Correlated noise and how it can disturb us listening to the symphony of the universe

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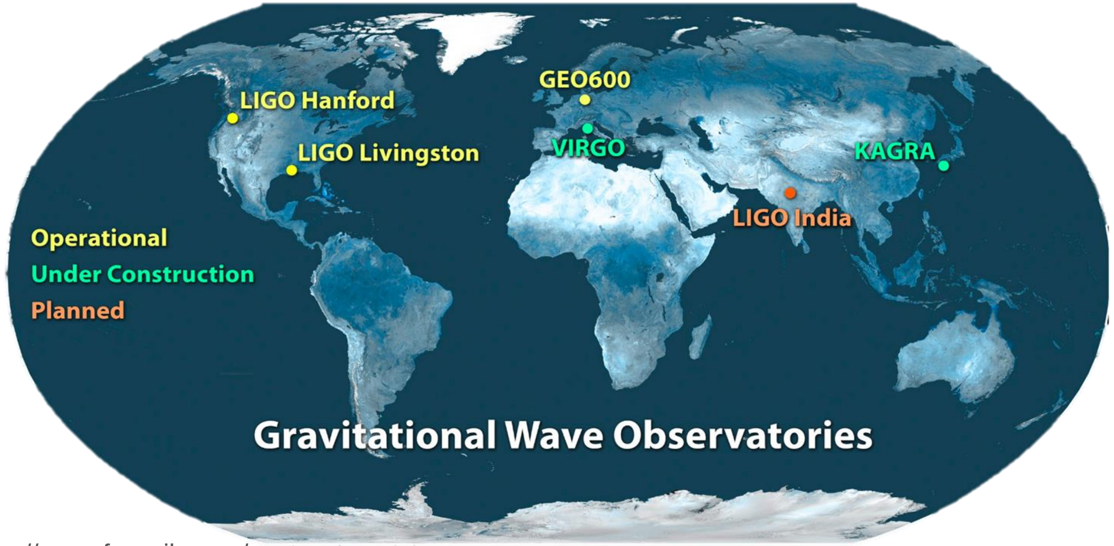
Gravitational Wave Orchestra
Louvain-la-Neuve, Belgium

8-9 September 2022

(Stochastic) gravitational wave background
The orchestra of the universe





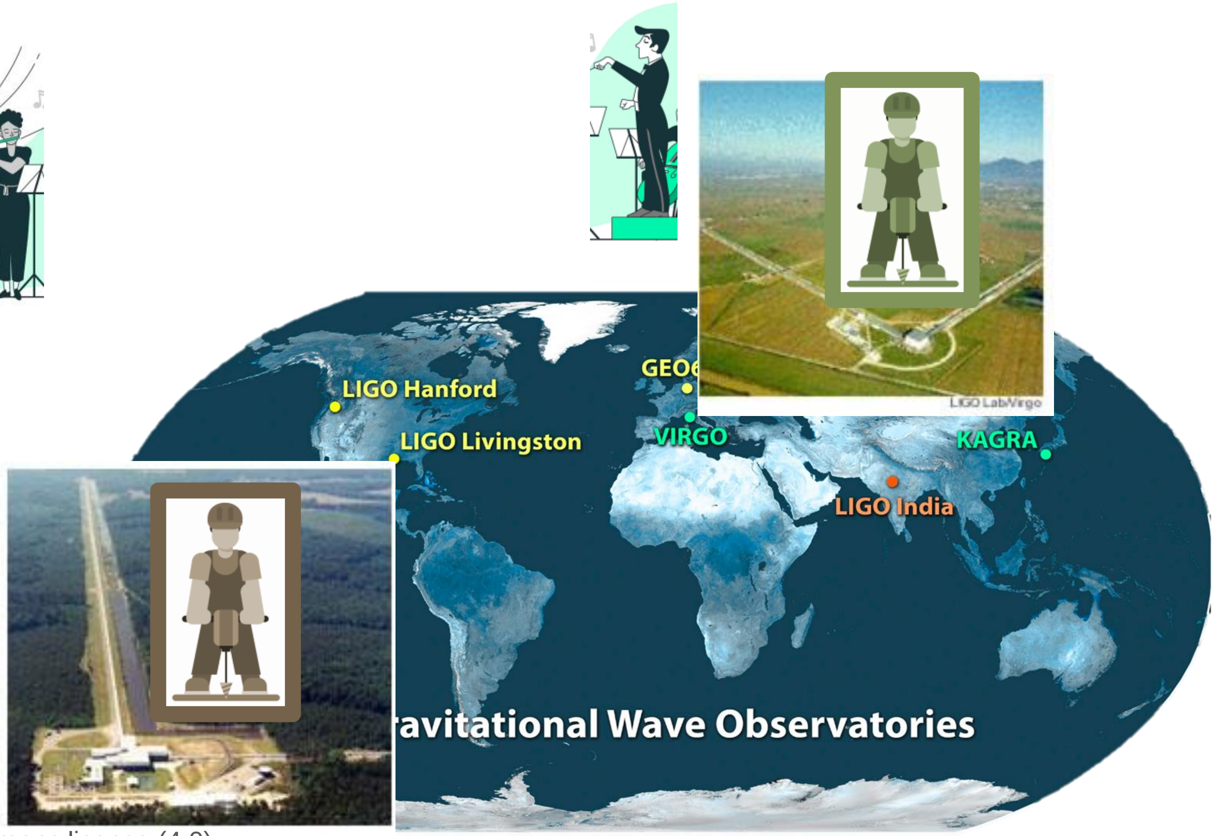


Credits: Musician vector created by storyset, available at https://www.freepik.com/vectors/musician
Map of GW detectors, Caltech/MIT/LIGO Lab, available at ligo.org

