中間質量ブラックホール合体モデルと重力波観測

真貝寿明，　戎崎俊一
(大阪工大)　(理研)
http://www.oit.ac.jp/is/~shinkai/

BH-BHの合体成長で，IMBH → SMBH へ

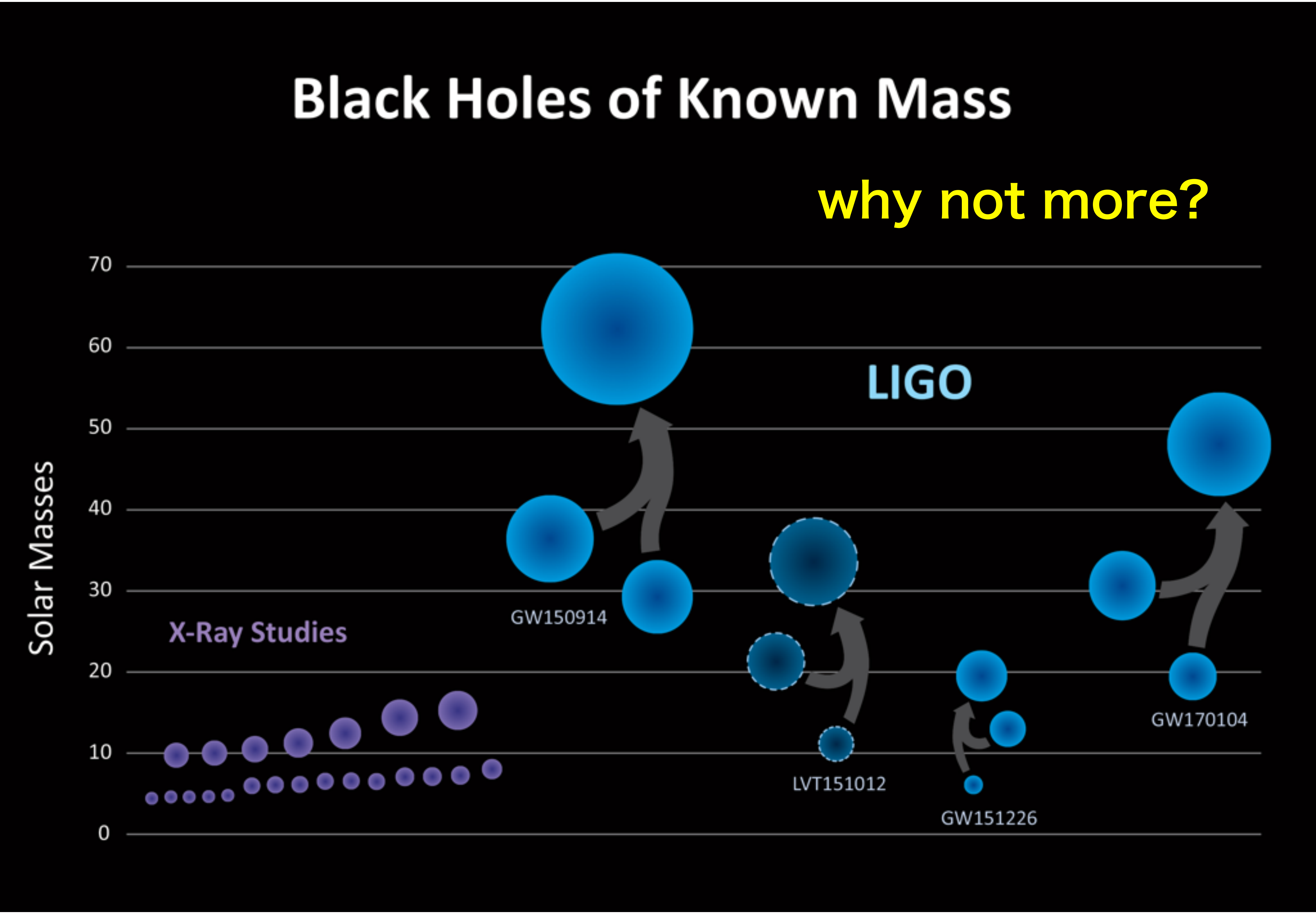
“Hierarchical Growth model”

Ref: HS, Kanda & Ebisuzaki, ApJ, 835 (2017) 276

+ spin evolution

Event Rates at bKAGRA/B-DECIGO/eLISA

2017/9/15 物理学会@宇都宮大



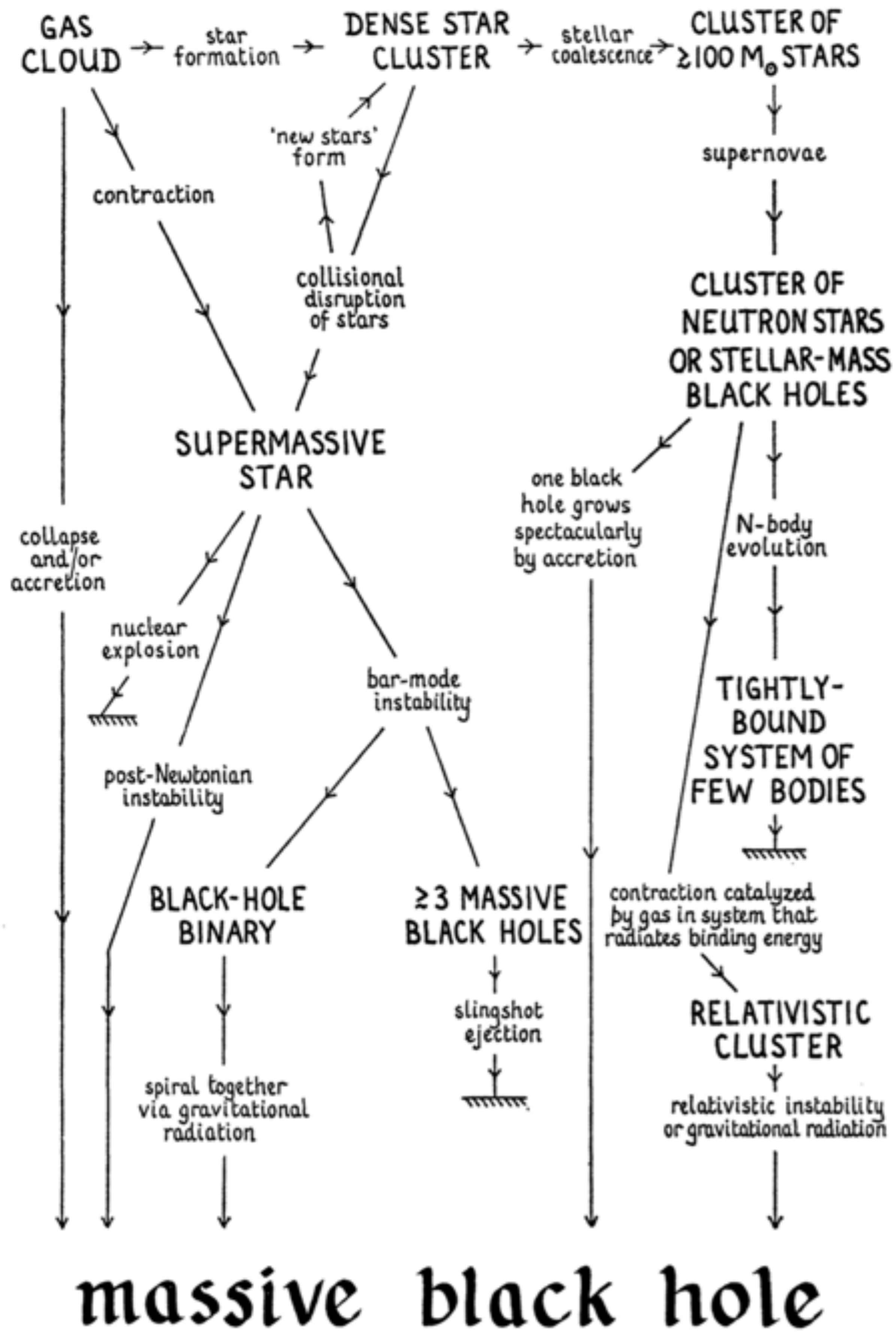
http://ligo.org/detections/GW170104.php

List of Detected GW events

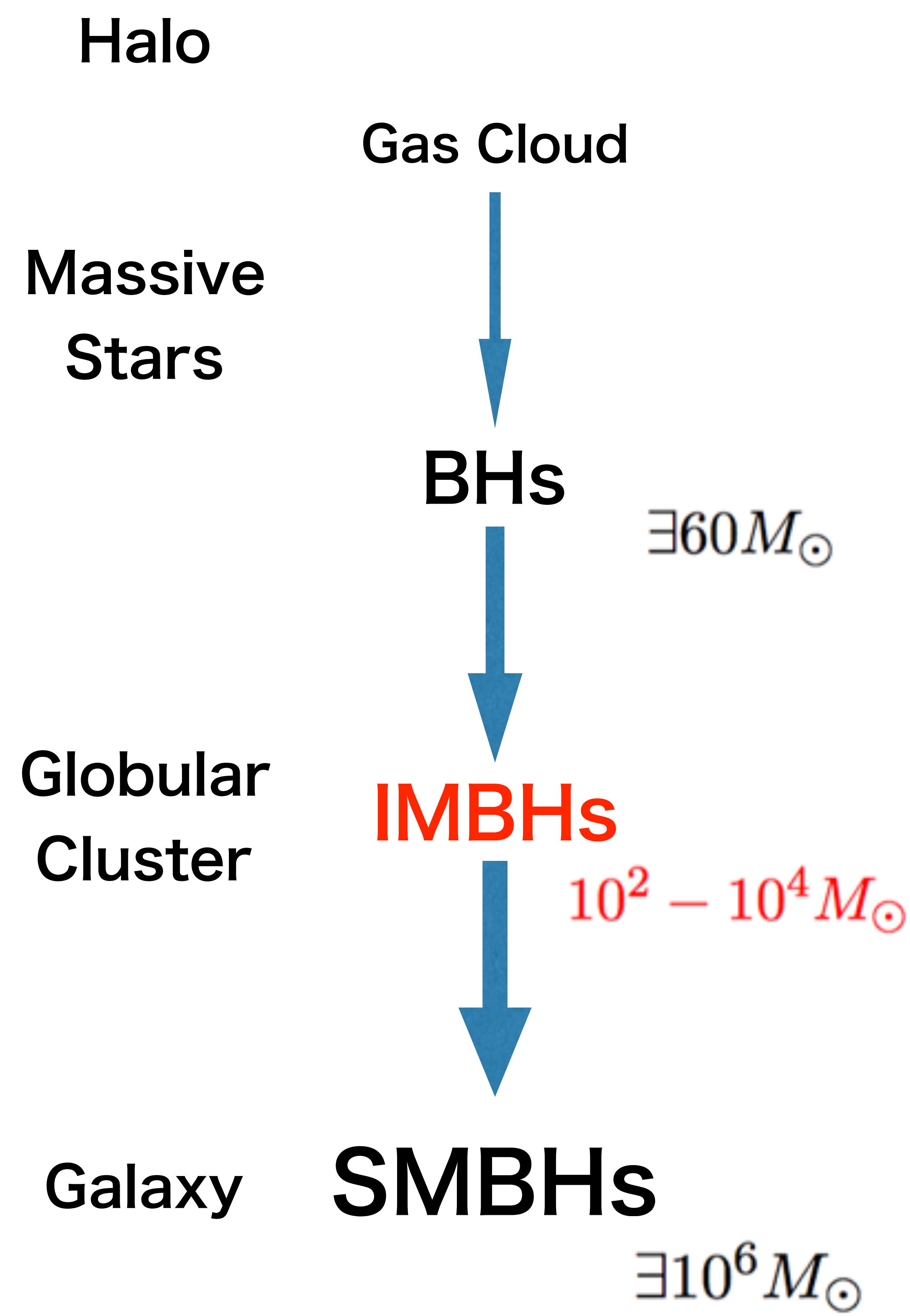
		M1+M2=Mf, Mdiff/Mtotal	spin a_final	Mpc z	SNR	deg^2
GW150914	PRL116, 061102 (2016/2/11)	36.2+29.1=62.3+3.0 **4.59%**	0.68	410Mpc 0.09	23.7	600
LVT151012	(2016/2/11)	23+13=35+1.5 **2.78%**	0.66	1000Mpc 0.20	9.7	
GW151226	PRL116, 241103 (2016/6/15)	14.2+7.5=20.8+0.9 **4.15%**	0.74	440Mpc 0.09	13.0	850
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/

2. Models of SMBH



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



Ebisuzaki +, ApJ, 562, L19 (2001)

Starburst galaxy M82 has 1000M BH

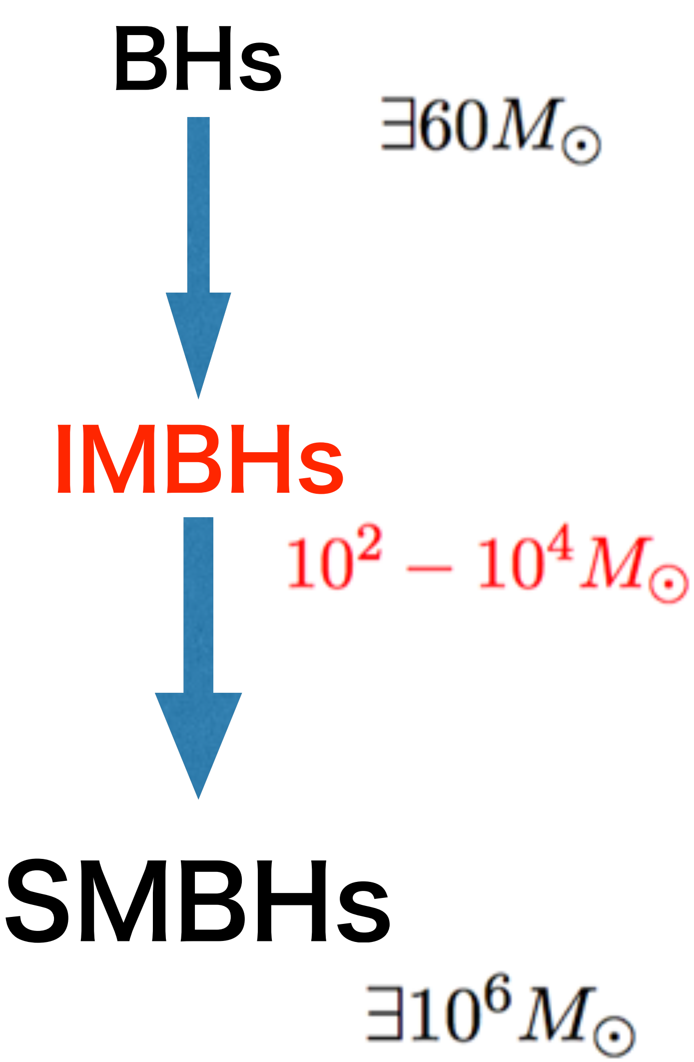
Matsushita+, ApJ, 545, L107 (2000)
Matsumoto+, ApJ, 547, L25 (2001)

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)

Publ. Astron. Soc. Japan (2016) 68 (3), L7 (1–6)
doi: 10.1093/pasj/psw031
Advance Access Publication Date: 2016 April 19
Letter

1602.05325

Letter

0.15pc from SgrA*

1-2 x 10^4 Msun

Galactic center mini-spiral by ALMA: Possible origin of the central cluster

Masato TSUBOI,[1,2,*] Yoshimi KITAMURA,[1] Makoto MIYOSHI,[3] Kenta UEHARA,[2] Takahiro TSUTSUMI,[4] and Atsushi MIYAZAKI[3,5]

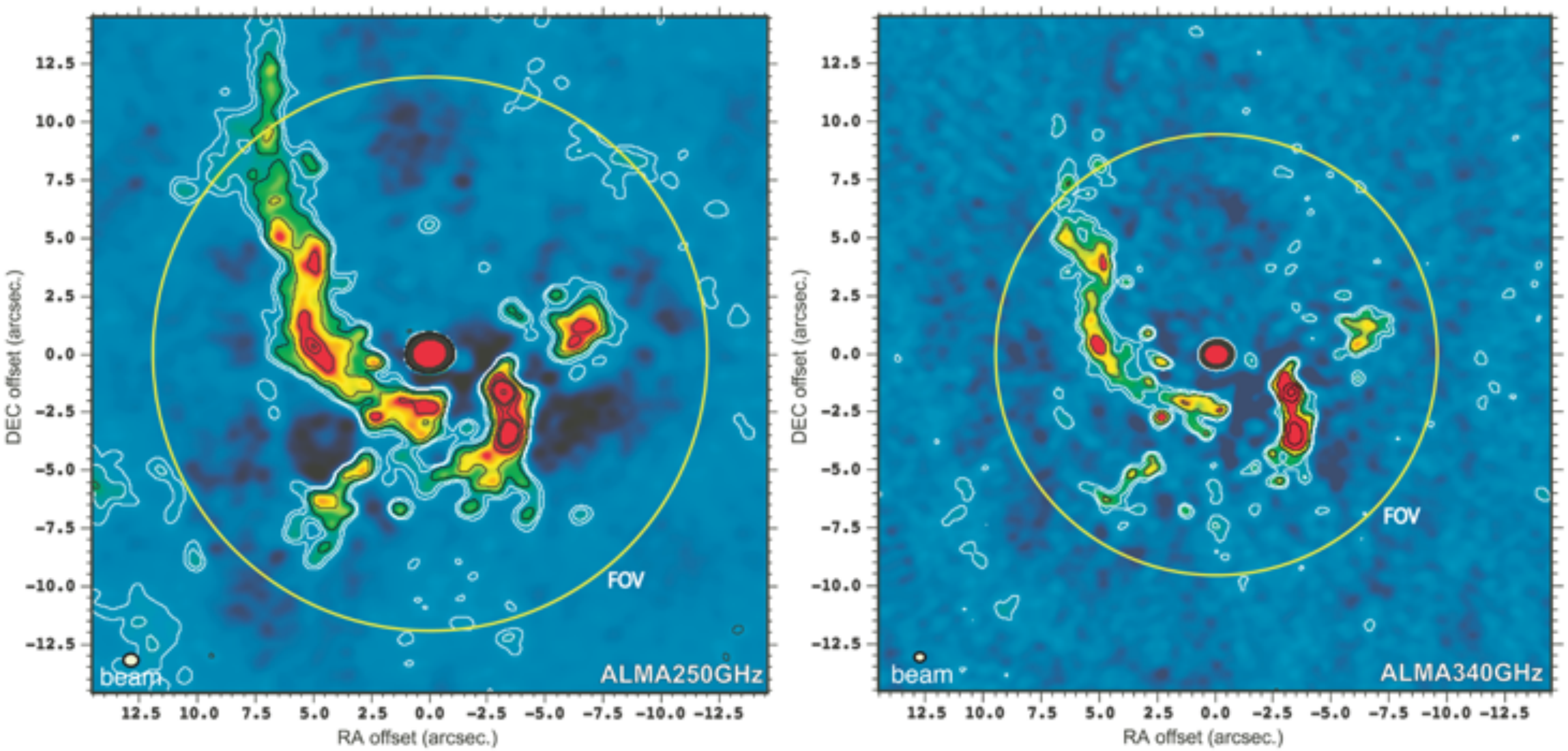


Fig. 2. Left panel: ALMA map in the 250 GHz band of the "mini-spiral" including Sgr A*. The four spectral windows of $f_c = 245$, 247, 257, and 259 GHz are combined to improve the sensitivity. The diameter of the FOV is 24″ (circle). The angular resolution is 0.″63 × 0.″53 at $PA = -84°$, which is shown as an oval in the lower left corner. The RMS noise level is 0.13 mJy beam^{-1}, and the contour levels are 0.31, 0.63, 1.3, 2.5, 5.0, 10, 20, 30, 40, 50, and 75 mJy beam^{-1}. The flux density of Sgr A* is $S_\nu = 3.55 \pm 0.35$ Jy at 250 GHz. Right panel: ALMA map in the 340 GHz band of the same region as the left panel. The four spectral windows of $f_c = 336$, 338, 348, and 350 GHz are combined to improve the sensitivity. The diameter of the FOV is 18″ (circle). The angular resolution is 0.″44 × 0.″38 at $PA = -89°$, which is shown as an oval in the lower left corner. The RMS noise level is 0.33 mJy beam^{-1}, and the contour levels are the same as in the left panel. The flux density of Sgr A* is $S_\nu = 3.44 \pm 0.51$ Jy at 340 GHz. (Color online)

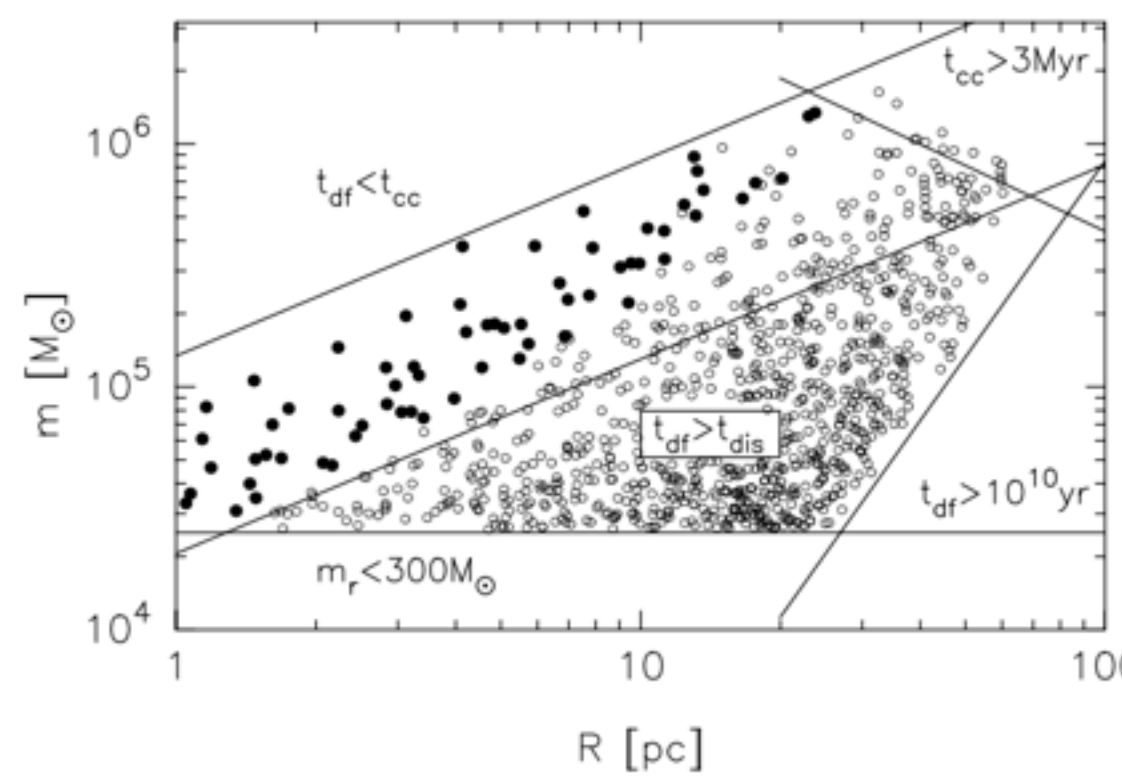
THE ECOLOGY OF STAR CLUSTERS AND INTERMEDIATE-MASS BLACK HOLES IN THE GALACTIC BULGE

SIMON F. PORTEGIES ZWART,[1,2] HOLGER BAUMGARDT,[3] STEPHEN L. W. MCMILLAN,[4]
JUNICHIRO MAKINO,[5] PIET HUT,[6] AND TOSHI EBISUZAKI[7]
Received 2005 November 11; accepted 2005 December 5

ABSTRACT

We simulate the inner 100 pc of the Milky Way to study the formation and evolution of the population of star clusters and intermediate-mass black holes (IMBHs). For this study we perform extensive direct *N*-body simulations of the star clusters that reside in the bulge, and of the inner few tenth of parsecs of the supermassive black hole in the Galactic center. In our *N*-body simulations the dynamical friction of the star cluster in the tidal field of the bulge are taken into account via semianalytic solutions. The *N*-body calculations are used to calibrate a semianalytic model of the formation and evolution of the bulge. We find that ~10% of the clusters born within ~100 pc of the Galactic center undergo core collapse during their inward migration and form IMBHs via runaway stellar merging. After the clusters dissolve, these IMBHs continue their inward drift, carrying a few of the most massive stars with them. We predict that a region within ~10 pc of the supermassive black hole (SMBH) is populated by ~50 IMBHs of ~1000 $M_\odot$. Several of these are still expected to be accompanied by some of the most massive stars from the star cluster. We also find that within a few milliparsecs of the SMBH there is a steady population of several IMBHs. This population drives the merger rate between IMBHs and the SMBH at a rate of about one per 10 Myr, sufficient to build the accumulated majority of mass of the SMBH. Mergers of IMBHs with SMBHs throughout the universe are detectable by *LISA* at a rate of about two per week.

