BH連星合体イベントからの重力波

IMBH形成シナリオが，KAGRA で判別できるか.

真貝寿明（大阪工大）

戎崎さん　神田さん

重力波干渉計の話

Ringdown 波形の話

KAGRA/ETでの話

DECIGO/LISA
ではできる

The Astrophysical Journal, 614:864–868, 2004 October 20

GRAVITATIONAL WAVES FROM MERGING INTERMEDIATE-MASS BLACK HOLES

Tatsushi Matsubayashi,[1] Hisa-aki Shinkai,[2] and
Toshikazu Ebisuzaki[2]

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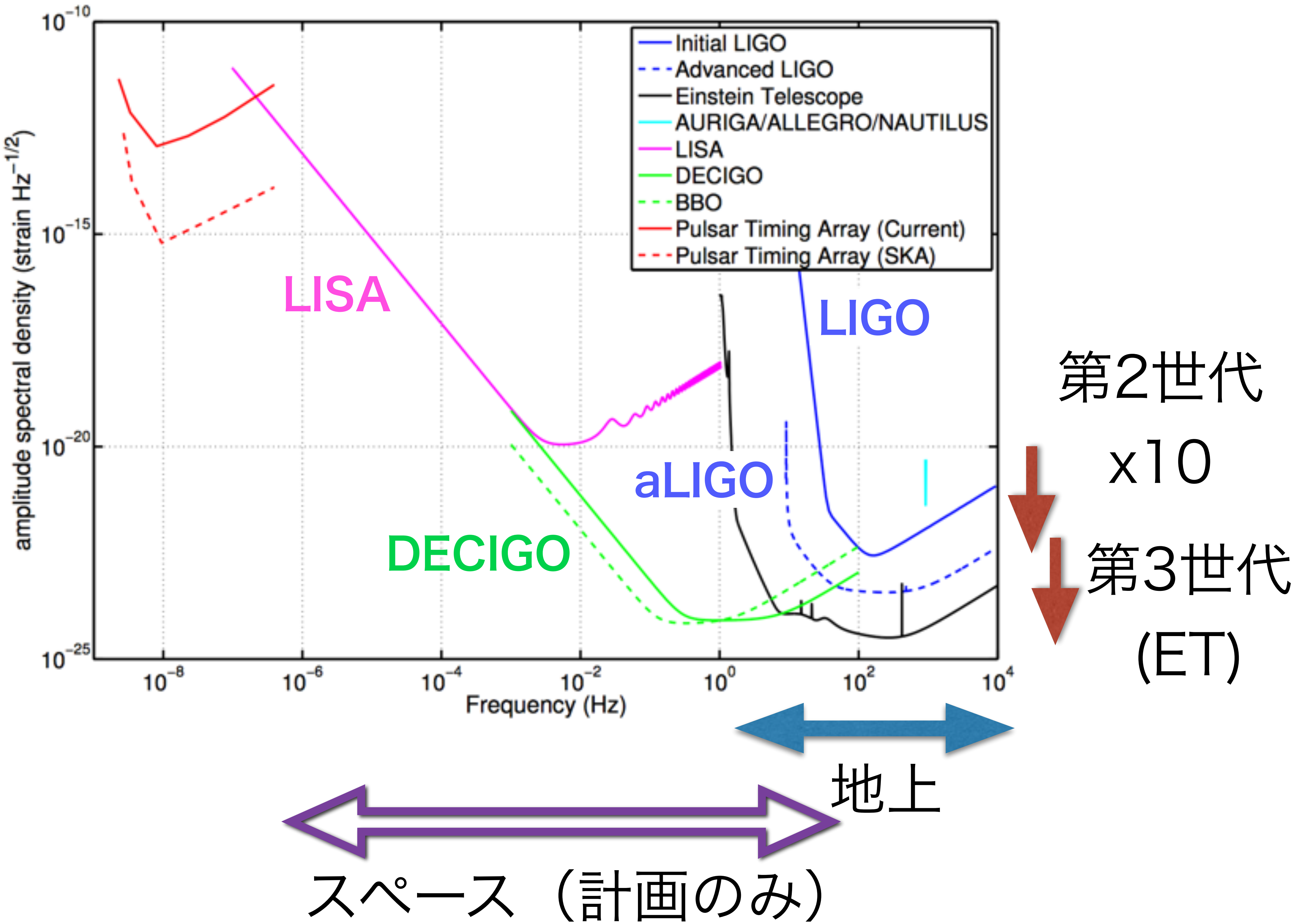
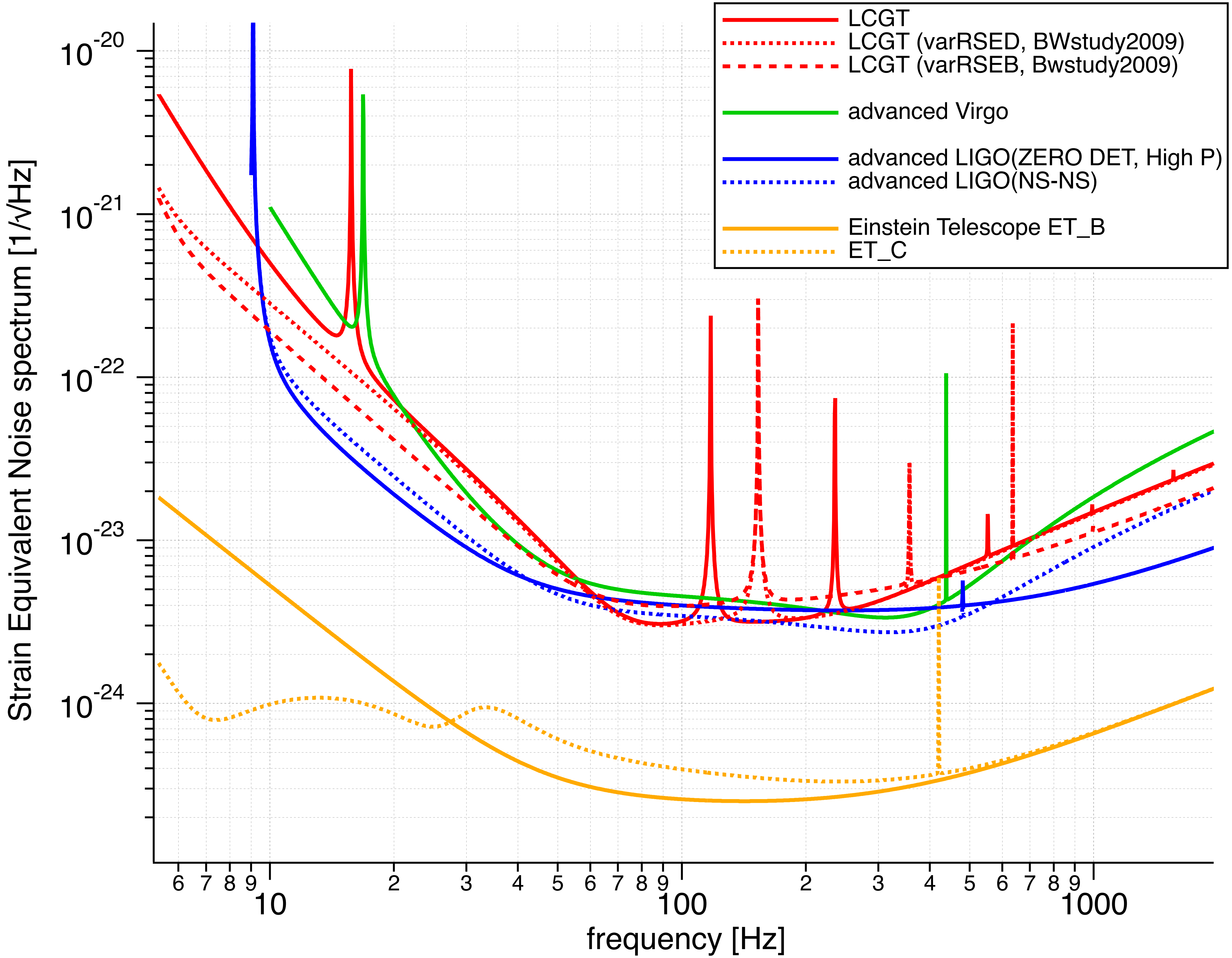
2014年8月25日@理研東京

重力波干渉計の感度

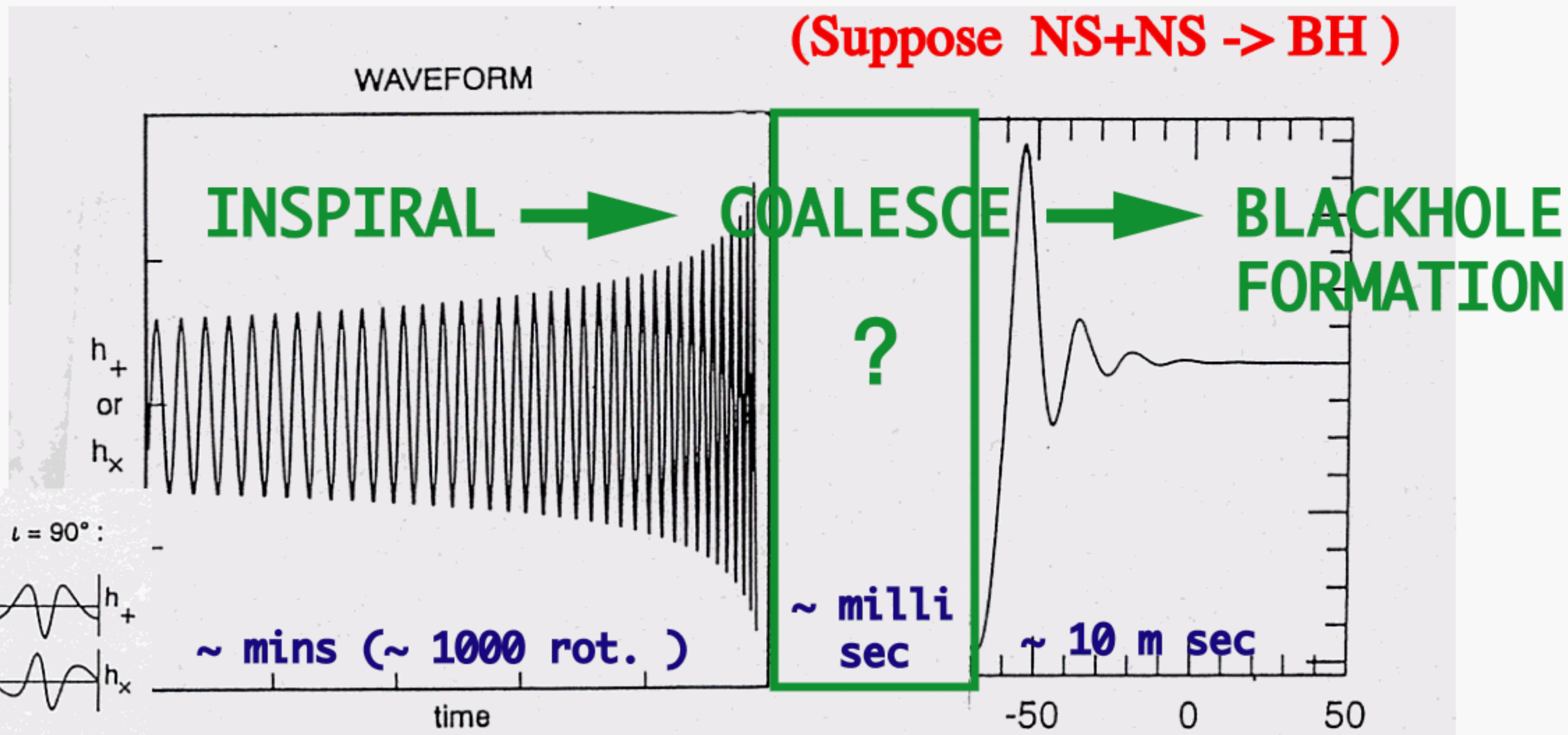


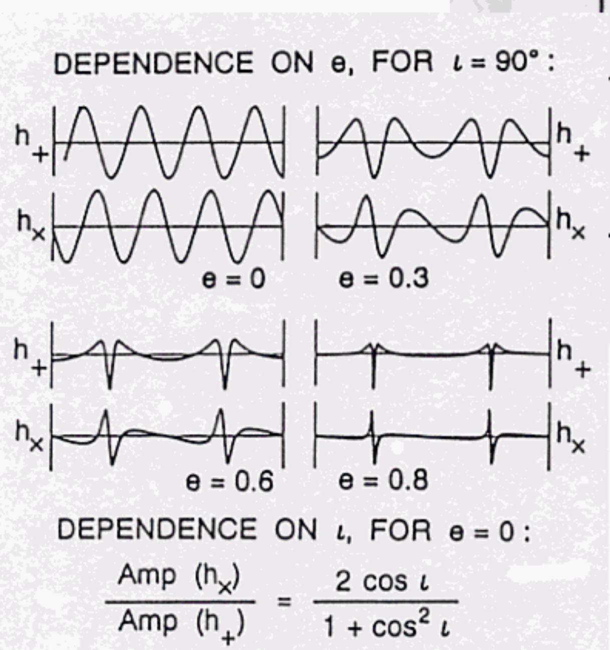
Pitkin+, Liv. Rev. Rel. 14 (2011) 5



神田さん提供のKagra(LCGT)感度予想曲線(2013/3)

What can we learn from gravitational waveform?





Post Newtonian Approx. | Numerical Relativity | BH. Perturbation

ISCO freq => EoS of NS,
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"chirps" df/dt => chirp mass, $M_c = (M_1 M_2)^{3/5} / (M_1+M_2)^{1/5}$
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moduration => spin, ...

statistics => cosmological parameters

BH-BH merger waveforms (non spinning)

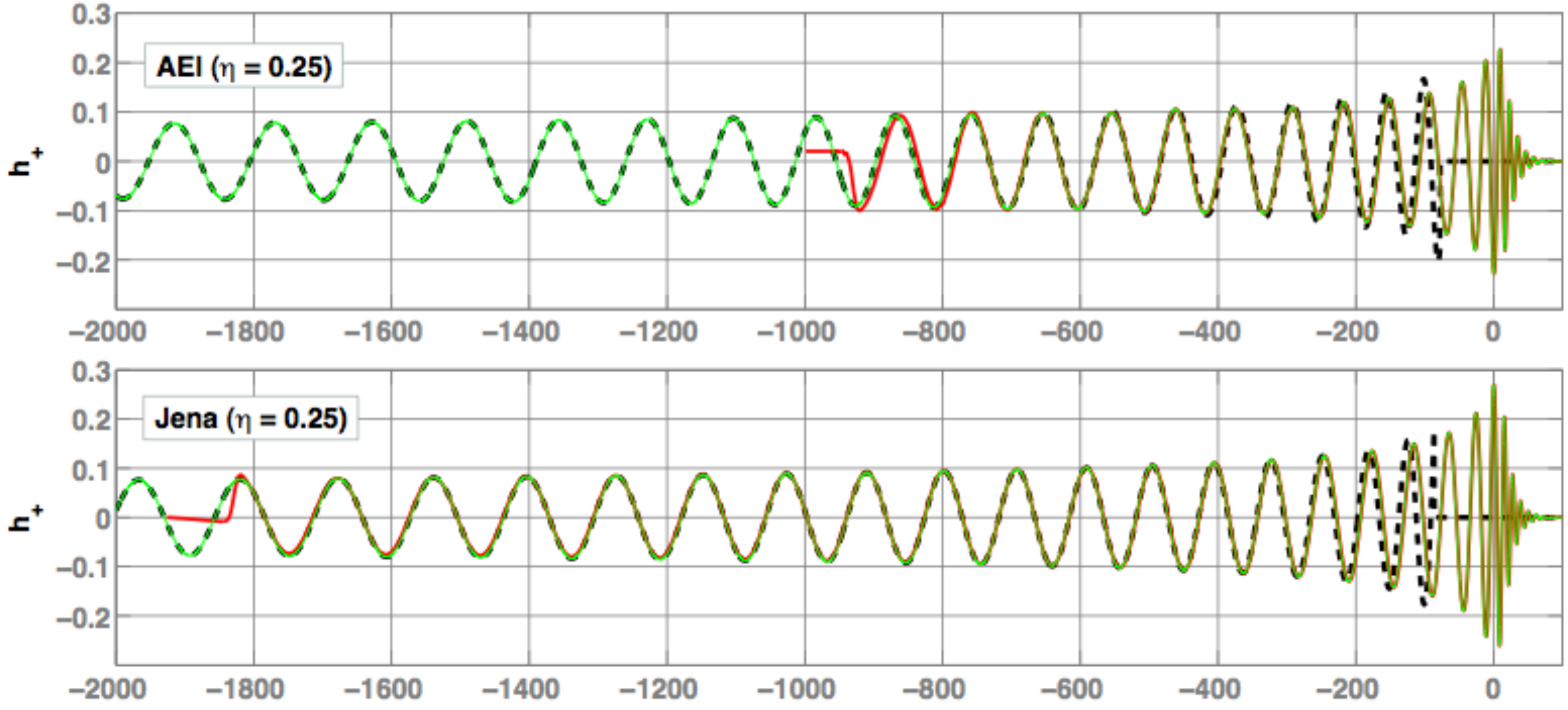

FIG. 2: NR waveforms (thick/red), the 'best-matched' 3.5PN waveforms (dashed/black), and the hybrid waveforms (thin/green) from three binary systems. The top panel corresponds to $\eta = 0.25$ NR waveform produced by the AEI-CCT group. The second, third and fourth panels, respectively, correspond to $\eta = 0.25, 0.22$ and 0.19 NR waveforms from produced by the Jena group. In each case, the matching region is $-750 \leq t/M \leq -550$ and we plot the real part of the complex strain (the '+' polarization).

