Master thesis:
Development of lock-loss classification system in large-scale cryogenic gravitational waves telescope, KAGRA

Fujikawa Yuta (Niigata Univ.)

Gravitational wave

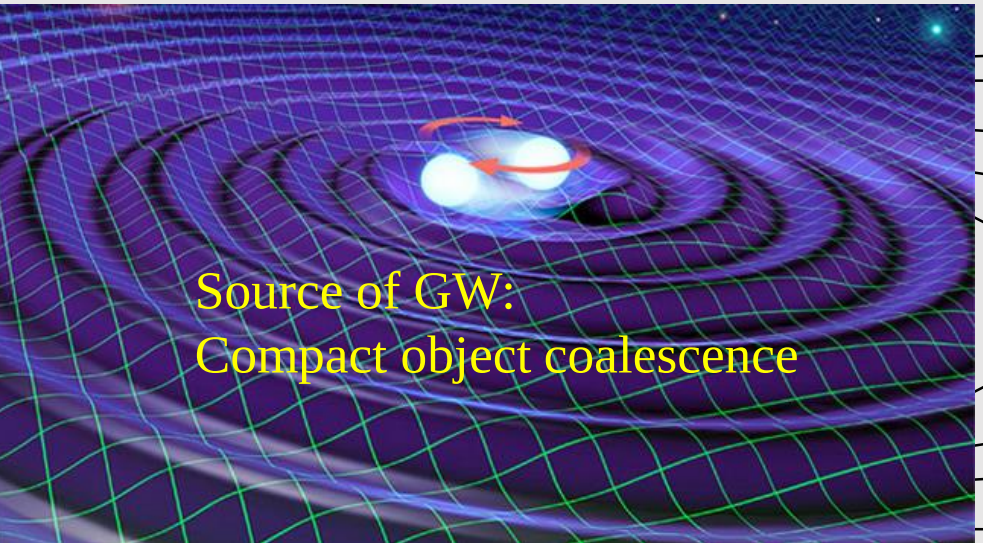
Gravitational wave (GW) is the wave of “space-time ripple”

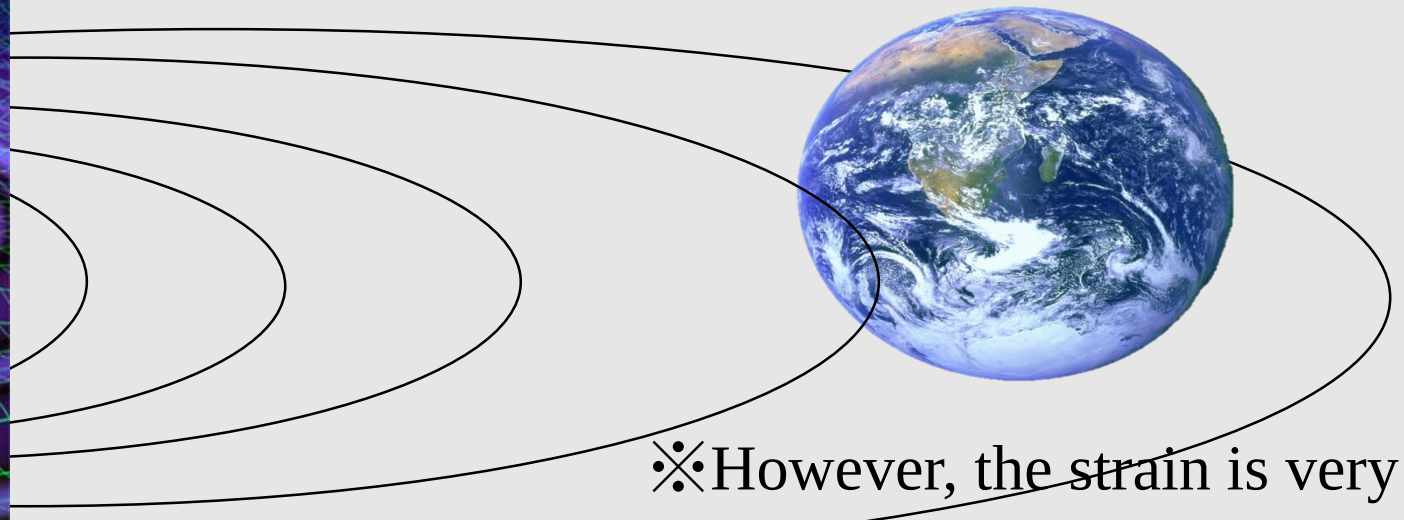
Heavy objects make space-time distortion

Distortion propagates as “Gravitational Wave”

