Calibration meeting

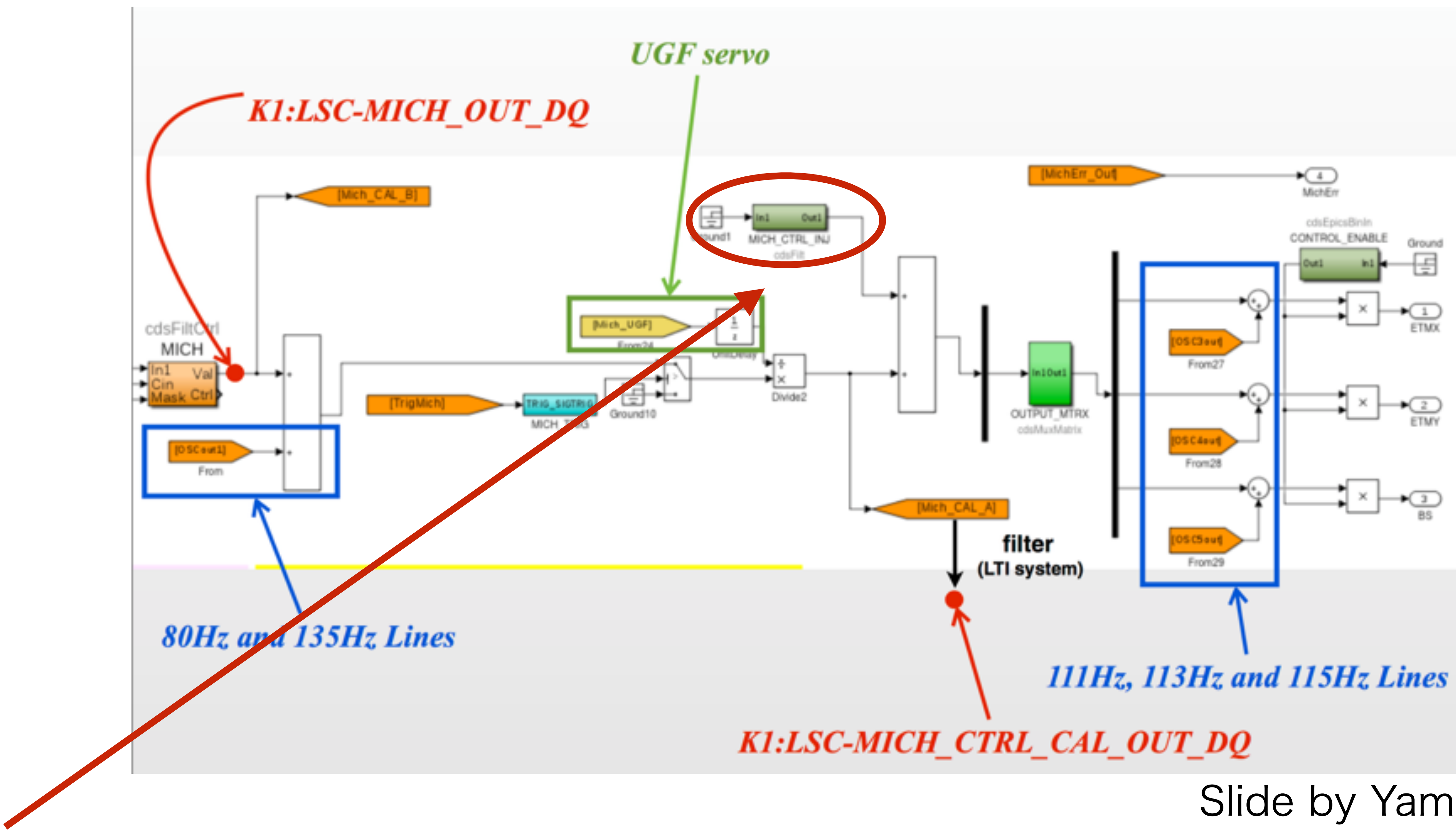
2017/05/10

ToDo list toward bKAGRA

In iKAGRA hardware injection, there are many processes by hands.
Automating them are one of the important task toward bKAGRA hardware injection test(HWI test).

1. Understanding and installing the detector model
   - Vibration and actuator model
   - Real Time Software
   (- Cavity model in future)
2. Preparing injection waveforms
   - What type of waveform should we inject?
   - Connection between 0 and waveform
   - Significant Sine Gauss waveform
   - Characteristic waveform
   - Higher frequency injection
   - Injection simulation
   - Maximum/Minimum amplitude
3. Automation processing
   - Injection planning (Guardian?)
   - Lock loss

