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Gravitational waves from merging intermediate-mass black-holes

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Outline & Summary

- Based on a dynamical formation model of a super-massive black-hole (SMBH), we estimate expected observational profile of gravitational wave at ground-based detectors, such as KAGRA or advLIGO/VIRGO. Focusing that the second generation of detectors have enough sensitivity from 10 Hz and up (especially with KAGRA due to its location at less seismic noise), we are able to detect the ring-down gravitational wave of a BH of the mass $M < 2 \times 10^3 M_\odot$. This enables us to check the sequence of BH mergers to SMBH via intermediate-mass black-holes (IMBHs).
- We estimate the number density of galaxy from halo formation model, and estimate the number of BH mergers from giant molecular cloud model together with hierarchical growth of merged cores. By estimating the event rate R at the designed KAGRA and predicted mass distribution of detected events, we find that, at the signal-to-noise ratio $\rho = 10$, the event of the BH mergers of its total mass $M \sim 60 M_\odot$ is at the peak of the mass distribution which is $R \sim 7$ per year.
- We also find that BH mergers of the range $40 M_\odot < M < 150 M_\odot$ are $R > 1$ per year, and the designed KAGRA (and/or advanced LIGO/VIRGO) will see ~ 200 events per year in the most optimistic case. Thus we conclude that the statistics of the signals will tell us both a galaxy distribution and a formation model of SMBHs. Especially, if we observe a BH with more than $100 M_\odot$ in future gravitational wave observations, our model naturally explains its source.

A route to a SMBH

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	106.9
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

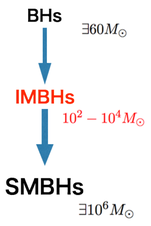
Yagi, CQG 29 075005 (2012)
[arXiv:1202.3512]

'Missing link' founded
Ebisuzaki +, ApJ, 562, L19 (2001)

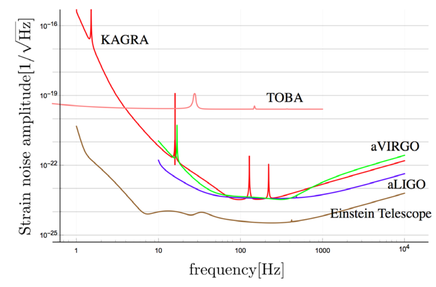
(1)formation of IMBHs by runaway mergers of massive stars in dense star clusters,
Marchant & Shapiro 1980; Portegies Zwart et al. 1999; Portegies Zwart & McMillan 2002; Portegies Zwart et al. 2004; Holger & Makino 2003

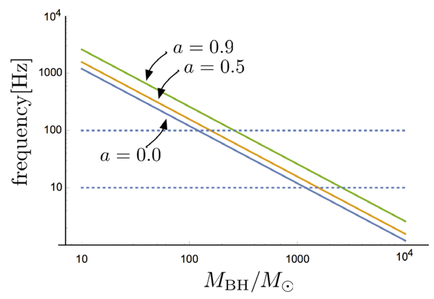
(2) accumulations of IMBHs at the center region of a galaxy due to sinkages of clusters by dynamical friction
Matsubayashi et al. 2007

(3) mergings of IMBHs by multi-body interactions and gravitational radiation.
Iwasawa et. al. 2010



IMBH ringdown freq. is within KAGRA band





How many BHs in a galaxy?

How many BHs in a Galaxy?

Mass Function of Giant Molecular Clouds

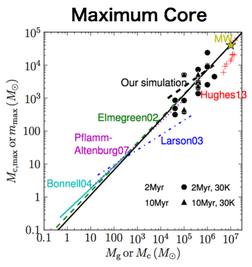
$n_{\rm cl}(M) \sim M^{-1.7} \exp\left(-\frac{M}{M_{\rm cut}}\right), \quad M_{\rm cut} = 10^6 M_\odot$

$10^{12} M_\odot$ galaxy mass
$10^9 M_\odot$
GMC mass $M_\odot$

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?

