Prospects of eLISA for Detecting (Galactic) Binary Black Holes Similar to GW150914

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introduction

- GW150914: the first direct detection of GWs
  - Existence of Binary black holes (BBHs)
  - Chirp mass (~28M_{sun}) much larger than expected
  - its formation mechanism: actively discussed (many talks)
    - Dynamical scenario (dense star cluster)
    - Isolated scenario (complicated binary evolution)
- This talk
  - Discuss impacts of GW150914 (+151226) on eLISA
    - Prospects of BBH detection
    - Dependence on specification

Plan of this talk

- Brief summary of recent GW detections (150914,..)
- Search for Galactic BBHs with eLISA
    - SNR of the loudest one
    - Expected number of detection
- Search for extra-Galactic BBHs with eLISA
    - Expected number of detection

For more details (e.g. eccentricity, sky localization), see our papers

Brief summary of recent GW detections

- Basic parameters relevant to this talk
  - Chirp masses (primary parameter for GW)
    - $M_c = (m_1 m_2)^{3/5} (m_1+m_2)^{-1/5}$
      - GW150914 $28M_{sun}$
      - GW151226 $8.9M_{sun}$
      - LVT151012 $15.1M_{sun}$
  - Merger rate of BBHs
    - $R=9\text{-}240\,Gpc^{-3}yr^{-1}$
  - Fiducial model parameters in this talk
    - $M_c=28M_{sun}$
    - $R=150\ Gpc^{-3}yr^{-1}$ (Galactic) , $R=100\ Gpc^{-3}yr^{-1}$ (extra Galactic)

Galactic BBH search

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- The loudest BBHs
  - Typical distance: ~8kpc
  - Shape of noise curves

→ the highest frequency one

- The highest frequency
  - Volume averaged BBH merger rate: R= 150 $Gpc^{-3}yr^{-1}$
  - Number density of Milkyway equivalent galaxy: 0.01Mpc^{-3}
    - Galactic merger rate R_G=1.5x$10^{-5}yr^{-1}$ (too simple?)
    - Loudest one: merger time $1/R_G$

$$f_{2L} = 0.5 \left(\frac{R_G}{1.5 \times 10^{-5} \mathrm{yr}^{-1}} \right)^{3/8} \left(\frac{M_c}{28 M_\odot} \right)^{-5/8} \mathrm{mHz}.$$

SNR of the loudest one

- almost stationary
- amplitude

$$A_2 = \frac{8G^{5/3}(\pi f_2)^{2/3}M_c^{5/3}}{5Dc^4}$$
$$= 9.3 \times 10^{-21} \left(\frac{D}{8\text{kpc}}\right)^{-1} \left(\frac{M_c}{28M_\odot}\right)^{5/3}$$
$$\times \left(\frac{f_2}{0.5\text{mHz}}\right)^{2/3}.$$

