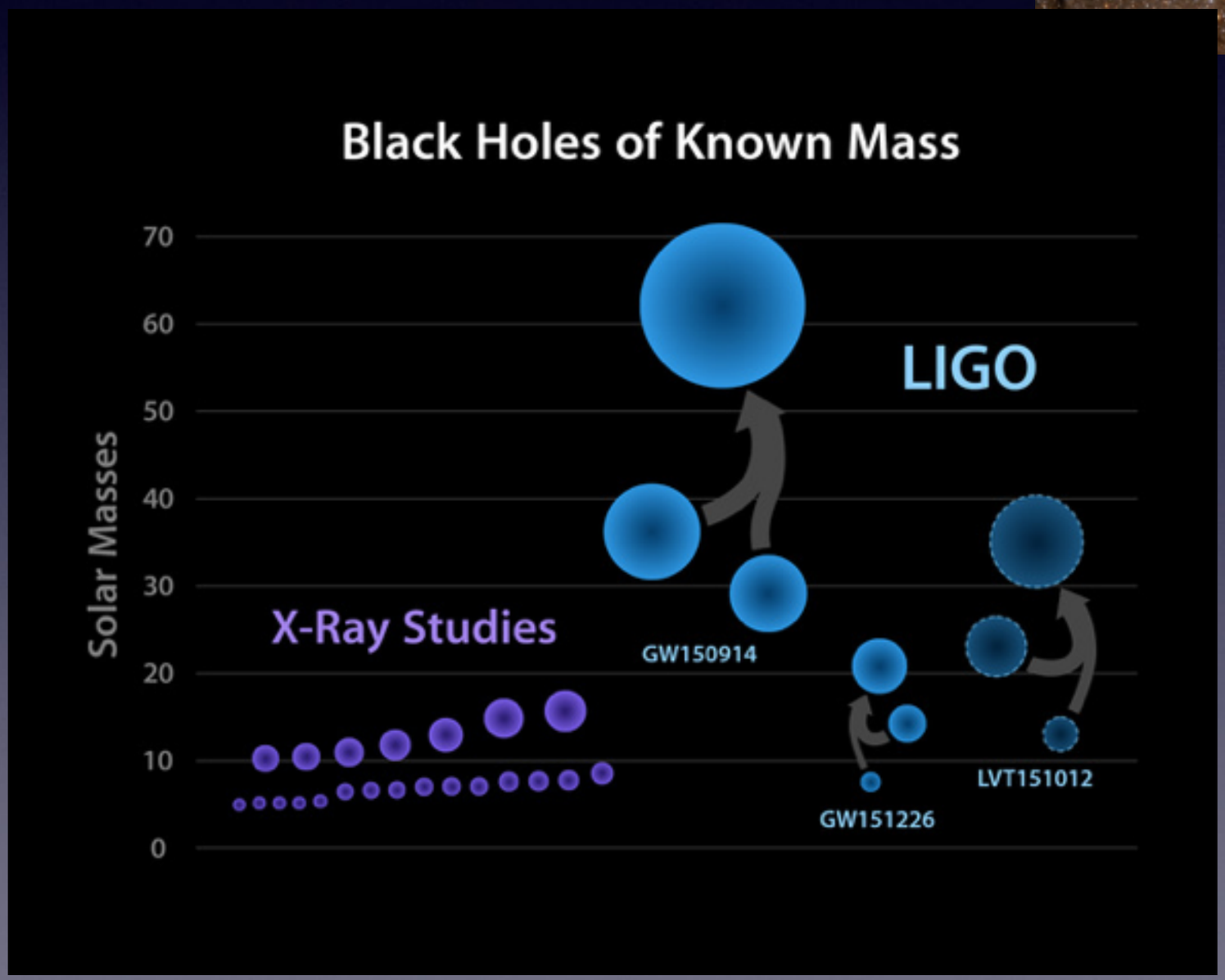
重力波観測による
巨大ブラックホール形成シナリオ解明 の可能性

真貝寿明　(大阪工業大)
神田展行　(大阪市立大)
戎崎俊一　(理化学研究所)

IMBH から SMBH のモデル
銀河内のBH数，銀河分布を仮定し，
KAGRAでのEvent Rateを予測する.

2016年９月15日　天文学会@愛媛大学
セッション「重力波初検出の意義と重力波天文学の幕開け」

BHs!

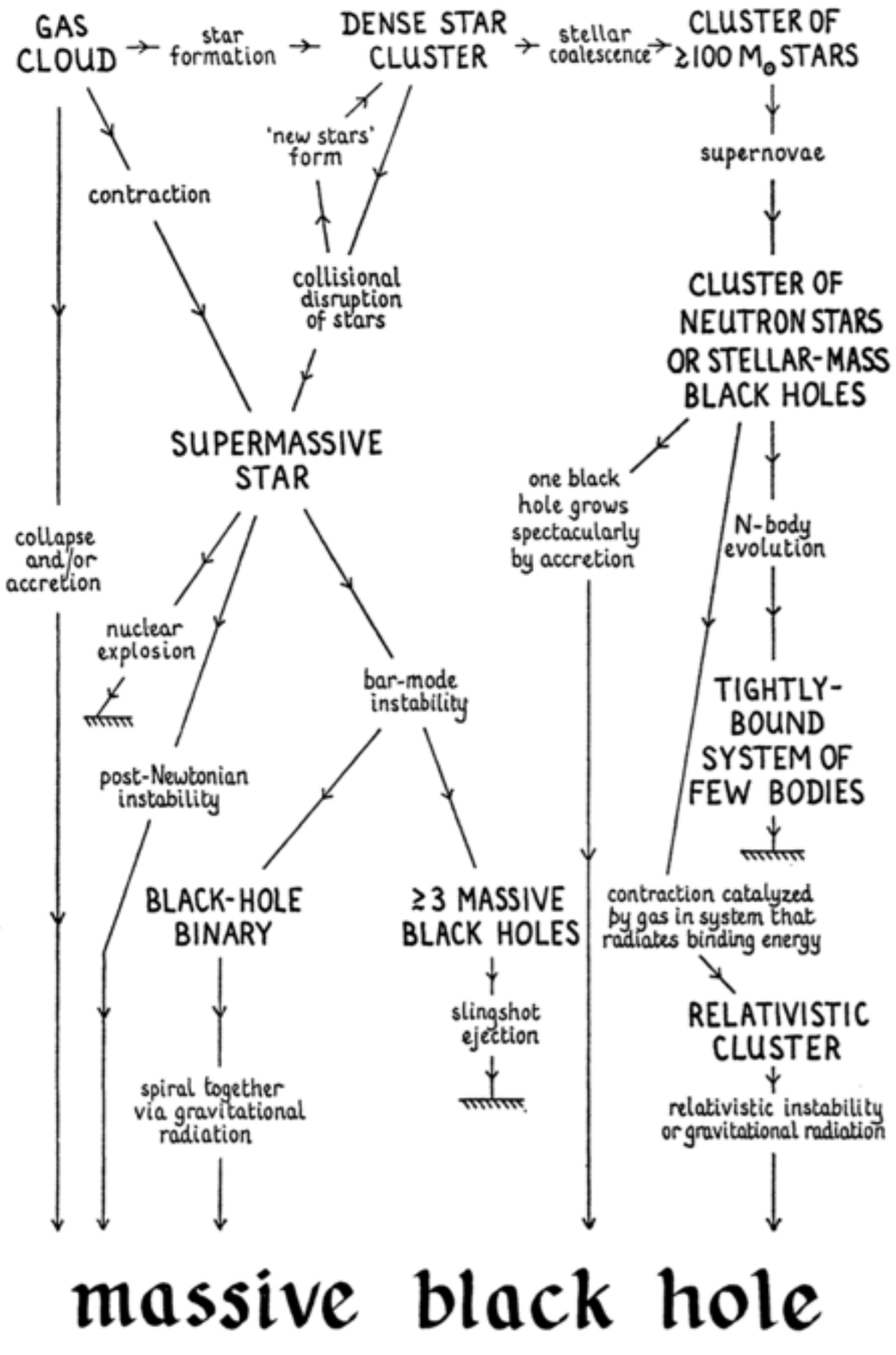


7M+14M=20M

29M+36M=62M

why not more?

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



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

Halo

Massive Stars

Gas Cloud

BHs

$\exists 60 M_\odot$

Globular Cluster

IMBHs

$10^2 - 10^4 M_\odot$

Galaxy

SMBHs

$\exists 10^6 M_\odot$

Starburst galaxy M82 has 1000M BH

Matsushita+, ApJ, 545, L107 (2000)

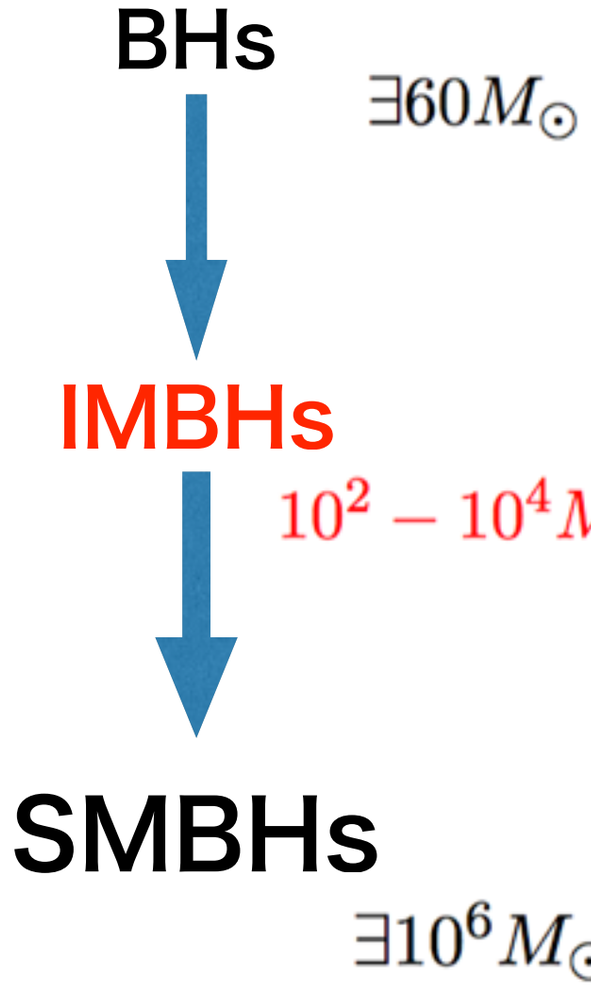
Matsumoto+, ApJ, 547, L25 (2001)

