Gravitational wave orchestra 17 Sept. 2024

Impact of correlated magnetic noise on directional stochastic gravitational-wave background searches

Presented by Stavros Venikoudis

In collaboration with

Federico De Lillo, Kamiel Janssens, Jishnu Suresh and Giacomo Bruno

Centre for Cosmology, Particle Physics and Phenomenology (CP3),

Universite catholique de Louvain, Louvain-la-Neuve, B-1348, Belgium and

Universiteit Antwerpen, Prinsstraat 13, 2000 Antwerpen, Belgium

stavros.venikoudis@uclouvain.be

Sources of correlated magnetic noise

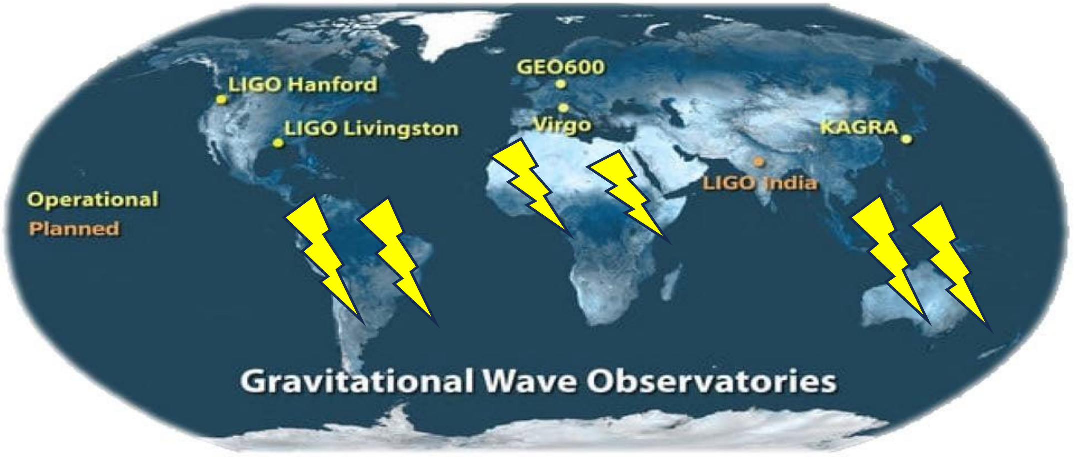
- Schumann resonances (8Hz – 60Hz)

Definition: Electromagnetic excitations formed inside the conducting cavity between the Earth and the ionoshere, generated by atmospheric dischargers.

Characteristic eigenmodes: 7.83Hz, 14.1Hz, 20.3 Hz

$$f_{\text{Schumann}} \simeq \frac{c\sqrt{l(l+1)}}{2\pi R_{\text{Earth}}} \quad \text{where} \quad l = 1, 2, \ldots$$

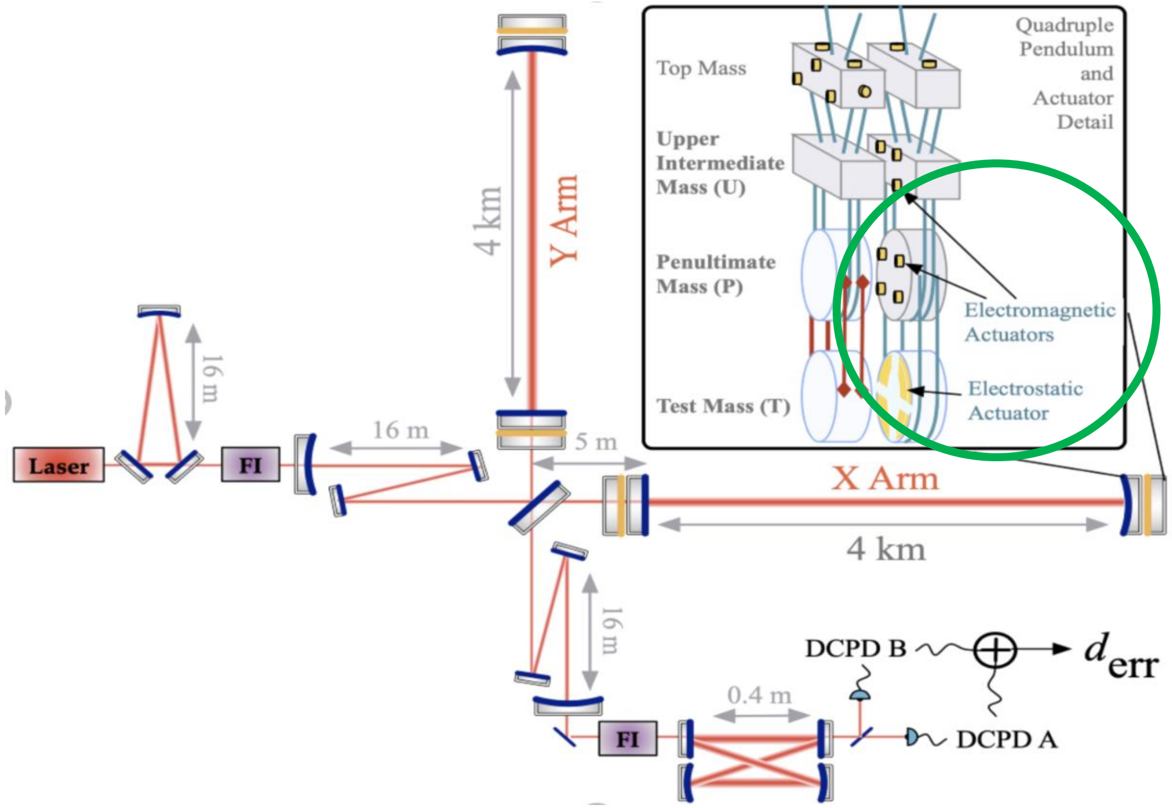
- Superposition of individual lighting strikes