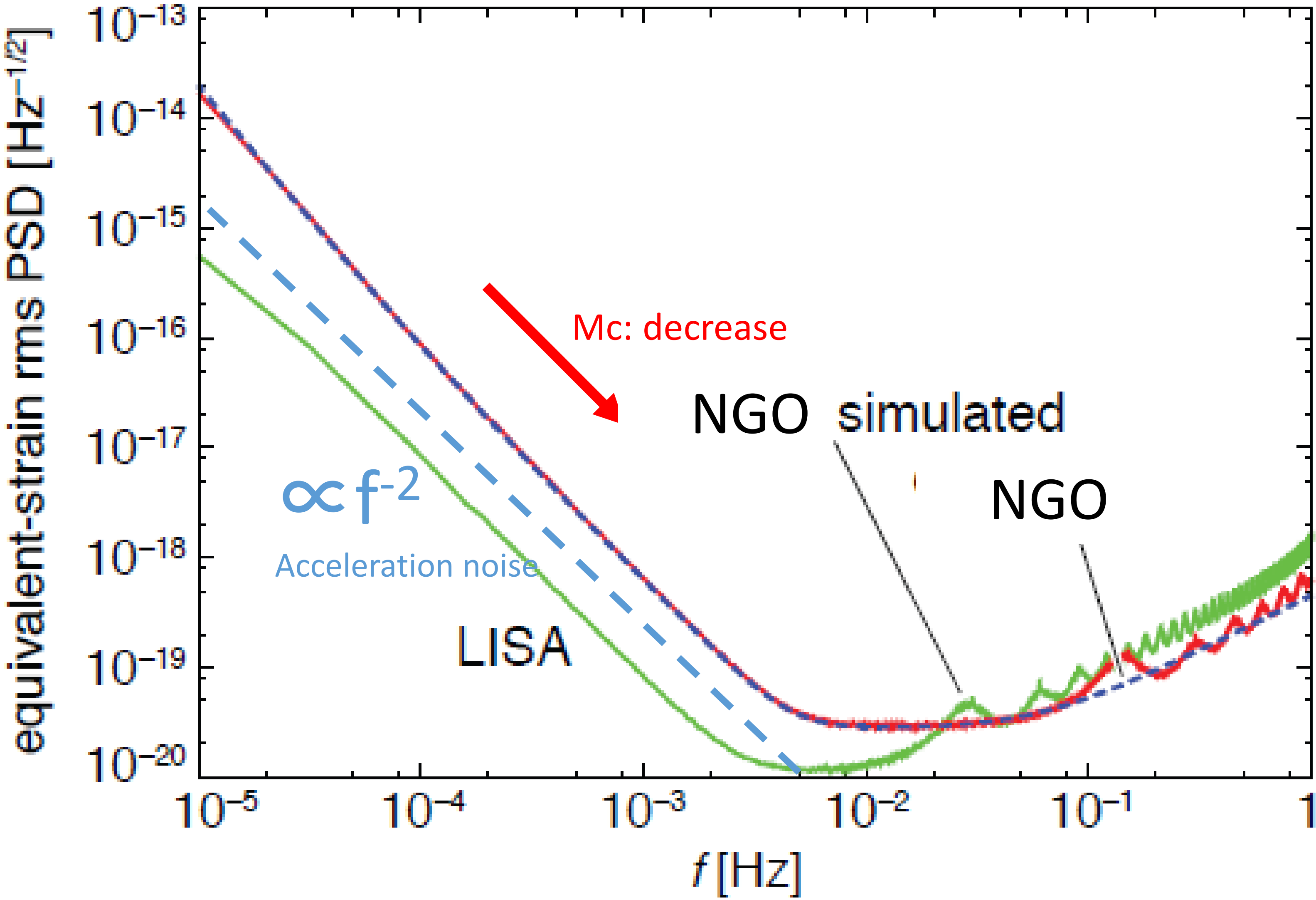
- SNR

$$SN_2 = \frac{A_2 T_{\rm obs}^{1/2}}{h_n(f_2)}$$

$$= 70 \left(\frac{A_2}{2.1 \times 10^{-20}}\right) \left(\frac{h_n(f_2)}{3 \times 10^{-18}\ \text{Hz}^{-1/2}}\right)^{-1} \left(\frac{T_{\rm obs}}{3\text{yr}}\right)^{1/2}$$