(Reminder) iKAGRA HWI test

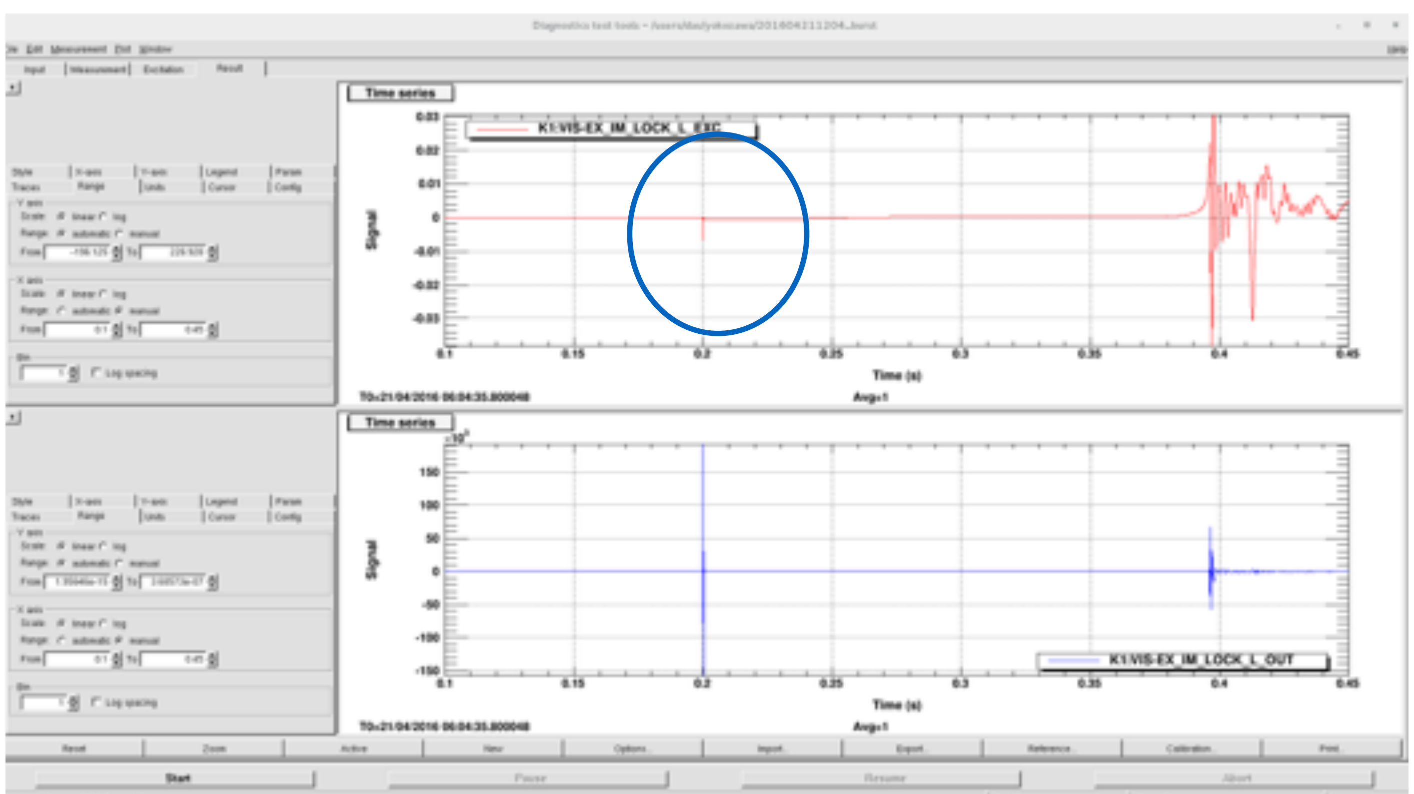


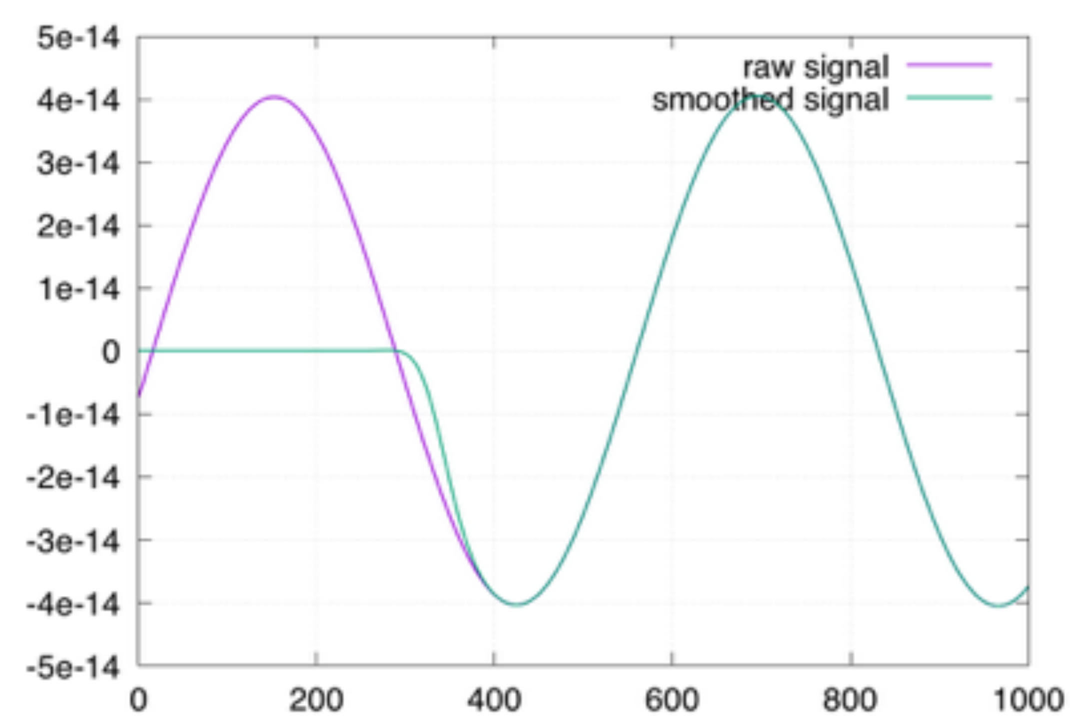
Slide by Yamamoto-san

Inject waveform to feedback signal(16kHz)
limitation of amplitude : less than ±32,768[count] preferred ±3,000[count]
after applying inverse actuation function (f^2 filter).

(Reminder) iKAGRA HWI test

1. Discussed what type of waveform are injected?
   - Sine Gauss(33,100,333Hz), Supernova, CBC(BHBH, NSNS)
2. Prepare waveforms
   - Important notice of preparing waveform
     - Amplitude : We should consider the force-to-length transfer function (~f^2 in higher frequency), investigate significant waveform
     - Connection between 0 and waveform : We noticed the existence of delta function if we didn't apply anything. By applying error function by hand, we can reduce this effect.





(Reminder) iKAGRA HWI test

3. Make waveform and apply error function
  - In case of Sine Gauss, we didn't need to apply error function because we can connect waveform from 0 smoothly because of Sine Gauss can be described by equation.
  - In case of supernova numerical simulation waveform, after applying re-sampling, we apply error function to start and finish of waveform, because there are memory effect.
  - In case of CBC(BHBH), Yuzurihara-san generated waveform using LALInference(EOBNR), start 10Hz, applying error function to start time. Tagoshi-san prepared NSNS (TaylorT4+numerical simulation by Shibata group) and applying error function to start time.

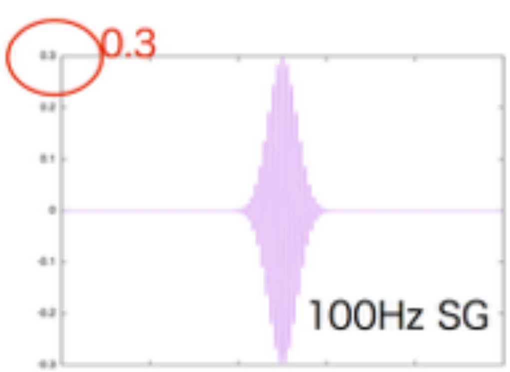
$$h_{\mathrm{count}} = A \exp\left(-\frac{(t-t_0)^2}{\tau^2}\right) \cos(2\pi f_0 (t-t_0)) \qquad \tau = Q/\sqrt{2}\pi f_0$$

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-at^2} dt$$

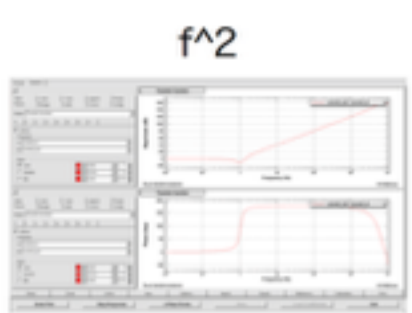
(Reminder) iKAGRA HWI test

4. Determine amplitude
   - SG case, we can calculate amplitude because of unique frequency.
   (Example: if we want to make SG waveform of 100Hz and 3,000[count], Amplitude(A) should be 0.3)
   - Supernova and CBC case, we tested by online inverse actuation filter and checked by eye. we determined amplitude to inject as maximum as possible for supernova and calculated SNR and determine amplitude for CBC.

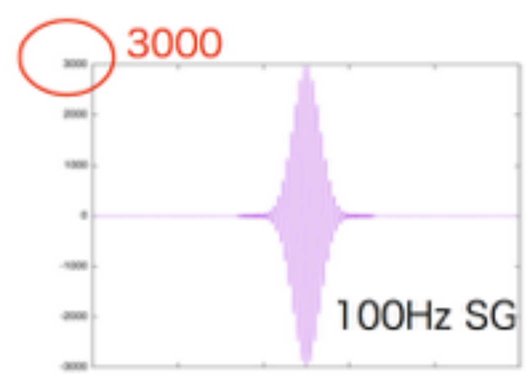
(I already prepared off-line injection test code, it will be explained later)



