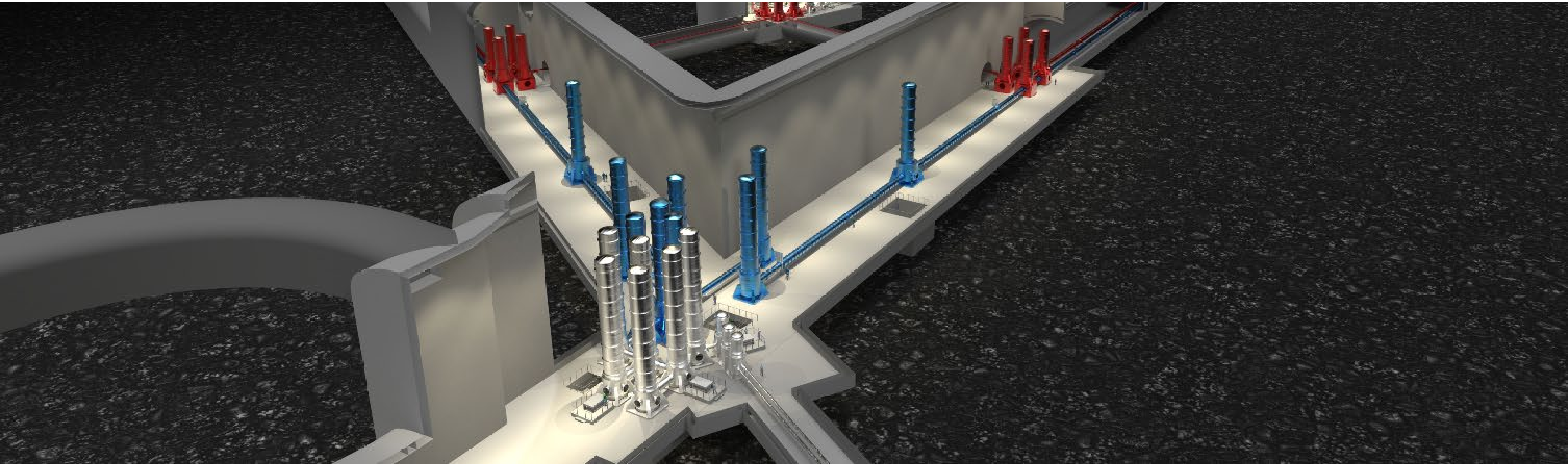
ISB - Active Noise Mitigation:
Effects of Environmental Noises on ET Performance



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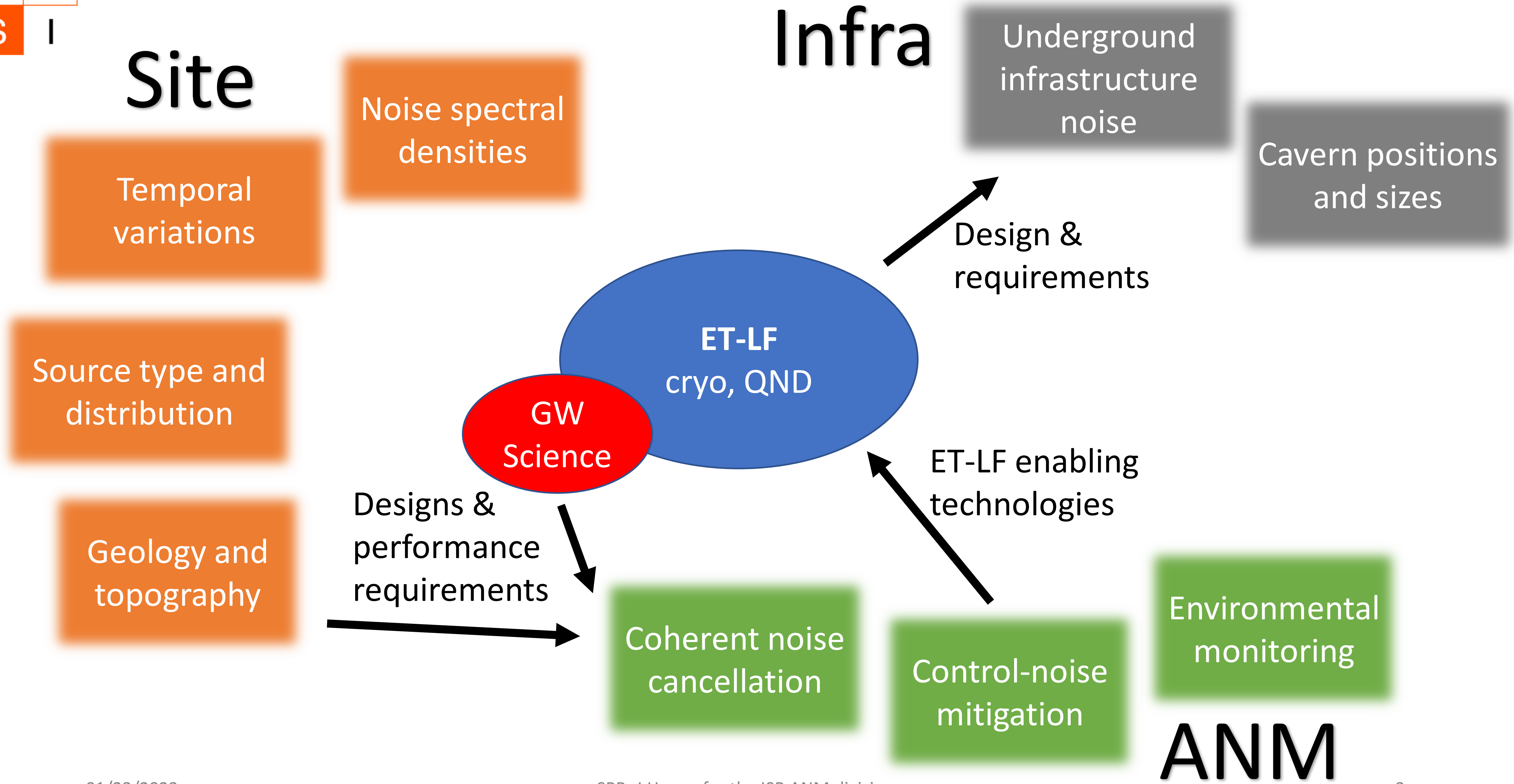
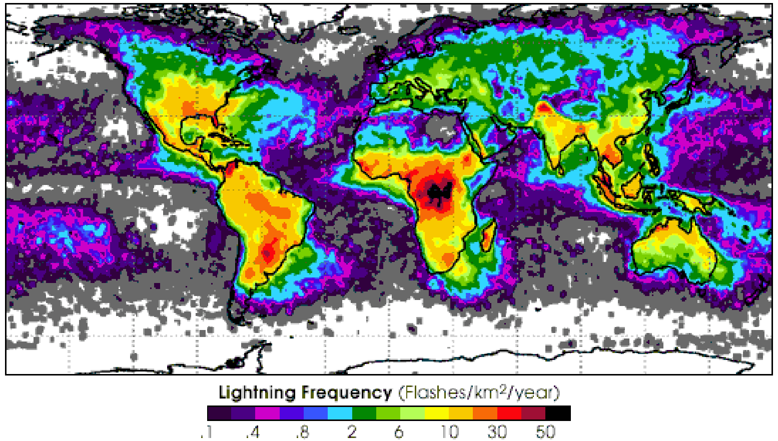
Interest of ISB in Site Quality