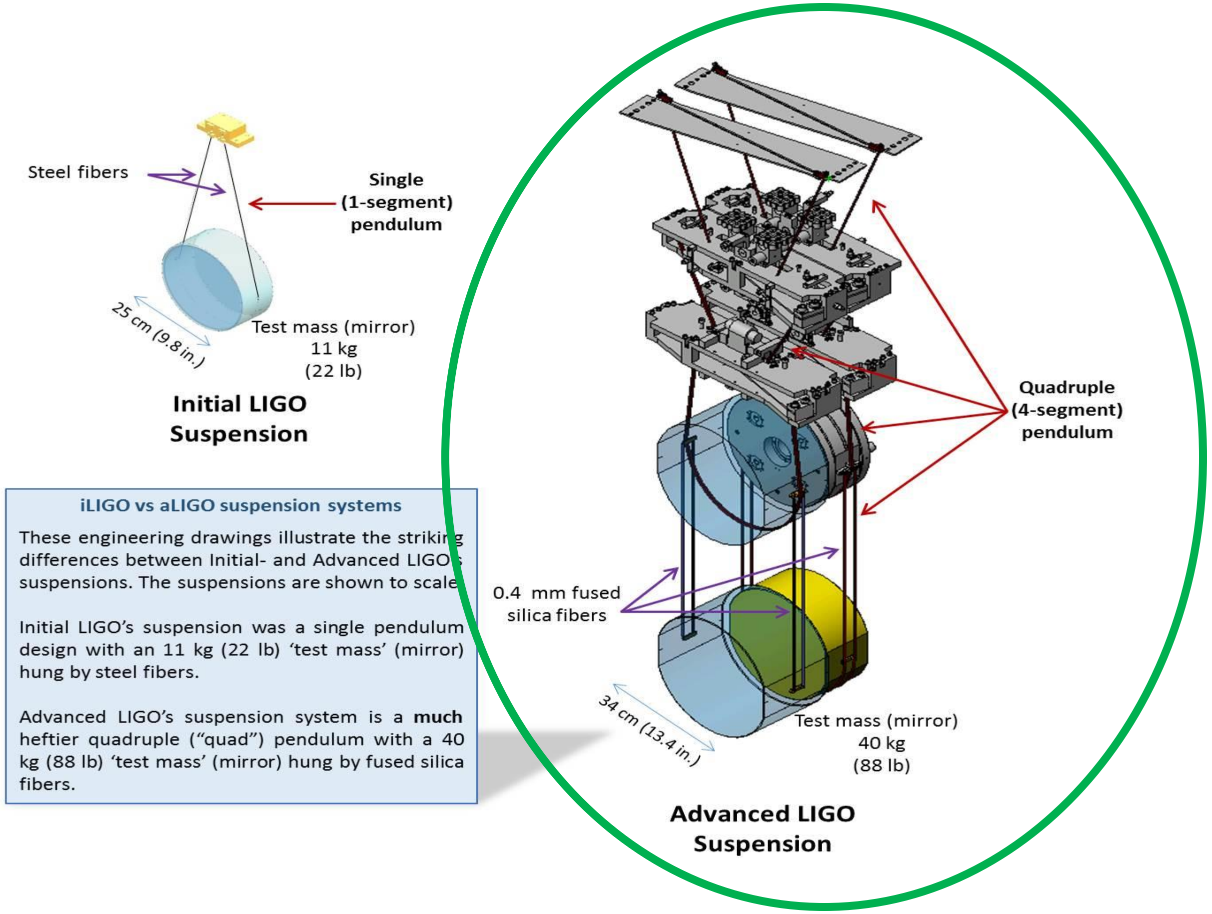


Credits: map GW detectors-LIGO LAB/Virgo, available at ligo.org

Coupling of magnetic fields with GW-strain channels

- Low frequencies: Coupling with permanent magnets of electromagnetic actuators and/or their suspensions





- High frequencies: Interaction with signal cables

Cross-Correlation statistic in the presence of correlated magnetic noise

- Output of detectors

$$\tilde{s}_I(f) = \tilde{h}_I(f) + \tilde{n}_I^{\rm inst}(f) + \tilde{n}_I^{\rm mag}(f)$$

$$\tilde{s}_J(f) = \tilde{h}_J(f) + \tilde{n}_J^{\rm inst}(f) + \tilde{n}_J^{\rm mag}(f)$$

signal Detector noise Correlated magnetic noise

- Expectation value of cross-correlation

0

$$\langle \tilde{s}_{\mathcal{I}}^*(f)\tilde{s}_{\mathcal{J}}(f')\rangle = \langle \tilde{h}_{\mathcal{I}}^*(f)\tilde{h}_{\mathcal{J}}(f')\rangle + \langle \tilde{n}_{\mathcal{I}}^{*\rm inst}(f)\tilde{n}_{\mathcal{J}}^{\rm inst}(f')\rangle + \langle \tilde{n}_{\mathcal{I}}^{*\rm mag}(f)\tilde{n}_{\mathcal{J}}^{\rm mag}(f')\rangle$$

$$\langle \tilde{s}_{\mathcal{I}}^*(f)\tilde{s}_{\mathcal{J}}(f')\rangle = \langle \tilde{h}_{\mathcal{I}}^*(f)\tilde{h}_{\mathcal{J}}(f')\rangle + \langle \tilde{n}_{\mathcal{I}}^{*\rm mag}(f)\tilde{n}_{\mathcal{J}}^{\rm mag}(f')\rangle$$

- We measure the term $\langle \tilde{n}_I^{*\rm mag}(f)\tilde{n}_J^{\rm mag}(f')\rangle$

External magnetometers

- LEMI-120 at LIGO sites and Metronix MFS-06e at Virgo site (labelled i,j).

- Cross-correlation spectra of each magnetometer pair $I_i J_j$ for every GW detector baseline $\mathcal{I} = IJ = \{H, L, V\}$.

$$\tilde{m}_{\mathcal{I}}^{\mathrm{mag}}(f) = \frac{2}{\tau}\left[|(\tilde{m}_{I_i}^{*}\tilde{m}_{J_i})(f)|^2 + |(\tilde{m}_{I_i}^{*}\tilde{m}_{J_j})(f)|^2 + |(\tilde{m}_{I_j}^{*}\tilde{m}_{J_i})(f)|^2 + |(\tilde{m}_{I_j}^{*}\tilde{m}_{J_j})(f)|^2\right]^{1/2}$$

Magnetic coupling function
(from the external magnetometers to GW-strain channel)

Outside to Inside (OTI)