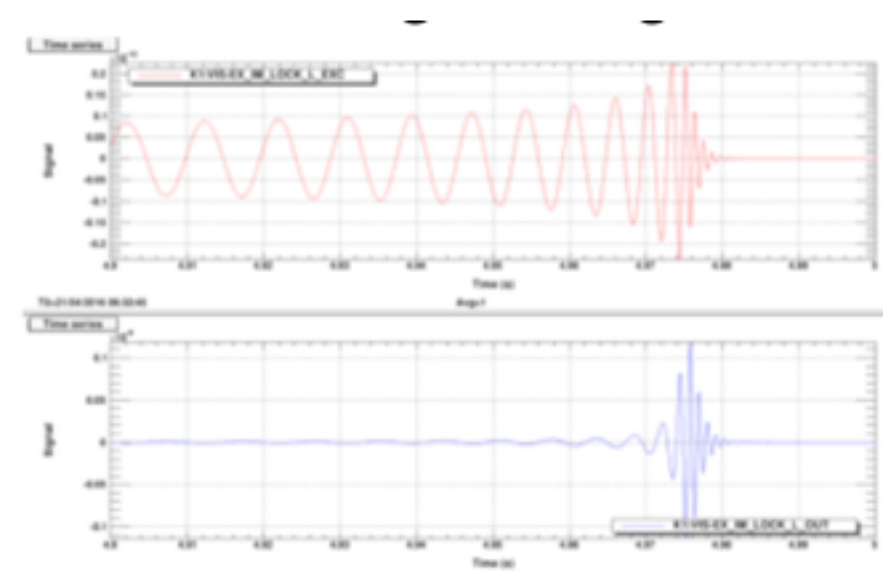
prepared waveform



Inverse actuator TF



injected waveform

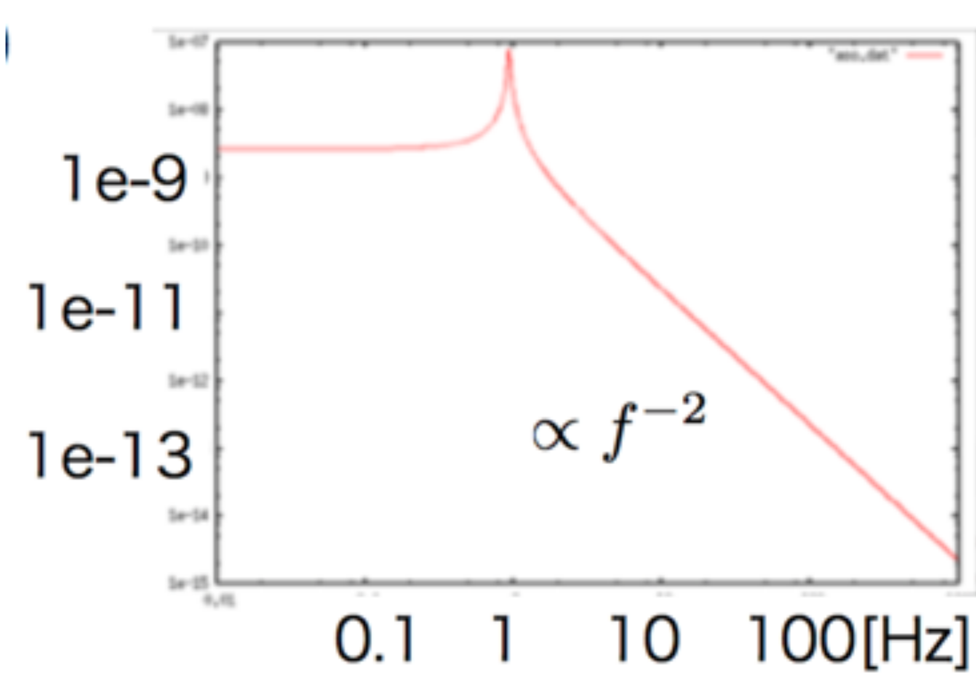


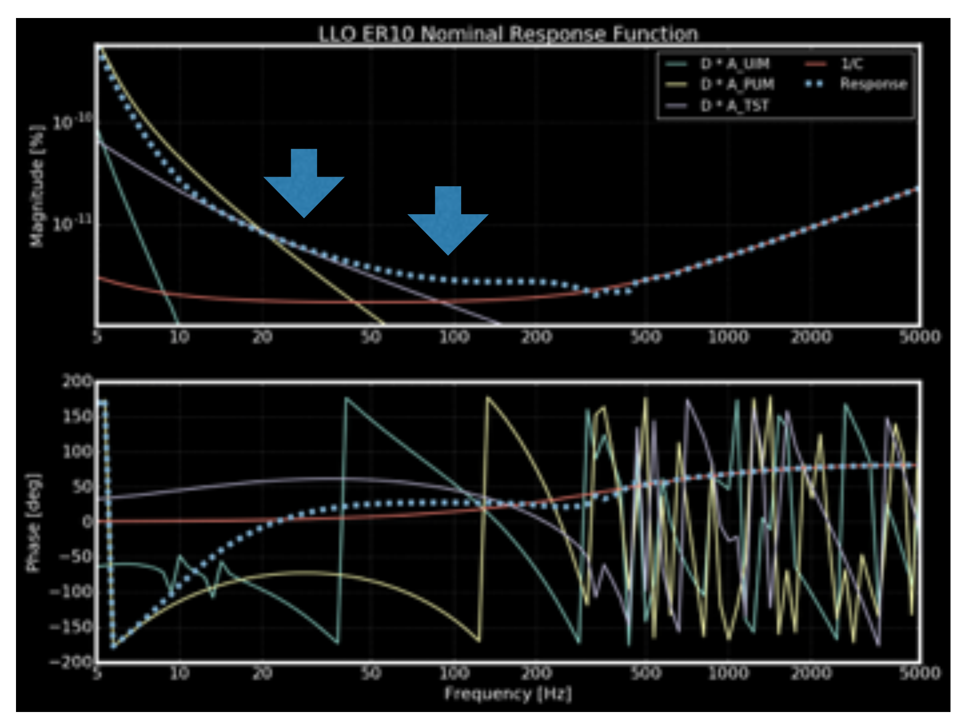
Plan toward bKAGRA HWI test

1. Understanding and installing the detector model
 - Vibration and actuator model
 - Real Time Software
 (- Cavity model in future)

We should know what frequency will be important for precise calibration
 - Dominant frequency to be reconstructed (v_err or v_fb?)
 - Unity gain frequency
 - Performance of lower frequency (proportional to f^-2?)

https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=30440





Plan toward bKAGRA HWI test

2. Preparing injection waveforms
   - What type of waveform should we inject?

As I already reported in last cal and F2F meeting,

1. Check the accuracy/confirmation of h(t) reconstruction
   - Sign, amplitude, phase, time delay …
   - Continuous sine, Swept sine, Sine Gaussian, Pulse signal, …

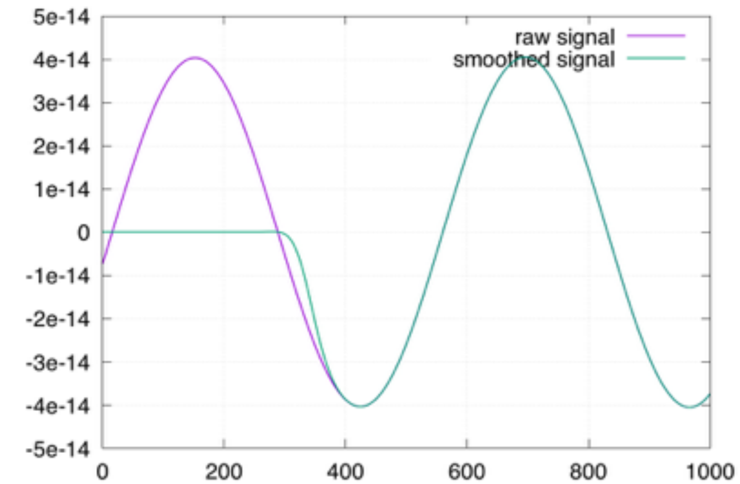
2. Waveforms which can describe analytically
   - Systematic study of search and parameter estimation algorithm
   - Effective One body, IMRFenom, TaylorT4, …
   - Inspiral signal (Post Newtonian Approximation)

3. Complex waveforms
   - Numerical simulation of NS-NS merger, supernovae, cosmic strings, …

Plan toward bKAGRA HWI test

2. Preparing injection waveforms
   - Connection between 0 and waveform

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-at^2} dt$$



I still don't have good idea, but I suggest some plan

1. Apply error function or suitable function
   Good : Established in iKAGRA HWI test
   Problem : Need to check by eye, distort waveform,
   optimize parameter (a) for each waveform
2. Apply low pass filter before applying inverse actuation filter
   Good : Easily installed
   Problem : Distort or reduce waveform, phase shift
3. Ignore pulse signal
   Problem : Detector lock loss

Plan toward bKAGRA HWI test

2. Preparing injection waveforms
   - Significant Sine Gauss waveform

In iKAGRA HWI, we injected 33, 100, 333Hz sine gaussian waveform
amplitude was 3000[count] after applying inverse actuation filter
Q value was fixed (Q=20)

I start the investigation of significant sine gaussian waveform
- Significant frequency to obtain maximum SNR for each bKAGRA phase (stable frequency region is preferred)
- Dominant frequency to be reconstructed
  - frequency region of D*A_U, D*A_P, D*A_T, 1/C
- Inject around UGF
- Inject higher frequency (Need to optimize Q value)

Plan toward bKAGRA HWI test

2. Preparing injection waveforms
   - Characteristic waveform

I didn't start investigation, I want to contact to other data analysis and theoretical people

CBC :
EOB?, IMRFenom?, TaylorT4?, all?, modified gravity waveform?
Mass, spin, start frequency, …
Discussion with Narikawa-san