- Requirements for environmental noise mitigation (isolation, cancellation, avoiding/eliminating sources)
- Noise from interferometer sensing and control
- Maintaining, losing, regaining interferometer lock (duty cycle)
- Infrastructure limitations

GSSI


Site
Noise spectral densities
Temporal variations
Source type and distribution
Geology and topography
Infra
Underground infrastructure noise
Cavern positions and sizes
Design & requirements
ET-LF
cryo, QND
GW Science
Designs & performance requirements
ET-LF enabling technologies
Coherent noise cancellation
Control-noise mitigation
Environmental monitoring
ANM

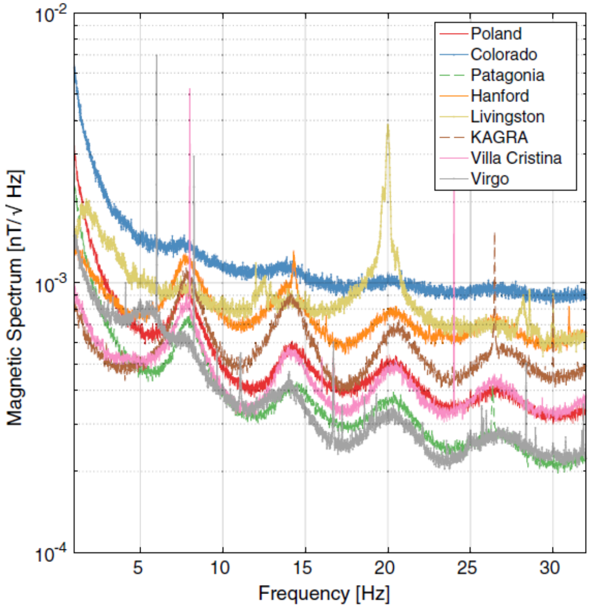
Magnetic Fluctuations



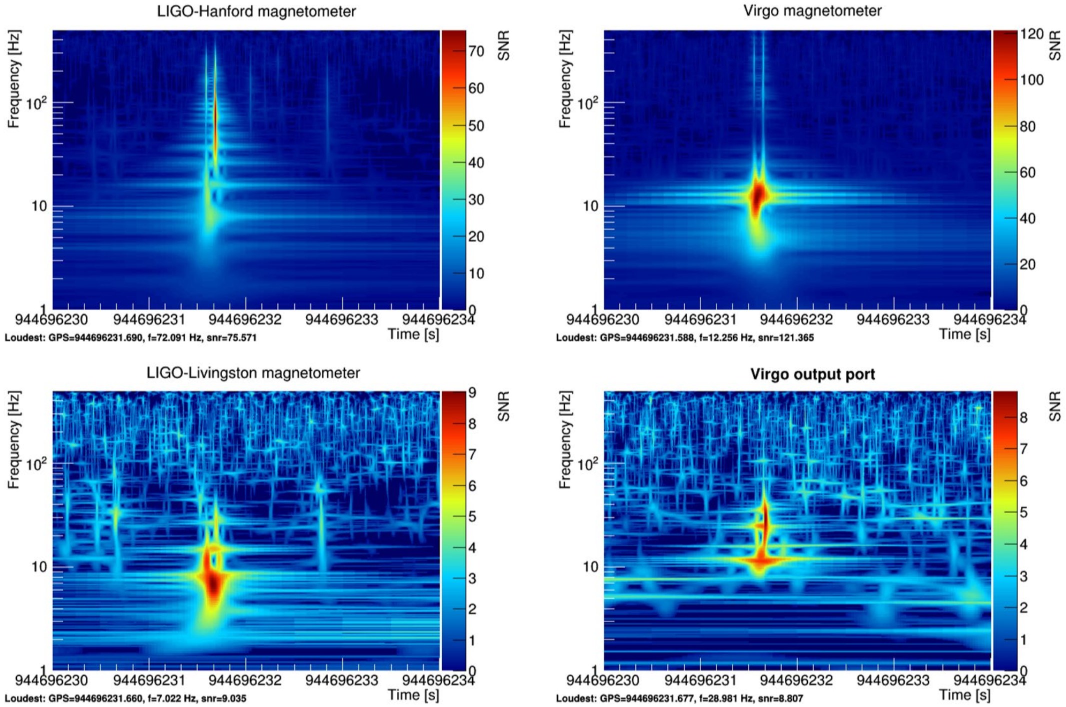
Magnetic disturbances can appear coherently in a global detector network.

