

A Fish out of Water:

How the Fisher information matrix can bias forecasts for gravitational waves detectors



Utrecht
University



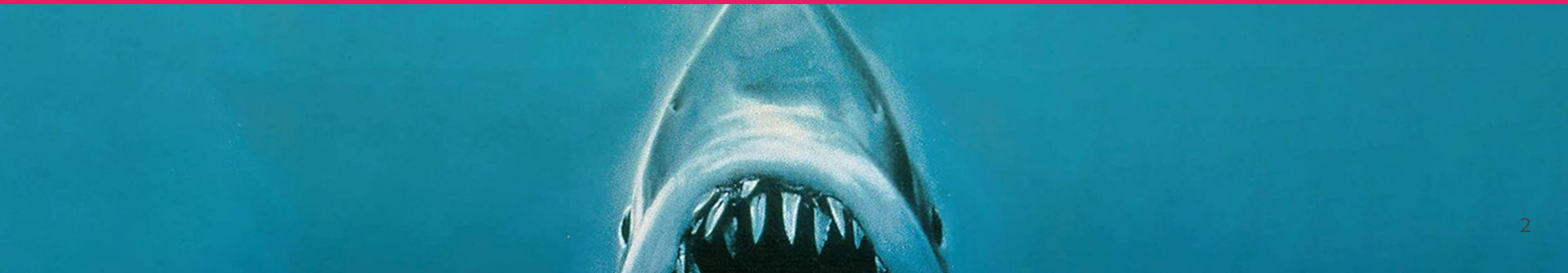
Luca Negri,

Thomas C.K. Ng, Thibaut Wouters, Harsh Narola,
Robin Chan, Kailib Ryan Doney, Francesco Cireddu,
Isaac C. F. Wong, Anuradha Samajdar, Justin
Janquart, Chris Van Den Broeck and Tjonnje G. F. Li

BE-NL meeting
9th october 2026

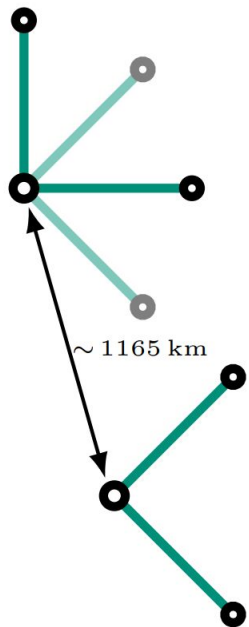


A fish





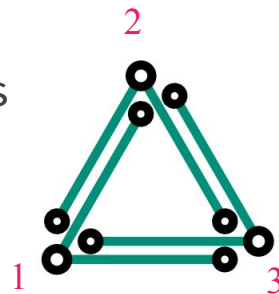
Why worry about next gen data now?



ET geometry still to be decided

ET-2L : Two 15 km L-shaped detectors

ET- Δ : Three 10 km nested V-shaped detectors

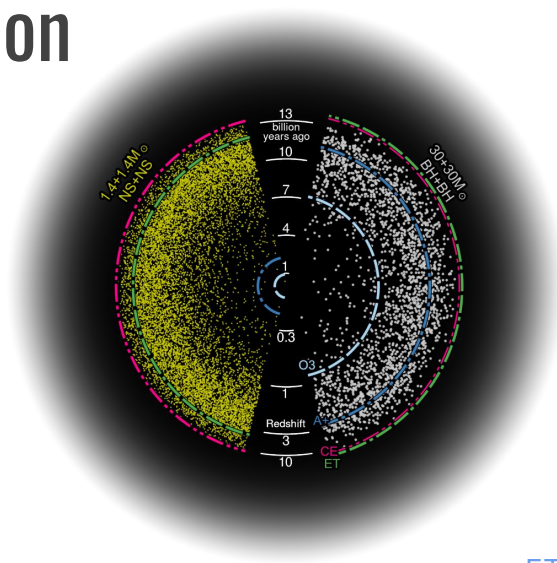
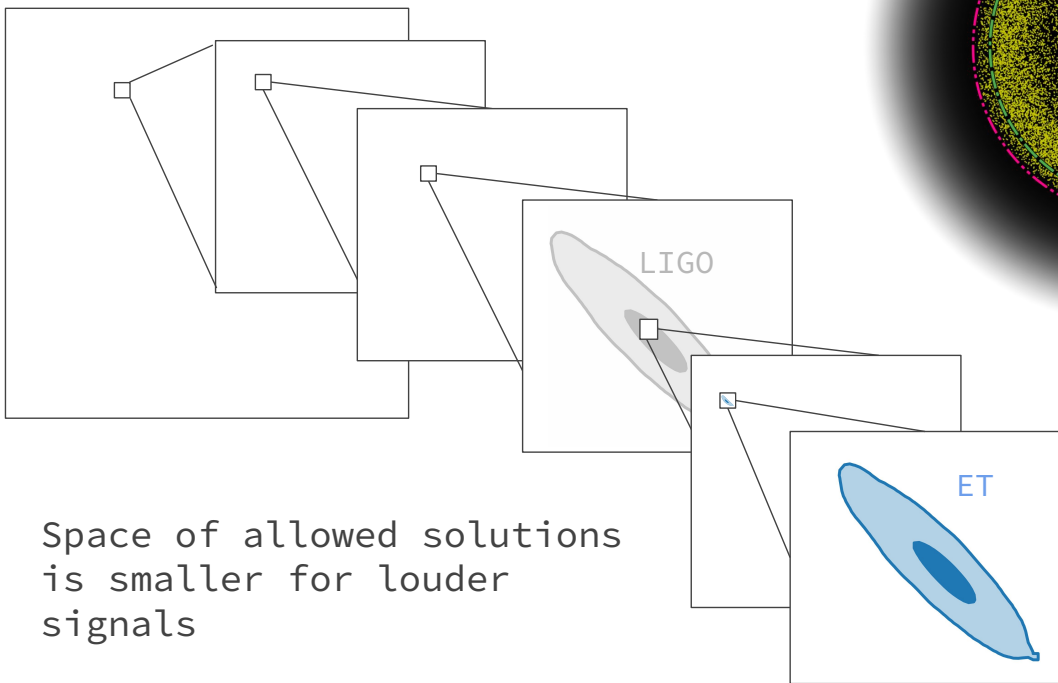


