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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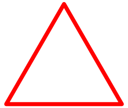
Introduction

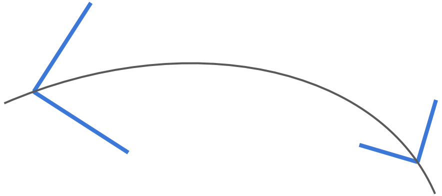
- We are in the design phase of the next-generation ground-based GW detectors

- 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
  - Characterizing Gravitational Wave Detector Networks: From $A^\sharp$ to Cosmic Explorer (Gupta et al.), arXiv:2307.10421

- Our study concentrates on stochastic background and CBC searches arXiv:2408.06032
  - Focus on the impact of detector orientation
  - Results should not depend on astrophysical models
  - Look at the global network
  - 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

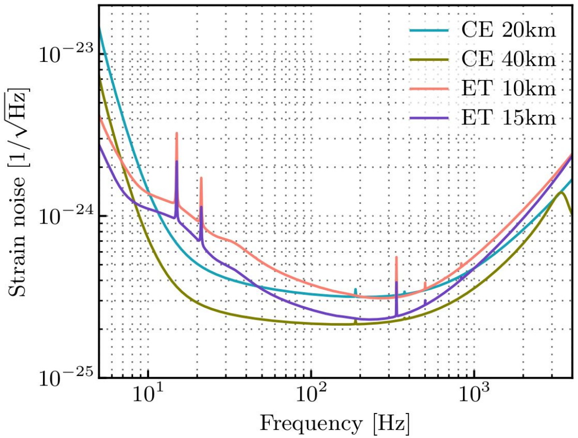
    ET 2L: one IFO each at candidate sites in the MeuseRhine region and Sardinia   Branchesi et al. 2023 arXiv:2303.15923

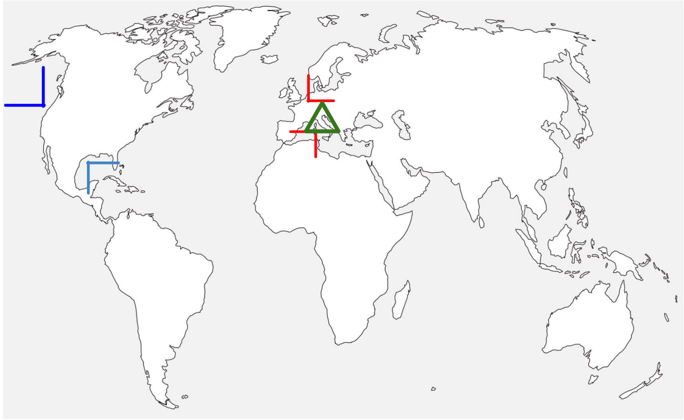
    CE: one IFO in the Pacific ocean, one IFO in the Atlantic ocean   Gupta et al. 2023 arXiv:2307.10421

    ET Δ : located at the Virgo site

  - ➢ Arm orientations

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



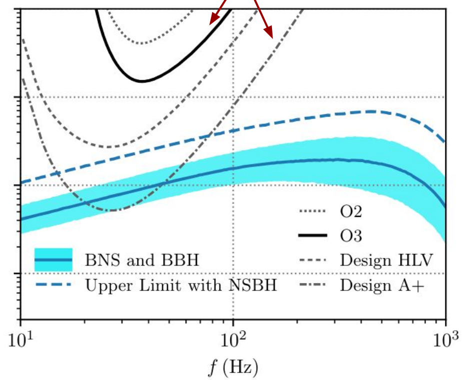


Metric for the sensitivity to the stochastic GWB

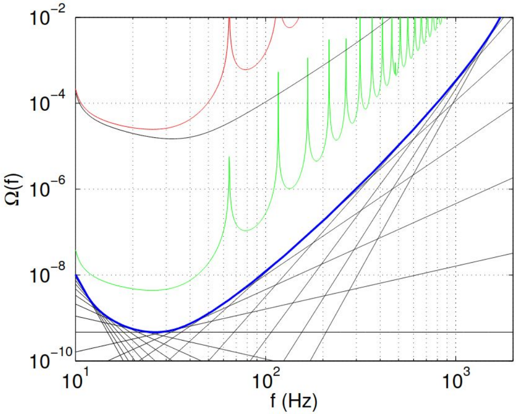
- Sensitivity to the stochastic background
  - Minimum of Power-law integrated (PI) sensitivity curves — Thrane et al. 2013 arXiv:1310.5300

