Newtonian noise from underground water in KAGRA

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TOBA + GGN workshop

Science Tokyo

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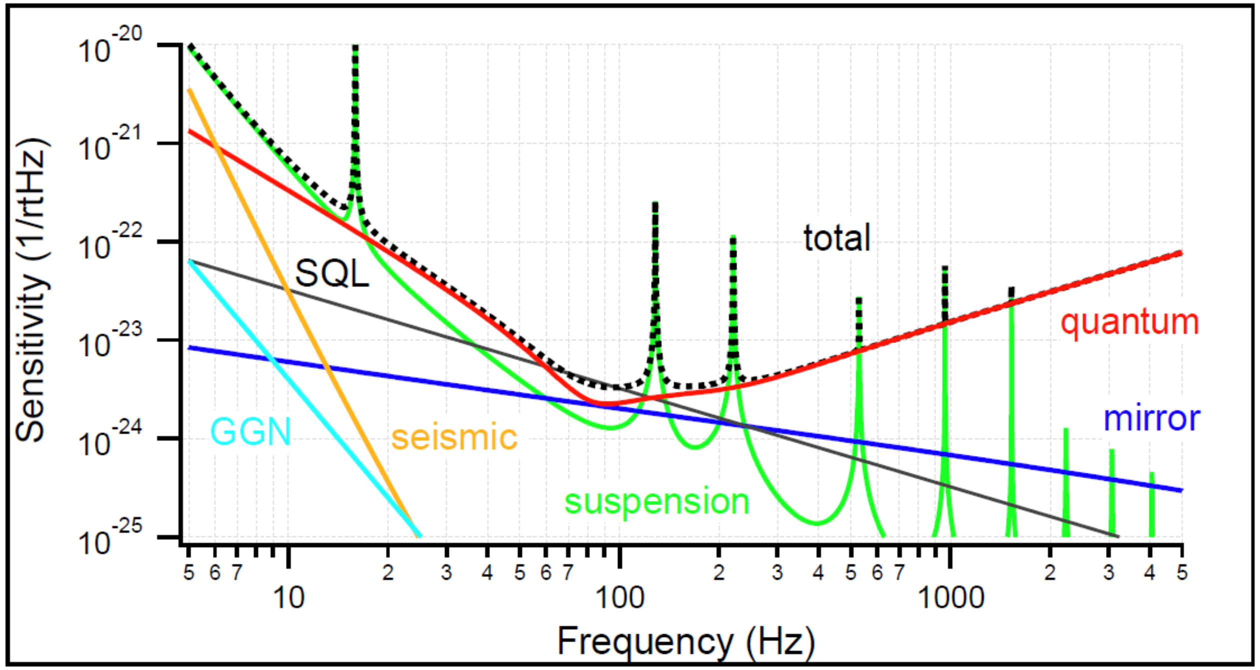
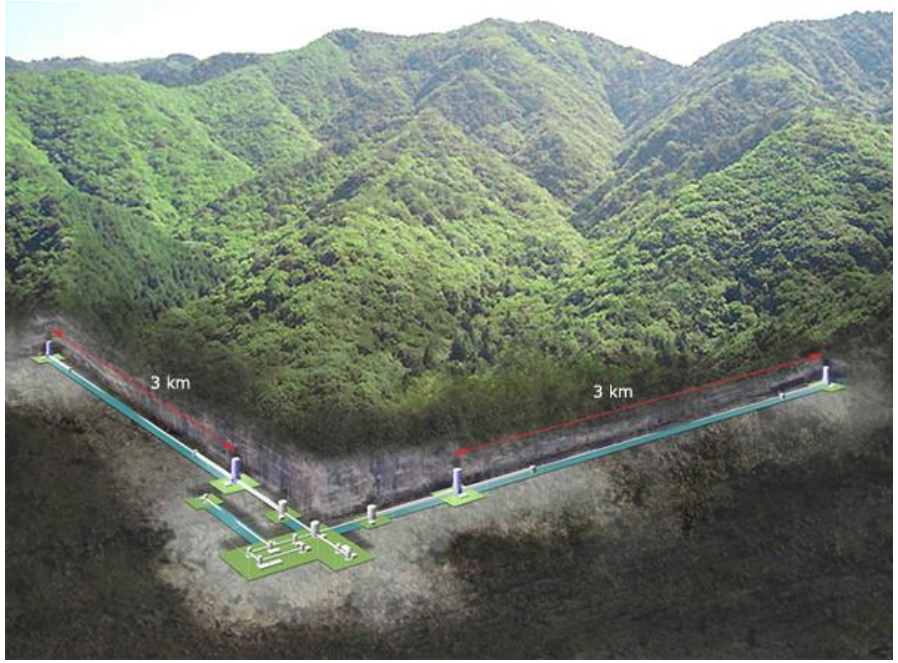
Gravity gradient noise in KAGRA