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,

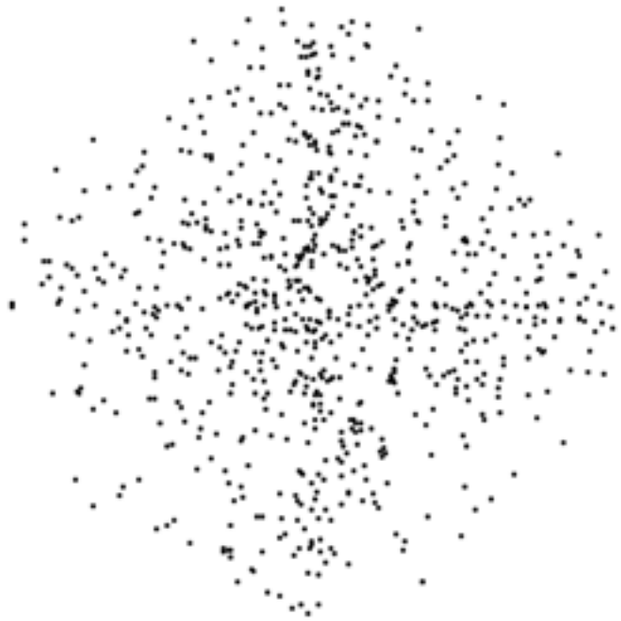
Marchant & Shapiro 1980; Portegies Zwart et al. 1999;
Portegies Zwart & McMillan 2002;
Portegies Zwart et al. 2004;
Holger & Makino 2003

(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



BHs $\exists 60 M_\odot$

IMBHs $10^2 - 10^4 M_\odot$

SMBHs $\exists 10^6 M_\odot$

宇宙空間での重力波干渉計で形成過程がわかる

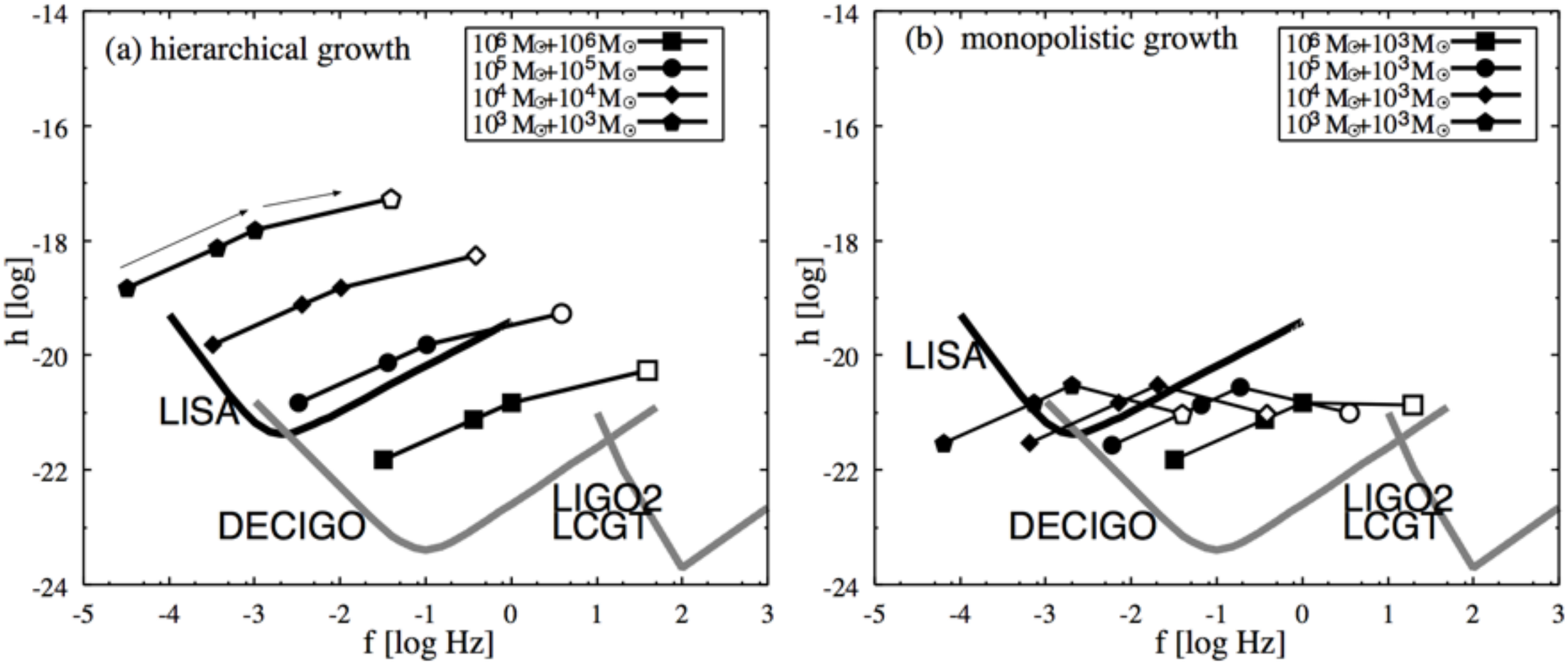
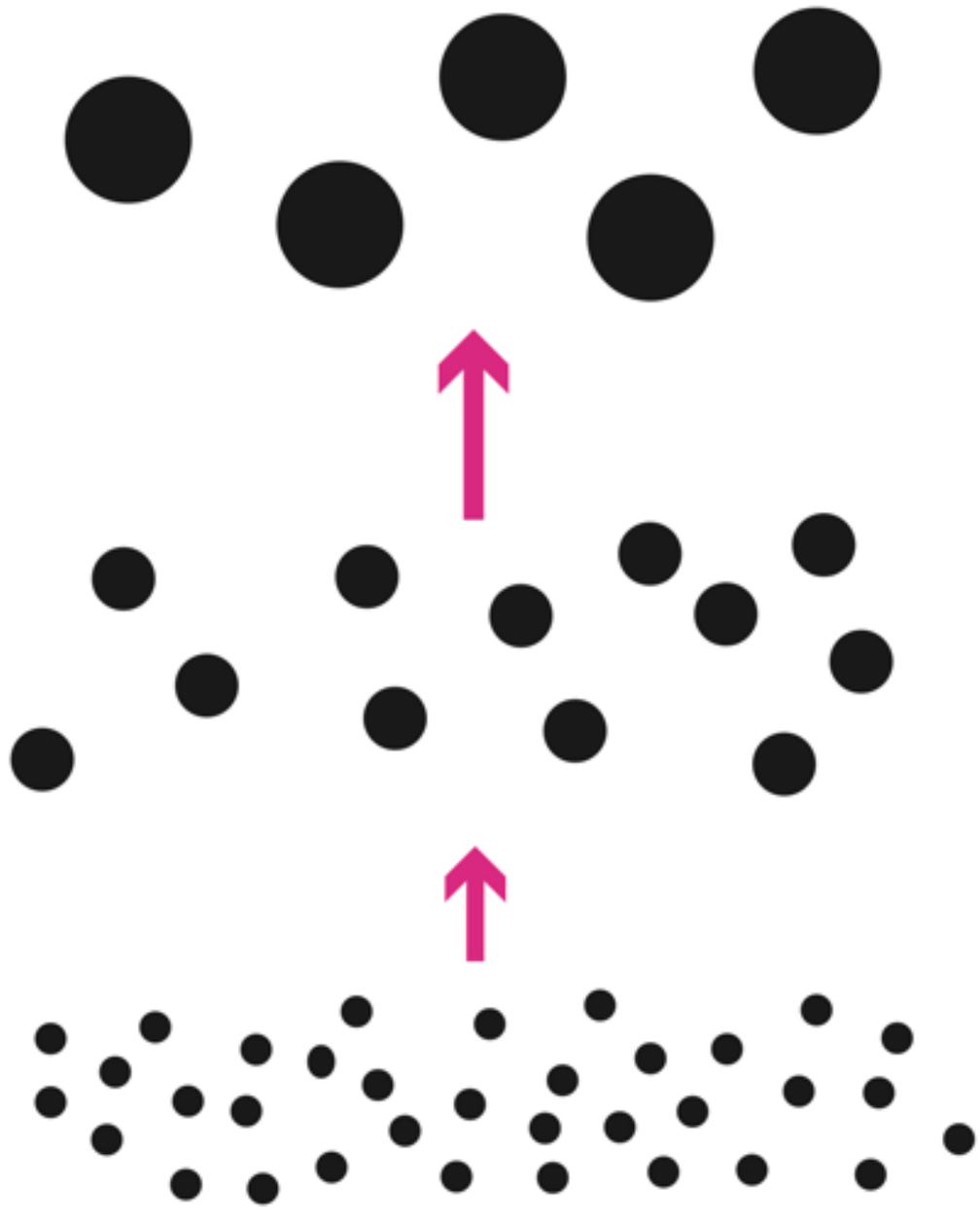


