Gravitational Waves from Intermediate-Mass Black Holes

真貝寿明 신카이 히사아키
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http://www.oit.ac.jp/is/~shinkai/

- ✓Origin of SMBH?
- ✓GW event rate?
  - ✓How many BHs in a galaxy?
  - ✓How many galaxies in the Universe?

HS, N.Kanda, T.Ebisuzaki, arXiv:1610.09505

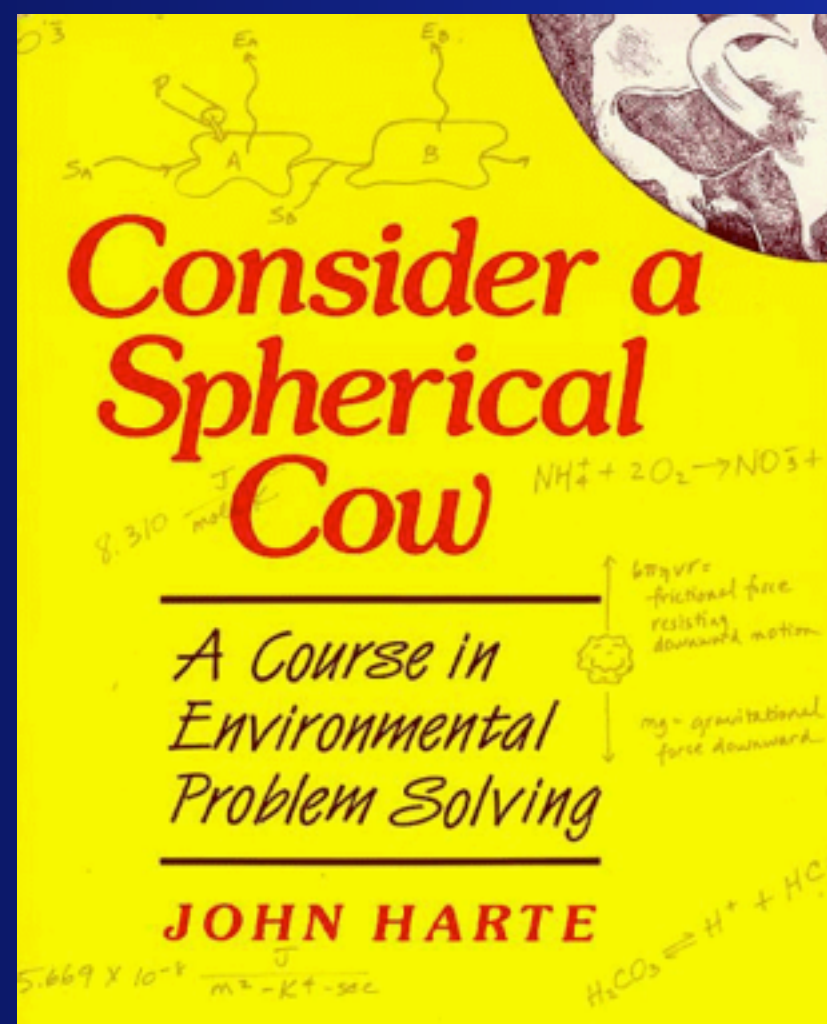
2016/12 Colloquim @ KASI, Korea

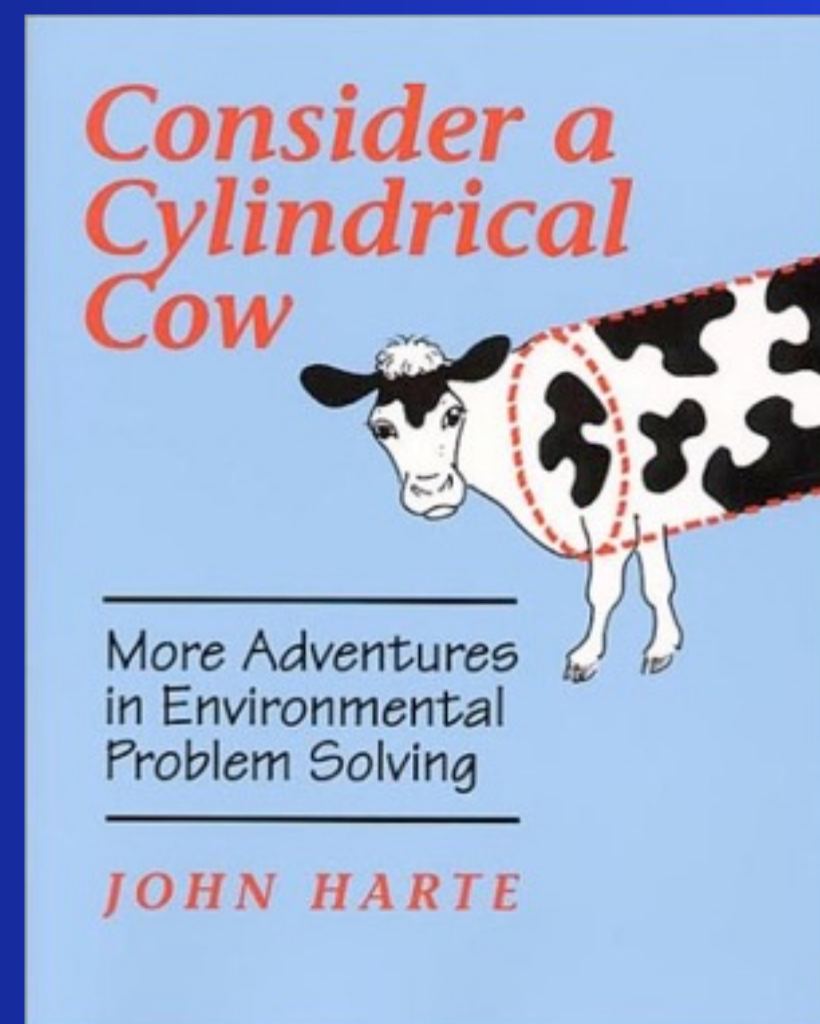
“Physicists start thinking from spherical model”

Black Holes,

Cosmology,

… … even for a cow



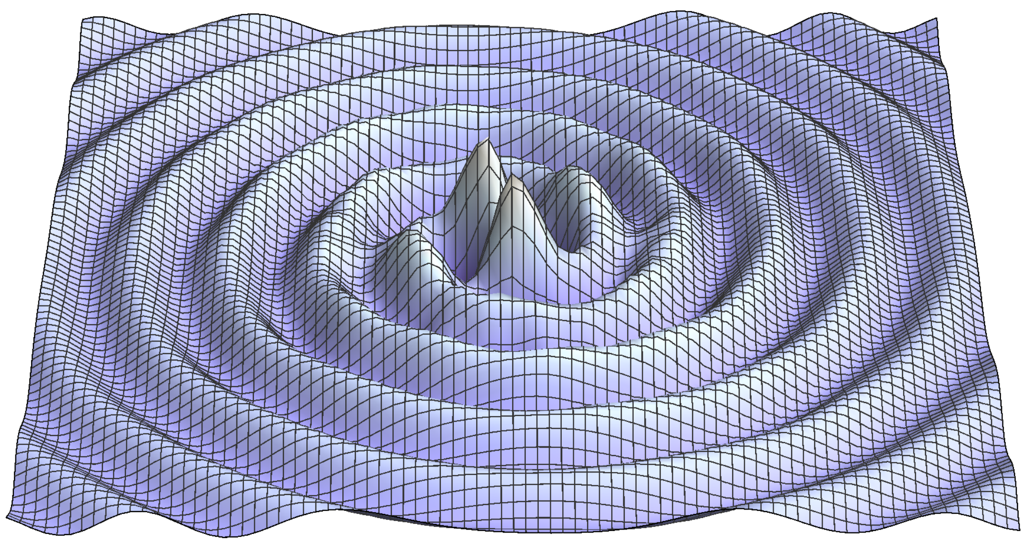


contents

1. Gravitational Wave
2. Model of SMBH via IMBHs
3. How many BHs in a galaxy?
4. How many galaxies in the Universe?
5. Event Rates, Profiles

http://www.oit.ac.jp/is/~shinkai/

HS, N.Kanda, T.Ebisuzaki, arXiv:1610.09505



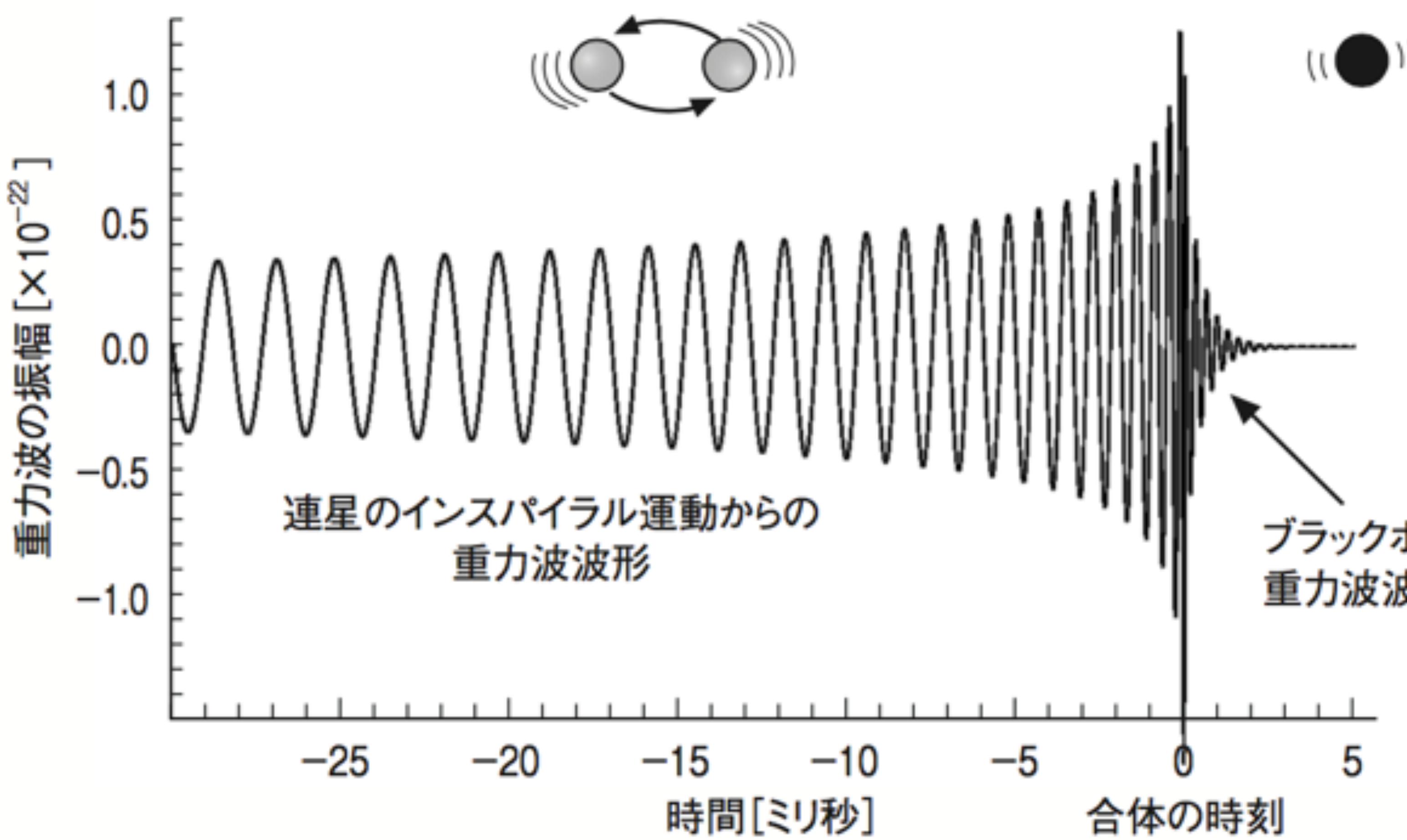
BHs, Expanding Universe, and GWs (HS, 2015/9)

Korean version (2017)
from Kachi Books

NS-NS
NS-BH
BH-BH

Inspiral **Merger** **Ringdown**

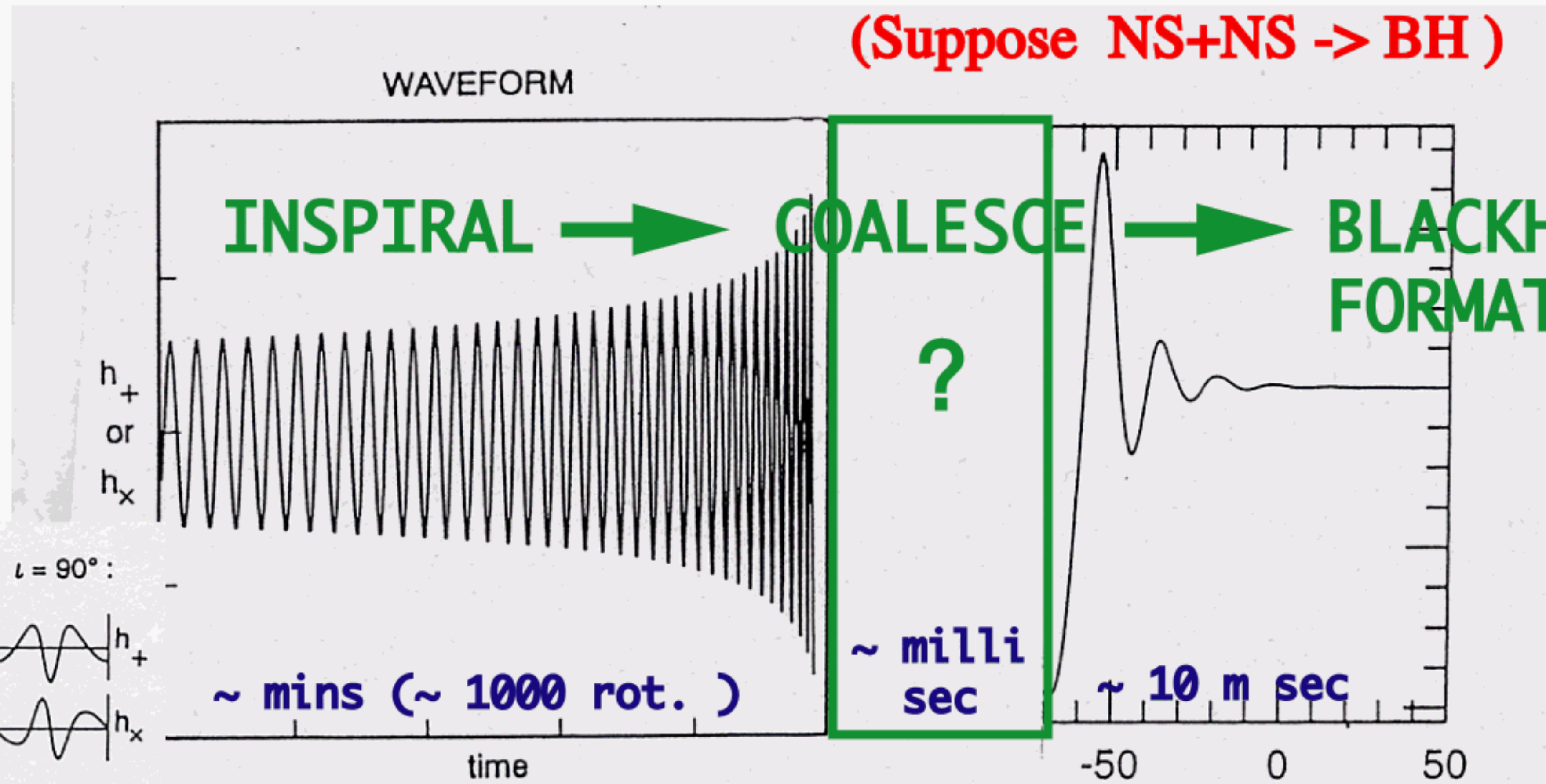
h

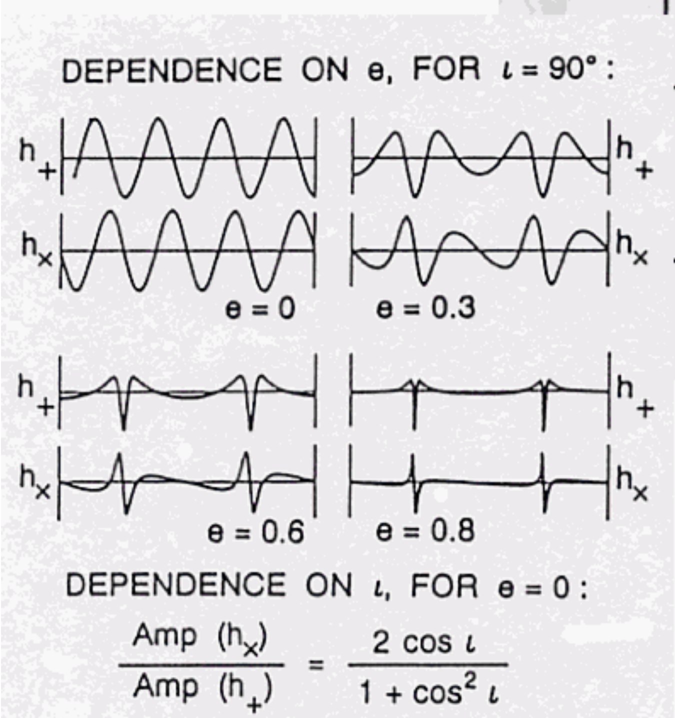


time

What can we learn from gravitational waveform?

(Suppose NS+NS -> BH)





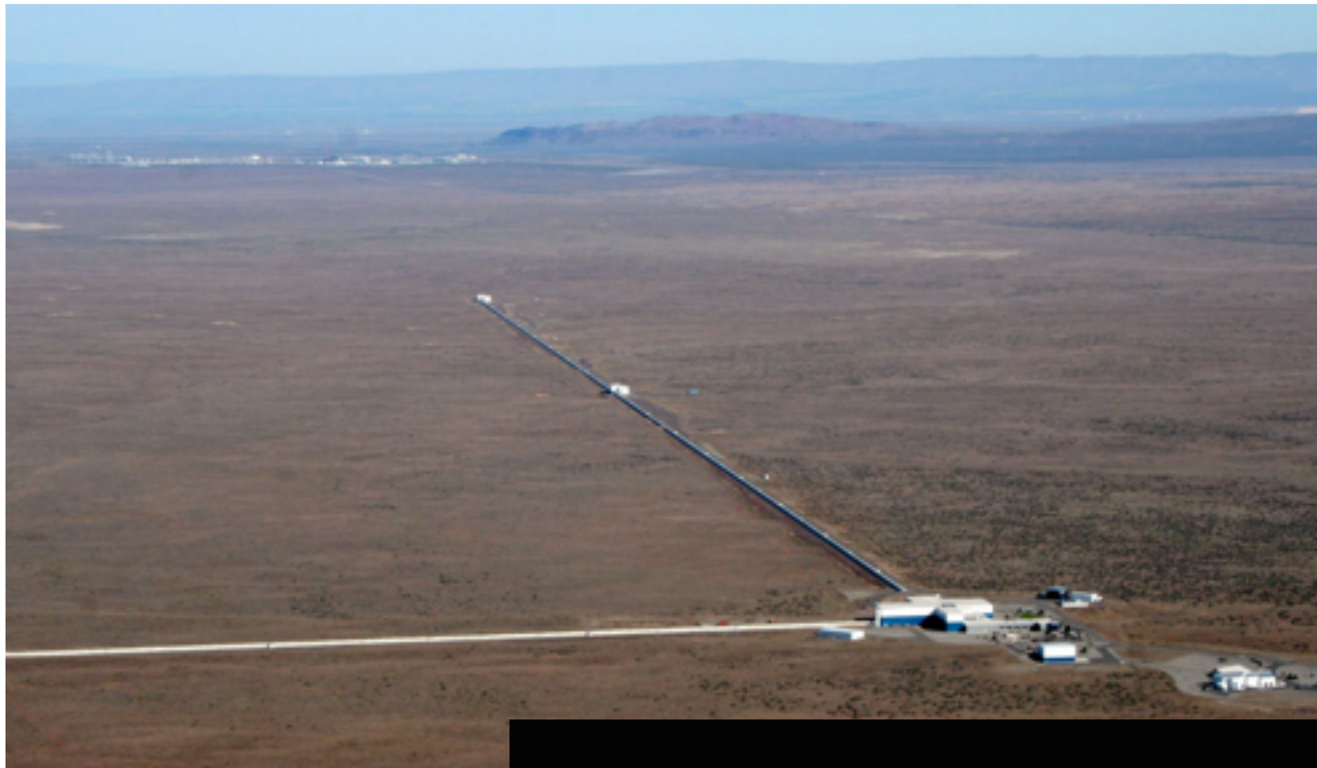
Post Newtonian Approx. | Numerical Relativity | BH. Perturbation

ISCO freq => EoS of NS,
waveform => Formation of BH or NS,
BH mass,
BH angular momentum,...

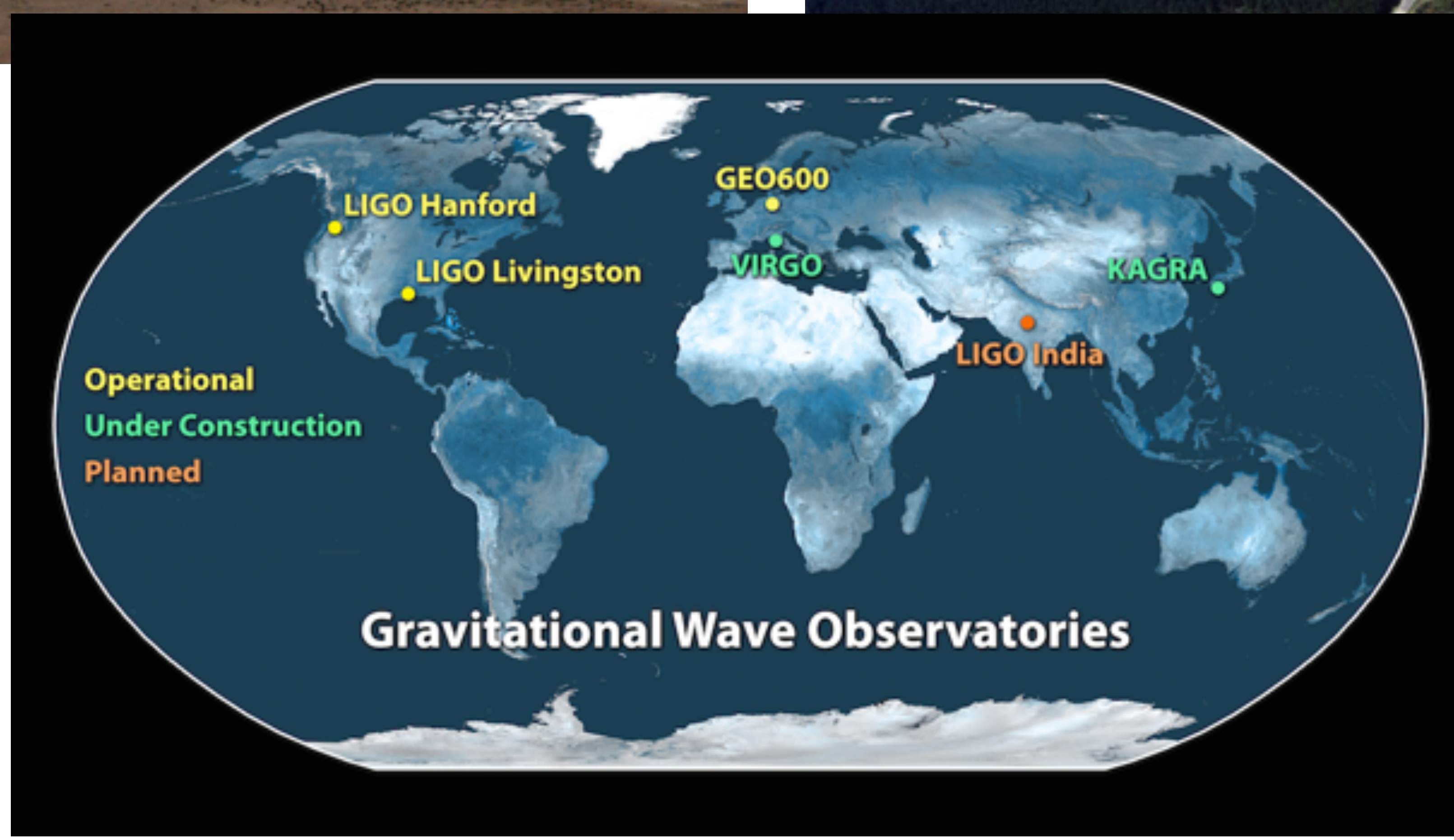
"chirps" df/dt => chirp mass, $M_c = (M_1 M_2)^{3/5} / (M_1+M_2)^{1/5}$
amplitude up => M_c, distance
amplitude h+/hx => inclination
waveform => eccentricity
moduration => spin, ...

