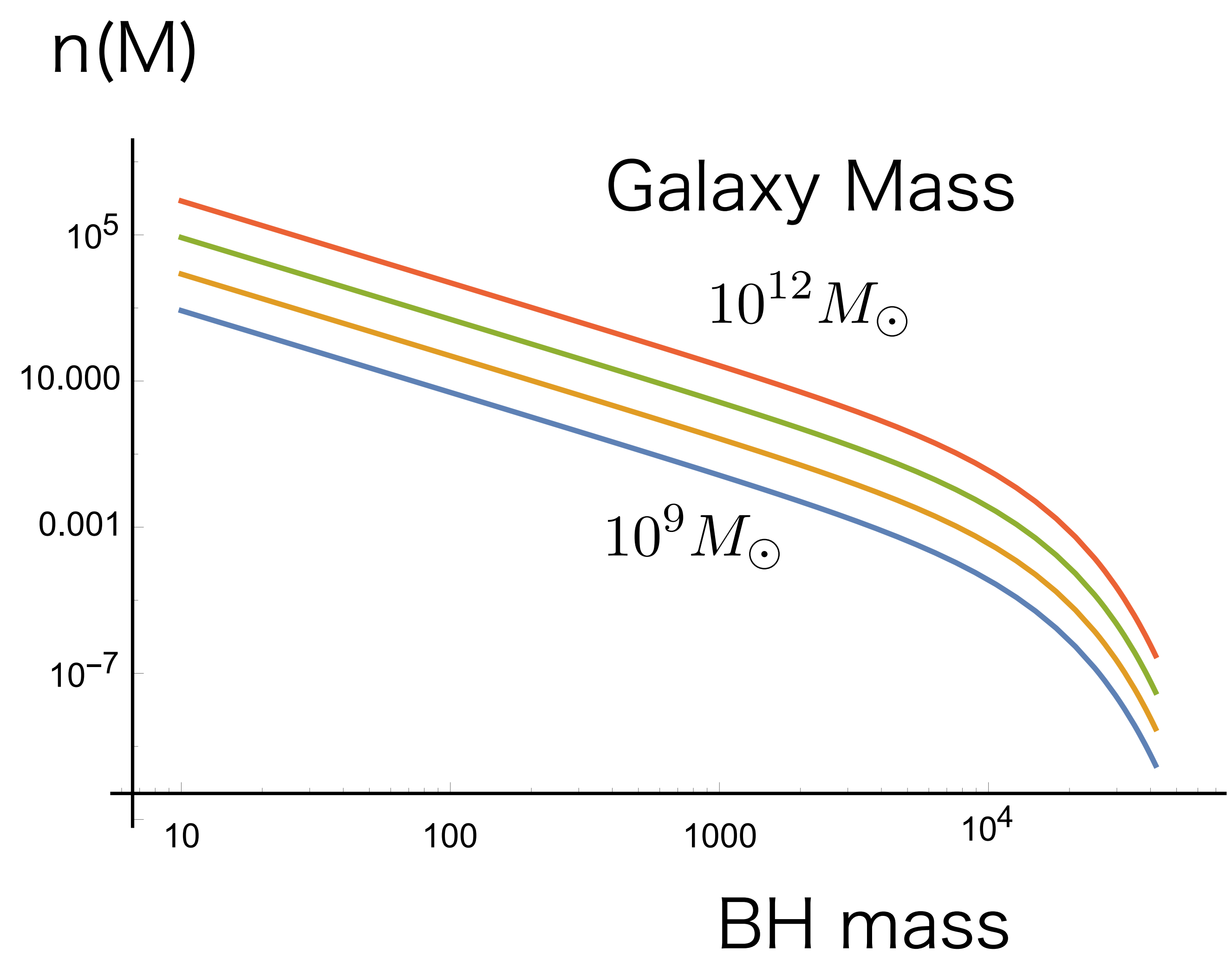
Count BHs to form a SMBH



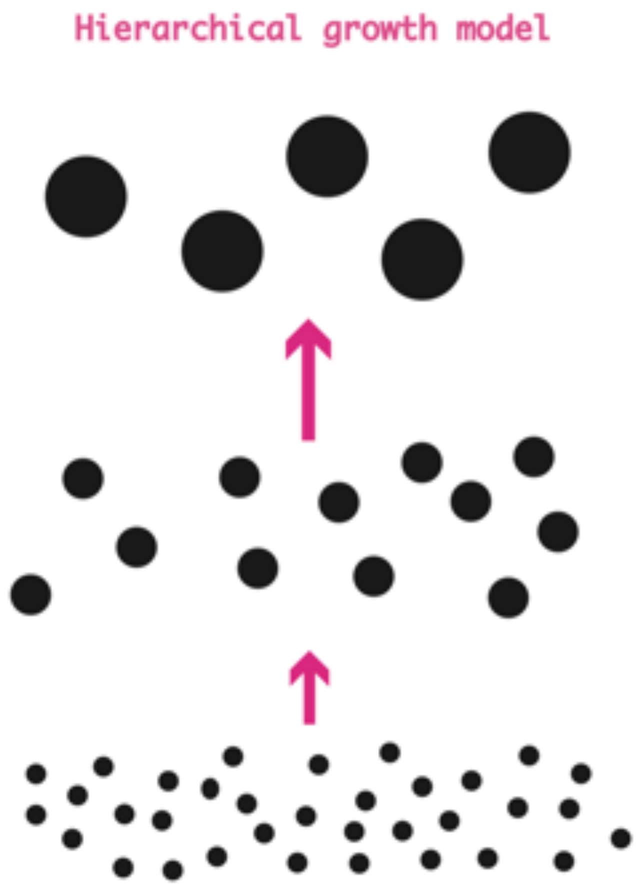
$$M_{k+1} = 2M_k$$
$$N_{k+1} = N_k/2$$



Building Block BH



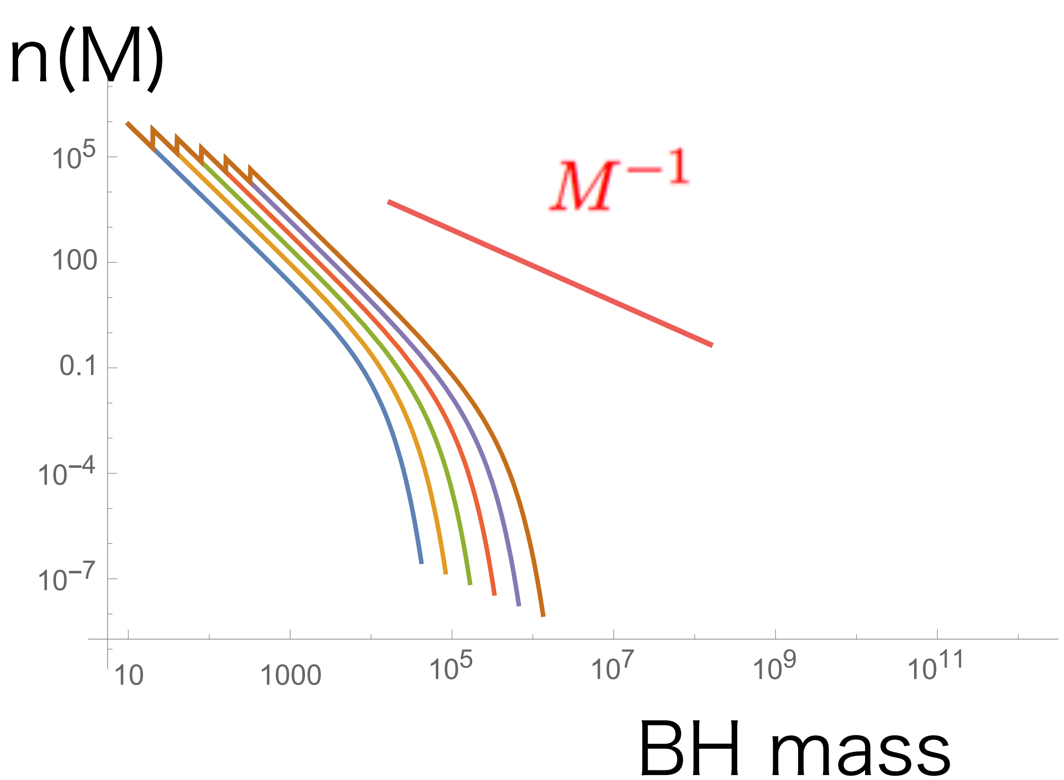
How many BHs in a Galaxy?



Count BHs to form a SMBH

$$M_{k+1} = 2M_k$$
$$N_{k+1} = N_k/2$$

dynamical friction



How many Galaxies in the Universe?

Count BHs to form a SMBH

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

(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

A. Vale[1★] and J. P. Ostriker[1,2]
[1]Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA
[2]Princeton University Observatory, Princeton University, Princeton, NJ 08544, USA

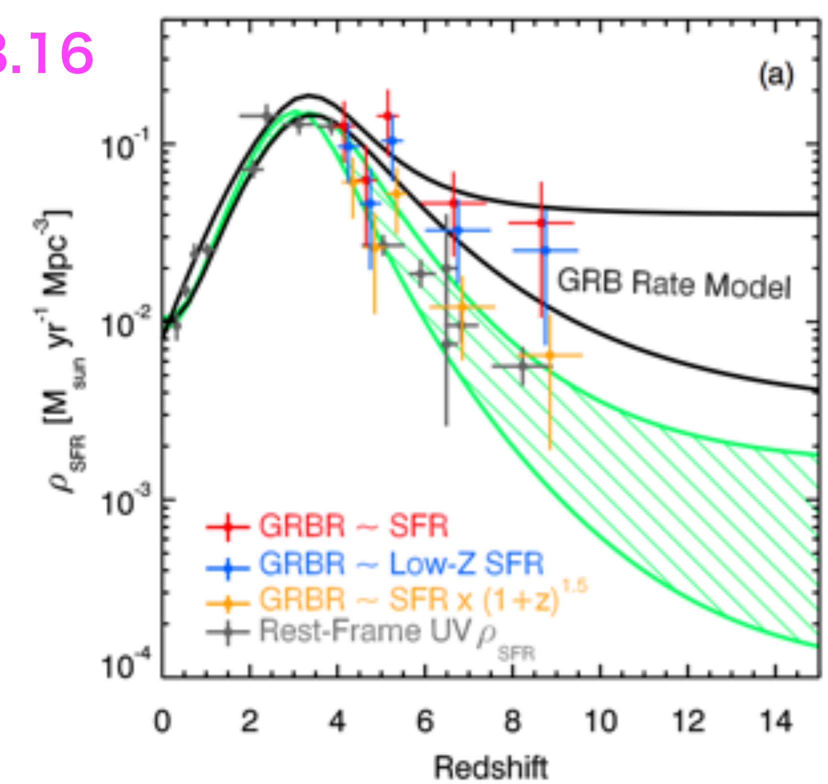
The Astrophysical Journal, 744:95 (13pp), 2012 January 10 doi:10.1088/0004-637X/744/2/95