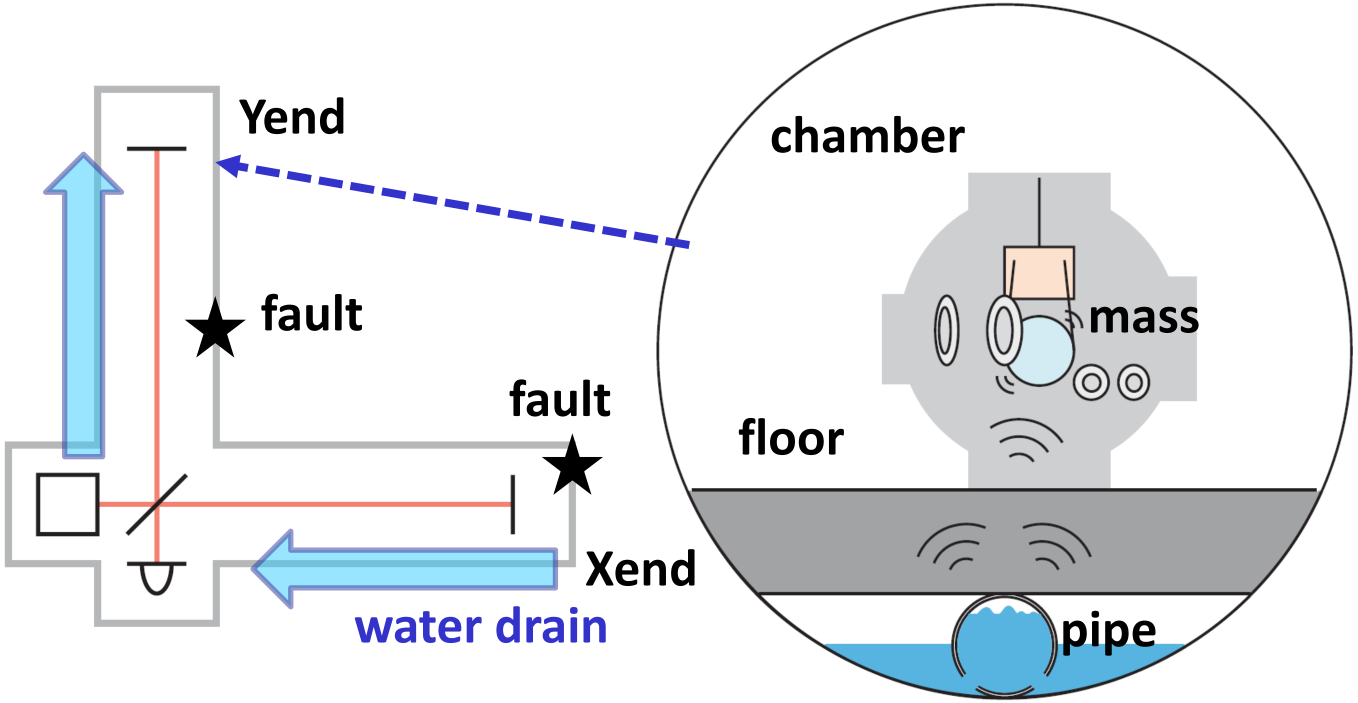


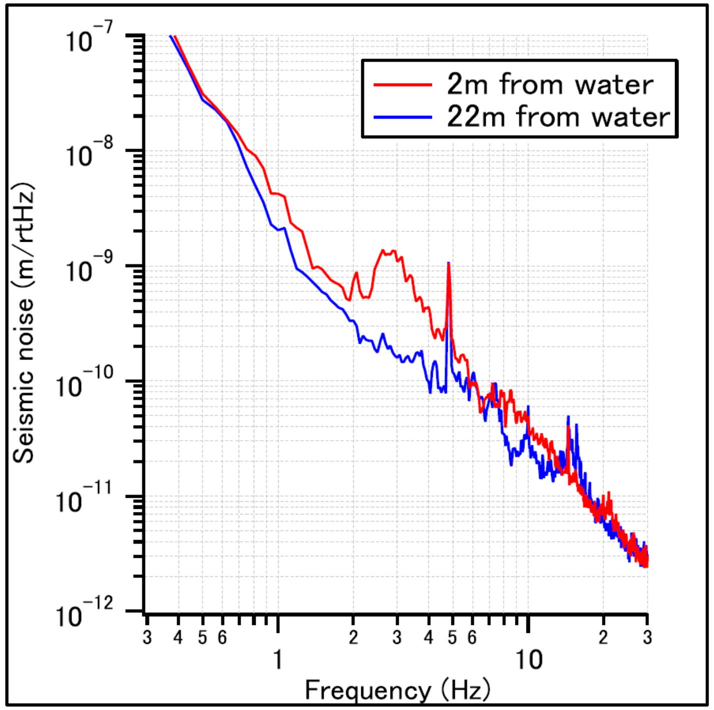


- According to the model, GGN is small in KAGRA for its low seismic motion and its distance from the ground surface
- However, there is a lot of water flowing behind the rock, which may or may not cause excess fluctuation of the gravity gradient

Can we estimate GGN from the spring water?