statistics => cosmological parameters

LIGO : Laser Interferometer Gravitational-Wave Observatory



4km Michelson



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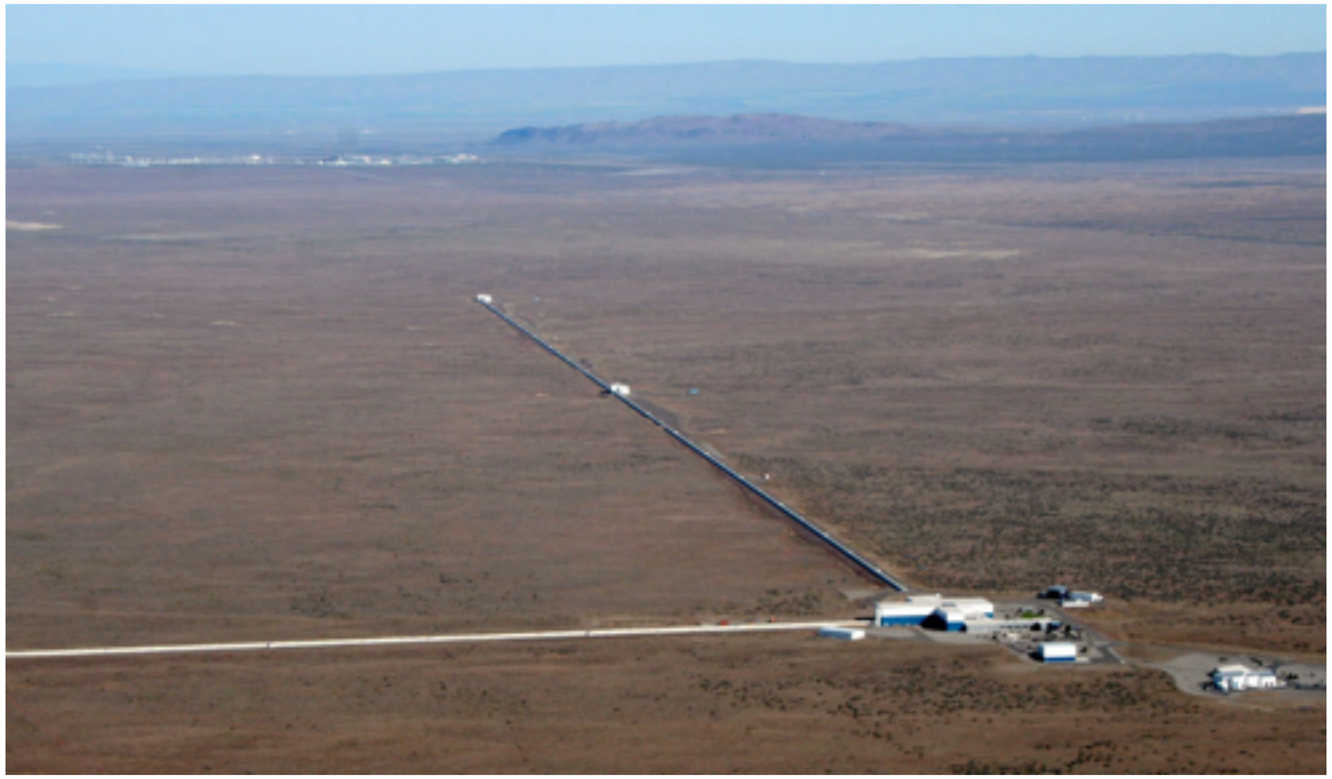
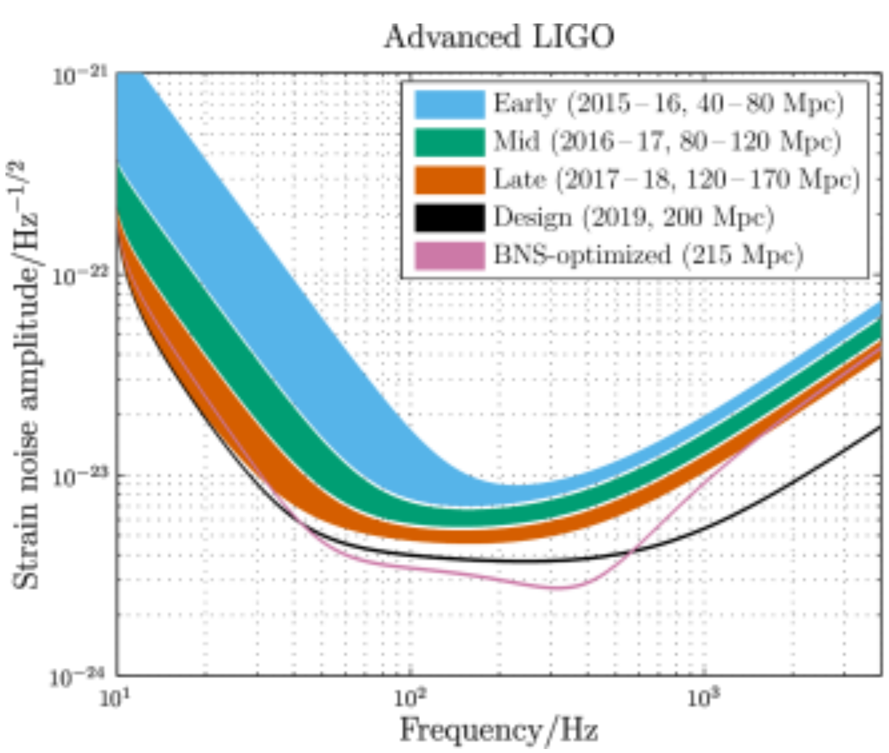
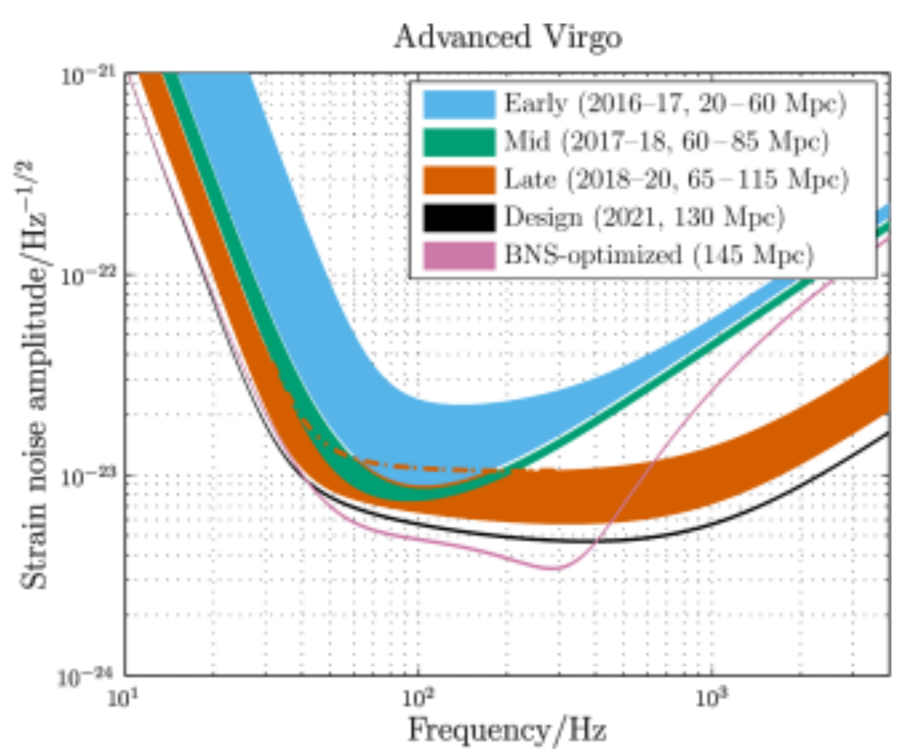


https://mediaassets.caltech.edu/gwave

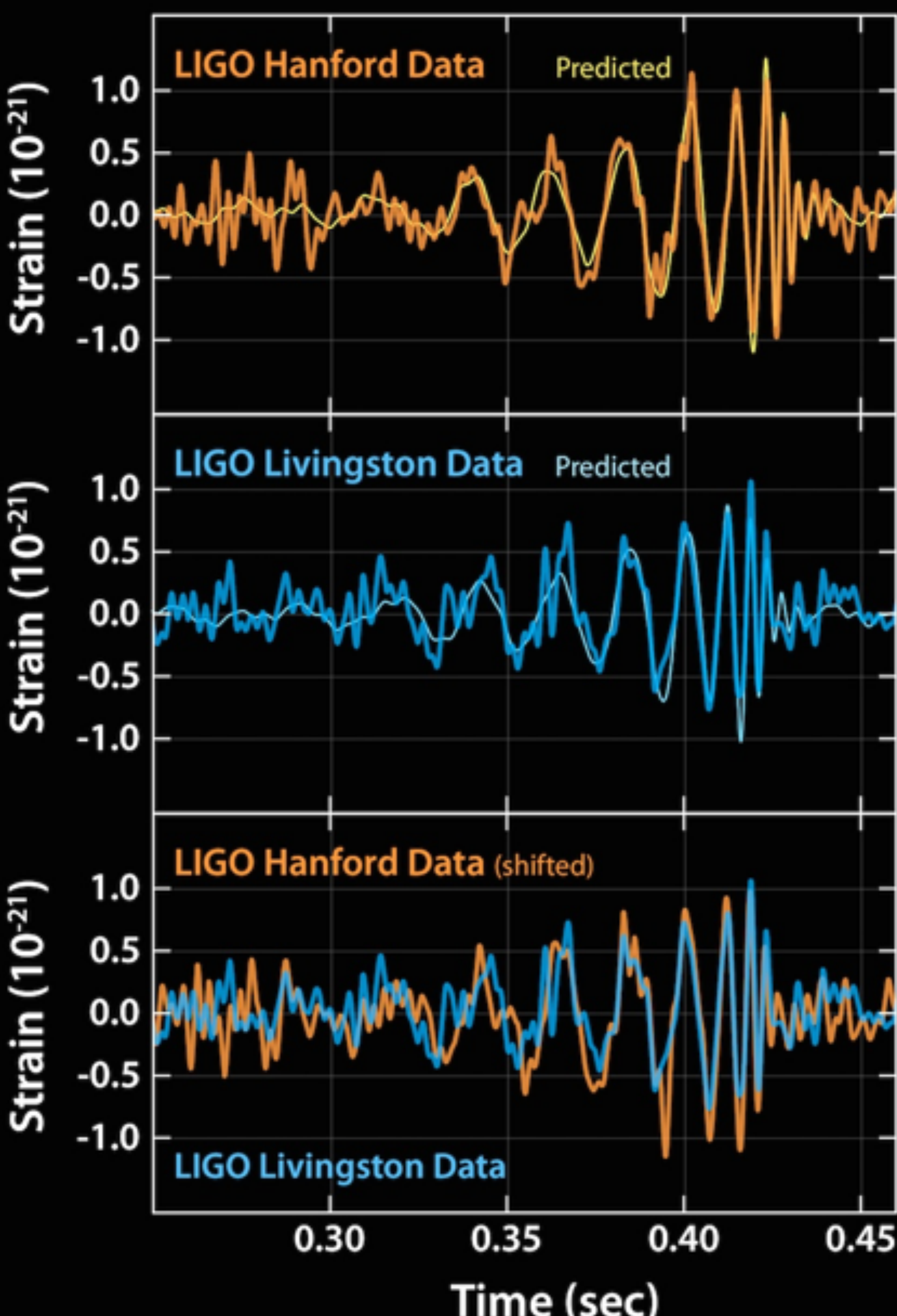




2015/9/16--2016/1/15
Observational run 1

2016/11/30—
Observational run 2

GW150914



GW150914:FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.
Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

GW150914

36Msun + 29 Msun

=> 62 Msun

13×10^9 lyr

(400±170 Mpc)

(z=0.054—0.136)

GW exists !

GW was detected !

BH exists !

BH binary exists !

GR is right !

GW150914:FACTSHEET

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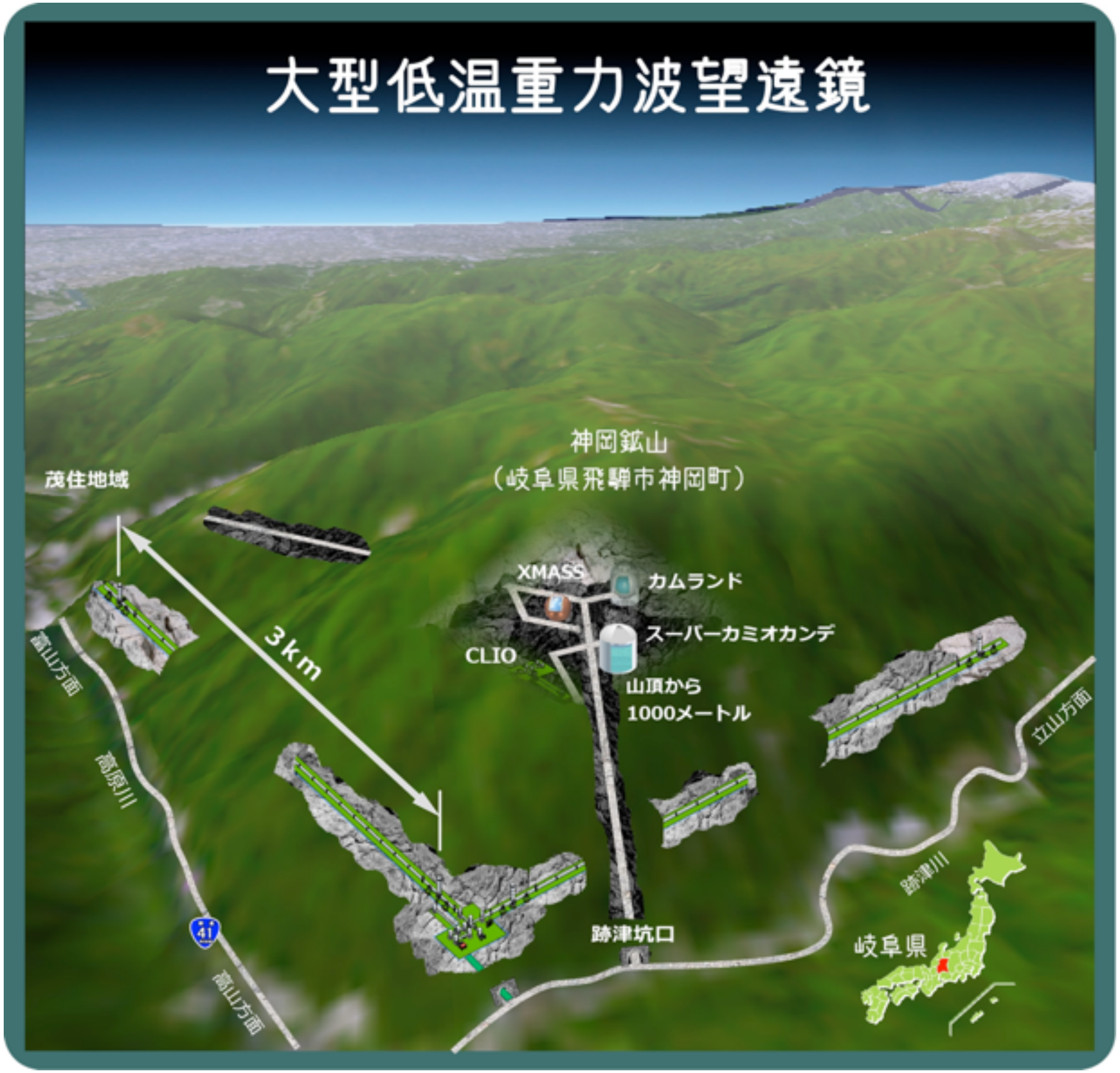
KAGRA : Kamioka Gravitational wave detector

(Large-scale Cryogenic Gravitational wave Telescope)



http://gwcenter.icrr.u-tokyo.ac.jp/plan/history

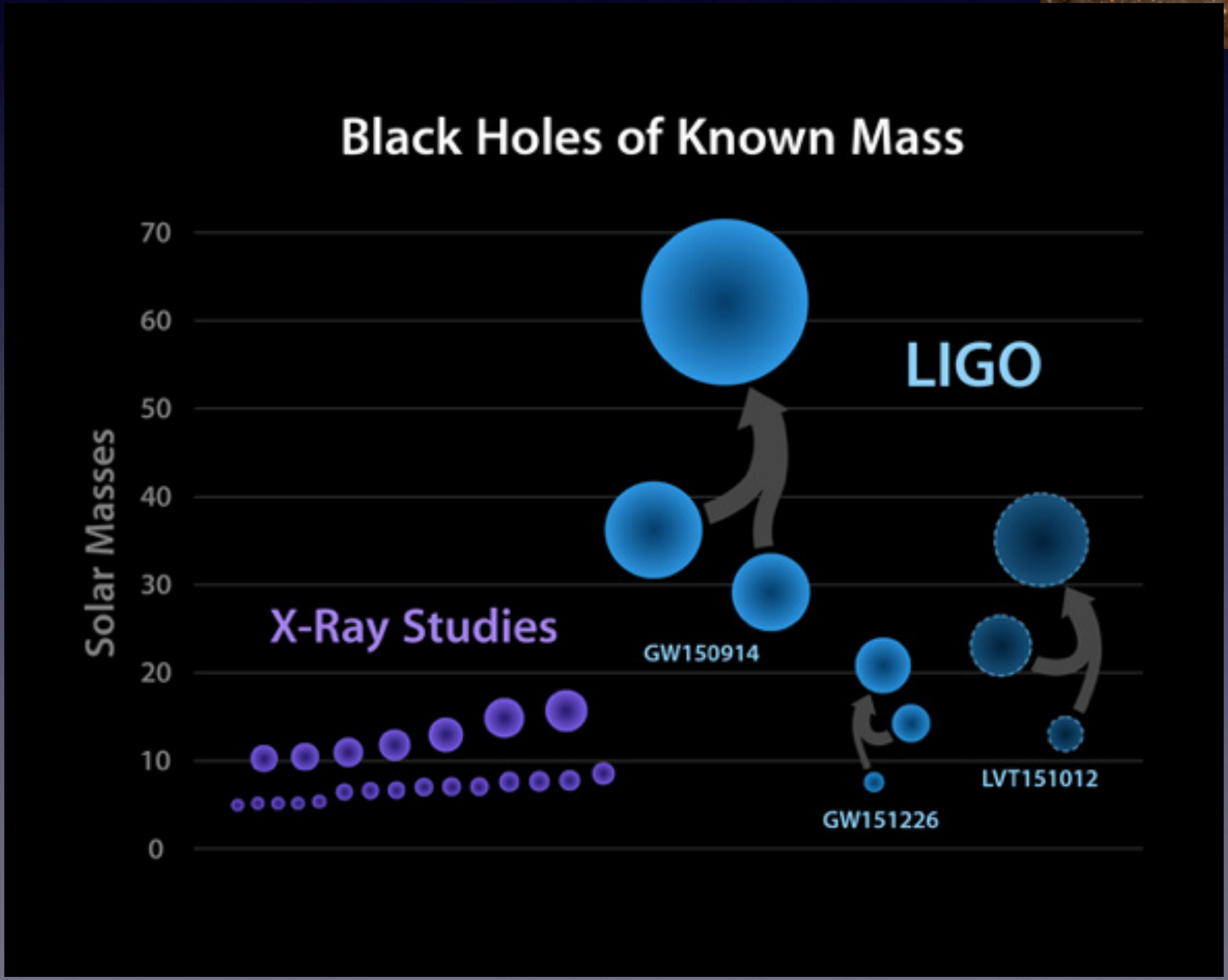
3km Michelson
Cryogenic (20K)

in quiet mountain site

Sapphira mirrors

神楽（かぐら）
Sinto Music

BHs!

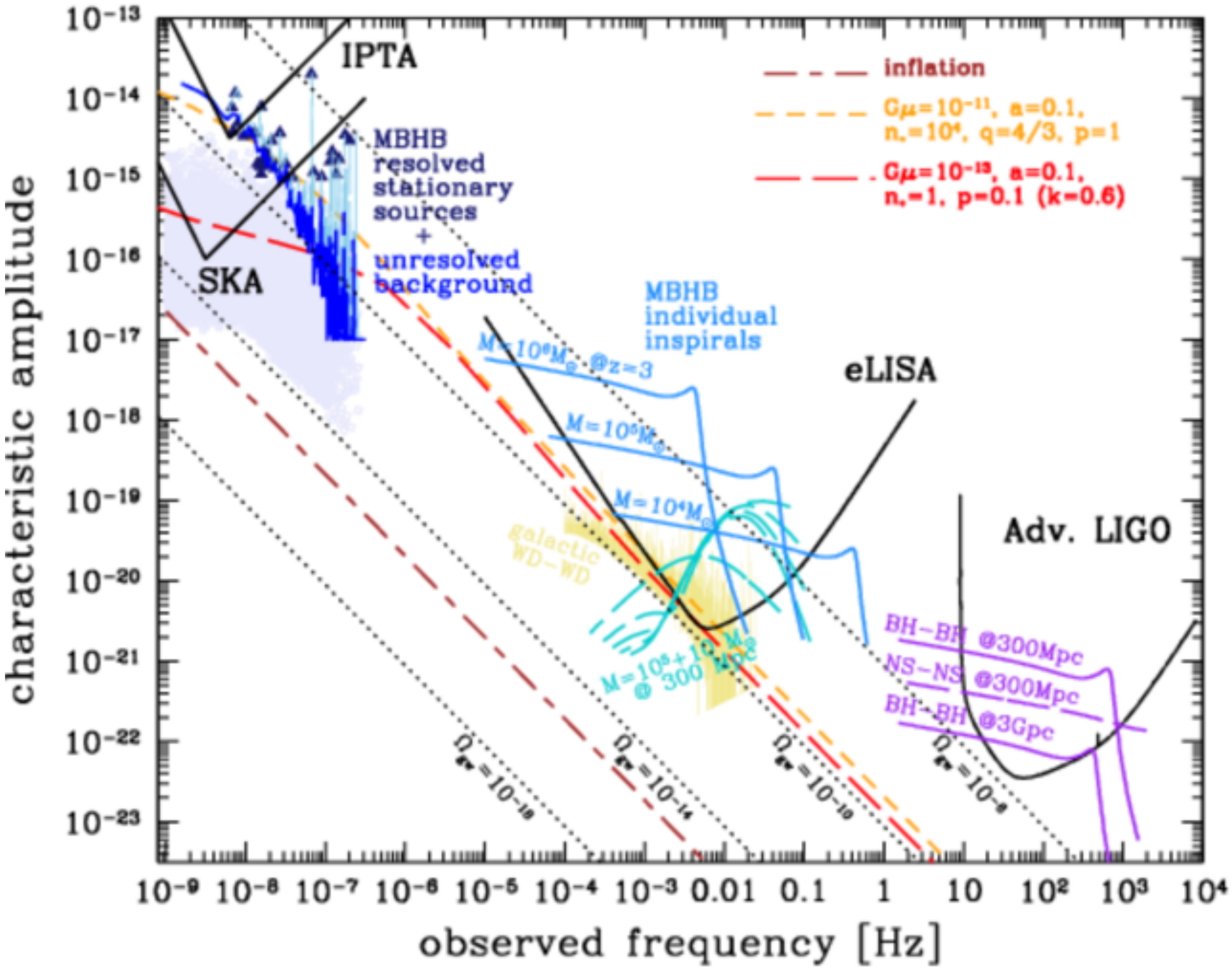


7M+14M=20M

29M+36M=62M

why not more?

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



The gravitational wave landscape: characteristic amplitude (h_c), vs frequency. In the nHz frequency range a selected realisation of the expected GW signal from the cosmological population of SMBHBs is shown. Small lavender squares are individual SMBHB contributions to the signal, the dark blue triangles are loud, individually resolvable systems and the blue jagged line is the level of the unresolved background. Nominal sensitivity levels for the IPTA and SKA are also shown. In the mHz frequency range, the eLISA sensitivity curve is shown together with typical circular SMBHB inspirals at z=3 (pale blue), the overall signal from Galactic WD-WD binaries (yellow) and an example of extreme mass ratio inspiral (aquamarine, only the first 5 harmonics are shown). In the kHz range an advanced LIGO curve (based on calculations for a single interferometer) is shown together with selected compact object inspirals (purple). The brown, red and orange lines running through the whole frequency range are expected cosmological backgrounds from standard inflation and selected string models, as labeled in figure. Black dotted lines mark different levels of GW energy density content as a function of frequency ($\Omega_{gw} \propto h_c^2 f^2$).

- Janssen, Gemma *et al.* PoS AASKA14 (2015) 037 arXiv:1501.00127

IMBH-IMBH mergers produce low freq. GW

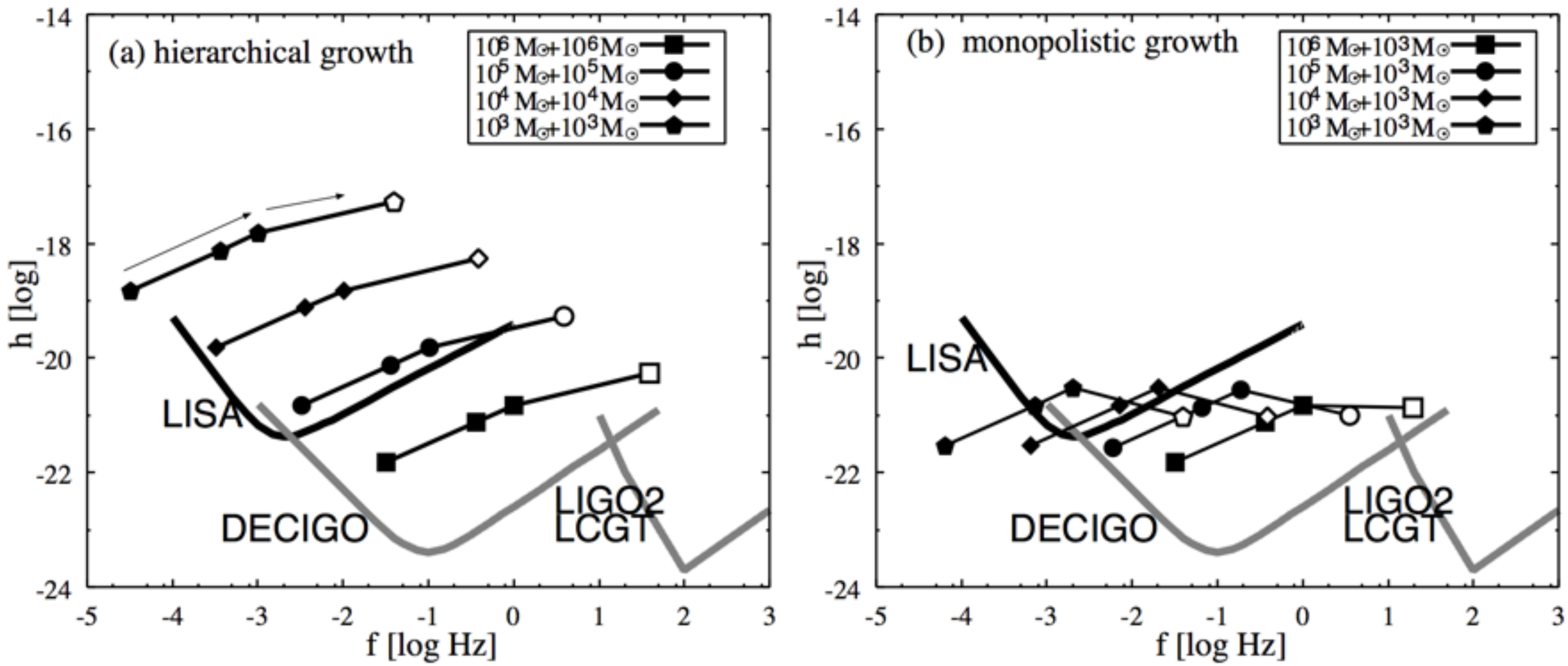
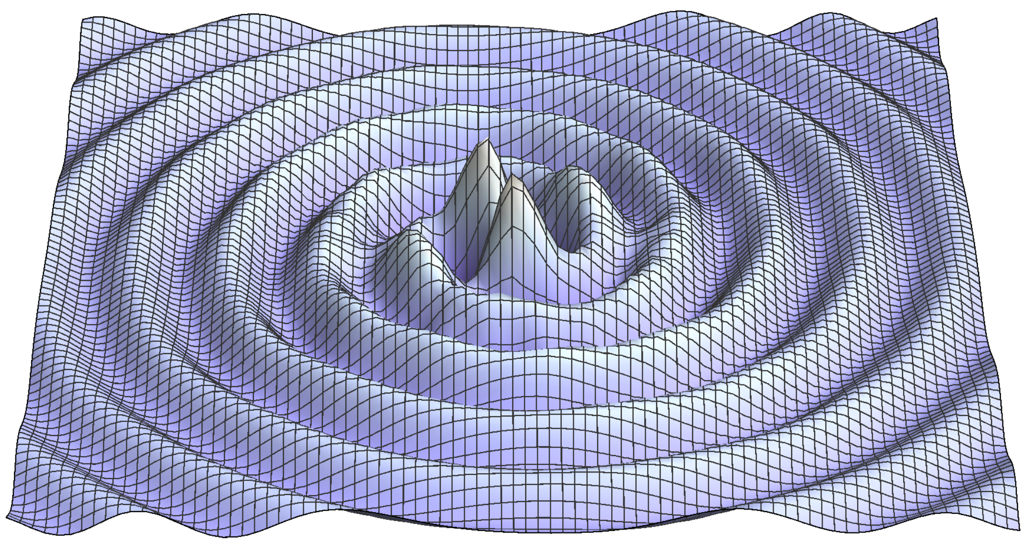


