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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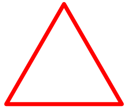
Swiss Cosmology Days

June 6, 2025

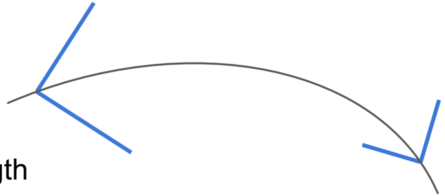
Universität Zürich[UZH]

Introduction

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



- Einstein Telescope (ET) reference Designs:
  - 10 km Triangle including 3 detectors each composed of two interferometers (low/high frequency)
  - 2 L-shaped detectors with 15km arm length



- Cosmic Explorer (CE) reference Design:
  - 2 L-shaped detectors with 40 km and 20 km arm length
- L-shaped detectors: Network sensitivity depends on the relative arm orientation
- What is the impact of arm orientation on Stochastic and CBC science? arXiv:2408.06032
- Cosmology: we are interested in a good performance regarding both

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

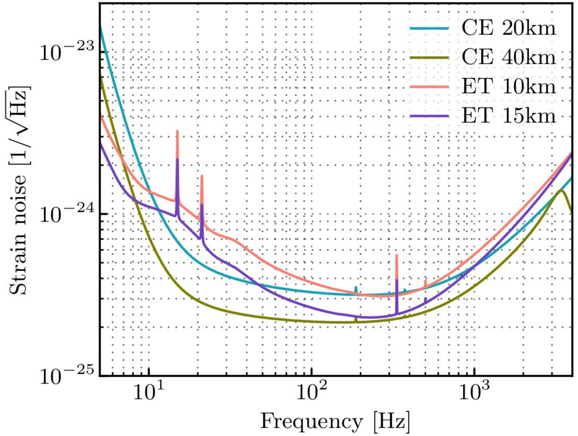
    ET 2L: one IFO each at candidate sites in the MeuseRhine region and Sardinia   Branchesi et al. 2023 arXiv:2303.15923

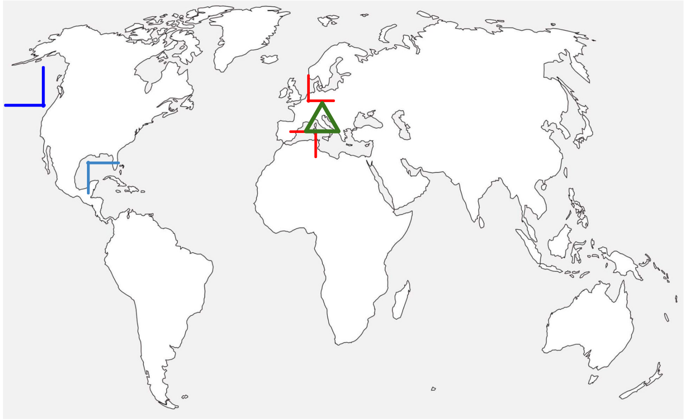
    CE: one IFO in the Pacific ocean, one IFO in the Atlantic ocean   Gupta et al. 2023 arXiv:2307.10421

    ET Δ : located at the Virgo site

  - ➢ Arm orientations

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



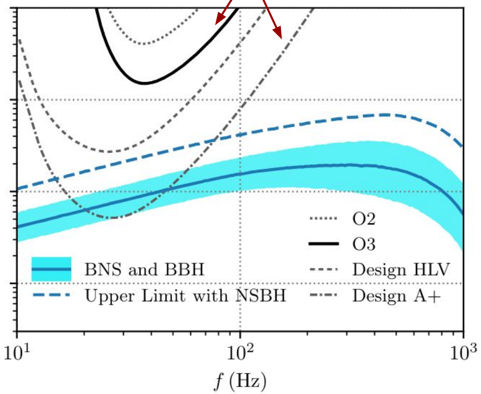


Metric for the sensitivity to the stochastic GWB

- Sensitivity to the stochastic background
  - 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