Globally coherent disturbances and noise

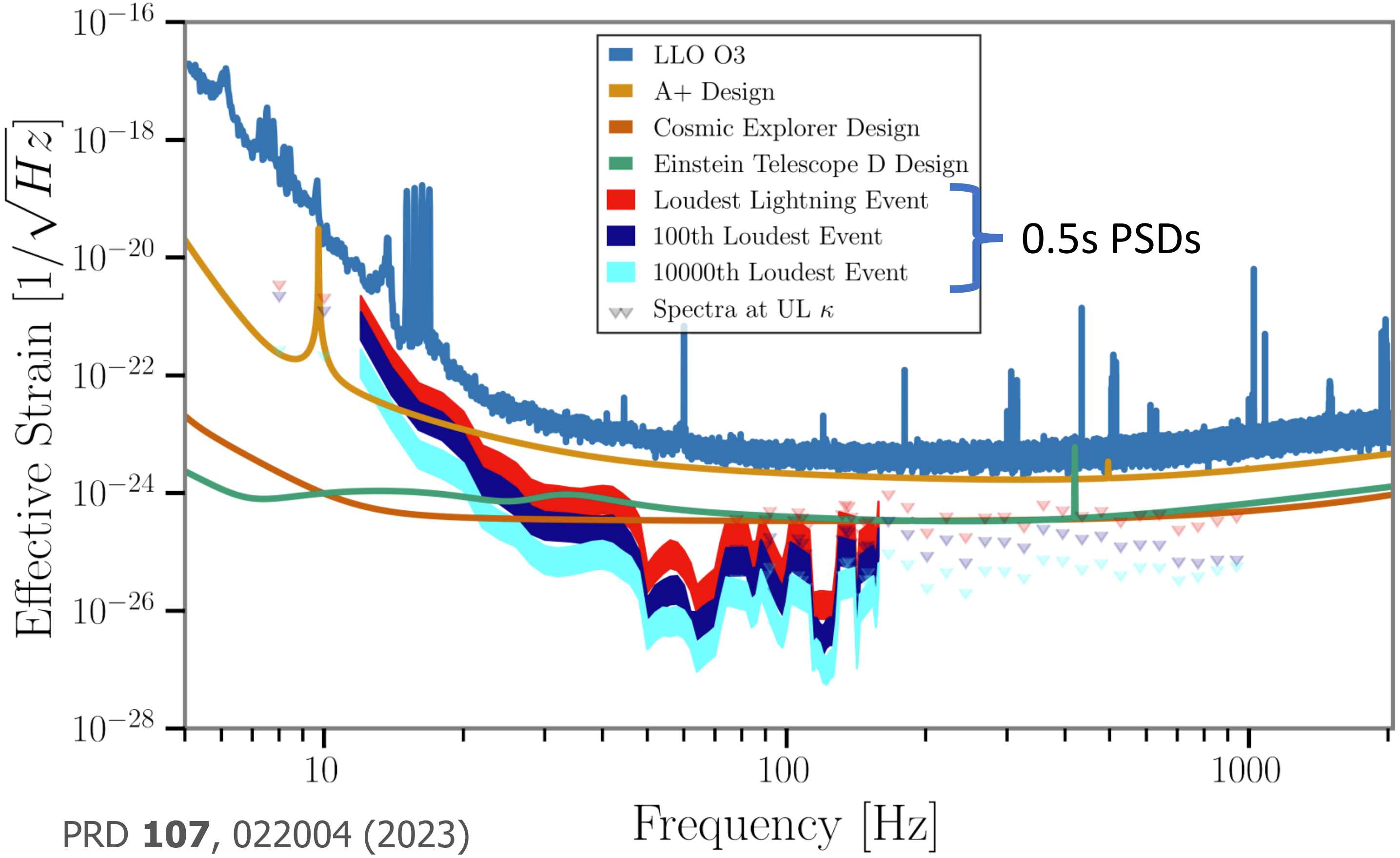
Schumann resonances



Lightning transient appearing in all detectors



Magnetic Noise: Potential ET-LF Show Stopper



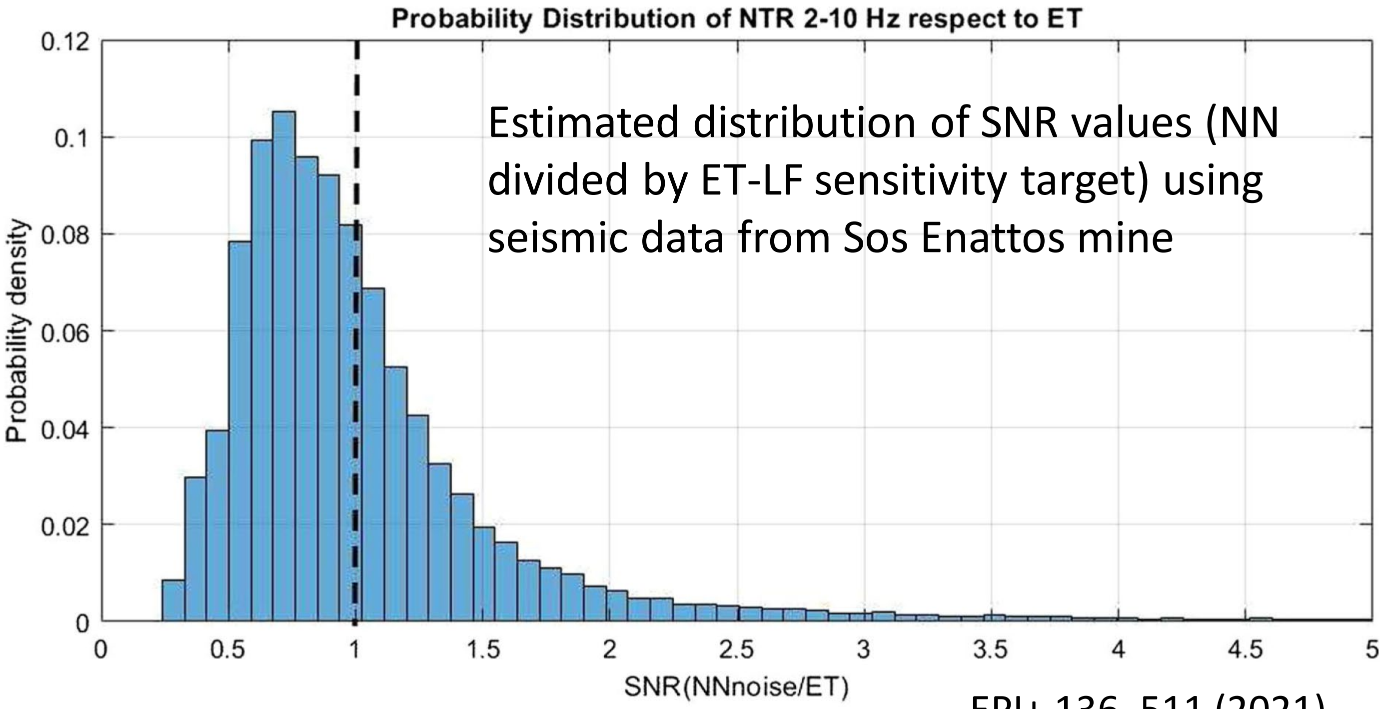
PRD **107**, 022004 (2023)

Schumann resonances as well as a large number of EM-provoked transients would be visible in ET-LF without improved payload design.

Magnetic shielding, noise subtraction, and removing coil actuators from last two suspension stages are proposed mitigation techniques.