Fig. 1.— Expected gravitational radiation amplitude from merging IMBHs of (a) hierarchical growth model, and (b) monopolistic growth model. We plotted both the inspiral phase ($f_{\rm insp}, h_{\rm insp}$), [eqs. (2) and (3)], and the ringdown phase ($f_{\rm QNM}, h_{\rm coal}$), [eqs. (4) and (6)],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

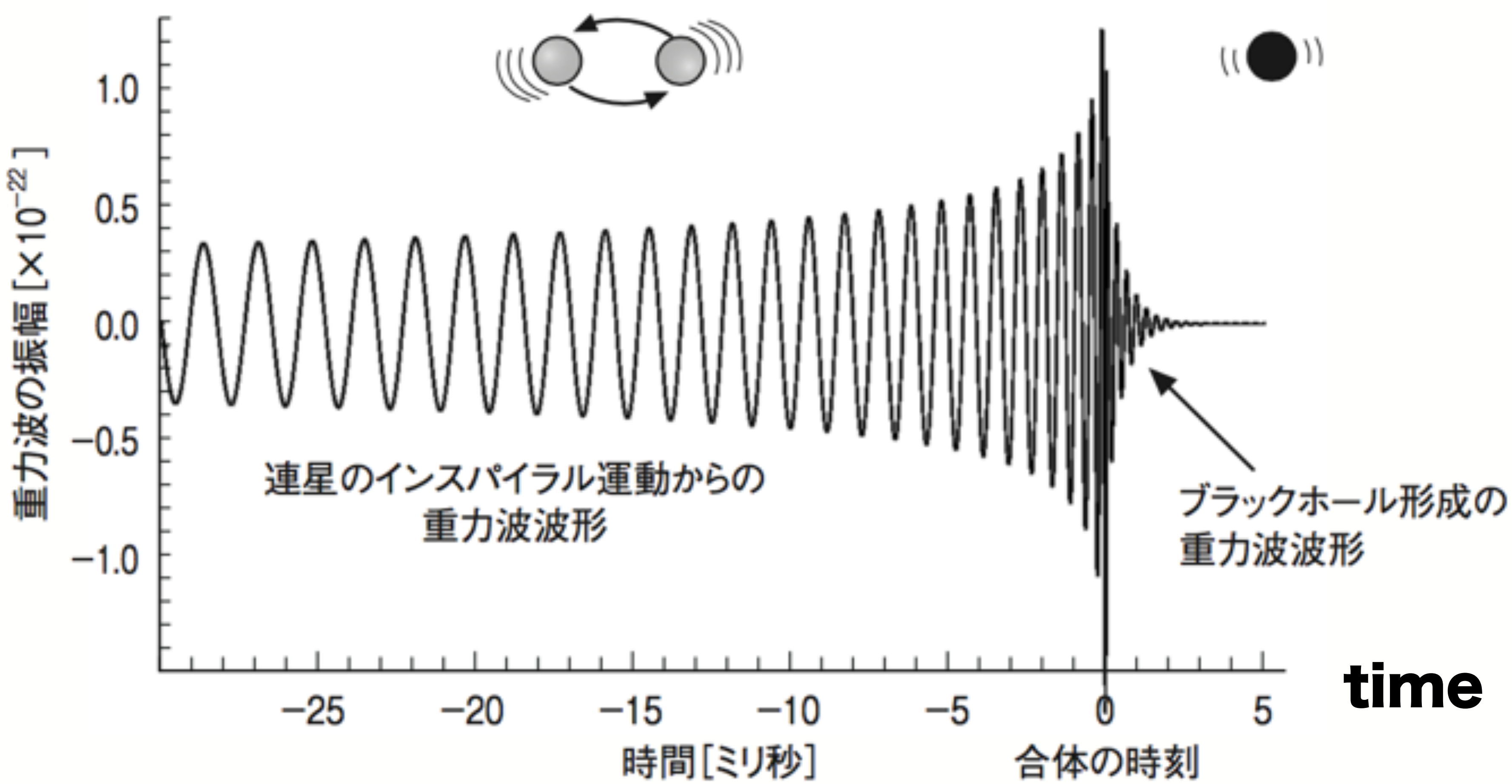
Matsubayashi, HS, Ebisuzaki, ApJ 614 (2004) 864



NS-NS
NS-BH
BH-BH

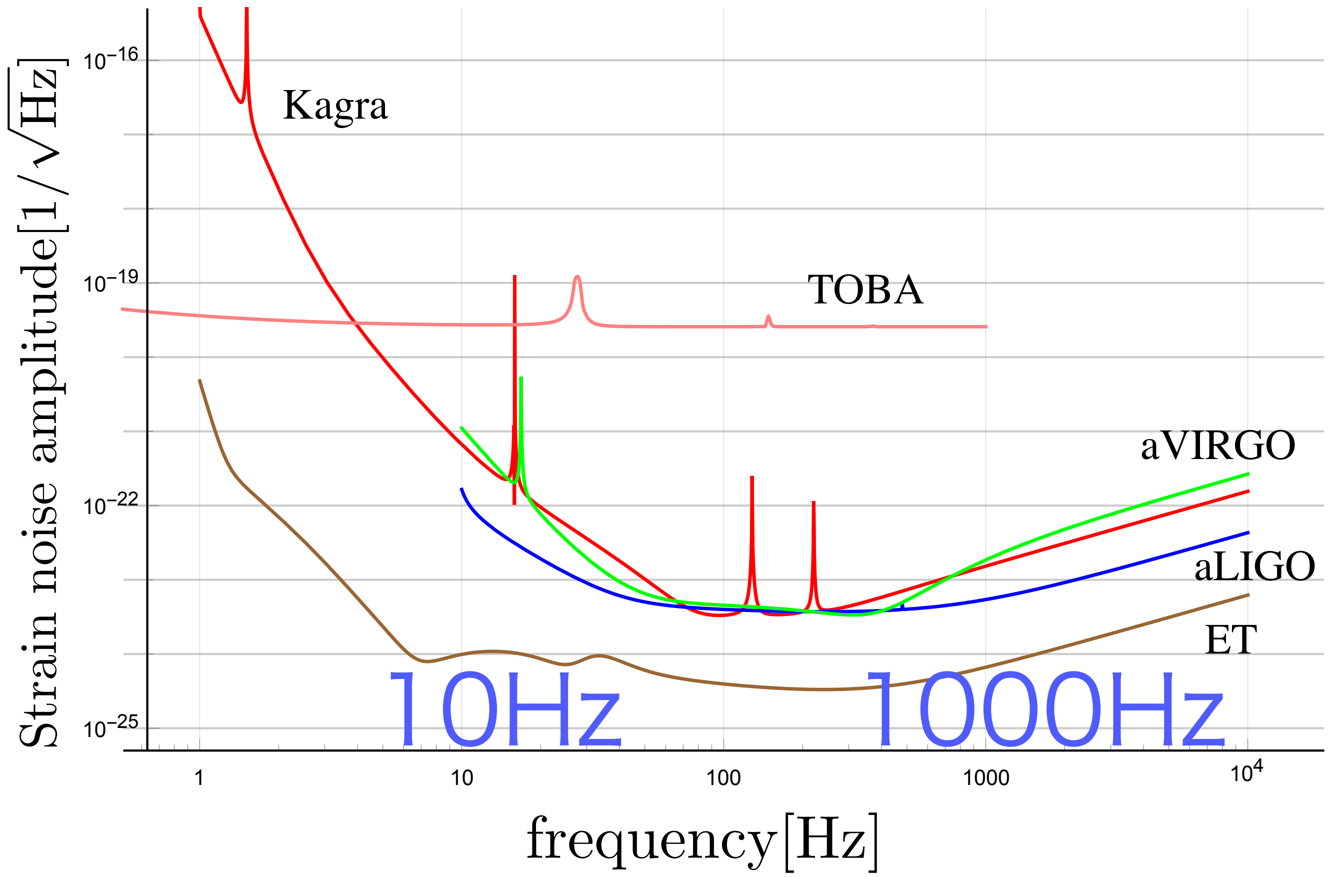
Inspiral **Merger** **Ringdown**

h

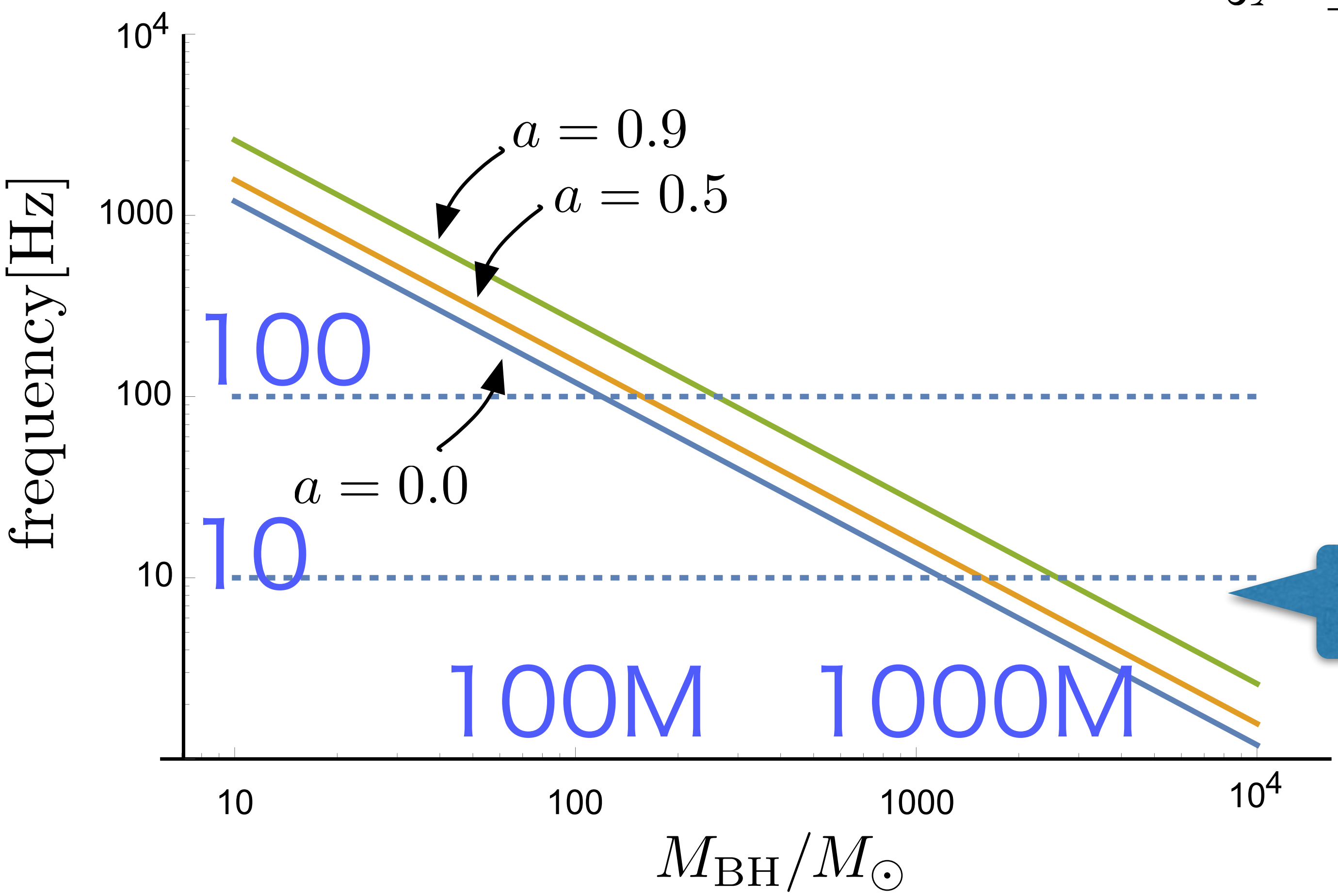


time

IMBH ringdown freq. is detectable at LIGO/KAGRA



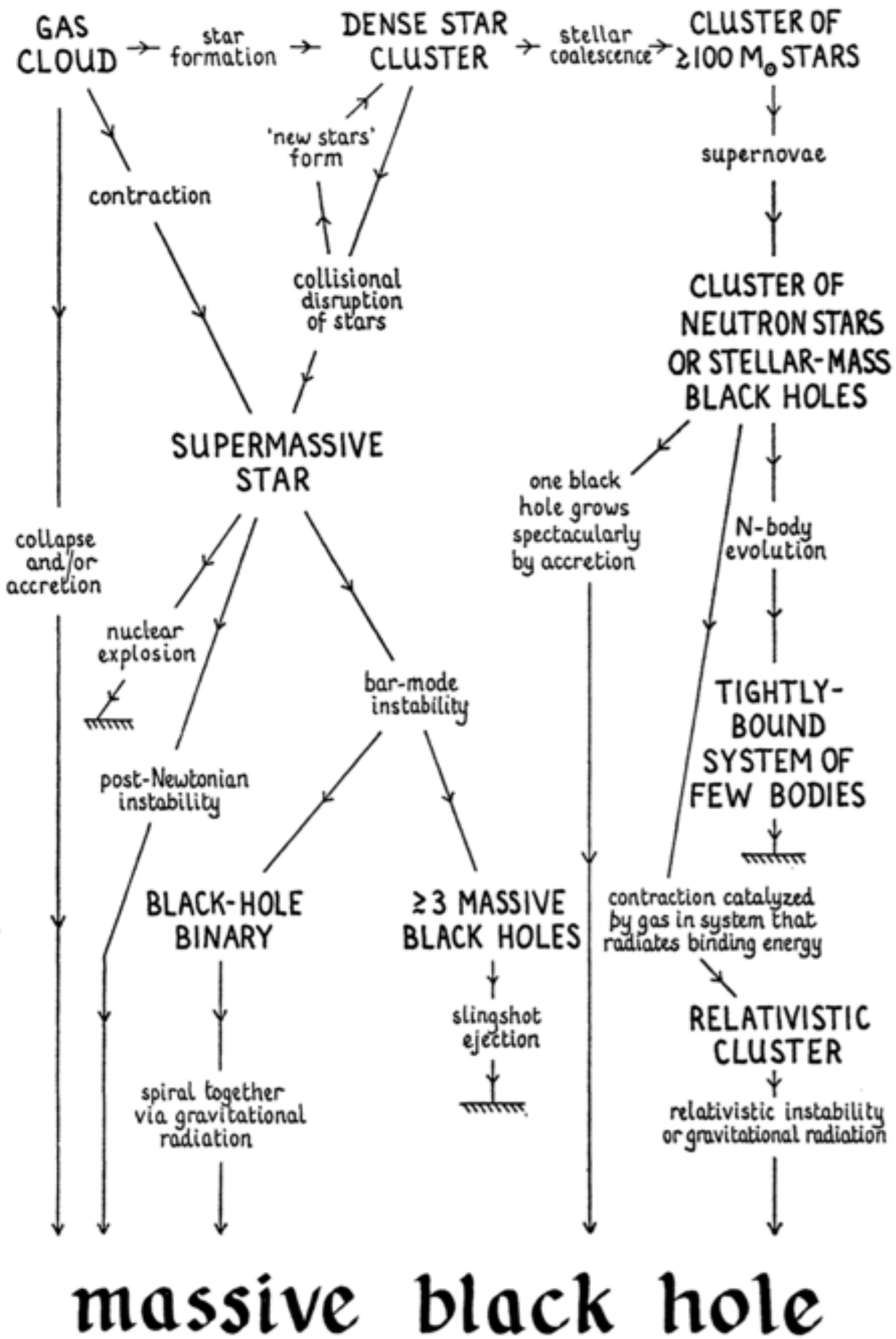
BH quasi-normal freq.
(ringdown freq.)



$$f_{\rm qnm} = \frac{c^3}{2\pi G M_T}\left(1 - 0.63(1-a)^{0.3}\right)$$

BH < 2000Msun can be a target

2. Model of SMBH



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

2. Model of SMBH

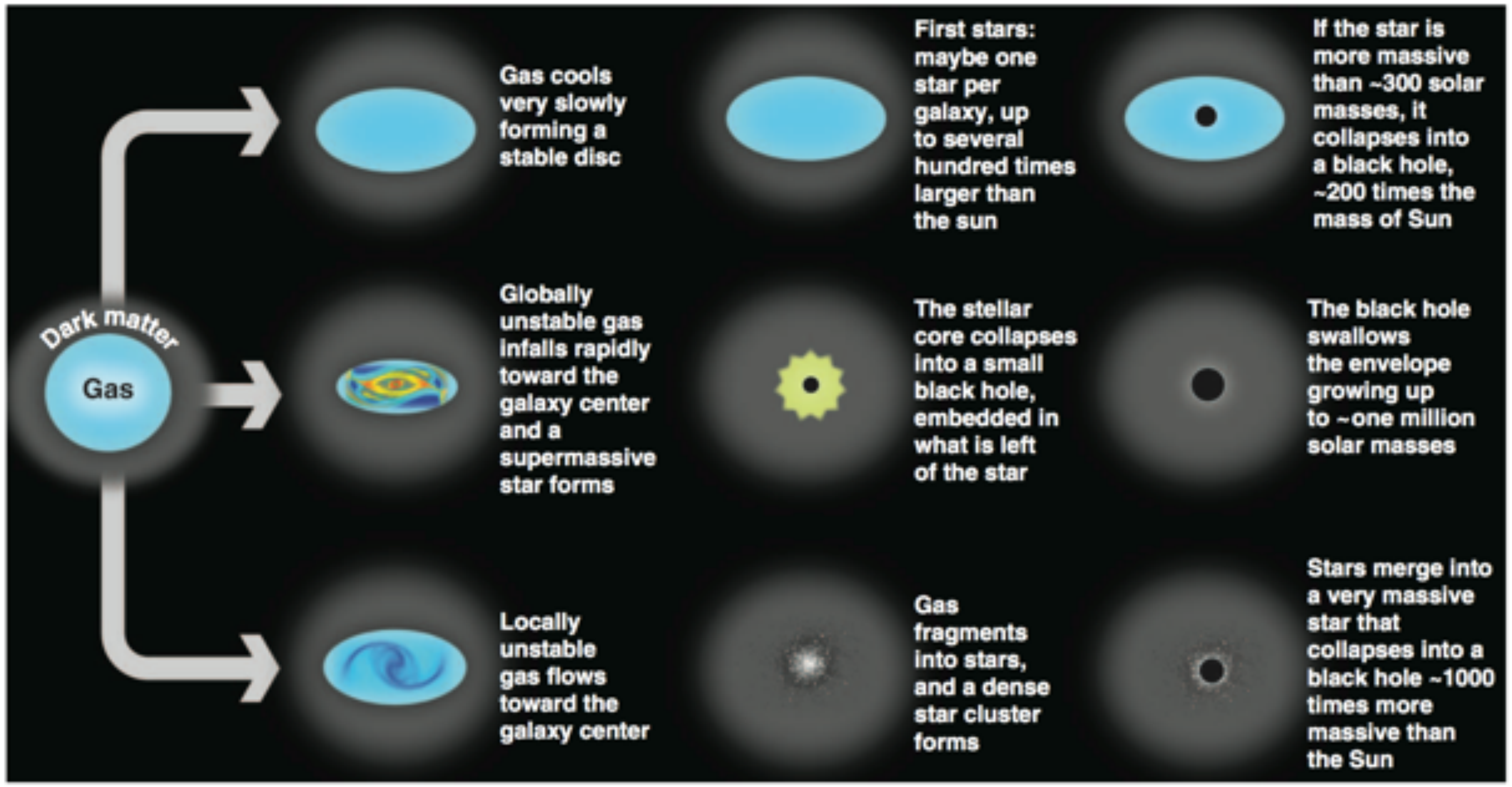


Fig. 1. Illustration showing three pathways to MBH formation that can occur in a distant galaxy (*56*). The starting point is a primeval galaxy, composed of a dark matter halo and a central condensation of gas. Most of this gas will eventually form stars and contribute to making galaxies as we know them. However, part of this gas has also gone into making a MBH, probably following one of these routes.

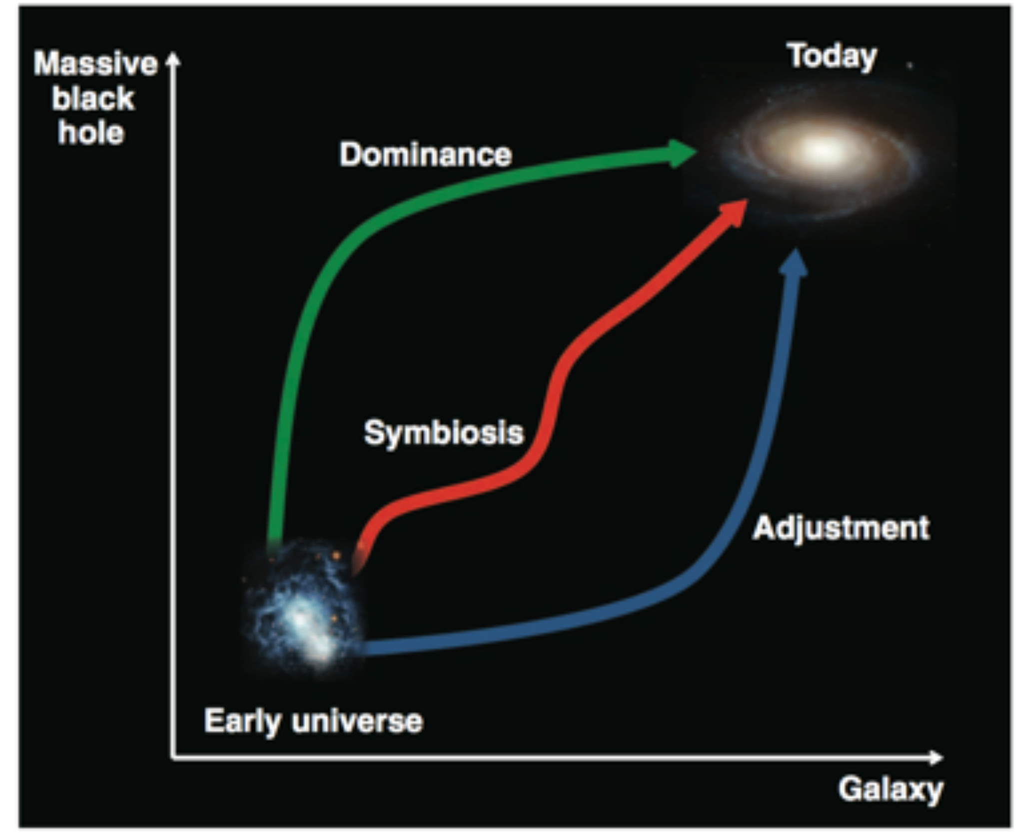


Fig. 3. Possible routes to MBH and galaxy coevolution, starting from black holes forming in distant galaxies in the early universe. [Image credits: NASA, European Space Agency (ESA), A. Aloisi (Space Telescope Science Institute and ESA, Baltimore, MD), and The Hubble Heritage Team (Space Telescope Science Institute/Association of Universities for Research in Astronomy)]

REVIEW

The Formation and Evolution of Massive Black Holes

M. Volonteri[1,2]

The past 10 years have witnessed a change of perspective in the way astrophysicists think about massive black holes (MBHs), which are now considered to have a major role in the evolution of galaxies. This appreciation was driven by the realization that black holes of millions of solar masses and above reside in the center of most galaxies, including the Milky Way. MBHs also powered active galactic nuclei known to exist just a few hundred million years after the Big Bang. Here, I summarize the current ideas on the evolution of MBHs through cosmic history, from their formation about 13 billion years ago to their growth within their host galaxies.

