

Next-generation global gravitational-wave detector network: Impact of detector orientation on compact binary coalescence and stochastic gravitational-wave background searches

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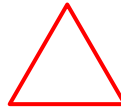
GWO Anecy
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Introduction

- We are in the design phase of the next-generation ground-based GW detectors

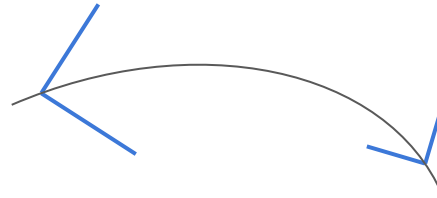
- Einstein Telescope (ET) reference Design:



- 10 km Triangle including 3 detectors each composed of two interferometers (low/high frequency)

- Cosmic Explorer (CE) reference Design:

- 2 L-shaped detectors with 40 km and 20 km arm length



- Different scenarios are studied in e.g.:

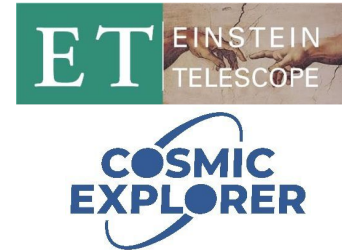
- Science with the Einstein Telescope: a comparison of different designs (Branchesi et al.), [arXiv:2303.15923](https://arxiv.org/abs/2303.15923)
- Characterizing Gravitational Wave Detector Networks: From A[#] to Cosmic Explorer (Gupta et al.), [arXiv:2307.10421](https://arxiv.org/abs/2307.10421)

- Our study concentrates on stochastic background and CBC searches [arXiv:2408.06032](https://arxiv.org/abs/2408.06032)

- Focus on the impact of detector orientation
- Look at the global network
- Results should not depend on astrophysical models
- We do not want to use Fisher matrix based parameter estimation

Goal of this study

- L-shaped detectors: Network sensitivity depends on the relative orientation
- For given detectors, what arm orientations maximize Stochastic and CBC science?
- In this study we consider different configurations of an ET - CE network
 - Einstein Telescope: 2L (15 km) or Triangle (10 km)
 - Cosmic Explorer: 2L (40 km + 20 km)
- We want to find the impact of different orientation choices
- Stochastic GWB: We show how the power-law integrated sensitivity curve is affected
- CBC: Localization and distance inference capabilities for BNS
 - Using Bayesian parameter estimation for a reference BNS system



GW Interferometers networks

■ Sensitivity of a GW detector network

➤ Amplitude spectral densities of individual interferometers

Sensitivity curves from ET collaboration and CE consortium

➤ Location on Earth

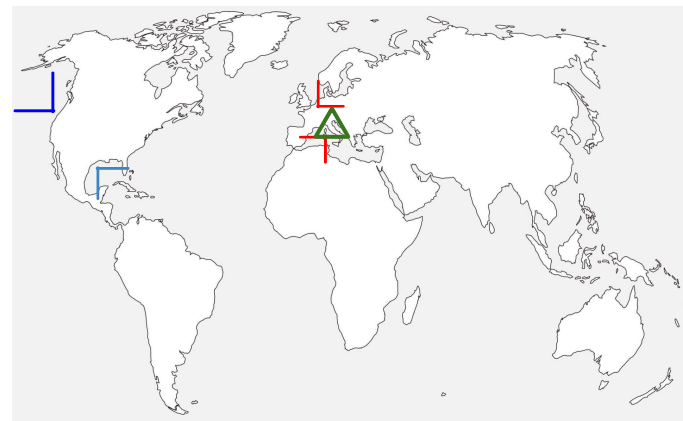
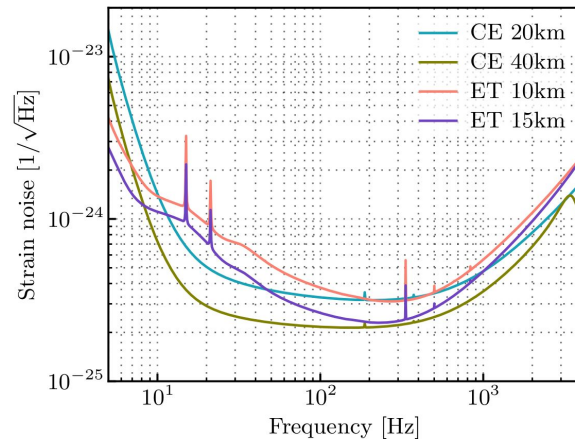
ET 2L: one IFO each at candidate sites in the MeuseRhine region
and Sardinia Branchesi et al. 2023 [arXiv:2303.15923](https://arxiv.org/abs/2303.15923)