Newtonian-noise Transients

Realizing ET-LF at Sardinia without NNC would mean that **of order one million detectable glitches would be produced per year by NN**. Study is required to estimate the number more precisely and the SNR distribution.



EPJ+ 136, 511 (2021)

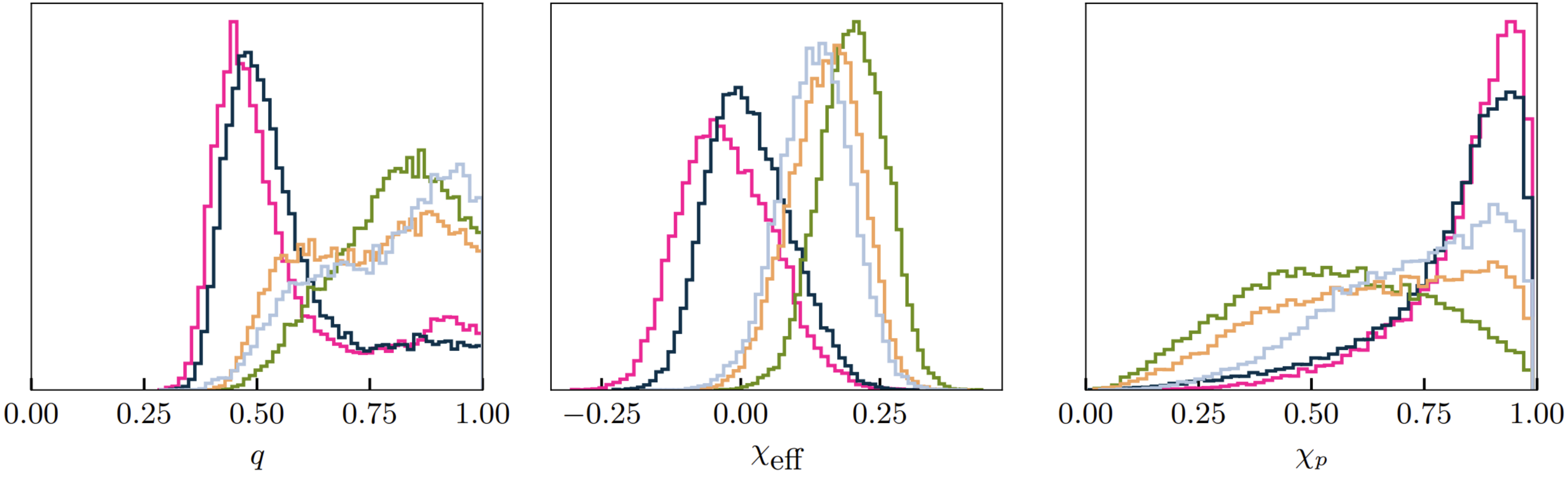
The distribution is calculated using 1min time windows. The distribution maintains its peak-SNR value and **becomes broader if shorter time windows are used**.

While the SNR values need to be recalculated using latest data, the **shape of the distribution is typical**.

More about Glitches

Each glitch needs to be mitigated in ET since GW signals are observed continuously. Each glitch leaves a significant residual.

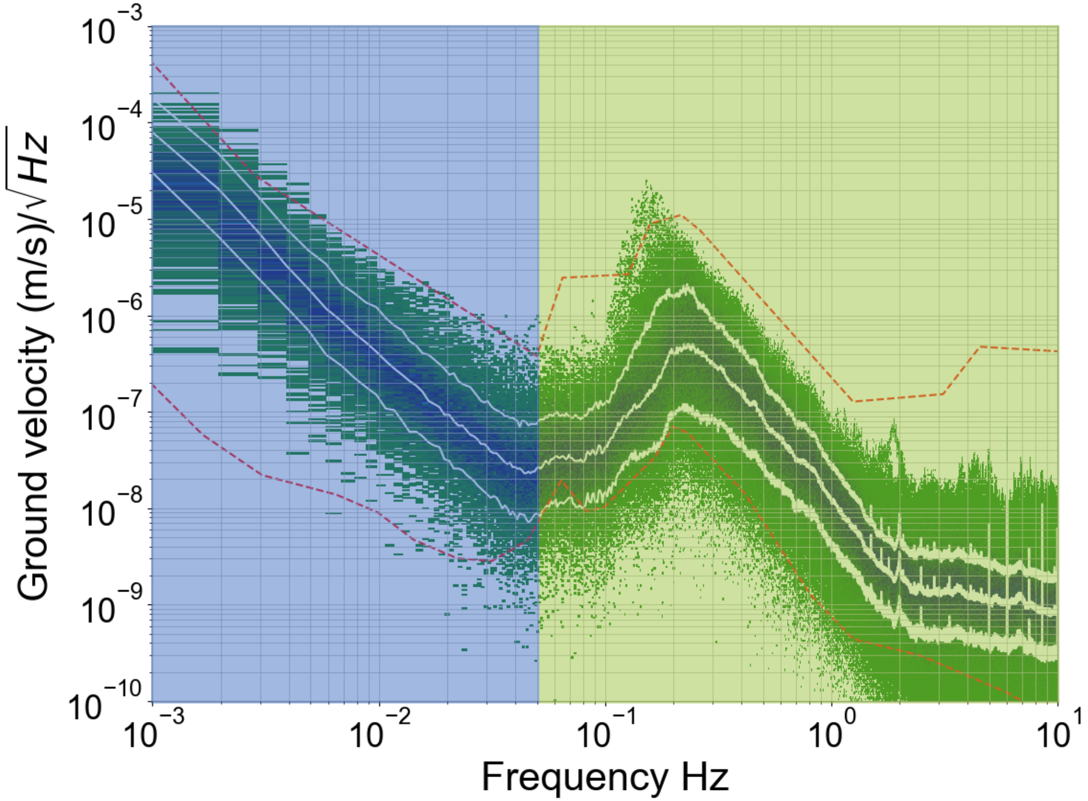
"While our results do not disprove the presence of spin-precession in GW200129, we argue that any such inference is contingent upon the statistical and systematic uncertainty of the glitch mitigation."



