Requirement for detector sensitivity toward observation of primordial gravitational wave

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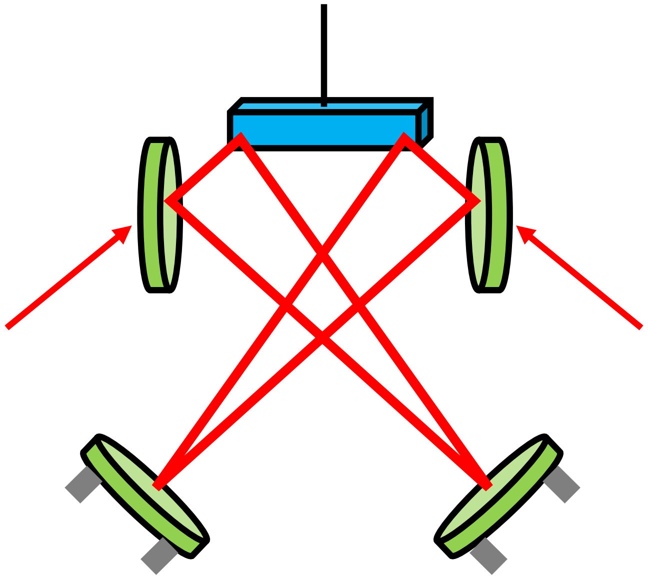
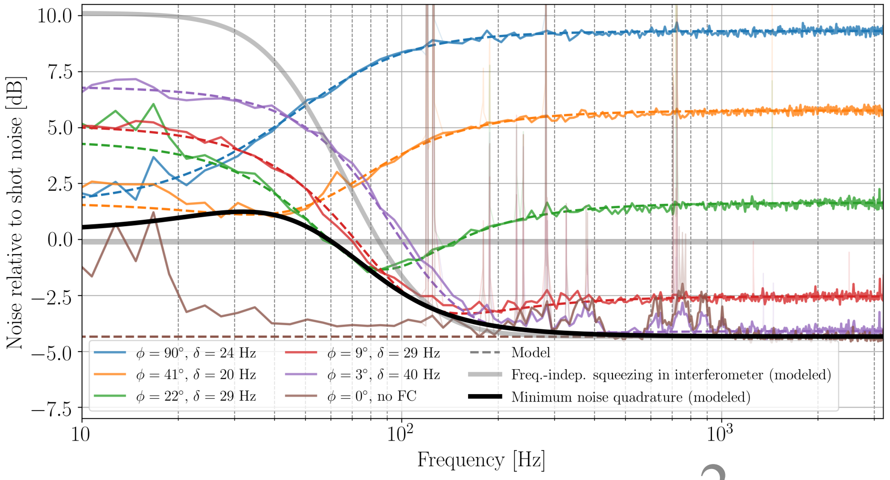
Self introduction

- Graduated from Ando Lab in March 2019

- Worked on optomechanical experiment using torsion pendulum with optical cavities on each edge



- Mainly working on demonstration of frequency-dependent squeezing in MIT as JSPS Overseas Fellow



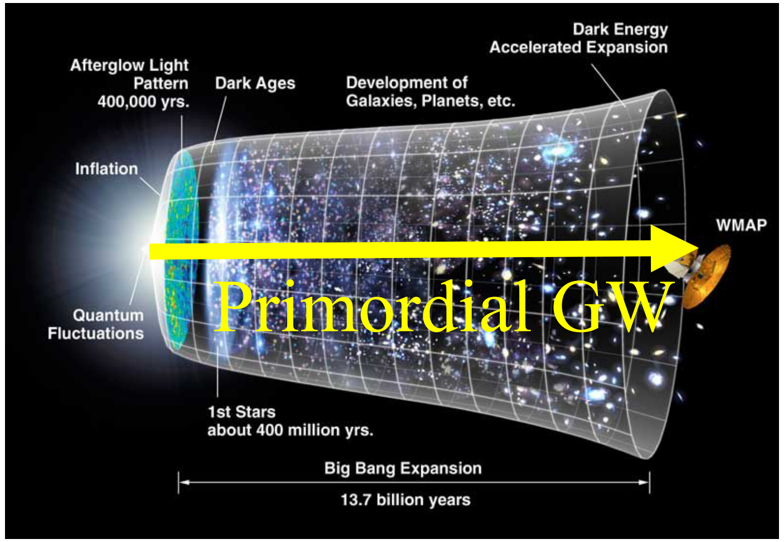
- Will work on LISA and DECIGO in JAXA as a postdoc from this October

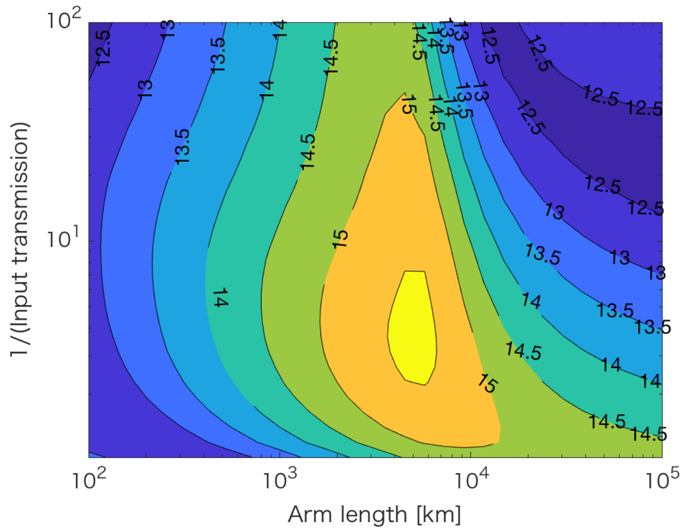
Abstract

- Direct observation of primordial GW generated during inflation is one of the biggest goals in our community.