PortegiesZwart+, ApJ 641(2006)319



nature astronomy

Altmetric: 660 More detail »

Letter

Millimetre-wave emission from an intermediate-mass black hole candidate in the Milky Way

Tomoharu Oka, Shiho Tsujimoto, Yuhei Iwata, Mariko Nomura & Shunya Takekawa

Nature Astronomy (2017)
doi:10.1038/s41550-017-0224-z
Download Citation

Received: 16 March 2017
Accepted: 14 July 2017
Published online: 04 September 2017

60pc from SgrA*

10^5 Msun

NAOJ ニュース 国立天文台とは プロジェクト アクセス・見学 天文情報 ギャラリー

天の川銀河で中質量ブラックホール候補の実体を初めて確認

2017年9月5日 | 研究成果

中質量ブラックホールによる重力散乱でガス雲が加速される様子の想像図 オリジナルサイズ（5.0MB）

慶應義塾大学理工学部物理学科の岡朋治（おかともはる）教授らの研究チームは、アルマ望遠鏡を使用して、天の川銀河の中心部分に発見された特異分子雲「CO-0.40-0.22」の詳細な電波観測を行いました。この特異分子雲は、天の川銀河中心核「いて座A*（エー・スター）」から約200光年離れた位置にあり、その異常に広い速度幅から内部に太陽の10万倍の質量をもつブラックホールが潜んでいる可能性が指摘されていました。観測の結果、特異分子雲「CO-0.40-0.22」の中心近くに、コンパクトな高密度分子雲と点状電波

https://www.nao.ac.jp/news/science/2017/20170905-alma.html

'Missing link' founded

Ebisuzaki +, ApJ, 562, L19 (2001)

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

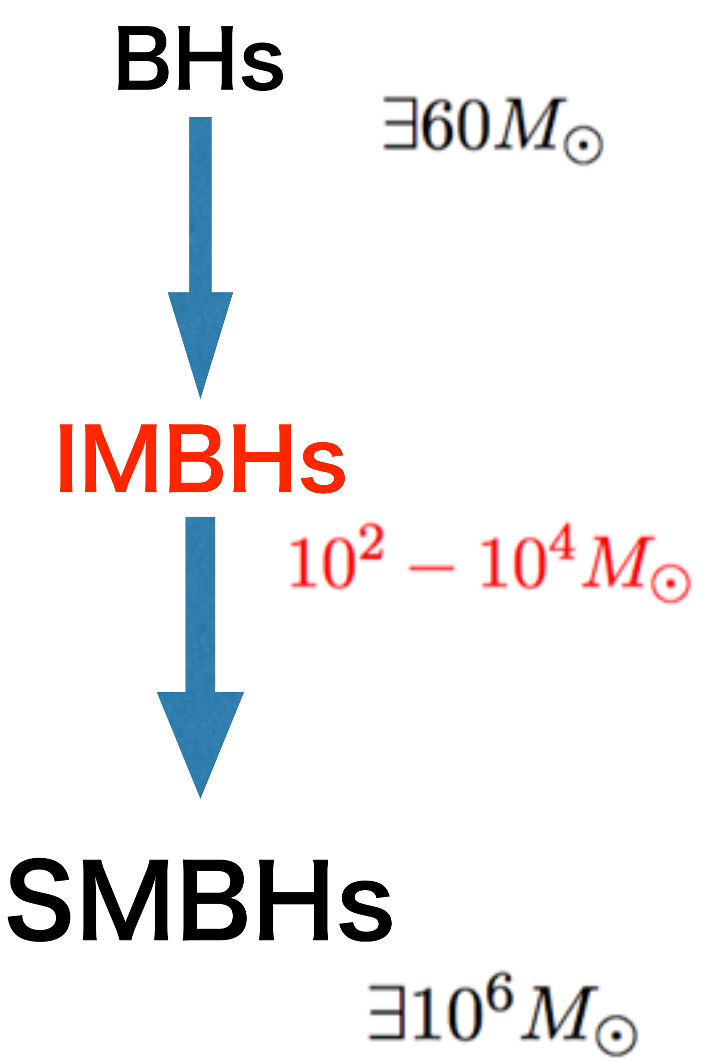
Marchant & Shapiro 1980; Portegies Zwart et al. 1999;
Portegies Zwart & McMillan 2002;
Portegies Zwart et al. 2004;
Holger & Makino 2003

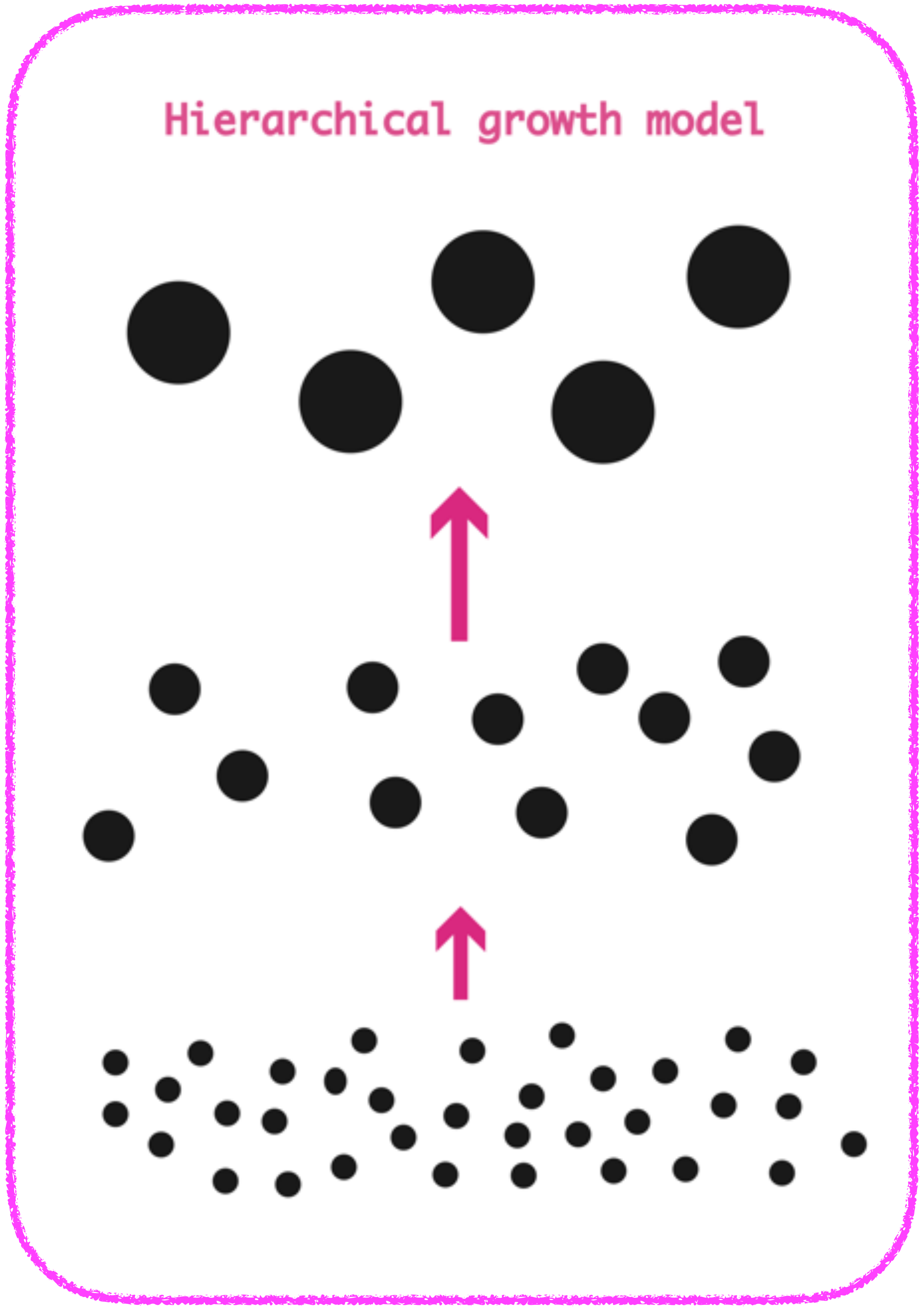
(2) accumulations of IMBHs at the center region of a galaxy due to sinkages of clusters by dynamical friction

Matsubayashi et al. 2007

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

Iwasawa et. al. 2010





銀河にはいくつBHがあるのか?
宇宙にはいくつ銀河があるのか?

宇宙にBH合体はいくつ生じるか

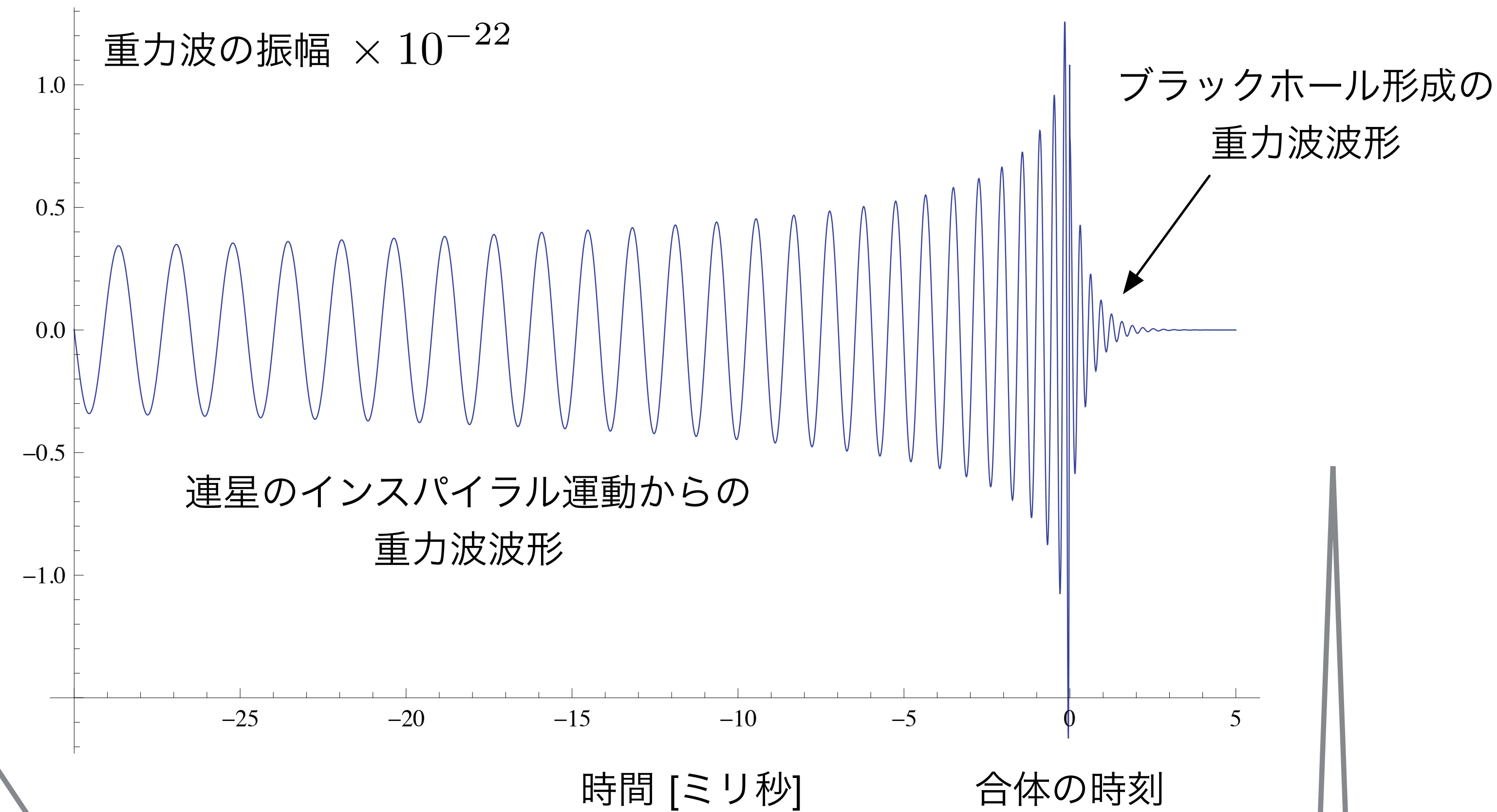
我々は1年間にいくつ観測できるか

重力波で観測可能な距離？
ground-base / space

宇宙モデル?
BH spin? Signal-to-Noise?

1. Gravitational Wave >> Expected Amplitude

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



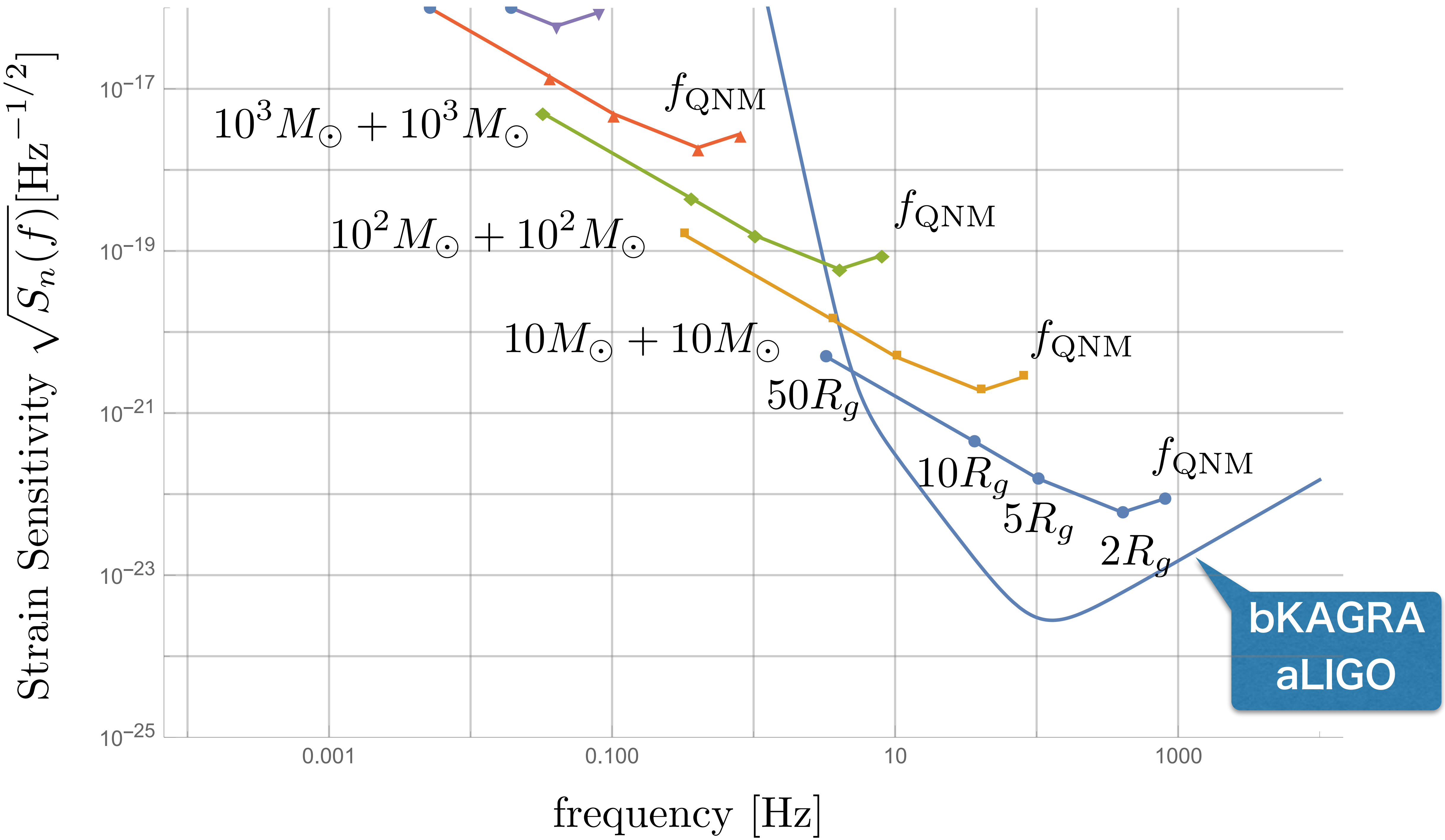
$$f_{\rm insp} = \frac{1}{\pi}\sqrt{\frac{GM_T}{a^3}}$$
$$\approx 11.4\left(\frac{a}{R_{\rm grav}}\right)^{-3/2}\left(\frac{2\times10^3\ M_\odot}{M_T}\right)\ \mathrm{Hz},$$

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

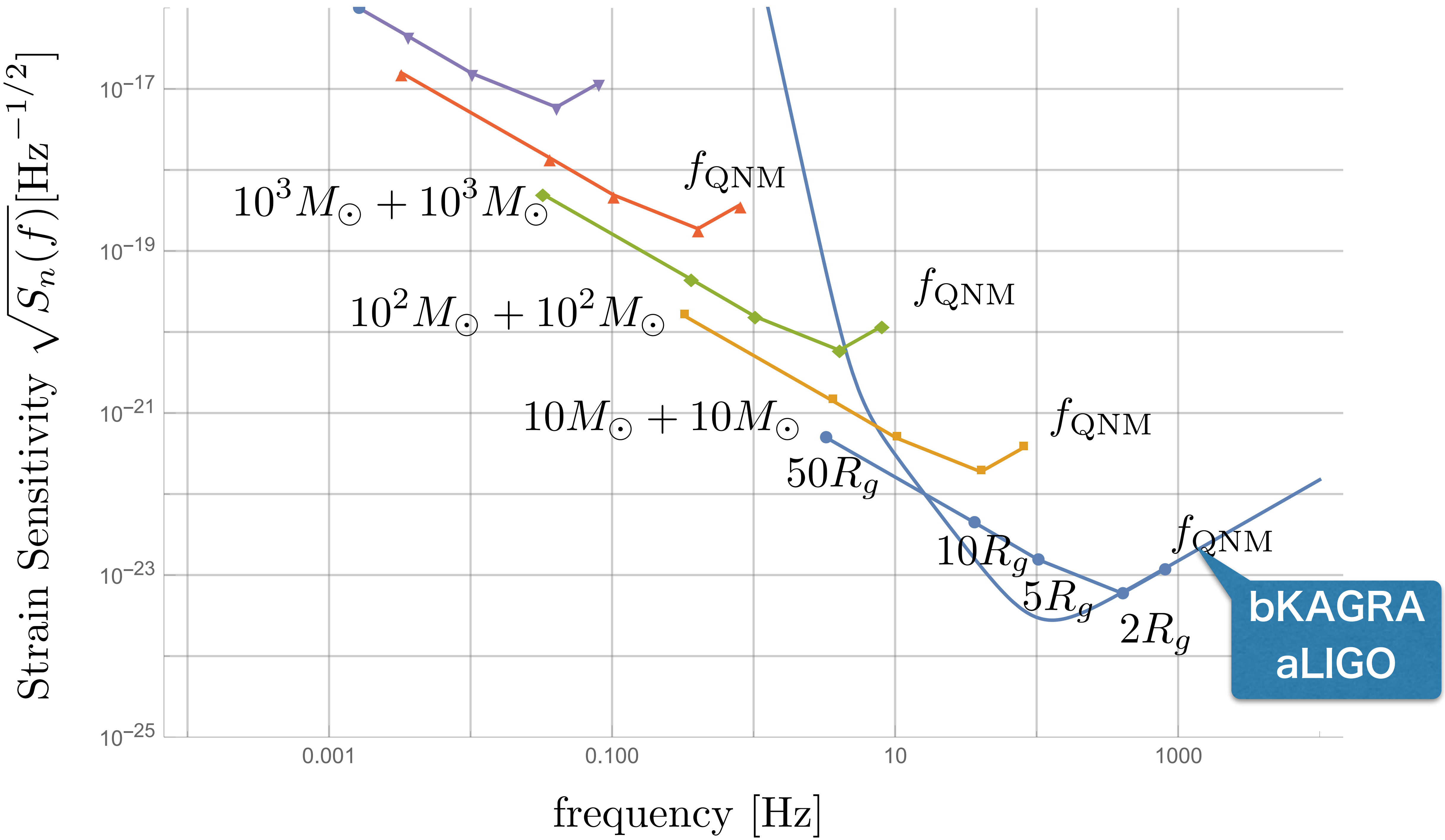
$$f_{\rm QNM} \approx \frac{lc^3}{\sqrt{27}GM_T} \sim 39.1\left(\frac{2\times10^3\ M_\odot}{M_T}\right)\ \mathrm{Hz},$$