Noise spectrum

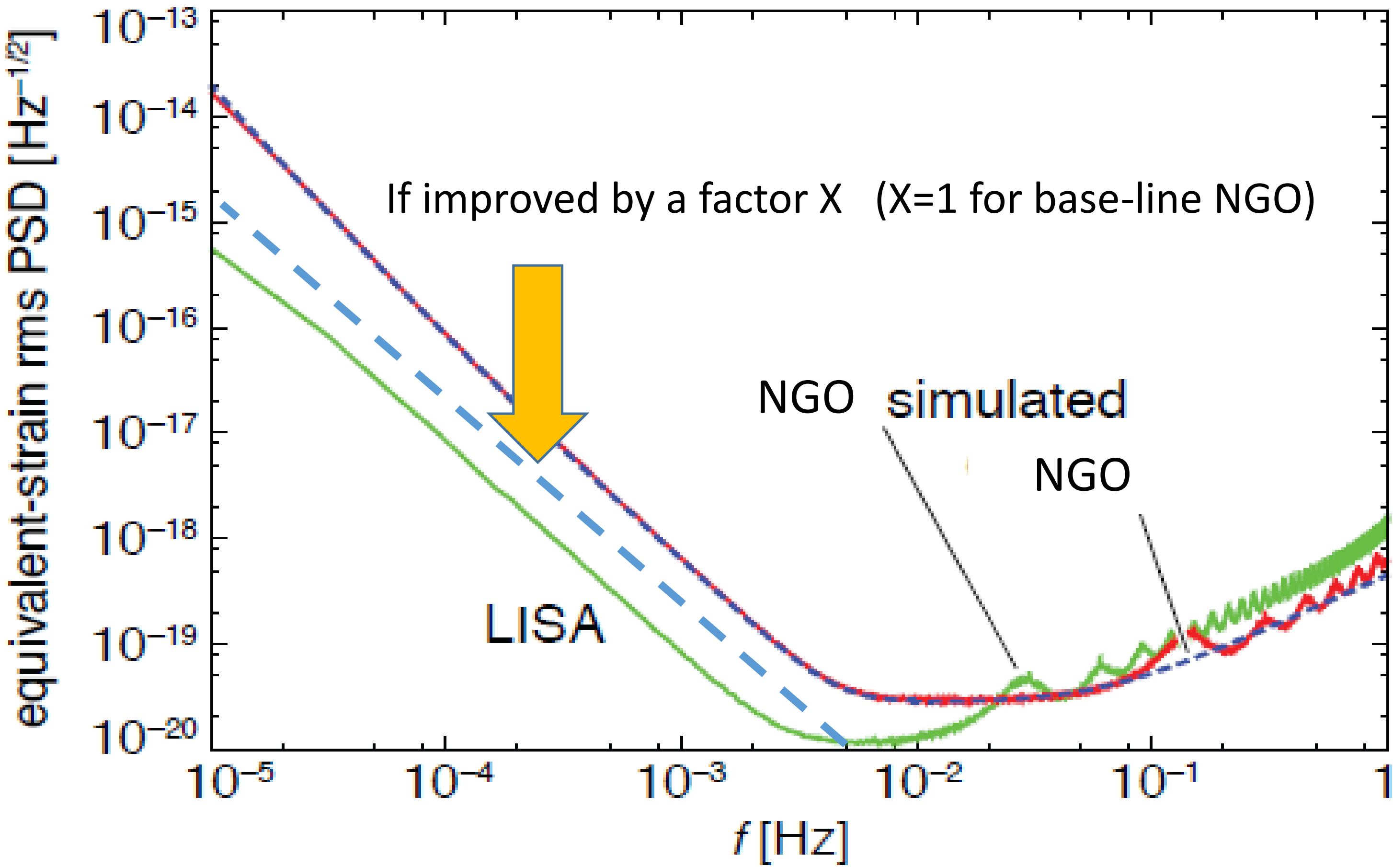
SNR: independent of M_c



Cancelation between M_c and f dependences

How many Galactic BBHs detectable?