Volonteri, Science 337 (2012) 544

2. Model of SMBH

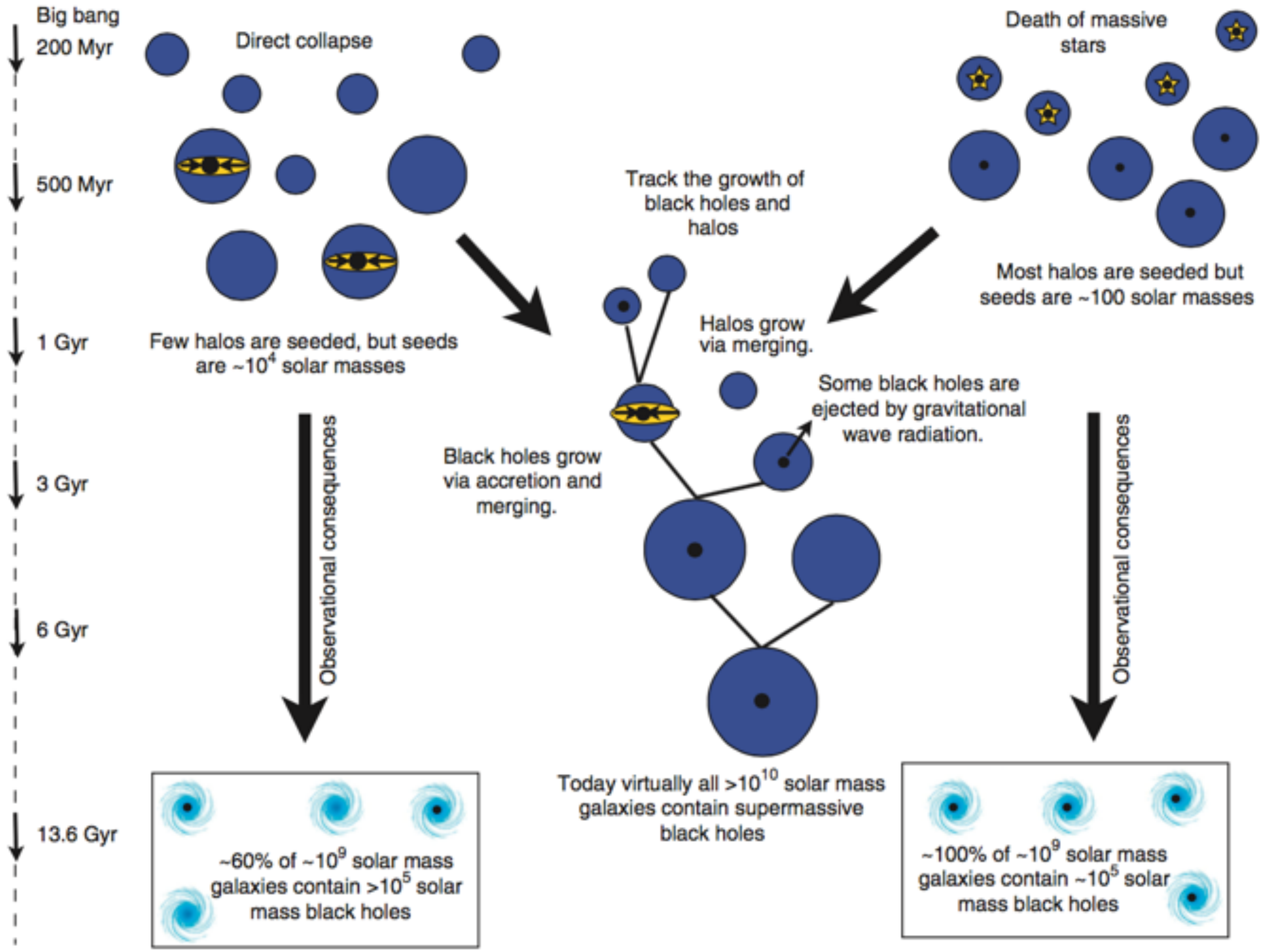
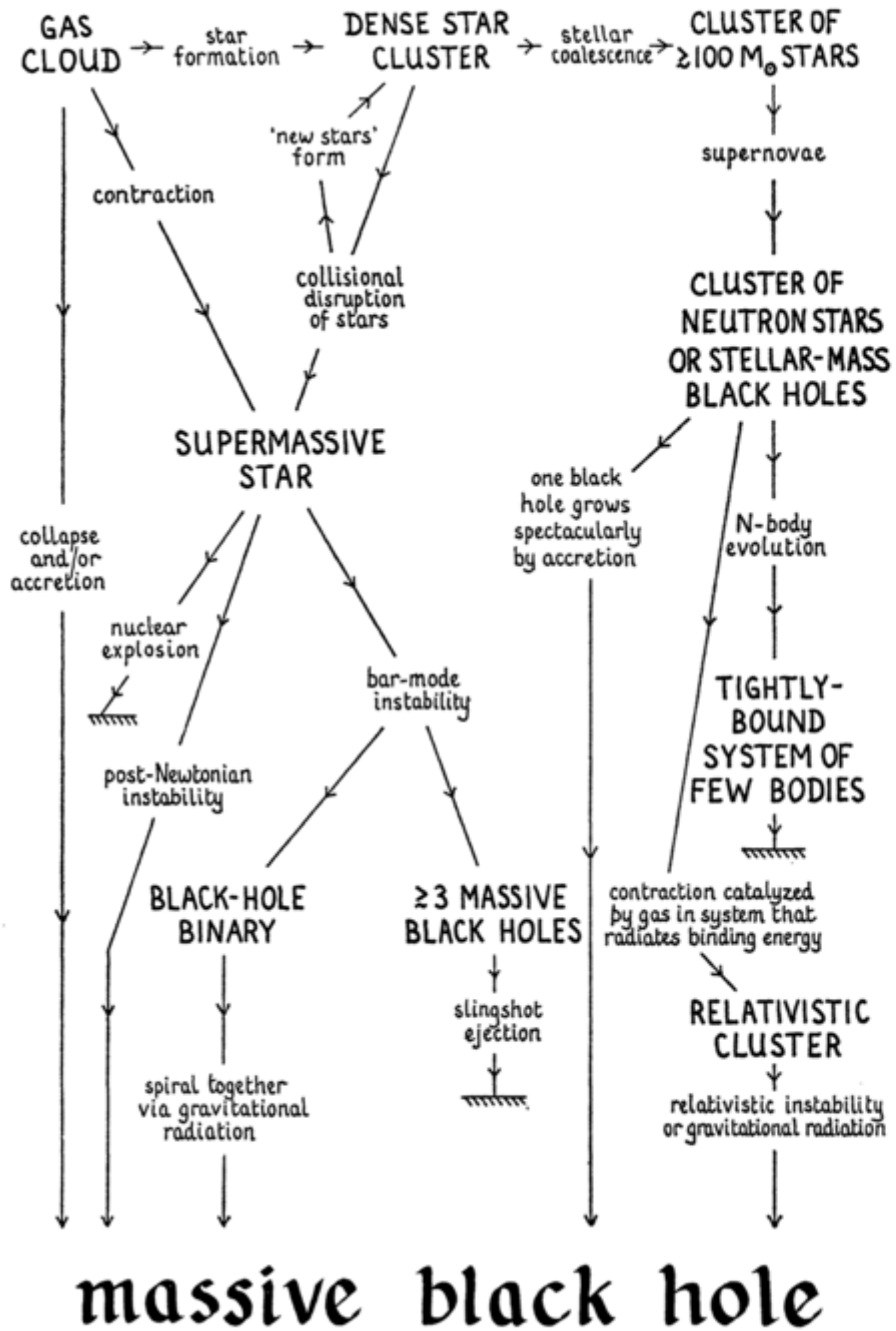


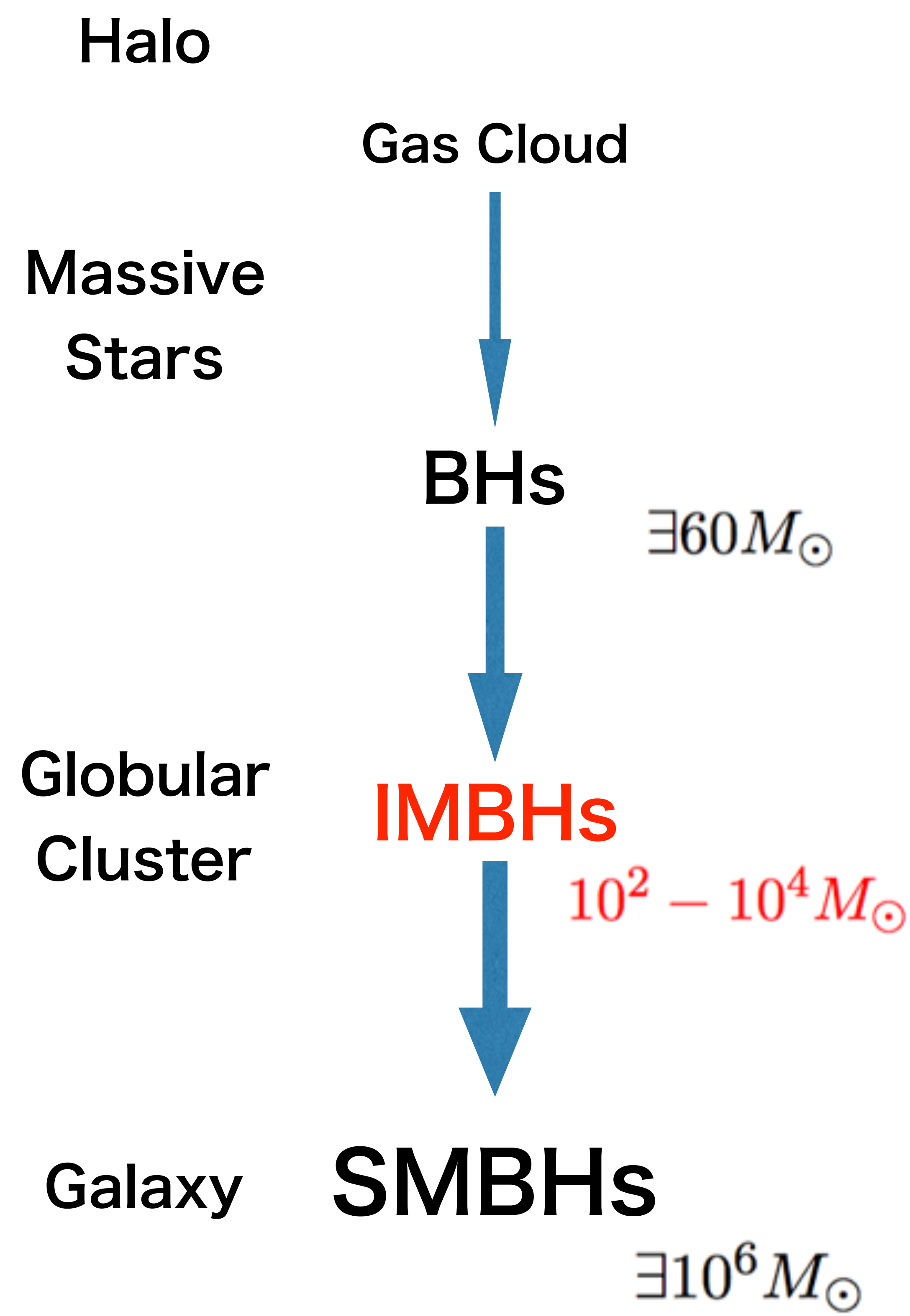
Figure 1 | Evolution of seed black holes. Schematic of the evolution of seed black holes assuming two different formation mechanisms (the death of the first generation of massive stars versus the direct collapse of gas into a black hole). Dark matter halos and the galaxies in them grow through merging. Black holes grow both via merging and by accreting gas. One additional complication is that after merging, gravitational radiation 'recoil' (see text for details) may send the black hole out of the galaxy. At present, we can distinguish between the two scenarios based on the fraction of small galaxies that contain massive black holes (we call this the 'occupation fraction').

Greene, Nature Comm 3 (2012) [arXiv:1211.7082]

2. Model of SMBH



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



Ebisuzaki +, ApJ, 562, L19 (2001)

Starburst galaxy M82 has 1000M BH

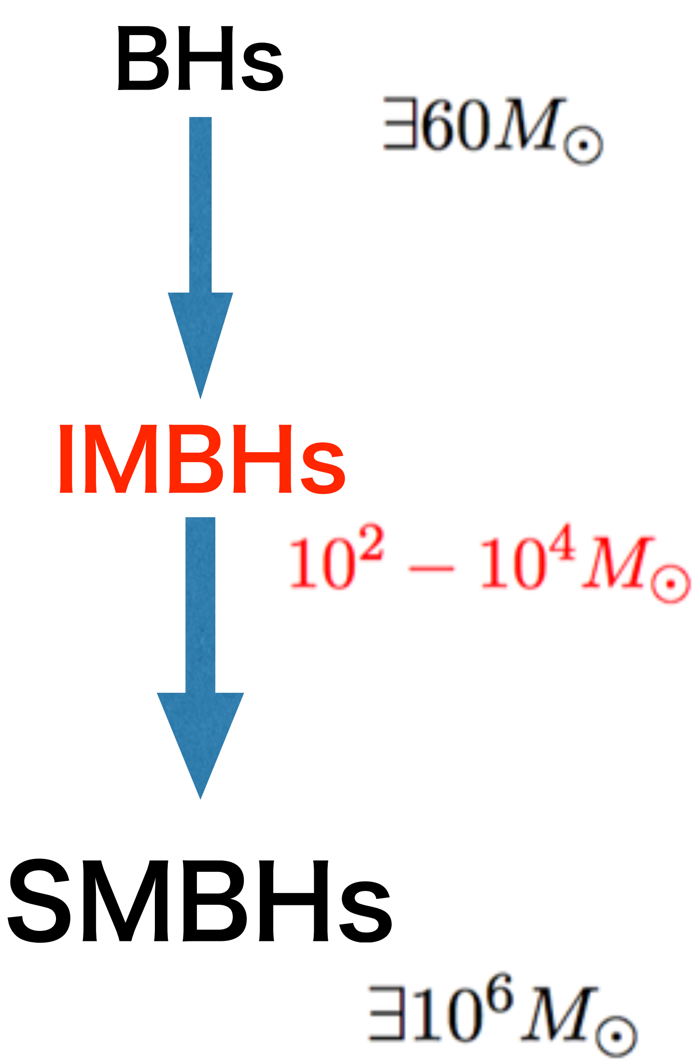
Matsushita+, ApJ, 545, L107 (2000)
Matsumoto+, ApJ, 547, L25 (2001)

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)

L7-1

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

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

0.15pc from SgrA*
1-2 x 10^4 Msun

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

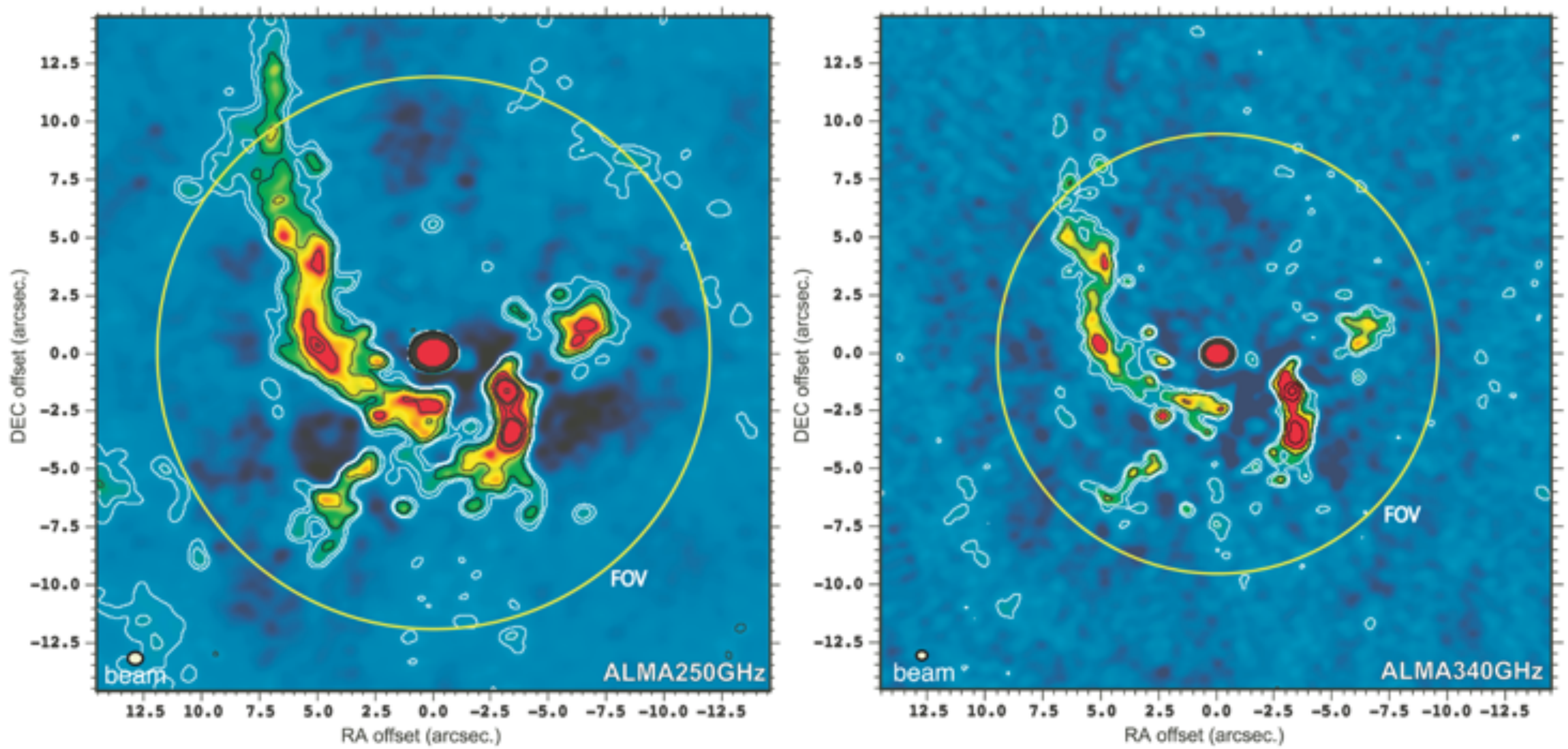


Fig. 2. Left panel: ALMA map in the 250 GHz band of the "mini-spiral" including Sgr A*. The four spectral windows of $f_c = 245$, 247, 257, and 259 GHz are combined to improve the sensitivity. The diameter of the FOV is 24″ (circle). The angular resolution is 0.″63 × 0.″53 at $PA = -84°$, which is shown 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)

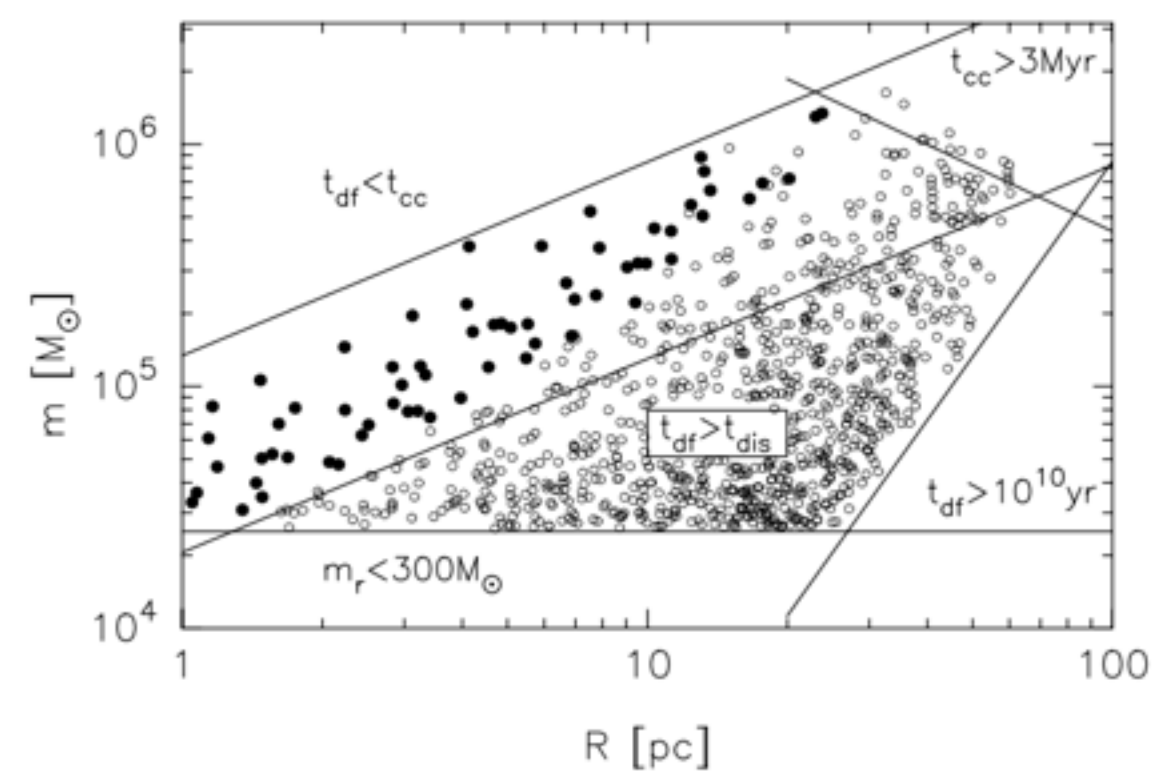
THE ECOLOGY OF STAR CLUSTERS AND INTERMEDIATE-MASS BLACK HOLES IN THE GALACTIC BULGE

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



IMBH-IMBH mergers produce low freq. GW

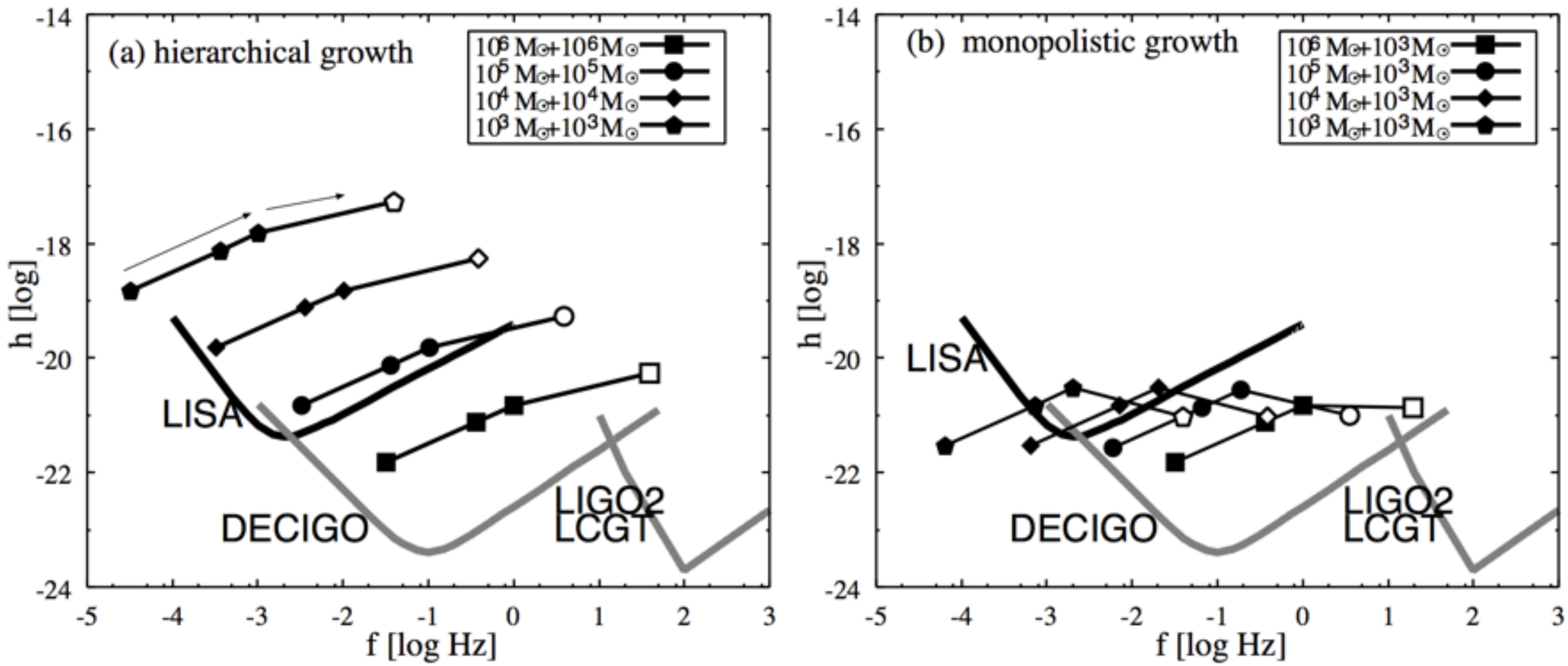
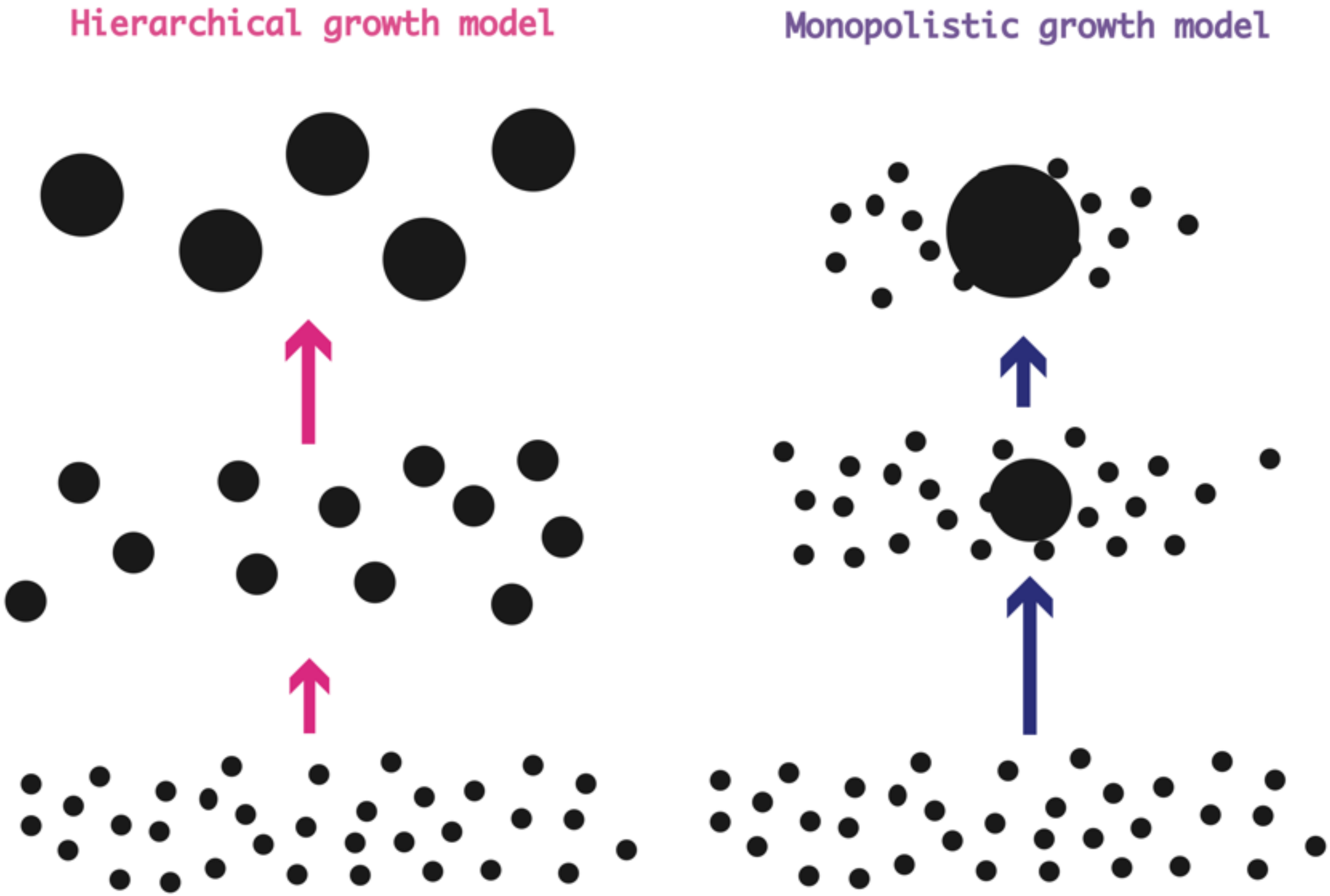