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

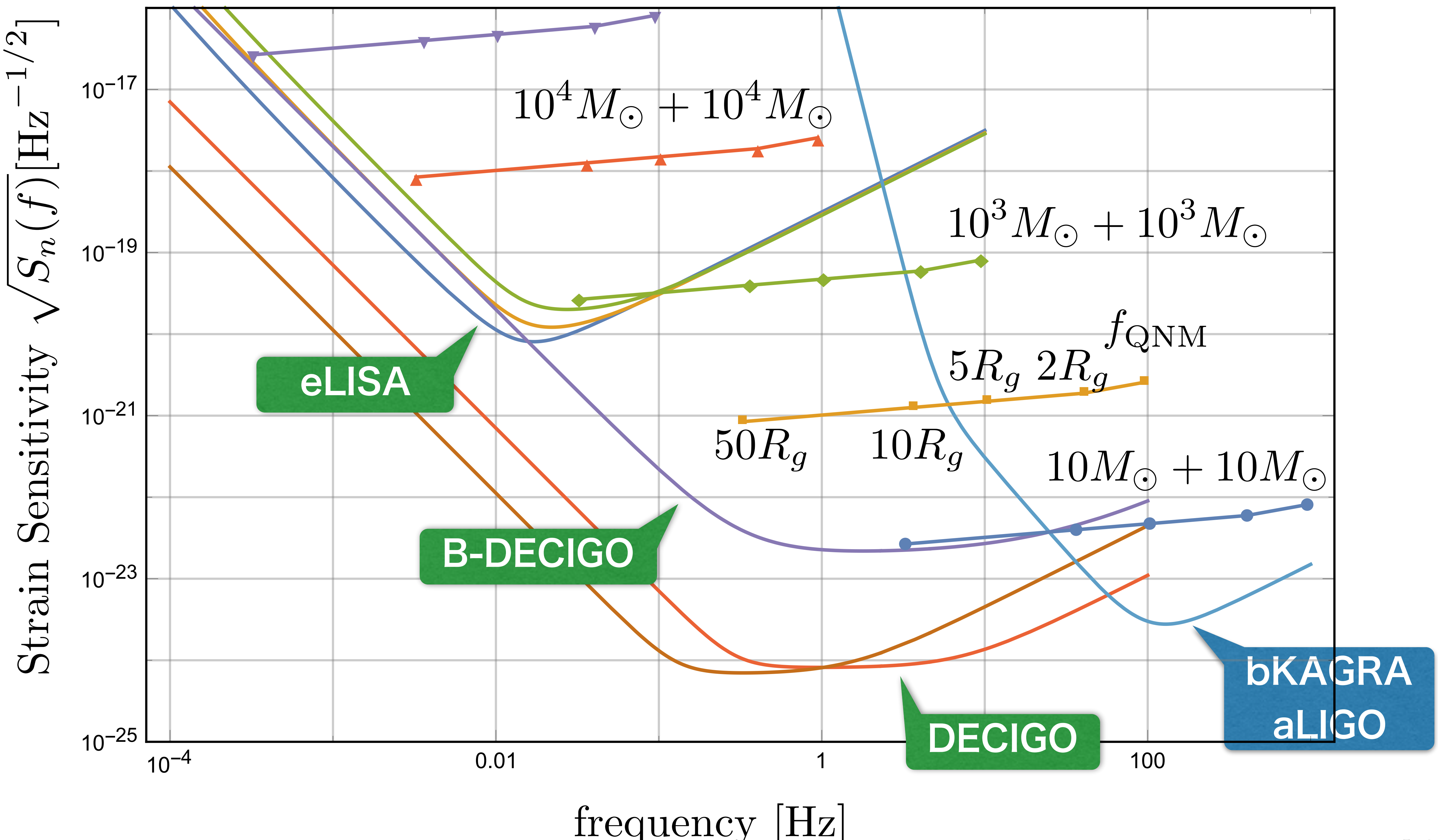
Typical frequency of BH-BH binary merger @ 100Mpc



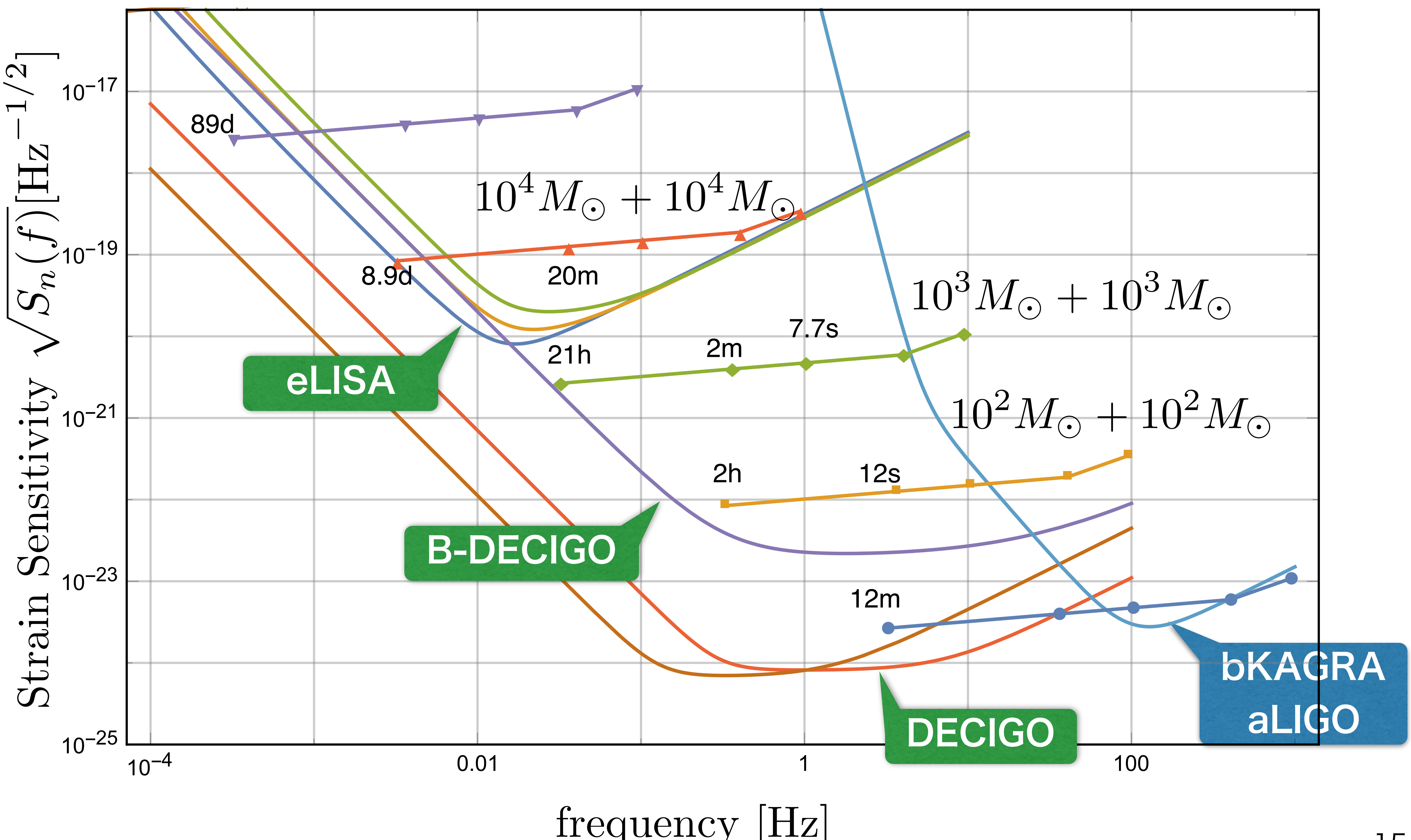
Typical frequency of BH-BH binary merger @ 1000Mpc



Typical frequency of BH-BH binary merger @ 100Mpc

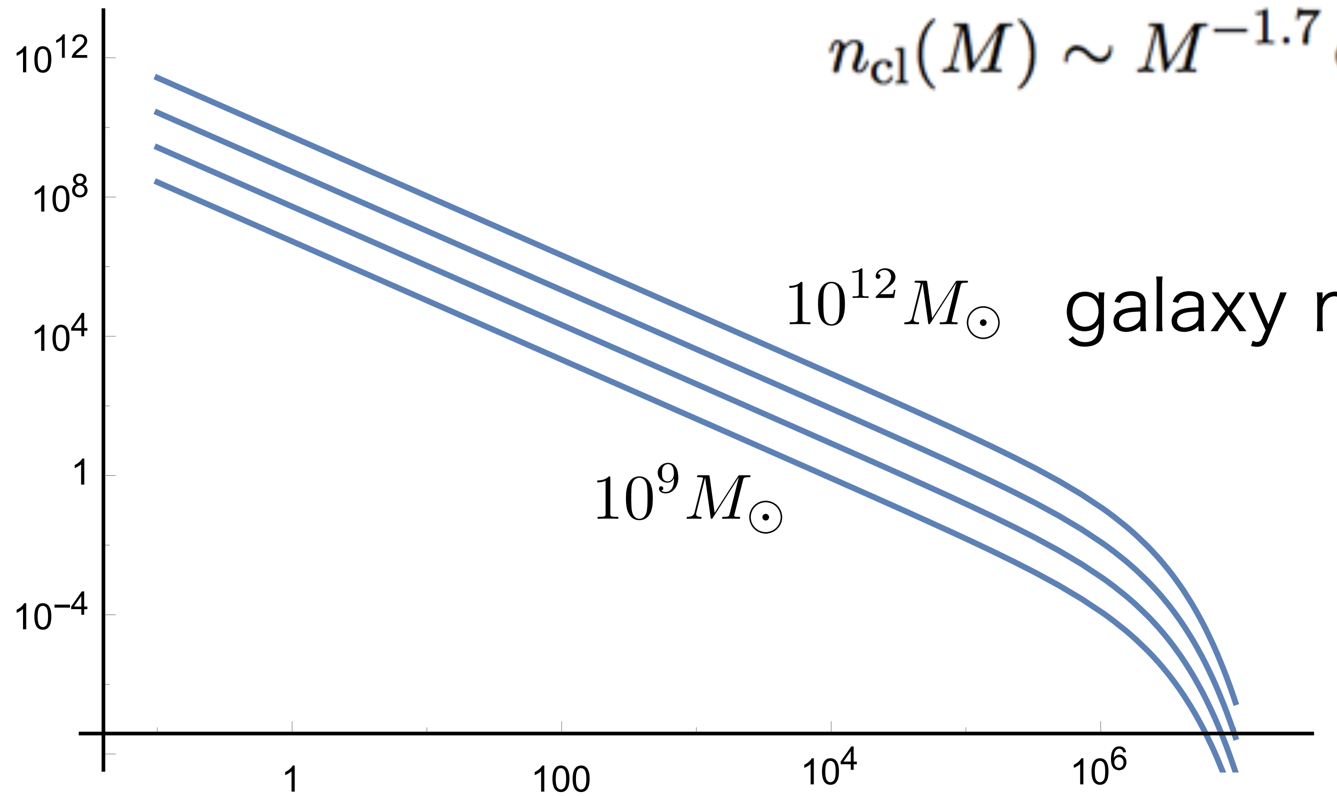


Typical frequency of BH-BH binary merger @ 1000Mpc



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

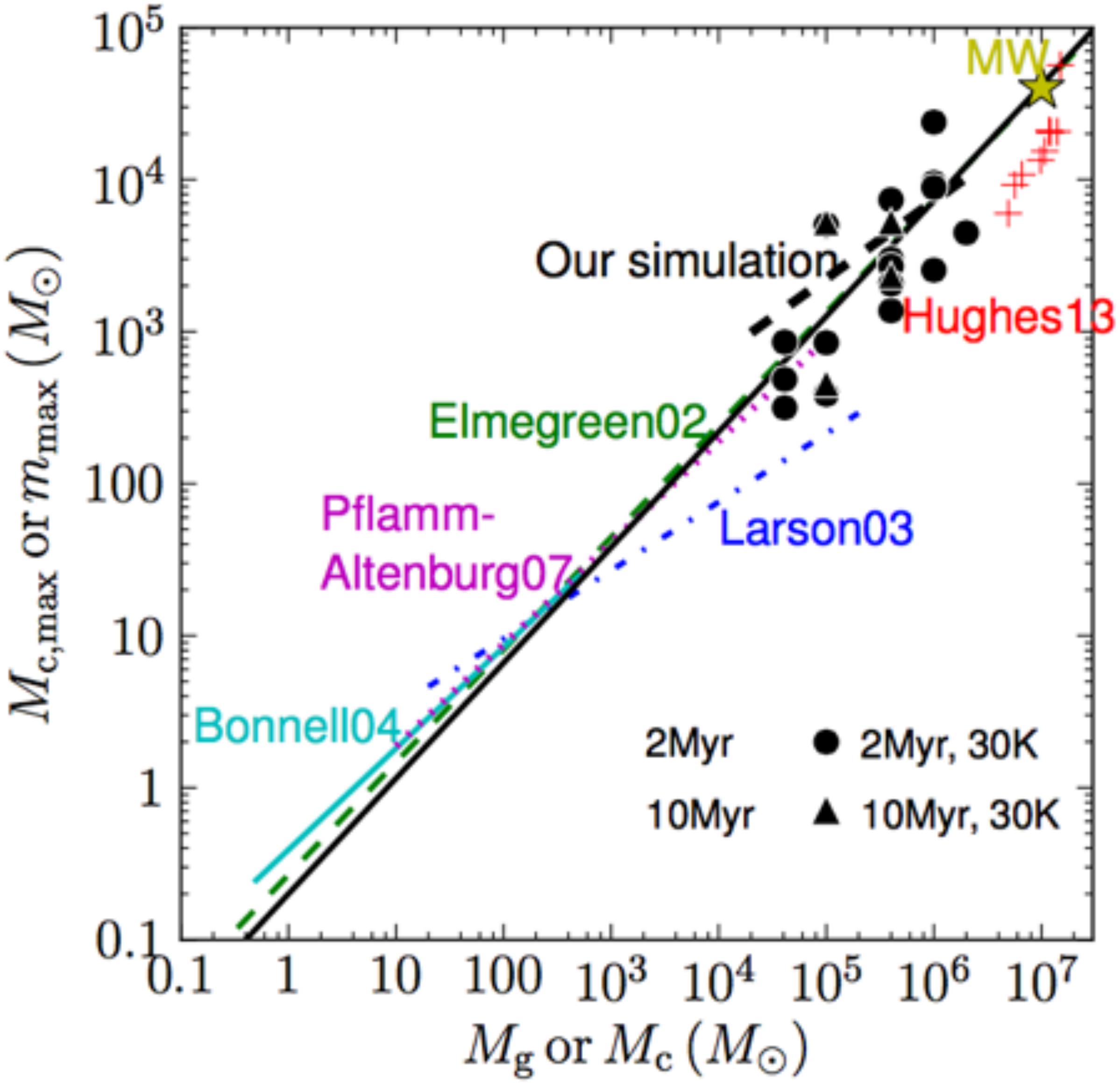
Shu-ichiro Inutsuka[1], Tsuyoshi Inoue,[2], Kazunari Iwasaki[1,3], and Takashi Hosokawa[4]

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

How many BHs in a Galaxy?

Molecular Clouds

Maximum Core



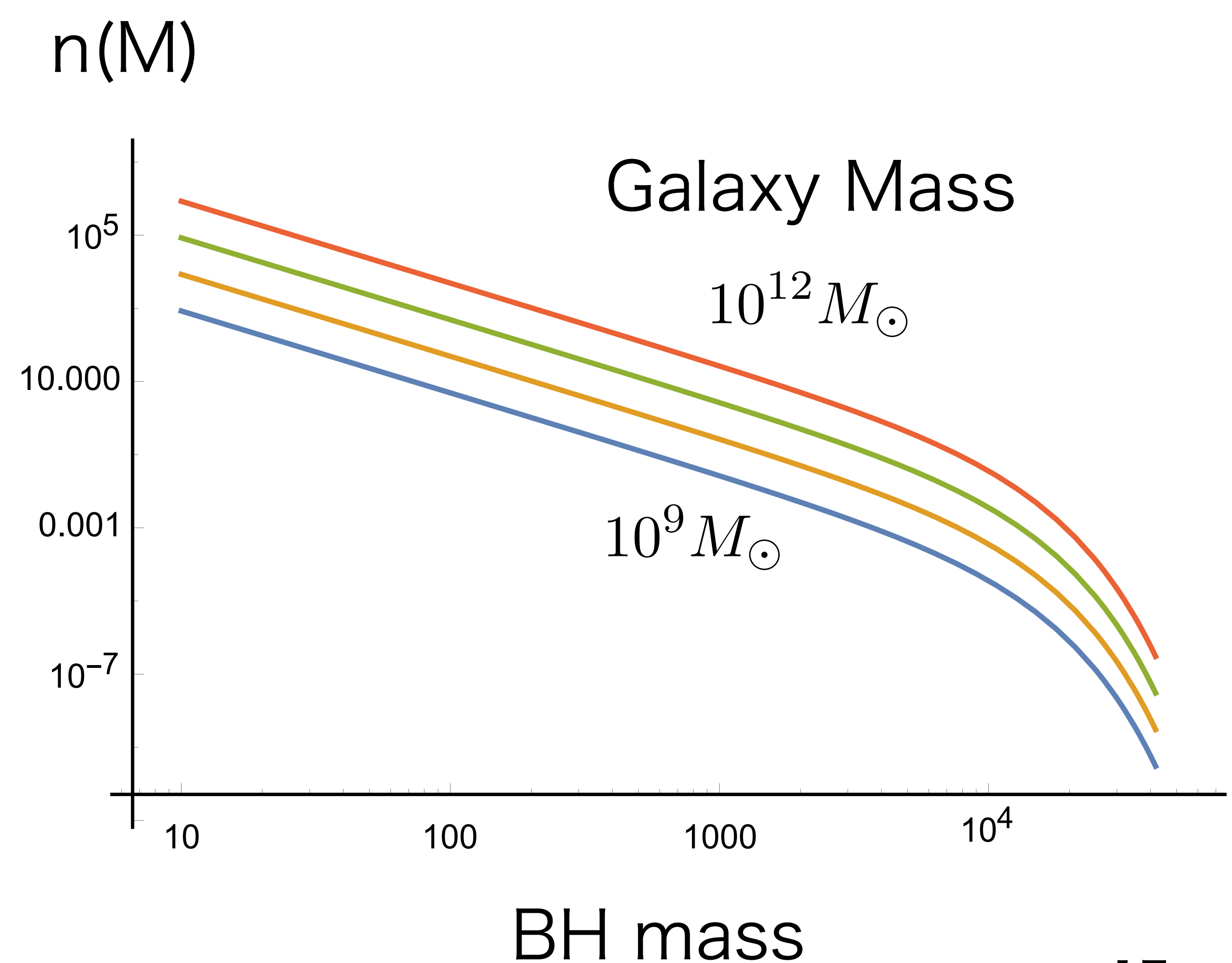
The initial mass function of star clusters that form in turbulent molecular clouds

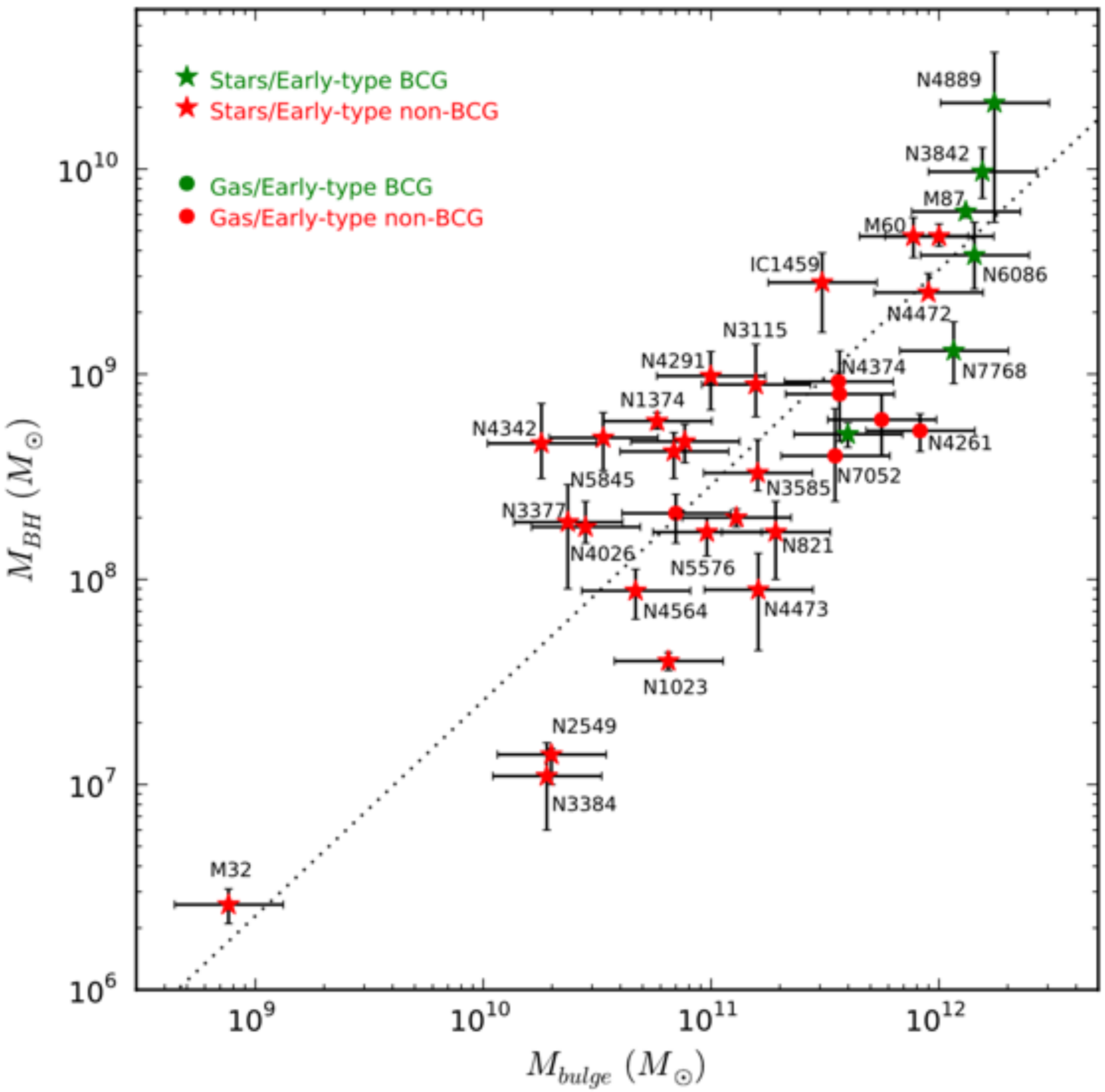
M. S. Fujii[1] * and S. Portegies Zwart[2]*
[1] Division of Theoretical Astronomy, National Astronomical Observatory of Japan 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[2] Leiden Observatory, Leiden University, NL-2300RA Leiden, The Netherlands

