Noise subtraction in offline analysis of KAGRA using Independent Component Analysis (ICA)

Jun'ya Kume (RESCEU, Univ. of Tokyo)
on behalf of the KAGRA collaboration

Collaborators :Yousuke Itoh(Osaka City Univ.)
Jun'ichi Yokoyama(RESCEU, UTokyo)
Tatsuki Washimi (NAOJ)
Takaaki Yokozawa(ICRR)

Contents

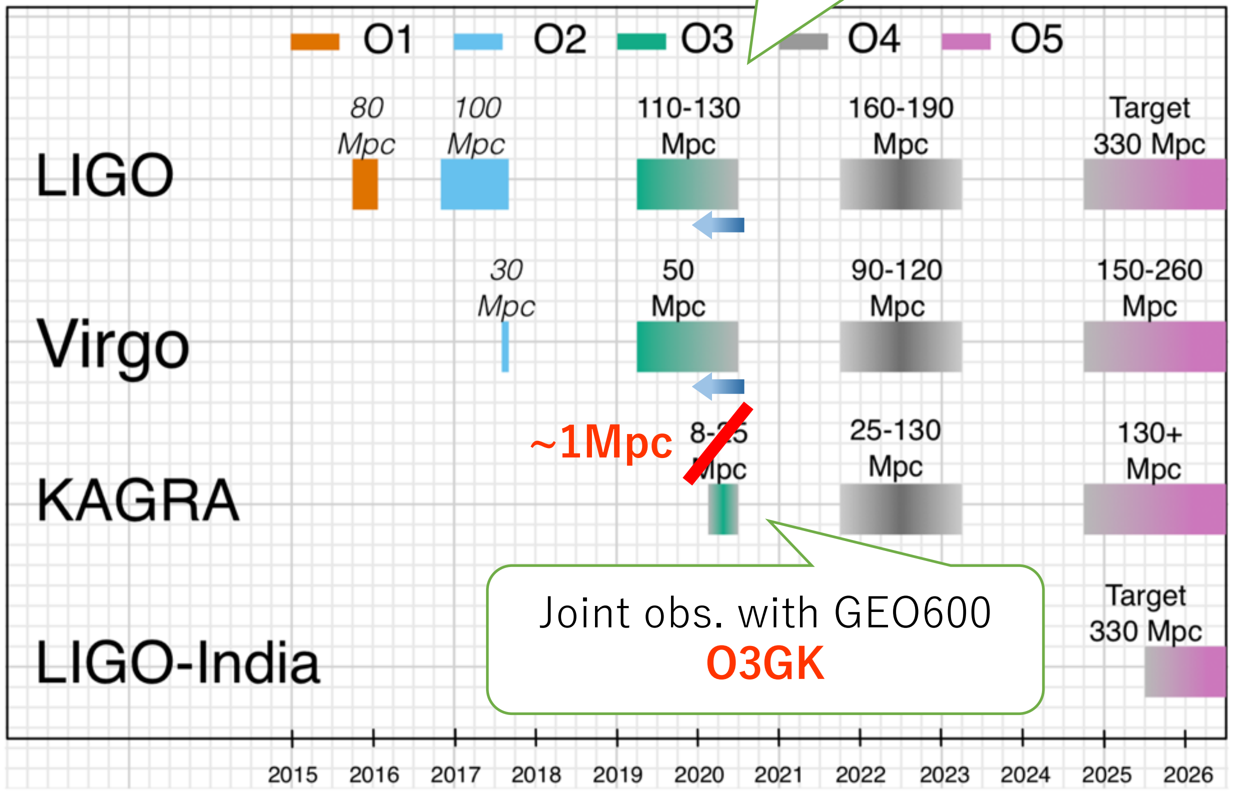
Limitation from environmental noise in KAGRA

- Current status of KAGRA

After achieving ~1Mpc sensitivity for BNS merger, KAGRA started first observing run with GEO600 in this April. (**O3GK**)

Now in the update to join O4 with
-Dual-Recycled FPMI
-high power laser
-Refurbishment of the suspension
-operating temperature ~20K…etc.
to achieve **higher sensitivity**.

arXiv:1304.0670



O3 of LV was shortened for 1month due to COVID-19

Joint obs. with GEO600
O3GK

Limitation from environmental noise in KAGRA

O3 of LV was
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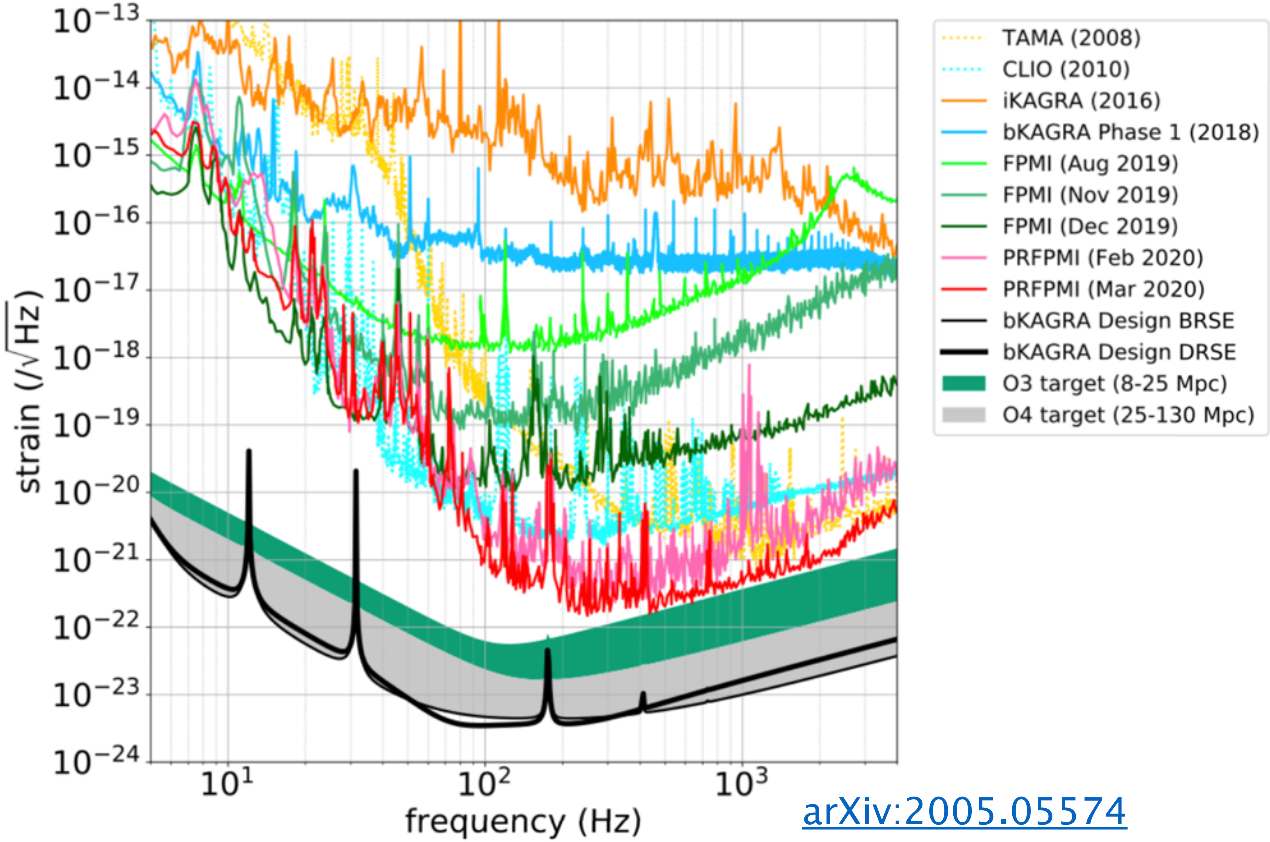
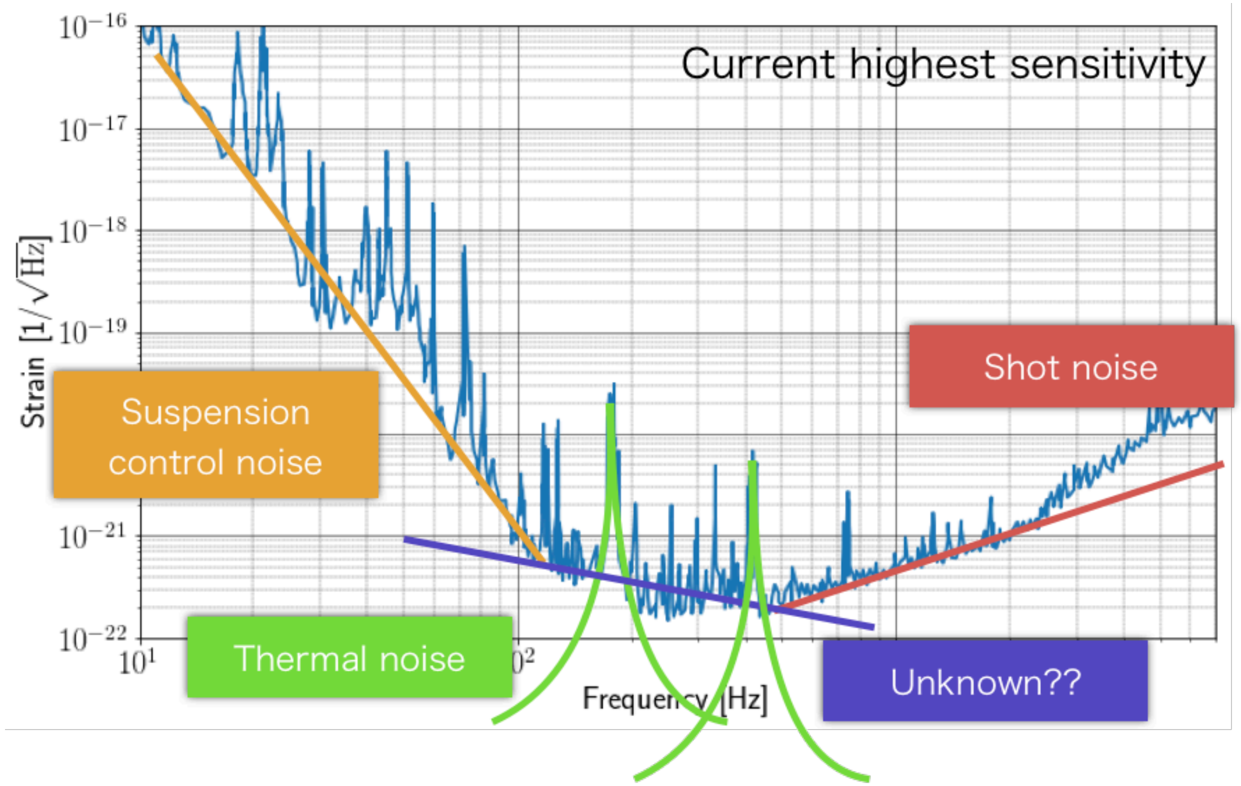


arXiv:2005.05574

Limitation from environmental noise in KAGRA

- Noise budgets

Dominant noise source is identified in low and high freq. regime.