(Stochastic) gravitational wave background
Uncorrelated noise …

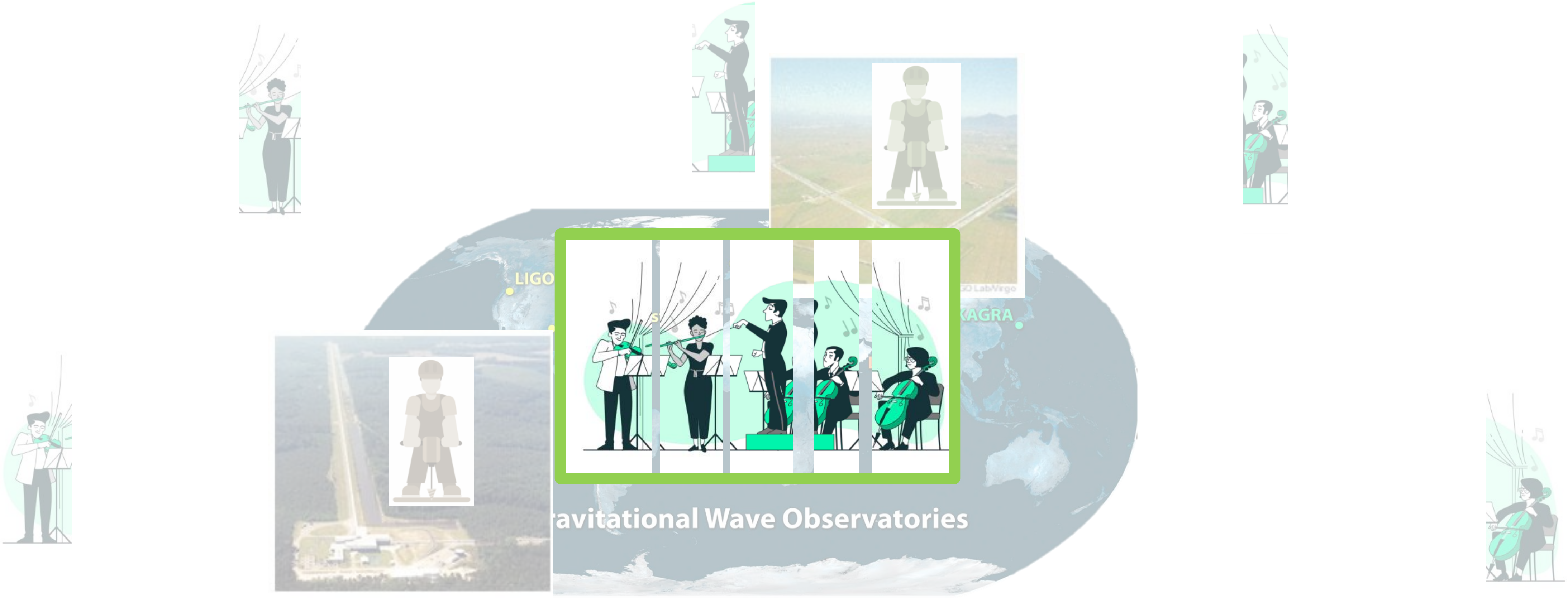






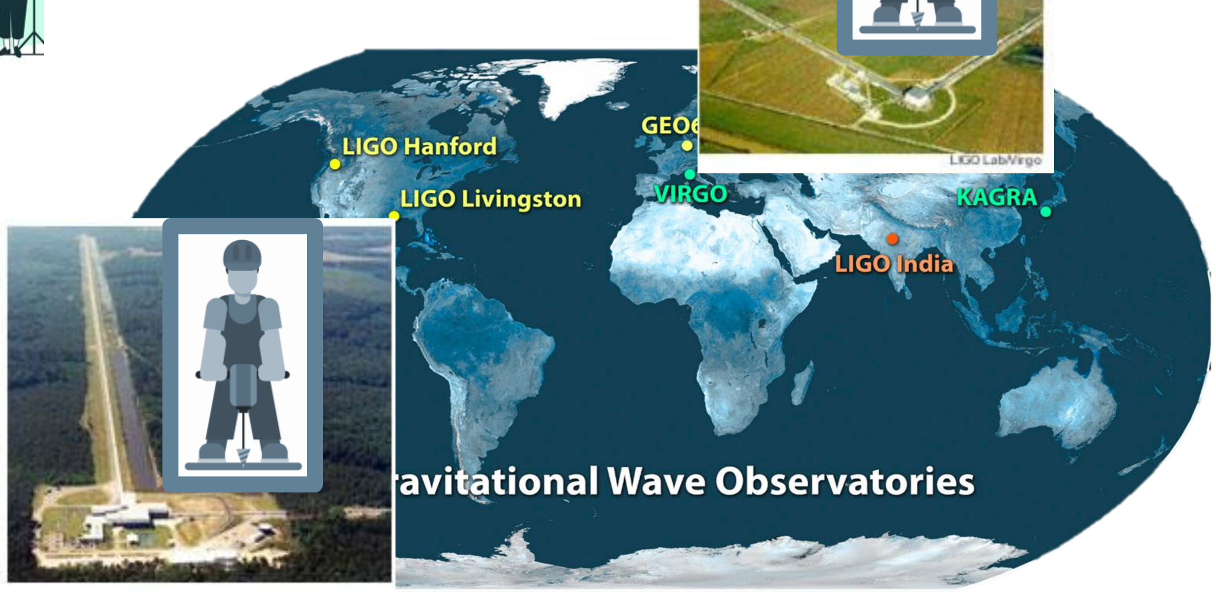
Credits: https://www.vectorportal.com, creative commons license (4.0)
GW detectors, LIGO Lab/Virgo, available at ligo.org

(Stochastic) gravitational wave background
… is washed out by correlation methods

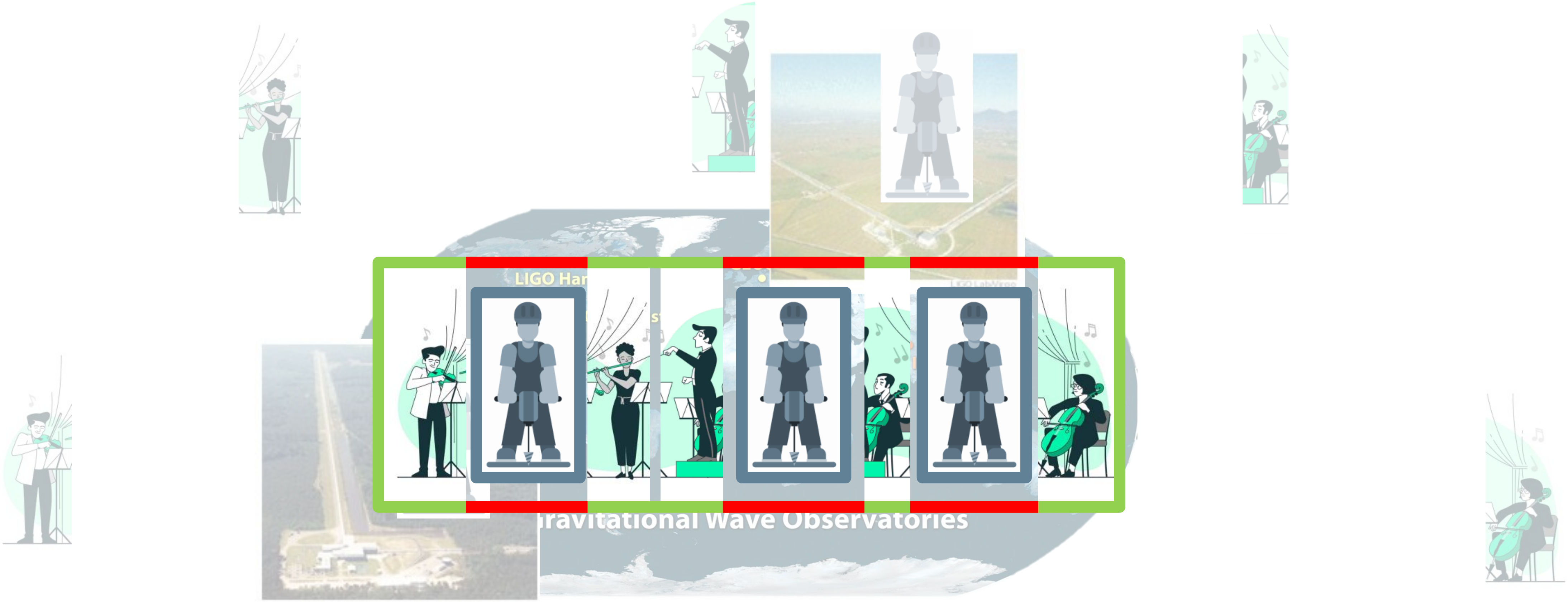


(Stochastic) gravitational wave background

Correlated noise …



(Stochastic) gravitational wave background
… is a potential bias for future searches



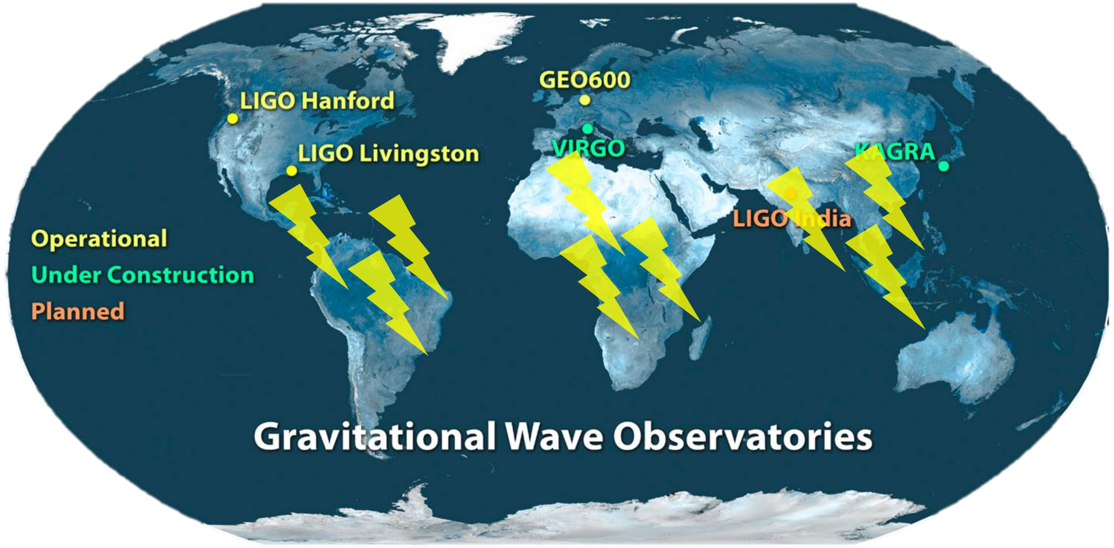
Outline

- ❖ Second generation GW interferometric detectors - LIGO, Virgo and KAGRA
  - ➢ Magnetic noise - Schumann resonances
- ❖ Third generation GW interferometric detectors - Einstein Telescope
  - ➢ Magnetic noise - Schumann resonances
  - ➢ Seismic noise
  - ➢ Newtonian noise (NN)
- ❖ Outlook

Schumann resonances

Schumann resonances …

- ❖ are standing waves in the Earth surface - Ionosphere cavity
- ❖ are sourced by lightning around the world
- ❖ are correlated over long distance (> 1.000 km)
- ❖ 7.8Hz, 14Hz, 21Hz, …
- ❖ 0.5 pT – 1 pT @ 7.8 Hz