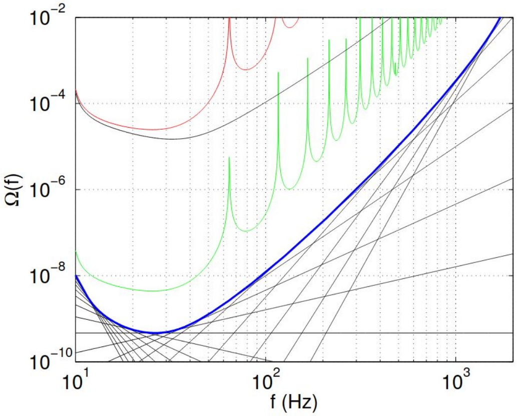


Abbott et al. 2021 arXiv:2101.12130

acquired SNR, here SNR = 3

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

observation time, here T = 1 yr



Thrane et al. 2013 arXiv:1310.5300

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

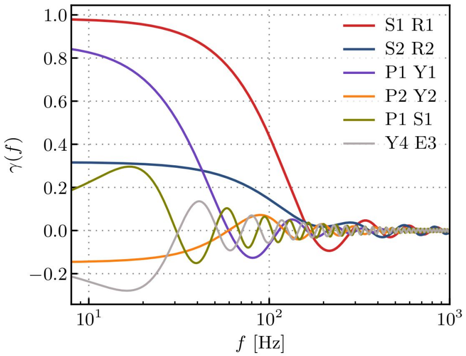
$$S_{\mathrm{eff}}(f) \equiv \left[\sum_{I=1}^{M}\sum_{J>I}^{M} \frac{\Gamma_{IJ}^2(f)}{P_{nI}(f)P_{nJ}(f)}\right]^{-1/2}$$

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



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: $F_{w,I}^{+,\times}(\hat{\Omega},k) = \dfrac{F_I^{+,\times}}{\sqrt{\frac{N}{2}P_{nI}(k)}}$ 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: $\left.\begin{aligned} |\boldsymbol{f}^+|^2 &\geq |\boldsymbol{f}^\times|^2 \\ \boldsymbol{f}^+ \cdot \boldsymbol{f}^\times &= 0 \end{aligned}\right\}$ Dominant polarization frame

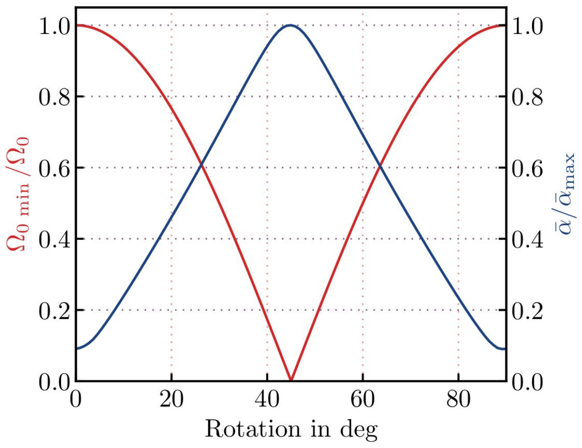
    Now we can define the alignment factor: $\alpha = \dfrac{|\boldsymbol{f}^\times|}{|\boldsymbol{f}^+|} \in [0,1]$ $\longrightarrow$ Take the sensitivity weighted sky-average

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

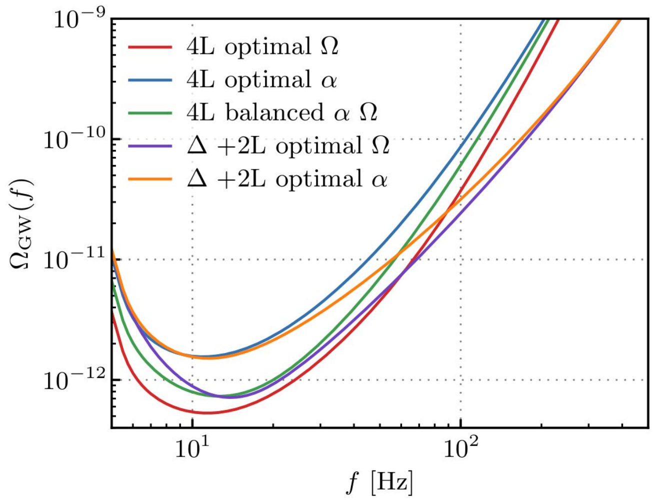
$\Omega_{0,\,\mathrm{min}} = 5.39 \times 10^{-13}$