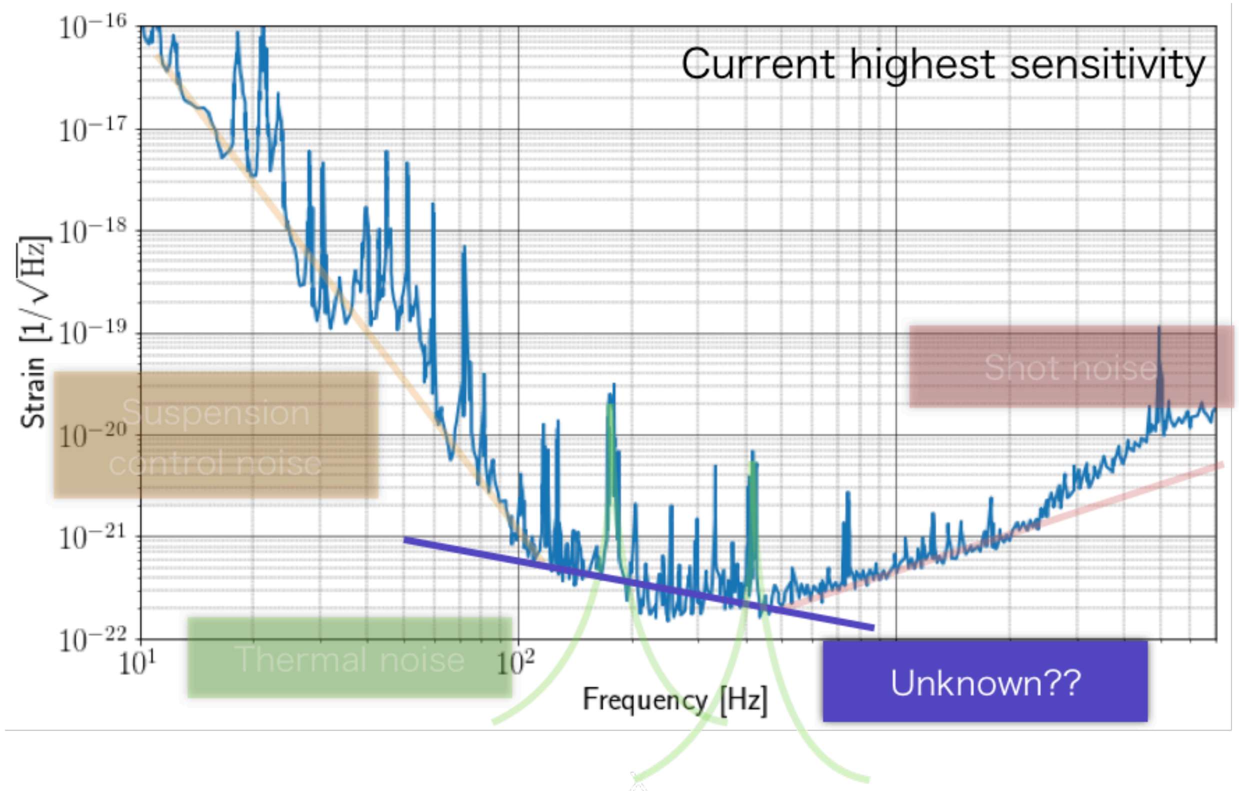


Limitation from environmental noise in KAGRA

- Noise budgets

Dominant noise source is identified in low and high freq. regime.

Still, identification of noise source in <u>mid freq. regime</u> is on going.
→crucial to the CBC observation!!



Limitation from environmental noise in KAGRA

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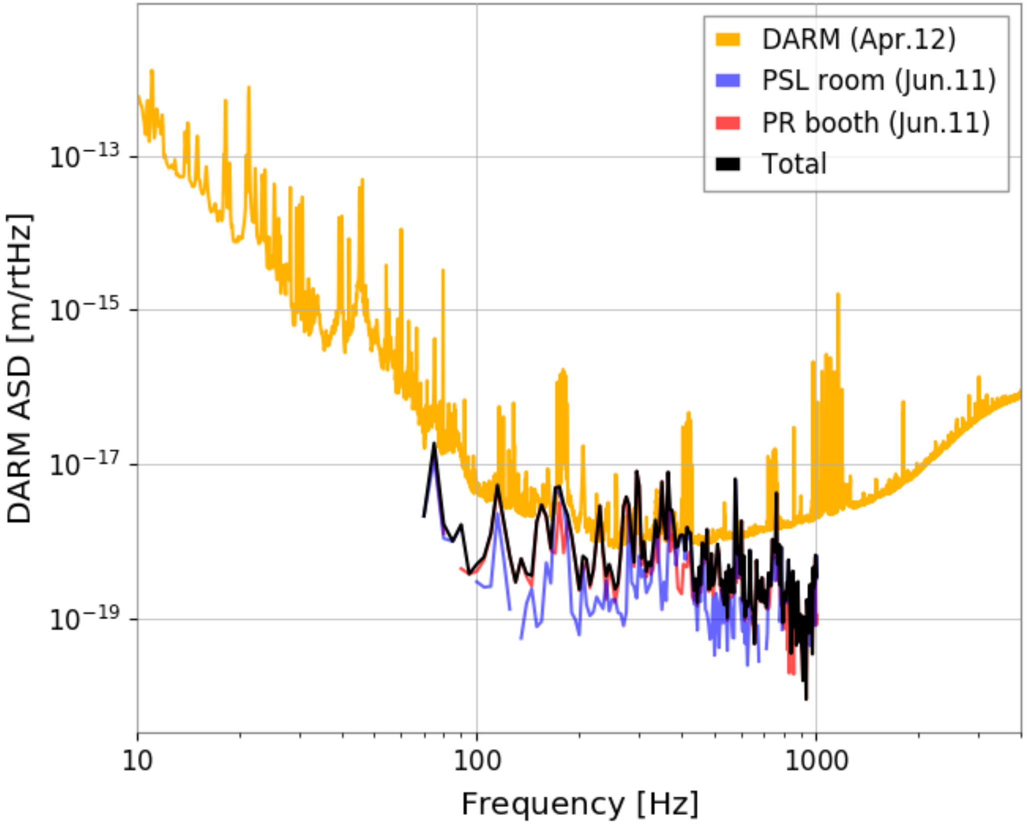

Acoustic noise (by post-O3GK swetp sine acoustic injection)

Contribution of environmental noise,
e.g. acoustic noise, is now investigated by Physical Environmental Monitor group.

(T. Washimi, T. Yokozawa, T. Tanaka, Y. Itoh, JK and J. Yokoyama, arXiv:2012.09294)

Limitation from environmental noise in KAGRA

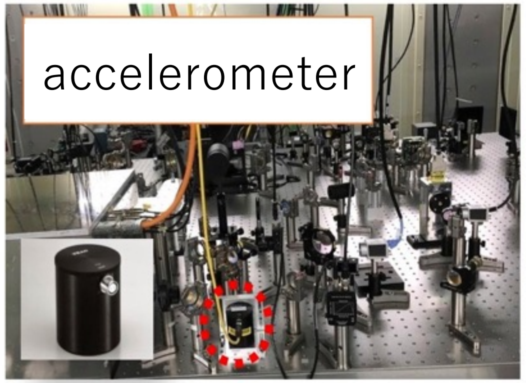
- Environmental noise subtraction

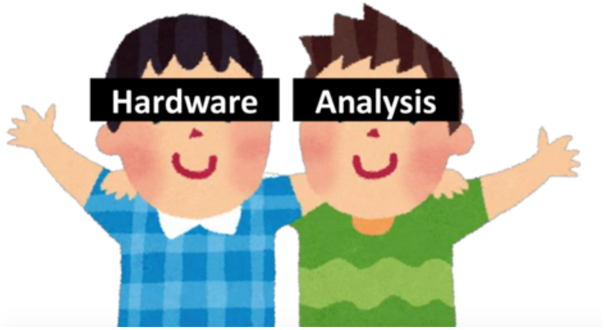
After identifying the dominant source, we need to <u>subtract them</u> to improve the sensitivity.

Our goal is to establish subtraction scheme in data analysis, making use of various PEM channels.

※Focusing on <u>microphone</u> in this work.