Fig. 1.— Expected gravitational radiation amplitude from merging IMBHs of (a) hierarchical growth model, and (b) monopolistic growth model. We plotted both the inspiral phase ($f_{\rm insp}, h_{\rm insp}$), [eqs. (2) and (3)], and the ringdown phase ($f_{\rm QNM}, h_{\rm coal}$), [eqs. (4) and (6)],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

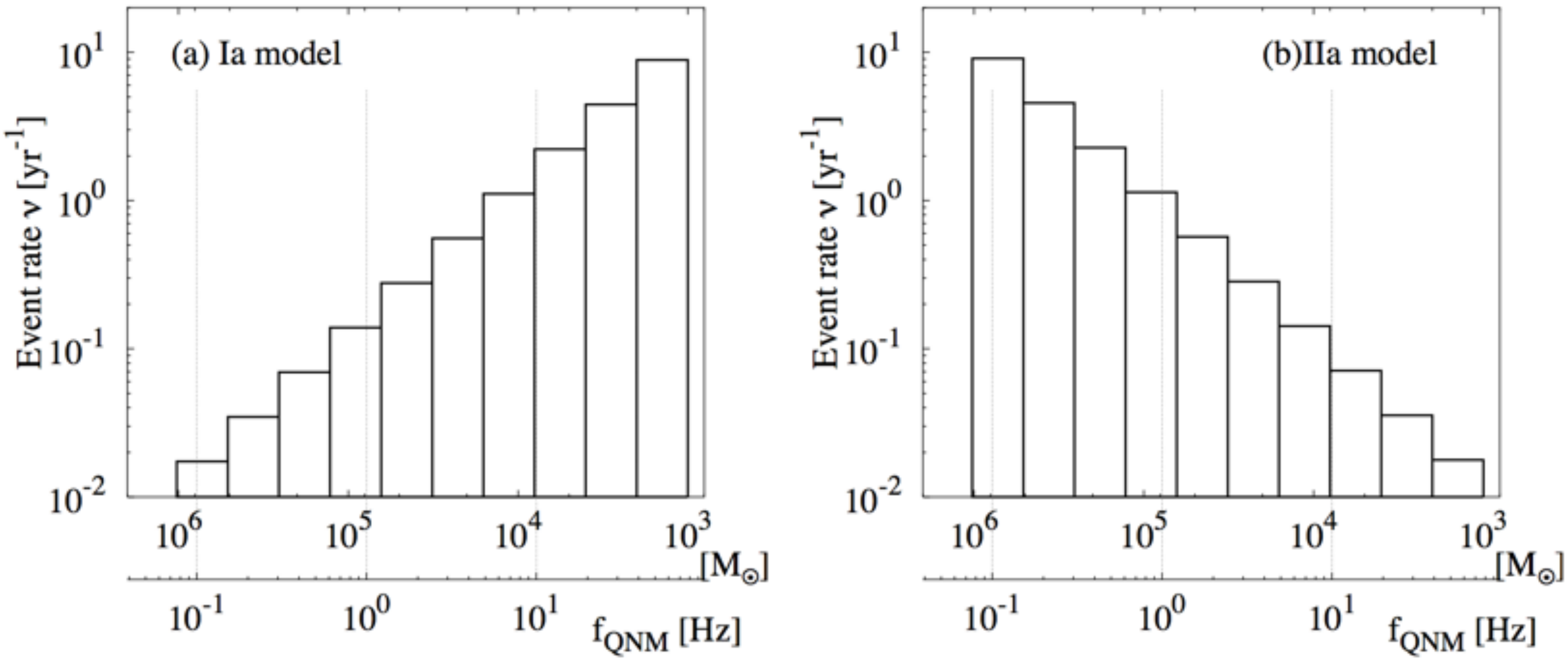
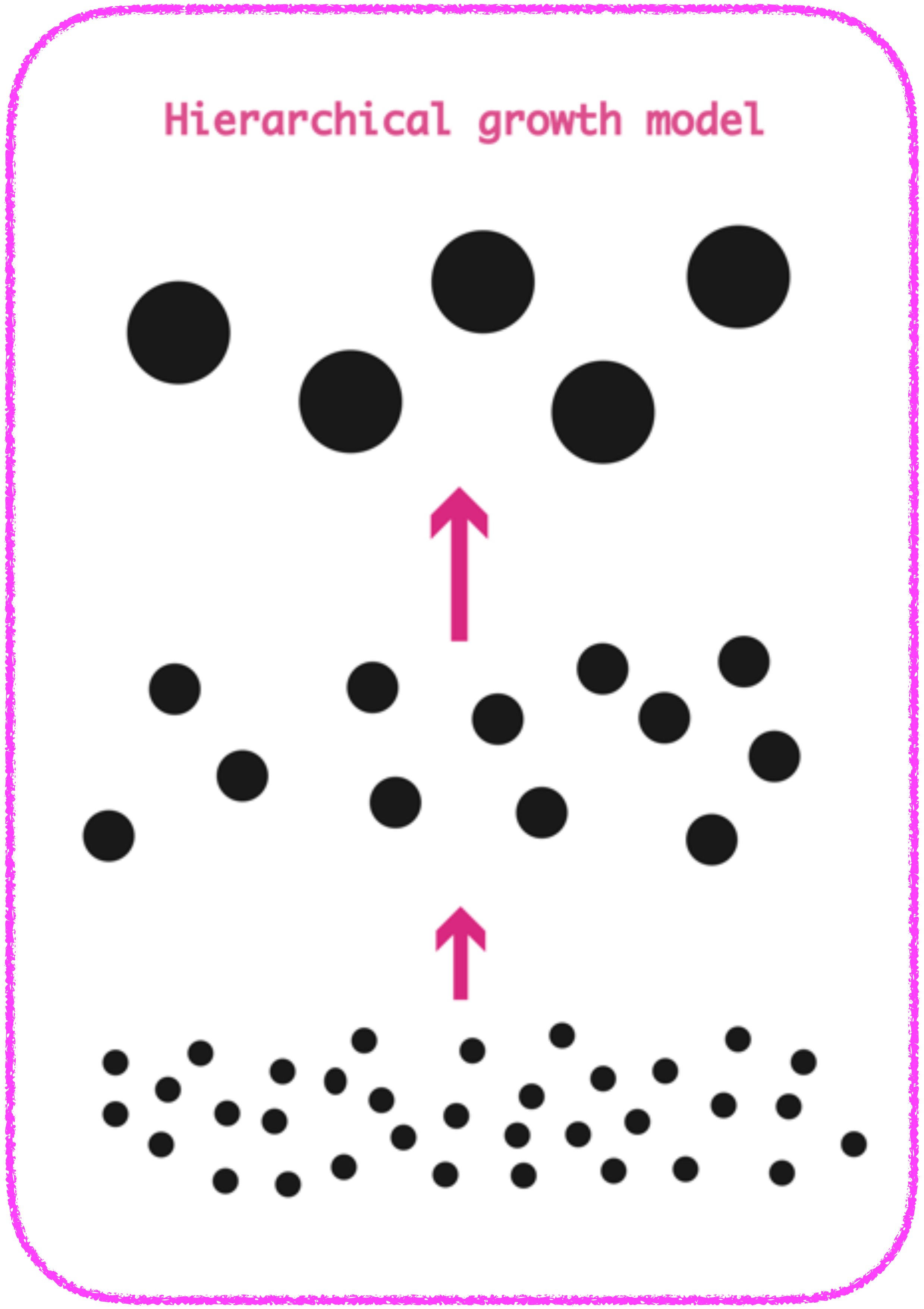


Fig. 2.— Event numbers of mergers starting from a thousand of $10^3 M_\odot$ IMBHs. The vertical axis is the event rate $\nu[\mathrm{yr}^{-1}]$, eqs. (12) and (14). The horizontal axis is the mass of the post-merger BH, M_T, which is also interpreted in the final gravitational radiation frequency $f_{\rm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

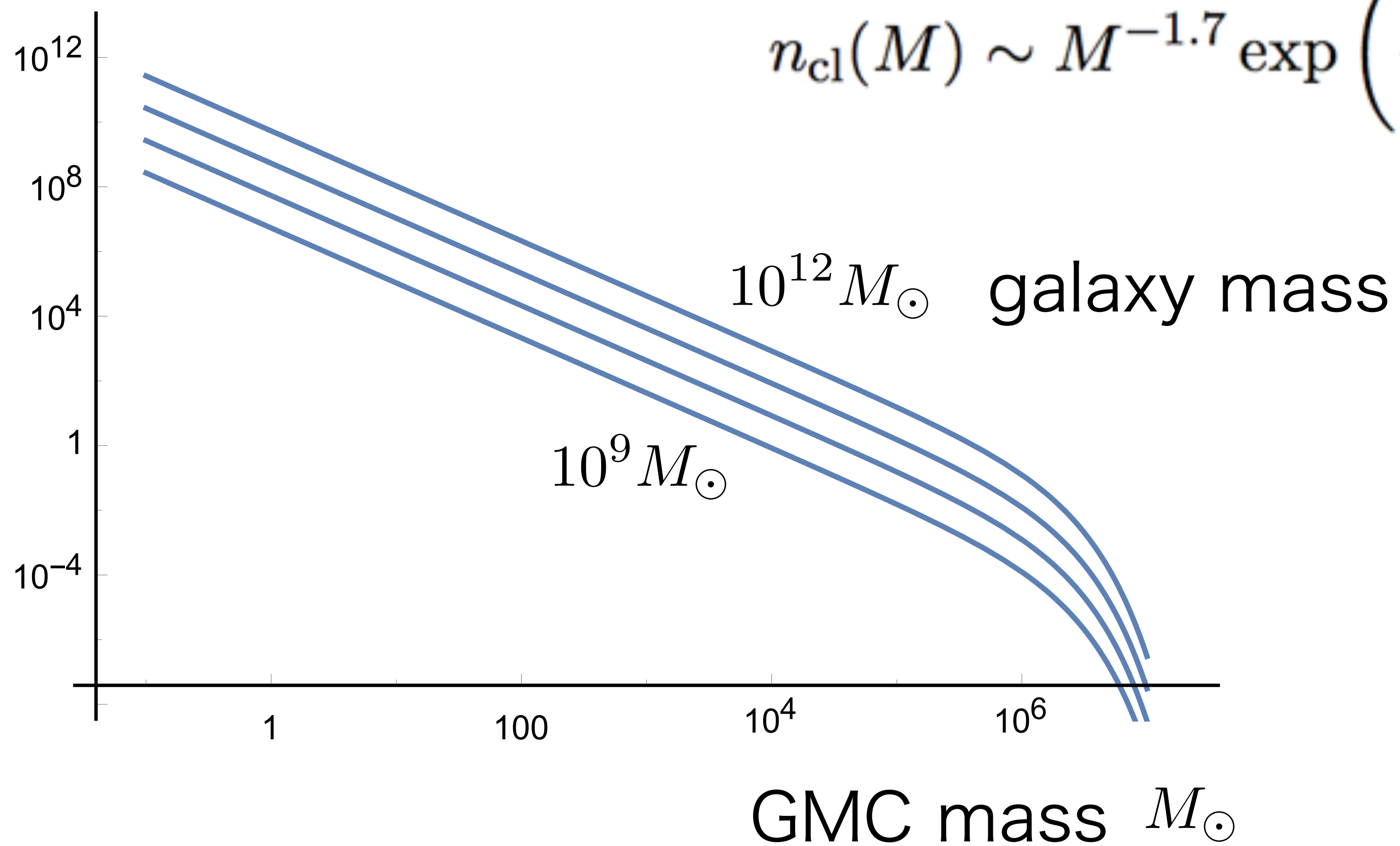
Detectable Distance ?
KAGRA/aLIGO/aVIRGO

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

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]

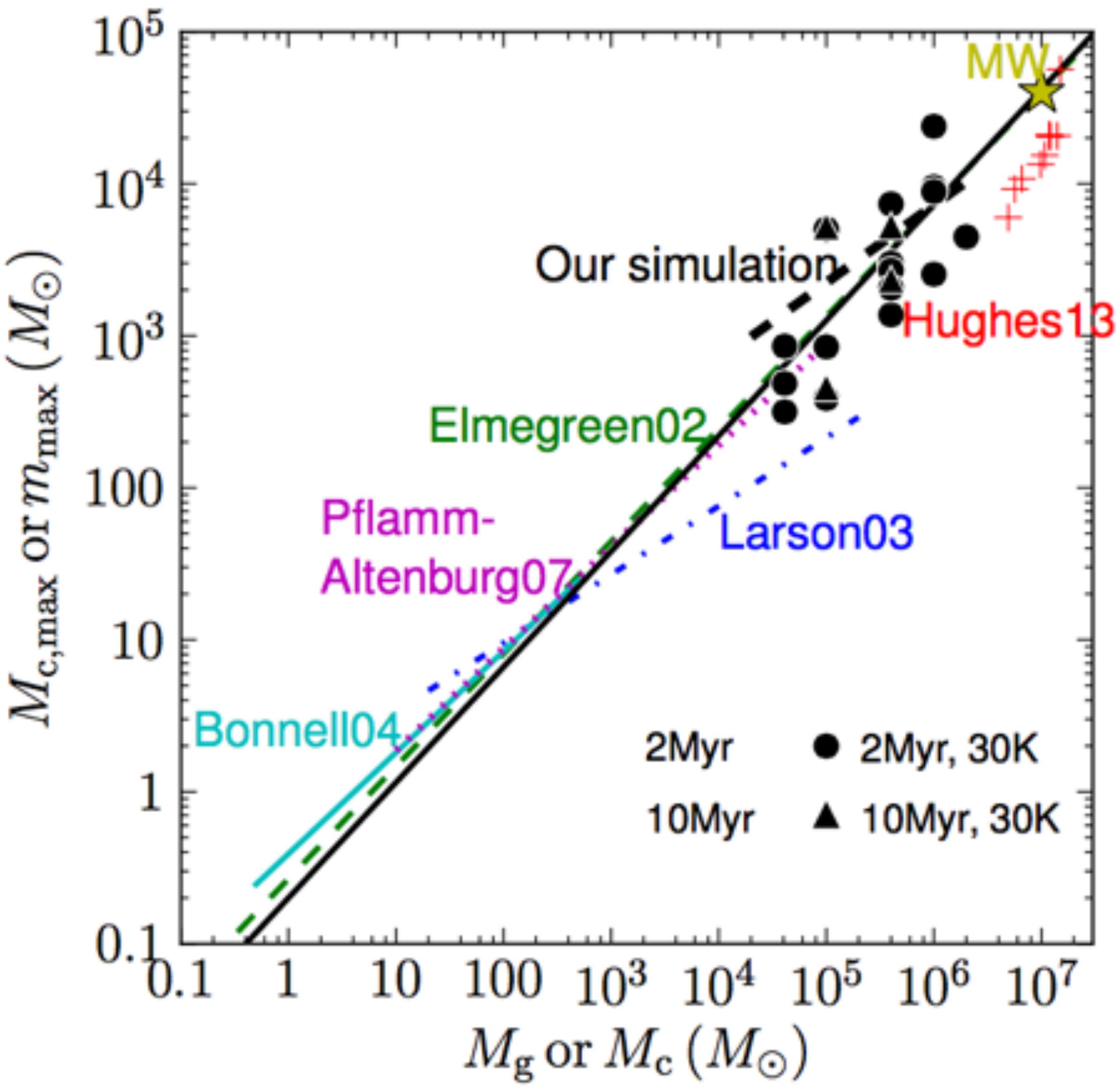
A&A 580, A49 (2015) [arXiv:1505.04696]

How many BHs in a Galaxy?

Molecular Clouds

Maximum Core

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

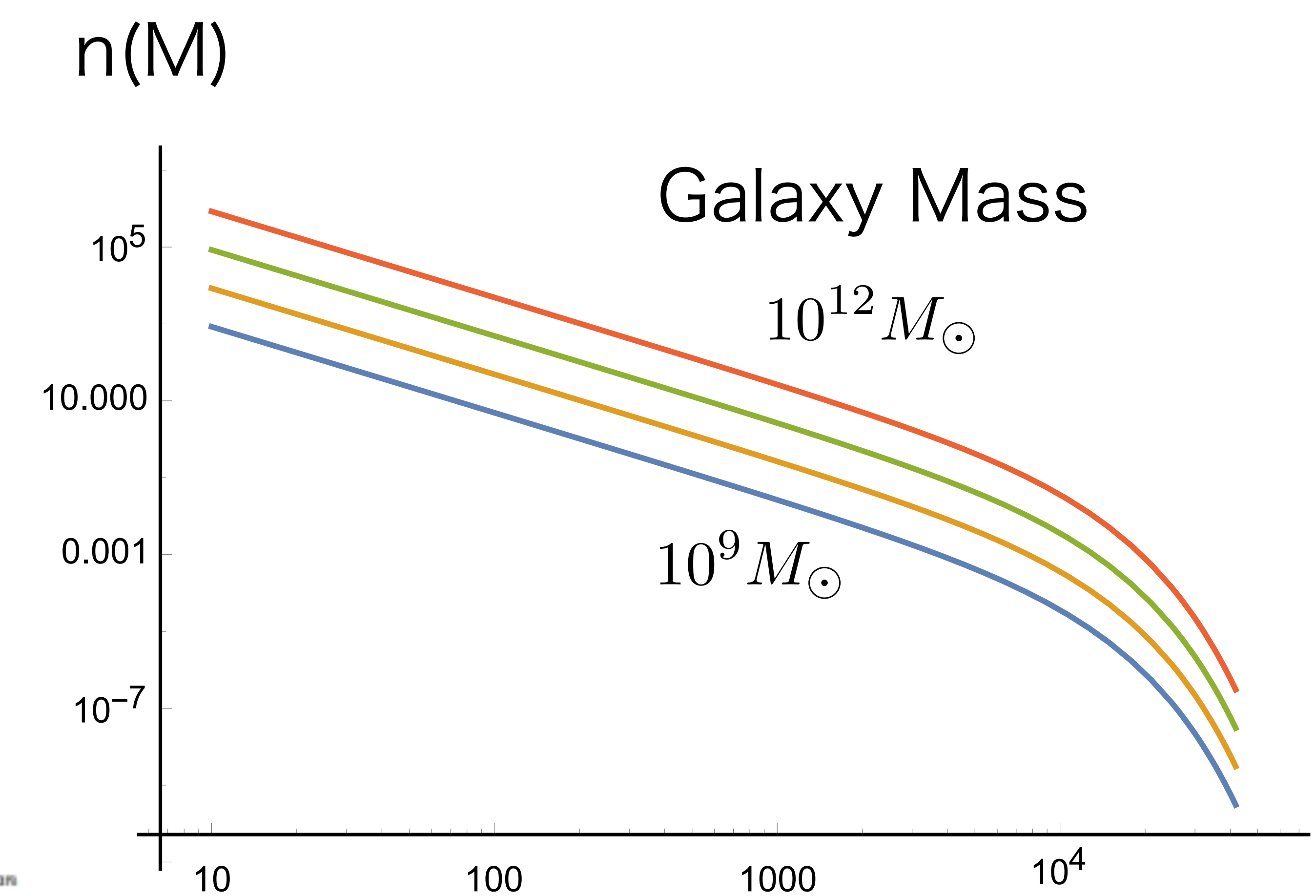


The initial mass function of star clusters that form in turbulent molecular clouds

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

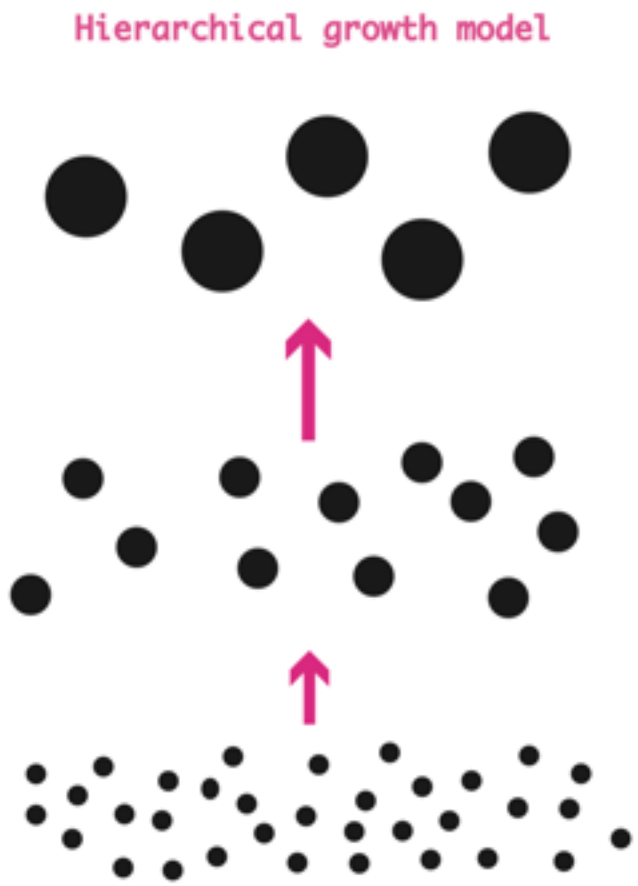
1309.1223v3

Building Block BH

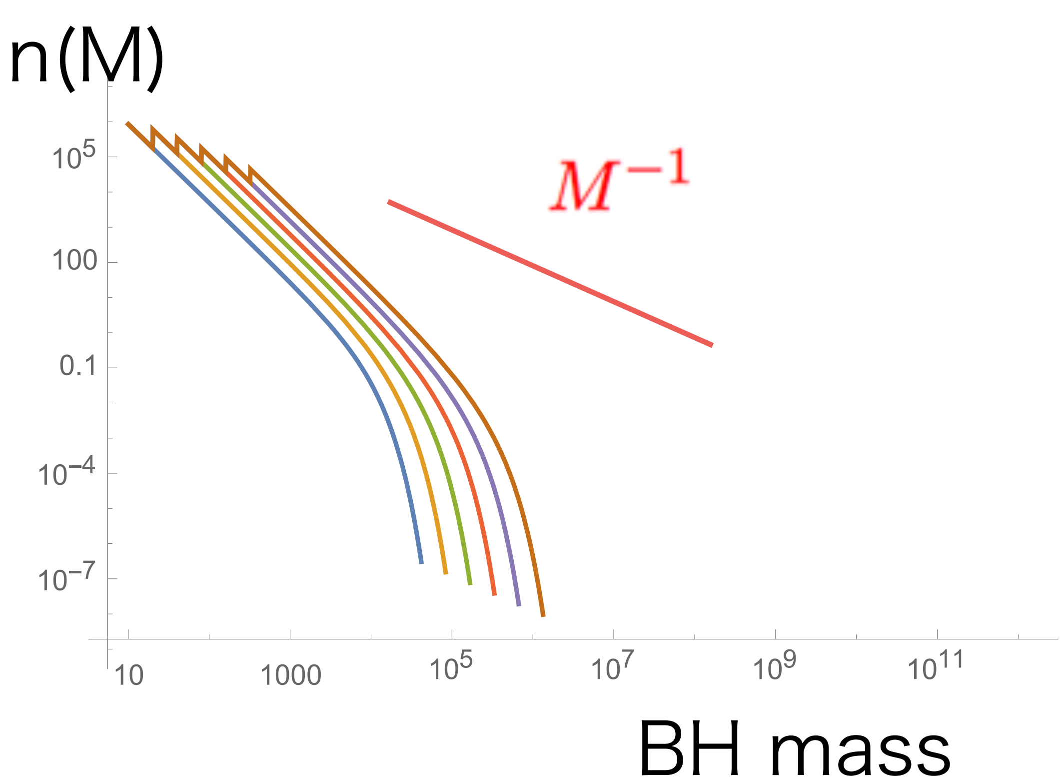


How many BHs in a Galaxy?