Distortion is detected as strain of interferometer

A detector of GW is KAGRA



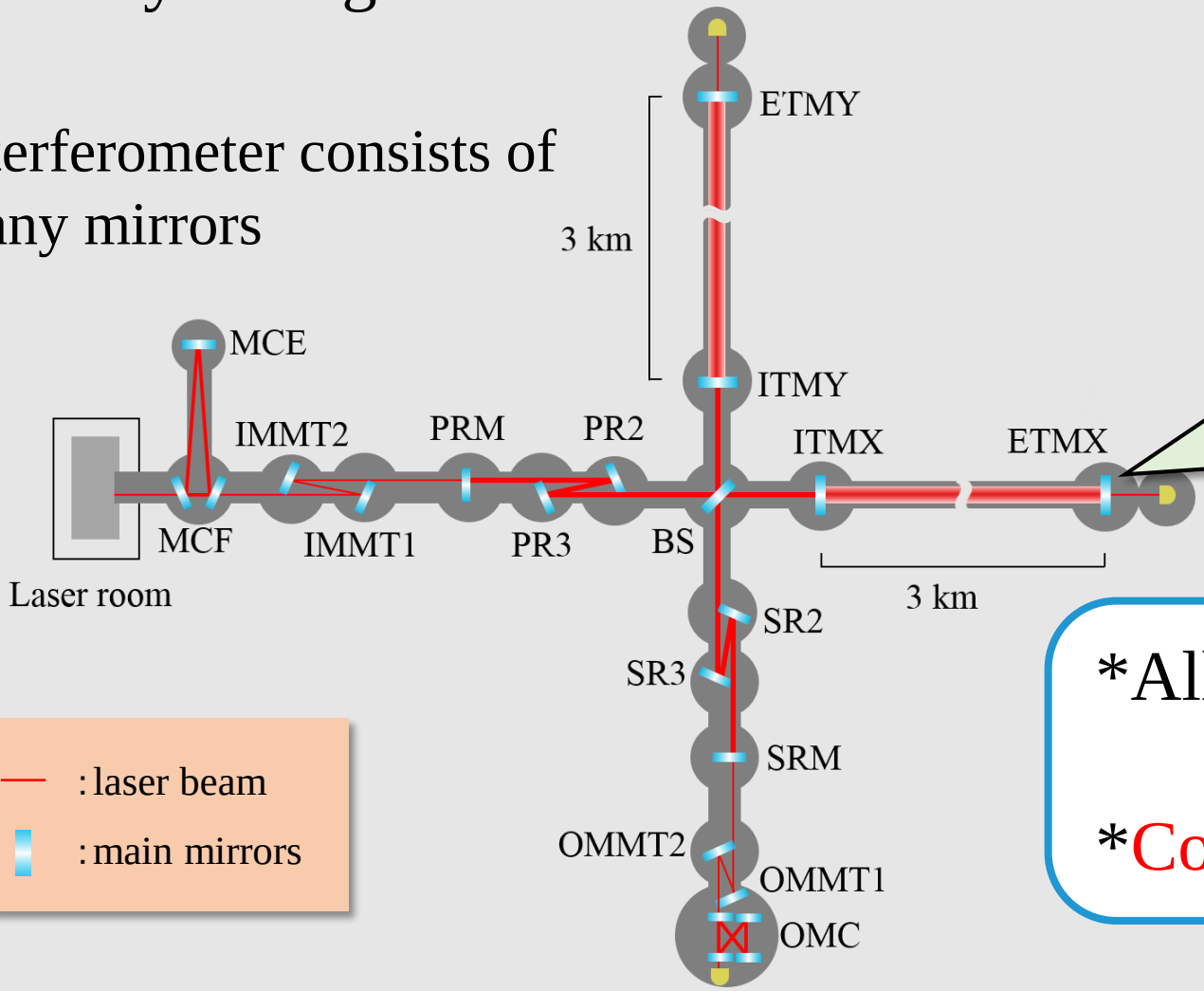


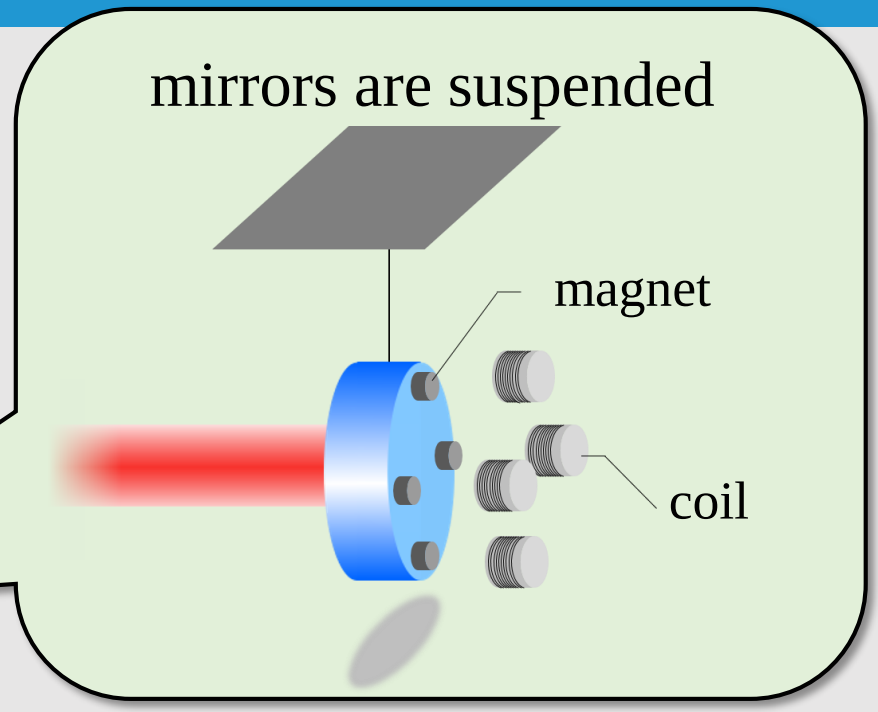
※However, the strain is very small

Importance of interferometer control

Basically configuration of KAGRA

Interferometer consists of many mirrors



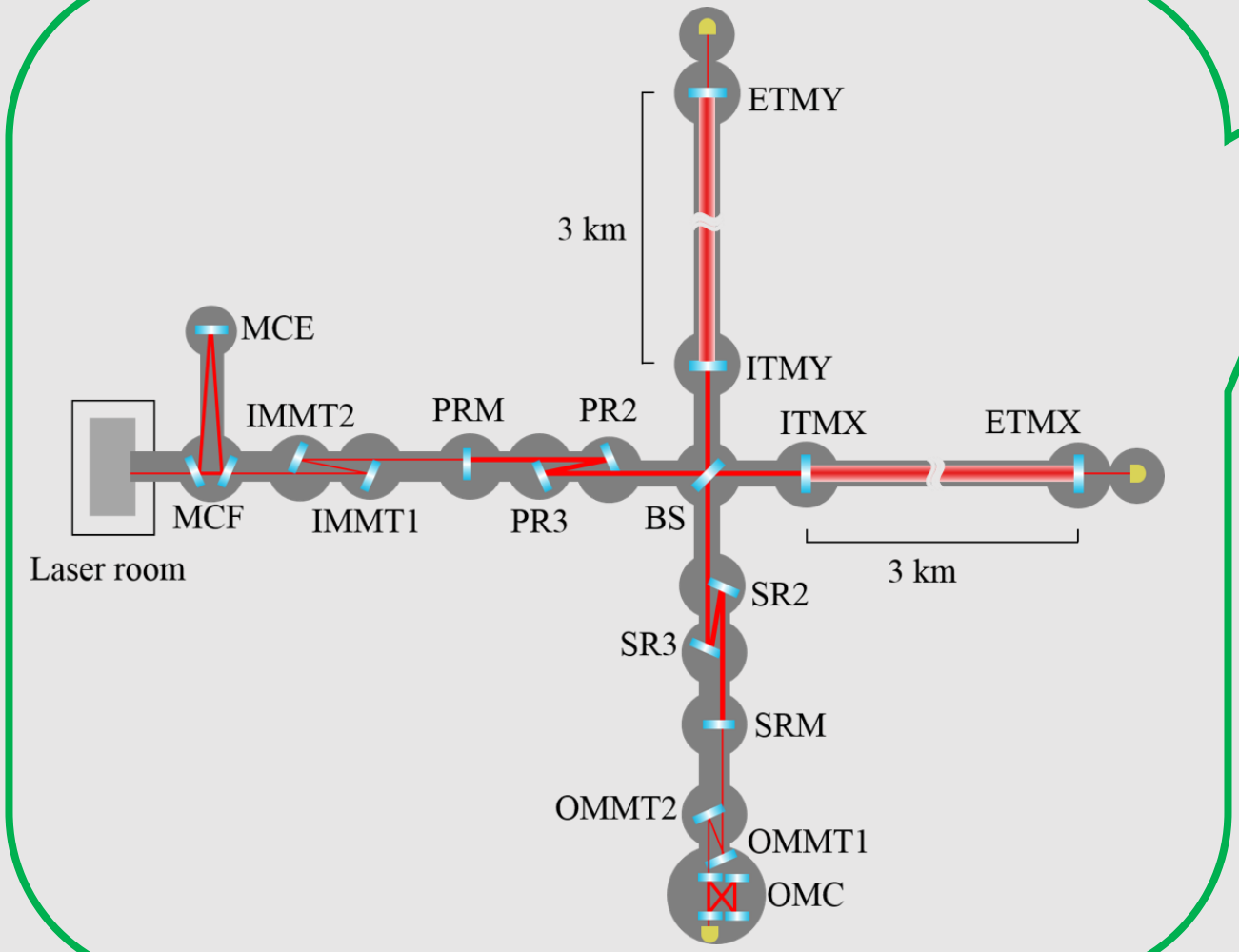


*All mirrors need to be adjusted to proper position and angle

*Control is essential to maintain state

※control refers to feedback control

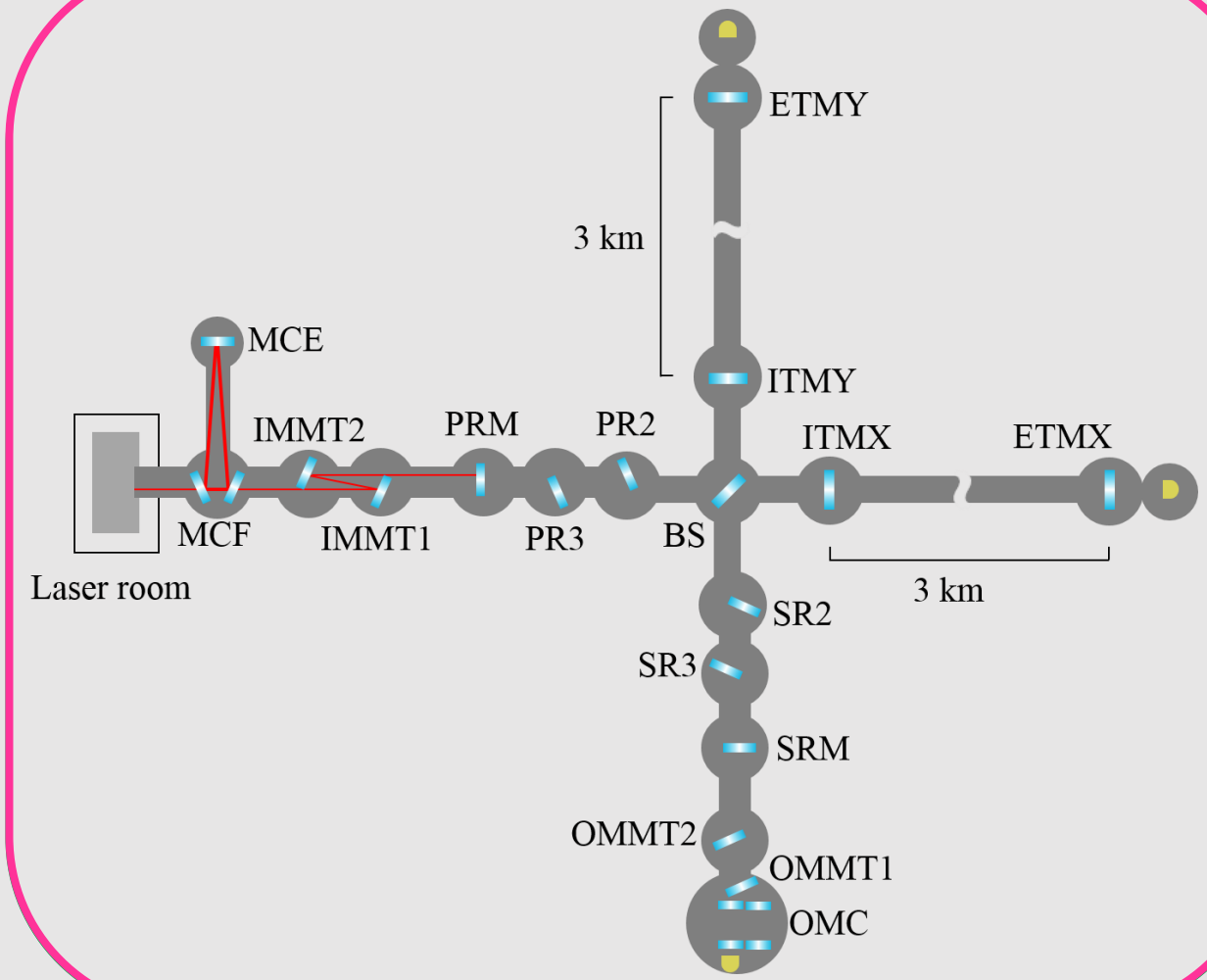
Lock-loss of interferometer



*LOCK:
A state in which all mirrors
are properly controlled

*LOCK-LOSS:
A state in which control is lost
Even if GW arrives with lock-loss state,
KAGRA can not detect GW

Lock-loss of interferometer



*LOCK:
A state in which all mirrors
are properly controlled

*LOCK-LOSS:
A state in which control is lost
Even if GW arrives with lock-loss state,
KAGRA can not detect GW

*want to avoid lock-loss during observation
*however, lock-loss process has not
been systematically studied
*want to investigate lock-loss reason
*Lock-loss study is meaningful

Position and purpose of this study

Lock-loss study is meaningful

Step of lock-loss study

Purpose of my study

Build an analysis method

using lock-loss of latest observation (O3GK)

KAGRA O3GK

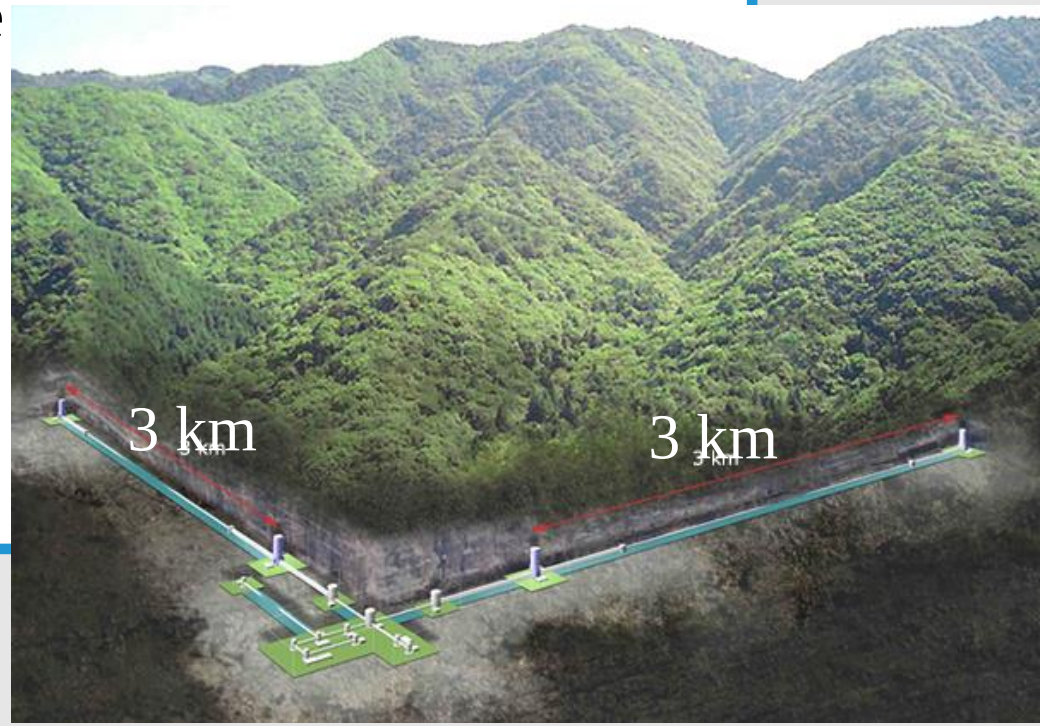
KAGRA is …

*Large-scale cryogenic gravitational waves telescope

*Located 200 m underground
at the Mt. Ikenoyama, Gifu

*Based on Michelson interferometer
(baseline length is 3 km)

*In cryogenic temperature (20 K)



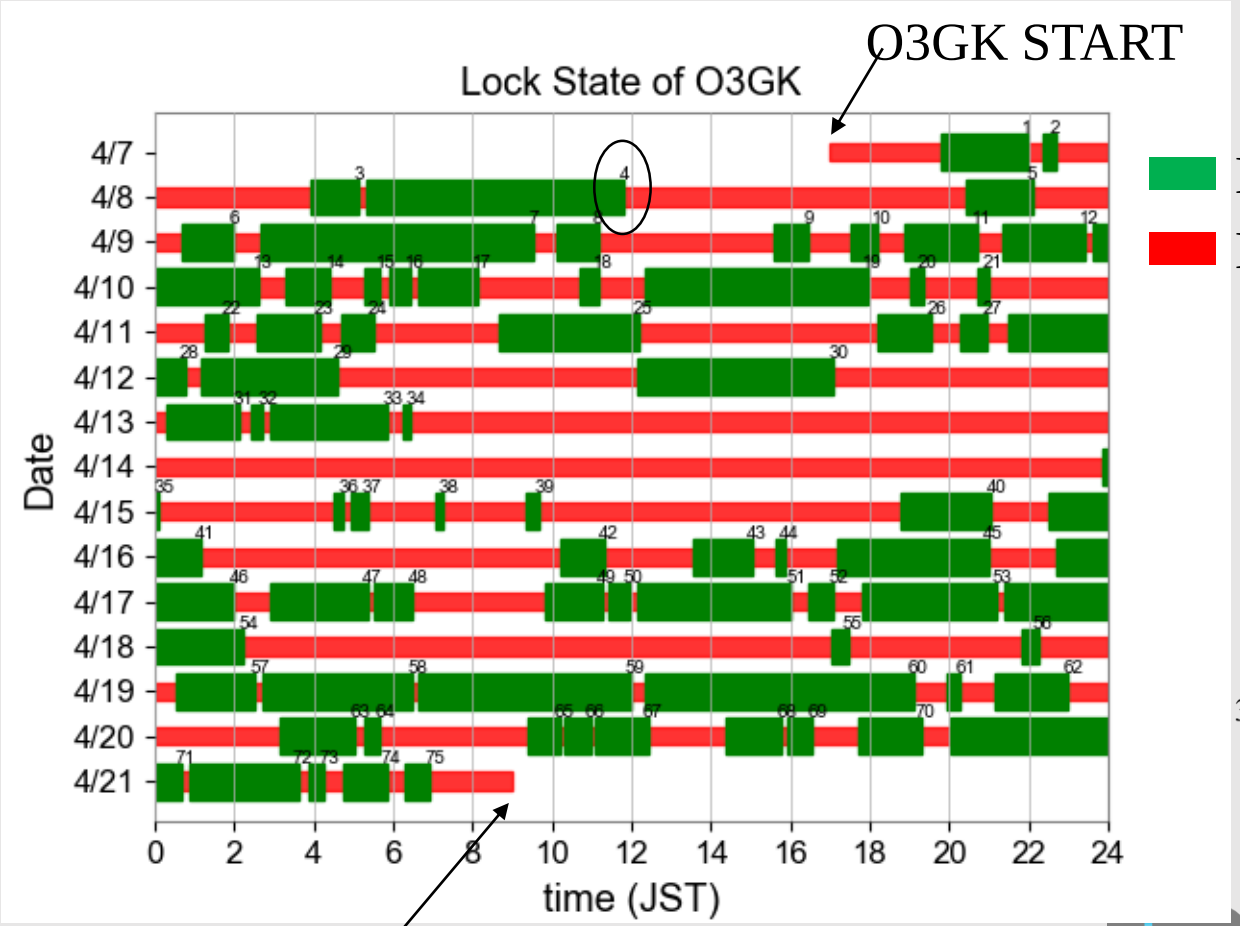
First international observation with GEO
was performed from 7th to 21st Apr, 2020 (O3GK)

Design : PRFPMI, Room temperature : about 270 K

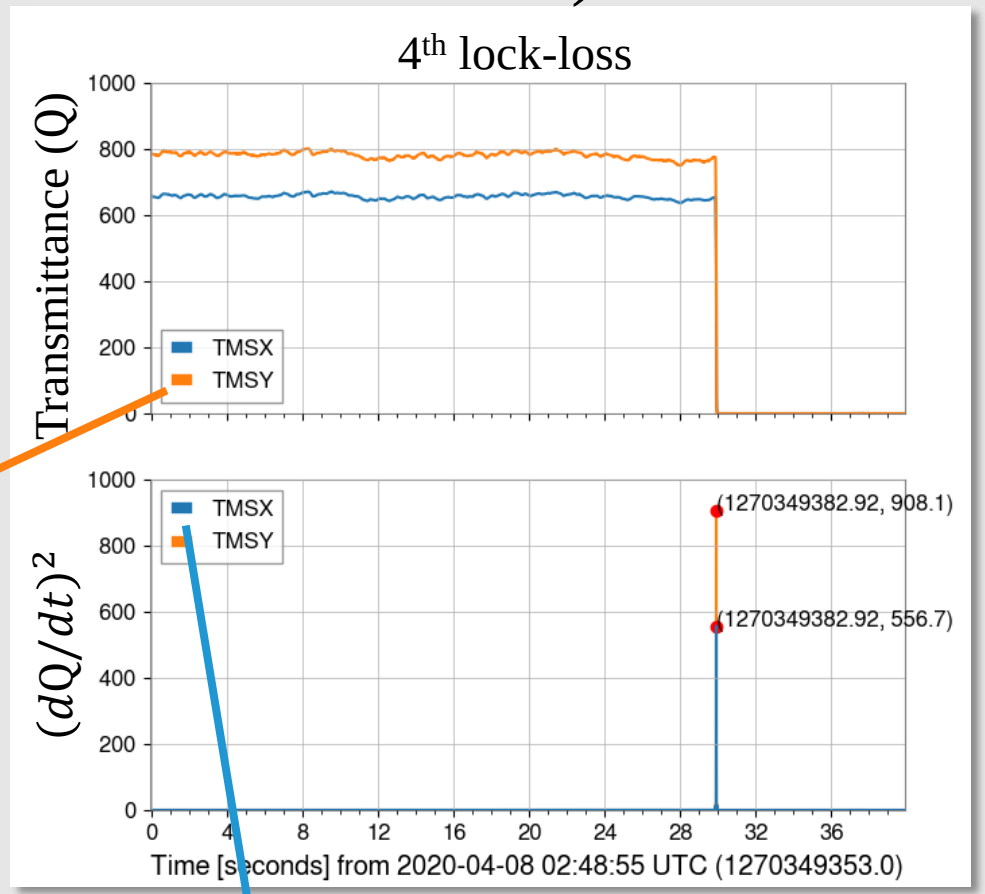
>> For the details, check O3 plenary session