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

PI sensitivity curves



Abbott et al. 2021 arXiv:2101.12130



Thrane et al. 2013 arXiv:1310.5300

acquired SNR, here SNR = 3

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

observation time, here T = 1 yr

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

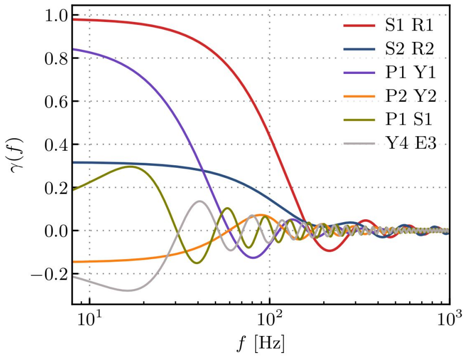
$$S_{\mathrm{eff}}(f) \equiv \left[\sum_{I=1}^{M} \sum_{J>I}^{M} \frac{\Gamma^2_{IJ}(f)}{P_{nI}(f) P_{nJ}(f)} \right]^{-1/2}$$

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



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

    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: $\boldsymbol{F}^+ = \begin{bmatrix} F_{w,1}^+ \\ F_{w,2}^+ \\ \vdots \\ F_{w,D}^+ \end{bmatrix}$ $\boldsymbol{F}^\times = \begin{bmatrix} F_{w,1}^\times \\ F_{w,2}^\times \\ \vdots \\ F_{w,D}^\times \end{bmatrix}$

    Since the choice of polarization angle is arbitrary, we can choose it such that:

    $$|\boldsymbol{f}^+|^2 \geq |\boldsymbol{f}^\times|^2$$
    $$\boldsymbol{f}^+ \cdot \boldsymbol{f}^\times = 0$$

    } Dominant polarization frame

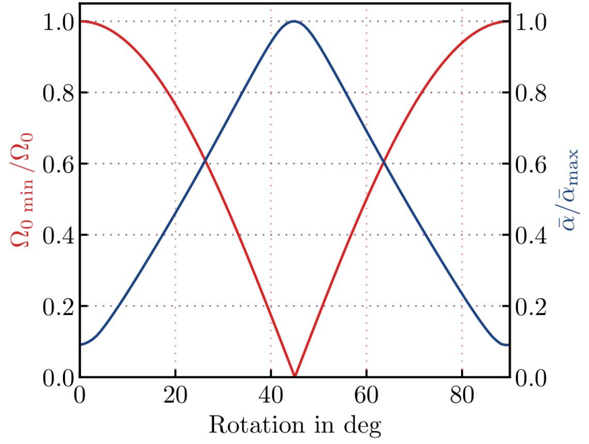
    Now we can define the alignment factor: $\alpha = \frac{|\boldsymbol{f}^\times|}{|\boldsymbol{f}^+|} \in [0,1]$ → Take the sensitivity weighted sky-average

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

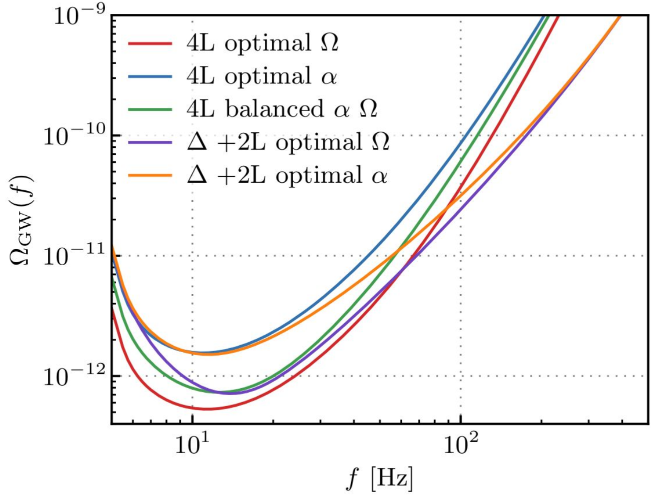
$\Omega_{0,\,min} = 5.39 \times 10^{-13}$