1309.1223v3

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

Building Block BH





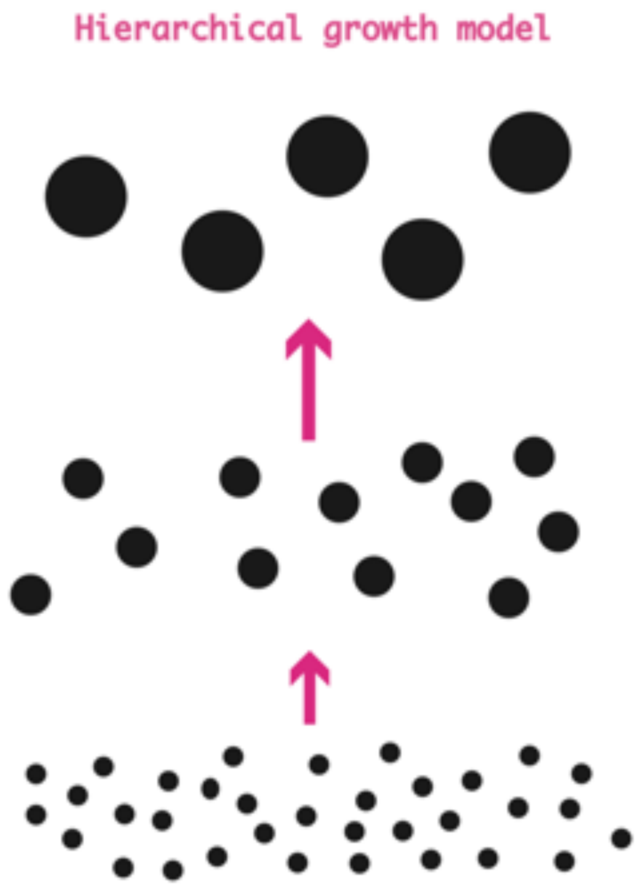
$$
\begin{aligned}
M_{\rm SMBH} &= 2\times 10^{-4} M_{\rm galaxy} \\
&= 10^{-3} M_{\rm bulge}
\end{aligned}
$$

McConnell-Ma
ApJ 764(2013)184

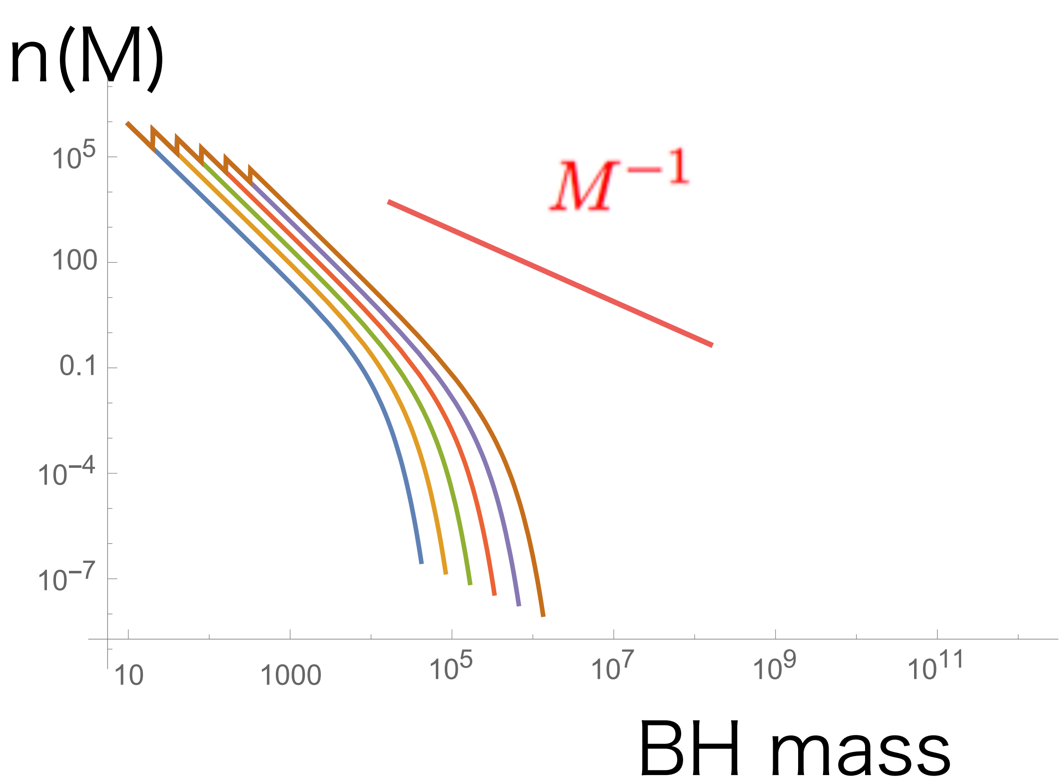
Figure 3. $M_\bullet$–$M_{\rm bulge}$ relation for the 35 early-type galaxies with dynamical measurements of the bulge stellar mass in our sample. The symbols are the same as in Figure 1. The black line represents the best-fitting power-law $\log_{10}(M_\bullet/M_\odot) = 8.46 + 1.05\ \log_{10}(M_{\rm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

How many BHs in a Galaxy?

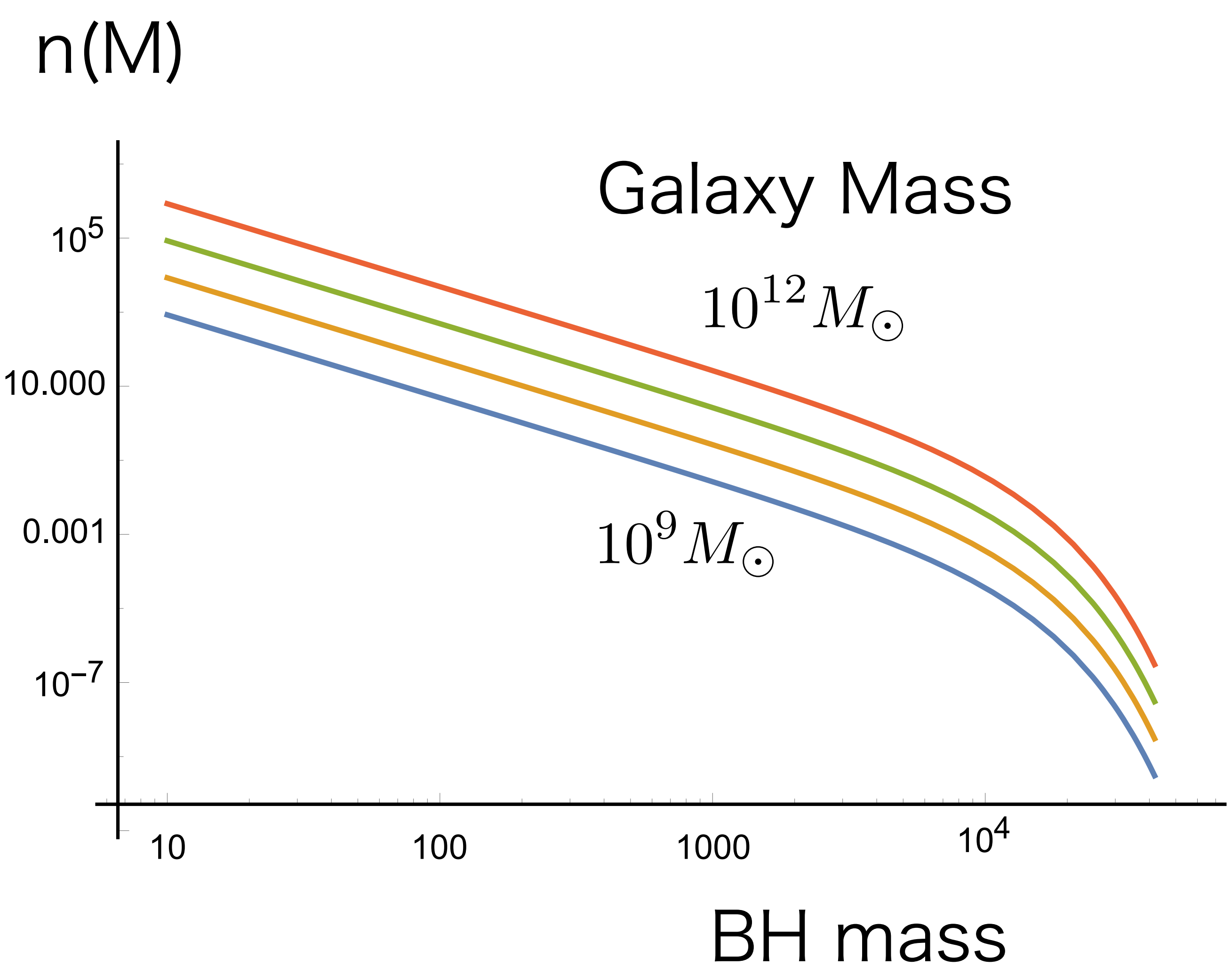
Count BHs to form a SMBH



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

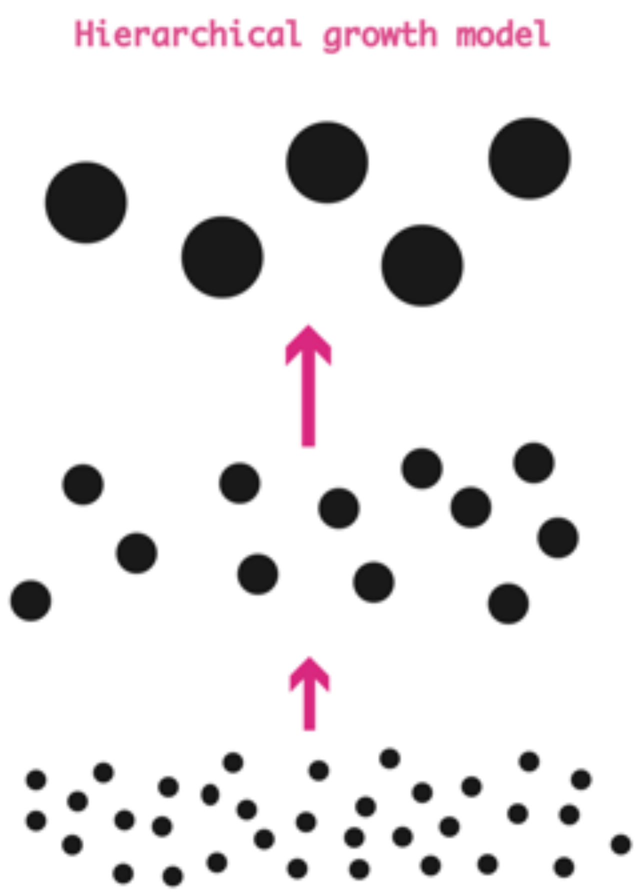


Building Block BH



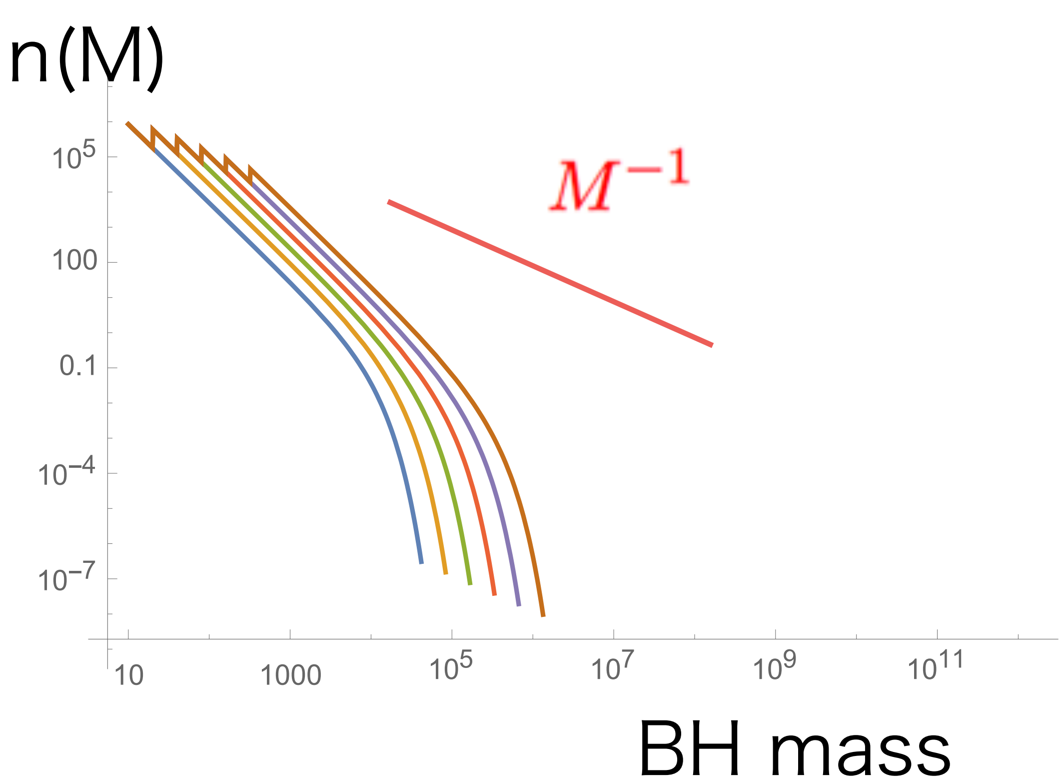
How many BHs in a Galaxy?

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

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

(sub-)Galaxy from Halo model

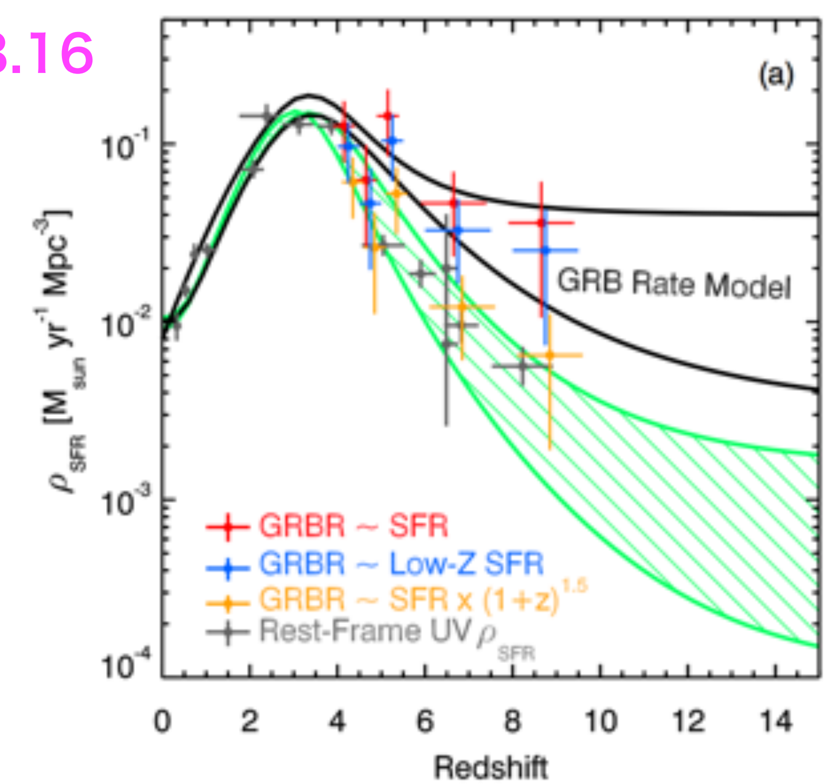
Mon. Not. R. Astron. Soc. 371, 1173–1187 (2006) doi:10

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



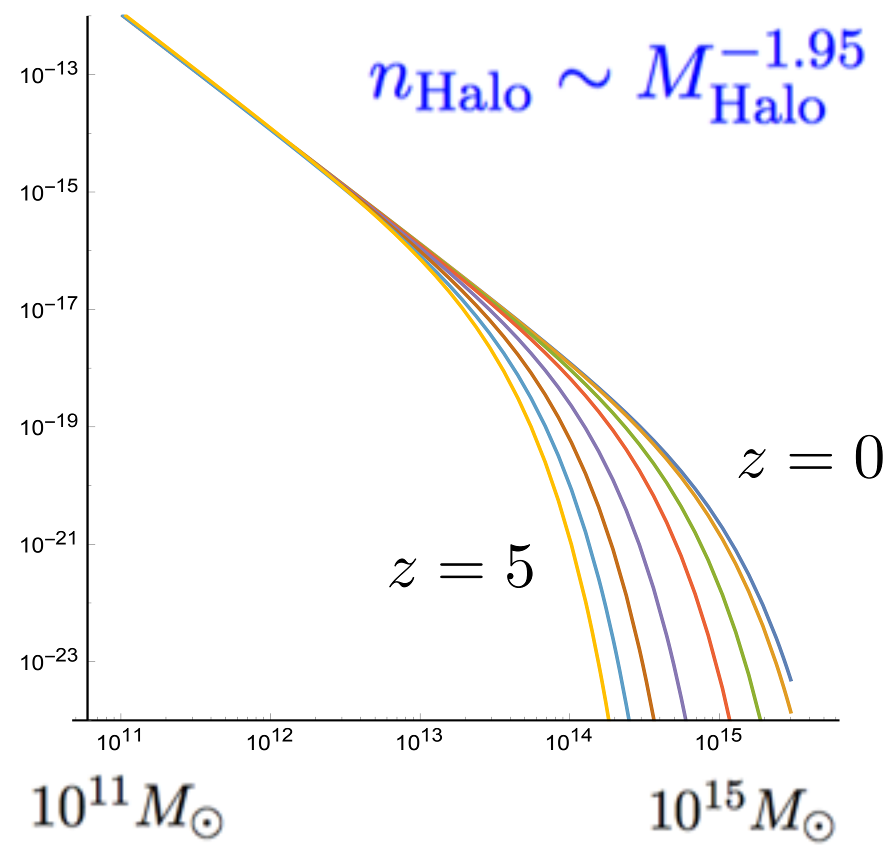
The Astrophysical Journal, 744:95 (13pp), 2012 January 10 doi:10.1088/0004-637X/744/2/95

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

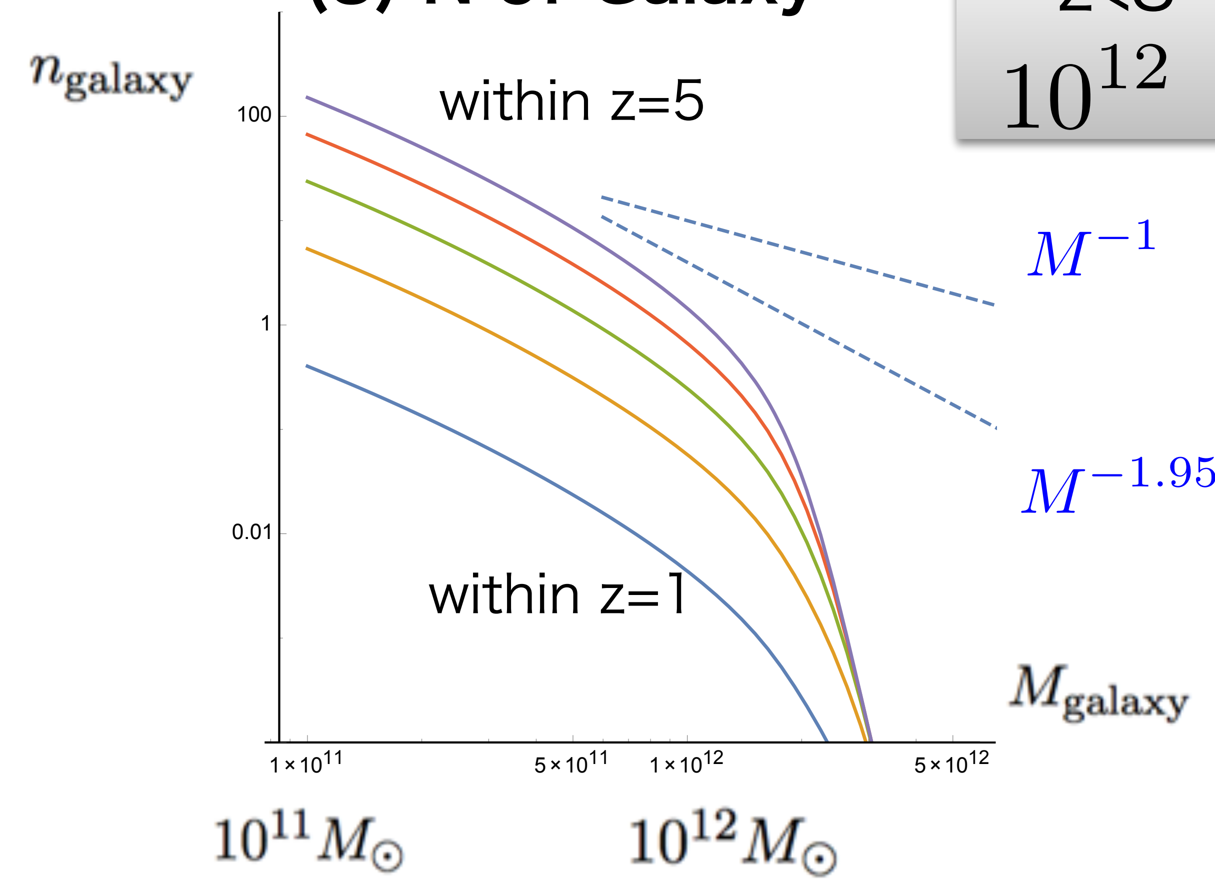
How many Galaxies in the Universe?