Gravity gradient noise from water

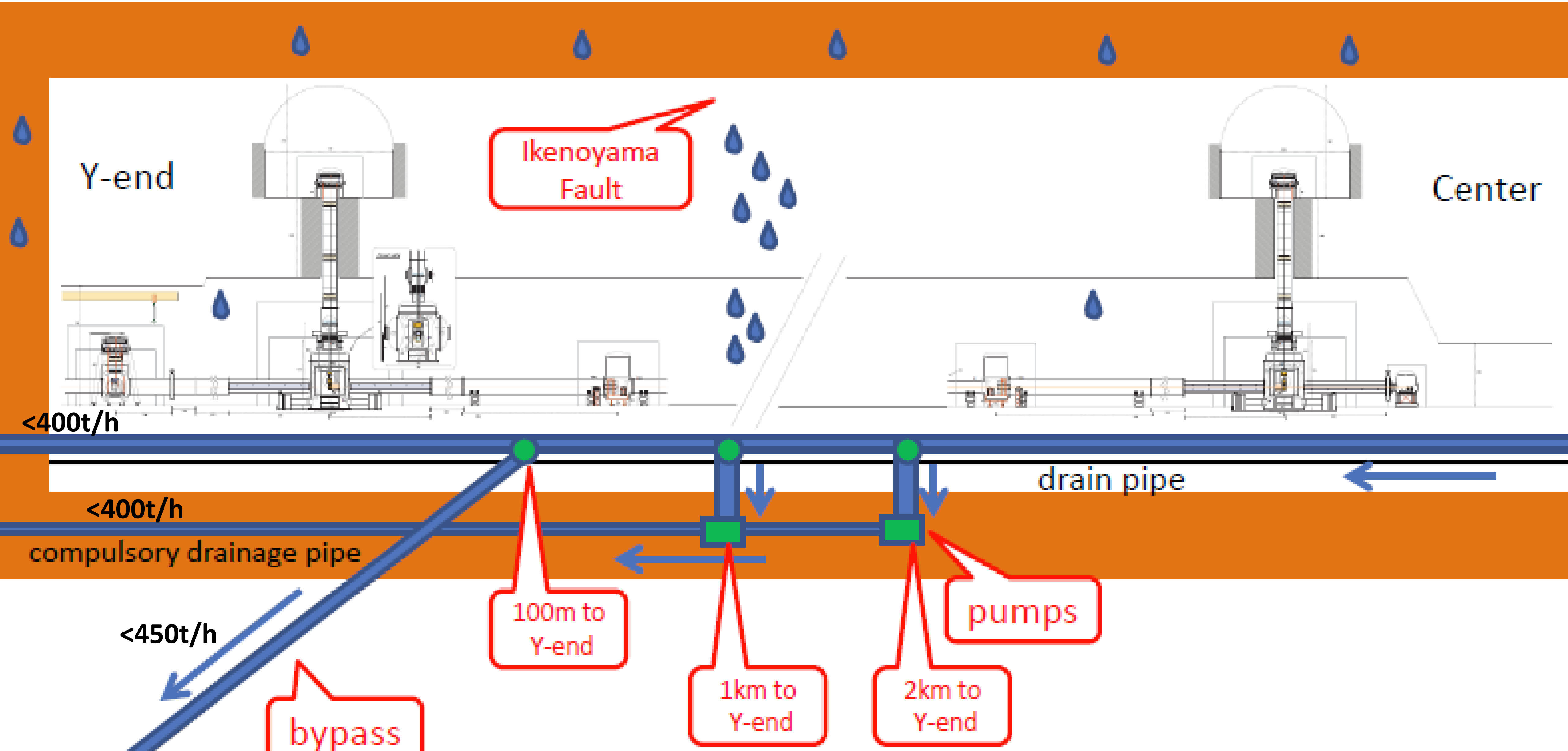




- The tunnel is made tilted by 1/300 to drain water (X->Center->Y)
- Main drainage pipe is located under the floor
- The largest water flow at the Yend

We built a bypass system and compulsory drainage pipes to decrease the amount of water underneath the Yend.

Water drainage system in KAGRA

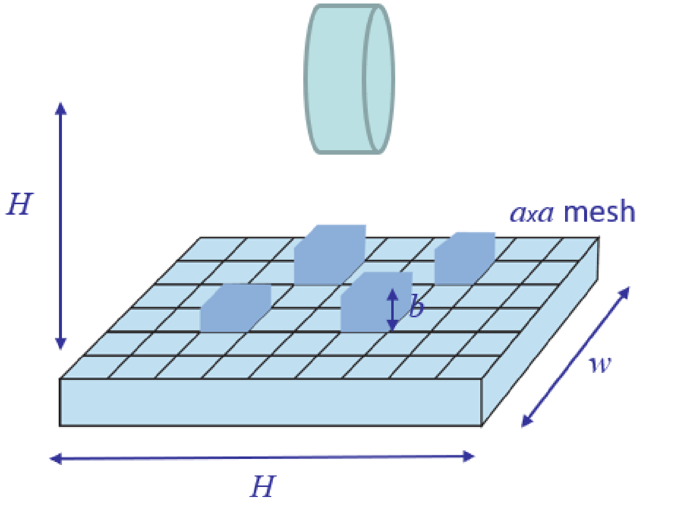


Water drainage system in KAGRA

left: 2km to Y-end
middle: after the bypass
right top: water flow meter
at the Y-end
right bottom: Y-end station
(photos taken in 2015)

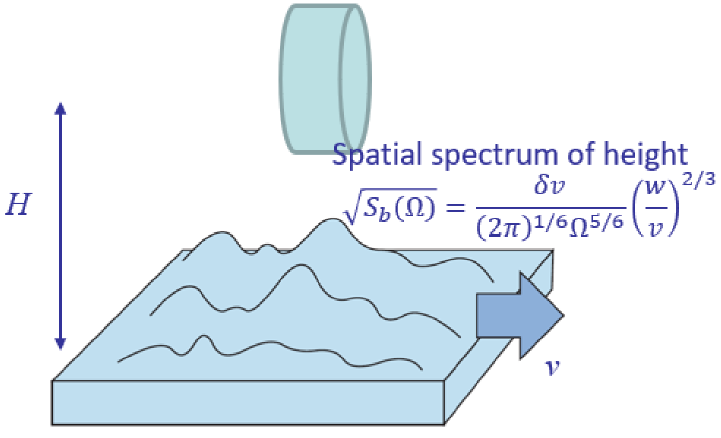
Water drainage system in KAGRA

[Y.Chen] [A.Nishizawa]



Model 1: uncorrelated height fluctuation

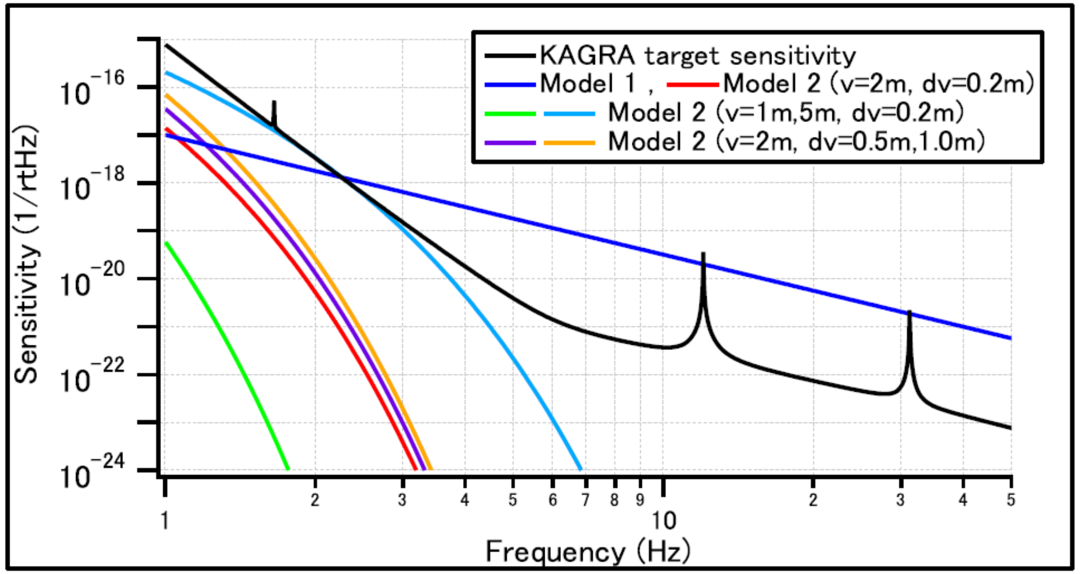
$$\sqrt{S_x(f)} = \frac{G\rho ab\sqrt{2\pi w}}{\Omega^{2.5}H^{1.5}}$$