Supernova :
Core bounce, convection, SASI, memory effect, etc…

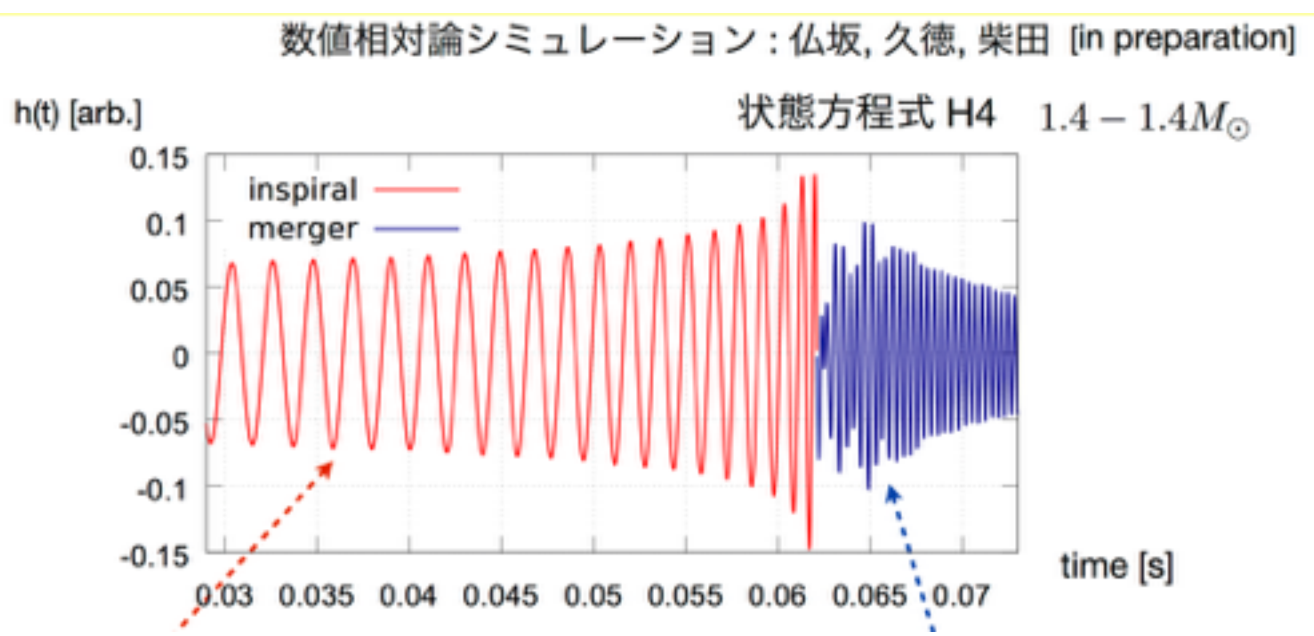
Other :
Cosmic string, stochastic gravitational wave, …

Plan toward bKAGRA HWI test

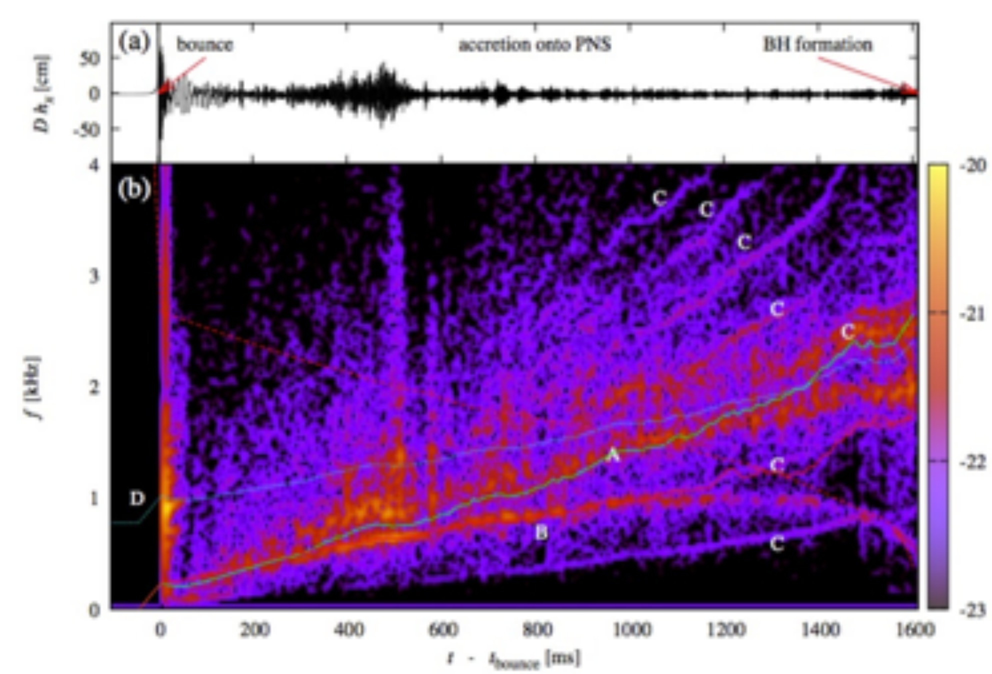
2. Preparing injection waveforms
   - Higher frequency injection

There are many important physics in higher frequency (>1kHz)
- Hyper massive neutron star oscillation (depend on EoS)
- g-mode oscillation of supernova proto-neutron star
- etc…

long duration continuous sine(>1min) injection will be necessary.
(in LIGO O2 case, ~3min injection was performed in 1000.1-5000.1Hz)



Slide from Yuzurihara-san

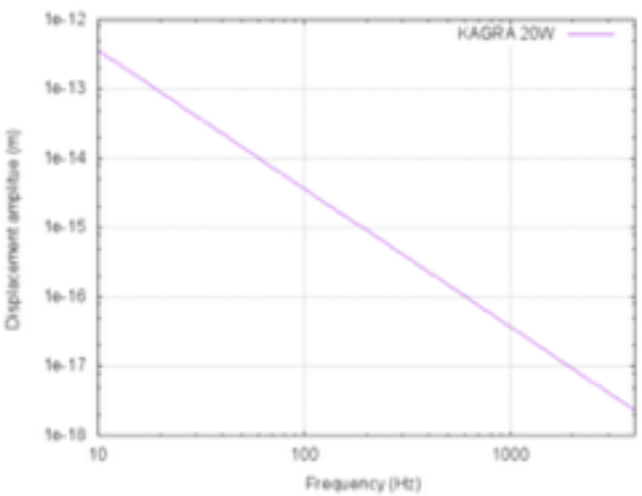


arXiv:1310.8290

Plan toward bKAGRA HWI test

2. Preparing injection waveforms
   - Injection simulation

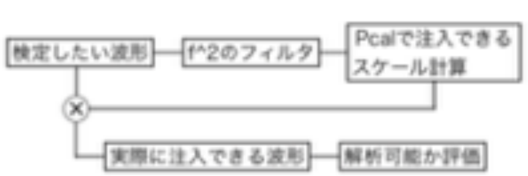
Reported in last cal meeting :