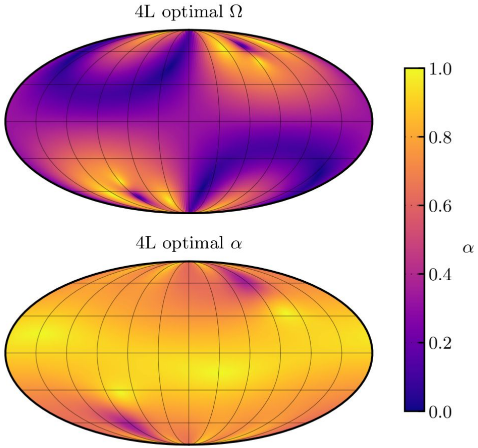
$\alpha_{max} = 0.734$



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





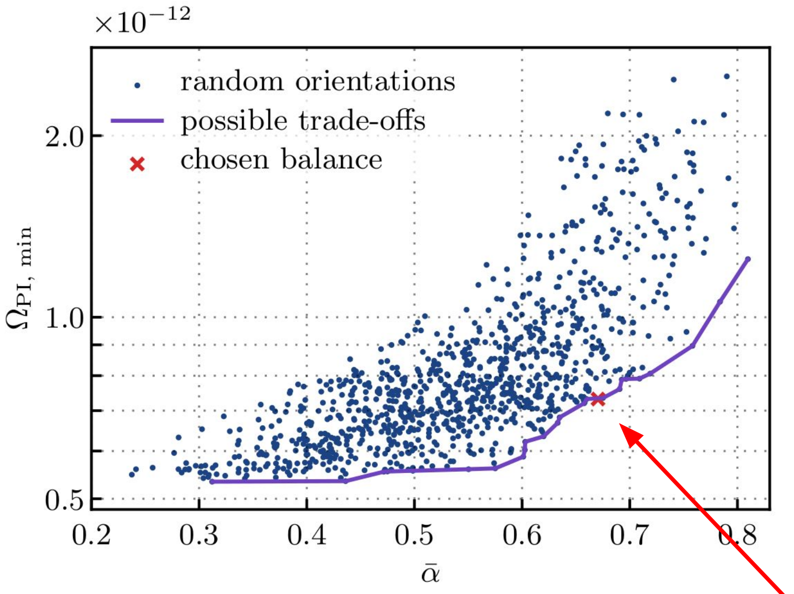
Sky-averaged network alignment factors:

- 4L optimal *Ω*: α = 0.36
- 4L optimal *α*: α = 0.83
- 4L balanced: α = 0.67
- Δ+2L optimal *Ω*: α = 0.55
- Δ+2L optimal *α*: α = 0.74

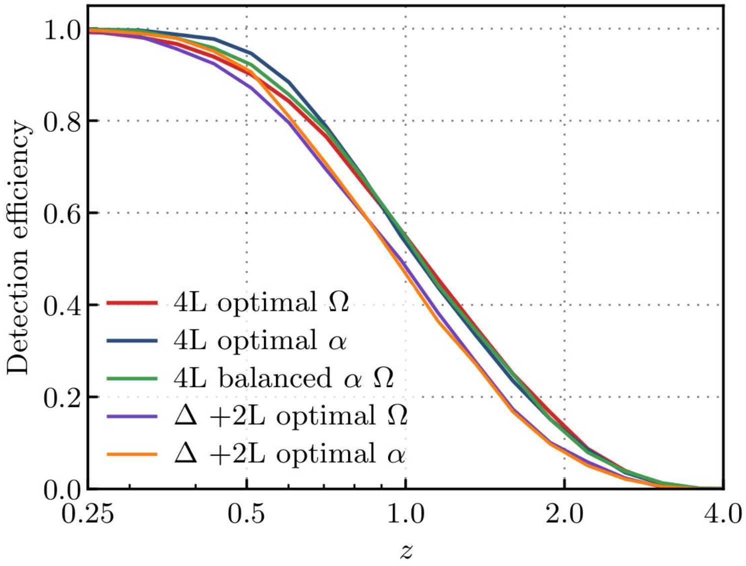
α should only be compared within the same network configuration