Ajith+, PRD77(2008)104017 [arXiv:0710.2335]

Inspiral Phase

Suppose two BHs with mass M_1 and M_2 ($M_1 \geq M_2$) form a binary with circular orbit of radius a. The quadrupole formula of the gravitational radiation gives us the time to coalesce $t_{\rm insp}$ as,

$$t_{\rm insp} = \frac{5}{256} a^3 \left(\frac{a}{c}\right) \left(\frac{c^2}{GM_1}\right) \left(\frac{c^2}{GM_2}\right) \left(\frac{c^2}{GM_T}\right)$$
$$\approx 1.23 \times 10^{-2} \left(\frac{a}{R_{grav}}\right)^4 \left(\frac{10^3 M_\odot}{M_1}\right) \left(\frac{10^3 M_\odot}{M_2}\right) \left(\frac{M_T}{2 \times 10^3 M_\odot}\right)^3 \text{ sec}, \quad (1)$$

where we used $R_{grav} = 2GM_T/c^2$ and $M_T = M_1 + M_2$. For $a = 10R_{grav}$, the inspiral time, $t_{\rm insp}$, is about 2.1 minutes if $M_1 = M_2 = 10^3 M_\odot$, about 3.4 hours if $M_1 = M_2 = 10^5 M_\odot$.

The typical frequency of gravitational wave, $f_{\rm insp}$, in this inspiral phase is,

$$f_{\rm insp} = \frac{1}{\pi} \sqrt{\frac{GM_T}{a^3}}$$
$$\approx 11.4 \left(\frac{a}{R_{grav}}\right)^{-3/2} \left(\frac{2 \times 10^3 M_\odot}{M_T}\right) \text{ Hz}, \quad (2)$$

and the amplitude of gravitational wave, of its angle and polarization averaged expression (Douglas & Braginsky 1979) is,

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

松林,真貝,戎崎, ApJ 614 (2004) 864

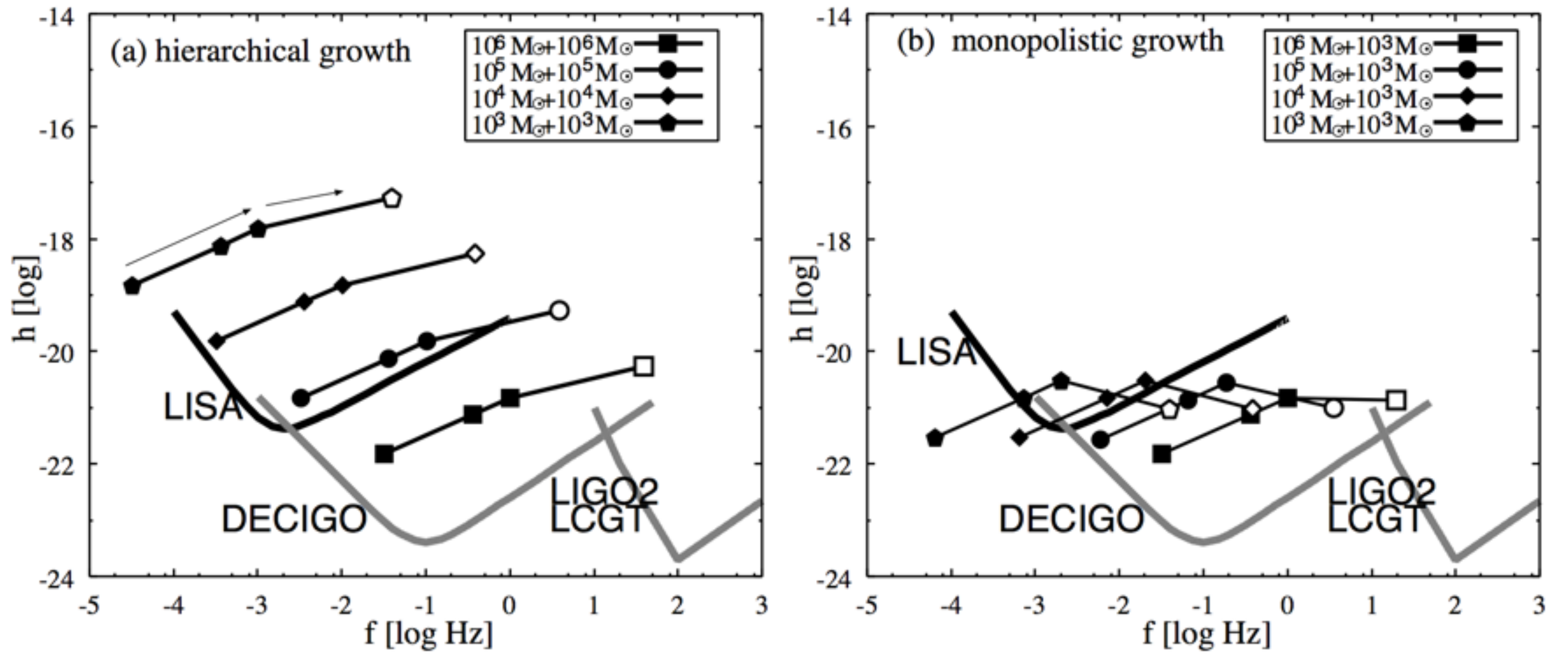

Fig. 1.— Expected gravitational radiation amplitude from merging IMBHs of (a) hierarchical growth model, and (b) monopolistic growth model. We plotted both the inspiral phase ($f_{\rm insp}, h_{\rm insp}$), [eqs. (2) and (3)], and the ringdown phase ($f_{\rm QNM}, h_{\rm coal}$), [eqs. (4) and (6)],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

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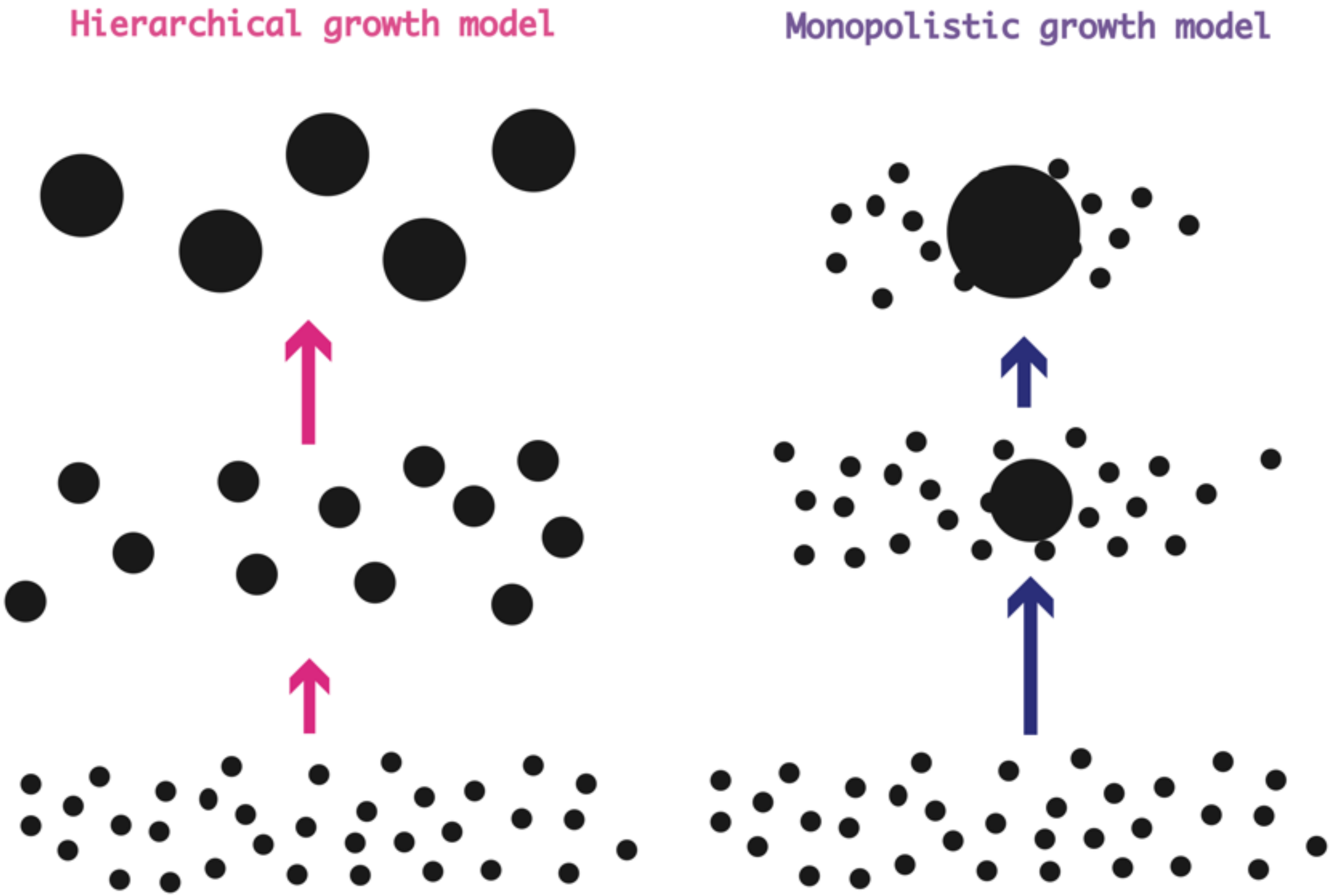
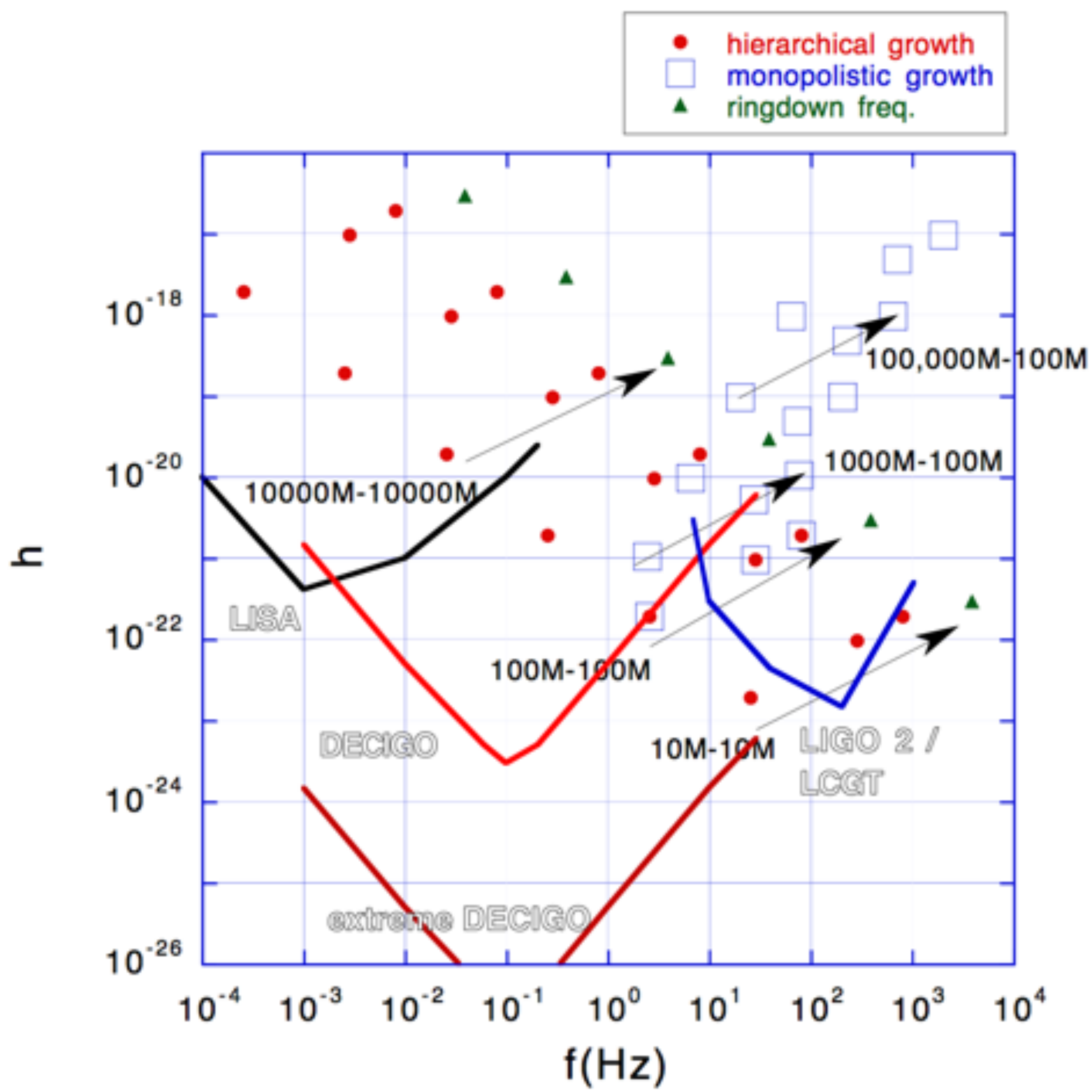
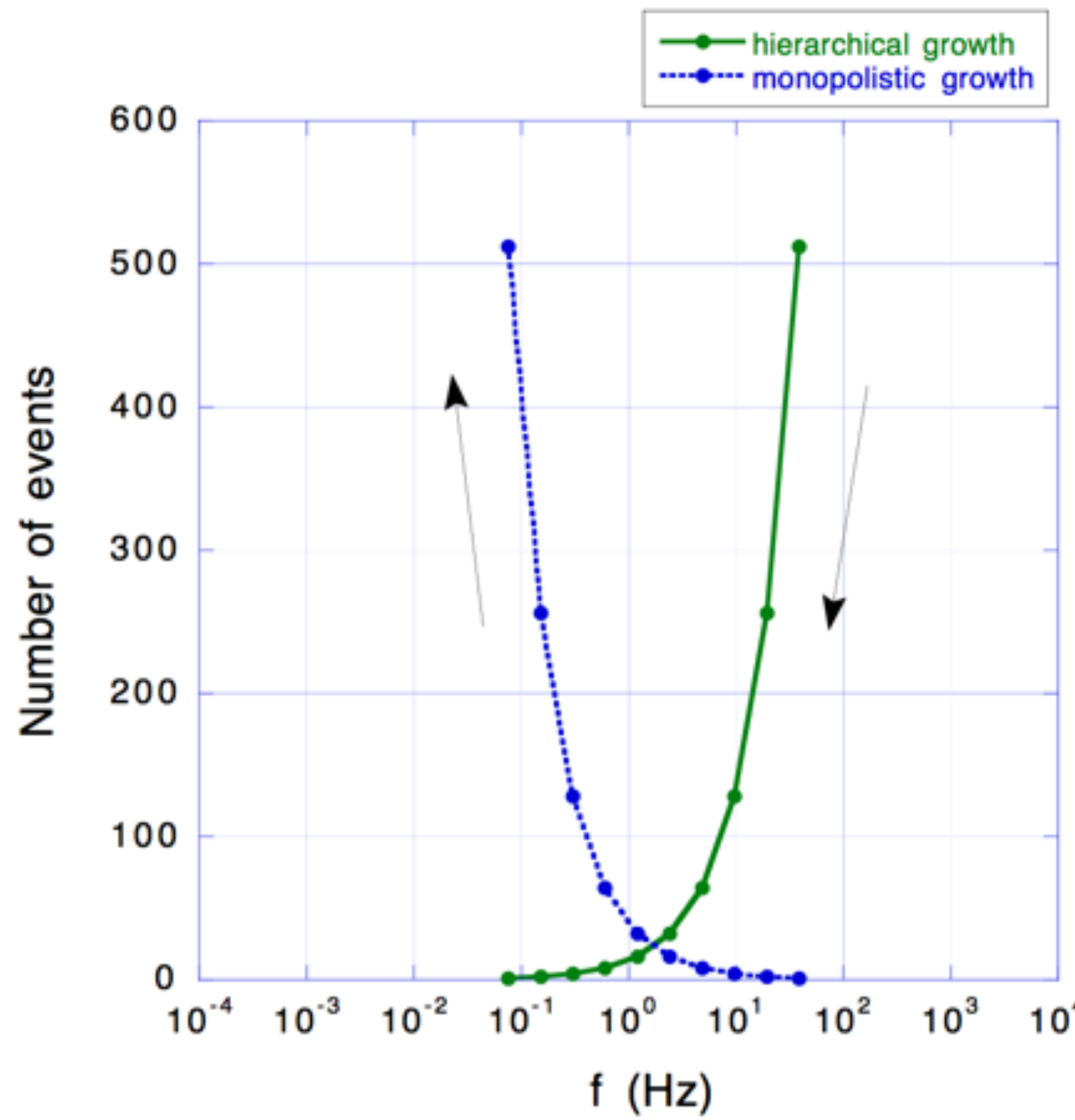

Hierarchical growth model
Monopolistic growth model

Hierarchical growth vs Monopolistic (or runaway) growth





Event numbers of mergers starting with a thousand of $10^3 M_\odot$ IMBHs. The solid line is the hierarchical growth model, that is each two equal-mass IMBHs merge together simultaneously. The dotted line is the monopolistic growth model, that is one single BH eats all other $10^3 M_\odot$ IMBHs and grows itself. Ringdown frequency f_{QNM}, is used for the plot. The arrows indicate a plausible evolution behavior.