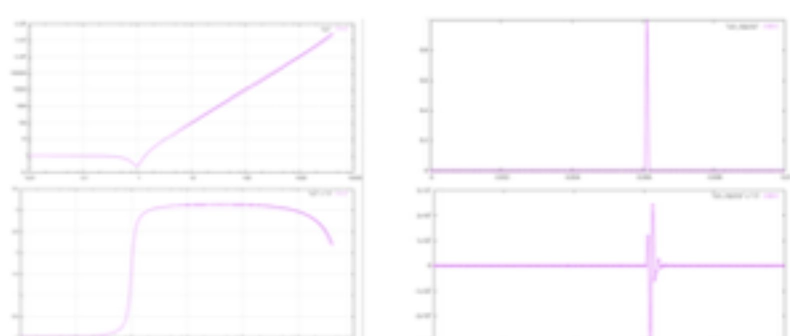


低周波の方は振り子の伝達関数の形がわからないため、記述することが難しいが、高周波(>>1Hz)では簡単には以下の式で書くことができる。

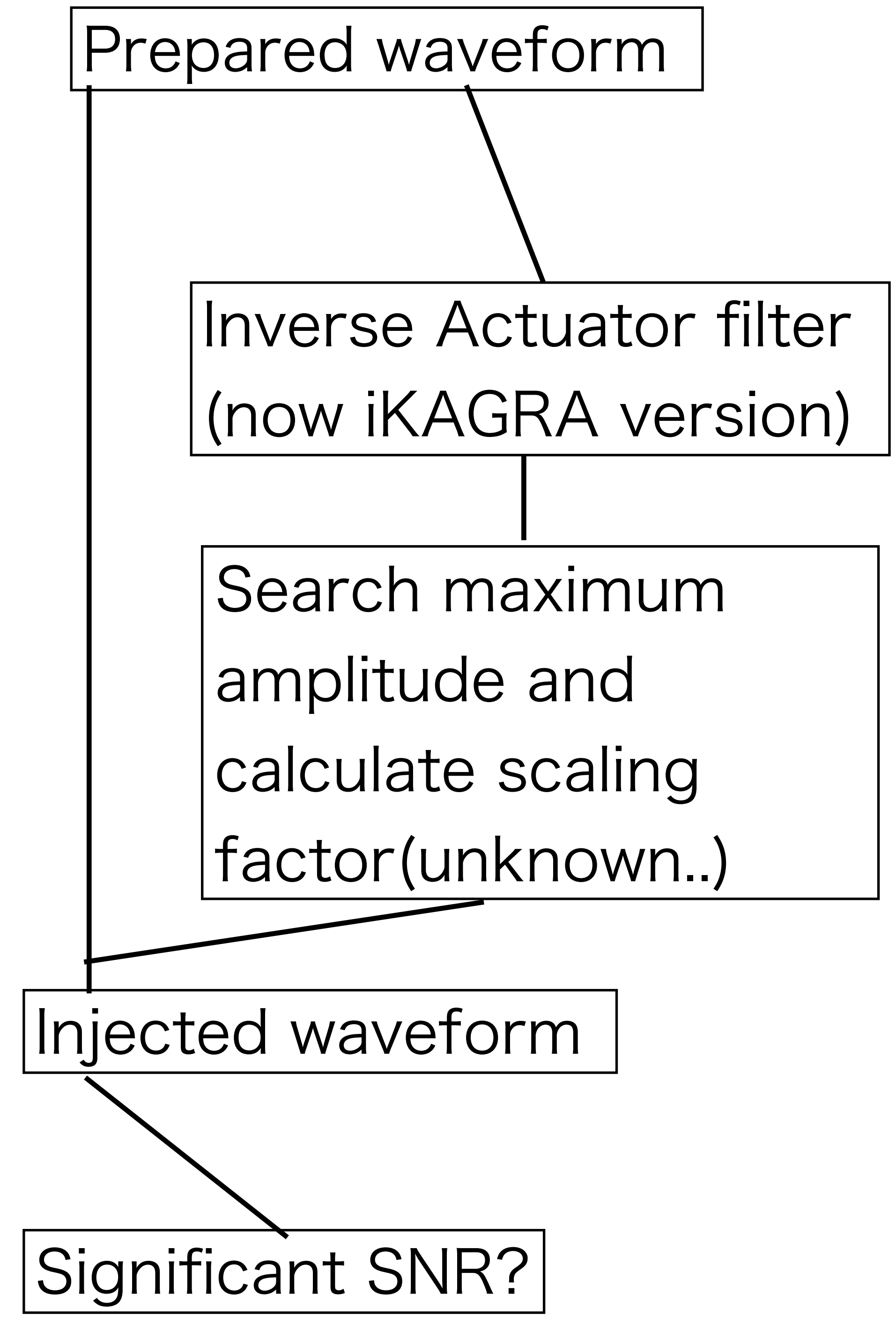
$$3.7 \times 10^{-11}/f^2 [\mathrm{m}]$$

用意波形にf^2フィルタをかけて、最大振幅が1.23e-14[strain]を超えないようなファクタを求めるツールを作成。





Update inverse actuation filter (discussed in P7)



Plan toward bKAGRA HWI test

2. Preparing injection waveforms
   - Maximum/Minimum amplitude

This is for Photon calibrator HWI study

Question from Michimura-san
“Maximum amplitude by pcal injection can be done without detector lock loss?”

That correspond to
“How large Gravitational wave can be detected without detector lock loss?”

We need to investigate and recognize maximum

Also, LIGO injected continuous signal from virtual rotating pulser
To know minimum injection is important

(Future : Estimate noise caused by pcal)

Plan toward bKAGRA HWI test

3. Automation processing
  - Injection planning (Guardian?)
  - Lock loss

In iKAGRA HWI test, We made injection schedule by hand, and fortunately, there were no lock loss during injection schedule, but we want to make it automatically(with considering waveform length)

```
#!/bin/sh

GPS=1145621548
ch_real="K1:LSC-MICH_CTRL_INJ_EXC"
fs=16384
scale=1.0

conf_file="0.config"

echo $GPS

multiawgstream ${ch_real} ${fs} ${conf_file} ${scale} ${GPS}
```

Start GPS time of injection schedule

File of injection schedule

Plan toward bKAGRA HWI test

3. Automation processing
   - Injection planning (Guardian?)
   - Lock loss

In iKAGRA HWI test, We made injection schedule by hand, and fortunately, there were no lock loss during injection schedule, but we want to make it automatically(with considering waveform length)

```
wffile ./cbc/EOBNRv2_m50_m50_fmin10_d4.597e-6_snr20.txt cbc_5050_20
wffile ./cbc/EOBNRv2_m50_m50_fmin10_d6.129e-6_snr15.txt cbc_5050_15
wffile ./cbc/EOBNRv2_m50_m50_fmin10_d9.194e-6_snr10.txt cbc_5050_10
wffile ./cbc/BNS_135DD2_SNR3_Smooth.txt                 BNS135DD2SNR3
wffile ./cbc/BNS_135DD2_SNR5_Smooth.txt                 BNS135DD2SNR5
wffile ./cbc/BNS_135DD2_SNR10_Smooth.txt                BNS135DD2SNR10
wffile ./sn/suwa_11m_00pi_16384.dat sw11_00
wffile ./sn/suwa_11m_02pi_16384.dat sw11_02
wffile ./sn/suwa_11m_05pi_16384.dat sw11_05
wffile ./sn/suwa_11m_10pi_16384.dat sw11_10
wffile ./sn/suwa_50m_16384.dat sw50
wffile ./sn/suwa_80m_16384.dat sw80
wffile ./sg/sg_33_20.dat sg33
wffile ./sg/sg_100_20.dat sg100
wffile ./sg/sg_333_20.dat sg333
```

Alias of waveform dat file

```
sg33     1.0    0.0
sg100    1.0    32.0
sg333    1.0    64.0
sg33     0.5    96.0
sg100    0.5    128.0
sg333    0.5    160.0
sw11_00  1000.0 192.0
sw11_02  1000.0 224.0
```

Injection waveform, scale, time

Plan toward bKAGRA HWI test

3. Automation processing
  - Injection planning (Guardian?)
  - Lock loss

In iKAGRA HWI test, We made injection schedule by hand, and fortunately, there were no lock loss during injection schedule, but we want to make it automatically(with considering waveform length)

Length of waveform
Sine Gauss(Q=20, >30Hz), Supernova : < or ~ 1s
CBC : strongly depend on start frequency and mass
1.35-1.35M, 10Hz : ~60s
20-20M, 10Hz : 12s
GW150914, 10Hz : 4.4s
50-50M, 10Hz : 2.6s

Future conference/meeting

- 3rd KAGRA International Meeting
  - I will summarize the pcal hardware injection simulation and its performance to CBC and continuous waveform
  - Also, show task list(shown today)
- Next JPS meeting
  - September 12-15 in Utsunomiya University
  - Abstract deadline : May 22nd(Mon) 14:00(JST)
  - I want to have presentation about Hardware injection plan

backups

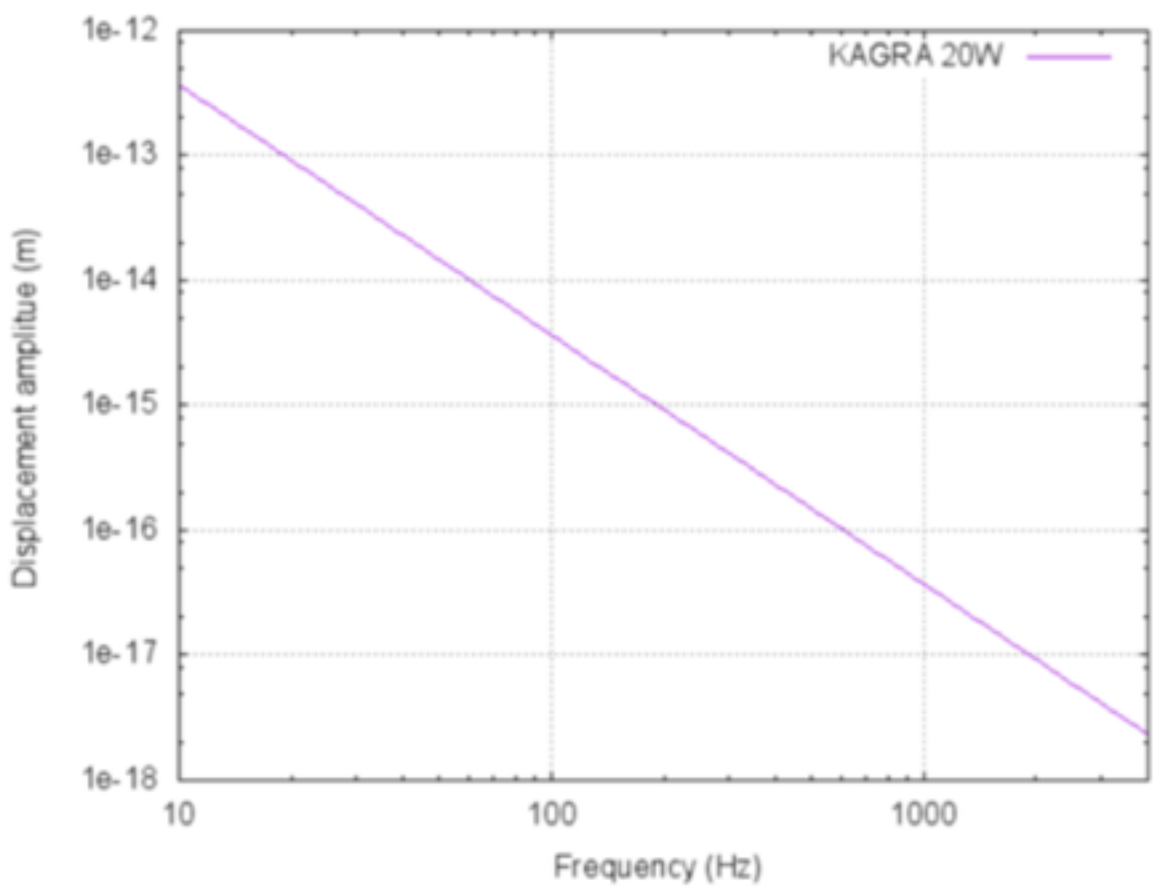
Pcal[1] の変位 (displacement)δx はレーザー強度 $P(f)$、懸架マスへの'force-to-length' 伝達関数 $S(f)$ と記述して、