- It is so tiny that we must subtract GW from any other sources such as compact binary inspiral.

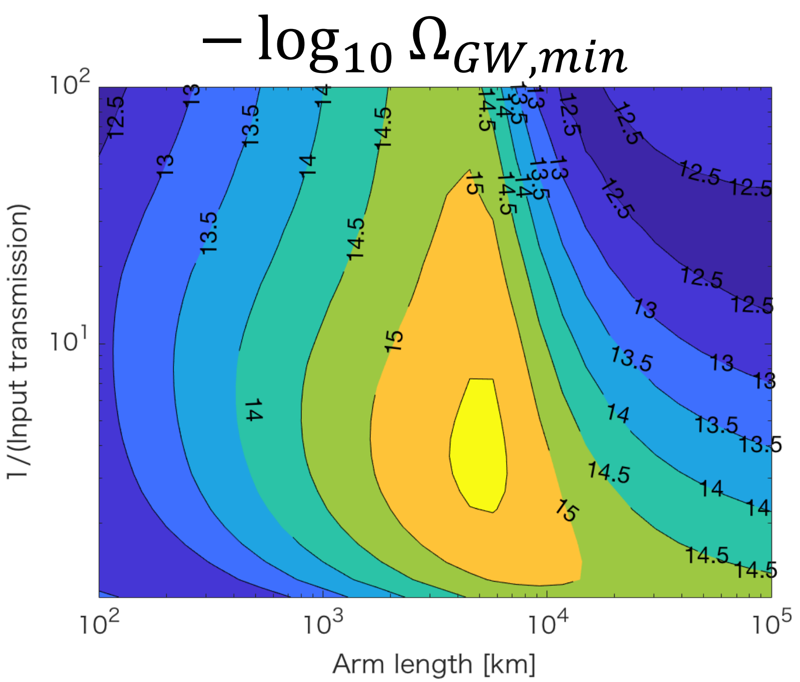
- I derive sensitivity requirement to subtract binary inspiral signals and reach primordial GW background.

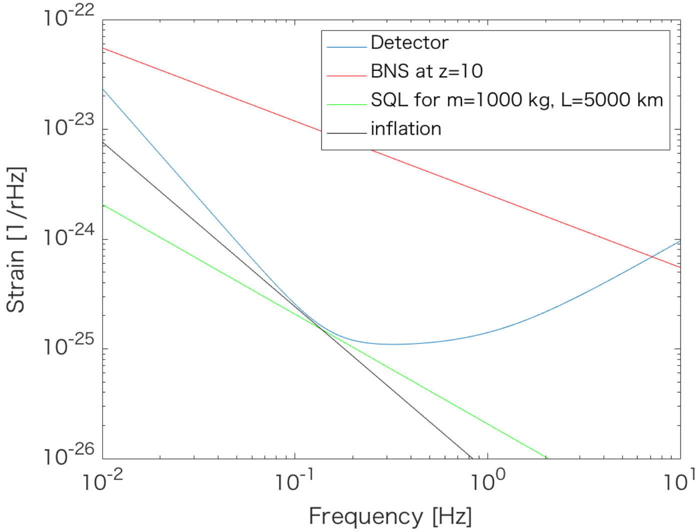




Summary

- At least, we need an extreme detector as below
  - Mass: m ~ 1000 kg
  - Input power: P ~ 100 W
  - Arm length: L ~ 5000 km
  - Input transmission of cavities: T ~ 30%





- The result is super preliminary, and every comment is highly appreciated

Contents

- Concept
- Method
- Break: interesting events in O3
- Result
- Future

Beginning of this work

- MIT is shut down.
- What can I do in this situation? I want to do some analytical works…

arxiv:2002.05365

Subtracting compact binary foreground sources to reveal primordial gravitational-wave backgrounds

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[2] *LAPP, Universit'e Grenoble Alpes, USMB, CNRS/IN2P3, F-74000 Annecy, France*
[3] *Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA, 16802, USA*
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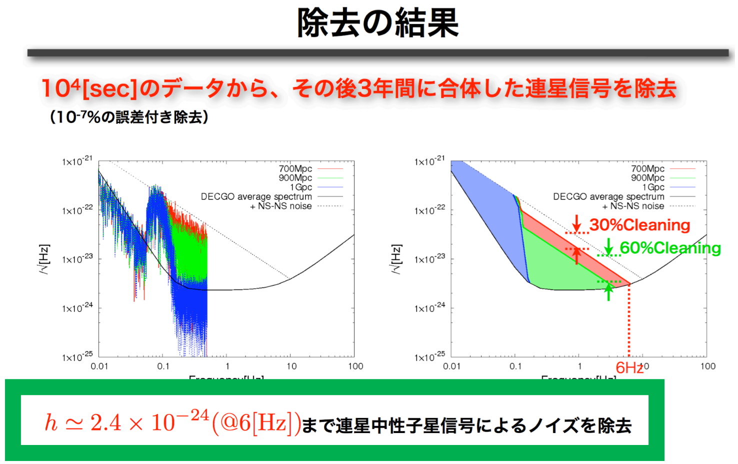
Detection of primordial gravitational-wave backgrounds generated during the early universe phase transitions is a key science goal for future ground-based detectors. The rate of compact binary mergers is so large that their cosmological population produces a confusion background that could masquerade the detection of potential primordial stochastic backgrounds. In this paper we study the ability of current and future detectors to resolve the confusion background to reveal interesting primordial backgrounds. The current detector network of LIGO and Virgo and the upcoming KAGRA and LIGO-India will not be able to resolve the cosmological compact binary source population and its sensitivity to stochastic background will be limited by the confusion background of these sources. We find that a network of three (and five) third generation (3G) detectors of Cosmic Explorer and Einstein Telescope will resolve the confusion background produced by binary black holes leaving only about 0.013% (respectively, 0.00075%) unresolved; in contrast, as many as 25% (respectively, 7.7%) of binary neutron star sources remain unresolved. Consequently, the binary black hole population will likely not limit observation of primordial backgrounds but the binary neutron star population will limit the sensitivity of 3G detectors to $\Omega_{GW} \sim 10^{-11}$ at 10 Hz (respectively, $\Omega_{GW} \sim 3 \times 10^{-12}$).

