Gravitational Waves from Merging Intermediate-Mass Black Holes

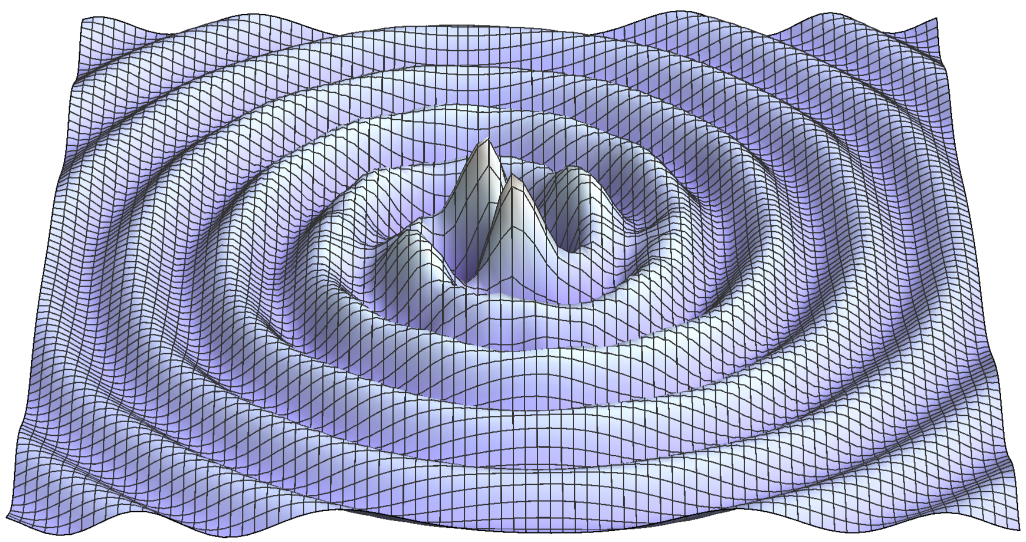
真貝寿明 (大阪工業大)
http://www.oit.ac.jp/is/~shinkai/

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

真貝・神田・戎崎, ApJ, 835 (2017) 276 [arXiv:1610.09505]

2017/3/7 東京大理 安東研セミナー

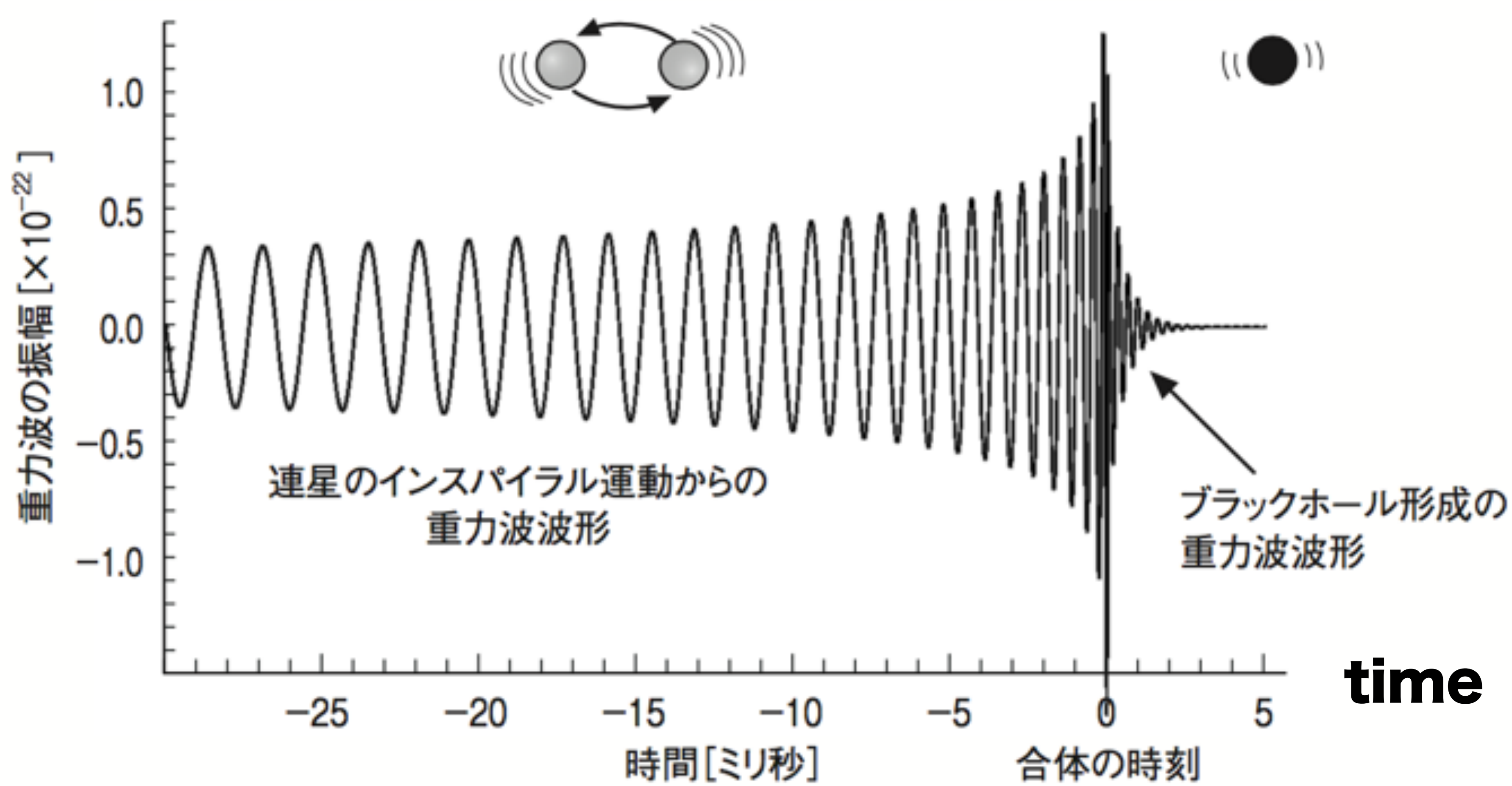
1. Gravitational Wave >> Expected Waveform



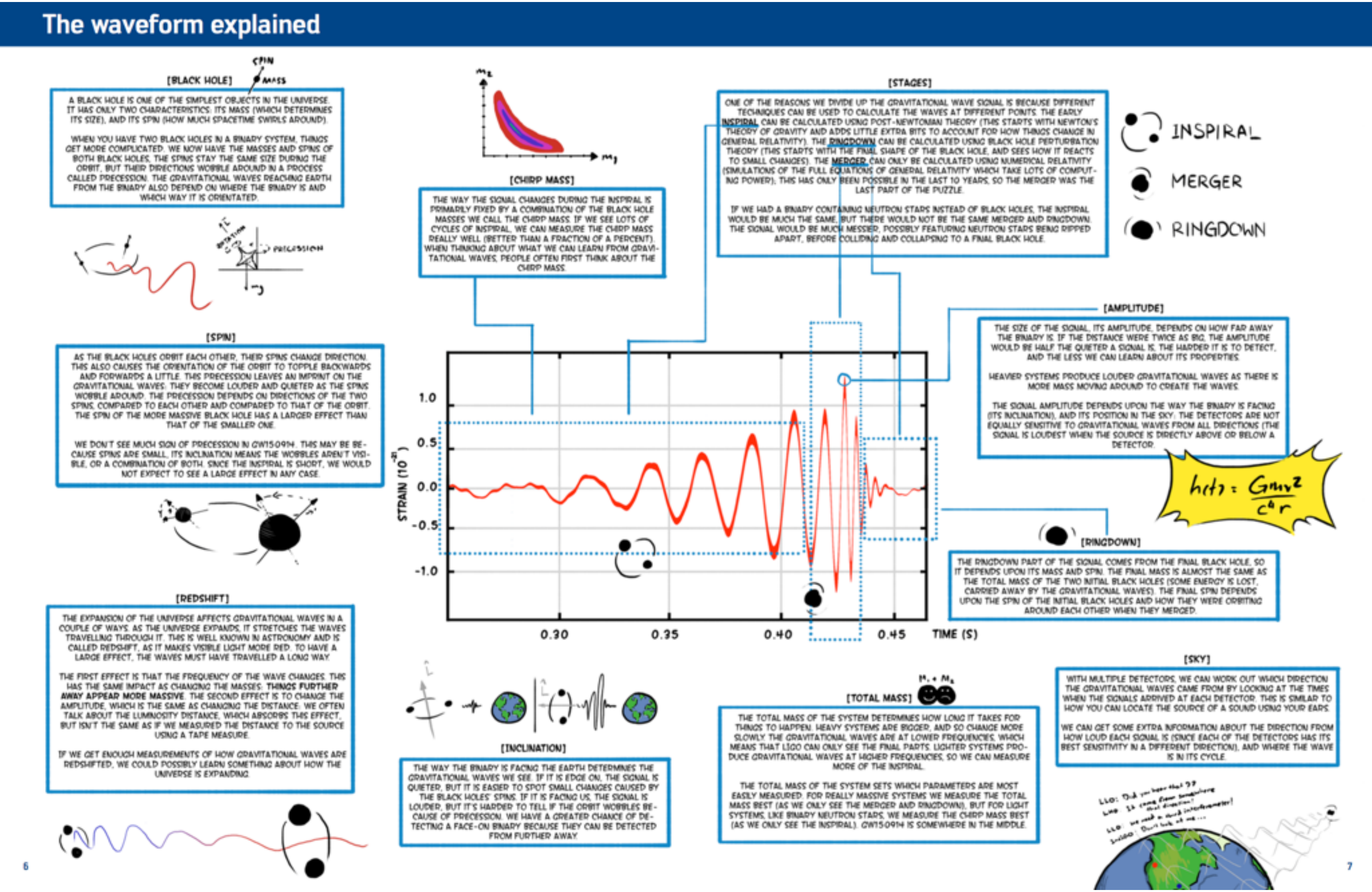
NS-NS
NS-BH
BH-BH

Inspiral **Merger** **Ringdown**

h



time



The waveform explained

[BLACK HOLE]

A BLACK HOLE IS ONE OF THE SIMPLEST OBJECTS IN THE UNIVERSE. IT HAS ONLY TWO CHARACTERISTICS: ITS MASS (WHICH DETERMINES ITS SIZE), AND ITS SPIN (HOW MUCH SPACETIME SWIRLS AROUND).

WHEN YOU HAVE TWO BLACK HOLES IN A BINARY SYSTEM, THINGS GET MORE COMPLICATED. WE NOW HAVE THE MASSES AND SPINS OF BOTH BLACK HOLES. THE SPINS STAY THE SAME SIZE DURING THE ORBIT, BUT THEIR DIRECTIONS WOBBLE AROUND IN A PROCESS CALLED PRECESSION. THE GRAVITATIONAL WAVES REACHING EARTH FROM THE BINARY ALSO DEPEND ON WHERE THE BINARY IS AND WHICH WAY IT IS ORIENTATED.

[SPIN]

AS THE BLACK HOLES ORBIT EACH OTHER, THEIR SPINS CHANGE DIRECTION. THIS ALSO CAUSES THE ORIENTATION OF THE ORBIT TO TOPPLE BACKWARDS AND FORWARDS A LITTLE. THIS PRECESSION LEAVES AN IMPRINT ON THE GRAVITATIONAL WAVES: THEY BECOME LOUDER AND QUIETER AS THE SPINS WOBBLE AROUND. THE PRECESSION DEPENDS ON DIRECTIONS OF THE TWO SPINS, COMPARED TO EACH OTHER AND COMPARED TO THAT OF THE ORBIT. THE SPIN OF THE MORE MASSIVE BLACK HOLE HAS A LARGER EFFECT THAN THAT OF THE SMALLER ONE.

WE DON'T SEE MUCH SIGN OF PRECESSION IN GW150914. THIS MAY BE BECAUSE SPINS ARE SMALL, ITS INCLINATION MEANS THE WOBBLES AREN'T VISIBLE, OR A COMBINATION OF BOTH. SINCE THE INSPIRAL IS SHORT, WE WOULD NOT EXPECT TO SEE A LARGE EFFECT IN ANY CASE.

[REDSHIFT]

THE EXPANSION OF THE UNIVERSE AFFECTS GRAVITATIONAL WAVES IN A COUPLE OF WAYS. AS THE UNIVERSE EXPANDS, IT STRETCHES THE WAVES TRAVELLING THROUGH IT. THIS IS WELL KNOWN IN ASTRONOMY AND IS CALLED REDSHIFT, AS IT MAKES VISIBLE LIGHT MORE RED. TO HAVE A LARGE EFFECT, THE WAVES MUST HAVE TRAVELLED A LONG WAY.

THE FIRST EFFECT IS THAT THE FREQUENCY OF THE WAVE CHANGES. THIS HAS THE SAME IMPACT AS CHANGING THE MASSES: **THINGS FURTHER AWAY APPEAR MORE MASSIVE**. THE SECOND EFFECT IS TO CHANGE THE AMPLITUDE, WHICH IS THE SAME AS CHANGING THE DISTANCE: WE OFTEN TALK ABOUT THE LUMINOSITY DISTANCE, WHICH ABSORBS THIS EFFECT, BUT ISN'T THE SAME AS IF WE MEASURED THE DISTANCE TO THE SOURCE USING A TAPE MEASURE.

IF WE GET ENOUGH MEASUREMENTS OF HOW GRAVITATIONAL WAVES ARE REDSHIFTED, WE COULD POSSIBLY LEARN SOMETHING ABOUT HOW THE UNIVERSE IS EXPANDING.

[CHIRP MASS]

THE WAY THE SIGNAL CHANGES DURING THE INSPIRAL IS PRIMARILY FIXED BY A COMBINATION OF THE BLACK HOLE MASSES WE CALL THE CHIRP MASS. IF WE SEE LOTS OF CYCLES OF INSPIRAL, WE CAN MEASURE THE CHIRP MASS REALLY WELL (BETTER THAN A FRACTION OF A PERCENT). WHEN THINKING ABOUT WHAT WE CAN LEARN FROM GRAVITATIONAL WAVES, PEOPLE OFTEN FIRST THINK ABOUT THE CHIRP MASS.

[STAGES]

ONE OF THE REASONS WE DIVIDE UP THE GRAVITATIONAL WAVE SIGNAL IS BECAUSE DIFFERENT TECHNIQUES CAN BE USED TO CALCULATE THE WAVES AT DIFFERENT POINTS. THE EARLY **INSPIRAL** CAN BE CALCULATED USING POST-NEWTONIAN THEORY (THIS STARTS WITH NEWTON'S THEORY OF GRAVITY AND ADDS LITTLE EXTRA BITS TO ACCOUNT FOR HOW THINGS CHANGE IN GENERAL RELATIVITY). THE **RINGDOWN** CAN BE CALCULATED USING BLACK HOLE PERTURBATION THEORY (THIS STARTS WITH THE FINAL SHAPE OF THE BLACK HOLE, AND SEES HOW IT REACTS TO SMALL CHANGES). THE **MERGER** CAN ONLY BE CALCULATED USING NUMERICAL RELATIVITY (SIMULATIONS OF THE FULL EQUATIONS OF GENERAL RELATIVITY WHICH TAKE LOTS OF COMPUTING POWER); THIS HAS ONLY BEEN POSSIBLE IN THE LAST 10 YEARS, SO THE MERGER WAS THE LAST PART OF THE PUZZLE.

IF WE HAD A BINARY CONTAINING NEUTRON STARS INSTEAD OF BLACK HOLES, THE INSPIRAL WOULD BE MUCH THE SAME, BUT THERE WOULD NOT BE THE SAME MERGER AND RINGDOWN. THE SIGNAL WOULD BE MUCH MESSIER, POSSIBLY FEATURING NEUTRON STARS BEING RIPPED APART, BEFORE COLLIDING AND COLLAPSING TO A FINAL BLACK HOLE.

INSPIRAL

MERGER

RINGDOWN

[AMPLITUDE]

THE SIZE OF THE SIGNAL, ITS AMPLITUDE, DEPENDS ON HOW FAR AWAY THE BINARY IS. IF THE DISTANCE WERE TWICE AS BIG, THE AMPLITUDE WOULD BE HALF. THE QUIETER A SIGNAL IS, THE HARDER IT IS TO DETECT, AND THE LESS WE CAN LEARN ABOUT ITS PROPERTIES.

HEAVIER SYSTEMS PRODUCE LOUDER GRAVITATIONAL WAVES AS THERE IS MORE MASS MOVING AROUND TO CREATE THE WAVES.

THE SIGNAL AMPLITUDE DEPENDS UPON THE WAY THE BINARY IS FACING (ITS INCLINATION), AND ITS POSITION IN THE SKY: THE DETECTORS ARE NOT EQUALLY SENSITIVE TO GRAVITATIONAL WAVES FROM ALL DIRECTIONS (THE SIGNAL IS LOUDEST WHEN THE SOURCE IS DIRECTLY ABOVE OR BELOW A DETECTOR.

[RINGDOWN]

THE RINGDOWN PART OF THE SIGNAL COMES FROM THE FINAL BLACK HOLE, SO IT DEPENDS UPON ITS MASS AND SPIN. THE FINAL MASS IS ALMOST THE SAME AS THE TOTAL MASS OF THE TWO INITIAL BLACK HOLES (SOME ENERGY IS LOST, CARRIED AWAY BY THE GRAVITATIONAL WAVES). THE FINAL SPIN DEPENDS UPON THE SPIN OF THE INITIAL BLACK HOLES AND HOW THEY WERE ORBITING AROUND EACH OTHER WHEN THEY MERGED.

[INCLINATION]

THE WAY THE BINARY IS FACING THE EARTH DETERMINES THE GRAVITATIONAL WAVES WE SEE. IF IT IS EDGE ON, THE SIGNAL IS QUIETER, BUT IT IS EASIER TO SPOT SMALL CHANGES CAUSED BY THE BLACK HOLES' SPINS. IF IT IS FACING US, THE SIGNAL IS LOUDER, BUT IT'S HARDER TO TELL IF THE ORBIT WOBBLES BECAUSE OF PRECESSION. WE HAVE A GREATER CHANCE OF DETECTING A FACE-ON BINARY BECAUSE THEY CAN BE DETECTED FROM FURTHER AWAY.

[TOTAL MASS] $M_1 + M_2$

THE TOTAL MASS OF THE SYSTEM DETERMINES HOW LONG IT TAKES FOR THINGS TO HAPPEN. HEAVY SYSTEMS ARE BIGGER, AND SO CHANGE MORE SLOWLY. THE GRAVITATIONAL WAVES ARE AT LOWER FREQUENCIES, WHICH MEANS THAT LIGO CAN ONLY SEE THE FINAL PARTS. LIGHTER SYSTEMS PRODUCE GRAVITATIONAL WAVES AT HIGHER FREQUENCIES, SO WE CAN MEASURE MORE OF THE INSPIRAL.

THE TOTAL MASS OF THE SYSTEM SETS WHICH PARAMETERS ARE MOST EASILY MEASURED. FOR REALLY MASSIVE SYSTEMS WE MEASURE THE TOTAL MASS BEST (AS WE ONLY SEE THE MERGER AND RINGDOWN), BUT FOR LIGHT SYSTEMS, LIKE BINARY NEUTRON STARS, WE MEASURE THE CHIRP MASS BEST (AS WE ONLY SEE THE INSPIRAL). GW150914 IS SOMEWHERE IN THE MIDDLE.

[SKY]

WITH MULTIPLE DETECTORS, WE CAN WORK OUT WHICH DIRECTION THE GRAVITATIONAL WAVES CAME FROM BY LOOKING AT THE TIMES WHEN THE SIGNALS ARRIVED AT EACH DETECTOR. THIS IS SIMILAR TO HOW YOU CAN LOCATE THE SOURCE OF A SOUND USING YOUR EARS.

WE CAN GET SOME EXTRA INFORMATION ABOUT THE DIRECTION FROM HOW LOUD EACH SIGNAL IS (SINCE EACH OF THE DETECTORS HAS ITS BEST SENSITIVITY IN A DIFFERENT DIRECTION), AND WHERE THE WAVE IS IN ITS CYCLE.

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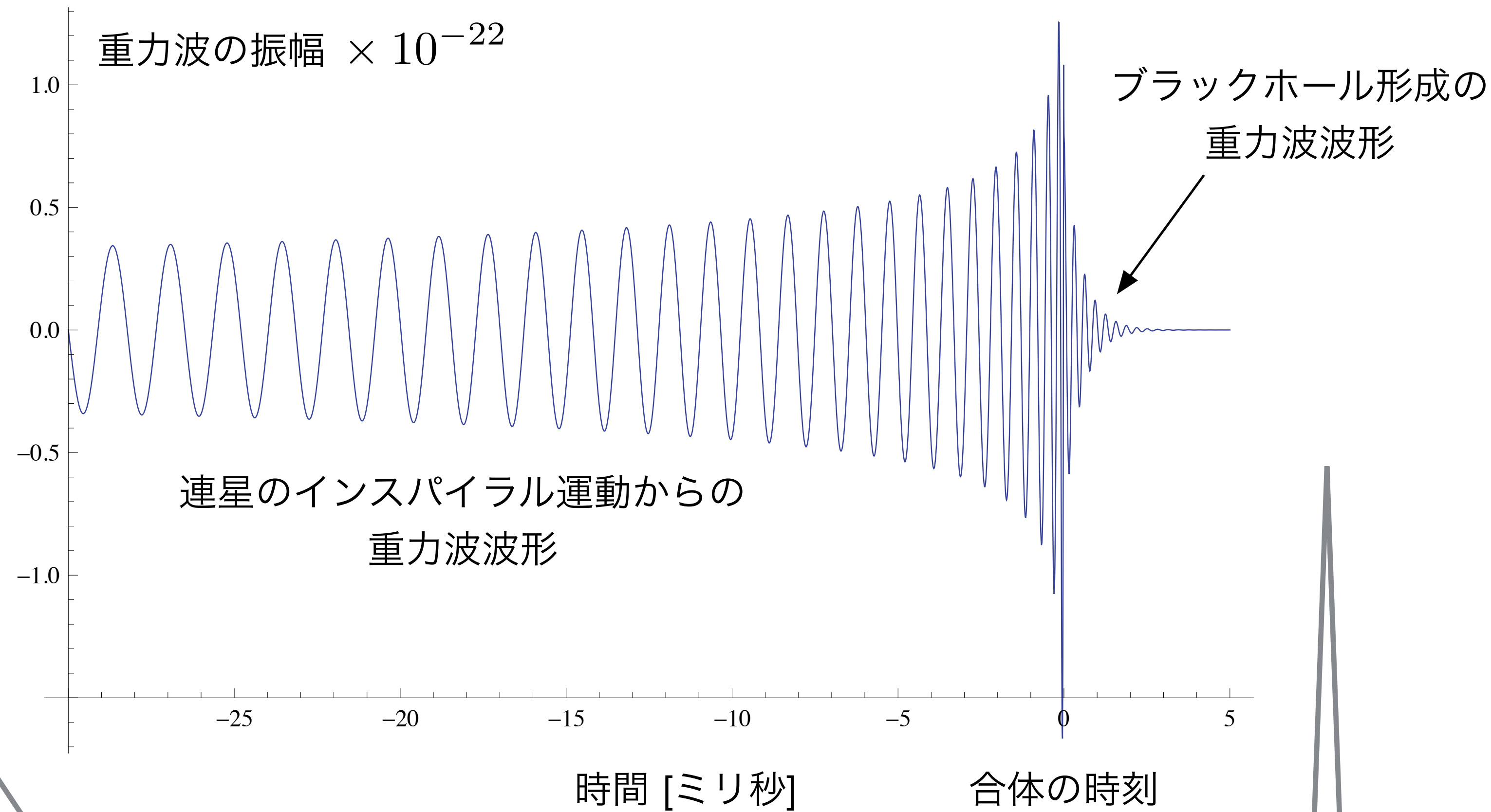
http://www.ligo.org/magazine/LIGO-magazine-issue-8.pdf

1. Gravitational Wave >> Expected Amplitude



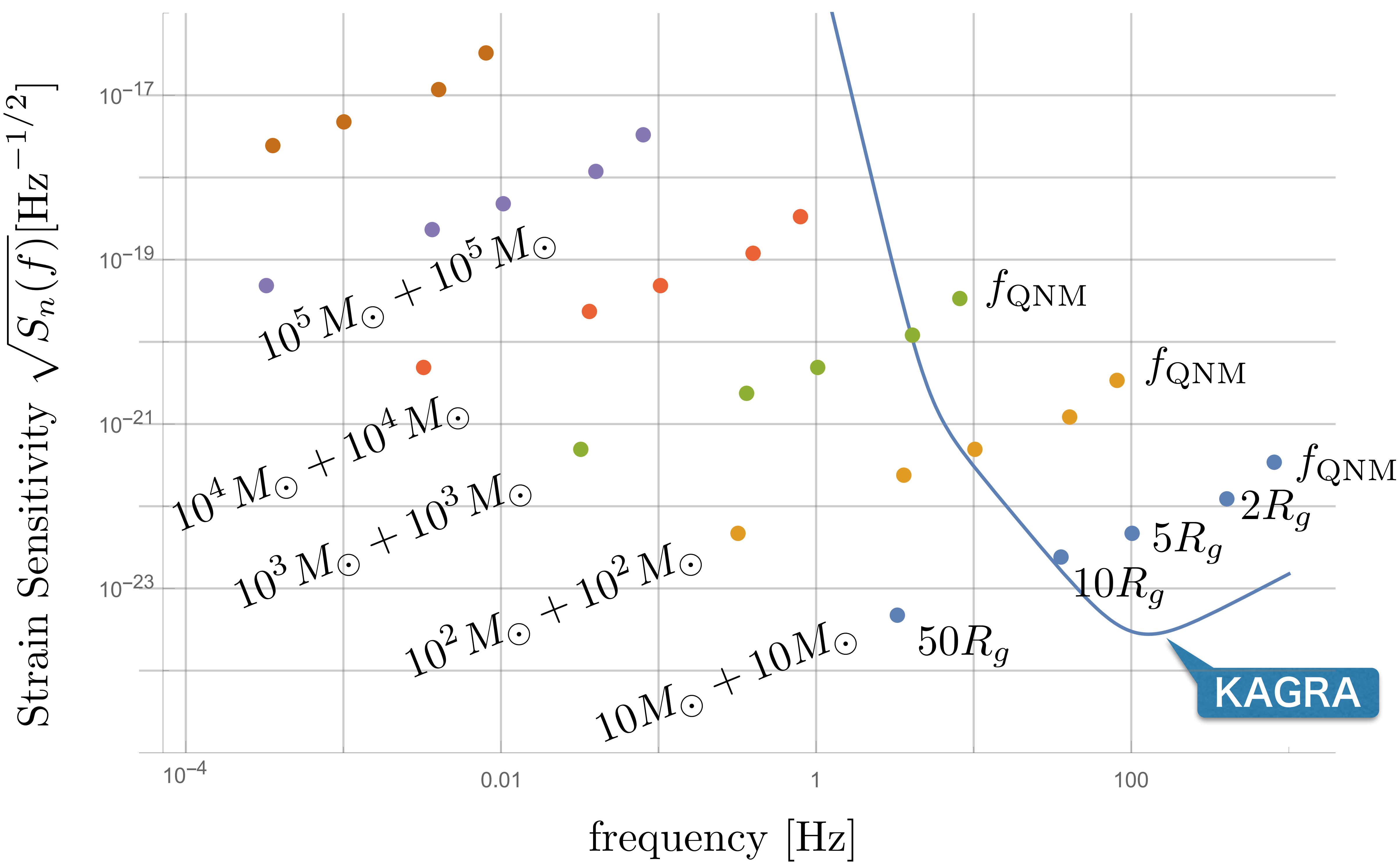
$$f_{\rm insp} = \frac{1}{\pi}\sqrt{\frac{GM_T}{a^3}}$$
$$\approx 11.4\left(\frac{a}{R_{\rm grav}}\right)^{-3/2}\left(\frac{2\times10^3\ M_\odot}{M_T}\right)\ \text{Hz},$$

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

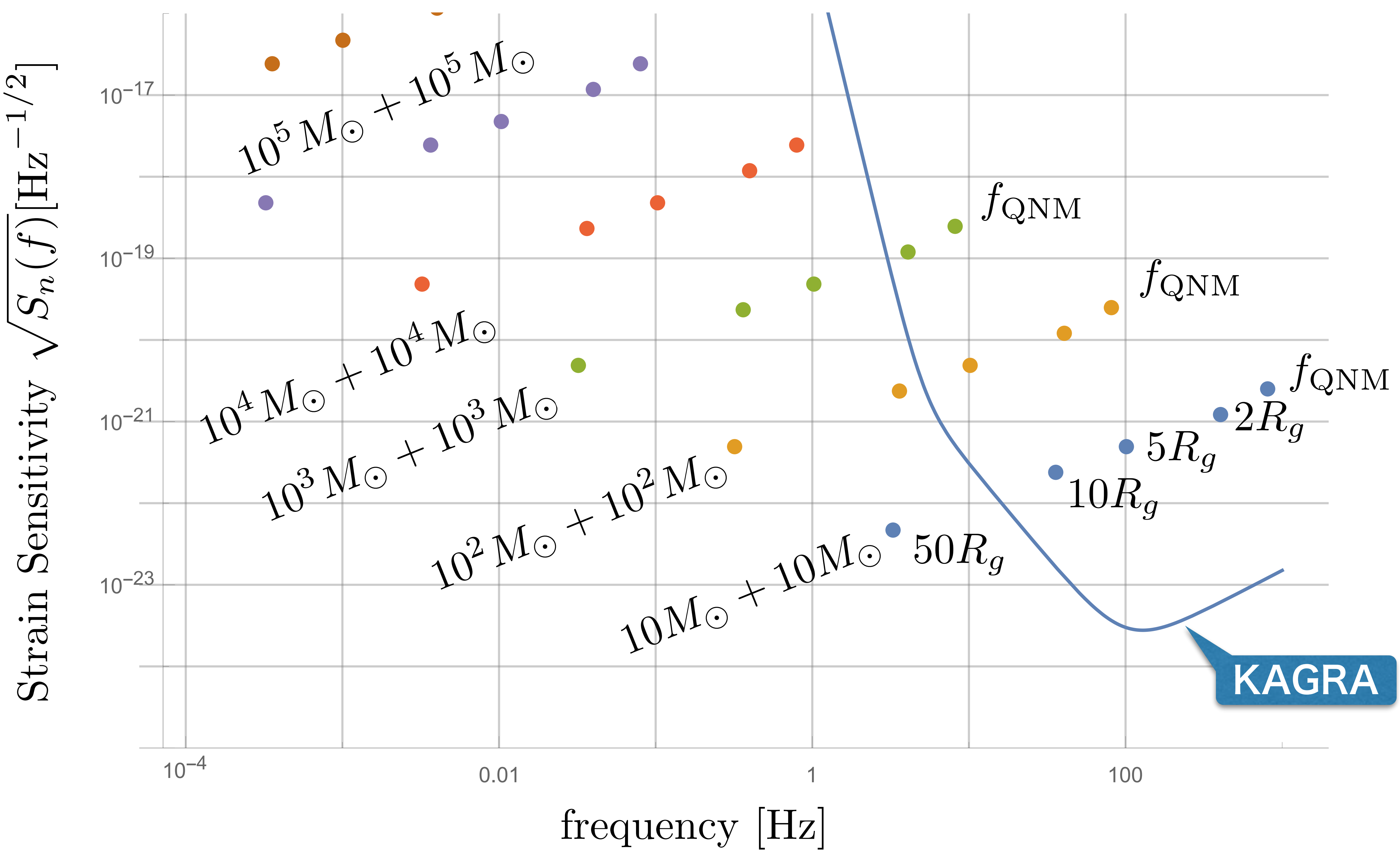
$$f_{\rm QNM} \approx \frac{lc^3}{\sqrt{27}GM_T} \sim 39.1\left(\frac{2\times10^3\ M_\odot}{M_T}\right)\ \text{Hz},$$

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

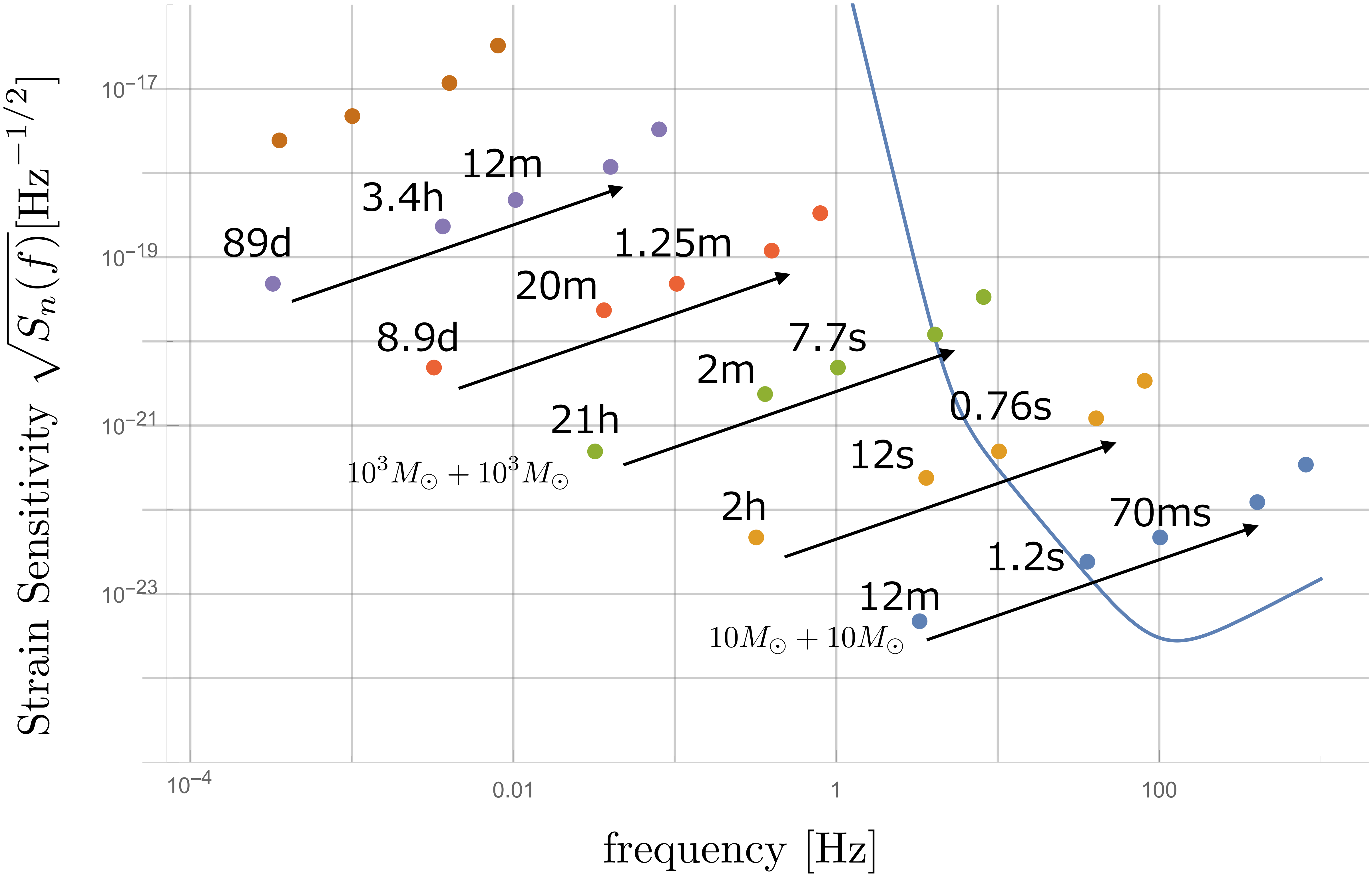
Typical frequency of BH-BH binary merger @ 1000Mpc