Continuity eq. in frequency space (density*velocity=flux)



$$N(>f_{2\mathrm{th}}) = 5.8X^{-1}\left(\frac{SN_{2\mathrm{th}}}{12}\right)^{-1}\left(\frac{R_V}{150\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}}\right)\left(\frac{T_{obs}}{3\mathrm{yr}}\right)^{1/2}$$

Again independent of M_c

Search for extra-Galactic BBHs

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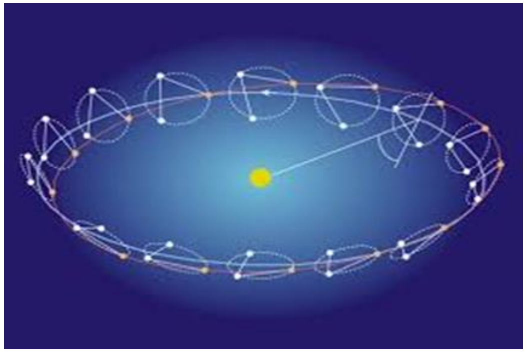
See also Sesana 16 for multiband obs

- Frequency distribution from continuity eq

$$\frac{dn}{d\ln f} = \frac{f}{\dot{f}}R = \frac{5c^5 R}{96\pi^{8/3}G^{5/3}\mathcal{M}^{5/3}f^{8/3}}$$
$$= 4.57 \times 10^{-6}\,\mathrm{Mpc}^{-3}$$
$$\times \left(\frac{f}{10\,\mathrm{mHz}}\right)^{-8/3} \left(\frac{\mathcal{M}}{28M_\odot}\right)^{-5/3} \left(\frac{R}{100\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}}\right)$$

- Detectable volume V as a function of obs time T and f_i

$$\rho^2 = 4\int_{f_i}^{f_f} \frac{|\tilde{h}(f)|^2}{(3/20)S(f)}df.$$



After appropriate angular averages

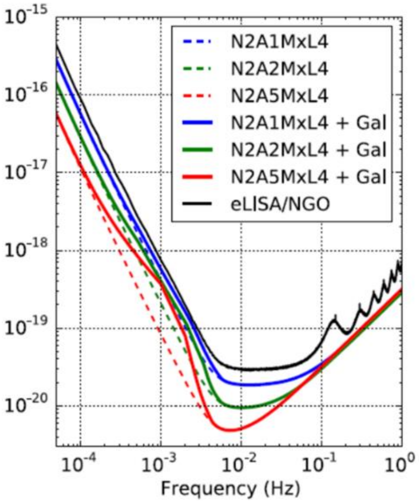
$$V(f_i,T) = \frac{4\pi}{3} \times 0.822\frac{A^3}{\rho_{\mathrm{thr}}^3}I_7(f_i,T)^{3/2}$$

$$A^2 \equiv \frac{G^{5/3}\mathcal{M}^{5/3}}{8\pi^{4/3}c^3} \quad I_7(f_i,T) \equiv \int_{f_i}^{f_f} \frac{f^{-7/3}}{(3/20)S(f)}df.$$

How many BBHs detectable?

