Event rates of gravitational waves in space-borne detectors based on a hierarchical growth model of SMBHs

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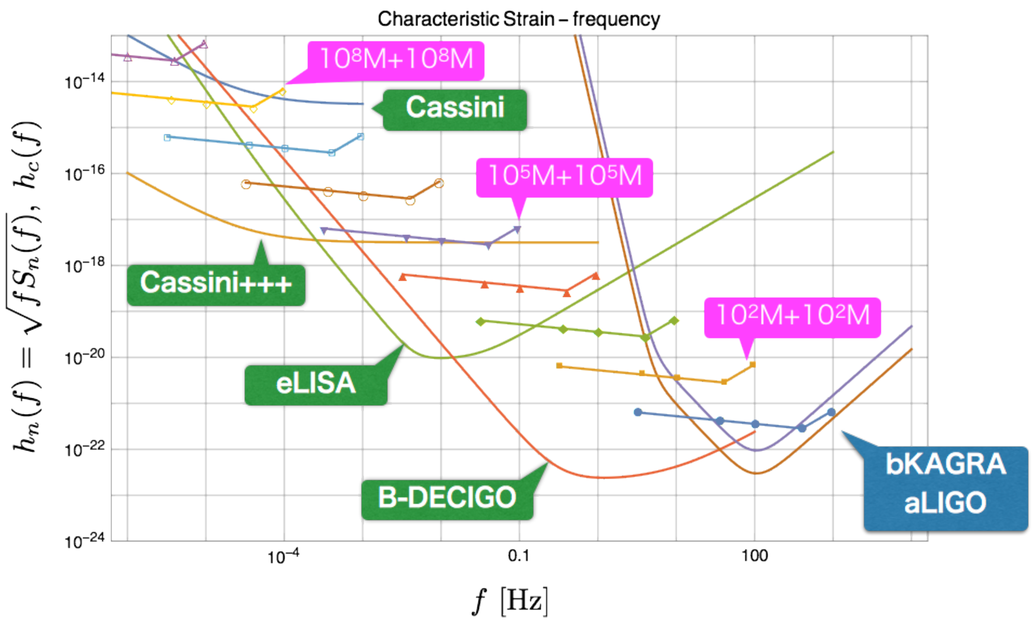
Outline & Summary

- Based on a dynamical formation model of a super-massive black-hole (SMBH), we estimate expected observational profile of gravitational wave at space-borne detectors; (a) the proposed interferometers such as eLISA & DECIGO, and (b) a planned Doppler-tracking measurement using a three-order-improved Cassini. We calculate the observable distance (horizon of the detector) both for inspiral and ringdown waves, and estimate the event-rate using a BH-BH merger model.
- We use a BH-BH merger model by Shinkai-Kanda-Ebisuzaki [ApJ, 835 (2017) 276]. That is, we estimate the number density of galaxy from halo formation model, and estimate the number of BH mergers from giant molecular cloud model together with hierarchical growth of merged cores.
- We find that at the signal-to-noise ratio $\rho = 10$, the event-rate of the BH mergers by B-DECIGO is 33 times higher than that of eLISA for detections of inspiral phase, and 20 times higher for detections of ringdown phase. We also find that there may be several events per year even at the improved Cassini for detections of inspiral phase.

Thus we conclude that the statistics of the signals will tell us both a galaxy distribution and a formation model of SMBHs.

Typical GW Strain of BH-BH merger @ 1000Mpc



A route to a SMBH

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) [83]	vel. disp. σ (km/s) [111]	BH mass ($M_\odot$)
104	4.5	10.0	794.7
362	8.5	6.2	116.3
1851	12.1	11.3	1299
1904	12.9	3.9	18.04
5272	10.4	4.8	41.57
5286	11.0	8.6	433.4
5694	34.7	6.1	108.9
5824	32.0	11.1	1209
5904	7.5	6.5	140.6
5946	10.6	4.0	19.97
6093	10.0	14.5	3539
6266	6.9	15.4	4508
6284	15.3	6.8	168.6
6293	8.8	8.2	357.9
6325	8.0	6.4	132.4
6342	8.6	5.2	57.35
6441	11.7	19.5	11645
6522	7.8	7.3	224.3
6558	7.4	3.5	11.68
6681	9.0	10.0	794.7
7099	8.0	5.8	88.96