Model 2: static pattern flowing at a constant velocity

$$\sqrt{S_x(f)} = \frac{4G\rho w}{\Omega v}\sqrt{S_b(\Omega)}K_0\left(\frac{H\Omega}{v}\right)$$

Modified Bessel function

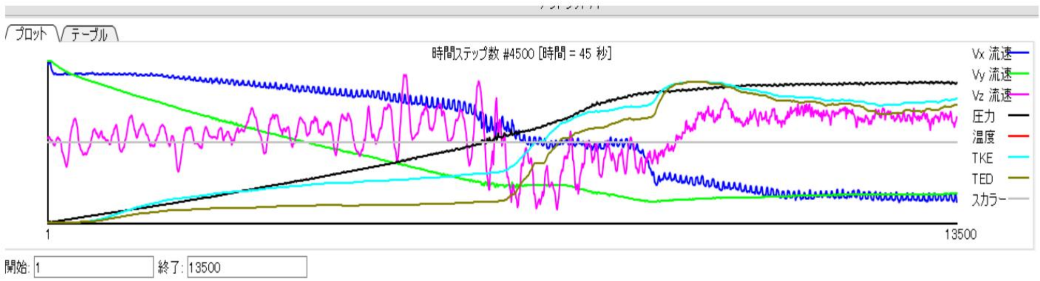


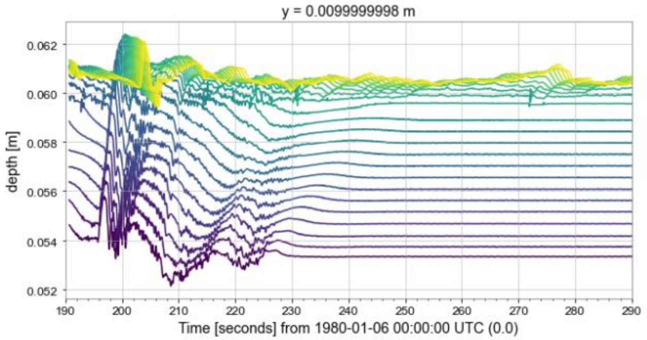
Model 1 is probably highly overestimate the noise level. An actual noise level would be somewhere in-between.

→ We need a numerical simulation of the water flow.

Water flow simulation history

- 2018, Inoue's study using Autodesk CFD
- 2019, Yuting's study using Flow3D
- 2020-22, Suzuki's study using Flow3D
  - implementation of KAGRA-like pipe setup
  - trustiness was questioned at thesis defense
- 2024, Yoshitome's study using Flow3D
  - several tests with different parameters