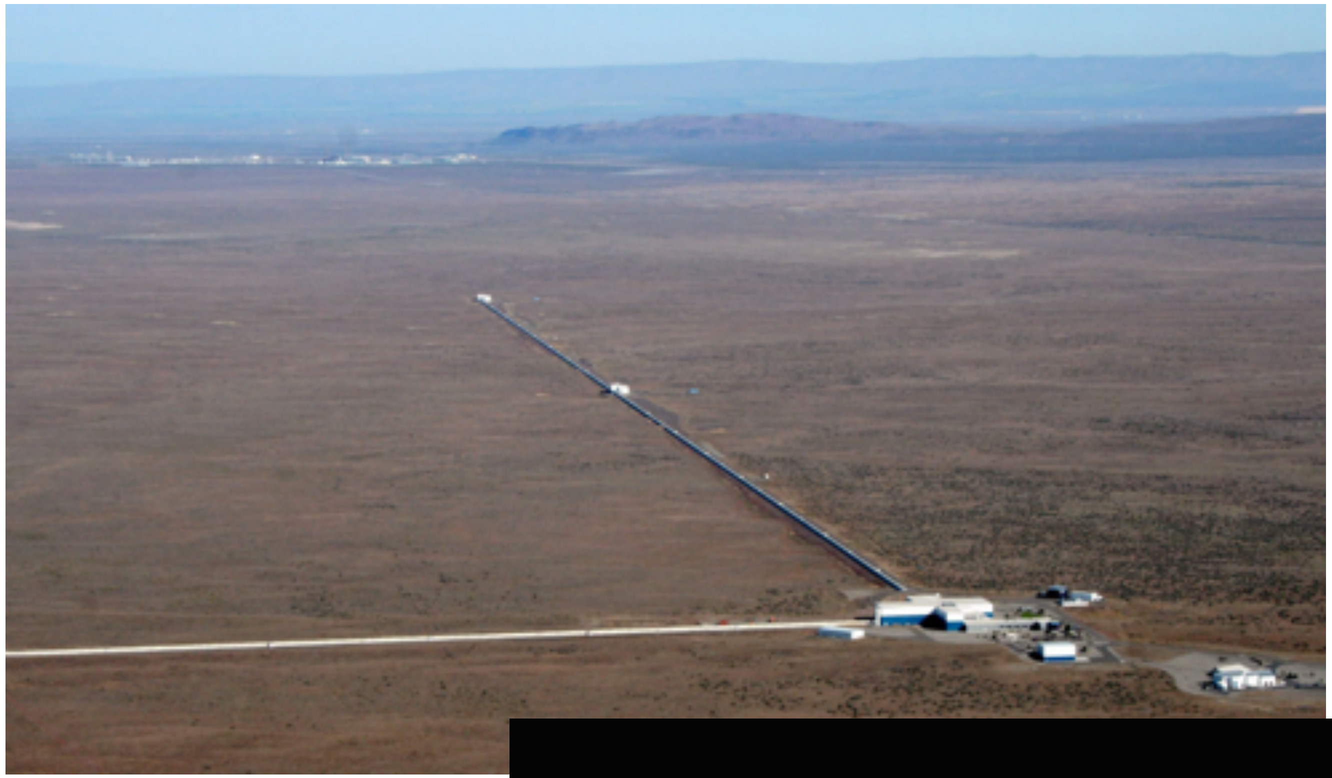
Typical frequency of BH-BH binary merger @ 100Mpc



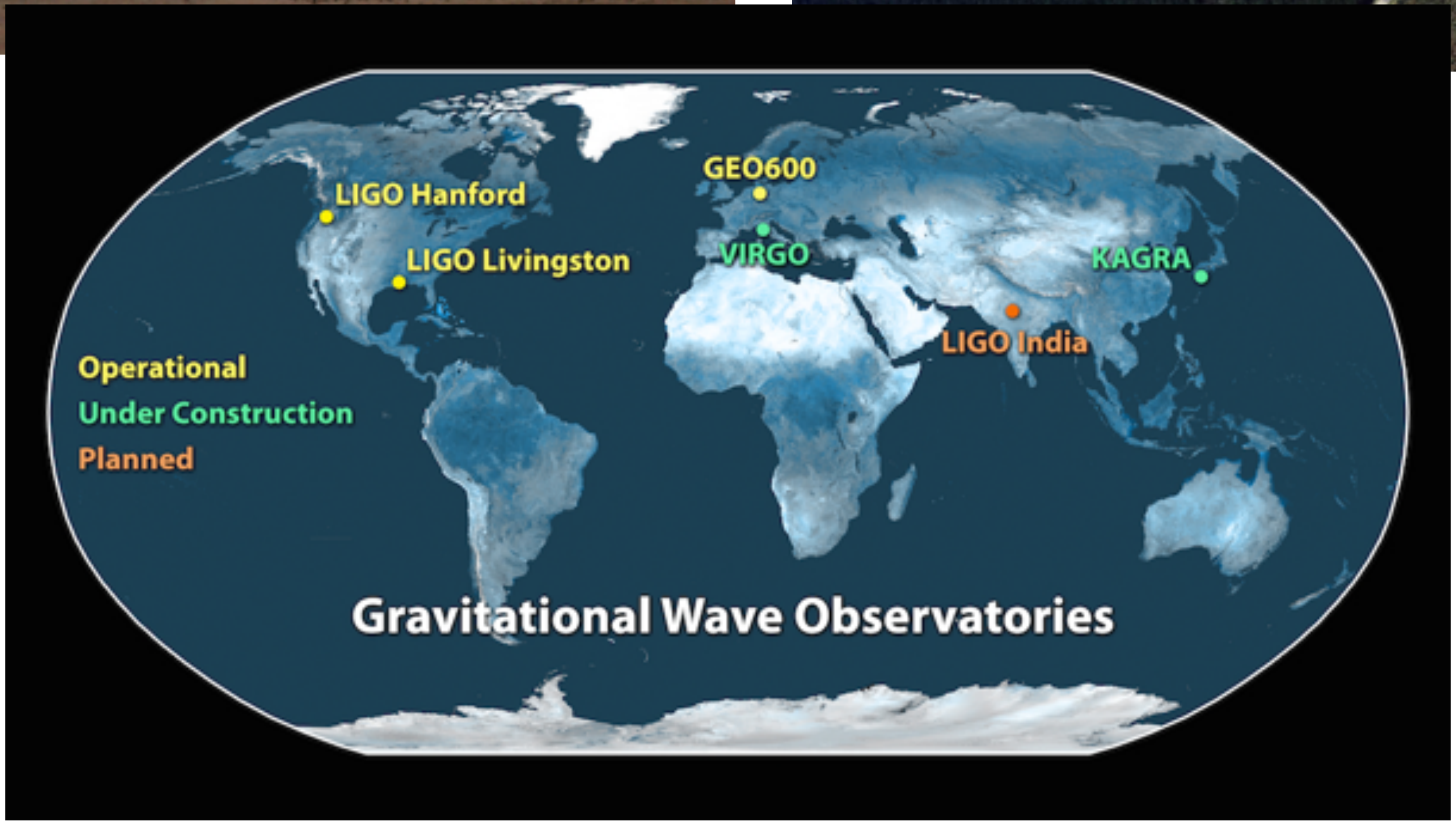
Typical merger duration of BH-BH binary merger @ 1000Mpc



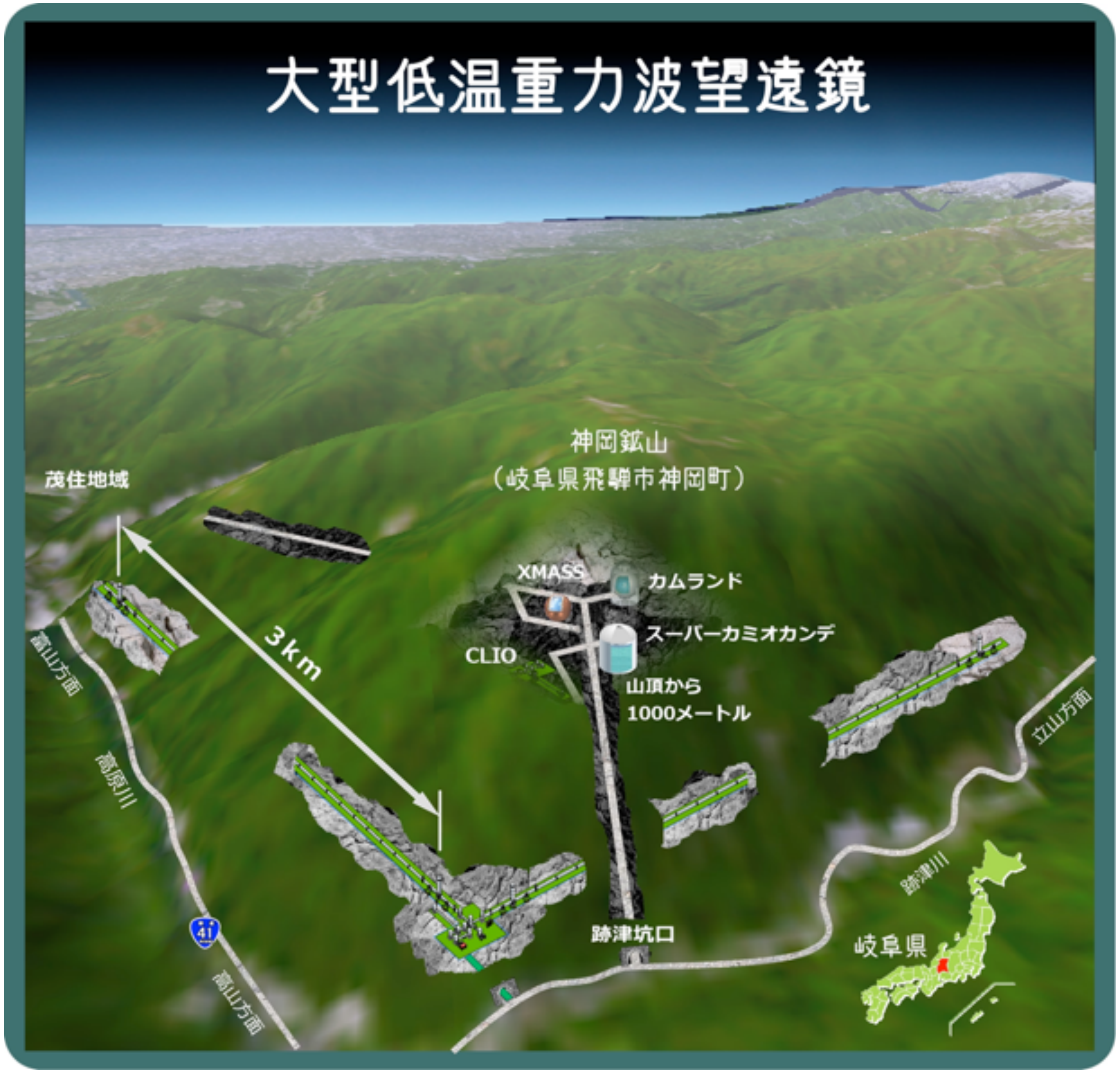
LIGO : Laser Interferometer Gravitational-Wave Observatory



4km Michelson



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

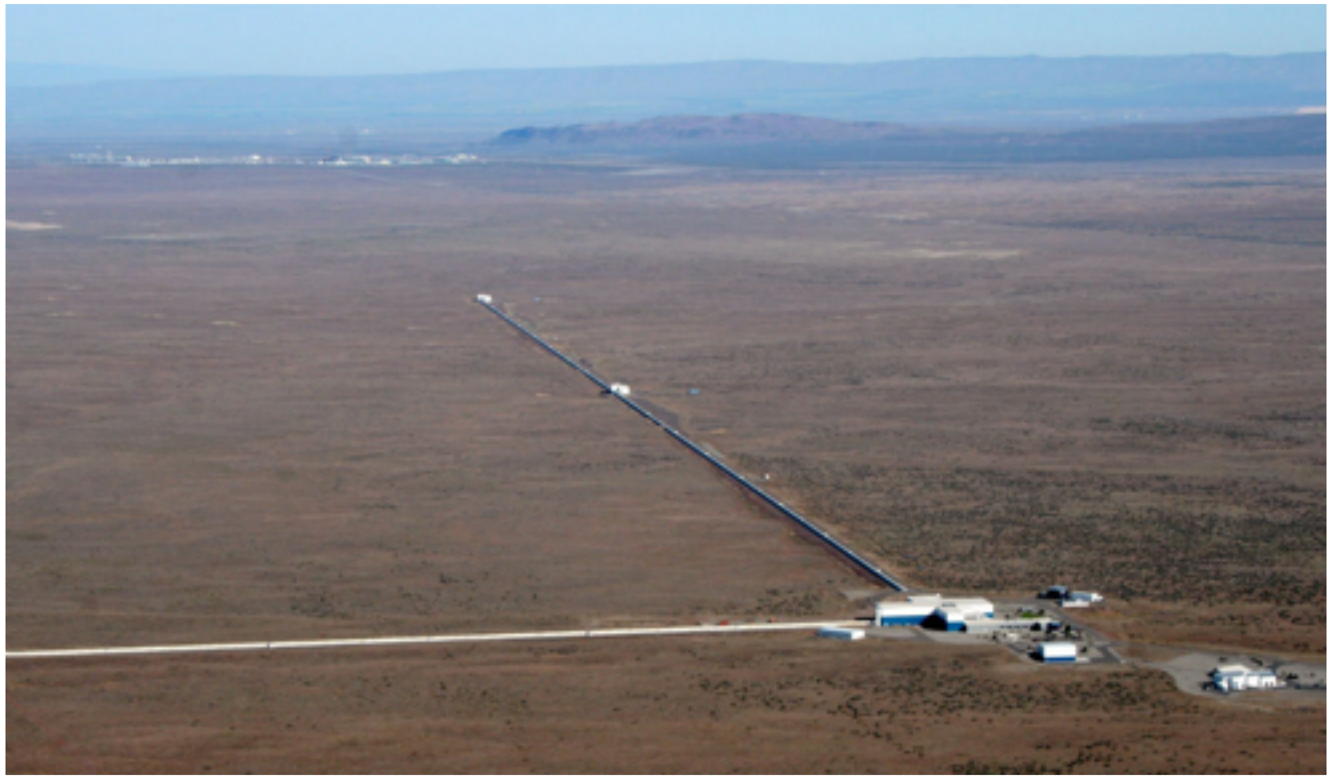
Sapphira mirrors

2016/3/25-31, 4/11-25
initial test run, *iKAGRA*

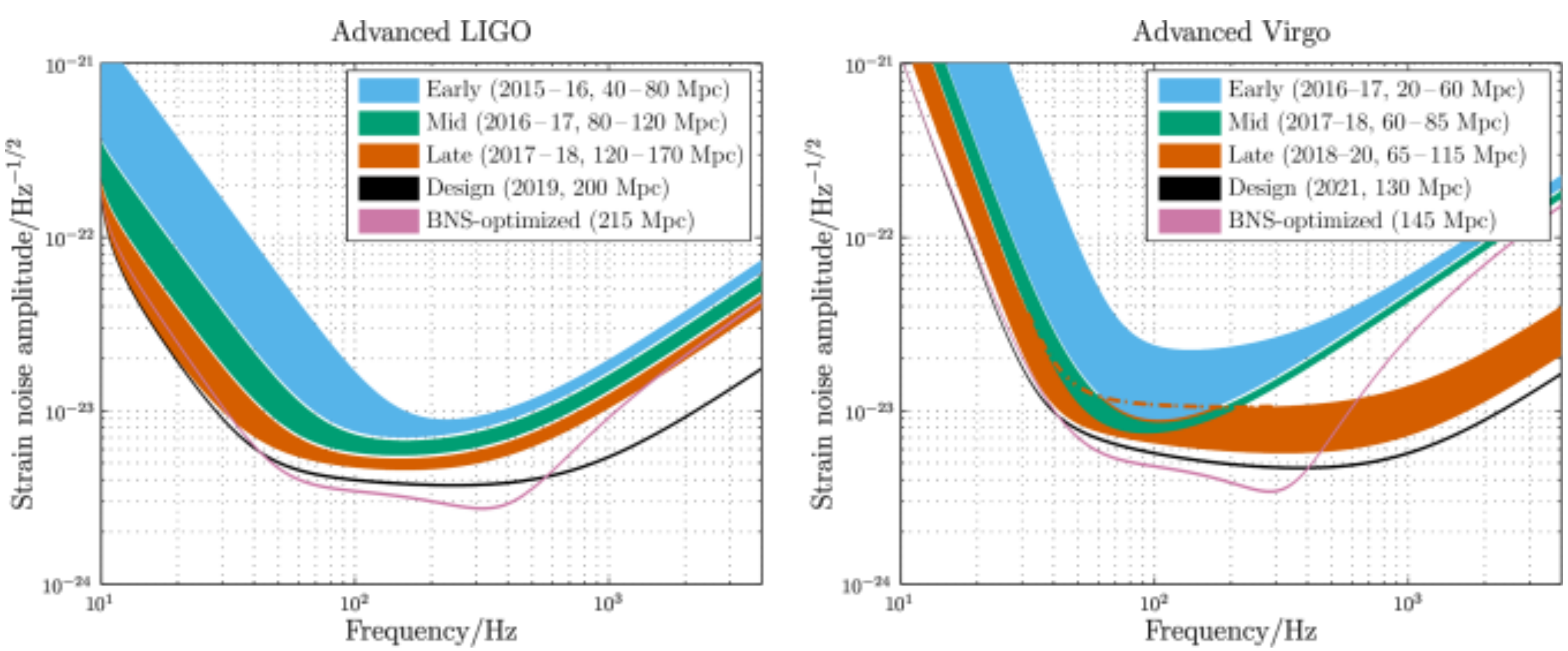
神楽（かぐら）

1. Gravitational Wave >> 2015 Detections

LIGO : Laser Interferometer Gravitational-Wave Observatory



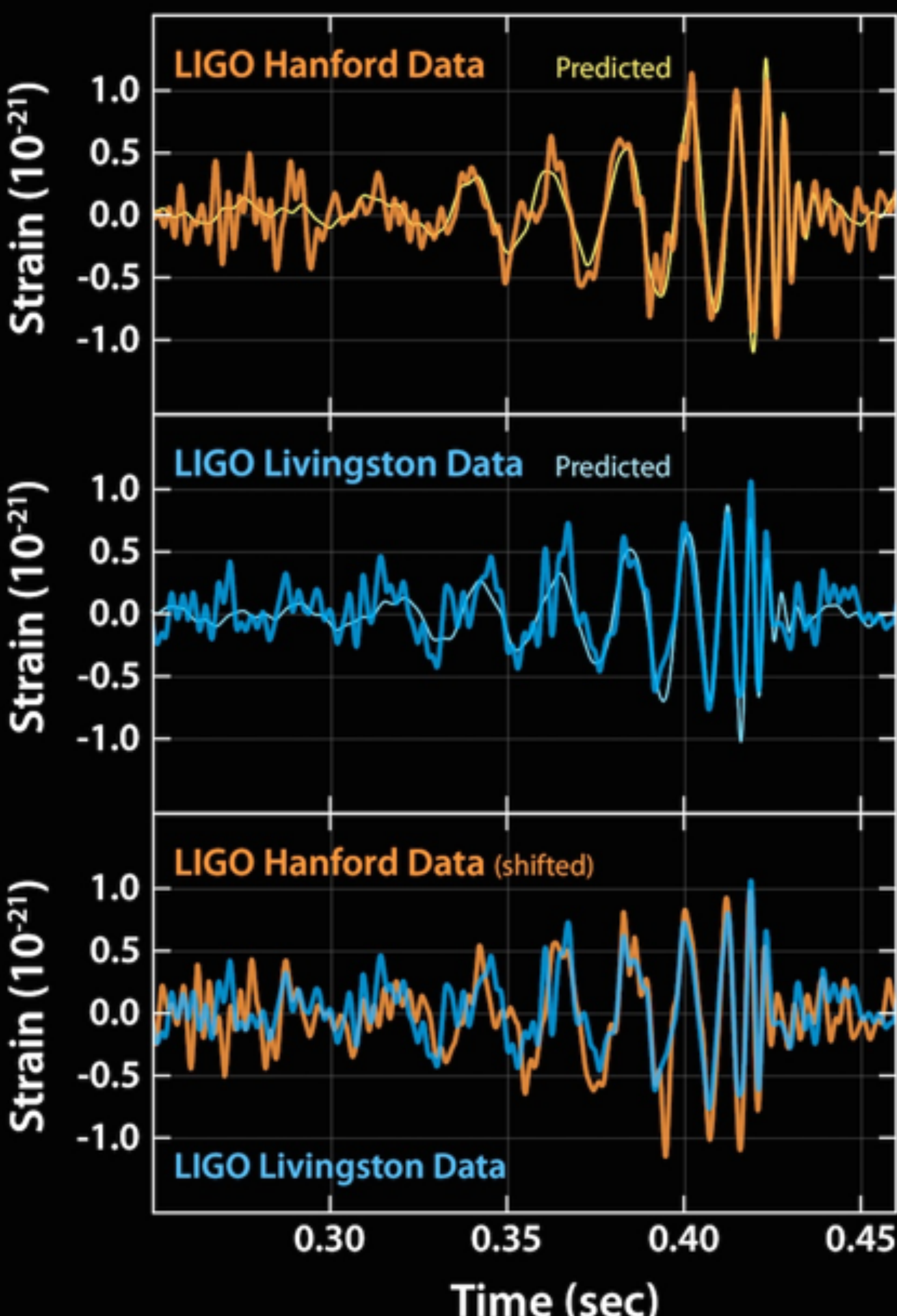
https://mediaassets.caltech.edu/gwave



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

36Msun + 29 Msun
のBHが合体して 62 Msun
（3 Msun分の質量が消失）

13億光年先
（400±170 Mpc）
（z=0.054—0.136）

重力波が検出された！
重力波が検出できた！
BHが存在した！
BH連星が存在した！
相対論が第0近似として正しい！

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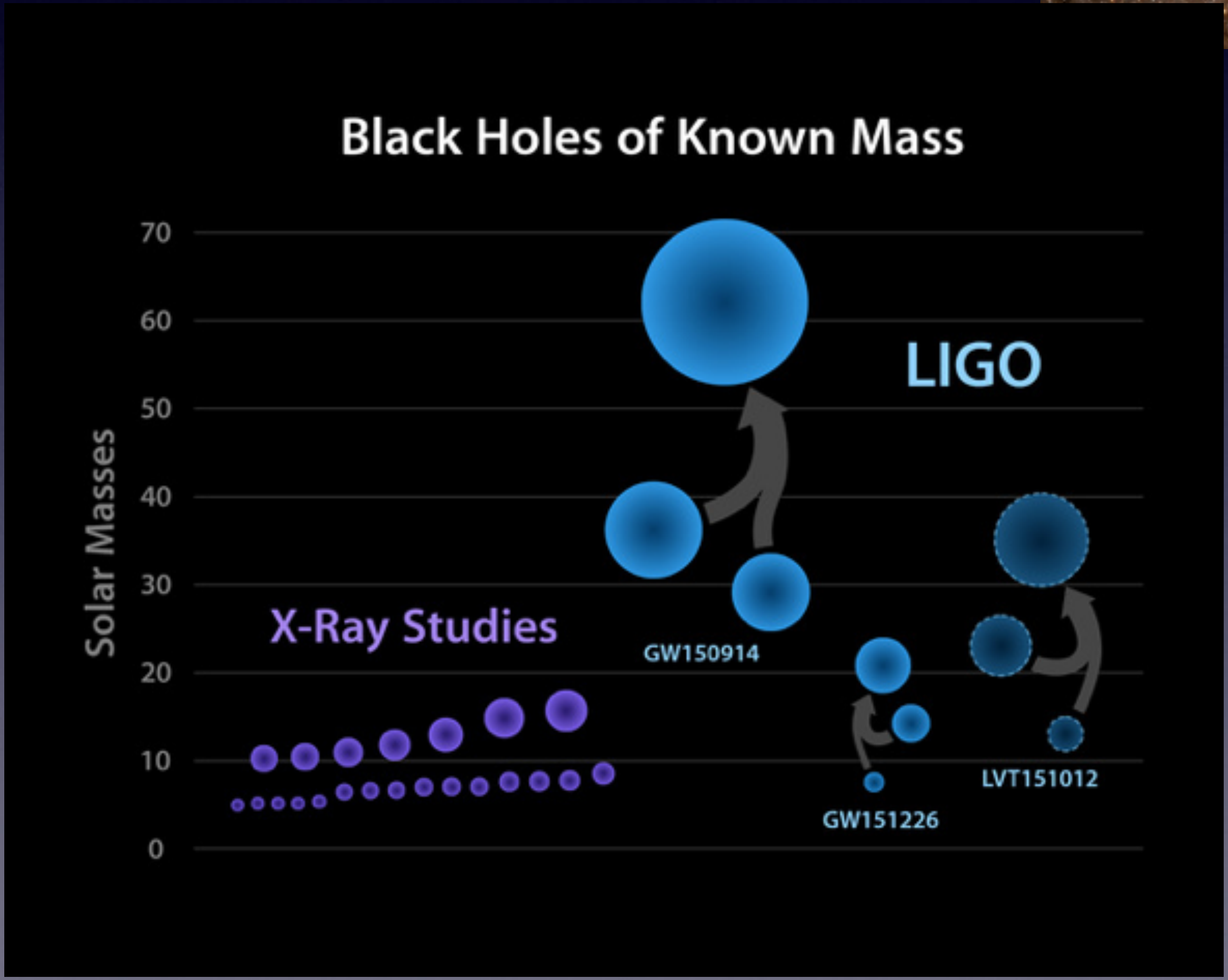
BHs!

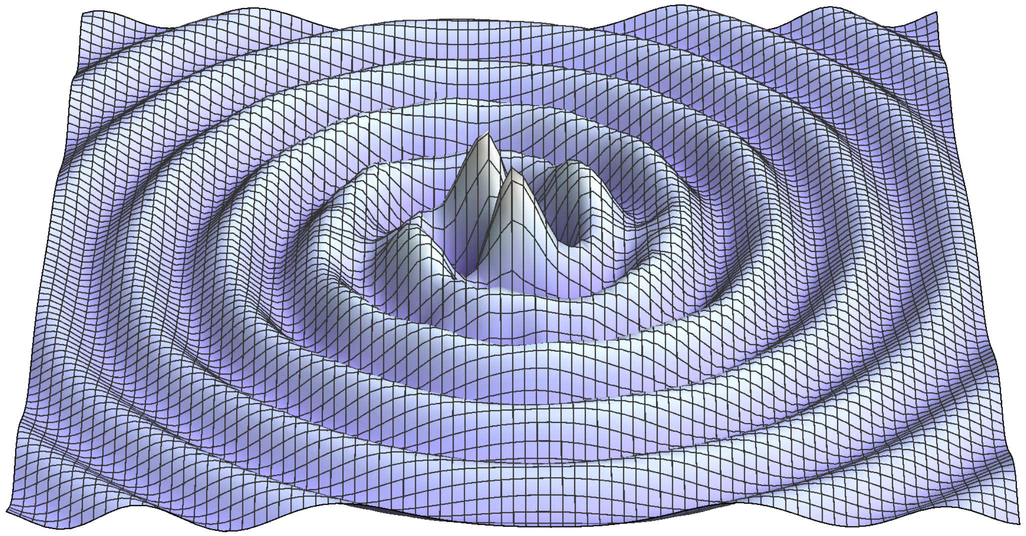


7M+14M=20M

29M+36M=62M

why not more?

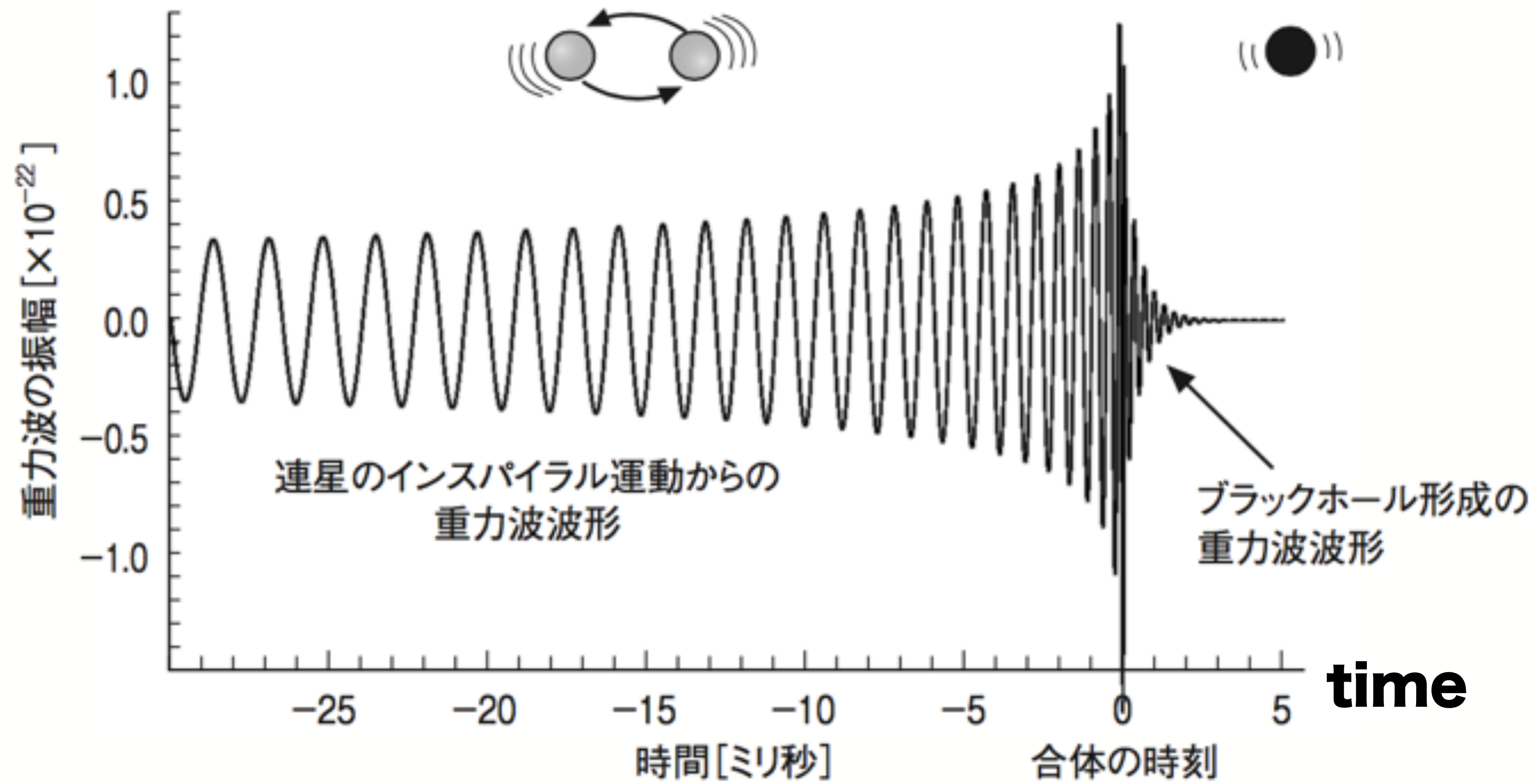
https://www.ligo.caltech.edu/system/avm_image_sqls/binaries/57/page/Black_Hole_Mass_Chart.jpg?1465864737