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

Brant E. Robertson[1,2,3] and Richard S. Ellis[1]
[1] Astronomy Department, California Institute of Technology, MC 249-17, 1200 East California Boulevard, Pasadena, CA 91125, USA; brant@astro.caltech.edu
[2] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA
Received 2011 September 5; accepted 2011 November 18; published 2011 December 19

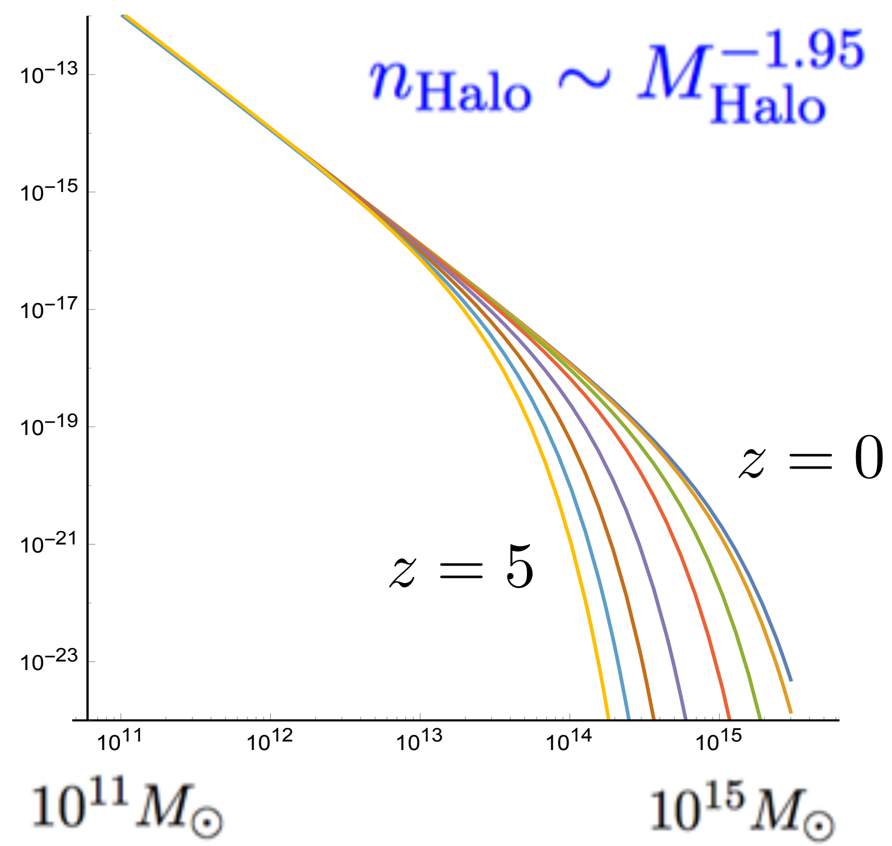
Star Formation Rate

peak z=3.16



How many Galaxies in the Universe?

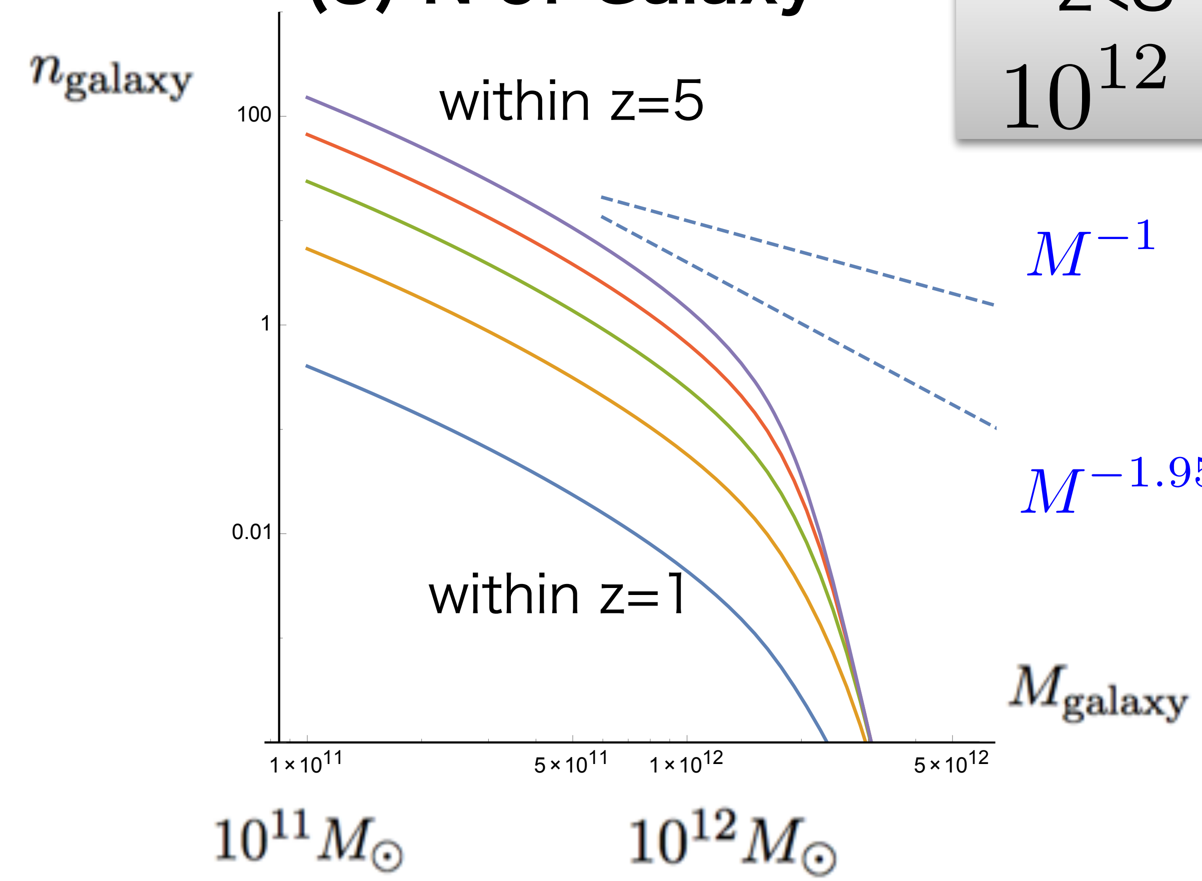
(1) Halo number density



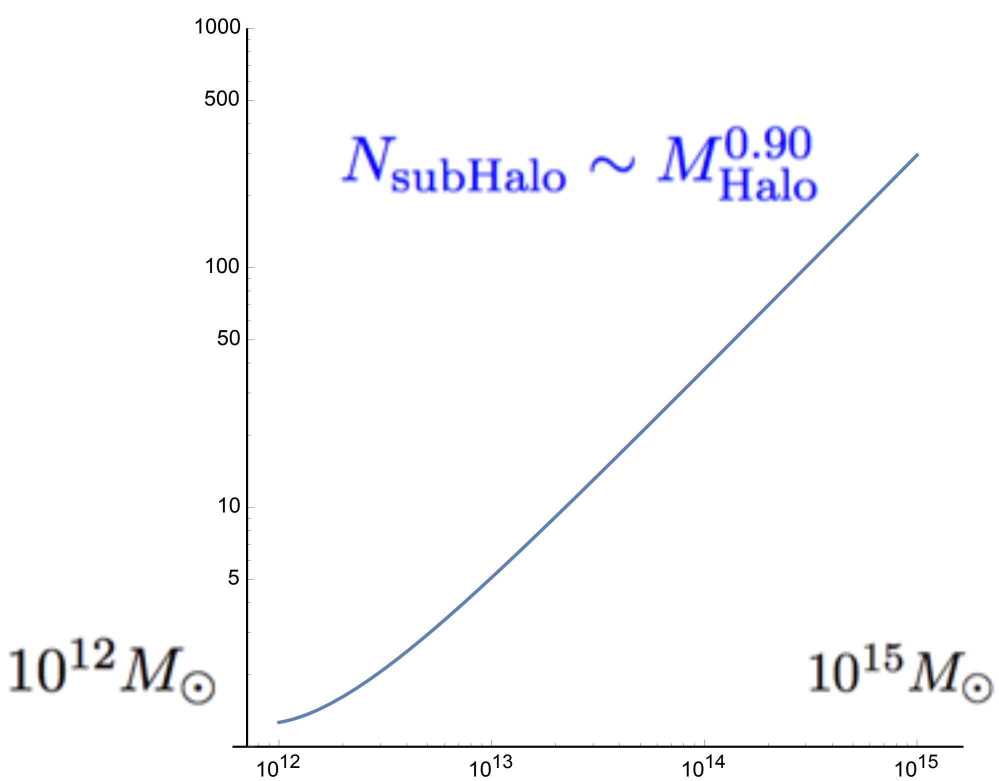
(3) N of Galaxy

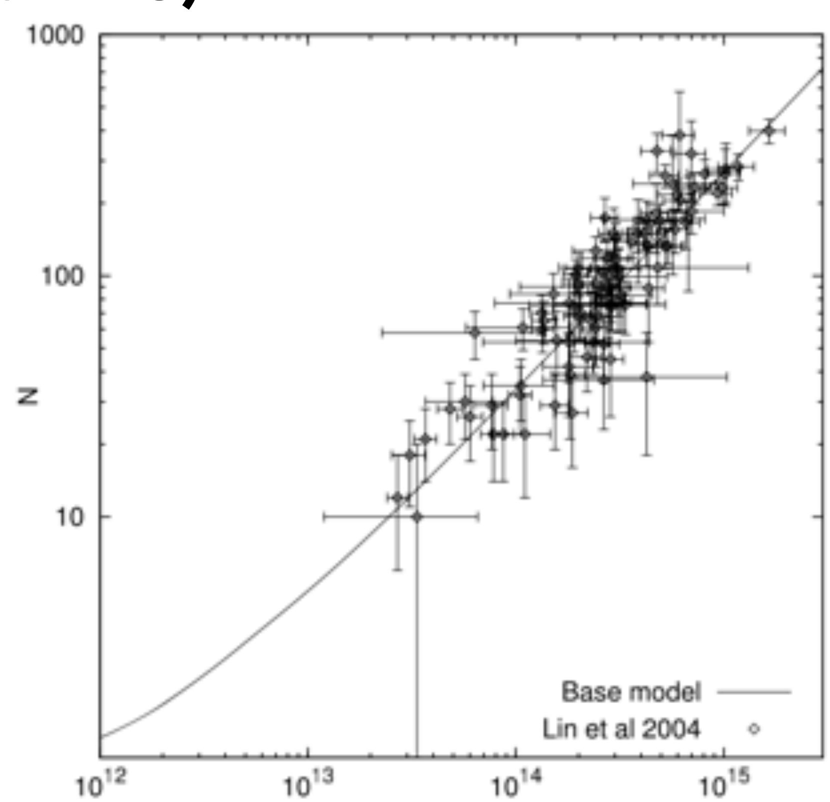
z<3

10^{12}



(2) N of seeds of Galaxy (subHalo)