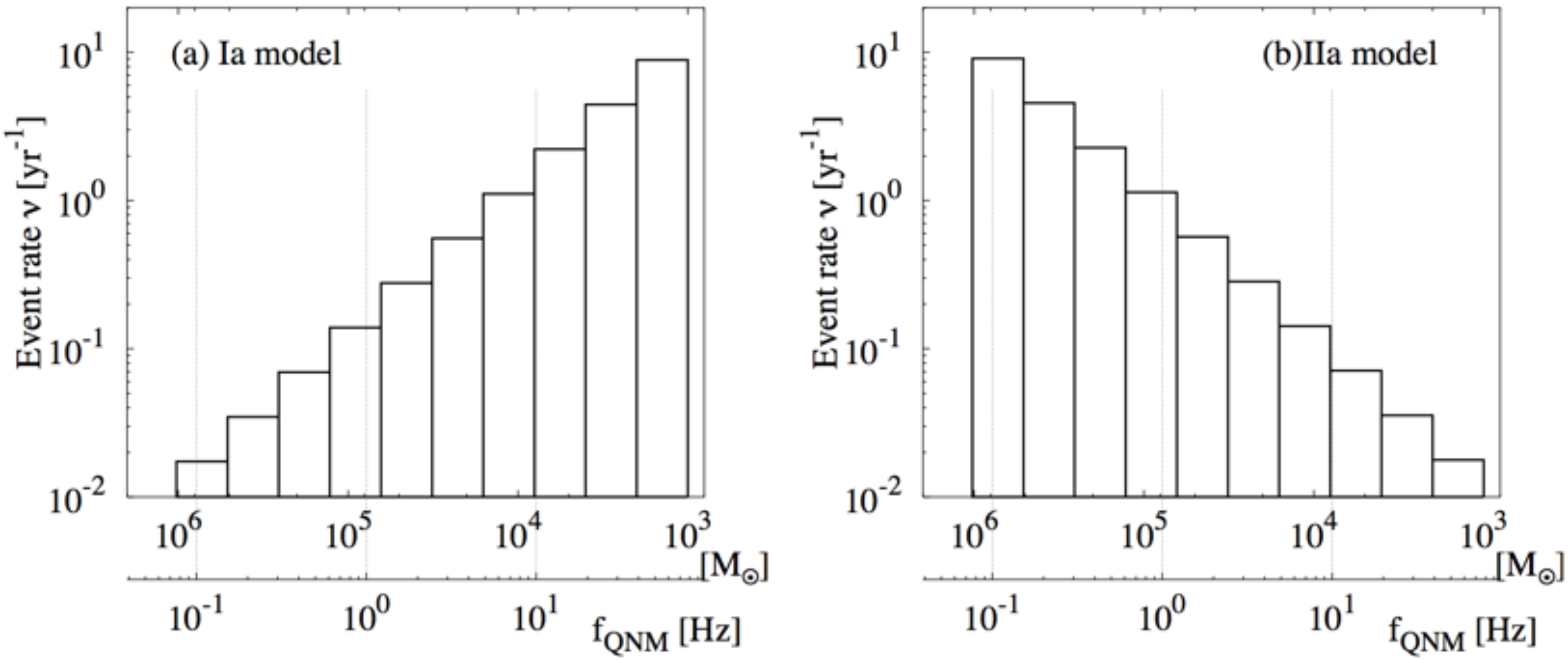


Fig. 2.— Event numbers of mergers starting from a thousand of $10^3 M_\odot$ IMBHs. The vertical axis is the event rate $\nu[\mathrm{yr}^{-1}]$, eqs. (12) and (14). The horizontal axis is the mass of the post-merger BH, M_T, which is also interpreted in the final gravitational radiation frequency $f_{\rm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

松林,真貝,戎崎, ApJ 614 (2004) 864

まとめ　松林,真貝,戎崎, ApJ 614 (2004) 864

中間質量ブラックホール IMBHs ($100M_\odot < M < 10^6 M_\odot$) からの重力波

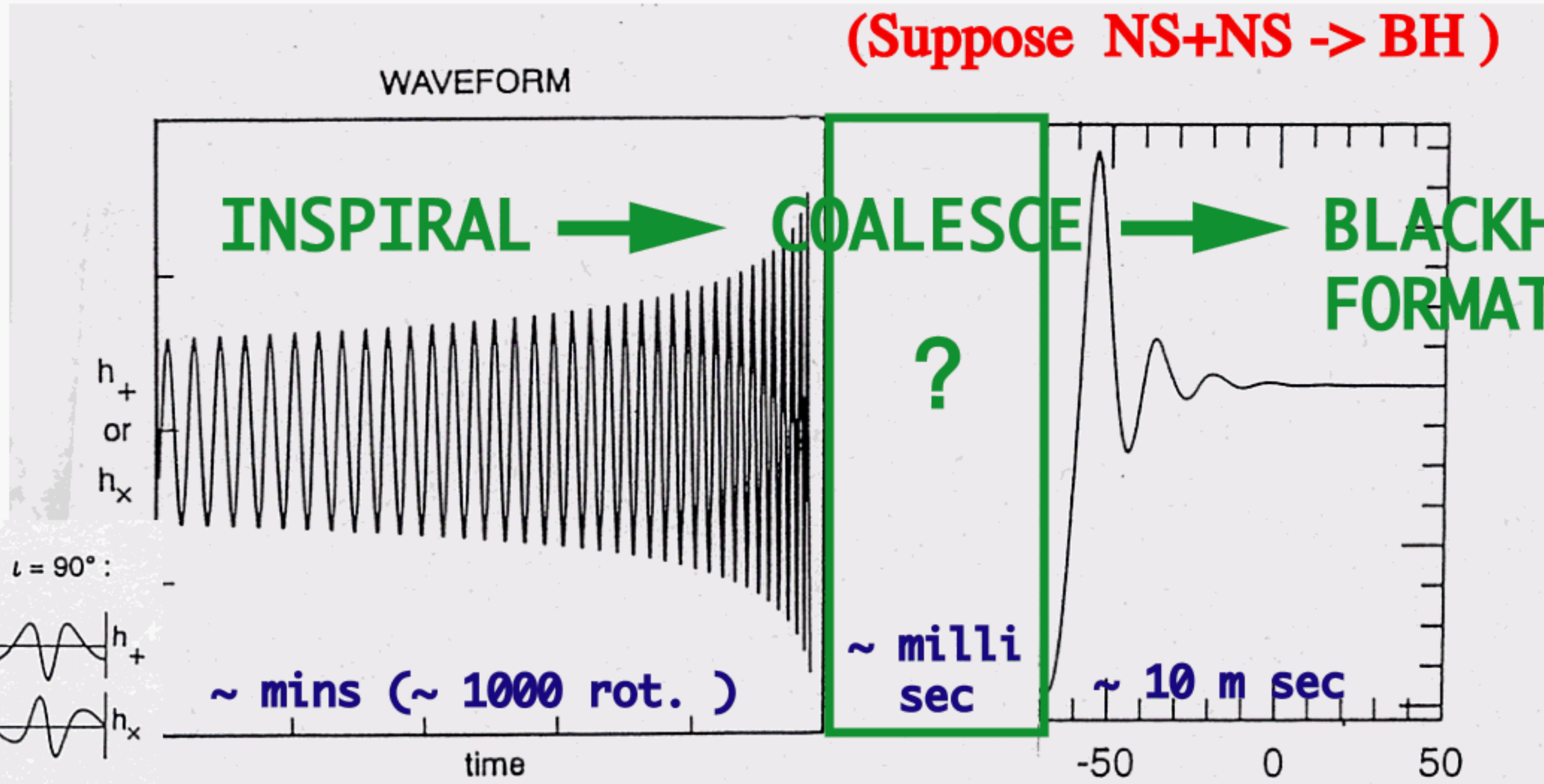
- 銀河中心に存在することがわかっている大質量ブラックホールの，形成シナリオとして，「star clusters からのrunaway growth」の説を裏付ける有力な証拠
  - 存在するのだから，それを作るシナリオが必要だ（ほぼconfirm）
  - その後の振る舞いを考えることが重要（そういう研究はまだない）
- 成長するシナリオによれば，どんどん合体するはず．重力波も出るだろう．

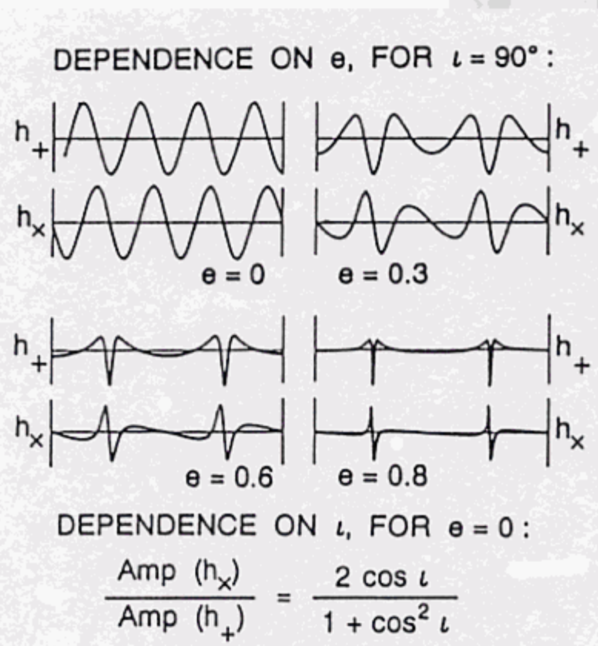
$$f = 10 \sim 10^{-2}\text{Hz}$$

すべての楕円銀河で 10^3 回の衝突があるならば，年間 数十 events
渦巻き銀河まで含めれば，その数倍

- 大質量ブラックホール形成までのプロセスは不明だが，極端な2つのモデル (Hierarchical growth / Monopolistic growth) を考えると，ブラックホール質量を固定したときの重力波イベント頻度が異なるので，合体時の周波数統計をとることで，大質量ブラックホール形成のモデルを決めることができる．
- そのための有力な観測手段は，LISAよりDECIGOである． ・・・めでたしめでたし

What can we learn from gravitational waveform?





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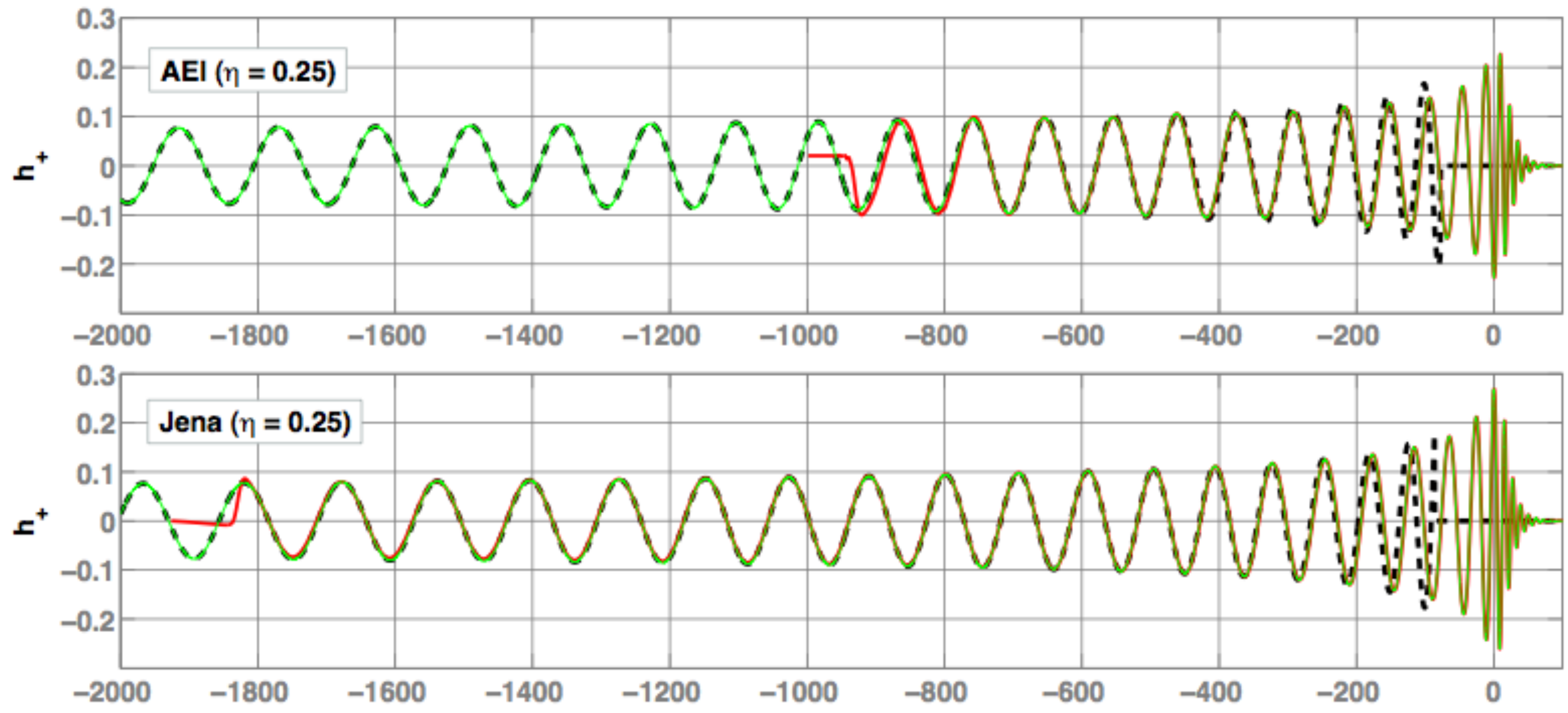

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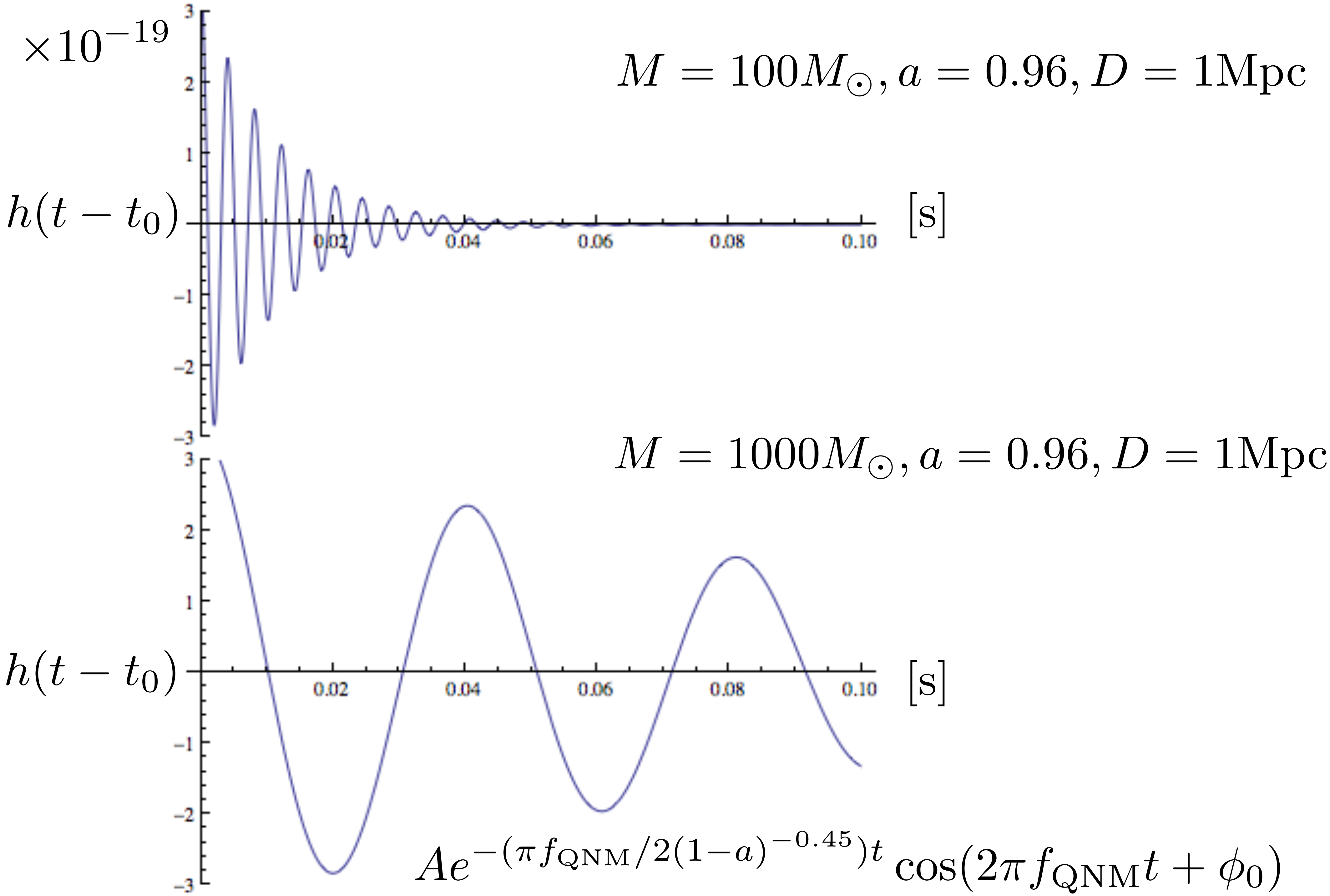
Ajith+, PRD77(2008)104017 [arXiv:0710.2335]

ここでは，BHBH合体のQNMを考える．

Black-Hole Ringdown waveform

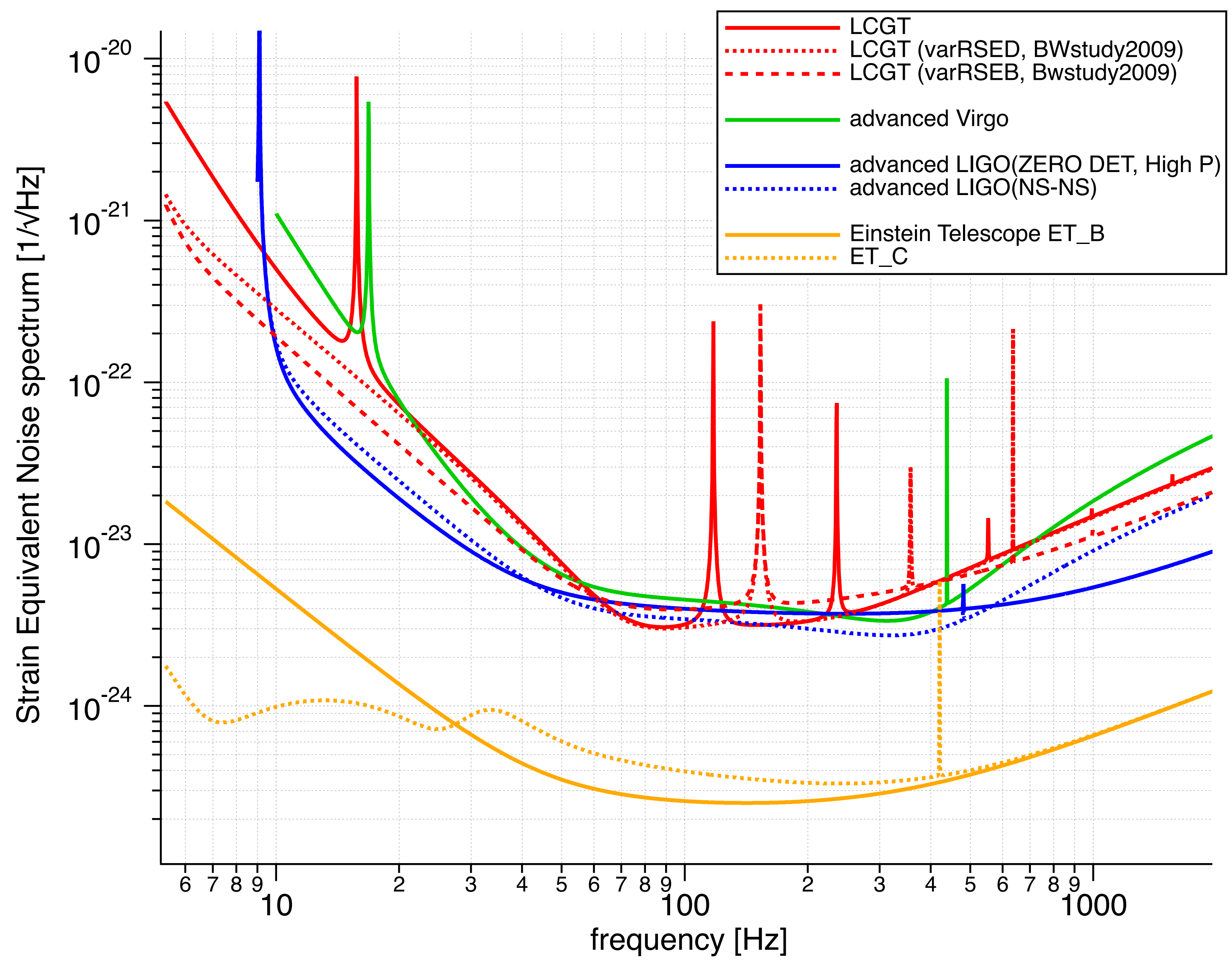


QNMの波形イメージ.