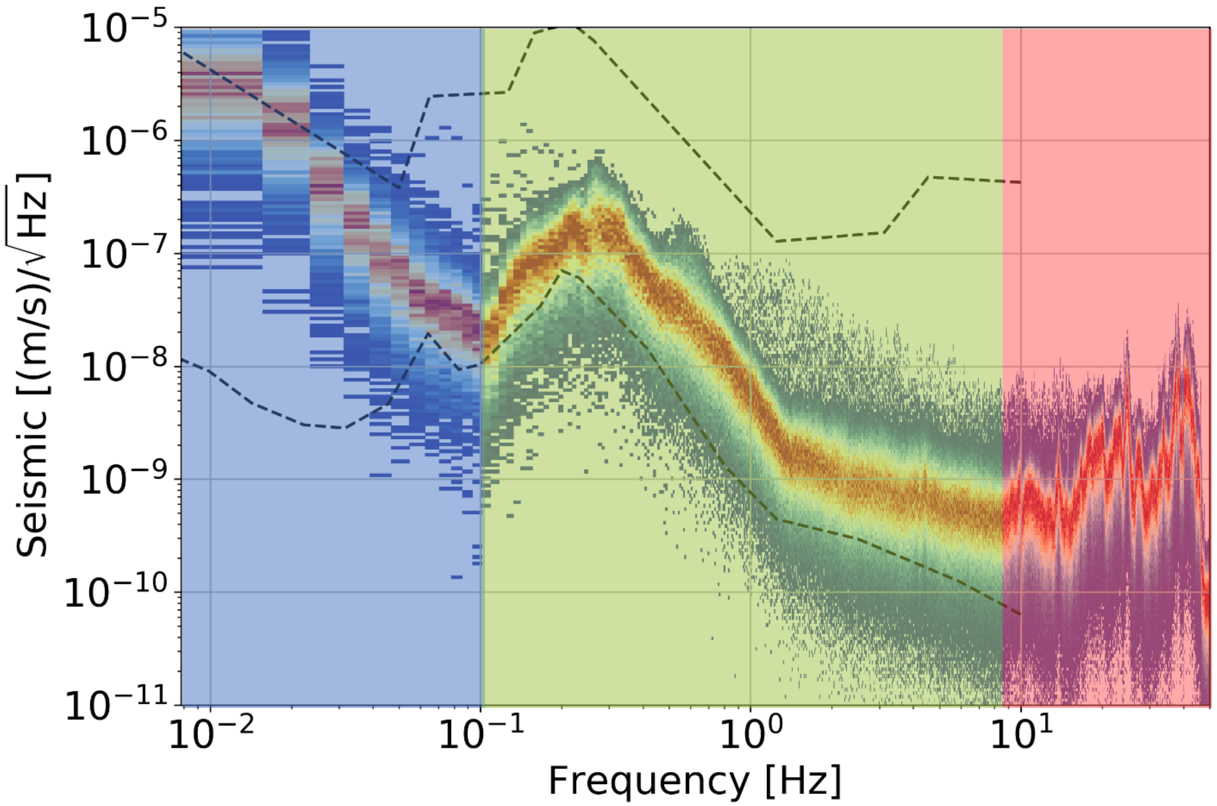
PRD **106**, 104017 (2022)

Seismic Background: KAGRA, LNGS

KAGRA



LNGS

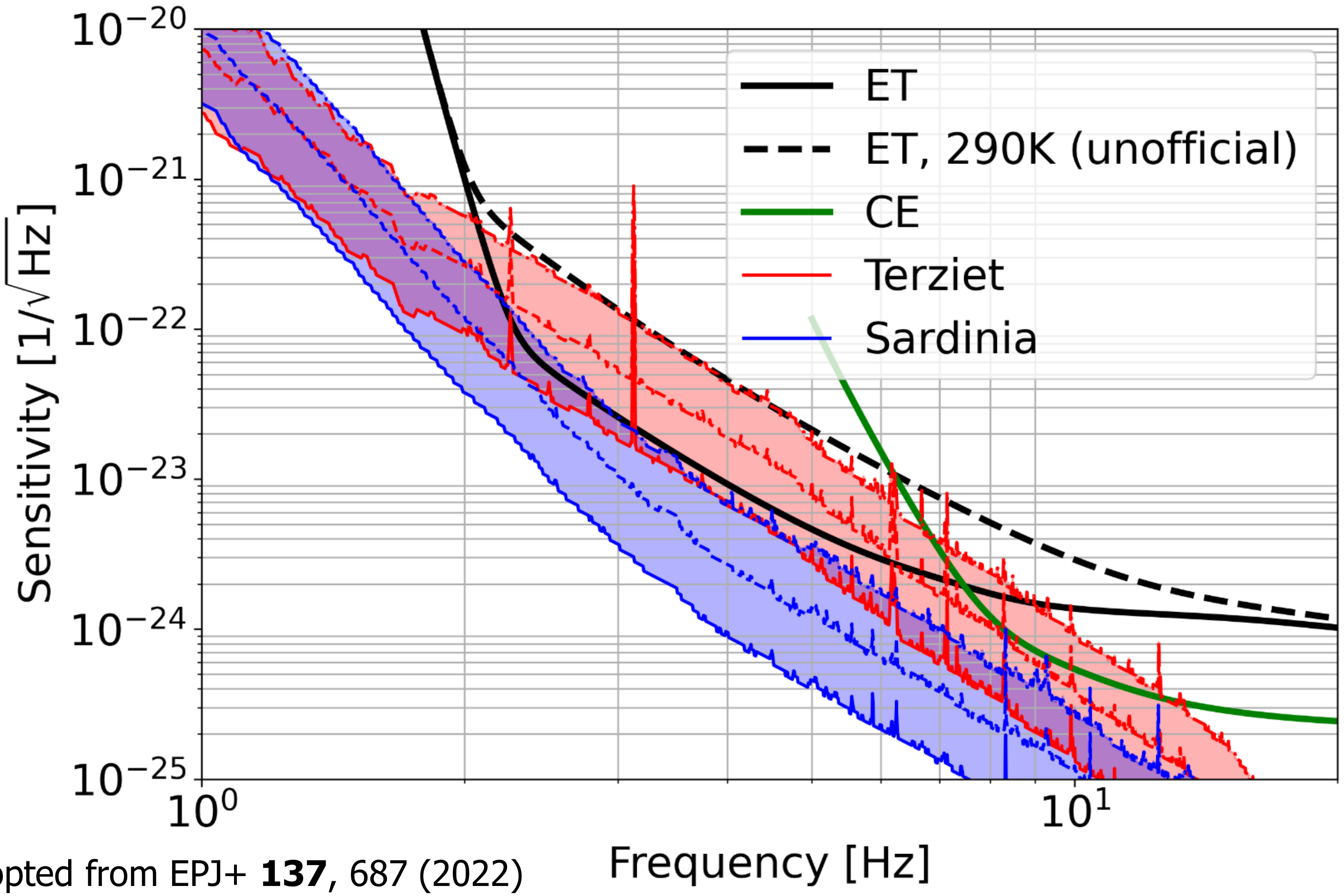


Blue: excess noise, which is probably ground tilt produced by pressure fluctuations [1], but generation mechanism not yet well understood for KAGRA/LNGS

Green: natural low underground seismic noise

Red: excess noise from machines (also present at KAGRA above 10Hz)

ET Newtonian Noise Predictions



Adopted from EPJ+ **137**, 687 (2022)

According to current NN estimates without NNC, Sardinia is compatible with ET-LF @ 10K, while EMR is compatible with ET-LF @ 290K.