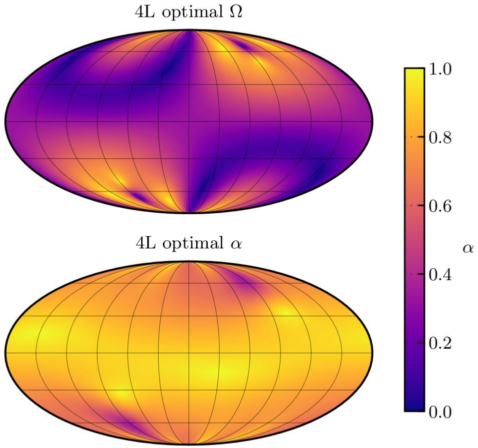
$\alpha_{\mathrm{max}} = 0.734$



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

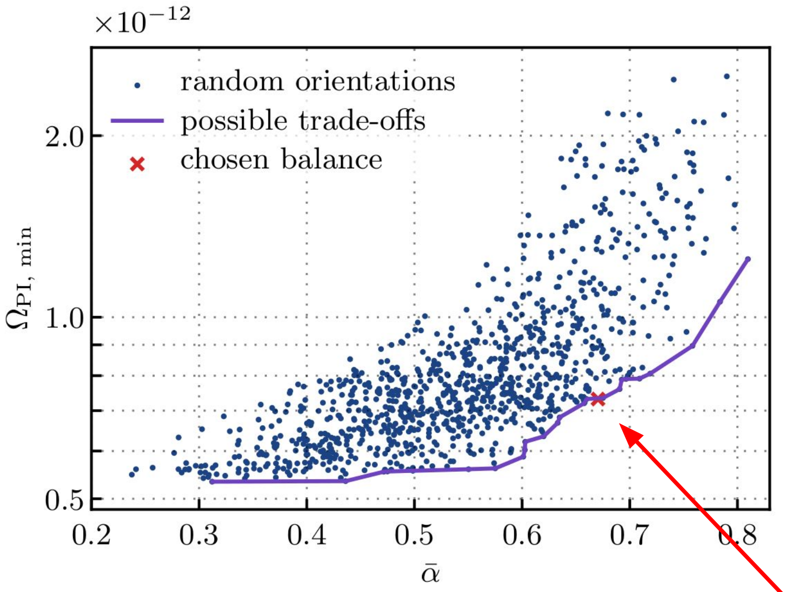
4L balanced: α = 0.67

Δ+2L optimal Ω: α = 0.55

Δ+2L optimal α: α = 0.74

Finding a trade-off

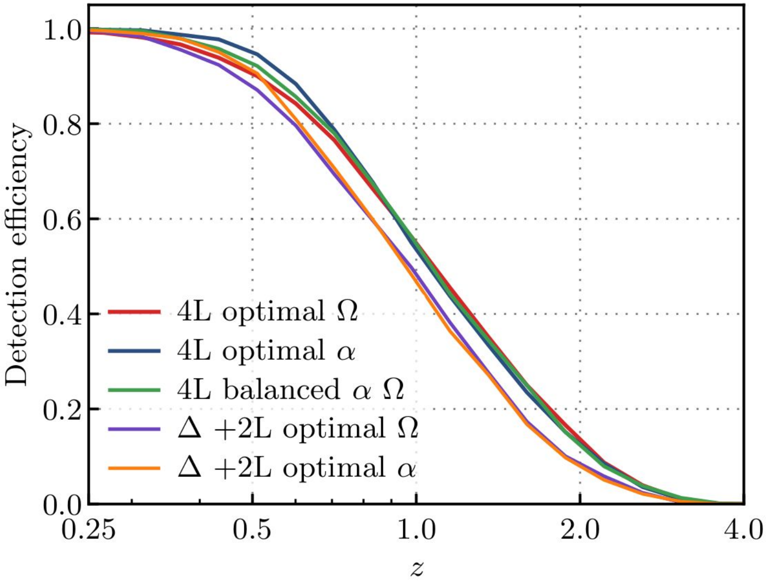
- What is a good trade-off between being sensitive to the stochastic background / both polarizations?
  - ➢ Each dot represents possible orientations
  - ➢ Along the violet line we find good trade-offs
  - ➢ There is no unique best trade-off
  - ➢ For this case e.g. we find the relative angle between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