$$\delta x \sim \frac{2P(f)}{c} S(f) \left(1 + \frac{M}{I}\vec{a}\cdot\vec{b}\right) cos\theta \tag{1}$$

と記述される。ここで c は光速、M は鏡の質量、I は鏡の慣性モーメント、θ は鏡表面における入射レーザーの角度、$\vec{a}\cdot\vec{b}$ は Pcal レーザーが間違った点に照射された際に生じる項で今回は 0 としている。$S(f)$ は 20Hz 以上では $S(f) \sim -1/[M(2\pi f)^2]$ と近似できる。すべての laser power を一つの周波数に押し込んだときに動かせる量は *1

$$\delta x(\omega) = \frac{P_{\text{power}}}{cM}\frac{cos\theta}{\omega^2}\ [\text{m}] \tag{2}$$

KAGRA PCalのパラメータを代入する。
transmitter module optical efficiency
とAOM diffraction efficiencyの合計を
pessimisticに50%と評価



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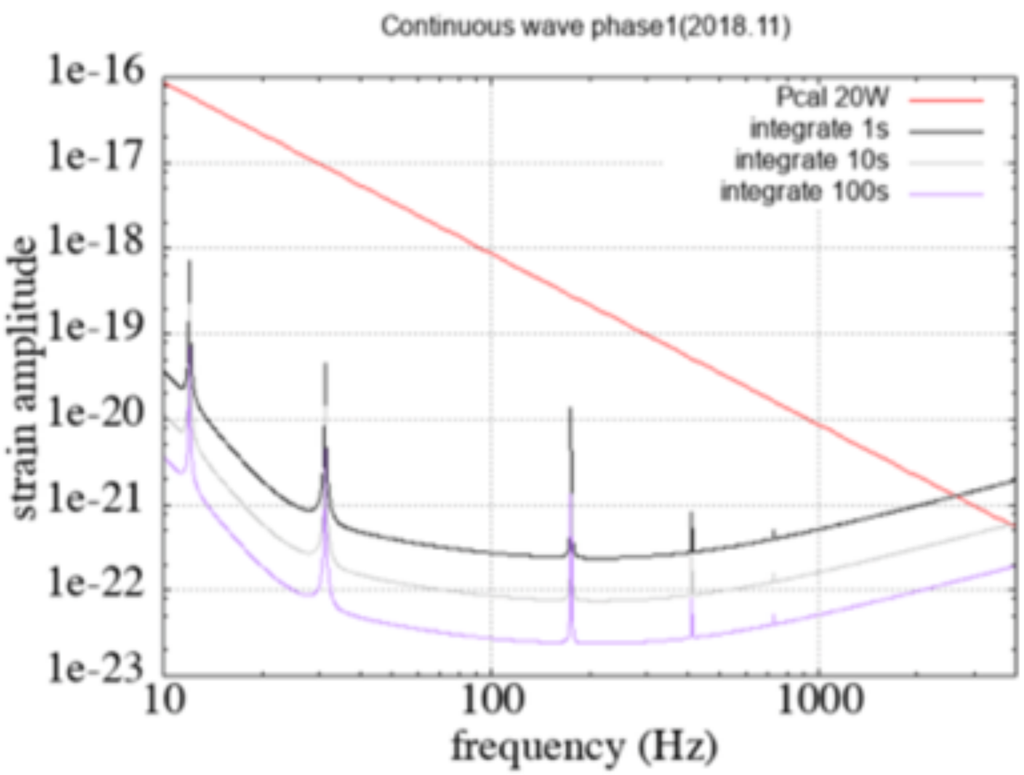
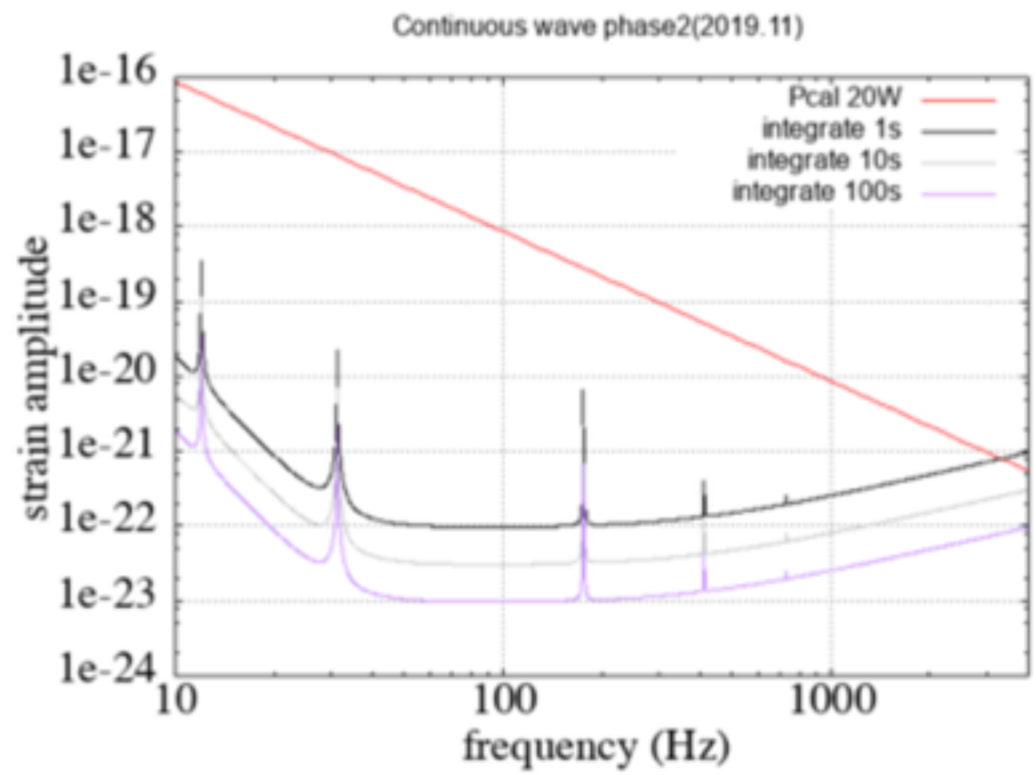
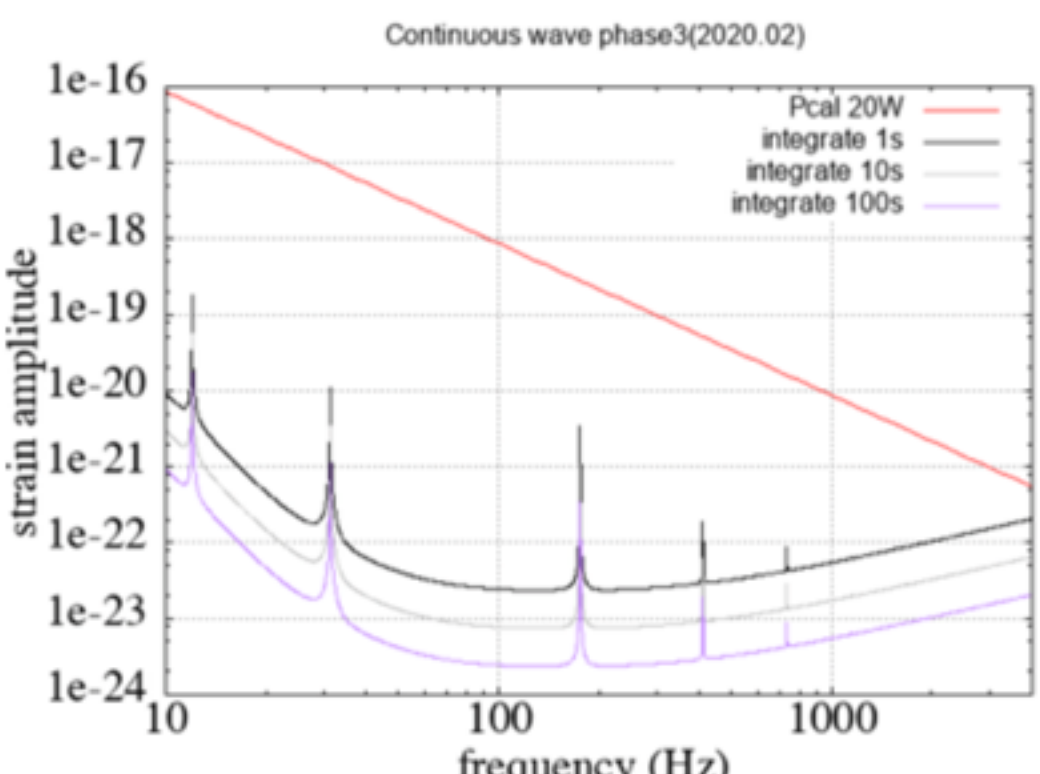
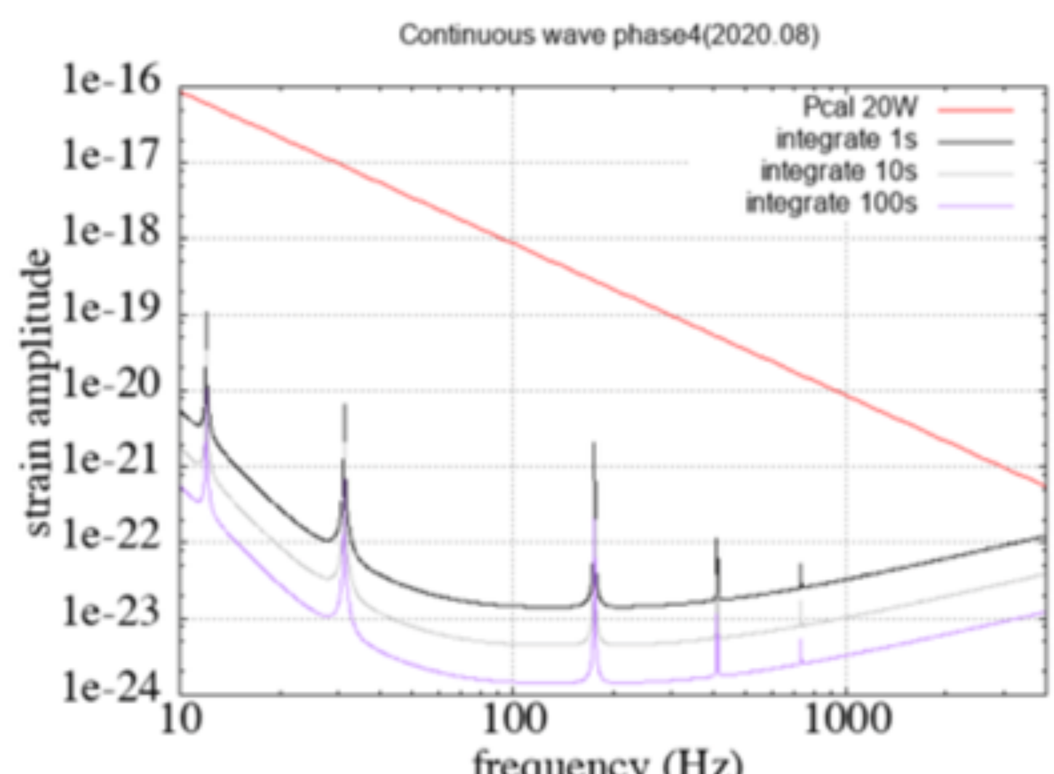
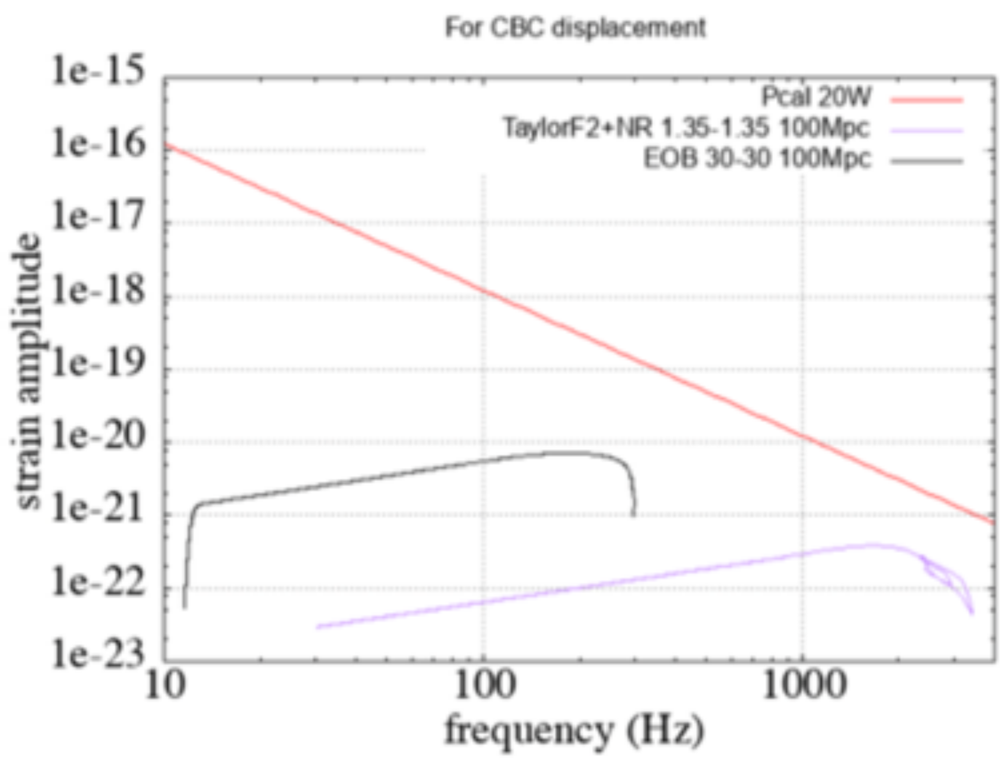
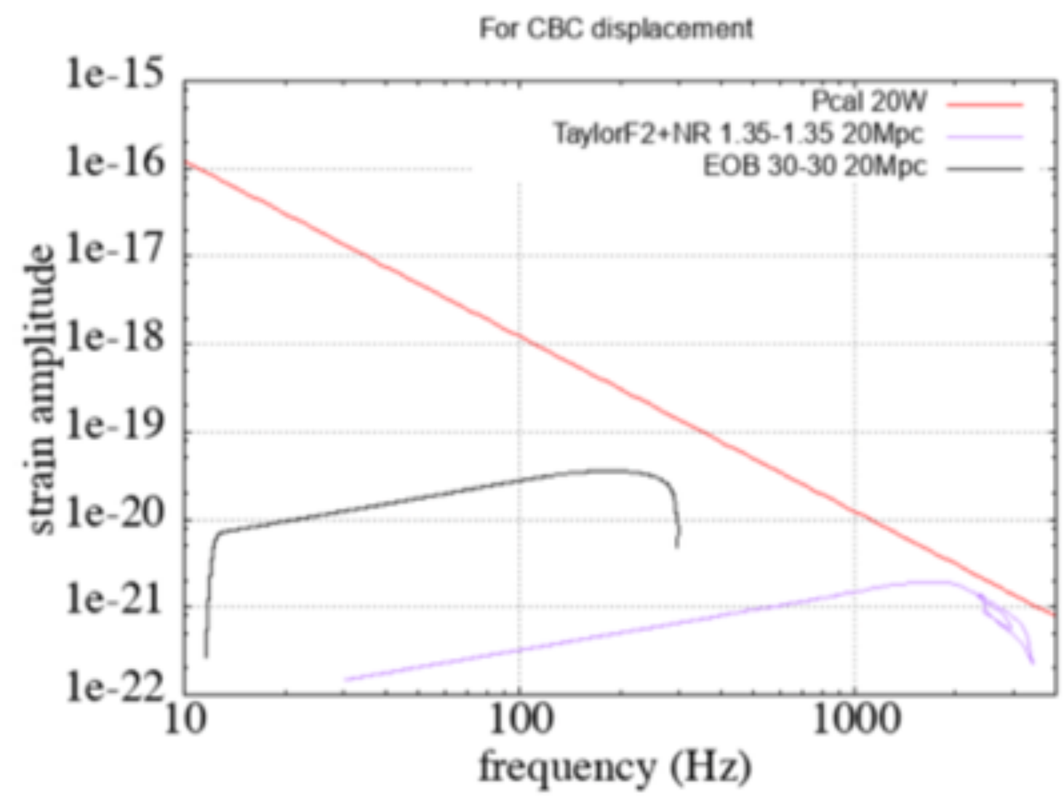