Lock-loss in O3GK

Number is identified lock-loss in O3GK is 75 (duration ≧ 10 minutes)



Lock rate:42.5 %



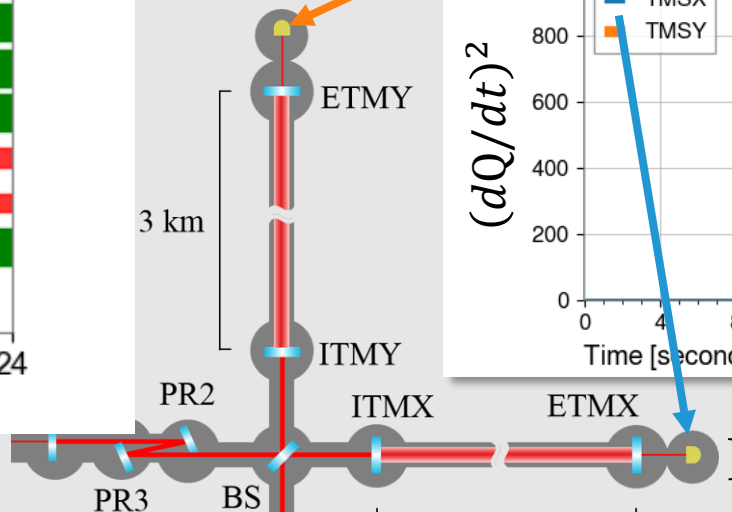


Photo detector

Lock-loss analysis methods

There are two main methods

1. Approach from the causation

   For known causes, find out if the phenomenon is occurring at lock-loss
   There is abnormal ground vibration in this study

2. Approach from the result side

   Usually cause is unknown, but various behavior is seen at lock-loss
   Show hints to lock-loss process from the behavior

Lock-loss analysis methods

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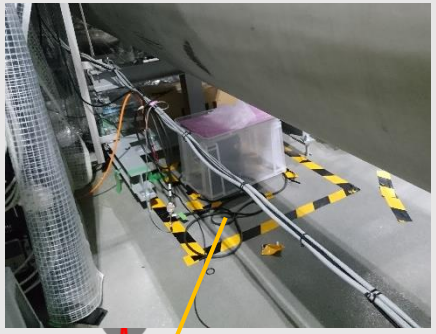
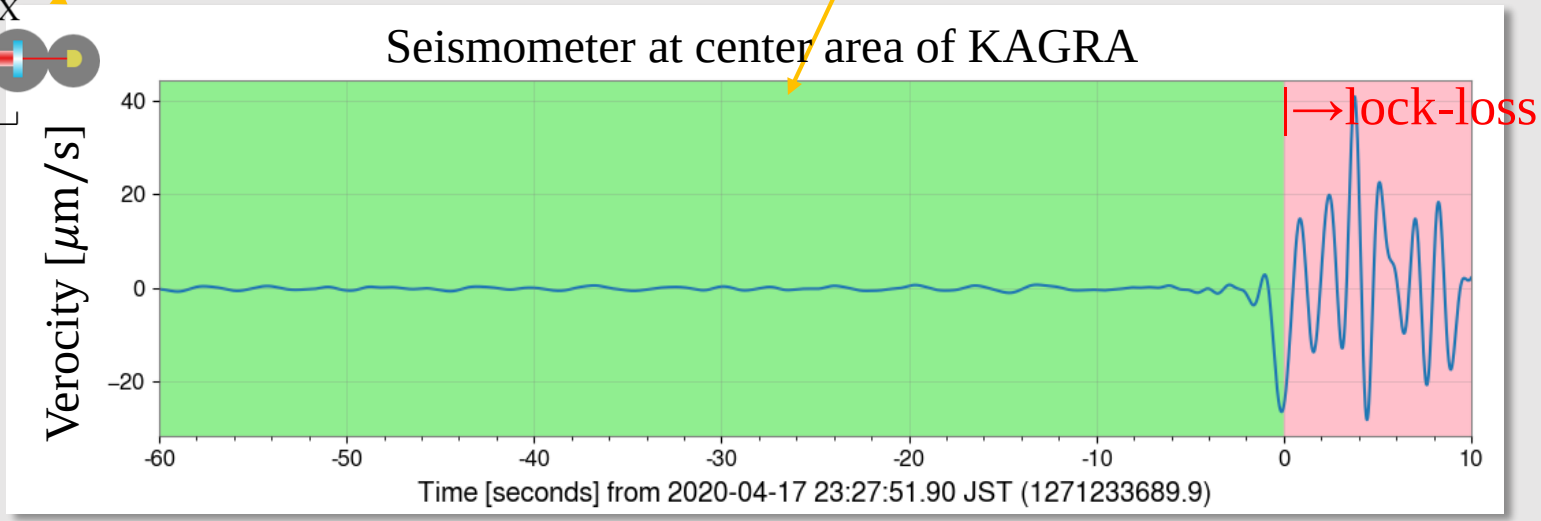
Approach from cause side

Whether abnormal ground vibration occurred
Check it using 5 seismometers

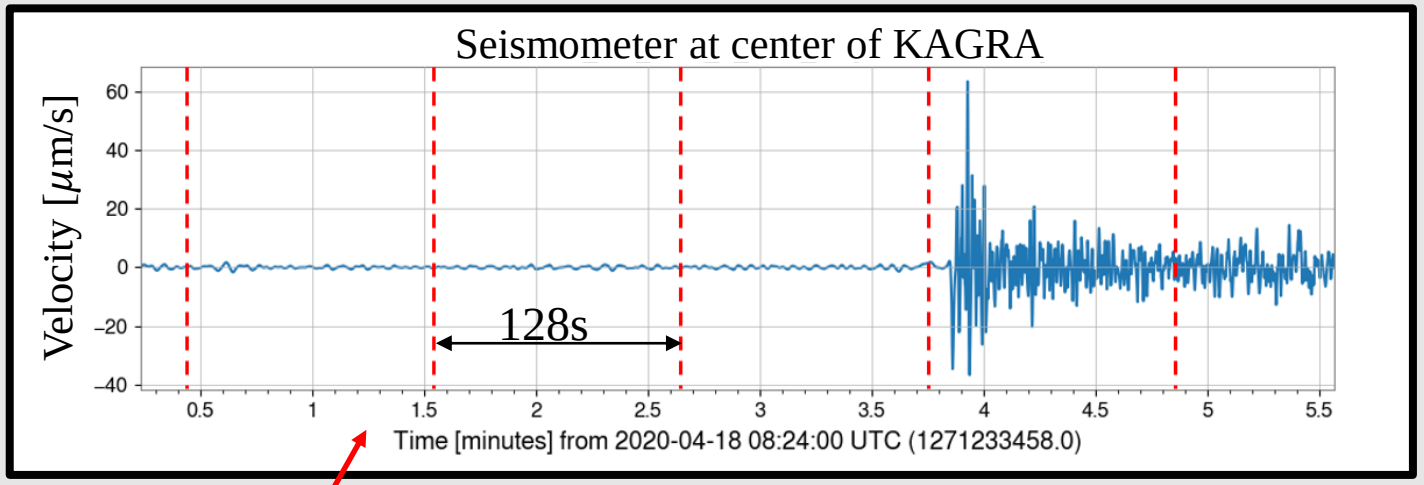


Seismometer at center area of KAGRA

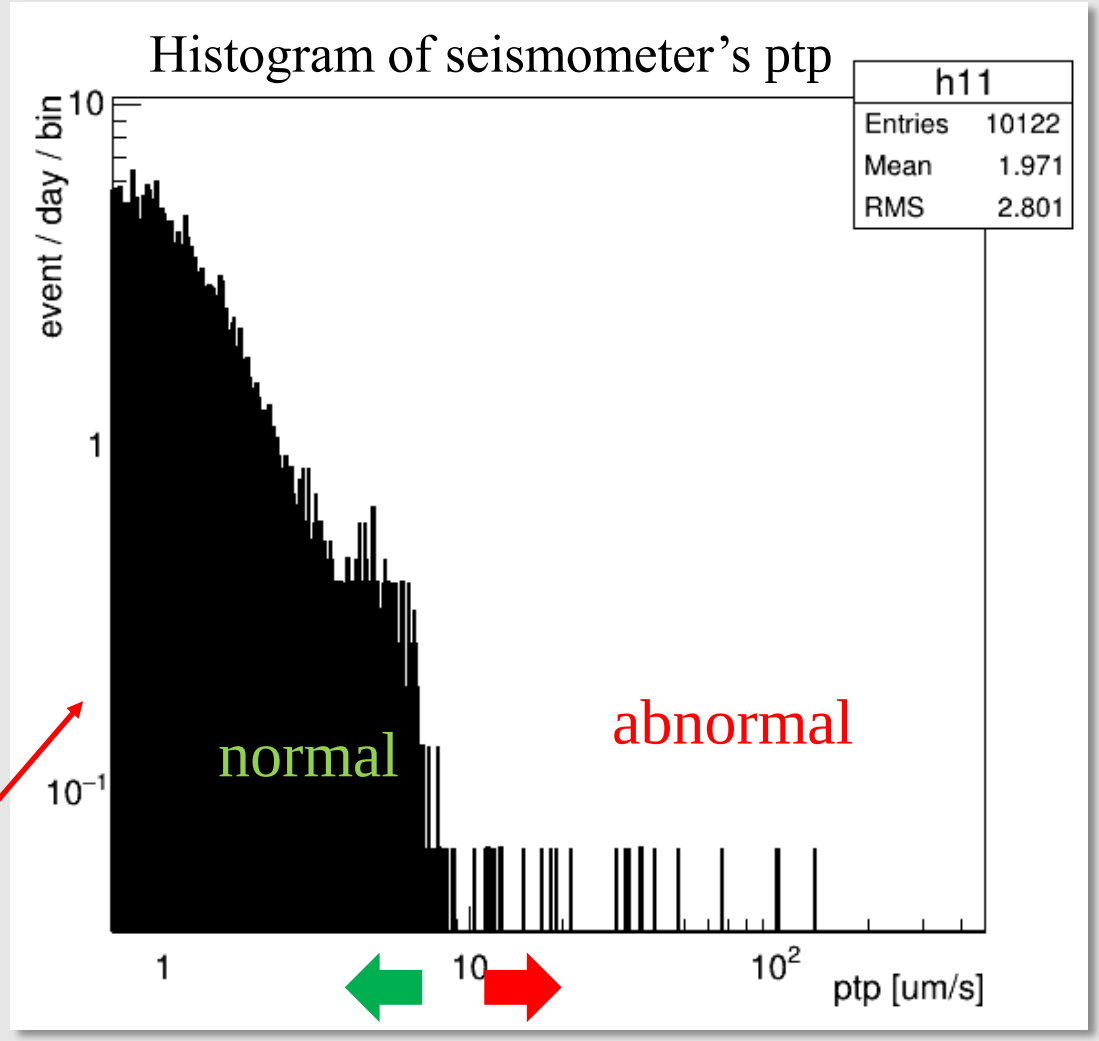


Threshold of seismometer

Threshold is determined from histogram



(i) Divide 15 days of O3GK every 128 seconds
(ii) Make histogram from peak to peak in the section
(iii) Fit normal distribution (next page)
(iv) Determine threshold (next page)



Threshold

Threshold of seismometer

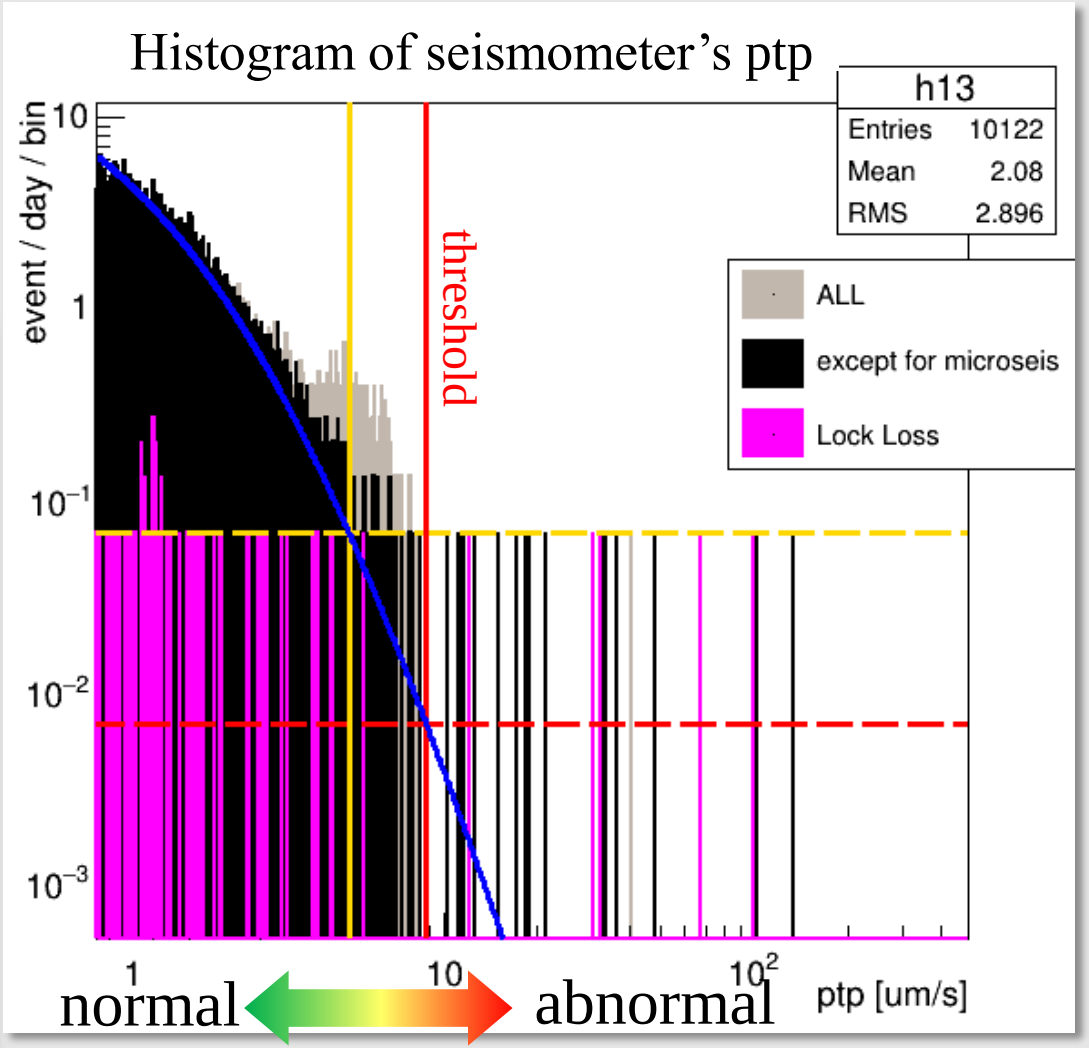
Distribution at normal time (black)
= Remove the large microseismic period