The question is, what can we achieve with NNC?

The Optimal Design of a NNC System

1. Is there an optimal type of sensor or an optimal combination of different types of sensors?

2. What are the optimal sensor locations?

3. What is the optimal filter?

Types of Seismic Sensors

Seismometers

Adv: Virgo experience when ET starts operating, 3-axis information
Disadv: Expensive installation, difficult to fix broken sensors, state-of-the-art: one istrument per borehole

Fiber-optic sensors (DAS)

Adv: Probably easier to deploy and maintain, larger number of readout points.
Disadv: Lower correlation with NN [2], single axis

Possible add-on

Distributed sensing system

Tiltmeters

Adv: Maybe helpful in combination with DAS and/or seismometers
Disadv: Can only be deployed at the surface or in caverns

Searching for a Miracle Sensor (Combination)

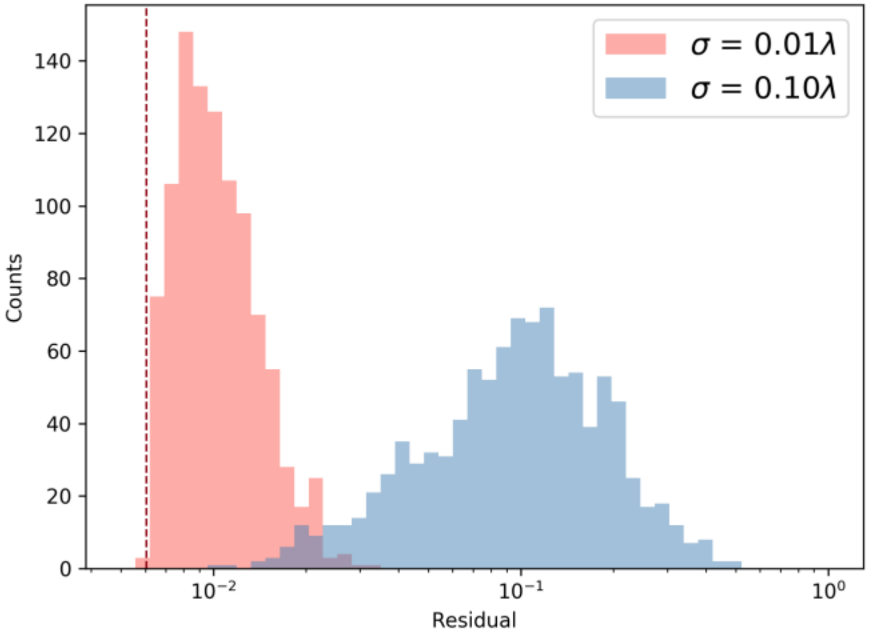
Wave type	$[\xi_x,\xi_y,\xi_z]$	$[\xi_{x,x},\xi_{y,y},\xi_{z,z}]$	$[\xi_{z,x},\xi_{z,y}]$	Gravity, F_x (flat surface, homogeneous medium, small cavern)	Note θ, ϕ: prop. direction
Rayleigh (surf)	$[\cos(\phi), \sin(\phi), \text{const1}]$	$[\cos^2(\phi), \sin^2(\phi), \text{const2}]$	$[\cos(\phi), \sin(\phi)]$	$\cos(\phi)$	$\xi_{z,x}$ optimal since vertical surface displacement is typically dominated by Rayleigh waves
P-wave (ug)	$[\sin(\theta)\cos(\phi), \sin(\theta)\sin(\phi), \cos(\theta)]$	$[\sin^2(\theta)\cos^2(\phi), \sin^2(\theta)\sin^2(\phi), \cos^2(\theta)]$	$[\sin(\theta)\cos(\theta)\cos(\phi), \sin(\theta)\cos(\theta)\sin(\phi)]$	$\sin(\theta)\cos(\phi)$	Generally, the body-wave field is a mix of P and S polarization
SH-wave (ug)	$[-\sin(\theta)\sin(\phi), \sin(\theta)\cos(\phi), 0]$	$[-\sin^2(\theta)\sin(\phi)\cos(\phi), \sin^2(\theta)\sin(\phi)\cos(\phi),0]$	$[0,0]$	$-\sin(\theta)\sin(\phi)$	Generally, the body-wave field is a mix of P and S polarization
SV-wave (ug)	$[\cos(\theta)\cos(\phi), \cos(\theta)\sin(\phi), -\sin(\theta)]$	$[\sin(\theta)\cos(\theta)\cos^2(\phi), \sin(\theta)\cos(\theta)\sin^2(\phi), -\sin(\theta)\cos(\theta)]$	$[-\sin^2(\theta)\cos(\phi), -\sin^2(\theta)\sin(\phi)]$	$\cos(\theta)\cos(\phi)$	Generally, the body-wave field is a mix of P and S polarization

For generic rotation measurements (not just tilt), see [3]