We need to analyze ET data today to better assess the merits of each design!

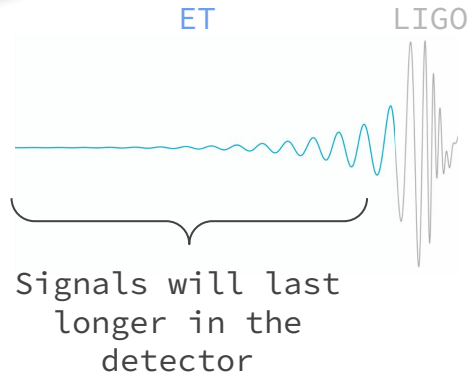


Going towards next generation

Prior



Signal rate will raise by 3 orders of magnitude





How is designs comparison carried out?

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General Relativity and Quantum Cosmology

[Submitted on 28 Mar 2023 (v1), last revised 17 Jun 2023 (this version, v2)]

Science with the Einstein Telescope: a comparison of different designs

Marica Branchesi, Michele Maggiore, David Alonso, Charles Badger, Biswajit Banerjee, Freija Beirnaert, Enis Belgacem, Swetha Bhagwat, Guillaume Boileau, Ssohrab Borhanian, Daniel David Brown, Man Leong Chan, Giulia Cusin, Stefan L. Danilishin, Jerome Degallaix, Valerio De Luca, Arnab Dhani, Tim Dietrich, Ulyana Dupletsa, Stefano Foffa, Gabriele Franciolini, Andreas Freise, Gianluca Gemme, Boris Goncharov, Archisman Ghosh, Francesca Gulminelli, Ish Gupta, Pawan Kumar Gupta, Jan Harms, Nandini Hazra, Stefan Hild, Tanja Hinderer, Ik Siong Heng, Francesco Iacovelli, Justin Janquart, Kamiel Janssens, Alexander C. Jenkins, Chinmay Kalaghatgi, Xhesika Korovesi, Tjonnie G.F. Li, Yufeng Li, Eleonora Loffredo, Elisa Maggio, Michele Mancarella, Michela Mapelli, Katarina Martinovic, Andrea Maselli, Patrick Meyers, Andrew L. Miller, Chiranjib Mondal, Niccolò Muttoni, Harsh Narola, Micaela Oertel, Gor Oganessian, Costantino Pacilio, Cristiano Palomba, Paolo Pani, Antonio Pasqualetti, Albino Perego, Carole Pèrgois, Mauro Pieroni, Ornella Juliana Piccinni, Anna Puecher, Paola Puppo, Angelo Ricciardone, Antonio Riotto, Samuele Ronchini, Mairi Sakellariadou, Anuradha Samajdar, Filippo Santoliquido, B.S. Sathyaprakash, Jessica Steinlechner, Sebastian Steinlechner, Andrei Utina, Chris Van Den Broeck, Teng Zhang

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General Relativity and Quantum Cosmology

[Submitted on 13 Apr 2024]