Physical Environmental Monitor(PEM)





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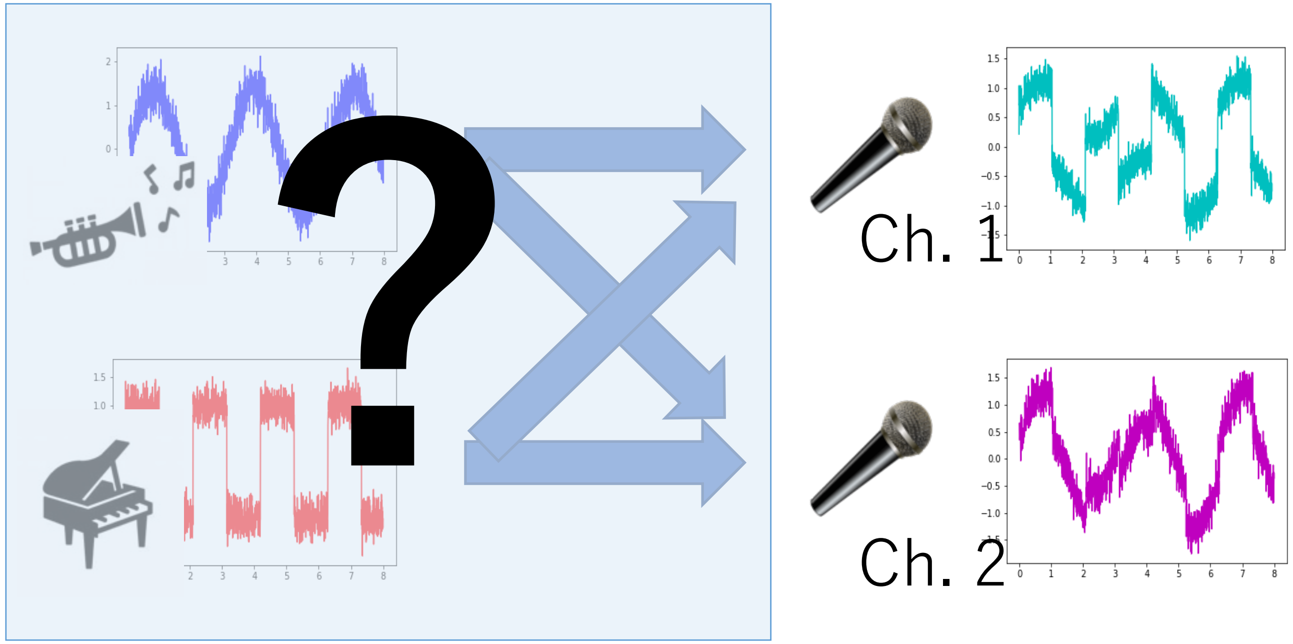
- ➢ICA and its application to the noise subtraction
- ➢Noise subtraction in the O3GK data
- ➢Future work and Summary

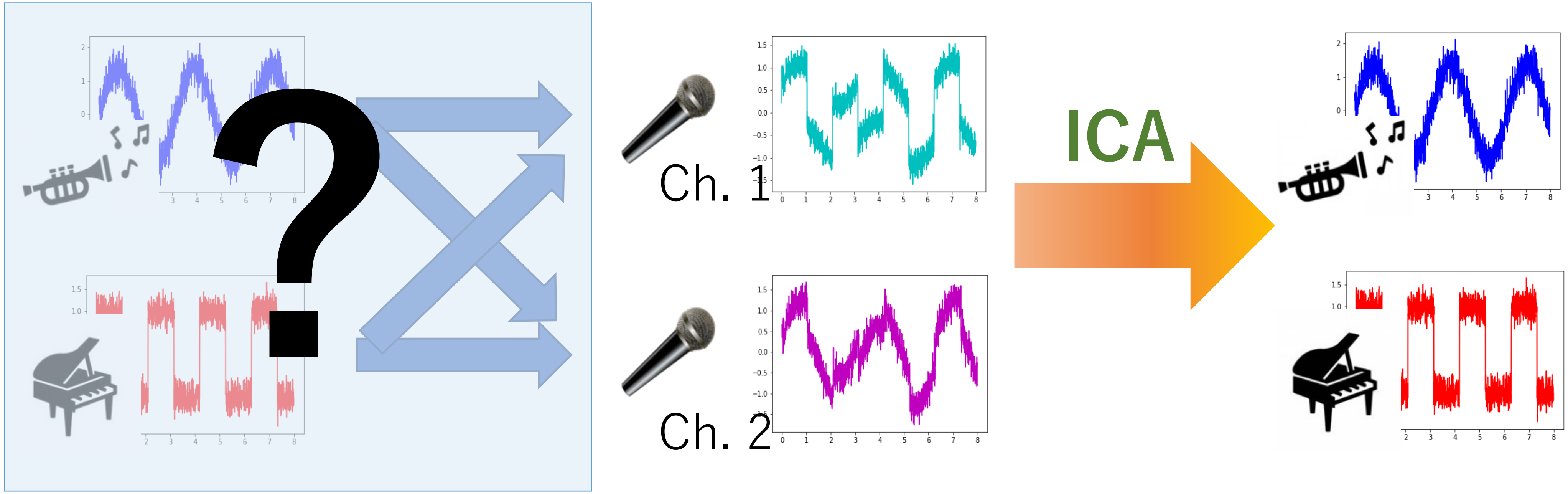
ICA and its application to the noise subtraction

- ICA = method of blind source separation



ICA and its application to the noise subtraction

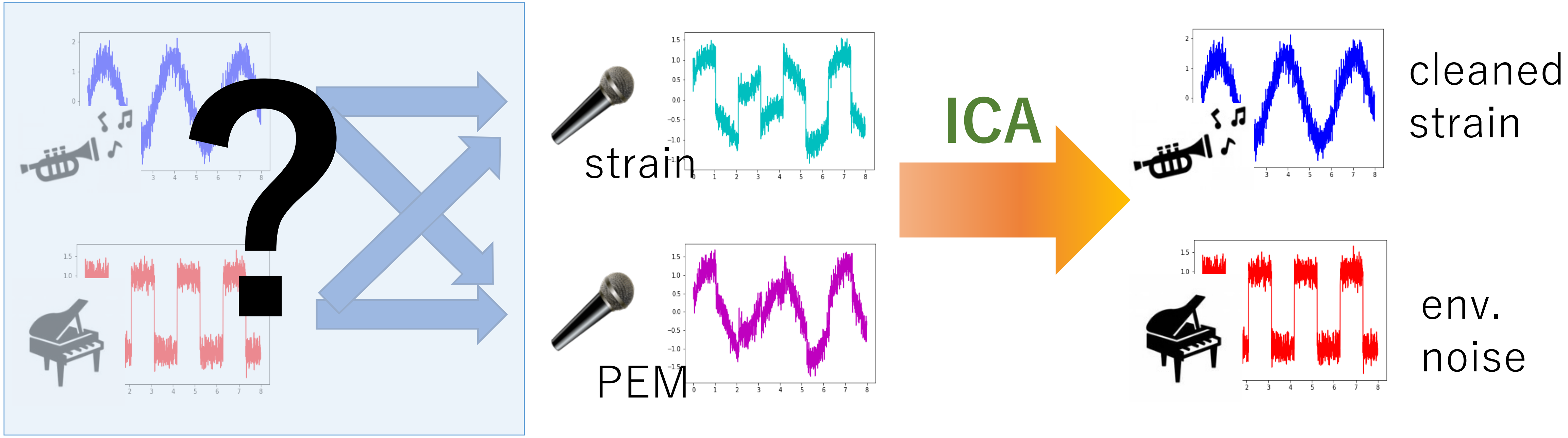
- ICA = method of blind source separation



ICA and its application to the noise subtraction

- ICA = method of blind source separation

This can be used as the **non-Gaussian noise subtraction method** by using auxiliary channels such as **PEM channels**.



ICA and its application to the noise subtraction

- **First step = linear mixing model with iKAGRA data**

(JK, T. Sekiguchi, S. Morisaki, Y. Itoh, J. Yokoyama and KAGRA collaboration 2020)

$$\begin{pmatrix} x_1(t) \\ x_2(t) \end{pmatrix} = \boxed{\begin{pmatrix} a_{11} & a_{12} \\ \underline{\underline{0}} & a_{22} \end{pmatrix}} \begin{pmatrix} h(t)+n(t) \\ k(t) \end{pmatrix}$$

$x_1(t)$: iKAGRA strain

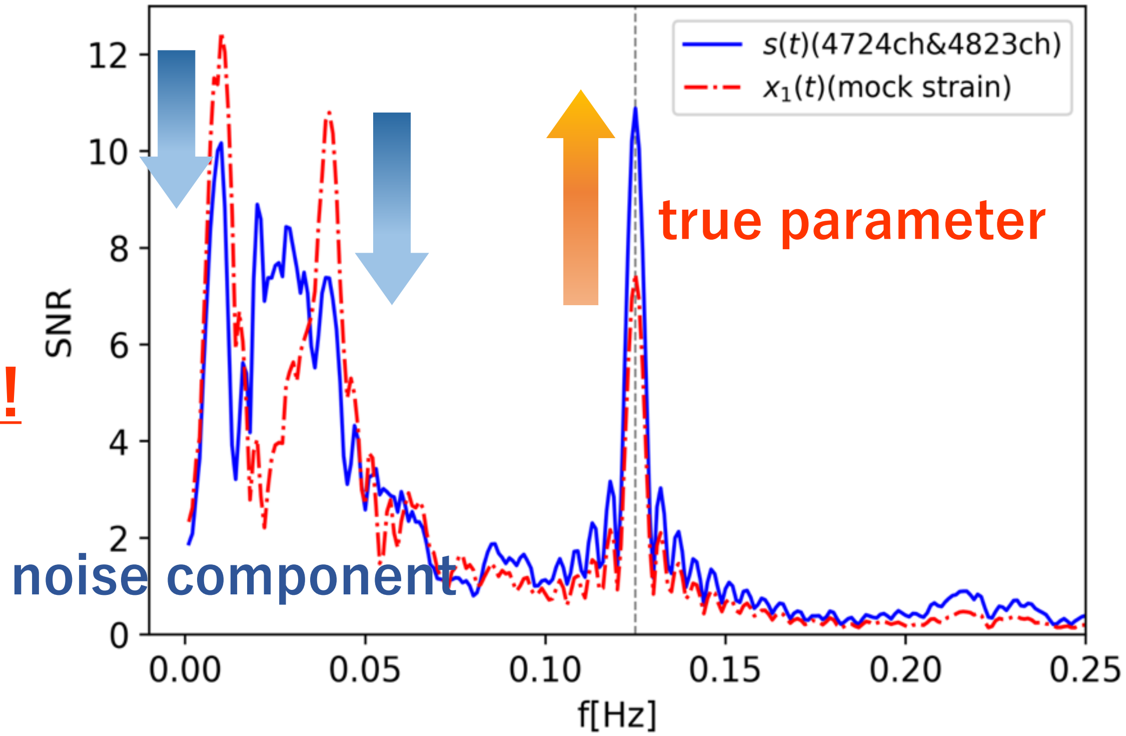
$x_2(t)$: seismograph

$k(t)$: seismic noise→**subtracted by ICA!!**

subtraction formula:

$$y_1(t) = x_1(t) - \frac{\langle x_1 x_2 \rangle}{\langle x_2^2 \rangle} x_2(t)$$

Parameter estimation for continuous wave



ICA and its application to the noise subtraction

- **Next step = extended ICA with bKAGRA data**

$\vec{x}(t) = \sum_{\tau} A(\tau)\,\vec{s}(t-\tau)$: Convoluted mixing in time domain

$$\begin{pmatrix} \tilde{x}_1(f;t_s) \\ \tilde{x}_2(f;t_s) \end{pmatrix} = \boxed{\begin{pmatrix} \tilde{a}_{11}(f) & \tilde{a}_{12}(f) \\ \underline{\underline{0}} & \tilde{a}_{22}(f) \end{pmatrix}} \begin{pmatrix} \tilde{h}(f;t_s) + \tilde{n}(f;t_s) \\ \tilde{k}(f;t_s) \end{pmatrix}$$

(Morisaki et al. 2016)

It is expected to be useful for mitigating line noise in strain channel.