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NEWS & PRESS

A universe of two trillion galaxies

Last Updated on Monday, 24 October 2016 11:26
Published on Thursday, 13 October 2016 14:00

An international team of astronomers, led by Christopher Conselice, Professor of Astrophysics at the University of Nottingham, have found that the universe contains at least two trillion galaxies, ten times more than previously thought. The team's work, which began with seed-corn funding from the Royal Astronomical Society, appears in the Astrophysical Journal today.

http://iopscience.iop.org/article/10.3847/0004-637X/830/2/83

https://www.ras.org.uk/news-and-press/2910-a-universe-of-two-trillion-galaxies

x10 more than before

# of galaxy (z<8) : 2×10^{12}

# of galaxy 10^6>Msun
reduces in evolution

THE EVOLUTION OF GALAXY NUMBER DENSITY AT $z < 8$ AND ITS IMPLICATIONS

Christopher J. Conselice, Aaron Wilkinson, Kenneth Duncan[1], and Alice Mortlock[2]

Published 2016 October 14 •
The Astrophysical Journal, Volume 830, Number 2

Metrics ▾

+ Article information

Abstract

The evolution of the number density of galaxies in the universe, and thus also the total number of galaxies, is a fundamental question with implications for a host of astrophysical problems including galaxy evolution and cosmology. However, there has never been a detailed study of this important measurement, nor a clear path to answer it. To address this we use observed galaxy stellar mass functions up to $z \sim 8$ to determine how the number densities of galaxies change as a function of time and mass limit. We show that the increase in the total number density of galaxies (ϕ_T), more massive than $M_* = 10^6\,M_\odot$, decreases as $\phi_T \sim t^{-1}$,

How many Galaxies in the Universe?

Count BHs to form a SMBH

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$$= 10^{-3} M_{\rm bulge}$$

(sub-)Galaxy
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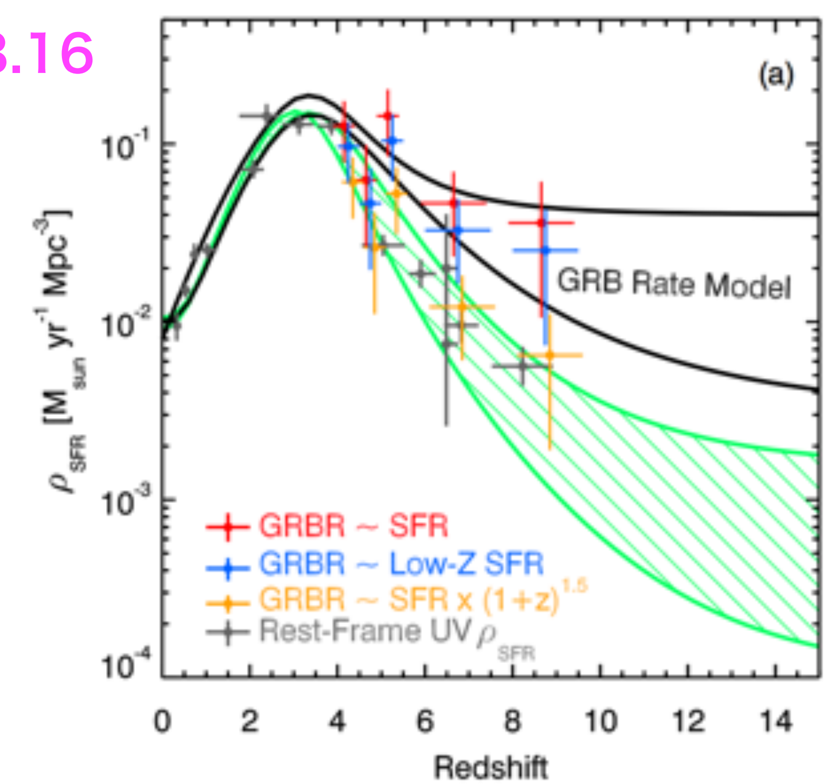
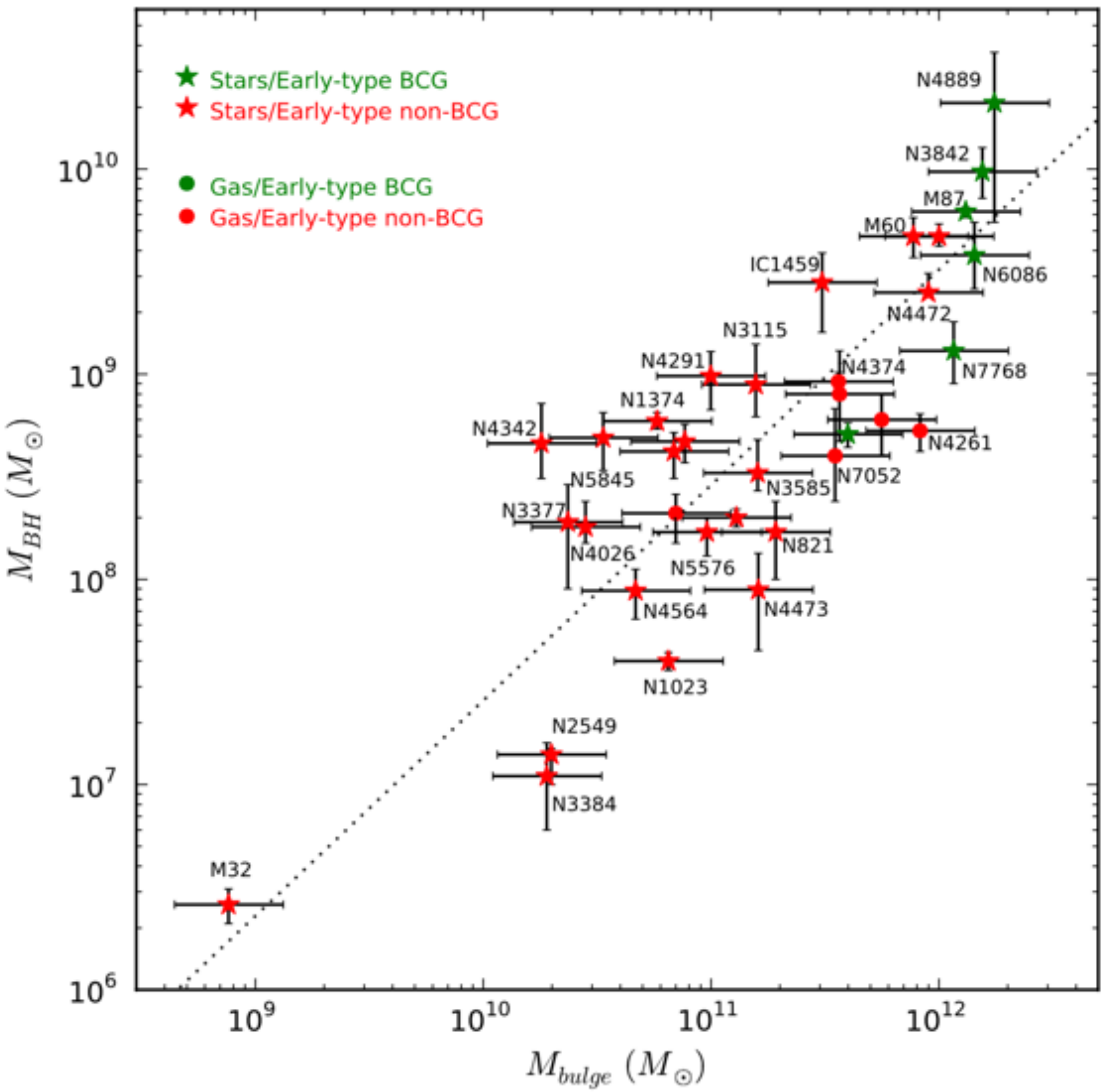


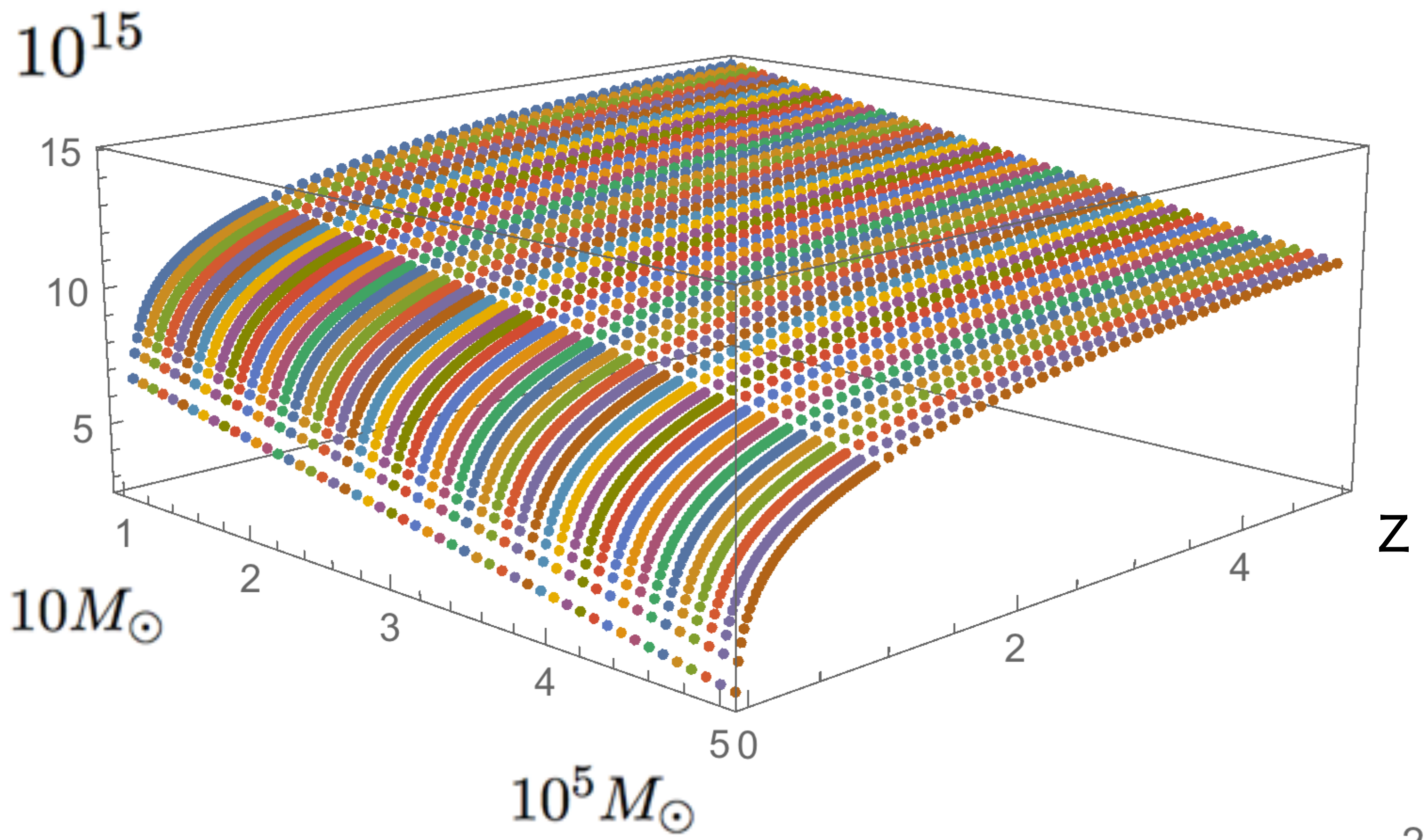


$$
\begin{aligned}
M_{\rm SMBH} &= 2\times 10^{-4} M_{\rm galaxy} \\
&= 10^{-3} M_{\rm bulge}
\end{aligned}
$$