- Expected number per log f

$$\frac{dN}{d\ln f} = V(f,T)\frac{dn}{d\ln f}$$



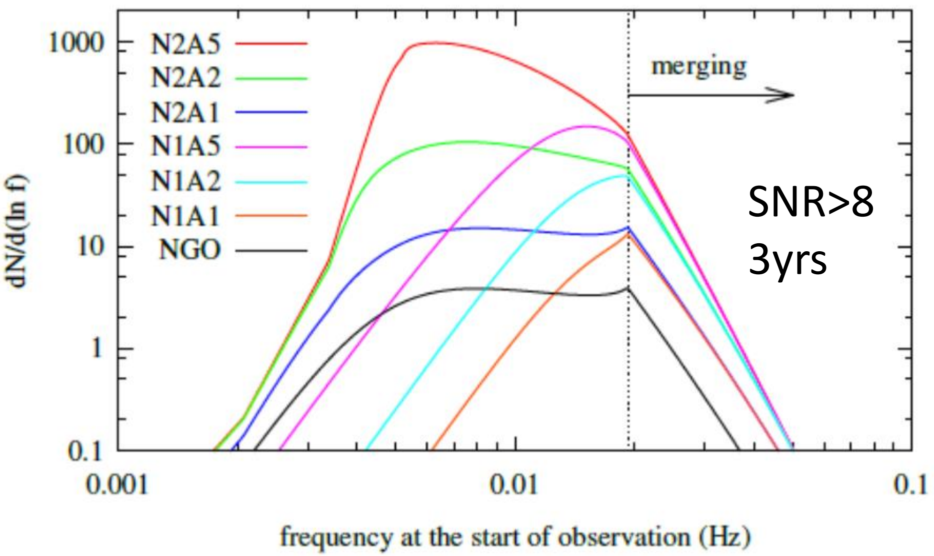


Figure 2. Frequency distribution of the expected number of detections for binary black holes similar to GW150914 in each logarithmic frequency interval for three-year observations of eLISA. The curve labeled by NGO is calculated with the noise curve of Amaro-Seoane et al. (2012), and the others are with those of Klein et al. (2016). Galactic binary white dwarfs are taken into account as the foreground for N2 configurations according to Klein et al. (2016). The vertical dotted line marks $f_{\rm merge}(3\,{\rm yr}) = 19.2\,{\rm mHz}$.

Table 1. The expected number of all the detected binary black holes and merging binary black holes for representative values of the observation period, T.

model	1 yr	2 yr	3 yr	4 yr	5 yr	10 yr
NGO	1.2	3.4	6.2	9.5	13.2	36.2
(merge)	0.07	0.3	0.7	1.3	2.0	7.9
N1A1	1.4	3.7	6.5	9.6	13.0	32.3
(merge)	0.3	1.1	2.5	4.4	6.6	21.6
N1A2	6.0	16.5	29.5	44.3	60.3	153
(merge)	0.6	3.3	8.1	15.2	23.9	88.8
N1A5	22.2	61.9	112	170	235	621
(merge)	0.8	5.3	15.1	31.2	53.2	249
N2A1	4.7	13.2	24.0	[illegible]	[illegible]	[illegible]
(merge)	0.3	1.2	2.8	[illegible]	[illegible]	[illegible]
N2A2	27.6	77.6	142	217	302	835
(merge)	0.6	3.5	9.1	17.7	29.2	135
N2A5	174	492	903	1390	1940	5420
(merge)	0.8	5.7	17.0	36.9	66.3	401

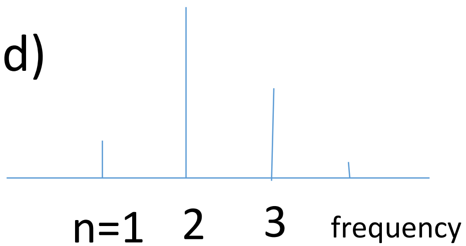
Majority: without merger

summary

- GW150914: significant impacts on eLISA science
- Galactic BBHs
  - Detectable number O(10) at <0.5mHz
    - Independent of M_c
    - Inversely proportional to acceleration noise level
- Extra Galactic BBHs
  - 3-1000 BBHs after 3yr observation
  - Majority without merger

Parameter estimation

- Eccentricity
  - Crucial to discriminate the origin of BBHs
    - Dynamical >> isolated
    - Residual at 1mHz: x10^4 larger than 10Hz (LIGO band)
  - Measurement: search for the n=3 mode



$$SN_3 \simeq 7.5 \left(\frac{e}{0.022}\right) \left(\frac{SN_2}{70}\right)$$

$$\Delta e \sim \frac{1}{350} \left(\frac{SN_2}{70}\right)^{-1}$$

- Localization: also useful for understanding the origin

$$\Delta\Omega_s \sim 1.4 \times 10^{-3} \left(\frac{SN}{70}\right)^{-2} \text{ sr.}$$