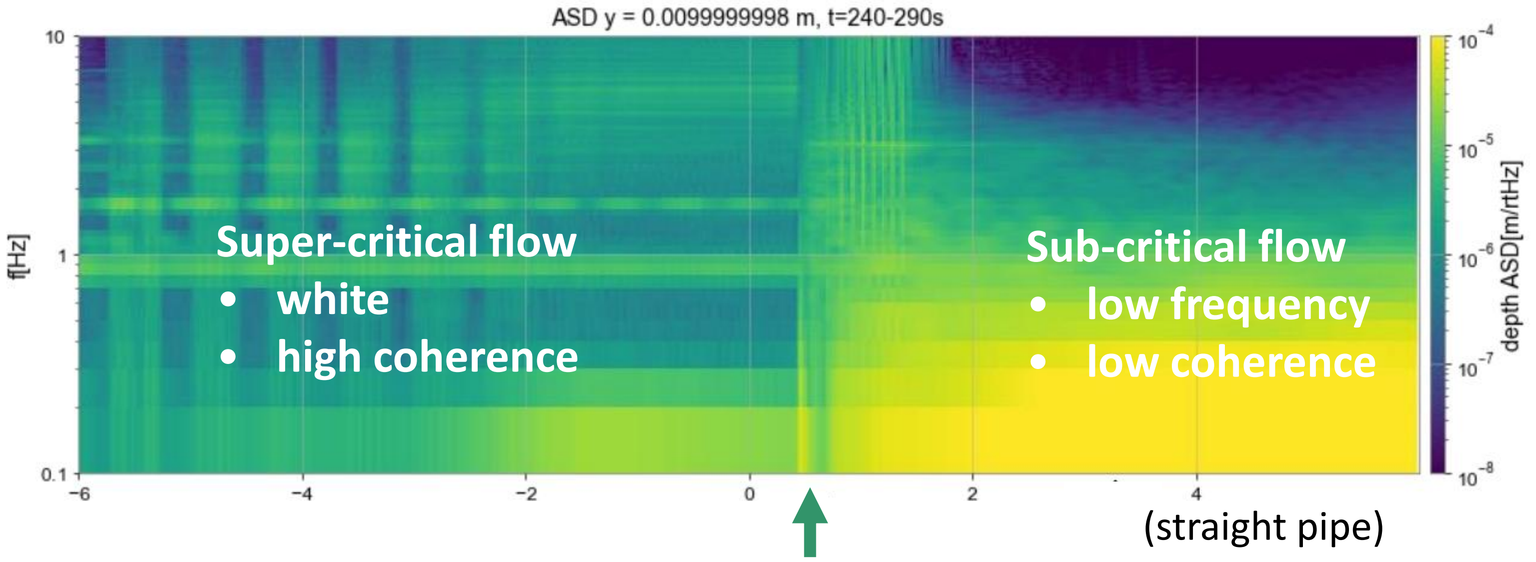


Suzuki’s work

Super-critical flow $v_{wave} < v_{flow}$

Hydraulic jump $v_{wave} = v_{flow}$

Sub-critical flow $v_{wave} > v_{flow}$



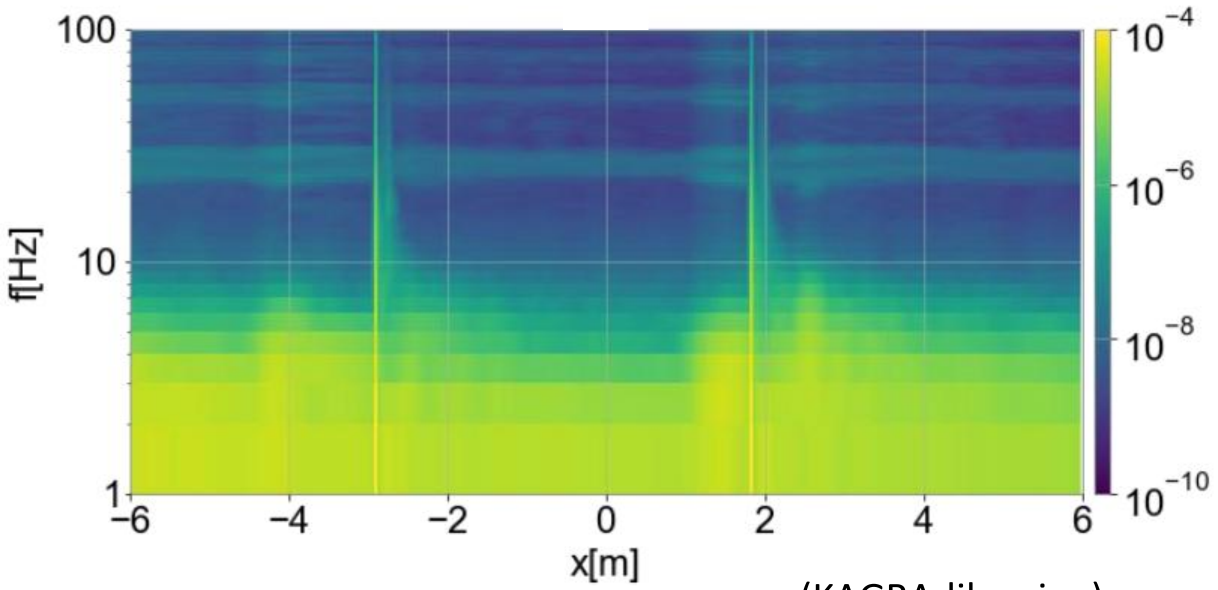
We thought we successfully reproduced well-known phenomena, but it turned out that a *free-slip condition* was chosen.

Suzuki's work

	Knudsen number	type of flow	relative speed at boundary
free-slip condition	$Kn > 1$	free-molecular	non zero
no-slip condition	$Kn < 1$	continuum	zero