NS-NS
NS-BH
BH-BH

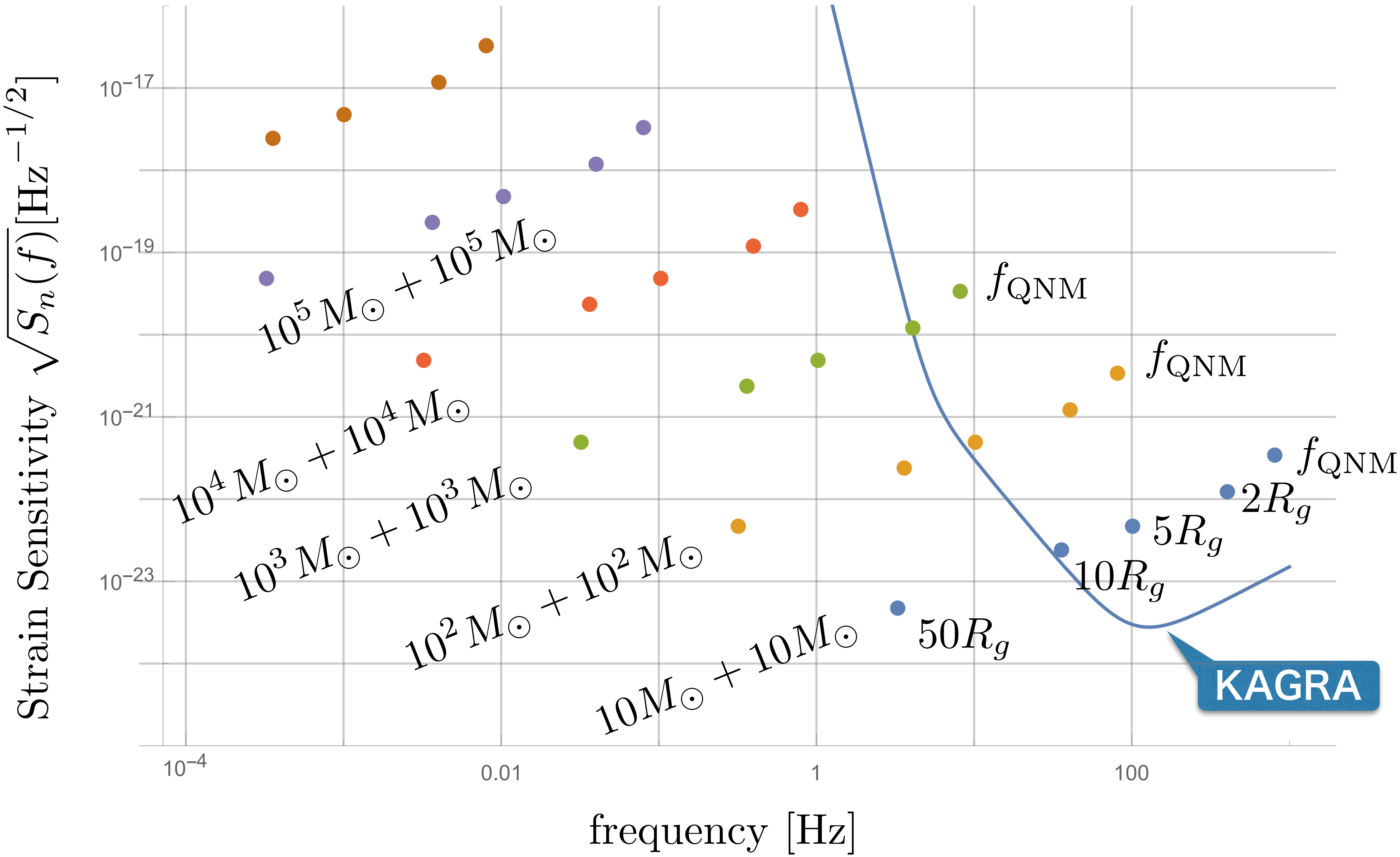
Inspiral | Merger | Ringdown

h

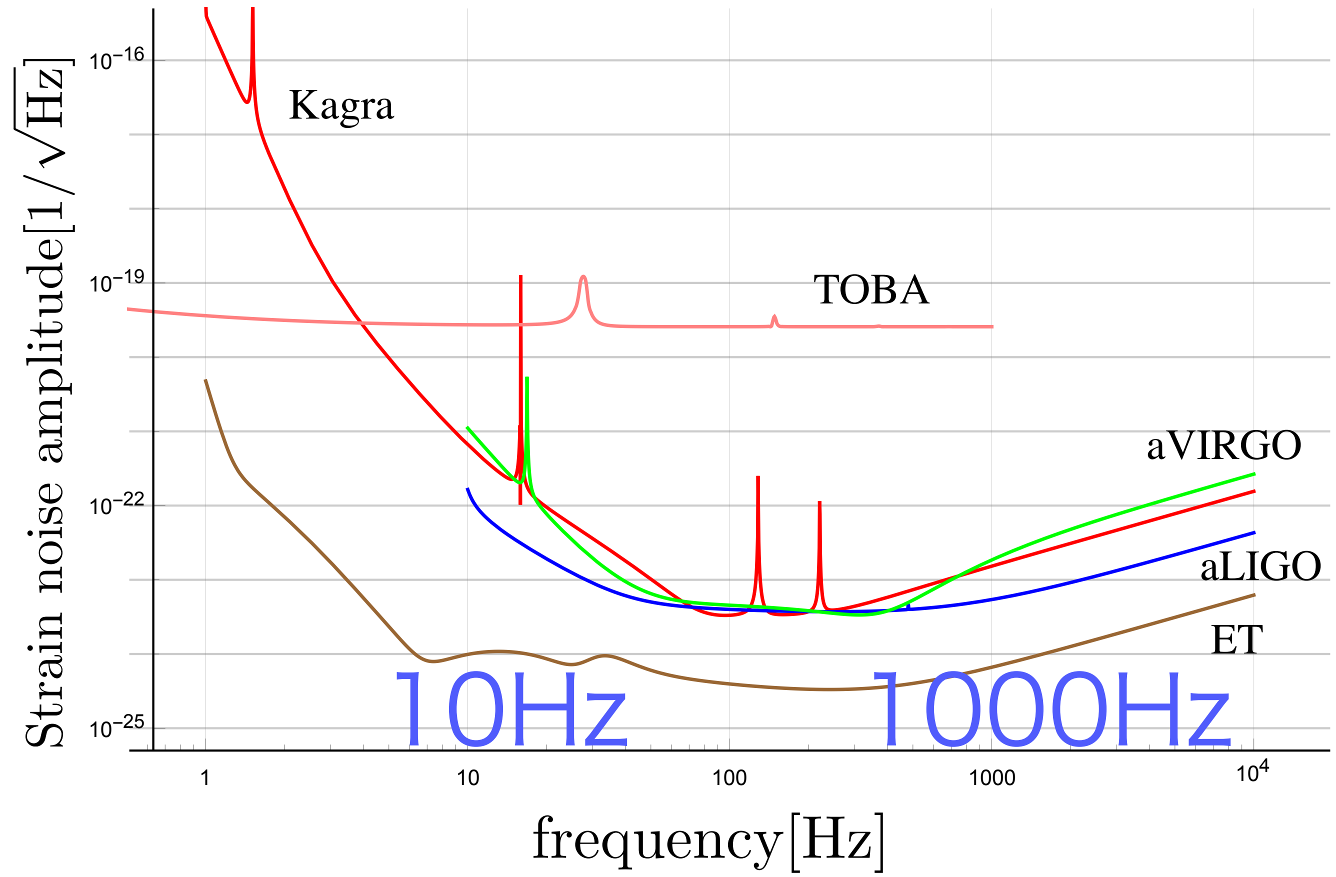


time

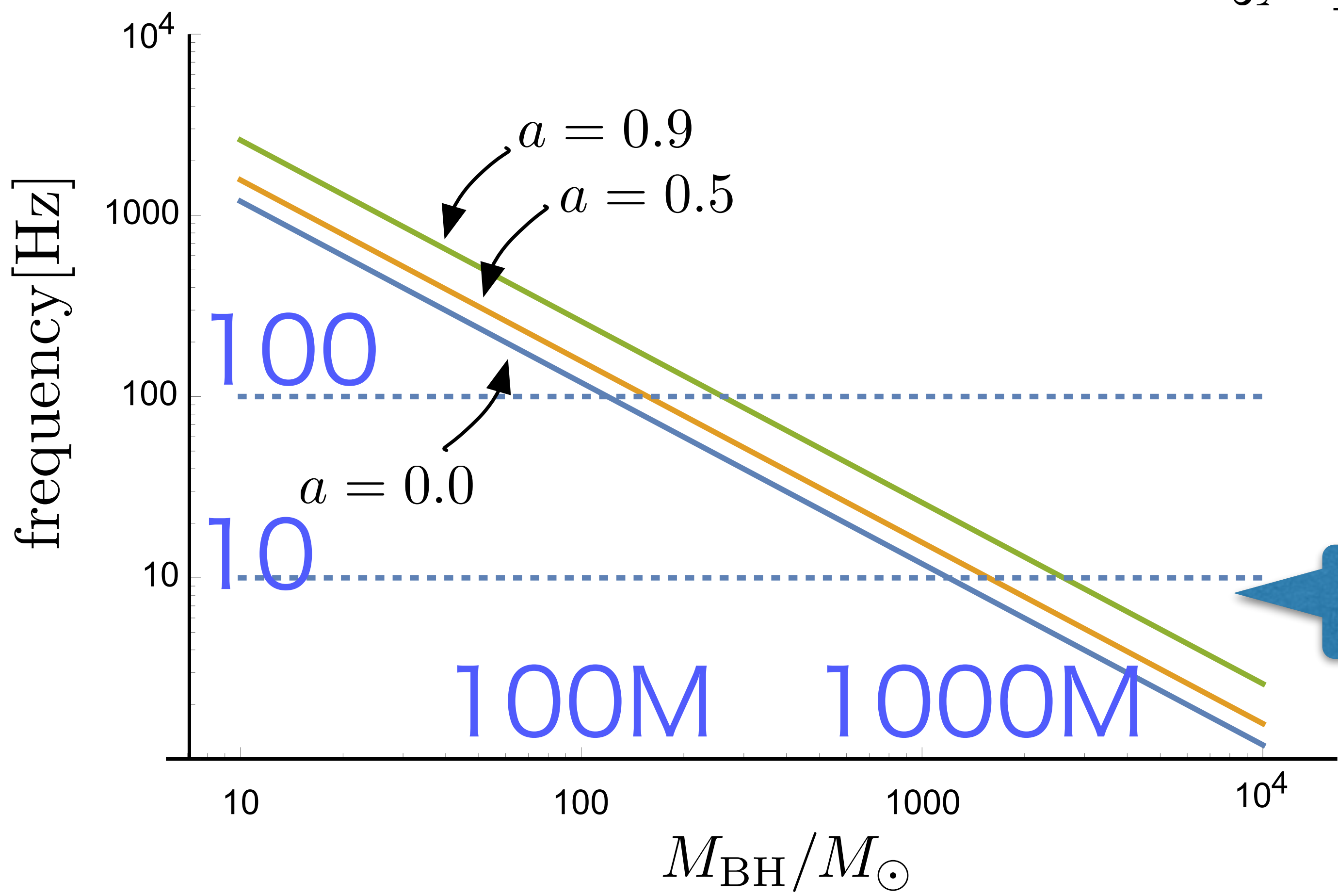
Typical frequency of BH-BH binary merger @ 1000Mpc



IMBH ringdown freq. is detectable at LIGO/KAGRA



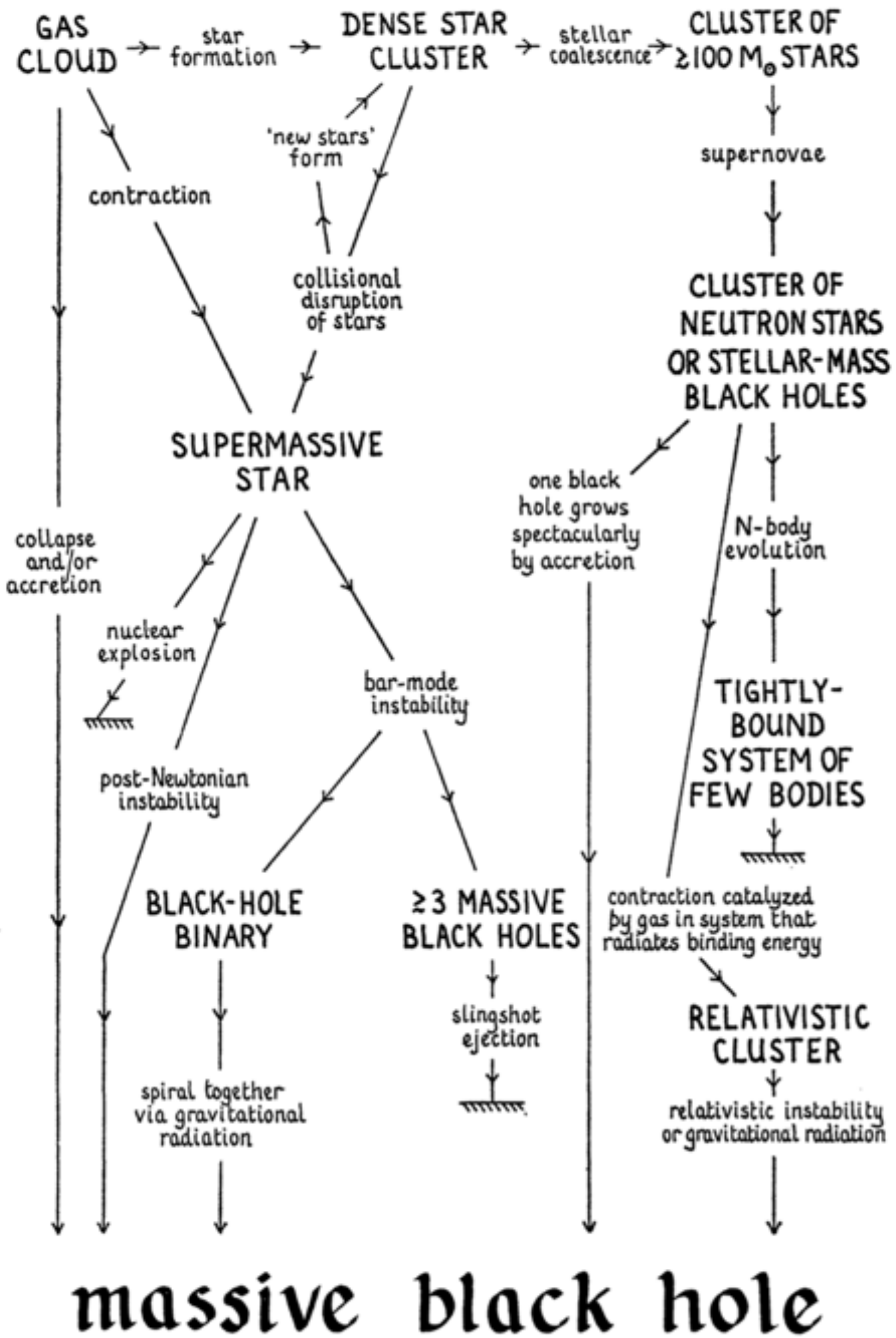
BH quasi-normal freq.
(ringdown freq.)



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

BH < 2000Msun can be a target

2. Model of SMBH



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

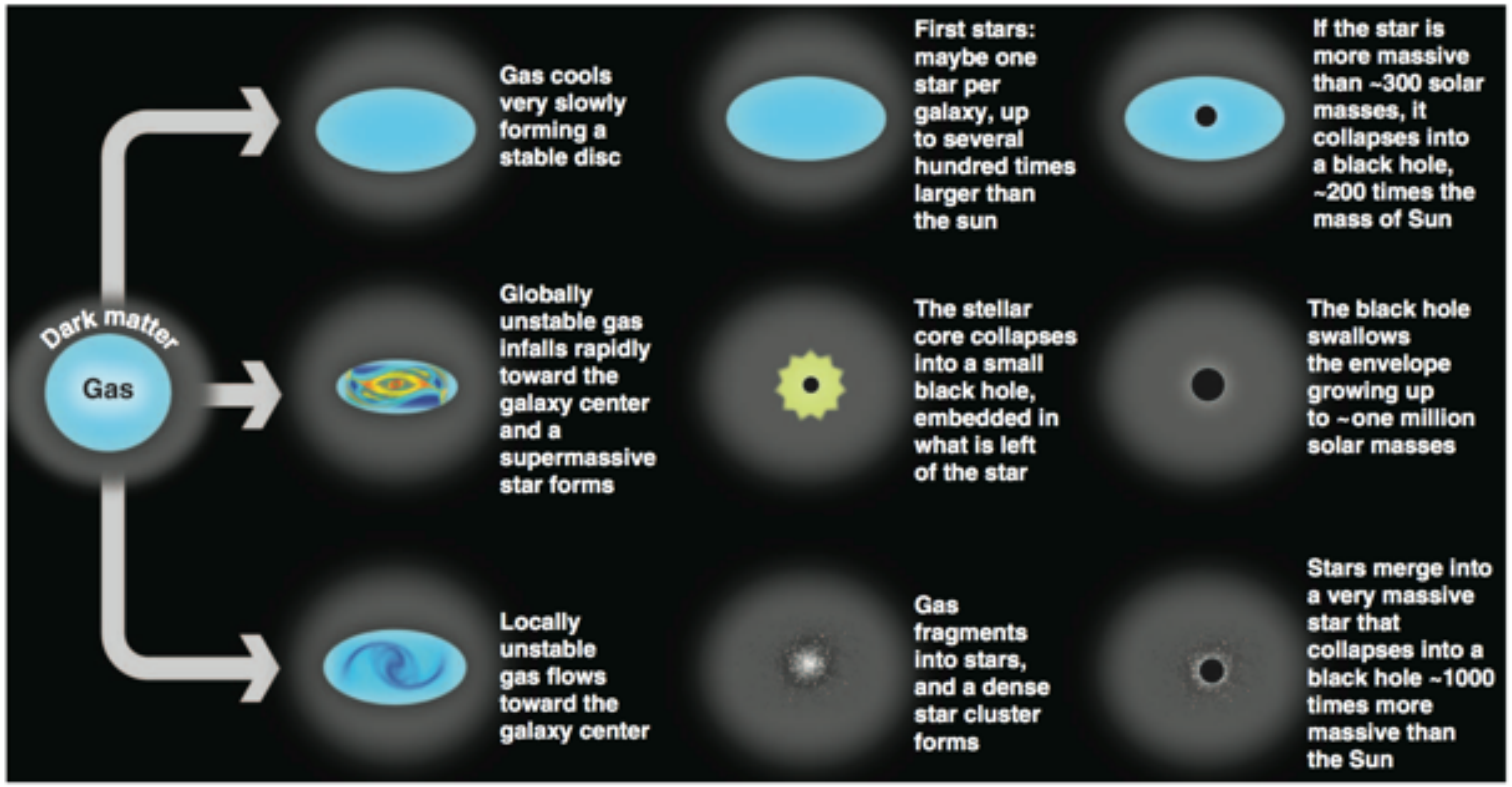


Fig. 1. Illustration showing three pathways to MBH formation that can occur in a distant galaxy (*56*). The starting point is a primeval galaxy, composed of a dark matter halo and a central condensation of gas. Most of this gas will eventually form stars and contribute to making galaxies as we know them.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

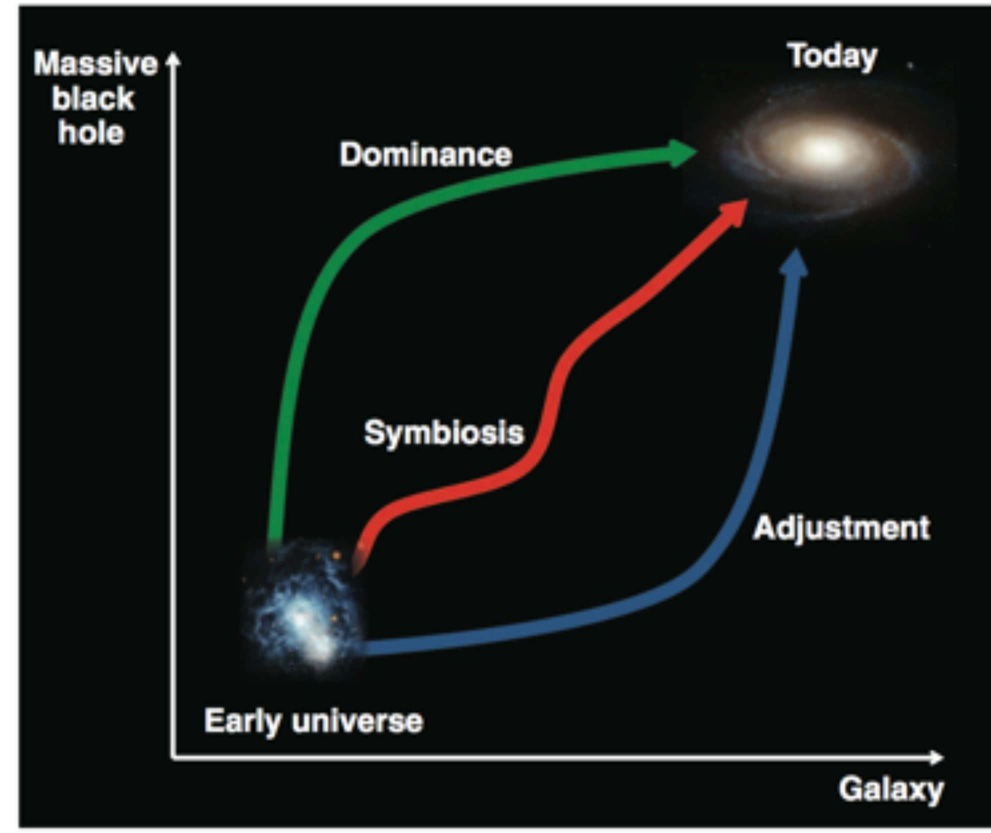


Fig. 3. Possible routes to MBH and galaxy coevolution, starting from black holes forming in distant galaxies in the early universe. [Image credits: NASA, European Space Agency (ESA), A. Aloisi (Space Telescope Science Institute and ESA, Baltimore, MD), and The Hubble Heritage Team (Space Telescope Science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

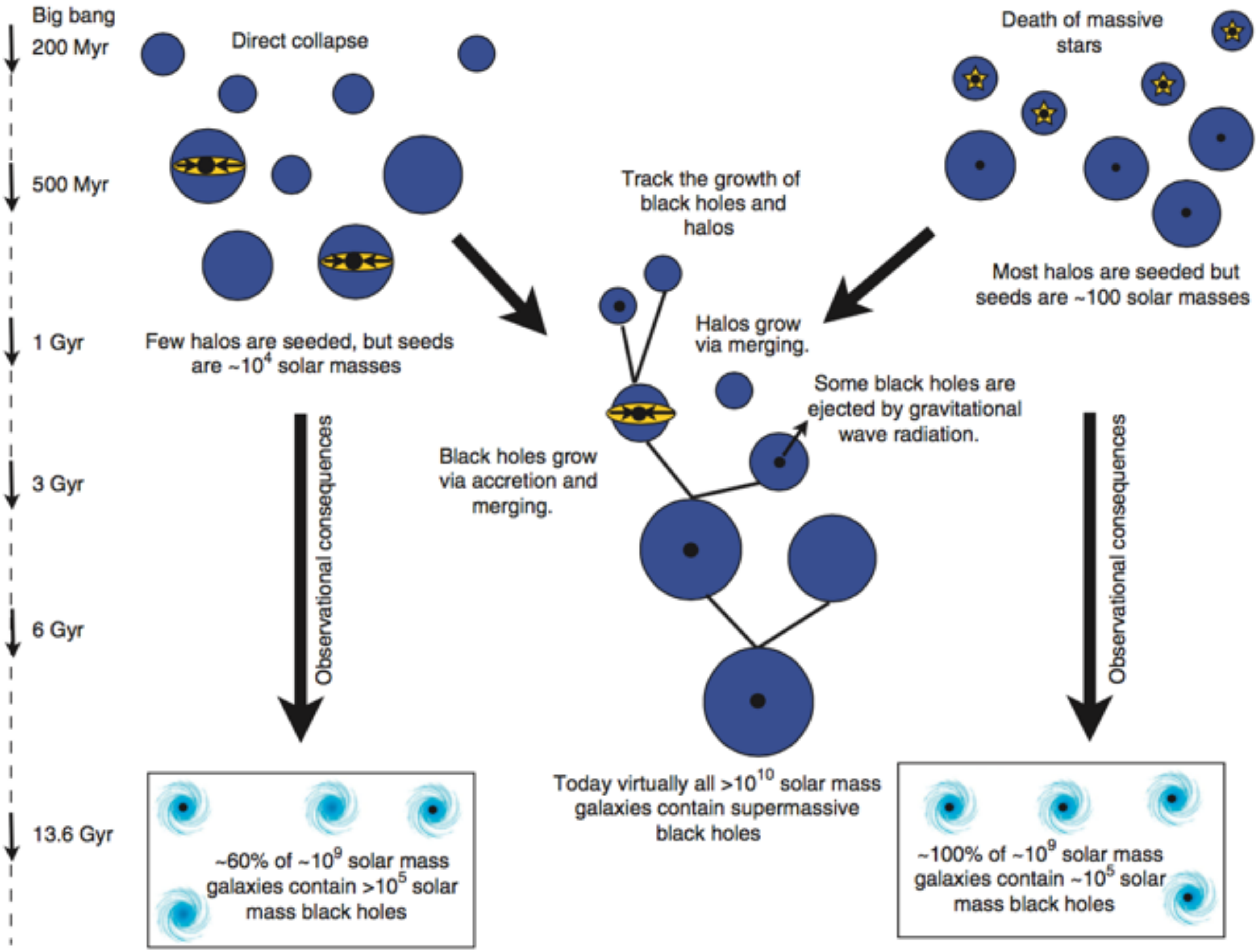
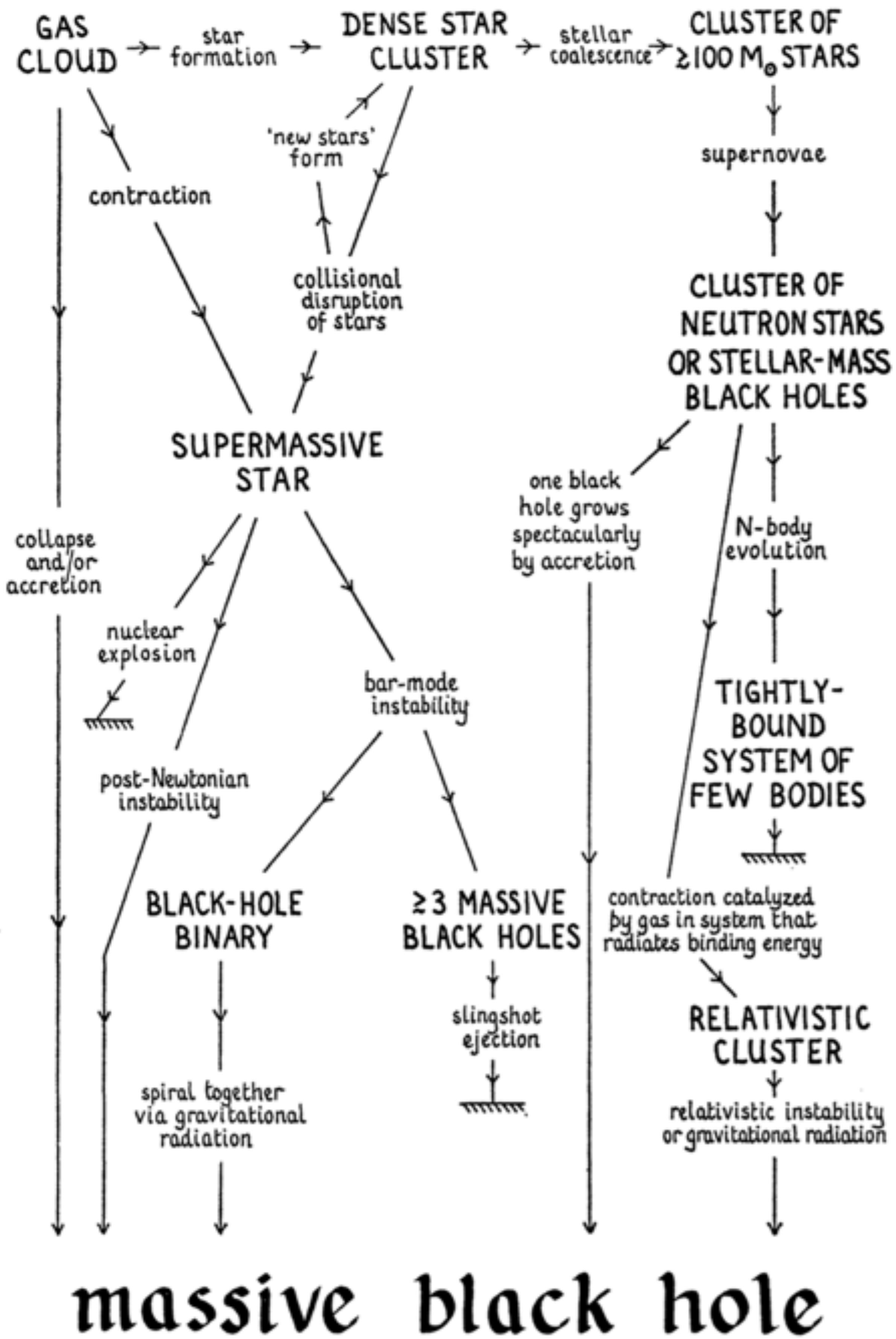


Figure 1 | Evolution of seed black holes. Schematic of the evolution of seed black holes assuming two different formation mechanisms (the death of the first generation of massive stars versus the direct collapse of gas into a black hole). Dark matter halos and the galaxies in them grow through merging. 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]



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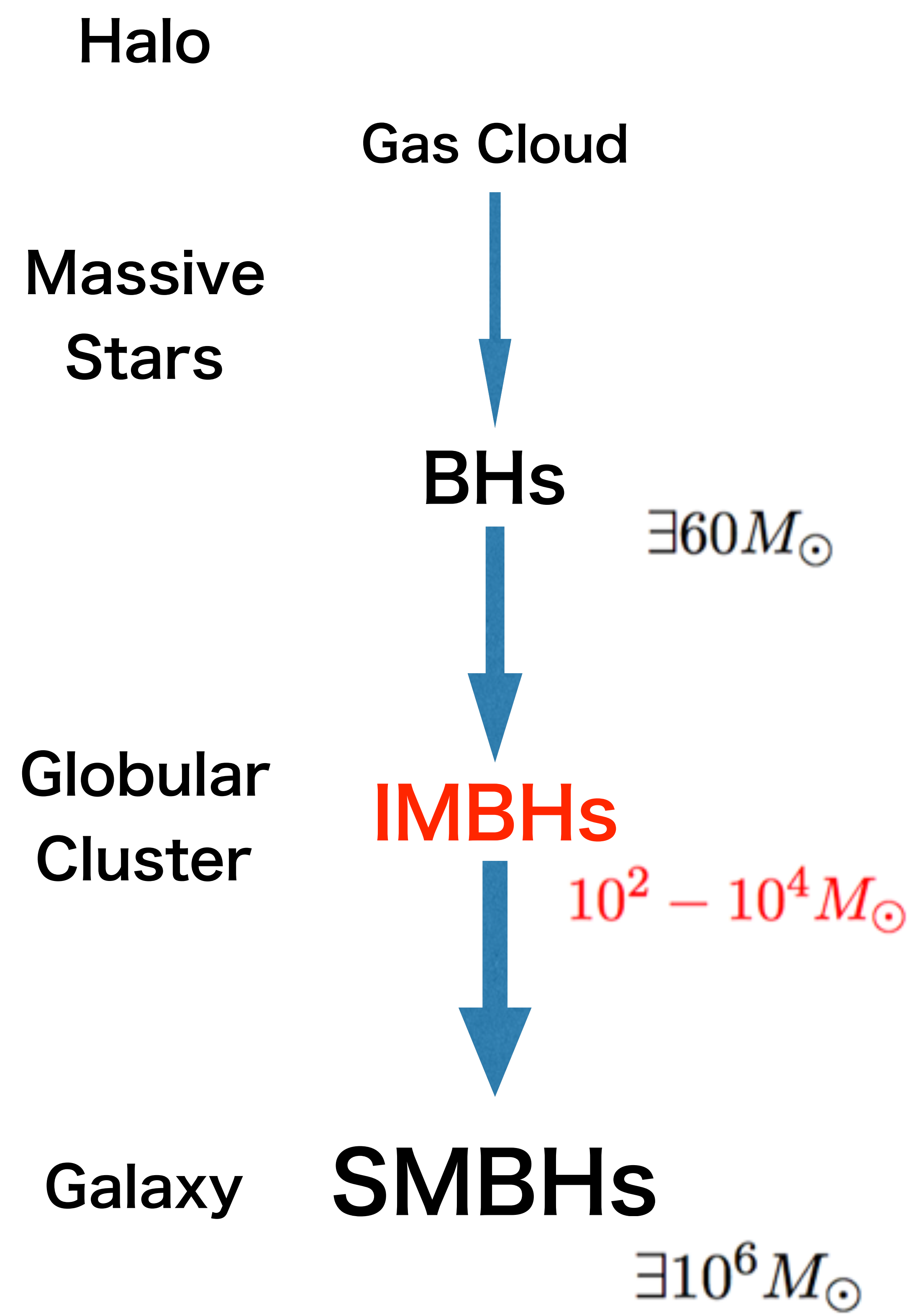


Ebisuzaki +, ApJ, 562, L19 (2001)

Starburst galaxy M82 has 1000M BH

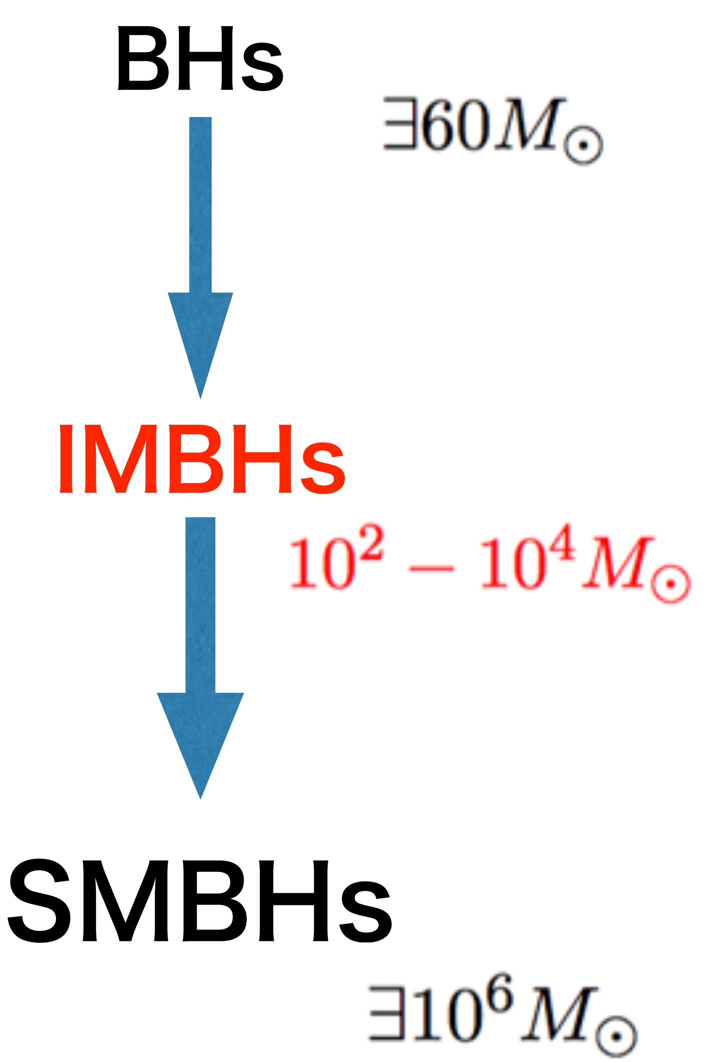
Matsushita+, ApJ, 545, L107 (2000)
Matsumoto+, ApJ, 547, L25 (2001)

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

0.15pc from SgrA*

1-2 x 10^4 Msun

Letter

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]