CE: one IFO in the Pacific ocean,
one IFO in the Atlantic ocean Gupta et al. 2023 [arXiv:2307.10421](https://arxiv.org/abs/2307.10421)

ET Δ : located at the Virgo site

➤ Arm orientations

Not fixed a priori, we first want to maximize/minimize certain metrics

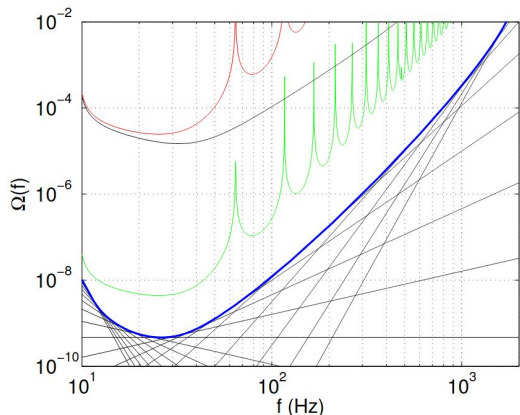


Metric for the sensitivity to the stochastic GWB

■ Sensitivity to the stochastic background

- Power-law integrated (PI) sensitivity curves Thrane et al. 2013 [arXiv:1310.5300](https://arxiv.org/abs/1310.5300)

Graphical method to display the sensitivity of detectors
searching for stochastic GW backgrounds



Thrane et al. 2013 [arXiv:1310.5300](https://arxiv.org/abs/1310.5300)

$$\Omega_\beta = \frac{\text{SNR}}{\sqrt{2T}} \left[\int_{f_{\min}}^{f_{\max}} df \frac{(f/f_{\text{ref}})^{2\beta}}{\Omega_{\text{eff}}^2(f)} \right]^{-1/2}$$

acquired SNR, here SNR = 3

observation time, here $T = 1$ yr

$$\Omega_{\text{eff}}(f) = \frac{2\pi^2}{3H_0^2} f^3 S_{\text{eff}}(f)$$

$$S_{\text{eff}}(f) \equiv \left[\sum_{I=1}^M \sum_{J>I}^M \frac{\Gamma_{IJ}^2(f)}{P_{nI}(f)P_{nJ}(f)} \right]^{-1/2}$$

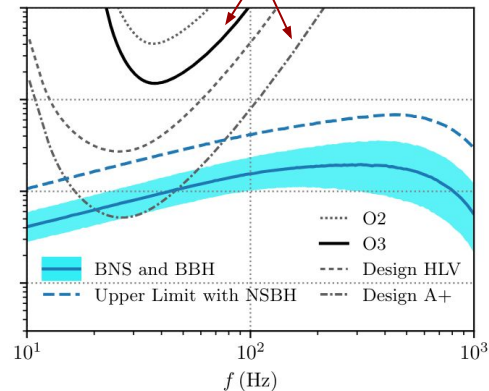
PSD of interferometers

$$\Gamma_{IJ}(f) = \frac{5}{\sin \theta_I \sin \theta_J} \Gamma_{IJ}(f)$$

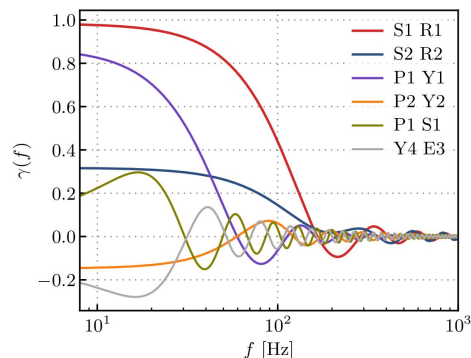
Overlap reduction function,
Geometry of the network