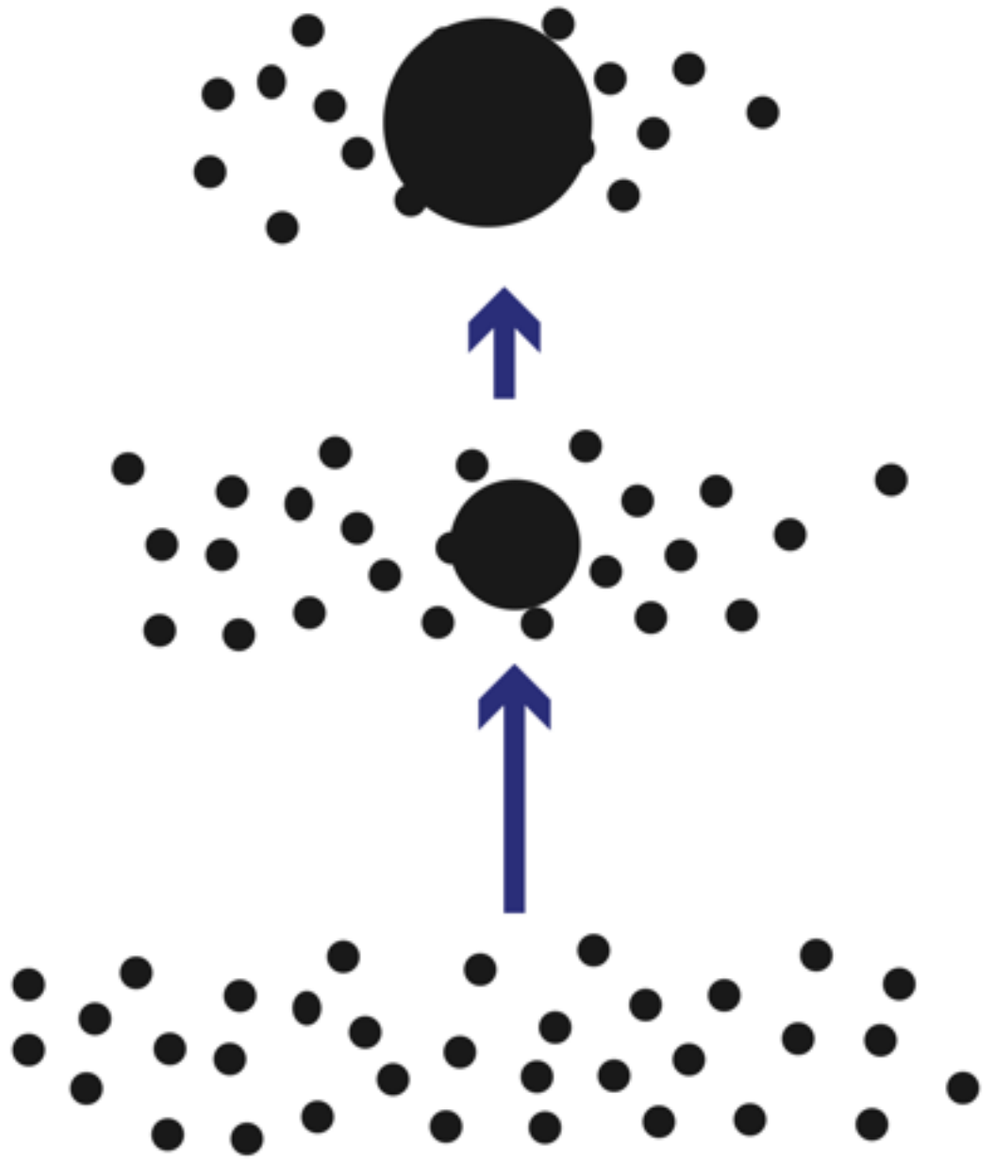
Fig. 1.— Expected gravitational radiation amplitude from merging IMBHs of (a) hierarchical growth model, and (b) monopolistic growth model. We plotted both the inspiral phase ($f_{\rm insp}, h_{\rm insp}$), [eqs. (2) and (3)], and the ringdown phase ($f_{\rm QNM}, h_{\rm coal}$), [eqs. (4) and (6)],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



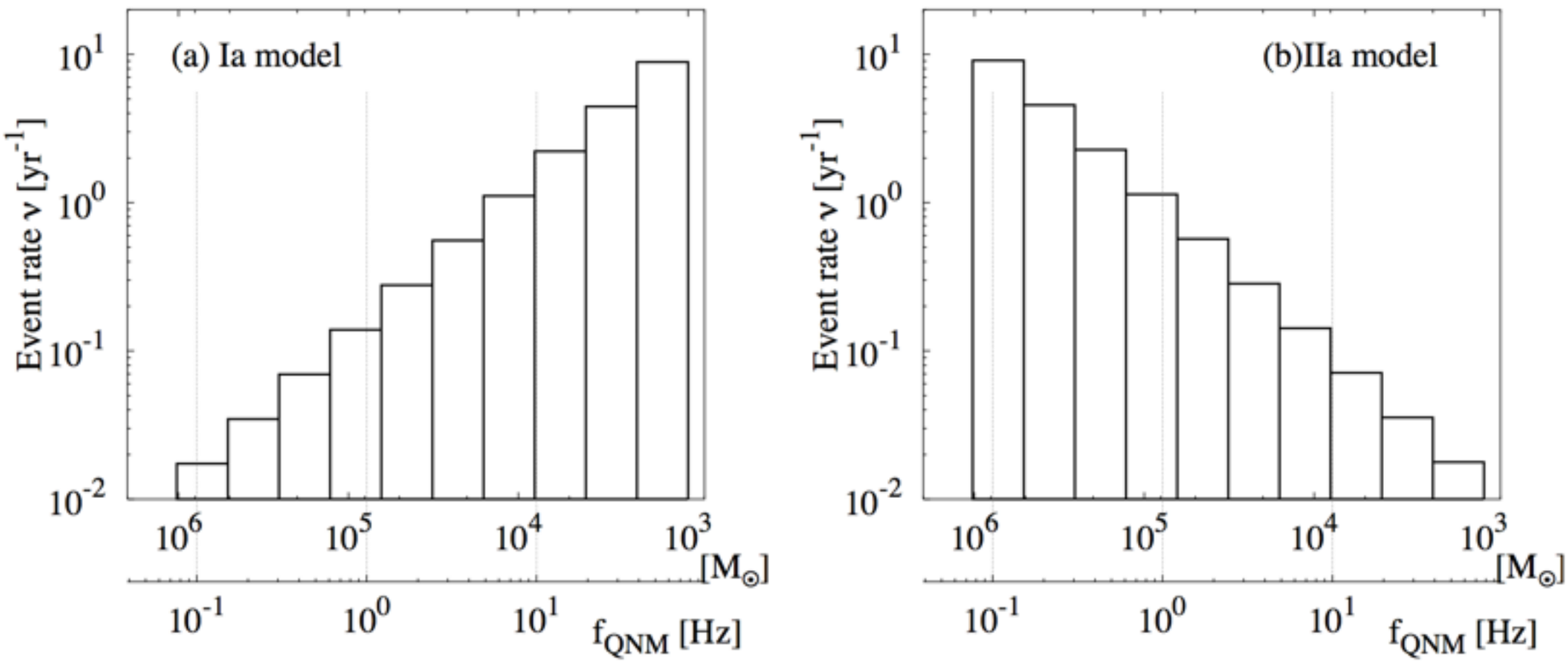
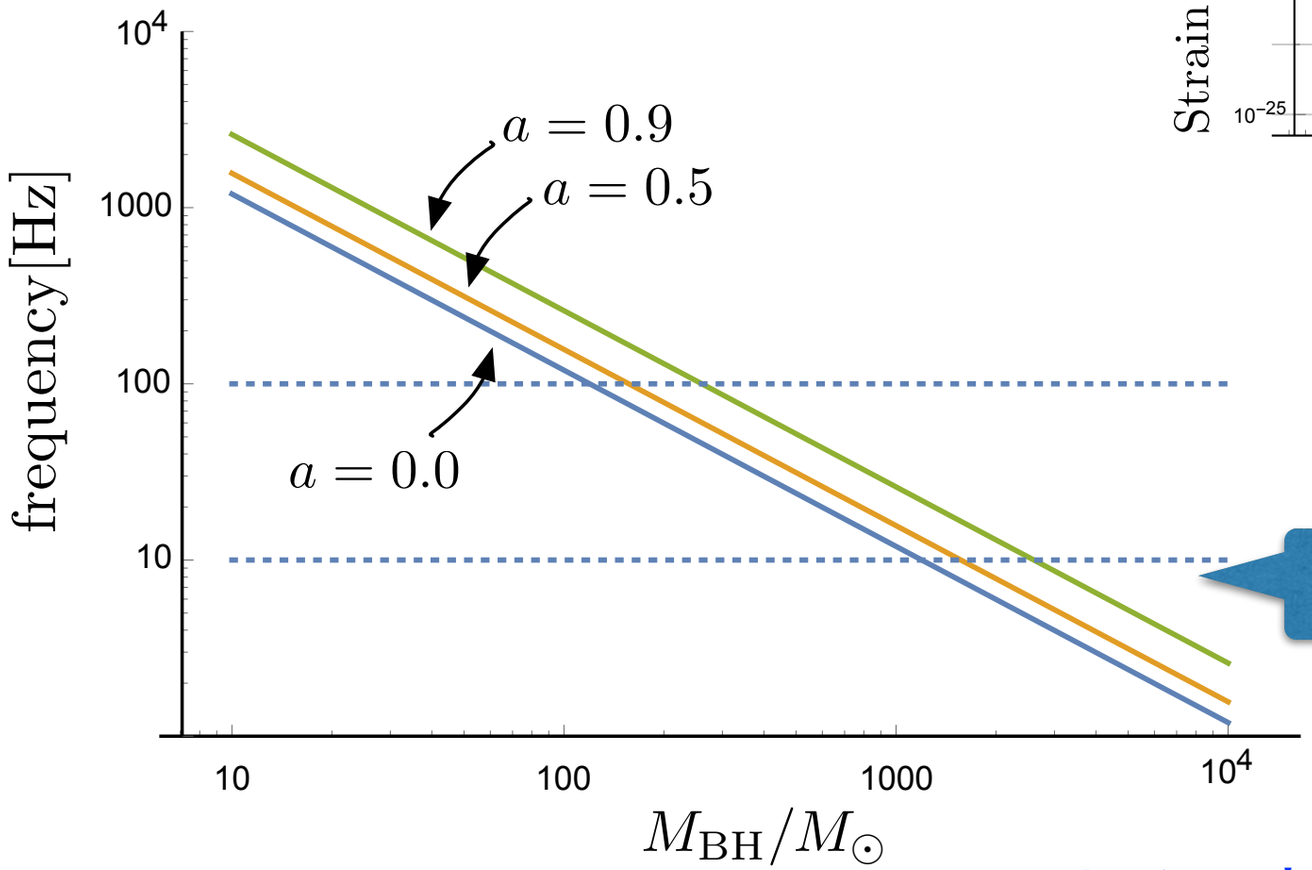
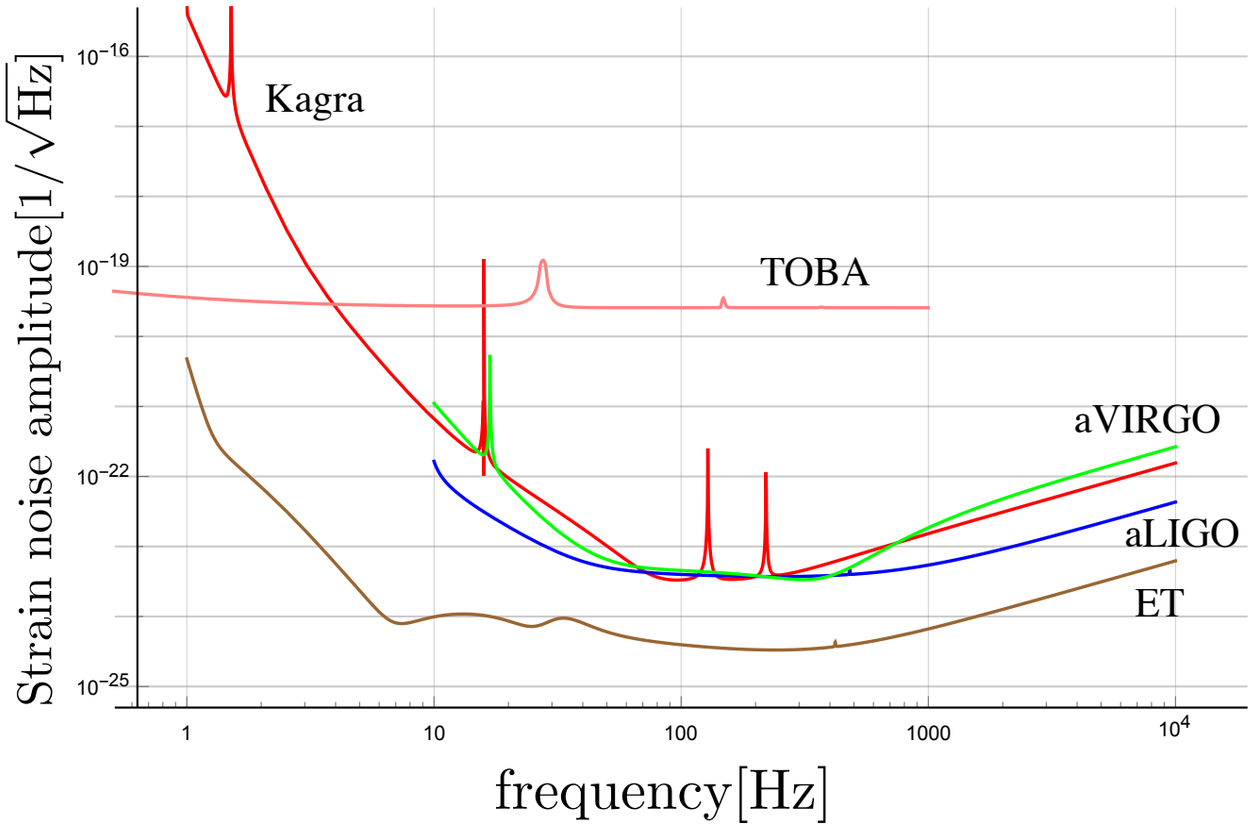