BH quasi-normal ringing frequency (spin=0のとき)

$$f_{\rm QNM} \approx \frac{lc^3}{\sqrt{27}GM_T} \sim 39.1 \left(\frac{2 \times 10^3 \ M_\odot}{M_T} \right) \ {\rm Hz}, \qquad (4)$$

Mtotal	f_QNM
1	78200 Hz
10	7820 Hz
100	782 Hz
1000	78.2 Hz
10000	7.82 Hz



神田さん提供のKagra(LCGT)感度予想曲線(2013/3)

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]
[1] Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), D-14476 Potsdam, Germany;
Pau.Amaro-Seoane@aei.mpg.de, Lucia.Santamaria@aei.mpg.de
[2] Institut de Ciències de l'Espai, IEEC/CSIC, Campus UAB, Torre C-5, parells, 2[na] planta, ES-08193 Bellaterra, Barcelona, Spain
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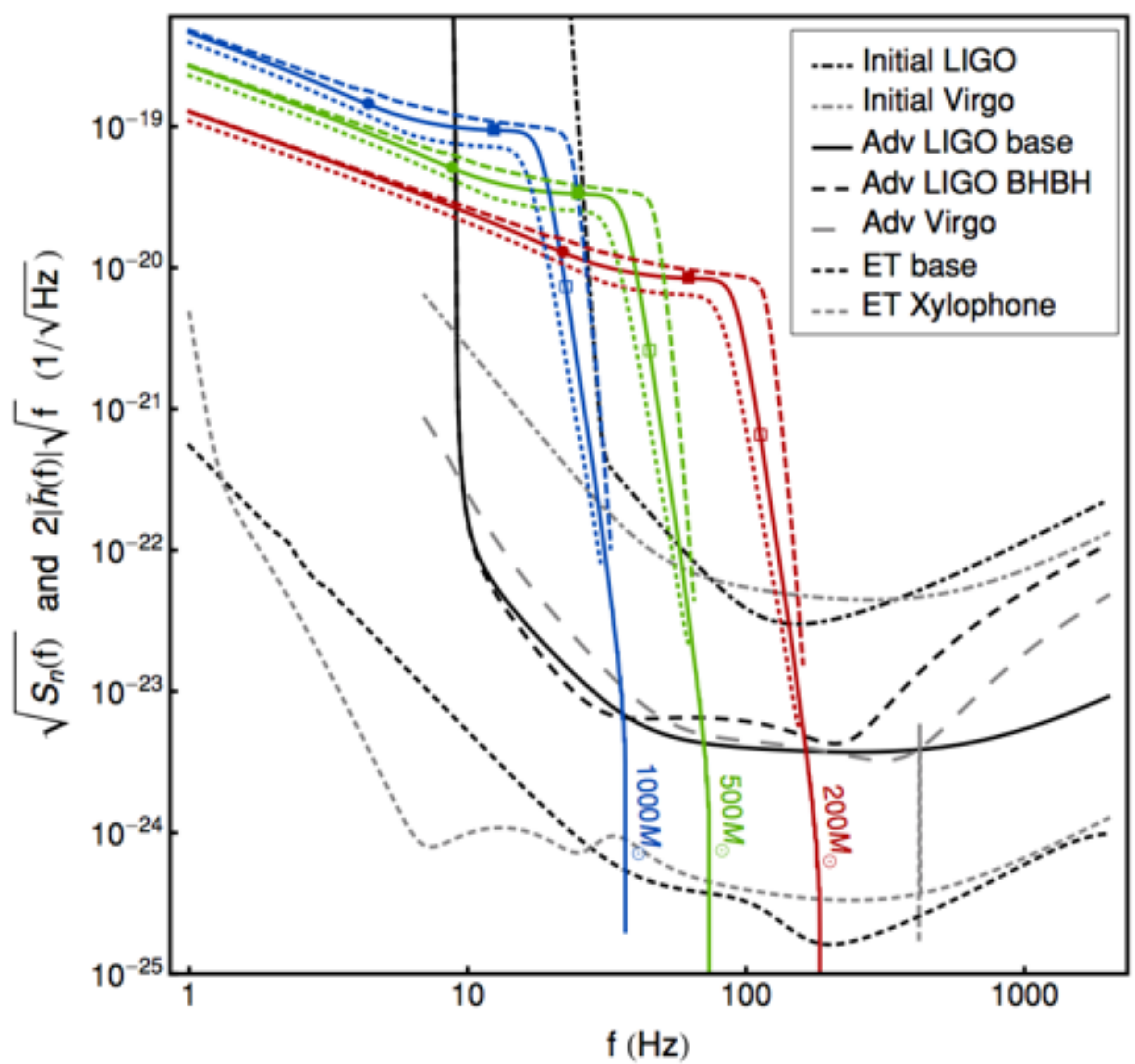
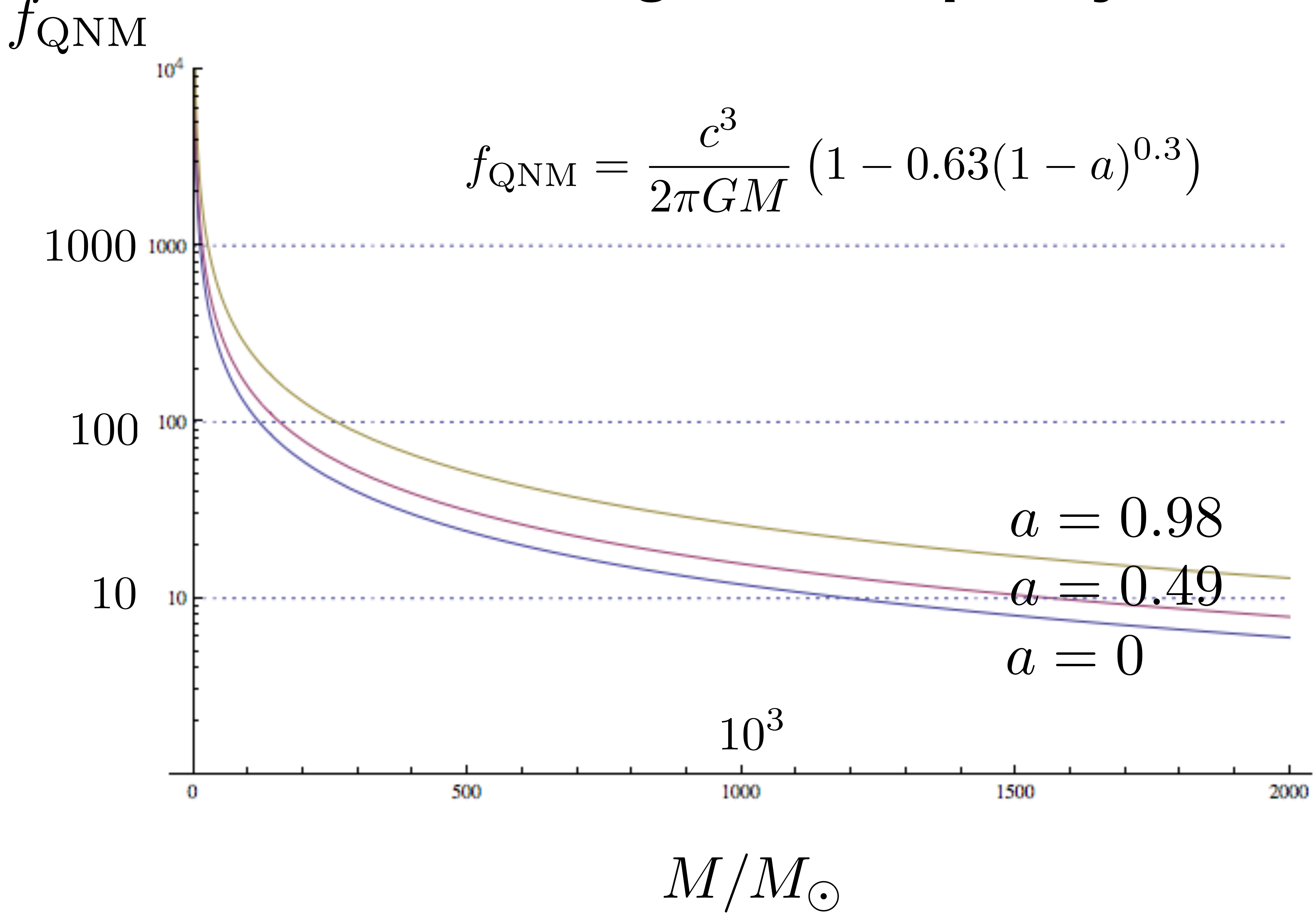


Figure 6. Hybrid waveform for three BBH configurations scaled to various IMBH masses. From top to bottom, we show BBH systems with total mass 1000, 500, and 200 $M_\odot$ in blue, green, and red, respectively. Solid lines correspond to the equal-mass, non-spinning configuration (1), dashed lines to the 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 $f_{\rm FRD}$), 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.

Black-Hole Ringdown frequency



BHのKerrパラメータ依存性を考えたもの.

回転していると，QNM周波数は高くなるが，これはKagraでは見えやすくなるということ.

Signal-to-Noise Ratio (SNR)

データ $s(t)$ は，重力波波形 $h(t)$ とノイズ $n(t)$ の和である．

$$s(t) = h(t) + n(t). \tag{1}$$

フィルタ $K(t)$ を乗じて

$$Y = \int K(t) s(t)\, dt, \tag{2}$$

とすると，標準的な signal to noise ratio は，次のように定義できる．

$$\frac{S}{N} = \frac{\text{expected value of } Y \text{ when signal present}}{\text{rms value of } Y \text{ when no signal present}} = \frac{\langle Y \rangle}{\sqrt{\langle Y^2 \rangle_{s=0}}} \tag{3}$$

ここで，Fourier 変換

$$\tilde{h}(f) = \int_{-\infty}^{\infty} e^{2\pi i f t}\, h(t)\, dt, \tag{4}$$

を行い，$S_h(f)$ を検出器の the power spectral density of strain noise とすれば，

$$\frac{S}{N} = \frac{4 \int_0^\infty df\, \Re\left[\tilde{h}(f)^* \tilde{K}(f)\right]}{\sqrt{4 \int_0^\infty df\, \left|\tilde{K}(f)\right|^2 S_h(f)}}. \tag{5}$$

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波形の bandwidth だけが既知のとき (band-pass filter)

$$\tilde{K}(f) = e^{2\pi i f t_{\rm start}} \Theta(\Delta f/2 - |f - f_{\rm char}|). \tag{6}$$

波形が既知のとき (matched filter)

$$\tilde{K}(f) = \frac{\tilde{h}(f)}{S_h(f)} \tag{7}$$

Signal-to-Noise Ratio (SNR)

(one sided) power spectral density of noise: $S_h(f)$

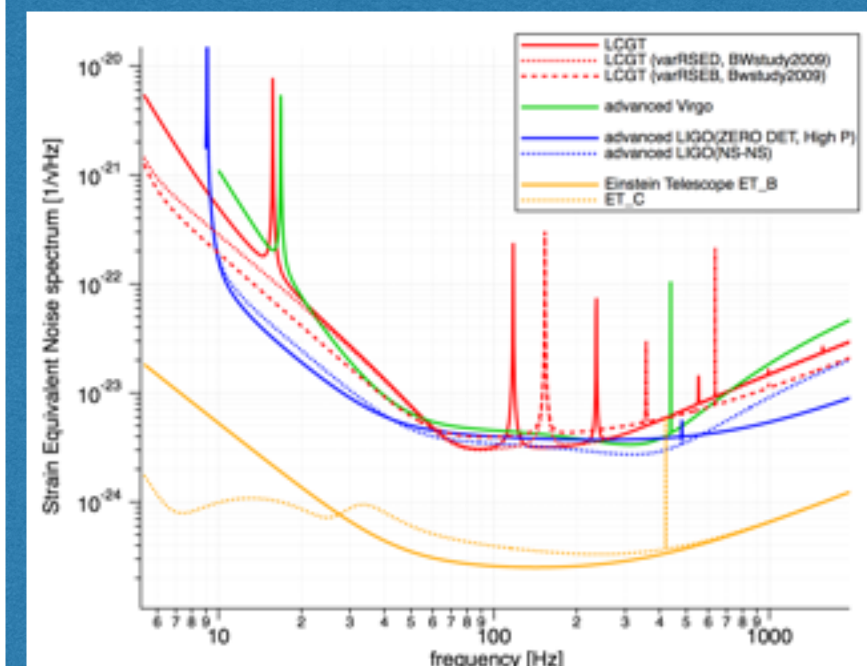
干渉計によって決まるノイズレベル

$$h_{\rm rms}(f) = \begin{cases} \infty & f < f_s, \\ h_m\,(\alpha f/f_m)^{-3/2} & f_s \le f < f_m/\alpha \\ h_m & f_m/\alpha \le f < \alpha f_m \\ h_m\,[f/(\alpha f_m)]^{3/2} & \alpha f_m < f. \end{cases}$$

より，

$$h_{\rm rms}(f) \equiv \sqrt{f S_h(f)}$$

として決まる．



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$$\frac{S}{N} = \frac{4\int_0^\infty df\,\Re\left[\tilde{h}(f)^*\tilde{K}(f)\right]}{\sqrt{4\int_0^\infty df\,\left|\tilde{K}(f)\right|^2 S_h(f)}}. \qquad (5)$$

Ringdown波形 のSNR (1)

波形

$$h(t) = h_0 \cos(2\pi f_{\rm qnr} t + \psi_0) e^{-t/\tau} \tag{1}$$

BH の摂動方程式における固有振動を求めると，スピンパラメータを a として（Leaver 1985, Echeverria 1989)

$$f_{\rm qnr} \approx \left[1 - 0.63(1-a)^{3/10}\right] \frac{1}{2\pi M} \tag{2}$$

$$Q \equiv \pi f_{\rm qnr} \tau \approx 2\,(1-a)^{-9/20} \qquad \text{quality factor} \tag{3}$$

Ringdown で放出される energy spectrum (Flanagan-Hughes 1998)

$$\frac{dE}{df} = \frac{\mathcal{A}^2 M^2 f^2}{32\pi^3 \tau^2} \left\{ \frac{1}{[(f - f_{\rm qnr})^2 + (2\pi\tau)^{-2}]^2} + \frac{1}{[(f + f_{\rm qnr})^2 + (2\pi\tau)^{-2}]^2} \right\}$$
$$\approx \frac{1}{8} \mathcal{A}^2 Q M^2 f_{\rm qnr}\, \delta(f - f_{\rm qnr}) \left[1 + O(1/Q)\right]. \tag{4}$$

四重極公式から，$\mathcal{A} \sim 0.4$ を見積もると，

$$E_{\rm ringdown} \approx \frac{1}{8} \mathcal{A}^2 M^2 f_{\rm qnr} Q = \frac{0.0063662(1 - 0.63(1-a)^{0.3})}{(1-a)^{9/20}} M \tag{5}$$

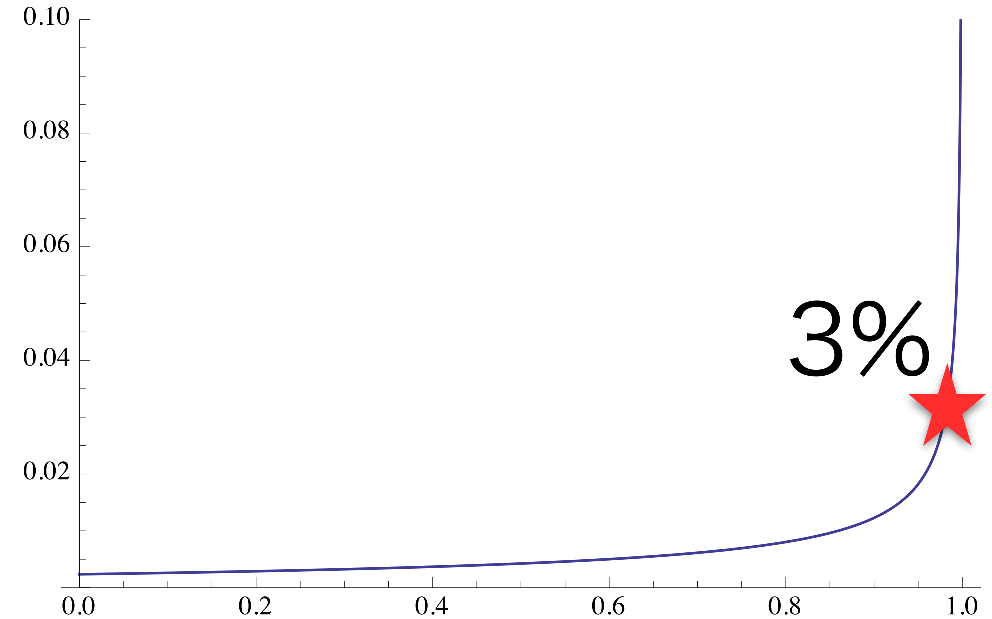
BH の spin を $a = 0.98$ と見積もれば，$E_{\rm ringdown} = 0.03M$. ?