ICA and its application to the noise subtraction

- **Next step = extended ICA with bKAGR**

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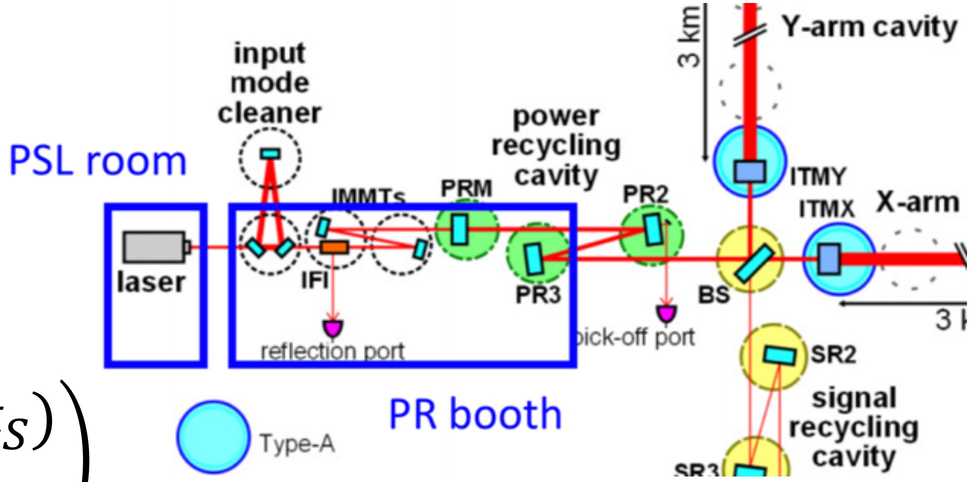


(Morisaki et al. 2016)

$$\begin{pmatrix} \tilde{x}_1(f;t_s) \\ \tilde{x}_2(f;t_s) \end{pmatrix} = \boxed{\begin{pmatrix} \tilde{a}_{11}(f) & \tilde{a}_{12}(f) \\ \underline{\underline{0}} & \tilde{a}_{22}(f) \end{pmatrix}} \begin{pmatrix} \tilde{h}(f;t_s) + \tilde{n}(f;t_s) \\ \tilde{k}(f;t_s) \end{pmatrix}$$

It is expected to be useful for mitigating line noise in strain channel.

In this work, we identify $\tilde{x}_2$ as the microphone in PSL room.

→acoustic noise is expected to be subtracted.

subtraction formula: $\tilde{y}_1(f;t_s) = \tilde{x}_1(f;t_s) - \dfrac{\langle \tilde{x}_1(f;t_s)\tilde{x}_2^*(f;t_s)\rangle_{t_s}}{\langle \tilde{x}_2(f;t_s)\tilde{x}_2^*(f;t_s)\rangle_{t_s}}\,\tilde{x}_2(f;t_s)$

ICA and its application to the noise subtraction

- Demonstration with acoustic injection data

To check the consistency, we first applied ICA to the injection data.

$x_1(t)$: bKAGRA data with **acoustic injection** in PSL room

$x_2(t)$: microphone in PSL room

※Acoustic injection was performed on 11th June, in commissioning term after O3GK

→Injected acoustic noise should be removed after ICA.

We compare the spectrum density of

raw strain data and processed data with ICA, around the line injection.

ICA and its application to the noise subtraction

- Demonstration with acoustic injection data

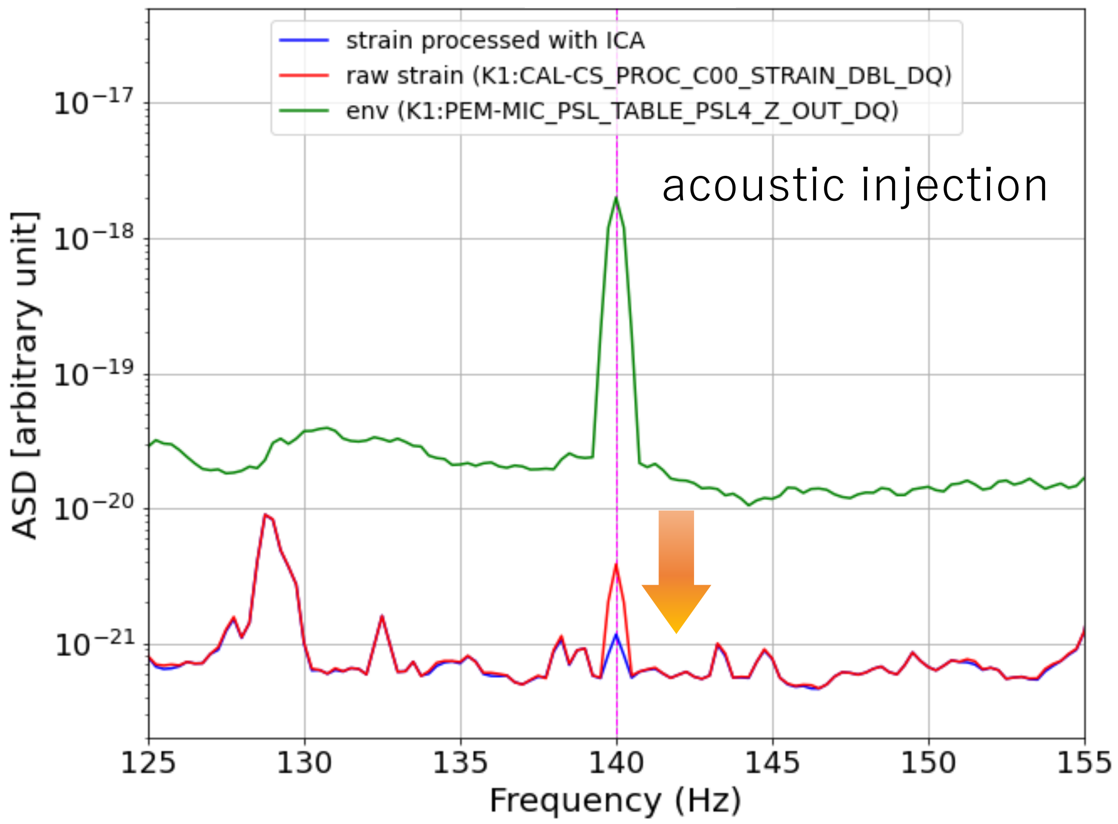
Line feature at 140Hz

= injected acoustic noise

After ICA, peak at 140Hz in the spectrum of strain was subtracted in a consistent way.

What if ICA is applied to the actual **observational data**?

Spectral density in arbitrary unit



ICA and its application to the noise subtraction

- Demonstration with acoustic injection data

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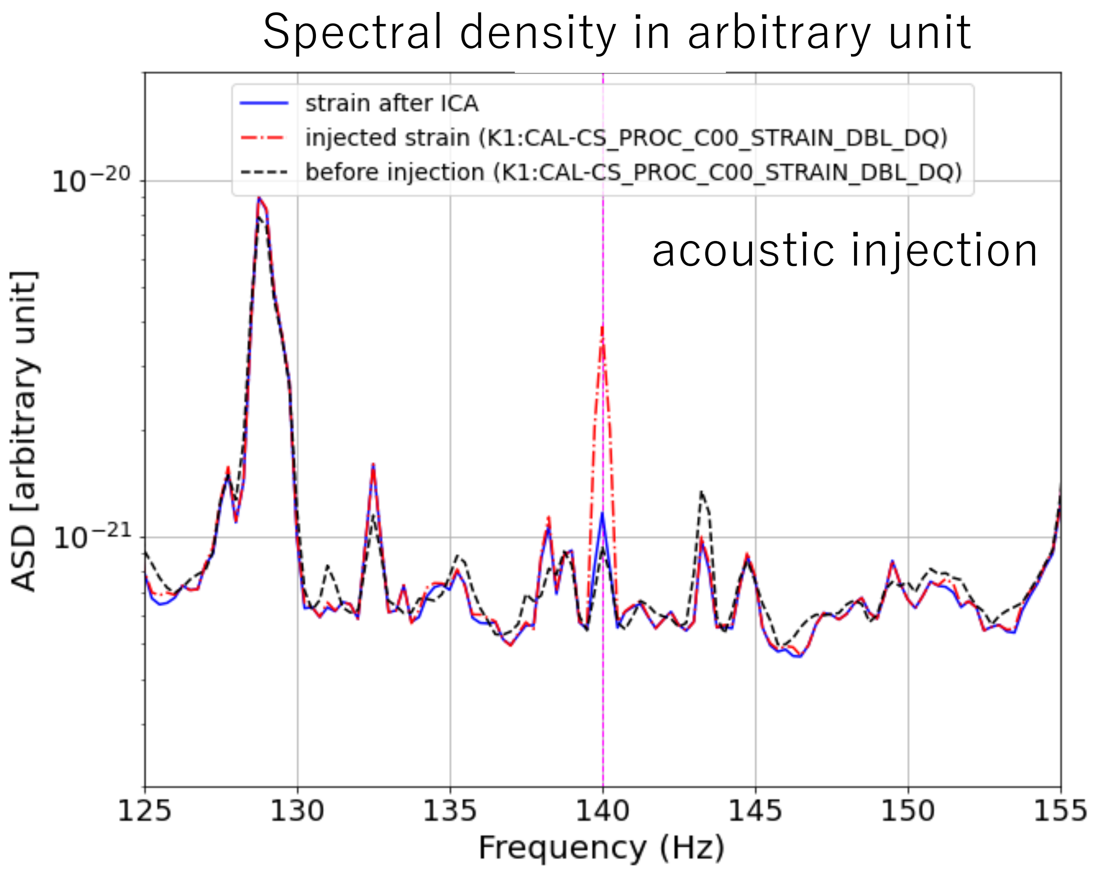
Spectral density in arbitrary unit

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Noise subtraction in the O3GK data

In this analysis, we use actual O3GK data on April 12.
→Detector performance was stable with the sensitivity ~0.6Mpc.