Fig. 2.— Event numbers of mergers starting from a thousand of $10^3 M_\odot$ IMBHs. The vertical axis is the event rate $\nu[\mathrm{yr}^{-1}]$, eqs. (12) and (14). The horizontal axis is the mass of the post-merger BH, M_T, which is also interpreted in the final gravitational radiation frequency f_{QNM}.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

地上重力波干渉計で形成過程がわかるか？





BH 準固有振動

(ringdown freq.)

数100MのBHまではターゲットになる.

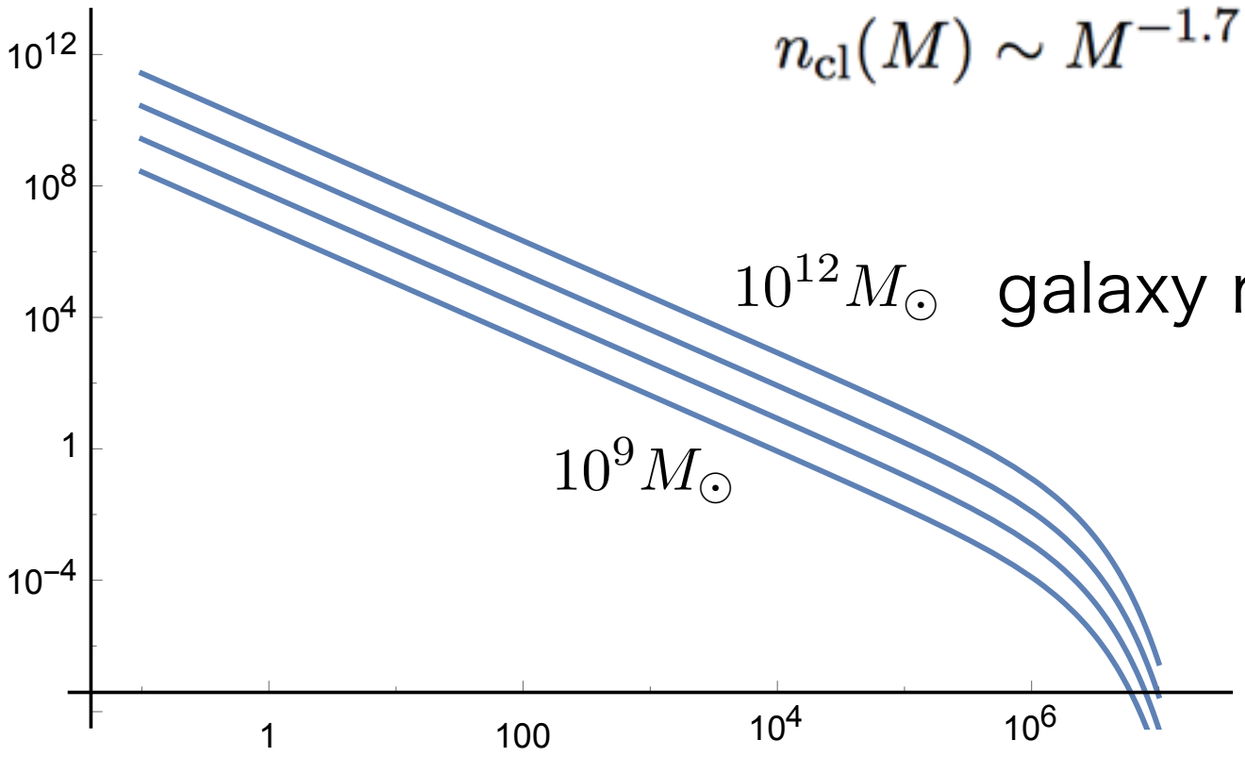
銀河内のBH数，銀河分布を仮定し，

KAGRAでのEvent Rateを予測する.

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

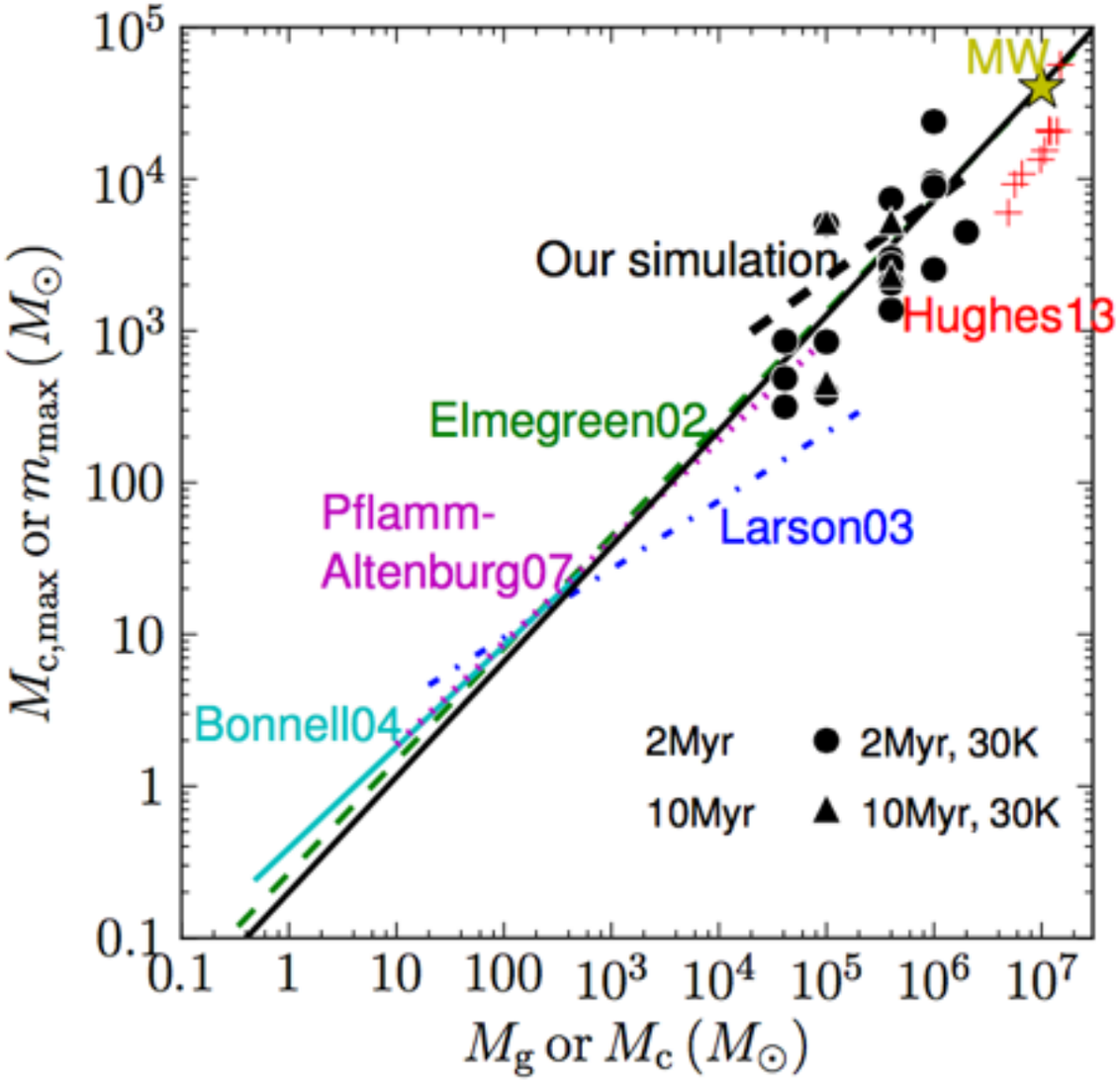
An Origin for The Cloud Mass Function and Star Formation Efficiency