(1) Halo number density

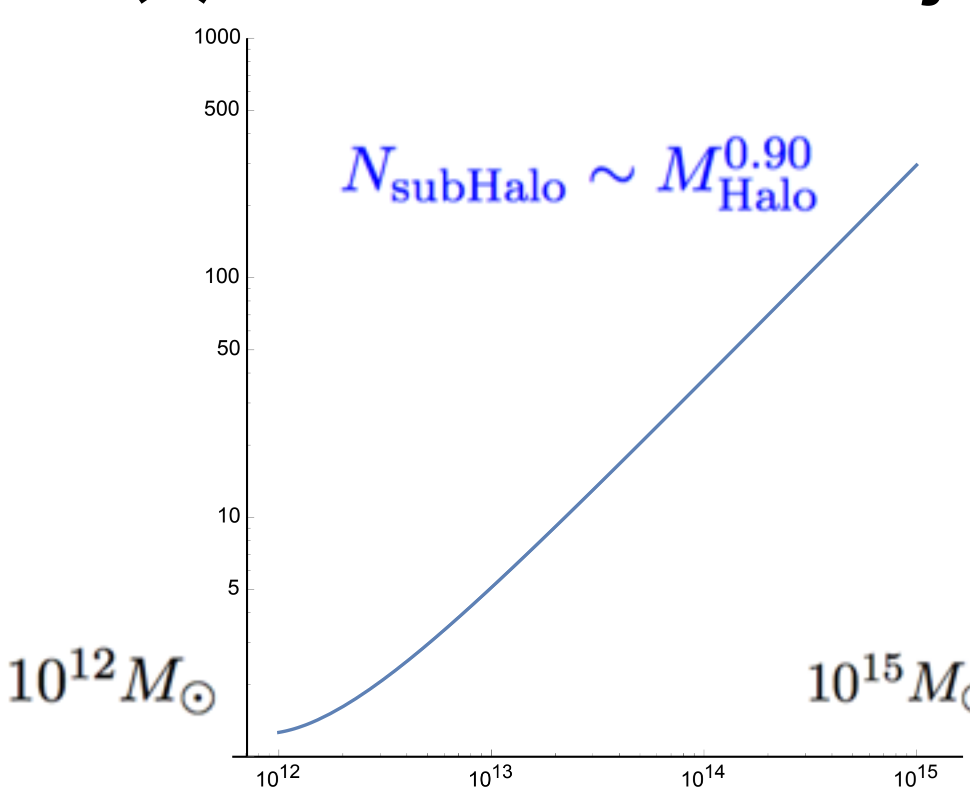


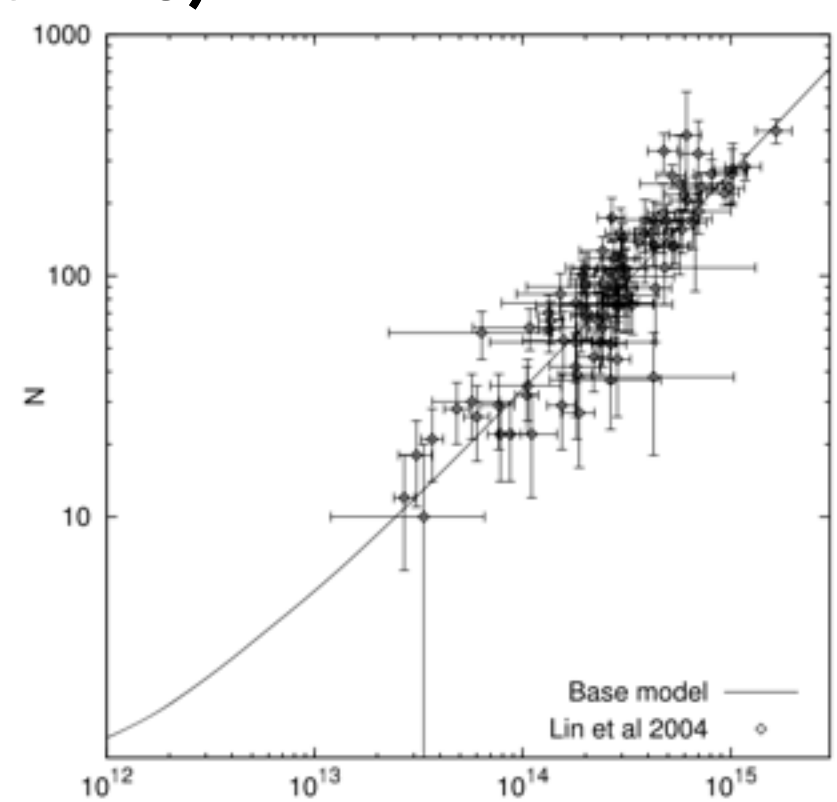
(3) N of Galaxy

z<3
10^{12}



(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,

ROYAL ASTRONOMICAL SOCIETY
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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

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

(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]
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[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

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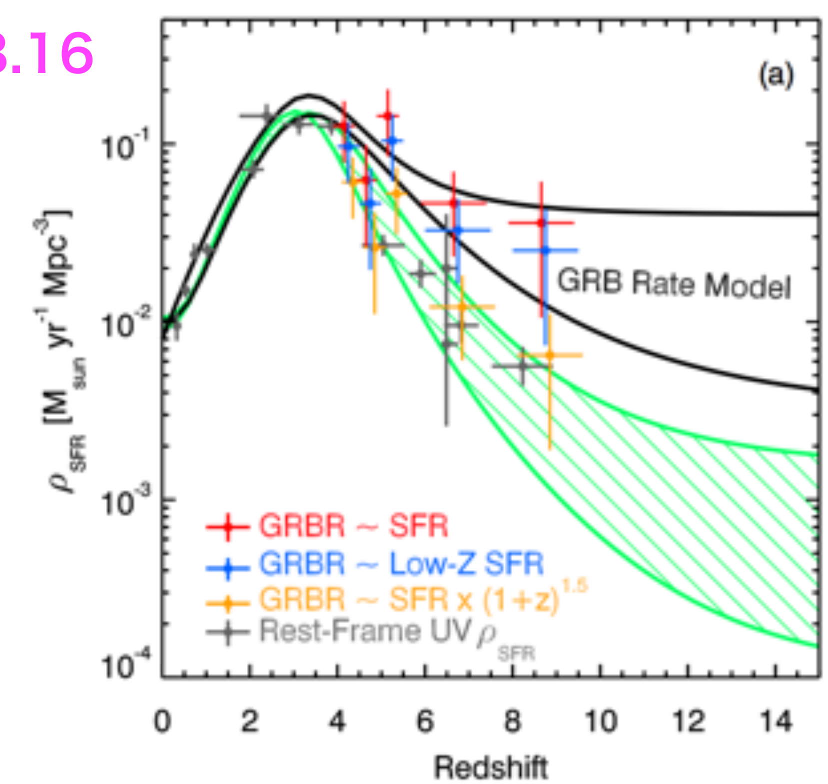
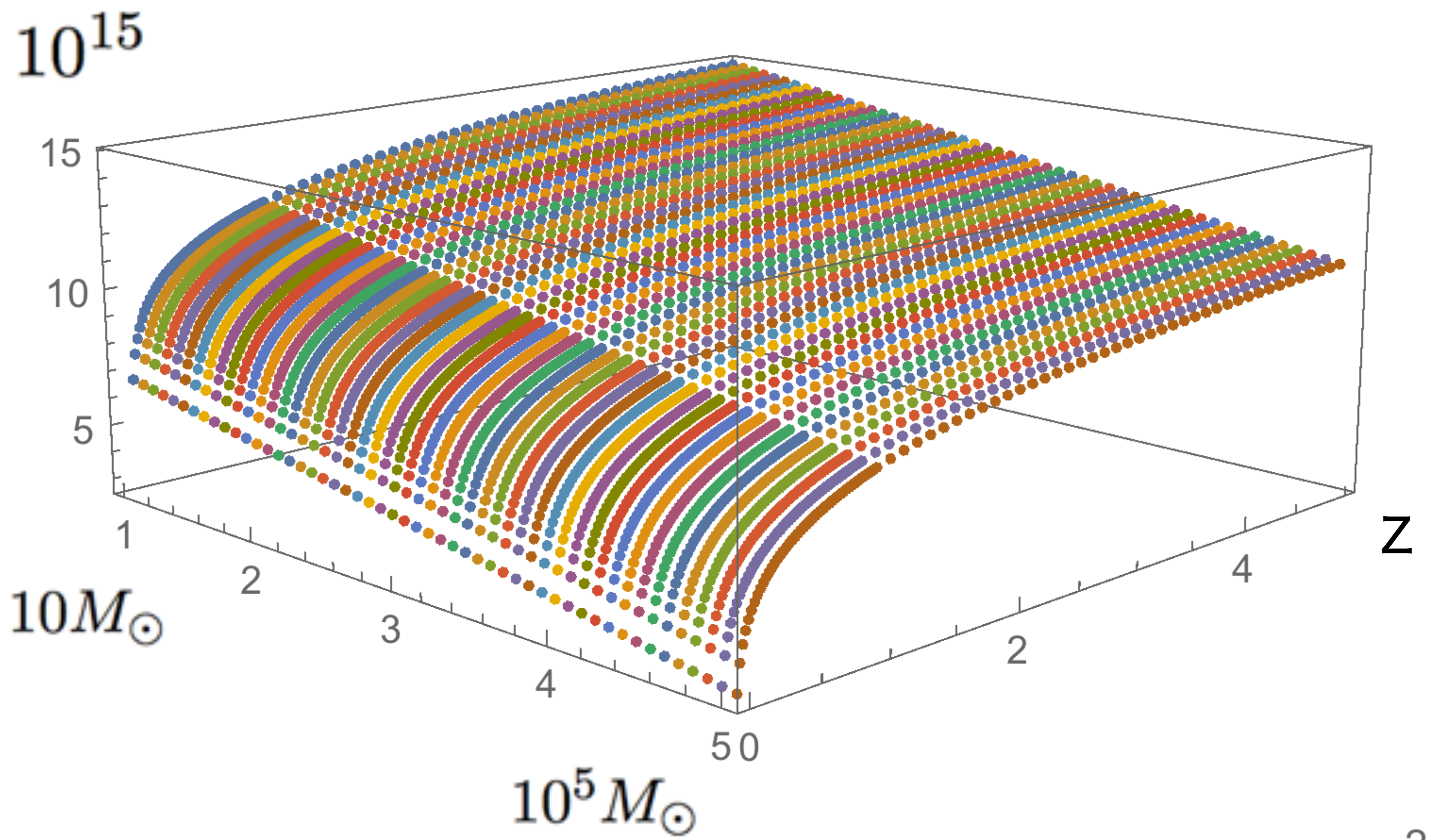
Star Formation Rate

peak z=3.16



How many BH mergers in the Universe?



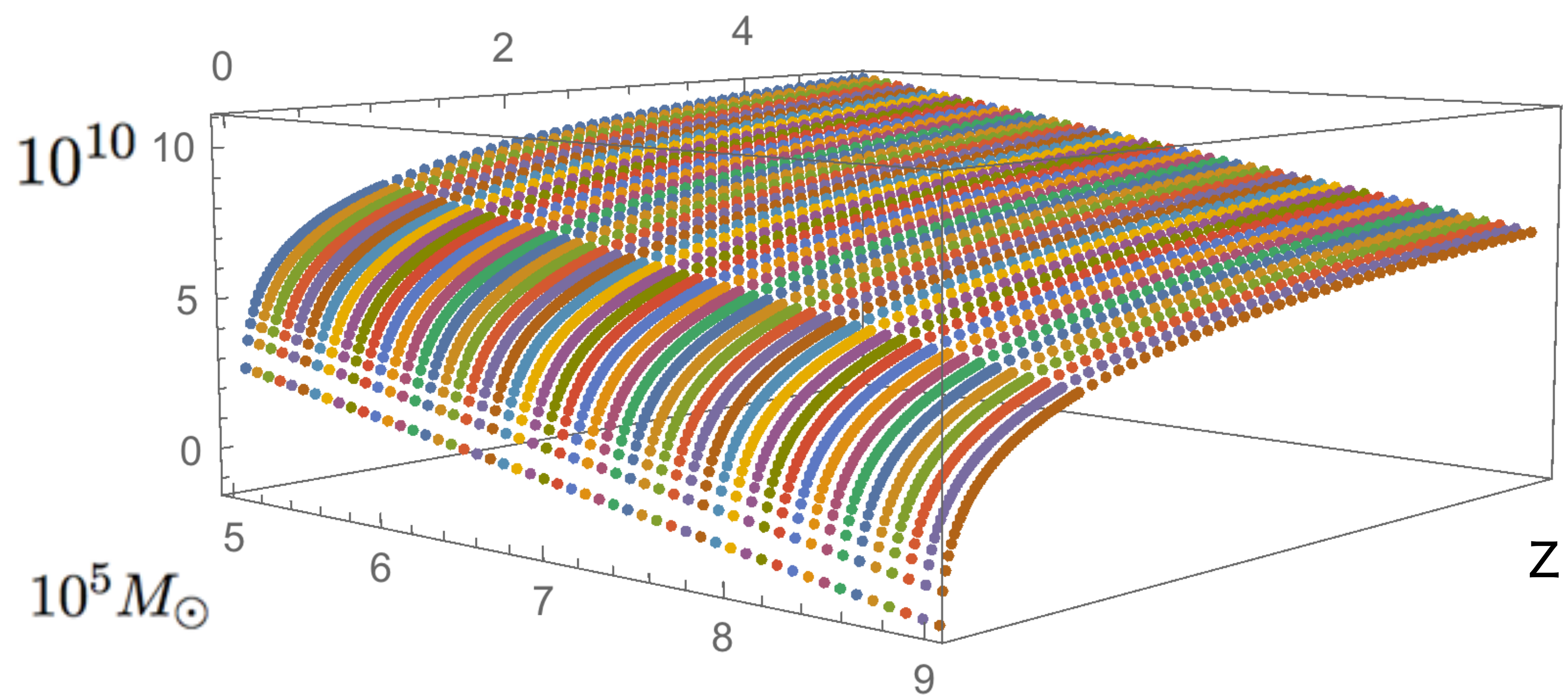
BH mass

in Standard Cosmology

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

Standard Cosmology

averaging distances for all directions



BH mass $10^9 M_\odot$

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, $n(t)$:

$$s(t) = h(t) + n(t). \qquad (17)$$

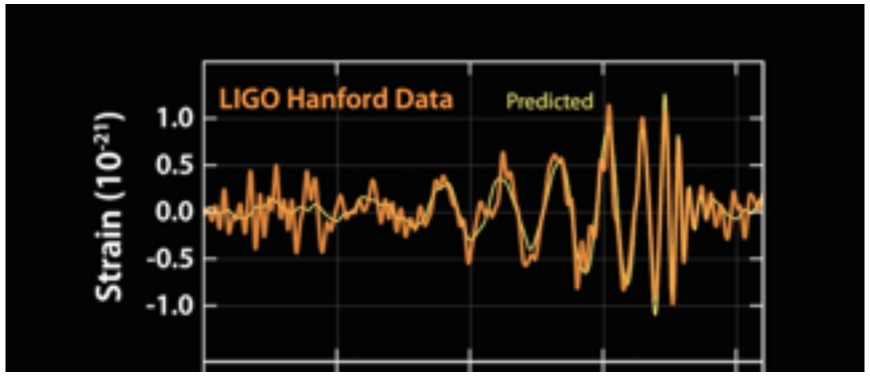
The standard procedure for the detection is judged by the optimal signal-to-noise ratio (SNR), ρ, which is given by

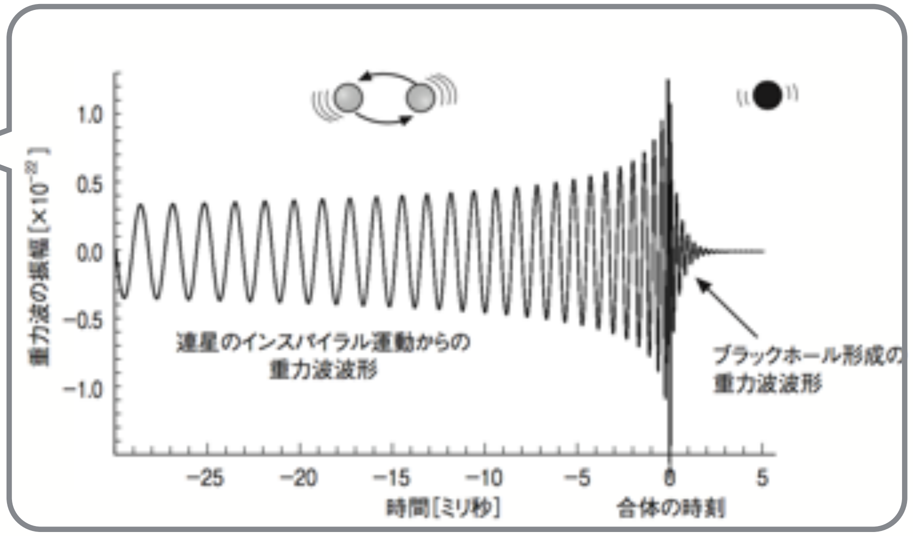
$$\rho = 2\left[\int_0^{\infty} \frac{\tilde{h}(f)\,\tilde{h}^*(f)}{S_n(f)}\,df\right]^{1/2}, \qquad (18)$$

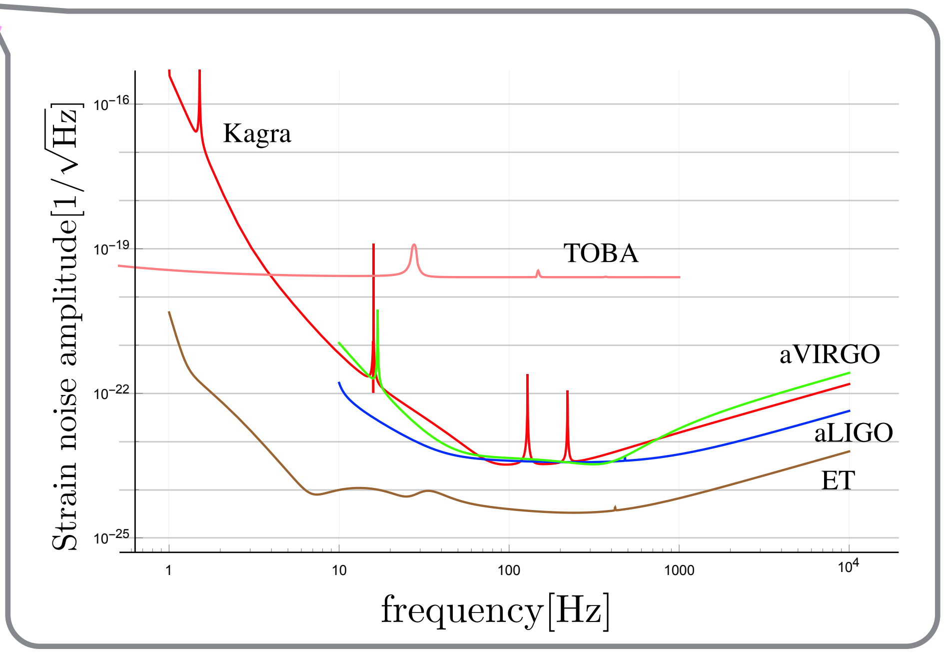
where $\tilde{h}(f)$ is the Fourier-transformed quantity of the wave,

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

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

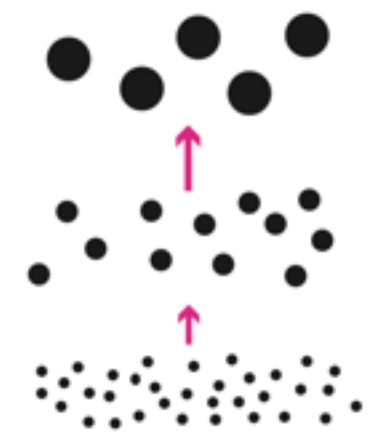
Flanagan&Hughes, PRD57(1998)4535

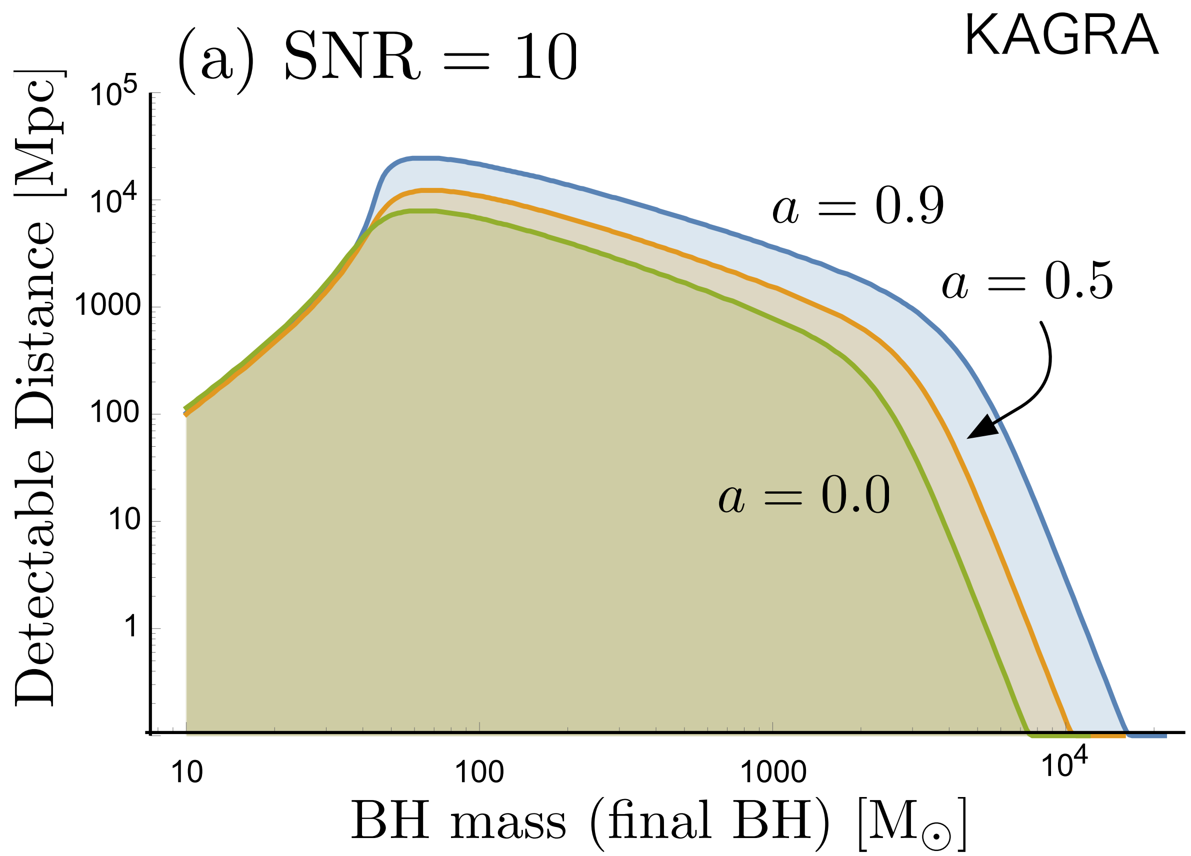
SNR $$\rho^2 = \frac{8}{5}\frac{\epsilon_r(a)}{f_R^2}\frac{(1+z)M}{S_h(f_R/(1+z))}\left(\frac{(1+z)M}{d_L(z)}\right)^2\left(\frac{4\mu}{M}\right)^2$$