$$Kn = \frac{\lambda}{L} = \frac{k_B T}{\sqrt{2}\pi\sigma^2 PL}$$

λ: mean free path, L: pipe diameter
σ: molecular diameter, P: pressure

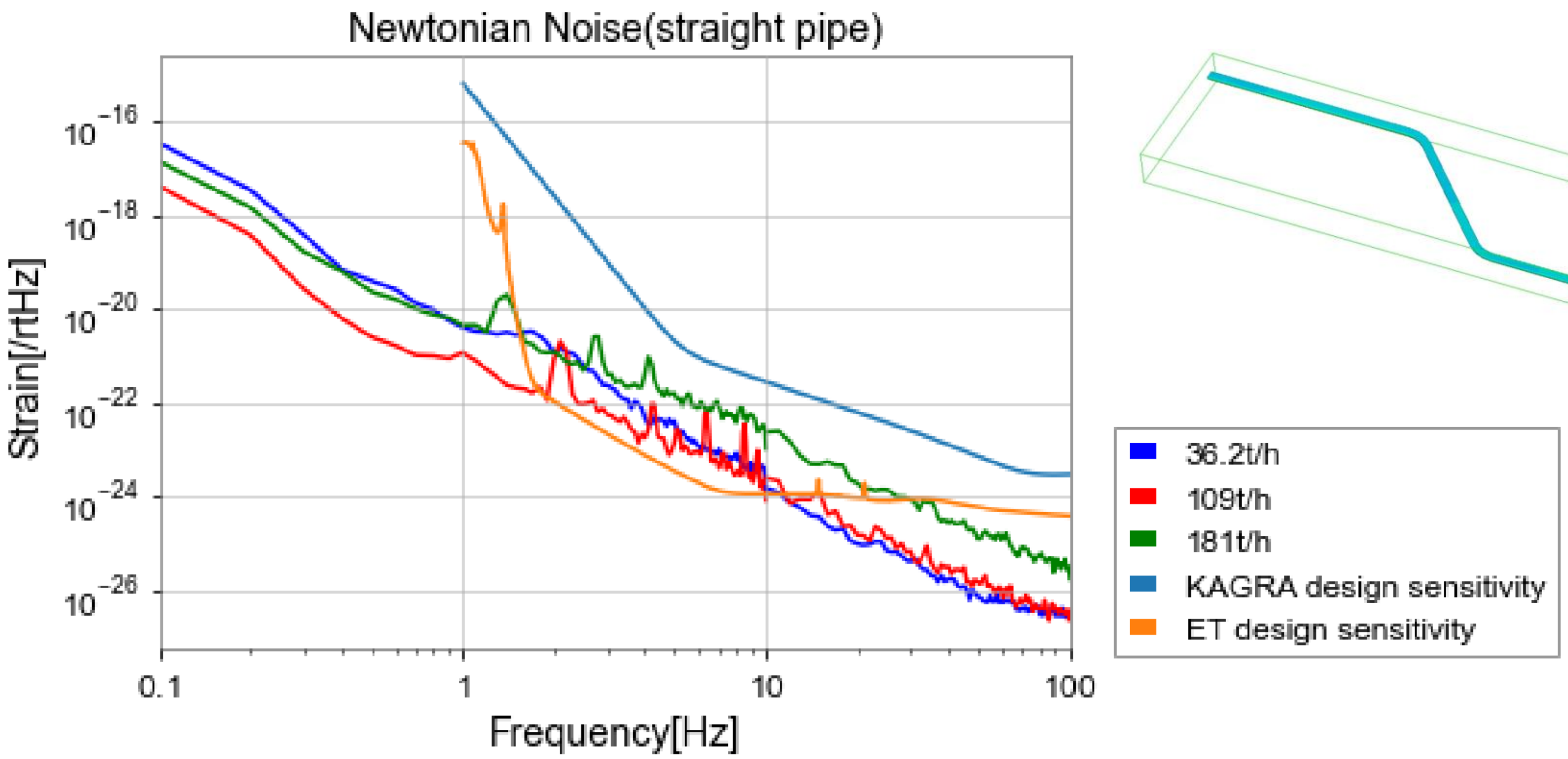


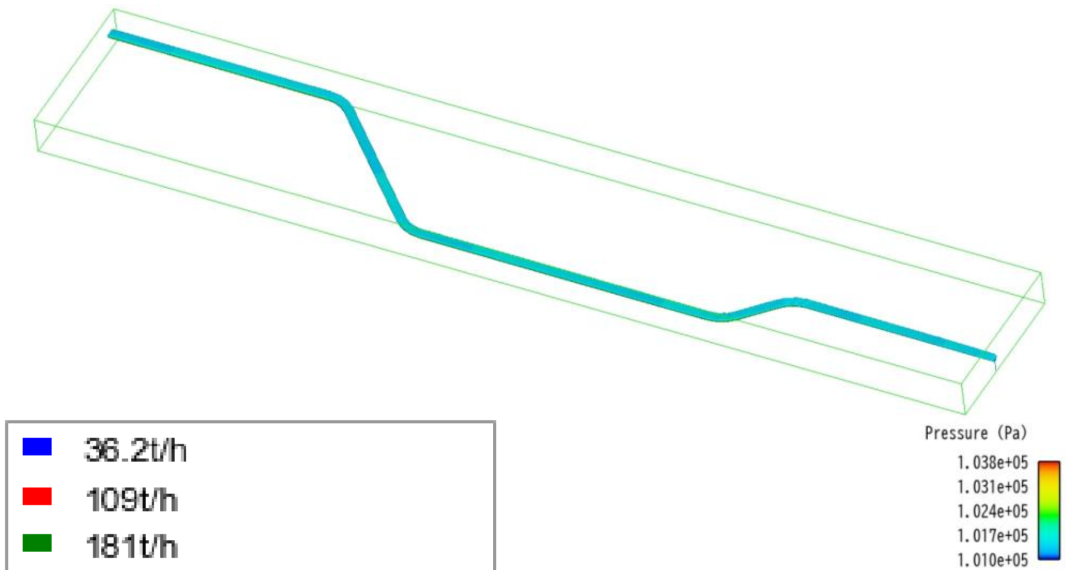
(KAGRA-like pipe)

The default setup was with the free-slip condition, but a proper choice turned out to be no-slip.

With a fixed setup, the flow in KAGRA is mostly subcritical, but we found hydraulic-jump-like glitches.

Suzuki's work





Suzuki-kun ran simulations with the KAGRA-like bend pipes and calculated Newtonian noise. The NN noise spectra were below the target sensitivity.

Yoshitome's work

Remaining concerns of Suzuki's work were:

(i) It is a bit hard to convince people that the simulation is correct.
(ii) Noise level increases with the mesh size and did not converge.
(iii) Only a limited number of simulations were performed.

I then asked Yoshitome-kun to

(i) double-check if the no-slip condition is correct
(ii) reproduce sub-/super-critical flows and a hydraulic jump to increase the convincing level
(iii) try to increase the mesh size.

Yoshitome's work

Calculation of Knudsen number:

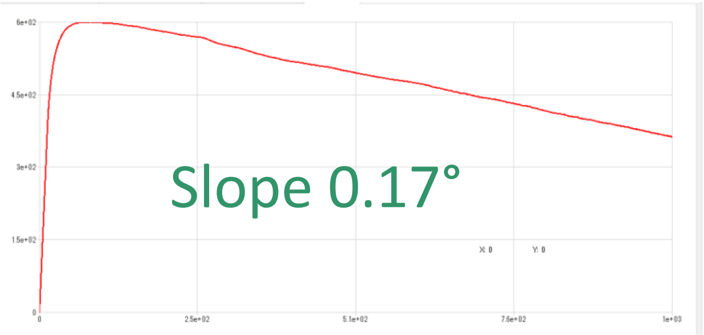
$$Kn = \frac{k_\mathrm{B} T}{\sqrt{2}\pi\sigma^2 PL} = [0.158\sim1.58] \times 10^{-5} \ll 1$$

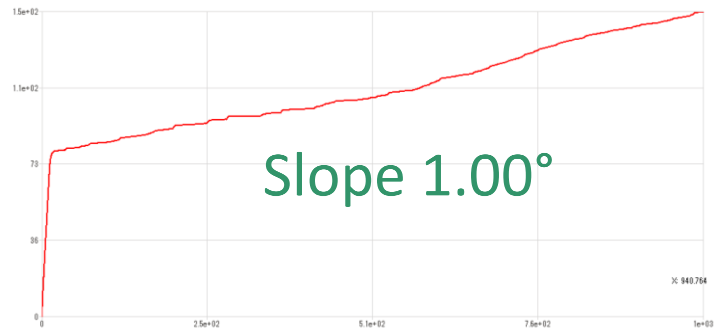
→ No-slip condition is good.