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

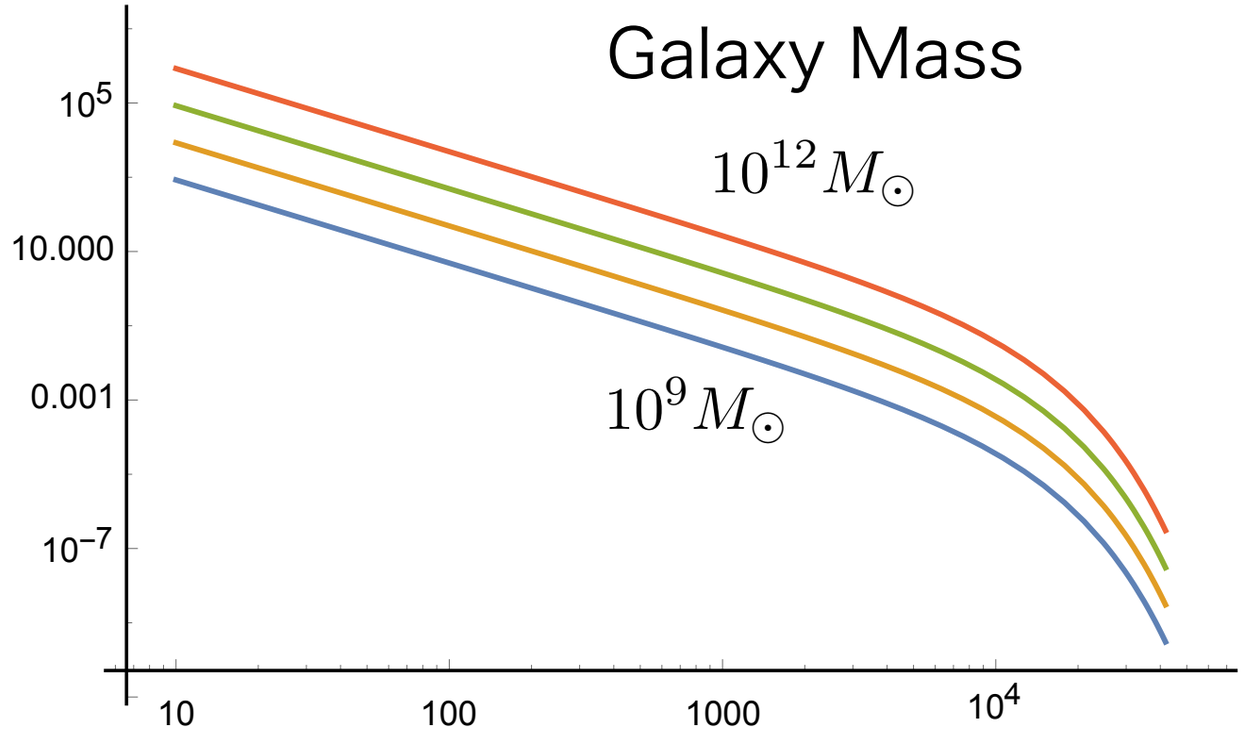
M. S. Fujii[1] * and S. Portegies Zwart[2*]
[1] *Division of Theoretical Astronomy, National Astronomical Observatory of Japan 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
[2] *Leiden Observatory, Leiden University, NL-2300RA Leiden, The Netherlands*

1309.1223v3

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

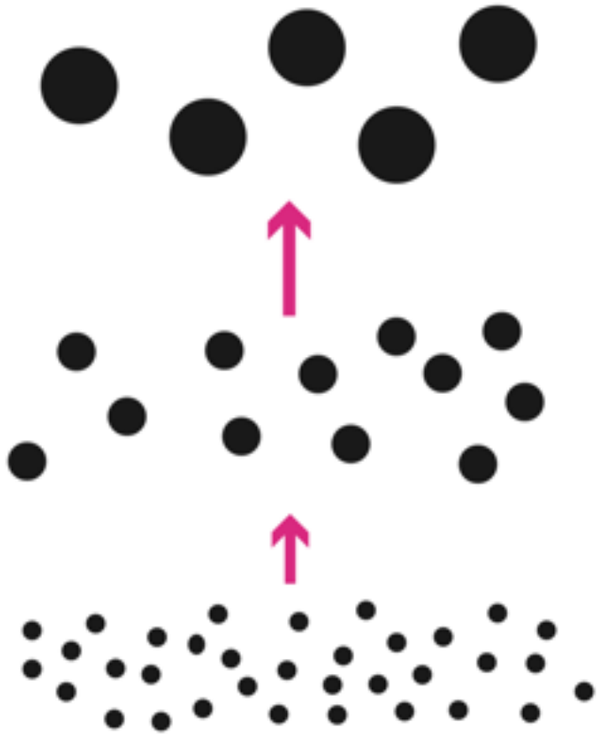
Building Block BH

n(M)



How many BHs in a Galaxy?

Hierarchical growth model

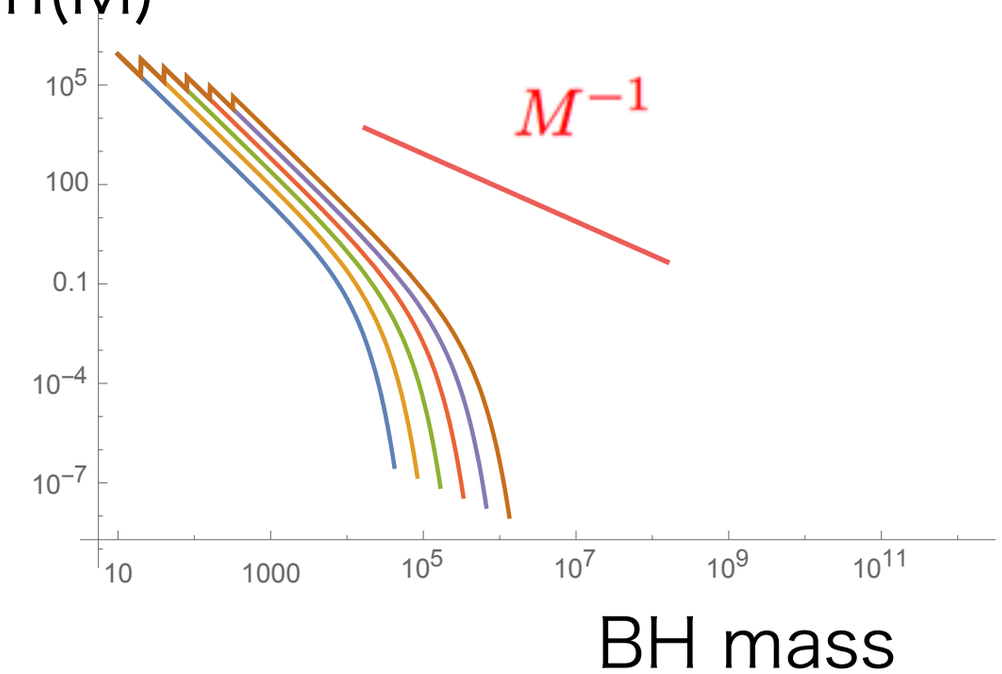


Count BHs to form a SMBH

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

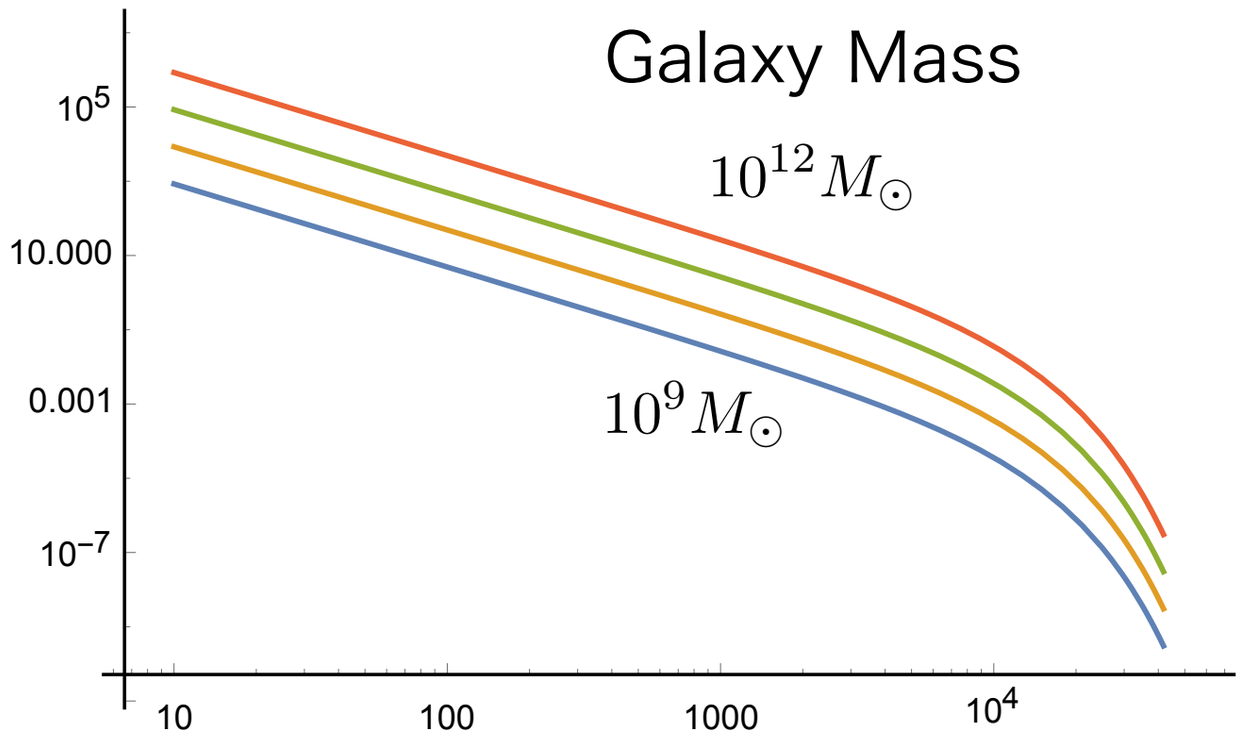
Building Block BH

n(M)



BH mass

n(M)



BH mass

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

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*

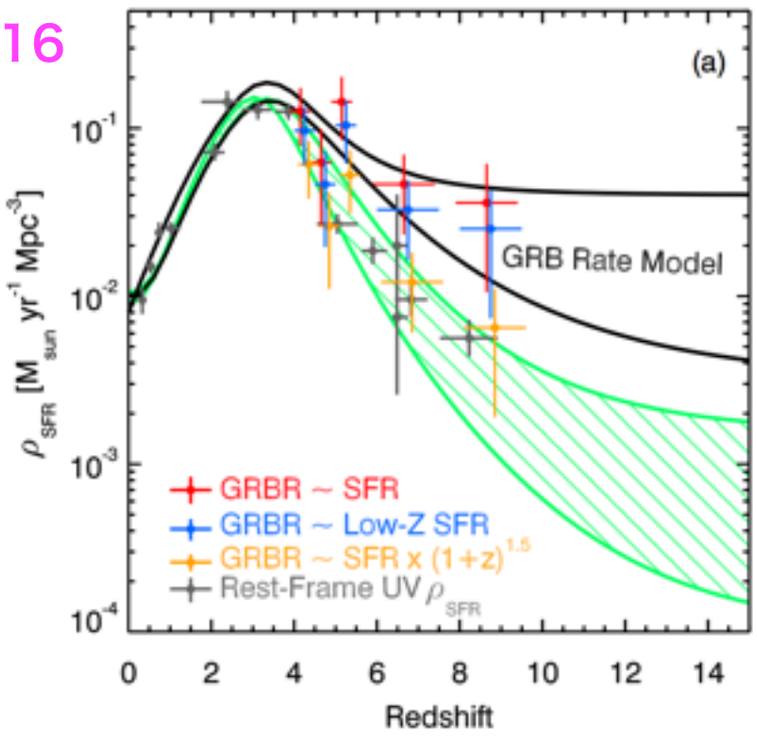
Star Formation Rate

peak z=3.16

THE ASTROPHYSICAL JOURNAL, 744:95 (13pp), 2012 January 10 doi:10.1088/0004-637X/744/2/95