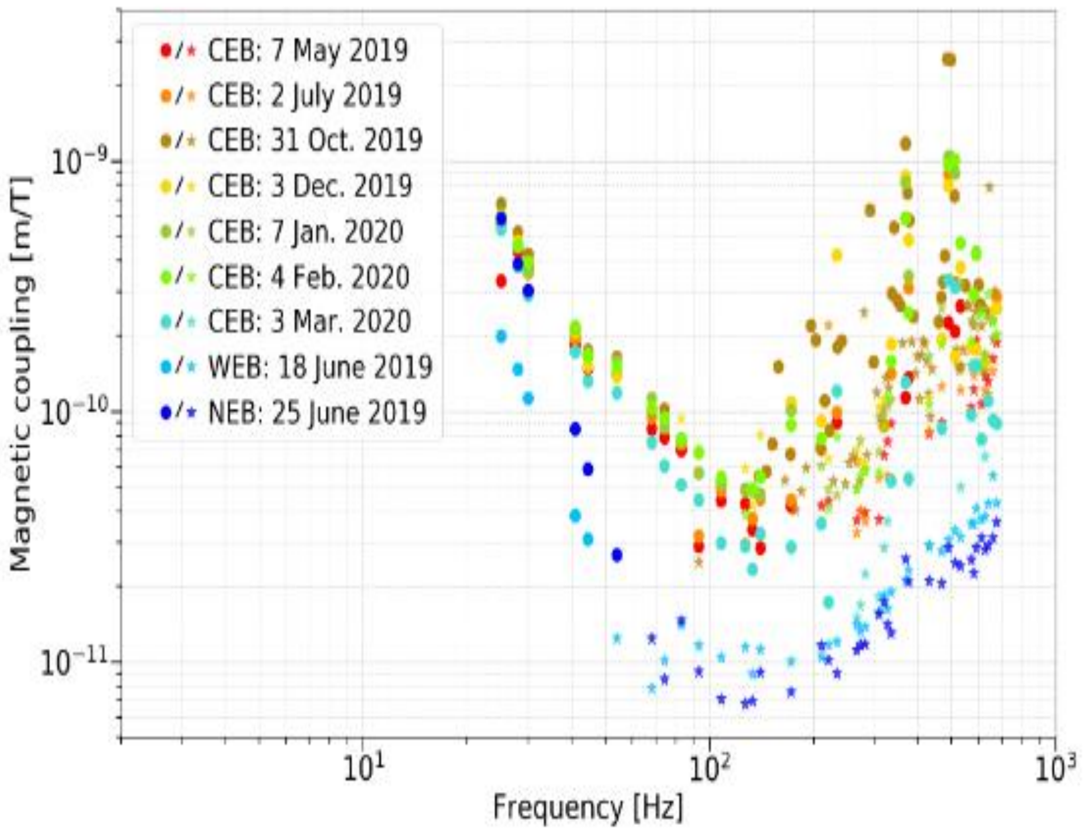
Provides a level of shielding/amplification due to the building structure.

Inside to GW channel (ITC)

Encodes the key coupling features.

Inside to GW-channel coupling function

Measured through environmental noise injections inside the GW buildings.

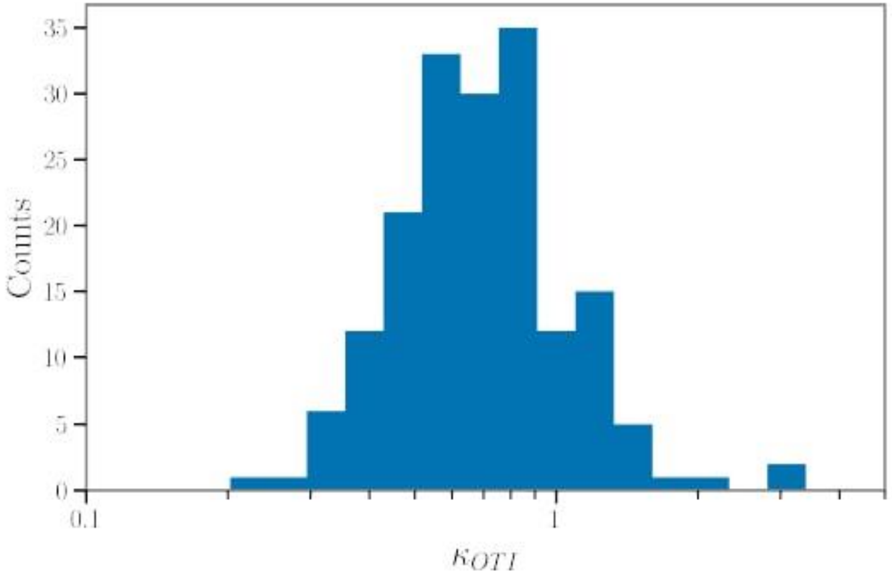


Virgo

- LIGO: Measurements before and after O3 → max. value of every freq. bin
- Virgo: Weekly injection during O3

  → average value

Outside-to-inside coupling function



Distribution of the outside-to-inside magnetic coupling based on 200 events.

Measurement of OTI:

Magnetic fields generated by lightning strikes near Livingston detector.

Log-normal distribution of coupling values with mean value 0.7 nT/nT.

Total magnetic coupling for every detector

$$\kappa_I(f) = \kappa_{I,\mathrm{OTI}}(f) \cdot \kappa_{I,\mathrm{ITC}}(f)$$

Directional searches for SGWB (1)

- Goal: Measure $\Omega_{\mathrm{mag}}(f, \hat{\boldsymbol{n}}) = \dfrac{2\pi^2}{3H_0^2} f^3 \mathcal{P}_{\mathrm{mag}}(f, \hat{\boldsymbol{n}})$

Angular power originating from the correlated magnetic noise term

- Decomposing the effective GW background angular power, induced by correlated magnetic noise in pixel basis,

$$\mathcal{P}_{\mathrm{mag}}(f, \hat{\boldsymbol{n}}) = \sum_{p} \mathcal{P}_{\mathrm{mag}_p}(f) e_p(\hat{\boldsymbol{n}}) \qquad e_p(\hat{\boldsymbol{n}}) = \delta^2(\hat{\boldsymbol{n}} - \hat{\boldsymbol{n}}_p)$$

Pixel number

- The effective angular power spectra $\mathcal{P}_{\mathrm{mag}}(f, \hat{n})$ can be measured by using as statistic the maximum likelihood estimator.

$$\hat{\boldsymbol{\mathcal{P}}}_{\mathrm{mag}}(f) = \boldsymbol{\Gamma}_{\mathrm{gw}}(f)^{-1} \boldsymbol{X}_{\mathrm{mag}}(f)$$

Directional searches for SGWB (2)

- Dirty map $$X^{\mathcal{I}}_{\mathrm{mag}_p}(f) = \tau \Delta f Re \sum_t \frac{\gamma^{\mathcal{I}*}_{ft,p} \tilde{m}^{\mathrm{mag}}_{\mathcal{I}}(f)}{P_I(t;f) P_J(t;f)} \mid \kappa_I(f) \mid\mid \kappa_J(f) \mid$$