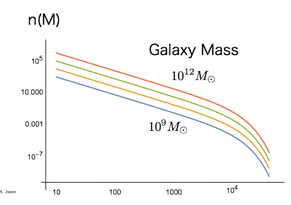
Molecular Clouds
Maximum Core



The initial mass function of star clusters that form in turbulent molecular clouds
M. S. Fujii[1,*] and S. Portegies Zwart[2,*]
1309.1223v3

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

Building Block BH



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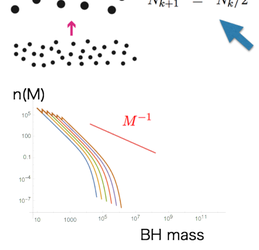
How many BHs in a Galaxy?

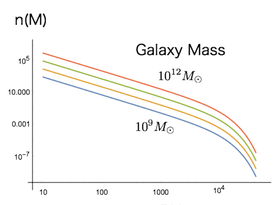
Hierachical growth model

Count BHs to form a SMBH

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



Building Block BH



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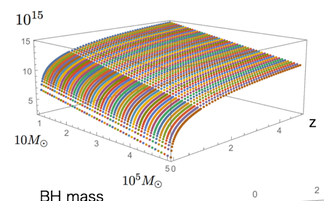
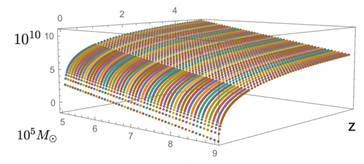
How many BH mergers ?

How many BH mergers in the Universe?



in Standard Cosmology

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



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How many galaxies in the Universe?

How many Galaxies in the Universe?

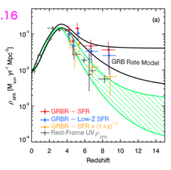
Count BHs to form a SMBH

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

(sub-)Galaxy from Halo model

Star Formation Rate
peak z=3.16

The non-parametric model for linking galaxy luminosity with halo/subhalo mass
A. Vale[1*] and J. P. Ostriker[1,2]

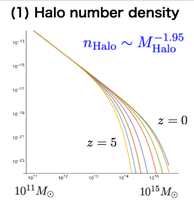


CONNECTING THE GAMMA RAY BURST RATE AND THE COSMIC STAR FORMATION HISTORY: IMPLICATIONS FOR REIONIZATION AND GALAXY EVOLUTION
BRANT E. ROBERTSON[1,2] AND RICHARD S. ELLIS[2]

How many Galaxies in the Universe?

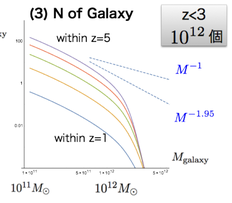
(1) Halo number density

$n_{\rm Halo} \sim M_{\rm Halo}^{-1.95}$



(3) N of Galaxy

z<3
10^{12} 個



(2) N of seeds of Galaxy (subHalo)

$N_{\rm subHalo} \sim M_{\rm Halo}^{0.90}$

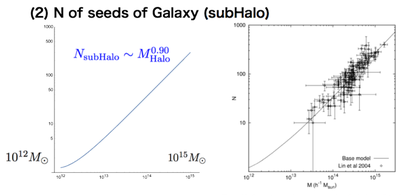


Figure 12. Occupation number: average number of galaxies predicted for a parent halo of mass M, given by the sum of the number of subhaloes with galaxies above a given luminosity plus one for the central galaxy. The luminosity threshold adopted was $M_R < -21$, which corresponds to the minimum used for the observed data points plotted, taken from Lin et al. (2004).

How many Galaxies in the Universe?

Count BHs to form a SMBH

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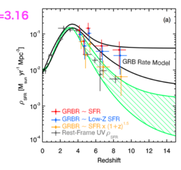

CONNECTING THE GAMMA RAY BURST RATE AND THE COSMIC STAR FORMATION HISTORY: IMPLICATIONS FOR REIONIZATION AND GALAXY EVOLUTION
BRANT E. ROBERTSON[1,2] AND RICHARD S. ELLIS[2]

IMBH inspiral at Space Interferometers

THE ASTROPHYSICAL JOURNAL, 614:864–868, 2004 October 20
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ApJ 614 (2004) 864

GRAVITATIONAL WAVES FROM MERGING INTERMEDIATE-MASS BLACK HOLES

TATSUSHI MATSUBAYASHI,[1] HISA-AKI SHINKAI,[2] AND TOSHIKAZU EBISUZAKI[2]

FIG. 1.—Expected gravitational radiation amplitude from merging IMBHs of (*a*) the hierarchical growth model and (*b*) the monopolistic growth model. We plot 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 filled circles and squares in the inspiral phase are of $a = 50R_{\rm grav}$, $10R_{\rm grav}$, and $5R_{\rm grav}$. The final burst frequency, $f_{\rm QNM}$, depends on the efficiency, ϵ, which we fix at $\epsilon \simeq 10^{-2}$ for the plots. The lines represent the sensitivities of 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.