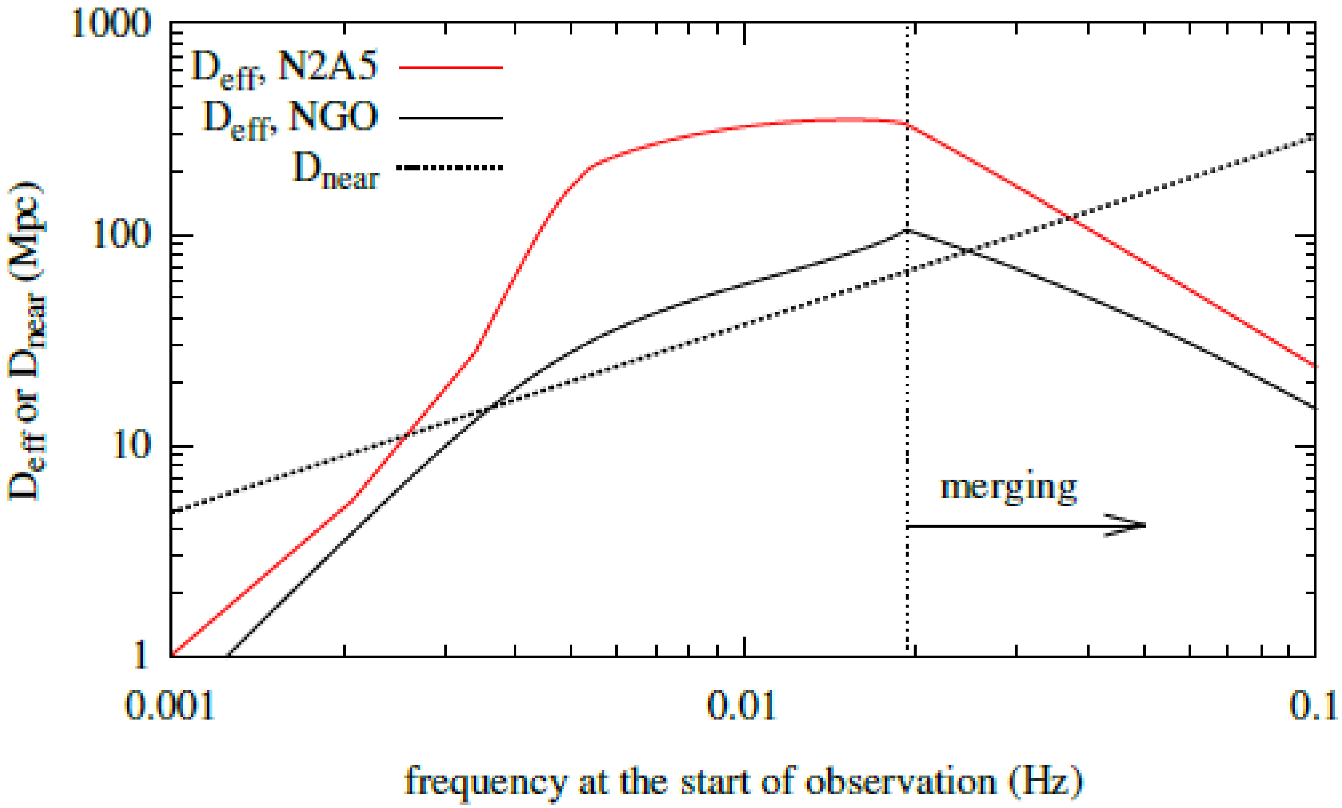


Figure 1. Effective range $D_{\rm eff}$ for three-year observations of eLISA and the distance $D_{\rm near}$ to the nearest binary black holes similar to GW150914. The curves for $D_{\rm eff}$ labeled by NGO and N2A5 are calculated with the noise curve of Amaro-Seoane et al. (2012) and that of Klein et al. (2016), respectively. Galactic binary white dwarfs are taken into account as the foreground for the latter according to Klein et al. (2016). The vertical dotted line marks $f_{\rm merge}(3\,{\rm yr}) = 19.2\,{\rm mHz}$.