Not too close! Evaluating the impact of the baseline on the localization of binary black holes by next-generation gravitational-wave detectors

Francesco Iacovelli, Luca Reali, Emanuele Berti, Alessandra Corsi, B. S. Sathyaprakash, Digvijay Wadekar

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Legend: Δ 10 km HFLF cryo, 2L 45° 15 km HFLF cryo, 1L 20 km HFLF cryo, LVKI O5

General Relativity and Quantum Cosmology

[Submitted on 14 Apr 2024 (v1), last revised 11 Nov 2024 (this version, v2)]

The Lunar Gravitational-wave Antenna: Mission Studies and Science Case

Parameswaran Ajith, Pau Amaro Seoane, Manuel Arca Sedda, Riccardo Arcodia, Francesca Badaracco, Biswajit Banerjee, Enis Belgacem, Giovanni Benetti, Stefano Benetti, Alexey Bobrick, Alessandro Bonforte, Elisa Bortolas, Valentina Brailo, Marica Branchesi, Adam Burrows, Enrico Cappellaro, Roberto Della Ceca, Chandrachur Chakraborty, Shreevathsa Chalathadka Subrahmanya, Michael W. Coughlin, Stefano Covino, Andrea Derdzinski, Aayushi Doshi, Maurizio Falanga, Stefano Foffa, Alessia Franchini, Alessandro Frigeri, Yoshifumi Futaana, Oliver Gerberding, Kiranjoti Gill, Matteo Di Giovanni, Ines Francesca Giudice, Margherita Giustini, Philipp Gläser, Jan Harms, Joris van Heijningen, Francesco Iacovelli, Bradley J. Kavanagh, Taichi Kawamura, Arun Kenath, Elisabeth-Adelheid Kepler, Chiaki Kobayashi, Goro Komatsu, Valeriya Korol, N. V. Krishnendu, Prayush Kumar, Francesco Longo, Michele Maggiore, Michele Mancarella, Andrea Maselli, Alessandra Mastrobuono-Battisti, Francesco Mazzarini, Andrea Daniele Melini, Sabrina Menina, Giovanni Miniutti, Deeshani Mitra, Javier Morán-Fraile, Suvodip Mukherjee, Mattia Muttoni, Marco Olivieri, Francesca Onori, Maria Alessandra Papa, Ferdinando Patat, Andrea Perali, Tsvi Piran, Roberto Roper Pol, Masroor C. Pookkillath, R. Prasad, Vaishak Prasad, Alessandra De Rosa, Iy Chowdhury, Roberto Serafinelli, Alberto Sesana, Paola Severgnini, Angela Stalione, Jacopo Tisino, Licia Tomasella, Martina Toscani, David Vartanyan, Cristian Vignali, Lucia Zaccarelli, Morgane Zeoli, uccarello

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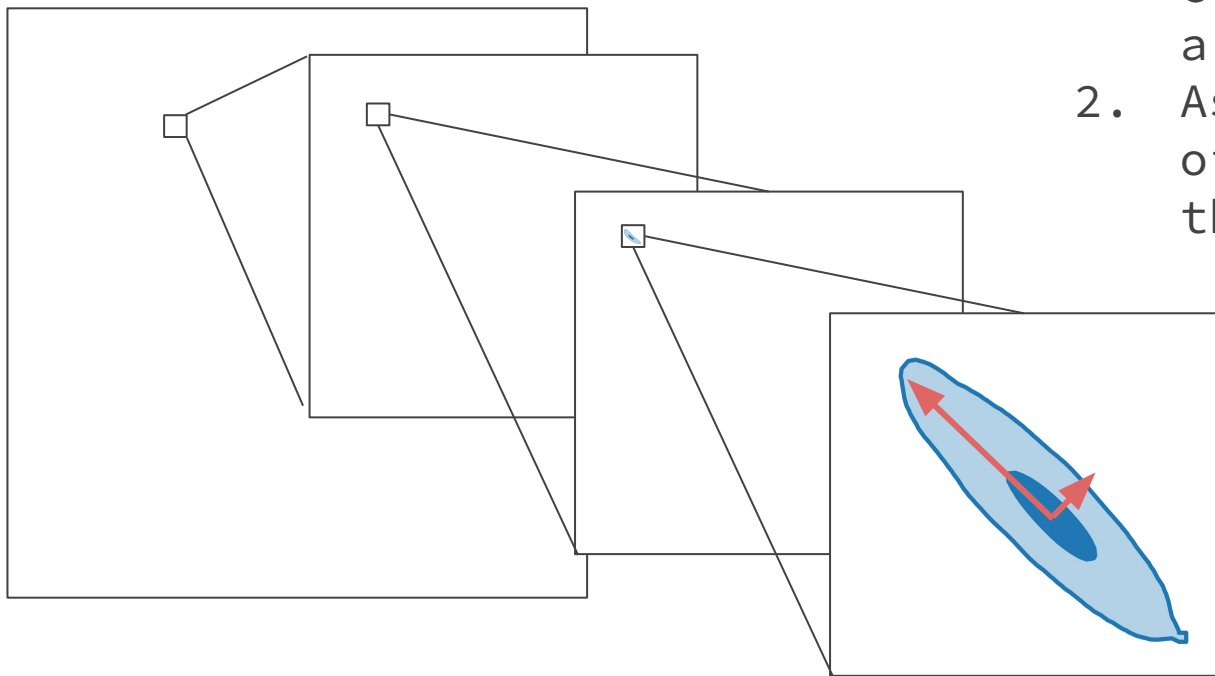
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By simplifying the problem!