McConnell-Ma
ApJ 764(2013)184

Figure 3. $M_\bullet$–$M_{\rm bulge}$ relation for the 35 early-type galaxies with dynamical measurements of the bulge stellar mass in our sample. The symbols are the same as in Figure 1. The black line represents the best-fitting power-law $\log_{10}(M_\bullet/M_\odot) = 8.46 + 1.05\ \log_{10}(M_{\rm bulge}/10^{11}\ M_\odot)$.

How many BH mergers in the Universe?

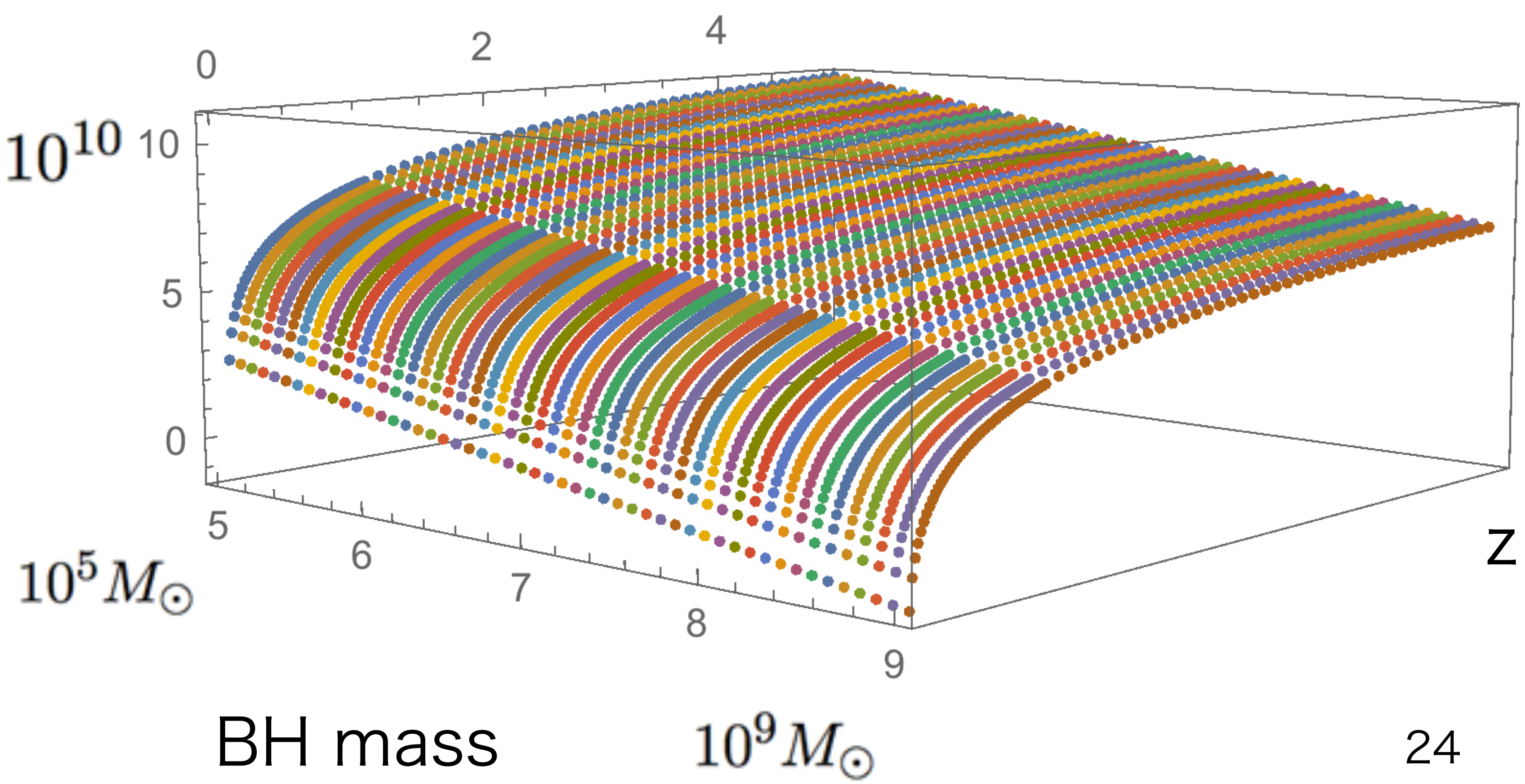


in Standard Cosmology

$$\text{Event Rate } R[/\text{yr}] = \frac{N_{\text{merger}}(z)}{V(D/2.26)}$$

Standard Cosmology

averaging distances for all directions



Signal-to-Noise Ratio (SNR)

Let the true signal $h(t)$, the function of time, is detected as a signal, $s(t)$, which also includes the unknown noise, $n(t)$:

$$s(t) = h(t) + n(t). \tag{17}$$

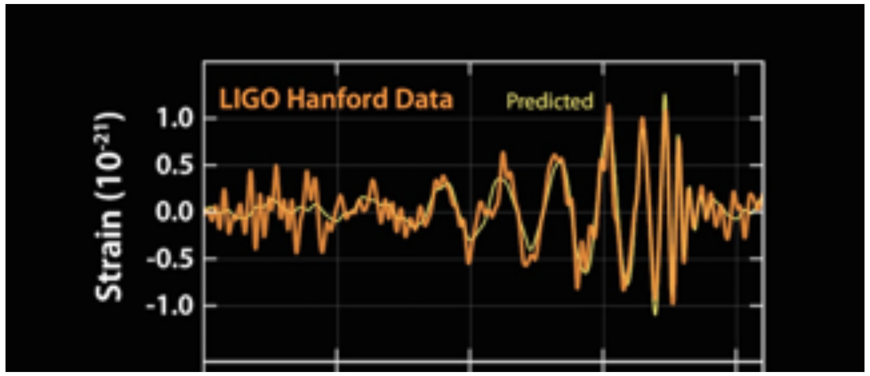
The standard procedure for the detection is judged by the optimal signal-to-noise ratio (SNR), ρ, which is given by

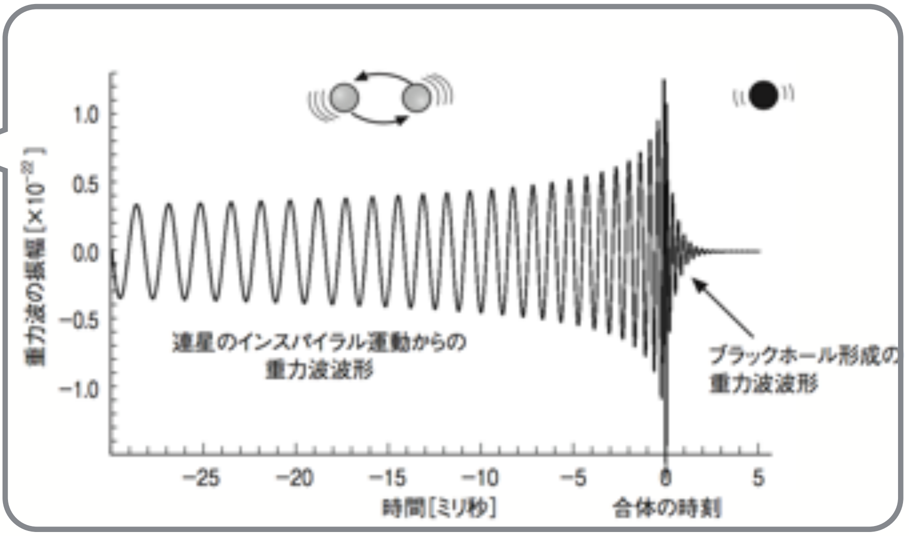
$$\rho = 2\left[\int_0^\infty \frac{\tilde{h}(f)\,\tilde{h}^*(f)}{S_n(f)}\,df\right]^{1/2}, \tag{18}$$

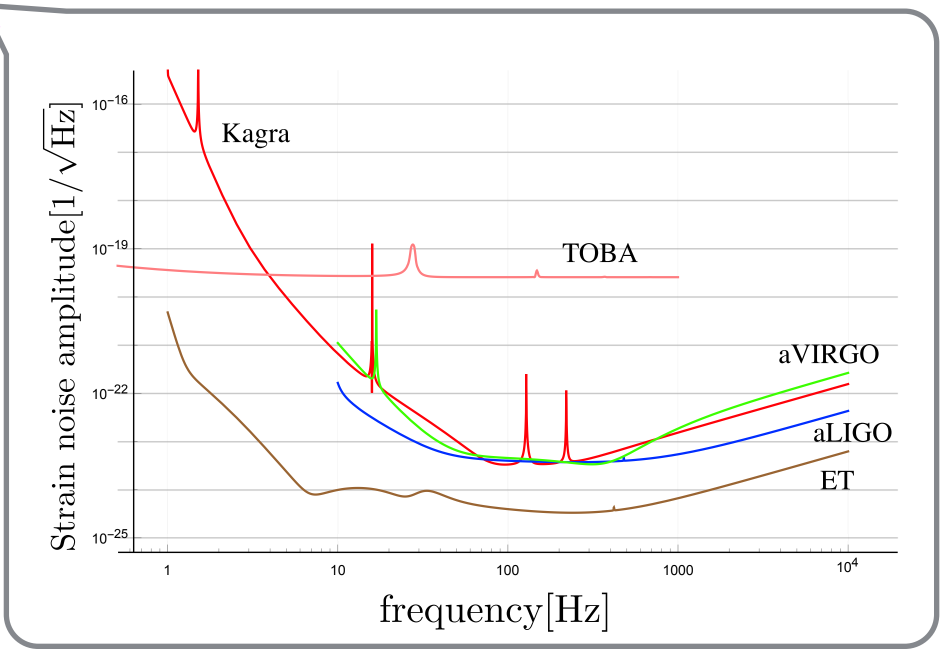
where $\tilde{h}(f)$ is the Fourier-transformed quantity of the wave,

$$\tilde{h}(f) = \int_{-\infty}^{\infty} e^{2\pi i f t}\, h(t)\, dt, \tag{19}$$

and $S_n(f)$ the (one-sided) power spectral density of strain noise of the detector, as we showed in Fig. 1.