Next page

*Fit normal distribution
with power function (solid blue line)

※natural phenomenon such as ground vibration
follows power distribution

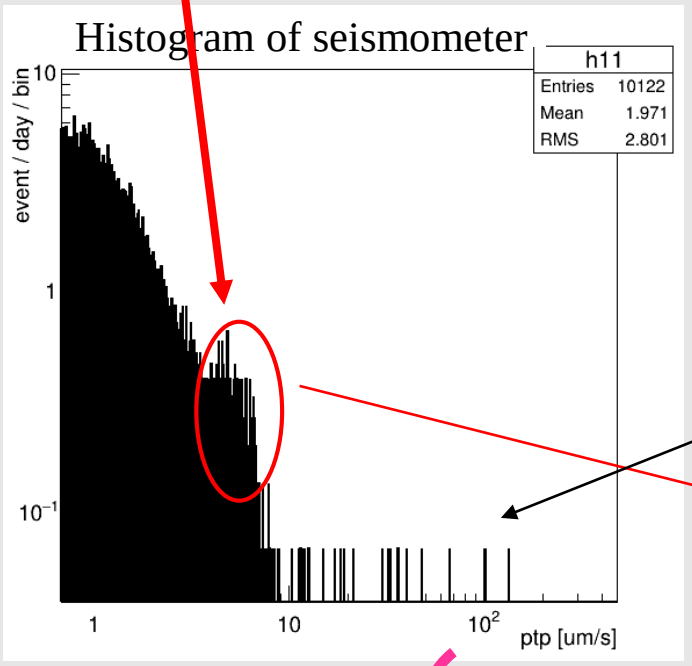
*Determine threshold:
value that occurs only 0.1 times
at 15 days (solid red line)



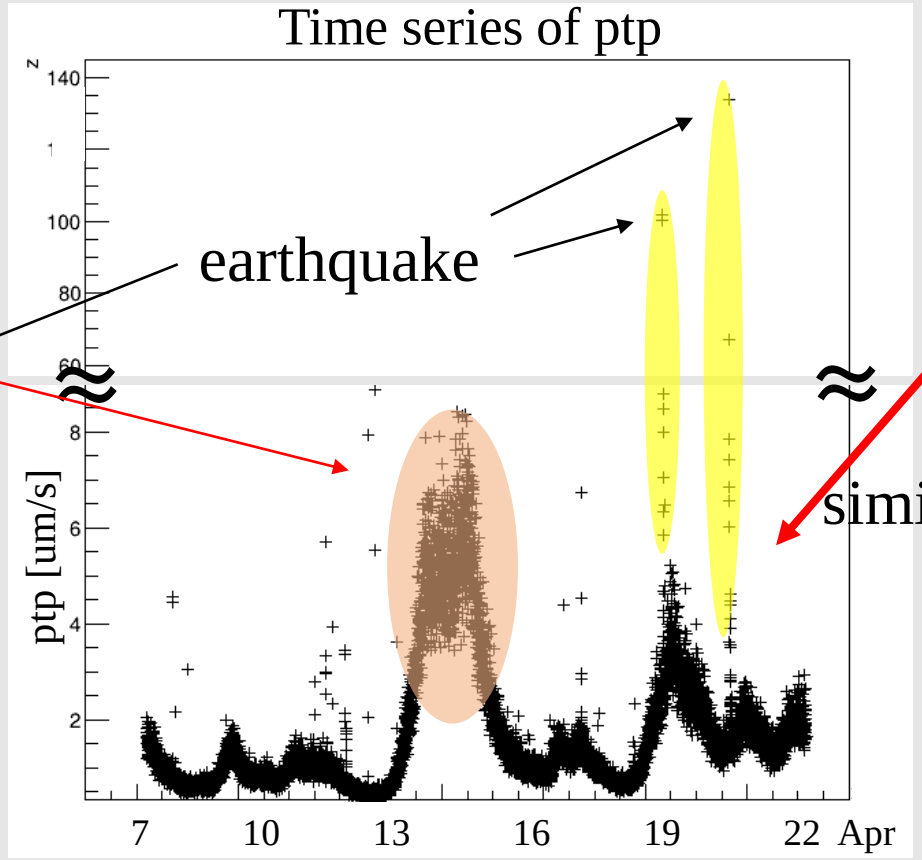
Yellow zone（1 time /15days）

Microseismic

Microseismic is ground vibration due to rough sea

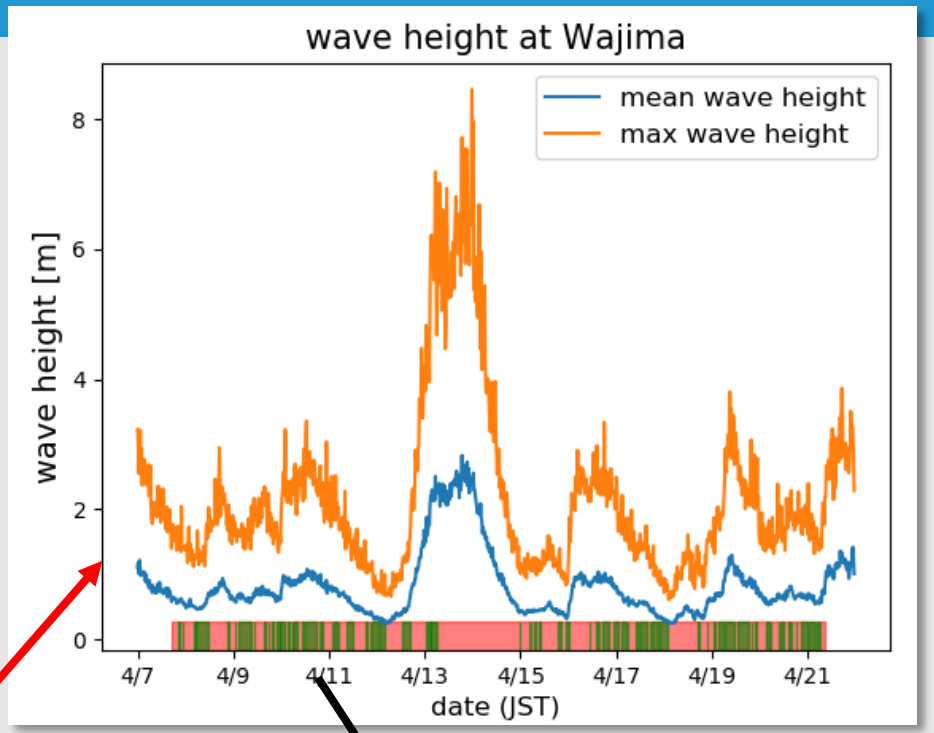


Time series



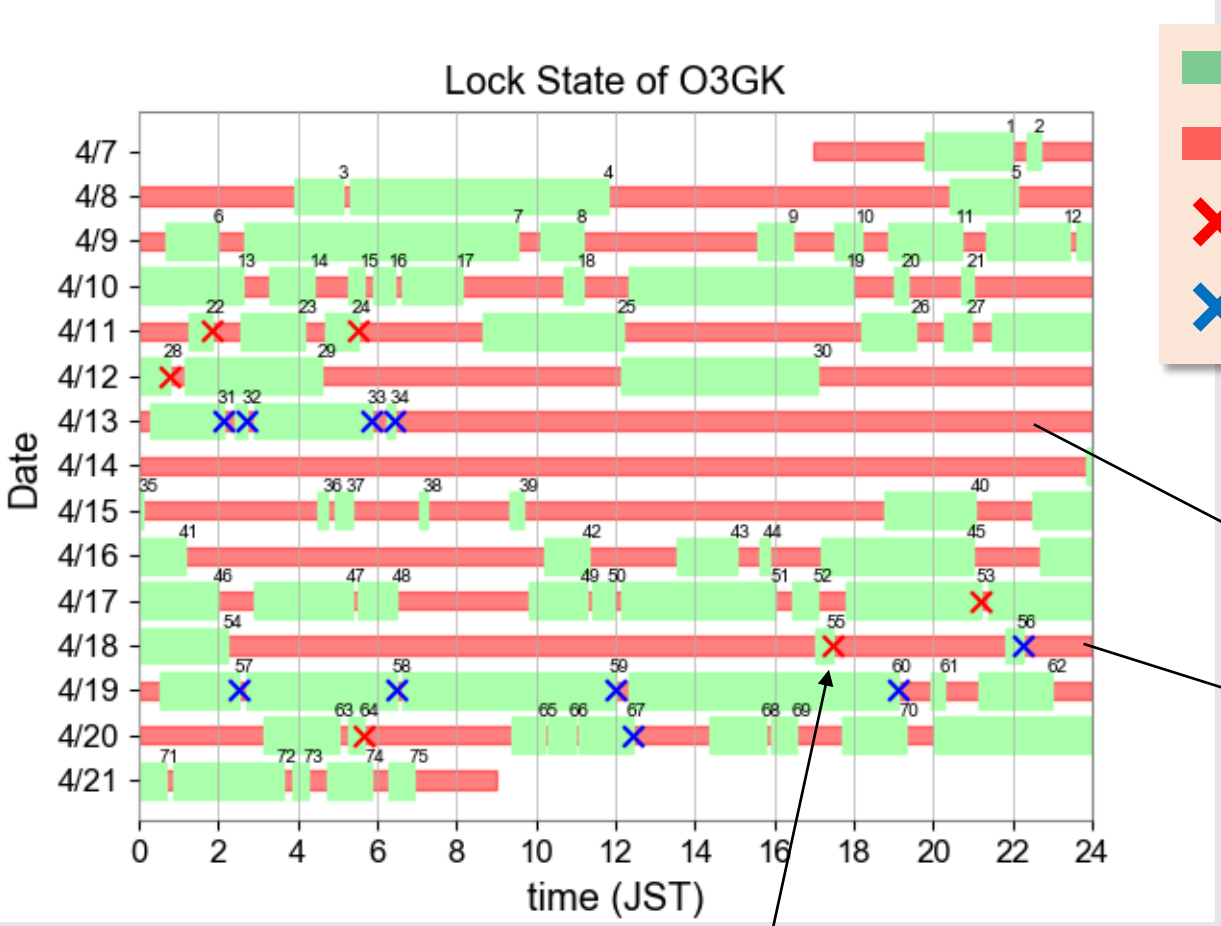
earthquake

≈ ≈



similar in shape

Analysis result from cause side

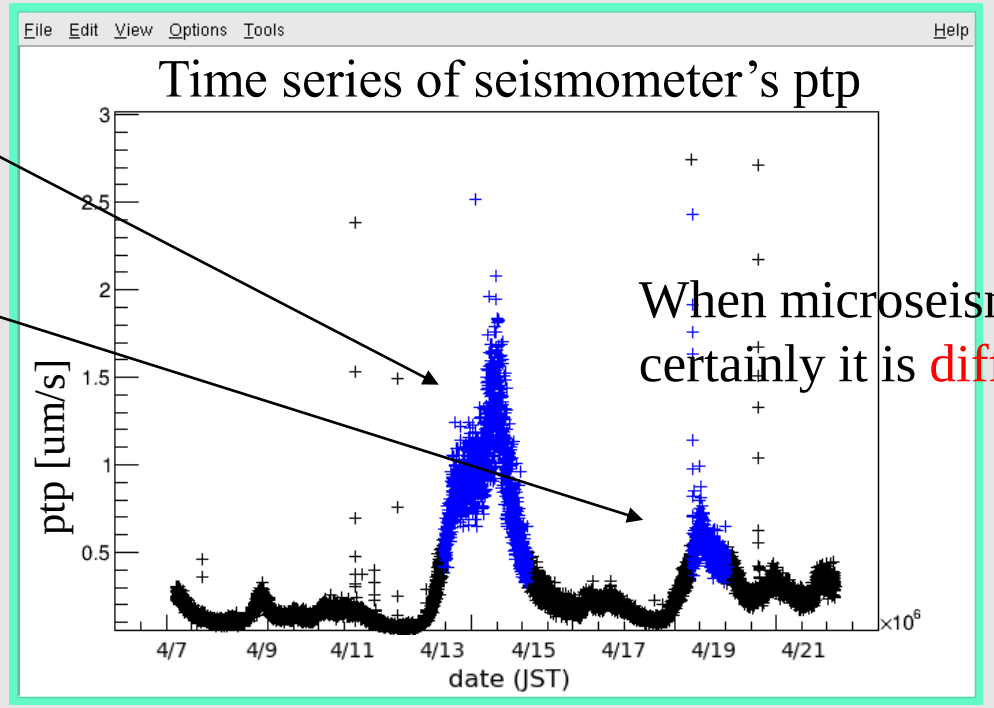


lock

Lock-loss

Lock-loss by abnormal ground vibration（6 times）

Lock-loss by large microseismic（9 times）



When microseismic is large certainly it is difficult to lock

Both detected

Lock-loss analysis methods

There are two main methods

1. Approach from the causation

   For known causes, find out if the phenomenon is occurring at lock-loss
   There is abnormal ground vibration in this study