Power spectral density

- Fisher matrix $$\Gamma^{IJ}_{\mathrm{gw}_{pp'}}(f) = \frac{\tau \Delta f}{2} Re \sum_t \frac{\gamma^{IJ*}_{ft,p} \gamma^{IJ}_{ft,p'}}{P_I(t;f) P_J(t;f)}$$

- Overlap reduction function $$\gamma^{\mathcal{I}}_{ft,p} = \sum_A F^A_I(\hat{\boldsymbol{n}}, t) F^A_J(\hat{\boldsymbol{n}}, t) e^{2\pi f \hat{\boldsymbol{n}} \cdot \boldsymbol{\Delta x_{\mathcal{I}}}(t)/c}$$

Antenna pattern functions

A={+,x}

Directional searches for SGWB (3)

Adding more baselines significantly enhances the search results as more blind spots due to the antenna pattern functions of detectors are covered.

$$X_{\rm mag}^{\rm HLV}(f,\hat{\boldsymbol{n}}) = \sum_{IJ} X_{\rm mag}^{IJ}(f,\hat{\boldsymbol{n}}), \qquad \Gamma^{\rm HLV}(f,\hat{\boldsymbol{n}}) = \sum_{IJ} \Gamma_{\rm gw}^{IJ}(f,\hat{\boldsymbol{n}}),$$

$$\hat{\mathcal{P}}_{\rm mag}^{\rm HLV}(f,\hat{\boldsymbol{n}}) = \Gamma^{\rm HLV}(f,\hat{\boldsymbol{n}})^{-1} X_{\rm mag}^{\rm HLV}(f,\hat{\boldsymbol{n}}) \qquad \sigma_{\hat{\boldsymbol{n}}}(f) = [\Gamma_{\hat{\boldsymbol{n}},\hat{\boldsymbol{n}}}(f)]^{-1/2}$$

Sky pixelization

Tool: Hierarchical Equal Area isoLatitude Pixelization (HEALPix)

Paramater: $N_{\rm side} = 8$ $\quad N_{\rm pixel} = 12 N_{\rm side}^2 = 768$

Results

Estimation of the impact of correlated magnetic noise on:

1. All-sky, all-frequency (ASAF) directional searches

2. Broadband (BBR) searches

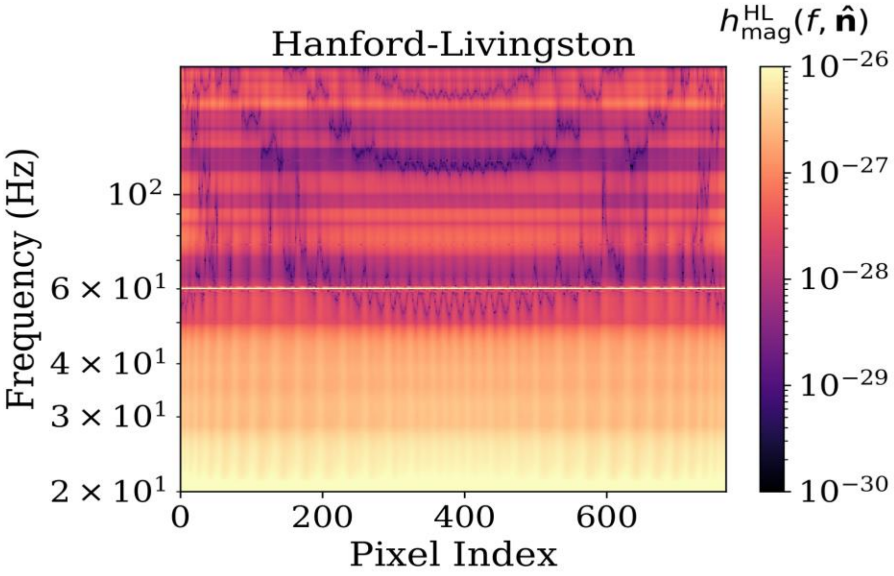
3. Isotropic searches

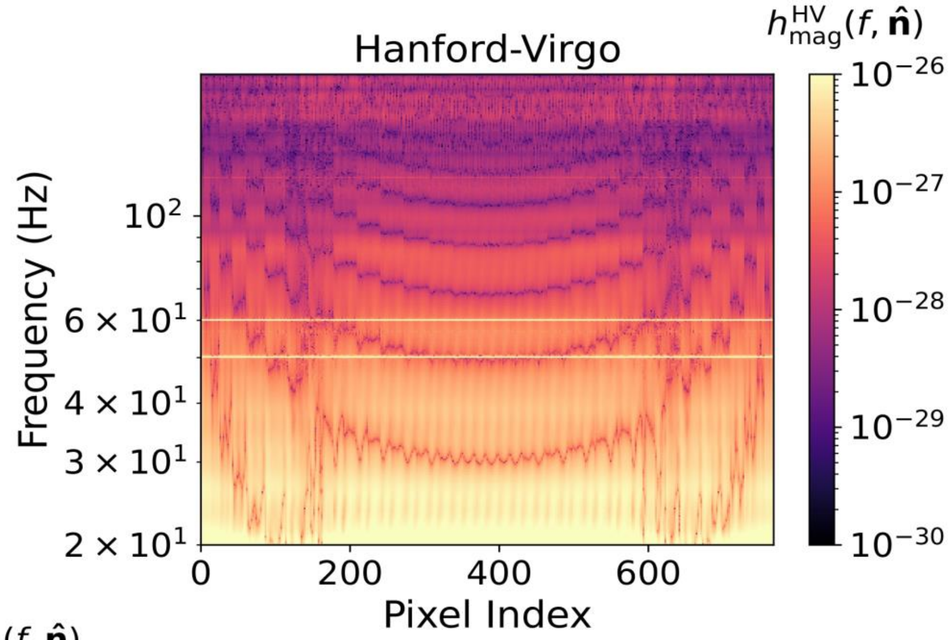
Impact on ASAF directional SGWB searches