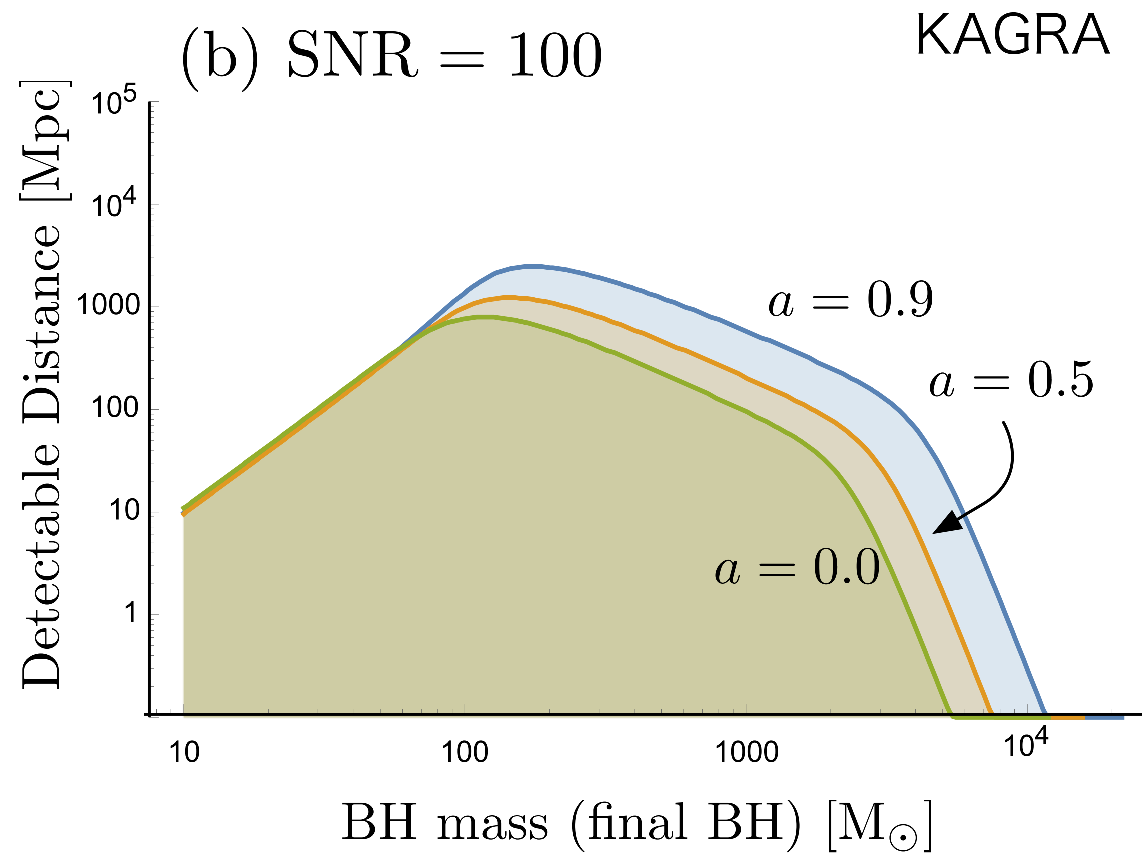
Energy emission=4% of total M, 1% at ringdown

Standard Cosmology

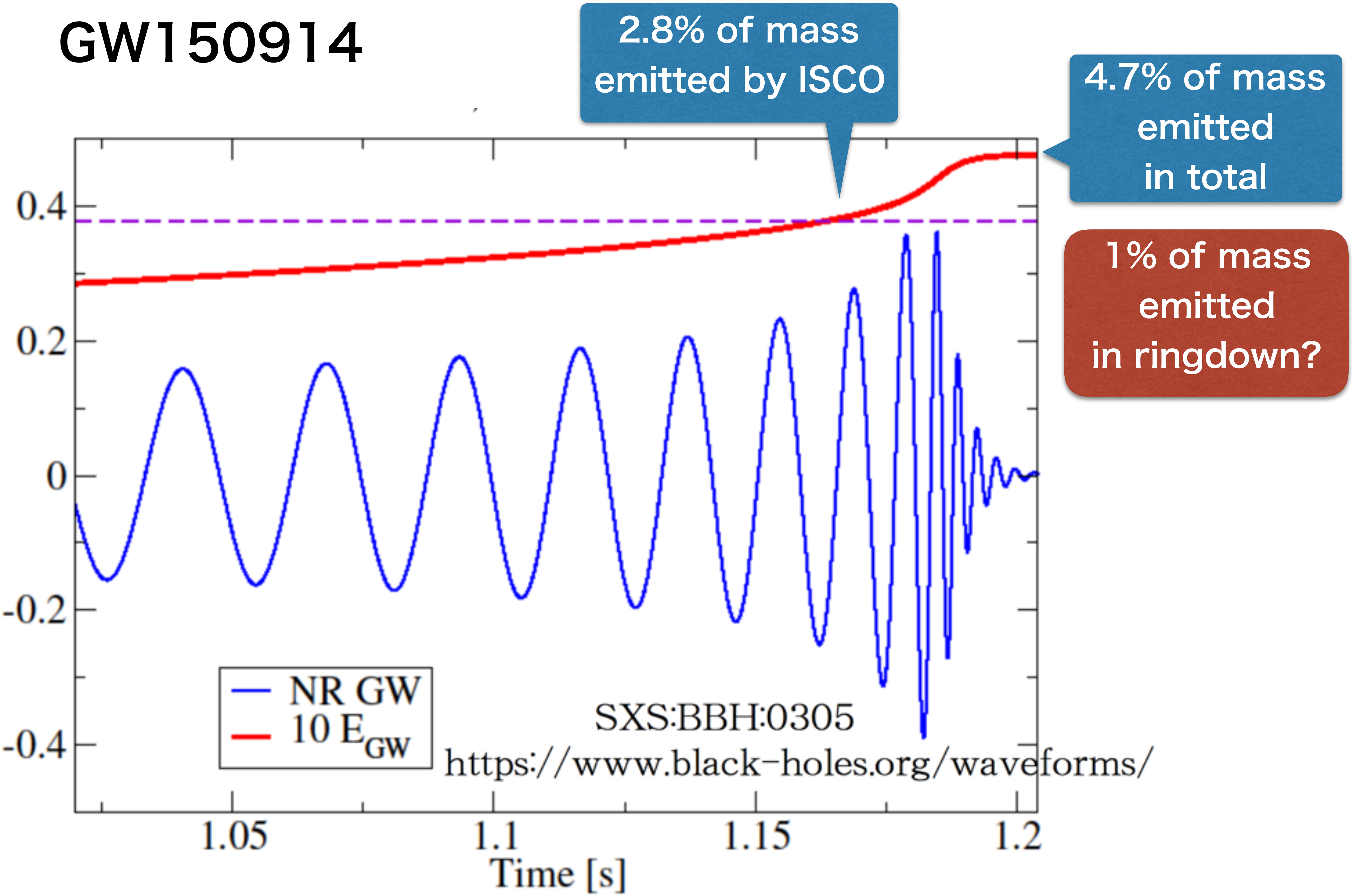
Hierarchical Growth







GW150914



Slide copy from Hiroyuki Nakano

How many BH mergers in the Universe?

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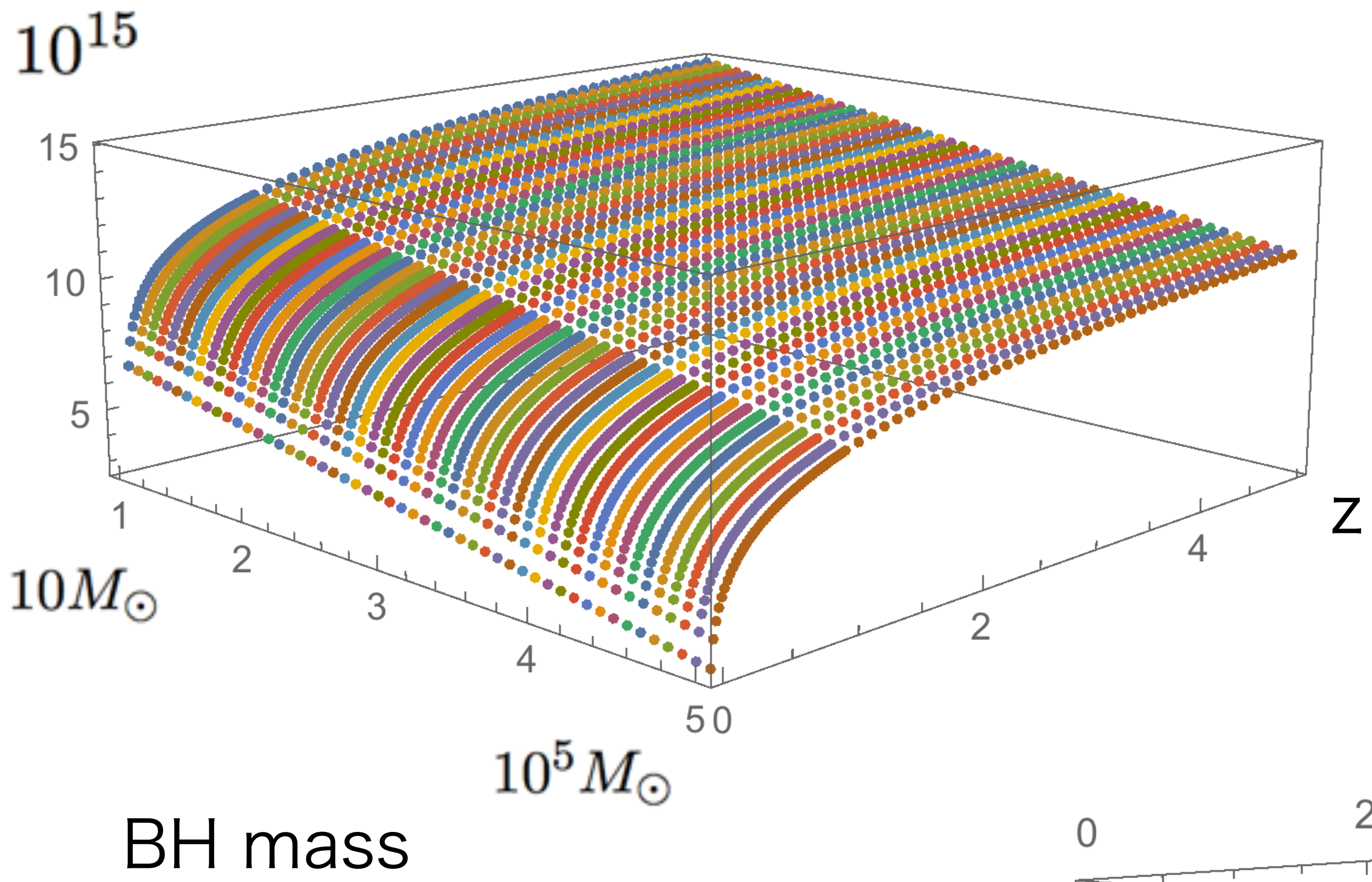
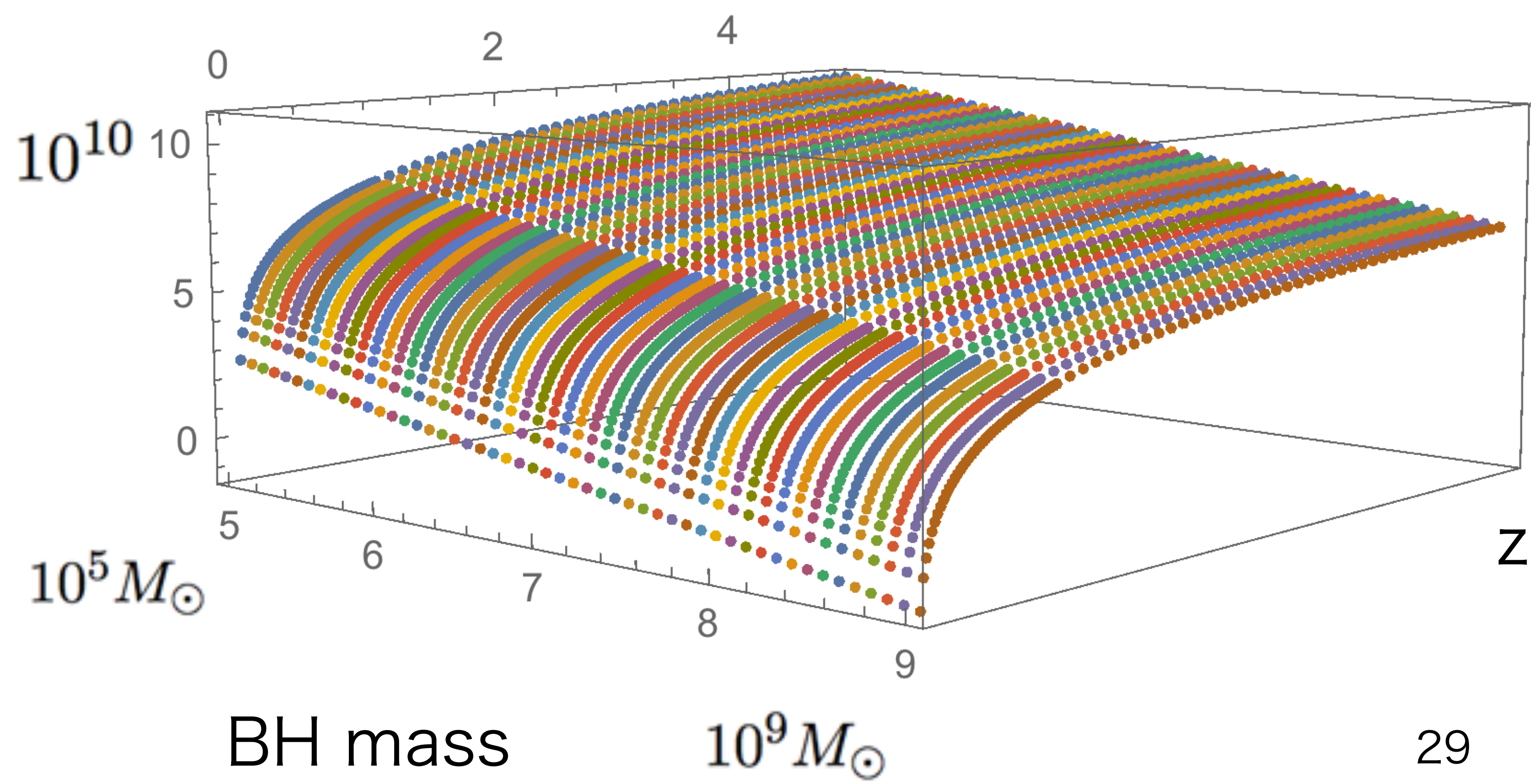
Standard Cosmology

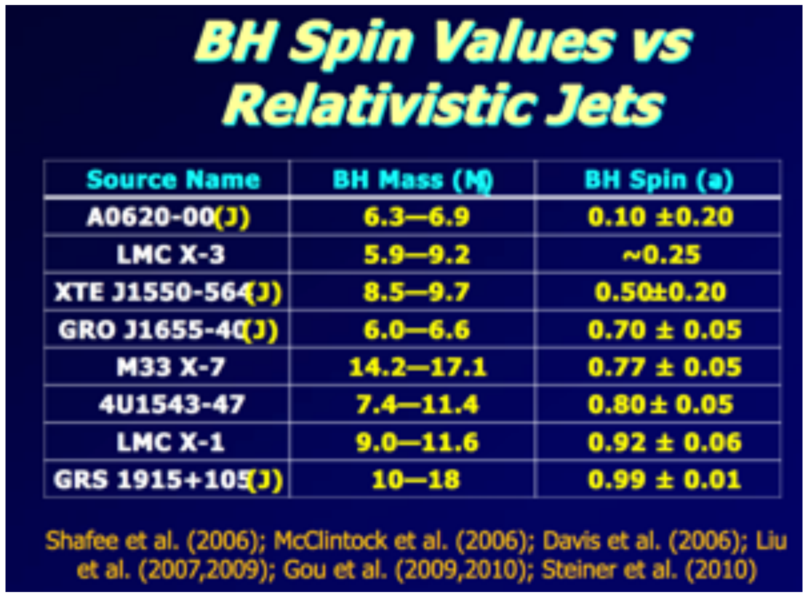
averaging distances for all directions





Spin evolution model of BHs

Narayan 2011

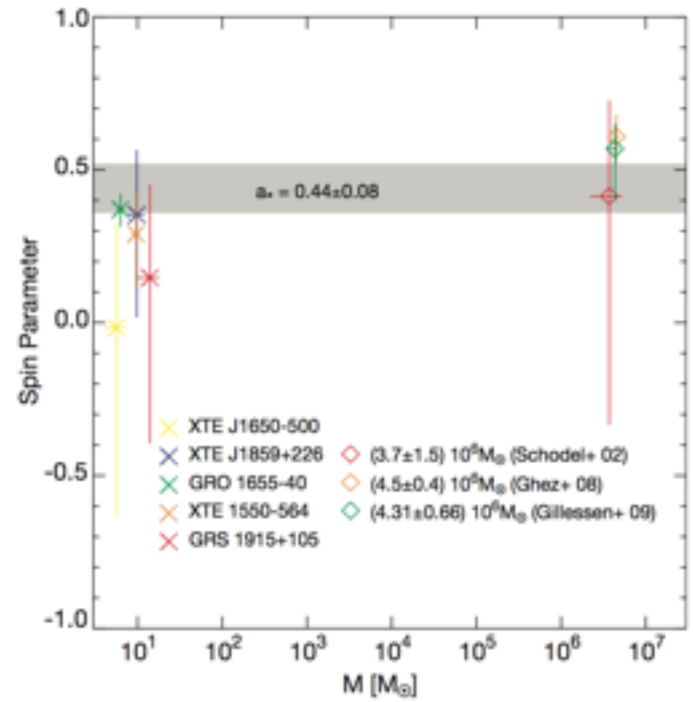


BH Spin Values vs Relativistic Jets

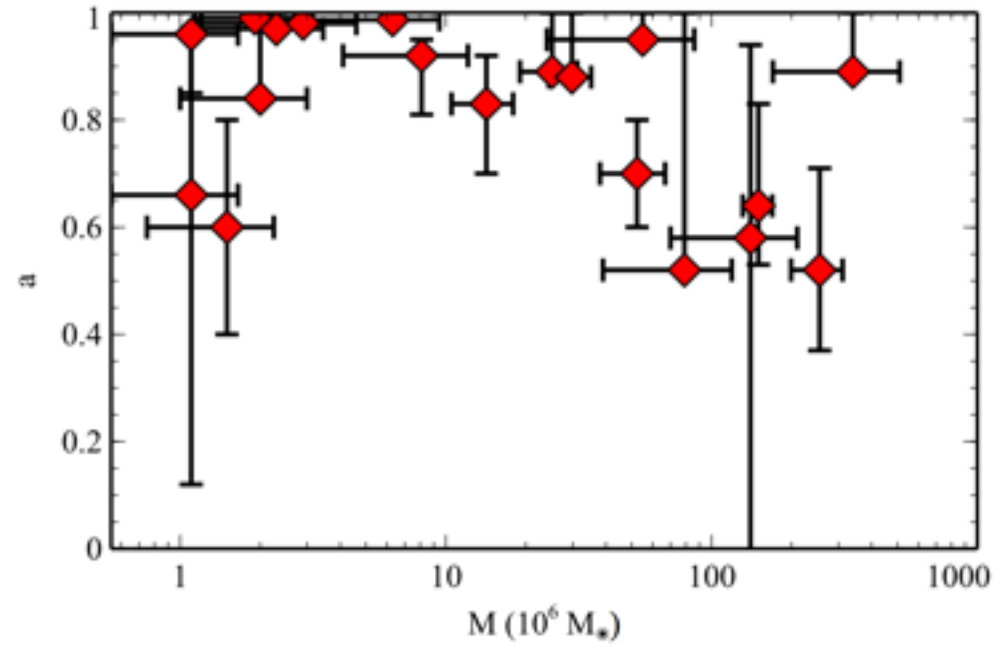
Source Name	BH Mass (M)	BH Spin (a)
A0620-00(J)	6.3—6.9	0.10 ±0.20
LMC X-3	5.9—9.2	~0.25
XTE J1550-564(J)	8.5—9.7	0.50±0.20
GRO J1655-40(J)	6.0—6.6	0.70 ± 0.05
M33 X-7	14.2—17.1	0.77 ± 0.05
4U1543-47	7.4—11.4	0.80± 0.05
LMC X-1	9.0—11.6	0.92 ± 0.06
GRS 1915+105(J)	10—18	0.99 ± 0.01