Prior



1. Assume posterior is concentrated only around the peak
2. Assume linear response of the detector around the peak

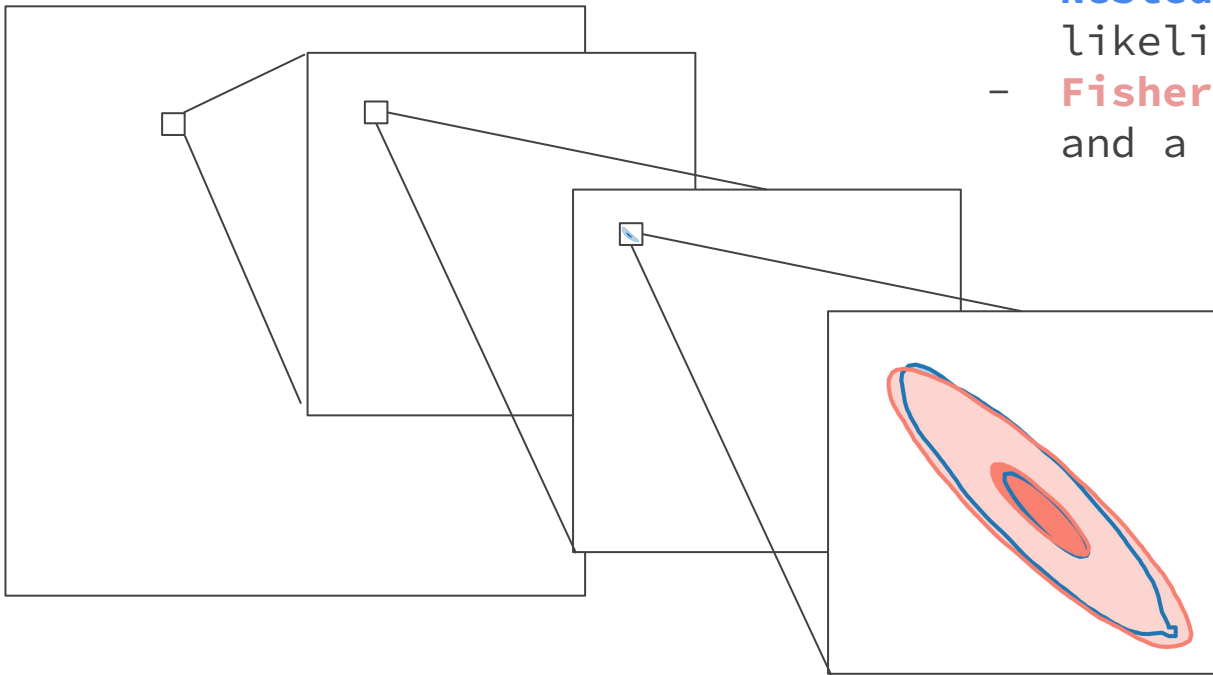
Fisher matrix:

$$\Gamma_{ij} = \langle h_i | h_j \rangle$$



Simplify the problem.

Prior



Computational costs:

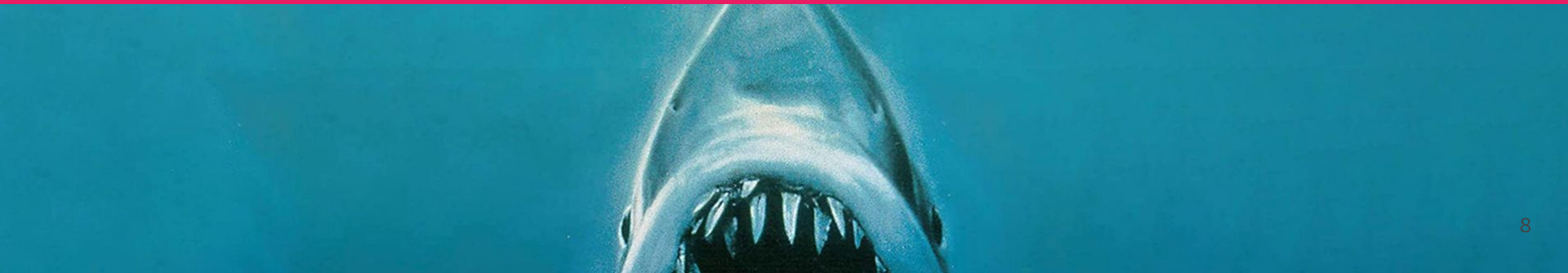
- **Nested sampling:** 10^6 – 10^8 likelihood evaluations
- **Fisher matrix:** 15 derivatives and a matrix inversion

$$\Gamma_{ij}^{-1} = \Sigma_{ij} \quad \text{First order posterior approximation}$$

$$p(\theta) \sim \mathcal{N}(\theta_{\text{true}}, \Sigma)$$



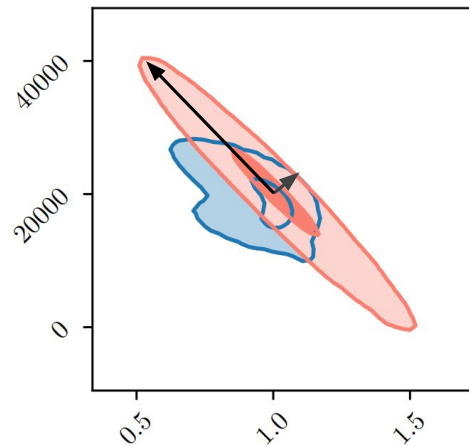
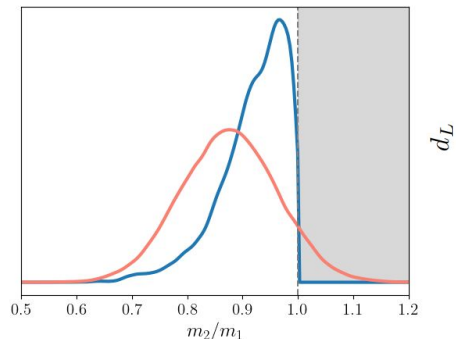
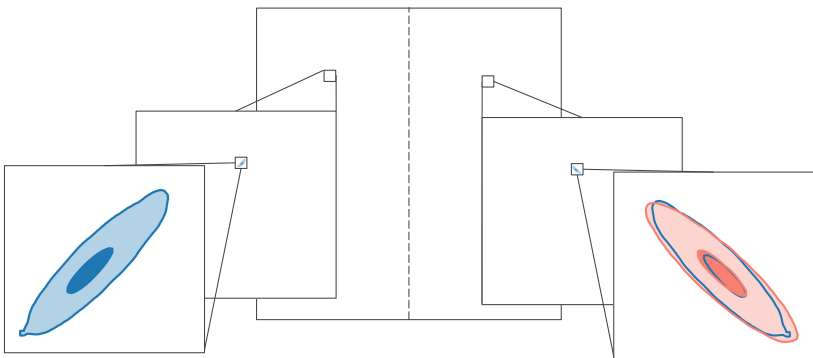
Out of water





Do our assumption hold for ET?

Fisher assumes the final posterior will be a multivariate Gaussian.
So it fails whenever its not



θ_{jn}



Do the assumption hold for ET?

Fisher is equivalent to the 1st order term in $1/\text{SNR}$ of the Bayesian posterior.

And High SNR signals

Break symmetries (unimodality)

Posterior signal- rather than prior-dominated

Higher order modes suppressed

(basically are just more gaussian)



Why we should worry for design comparisons

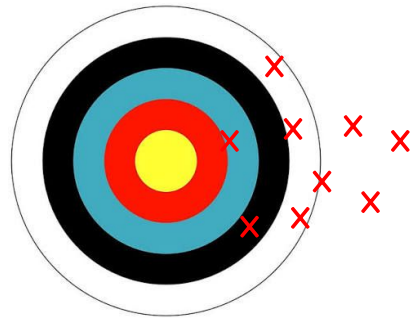
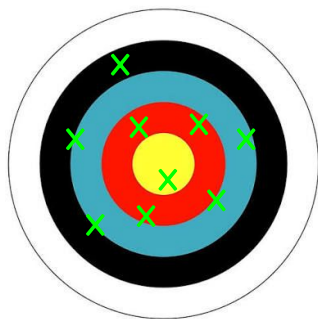
Different networks -> **Different likelihood morphologies**

Fisher should be more inaccurate for more degenerate networks

But inaccurate does not imply bias



VS





Do the assumption hold for ET?