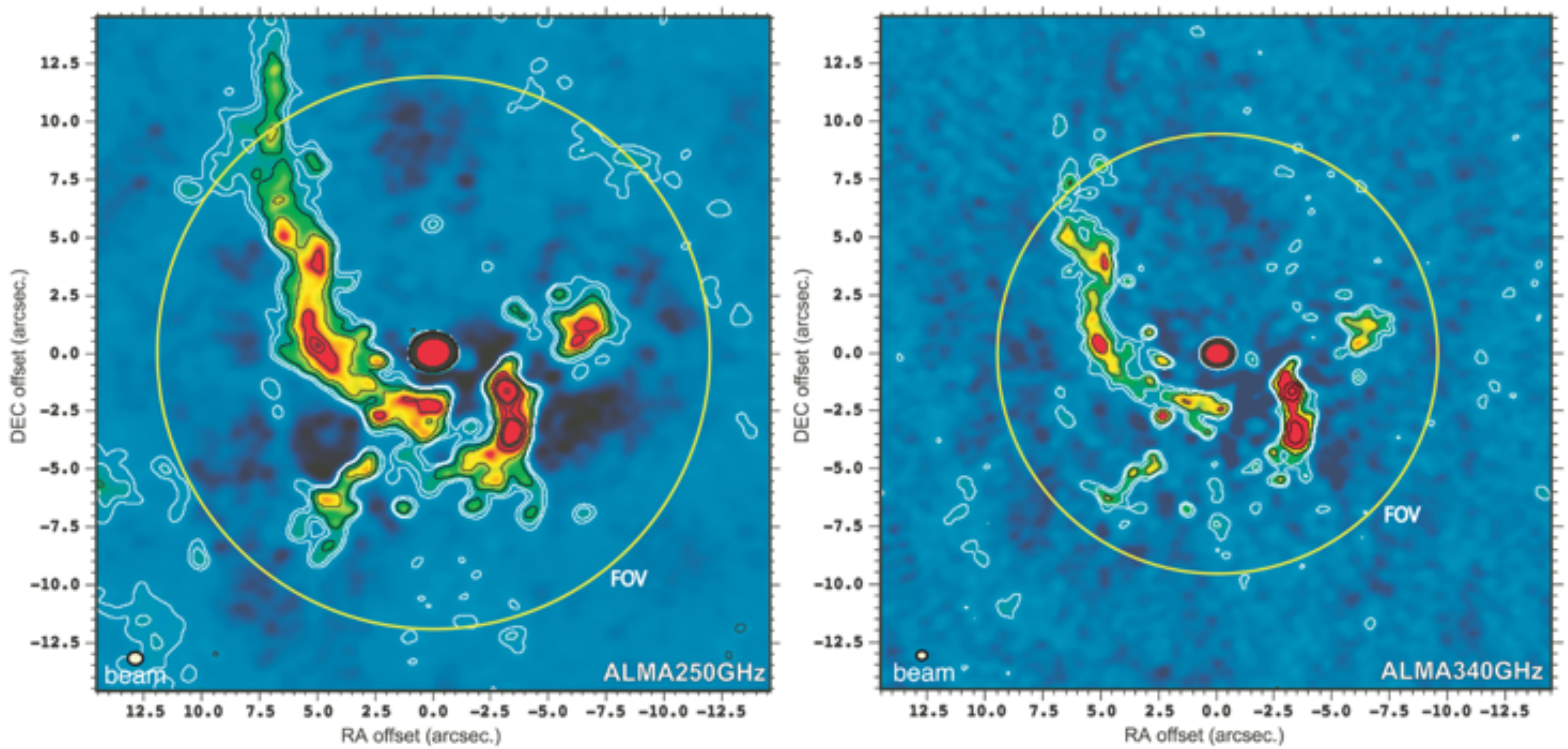


Fig. 2. Left panel: ALMA map in the 250 GHz band of the "mini-spiral" including Sgr A*. The four spectral windows of $f_c = 245$, 247, 257, and 259 GHz are combined to improve the sensitivity. The diameter of the FOV is 24″ (circle). The angular resolution is 0.″63 × 0.″53 at $PA = -84°$, which is shown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

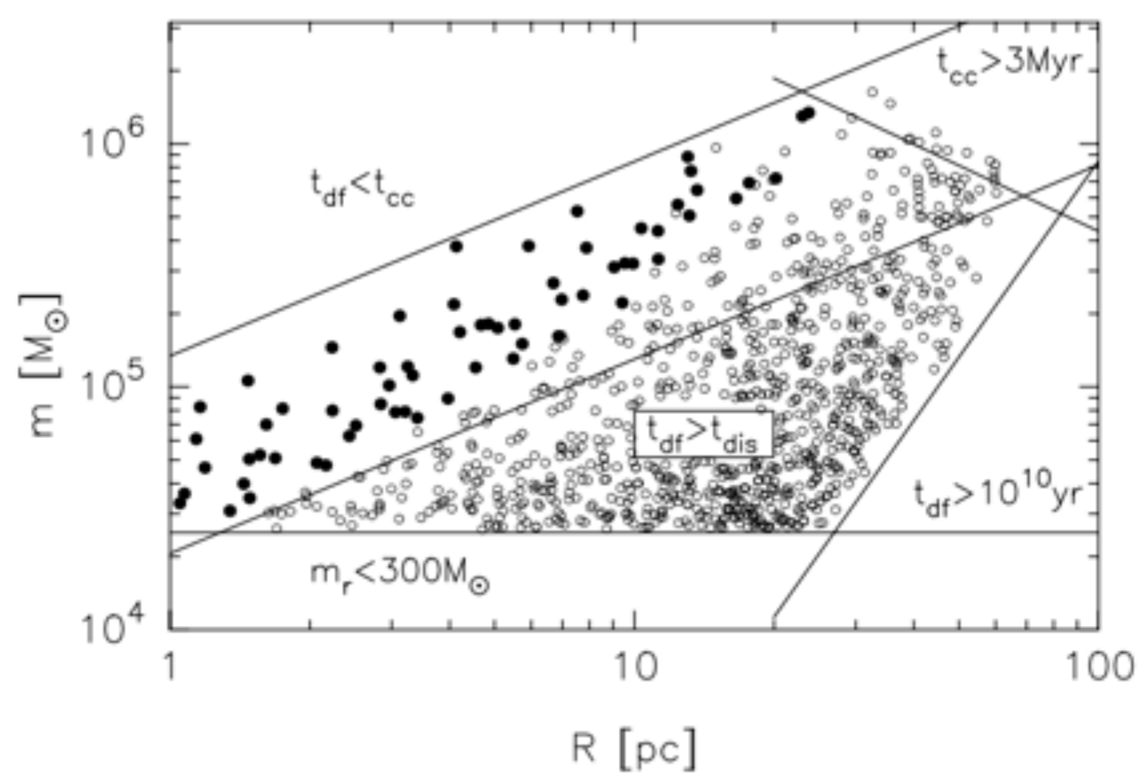
Simon F. Portegies Zwart,[1,2] Holger Baumgardt,[3] Stephen L. W. McMillan,[4]
Junichiro Makino,[5] Piet Hut,[6] and Toshi Ebisuzaki[7]

Received 2005 November 11; accepted 2005 December 5

ABSTRACT

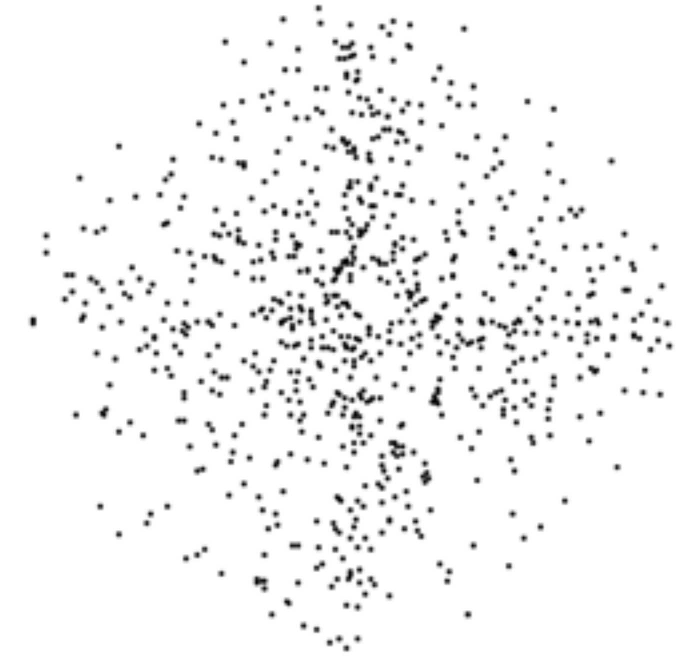
We simulate the inner 100 pc of the Milky Way to study the formation and evolution of the population of star clusters and intermediate-mass black holes (IMBHs). For this study we perform extensive direct *N*-body simulations of the star clusters that reside in the bulge, and of the inner few tenth of 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



'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 $\exists 10^6 M_\odot$

雰囲気（巡り逢い）＋仲良し成長　モデル

The Astrophysical Journal, 722:1197–1206, 2010 October 20 doi:10.1088/0004-637X/722/2/1197

DETECTION OF IMBHs WITH GROUND-BASED GRAVITATIONAL WAVE OBSERVATORIES: A BIOGRAPHY OF A BINARY OF BLACK HOLES, FROM BIRTH TO DEATH

Pau Amaro-Seoane[1,2] and Lucía Santamaría[1]
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[2] Institut de Ciències de l'Espai, IEEC/CSIC, Campus UAB, Torre C-5, parells, 2[na] planta, ES-08193 Bellaterra, Barcelona, Spain
Received 2009 January 10; accepted 2010 August 16; published 2010 September 28

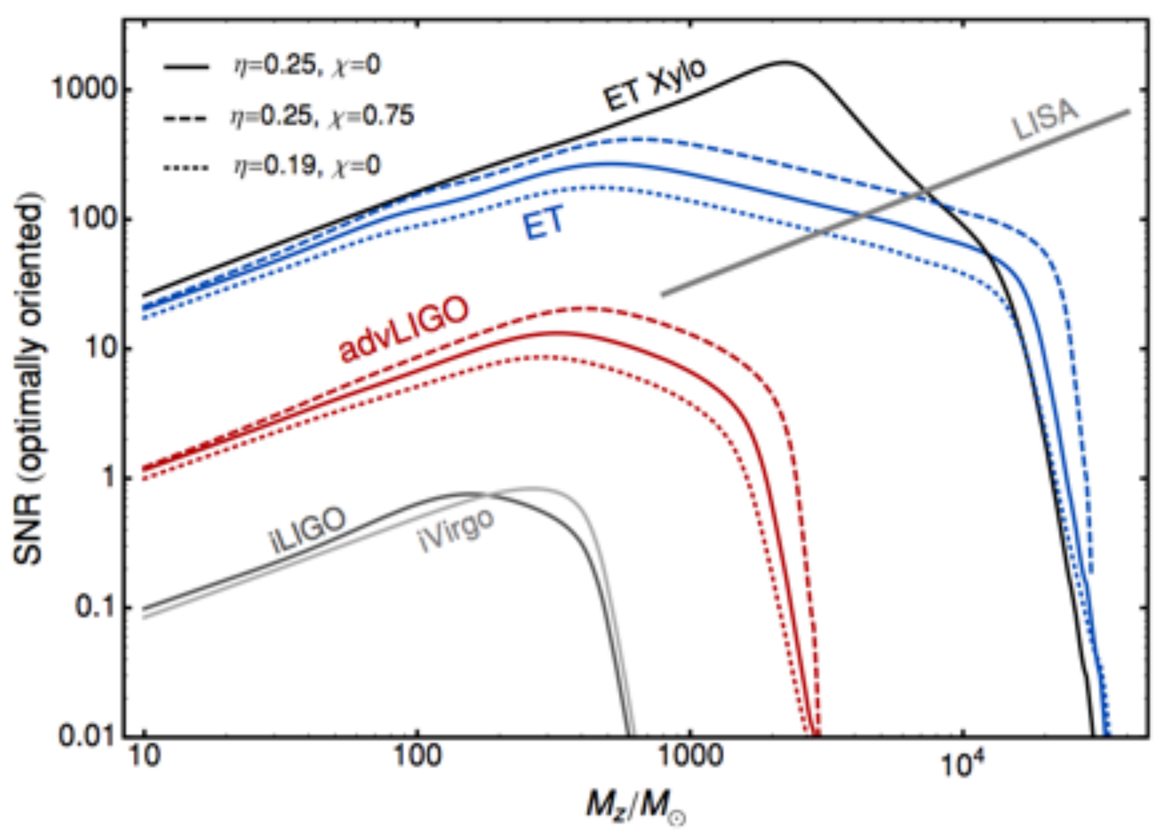

Figure 7. S/N as a function of the redshifted total mass of the BBH for the present and future generations of GW detectors and *LISA*. The sources are placed at a distance of 6.68 Gpc ($z = 1$) and the S/Ns correspond to sources optimally oriented and located. Solid lines indicate S/Ns for the equal-mass, non-spinning configuration (1); for Advanced LIGO and ET we have included the S/Ns produced by configurations (2) and (3) as well, indicated with dashed and dotted lines, respectively.

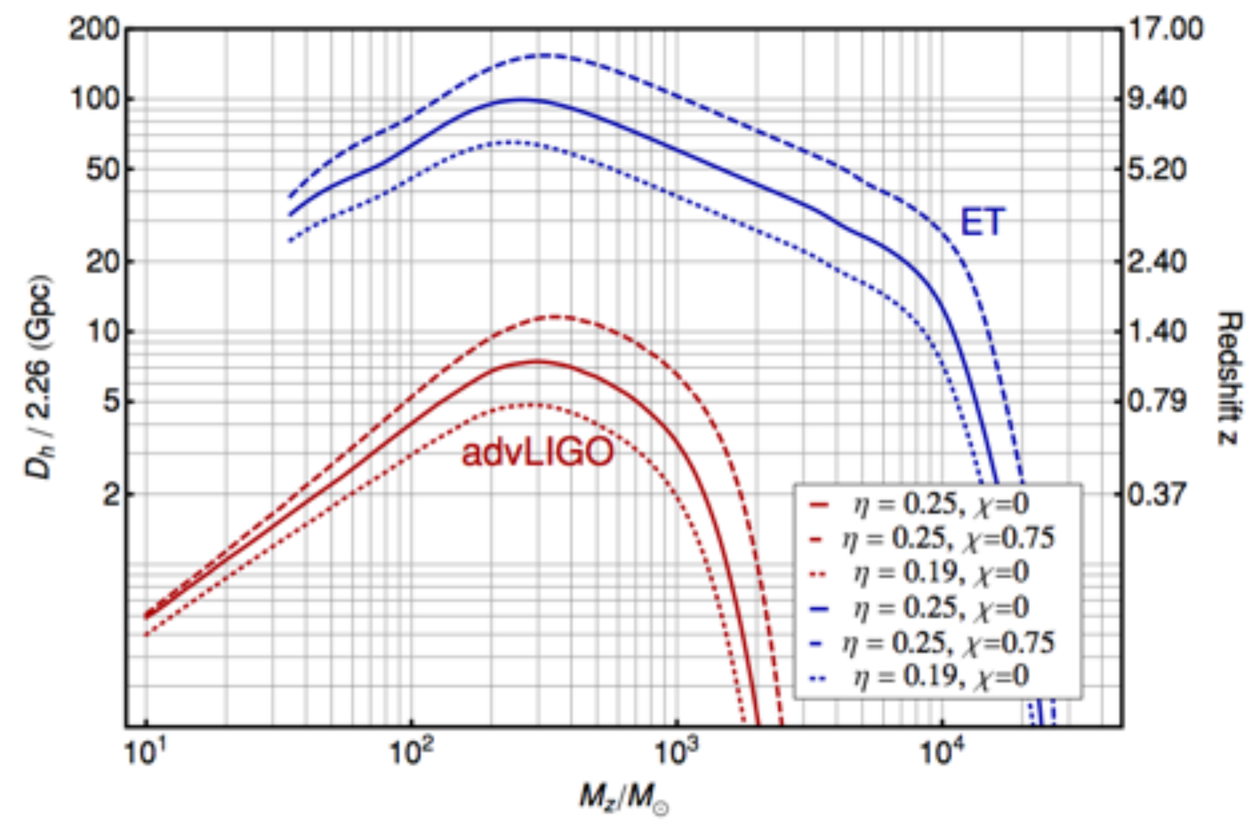

Figure 8. Orientation-averaged distance vs. redshifted mass for three binary configurations obtained with the design sensitivity curves of Advanced LIGO and the ET. The solid, dashed, and dotted lines correspond to the configurations denoted in the text as (1), (2), and (3), respectively. Note the ∼40% increase in reach given by the hang-up configuration with $\chi = 0.75$ with respect to the non-spinning case.

The Astrophysical Journal, 722:1197–1206, 2010 October 20 doi:10.1088/0004-637X/722/2/1197

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Pau.Amaro-Seoane@aei.mpg.de, Lucia.Santamaria@aei.mpg.de
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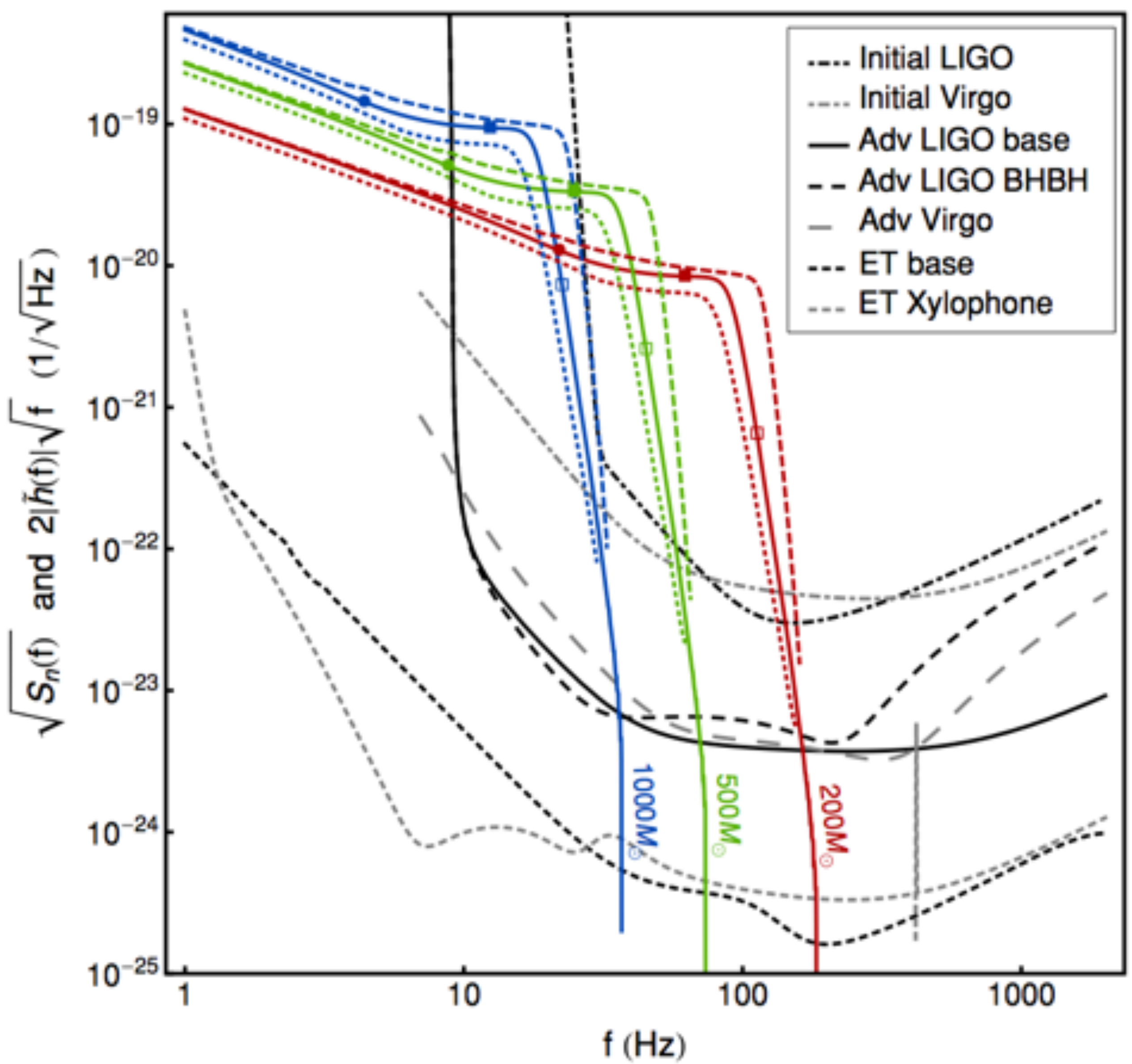


Figure 6. Hybrid waveform for three BBH configurations scaled to various IMBH masses. From top to bottom, we show BBH systems with total mass 1000, 500, and 200 $M_\odot$ in blue, green, and red, respectively. Solid lines correspond to the equal-mass, non-spinning configuration (1), dashed lines to the equal-mass, $\chi = 0.75$ configuration (2), and dotted lines to the non-spinning, $q = 3$ configuration (3). The sources are optimally oriented and placed at 100 Mpc of the detectors. The symbols on top of configuration (1) mark various stages of the BBH evolution: solid circles represent the ISCO frequency, squares the light ring frequency, and open squares the Lorentzian ringdown frequency (corresponding to 1.2 times the fundamental ringdown frequency f_{FRD}), when the BBH system has merged and the final BH is ringing down. Currently operating and planned ground-based detectors are drawn as well: plotted are the sensitivity curves of initial LIGO and Virgo, two possible configurations for Advanced LIGO (zero detuning and 30–30 $M_\odot$ BBH optimized), Advanced Virgo, and the proposed ET in both its broadband and xylophone configurations.

IMBH-IMBH mergers produce low freq. GW

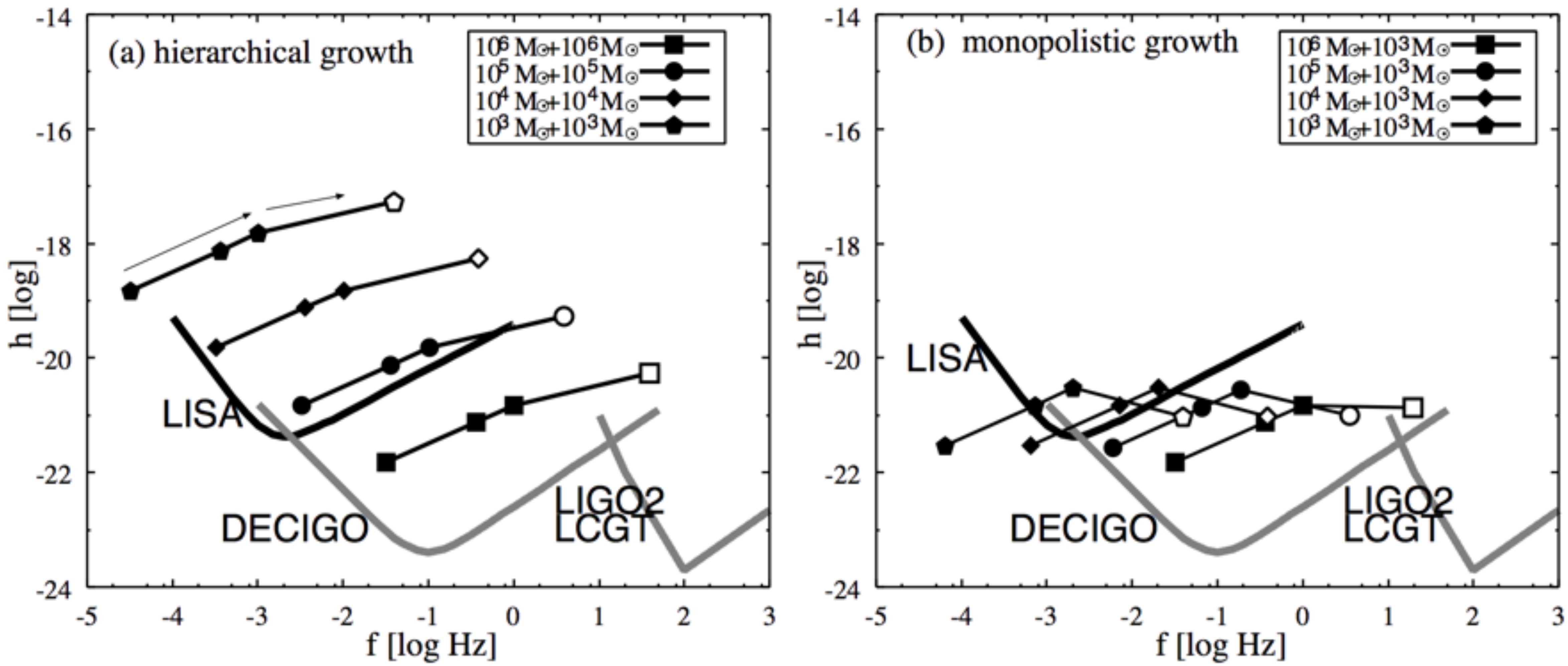
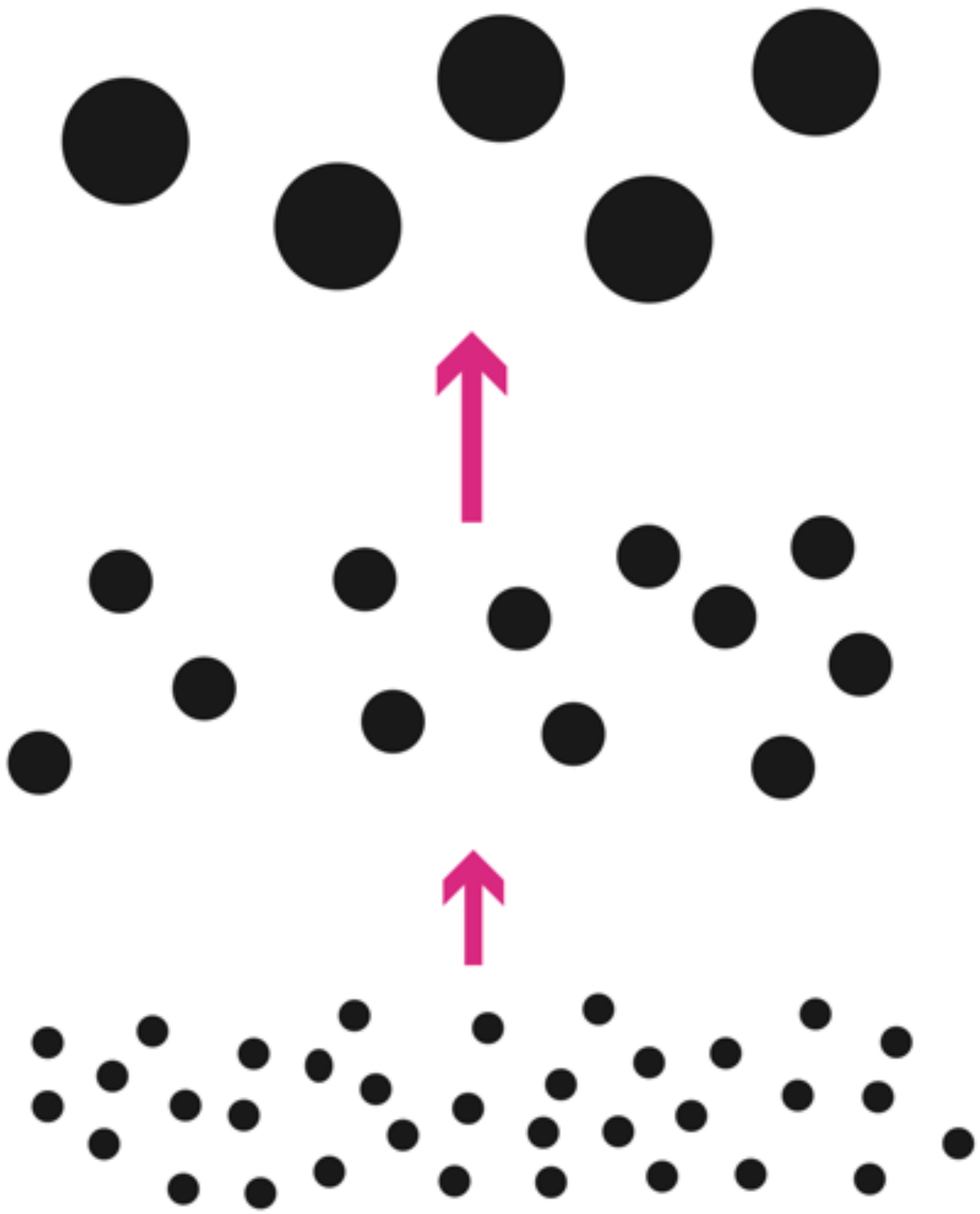


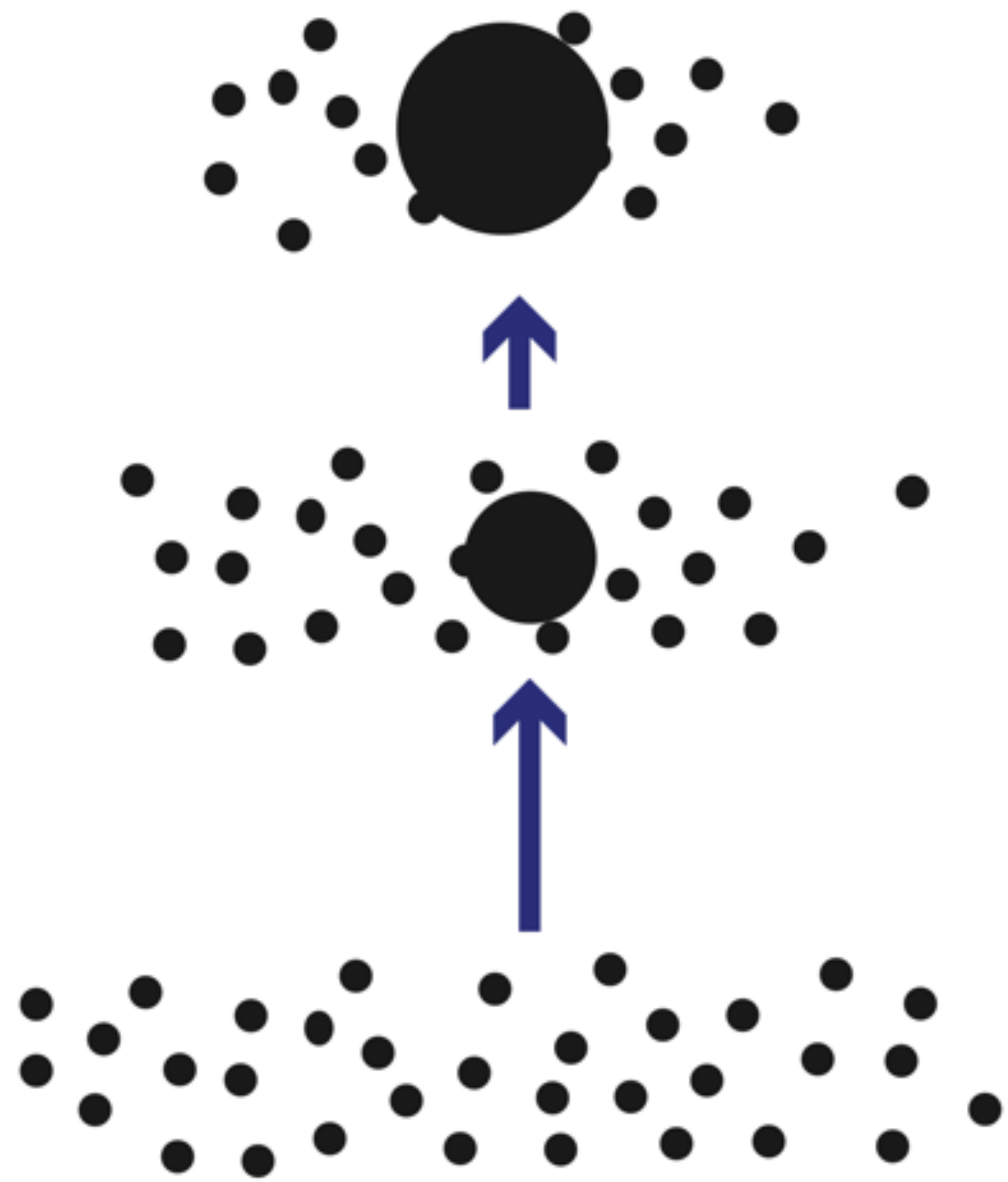
Fig. 1.— Expected gravitational radiation amplitude from merging IMBHs of (a) hierarchical growth model, and (b) monopolistic growth model. We plotted both the inspiral phase ($f_{\rm insp}, h_{\rm insp}$), [eqs. (2) and (3)], and the ringdown phase ($f_{\rm QNM}, h_{\rm coal}$), [eqs. (4) and (6)],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



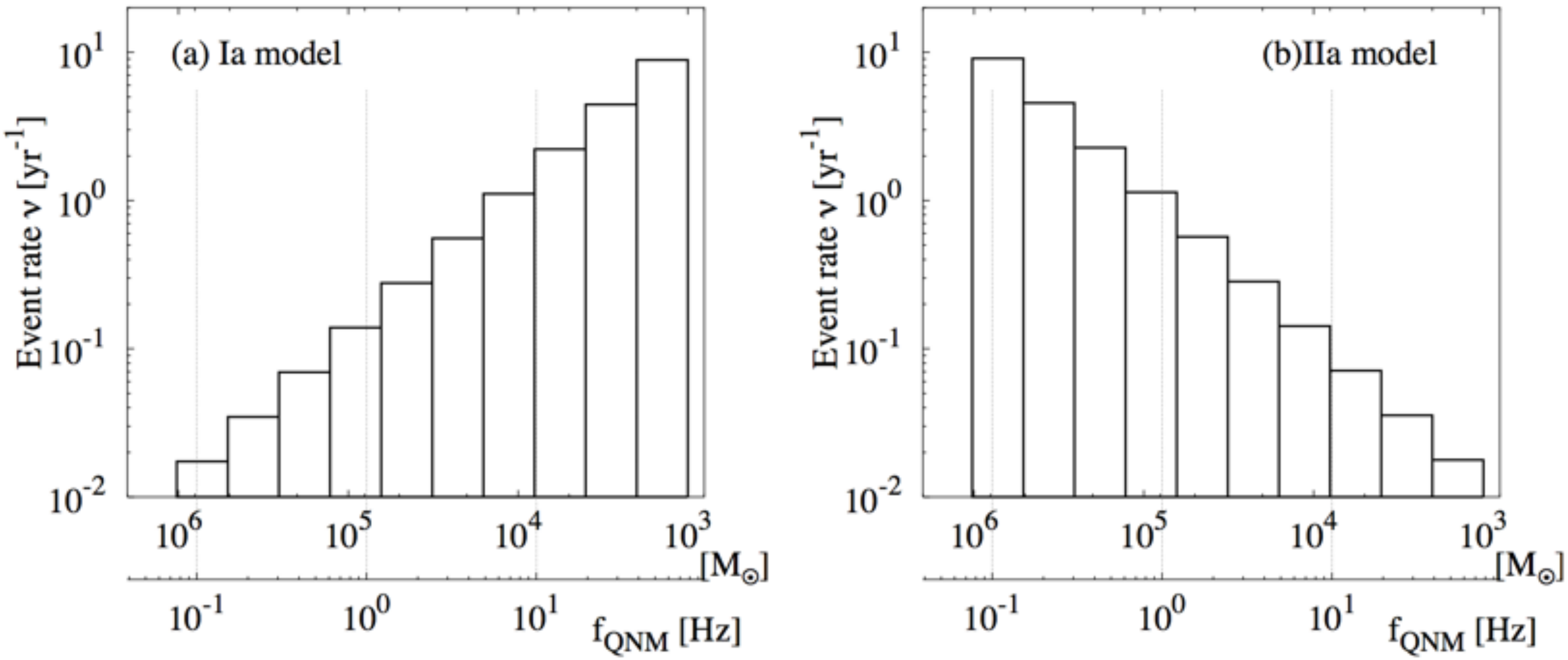
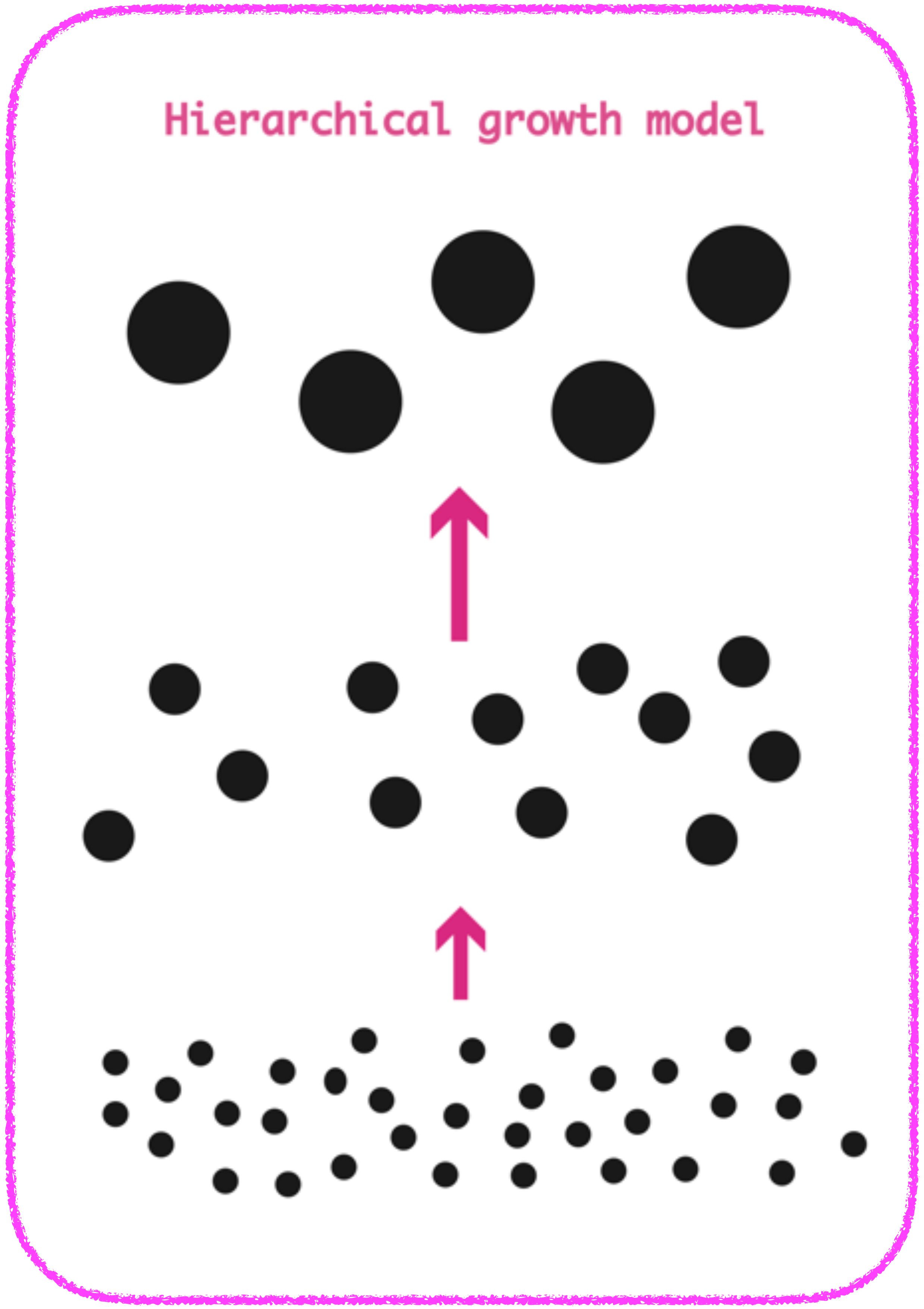


Fig. 2.— Event numbers of mergers starting from a thousand of $10^3 M_\odot$ IMBHs. The vertical axis is the event rate $\nu[\mathrm{yr}^{-1}]$, eqs. (12) and (14). The horizontal axis is the mass of the post-merger BH, M_T, which is also interpreted in the final gravitational radiation frequency f_{QNM}. Fig. (a) and (b) are for the hierarchical growth model and for the monopolistic growth model, respectively. Both plots are for the homogeneous distribution model, while we just multiply three for each event rate for the thin-shell galaxy distribution model. If a SMBH grows up hierarchically, then the bursts of gravitational radiation appear in higher frequency region. In the monopolistic model, the bursts appear in lower frequency region. We fix the increasing-mass rate, α, as unity for the plots.