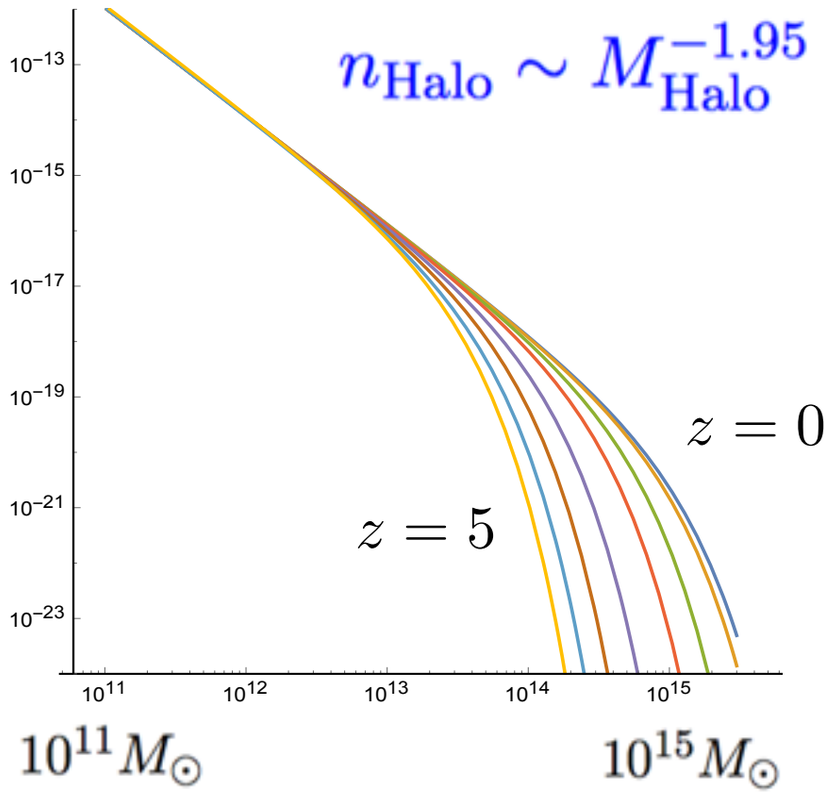
CONNECTING THE GAMMA RAY BURST RATE AND THE COSMIC STAR FORMATION HISTORY: IMPLICATIONS FOR REIONIZATION AND GALAXY EVOLUTION

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

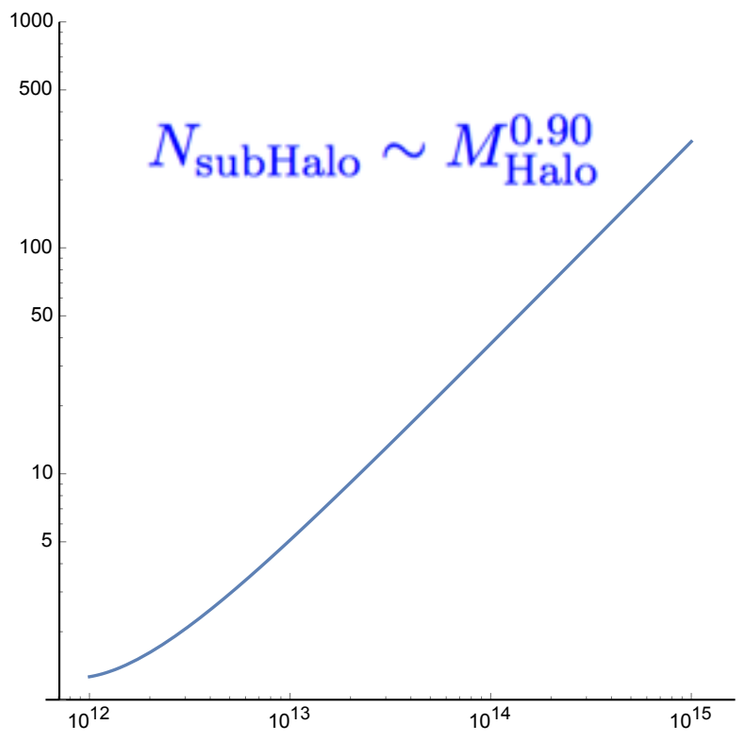


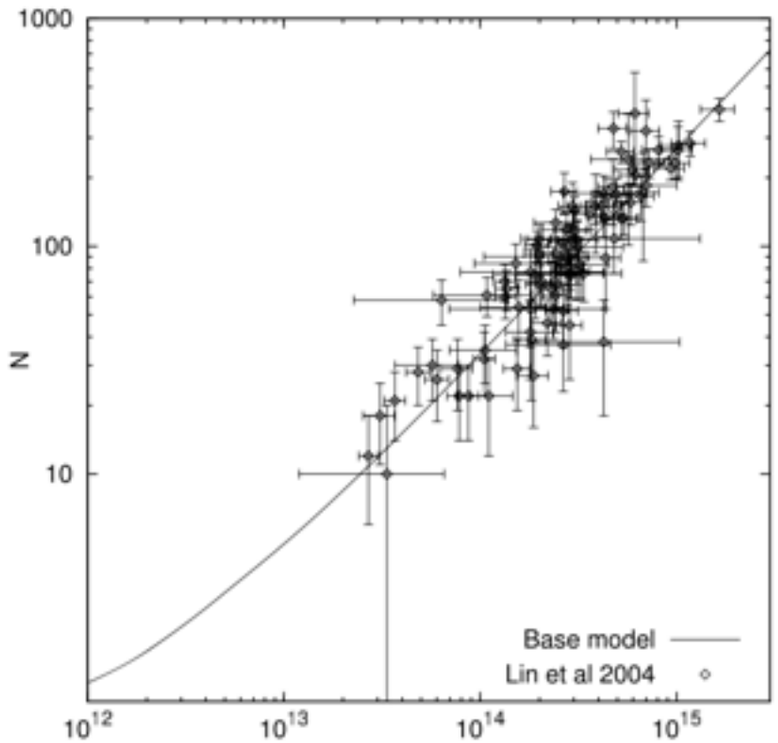
How many Galaxies in the Universe?

(1) Halo number density

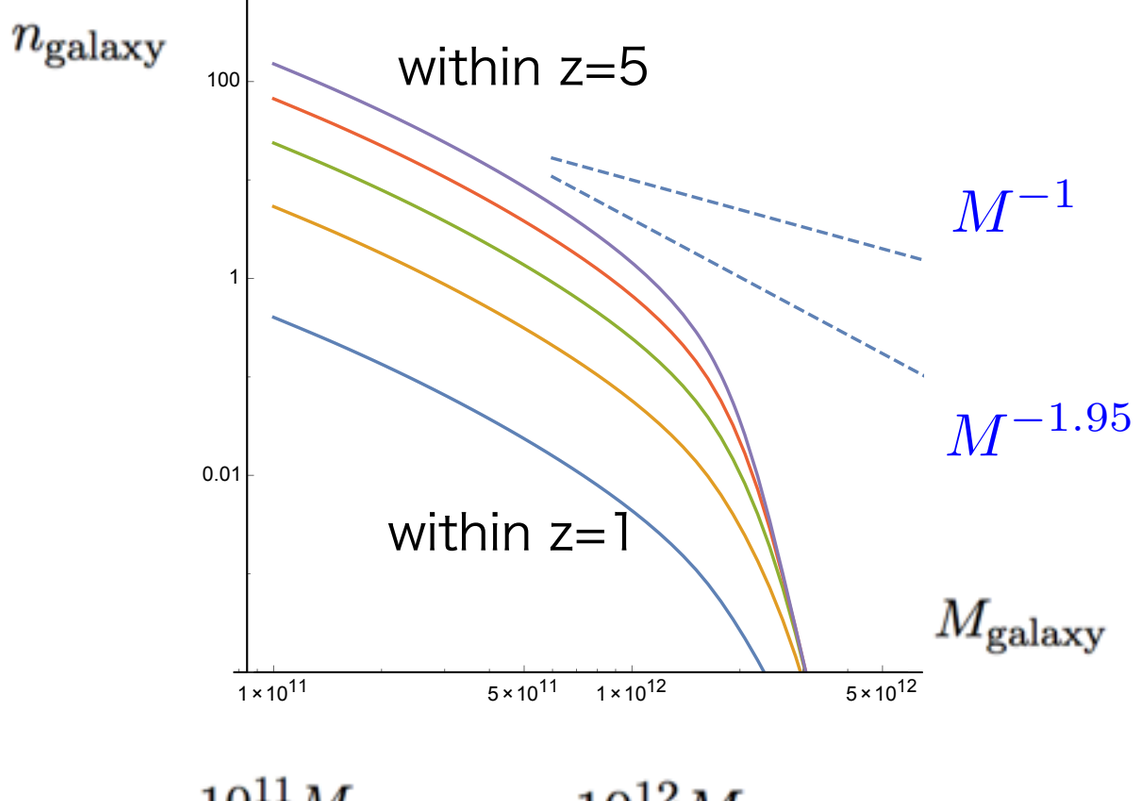


(2) N of seeds of Galaxy (subHalo)





(3) N of Galaxy



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,*
[2]*Princeton University Observatory, Princeton University, Princeton,*