We compare the spectral density of
- Raw strain data
- Processed strain data with ICA using microphone

to investigate to what extent acoustic noise contaminates the strain and whether we can subtract it by ICA.

(※In the following, the spectrum of microphone is normalized for the comparison)

Noise subtraction in the O3GK data

➢Acoustic noise

- 363Hz, 372Hz and 402Hz

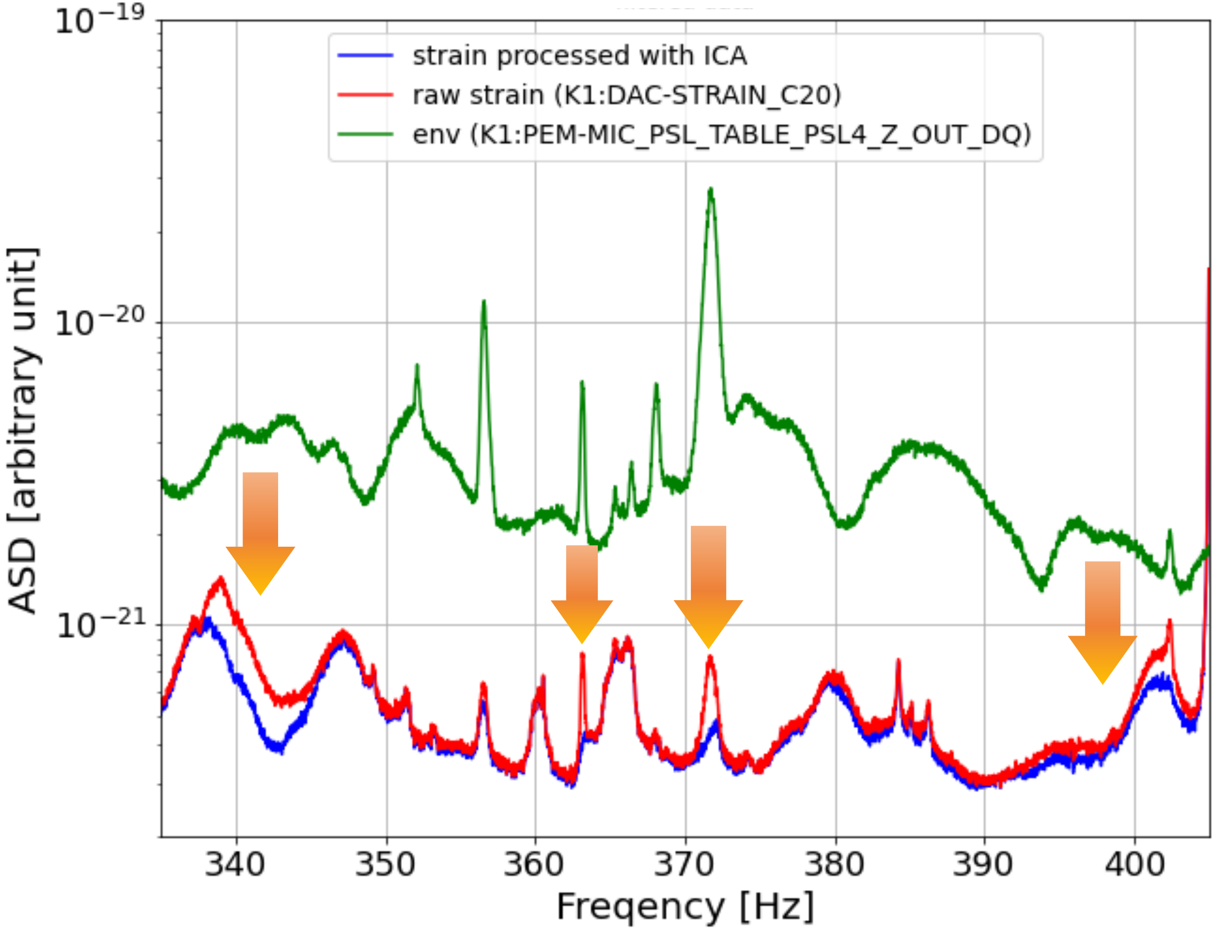
Line feature is subtracted!!

- around 340Hz

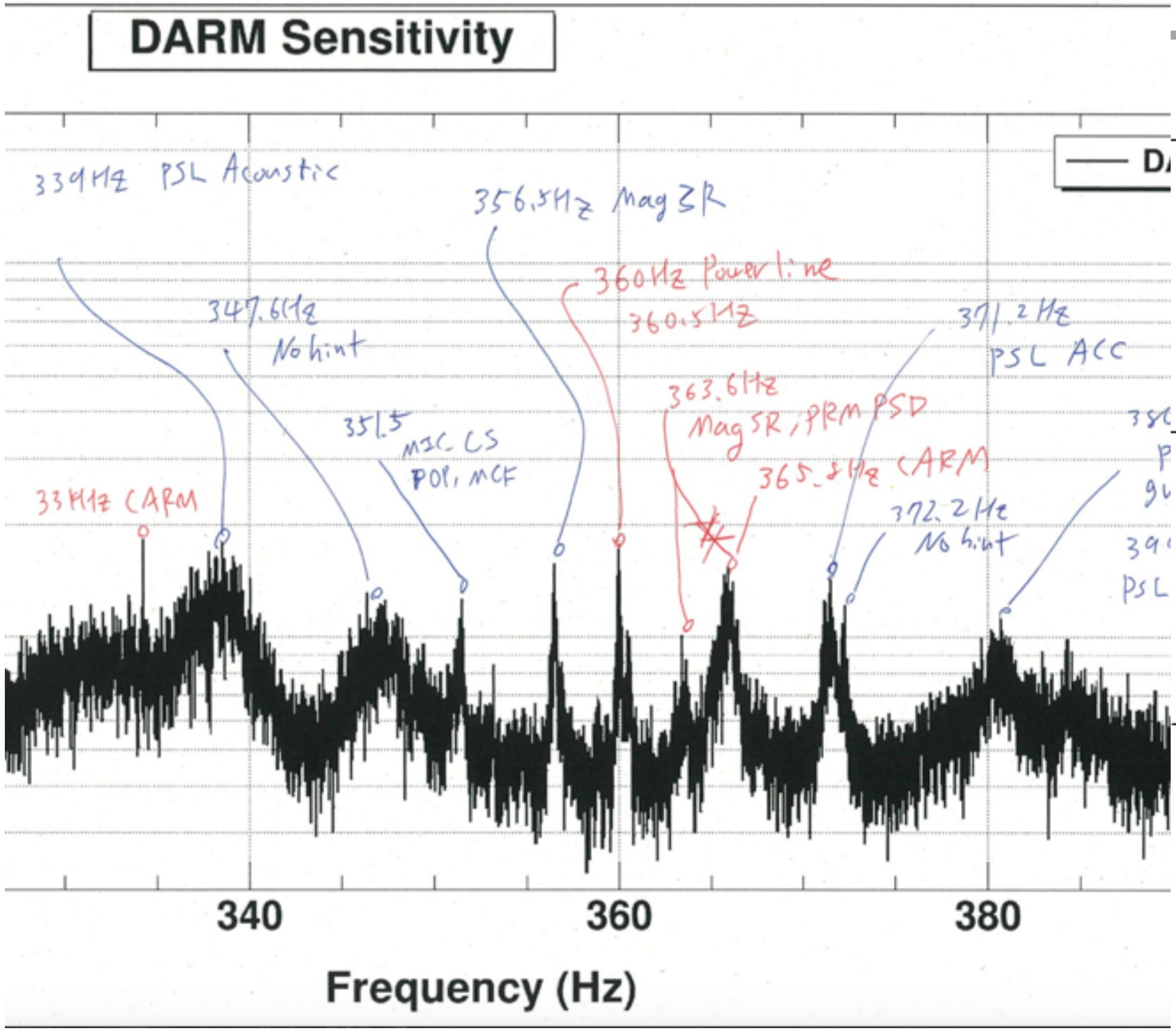
broader peak is reduced!!