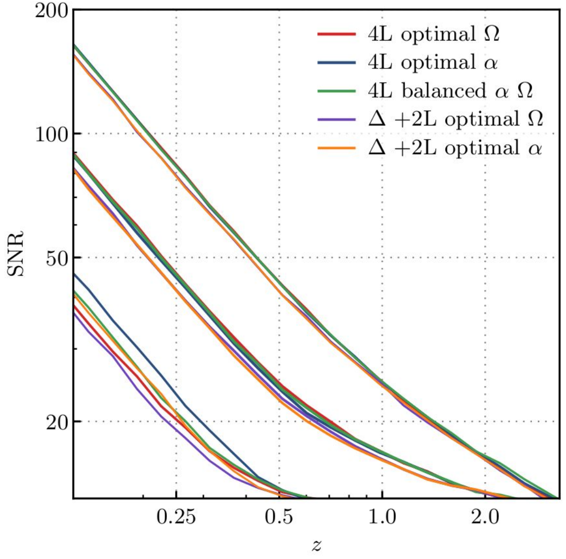
Finding a trade-off

- 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



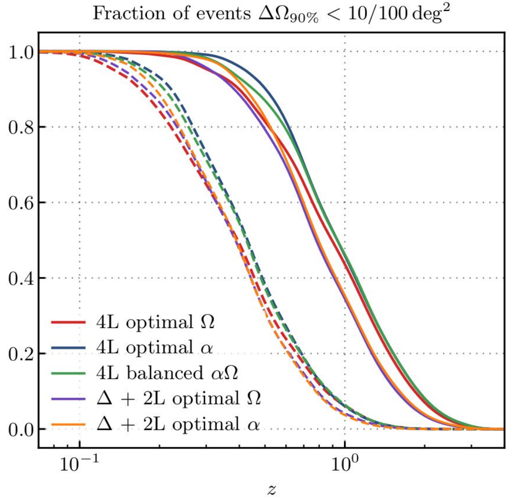
- Detection efficiency (network SNR > 12) as a function of redshift for a reference (1.4 $M_\odot$, 1.4 $M_\odot$) non-spinning BNS system injected into Gaussian noise (*IMRPhenomXAS_NRTidalv2* waveform, arXiv:2311.15978)
- The arm orientation only slightly affects the SNR that can be picked up

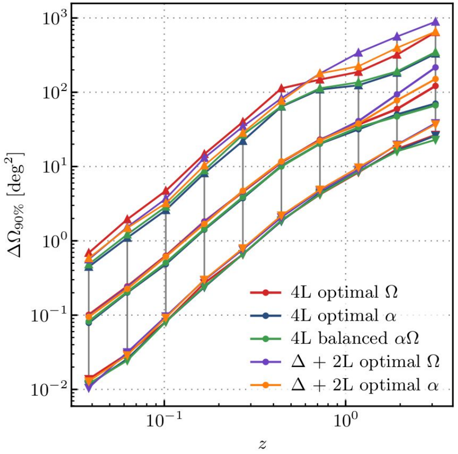


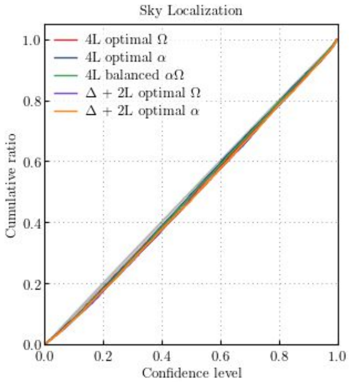


Localization of BNS

- 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)



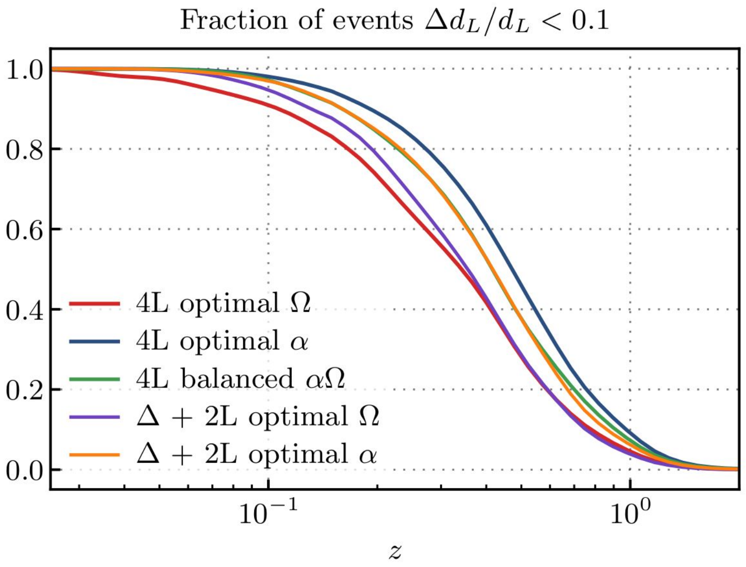


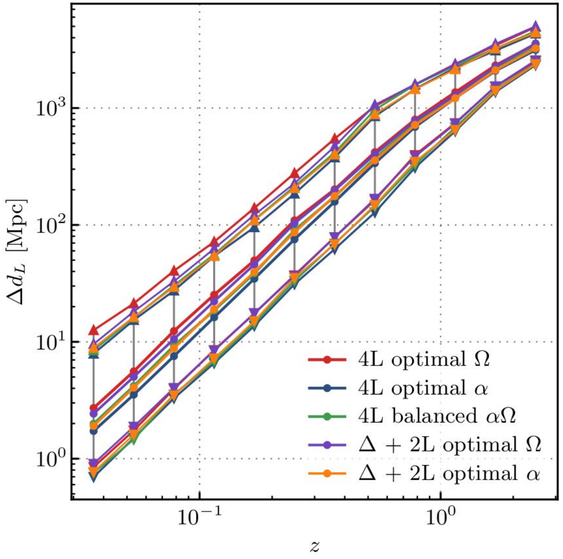


- Sky localization is only mildly affected by the arm orientation
- The pp-plot is diagonal, thus the uncertainties are estimated correctly

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?