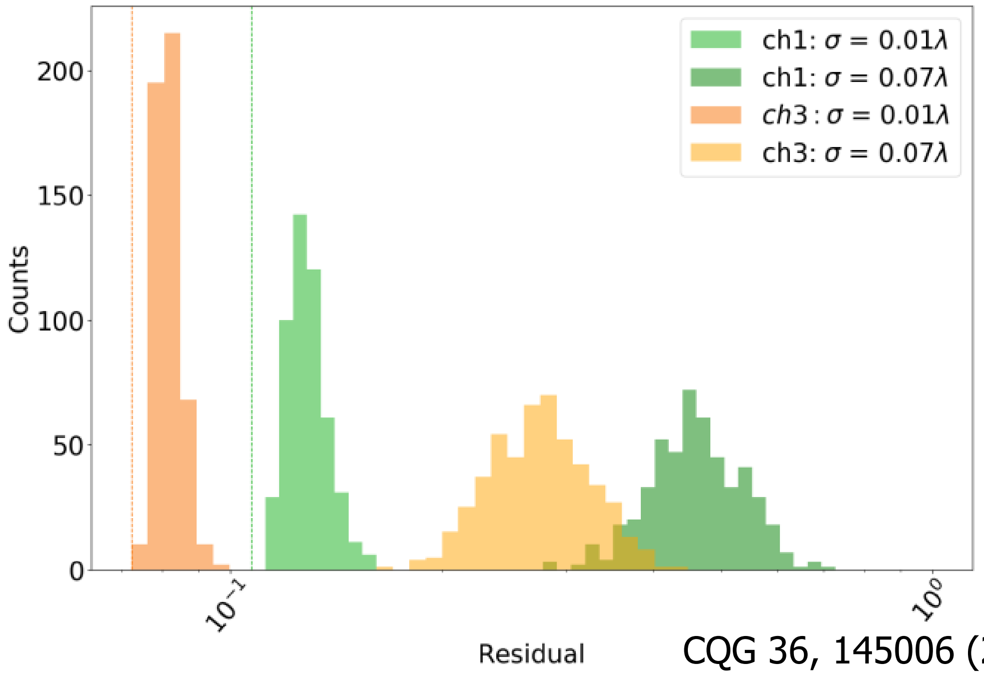
NNC with non-ideal Arrays

Optimized for single frequency, homogeneous ground, isotropic seismic field

Rayleigh-wave analysis

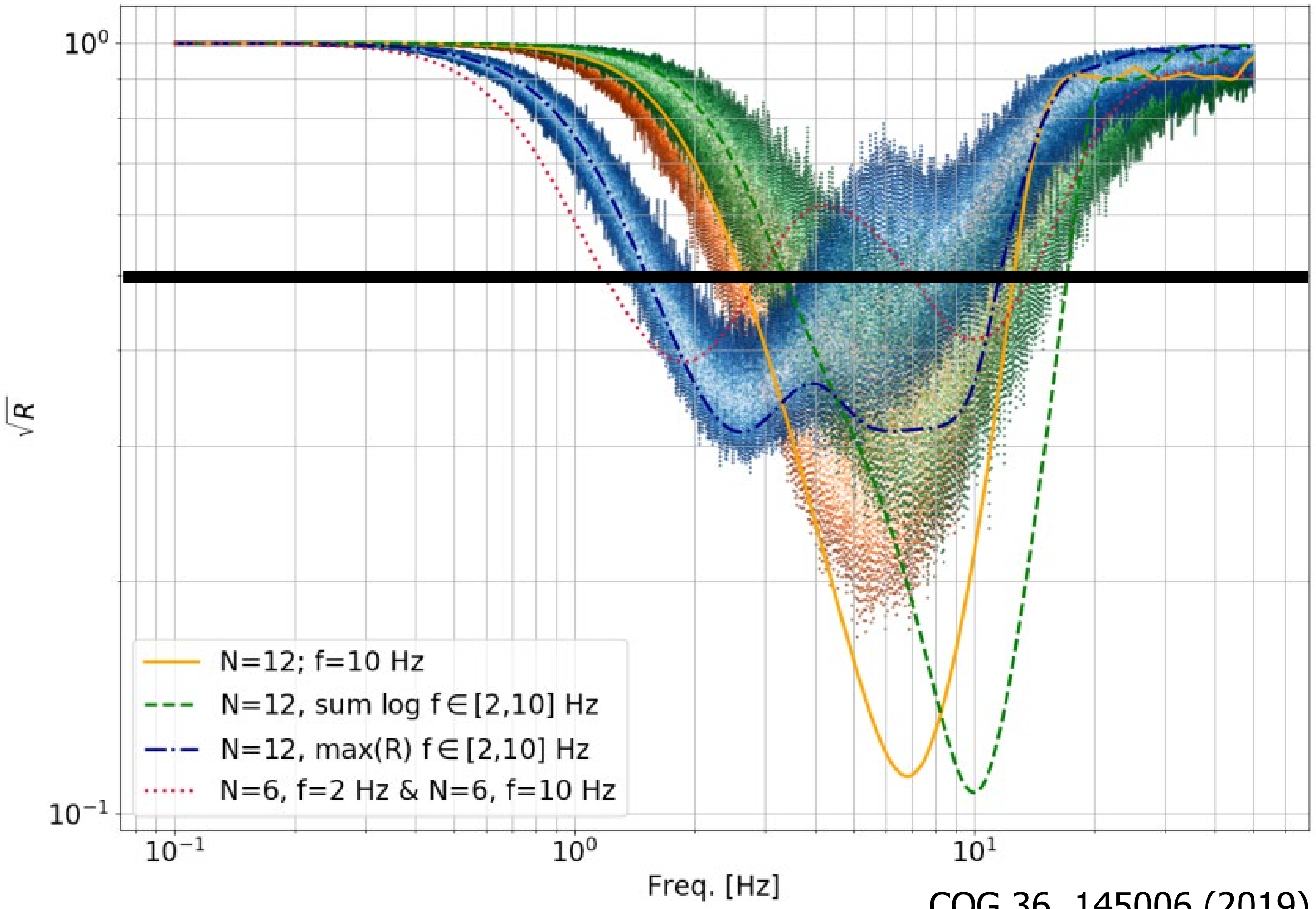


Body-wave analysis



CQG 36, 145006 (2019)