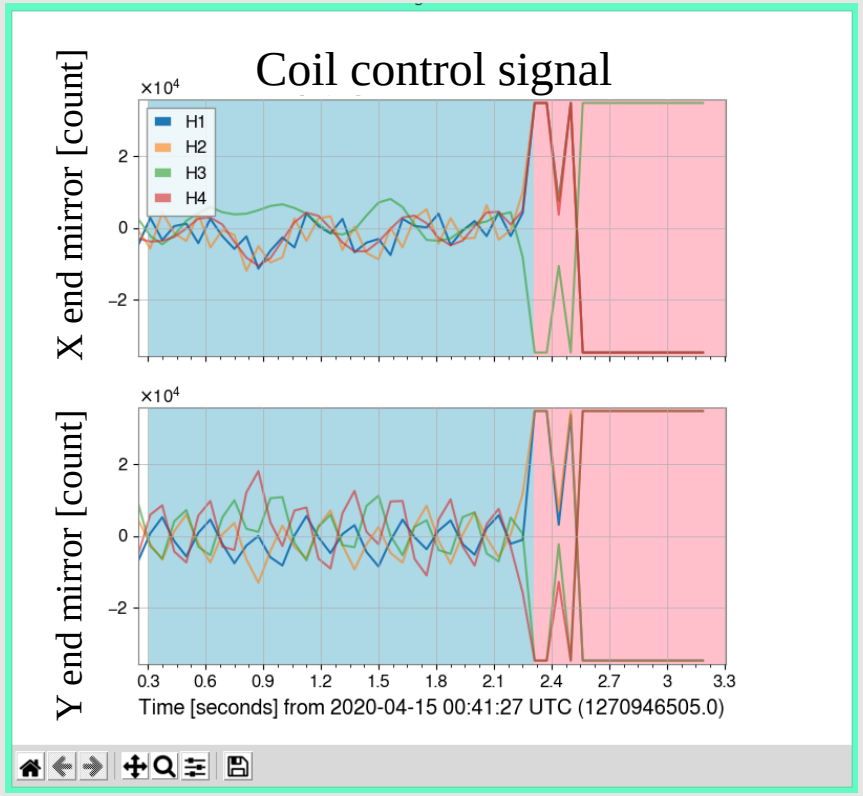
2. Approach from the result side

   Usually cause is unknown, but various behavior is seen at lock-loss
   Show hints to lock-loss process from the behavior

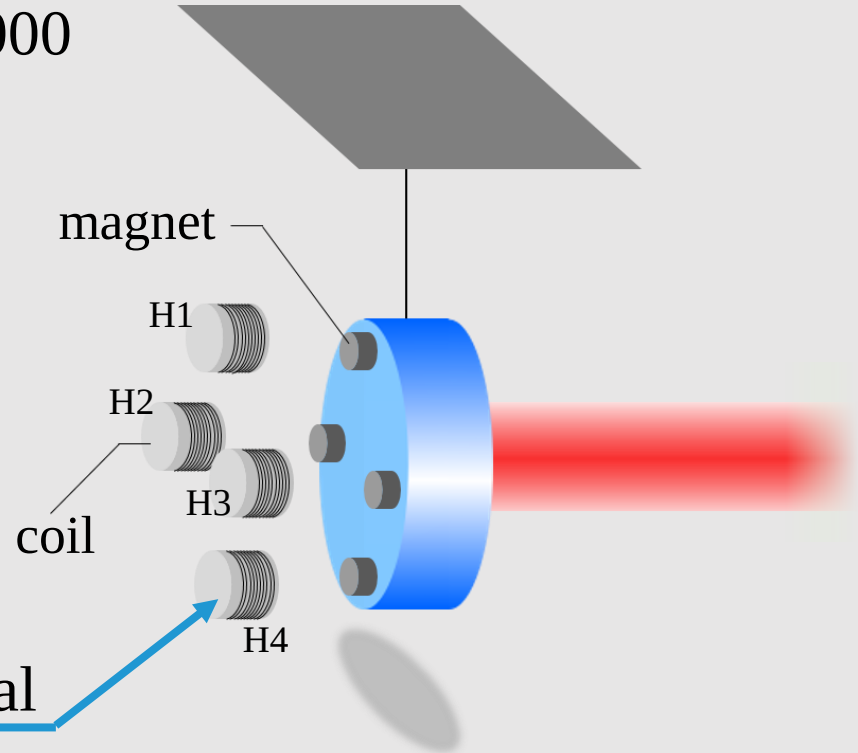
Approach from result side (1/4)

- Saturation
- Abnormal feedback signal
- Bad alignment
- Mirror vibration

Sometimes DAC saturation is detected before lock-loss



Saturation:
count ≧ 35000



Control signal (digital) → DAC → Control signal (analog)

Approach from result side (2/4)

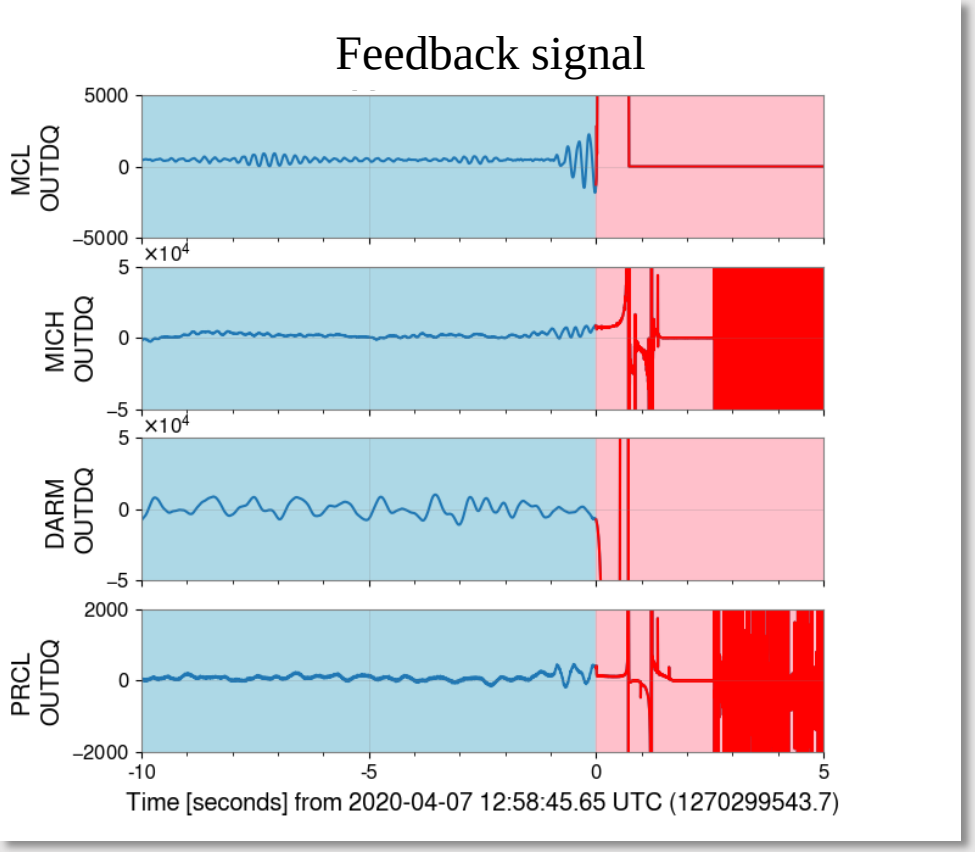
Saturation

Abnormal feedback signal

Bad alignment

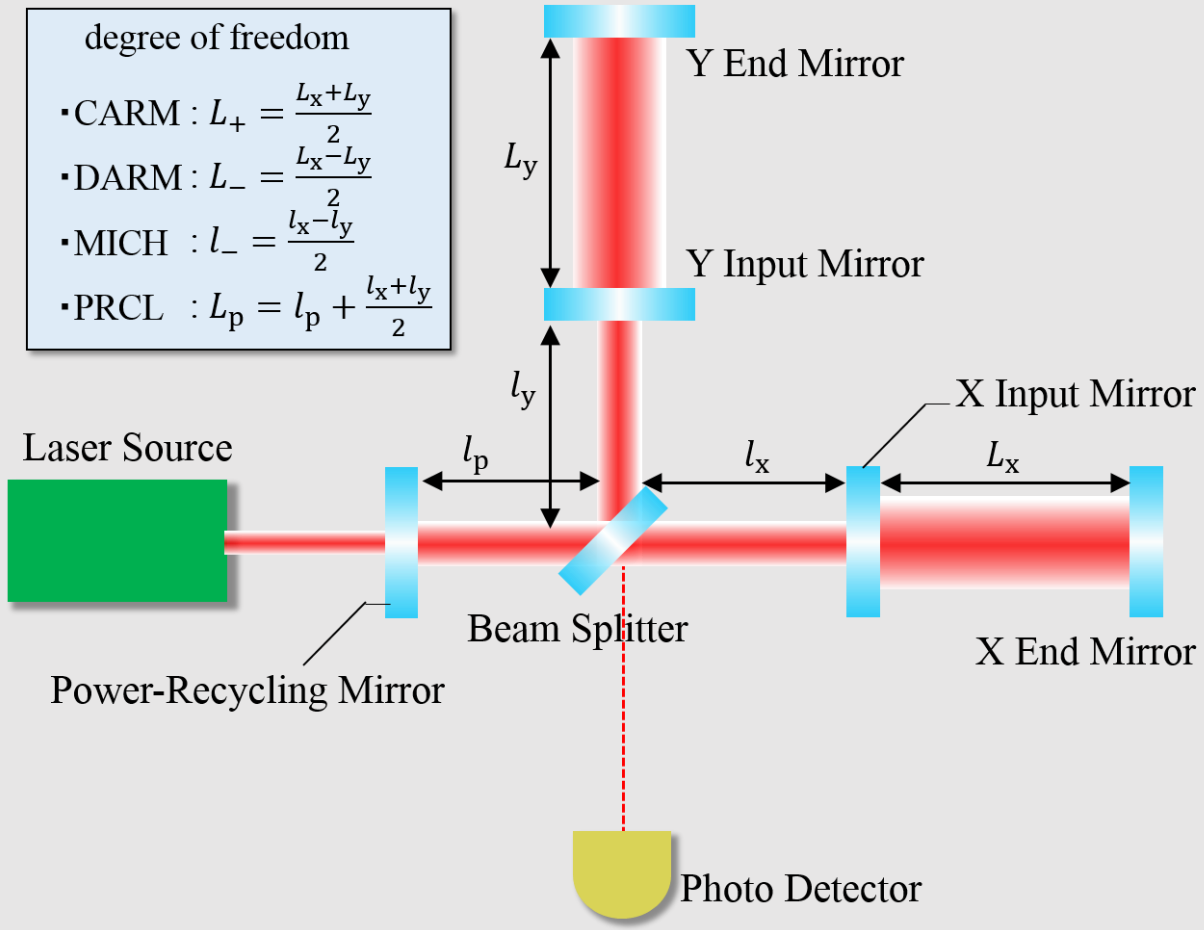
Mirror vibration

Find out which loop broke from error and feedback signal



degree of freedom

- CARM : $L_+ = \frac{L_x+L_y}{2}$
- DARM : $L_- = \frac{L_x-L_y}{2}$
- MICH : $l_- = \frac{l_x-l_y}{2}$
- PRCL : $L_p = l_p + \frac{l_x+l_y}{2}$



Approach from result side (3/4)