Detectable Distances at bKAGRA

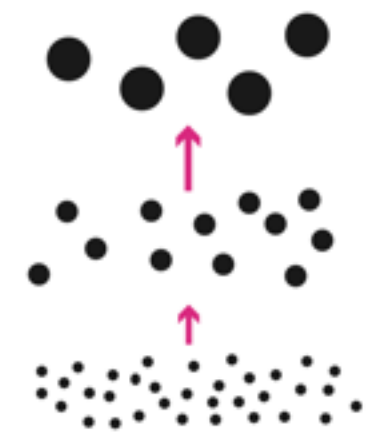
Flanagan&Hughes, PRD57(1998)4535

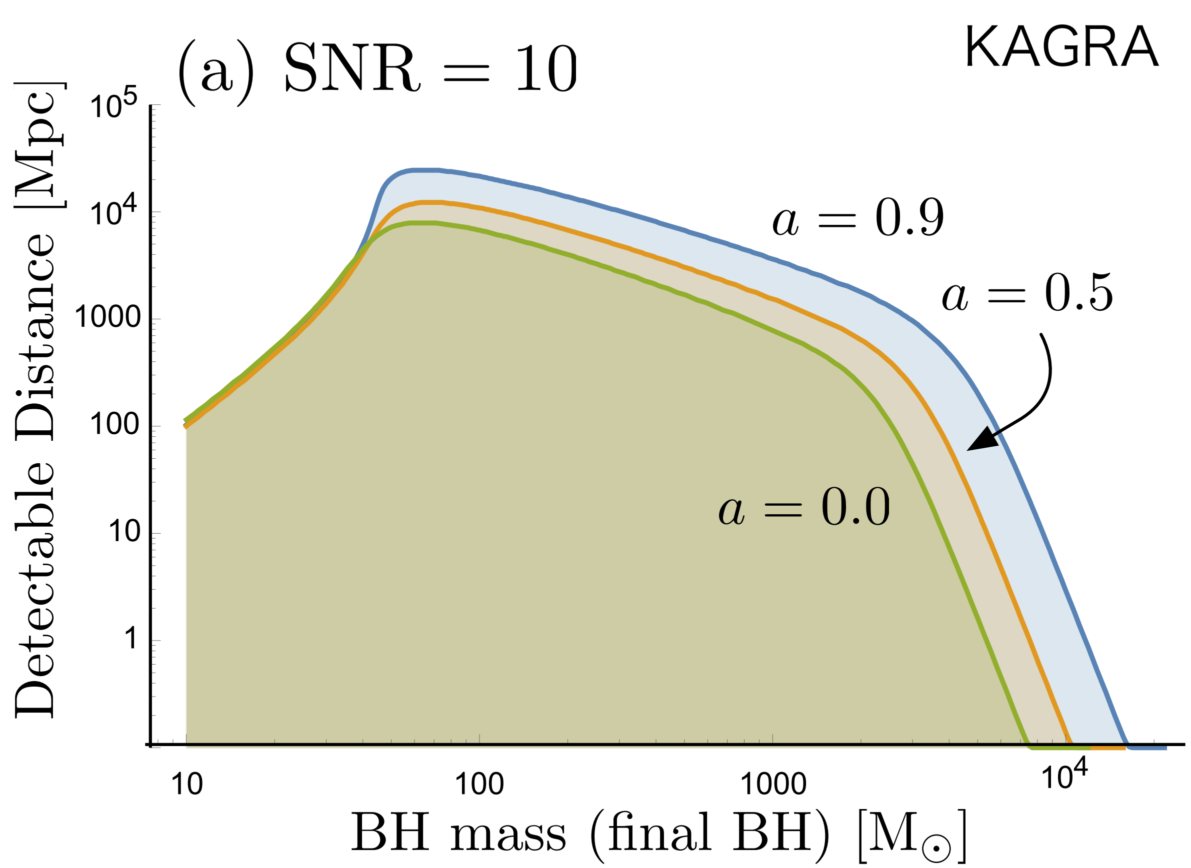
SNR $$\rho^2 = \frac{8}{5}\frac{\epsilon_r(a)}{f_R^2}\frac{(1+z)M}{S_h(f_R/(1+z))}\left(\frac{(1+z)M}{d_L(z)}\right)^2\left(\frac{4\mu}{M}\right)^2$$

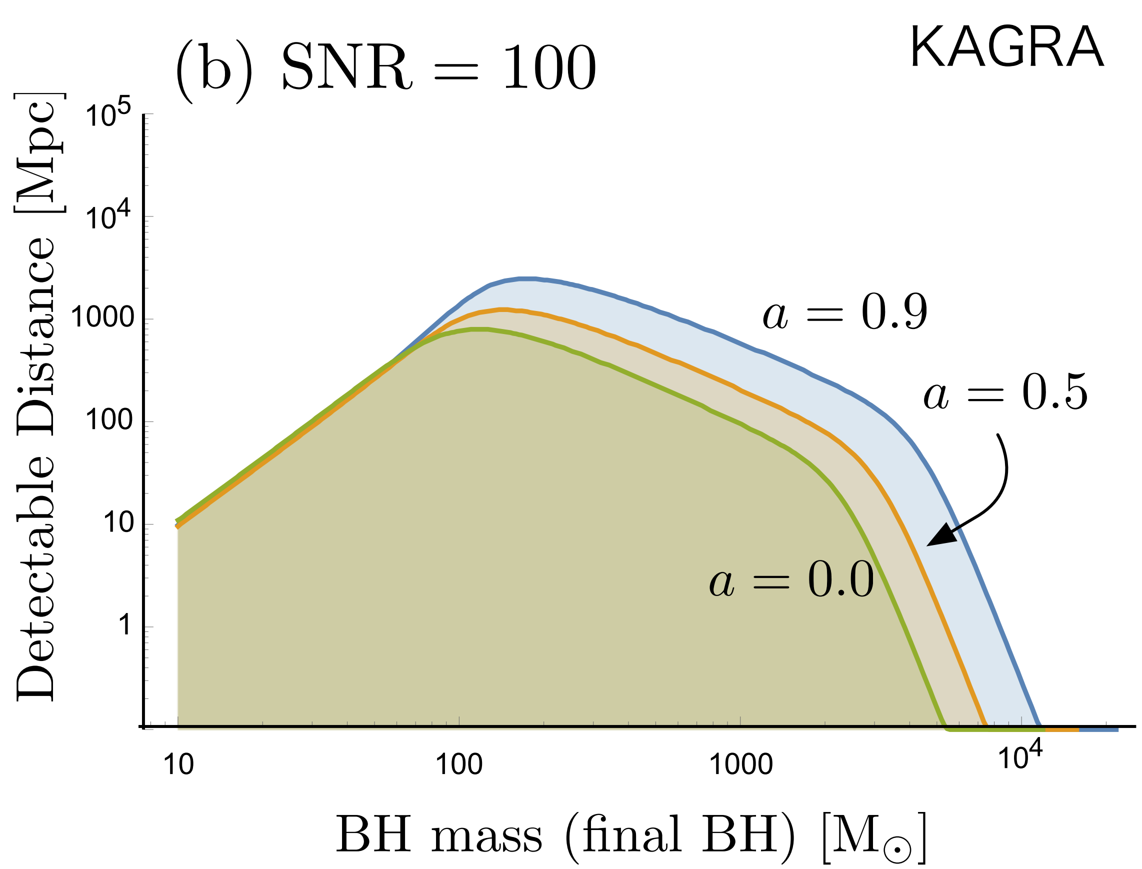
Energy emission=4% of total M, 1% at ringdown