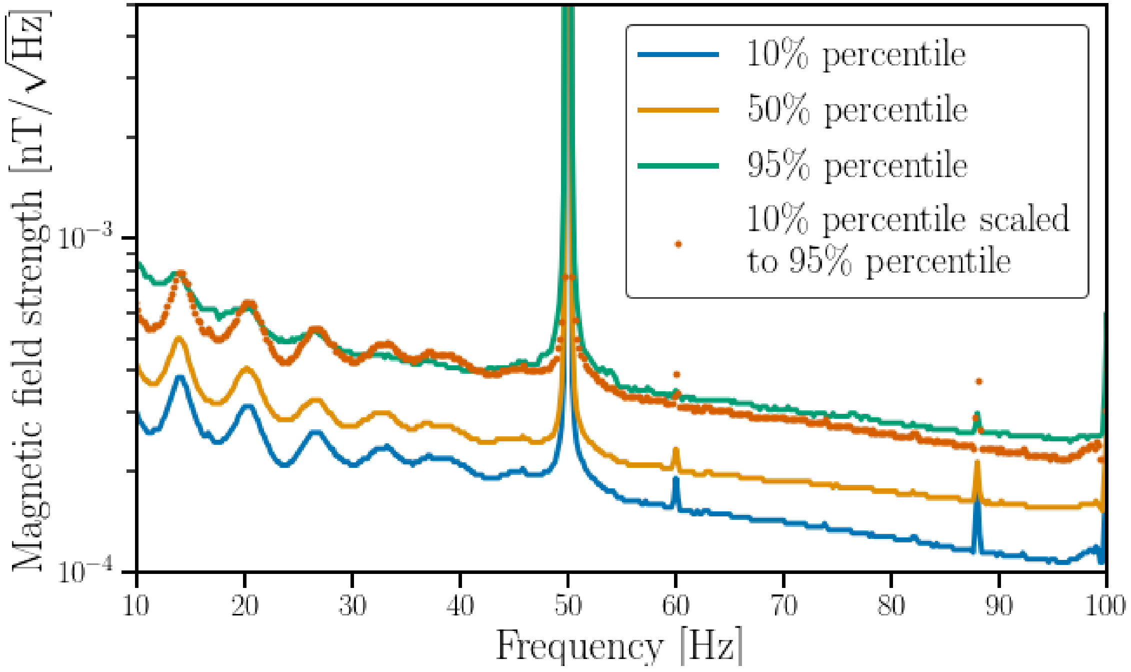


Fig. 1 : Magnetic spectrum measured at Sos Enattos, ET candidate site (It).

K. Janssens, et al, Phys. Rev. D 104, 122006 – https://doi.org/10.1103/PhysRevD.104.122006

Magnetic coupling function ‘inside-to-DARM’*

* DARM is the gravitational wave sensitive channel

Magnetic coupling functions …

- describe the coupling between ambient magnetic fields and h(t).
- are measured on a regular (weekly) basis.
- low frequency (<100Hz) coupling dominated by coupling to test mass magnets
- high frequency coupling (> 100Hz) dominated by coupling to cables, …

$$CF(f)_{measured} = \sqrt{\frac{Y^2_{inj}(f) - Y^2_{bkg}(f)}{X^2_{inj}(f) - X^2_{bkg}(f)}}$$

$$CF(f)_{upper\ limit} = \frac{Y_{bkg}(f)}{\sqrt{X^2_{inj}(f) - X^2_{bkg}(f)}}$$

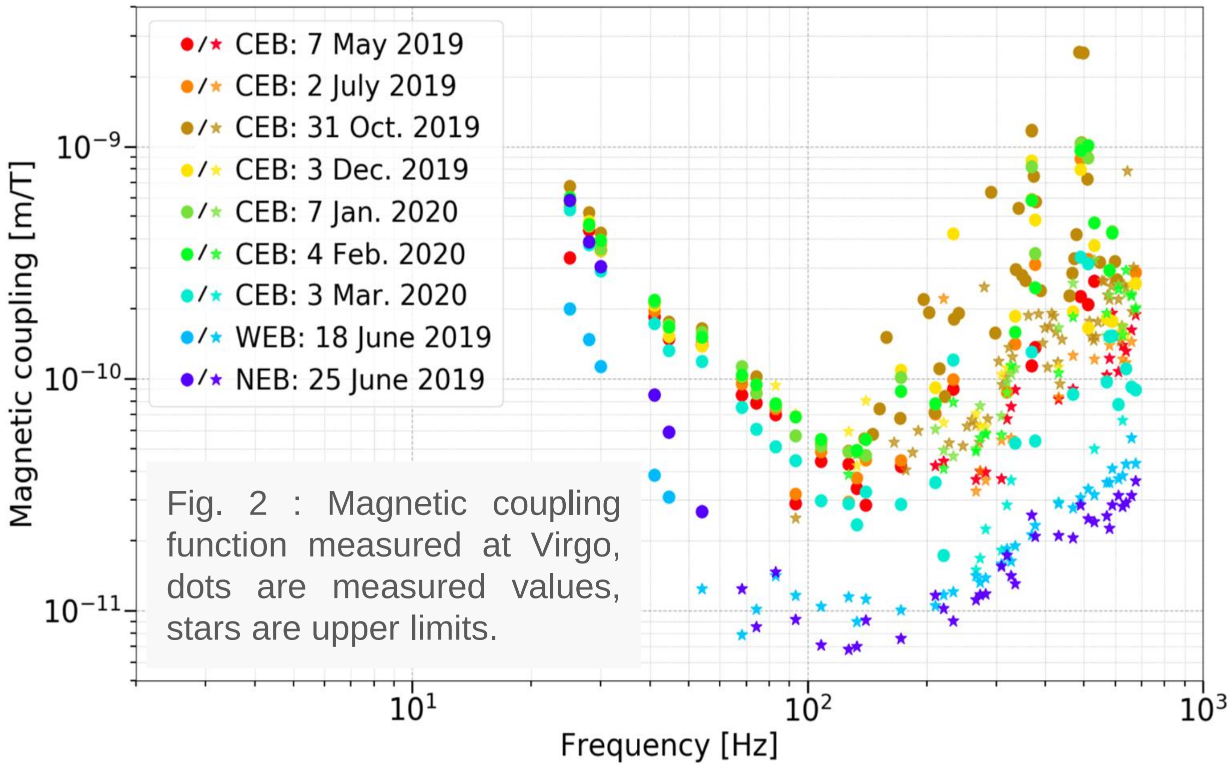


Fig. 2 : Magnetic coupling function measured at Virgo, dots are measured values, stars are upper limits.

I. Fiori, et al, Galaxies 2020, 8(4), 82 - https://doi.org/10.3390/galaxies8040082

Impact on LVK isotropic GWB search

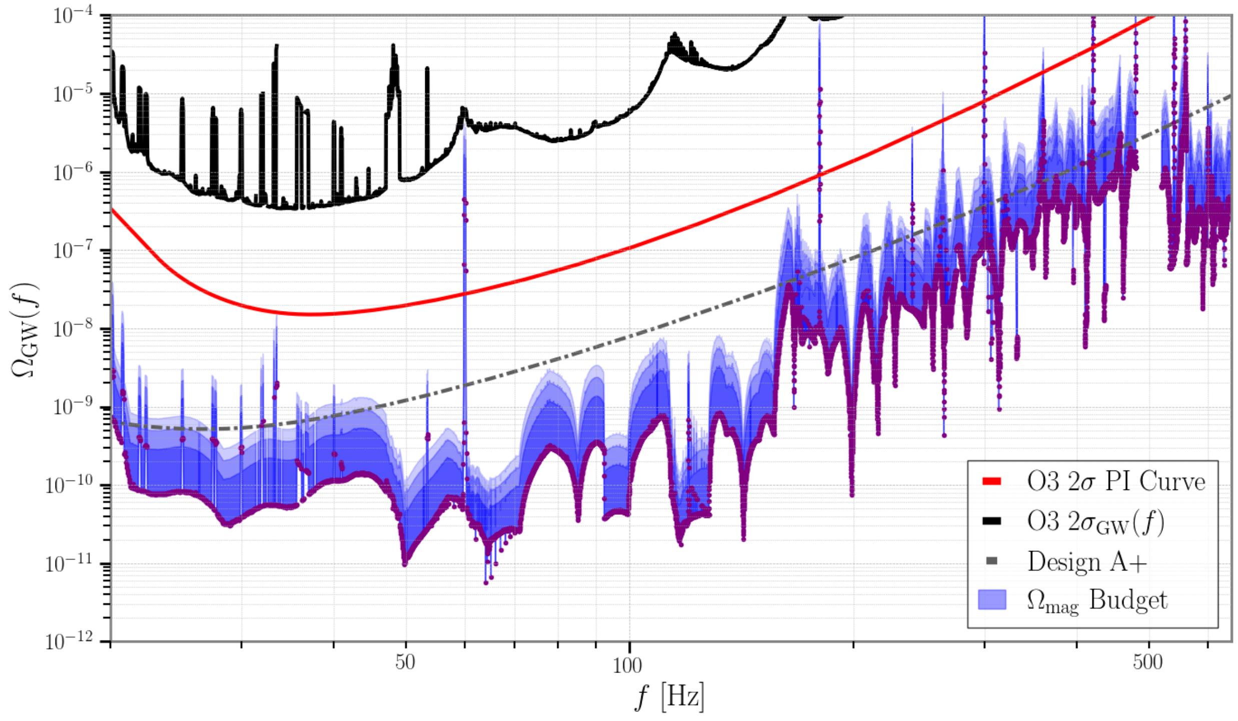


Fig. 3 : Projected impact of correlated magnetic noise on the search for an isotropic GWB.