Continuous wave phase1(2018.11)
Pcal 20W
integrate 1s
integrate 10s
integrate 100s
strain amplitude
frequency (Hz)

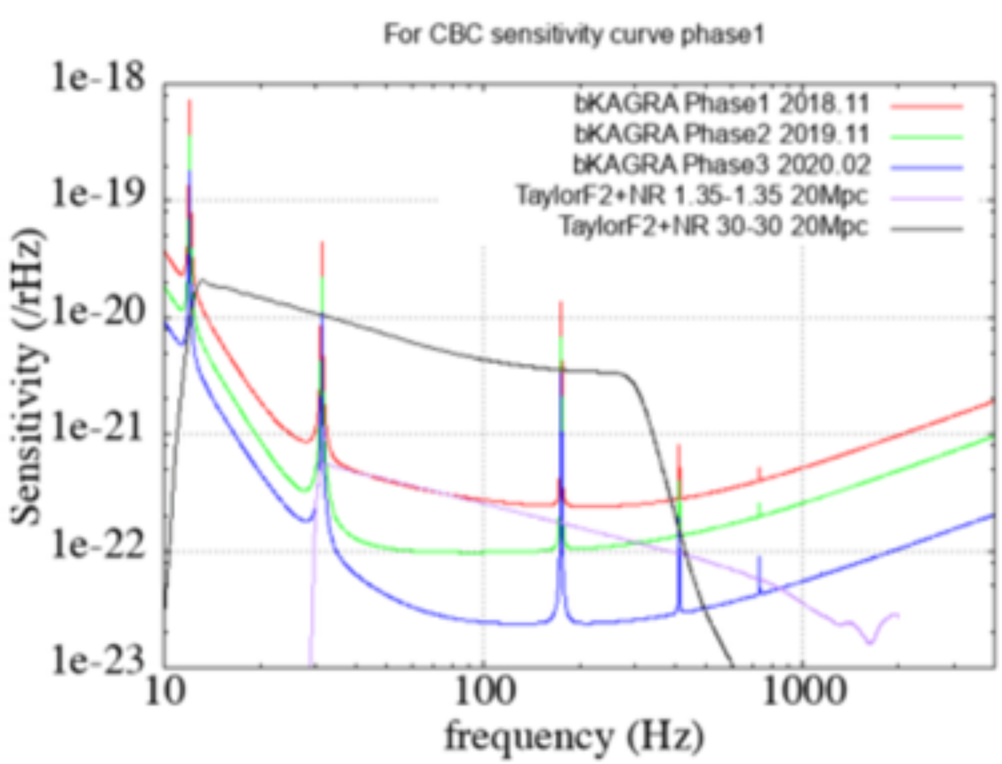

Continuous wave phase2(2019.11)
Pcal 20W
integrate 1s
integrate 10s
integrate 100s
strain amplitude
frequency (Hz)


Continuous wave phase3(2020.02)
Pcal 20W
integrate 1s
integrate 10s
integrate 100s
strain amplitude
frequency (Hz)


Continuous wave phase4(2020.08)
Pcal 20W
integrate 1s
integrate 10s
integrate 100s
strain amplitude
frequency (Hz)







$$\rho_{\rm opt} = G^{5/6}c^{-3/2}\frac{M^{5/6}}{r\pi^{2/3}}\left(\frac{5\eta}{6}\right)^{1/2}\left[\int_{f_{\rm min}}^{f_{\rm max}} df\,\frac{f^{-7/3}}{S_n(f)}\right]^{1/2}$$

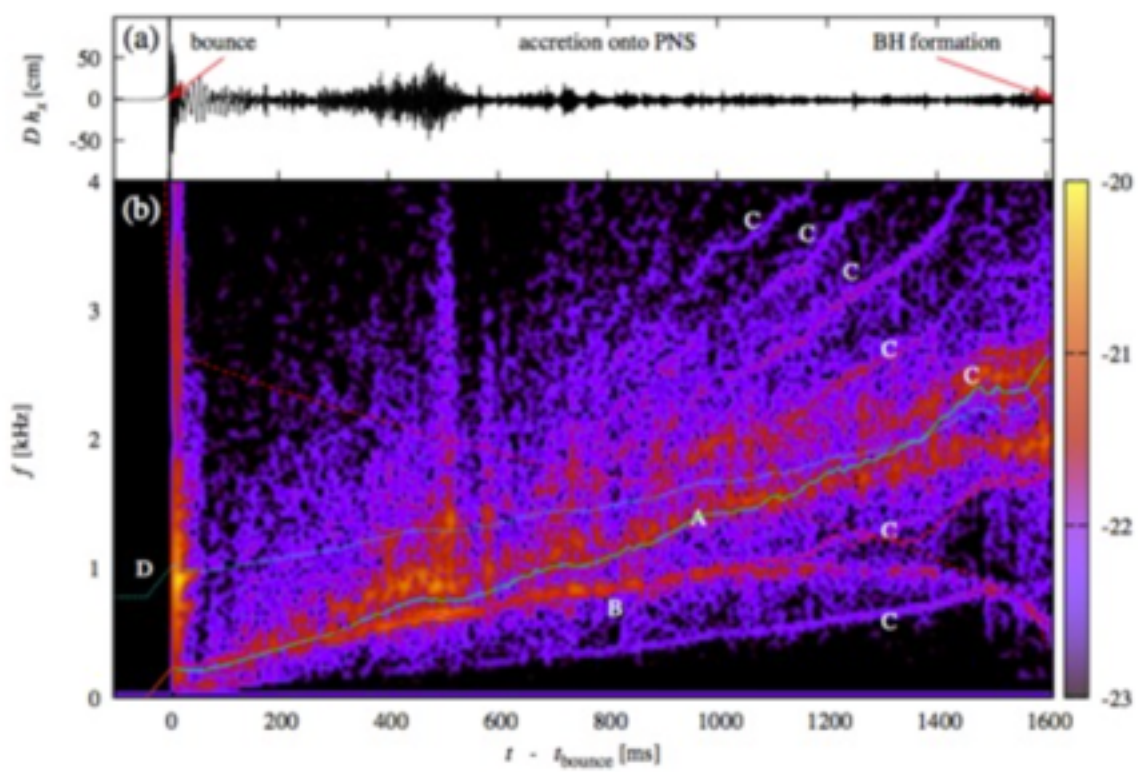
Phase	NS-NS(1.35-1.35$M_\odot$) 20Mpc	BH-BH(30-30$M_\odot$) 20Mpc
Phase1	2.25	21.0
Phase2	6.83	71.5
Phase3	21.7	182.2
Phase4	36.2	303.7

rapid rotation(central period~1.5ms at bounce)
polar-to-equatorial radius ratio~0.64 PNSできる
PNS cool down 14km BH formation

ラベルA;
monotonic increase of the frequency with time
g-modes on the surface of the PNS
時間とともに縮小しmassが重くなる。

$$f_{\mathrm{g,PNS}} \sim \frac{1}{2\pi} \frac{M_{\mathrm{PNS}}}{R_{\mathrm{PNS}}^2} \left(1 + \frac{M_{\mathrm{PNS}}}{2R_{\mathrm{PNS}}}\right)^{-4} \sqrt{\frac{\Gamma - 1}{\Gamma} \frac{m_n}{k_b T}}$$

$$\Gamma = 4/3 \quad k_b T = 15\mathrm{MeV}$$



ラベルB;
ラベルAと同様、1kHzぐらいまでincreaseするが、突然減少する
inner coreに由来する。
velocityがquasi-radialになりBHが生成される。
点線がBH生成から予想される曲線で、B線->BH点線

ラベルC;
SASI motionが音波を生成しPNS表面を励起させる

ラベルD;
バウンスにより励起されたf-mode
即座にそばのhot bubbleにより
消えてしまう。