— — —

Compare Fisher,
Fisher + priors and
nested sampling for
130 signals,
injected in 10 next
generation networks
of ET (+CE)

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General Relativity and Quantum Cosmology

[Submitted on 17 Jun 2026 (v1), last revised 22 Jun 2026 (this version, v2)]

Impact of the Einstein Telescope's duty cycle on the estimation of binary black holes parameters

[Luca Negri](#), [Thomas C.K. Ng](#), [Thibaud Wouters](#), [Tim J. Kuhlbusch](#), [Harsh Narola](#), [Robin Chan](#), [Kailib Ryan Doney](#), [Francesco Cireddu](#), [Isaac C. F. Wong](#), [Fabian Gittins](#), [Peter T. H. Pang](#), [Anuradha Samajdar](#), [Achim Stahl](#), [Justin Janquart](#), [Chris Van Den Broeck](#), [Tjonnie G. F. Li](#)

The geometry of the Einstein Telescope, the proposed next-generation European gravitational-wave observatory, is yet to be finalized. Two competing designs are under consideration: a nested triangular configuration (ET- Δ) and two separated L-shaped detectors (ET-2L). Extensive prior comparisons of ET designs established the scientific landscape using the Fisher-information-matrix formalism and identified that duty-cycle-induced single-detector operation is precisely the regime where this approximation becomes less reliable, underscoring the need for a refined, principled treatment of the duty cycle. In this manuscript, we build on that foundation by revisiting the comparison with full Bayesian parameter estimation of gravitational-wave signals from binary black-hole

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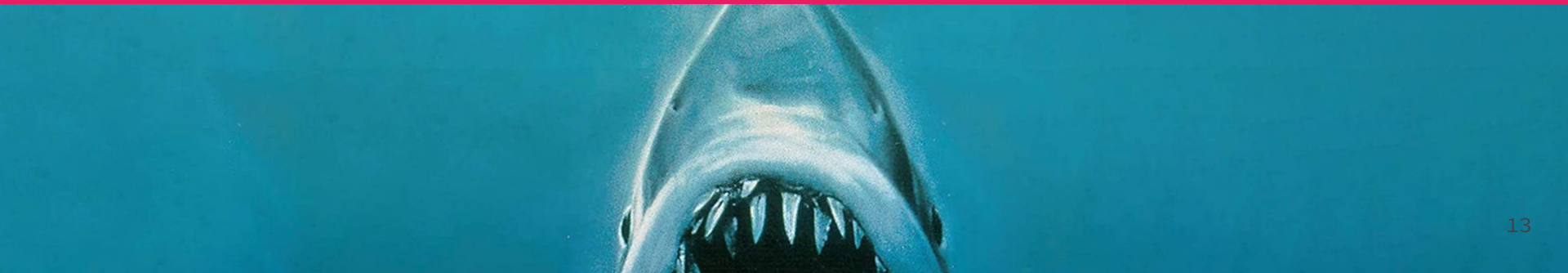
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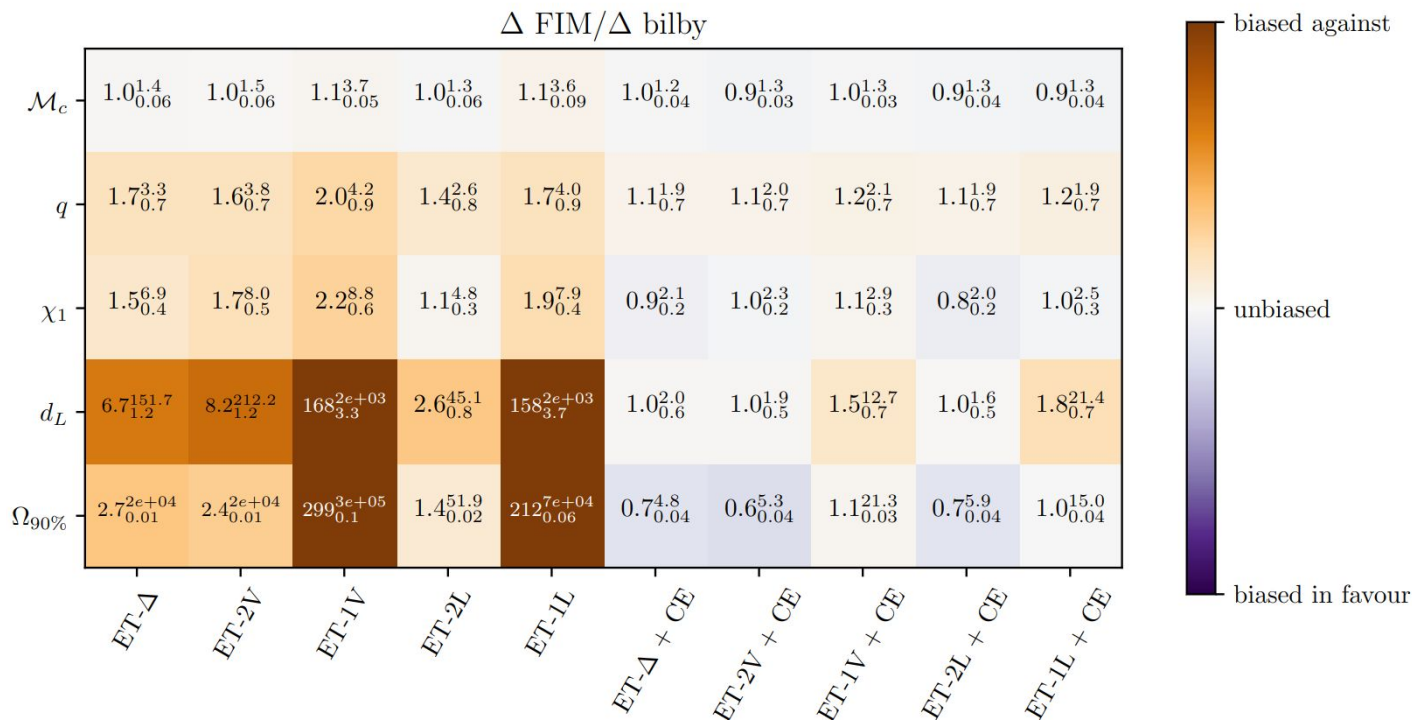