Yagi, CQG 29 075005 (2012) [arXiv:1202.3512]

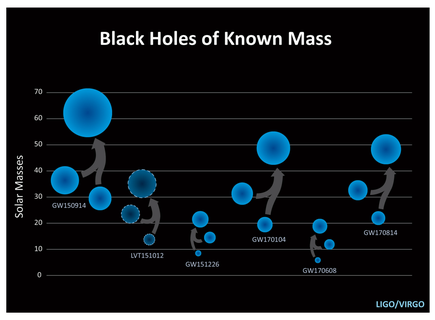
'Missing link' founded
Ebisuzaki +, ApJ, 562, L19 (2001)

(1)formation of IMBHs by runaway mergers of massive stars in dense star clusters,
Marchant & Shapiro 1980; Portegies Zwart et al. 1999; Portegies Zwart & McMillan 2002; Portegies Zwart et al. 2004; Holger & Makino 2003

(2) accumulations of IMBHs at the center region of a galaxy due to sinkages of clusters by dynamical friction
Matsubayashi et al. 2007

(3) mergings of IMBHs by multi-body interactions and gravitational radiation.
Iwasawa et. al. 2010

BHs $\exists 60 M_\odot$ → IMBHs $10^2 - 10^4 M_\odot$ → SMBHs $\exists 10^6 M_\odot$



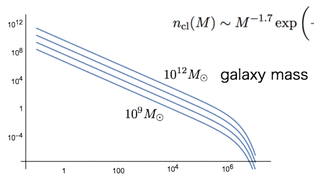
How many BHs in a galaxy?

ApJ. 835 (2017) 276

How many BHs in a Galaxy?

Mass Function of Giant Molecular Clouds

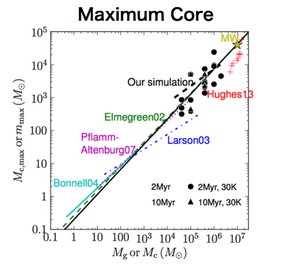
$n_{\rm cl}(M) \sim M^{-1.7} \exp\left(-\frac{M}{M_{\rm cut}}\right), \quad M_{\rm cut} = 10^6 M_\odot$



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?

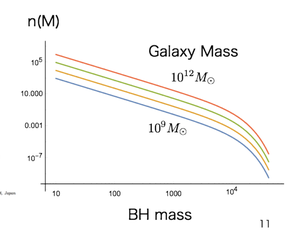
Molecular Clouds Maximum Core



The initial mass function of star clusters that form in turbulent molecular clouds
M. S. Fujii[1,*] and S. Portegies Zwart[2,*]
1309.1223v3

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

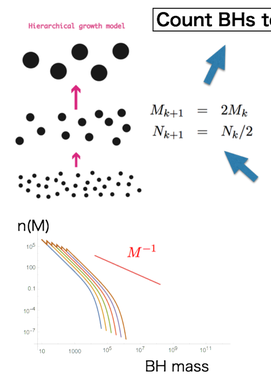
Building Block BH



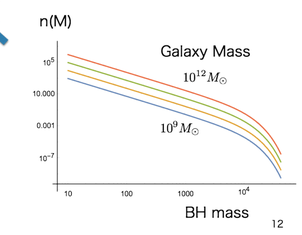
11

How many BHs in a Galaxy?

Count BHs to form a SMBH



Building Block BH



12

How many galaxies in the Universe?

How many Galaxies in the Universe?

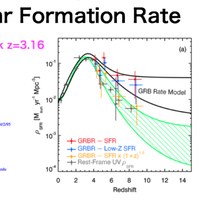
Count BHs to form a SMBH

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

(sub-)Galaxy from Halo model

Star Formation Rate

peak z=3.16

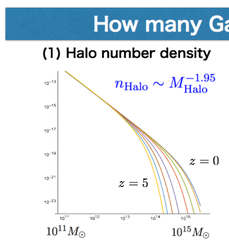


The non-parametric model for linking galaxy luminosity with halo/subhalo mass
A. Vale[1*] and J. P. Ostriker[1,2]
CONNECTING THE GAMMA RAY BURST RATE AND THE COSMIC STAR FORMATION HISTORY: IMPLICATIONS FOR REIONIZATION AND GALAXY EVOLUTION
BRANT E. ROBERTSON[1,2,3] AND RICHARD S. ELLIS[1]

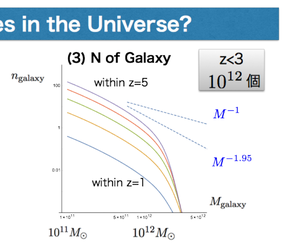
How many Galaxies in the Universe?