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



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

How many BH mergers in the Universe?

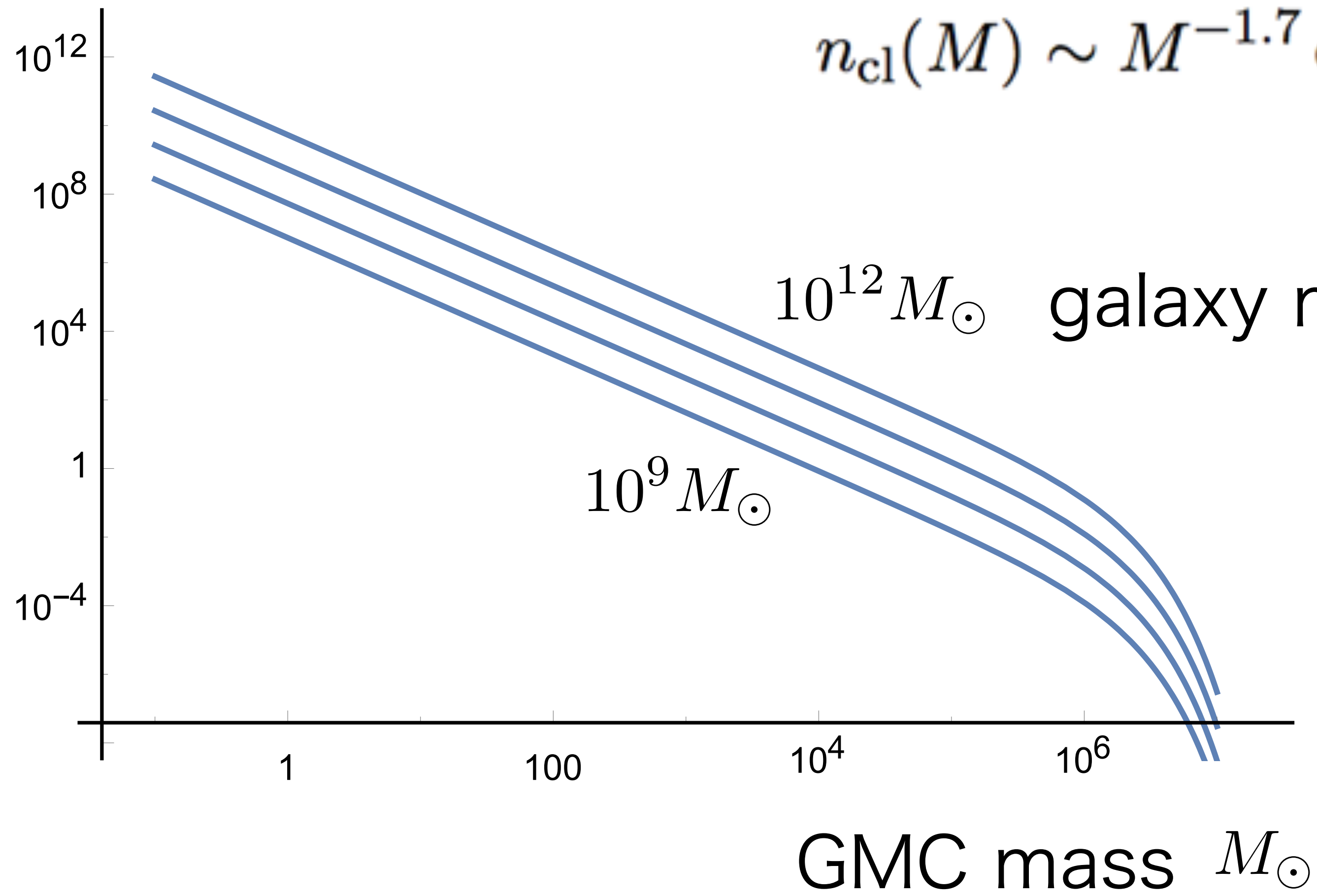
How many BH mergers we observe in a year?

Detectable Distance ?
KAGRA/aLIGO/aVIRGO

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

Mass Function of Giant Molecular Clouds

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



The Formation and Destruction of Molecular Clouds and Galactic Star Formation

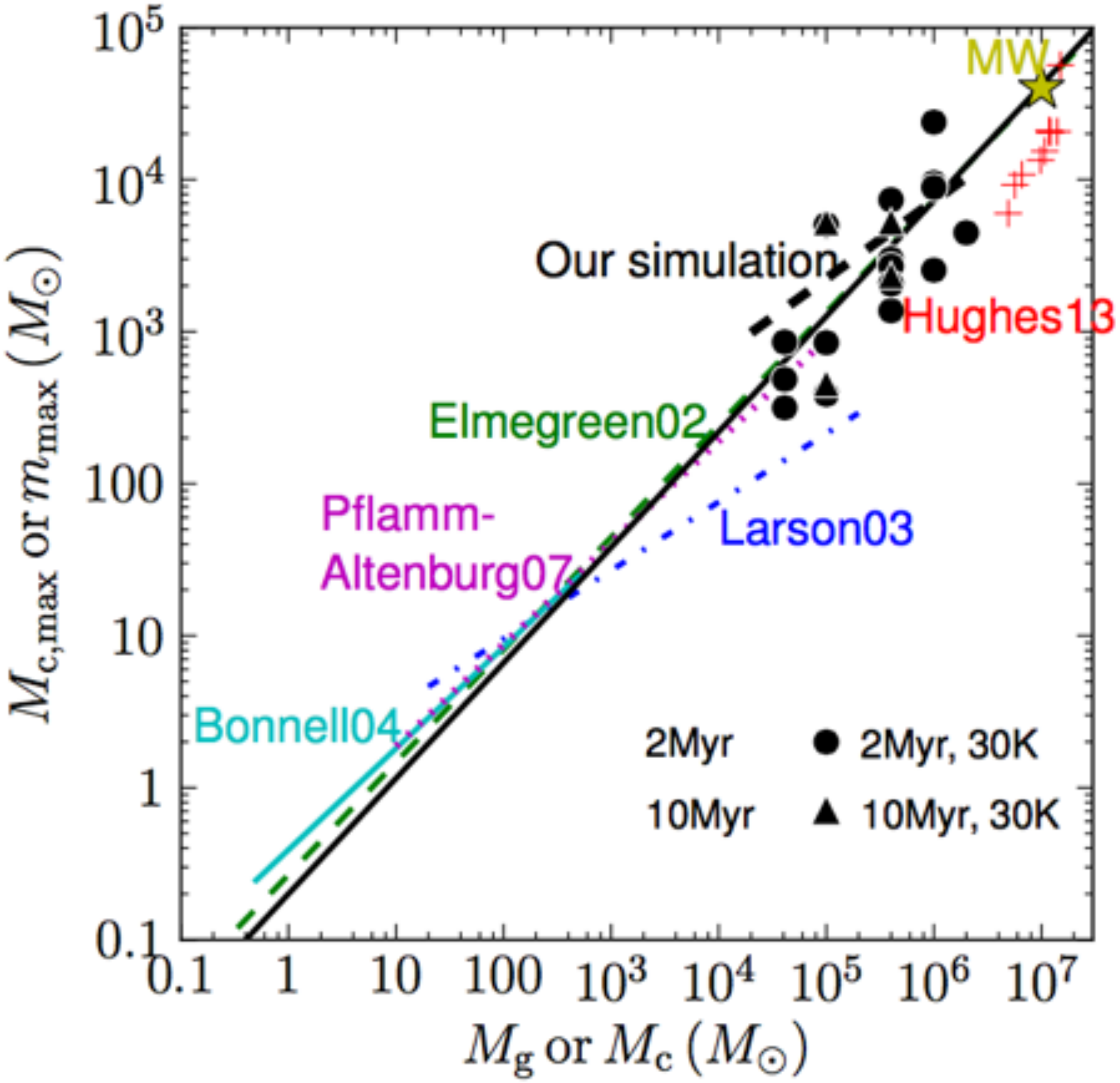
An Origin for The Cloud Mass Function and Star Formation Efficiency

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



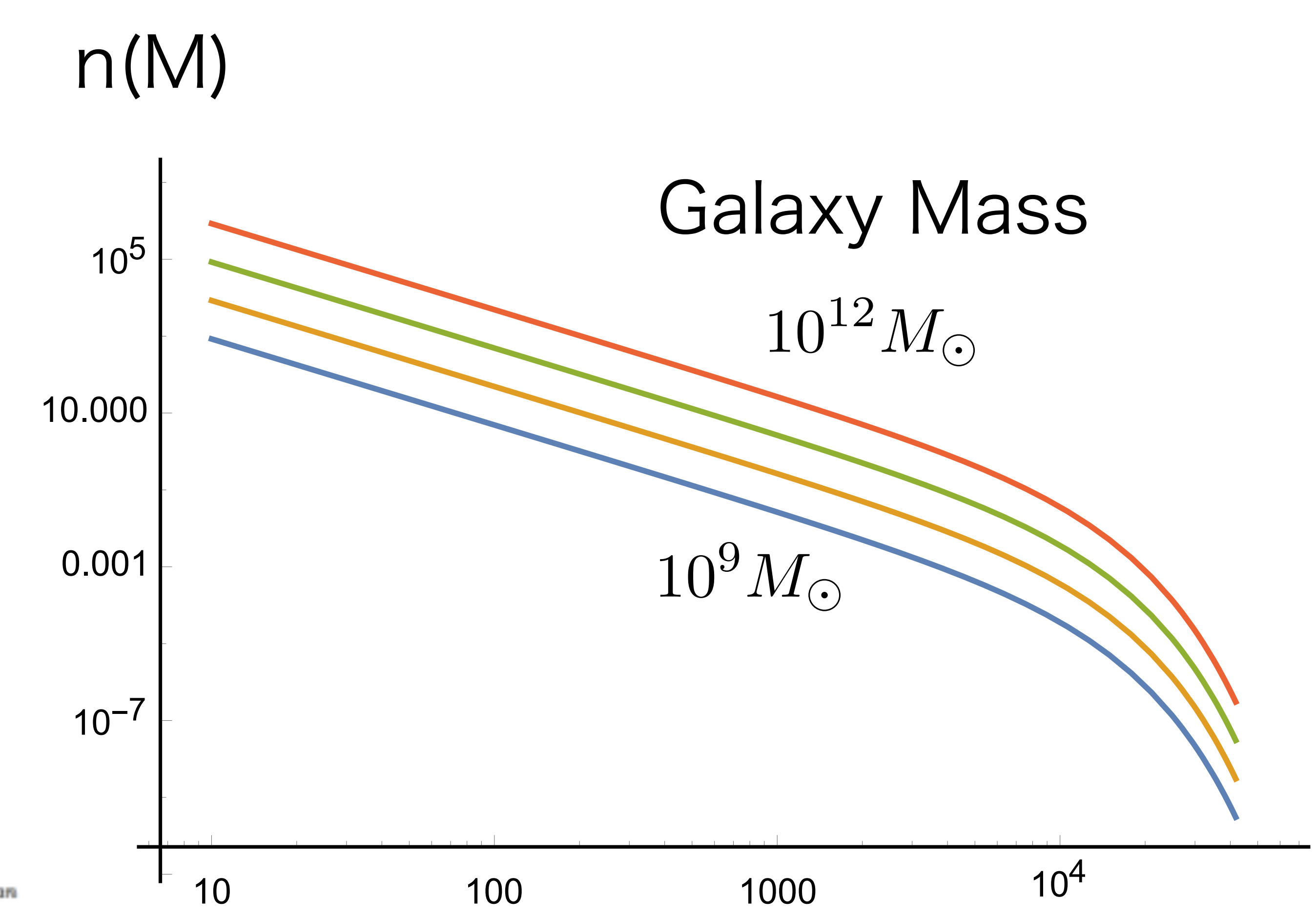
The initial mass function of star clusters that form in turbulent molecular clouds

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

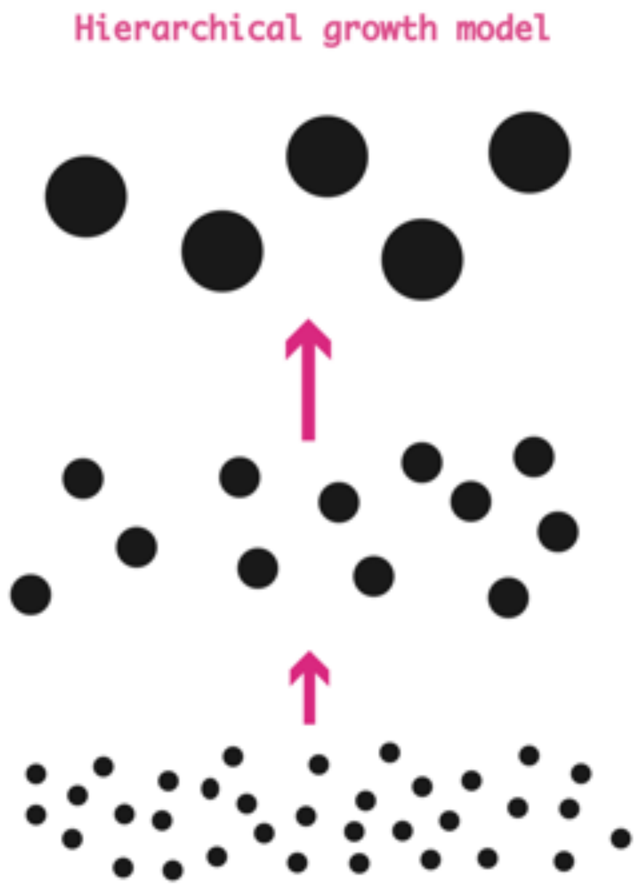
$$M_{c,\max} = 0.20 M_c^{0.76}$$

Building Block BH

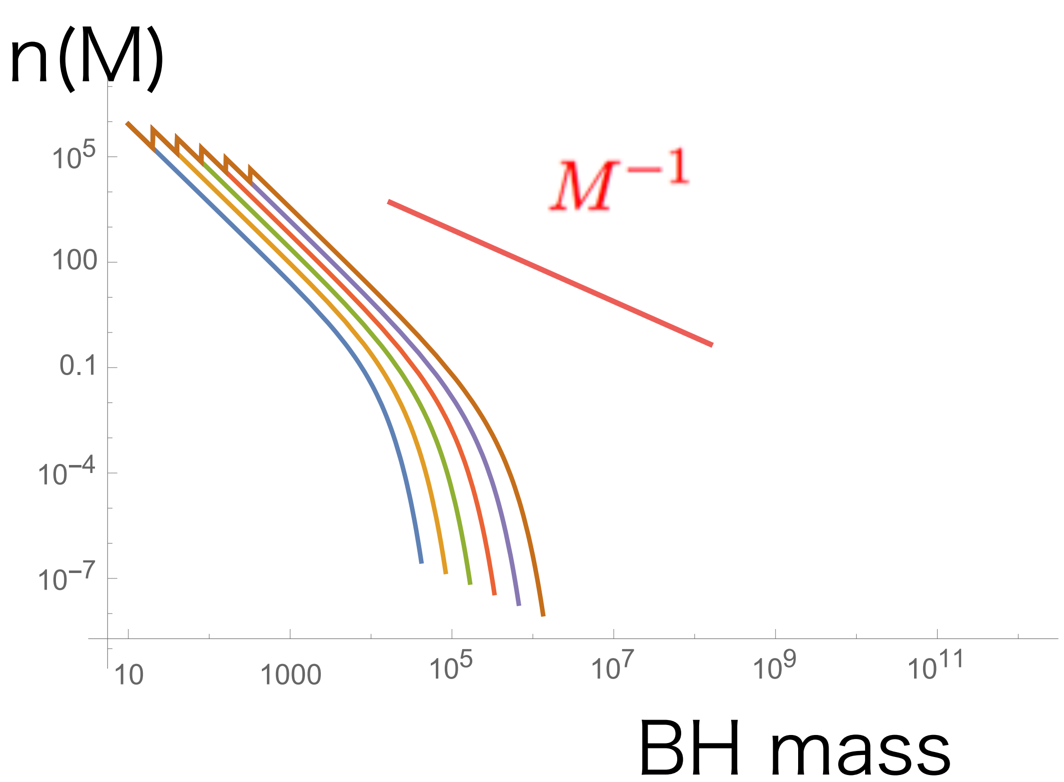


How many BHs in a Galaxy?

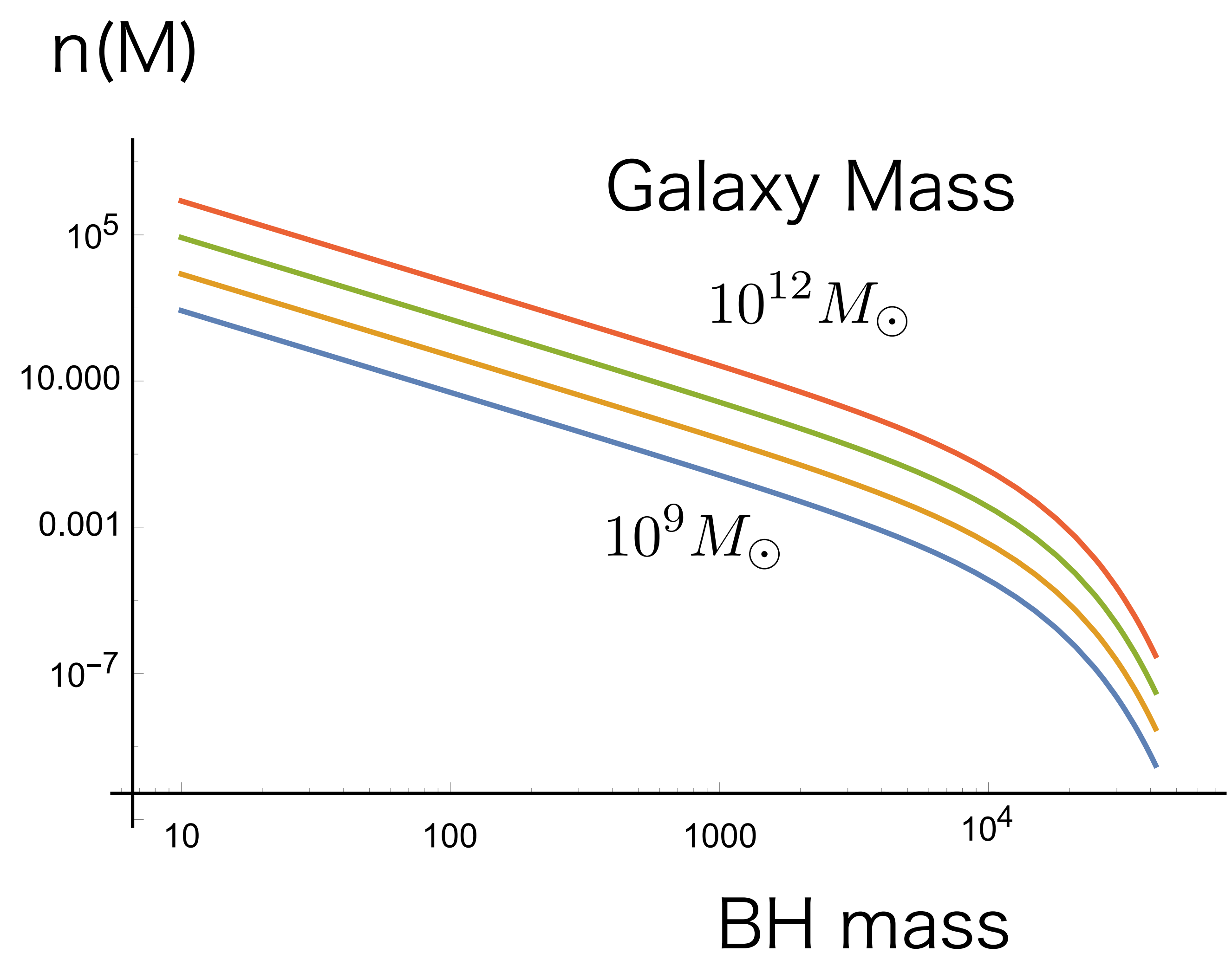
Count BHs to form a SMBH



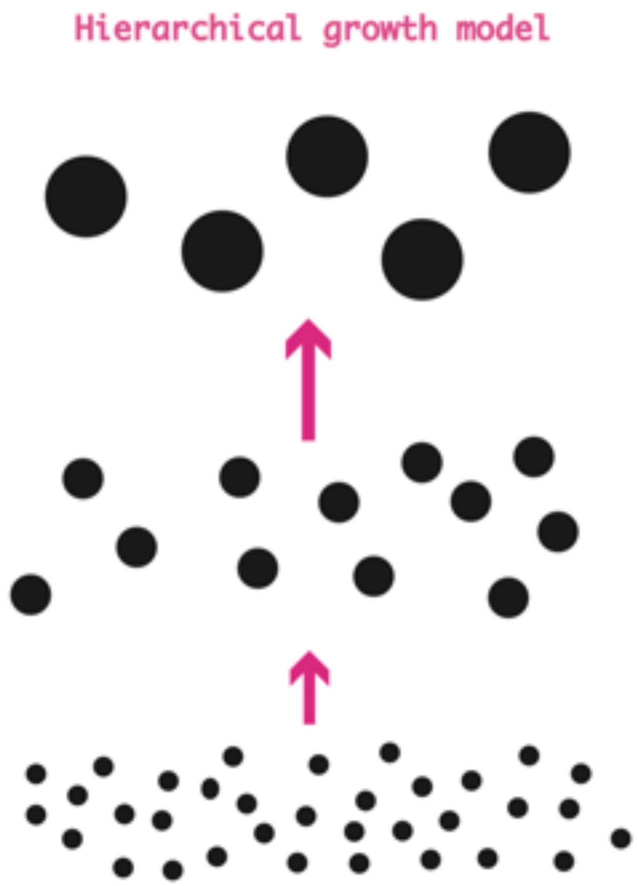
$$M_{k+1} = 2M_k$$
$$N_{k+1} = N_k/2$$



Building Block BH



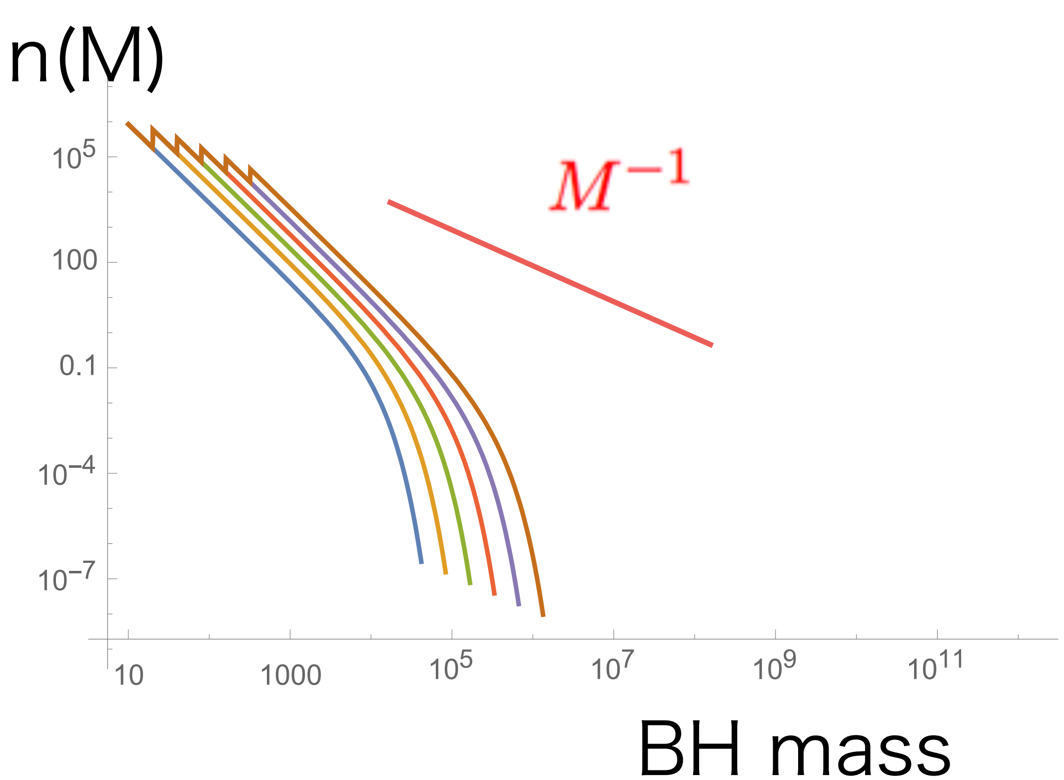
How many BHs in a Galaxy?



Count BHs to form a SMBH

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

dynamical friction



How many Galaxies in the Universe?

Count BHs to form a SMBH

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

(sub-)Galaxy from Halo model


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

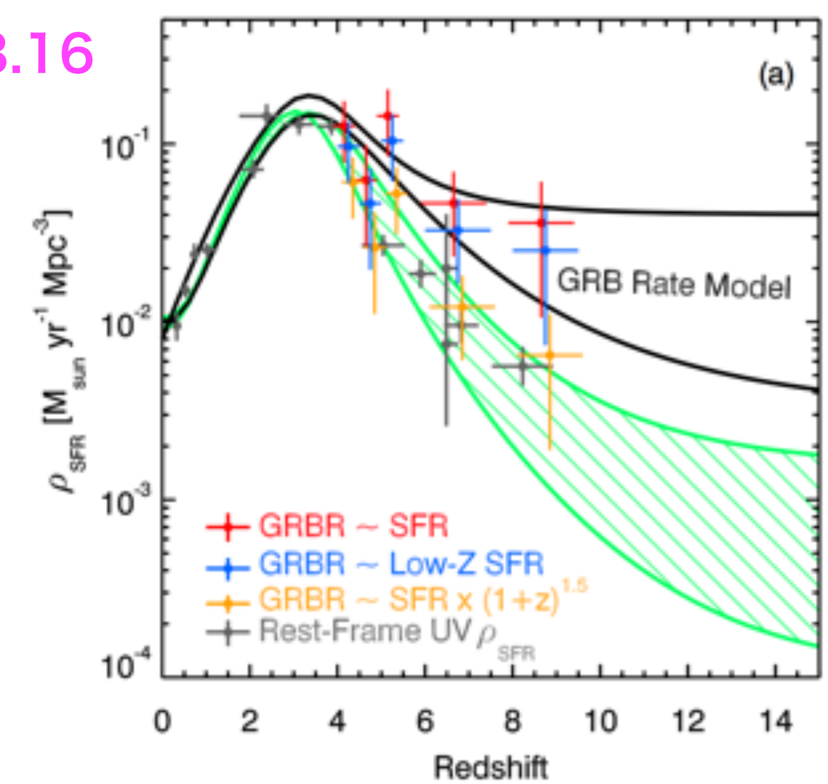
The non-parametric model for linking galaxy luminosity with halo/subhalo mass

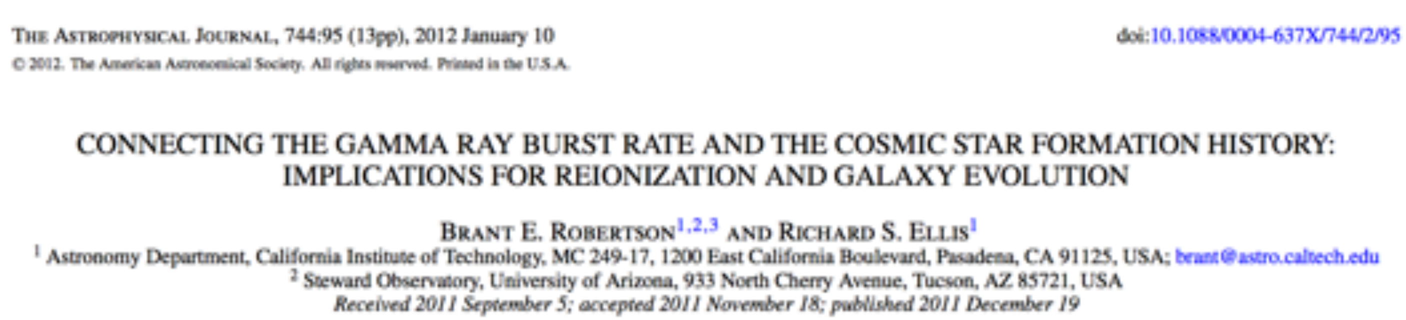
A. Vale[1]★ and J. P. Ostriker[1,2]

[1]Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA
[2]Princeton University Observatory, Princeton University, Princeton, NJ 08544, USA

Star Formation Rate

peak z=3.16




The Astrophysical Journal, 744:95 (13pp), 2012 January 10 doi:10.1088/0004-637X/744/2/95
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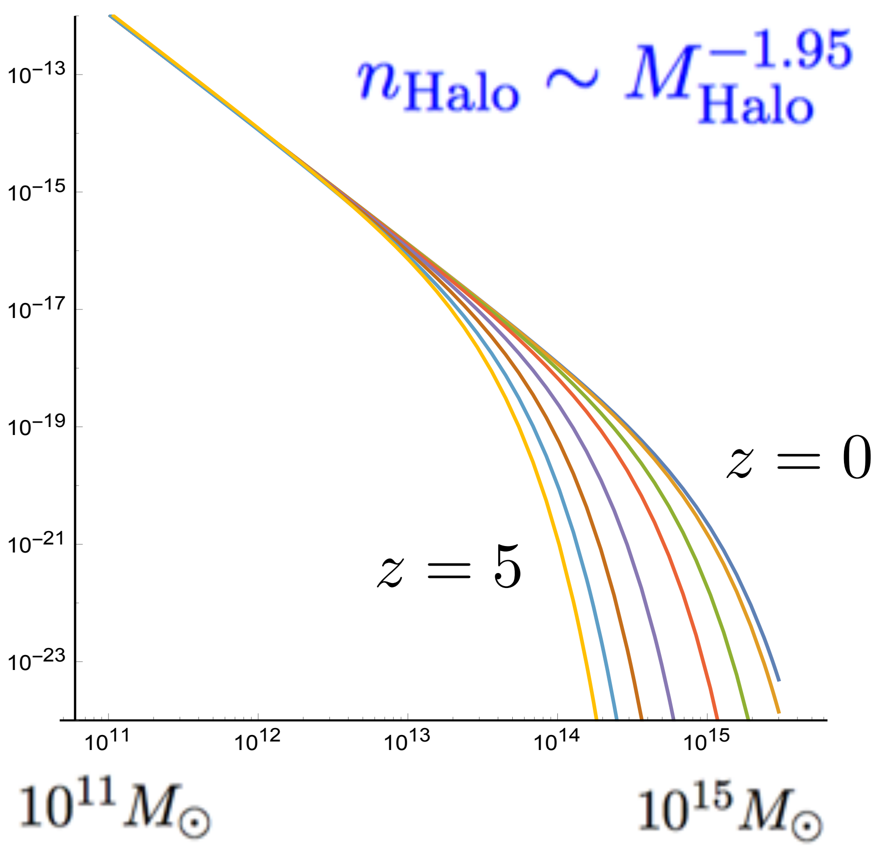
CONNECTING THE GAMMA RAY BURST RATE AND THE COSMIC STAR FORMATION HISTORY: IMPLICATIONS FOR REIONIZATION AND GALAXY EVOLUTION

Brant E. Robertson[1,2,3] 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

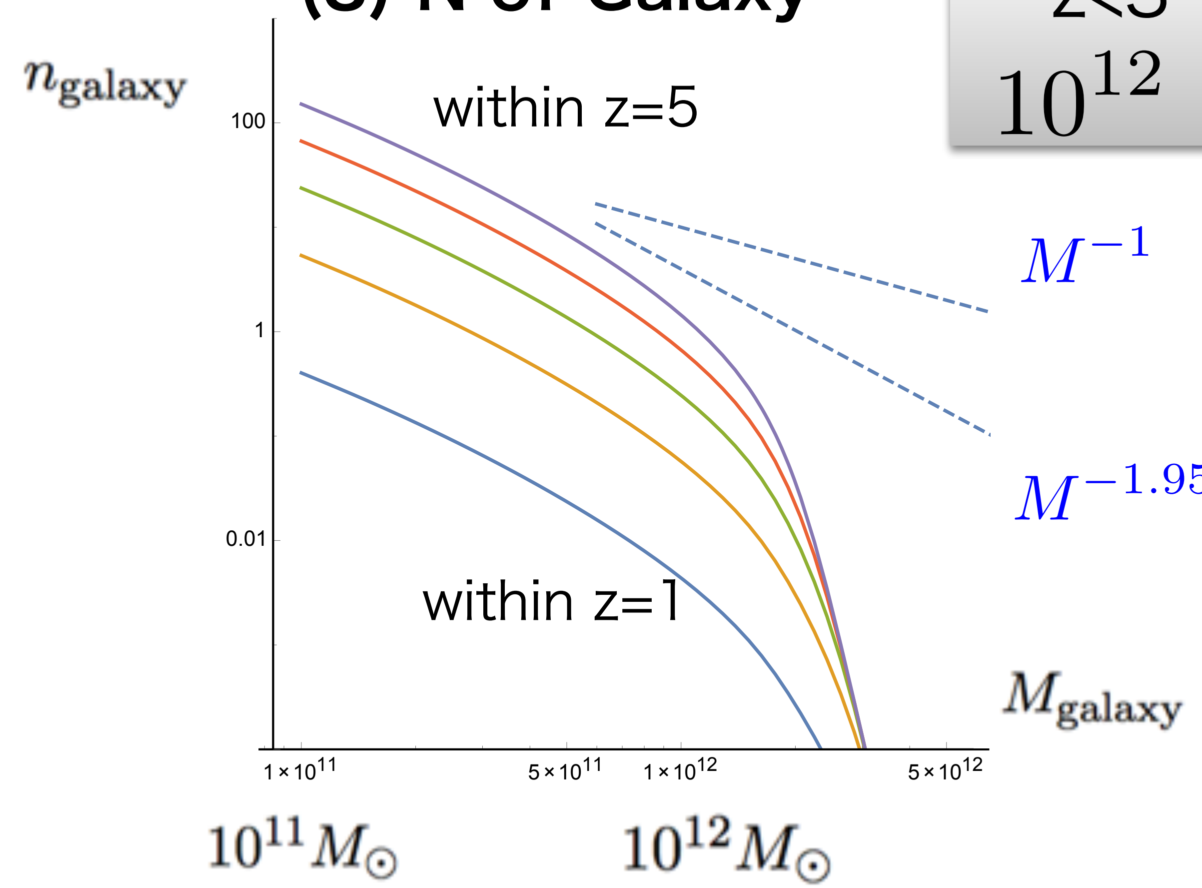
How many Galaxies in the Universe?