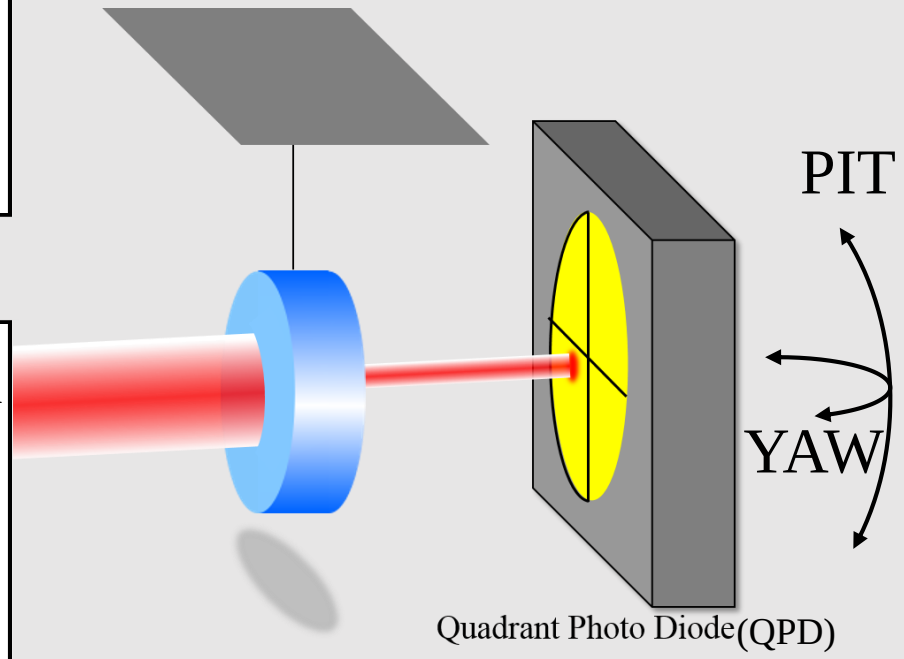
Saturation

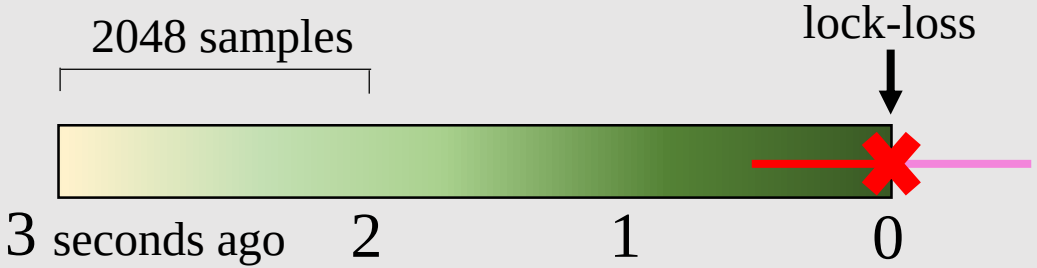
Abnormal feedback signal

Bad alignment

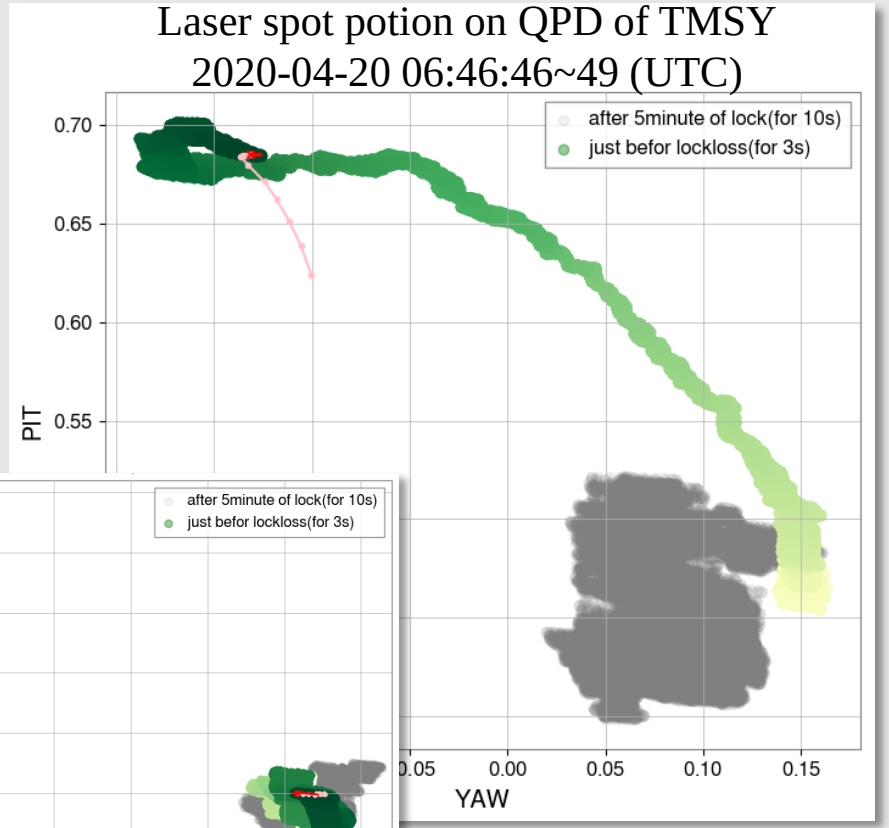
Mirror vibration

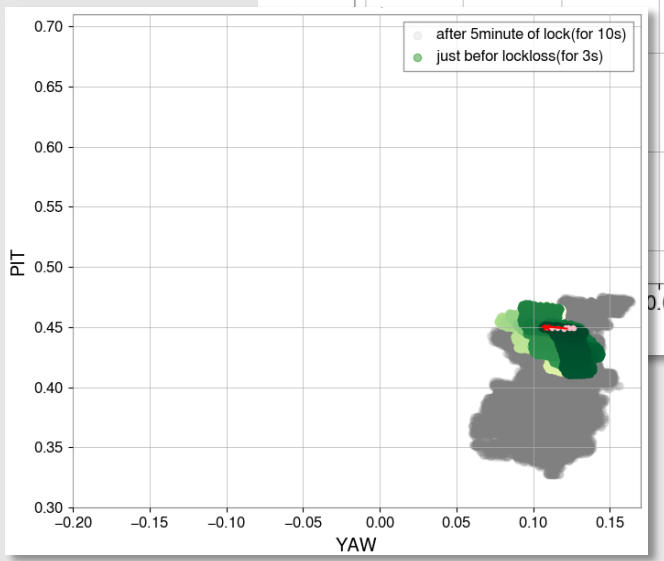
Check Alignment of mirrors using QPDs (Oplev, TMS, OMC,…)





Laser spot potion on QPD of TMSY
2020-04-20 06:46:46~49 (UTC)





←other time

Approach from result side (4/4)

Saturation

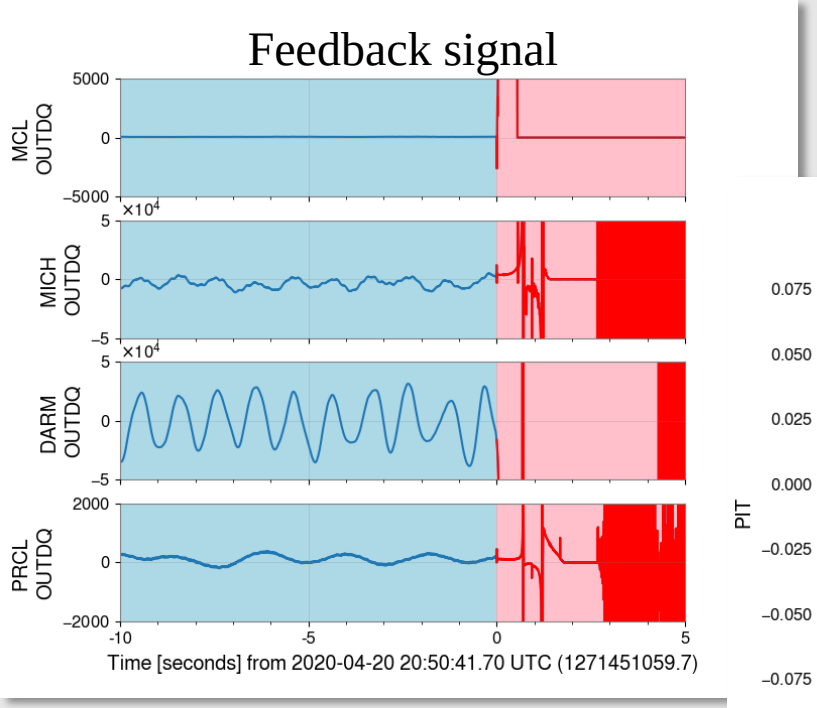
Abnormal feedback signal

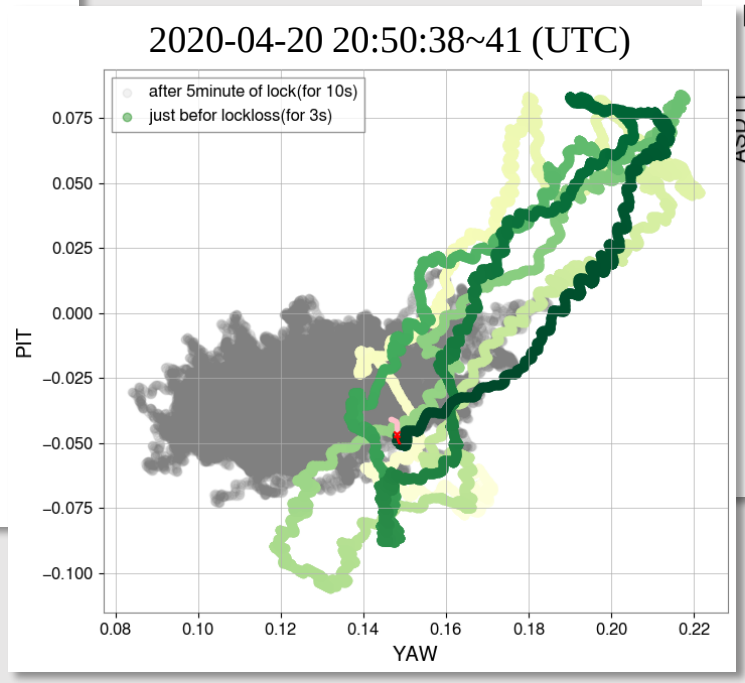
Bad alignment

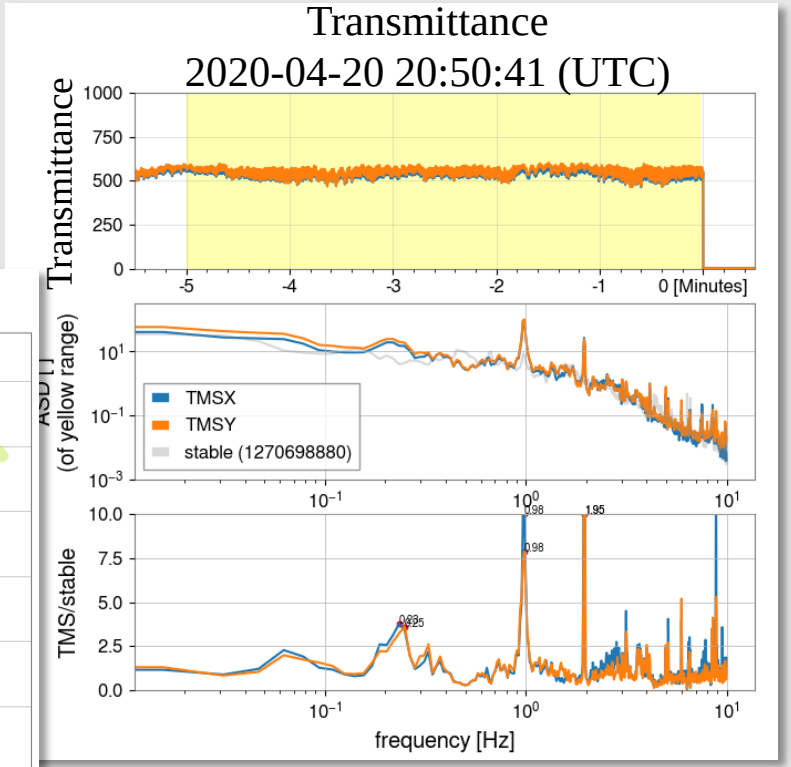
Mirror vibration

Sometimes <u>1 Hz oscillation</u> of mirror is seen before lock-loss

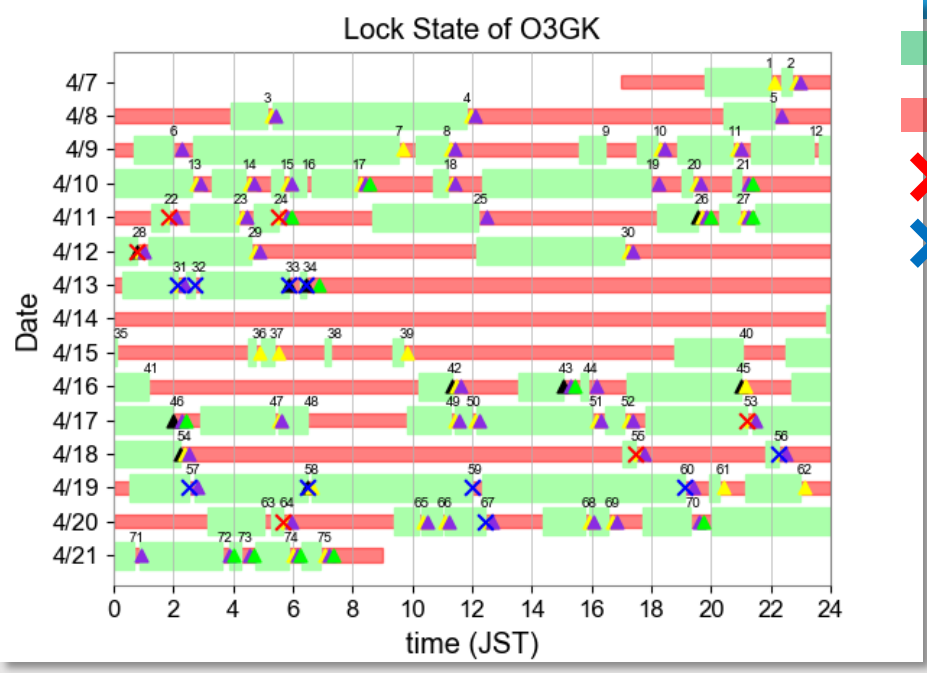
→by optical spring







Analysis result from result side



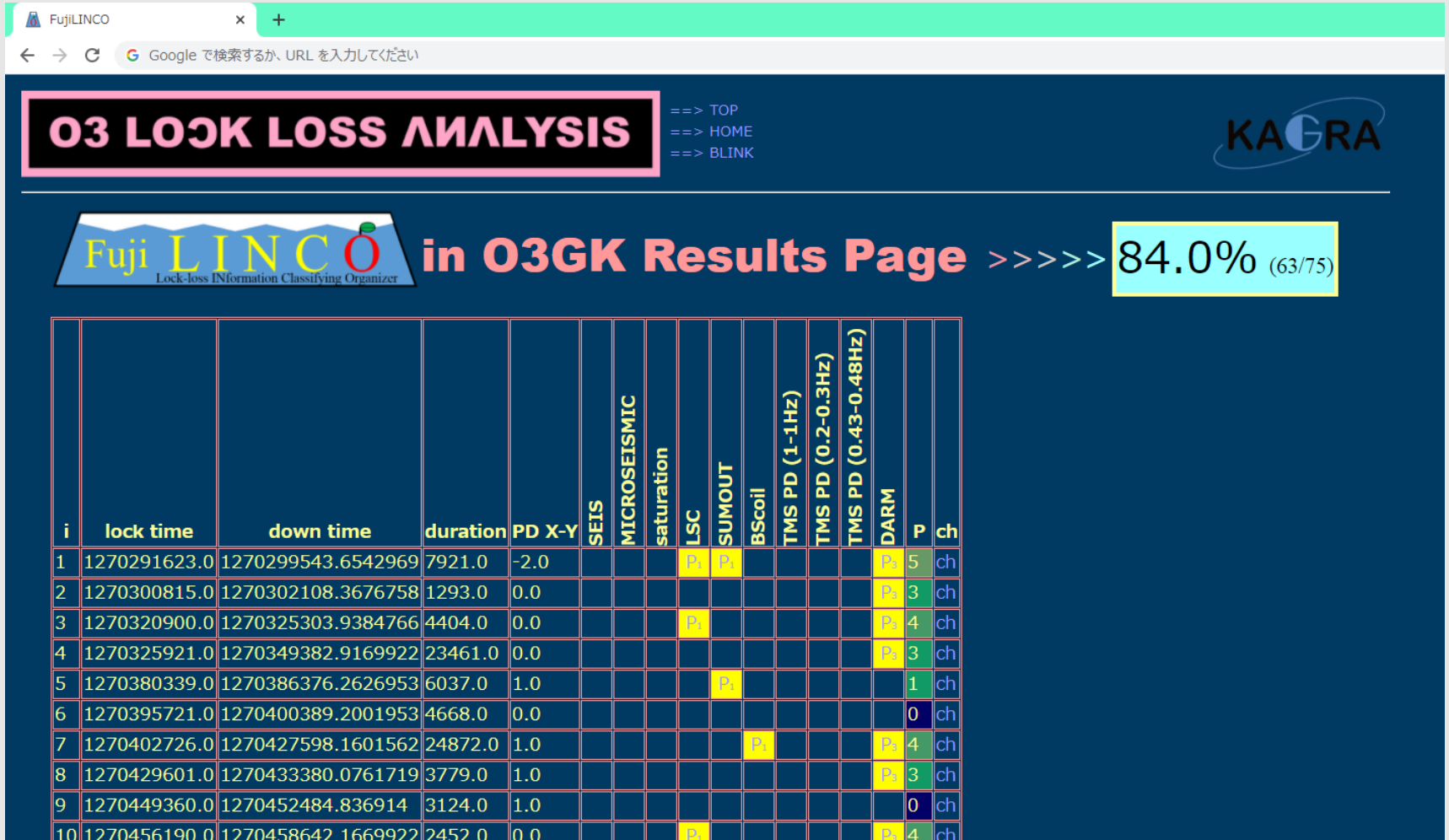
- Lock
- Lock-loss
- Lock-loss by abnormal ground vibration
- Lock-loss by large microseismic