Opening angle of interferometers

PI sensitivity curves



Abbott et al. 2021 [arXiv:2101.12130](https://arxiv.org/abs/2101.12130)



Metric for CBC searches

- Localization of compact binaries

- Depends mostly on the number of and distance between interferometers, less on orientation

- Measurement of both GW polarizations

- Network alignment factor α Klimenko et al. 2005 [arXiv:gr-qc/0508068](https://arxiv.org/abs/gr-qc/0508068)

Measure of how sensitive a detector network is to the second polarization for each sky location

- Construction: Take antenna pattern function of detector I : $F_I^{+, \times}(\hat{\Omega})$

Compute noise-spectrum weighted quantities: $F_{w,I}^{+, \times}(\hat{\Omega}, k) = \frac{F_I^{+, \times}}{\sqrt{\frac{N}{2} P_{nI}(k)}}$ and form vectors: $F^+ = \begin{bmatrix} F_{w,1}^+ \\ F_{w,2}^+ \\ \vdots \\ F_{w,D}^+ \end{bmatrix}$ $F^\times = \begin{bmatrix} F_{w,1}^\times \\ F_{w,2}^\times \\ \vdots \\ F_{w,D}^\times \end{bmatrix}$

Since the choice of polarization angle

is arbitrary, we can choose it such that:

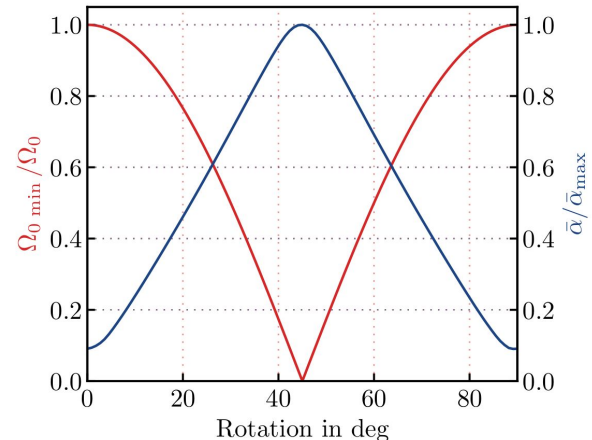
$$\left. \begin{aligned} |\mathbf{f}^+|^2 &\geq |\mathbf{f}^\times|^2 \\ \mathbf{f}^+ \cdot \mathbf{f}^\times &= 0 \end{aligned} \right\} \text{Dominant polarization frame}$$

Now we can define the alignment factor: $\alpha = \frac{|\mathbf{f}^\times|}{|\mathbf{f}^+|} \in [0, 1] \longrightarrow \text{Take the sensitivity weighted sky-average}$

Two interferometer balance problem

- Assume two 15 km L-shaped interferometers, at the two ET candidate sites
- Think about the relative arm orientation with respect to the great circle connecting the two sites
 - If e.g. both x-arms would point to the North, their relative angle would be 2.51 deg
- Sensitivity towards **both polarizations** / the **stochastic background** prefer opposite configurations
 - Align the detectors for a good sensitivity towards the stochastic background
 - Put the detectors at 45 deg to have a better chance of measuring both polarizations