Noise Reduction

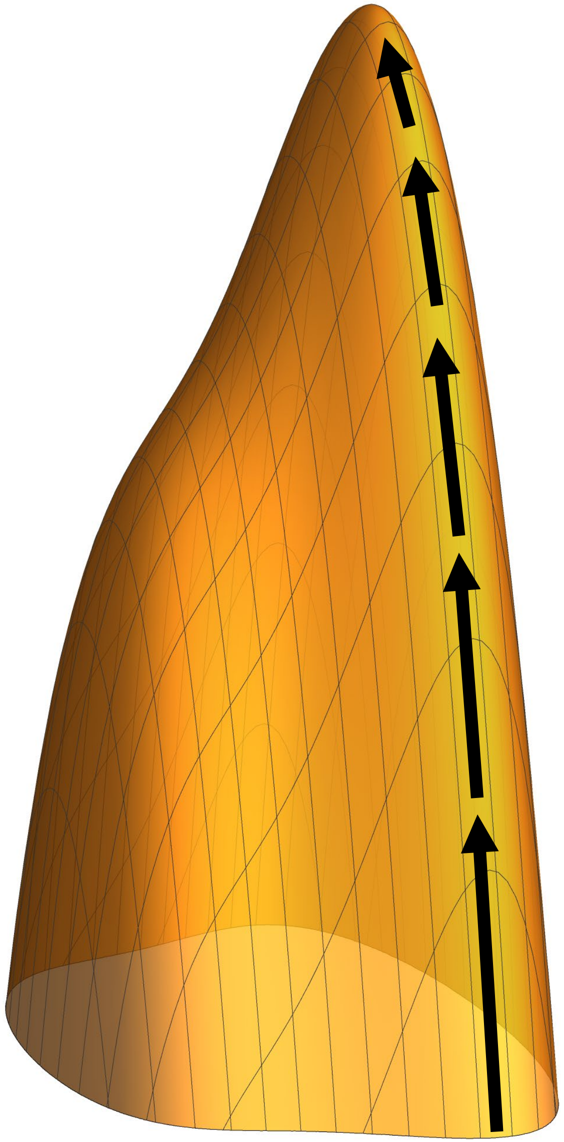


CQG 36, 145006 (2019)

NNC gets more challenging if the noise needs to be mitigated over a broader band.

Example:
NNC system with 12 sensors per test mass (144 in total) cannot guarantee factor 2 at any frequency assuming typical sensor misplacements from optimal positions of <0.1λ.

Detector Control: Climbing up the Hill



The goal of a control can be formulated in terms of a **cost/value function**, which is to be minimized/maximized.

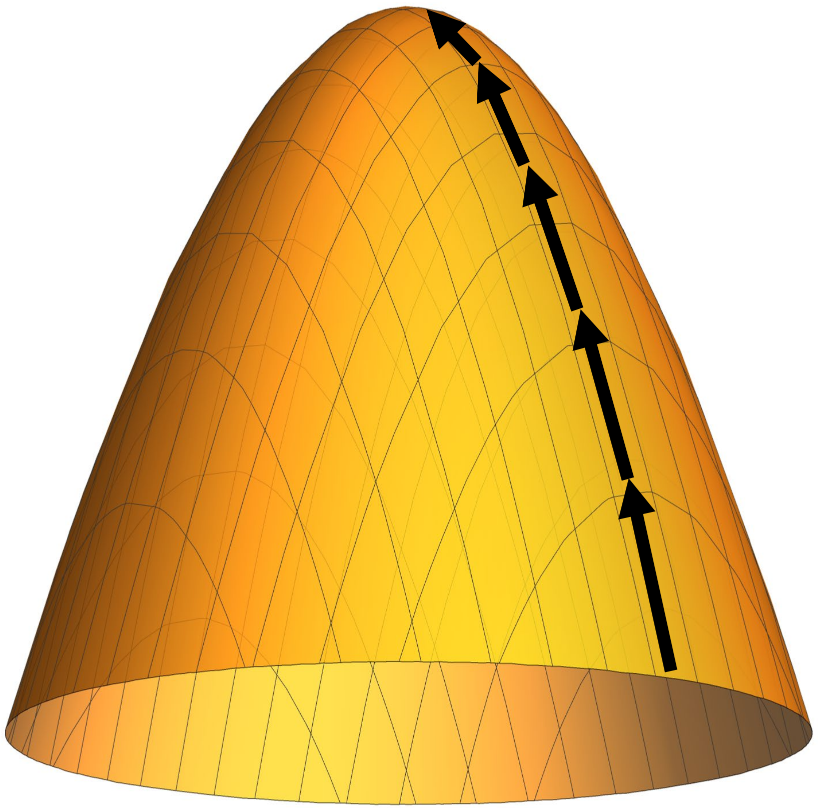
Generally, the **sequence of outputs** of a controller describes a **path on the cost function**.

There is an **optimal controller**, which represents a gradient descent/ascent [4].

The cost function depends on the plant model, on control inputs, and on a **target freely chosen by a human being**.

If the control is feedback, the **plant model may include the controller**.

Optimal Newtonian-noise Cancellation



The cost function is the **detector noise PSD**.

The control is **feedforward**, and so the controller plays no role in the plant model.

The **plant is to a very good approximation linear**: seismic-wave propagation, gravitational coupling to test mass, detector response.

It follows that the **cost function is quadratic**.

It follows that the gradient descent, i.e., the optimal control, is described by a **linear controller**.

The best Newtonian-noise cancellation filter is the Wiener filter.

Really nothing better than Wiener Filters?

You could consider different goals of the noise cancellation (instead of PSD reduction).

For example, what about **time-variant cost functions**? Plant is time-variant, e.g., noise PSDs and correlations between sensors change with time.

Kalman filters and time-variant machine-learning methods can potentially cope better with time-variant plants.

GSSI

A Change of Optimism

One of my slides in 2009 (GWADW in Ft Lauderdale)

UNIVERSITY OF MINNESOTA

The 99% Commitment

We will subtract 99% of the GGN in third-generation detectors.

1. We need to calibrate the strainmeters / dilatometers / seismometers with higher accuracy / precision than 99% (includes dependence on temperature, pressure, …)
2. We need to measure the seismic field with higher accuracy / precision than 99% (STS-2 and T240 cannot)
3. We need to understand the seismic signal better than 99% (analyze different modes)
4. We need to model GGN with input from seismic measurements better than 99%

14 years and 41 Newtonian-noise publications later (apart from the fact that only half of the 4 items on the slide turned out to be correct):

Maybe we will be able to reduce seismic Newtonian noise by a factor 2.

Conclusions

The ET infrastructure will have a several decades-long lifetime, and **sensitivity limitations caused by infrastructure** (set by dimension, geometry, quality) are extremely important to consider in detector planning.

Magnetic noise deserves maximal attention. We don't have any analysis so far to estimate the effectiveness of proposed mitigation techniques. Understanding of magnetic coupling in Virgo/LIGO is incomplete and we cannot promise fail-safe solutions to ET-LF magnetic noise.

There is **no known «solution» to NN**. It will be a major challenge and significant financial and R&D commitment to achieve the modest NN reduction predicted in simulations.

G S
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https://doi.org/10.1111/j.1365-246X.2007.03553.x
[2] Terrestrial Gravity Fluctuations
https://link.springer.com/article/10.1007/s41114-019-0022-2
[3] Six-component seismology: Joint processing of translational and rotational ground-motion
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[4] Optimal and Learning Control for Autonomous Robots
https://doi.org/10.48550/arXiv.1708.09342