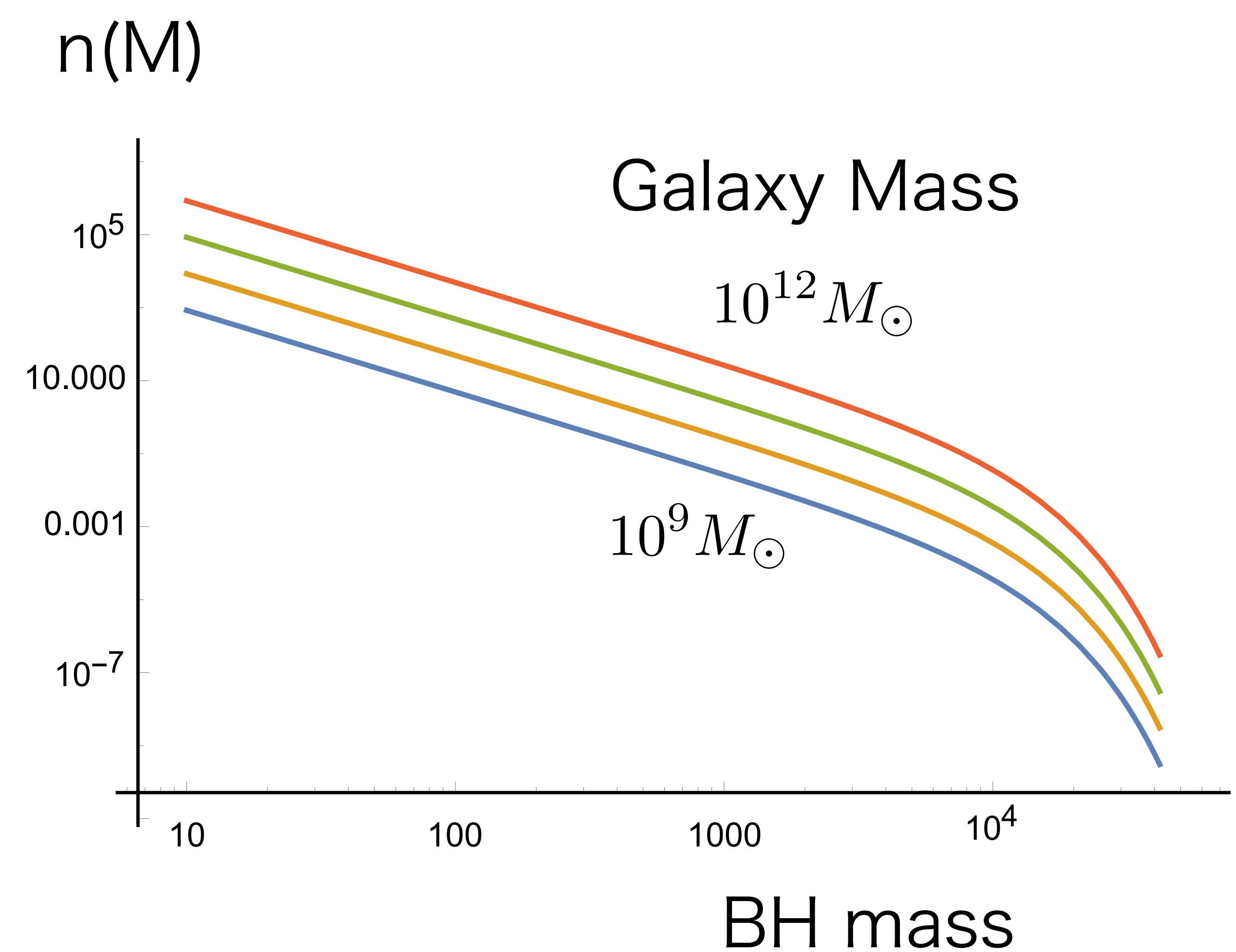
Count BHs to form a SMBH



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

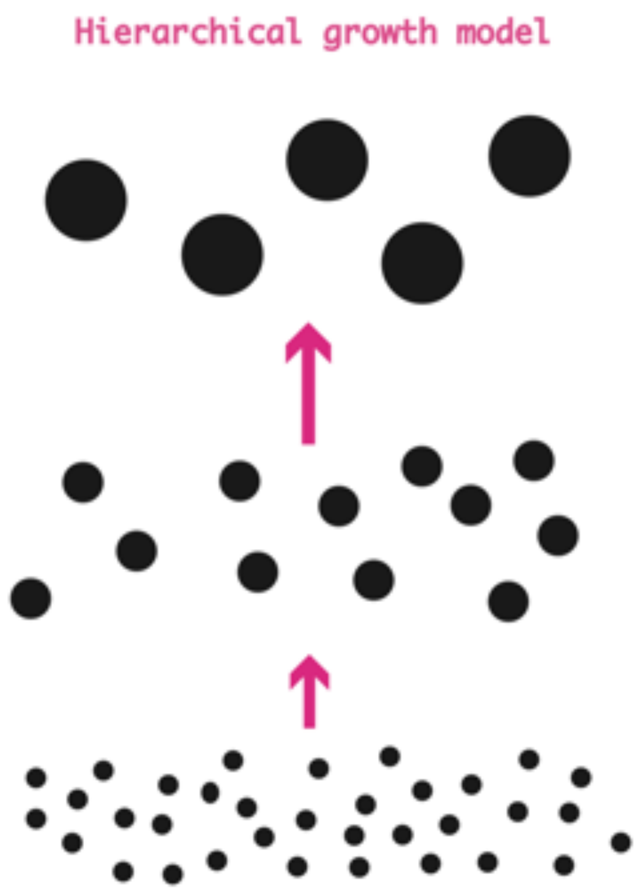


Building Block BH



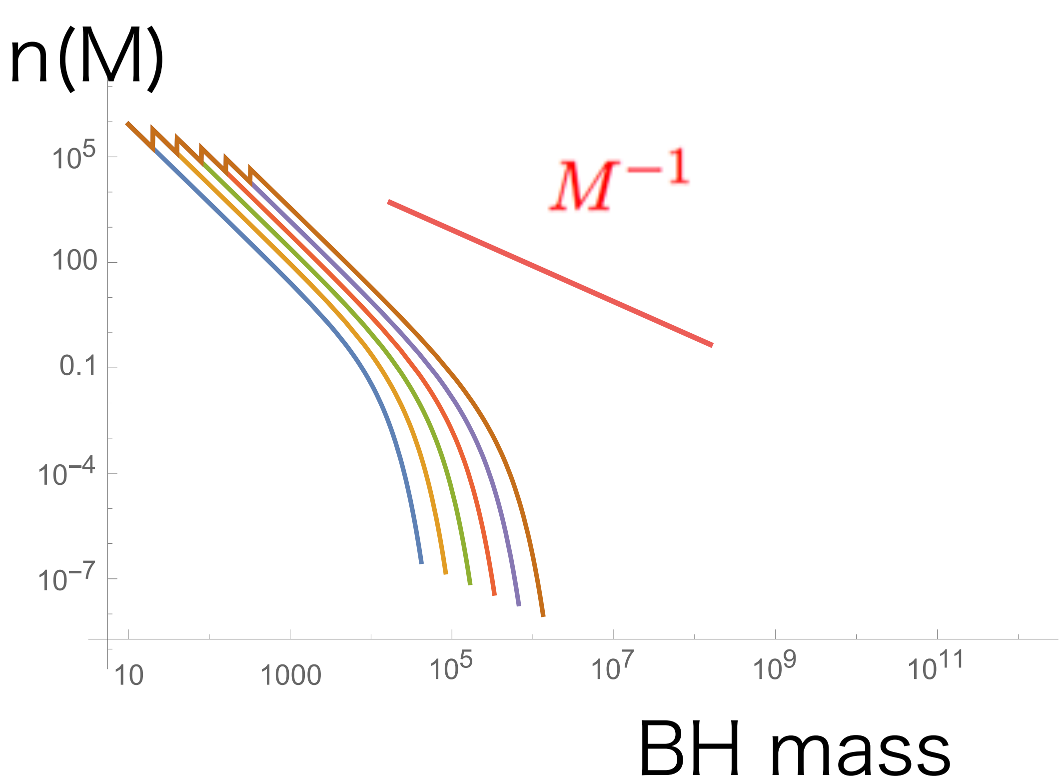
How many BHs in a Galaxy?

Count BHs to form a SMBH



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

dynamical friction



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

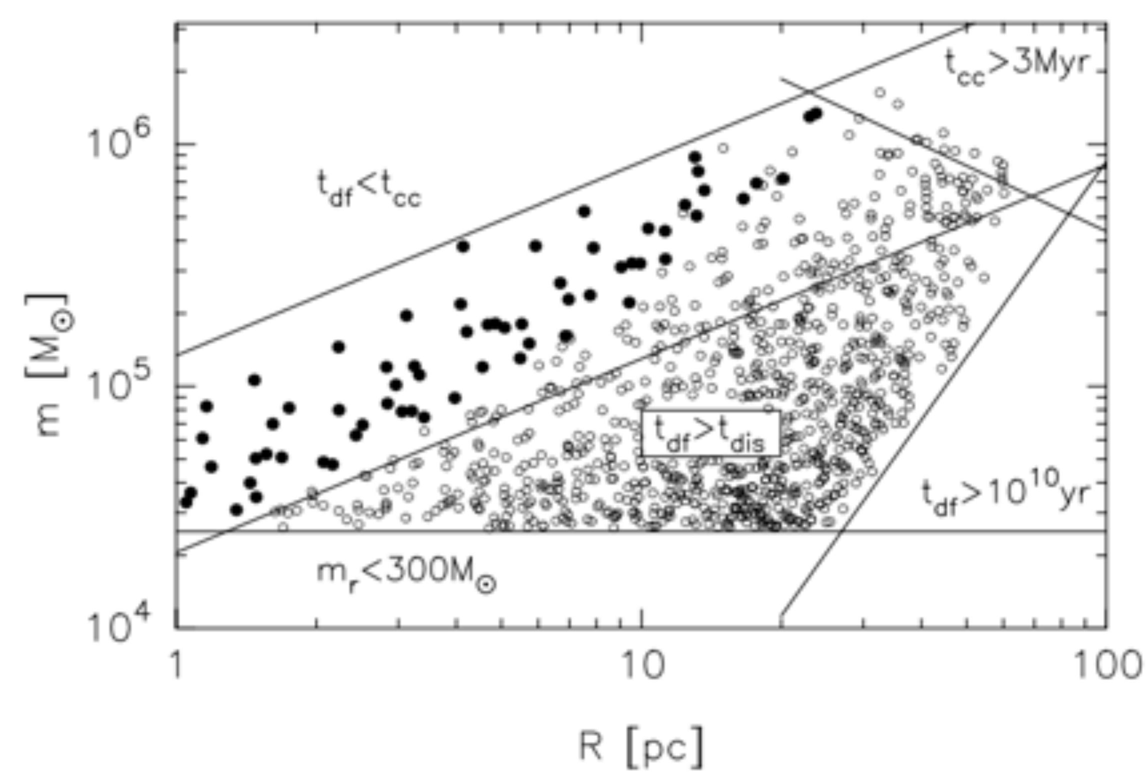
Simon F. Portegies Zwart,[1,2] Holger Baumgardt,[3] Stephen L. W. McMillan,[4] Junichiro Makino,[5] Piet Hut,[6] and Toshi Ebisuzaki[7]

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



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

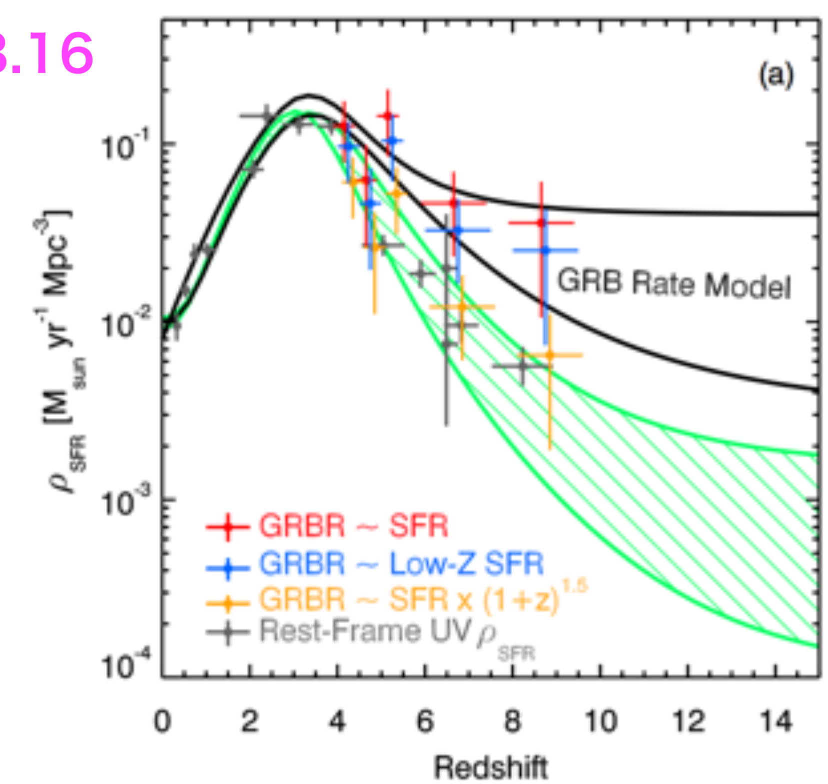
The Astrophysical Journal, 744:95 (13pp), 2012 January 10 doi:10.1088/0004-637X/744/2/95

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

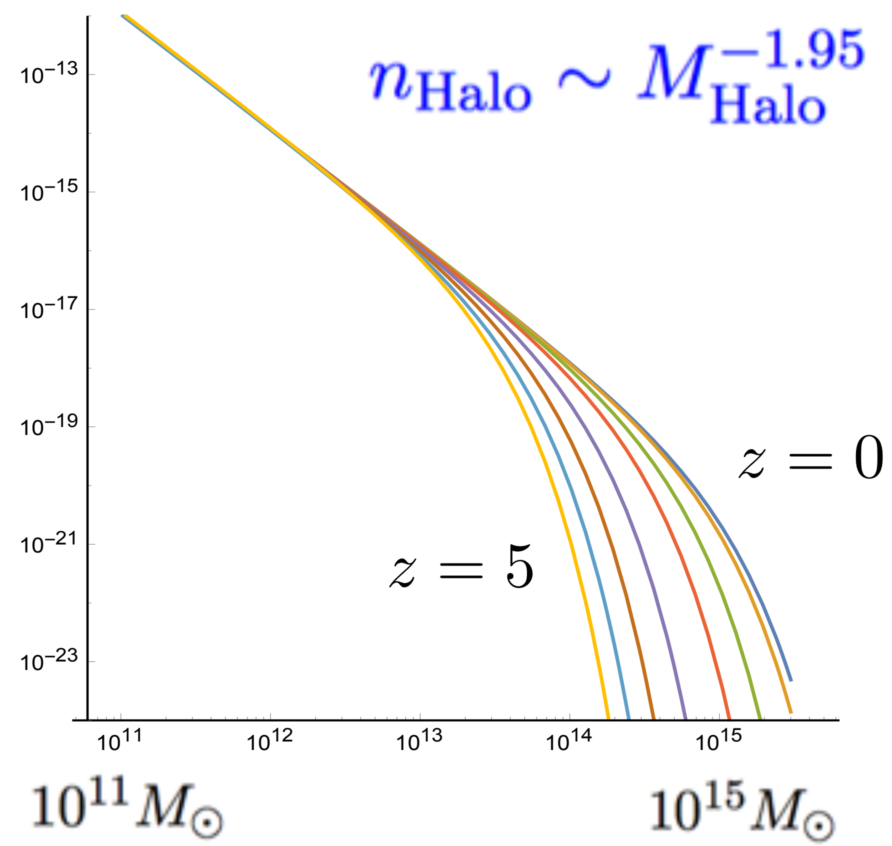
Star Formation Rate

peak z=3.16



How many Galaxies in the Universe?

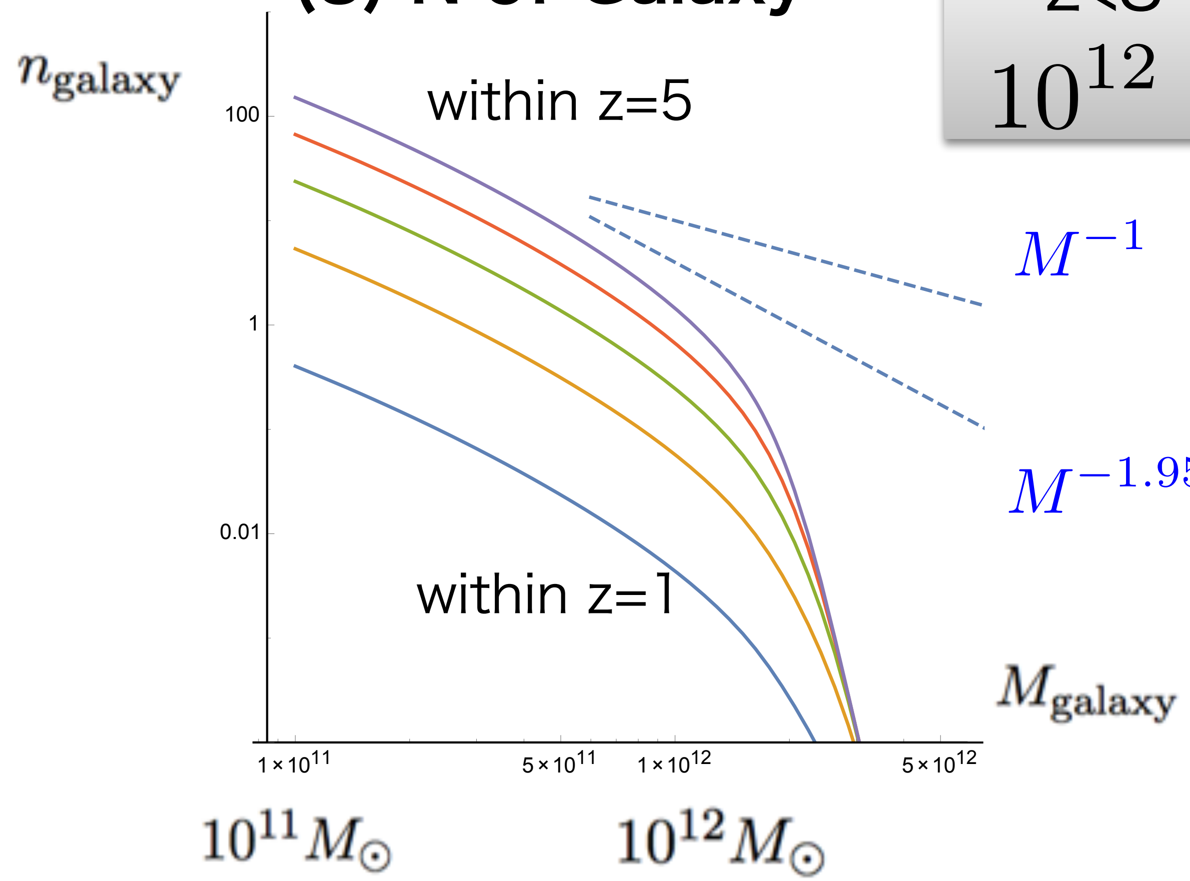
(1) Halo number density



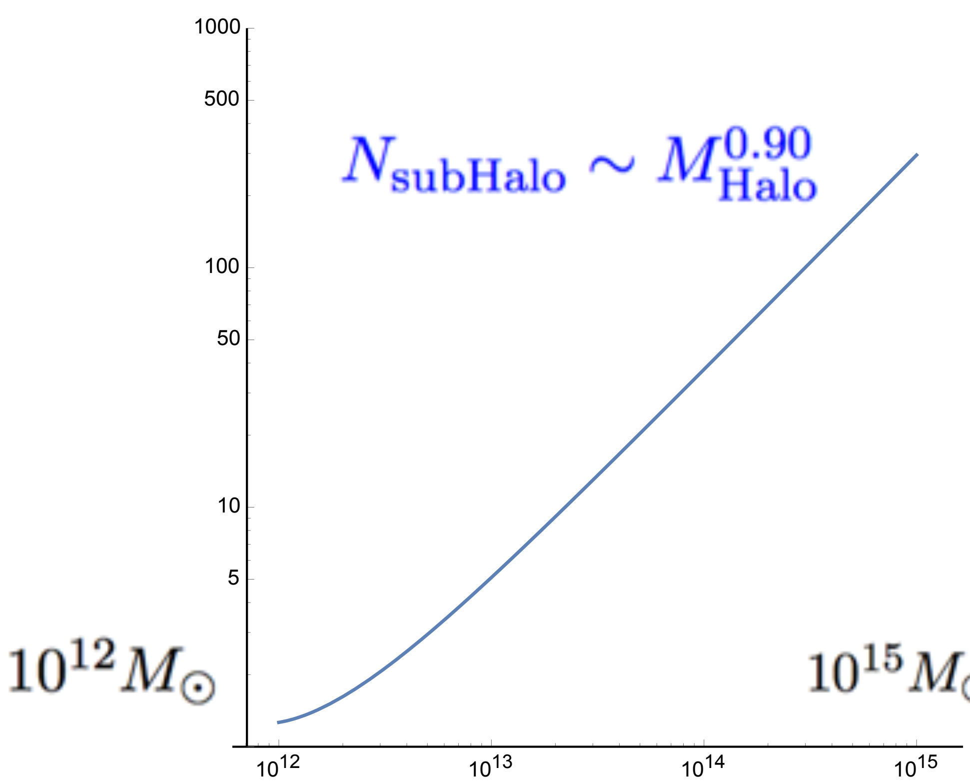
(3) N of Galaxy

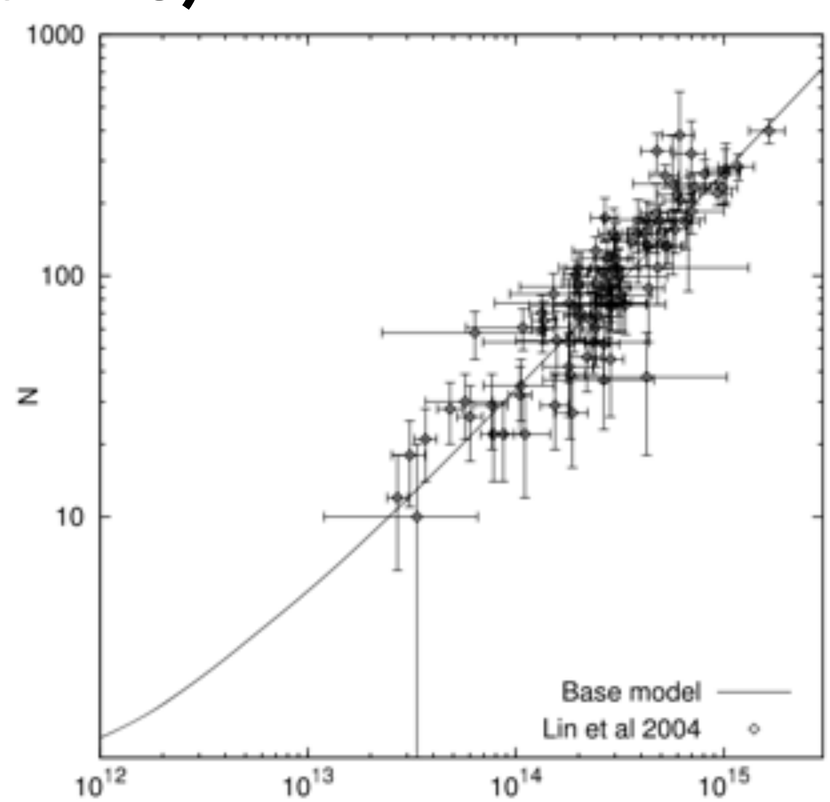
z<3

10^{12}



(2) N of seeds of Galaxy (subHalo)





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

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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 • © 2016. The American Astronomical Society. All rights reserved.
The Astrophysical Journal, Volume 830, Number 2

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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?

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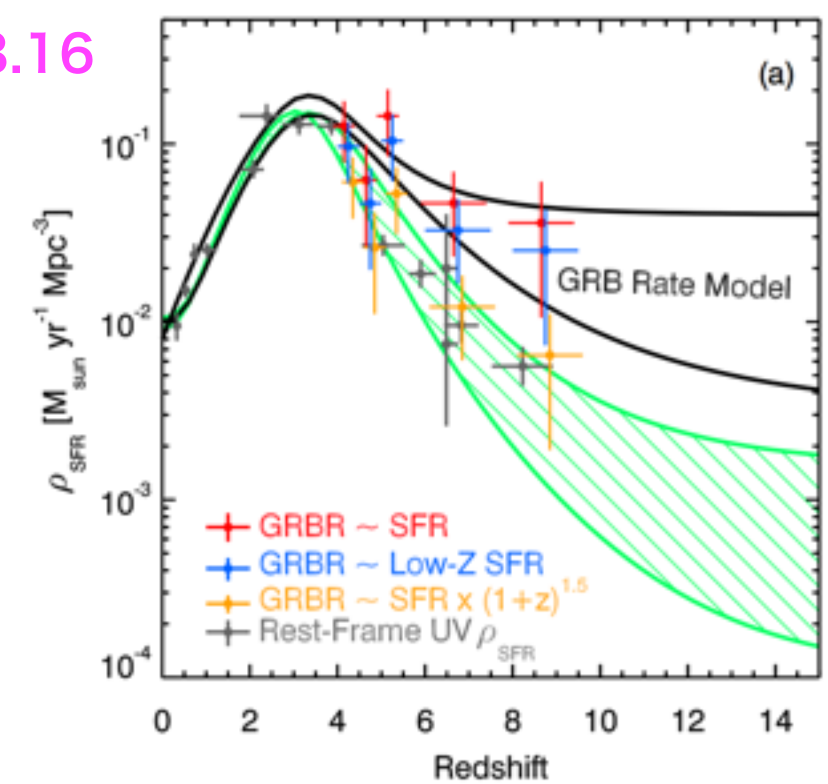
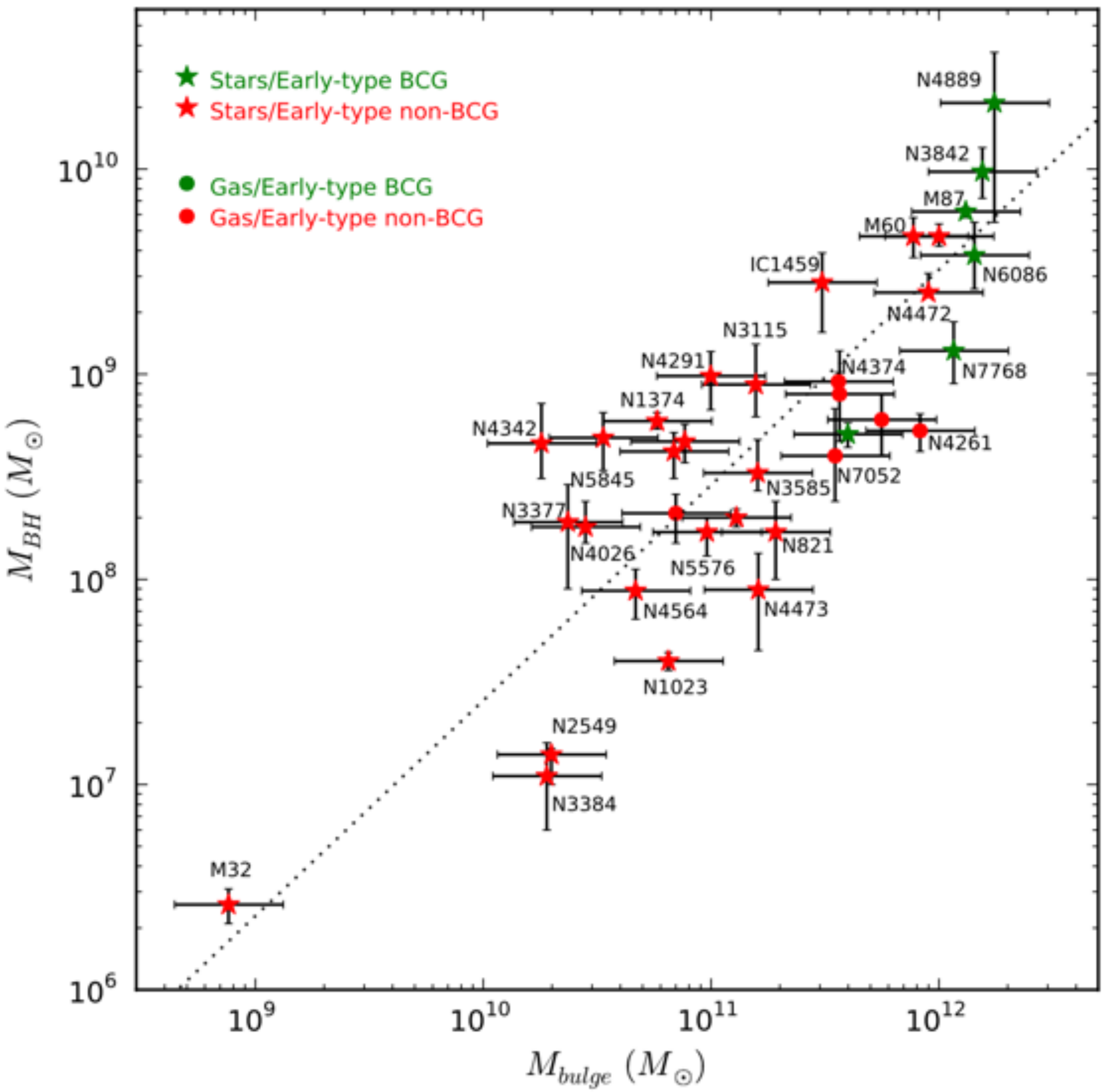




$$
\begin{aligned}
M_{\mathrm{SMBH}} &= 2\times10^{-4}M_{\mathrm{galaxy}}\\
&= 10^{-3}M_{\mathrm{bulge}}
\end{aligned}
$$

McConnell-Ma
ApJ 764(2013)184

Figure 3. $M_\bullet$–M_{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 $\log_{10}(M_\bullet/M_\odot) = 8.46 + 1.05\ \log_{10}(M_{\mathrm{bulge}}/10^{11}\ M_\odot)$.