K. Janssens, et al arXiv 2209,00284 – https://arxiv.org/abs/2209.00284

$$\hat{C}_{mag,IJ}(f) = |\kappa_I(f)||\kappa_J(f)| \boxed{\frac{CSD_{IJ}}{\gamma_{IJ}(f)S_0(f)}} \equiv M_{IJ}$$

'Magnetic budget'…

- ❖ describes the effect from magnetic noise on the search for an isotropic GWB, i.e. the cross-correlation statistic
- ❖ uses the outside-to-inside ĸ & inside-to-DARM ĸ
- ❖ includes intrinsic uncertainty of inside-to-DARM ĸ (dominant)
- ❖ includes intrinsic uncertainty of the outside-to-inside ĸ
- ❖ uncertainty of weekly variation not included (minimal effect)
- ❖ no contamination in O3, significant risk at contamination at Design A+ sensitivity

Impact on the Einstein Telescope

Provide upper limits for κ_{ET}

- can be used in design of the Einstein telescope
- ASD UL: maximal 1/10 (=k) of ET's ASD sensitivity
- GWB UL: no effect on the broadband sensitivity the 'PI-curve' $\Omega^{PI}_{ET_1 ET_2}$
- up to 10^3 improvement needed <20Hz compared to second generation for ASD

$$\hat{C}_{\mathrm{mag,ET_1ET_2}}(f) = |\kappa_{\mathrm{ET}}(f)|^2 M_{\mathrm{ET_1ET_2}},$$

$$\text{where} \quad M_{\mathrm{ET_1ET_2}} = \frac{2}{T_{\mathrm{obs}}} \frac{|\tilde{m}^*_{\mathrm{ET_1}}(f)\tilde{m}_{\mathrm{ET_2}}(f)|}{\gamma_{\mathrm{ET_1ET_2}}(f) S_0(f)}$$

$$\kappa^{\mathrm{GWB}}_{\mathrm{ET}}(f) \equiv \sqrt{\frac{\Omega^{\mathrm{PI}}_{\mathrm{ET_1ET_2}}}{M_{\mathrm{ET_1ET_2}}}} \qquad \kappa^{\mathrm{ASD}}_{\mathrm{ET}}(f) \equiv k\,\frac{P_{\mathrm{ET}}(f)}{P_{\mathrm{mag}}(f)}$$

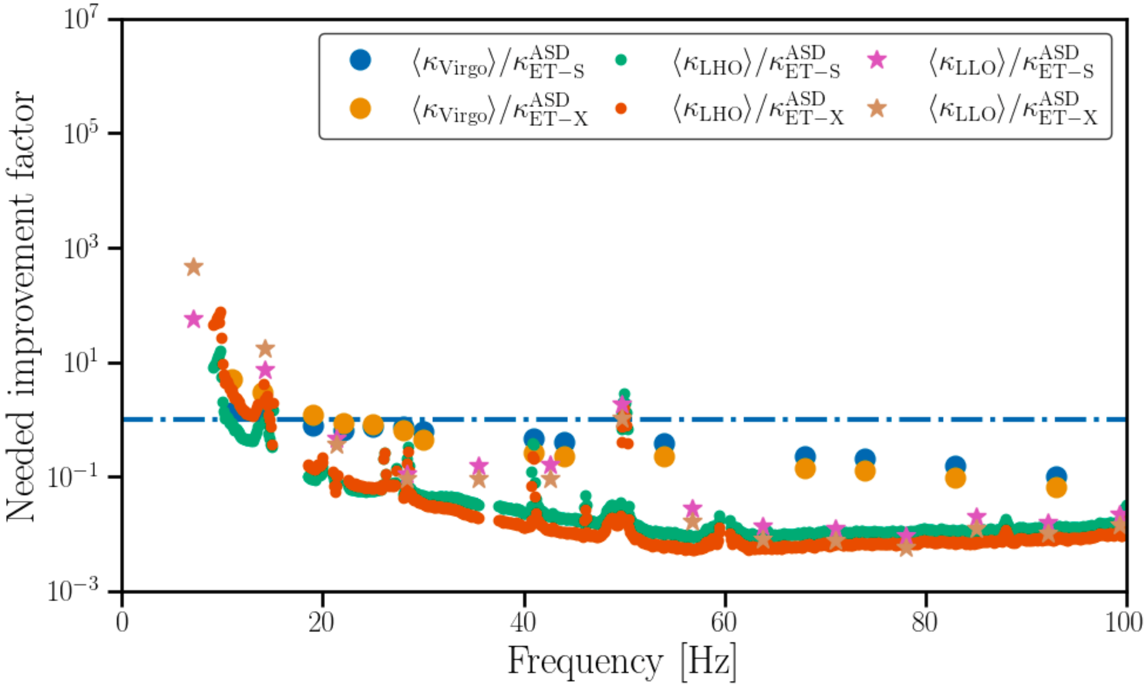


Fig. 4 : Upper limits on the magnetic coupling such that the magnetic noise is at most 1/10 of ET's ASD.

K. Janssens, et al, Phys. Rev. D 104, 122006 – https://doi.org/10.1103/PhysRevD.104.122006

Impact on the Einstein Telescope

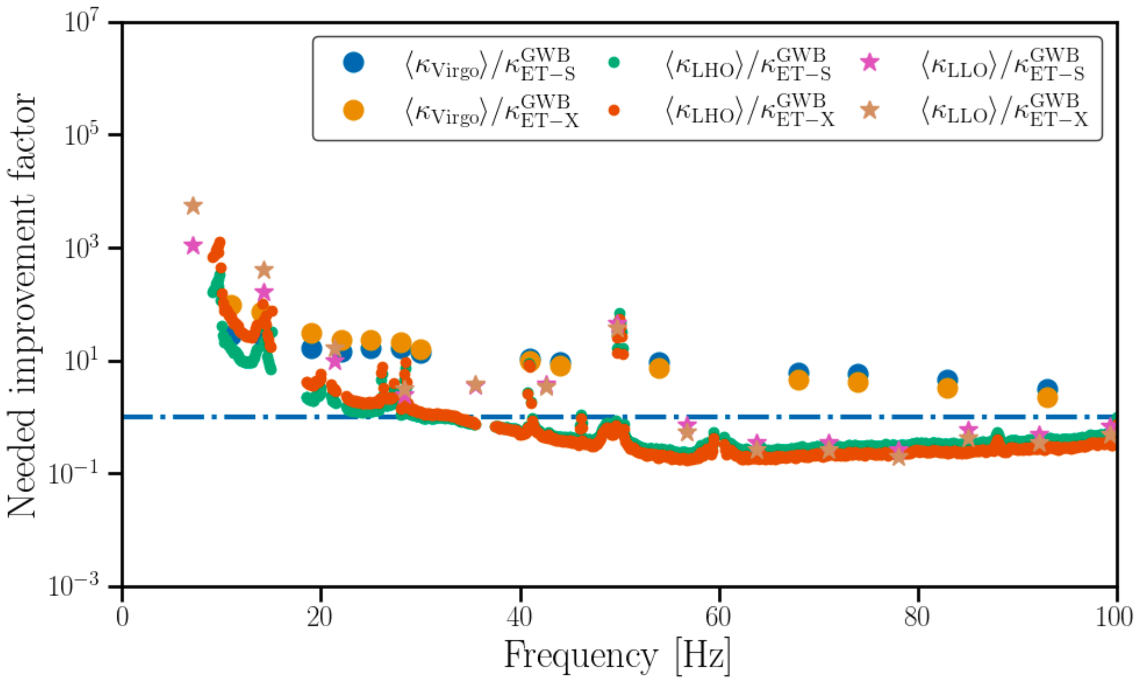


Fig. 5 : Upper limits on the magnetic coupling such that the magnetic noise does not limit the search for an isotropic GWB (PI-curve).