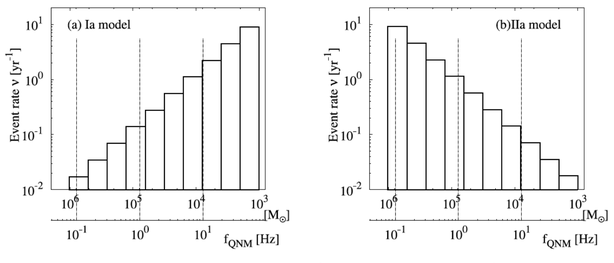


FIG. 2.—Event numbers of mergers starting from 1000 IMBHs with masses of $10^3\ M_\odot$. The vertical axis is the event rate ν(yr^{-1}) from eqs. (12), and (14). The horizontal axis is for the mass of the postmerger BH, M_T, which is also interpreted in the final gravitational radiation frequency $f_{\rm QNM}$. Panels (*a*) and (*b*) are for the hierarchical growth model and for the monopolistic growth model, respectively. Both plots are for a homogeneous distribution model in which we just multiply by 3 each event rate for the thin-shell galaxy distribution model. If a SMBH expands hierarchically, then the bursts of gravitational radiation appear in the higher frequency region. In the monopolistic model, the bursts appear in lower frequency region. We fix the increasing-mass rate, α, at unity for the plots.

MODELS IN THIS PAPER

SMBH FORMATION MODEL	GALAXY DISTRIBUTION: Thin Shell (eq. 8)	GALAXY DISTRIBUTION: Homogeneous (eq. [9])
Hierarchical growth (eq. [11b])	Ia	Ib
Monopolistic growth (eq. [11c])	IIa	IIb

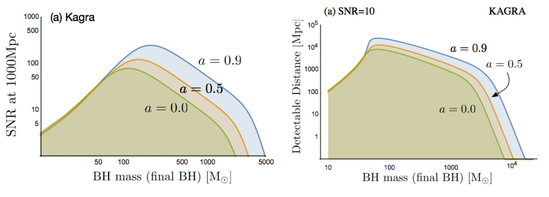
Event Rates at KAGRA

Detectable Distances at bKAGRA

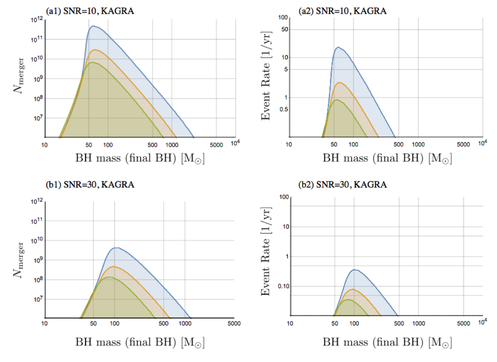
SNR $\rho^2 = \frac{8}{5} \frac{\epsilon_E(a)}{f_R^2} \frac{(1+z)M}{S_h(f_R/(1+z))} \left(\frac{(1+z)M}{d_L(z)}\right)^2 \left(\frac{4\mu}{M}\right)^2$

Hierachical Growth

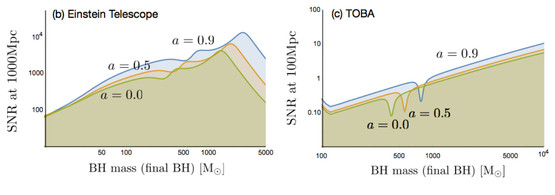
4% of total mass, 1% at ringdown part



Event Rates at bKAGRA



Detectable Distances at ET/TOBA



SNR = 10, KAGRA, spin parameter averaged