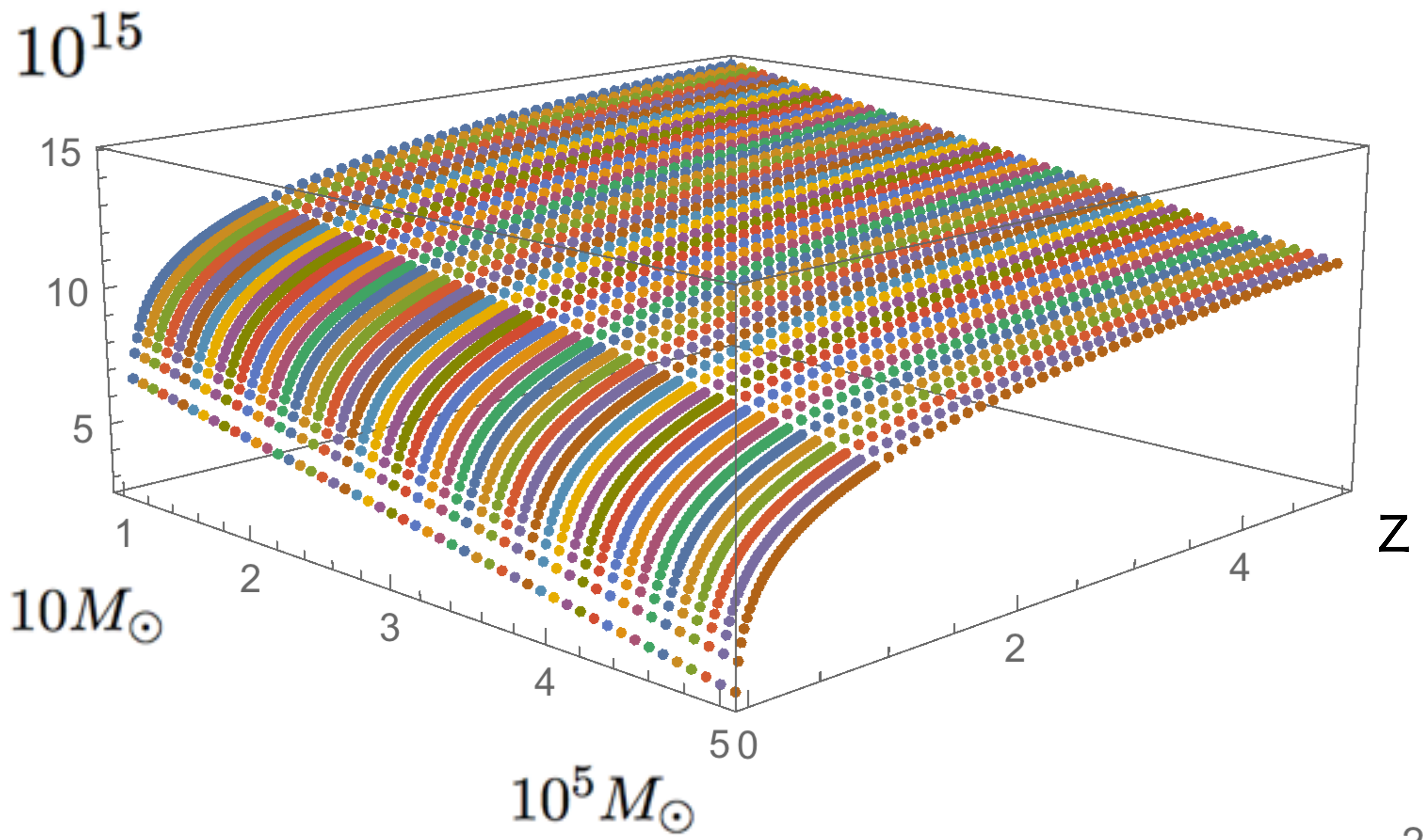
How many BH mergers in the Universe?

in Standard Cosmology

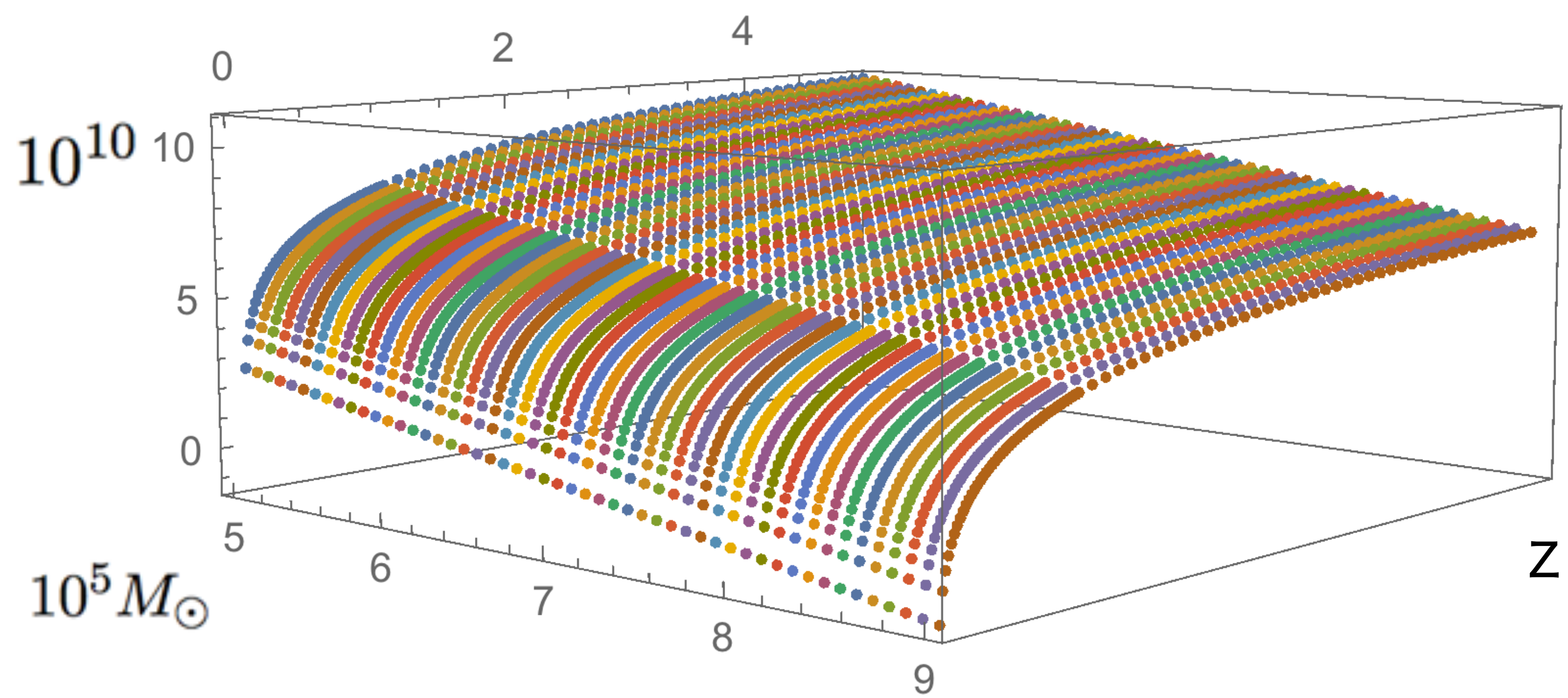
$$\text{Event Rate } R[/\text{yr}] = \frac{N_{\text{merger}}(z)}{V(D/2.26)}$$

Standard Cosmology

averaging distances for all directions



BH mass



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, $n(t)$:

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

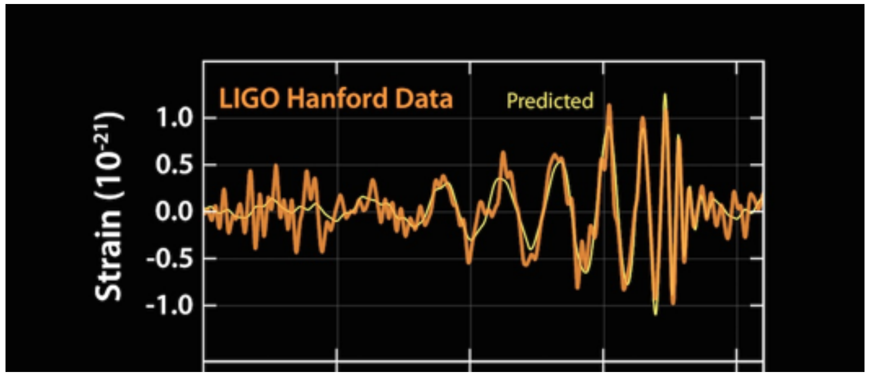
The standard procedure for the detection is judged by the optimal signal-to-noise ratio (SNR), ρ, which is given by

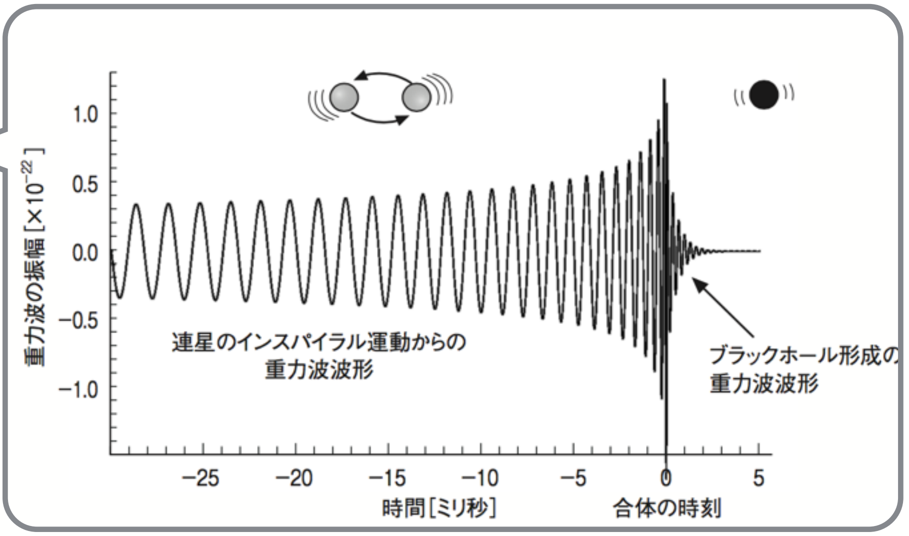
$$\rho = 2\left[\int_0^\infty \frac{\tilde{h}(f)\,\tilde{h}^*(f)}{S_n(f)}df\right]^{1/2}, \tag{18}$$

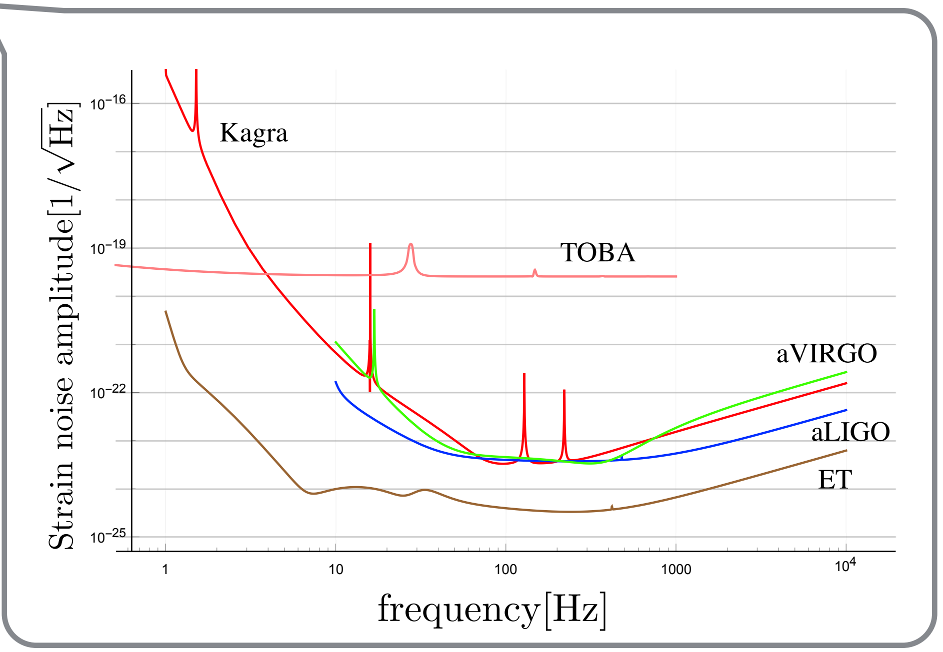
where $\tilde{h}(f)$ is the Fourier-transformed quantity of the wave,

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

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

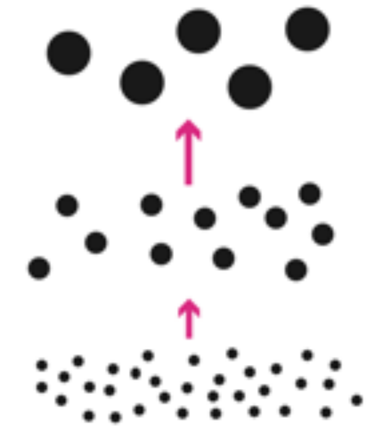
Flanagan&Hughes, PRD57(198)4535

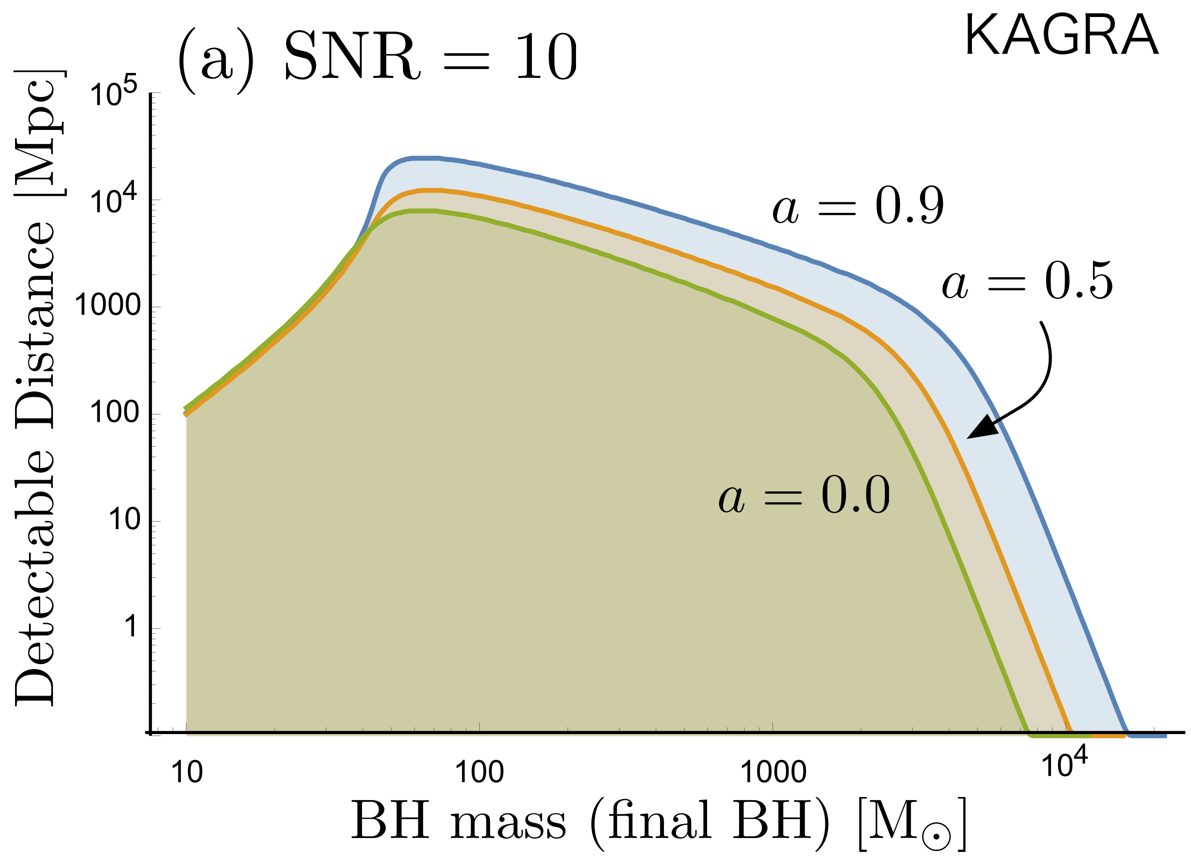
SNR $$\rho^2 = \frac{8}{5}\frac{\epsilon_r(a)}{f_R^2}\frac{(1+z)M}{S_h(f_R/(1+z))}\left(\frac{(1+z)M}{d_L(z)}\right)^2\left(\frac{4\mu}{M}\right)^2$$

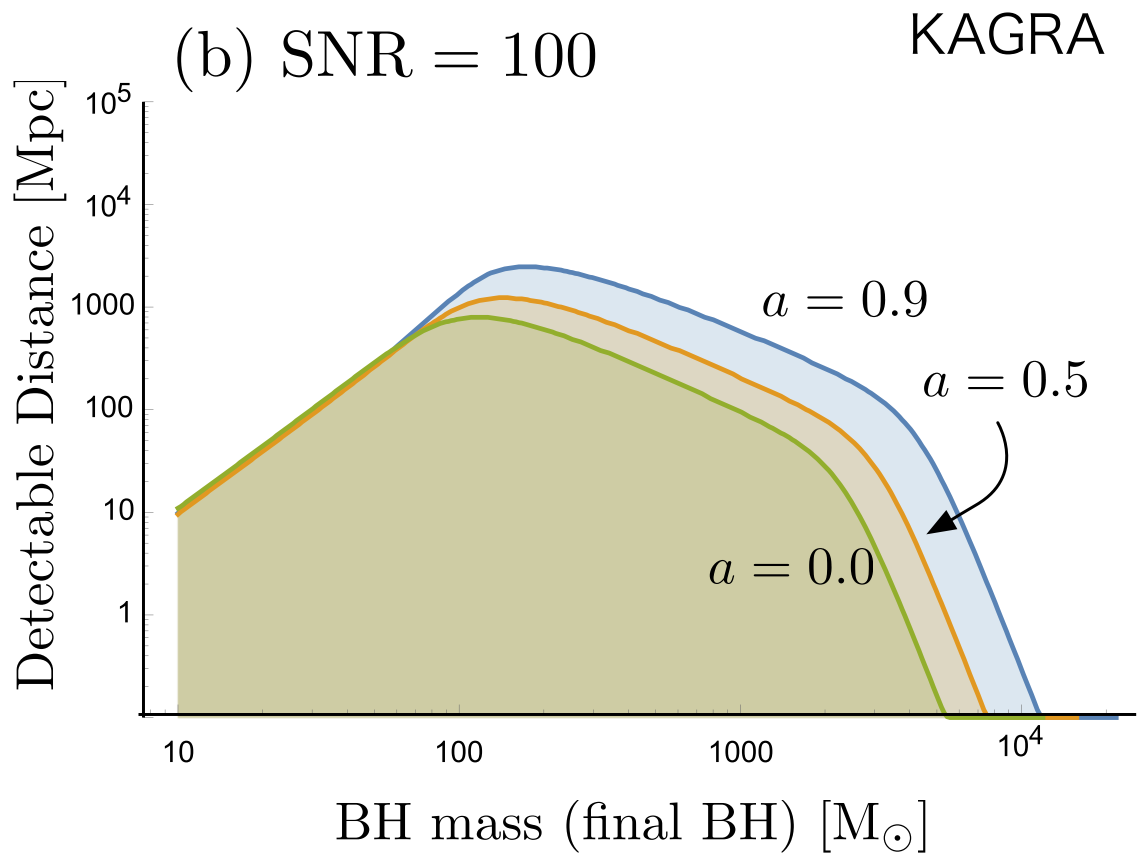
Energy emission=4% of total M, 1% at ringdown

Standard Cosmology

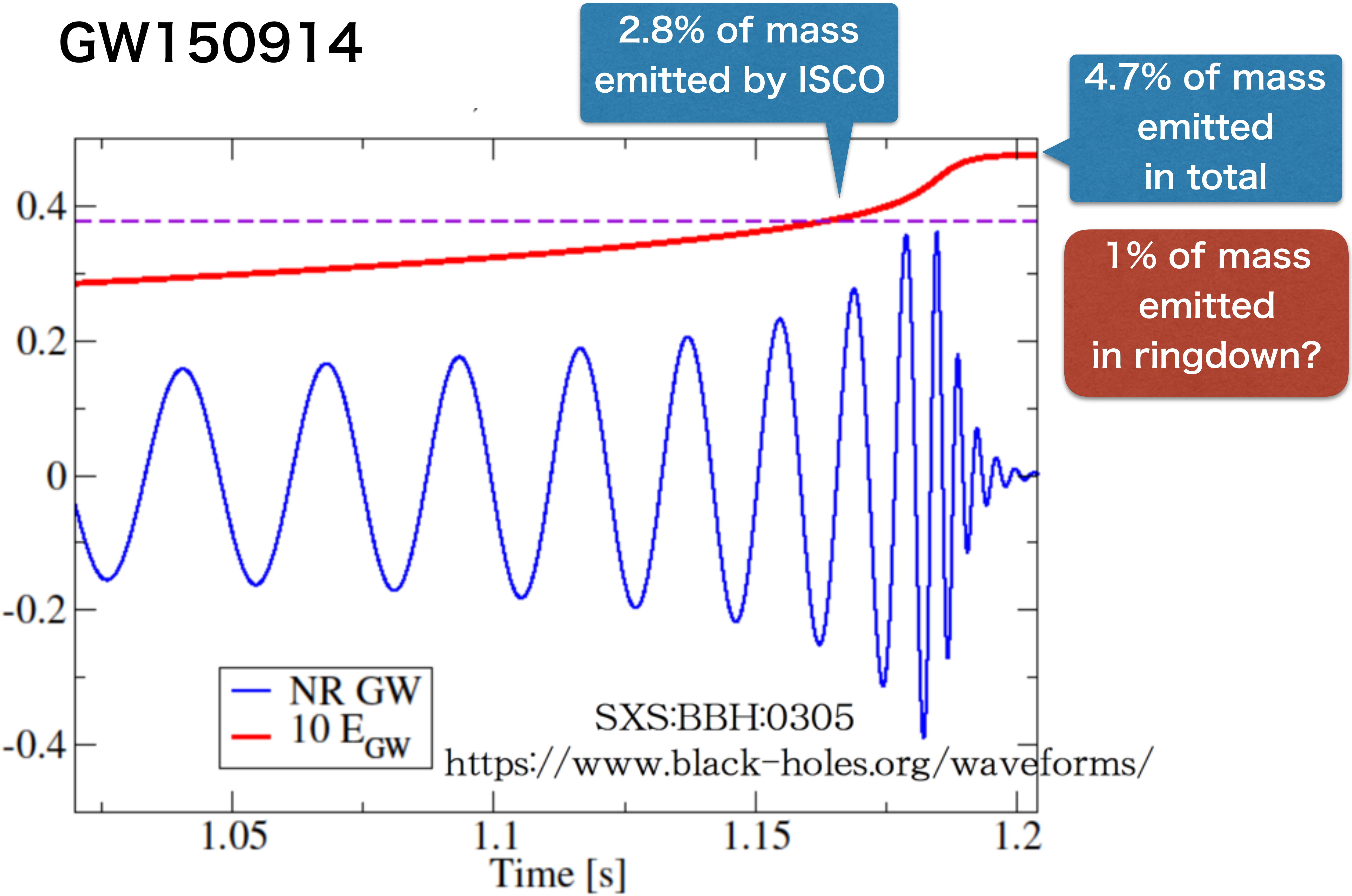
Hierarchical Growth





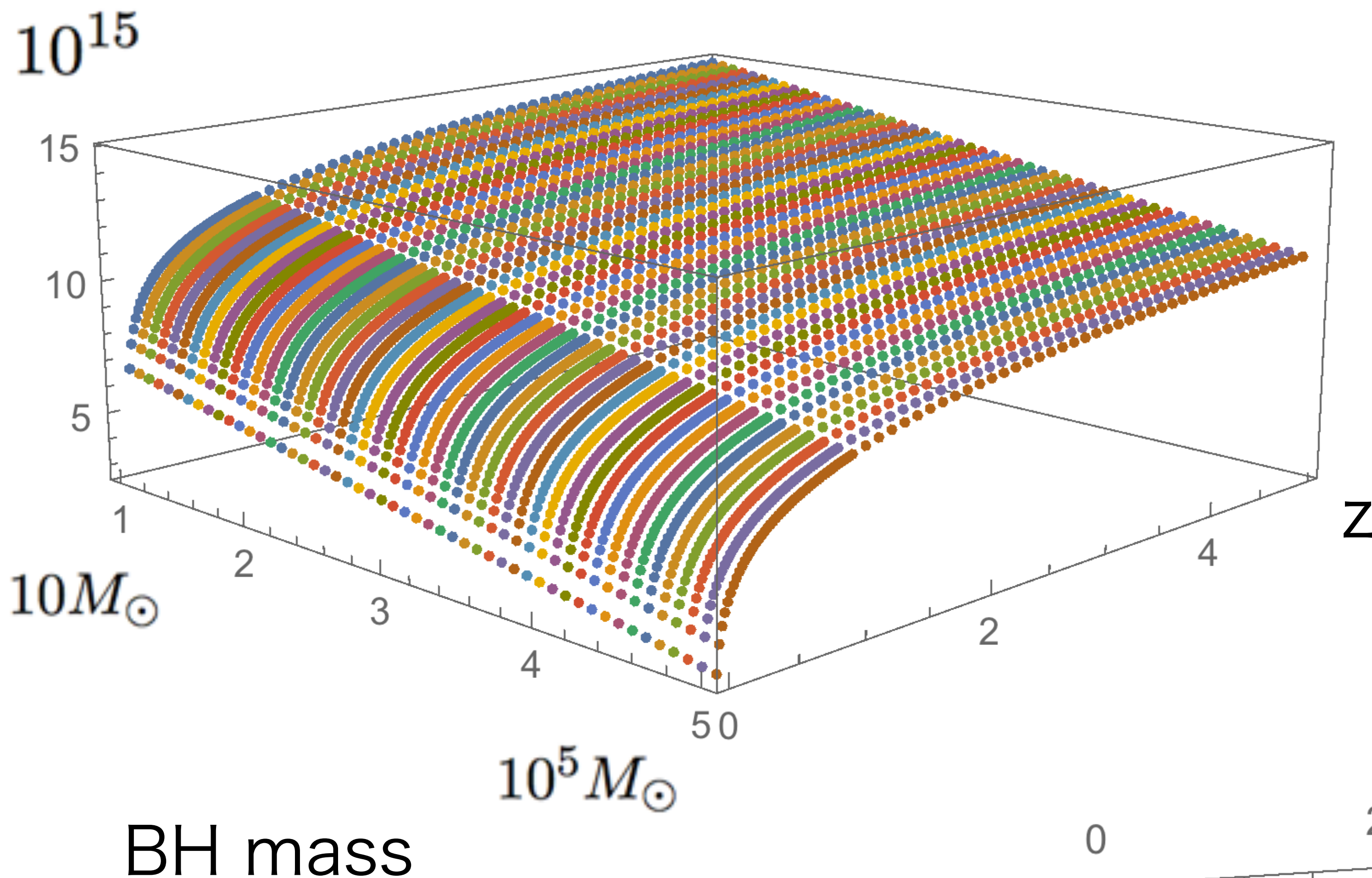


GW150914



Slide copy from Hiroyuki Nakano

How many BH mergers in the Universe?