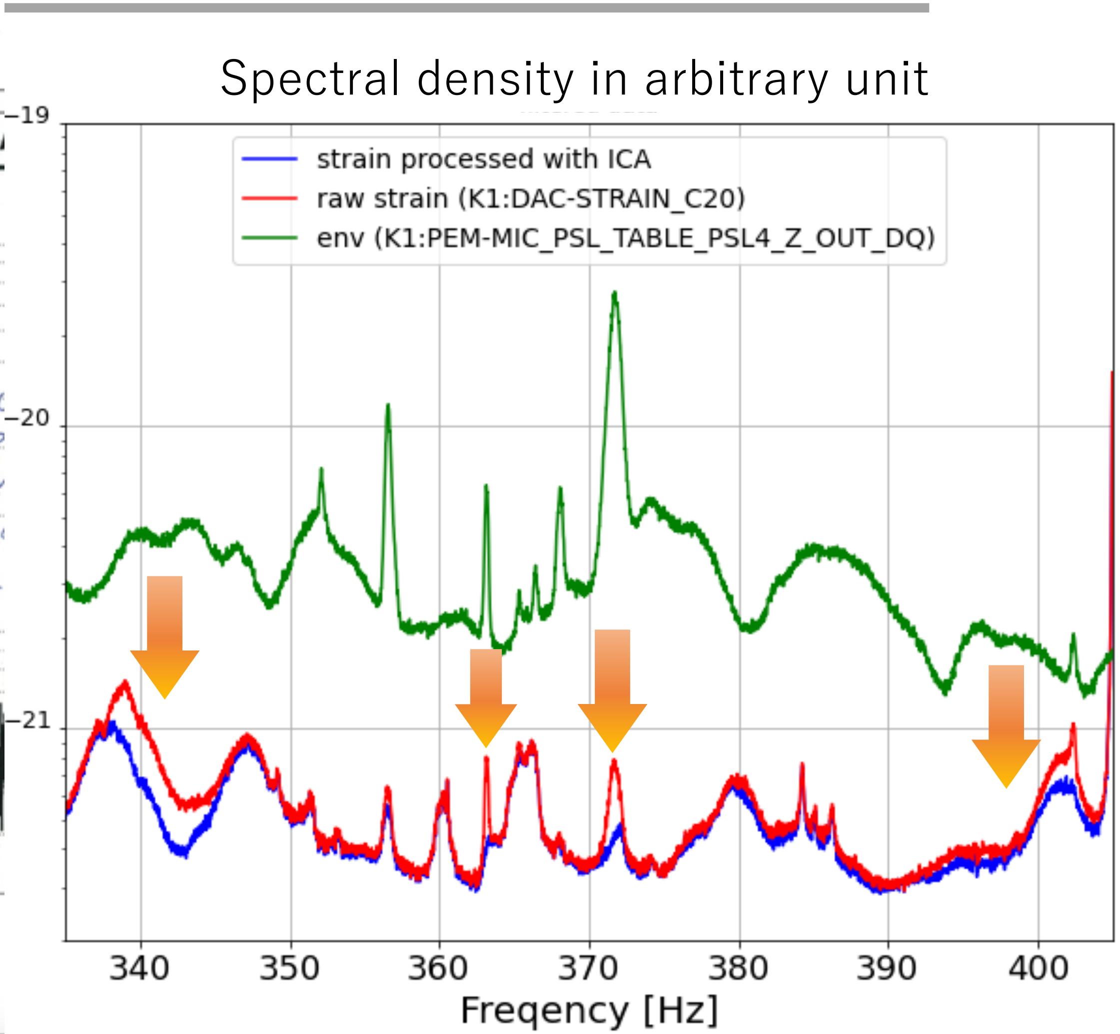
Acoustic contamination predicted in coherence search is successfully subtracted.

Spectral density in arbitrary unit



Noise subtraction in the O3GK data





Noise subtraction in the O3GK data

➢Other line noise

- 60Hz

Line feature due to the AC power is shown up in both channel.

→partially subtracted!!

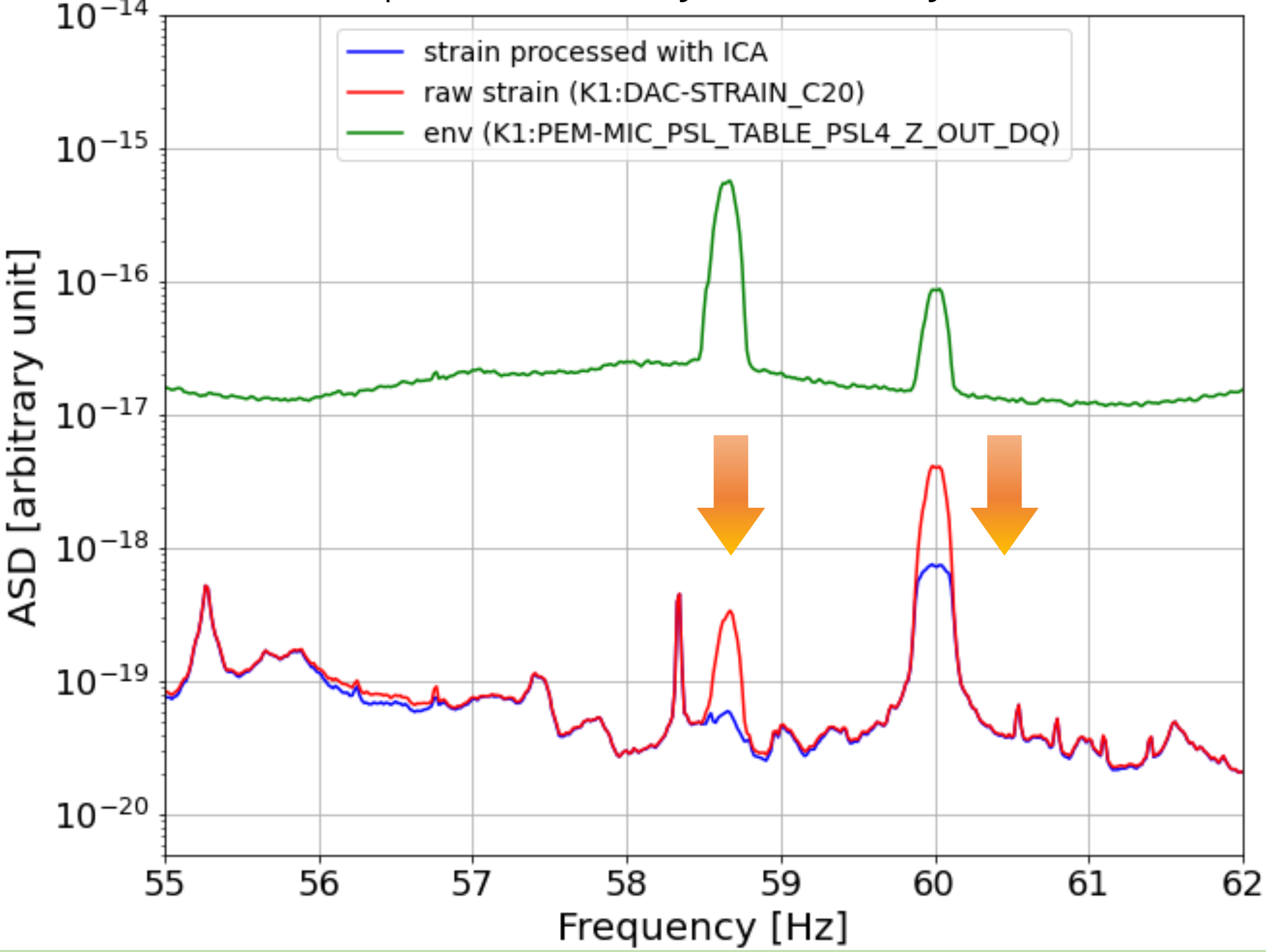
- 58.68Hz

→subtracted!

Powerline related?

or environmental noise?