Ringdown波形 のSNR (2)

- スピンパラメータ a が大きいほど大きい.

$$E_{\rm ringdown} \approx \frac{1}{8}\mathcal{A}^2 M^2 f_{\rm qnr} Q = \frac{0.0063662(1-0.63(1-a)^{0.3})}{(1-a)^{9/20}} M \qquad (5)$$

a	$\epsilon_r \equiv E_{\rm ringdown}/M$
0.0	0.00236
0.5	0.00425
0.9	0.01228
0.98	0.02980
1.0	∞



- $E_{\rm ringdown}$ は，連星の質量比が大きければ減少する．
  慣性質量 $\mu = \frac{m_1 m_2}{M} = \frac{m_1 m_2}{m_1 + m_2}$ を用いて，$\left(\frac{4\mu}{M}\right)^2$ 倍.

結局

$$\langle \rho^2 \rangle = \left(\frac{S}{N}\right)^2 = \frac{1}{20\pi^2}\frac{(1+z)Q\mathcal{A}^2}{f_{\rm qnr}S_h[f_{\rm qnr}/(1+z)]}\left[\frac{(1+z)M}{D(z)}\right]^2\left[\frac{4\mu}{M}\right]^2 \qquad (6)$$

$$= \frac{8}{5}\frac{1}{[1-0.63(1-a)^{0.3}]^2}\epsilon_r \frac{(1+z)M}{S_h[f_{\rm qnr}/(1+z)]}\left[\frac{(1+z)M}{D(z)}\right]^2\left[\frac{4\mu}{M}\right]^2 \qquad (7)$$

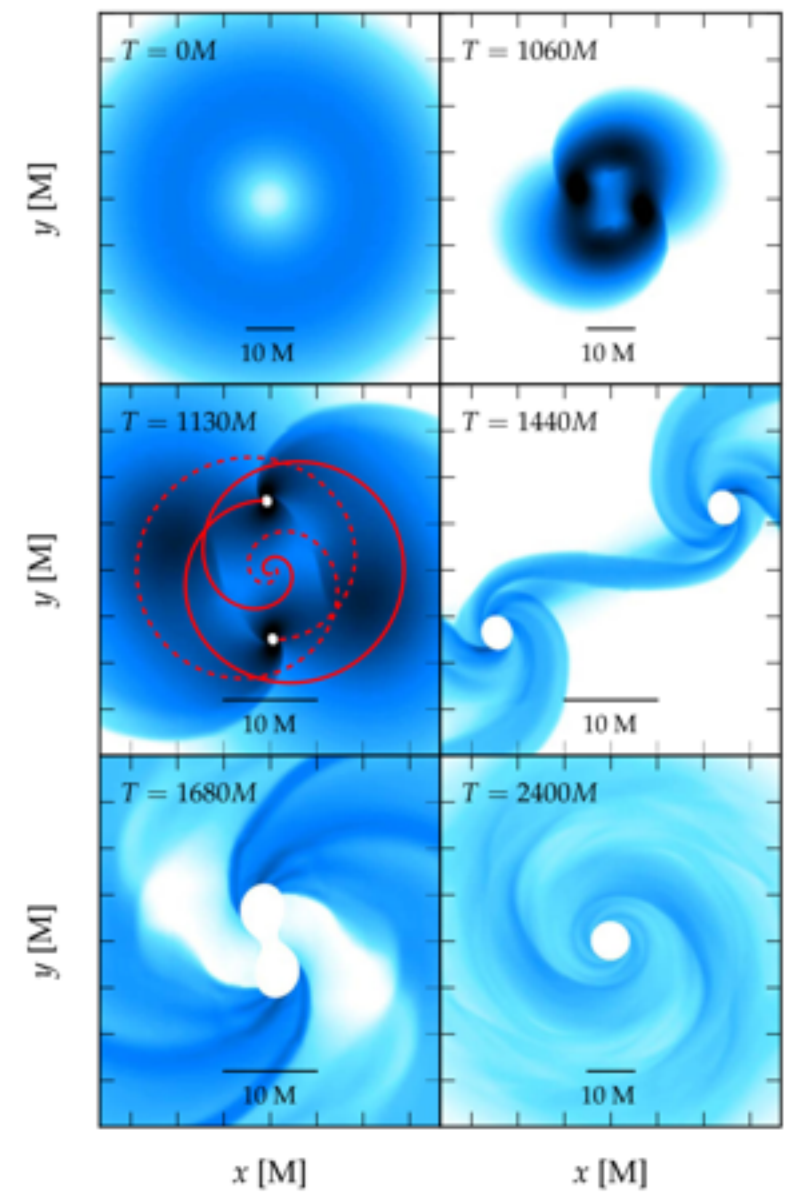
Formation and Coalescence of Cosmological Supermassive-Black-Hole Binaries in Supermassive-Star Collapse

C. Reisswig,[1,*] C. D. Ott,[1,2] E. Abdikamalov,[1] R. Haas,[1] P. Mösta,[1] and E. Schnetter[3,4,5]

[1]*TAPIR, MC 350-17, California Institute of Technology, 1200 East California Boulevard, Pasadena, California 91125, USA*
[2]*Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU WPI), The University of Tokyo, Kashiwa 277-8583, Japan*
[3]*Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, Ontario N2L 2Y5, Canada*
[4]*Department of Physics, University of Guelph, 50 Stone Road East, Guelph, Ontario N1G 2W1, Canada*
[5]*Center for Computation and Technology, 216 Johnston Hall, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
(Received 29 April 2013; published 7 October 2013)

We study the collapse of rapidly rotating supermassive stars that may have formed in the early Universe. By self-consistently simulating the dynamics from the onset of collapse using three-dimensional general-relativistic hydrodynamics with fully dynamical spacetime evolution, we show that seed perturbations in the progenitor can lead to the formation of a system of two high-spin supermassive black holes, which inspiral and merge under the emission of powerful gravitational radiation that could be observed at redshifts $z \gtrsim 10$ with the DECIGO or Big Bang Observer gravitational-wave observatories, assuming supermassive stars in the mass range 10^4–$10^6 M_\odot$. The remnant is rapidly spinning with dimensionless spin $a^* = 0.9$. The surrounding accretion disk contains ~10% of the initial mass.

	M1G1	M2G1	M2G2
BH mass M_{BH} (units of M)	5.5	5.8	3.0 ± 0.1
	⋯	⋯	3.0 ± 0.1
	⋯	⋯	5.8 ± 0.2
BH spin a^*_{BH}	0.9	0.9	0.7 ± 0.02
	⋯	⋯	0.7 ± 0.02
	⋯	⋯	0.9 ± 0.01
Baryonic disk mass M_{disk} (units of M)	1.3	1	0.7 ± 0.2
Accretion rate $\dot{M}$	1.2×10^{-3}	2×10^{-4}	6.7×10^{-5}
Radiated GW energy E_{GW} (%)	0.02	0.16	3.71



Measuring spin of a supermassive black hole at the Galactic Centre – Implications for a unique spin

Y. Kato[1]⋆, M. Miyoshi[2], R. Takahashi[3], H. Negoro[4], R. Matsumoto[5]

[1] *Japan Aerospace Exploration Agency (JAXA), 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan*
[2] *National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan*
[3] *The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan*
[4] *Department of Physics, College of Science and Technology, Nihon University, 1-8 Kanda-Surugadai, Chiyoda-ku, Tokyo 101-8308, Japan*
[5] *Department of Physics, Graduate School of Science, Chiba University, 1-33 Yayoi-Cho, Inage-Ku, Chiba 263-8522, Japan*

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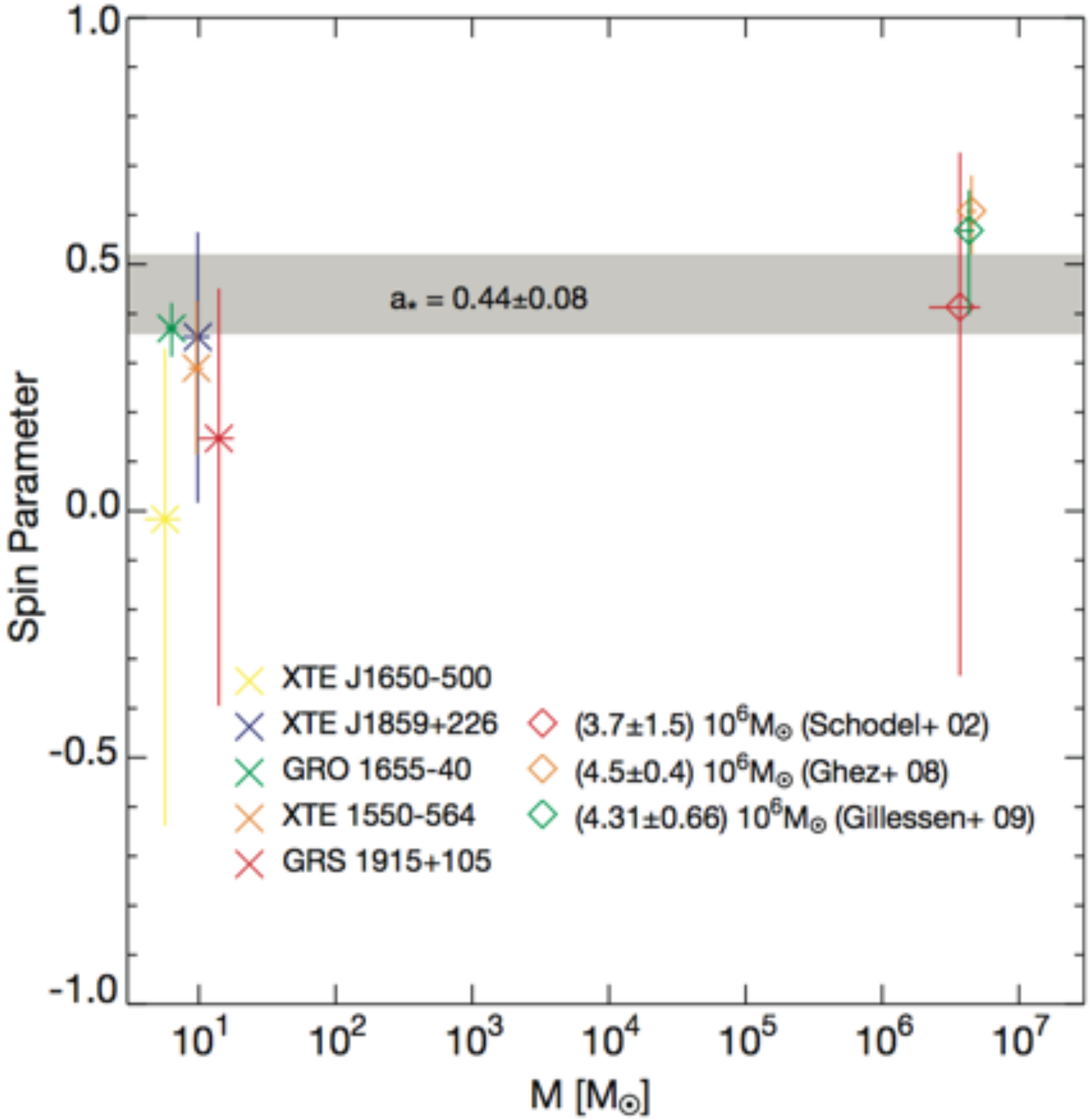
ABSTRACT

We determine the spin of a supermassive black hole in the context of discseismology by comparing newly detected quasi-periodic oscillations (QPOs) of radio emission in the Galactic centre, Sagittarius A* (Sgr A*), as well as infrared and X-ray emissions with those of the Galactic black holes. We find that the spin parameters of black holes in Sgr A* and in Galactic X-ray sources have a unique value of ≈ 0.44 which is smaller than the generally accepted value for supermassive black holes, suggesting evidence for the angular momentum extraction of black holes during the growth of supermassive black holes. Our results demonstrate that the spin parameter approaches the equilibrium value where spin-up via accretion is balanced by spin-down via the Blandford-Znajek mechanism regardless of its initial spin. We anticipate that measuring the spin of black holes by using QPOs will open a new window for exploring the evolution of black holes in the Universe.

arXiv:0906.5423
MNRAS



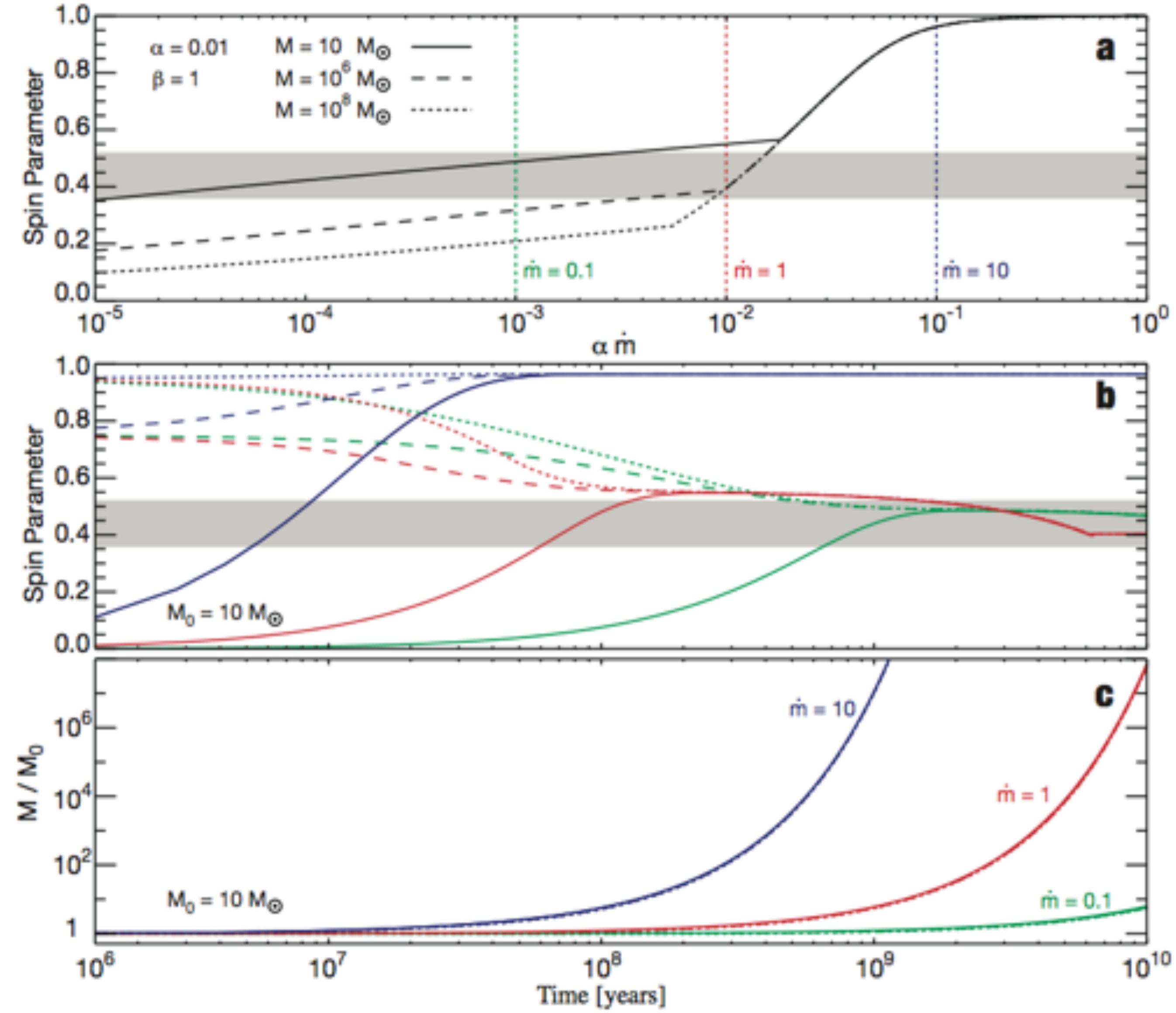
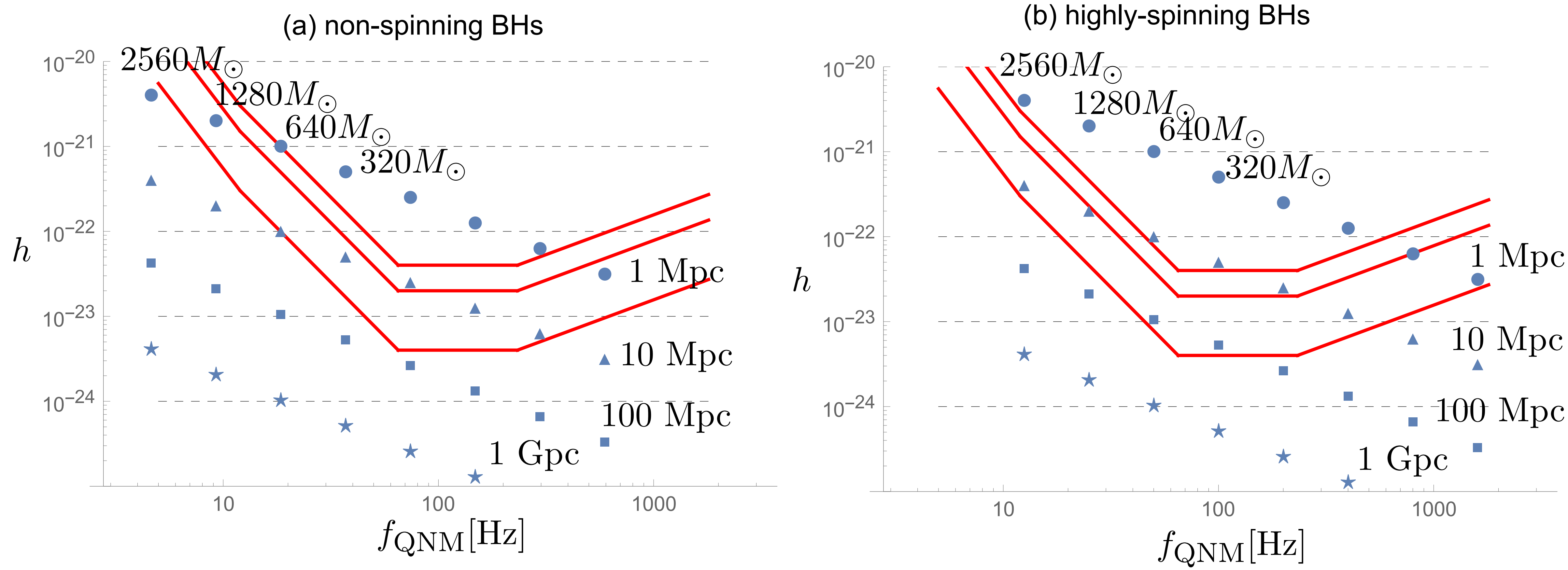