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

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*

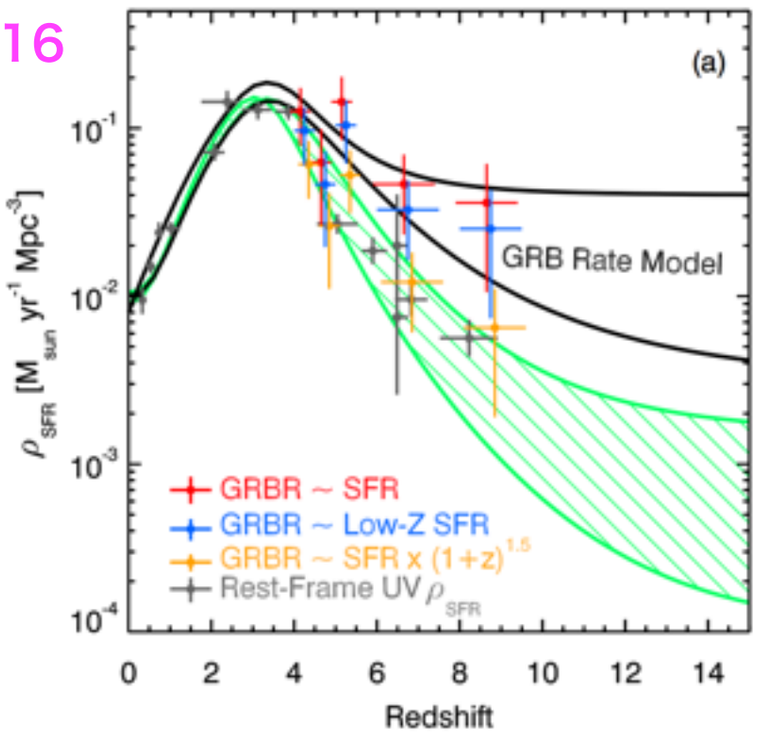
Star Formation Rate

peak z=3.16

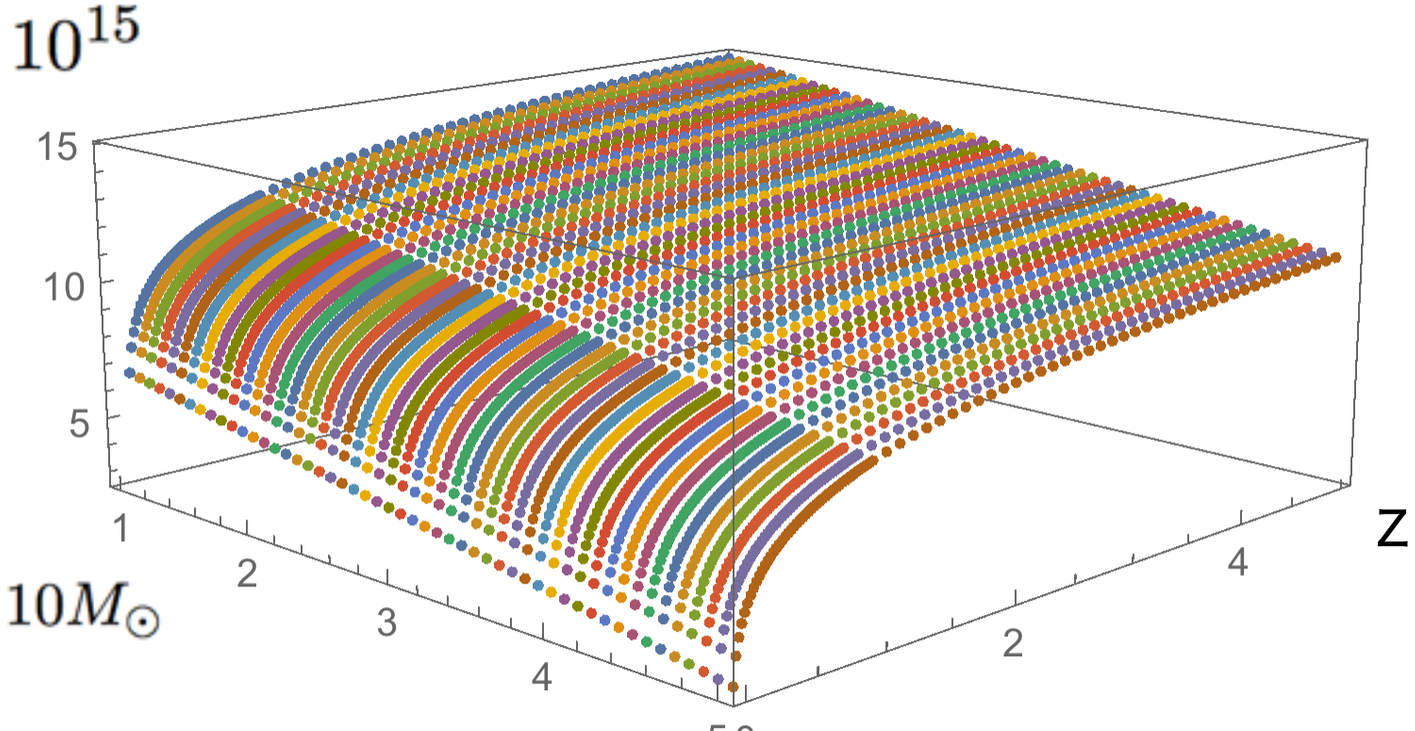
THE ASTROPHYSICAL JOURNAL, 744:95 (13pp), 2012 January 10 doi:10.1088/0004-637X/744/2/95

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

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



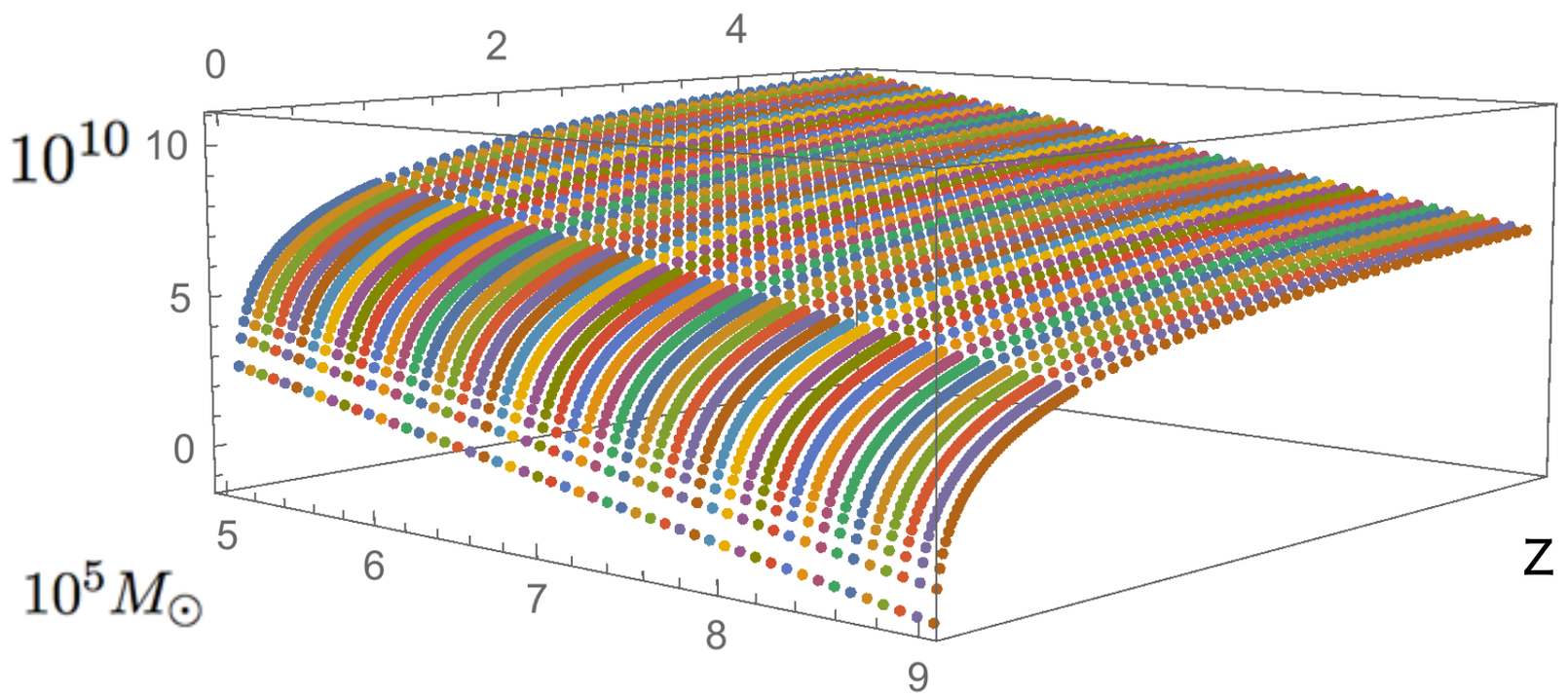
How many BH mergers in the Universe?



BH mass

in Standard Cosmology

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



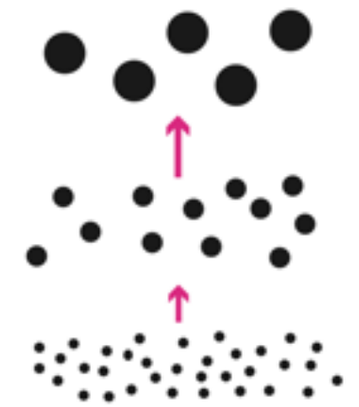
BH mass $10^9 M_\odot$

Detectable Distances at bKAGRA

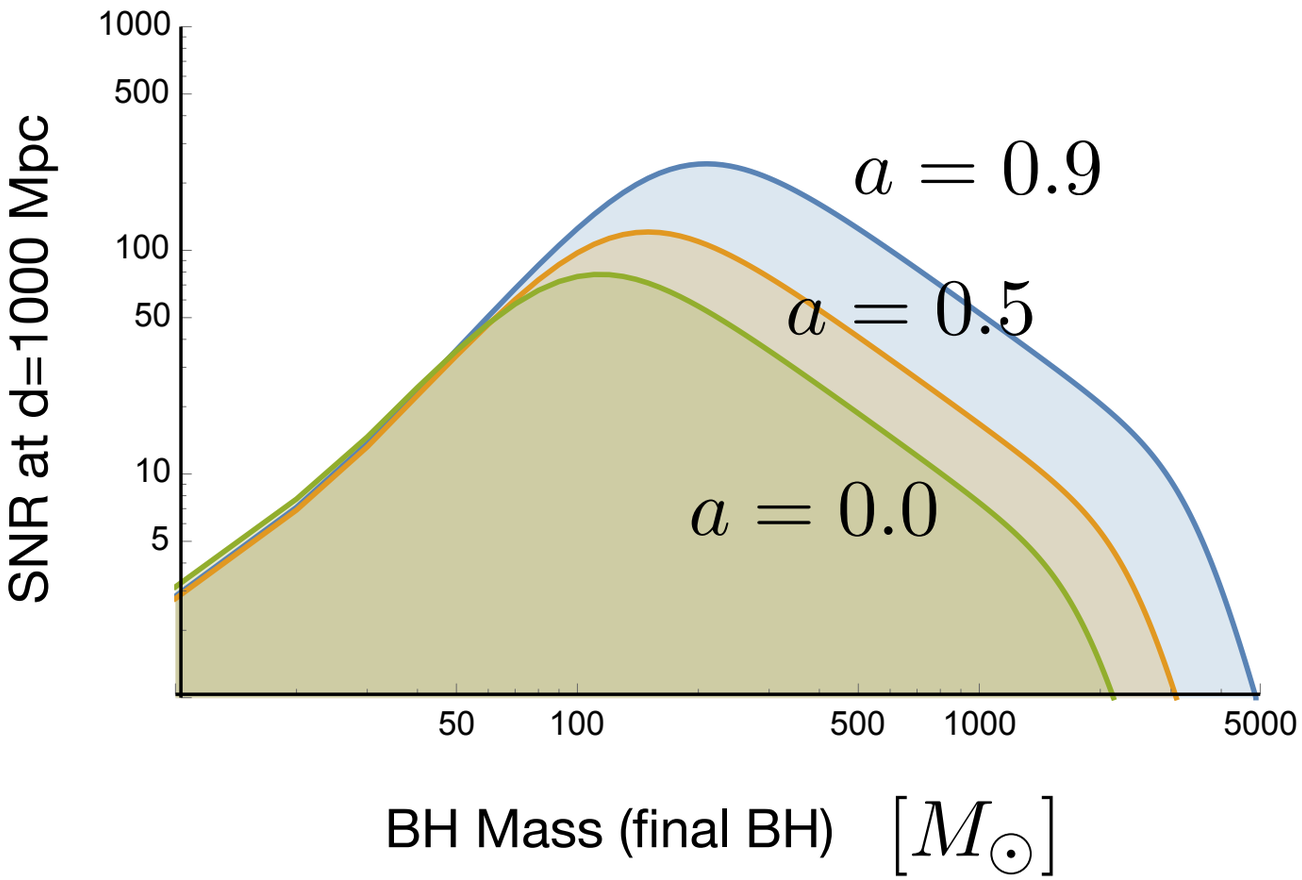
SNR $\rho^2 = \frac{8}{5} \frac{\epsilon_r(a)}{f_R^2} \frac{(1+z)M}{S_h(f_R/(1+z))} \left(\frac{(1+z)M}{d_L(z)}\right)^2 \left(\frac{4\mu}{M}\right)^2$