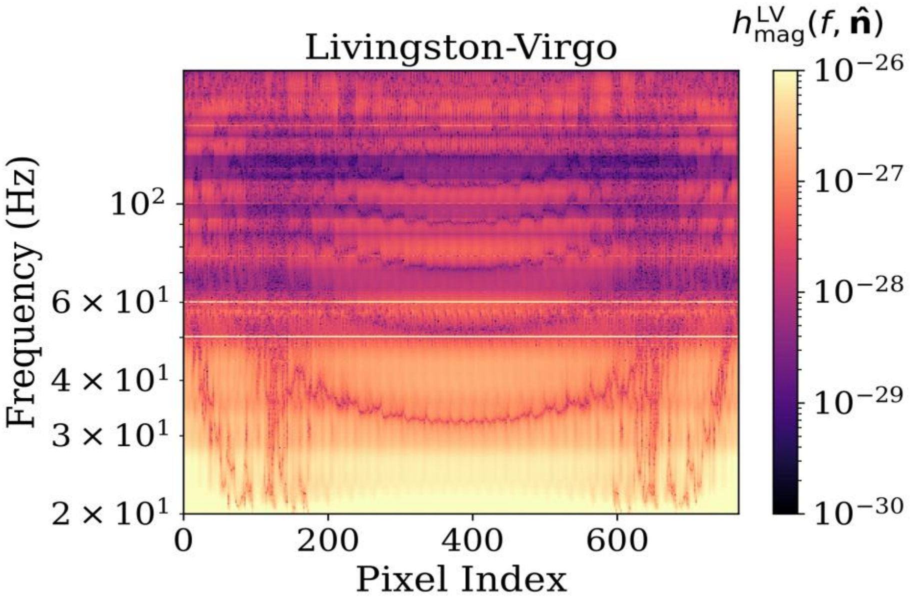
- ASAF : Unmodeled search for unknown persistent signals in narrow frequency bins.

- Effective GW strain of magnetic origin $h_{\mathrm{mag}}(f, \hat{\boldsymbol{n}}) = \sqrt{\mathcal{P}_{\mathrm{mag}}(f, \hat{\boldsymbol{n}}) \Delta f}$

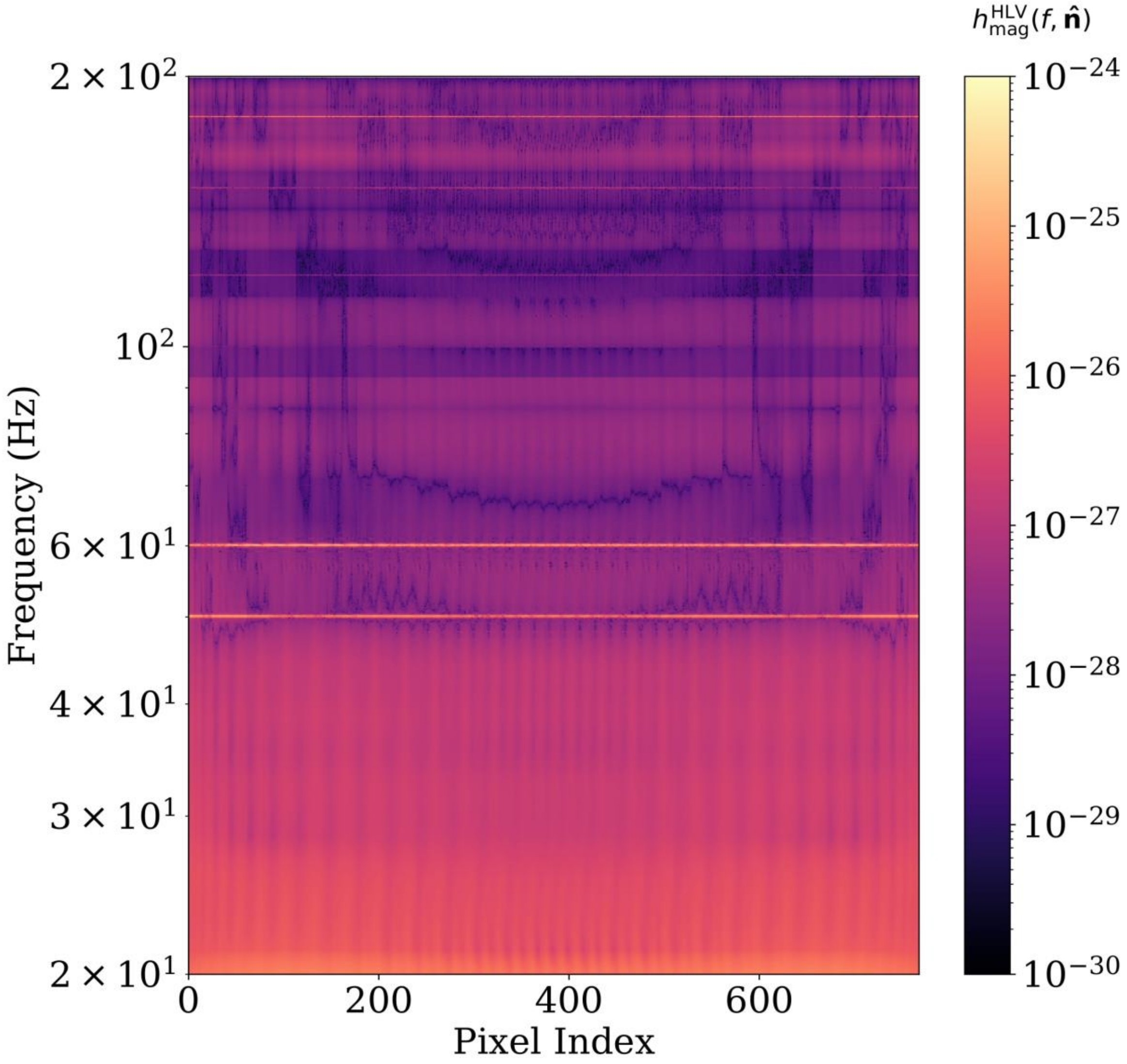
Effective GW-strain induced by correlated magnetic noise