- Try to do the same thing at deci-Hz and compare to primordial GW background!

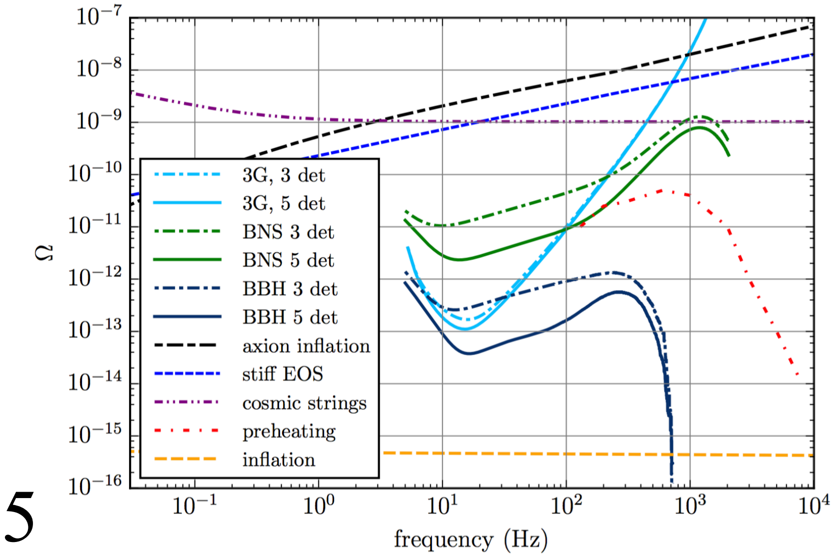
Previous work

- ➢Subtraction of GW from compact binary for DECIGO
- ➢Realistic subtraction including detailed process

2008/3/25, 日本物理学会第６３回年次大会



- ➢Estimation of residual error after subtraction with Fisher matrix
- ➢An actual error can be larger, but this method is much more simple and it gives a fundamental limit



arxiv:2002.05365

Method

$$\Omega_{GW} = \Omega_{cbc} + \Omega_{inf} + \Omega_{astro}$$

Total energy density of GW

$$= \underbrace{\Omega_{rec}}_{\text{recovered (subtracted) signal}} + \underbrace{\Omega_{error}}_{\text{residual error after subtraction}} + \underbrace{\Omega_{unres}}_{\text{unresolved signal because of low SNR}} + \underbrace{\Omega_{inf}^{\sim 10^{-16}}}_{\text{inflation}} + \underbrace{\Omega_{astro}^{=0}}_{\text{astrophysical sources}}$$

recovered (subtracted) signal

residual error after subtraction

unresolved signal because of low SNR

inflation

astrophysical sources
- phase transition
- cosmic string

$$\Omega_{error} = T^{-1} \frac{4\pi^2}{3H_0^2} f^3 \sum_{k=1}^{N} (h_k^{true} - h_k^{rec})^2$$

Method

$$\underline{\Omega_{rec}} + \underline{\Omega_{error}} + \underline{\Omega_{unres}}$$

recovered (subtracted) signal

residual error after subtraction

unresolved signal because of low SNR

Assumption in current work

- T: observation time = 1 yr
- Antenna pattern, inclination, and polarization angle are averaged
- SNR threshold: 8
- Only BNS

$$\Omega_{error} = T^{-1} \frac{4\pi^2}{3H_0^2} f^3 \sum_{k=1}^{N} (h_k^{true} - \boxed{h_k^{rec}})^2$$

Assuming merger distribution

With error calculated by Fisher matrix

Method

$$\Omega_{rec} + \Omega_{error} + \Omega_{unres}$$

$$\Omega_{error} = T^{-1}\frac{4\pi^2}{3H_0^2}f^3\sum_{k=1}^{N}(h_k^{true} - h_k^{rec})^2$$

Assuming merger distribution

Merger distribution

total merger number

co-moving volume

$$R(z) \equiv \frac{dN}{dt_d dz} = \frac{1}{1+z}\frac{dV_c}{dz}\mathcal{R}_m(t_m)$$

detector-frame time

$$\frac{dt_m}{dt_d}$$

time delay distribution

$$p(t_m, t_f) = \frac{1}{\underbrace{\tau}_{=3\ \text{Gyr}}} e^{-(t_f - t_m)/\tau}$$

typical timescale

$$\mathcal{R}_m(t_m) = \mathcal{R}_0 \int_{t_m}^{t(z=15)} dt_f\ \underbrace{\eta(t_f)}_{=1}\psi(t_f)\, p(t_m, t_f)$$