(1) Halo number density

$n_{\rm Halo} \sim M_{\rm Halo}^{-1.95}$



(3) N of Galaxy



(2) N of seeds of Galaxy (subHalo)

$N_{\rm subHalo} \sim M_{\rm Halo}^{0.90}$

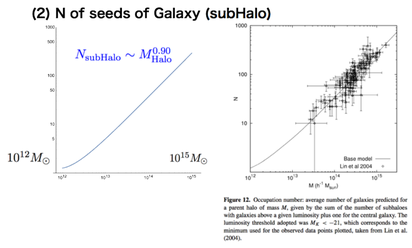


Figure 12. Occupation number: average number of galaxies predicted for a parent halo of mass M_h given by the sum of the number of subhaloes with galaxies above a given luminosity plus one for the central galaxy. The luminosity threshold adopted was $M_K < -21$, which corresponds to the minimum used for the observed data points plotted, taken from Lin et al. (2004).

How many Galaxies in the Universe?

Count BHs to form a SMBH

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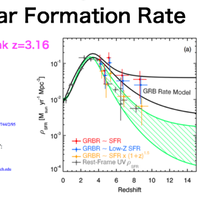
$= 10^{-3} M_{\rm bulge}$

(sub-)Galaxy from Halo model

Star Formation Rate

peak z=3.16



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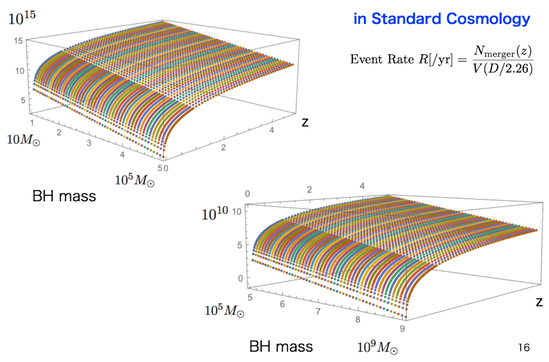
Observational Profiles at eLISA, B-DECIGO, & Cassini+++

How many BH mergers ?

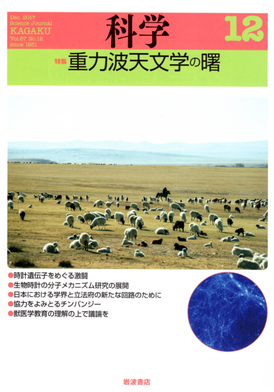
How many BH mergers in the Universe?

in Standard Cosmology

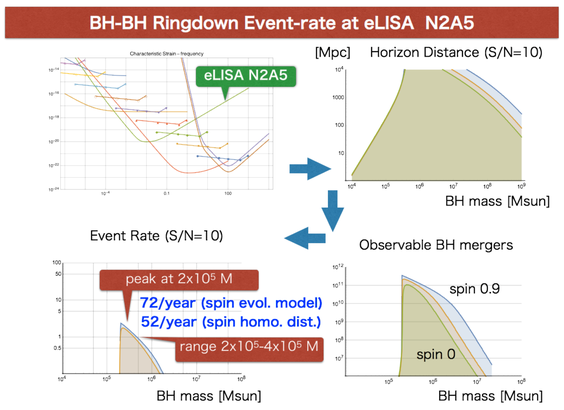
Event Rate $R[/{\rm yr}] = \frac{N_{\rm merger}(z)}{V(D/2.26)}$