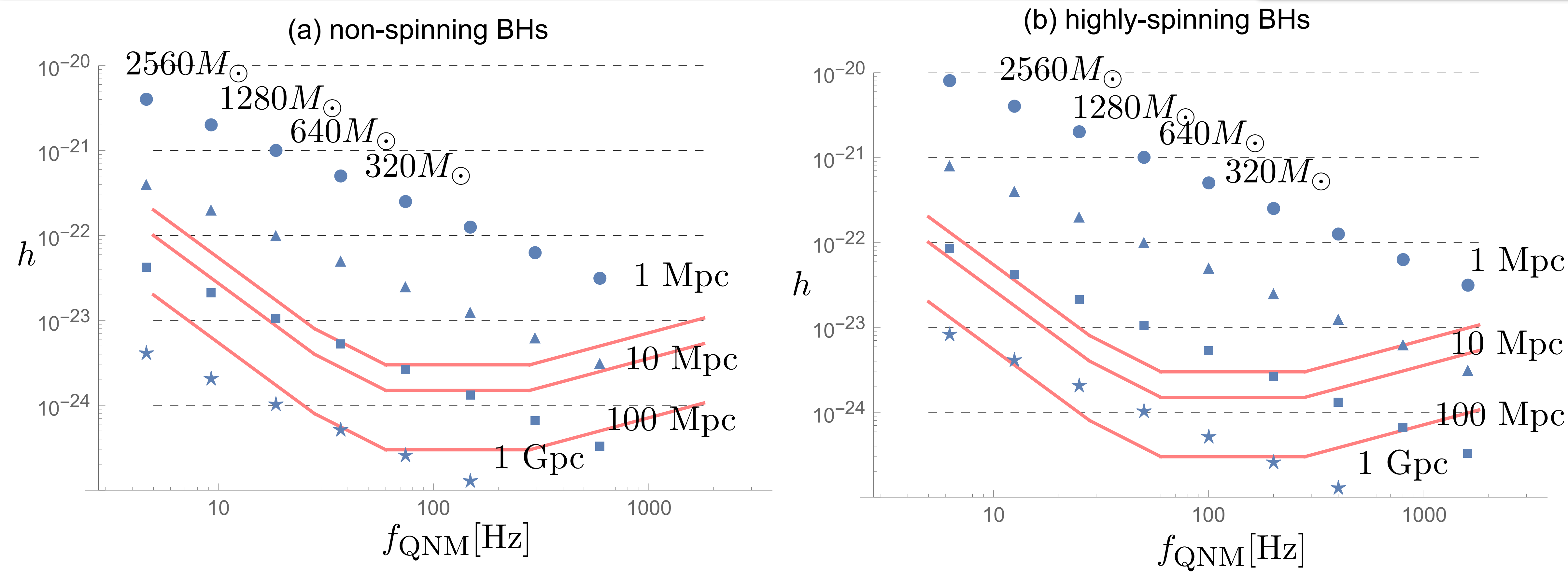
Figure 3. Time evolution of the black hole surrounded by the standard accretion disc with the suitable disc parameter $\alpha = 0.01$ and $\beta = 1$ for different mass accretion rates ($\dot{m} = 0.1$, 1.0, and 10 denoted by a green, red, and blue line, respectively). (a) is the equilibrium spin parameter in terms of $\alpha\dot{m}$ for given black hole masses ($M = 10, 10^6, 10^8 M_\odot$ denoted by a black sold, dashed, and dotted line, respectively). (b) is the time evolution of spin parameter for the initial black hole mass $M_0 = 10 M_\odot$ with different initial spin parameters ($a_* = 0.0$, 0.75, and 0.95 denoted by a solid, dashed, and dotted line, respectively). A gray shaded region in (a) and (b) indicates the best-fit spin parameter $a_* = 0.44 \pm 0.08$ determined by the discseismic measurement. (c) is the time evolution of mass ratio M/M_0 with different mass accretion rate and initial spin parameters. The curves are almost independent of the initial spin parameters.