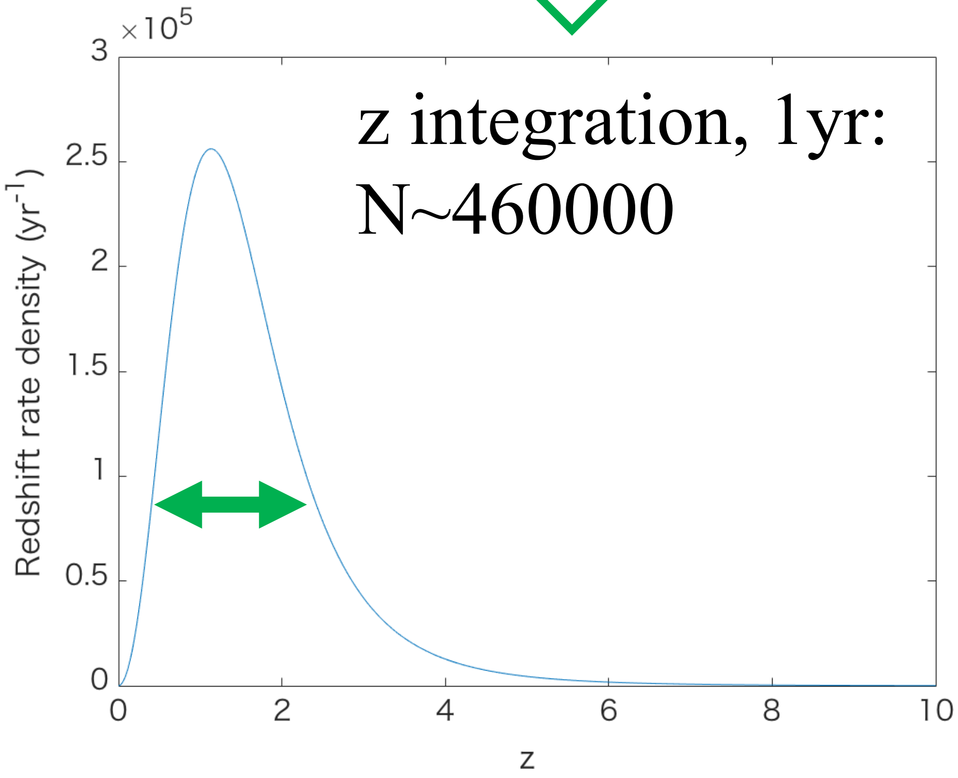
normalized factor

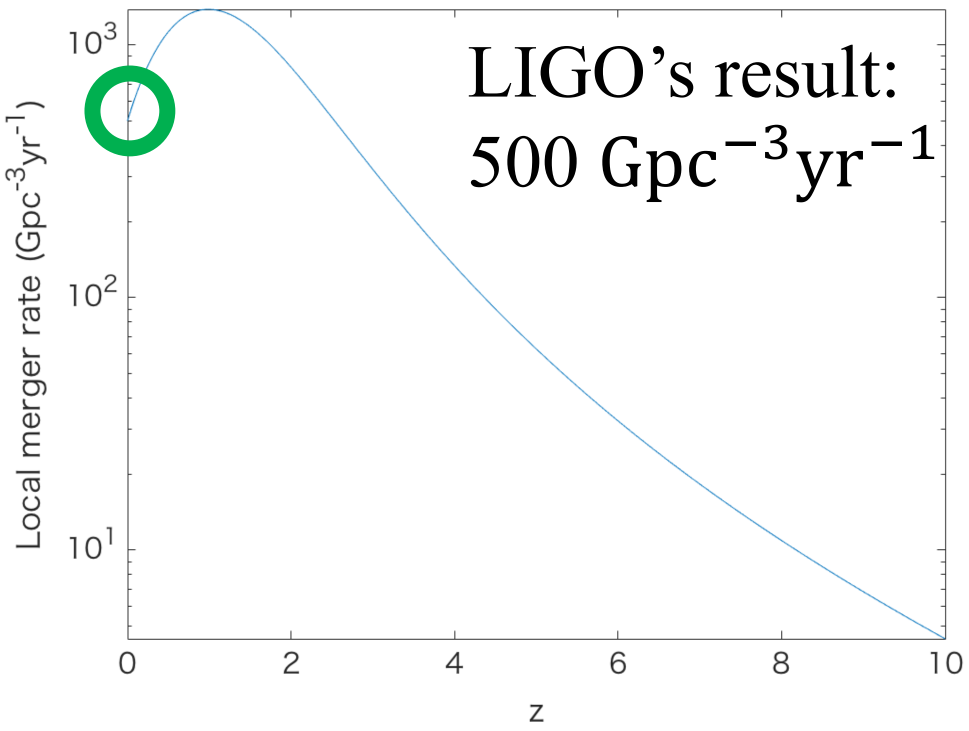
efficiency from formation to compact stars

Madau's star formation rate

Merger distribution

$$R(z) \equiv \frac{dN}{dt_d dz} = \frac{1}{1+z}\frac{dV_c}{dz}\mathcal{R}_m(t_m)$$