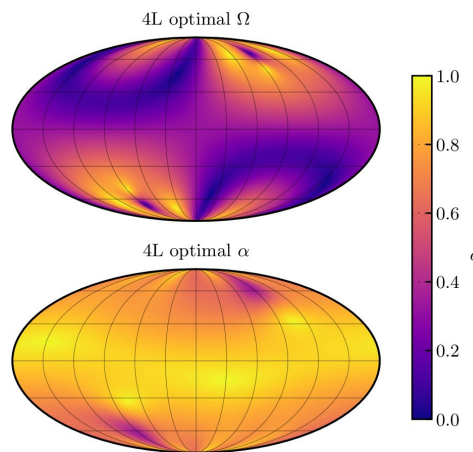
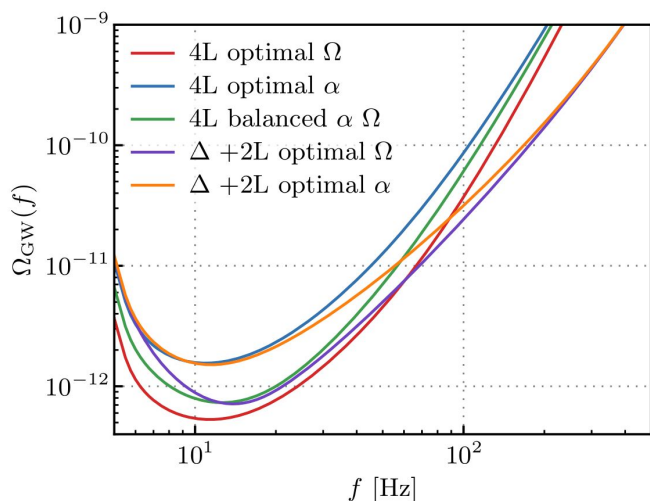
$$\begin{aligned}\Omega_{0, \min} &= 5.39 \times 10^{-13} \\ \alpha_{\max} &= 0.734\end{aligned}$$



ET + CE network

- Look at five detector networks with different choices of arm orientation

- Three networks with 4L interferometers: **optimal Ω** **optimal α** **balanced**
- Two networks 2L CE + ET Triangle: **optimal Ω** **optimal α**
- All orientations can be chosen modulo 90 degrees

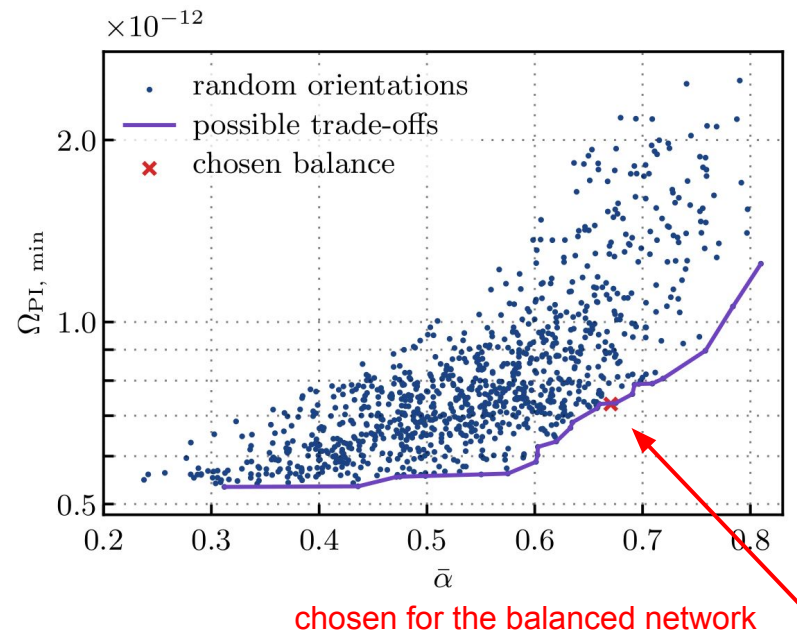


Sky-averaged network alignment factors:

- 4L optimal Ω** : $\alpha = 0.36$
- 4L optimal α** : $\alpha = 0.83$
- 4L balanced**: $\alpha = 0.67$
- $\Delta+2L$ optimal Ω** : $\alpha = 0.55$
- $\Delta+2L$ optimal α** : $\alpha = 0.74$