(1) Halo number density

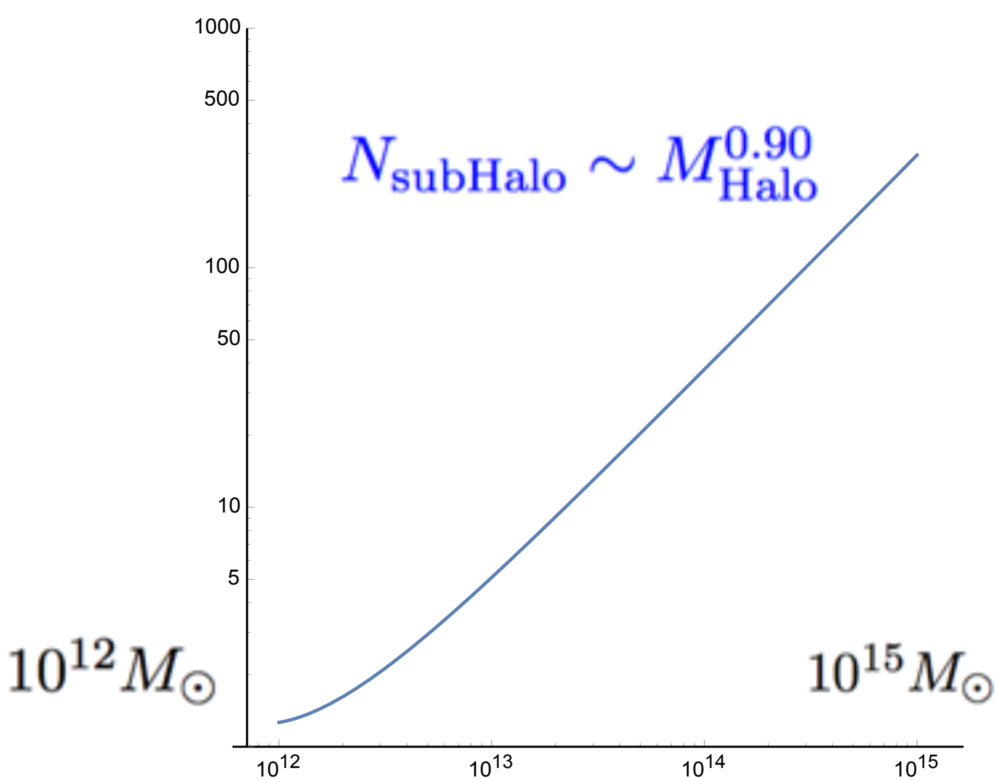


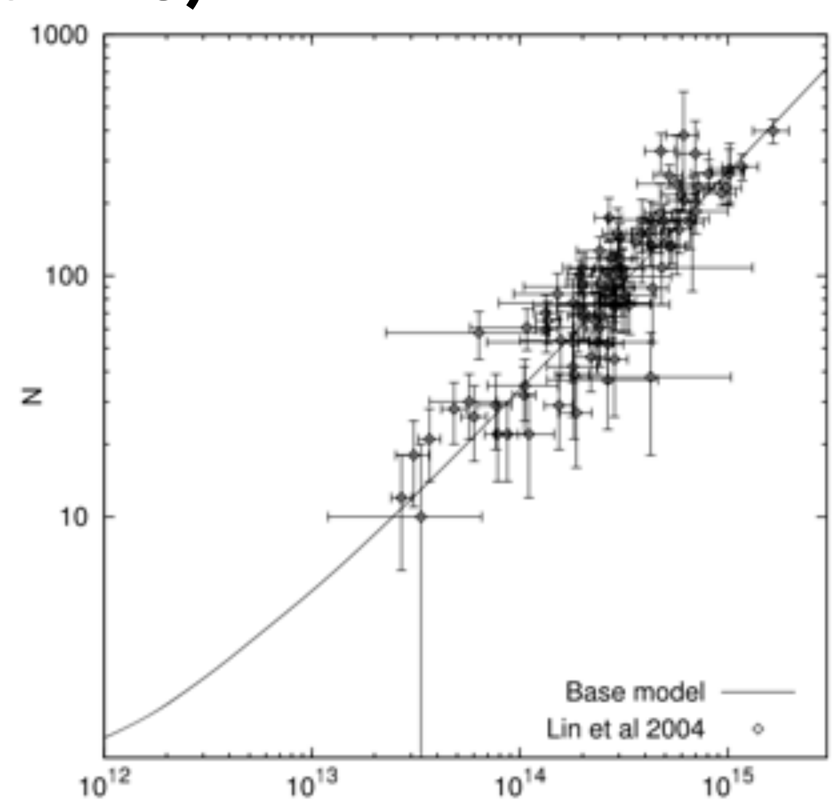
(3) N of Galaxy

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,

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YOU ARE HERE: Home > News & Press > A universe of two trillion galaxies

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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 $z\sim8$ 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

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

(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

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[2]Princeton University Observatory, Princeton University, Princeton, NJ 08544, USA

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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

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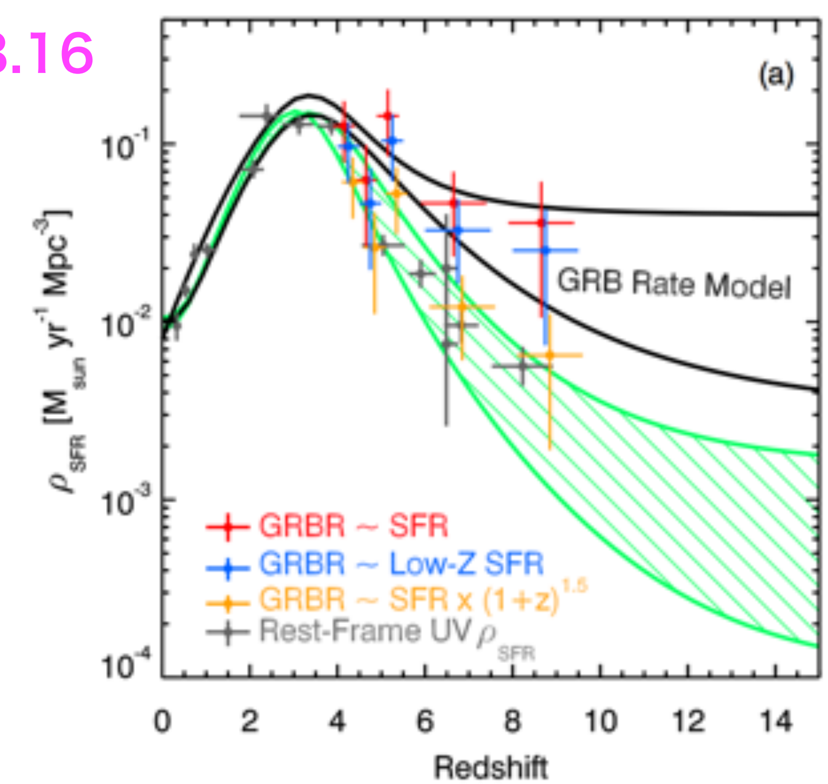
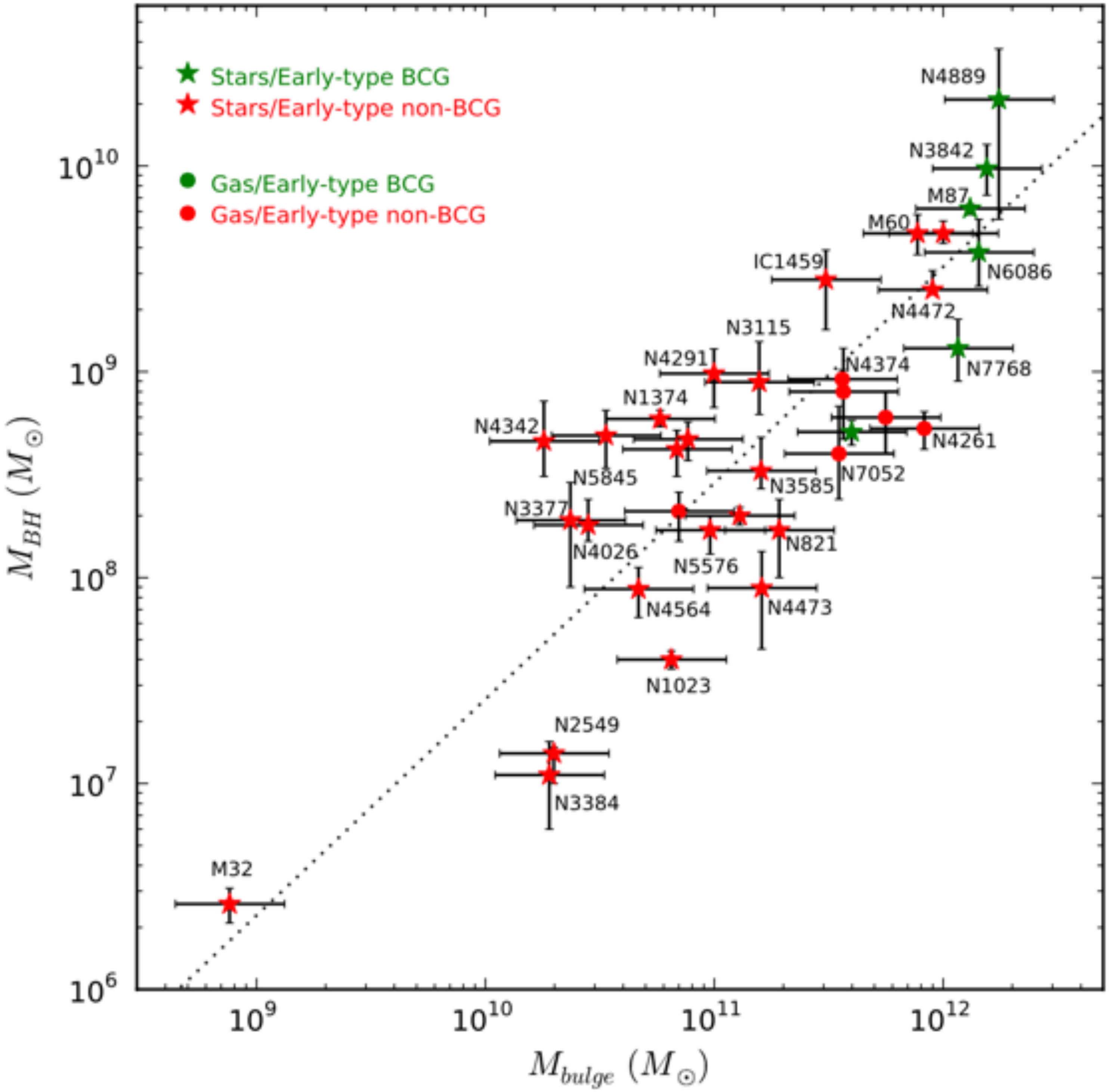


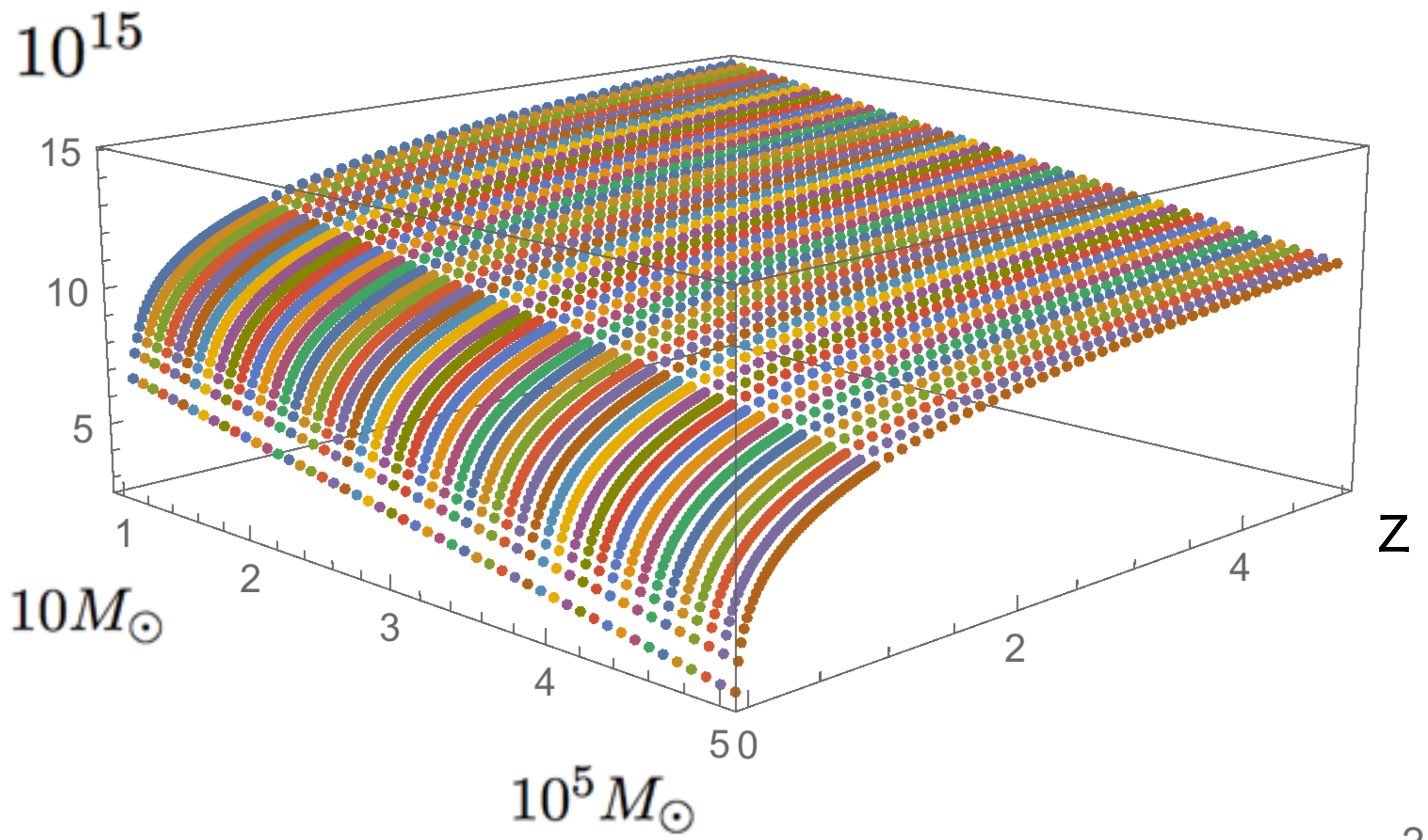


$$
\begin{aligned}
M_{\rm SMBH} &= 2\times 10^{-4} M_{\rm galaxy} \\
&= 10^{-3} M_{\rm bulge}
\end{aligned}
$$

McConnell-Ma
ApJ 764(2013)184

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

How many BH mergers in the Universe?



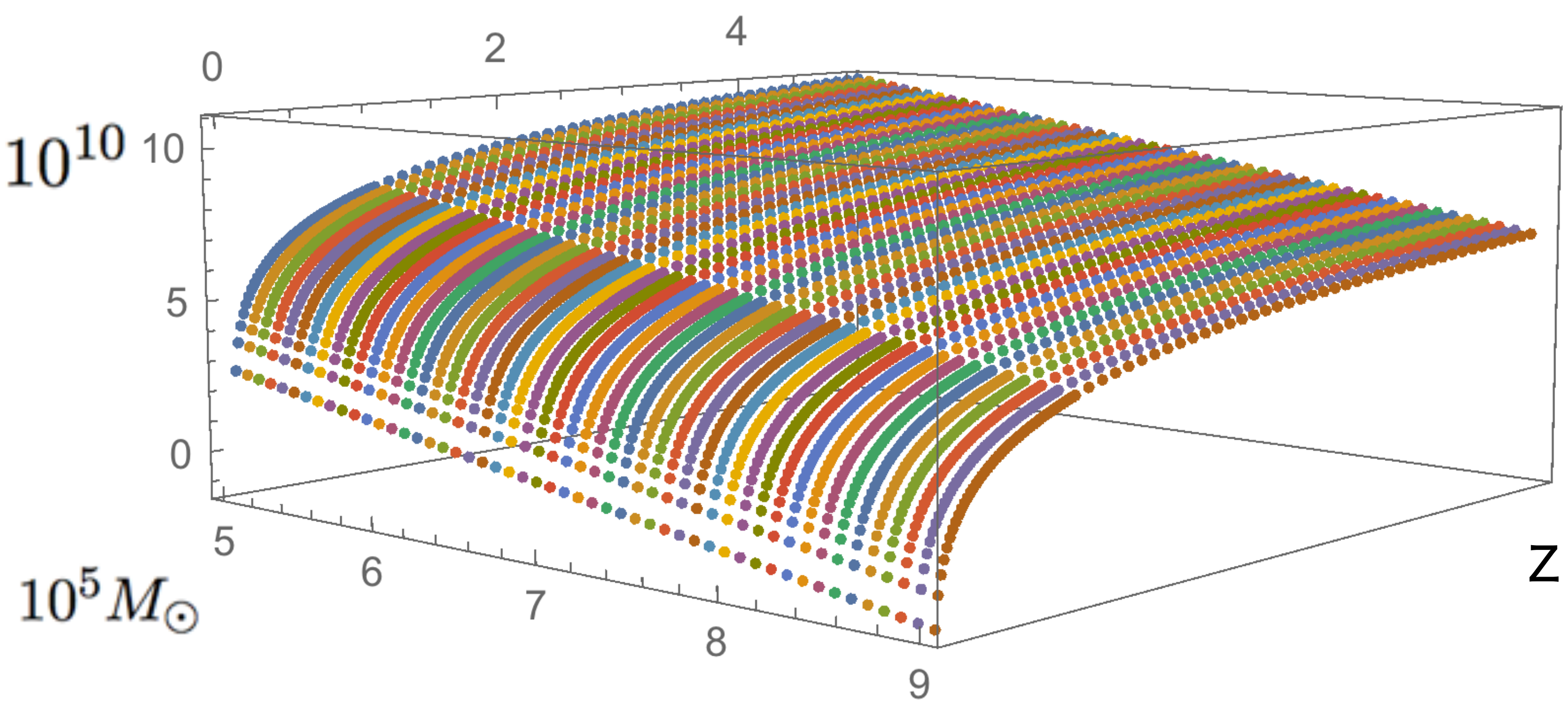
BH mass

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, $n(t)$:

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

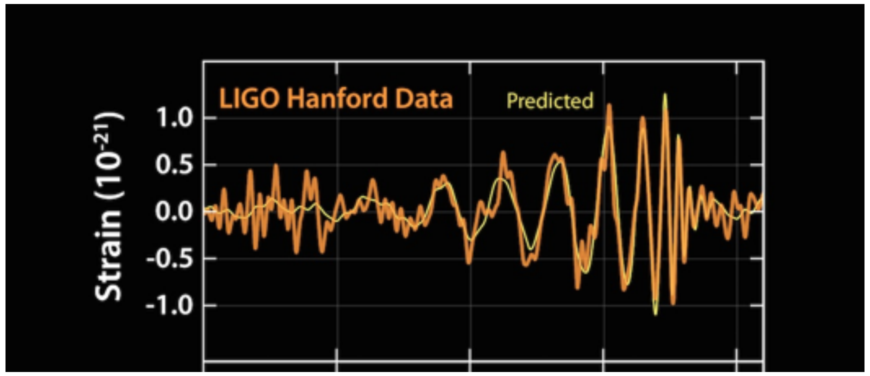
The standard procedure for the detection is judged by the optimal signal-to-noise ratio (SNR), ρ, which is given by

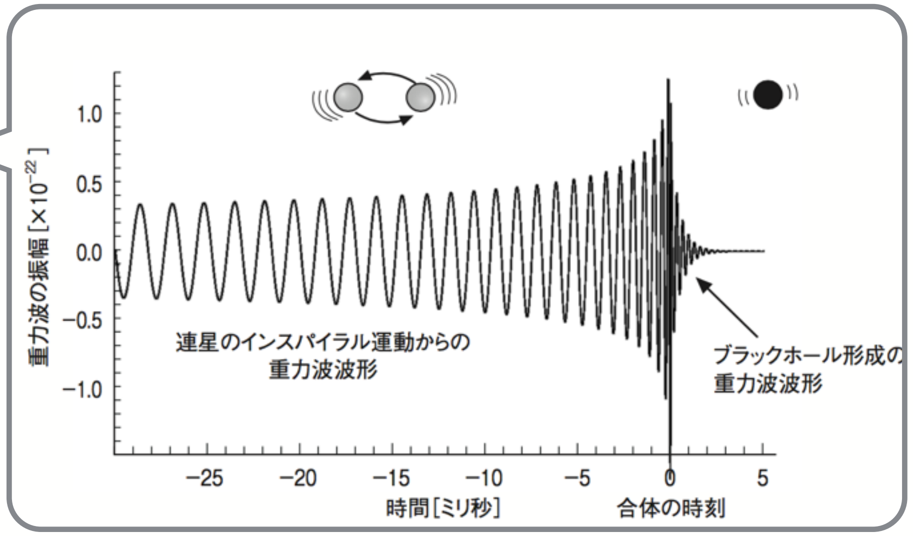
$$\rho = 2\left[\int_0^\infty \frac{\tilde{h}(f)\,\tilde{h}^*(f)}{S_n(f)}\,df\right]^{1/2}, \tag{18}$$

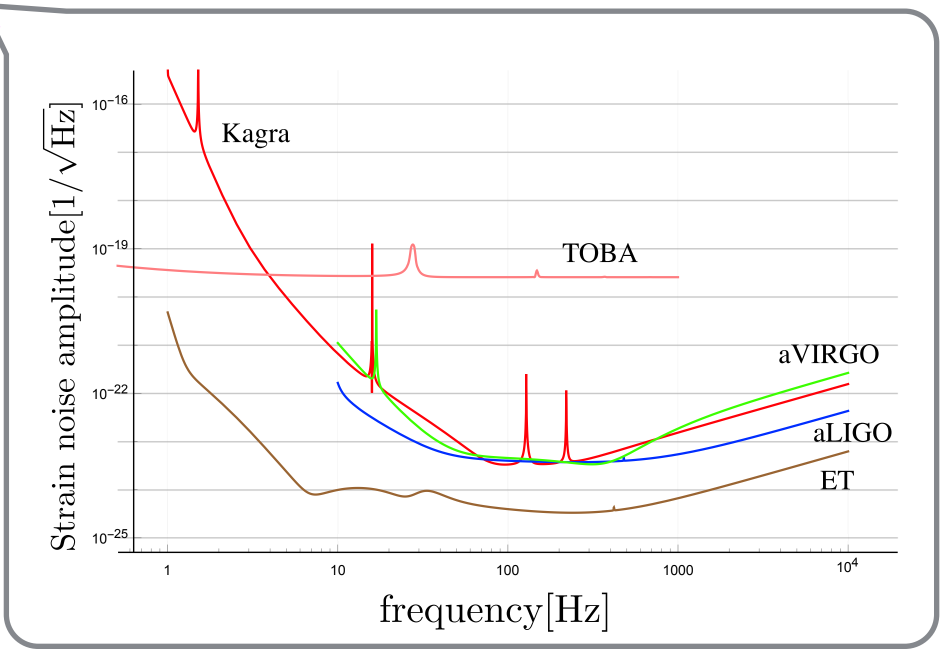
where $\tilde{h}(f)$ is the Fourier-transformed quantity of the wave,

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

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

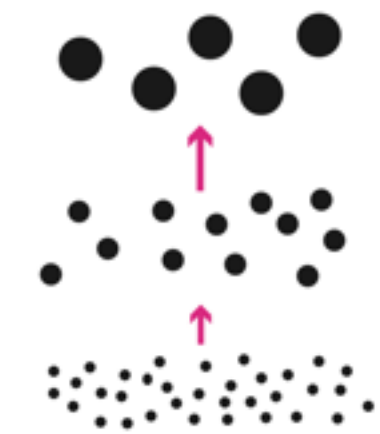
Flanagan&Hughes, PRD57(198)4535

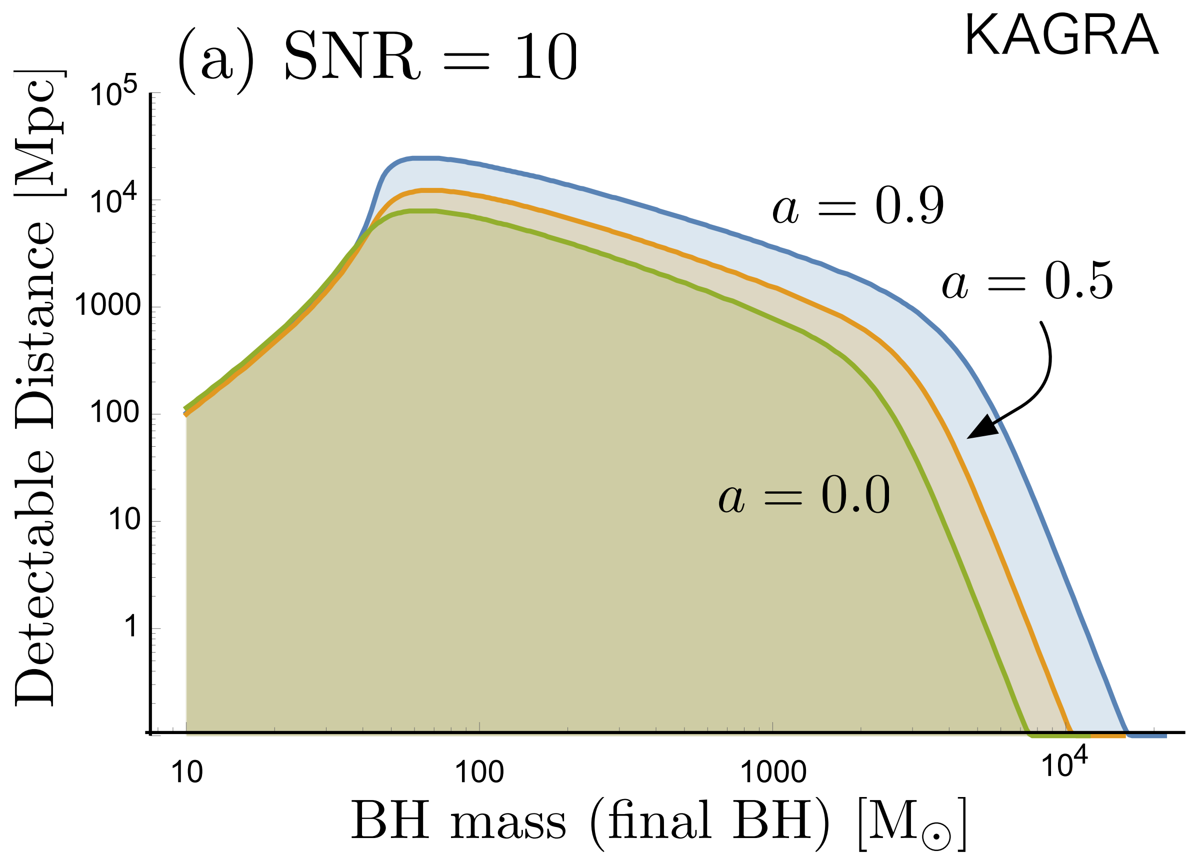
SNR $$\rho^2 = \frac{8}{5}\frac{\epsilon_r(a)}{f_R^2}\frac{(1+z)M}{S_h(f_R/(1+z))}\left(\frac{(1+z)M}{d_L(z)}\right)^2\left(\frac{4\mu}{M}\right)^2$$

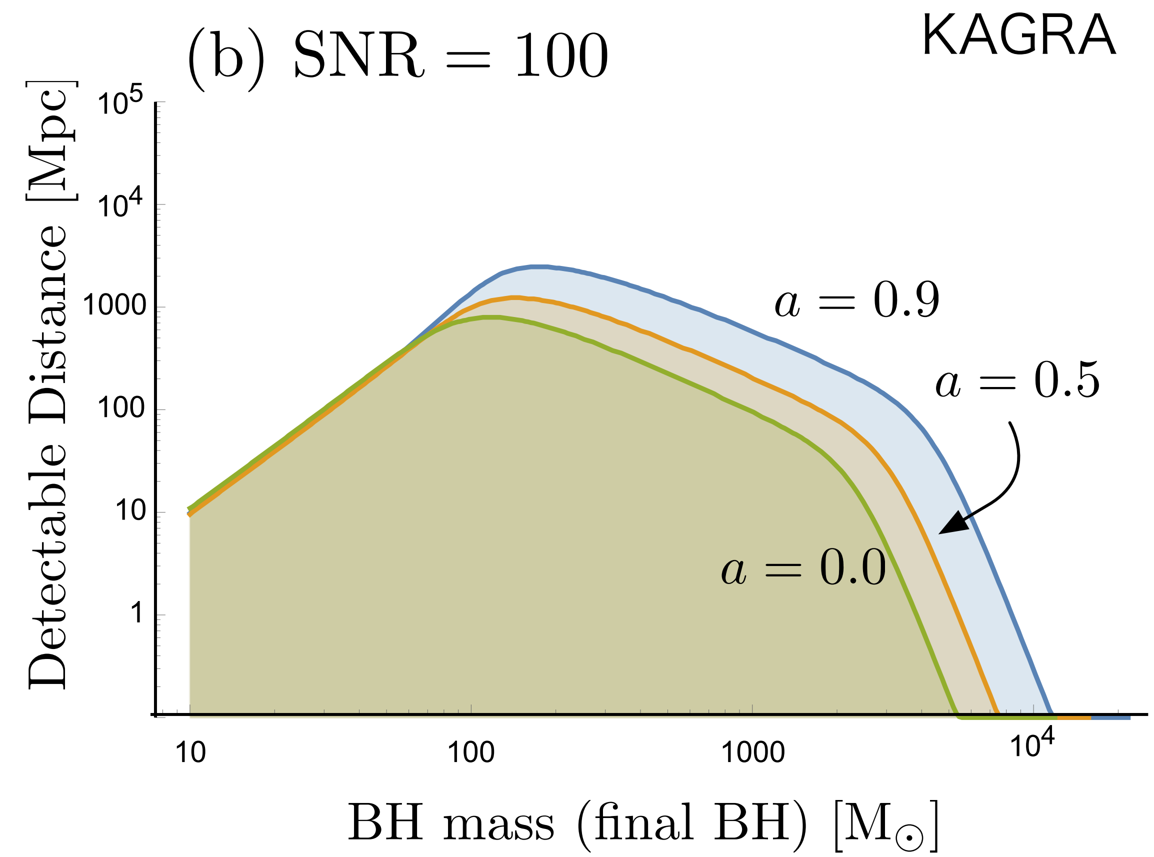
Energy emission=4% of total M, 1% at ringdown