L : KAGRA pipe diameter → 0.4m
T : temperature → 293K
k_B : Boltzmann constant → 1.38×10^{-28} J/K
P : pressure → $0.01\sim0.1$Pa
σ : Water molecule diameter → 3.8×10^{-10} m

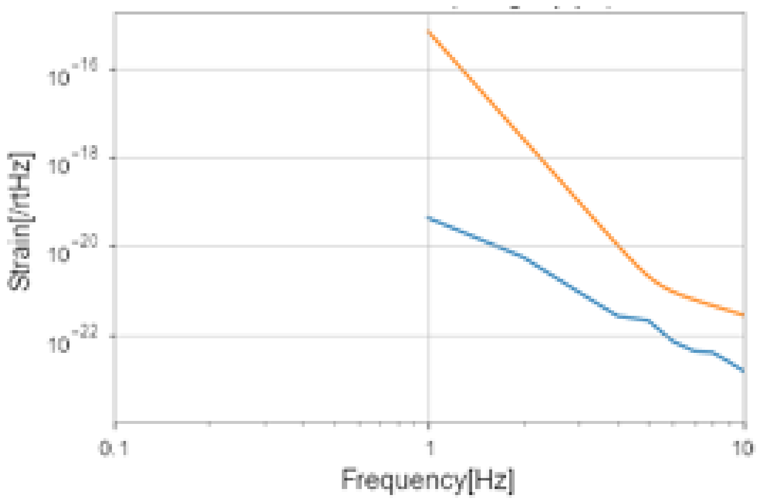
Yoshitome's work

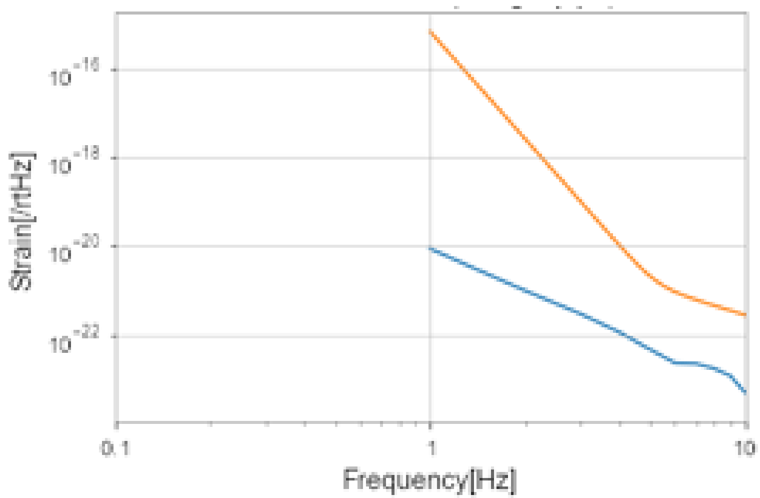
(straight pipe)