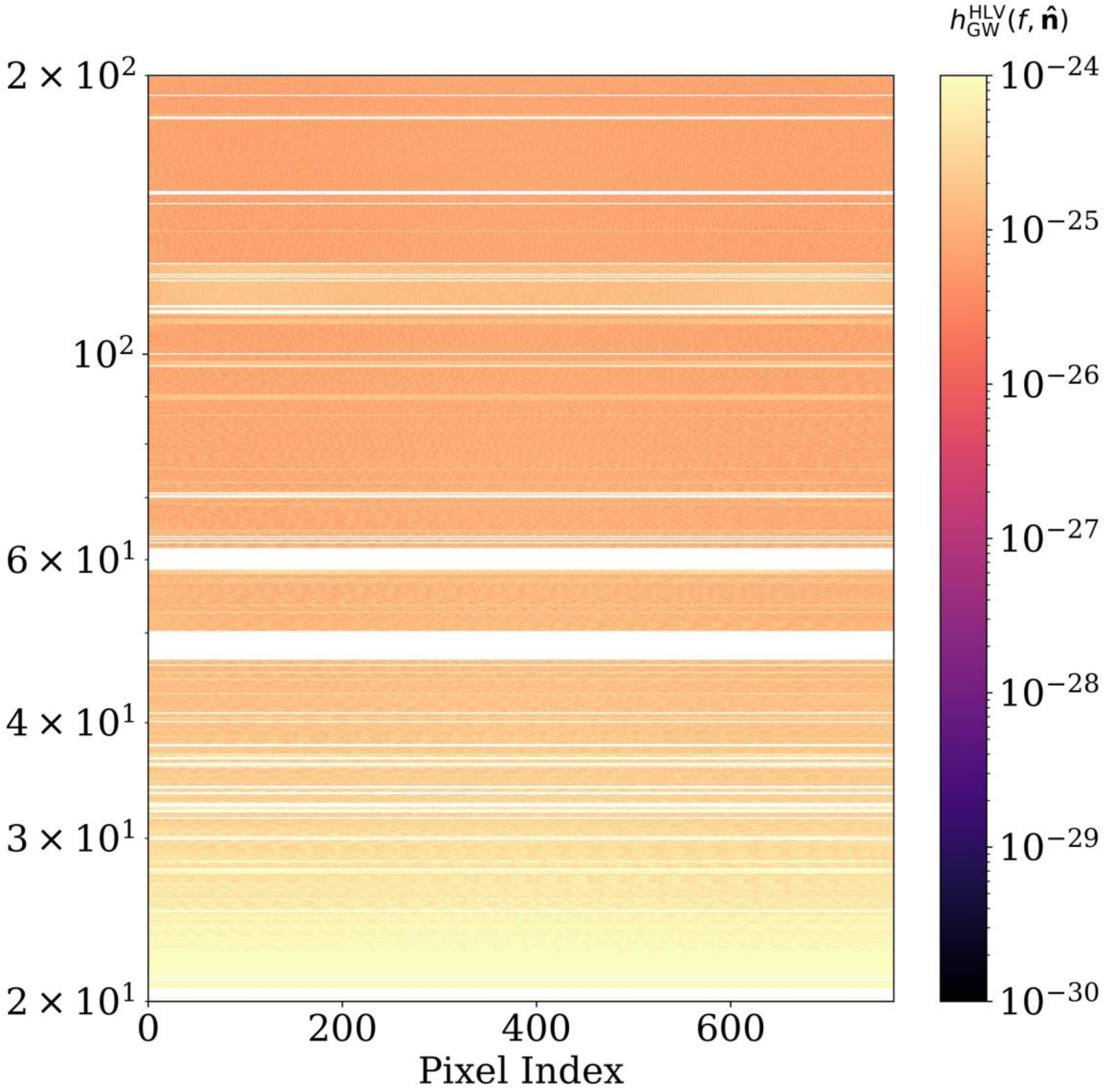




Impact on ASAF directional SGWB searches

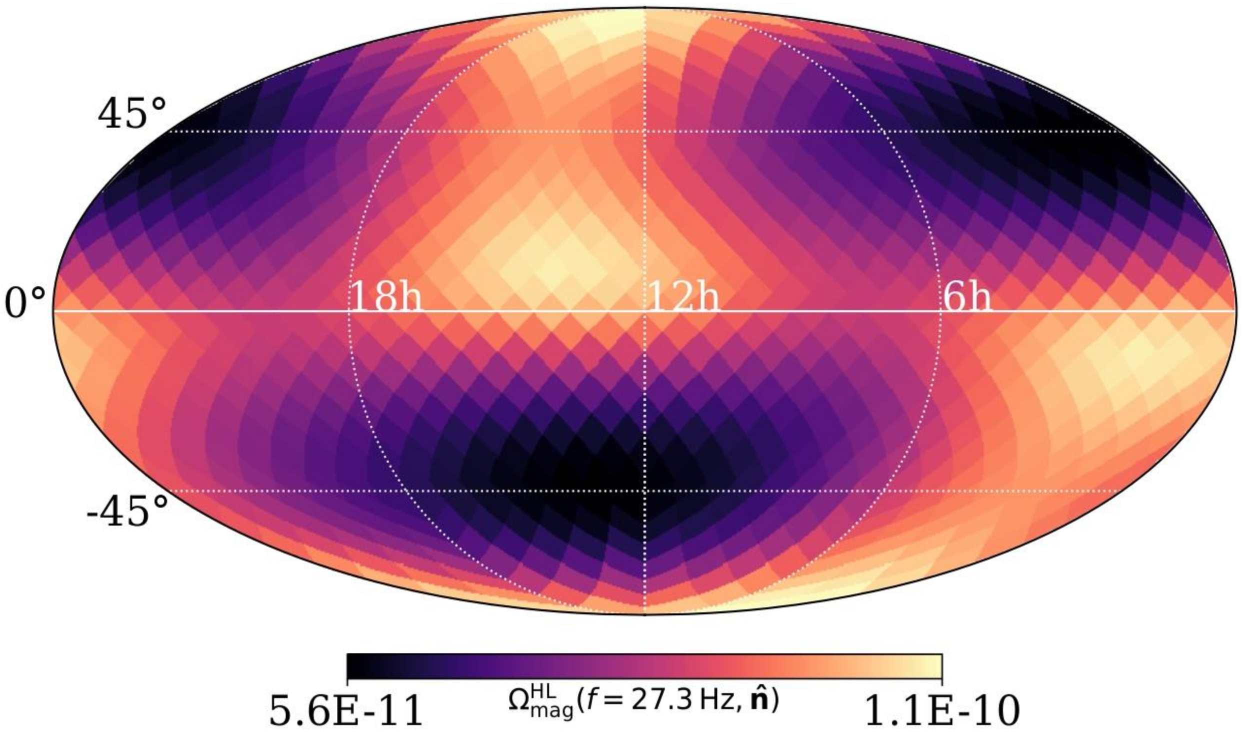


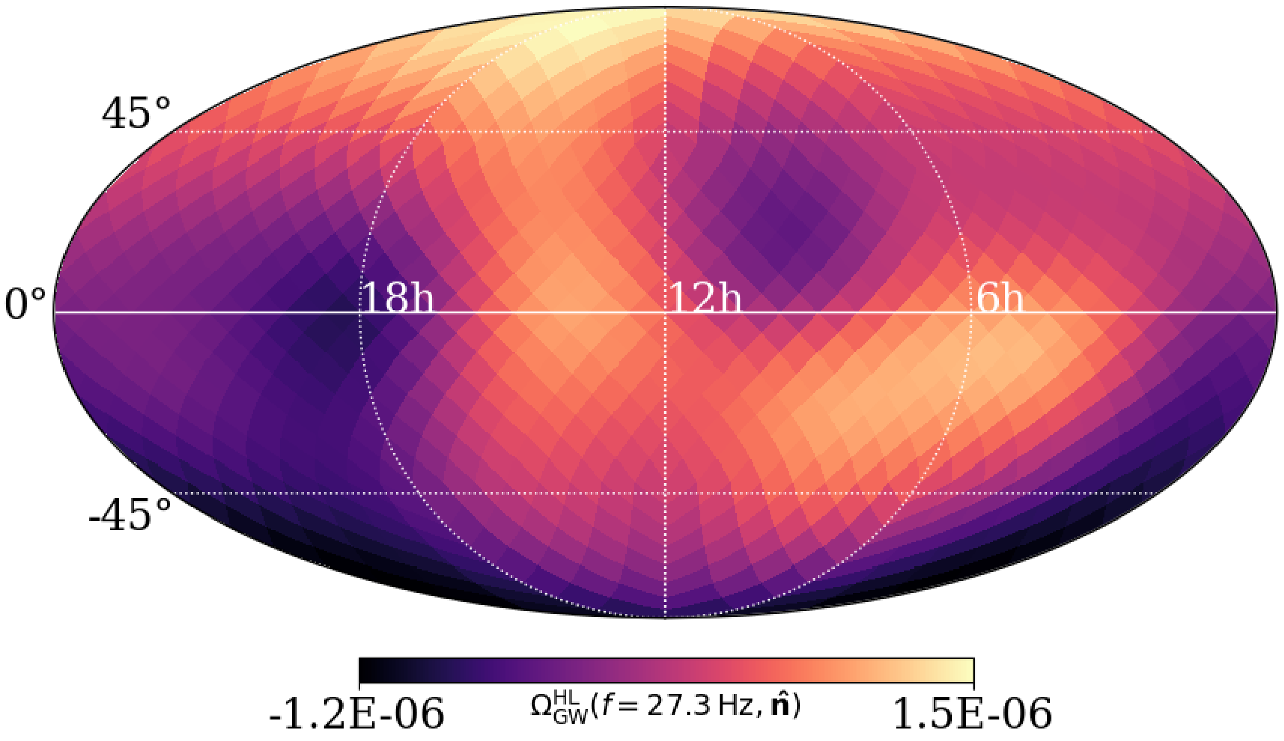
Effective GW strain induced by magnetic correlated noise



95 % U.L. h_{gw} from O3 run

4th Schumann resonance peak of 27.3 Hz





Intensity of the effective GW energy density as Mollweide projection of the sky in equatorial coordinates at 27.3 Hz for HL baseline (left sky map) and GW energy density on the right.