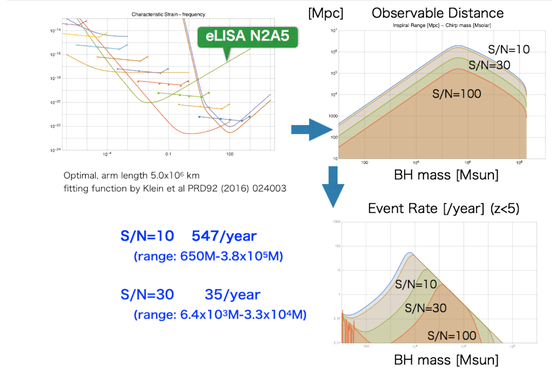
16



BH-BH Ringdown Event-rate at eLISA N2A5



BH-BH Inspiral Event-rate at eLISA N2A5

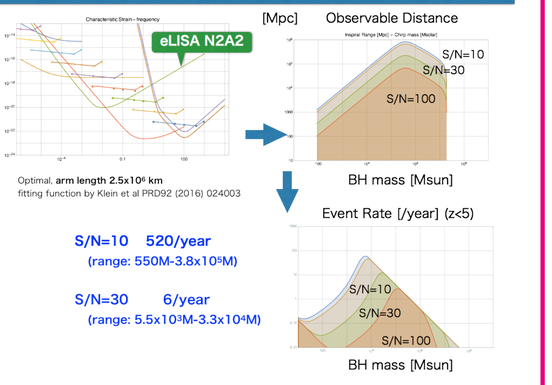


Optimal, arm length 5.0x10^6 km
fitting function by Klein et al PRD92 (2016) 024003

S/N=10 547/year
(range: 650M-3.8x10^{5}M)

S/N=30 35/year
(range: 6.4x10^{3}M-3.3x10^{4}M)

BH-BH Inspiral Event-rate at eLISA N2A2

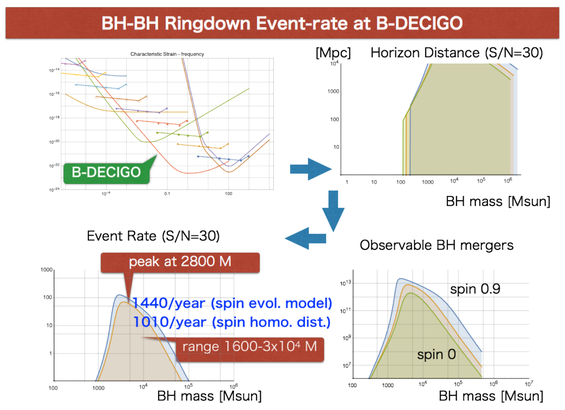


Optimal, **arm length 2.5x10^6 km**
fitting function by Klein et al PRD92 (2016) 024003

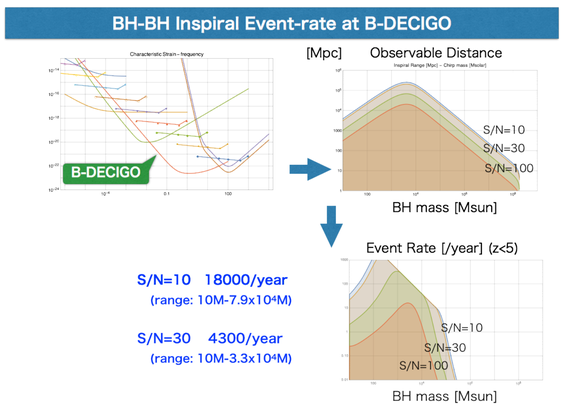
S/N=10 520/year
(range: 550M-3.8x10^{5}M)

S/N=30 6/year
(range: 5.5x10^{3}M-3.3x10^{4}M)

BH-BH Ringdown Event-rate at B-DECIGO



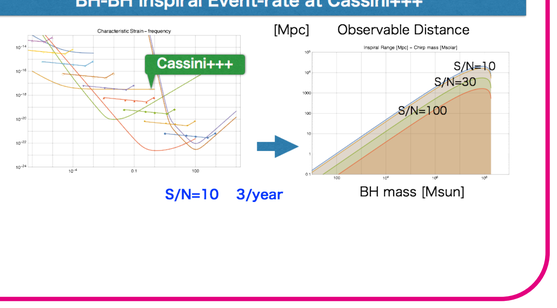
BH-BH Inspiral Event-rate at B-DECIGO



S/N=10 18000/year
(range: 10M-7.9x10^{4}M)

S/N=30 4300/year
(range: 10M-3.3x10^{4}M)

BH-BH Inspiral Event-rate at Cassini+++



S/N=10 3/year

Cassini+++ については，岩波「科学」2017 年 12 月号掲載
『光格子時計による重力波検出』（玉川徹，真貝寿明，野田篤司，香取秀俊，牧野淳一郎，戎崎俊一）をご参照ください．