Method

$$\Omega_{rec} + \Omega_{error} + \Omega_{unres}$$

$$\Omega_{error} = T^{-1}\frac{4\pi^2}{3H_0^2}f^3\sum_{k=1}^{N}(h_k^{true} - \boxed{h_k^{rec}})^2$$

With error calculated by Fisher matrix

Inspiral waveform and Fisher matrix

$$\boxed{h(f) = A\, f^{-7/6}\, e^{i\Psi(f)}} \qquad \Psi(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \underbrace{\frac{3}{128}\left(\frac{f}{f_c}\right)^{-5/3}}_{\text{0PN}}$$

$$\mathrm{A} = \frac{1}{\sqrt{30\pi^3}} \frac{c}{d_L} f_c^{-5/6} \qquad f_c = \frac{c^3}{\pi G(1+z)M_c}$$

d_L: luminosity distance

M_c: chirp mass

➢Assuming (only) 4 parameters:
$\boldsymbol{\theta} = (\log A,\ t_c,\ \phi_c,\ \log M_c)$

Fisher matrix

$$\Gamma_{ij} = 4\int_{f_L}^{f_H} df\, Re\left[\frac{h^*_{\theta_i}(f) h_{\theta_j}(f)}{S_n(f)}\right]$$

$$h_{\theta_i}(f) = \frac{\partial h(f)}{\partial \theta_i}$$

Inspiral waveform and Fisher matrix

$$\Gamma_{ij} = 4\int_{f_L}^{f_H} df\, Re\left[\frac{h^*_{\theta_i}(f)h_{\theta_j}(f)}{S_n(f)}\right]$$

$$\rho^2 = 4\int_{f_L}^{f_H} df\, \frac{|h(f)|^2}{S_n(f)}$$

f_H = 10 Hz or f_{ISCO}

f_L = 0.1 Hz

SNR

➢Fundamental error of the parameter corresponds to diagonal component of inversed matrix

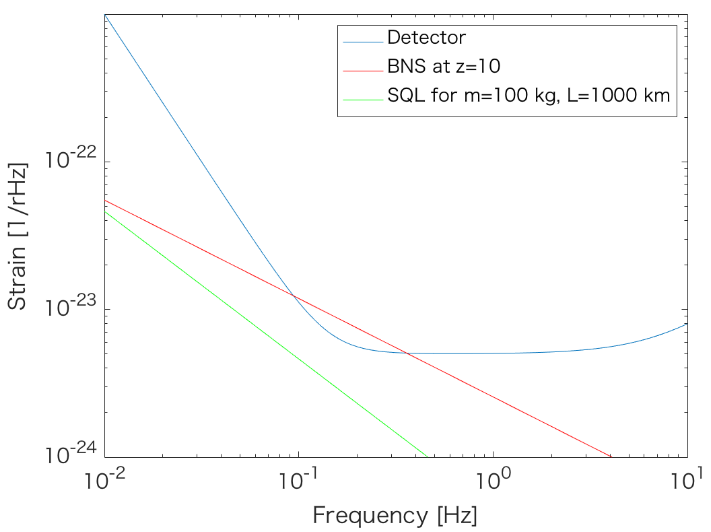
$$\boxed{\Delta\theta_i = (\Gamma^{-1})_{ii}}$$