Standard Cosmology

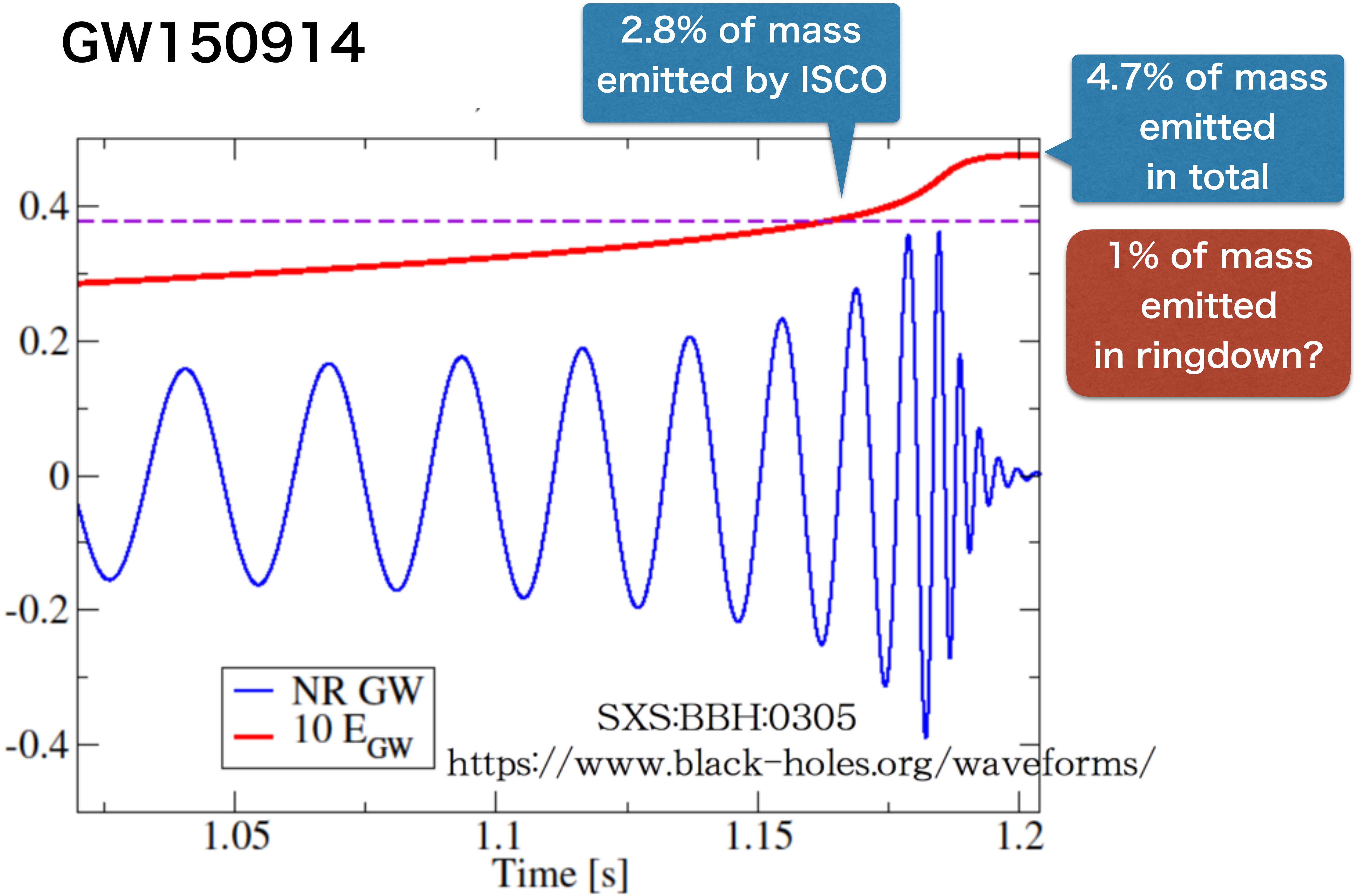
Hierarchical Growth





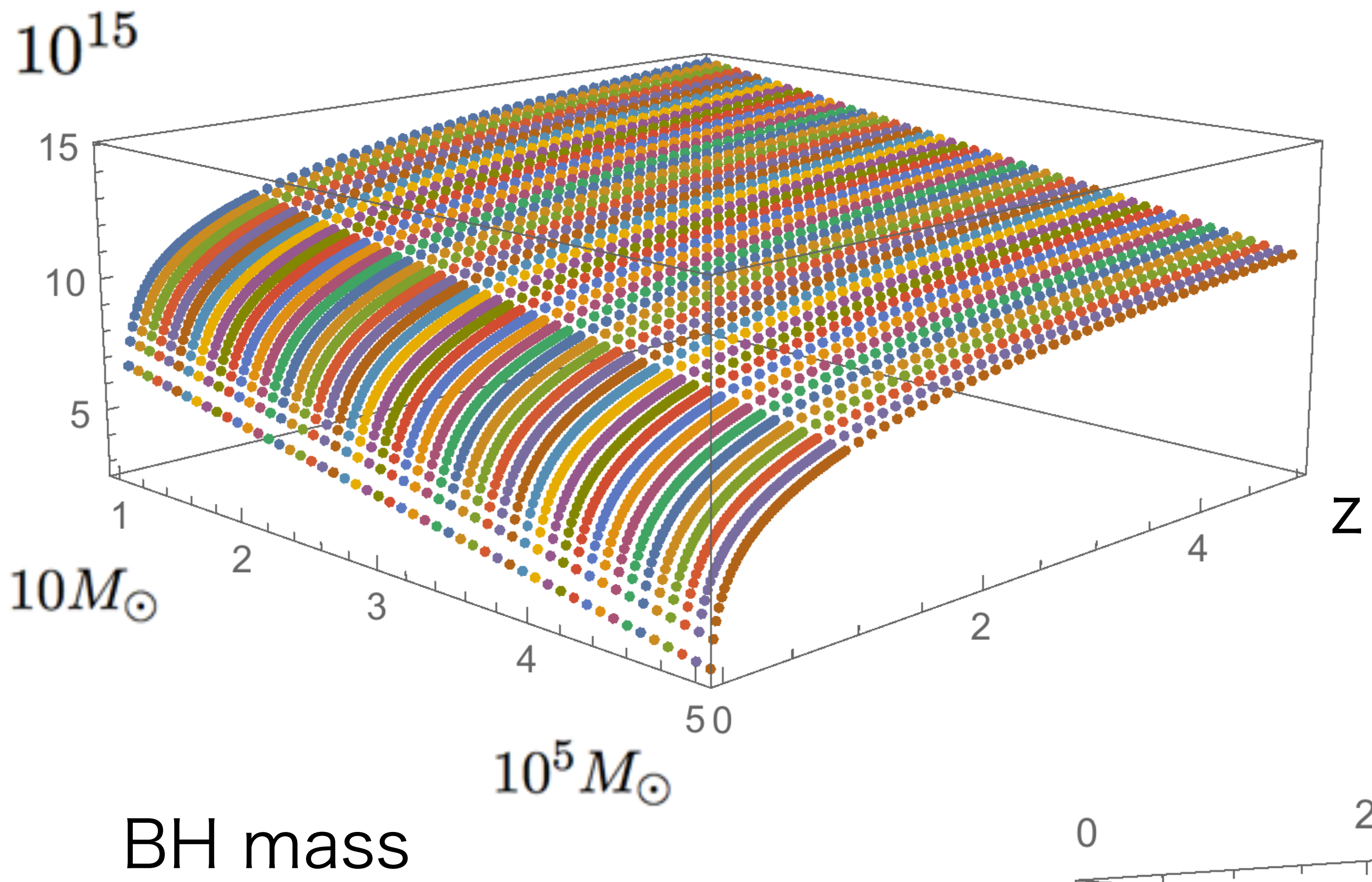


GW150914



Slide copy from Hiroyuki Nakano

How many BH mergers in the Universe?

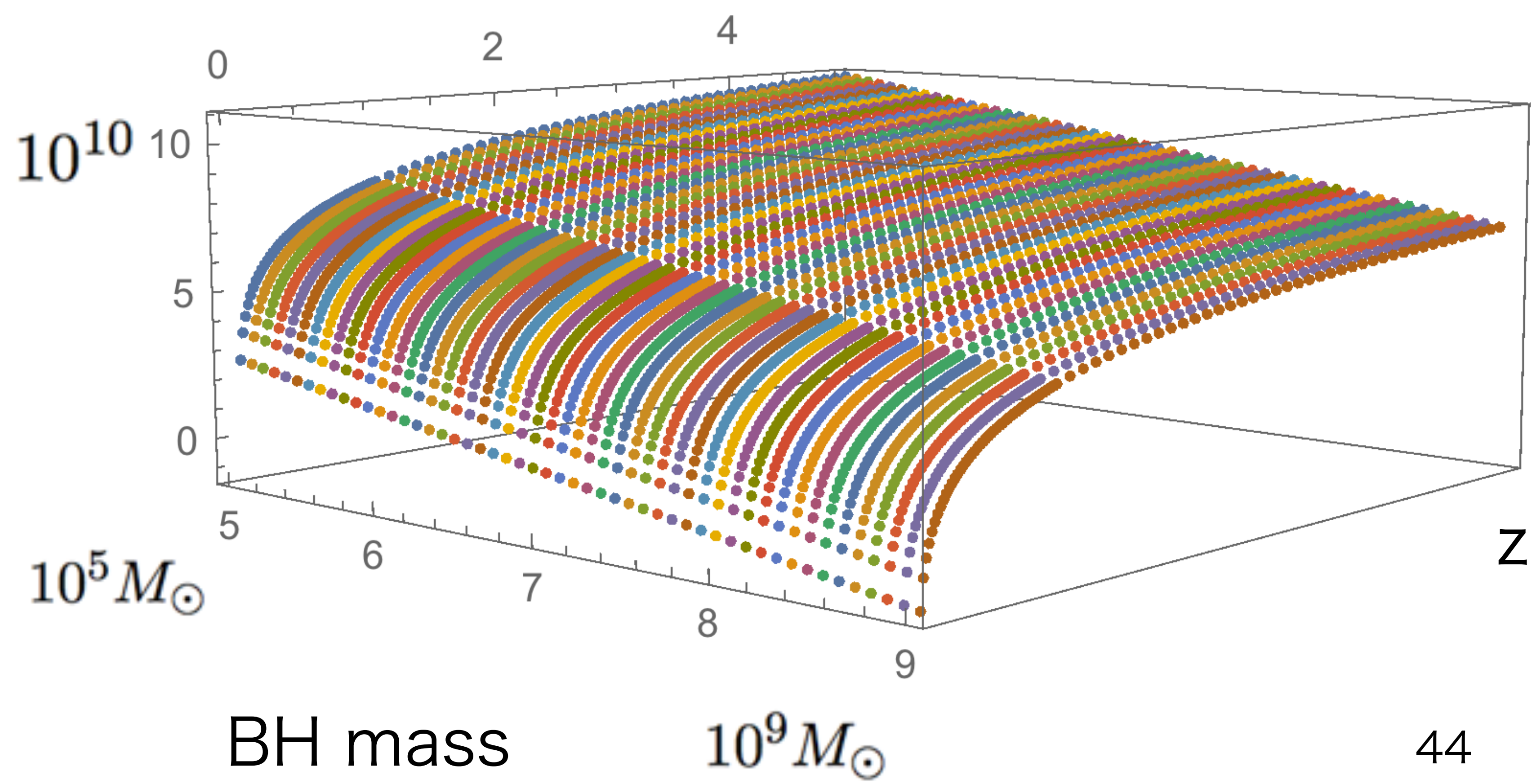


in Standard Cosmology

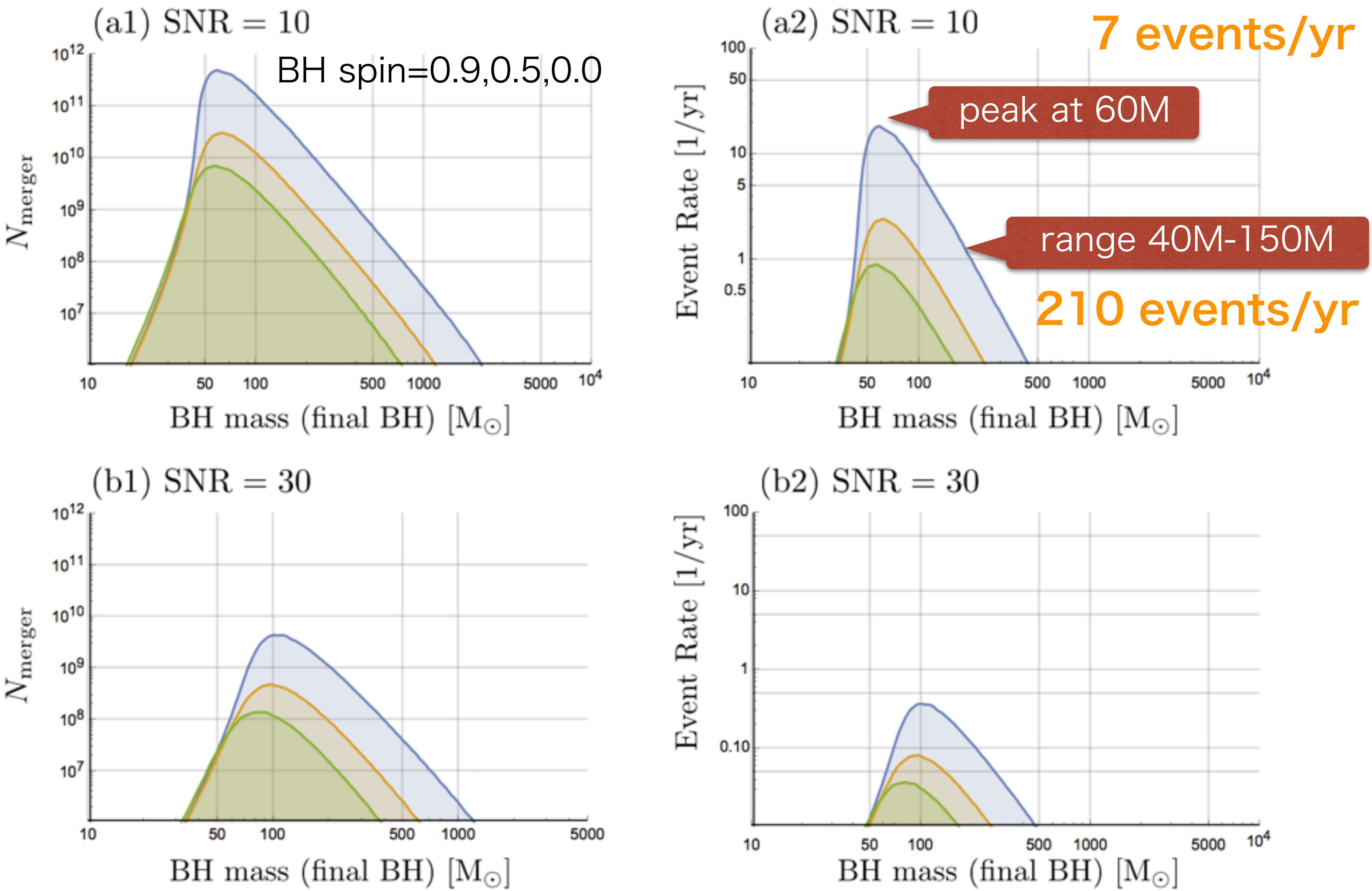
$$\text{Event Rate } R[/\text{yr}] = \frac{N_{\text{merger}}(z)}{V(D/2.26)}$$

Standard Cosmology

averaging distances for all directions



Event Rates at bKAGRA



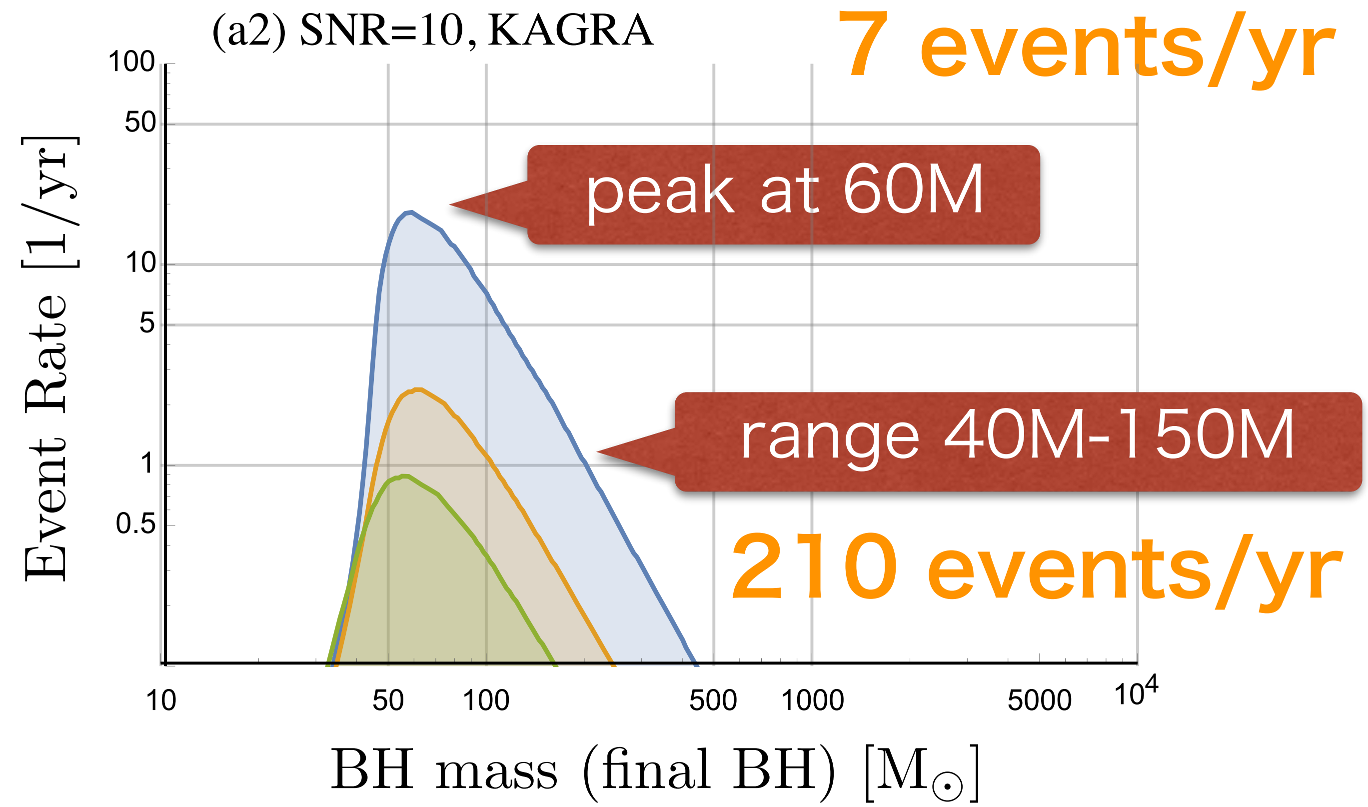
Event Rates at bKAGRA/aLIGO

LIGO group [1602.03842]

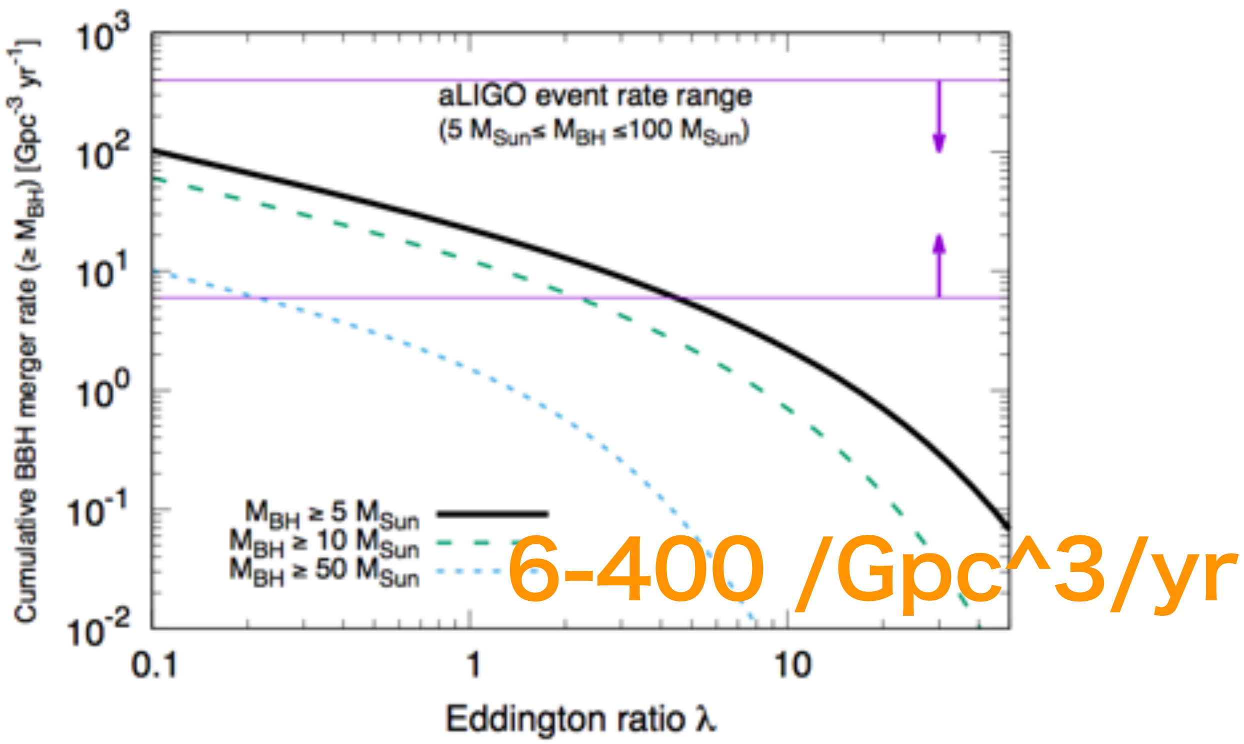
The Astrophysical Journal Letters, 833:L1 (8pp), 2016 December 10

Table 1
Rates of BBH Mergers Estimated under Various Assumptions

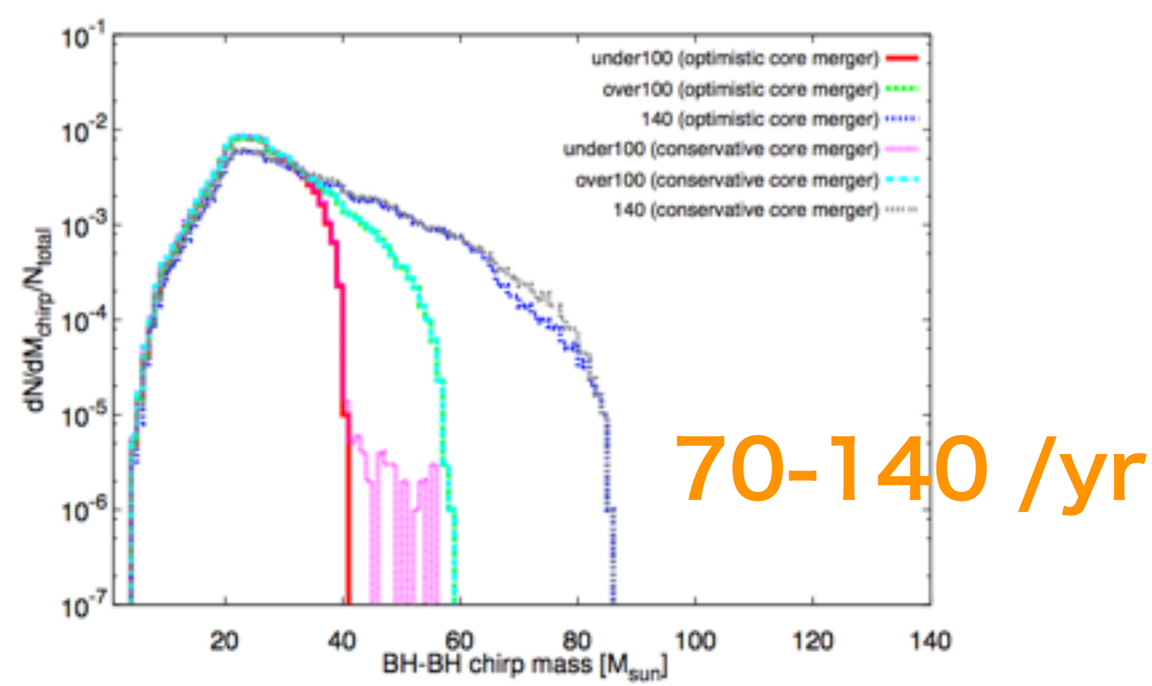
Mass Distribution	$R/(\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1})$		
	pycbc	gstlal	Combined
GW150914	16^{+38}_{-13}	17^{+39}_{-14}	17^{+39}_{-13}
LVT151012	61^{+152}_{-53}	62^{+164}_{-55}	62^{+165}_{-54}
Both	82^{+155}_{-61}	84^{+172}_{-64}	83^{+168}_{-63}
Astrophysical			
Flat in log mass	63^{+121}_{-49}	60^{+122}_{-48}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