K. Janssens, et al, Phys. Rev. D 104, 122006 – https://doi.org/10.1103/PhysRevD.104.122006

- ❖ up to 10^4 improvement needed <30Hz compared to second generation for GWB
- ❖ above >100Hz minimal effect (to be further investigated for exact candidate site)

Possible improvements:

- ❖ better shielding
- ❖ move magnets (and metallic components) higher up in seismic suspension
- ❖ use of optical fibres

Co-located interferometers

The ET's triangular design

- ❖ leads to (nearly) co-located interferometers
- ❖ 5 possible short distance coupling locations
- ❖ B and C; aligned; 300m - 500m
- ❖ A, D and E; 60° angle ; 330m - 560m
- ❖ understand risk of other noise sources to be correlated on these short distance
- ❖ if correlated over long distances (~10km), additional coupling locations

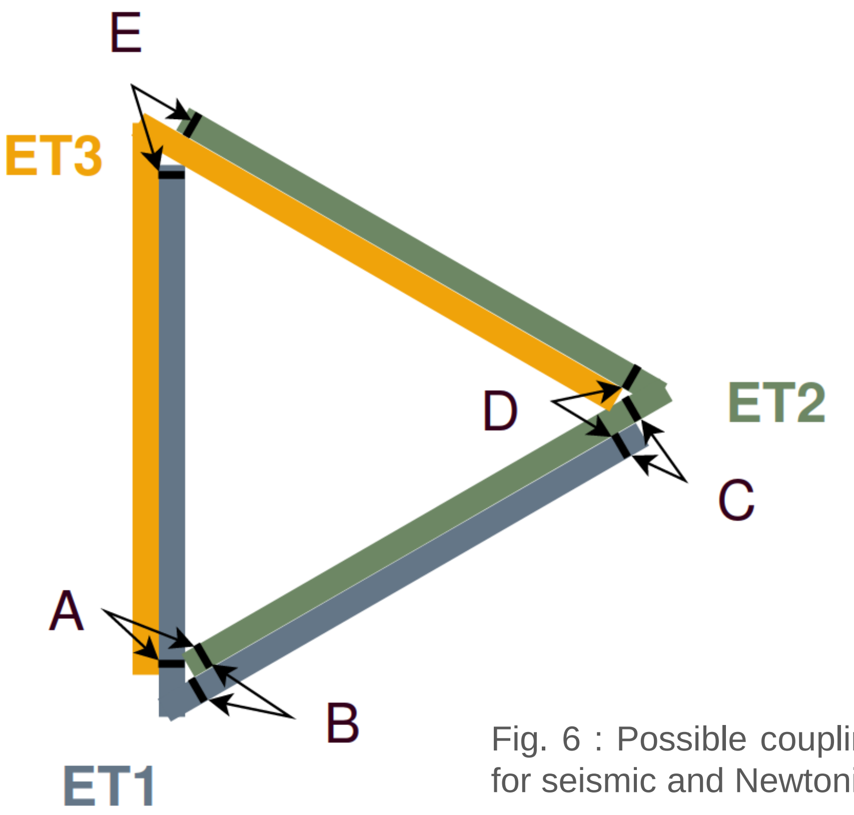


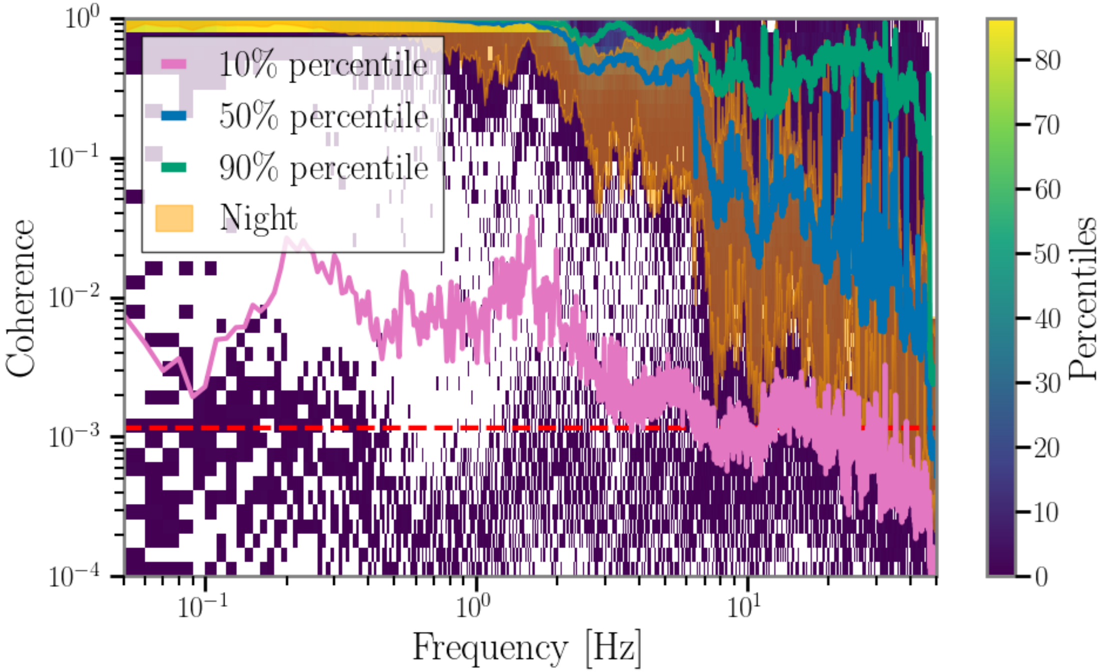
Fig. 6 : Possible coupling locations for seismic and Newtonian noise.

K. Janssens, et al, Phys. Rev. D 106, 042008 - https://doi.org/10.1103/PhysRevD.106.042008

Correlated seismic noise

Seismic correlations (Δx=400m, depth = 610m)

- ❖ 50% of time significant coherence ~40Hz
- ❖ night = less anthropogenic noise = higher coherence = lower CSD



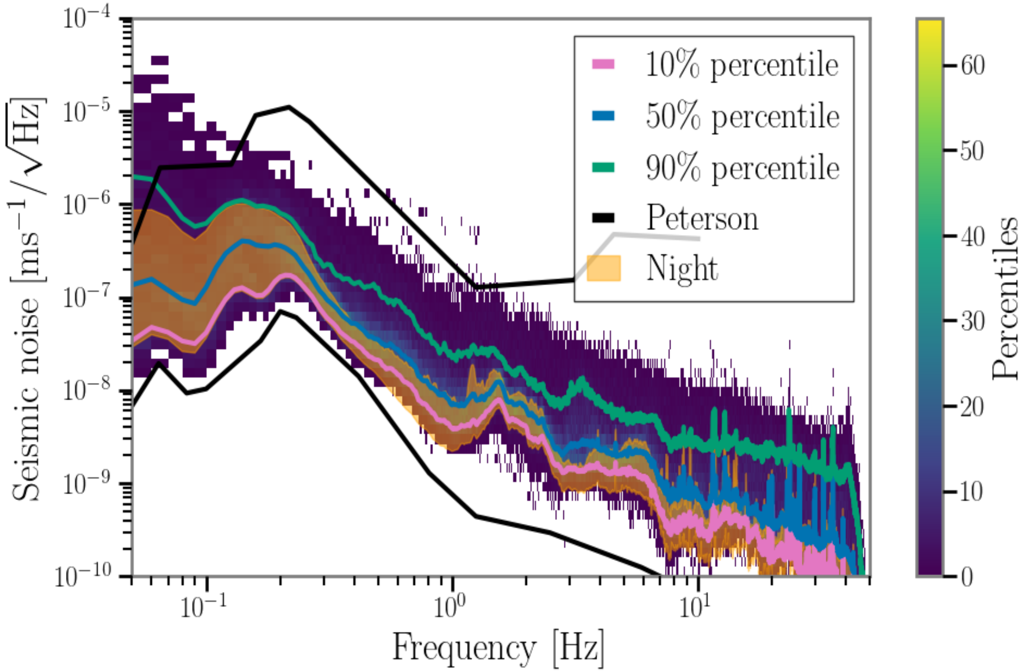


Fig. 7 (8) : Seismic coherence (correlation), measured at Homestake (US).