Spectral density in arbitrary unit



Nois he O3GK data

➢Othe

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Line fe

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→parti

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Powerl

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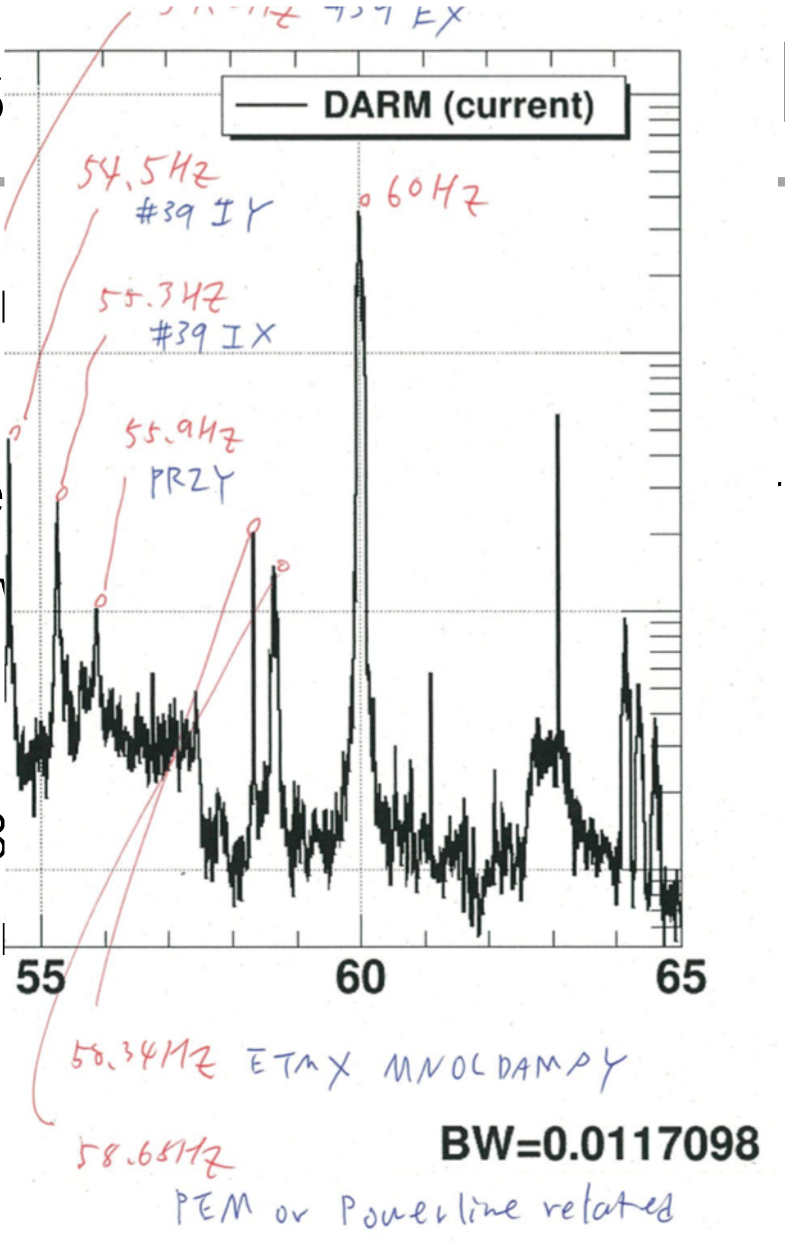
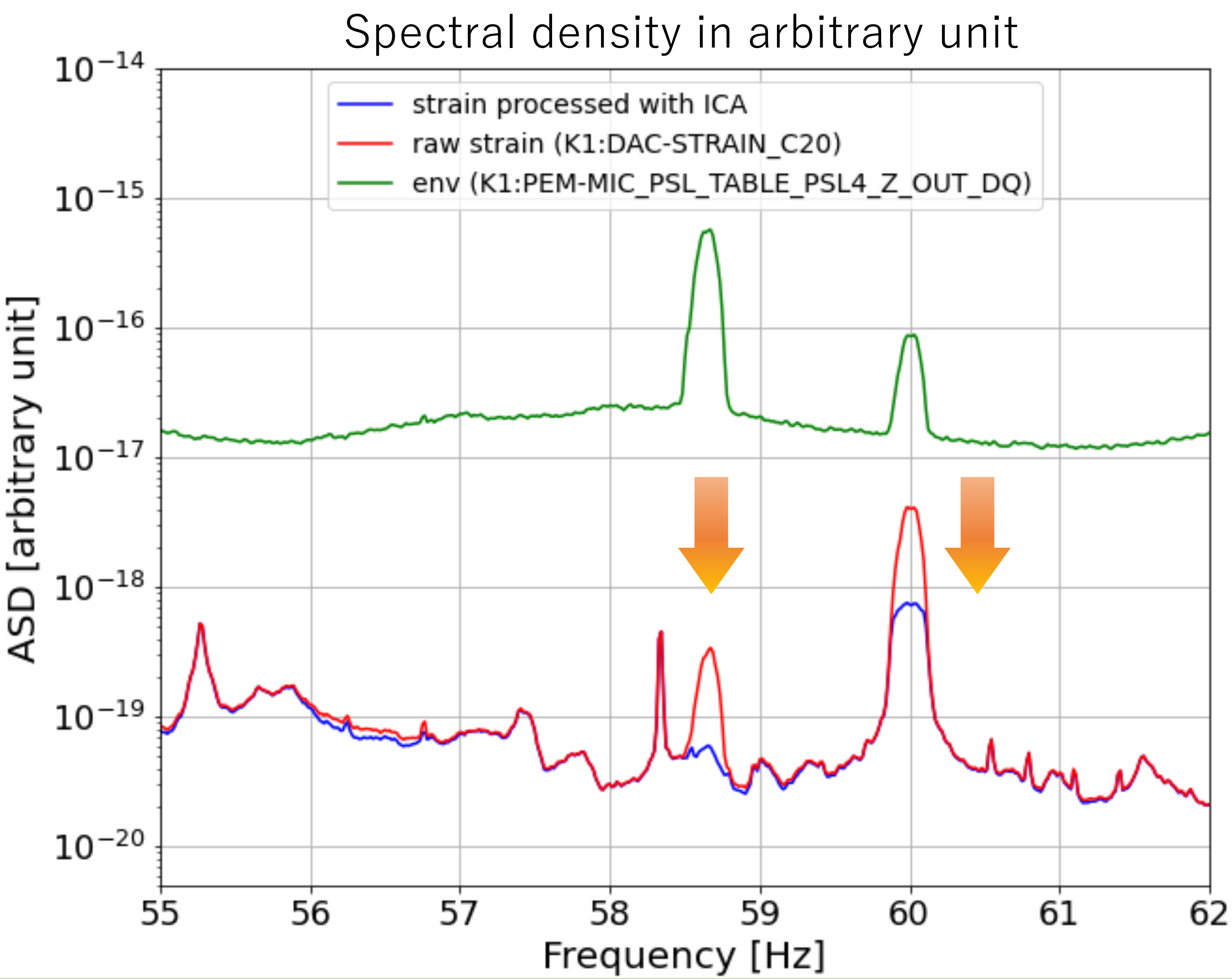




Noise subtraction in the O3GK data

➢Other line noise

- 120Hz

Partially subtracted.

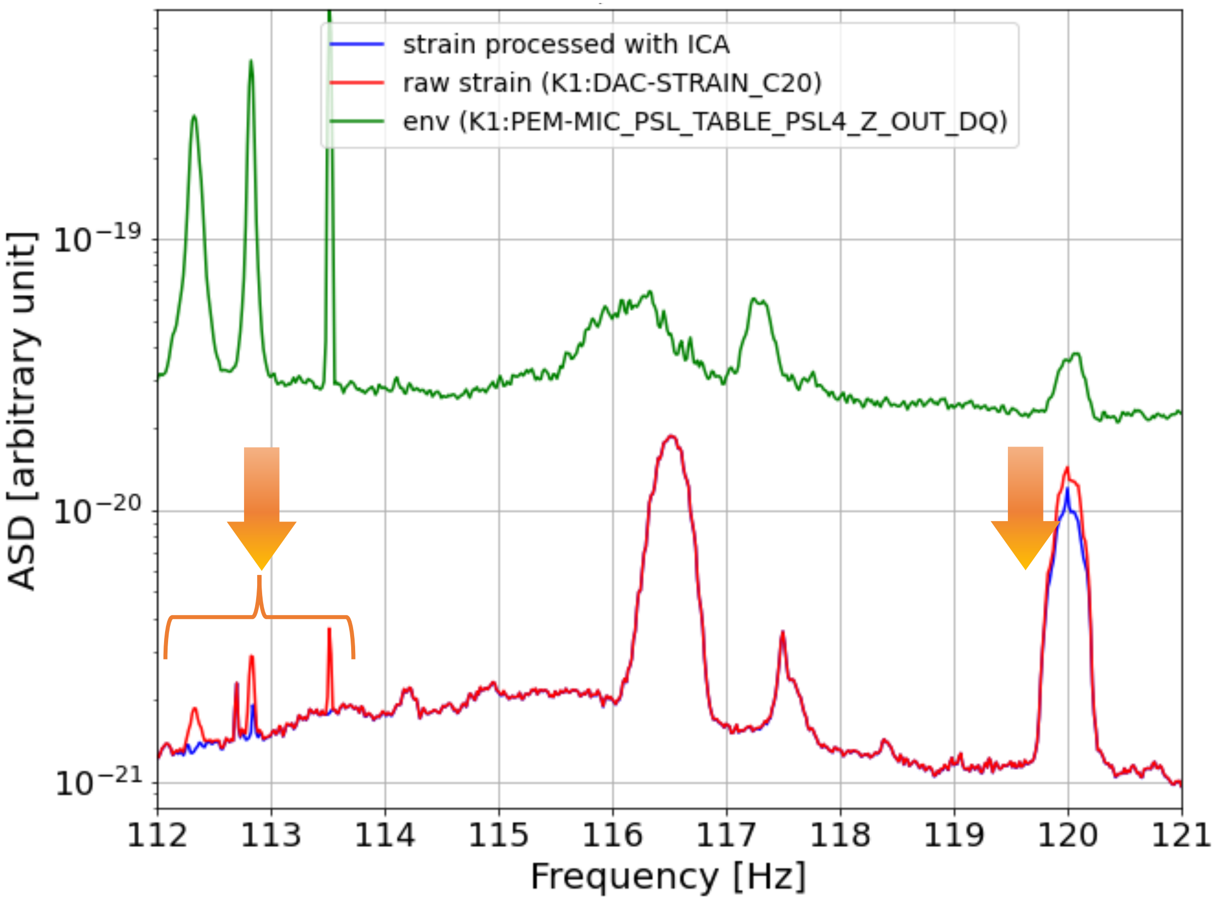
→Harmonics of AC power

- around 113Hz

These were not found at the time of coherence search.

→ICA may provide new insights on environmental contamination.

Spectral density in arbitrary unit



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Future work and Summary

✓Combining multiple PEM channels

In previous work, we confirmed that the effect of ICA can be enhanced by combining different monitors. We expect this is also true for Fourier ICA.

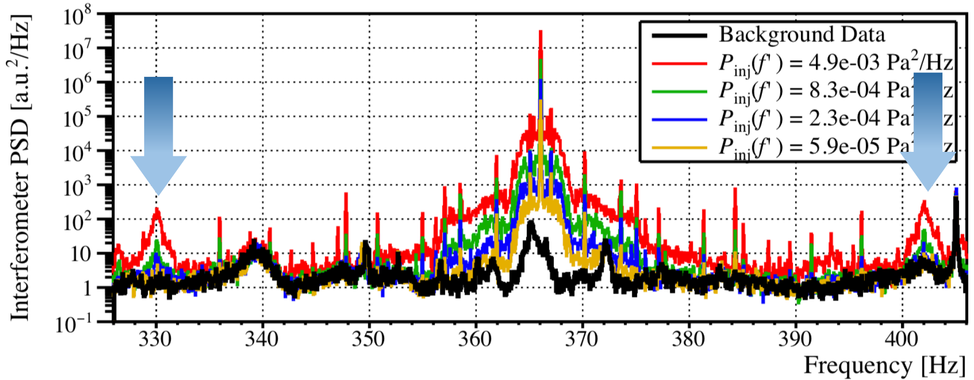
✓Side band subtraction

Linear mixing model cannot deal with this noise.

Non-linear mixing model is expected to be useful.

$$\vec{x}(t) = \begin{pmatrix} a & b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} h(t) + n(t) \\ k(t) \end{pmatrix} + \begin{pmatrix} c\big(h(t) + n(t)\big)k(t) \\ 0 \end{pmatrix}$$

Acoustic injection



arXiv:2012.09294

Future work and Summary

- KAGRA is on step-by-step upgrade to improve the sensitivity.
→Subtraction of environmental noise is quite important!!

- ICA works well for O3GK strain data. It can provide some insights into how the environment contaminate the strain.

- Using multiple PEM channels and further implementation of non-linear model can enrich the performance of ICA.