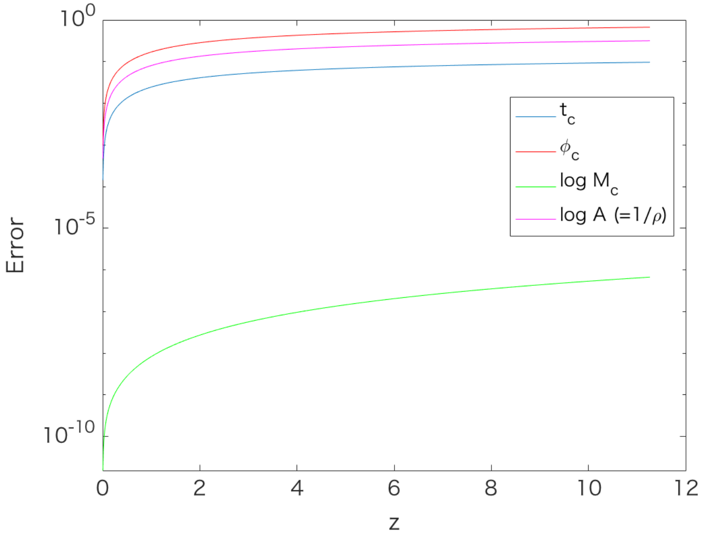
random number generator

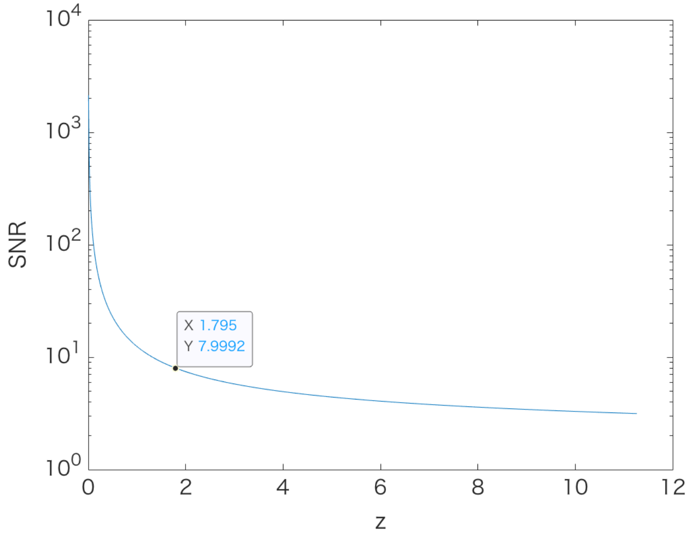
$$h(f) = A\, f^{-7/6}\, e^{i\Psi(f)}$$

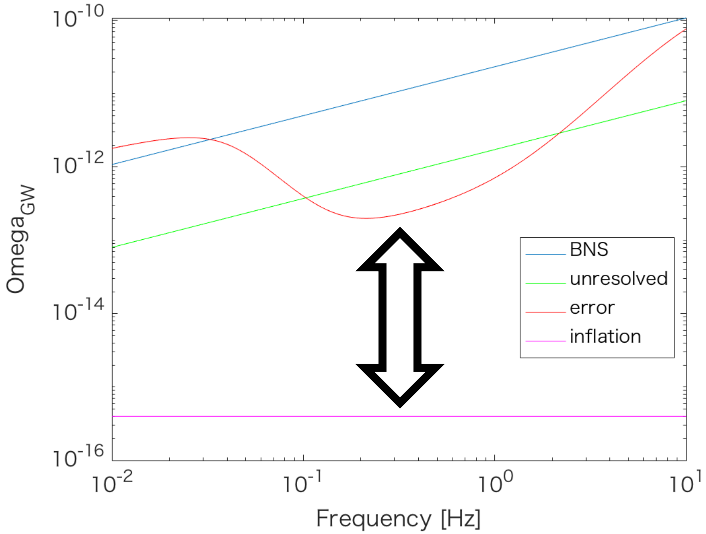
$$\Omega_{error} = T^{-1}\frac{4\pi^2}{3H_0^2}f^3\sum_{k=1}^{N}(h_k^{true} - h_k^{rec})^2$$

Result with DECIGO





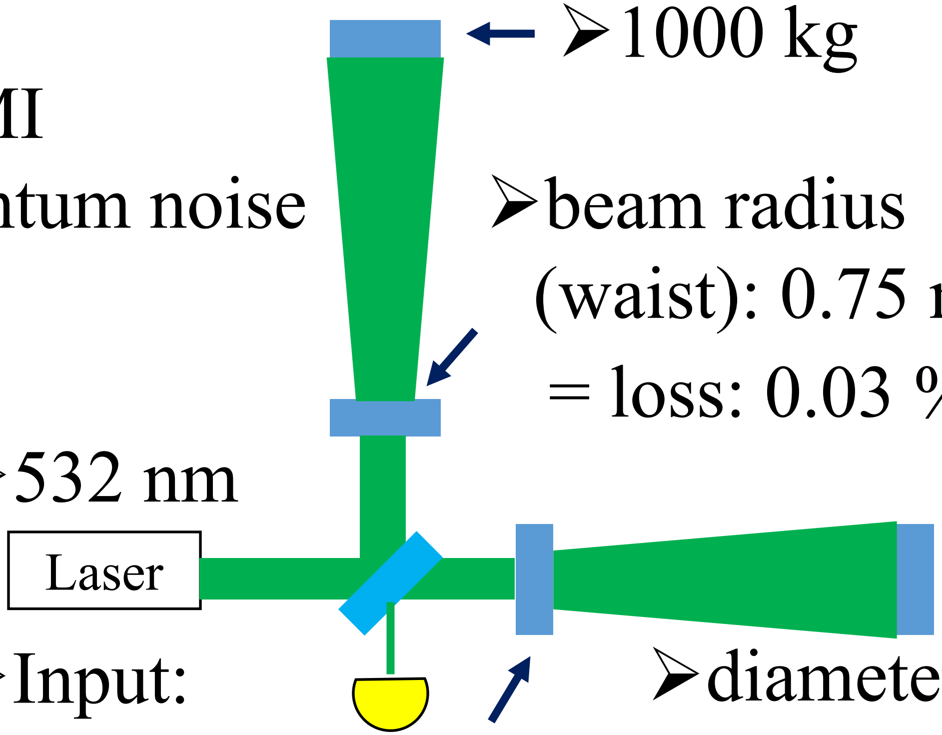




- BNS at z>1.8 has SNR<8, unresolved
- $\Delta\phi_c$ is largest, 0.1~1
- The unresolved signal and error veil $\Omega_{GW} < 10^{-13}$!

More and more extreme…!

- Fixed configuration and parameters



- ➢FPMI
- ➢quantum noise
- ➢1000 kg
- ➢beam radius (waist): 0.75 m
  = loss: 0.03 %
- ➢532 nm
- ➢Input: 100W
- ➢fixed
- ➢diameter: 3 m
  = thickness: 6.4 cm
  = aspect ratio: 1:47

- Variable
  - ➢arm length
  - ➢input transmission

$$R_{end} = 1 - \exp\left(-\frac{2\pi}{\lambda}\frac{z_R}{L^2 + z_R^2}r^2\right)$$