K. Janssens, et al, Phys. Rev. D 106, 042008 - https://doi.org/10.1103/PhysRevD.106.042008

Impact on the Einstein Telescope

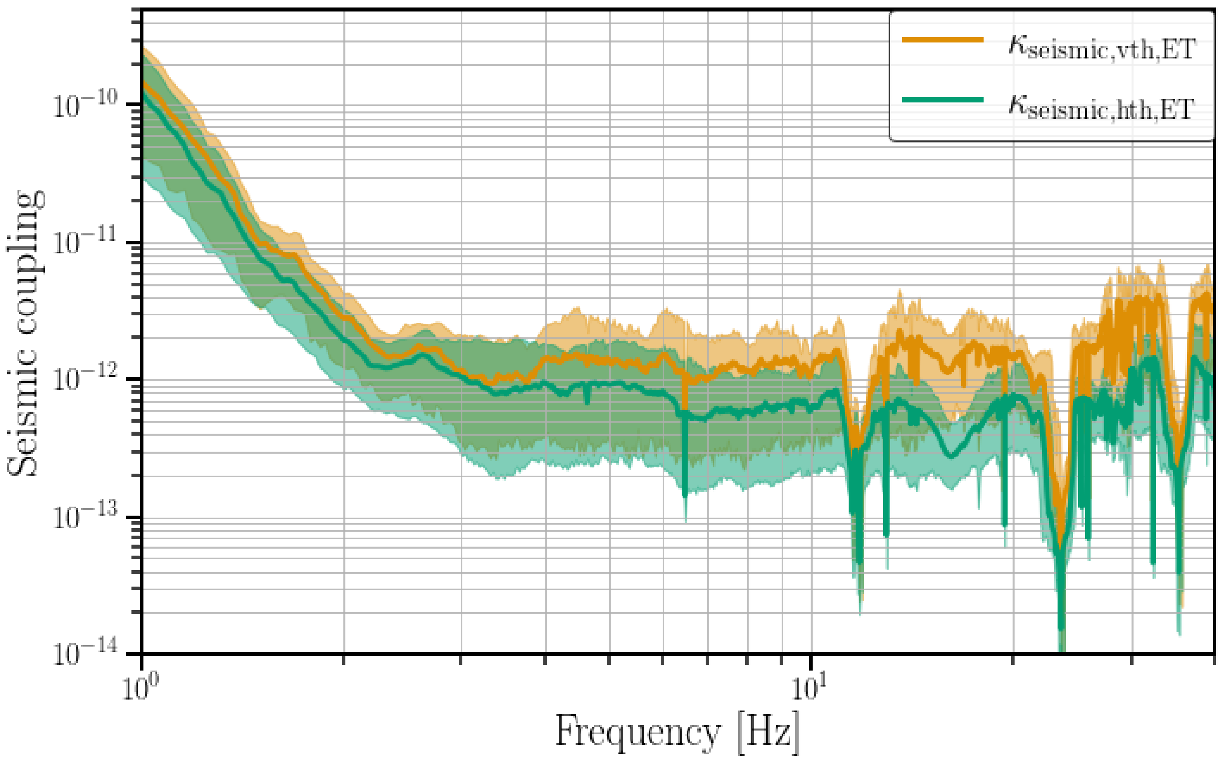


Fig. 9 : Upper limits on the seismic coupling function, such that there is no effect on the search for an isotropic GWB.

K. Janssens, et al, Phys. Rev. D 106, 042008 - https://doi.org/10.1103/PhysRevD.106.042008

Provide upper limits for seismic coupling

- can be used in design of the Einstein telescope
- assume independent vertical-to-horizontal (vth) and horizontal-to-horizontal (hth) coupling
- neglect tilt-to-horizontal coupling
- Fig. 9 presents UL on GWB: no effect on the broadband sensitivity the 'PI-curve' $\Omega^{PI}_{ET_1 ET_2}$
- h-t-h coupling from Virgo extrapolation reaches 10^{-12} at ~4Hz

Correlated Newtonian noise
Rayleigh waves

$$S_{h,\mathrm{Rayleigh}}(f) = \left(\sqrt{2}\pi G\gamma\rho_{0,\mathrm{Surface}}\right)^2 \frac{1}{L^2(2\pi f)^4} \mathcal{R}(h,f) S_{\xi_z}(f)$$

$$\mathcal{R}(h,f) = \left| \frac{-k_R(1+\zeta)e^{-k_R h} + \frac{2}{3}\left(2k_R e^{-q_P h} + \zeta q_S e^{-q_S h}\right)}{k_R(1-\zeta)} \right|^2$$

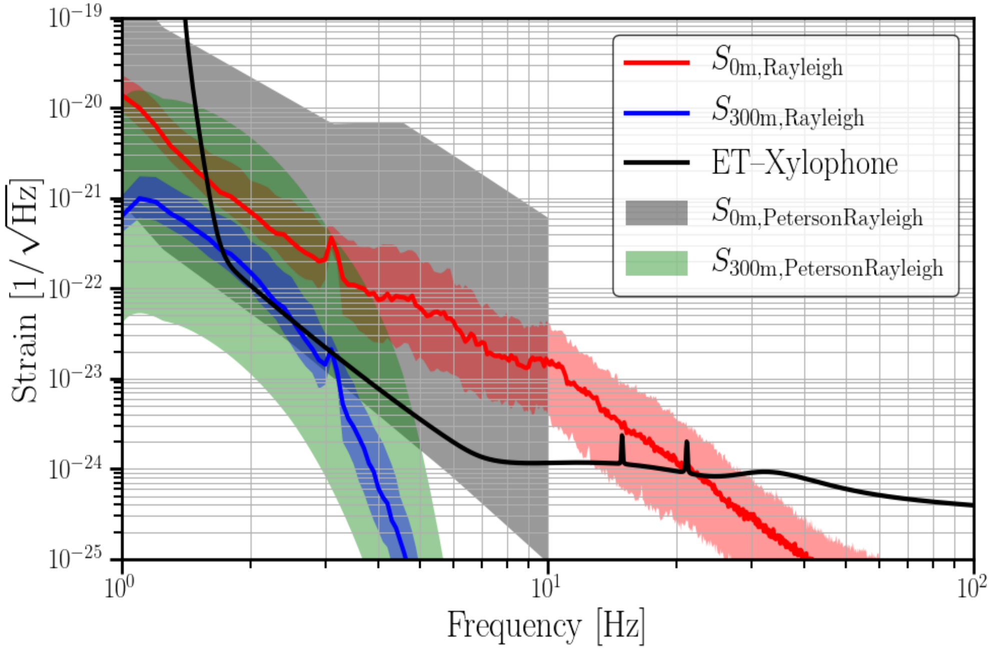


Fig. 10 : Predicted strain from NN from Rayleigh waves.

K. Janssens, et al, Phys. Rev. D 106, 042008 - https://doi.org/10.1103/PhysRevD.106.042008

Newtonian noise
- force directly exerted on test mass by density fluctuations in gravitational field.
- Rayleigh waves only type of surface waves producing density fluctuations
- seismic data measured at the surface (Terziet, NL) (Δx=400m)
- used data contains anisotropies
- underground facility (depth = 300m) significantly reduces induced effect
- similar contamination as earlier studies (Note: here corelated fields)

$$q_P(f) = \frac{2\pi f}{v_R(f) v_P}\sqrt{v_P^2 - v_R^2(f)}$$

$$q_S(f) = \frac{2\pi f}{v_R(f) v_S}\sqrt{v_S^2 - v_R^2(f)}$$

$$\zeta(f) = \sqrt{\frac{q_P(f)}{q_S(f)}}$$

Impact on the Einstein Telescope

Rayleigh waves

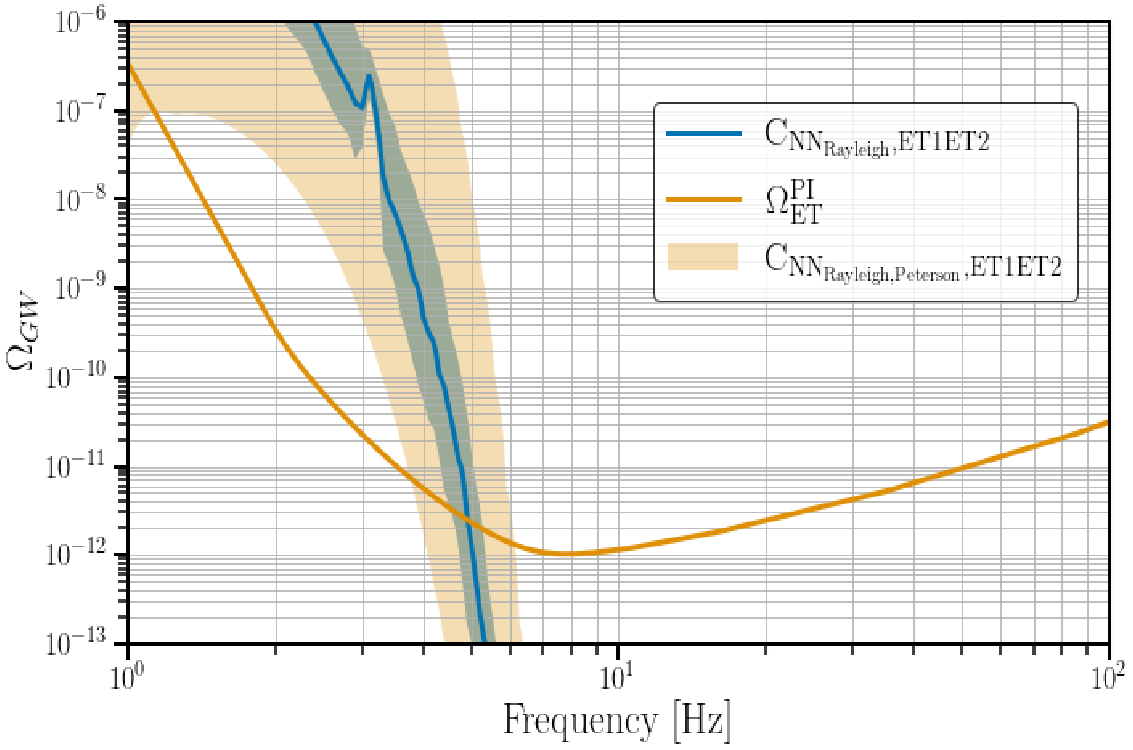


Fig. 11 : Predicted impact of correlated NN from Rayleigh waves on the search for an isotropic GWB.