Standard Cosmology

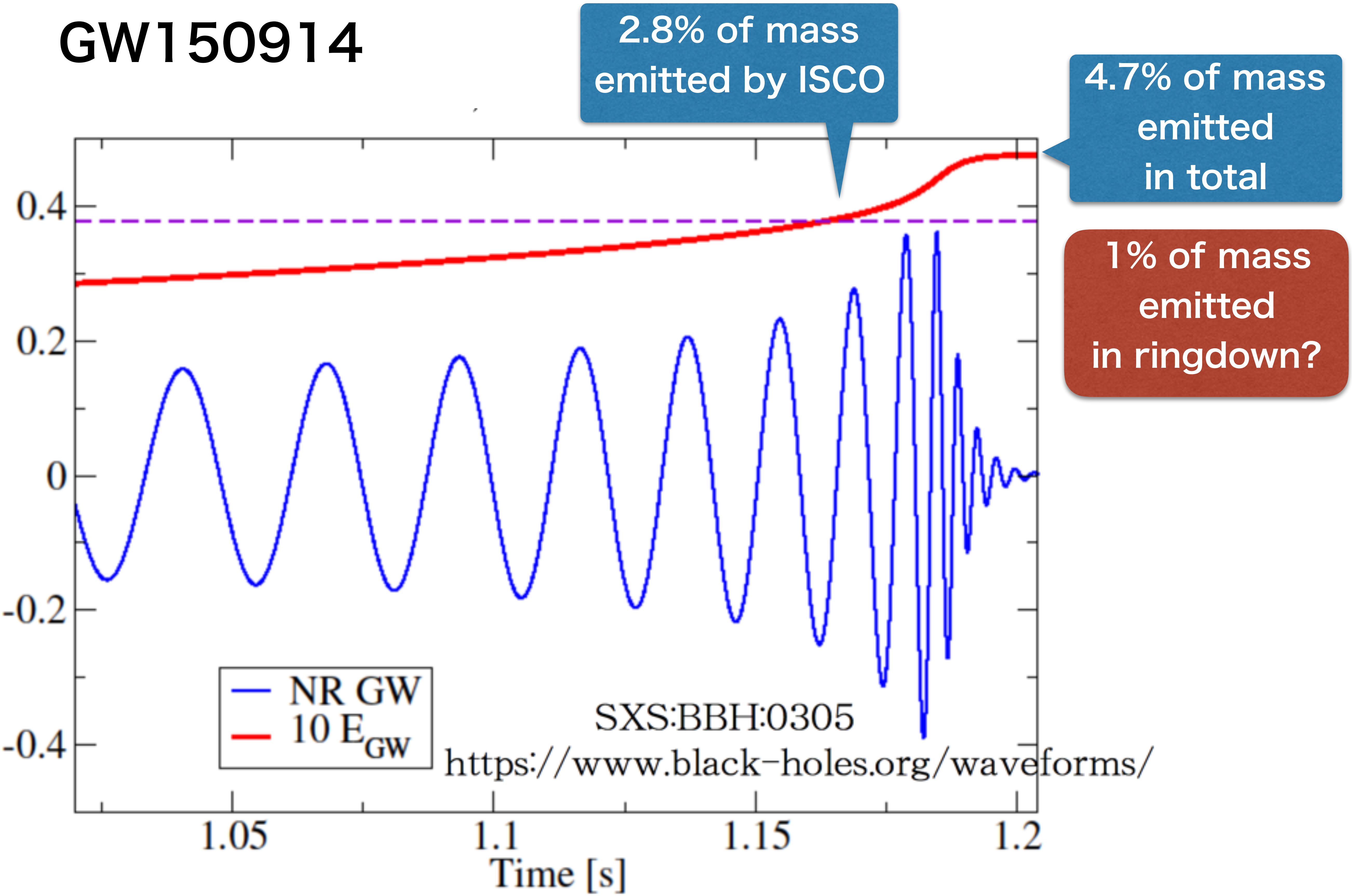
Hierarchical Growth





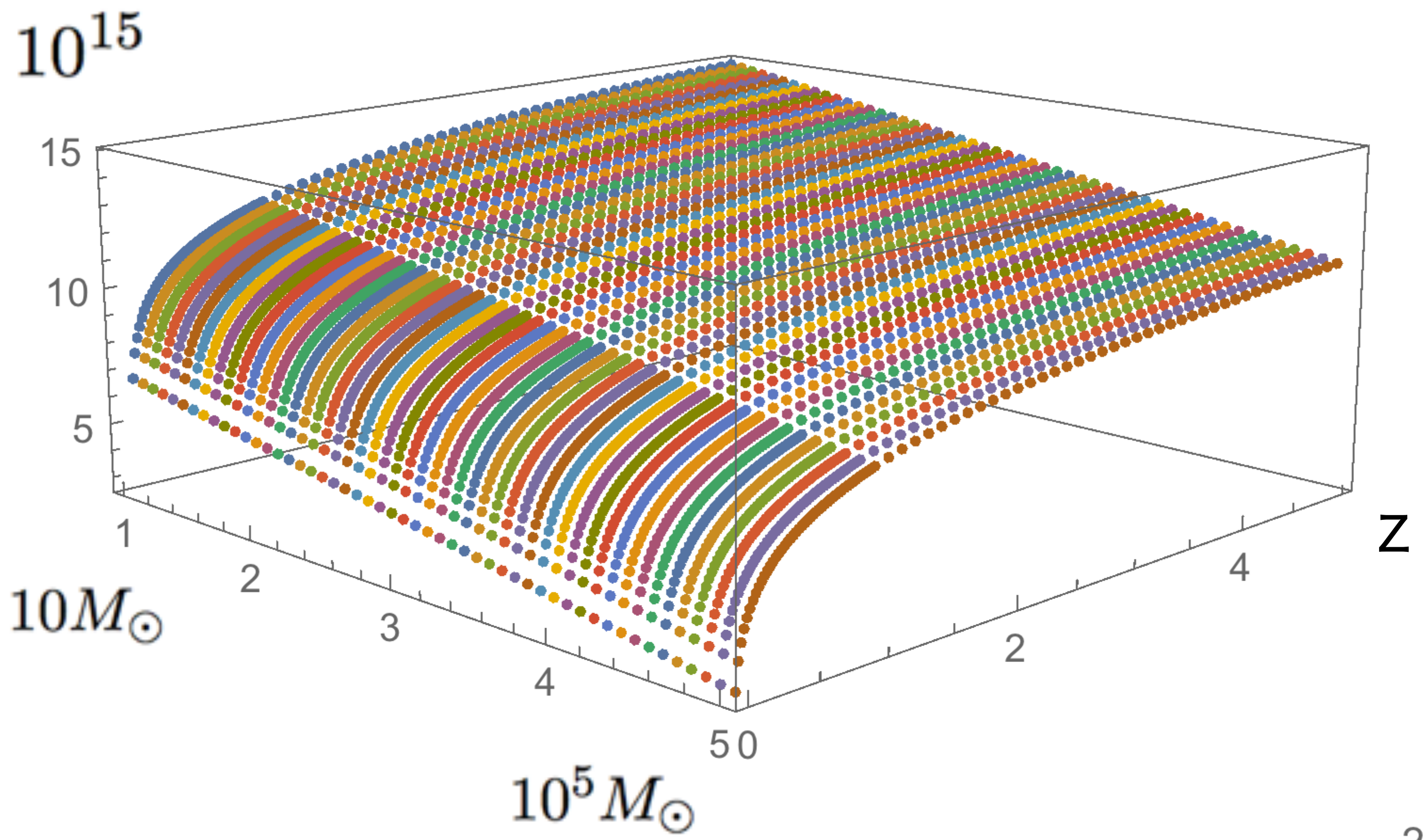


GW150914



Slide copy from Hiroyuki Nakano

How many BH mergers in the Universe?



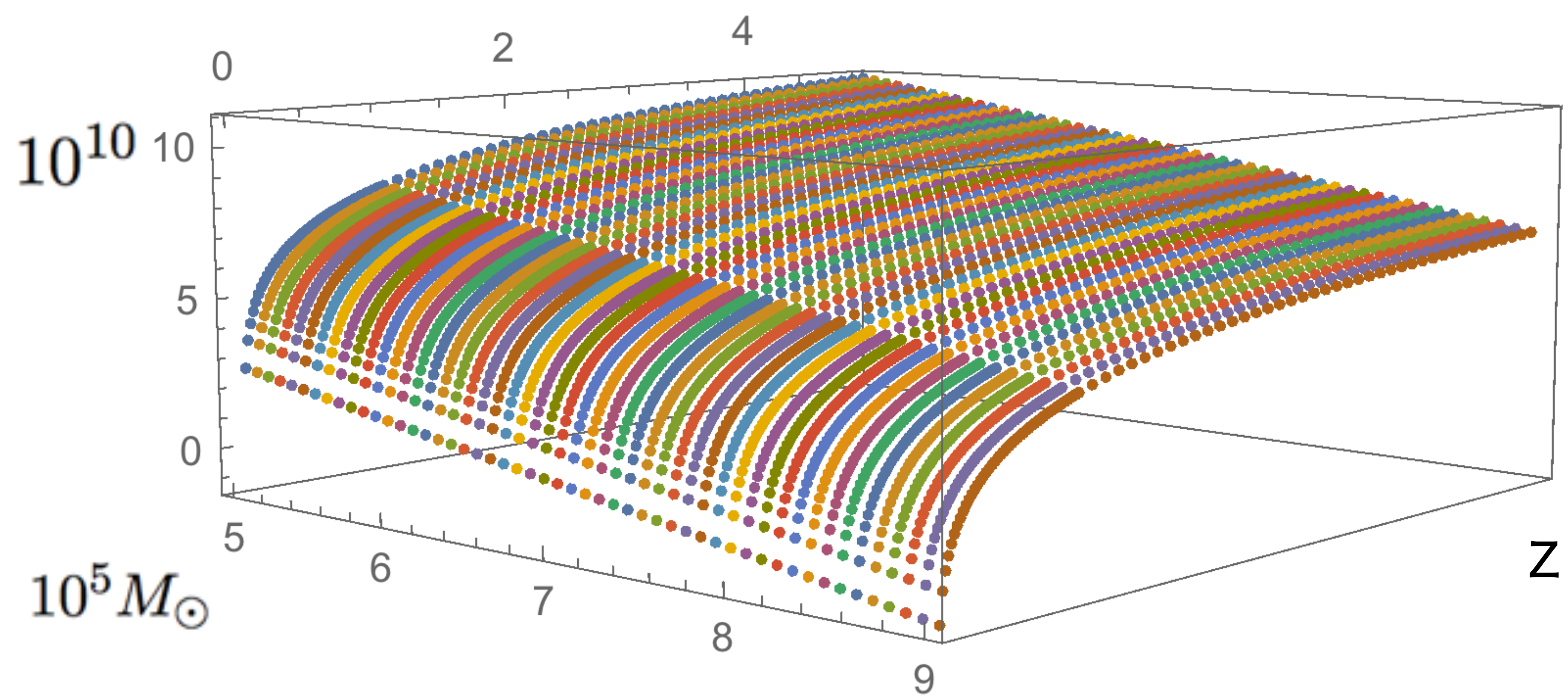
BH mass

in Standard Cosmology

$$\text{Event Rate } R[/\mathrm{yr}] = \frac{N_{\mathrm{merger}}(z)}{V(D/2.26)}$$