chosen for the balanced network

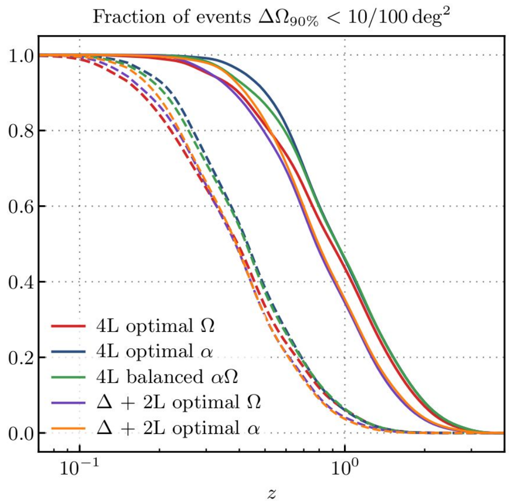
Detection efficiency for BNS

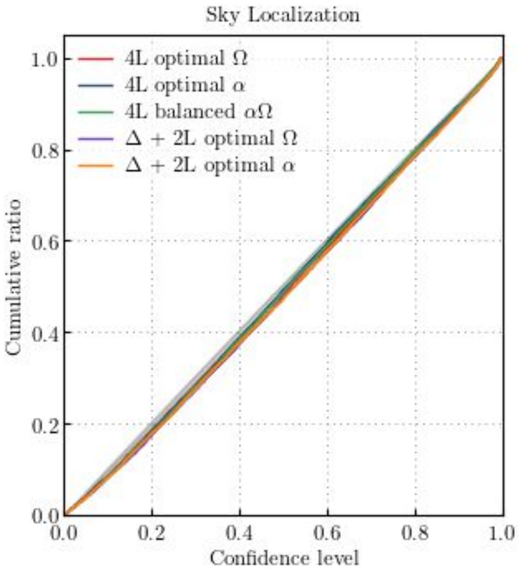
- Detection efficiency (network SNR > 12) as a function of redshift for a reference (1.4 $M_\odot$, 1.4 $M_\odot$) non-spinning BNS system injected into Gaussian noise (*IMRPhenomXAS_NRTidalv2* waveform, arXiv:2311.15978)
- The arm orientation only slightly affects the SNR that can be picked up



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)

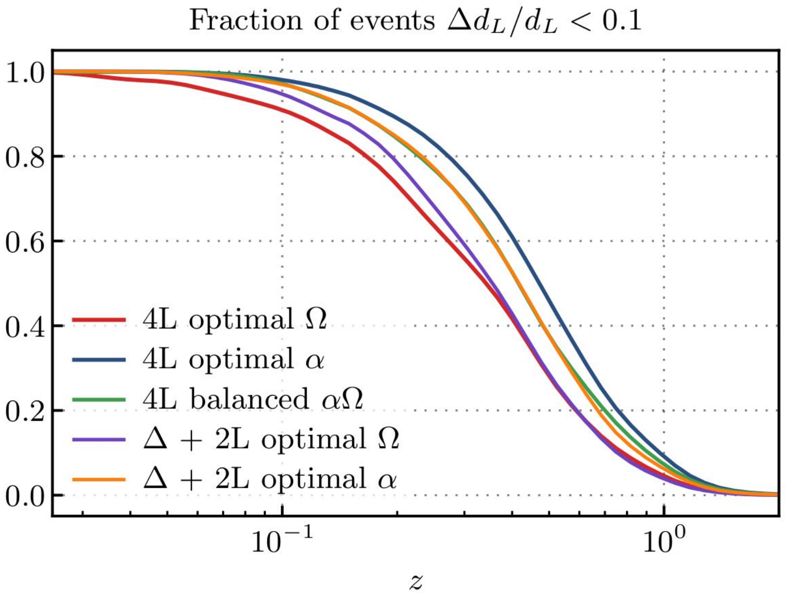




- Sky localization is only mildly affected by the arm orientation
- The pp-plot is diagonal, thus the uncertainties are estimated correctly

Distance estimation for BNS

- With PyCBC Inference we 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?