= 1.5 m

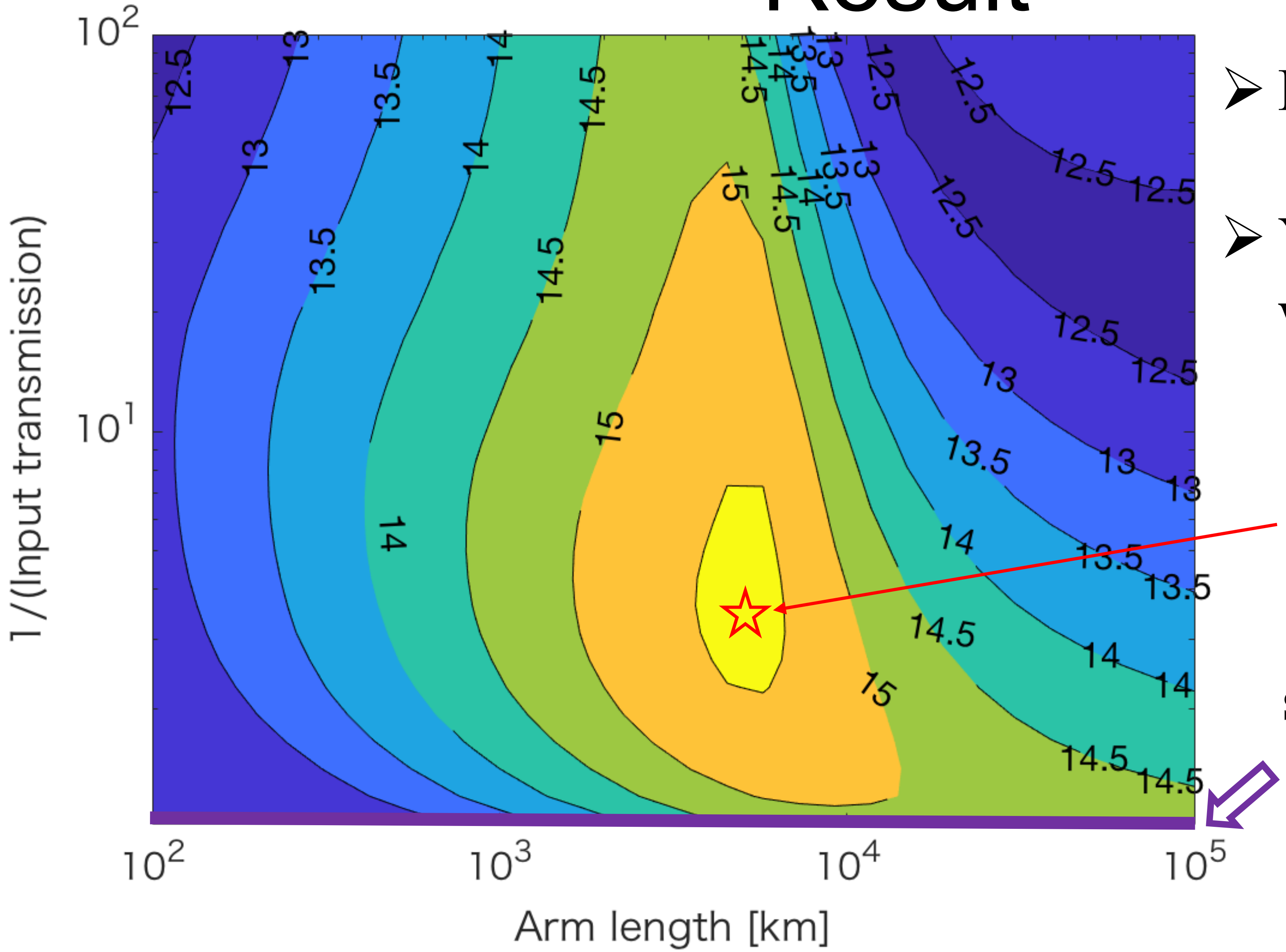
$$R_{end} = 0.5 \text{ @L}\sim 10000 \text{ km}$$

$$z_R = \frac{\pi w_0^2}{\lambda}$$

= 0.75 m

= 3300 km

Result



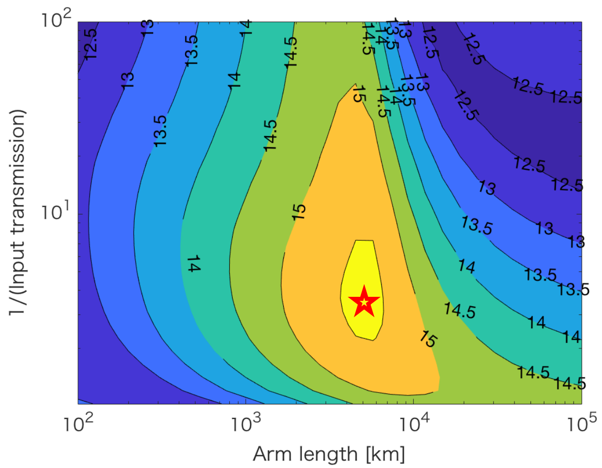
- Plotting $-\log_{10}\Omega_{GW,min}$
- Yellow area is comparable with inflation level