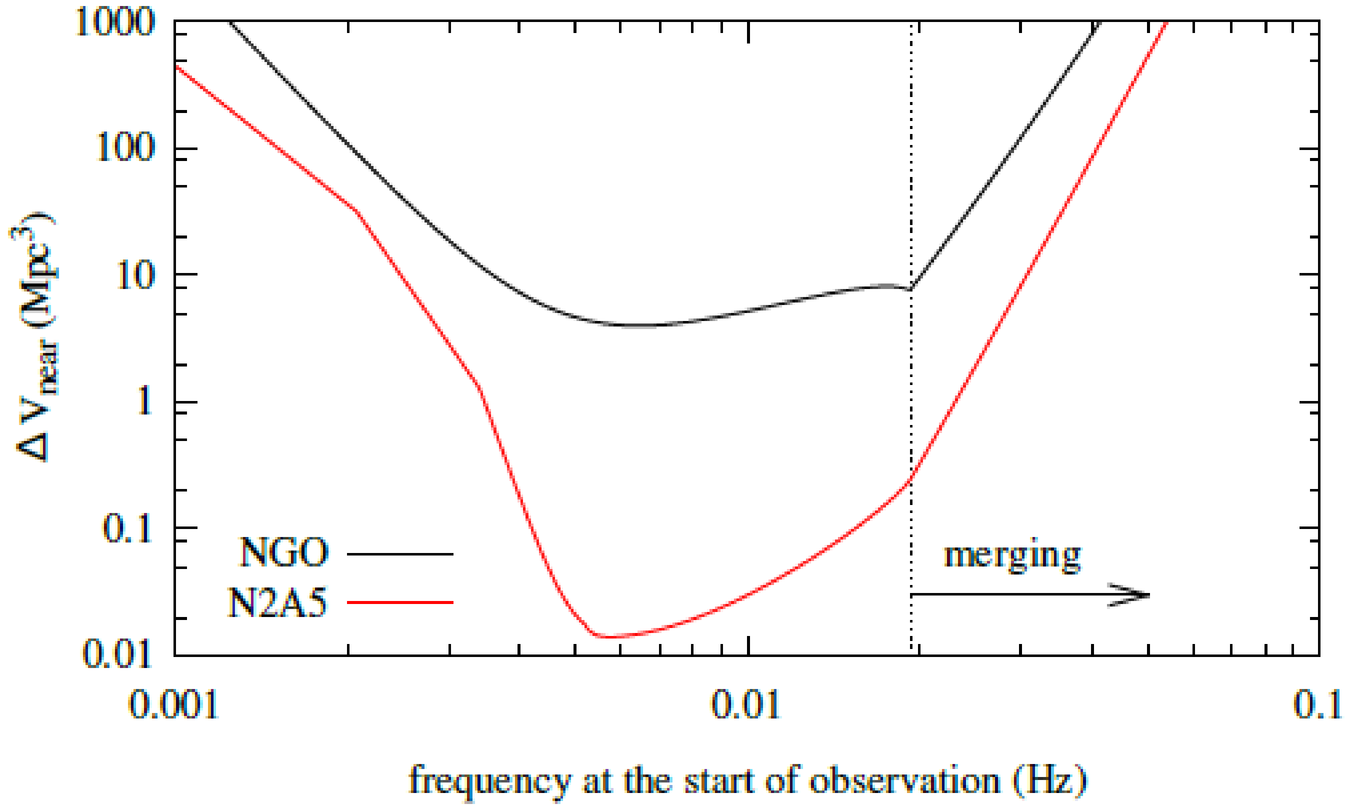


Figure 7. Error volume $\Delta V(f)$ for the nearest and thus loudest binaries located at $D_{\rm near}(f)$ for three-year observations of eLISA. The black and red curves are for N2A5 and NGO, respectively. It should be cautioned that the result below $\sim 2\,$mHz is poorly described by the empirical formula adopted in this study, Eq. (24). The vertical dotted line marks $f_{\rm merge}(3\,{\rm yr}) = 19.2\,$mHz.