Kato+, arXiv:0906.5423
MNRAS

KAGRA | BH Ringdown wave

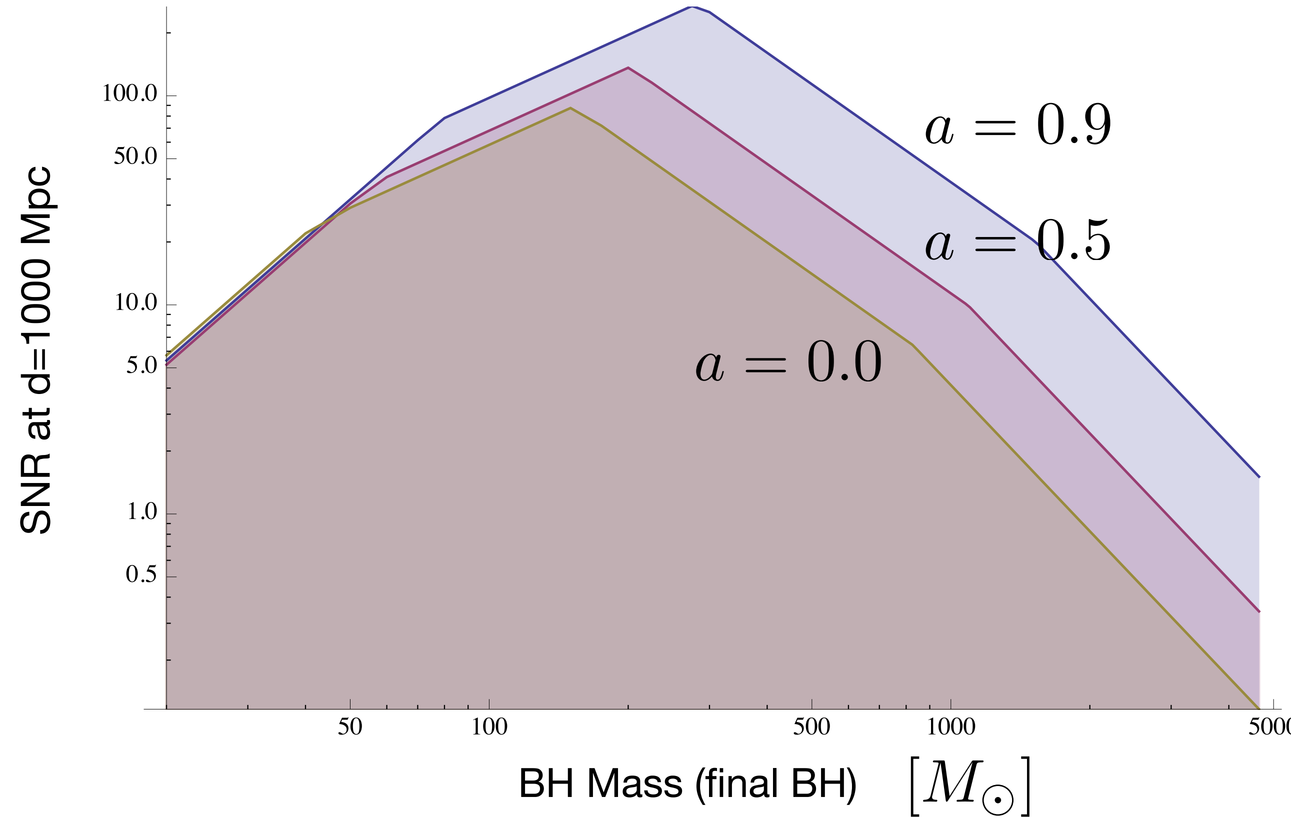


Einstein Telescope | BH Ringdown wave

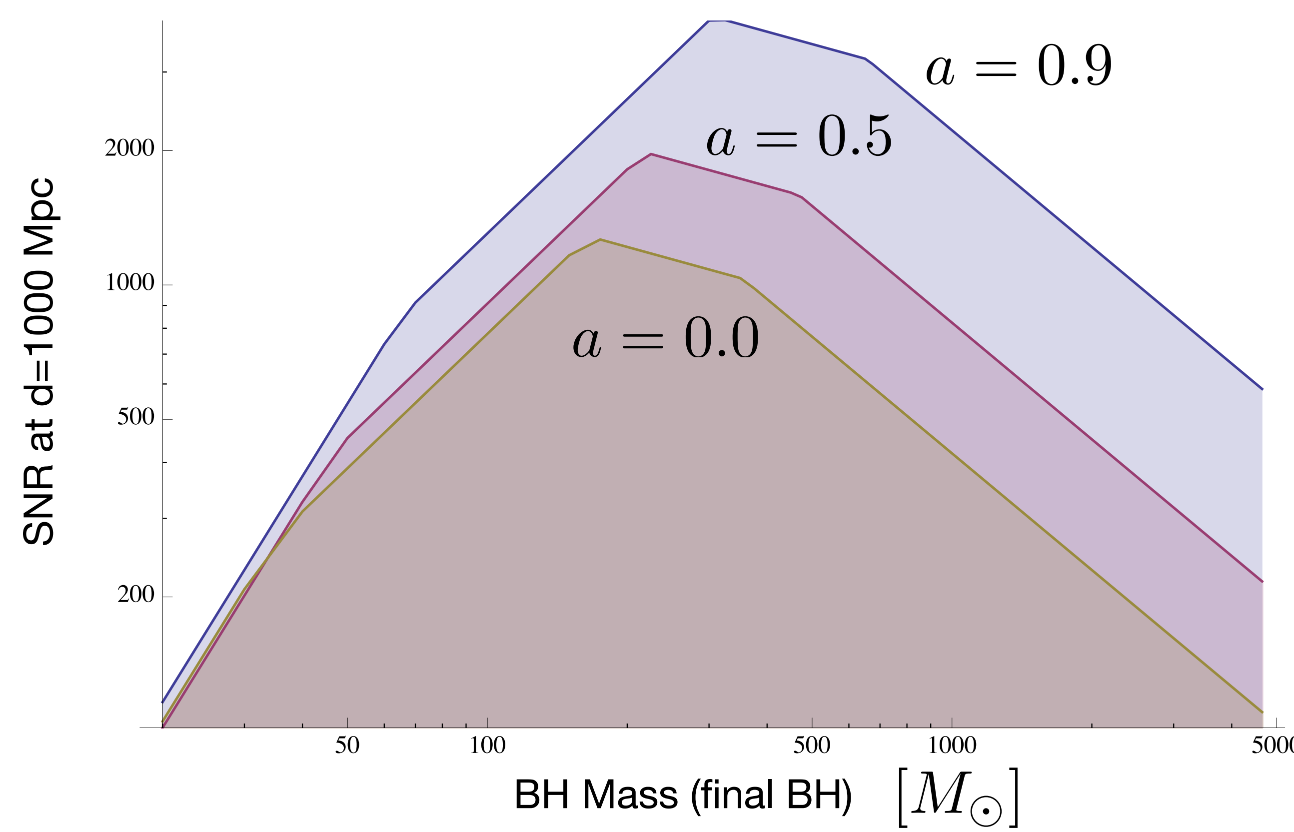


1Gpc先の感度

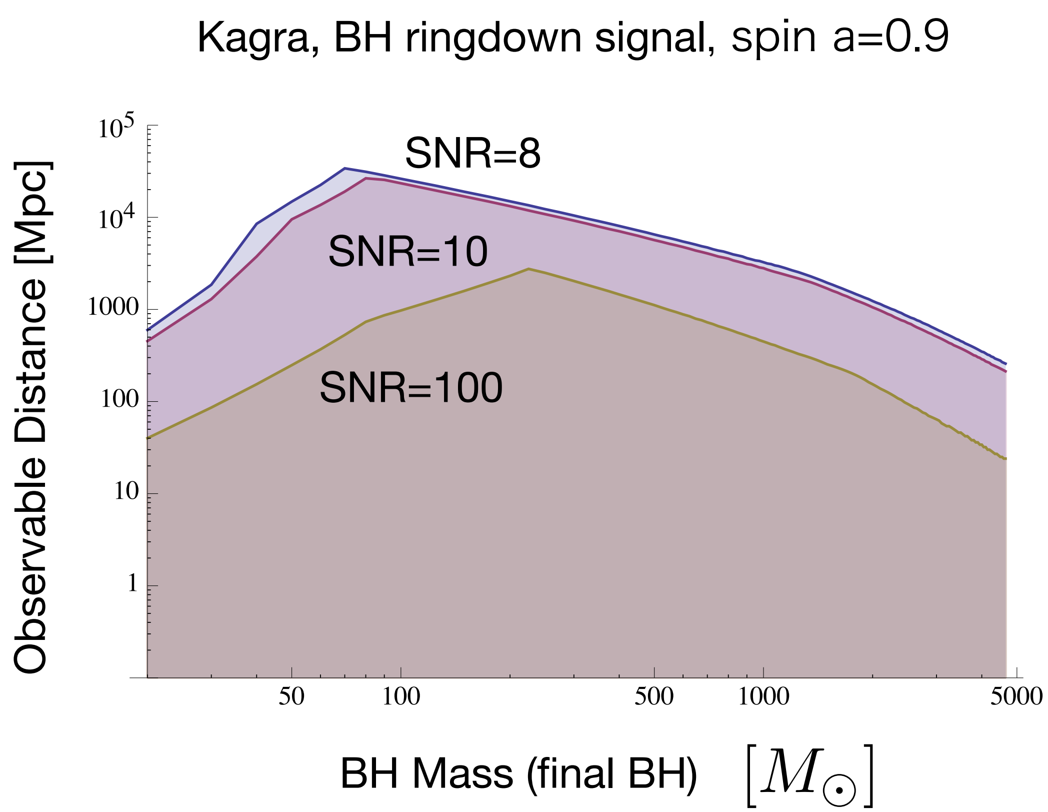
KAGRA

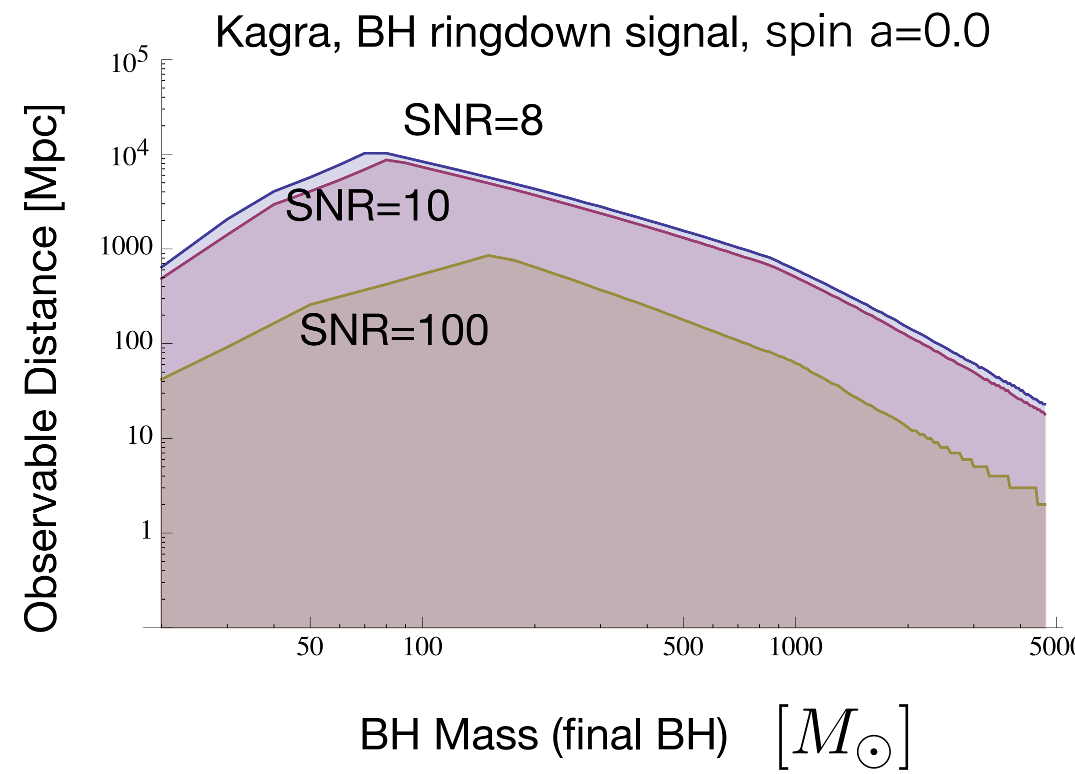


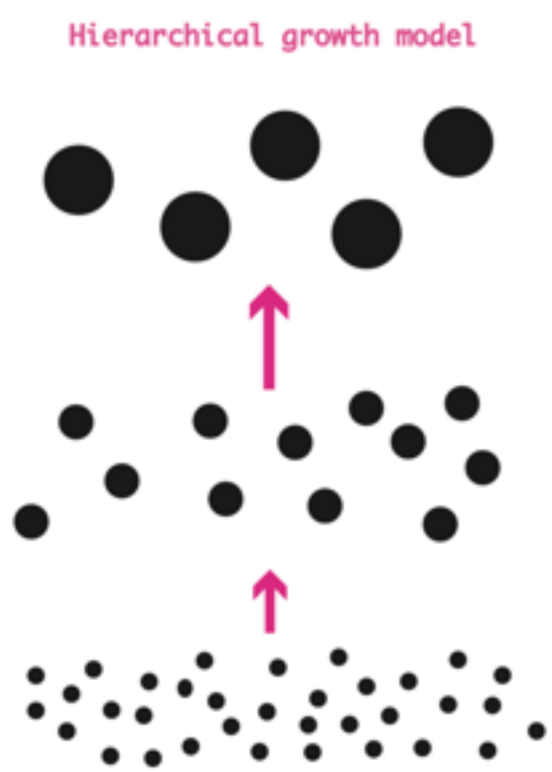
Einstein Telescope

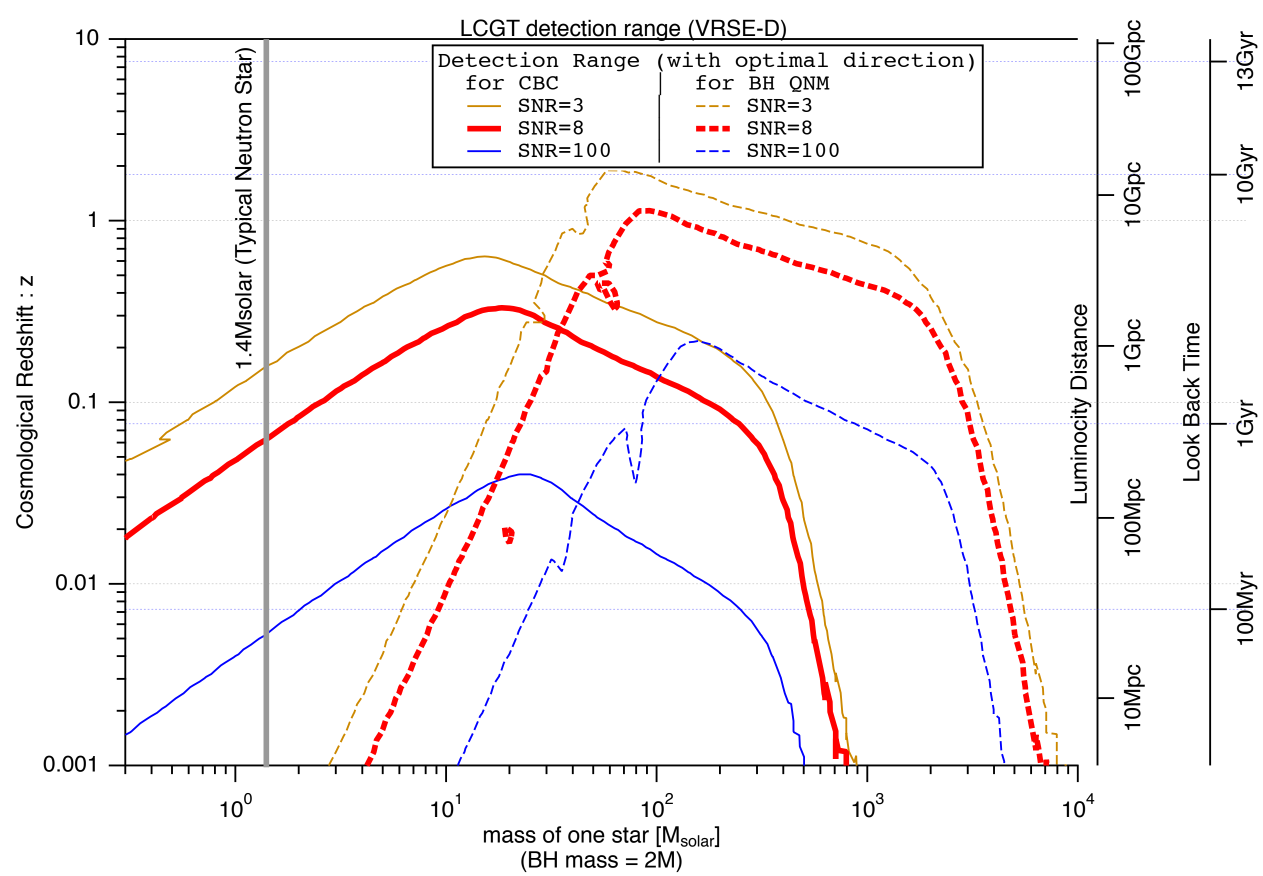


観測可能距離 (等質量連星合体)



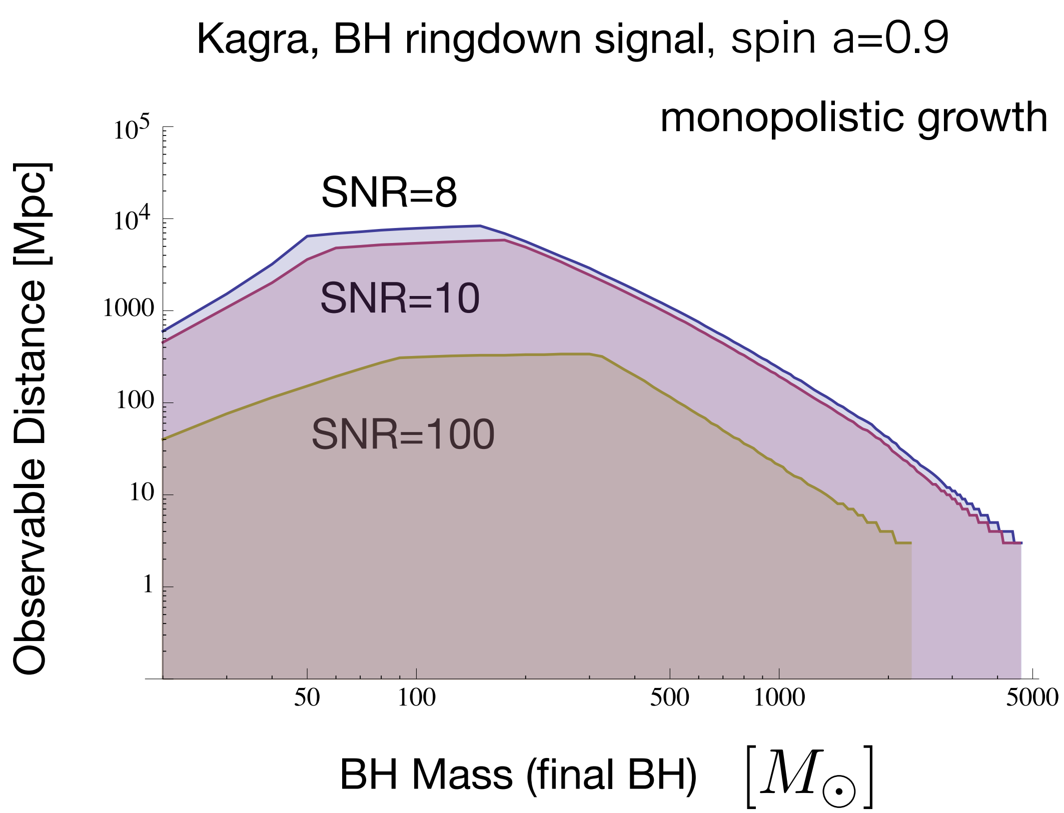


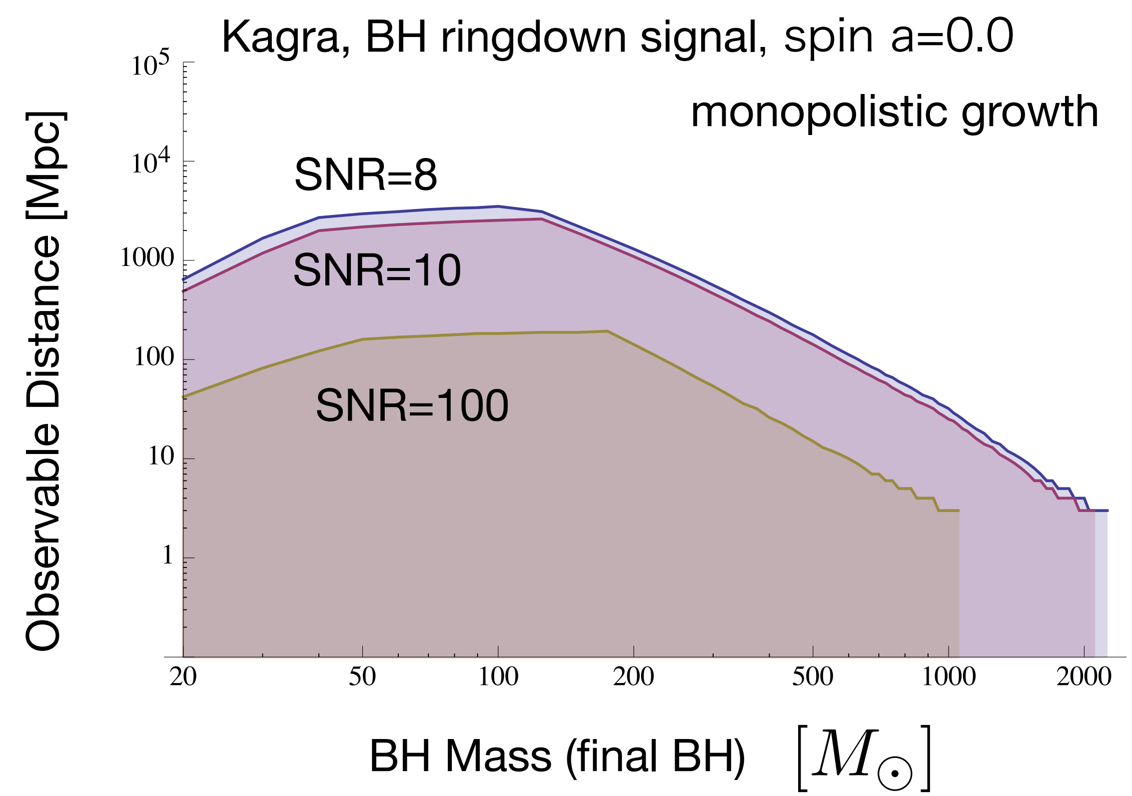




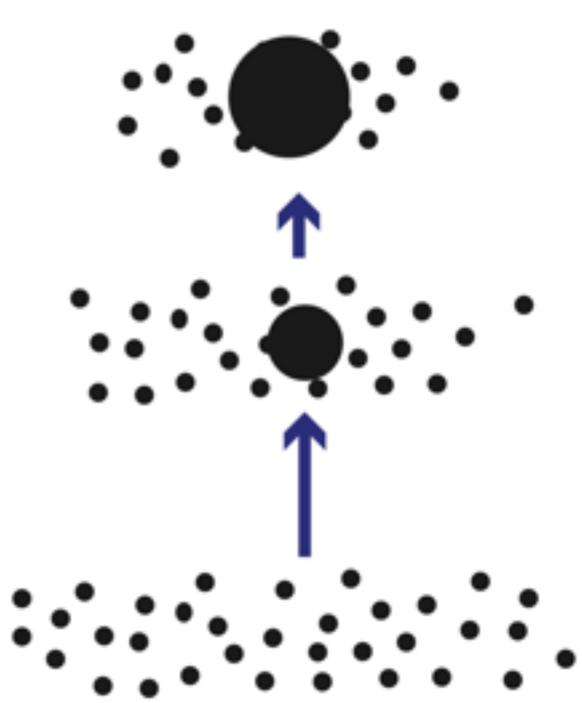
Kanda+,
arXiv:1112.3092

観測可能距離 (monopolistic growth)





Monopolistic growth model



$$\langle \rho^2 \rangle = \left(\frac{S}{N}\right)^2 = \frac{1}{20\pi^2}\frac{(1+z)Q\mathcal{A}^2}{f_{\rm qnr}S_h[f_{\rm qnr}/(1+z)]}\left[\frac{(1+z)M}{D(z)}\right]^2\left[\frac{4\mu}{M}\right]^2$$

$$= \frac{8}{5}\frac{1}{[1-0.63(1-a)^{0.3}]^2}\epsilon_r\frac{(1+z)M}{S_h[f_{\rm qnr}/(1+z)]}\left[\frac{(1+z)M}{D(z)}\right]^2\boxed{\left[\frac{4\mu}{M}\right]^2}$$

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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]
[1] Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), D-14476 Potsdam, Germany;
Pau.Amaro-Seoane@aei.mpg.de, Lucia.Santamaria@aei.mpg.de
[2] Institut de Ciències de l'Espai, IEEC/CSIC, Campus UAB, Torre C-5, parells, 2[na] planta, ES-08193 Bellaterra, Barcelona, Spain
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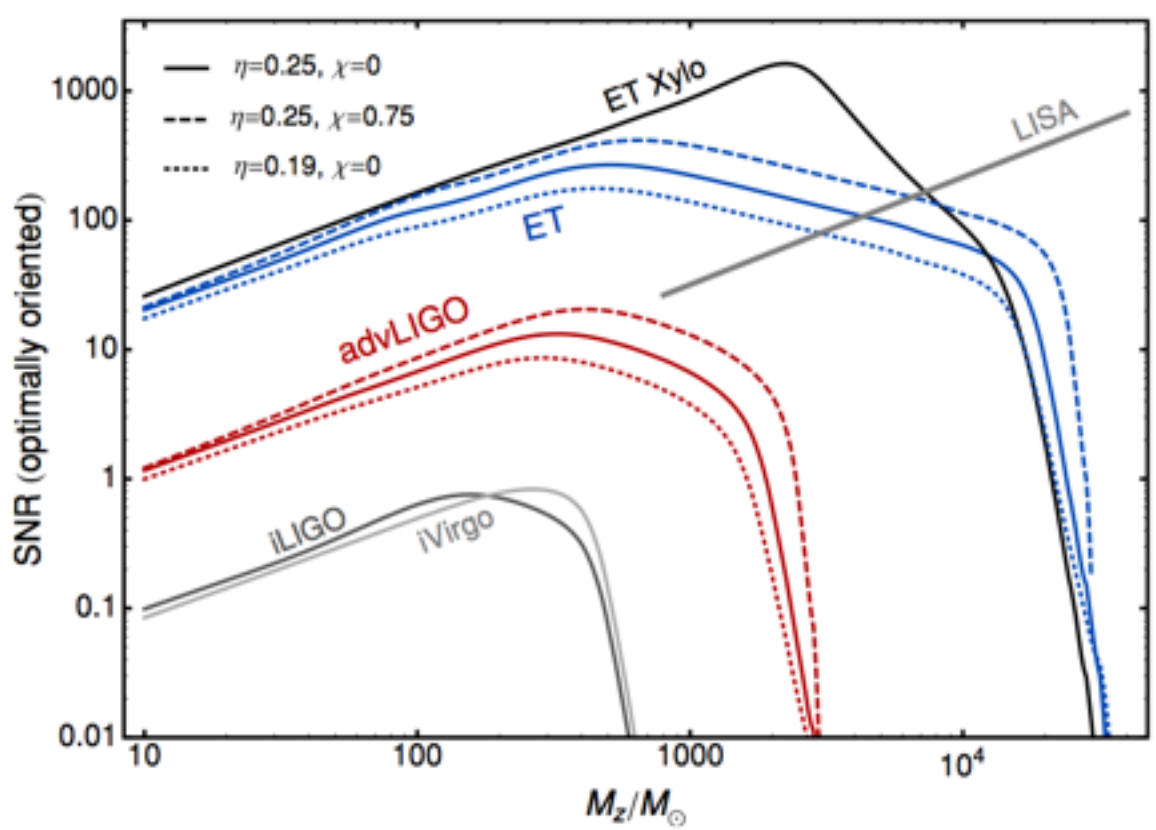


Figure 7. S/N as a function of the redshifted total mass of the BBH for the present and future generations of GW detectors and *LISA*. The sources are placed at a distance of 6.68 Gpc ($z = 1$) and the S/Ns correspond to sources optimally oriented and located. Solid lines indicate S/Ns for the equal-mass, 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.

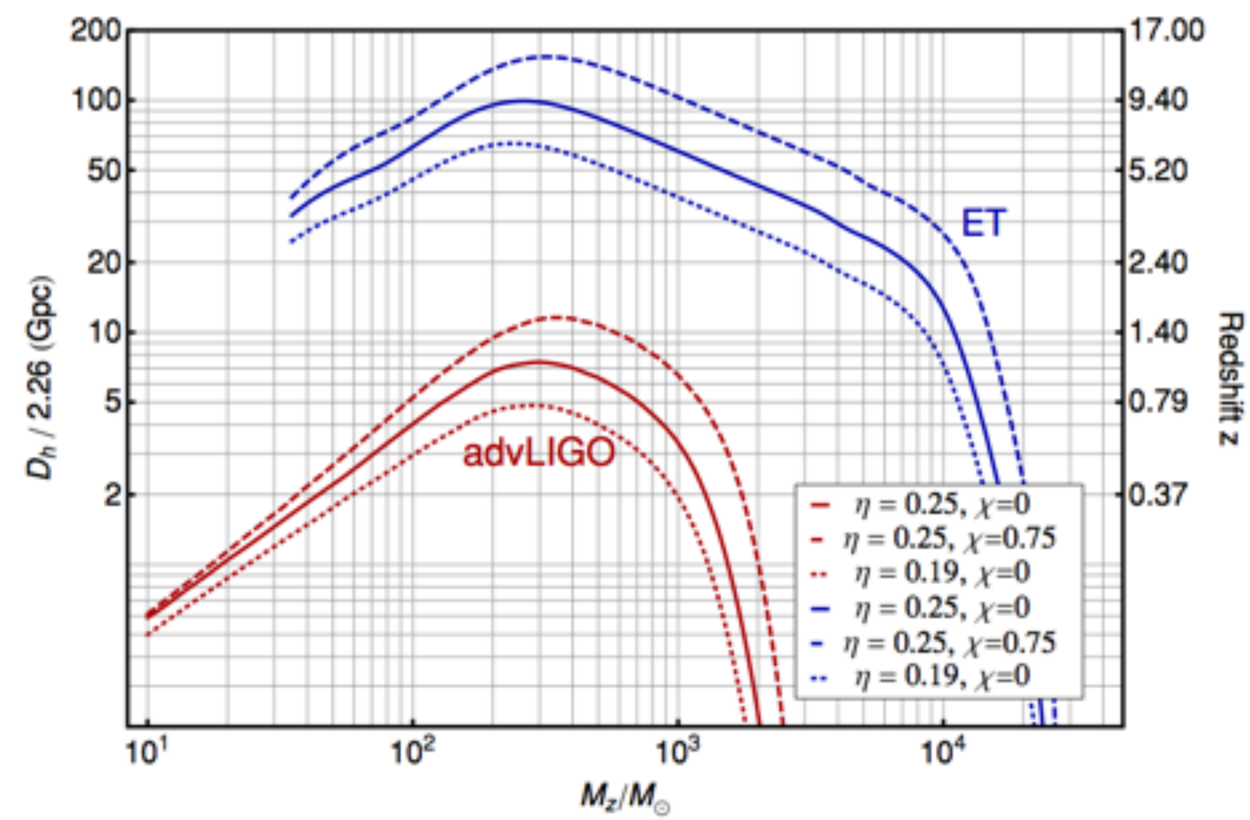


Figure 8. Orientation-averaged distance vs. redshifted mass for three binary configurations obtained with the design sensitivity curves of Advanced LIGO and the ET. The solid, dashed, and dotted lines correspond to the configurations denoted in the text as (1), (2), and (3), respectively. Note the ∼40%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

Event Rate?