L=5000 km, T=30%

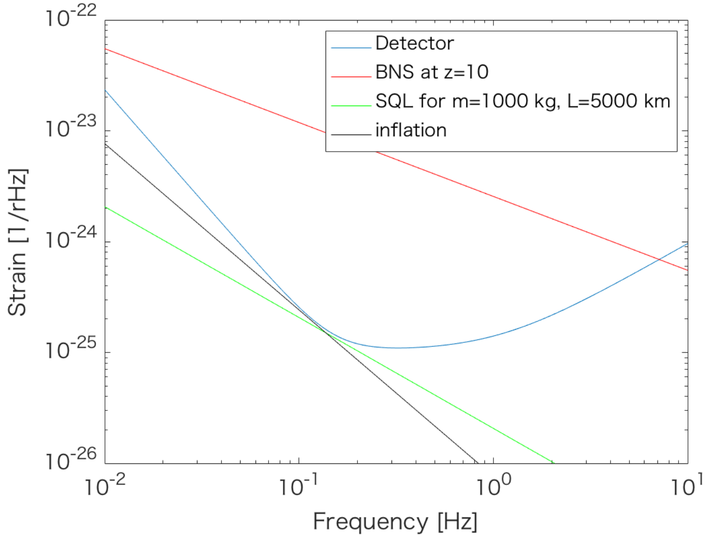
simple Michelson

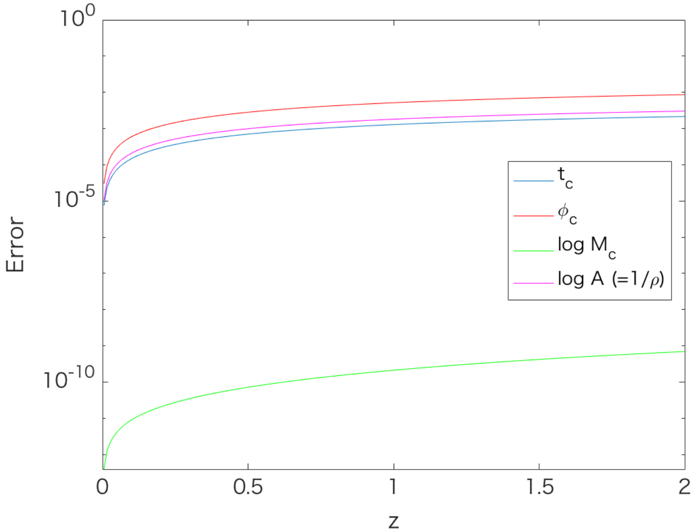
$\mathcal{F} = \pi/2$

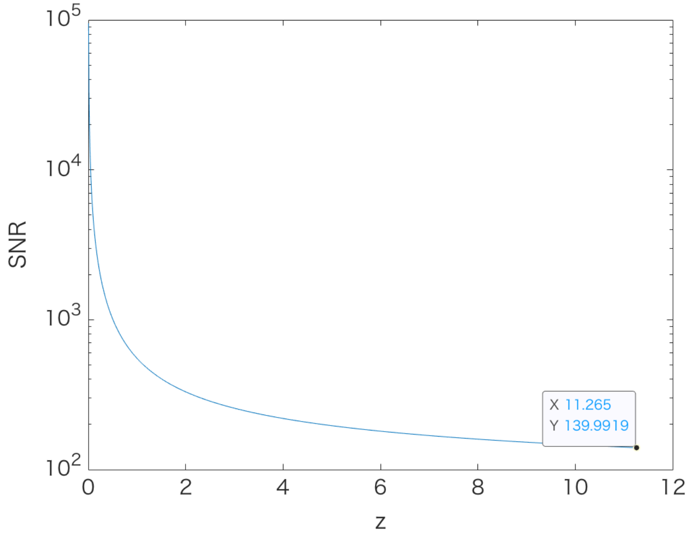
Result

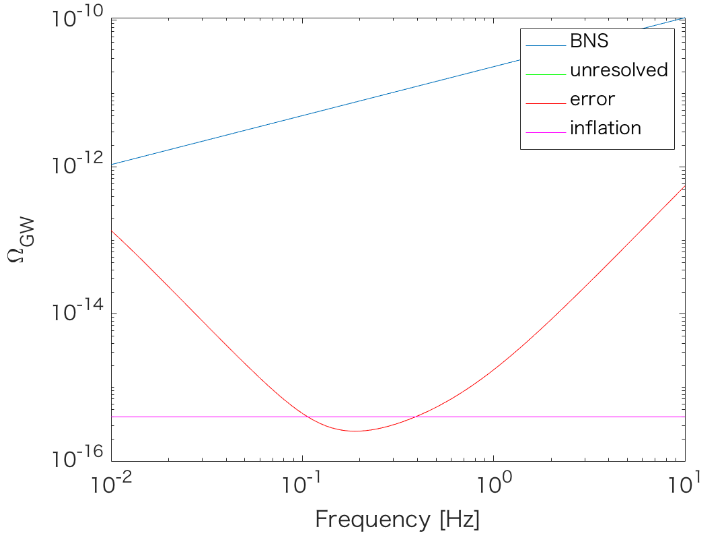


- All BNS detected with SNR>140
- $\Delta\phi_c$ is below 0.01
- Fundamentally can reach inflation level









Future

- More precise distribution
  - time delay, local rate
- BBH (the error should be much lower)
  - mass distribution
- Lower limit of integration is 0.1 Hz?
  - BNS takes ~7 years from 0.1 Hz to merger v.s. current assumed 1-year observation
- Multiple inspirals in the same frequency bin - fundamentally unresolved
- Detector configuration
  - Other valuable?
  - How many detectors?
  - What is realistic assumption such as power and mirror mass?
  - Changing antenna pattern

Summary

- At least, we need an extreme detector as below
  - Mass: m ~ 1000 kg
  - Input power: P ~ 100 W
  - Arm length: L ~ 5000 km
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- The result is super preliminary, and every comment is highly appreciated

$-\log_{10}\Omega_{GW,min}$