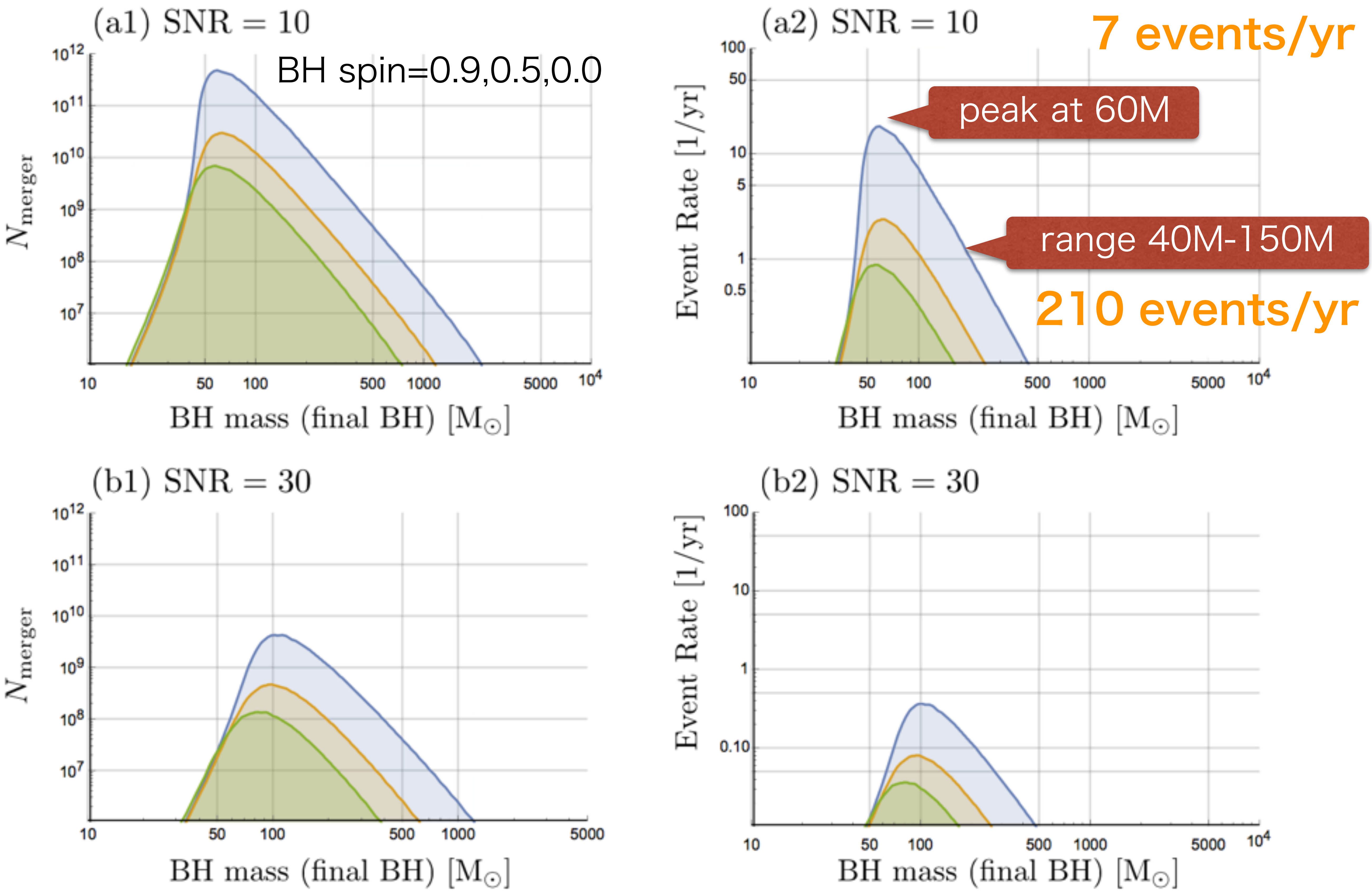
Standard Cosmology

averaging distances
for all directions



BH mass $10^9 M_\odot$

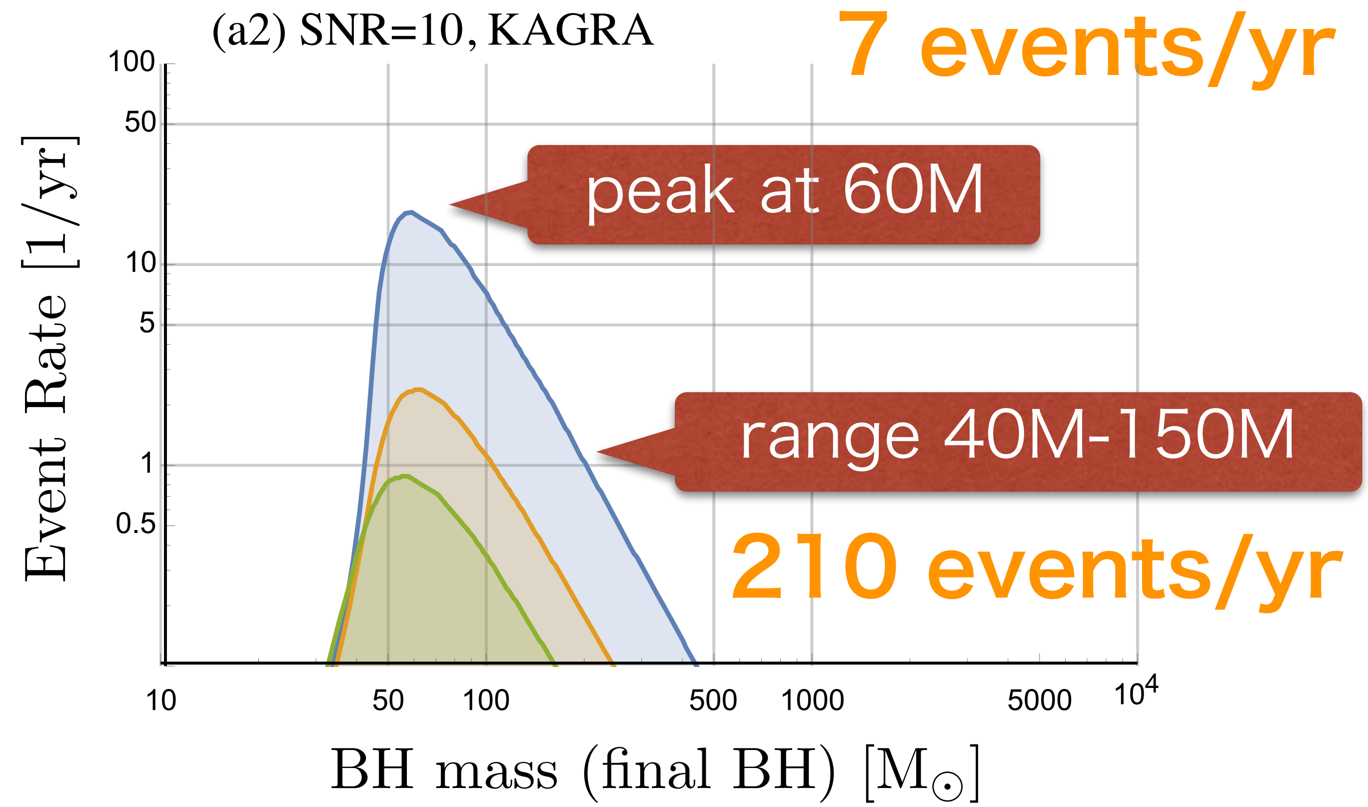
Event Rates at bKAGRA



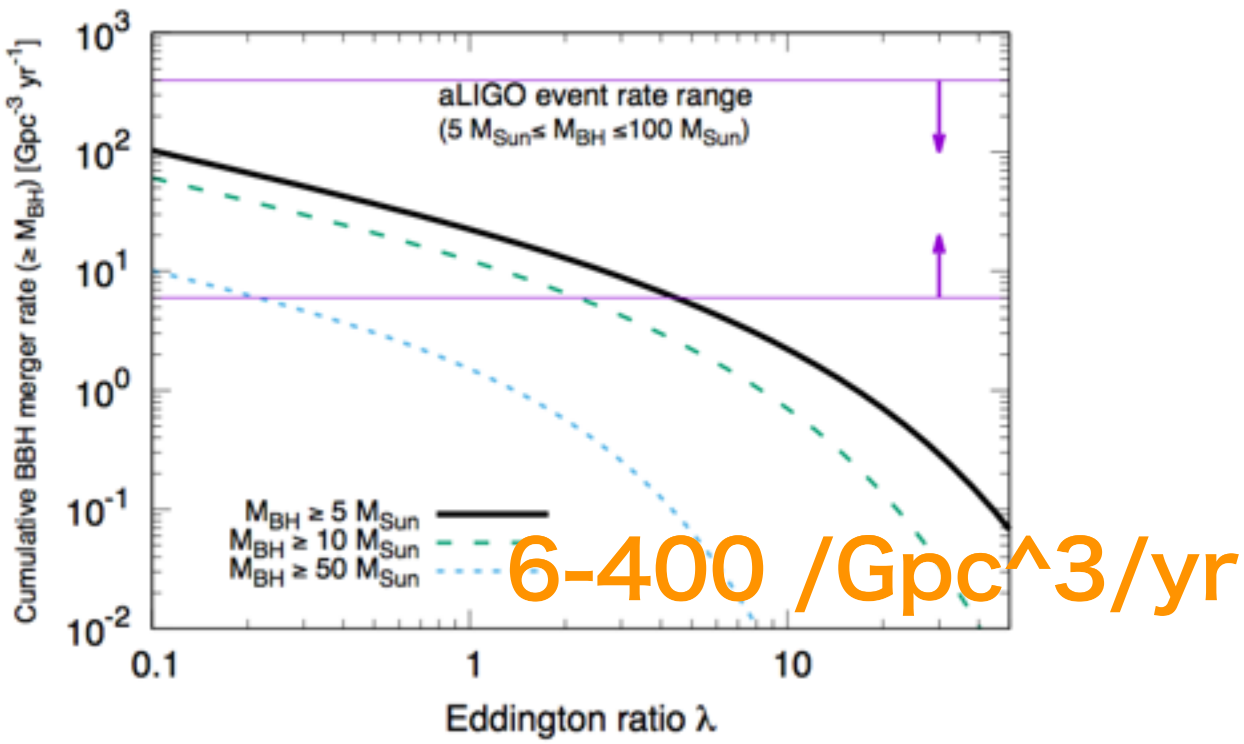
Event Rates at bKAGRA/aLIGO

LIGO group　PRX6(2016)041015

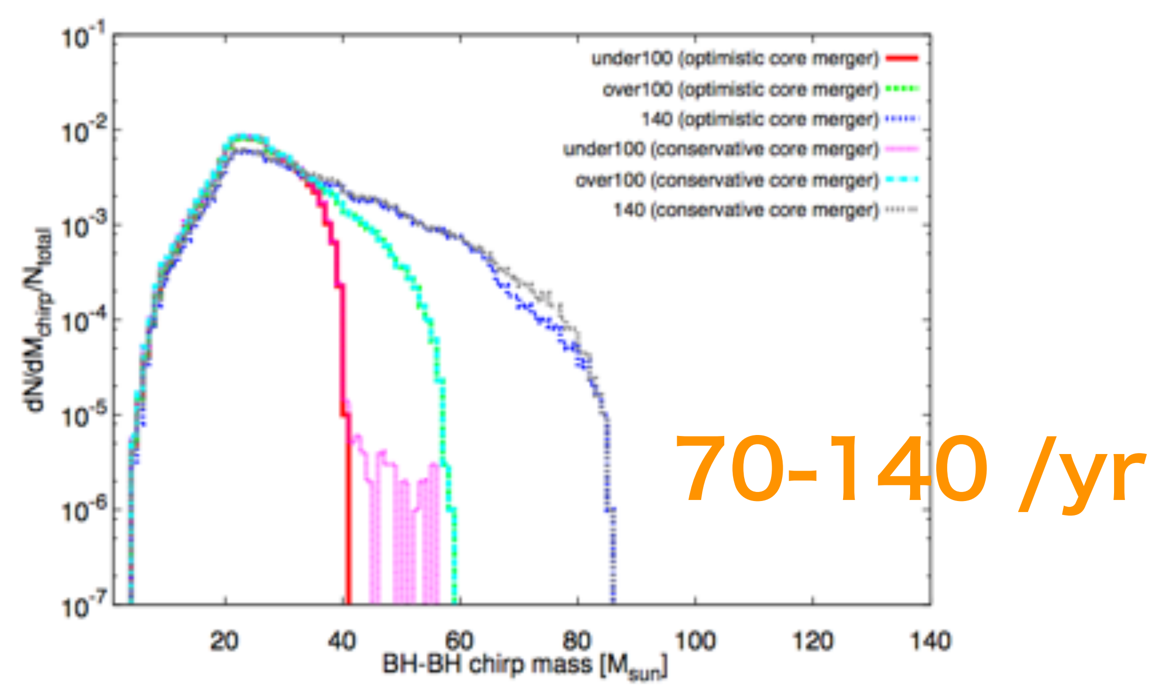
Mass distribution	PyCBC	GstLAL	Combined
	$R/(\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1})$		
	Event based		
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.8}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.1^{+31.0}_{-8.5}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	36^{+95}_{-30}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+103}_{-41}
	Astrophysical		
Flat in log mass	31^{+43}_{-21}	29^{+43}_{-21}	31^{+42}_{-21}
Power law (−2.35)	100^{+136}_{-69}	94^{+137}_{-66}	97^{+135}_{-67}