Inoue+ MNRAS461(16)4329



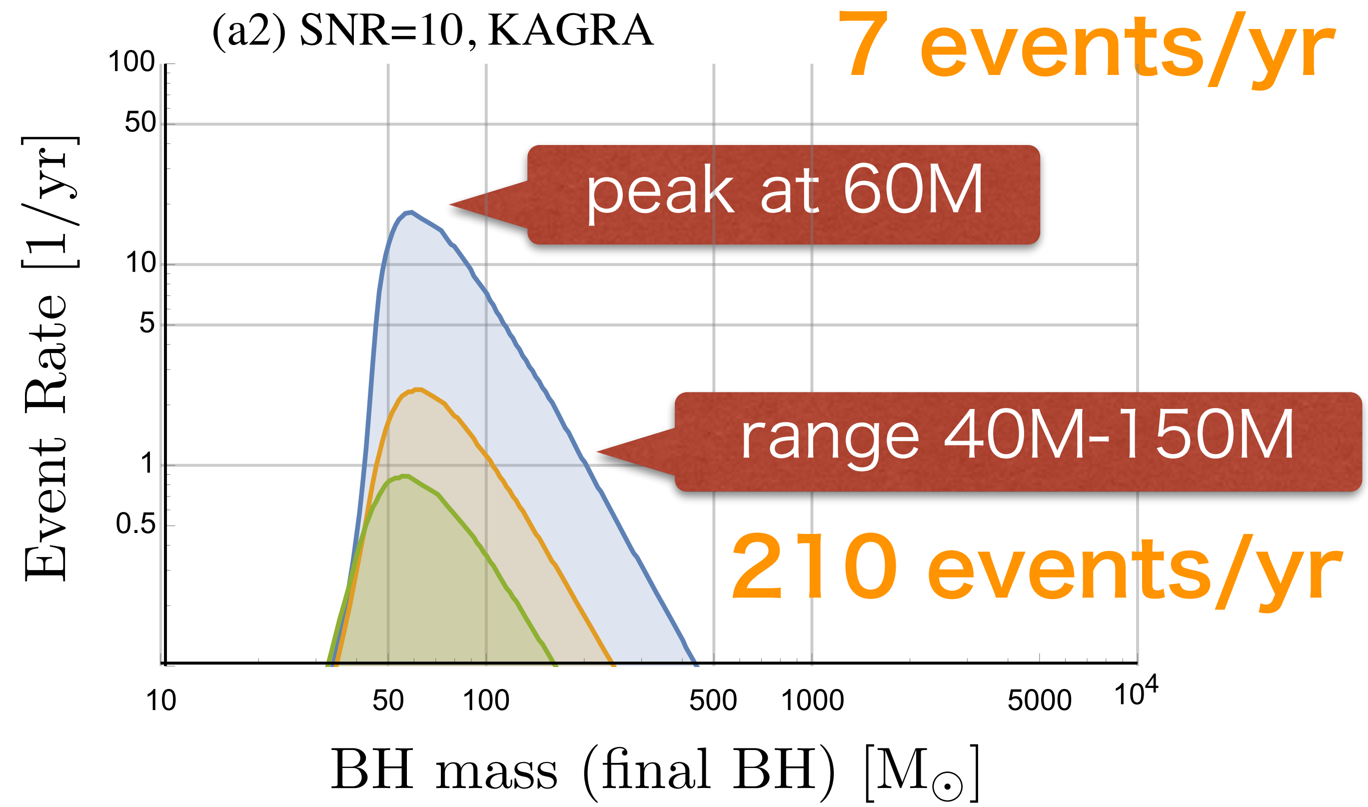
Kinugawa+ MNRAS456(15)1093



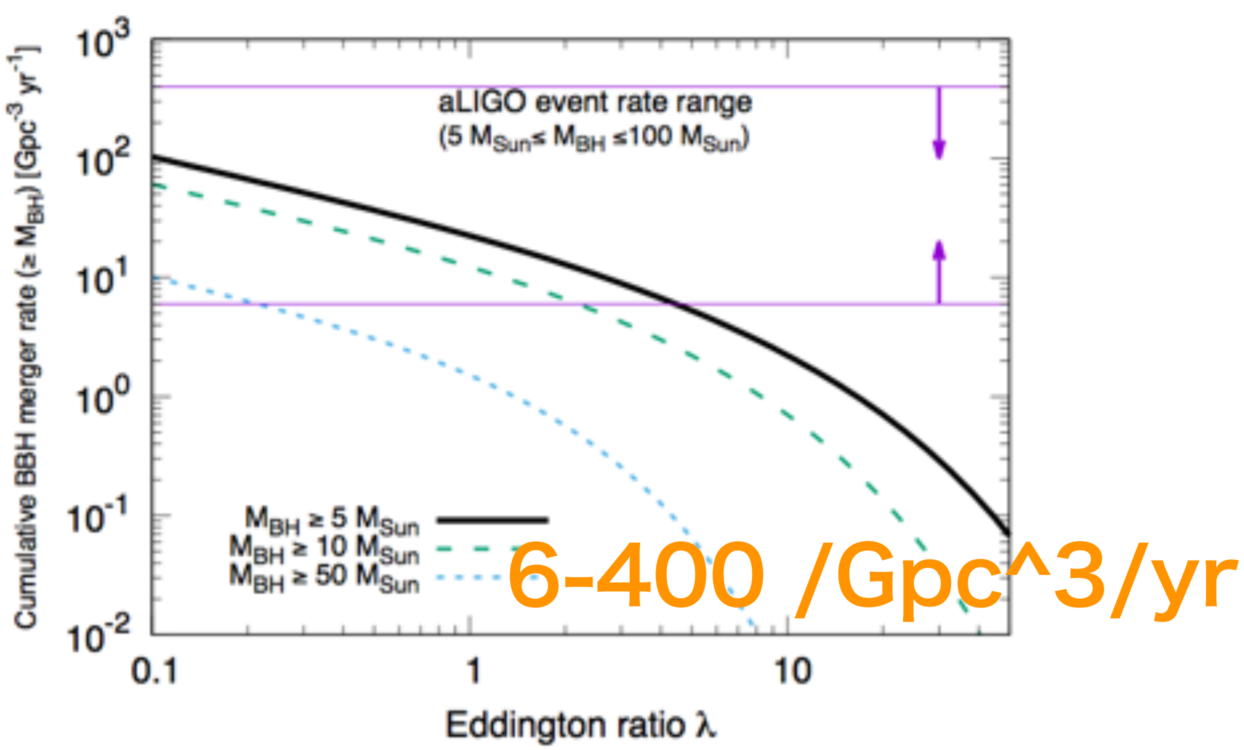
Event Rates at bKAGRA/aLIGO

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}



Inoue+ MNRAS461(16)4329



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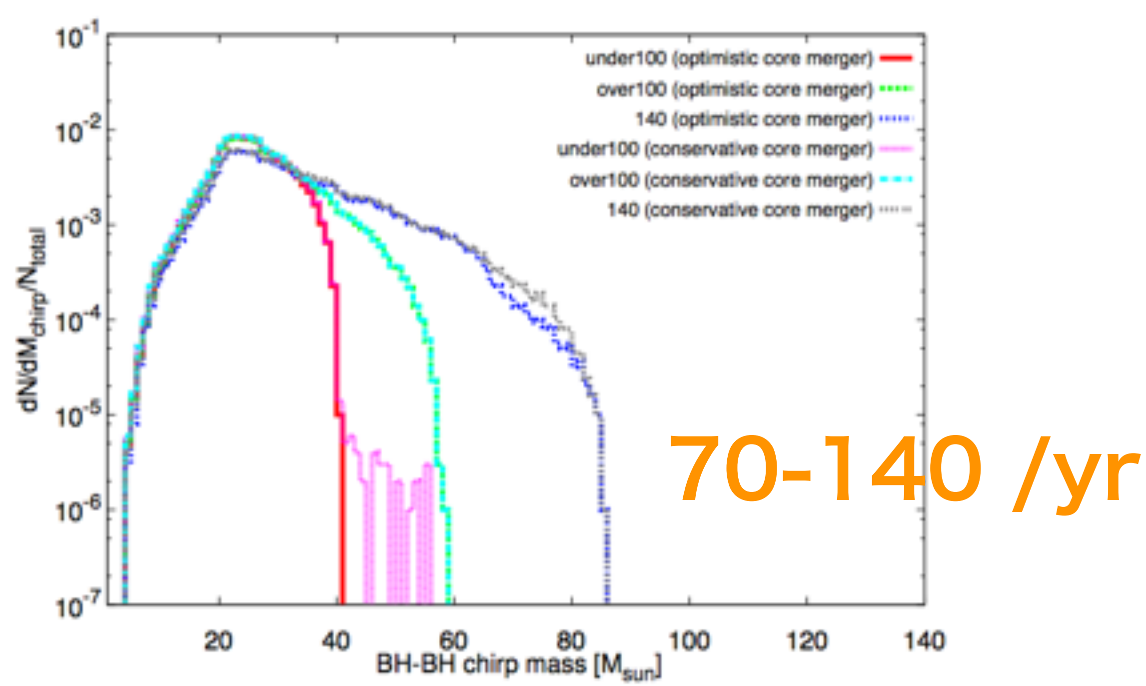
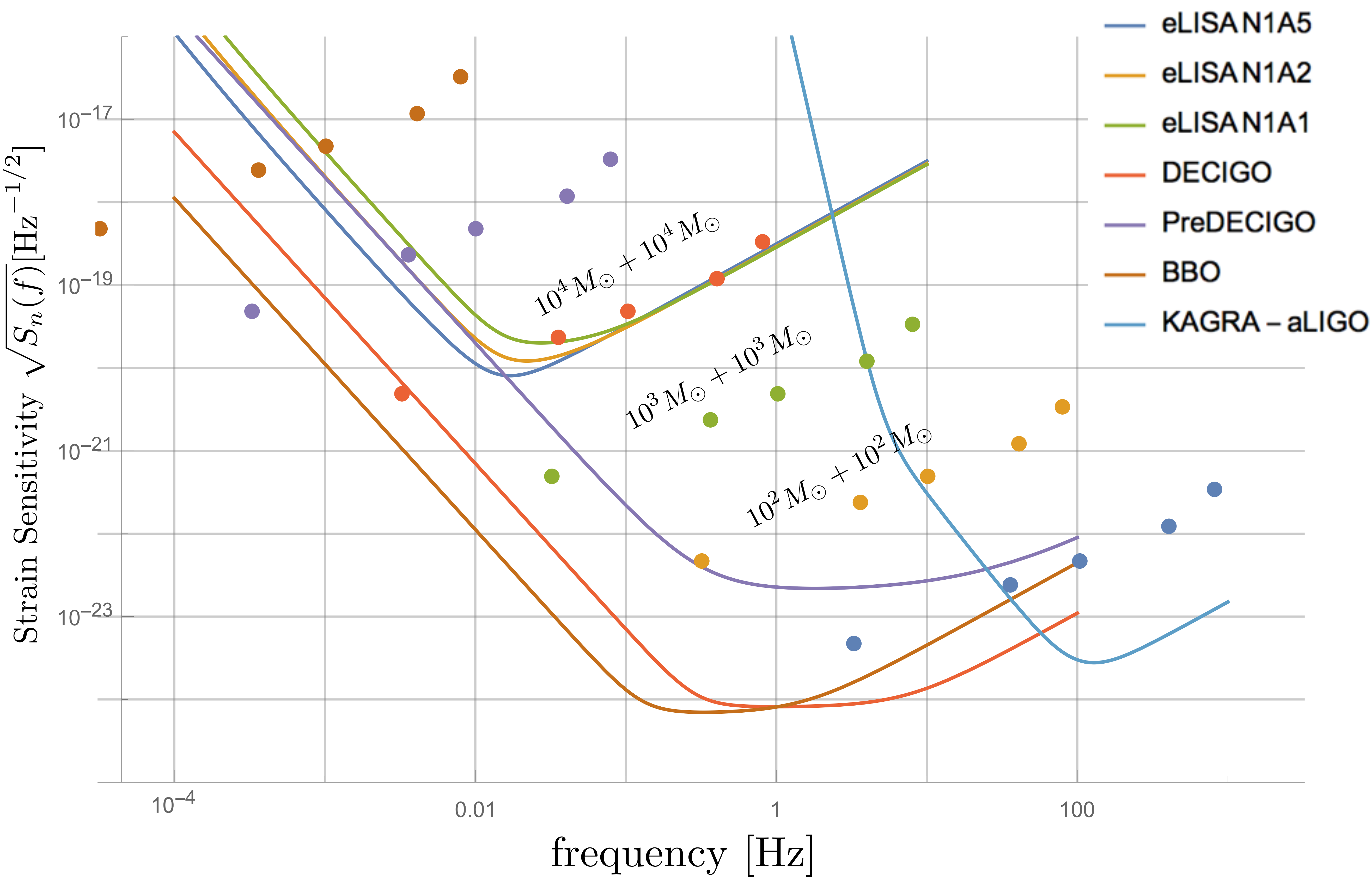
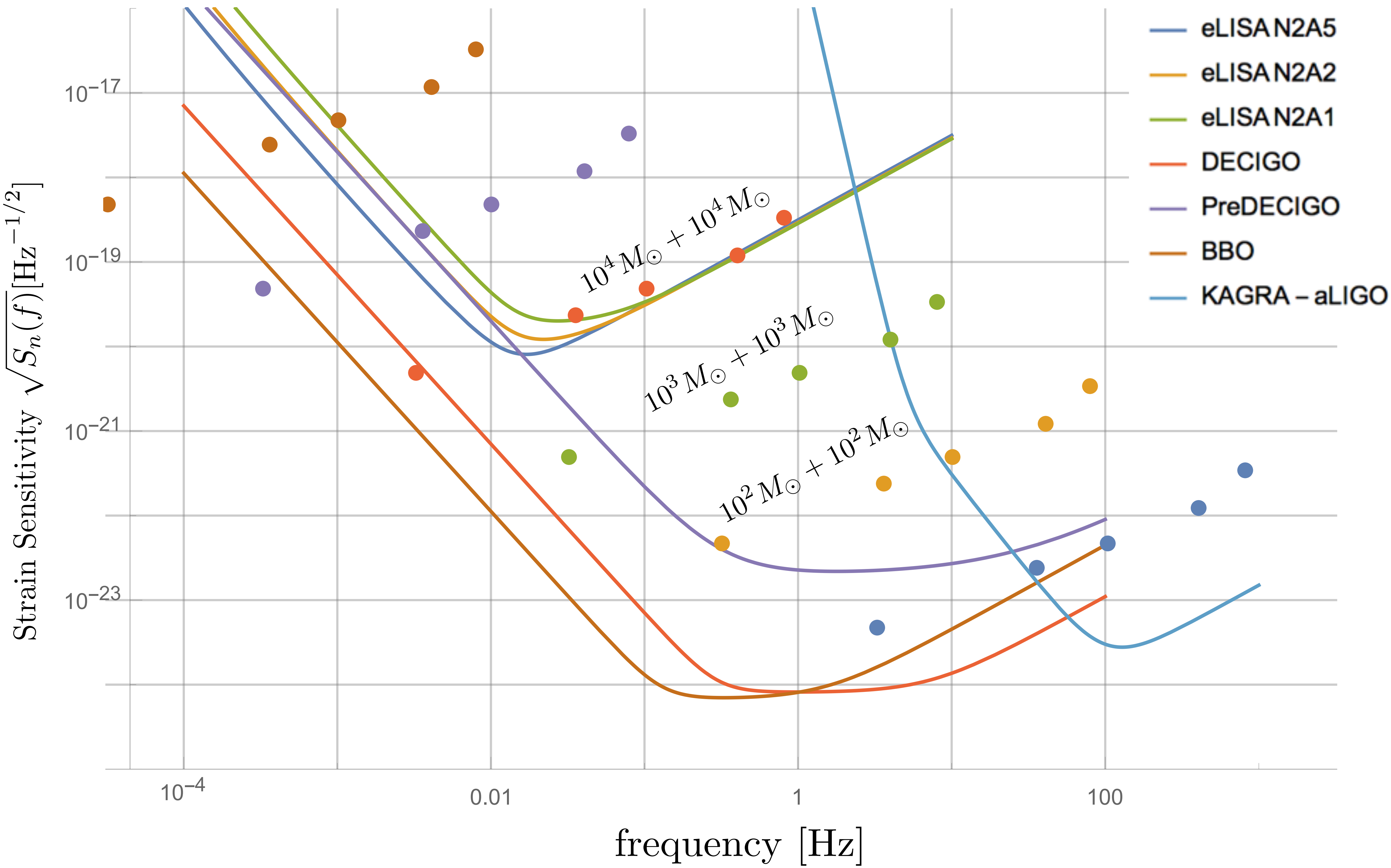


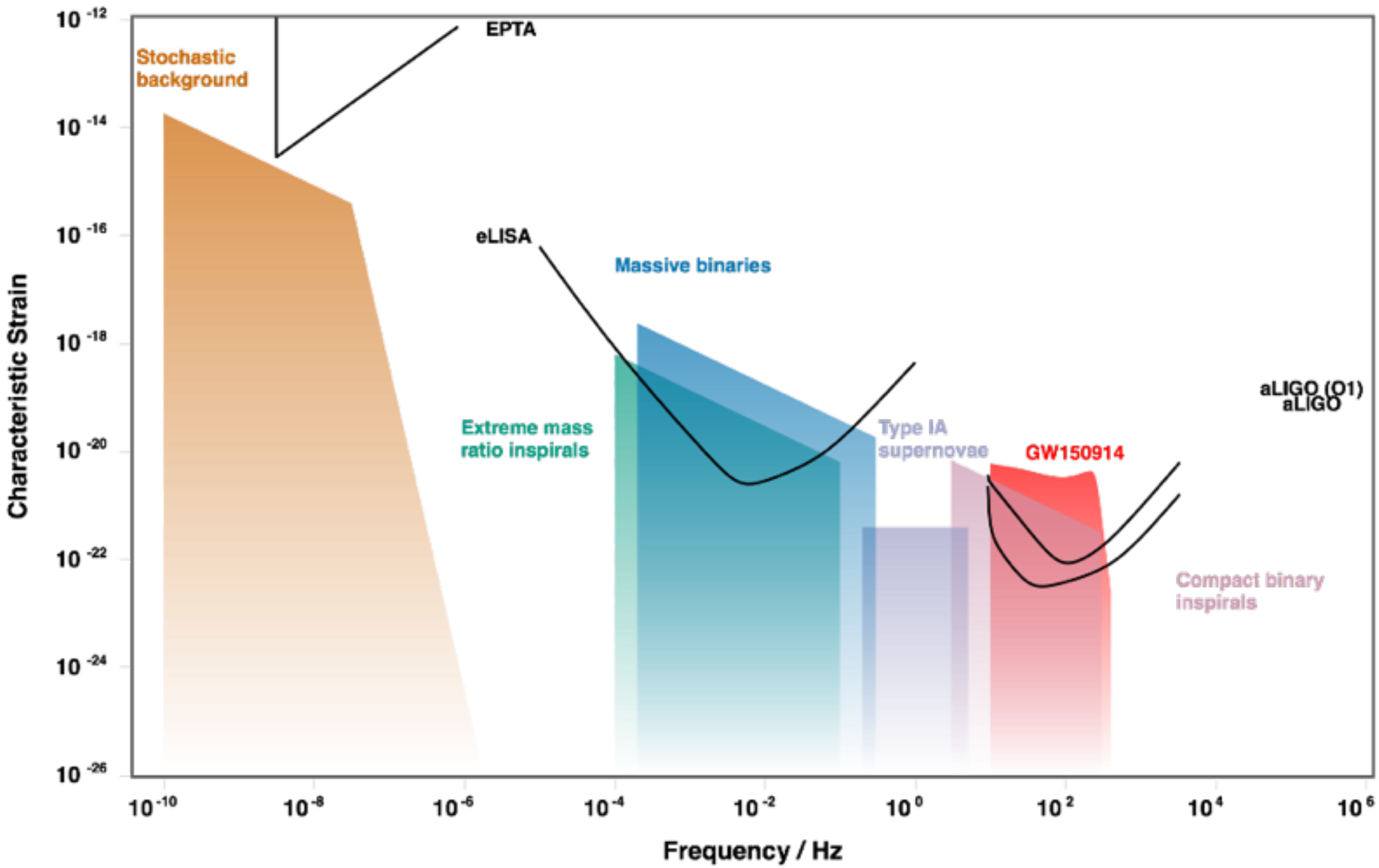
Sensitivity of Space GW Interferometers



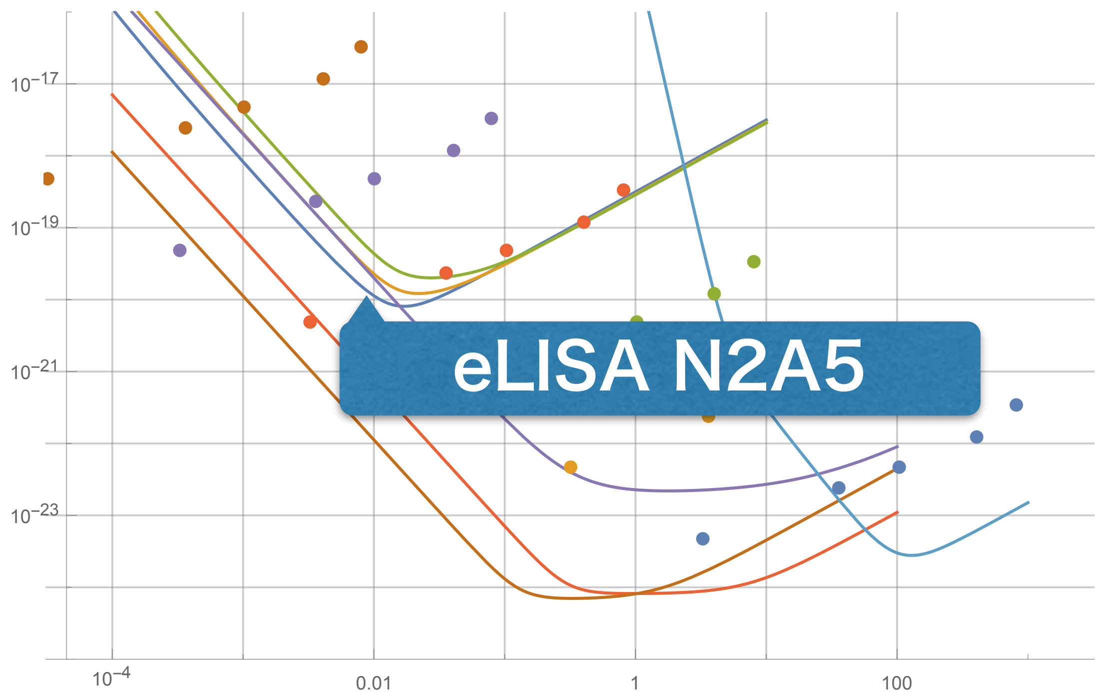
Sensitivity of Space GW Interferometers



これは遊べる　GWplotter
http://rhcole.com/apps/GWplotter/

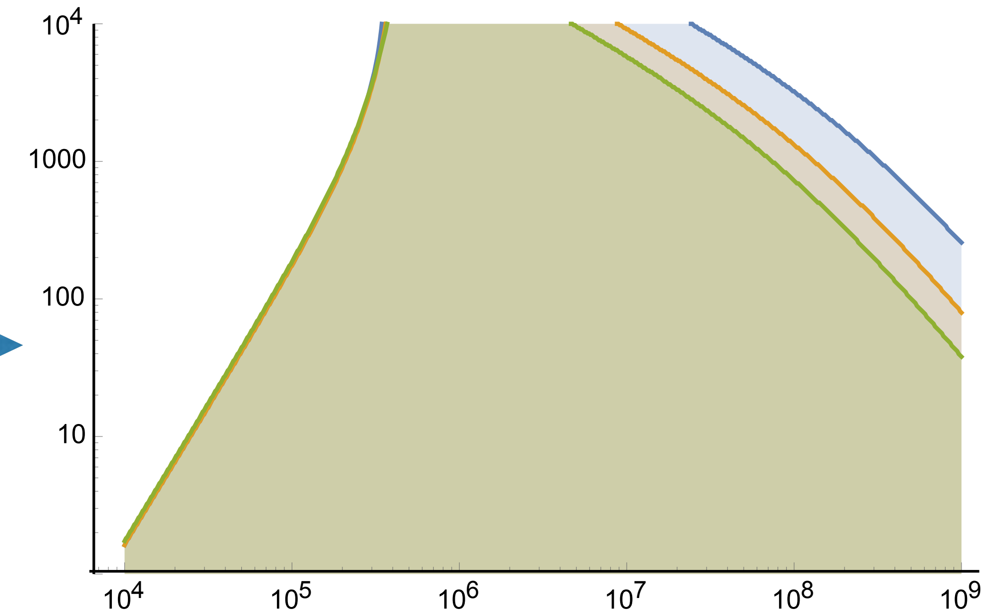


Event Rates at eLISA



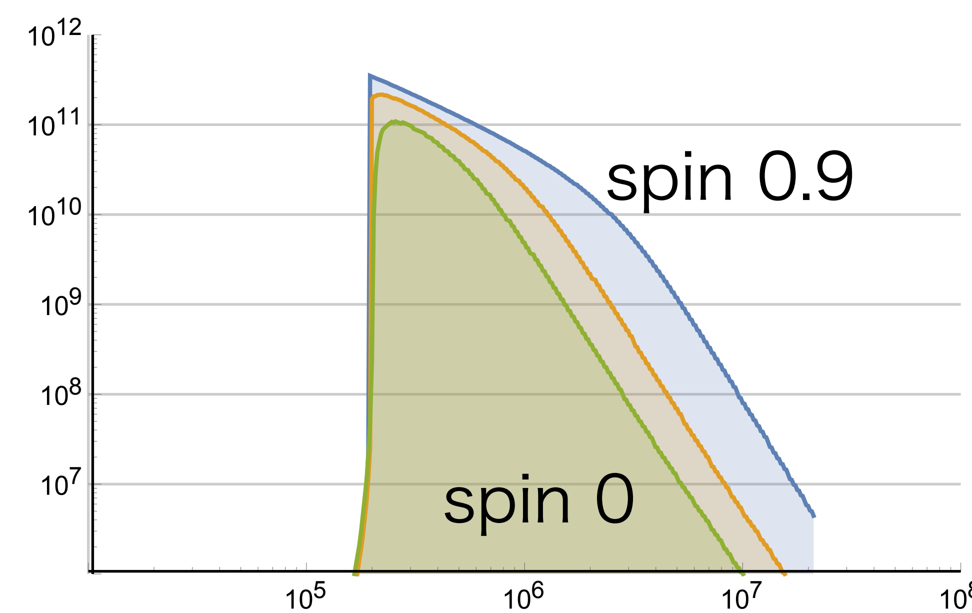
観測できるBH合体距離

[Mpc] (S/N=10)



BH質量[Msun]

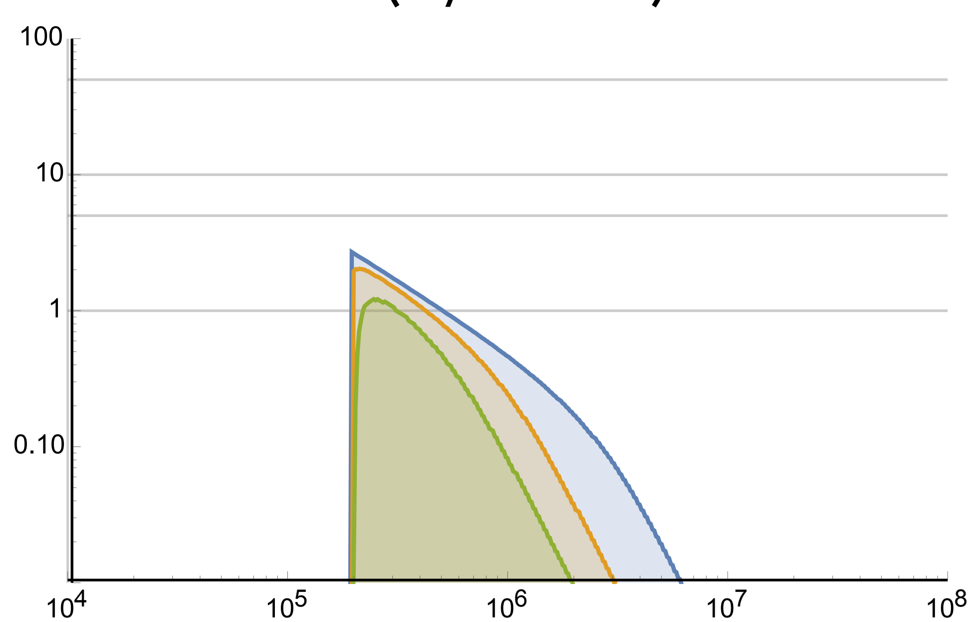
観測できるBH数分布



BH質量[Msun]

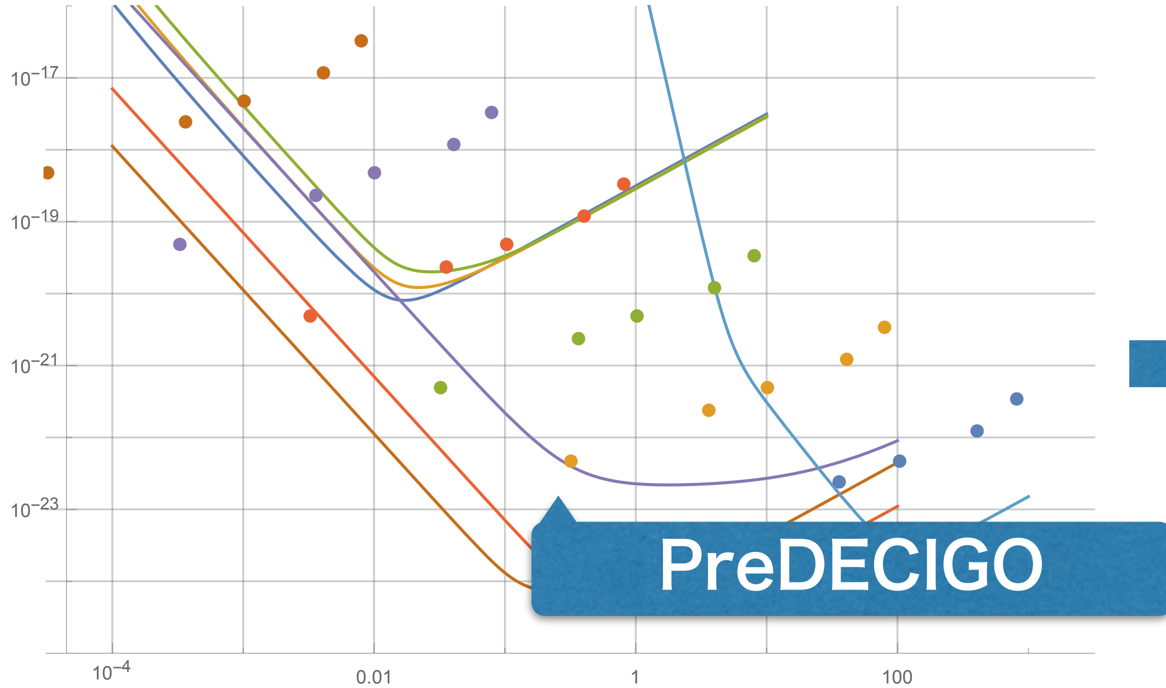
1年間で観測できるBH数分布

(S/N=10) **年55個**

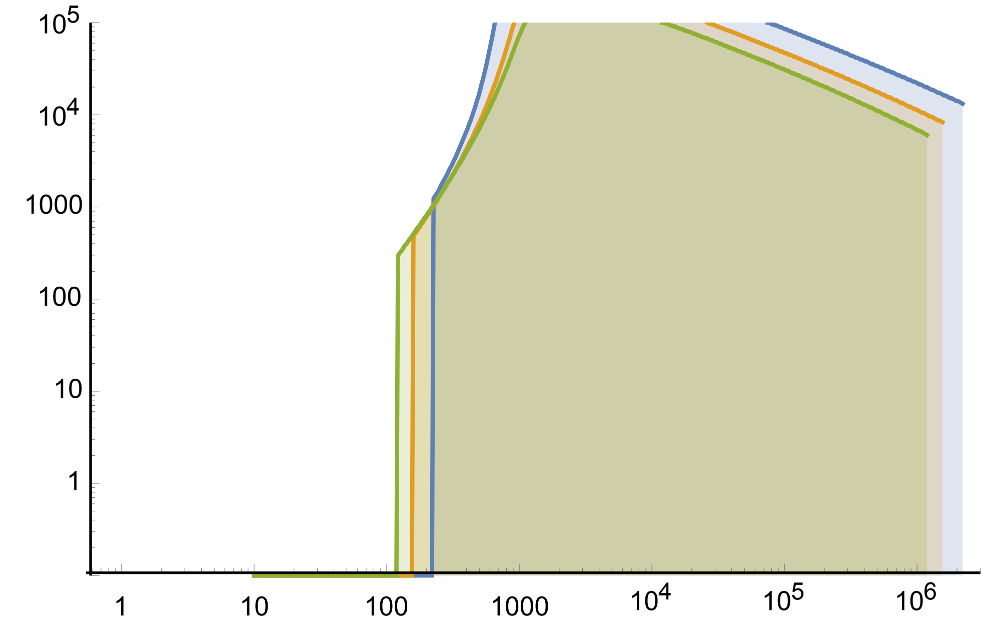


BH質量[Msun]

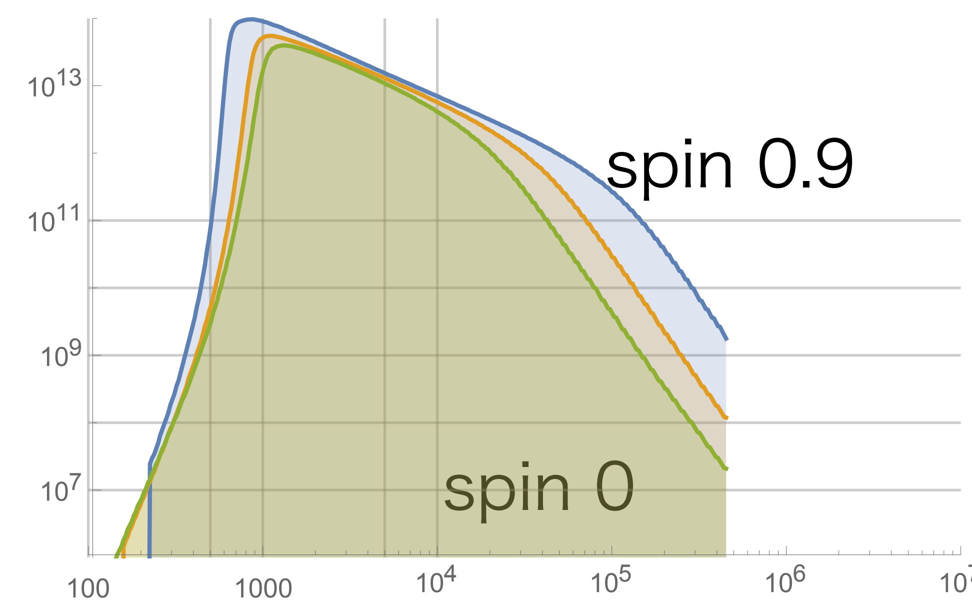
Event Rates at PreDECIGO



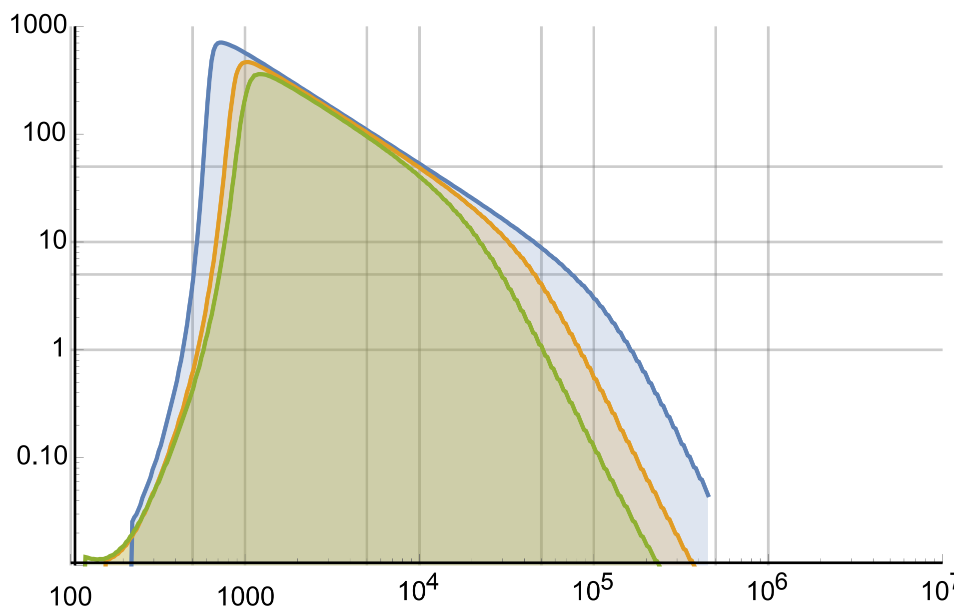
観測できるBH合体距離
(S/N=10)



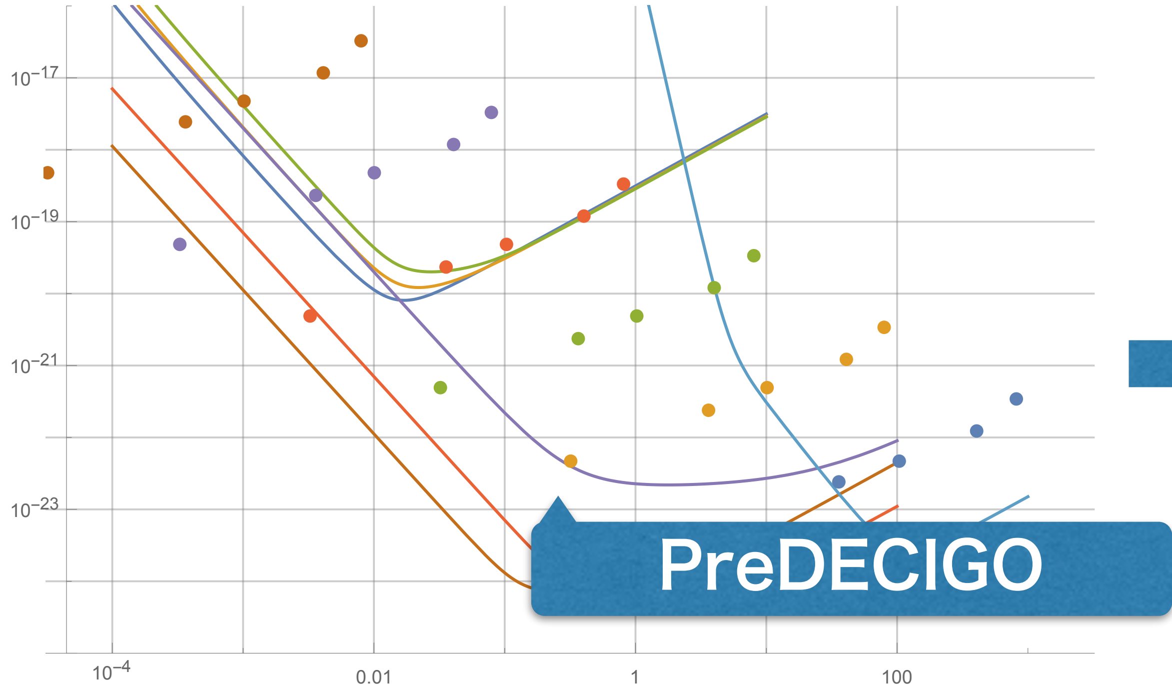
観測できるBH数分布



1年間で観測できるBH数分布
(S/N=10)

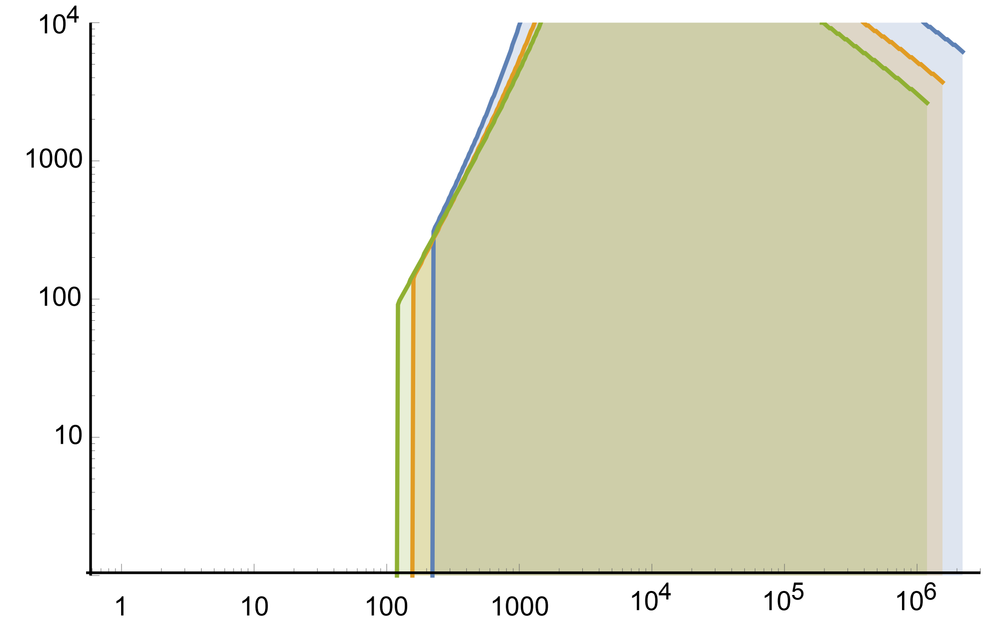


Event Rates at PreDECIGO



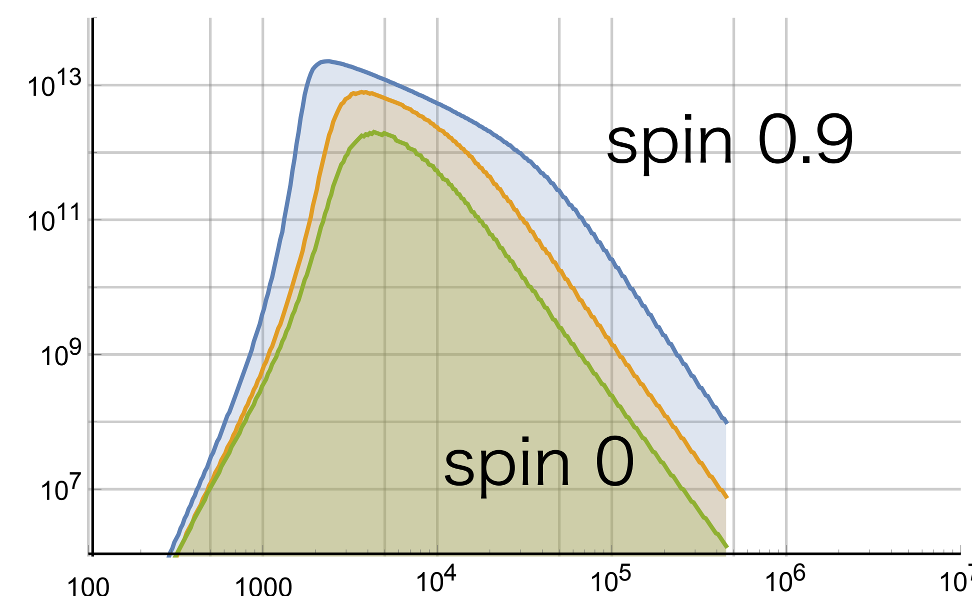
観測できるBH合体距離

[Mpc] (S/N=30)



BH質量[Msun]

観測できるBH数分布

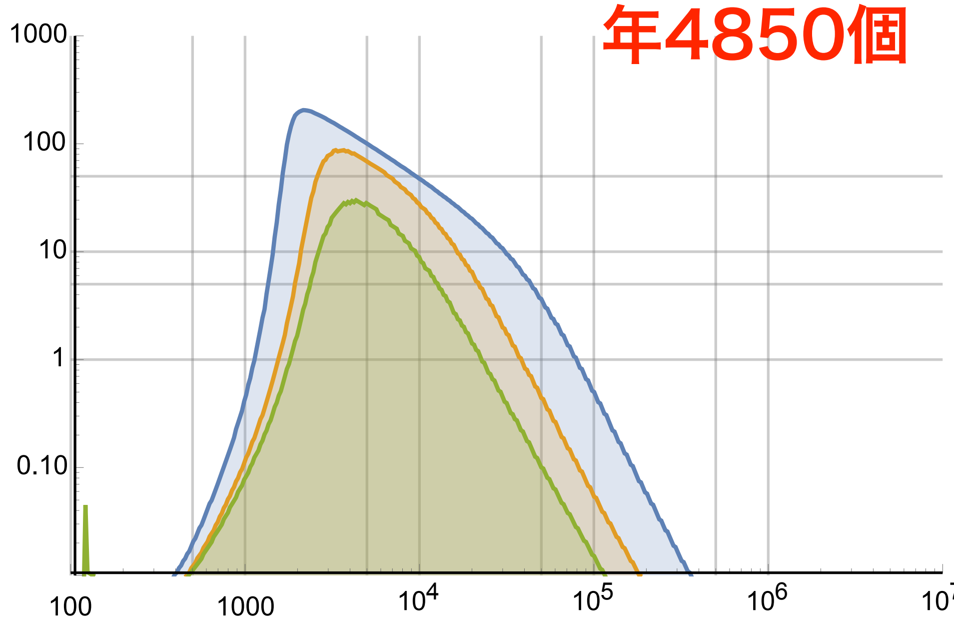


BH質量[Msun]

１年間で観測できるBH数分布

(S/N=30)

年4850個



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.
銀河どうしの合体は考えていない.

SMBHは，宇宙初期のガスのdirect collapseによって生じたという説もあるが，そのような形成仮定があれば，このモデルで得た検出頻度は減る.

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.

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.