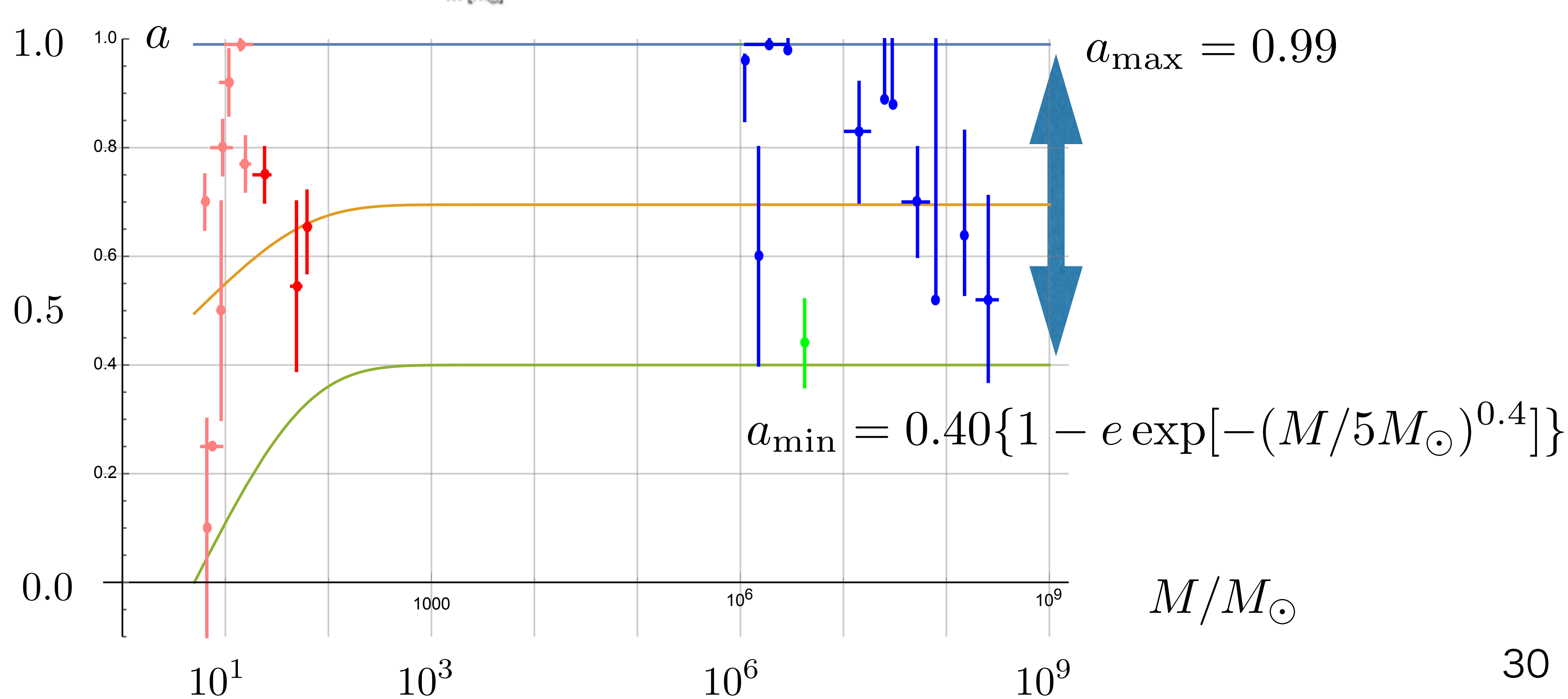
Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007,2009); Gou et al. (2009,2010); Steiner et al. (2010)

Kato+, MNRAS 403 (2010) L74
(arXiv:0906.5423)

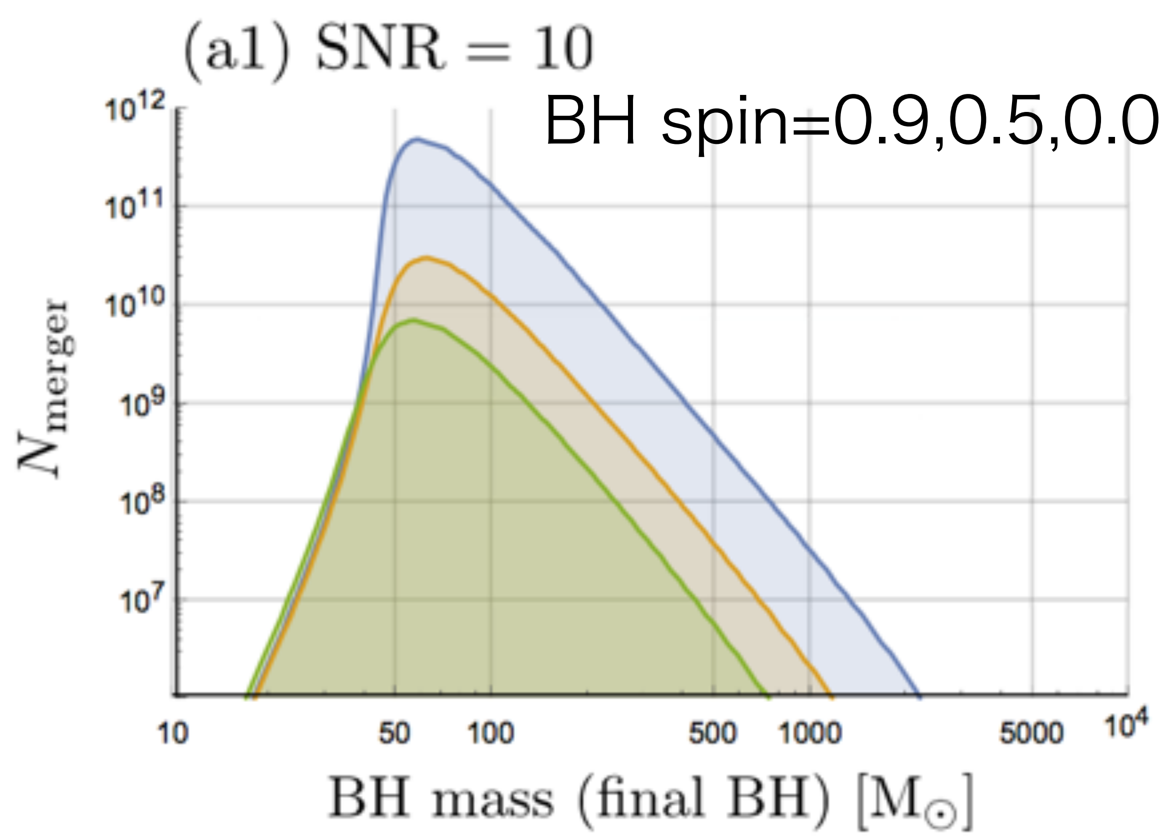


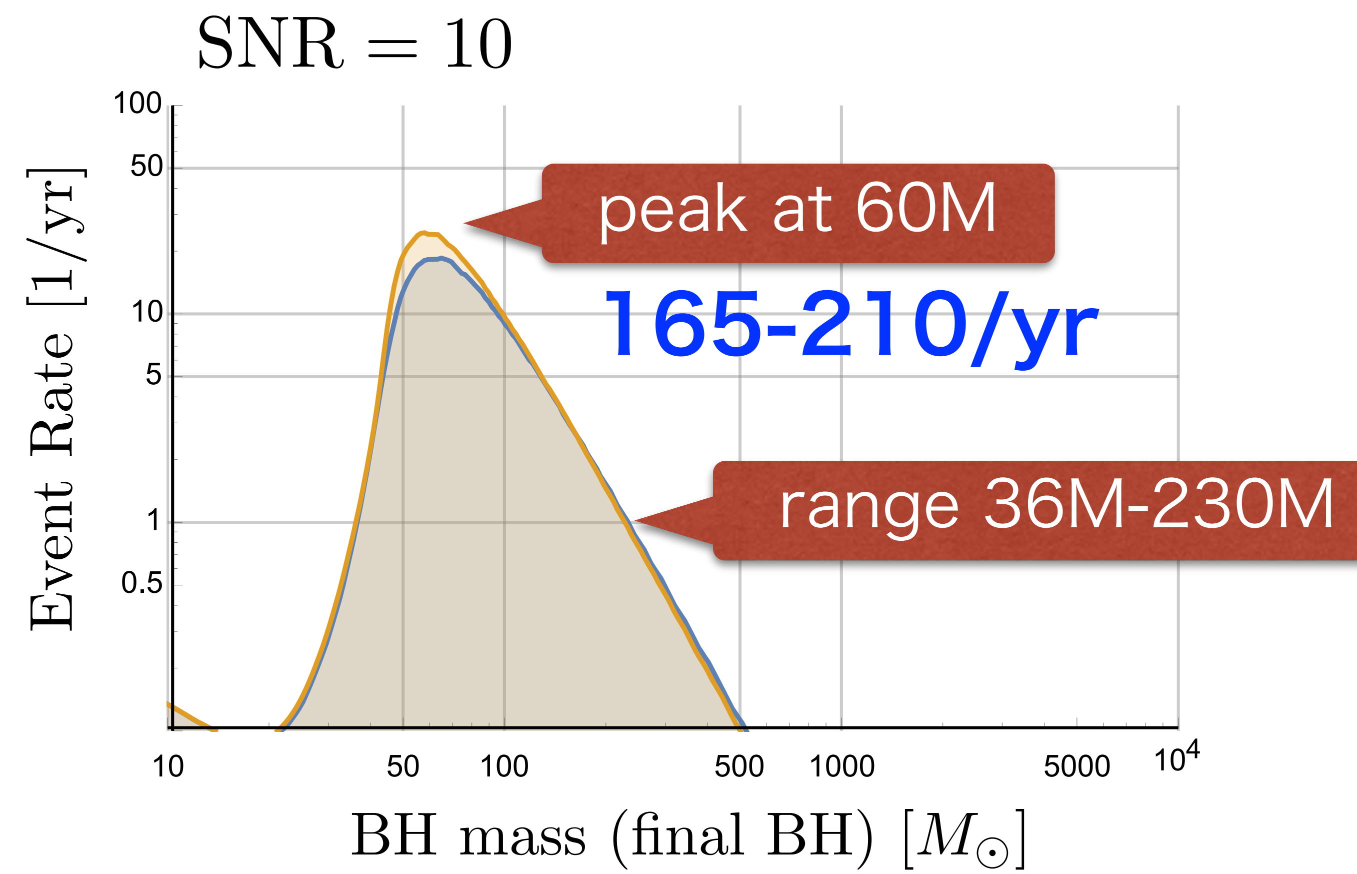
Reynolds, CQG 30 (2013) 244004
(arXiv:1307.3246)

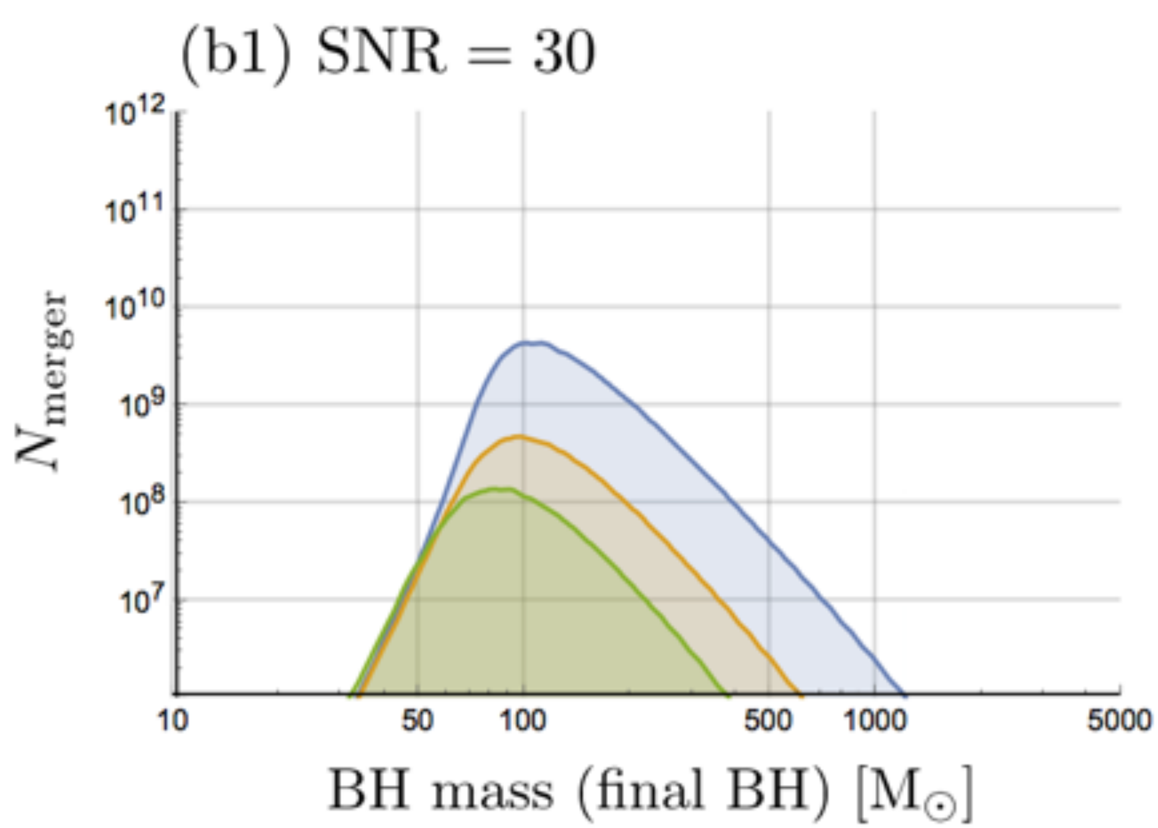


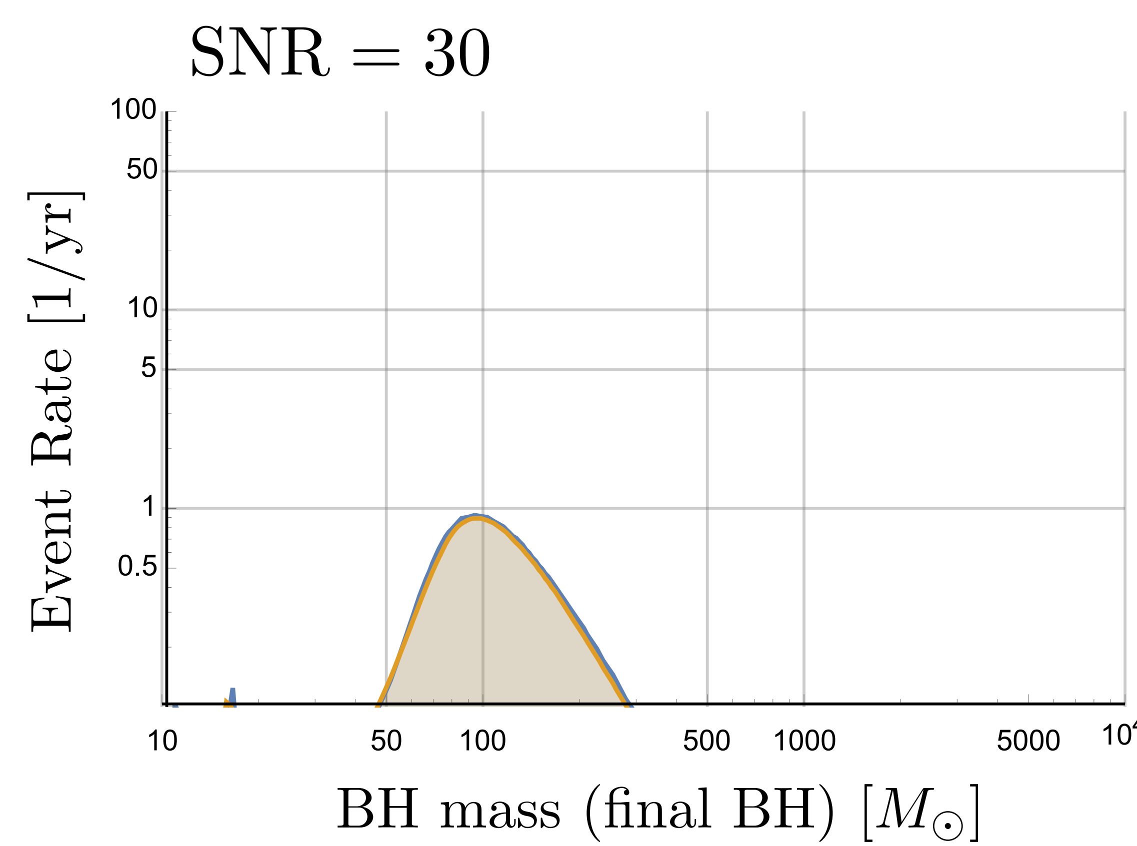


Event Rates at bKAGRA





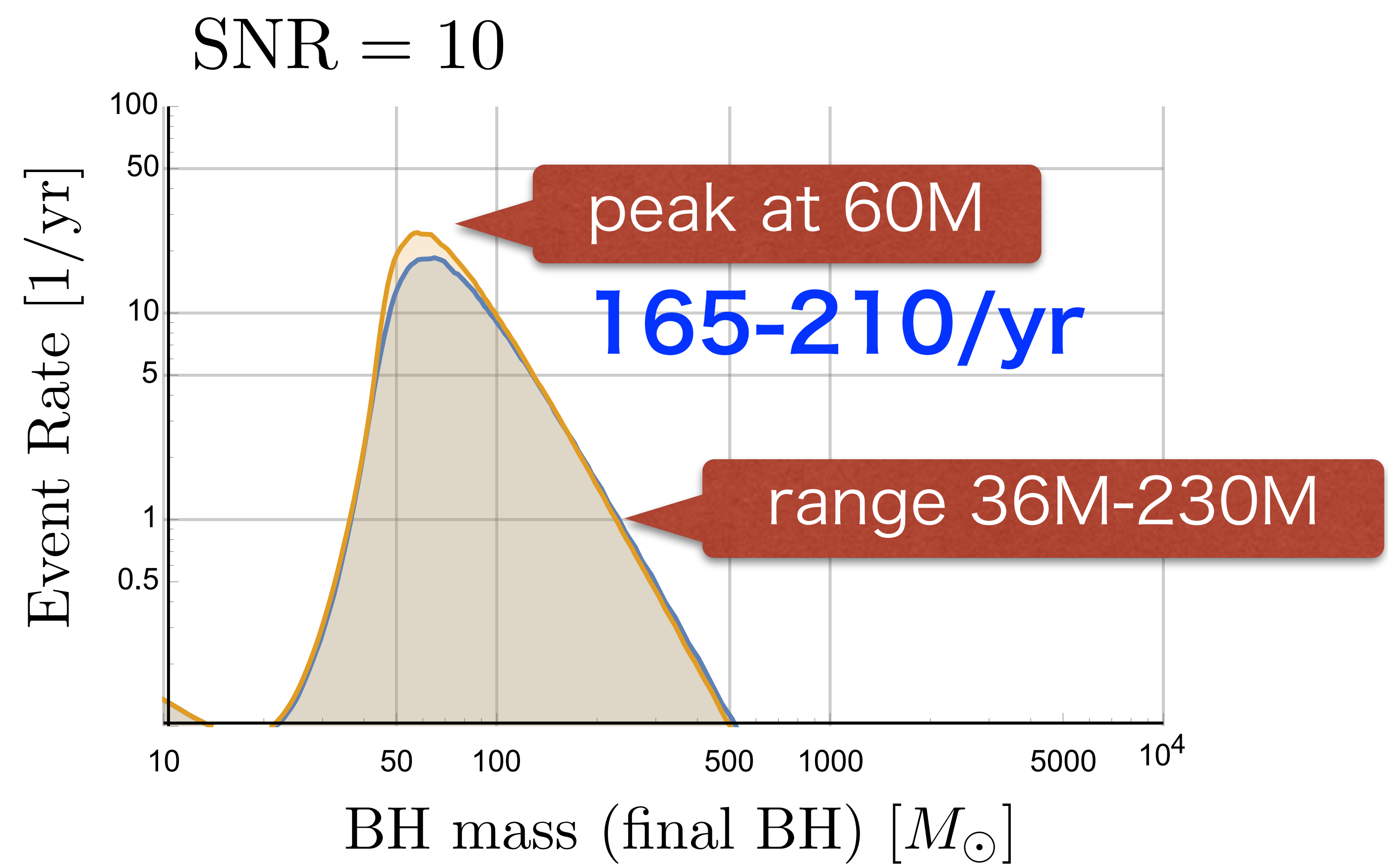




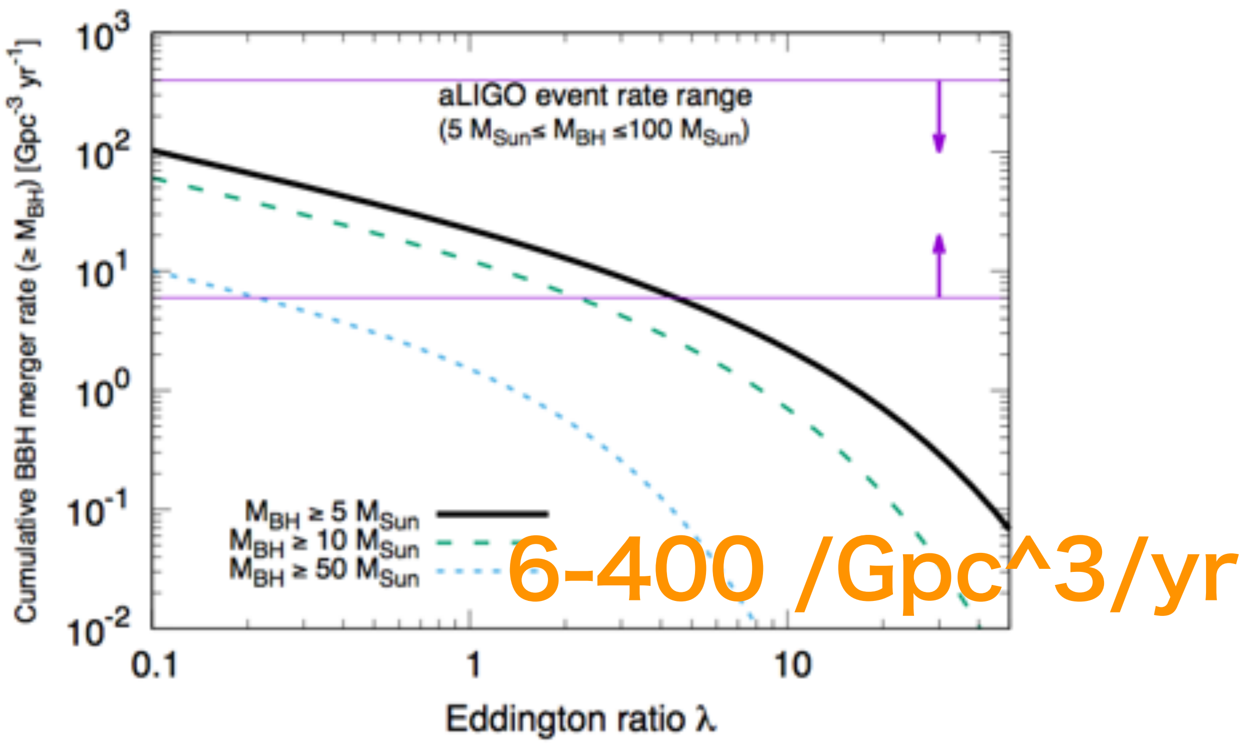
Event Rates at bKAGRA/aLIGO

LIGO group PRX6(2016)041015

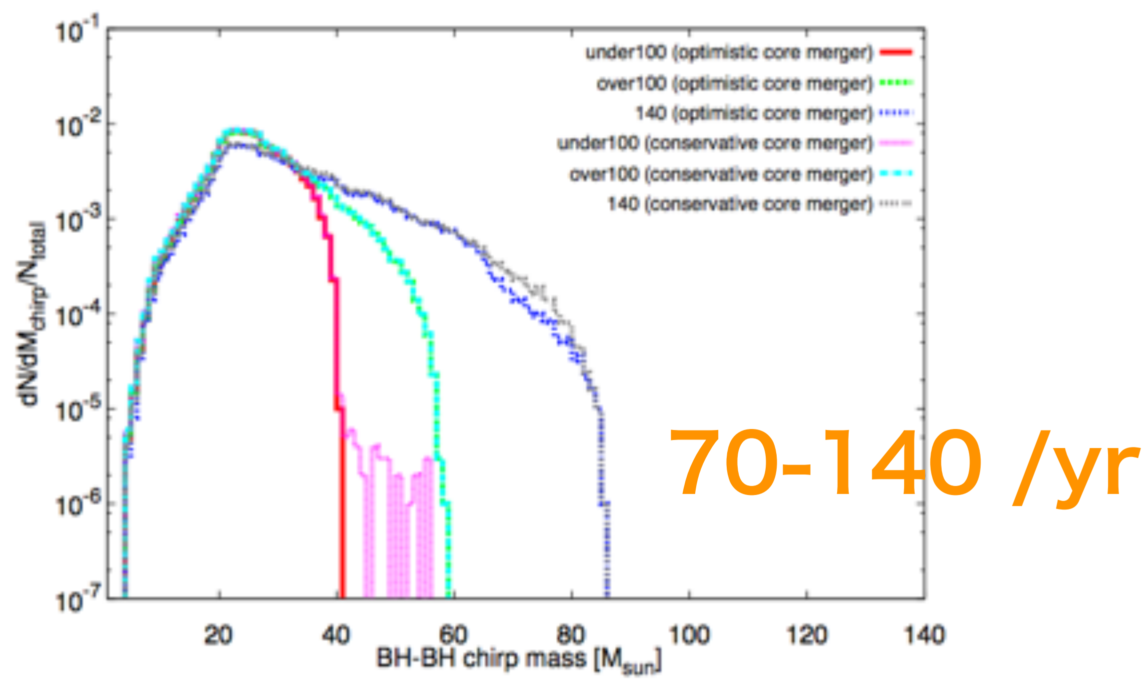
Mass distribution	PyCBC	GstLAL	Combined
	$R/(\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1})$		
	Event based		
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.8}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.1^{+31.0}_{-8.5}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	36^{+95}_{-30}
All	53^{+100}_{-40}	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}