K. Janssens, et al, Phys. Rev. D 106, 042008 - https://doi.org/10.1103/PhysRevD.106.042008

$$\hat{C}_{\mathrm{NN,ET_1ET_2}}(f) = N_{\mathrm{NN,ET_1ET_2}},$$

$$\text{where} \quad N_{\mathrm{NN,ET_1ET_2}} = \frac{\mathrm{S_{NN}}}{\gamma_{\mathrm{ET_1ET_2}}(f) S_0(f)}$$

Stochastic budget

- isotropic GWB search impacted up to ~5Hz
- mainly independent of site, day-night, … dominant reduction caused by underground facility

Correlated Newtonian noise
Body waves

$$S_{\text{Body-wave}}(f) = \left(\frac{4\pi}{3} G\rho_{0,\text{Bulk}}\right)^2 (3p+1) \frac{1}{L^2(2\pi f)^4} S_{\xi_x}(f)$$

Newtonian noise
- force directly exerted on test mass by density fluctuations in gravitational field.
- seismic data measured underground (Homestake, US) (Δx=400m, depth = 610m)
- similar contamination as earlier studies (Note: here corelated fields)

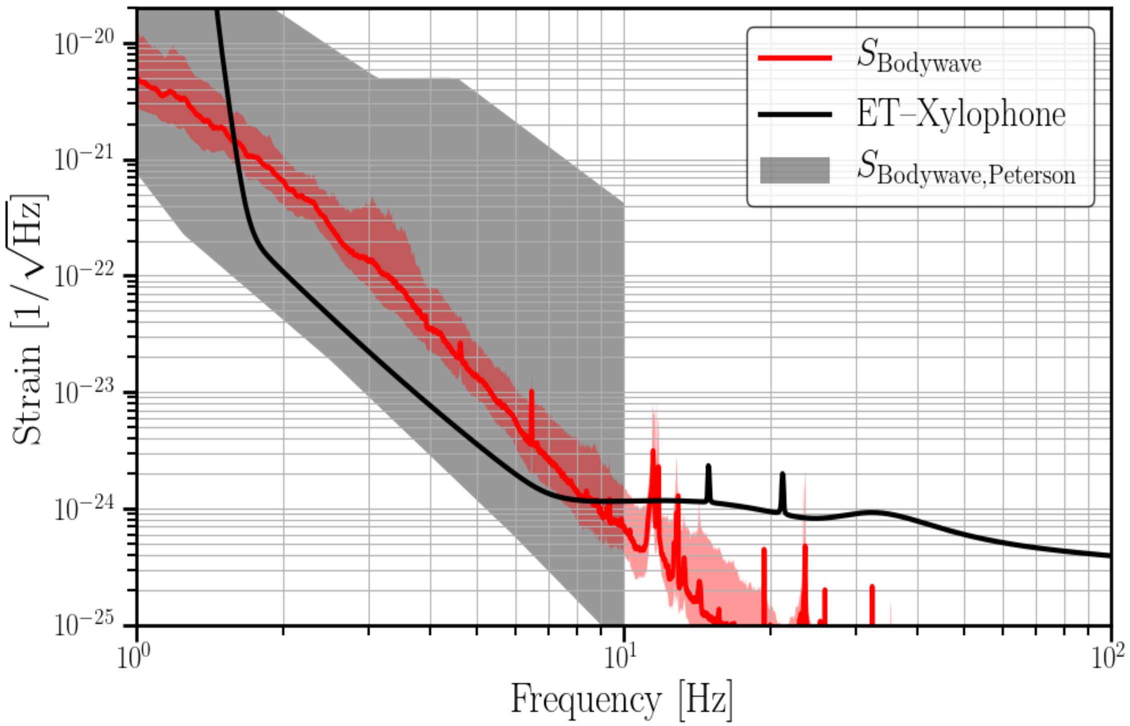


Fig. 12 : Predicted strain from NN from body waves.

K. Janssens, et al, Phys. Rev. D 106, 042008 - https://doi.org/10.1103/PhysRevD.106.042008

Impact on the Einstein Telescope
Body waves

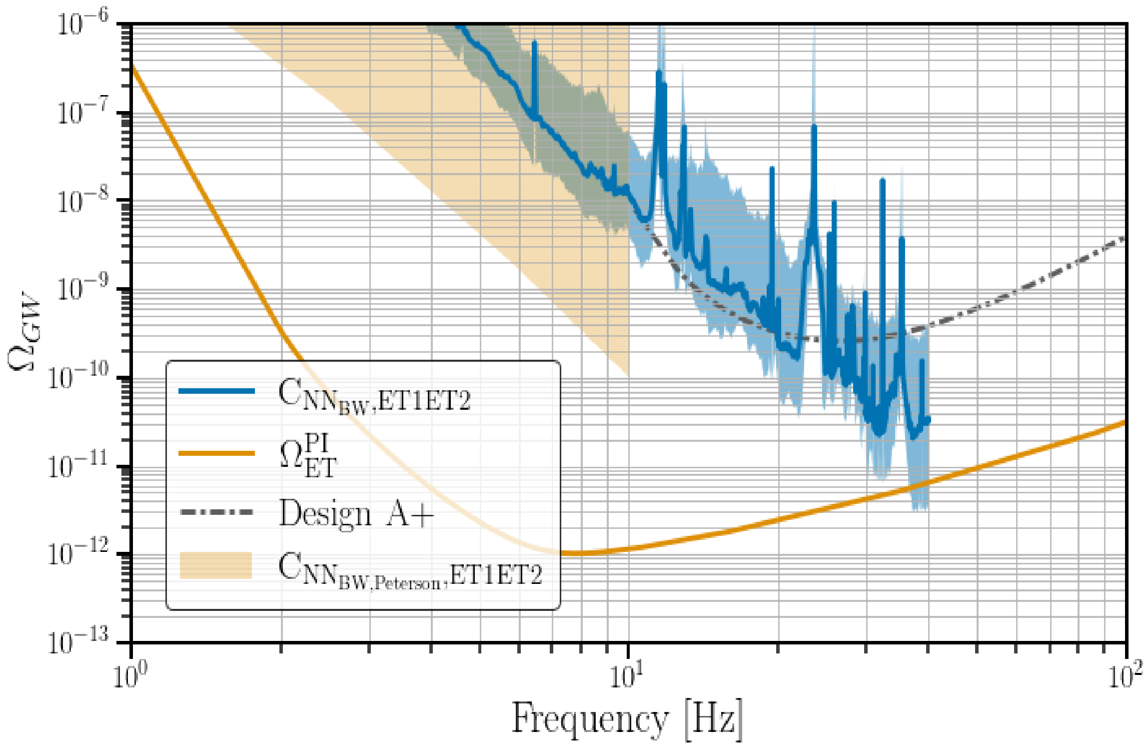


Fig. 13 : Predicted impact of correlated NN from body waves on the search for an isotropic GWB.

K. Janssens, et al, Phys. Rev. D 106, 042008 - https://doi.org/10.1103/PhysRevD.106.042008

Stochastic budget

- serious threat for the isotropic GWB search impacted up to ~40Hz
- @ 3Hz: $8 \cdot 10^6$(90% percentile), $6 \cdot 10^5$(50% percentile)
- understand better site specific noise budgets
- NN subtraction, factor ~100 (10 per detector) is optimistic

Tools (1/3)
Gravitational wave geodesy

GW geodesy

- Hypothesis H_γ: measured cross-correlation is consistent with *true* baseline geometry
- Hypothesis H_{Free} : measured cross-correlation is consistent with *unphysical* baseline geometry

- able to differentiate an astrophysical GWB and Schumann resonances
- definition of a FAR by using 'Gaussian process priors' as a conservative assumption for possible correlated noise terms

$$\mathcal{B} = \frac{p(\hat{C}|\mathcal{H}_\gamma)}{p(\hat{C}|\mathcal{H}_{\rm Free})}$$

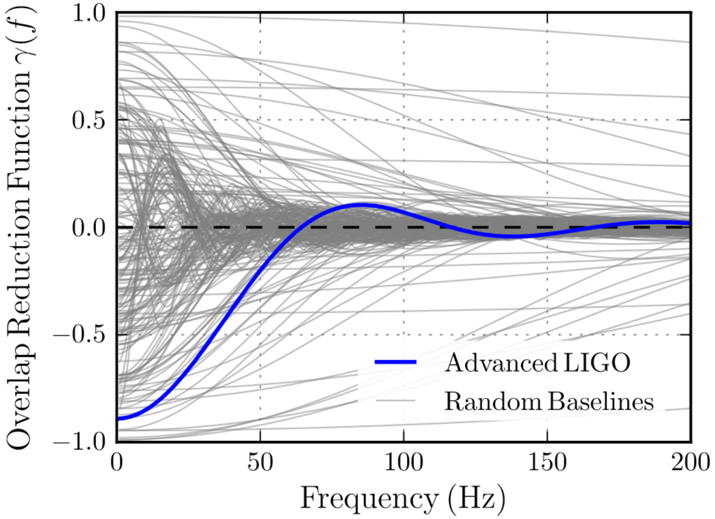


Fig. 14 : Advanced LIGO's overlap reduction function compared to random detector geometries.