Impact on Broadband Radiometer searches

- Motivation: The broad-band radiometer (BBR) search is focused on sources that emit GWs over a wide frequency band.

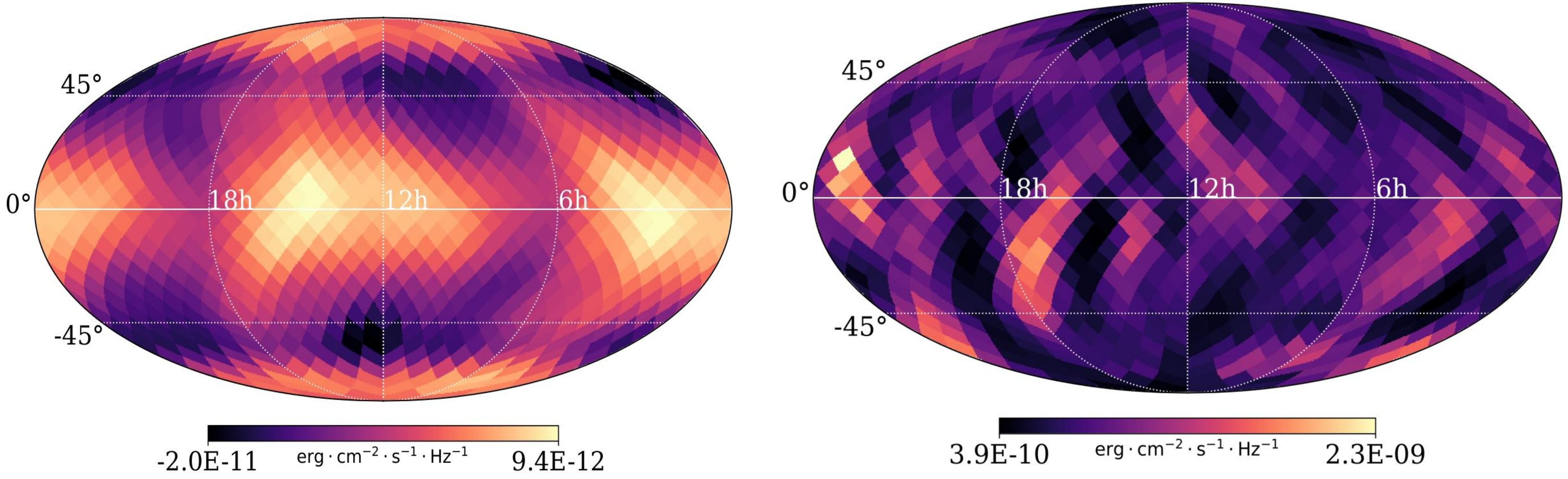
- Schumann resonances have broad-band features (8 – 60 Hz)

- We apply a discrete integration to the effective anisotropic estimator over the entire frequency range 20-200Hz.