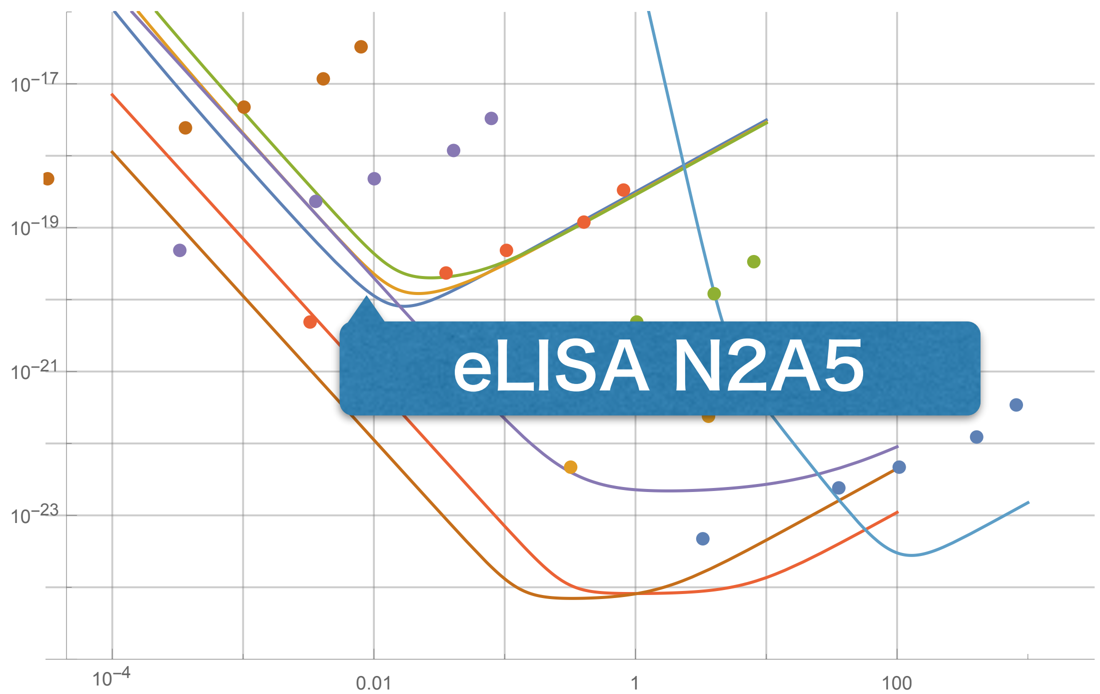
Inoue+ MNRAS461(16)4329



Kinugawa+ MNRAS456(15)1093

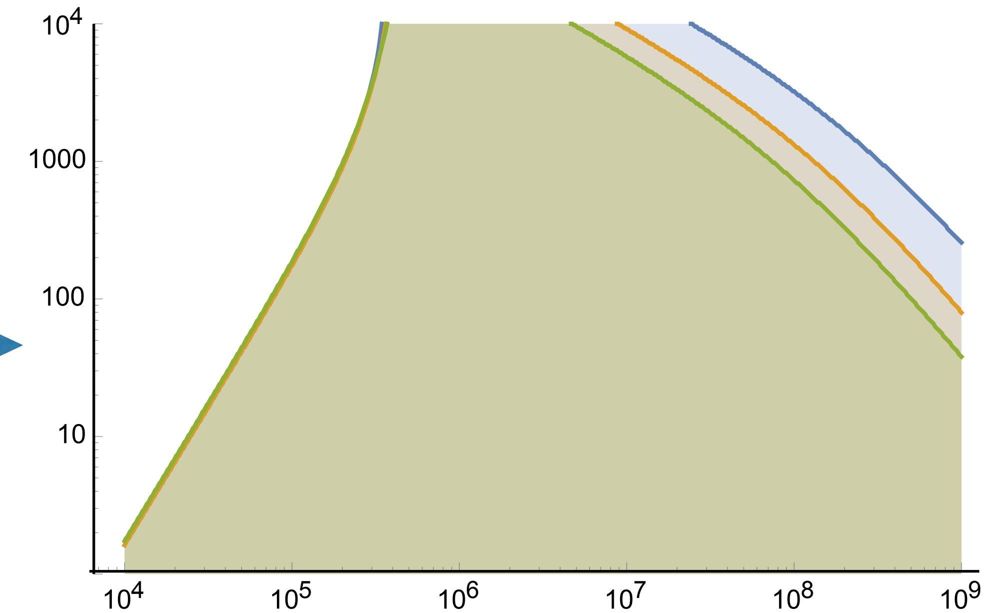


Event Rates at eLISA



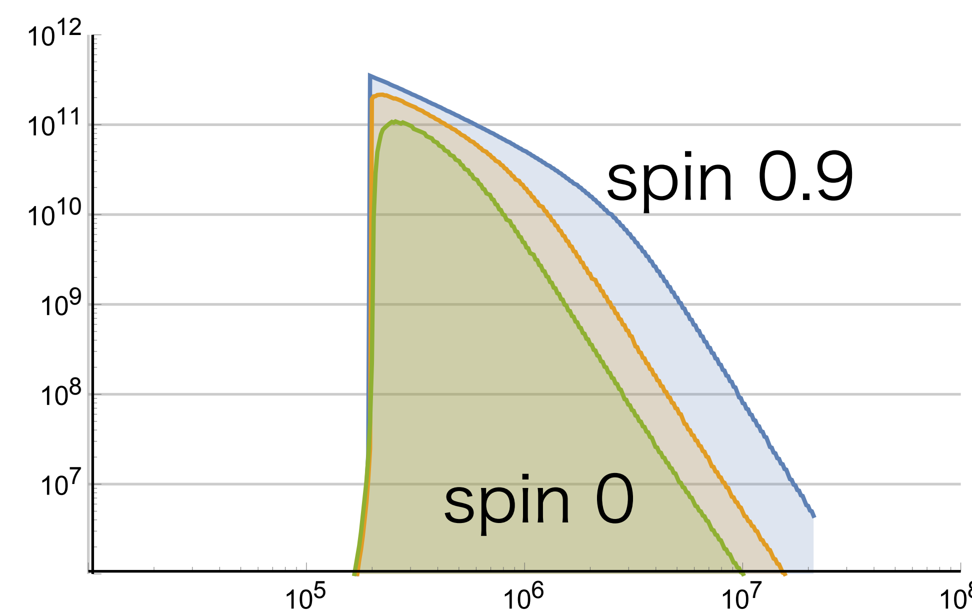
Horizon Distance

[Mpc] (S/N=10)



BH mass [Msun]

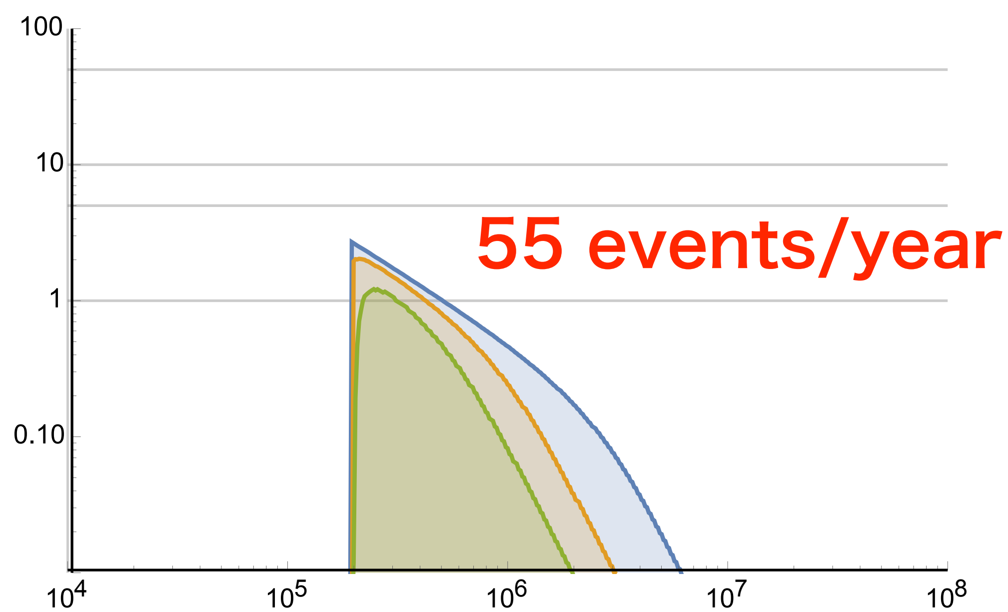
Observable BH mergers



BH mass [Msun]

Event Rate

(S/N=10)



BH mass [Msun]

Summary

Based on a bottom up formation model of a SMBH via IMBHs, we estimate expected observational profile of gravitational wave at ground-based detectors.

We simply modeled that cores of molecular clouds become BHs if it is more than 10 Msun, which become building blocks of forming larger BHs. We also modeled that BH mergers are accumulations of equal-mass ones and suppose these occurs hierarchically. We did not include gas accretion after a BH is formed.
Details numbers are, of course, depend on model settings and model parameters.
We assume all the galaxies in the Universe evolve in the single scenario, which will over-estimate the event rate if some SMBHs are formed from the direct collapse of gas cloud. We also ignore galaxy mergers, which are another route of forming SMBHs.

If we will observe BH-BH mergers above 100 Msun, this model is the only one to predict such an event.

The statistics of the signals will tell us both a galaxy distribution and a formation model of SMBHs, and also in future cosmological models/gravitational theories.