- Saturation (10 times)
- Abnormal feedback signal (48times)
- Bad alignment (53 times)
- 1 Hz oscillation (13 times)

date (JST)	4/7	4/8	4/9	4/10	4/11	4/12	4/13	4/15	4/16	4/17	4/18	4/19	4/20	4/21
index	1 2	3 4 5	6 7 8 9 10 1 2	3 4 5 6 7 8 9 20 1	2 3 4 5 6 7	8 9 30	1 2 3 4	5 6 7 8 9 40	1 2 3 4 5	6 7 8 9 50 1 2 3	4 5 6	7 8 9 60 1 2	3 4 5 6 7 8 9 70	1 2 3 4 5
ground														
microseis														
saturation														
FBsignal														
alignment														
1Hz osci														

Lock-loss classifying system FujiLINCO$_{18}$

FujiLINCO can classifying lock-loss automatically



i	lock time	down time	duration	PD X-Y	SEIS	MICROSEISMIC	saturation	LSC	SUMOUT	BScoil	TMS PD (1-1Hz)	TMS PD (0.2-0.3Hz)	TMS PD (0.43-0.48Hz)	DARM	P	ch
1	1270291623.0	1270299543.6542969	7921.0	-2.0				P1	P1					P3	5	ch
2	1270300815.0	1270302108.3676758	1293.0	0.0										P3	3	ch
3	1270320900.0	1270325303.9384766	4404.0	0.0				P1						P3	4	ch
4	1270325921.0	1270349382.9169922	23461.0	0.0										P3	3	ch
5	1270380339.0	1270386376.2626953	6037.0	1.0					P1						1	ch
6	1270395721.0	1270400389.2001953	4668.0	0.0											0	ch
7	1270402726.0	1270427598.1601562	24872.0	1.0						P1				P3	4	ch
8	1270429601.0	1270433380.0761719	3779.0	1.0										P3	3	ch
9	1270449360.0	1270452484.836914	3124.0	1.0											0	ch
10	1270456190.0	1270458642.1669922	2452.0	0.0				P1						P3	4	ch

We can get result as HTML

Summary and Conclusion

Summary

*Lock-loss study is meaningful to detect GW
*Lock-loss in O3GK was analyzed by two methods
*Ground vibration was checked with threshold of seismometer
*Abnormal behavior was checked using various signals

Conclusion

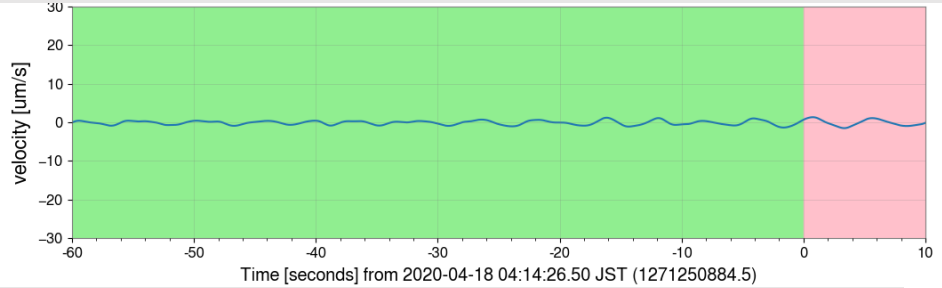
*Ground vibration could be judged accurately
*It is unknown to how much behaviors contribute to elucidation
*There are still many unclear point about lock-loss,
but this study could show analysis methods as the first step

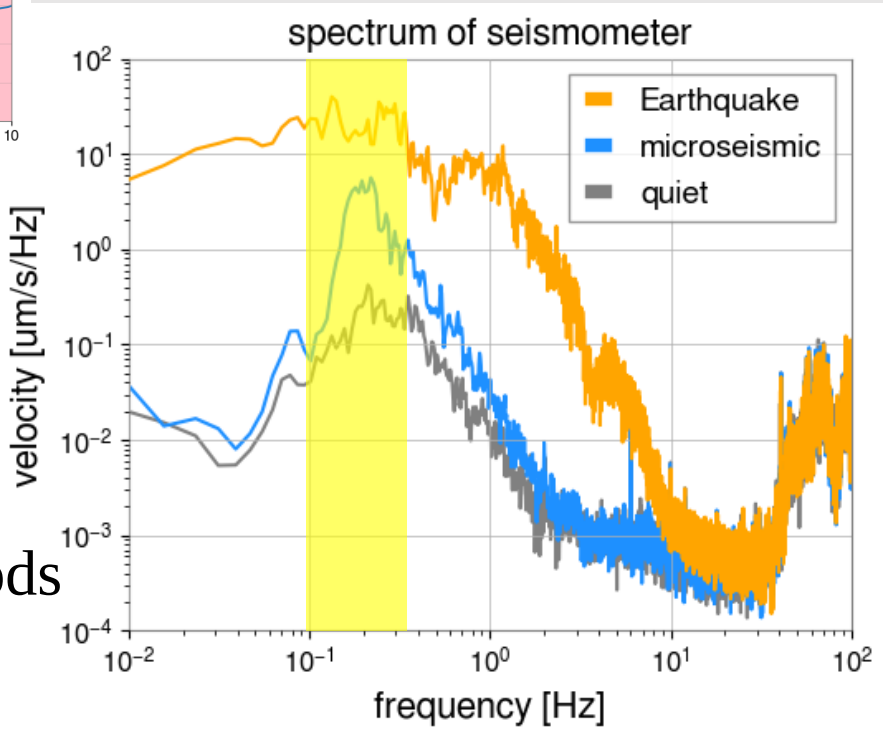
Backup

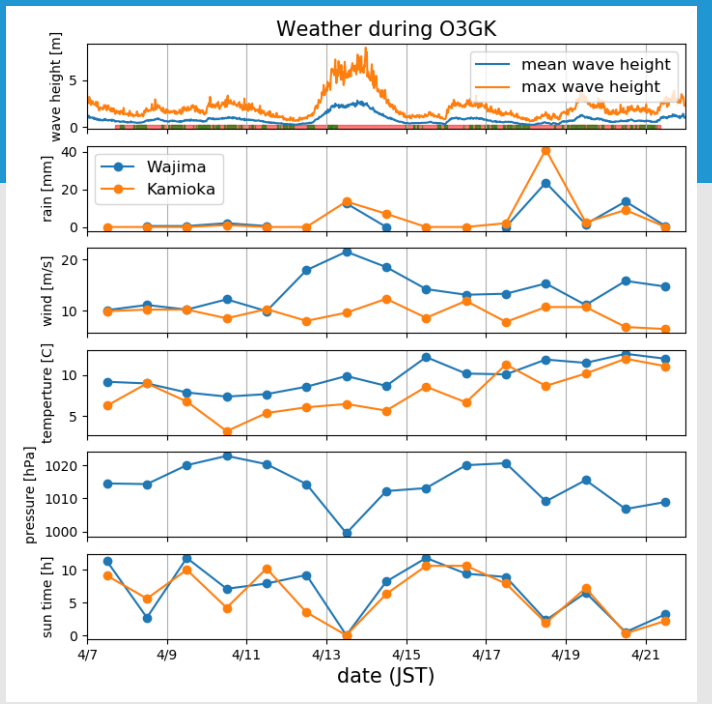
Detection of microseismic

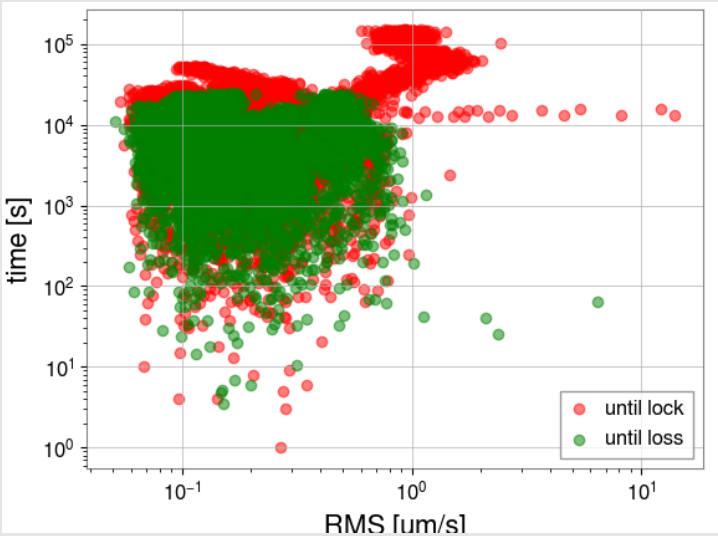
Amplitude is small and not sudden ==> detection is hard

But in fact, it has significant effect on lock









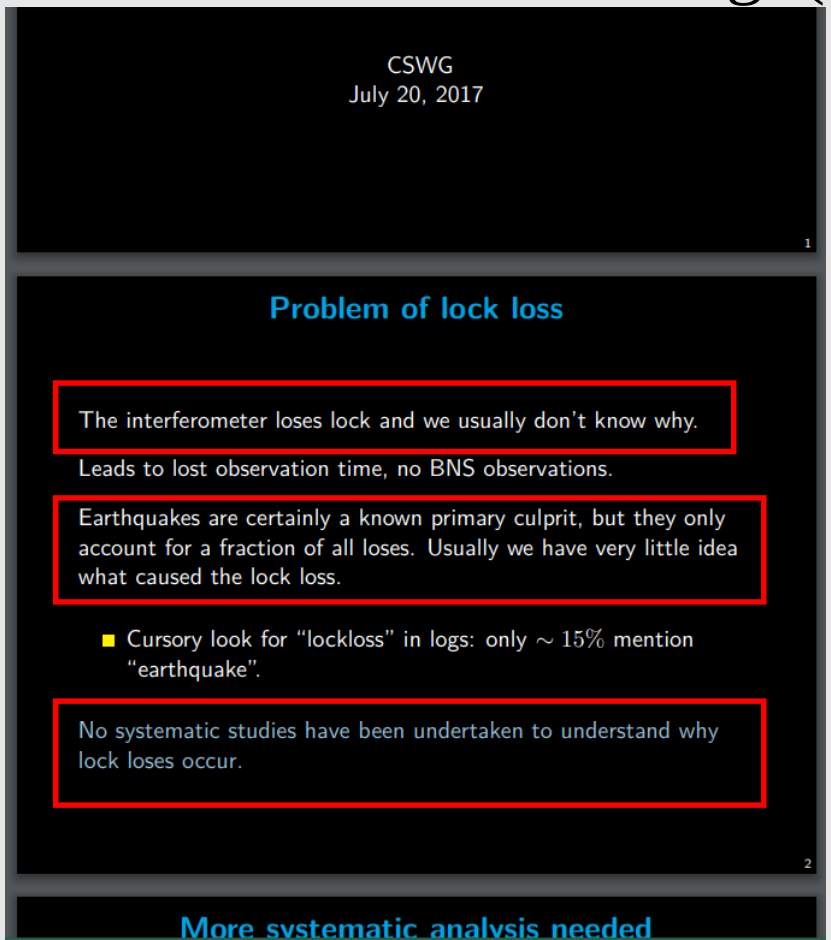
We tried to detect by various methods

But there is no good way yet

Lock-loss study

KAGRA : almost no one is systematically studying

LIGO : relies on machine learning (not possible with man power…?)



CSWG
July 20, 2017

1

Problem of lock loss

The interferometer loses lock and we usually don't know why.

Leads to lost observation time, no BNS observations.