$$\hat{\mathcal{P}}_{\rm mag}(f_{\rm ref},\,\hat{\boldsymbol{n}}) = \frac{\sum_f \hat{\mathcal{P}}_{\rm mag}(f,\hat{\boldsymbol{n}})\sigma_{\hat{\boldsymbol{n}}}^{-2}(f)H_{\rm mag}(f)}{\sum_f \sigma_{\hat{\boldsymbol{n}}}^{-2}(f)H^2_{\rm mag}(f)} \quad H_{\rm mag}(f) = \frac{\Omega_{\rm mag}(f)}{\Omega_{\rm mag}(f_{\rm ref})}\left(\frac{f}{f_{\rm ref}}\right)^{-3}$$

- Effective GW flux in every sky direction $\mathcal{F}_{\rm mag}(\hat{\boldsymbol{n}}) = \frac{c^3\pi}{4G} f_{\rm ref}^2 \mathcal{P}_{\rm mag}(\hat{\boldsymbol{n}})$

Impact on Broadband Radiometer searches



$\mathcal{F}_{\rm mag}(\hat{\boldsymbol{n}})$ $\quad f_{\rm ref} = 25{\rm Hz}$ $\quad \mathcal{F}_{\rm gw}^{95\%,{\rm UL}}(\hat{\boldsymbol{n}})$

Comparison between the effective GW flux from correlated magnetic noise measurements (left sky map) with the broadband flux of strain (right sky map) for the LVK detector network. The right sky map of the GW flux corresponds to a flat power spectral density labelled with α=3.

Impact on Isotropic SGWB-searches

- Isotropic effective GW estimator induced by correlated magnetic noise

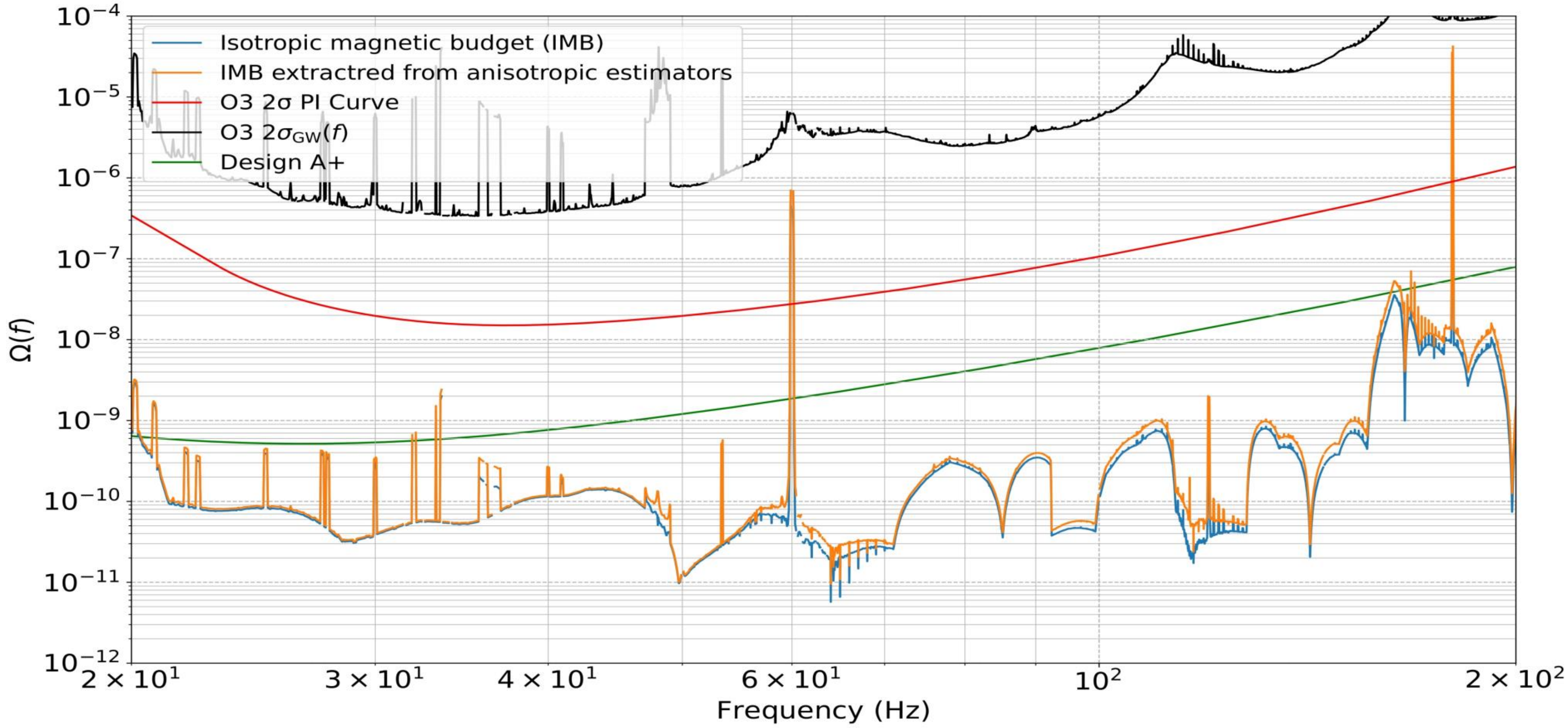
$$\hat{\mathcal{P}}_{\rm iso}\sigma^2_{\rm iso}(f) = \frac{5}{4\pi}\int d\hat{\boldsymbol{n}}\hat{\mathcal{P}}_{\rm mag}(f,\hat{\boldsymbol{n}})\sigma^{-2}_{\hat{\boldsymbol{n}}}(f)$$

$$\sigma^{-2}_{\rm iso}(f) = (\frac{5}{4\pi})^2\int d\hat{\boldsymbol{n}}\int d\hat{\boldsymbol{n}}'\Gamma_{\hat{\boldsymbol{n}},\hat{\boldsymbol{n}}'}(f)$$

Full fisher matrix

$$d\hat{\boldsymbol{n}} = 4\pi/N_{\rm pix}$$

Isotropic magnetic budget



Reference: Kamiel Janssens et al. Correlated 1–1000 Hz magnetic field fluctuations from lightning over Earth-scale distances and their impact on gravitational wave searches. Phys. Rev. D, 107(2):022004, 2023. doi:10.1103/PhysRevD.107.022004

Conclusions

- Correlated magnetic noise did not affect searches for isotropic and anisotropic SGWBs during the O3 LVK run.

- The possibility that Schumann resonances could limit the sensitivity of terrestrial detectors to SGWB in the frequency range of 20-30 Hz in the future runs, particularly after the upgrade to Advanced LIGO+ and Advanced Virgo+ , is under investigation.

Thank you for your attention!