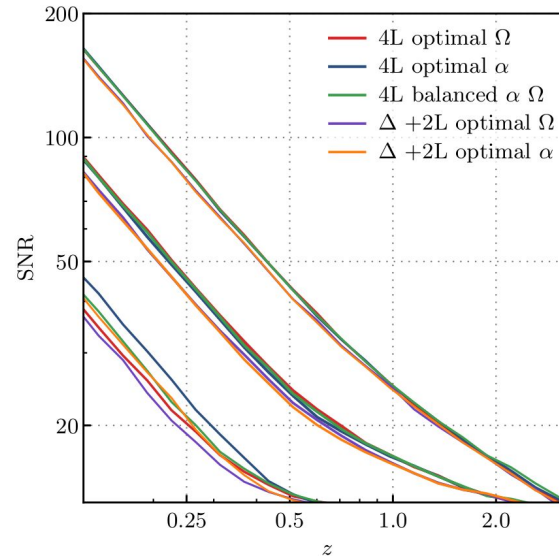
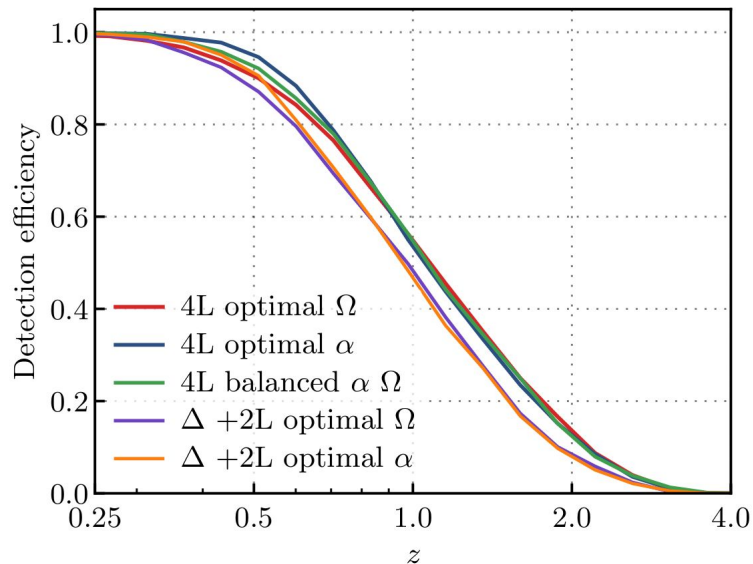
Finding a trade-off

- What is a good trade-off between being sensitive to the stochastic background / both polarizations?
 - Each dot represents possible orientations
 - Along the violet line we find good trade-offs
 - There is no unique best trade-off
 - For this case e.g. we find the relative angle between the ETs to be 28 deg and between the CEs 75 deg



Detection efficiency for BNS

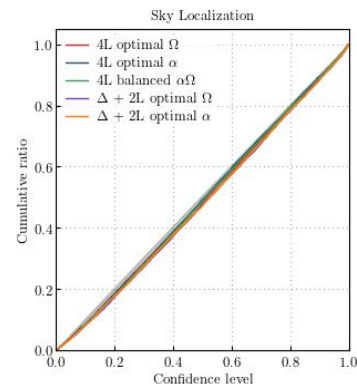
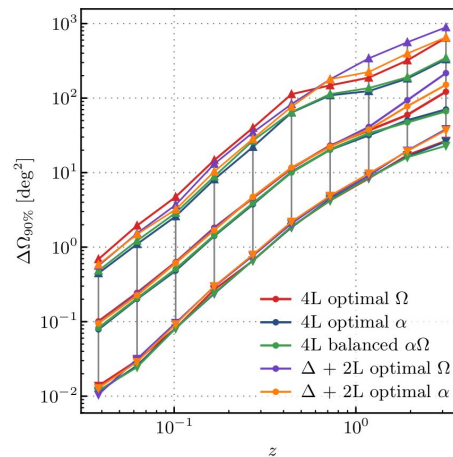
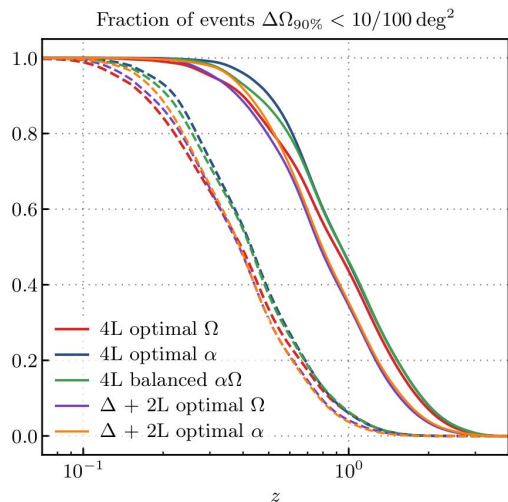
- Detection efficiency (network SNR > 12) as a function of redshift for a reference ($1.4 M_{\odot}$, $1.4 M_{\odot}$) non-spinning BNS system injected into Gaussian noise (*IMRPhenomXAS_NRTidalv2* waveform, [arXiv:2311.15978](https://arxiv.org/abs/2311.15978))
- The arm orientation only slightly affects the SNR that can be picked up