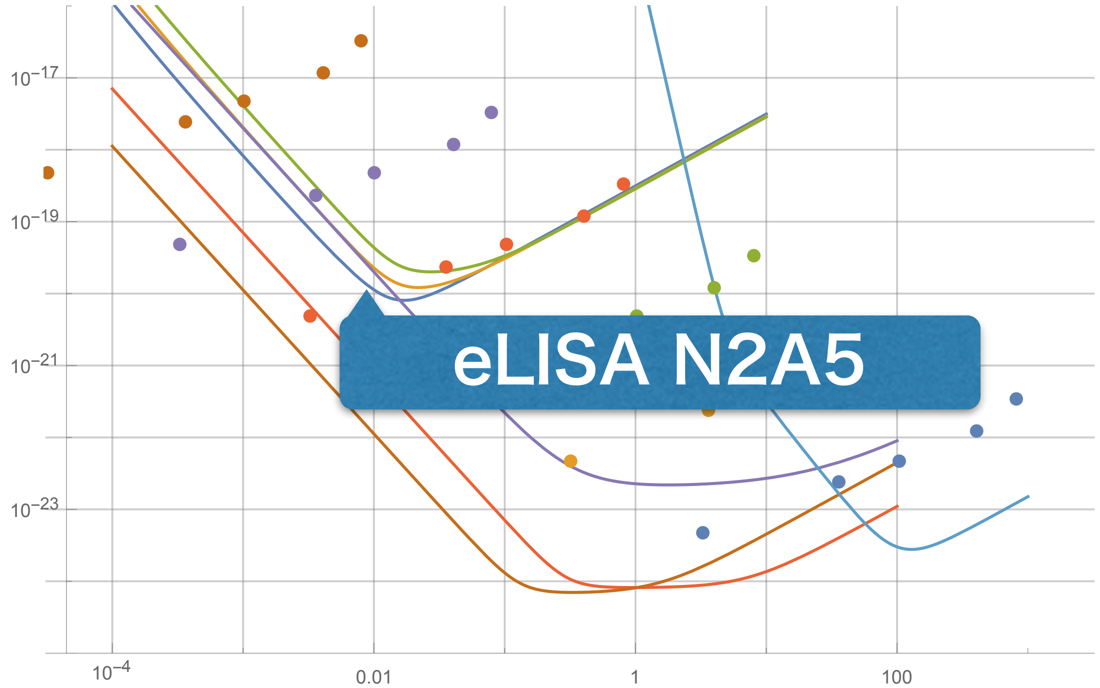
Inoue+ MNRAS461(16)4329



Kinugawa+ MNRAS456(15)1093

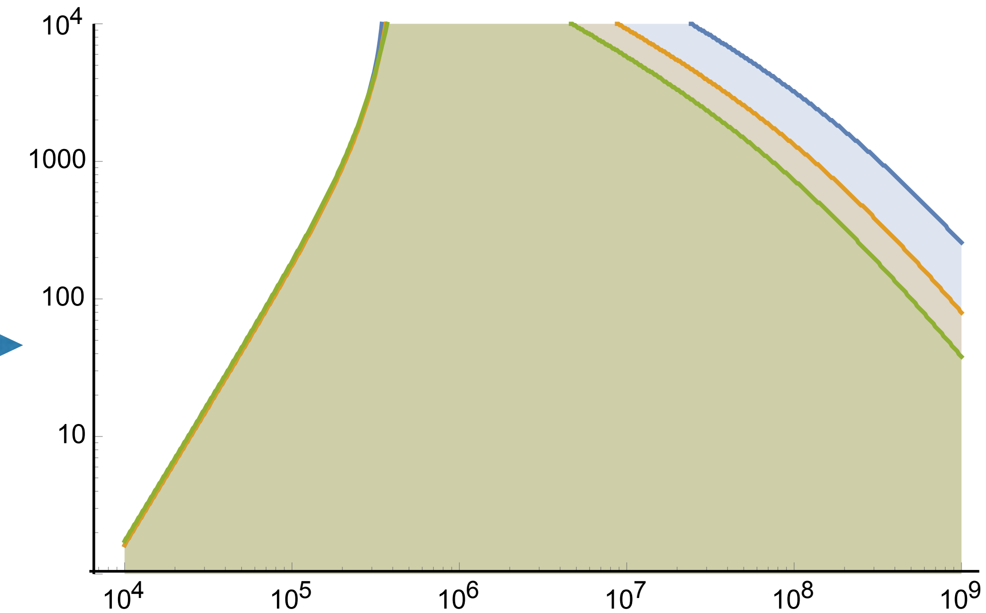


Event Rates at eLISA



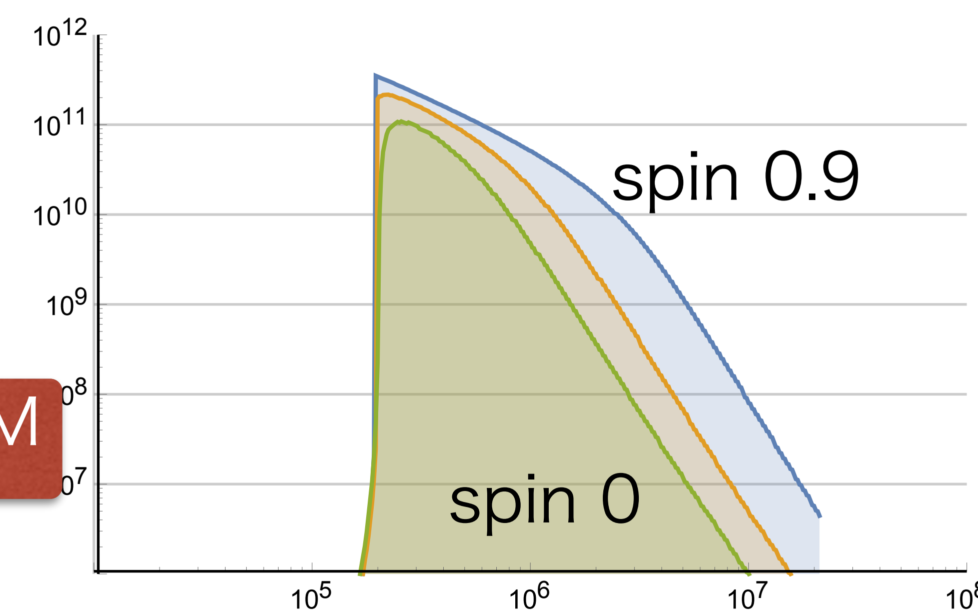
Horizon Distance
(S/N=10)

[Mpc]



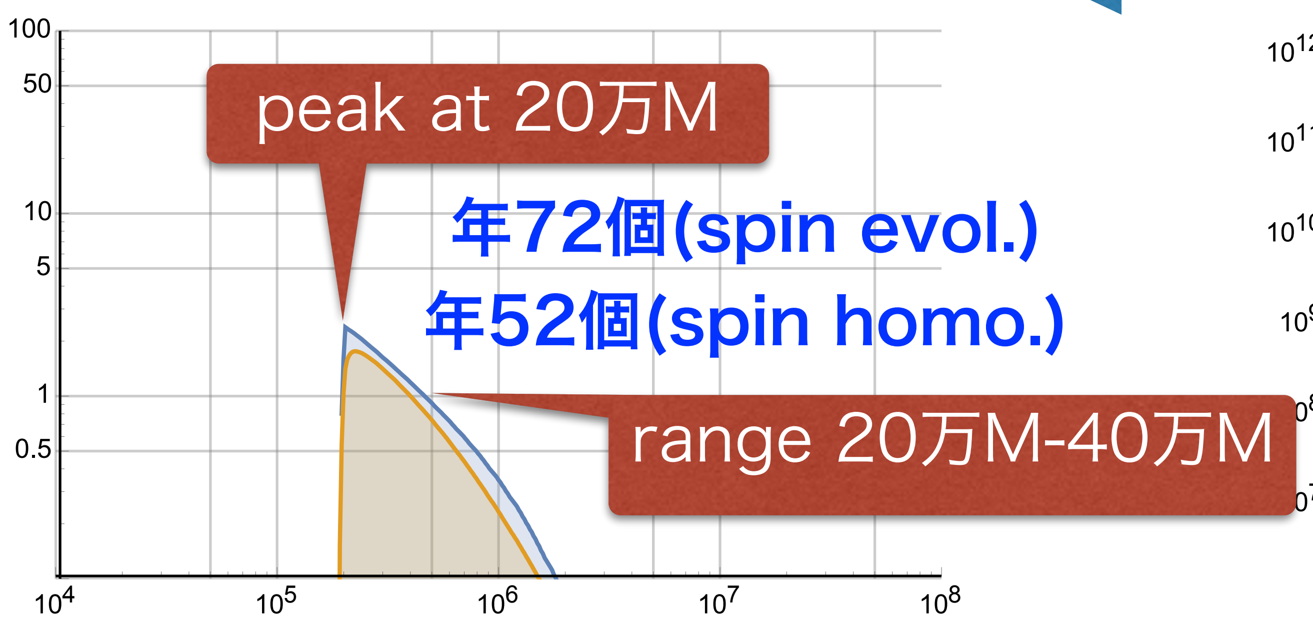
BH mass [Msun]

Observable BH mergers



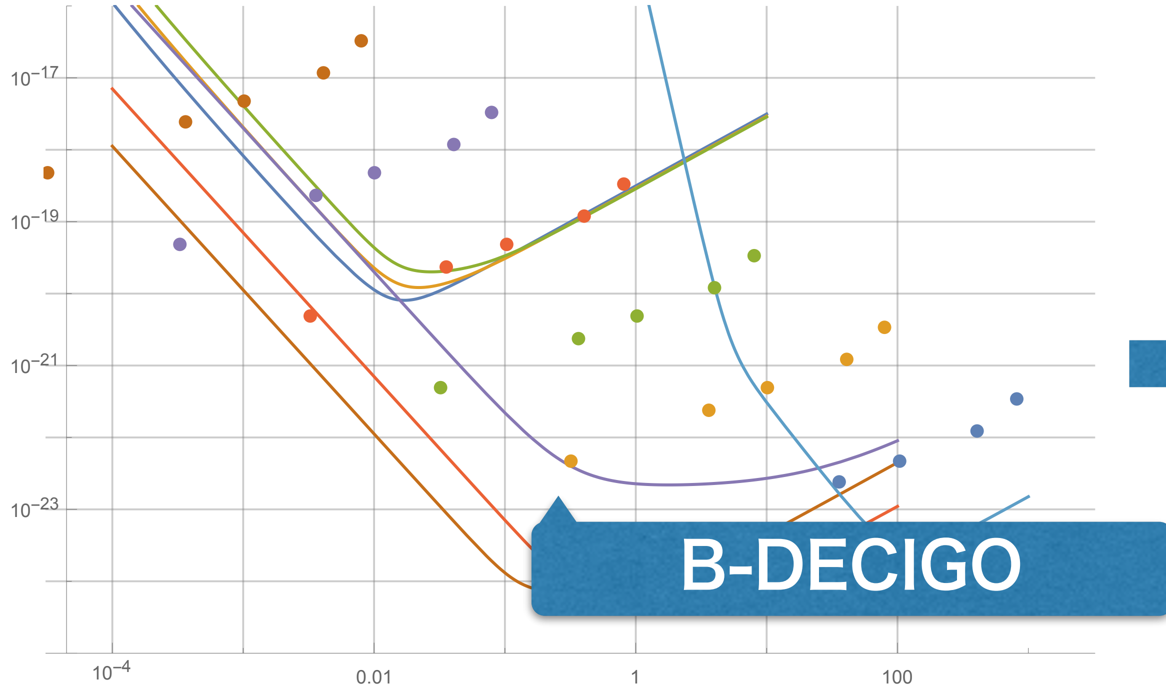
BH mass [Msun]

Event Rate
(S/N=10)



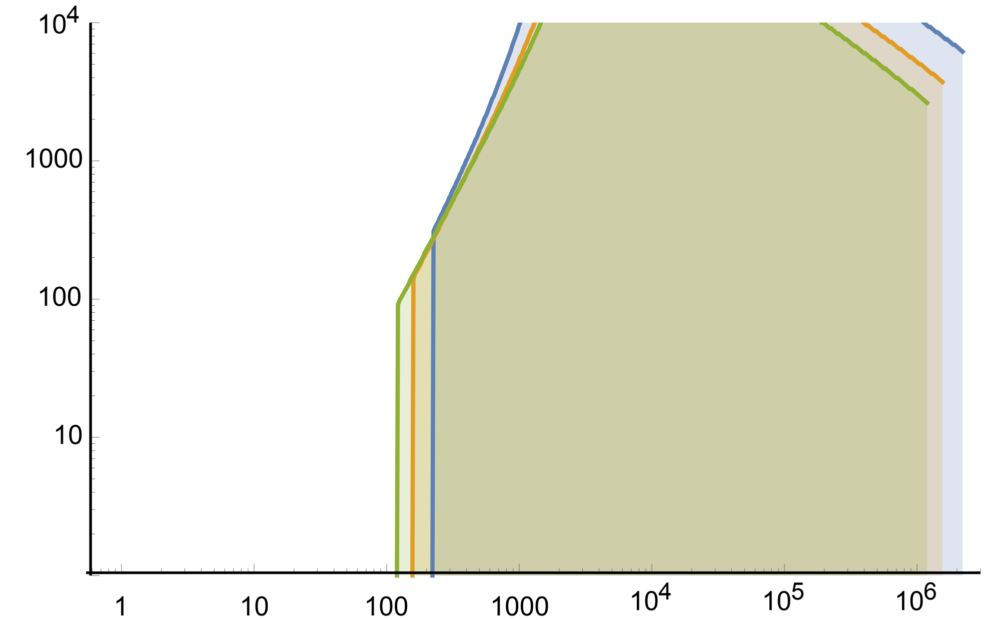
BH mass [Msun]

Event Rates at B-DECIGO



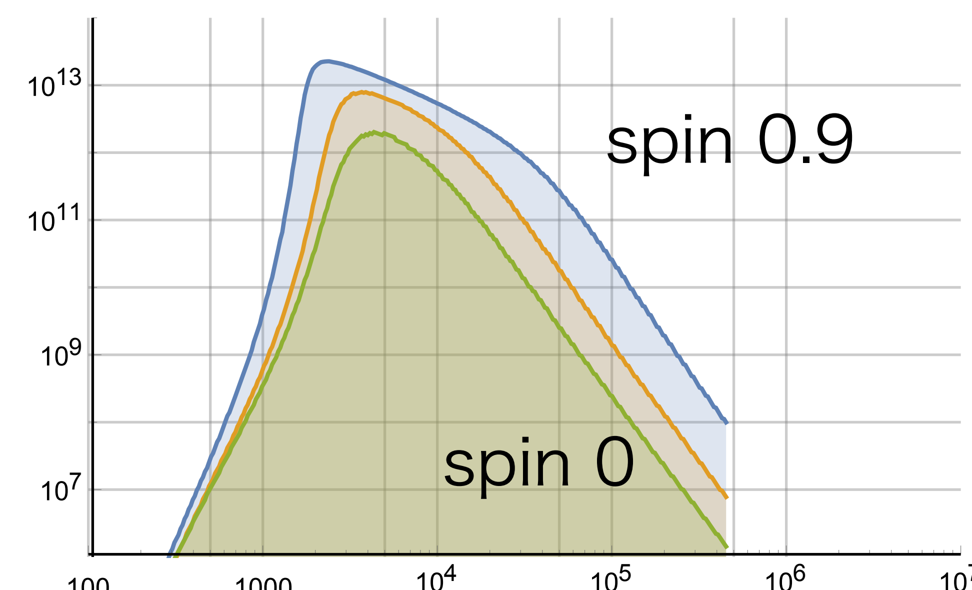
観測できるBH合体距離

[Mpc] (S/N=30)



BH質量[Msun]

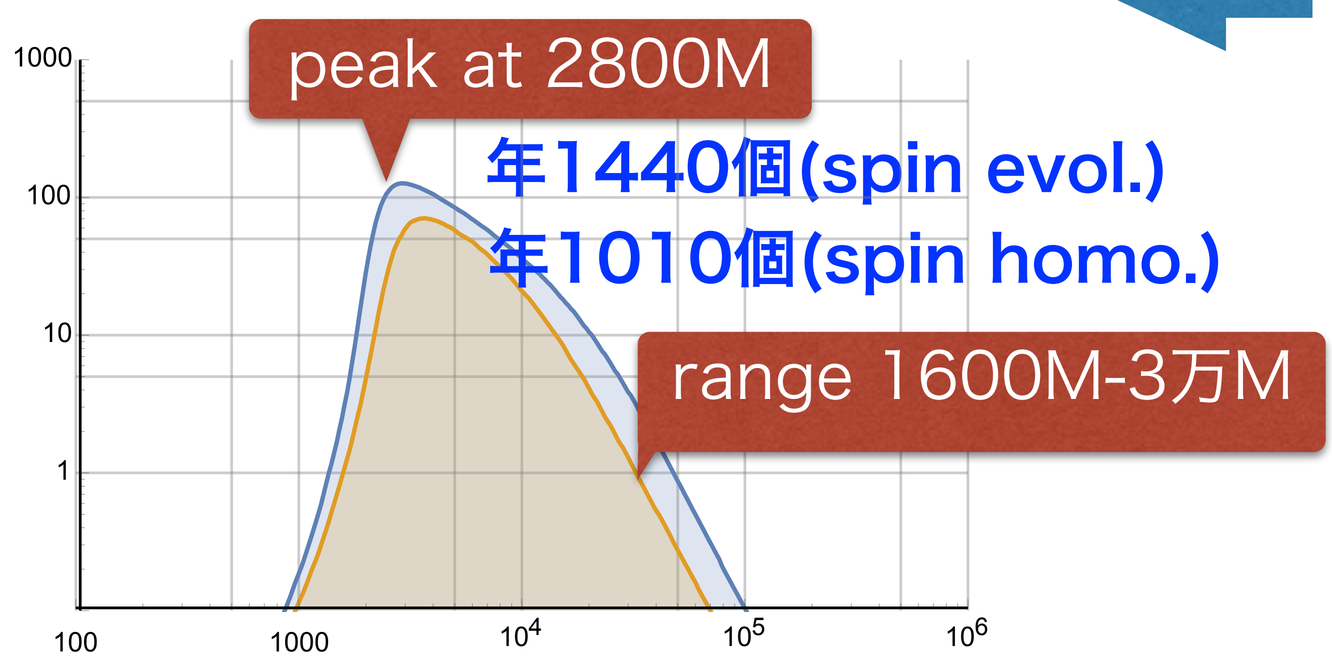
観測できるBH数分布



BH質量[Msun]

1年間で観測できるBH数分布

(S/N=30)



BH質量[Msun]

まとめ

SMBHの形成シナリオとして，IMBHsの合体を経由するボトムアップシナリオ(Hierarchical Growth model)を仮定して，重力波検出頻度を計算した.

モデルの仮定：

- ★ 分子雲のコアが10Msun以上になったら，BHになると仮定した.
- ★ BHは等質量同士のものが次々に合体して成長していくものと仮定した.
- ★ BHが形成された後，ガス降着で太ることは考慮していない.
- ★ 銀河数分布は，サブハローモデルと，星形成率を乗じたものから計算した.
- ★ リングダウン部分の重力波を直接検出できる，と仮定した.

今回の考察：

- ★ **BHのspinが，SMBHでは0.4以上である，という観測結果を考慮したspin進化の効果を入れた.**
- ★ **bKAGRAだけではなく，B-DECIGO, eLISAも含めて考察した.**

このモデルの予言するBHBH合体event rateは,

B-DECIGO > bKAGRA > eLISA

重力波検出のデータを蓄積することによって，銀河分布やSMBH形成シナリオを特定したり，宇宙膨張モデルの検証や，重力理論の検証が可能になる.