合体のGW放出=全質量の4%, ringdownで1%

Hierarchical Growth

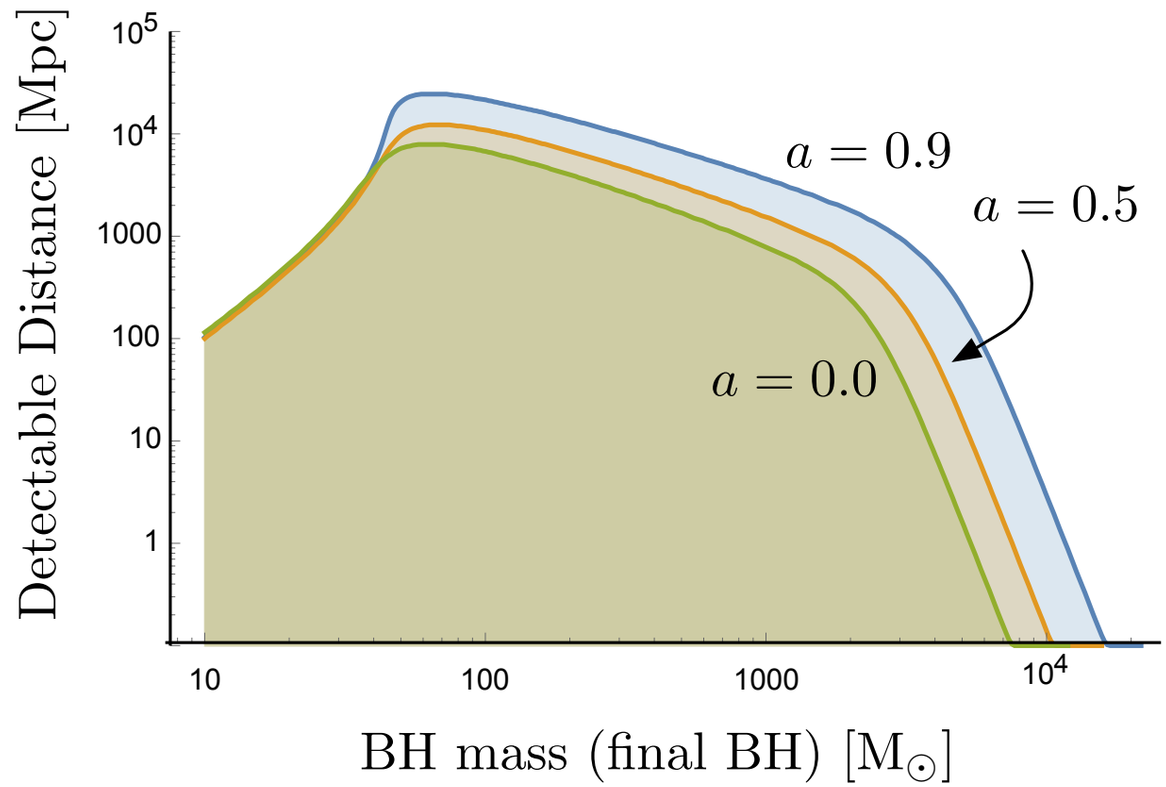


KAGRA

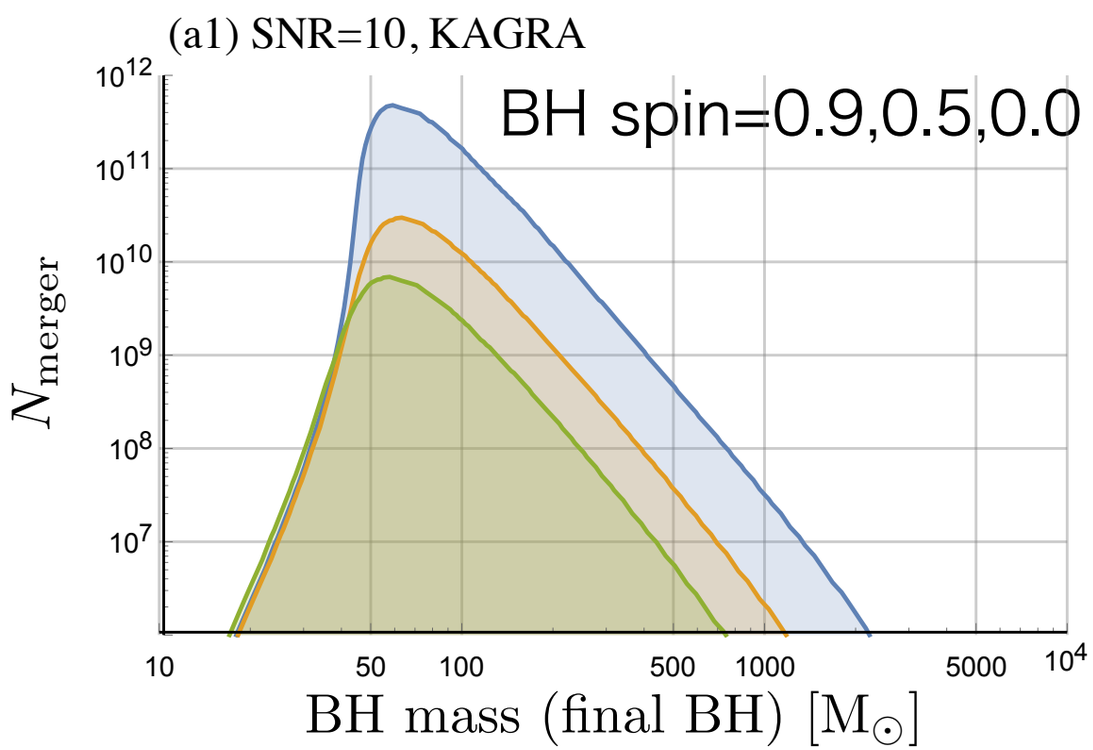


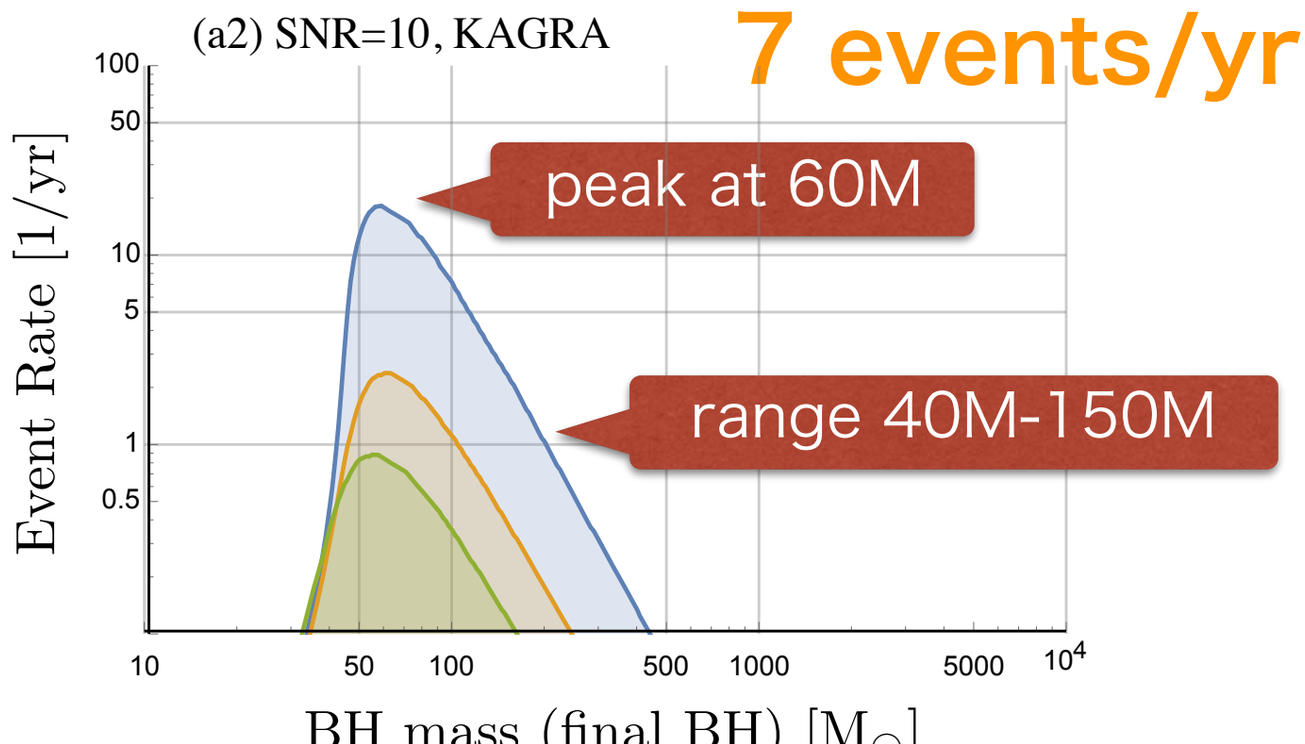
(a) SNR=10

KAGRA



Event Rates at bKAGRA





210 events/yr

Summary

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