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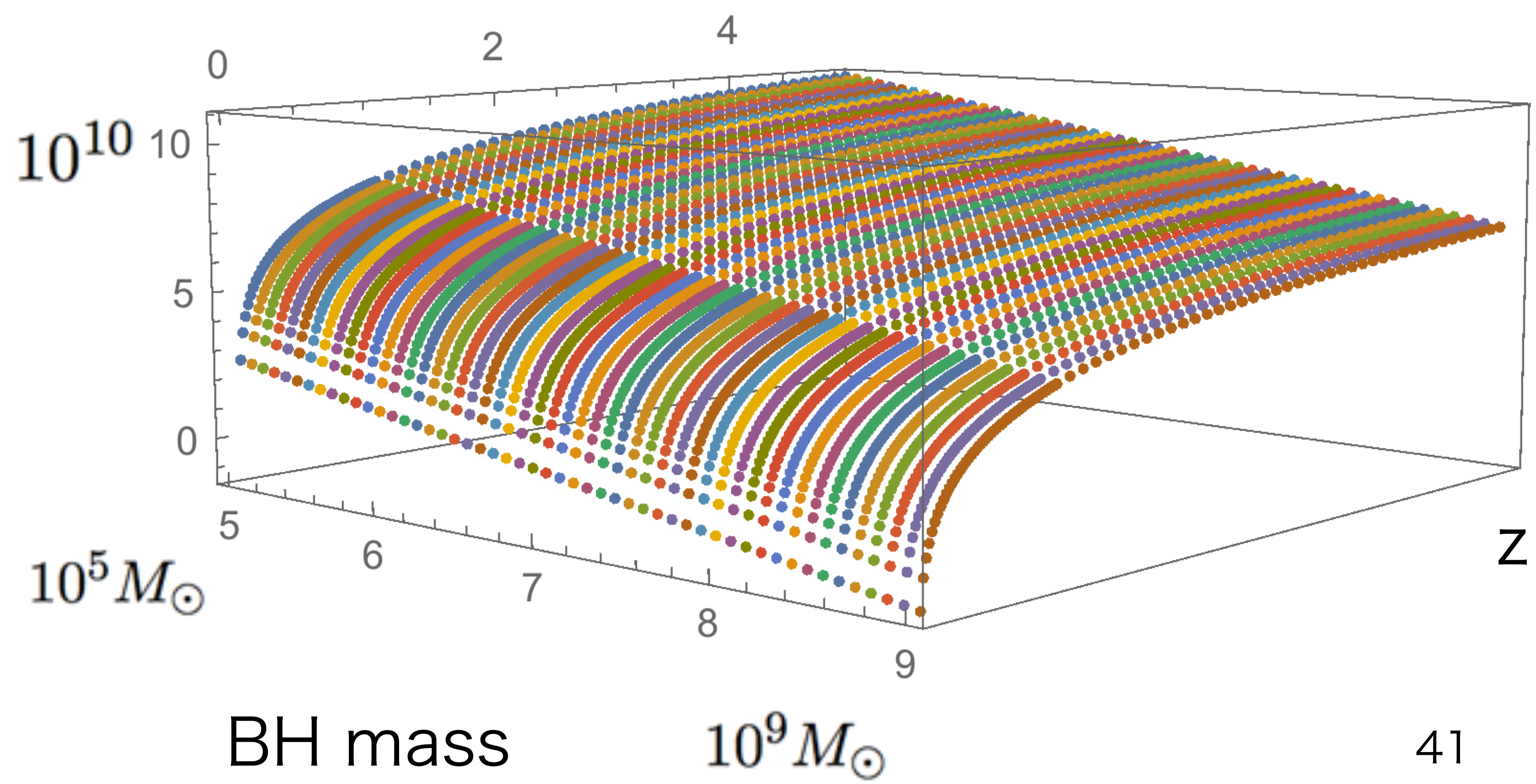
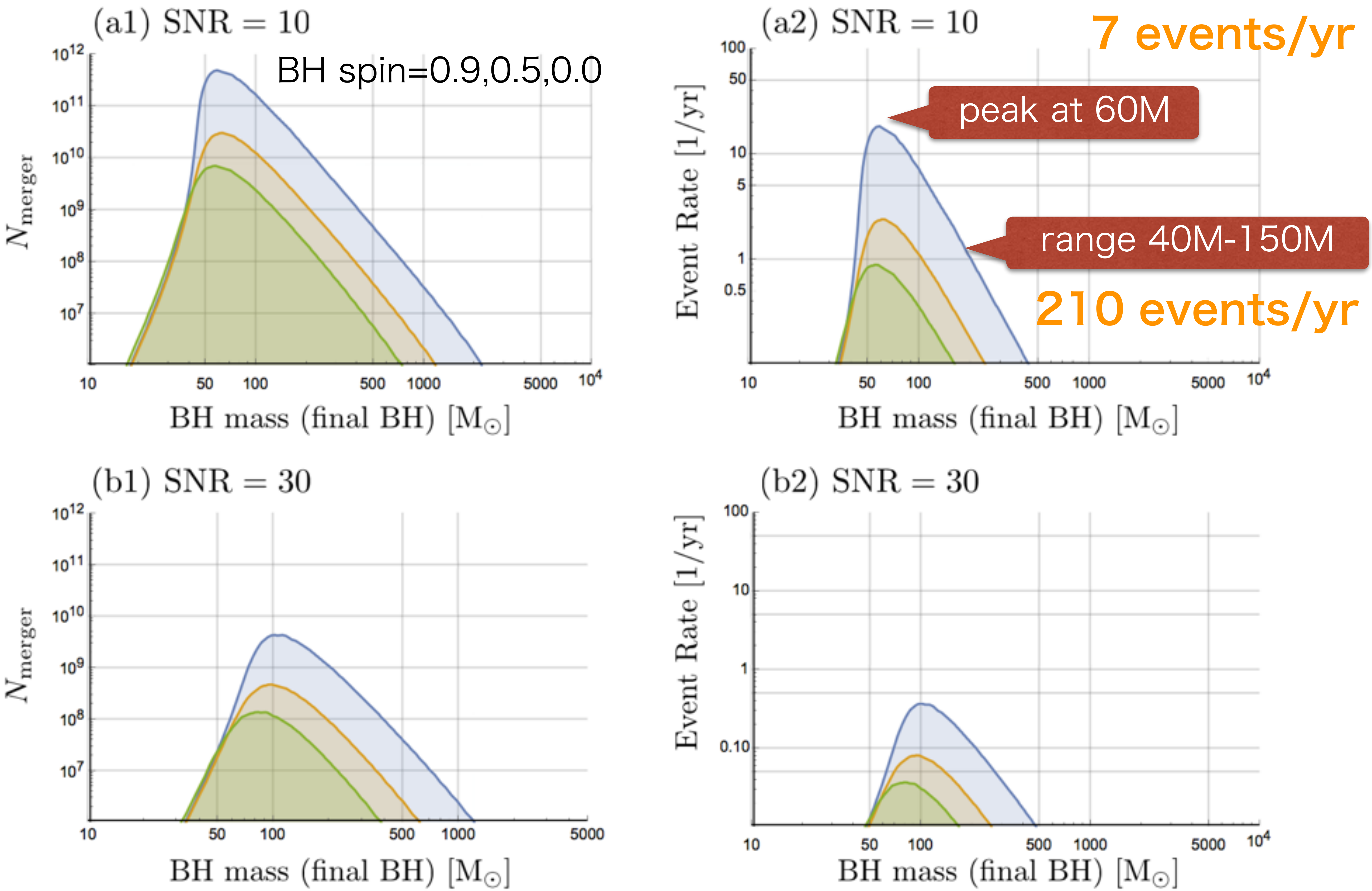
Standard Cosmology

averaging distances for all directions



Event Rates at bKAGRA



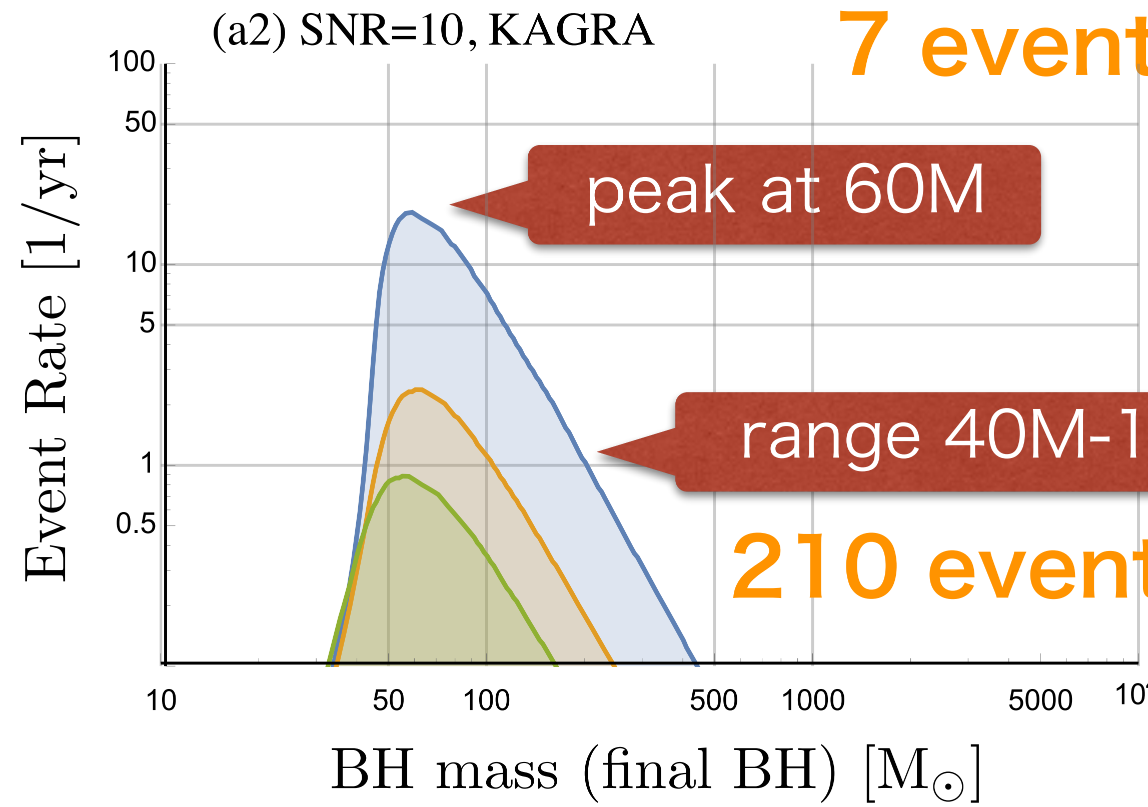
Event Rates at bKAGRA/aLIGO

LIGO group [1602.03842]

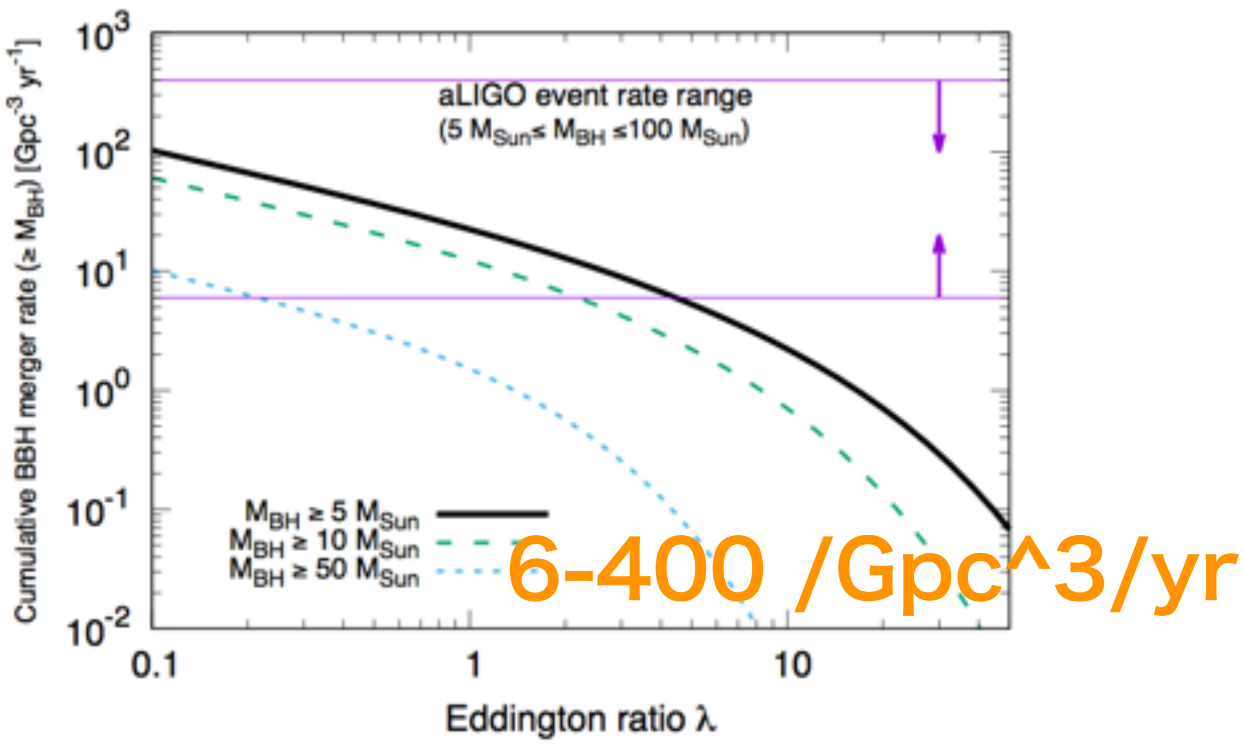
The Astrophysical Journal Letters, 833:L1 (8pp), 2016 December 10

Table 1
Rates of BBH Mergers Estimated under Various Assumptions

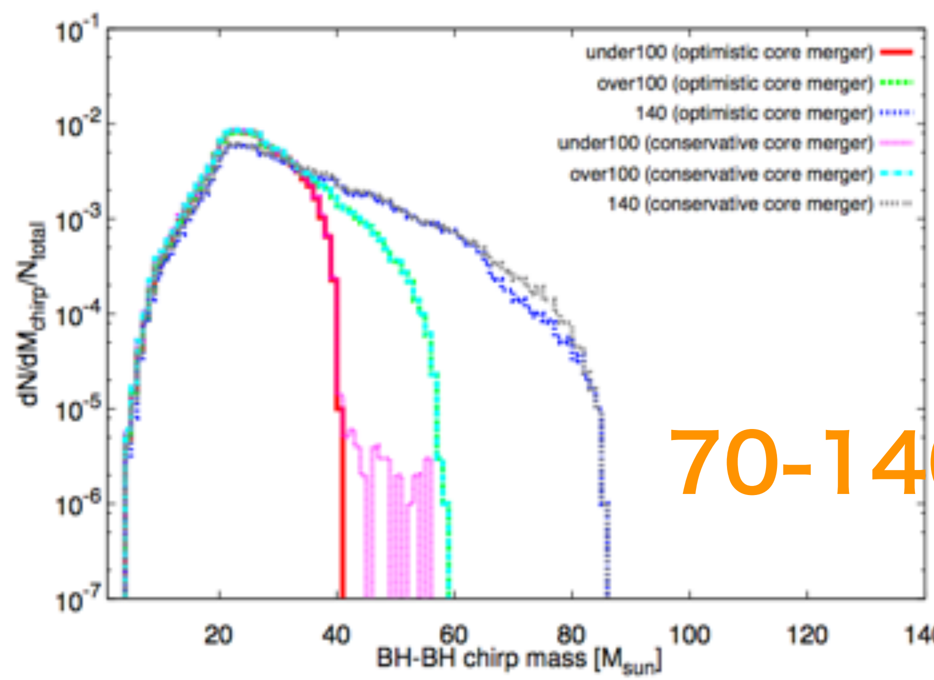
Mass Distribution	$R/(\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1})$		
	pycbc	gstlal	Combined
GW150914	16^{+38}_{-13}	17^{+39}_{-14}	17^{+39}_{-13}
LVT151012	61^{+152}_{-53}	62^{+164}_{-55}	62^{+165}_{-54}
Both	82^{+155}_{-61}	84^{+172}_{-64}	83^{+168}_{-63}
Astrophysical			
Flat in log mass	63^{+121}_{-49}	60^{+122}_{-48}	61^{+124}_{-48}
Power Law (−2.35)	200^{+390}_{-160}	200^{+410}_{-160}	200^{+400}_{-160}



Inoue+ MNRAS461(16)4329



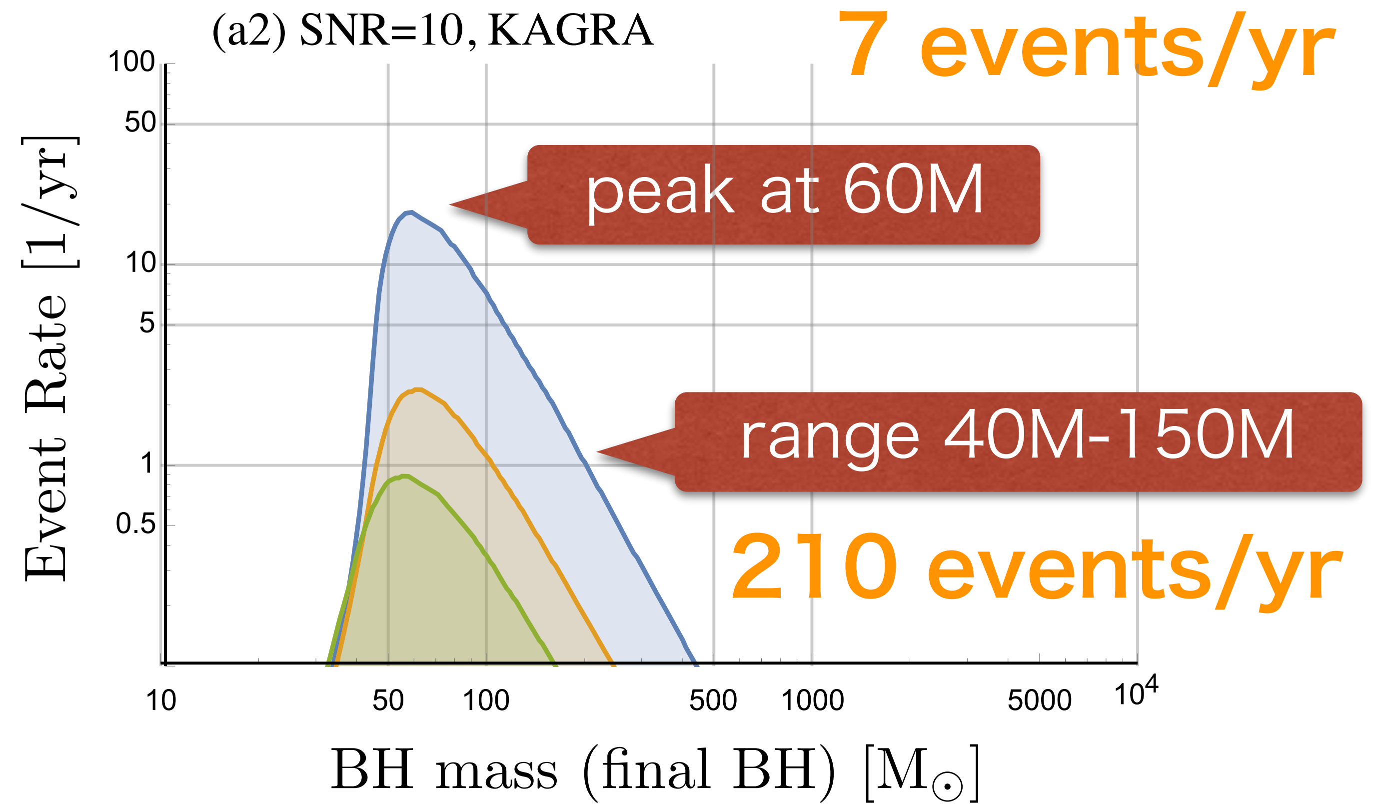
Kinugawa+ MNRAS456(15)1093



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}



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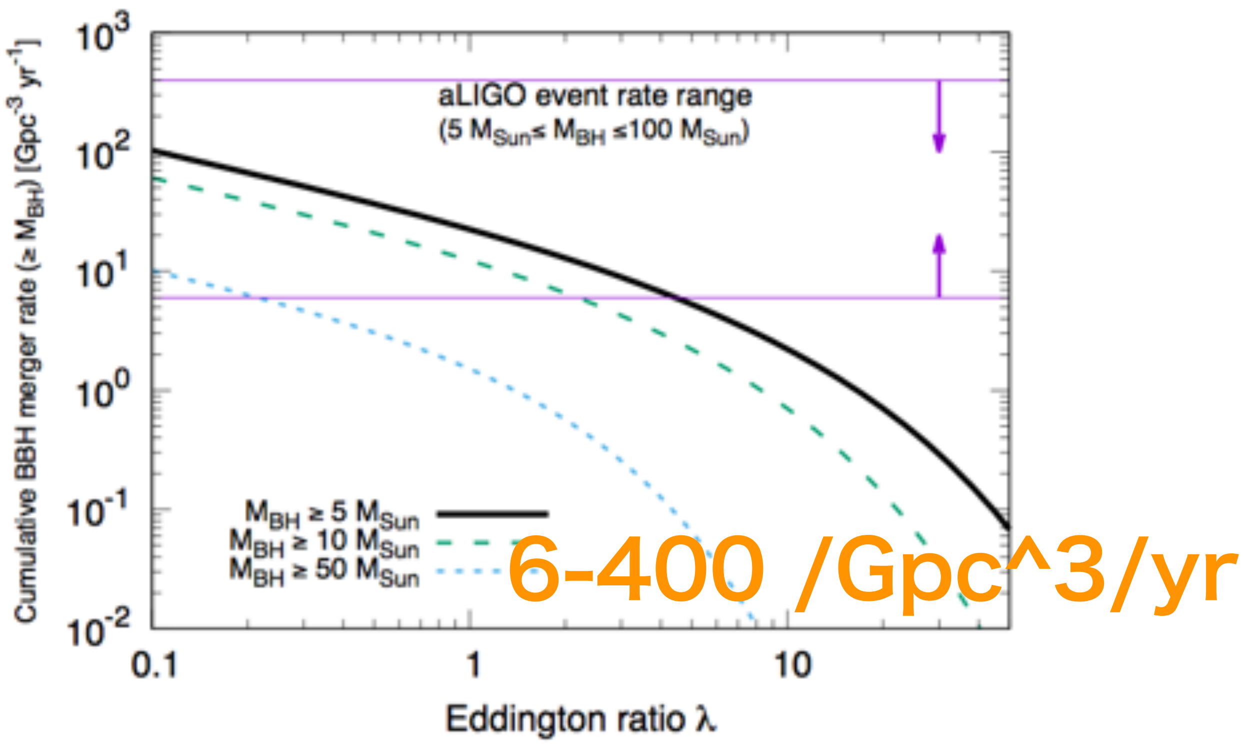
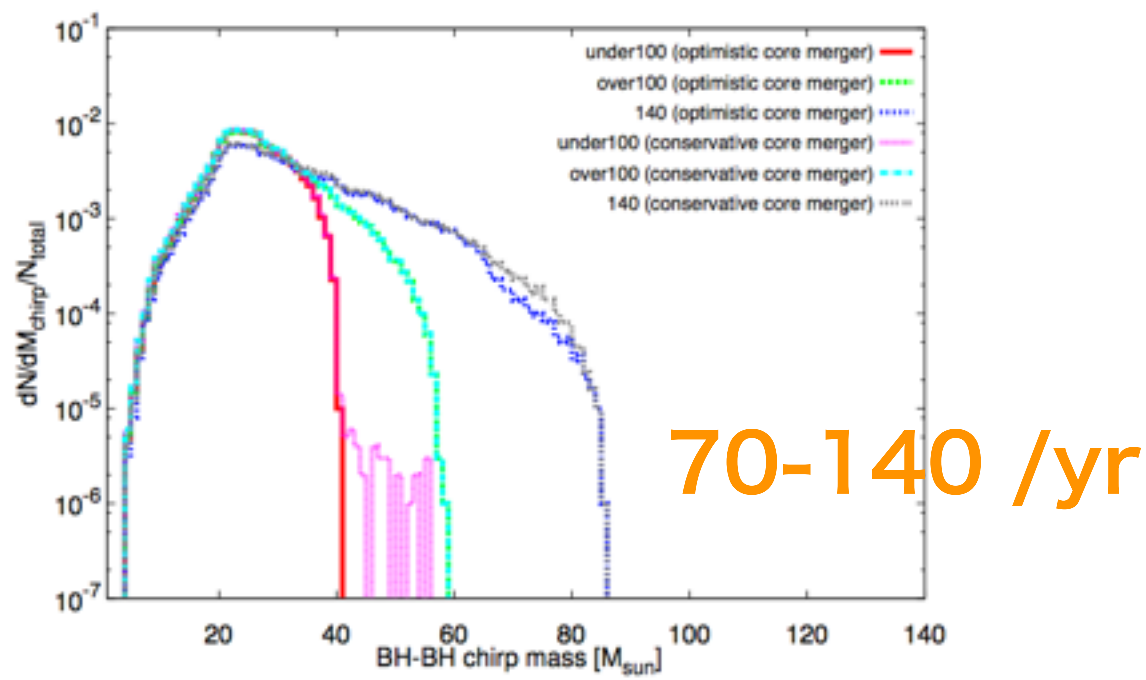


Kinugawa+ MNRAS456(15)1093



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.

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.