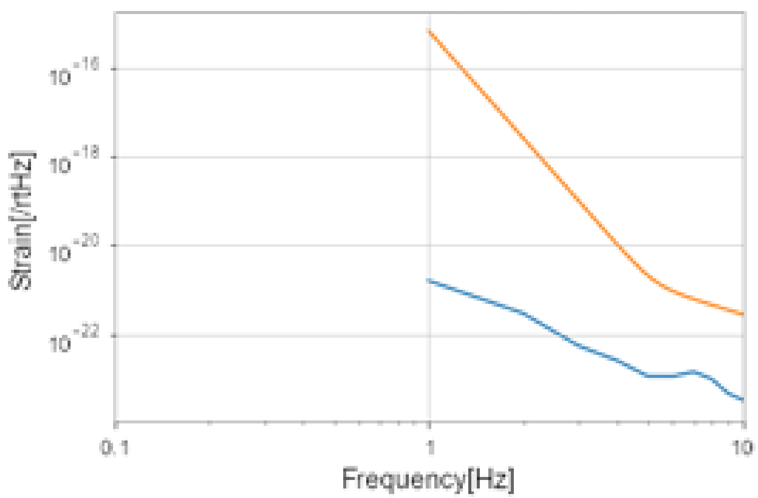




start 1000s start 1000s start 1000s

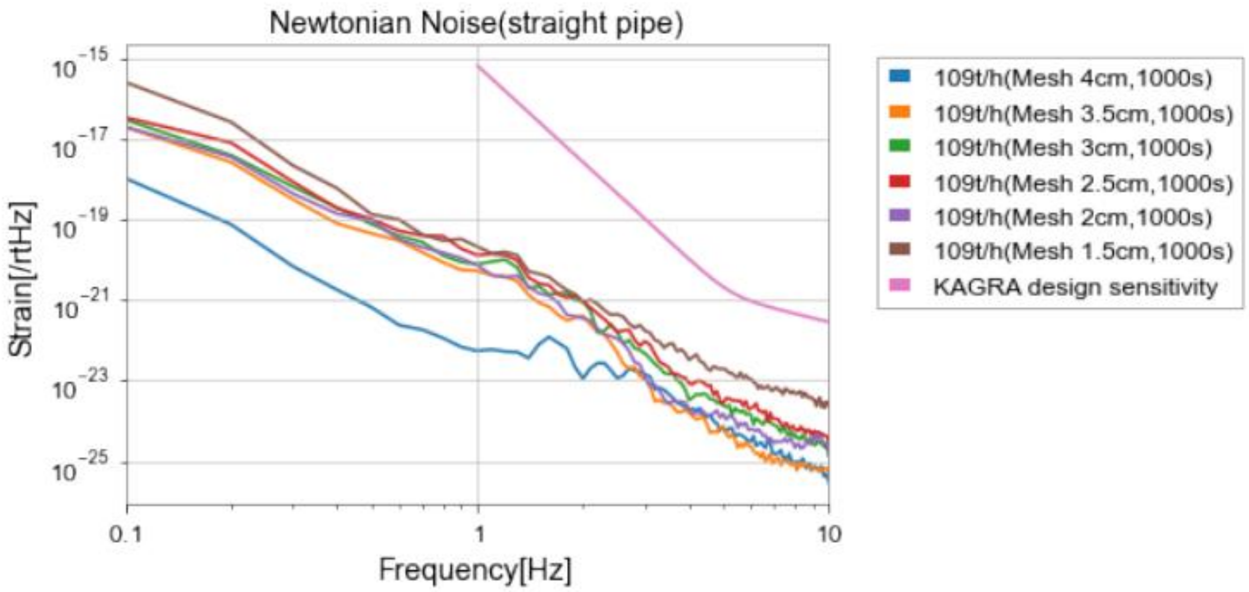


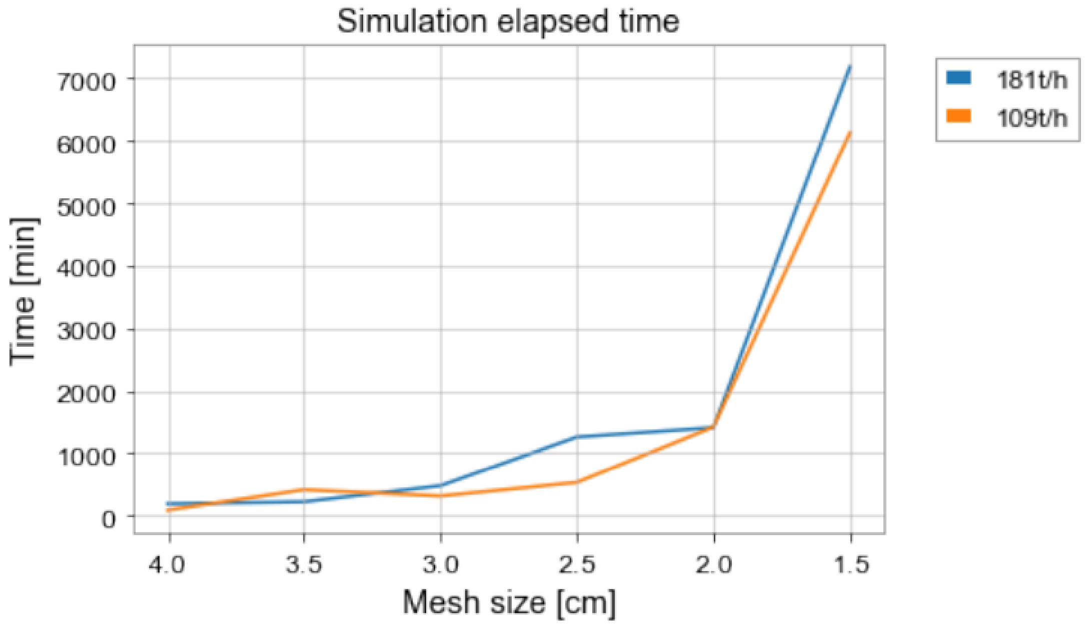


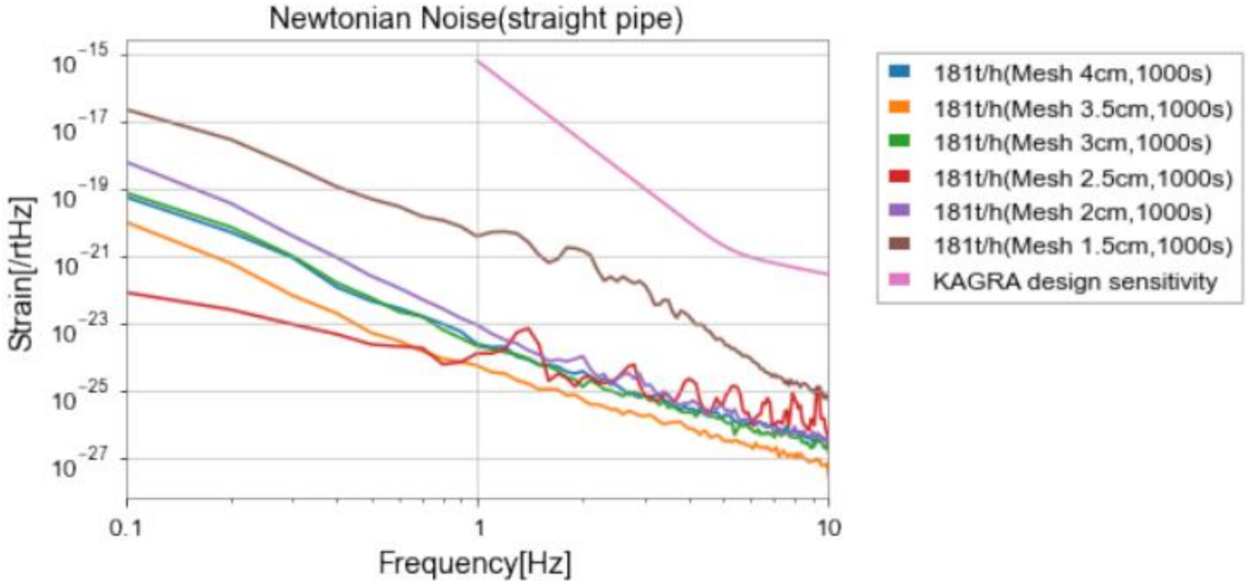


Simulation of water flow in the straight pipe with different slope did not show hydraulic jump, and NN level was lower than sensitivity.

Mesh size







Suzuki found the noise level increase with the mesh size. We haven't confirmed if it converges as the simulation times jumped up at $\Delta = 1.5$cm.

Summary

- We did water flow simulation with (i) straight pipe to check the reasonability, and (ii) KAGRA-like pipe to calculate NN.
- Sub/Super-critical flow and hydraulic jump were observed but only under the free-slip condition (which is not right!).
- With the KAGRA-like pipe, we observed another kind of jump regardless of the total amount of water.
- The simulation has not converged yet with increasing mesh size.