Miller (2002) ApJ 581, 438
Will (2004) ApJ 611, 1080
Fregeau + (2006) ApJ 646, L135

$$R(M, a, \rho) \;=\; \left(\frac{4\pi}{3} n_{gc} d_L(M, a, \rho)^3\right) \nu(M, \mu) f(M) \qquad (1)$$

where

- $d_L(M, a, \rho)$ is the distance reached for a given SNR ρ as a function of total mass M, and spin of BH a.
- $n_{gc} = 8h^3$ Mpc^{-3} is the number density of globular cluster.
- $\nu(M) = 10^{-10} M/\mu$ [/yr] is the rate of small mass BH merge with BH of mass M.
- $f(M)$ is the fraction of globular clusters.

Event Rate?

Miller (2002) ApJ 581, 438
Will (2004) ApJ 611, 1080
Fregeau + (2006) ApJ 646, L135

cosmological model

- H_0=72 km/s/Mpc
- $\Omega_{m0} = 0.27$, $\Omega_{k0} = 0$, and $\Omega_{d0} = 0.73$.

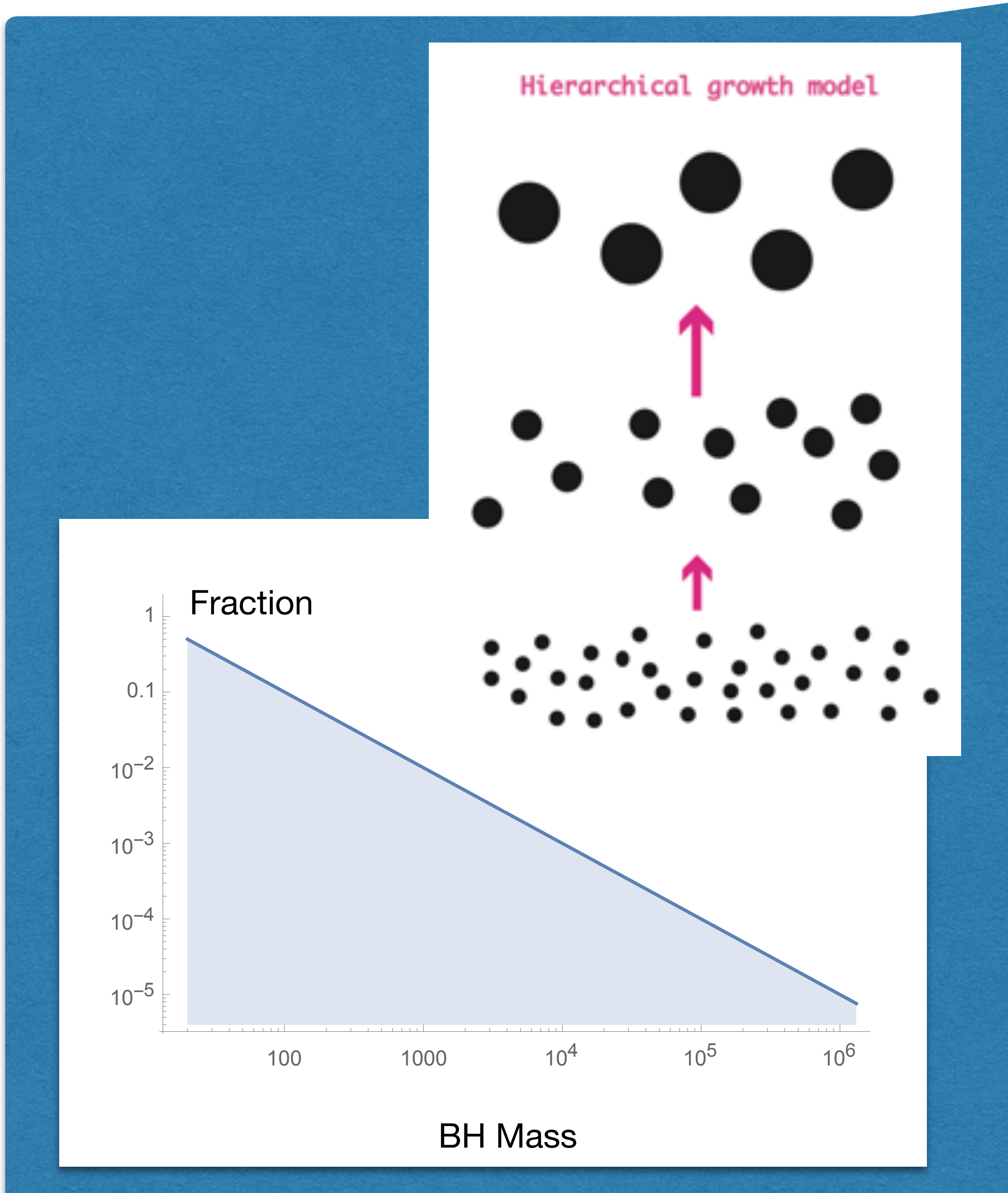
$$R(M, a, \rho) = \left(\frac{4\pi}{3} n_{gc} d_L(M, a, \rho)^3\right) \nu(M, \mu) f(M) \quad (1)$$

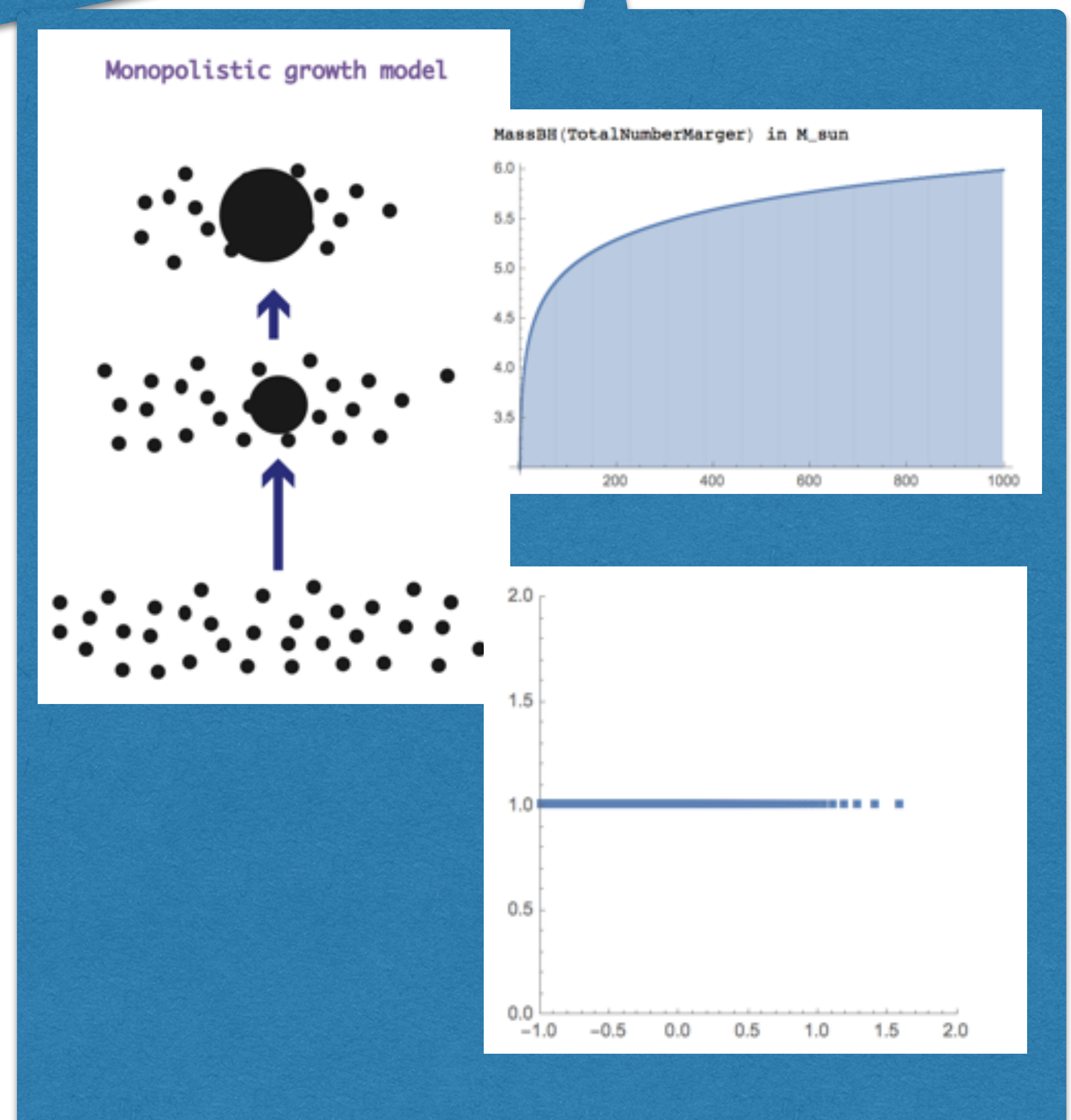
where

- $d_L(M, a, \rho)$ is the distance reached for a given SNR ρ as a function of total mass M, and spin of BH a.
- $n_{gc} = 8h^3$ Mpc^{-3} is the number density of globular cluster.
- $\nu(M) = 10^{-10} M/\mu$ [/yr] is the rate of small mass BH merge with BH of mass M.
- $f(M)$ is the fraction of globular clusters.

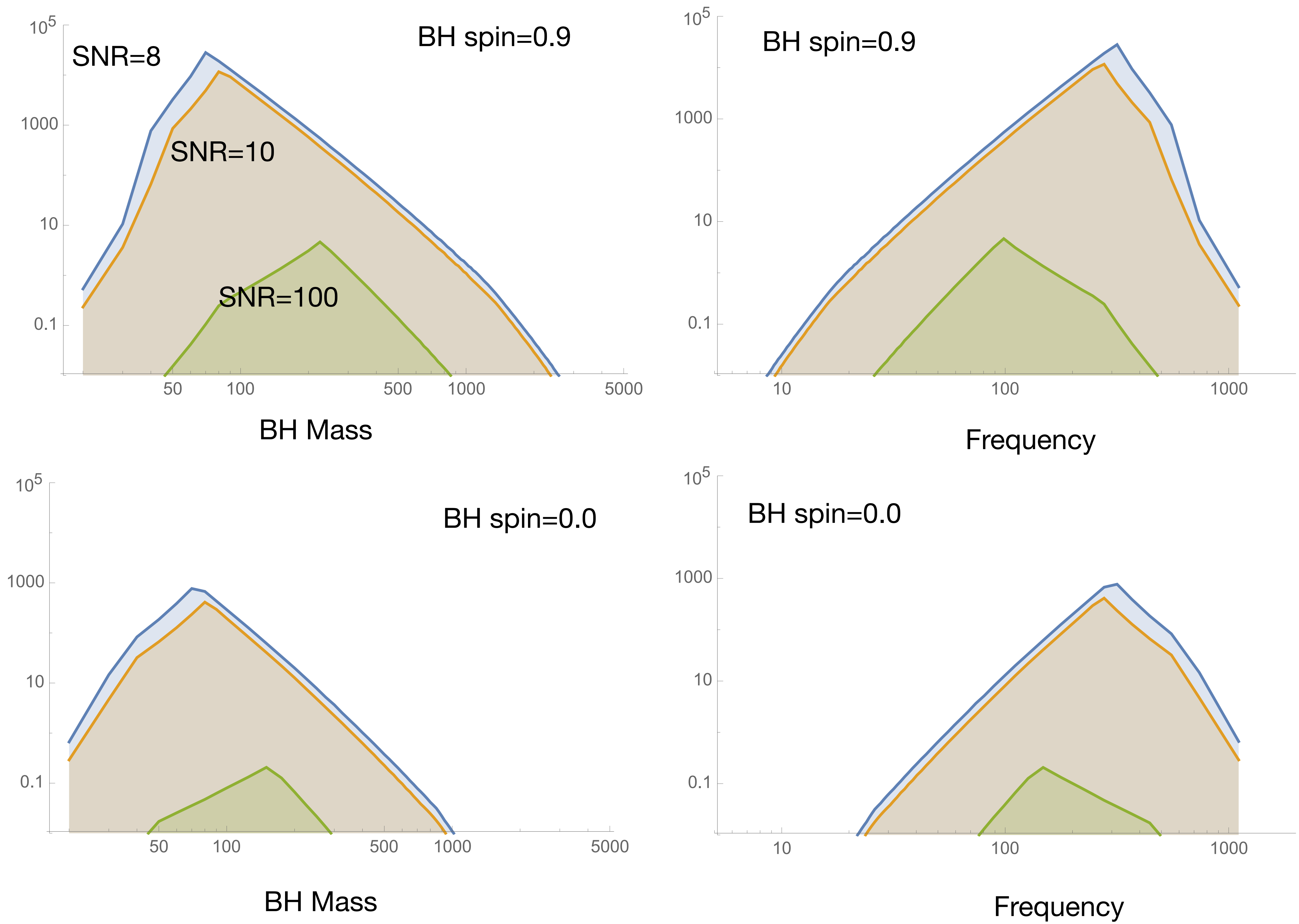
Fraction Rate

$$R(M,a,\rho) \;=\; \left(\frac{4\pi}{3} n_{gc} d_L(M,a,\rho)^3\right) \nu(M,\mu) f(M)$$

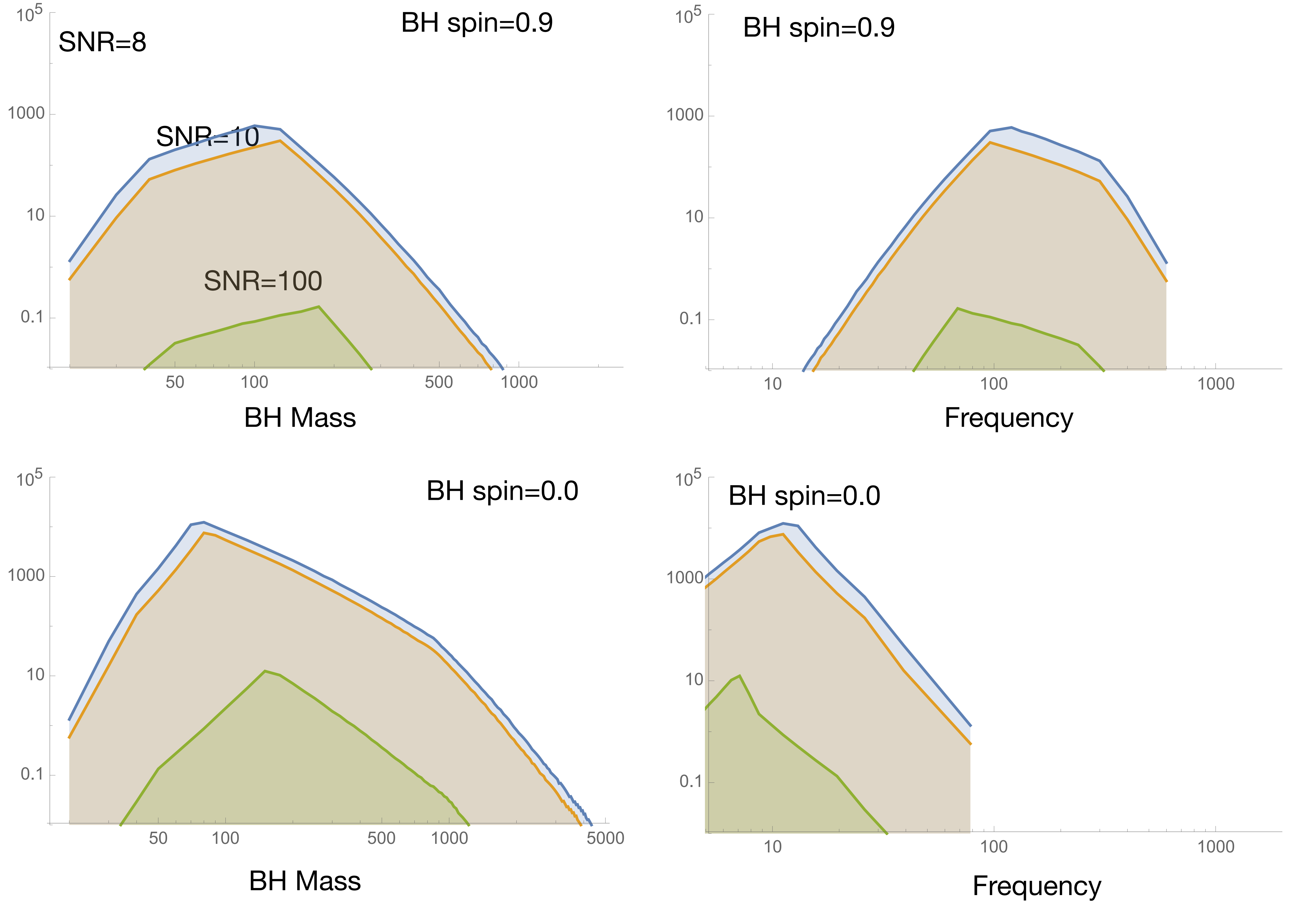




Event Rate (hierarchical growth)



Event Rate (monopolistic growth)



BH連星合体イベントからの重力波

IMBH形成シナリオが，KAGRA で判別できるか.

KAGRAでも
できる

DECIGO/LISA
ではできる

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

GRAVITATIONAL WAVES FROM MERGING INTERMEDIATE-MASS BLACK HOLES

TATSUSHI MATSUBAYASHI,[1] HISA-AKI SHINKAI,[2] AND
TOSHIKAZU EBISUZAKI[2]
Received 2004 February 26; accepted 2004 June 29