T. A. Callister et al 2018 ApJL 869 L28 - https://doi.org/10.3847/2041-8213/aaf3a5

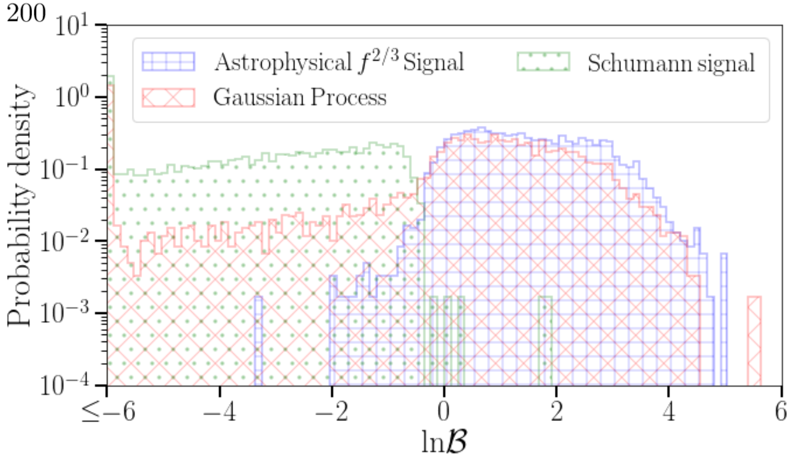


Fig. 15 : Probability density for an astrophysical GWB versus correlated noise scenario's.

K. Janssens, et al, Phys. Rev. D 105, 082001 - https://doi.org/10.1103/PhysRevD.105.082001

Tools (2/3)
Bayesian parameter estimation

$$p(\hat{C}_k^{IJ}|\Theta_{\rm GW},\Theta_{\rm Mag}) \propto \exp\left[-\frac{1}{2}\sum_{IJ}\sum_{k}\left(\frac{\hat{C}_k^{IJ}-\Omega_{\rm GW}(f_k|\Theta_{\rm GW})-\Omega_{\rm Mag}(f_k|\Theta_{\rm Mag})}{\sigma_{IJ}^2(f_k)}\right)\right]$$

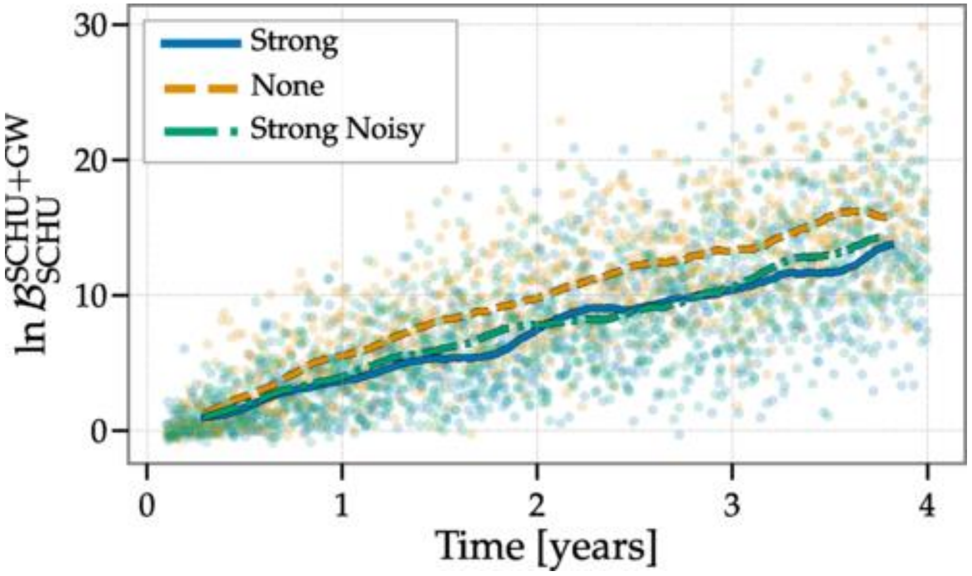


Fig. 17 : Log-Bayes factor for a model with both a GWB and magnetic noise compared to only magnetic noise in function of time.

P. Meyers, et al, Phys. Rev. D 102, 102005 – https://doi.org/10.1103/PhysRevD.102.102005

Joined parameter estimation

- ❖ estimate both GWB and correlated noise simultaneously in data

- ❖ addition of more detectors to the network might improve correlated noise estimation
- ❖ evidence for GWB is reduced in the presence of (strong) correlated noise, however an unbiased estimate can be gained

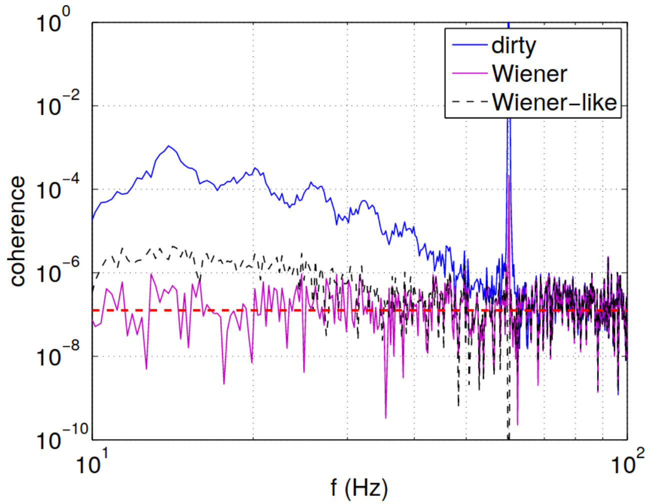
Tools(3/3)
Noise subtraction

Noise subtraction
- ❖ Wiener filter noise subtraction
- ❖ Noise subtraction based on measured coupling (‘Wiener-like’)

- ❖ (partial) subtraction is possible
- ❖ dependency on noise in witness sensors, locations of witness sensors, …

Fig. 17 : Simulated example comparing wiener filter subtraction with ‘Wiener-like’ (measured coupling function).

E. Thrane, et al, Phys. Rev. D 90, 023013 – https://doi.org/10.1103/PhysRevD.90.023013

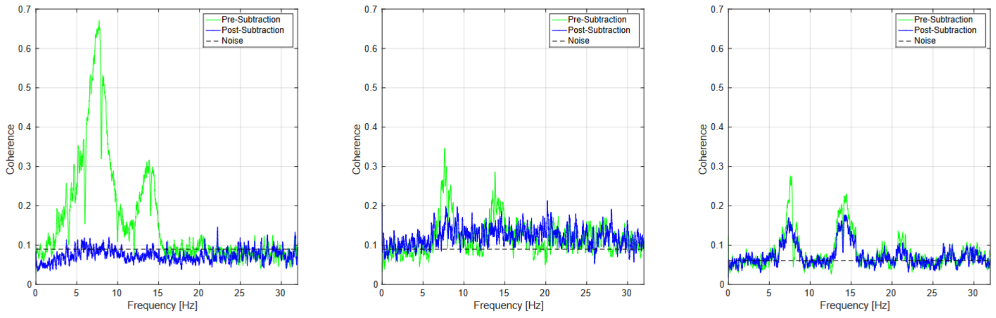


$$\tilde{s}(f) = \tilde{h}(f) + t(f)\tilde{m}(f) + \tilde{n}(f)$$

$$\tilde{w}(f) = \tilde{\eta}(f) + \tilde{m}(f),$$

$$\hat{t}(f) = \frac{\overline{\tilde{s}(f)\tilde{w}^*(f)}}{\overline{|\tilde{w}(f)|^2}}$$

$$\tilde{s}'(f) = \tilde{s}(f) - \hat{t}(f)\tilde{w}(f).$$



KAGRA/Villa Cristina LIGO Livingston/Villa Cristina LIGO Hanford/Virgo

Fig. 18 : Demonstration of wiener-filter noise subtraction on magnetometers

M. Coughlin et al. Phys. Rev. D 97, 102007 – https://doi.org/10.1103/PhysRevD.97.102007

Conclusions & outlook

Correlated magnetic noise
- potential to limit stochastic searches at second and third generation GW detectors
- impacts both co-located as well as separated detectors
- effect from infrastructural noise for co-located facilities should be understood

Possible mitigation techniques:
- better shielding
- move magnets (and metallic components) higher up in seismic suspension
- use of optical fibres
- noise subtraction

Correlated (seismic) and Newtonian noise
- impacts only co-located detectors, e.g. ET
- serious limit stochastic searches
- effect from infrastructural noise should be understood

Possible mitigation techniques
- noise mitigation (factor 100 is already optimistic)
- consider separated non-triangular design?

What about …
- data quality for GWB searches for intermittent signals?
- effect of correlated noise on anisotropic searches?