Localization of BNS

- We inject many events into simulated detector noise and use the PyCBC inference single template model to reconstruct the sky localization

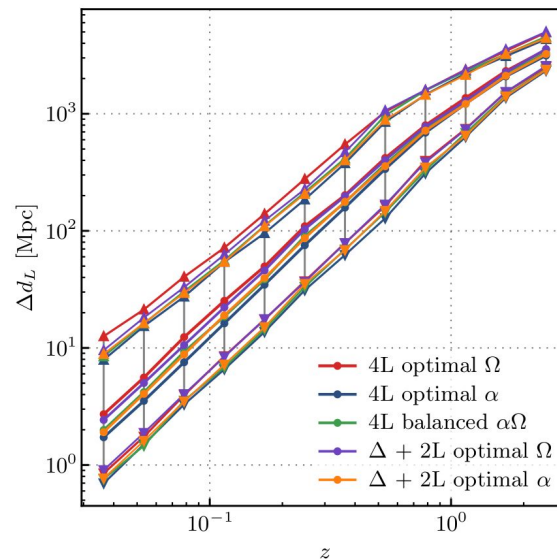
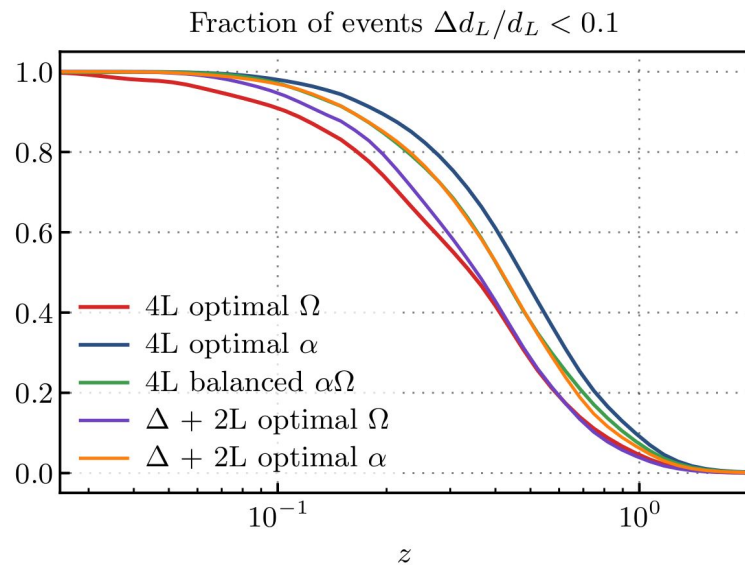
➤ Assumes the intrinsic parameters are known, sample only in the extrinsic parameters (much faster)



- Sky localization is only mildly affected by the arm orientation
- The pp-plot is diagonal, thus the uncertainties are estimated correctly

Distance estimation for BNS

- From PyCBC Inference we can also recover the distance
 - Seeing both polarizations is very helpful to break the distance-inclination angle degeneracy



Conclusion

- We investigated how the capabilities of a global next-generation GW detector network depend on the arm orientation
- While detection efficiency and sky localization depend only mildly on the orientation of the arms
- It is important for measuring the stochastic background and getting good distance estimates
- Impact of correlated seismic noise is not discussed
- It is important to consider the global detector network
- The study could be extended to other metrics and detector networks

Thank you very much for your attention!

Questions?