Offline noise subtraction in KAGRA using **Independent Component Analysis** (ICA)

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Theory of ICA

Ex.) instantaneous linear mixing

$$\vec{x}(t) = A\,\vec{s}(t)$$

mixing matrix: $A = \begin{pmatrix} a_{11} & \cdots & a_{1N} \\ \vdots & \ddots & \vdots \\ a_{N1} & \cdots & a_{NN} \end{pmatrix}$

data: $\vec{x}(t) = \left(\underbrace{x_1(t)}_{\text{strain}},\ \underbrace{x_2(t),\ \dots, x_N(t)}_{\text{environmental channels}} \right)^T$ ←What we can observe

source: $\vec{s}(t) = \left(\underbrace{s_1(t)}_{\text{GW}},\ \underbrace{s_2(t),\ \dots, s_N(t)}_{\text{environmental noise}} \right)^T$ ←Assumption

- statistically independent
- non-Gaussian distribution

Theory of ICA

Ex.) instantaneous linear mixing

linear tr.：$\vec{y}(t) = W\vec{x}(t)$

$$p_y(\vec{y}) = \det W^{-1}\, p_x\,(\vec{x}) = p(\vec{x}, W)$$

If one realize $p_y(\vec{y}) = p_1(y_1)p_2(y_2)\cdots p_N(y_N) \longrightarrow W = A^{-1},\ \vec{y}(t) = \vec{s}(t)$

$$\equiv \tilde{p}(\vec{y})$$

This is done by minimizing cost function (Kullback-Leibler div.)

$$L(W) = D\left[p_y(\vec{y}); \tilde{p}(\vec{y})\right] = \int p_y(\vec{y}) \ln\left(\frac{p_y(\vec{y})}{\tilde{p}(\vec{y})}\right) d\vec{y} \geq 0$$

$$\partial L(W)/\partial w_i = 0 \rightarrow\ W = A^{-1},\ \vec{y}(t) = \vec{s}(t)$$

Theory of ICA

Ex.) instantaneous linear mixing

For GW data analysis,

$$\begin{pmatrix} y_1(t) \\ y_2(t) \end{pmatrix} = \begin{pmatrix} w_{11} & w_{12} \\ \underline{\underline{0}} & w_{22} \end{pmatrix} \begin{pmatrix} x_1(t) \\ x_2(t) \end{pmatrix}$$

(Morisaki et al. 2016)

From $a_{21} = 0, w_{21} = 0.$ → y_1 always contain GW signal.

Distributions of separated component are assumed to be

$$q_1(y_1) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\left(y_1(t) - h(t, \vec{\lambda})\right)^2 / 2\sigma^2\right]$$

→by minimizing cost function

$$y_1(t) = x_1(t) - \frac{\langle x_1 x_2 \rangle}{\langle x_2^2 \rangle} x_2(t)$$

$q_2(y_2)$: super-Gaussian

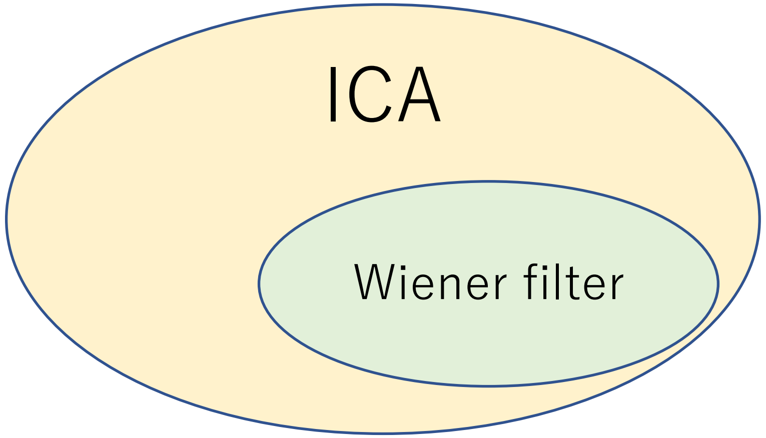
$$\rightarrow -\frac{d}{dy_2} \ln q_2(y_2) = c \tanh y_2$$

Wiener filter and ICA

Wiener filter

:**minimizing mean-square-error** of the primary channel

$$e(n) \equiv x_1(n) - y(n) = x_1(n) - \sum_{i=0}^{N} w_i x_2(n-i)$$



ICA

estimating mixing matrix by minimizing KL div.

(to find maximally **independent components**)

→linear mixing ICA with $a_{21} = 0$ coincides with Wiener filter.

Wiener filter applied to LIGO O2 data improves the sensitivity.

Wiener filter and ICA

Wiener filter

:**minimizing mean-square-error** of

$$e(n) \equiv x_1(n) - y(n) = x_1(n) - \sum_{i=0}^{N} w_i x_2(n-i)$$

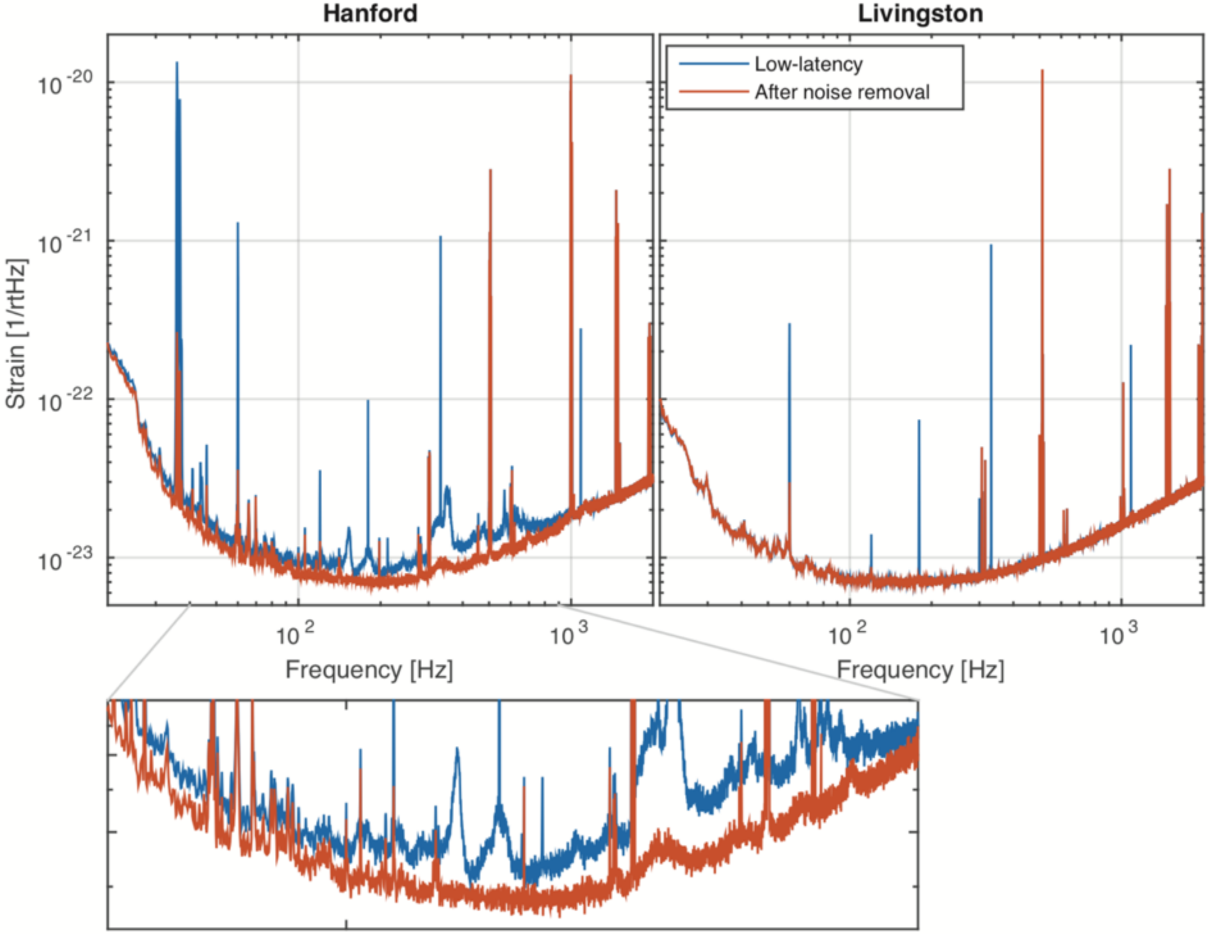
ICA

estimating mixing matrix by minimi

(to find maximally **independent co**

→linear mixing ICA with $a_{21} = 0$ coi

(J. C. Driggers, LIGO scientific collaboration 2018)



Wiener filter applied to LIGO O2 data improves the sensitivity.

Coherence

$$S_{11}(f) = \frac{\langle \tilde{x}_1(f;t_s)\tilde{x}_1^*(f;t_s)\rangle_{t_s}}{T} \qquad S_{22}(f) = \frac{\langle \tilde{x}_2(f;t_s)\tilde{x}_2^*(f;t_s)\rangle_{t_s}}{T}$$

$$S_{12}(f) = \frac{\langle \tilde{x}_1(f;t_s)\tilde{x}_2^*(f;t_s)\rangle_{t_s}}{T}$$

Coherence is defined from the above quantities as $\gamma_{12}(f) = \frac{|S_{12}|}{\sqrt{S_{11}S_{22}}}$

→Quantifying which characterize the correlation
in a frequency bin between two channels.

Coherence

- Convoluted linear mixing

$$\tilde{y}_1(f;t_s) = \tilde{x}_1(f;t_s) - \boxed{\frac{\langle \tilde{x}_1(f;t_s)\tilde{x}_2^*(f;t_s)\rangle_{t_s}}{\langle \tilde{x}_2(f;t_s)\tilde{x}_2^*(f;t_s)\rangle_{t_s}}}\tilde{x}_2(f;t_s)$$

$$\simeq \gamma_{12}^2(f)S_{11}(f)$$

subtraction is characterized by coherence.

→need to set threshold value to mitigate the estimation error.

ex.)95% confidence level