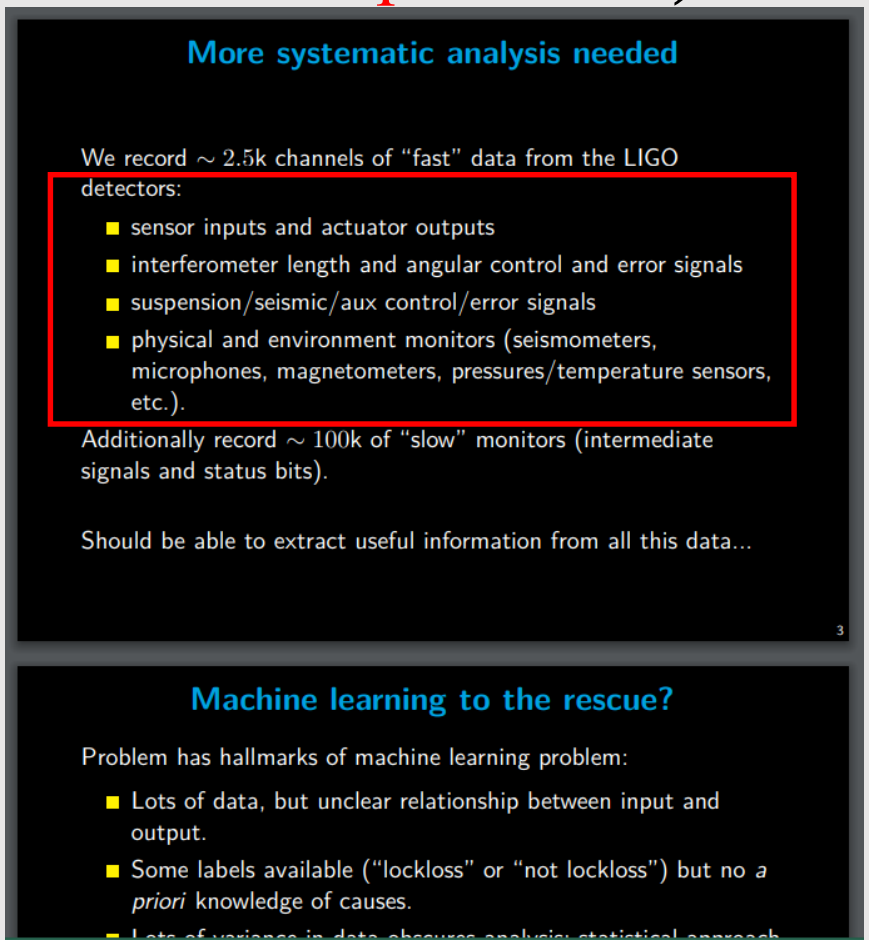
Earthquakes are certainly a known primary culprit, but they only account for a fraction of all loses. Usually we have very little idea what caused the lock loss.

- Cursory look for "lockloss" in logs: only $\sim 15\%$ mention "earthquake".

No systematic studies have been undertaken to understand why lock loses occur.

2

More systematic analysis needed



More systematic analysis needed

We record ~ 2.5k channels of "fast" data from the LIGO detectors:

- sensor inputs and actuator outputs
- interferometer length and angular control and error signals
- suspension/seismic/aux control/error signals
- physical and environment monitors (seismometers, microphones, magnetometers, pressures/temperature sensors, etc.).

Additionally record ~ 100k of "slow" monitors (intermediate signals and status bits).

Should be able to extract useful information from all this data...

3

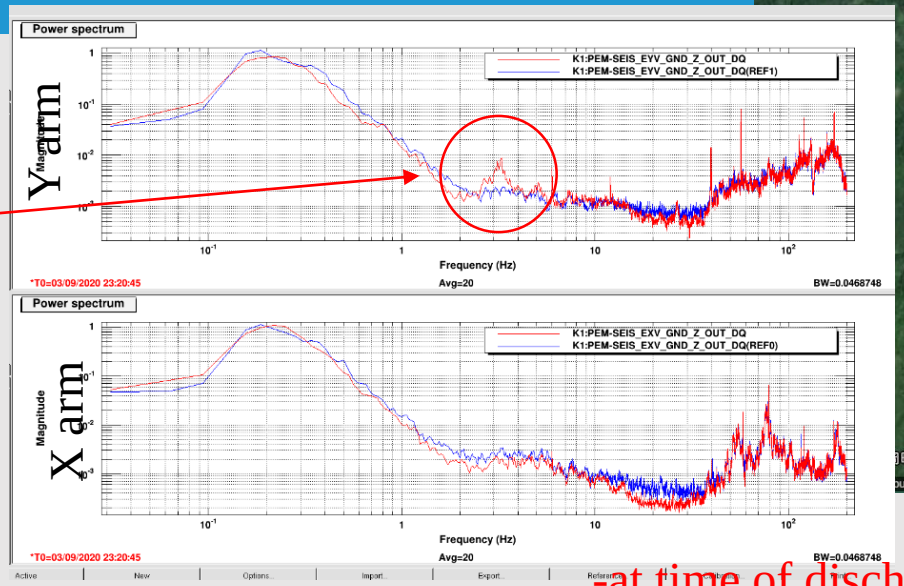
Machine learning to the rescue?

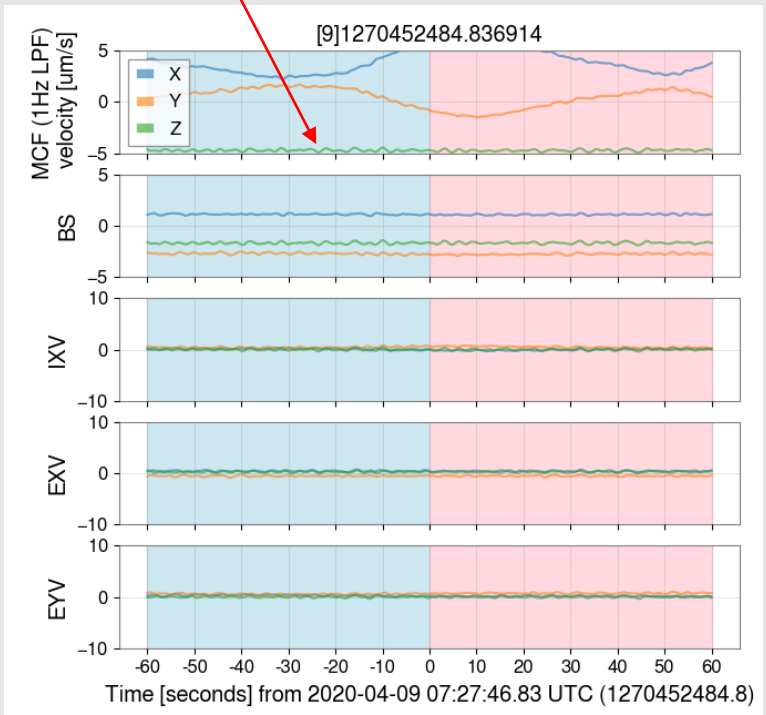
Problem has hallmarks of machine learning problem:

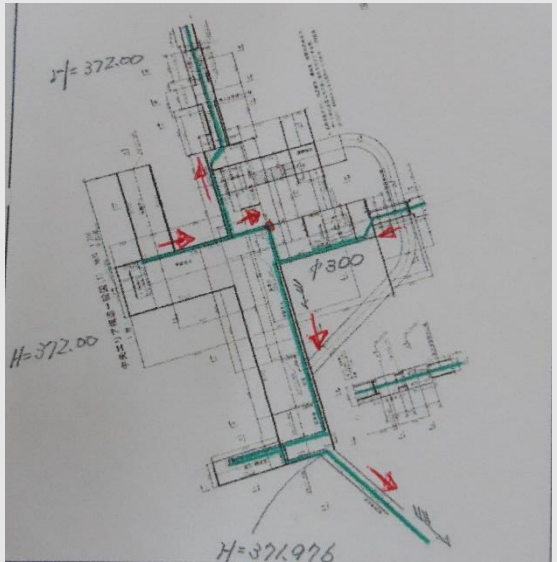
- Lots of data, but unclear relationship between input and output.
- Some labels available ("lockloss" or "not lockloss") but no *a priori* knowledge of causes.

Ground vibration

*earthquake
- microseismic
- discharge of dam
- pump of underground water



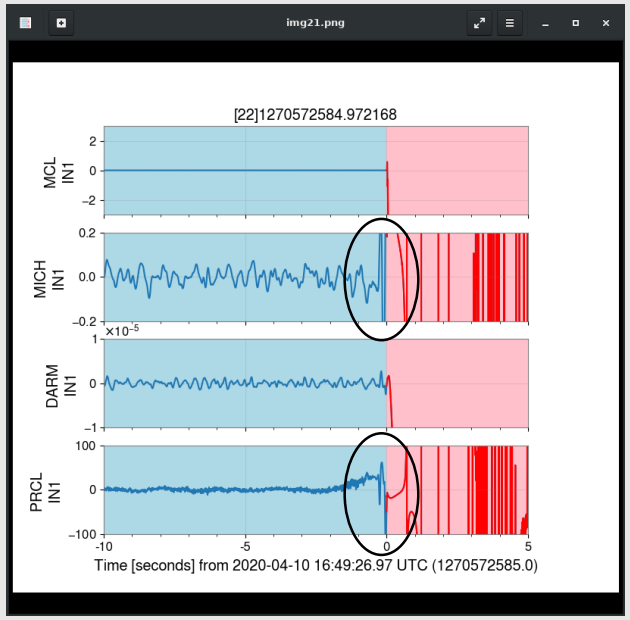


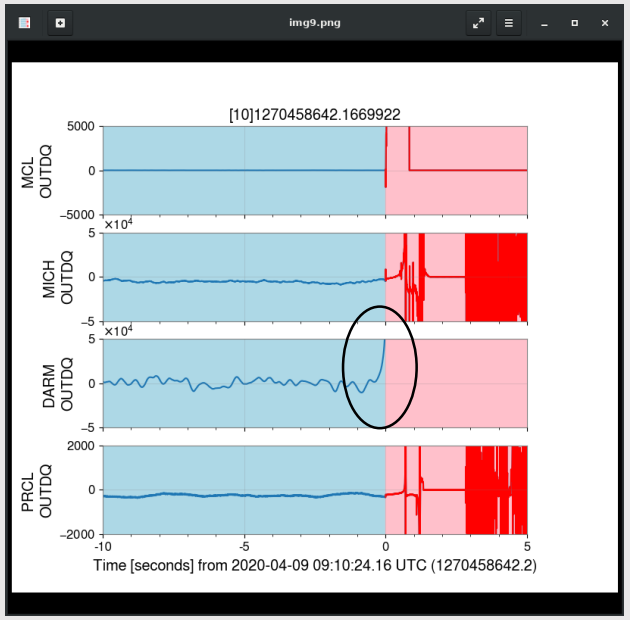


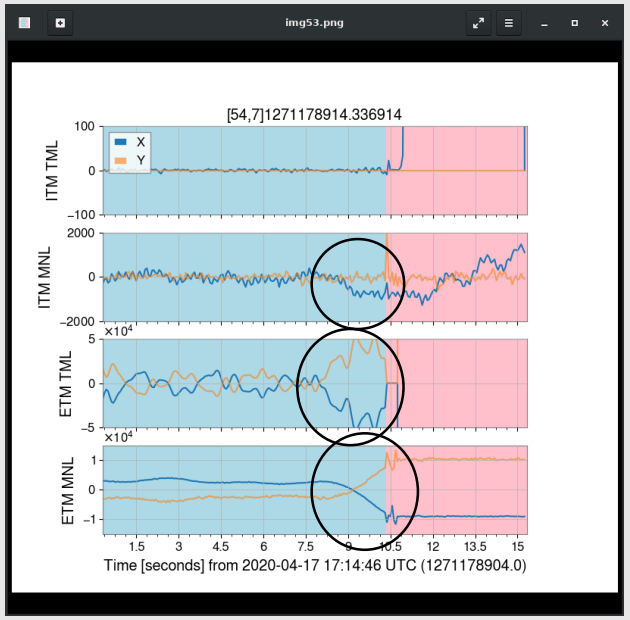
-at time of discharge
-the day before

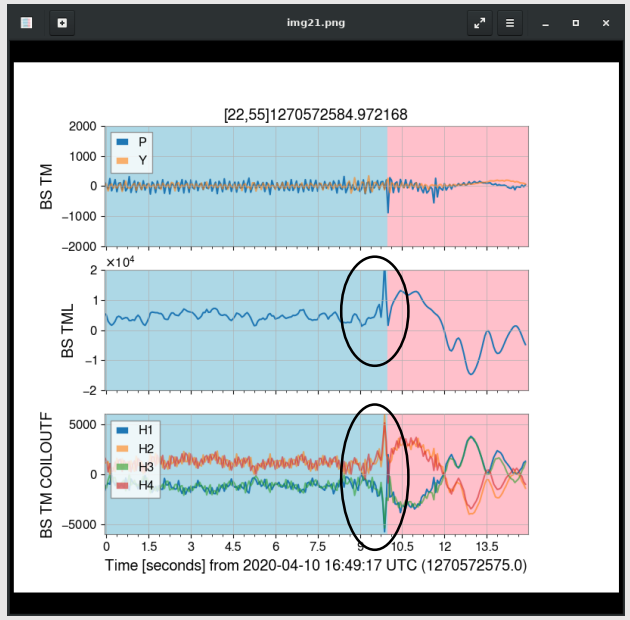
Abnormal behavior of signal

One way to detection abnormal behavior









$$\frac{\text{(Maximum rms for 4 seconds just before lock-loss) – (mean)}}{\text{(Maximum rms for 100 s of 150 s before lock-loss) – (mean)}} \geqq 2 \quad \Longrightarrow \text{abnormal}$$

ロックロス分類システムFujiLINCO

ロックロスを自動で分析してくれる

GPS時刻を指定（指定された時刻から遡って最も近いロックロスを扱う）

```
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$ gpstime
JST: 2020-10-27 10:17:30.211544 JST
UTC: 2020-10-27 01:17:30.211544 UTC
GPS: 1287796668.211544
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$ python FujiLINCO.py 1287796668.211544
```

または日時を指定（UTC）

```
[yuta.fujikawa@m31-01 ~]$ gpstime
JST: 2020-10-27 10:17:30.211544 JST
UTC: 2020-10-27 01:17:30.211544 UTC
GPS: 1287796668.211544
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$ python FujiLINCO.py 2020-10-27_01:17:30.211544
```

または「now」で最新のロックロス

```
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$ python FujiLINCO.py now
```

オプションで期間を指定することもできる

>FujiLINCO.py *t1* -from *t2* : t2からt1まで
>FujiLINCO.py *t1* -to *t2* : t1からt2まで
>FujiLINCO.py *t1* -before *t2* : t1までt2秒間
>FujiLINCO.py *t1* -after *t2* : t1からt2秒間

今回はO3GKのロックロスを扱うため O3GK期間のロックロスを指定する

```
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$
[yuta.fujikawa@m31-01 ~]$ python FujiLINCO.py O3GK
```