No





The results



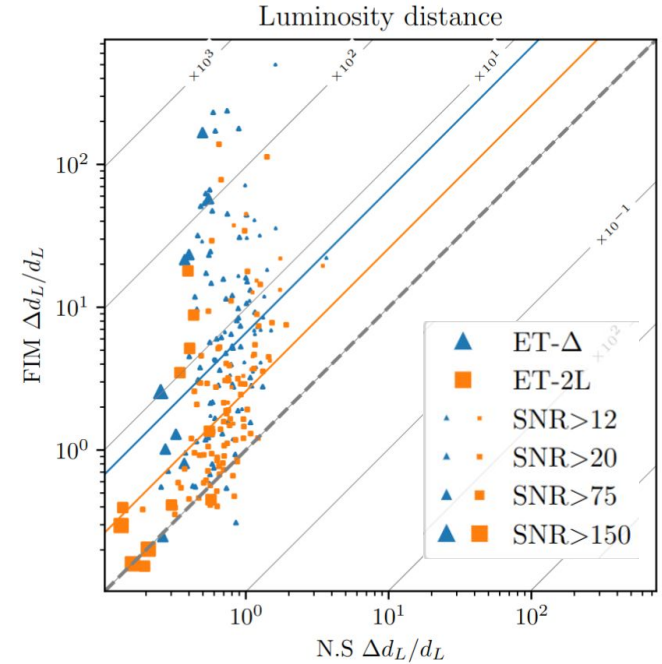
Unbiased
results:
white
block



Distance

$\Delta \text{FIM} / \Delta \text{bilby}$

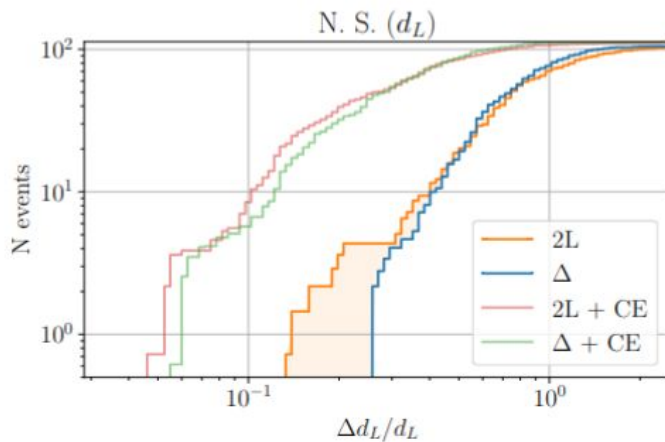
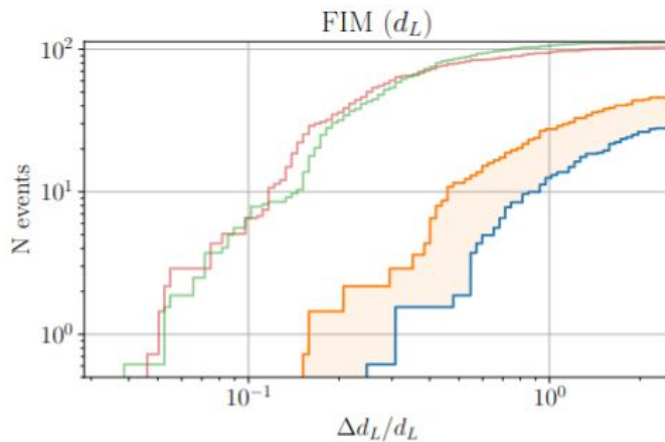
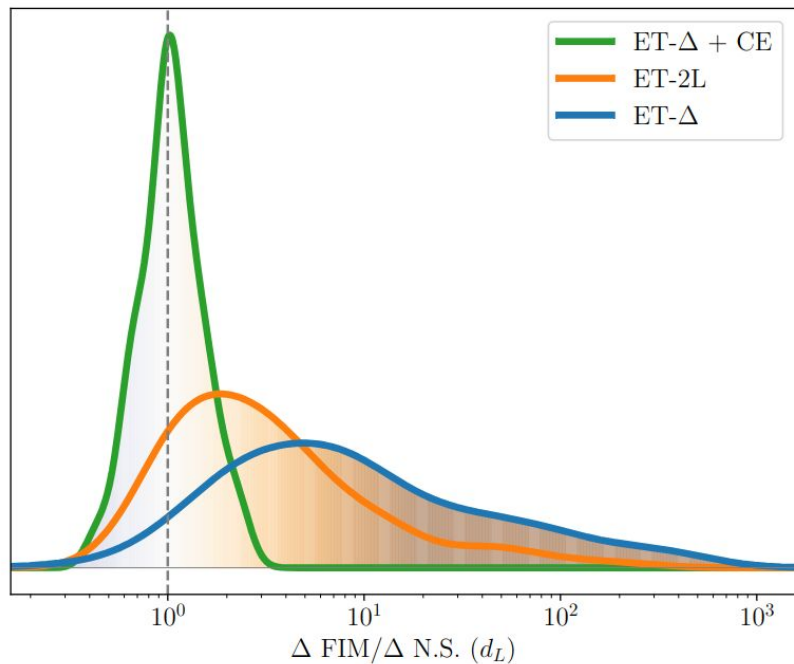
$\mathcal{M}_c$	$1.0^{1.4}_{0.06}$	$1.0^{1.5}_{0.06}$	$1.1^{3.7}_{0.05}$	$1.0^{1.3}_{0.06}$	$1.1^{3.6}_{0.09}$	$1.0^{1.2}_{0.04}$	$0.9^{1.3}_{0.03}$	$1.0^{1.3}_{0.03}$	$0.9^{1.3}_{0.04}$	$0.9^{1.3}_{0.04}$
q	$1.7^{3.3}_{0.7}$	$1.6^{3.8}_{0.7}$	$2.0^{4.2}_{0.9}$	$1.4^{2.6}_{0.8}$	$1.7^{4.0}_{0.9}$	$1.1^{1.9}_{0.7}$	$1.1^{2.0}_{0.7}$	$1.2^{2.1}_{0.7}$	$1.1^{1.9}_{0.7}$	$1.2^{1.9}_{0.7}$
χ_1	$1.5^{6.9}_{0.4}$	$1.7^{8.0}_{0.5}$	$2.2^{8.8}_{0.6}$	$1.1^{4.8}_{0.3}$	$1.9^{7.9}_{0.4}$	$0.9^{2.1}_{0.2}$	$1.0^{2.3}_{0.2}$	$1.1^{2.9}_{0.3}$	$0.8^{2.0}_{0.2}$	$1.0^{2.5}_{0.3}$
d_L	$6.7^{151.7}_{1.2}$	$8.2^{212.2}_{1.2}$	$168^{2e+03}_{3.3}$	$2.6^{45.1}_{0.8}$	$158^{2e+03}_{3.7}$	$1.0^{2.0}_{0.6}$	$1.0^{1.9}_{0.5}$	$1.5^{12.7}_{0.7}$	$1.0^{1.6}_{0.5}$	$1.8^{21.4}_{0.7}$
$\Omega_{90\%}$	$2.7^{2e+04}_{0.01}$	$2.4^{2e+04}_{0.01}$	$299^{3e+05}_{0.1}$	$1.4^{51.9}_{0.02}$	$212^{7e+04}_{0.06}$	$0.7^{4.8}_{0.04}$	$0.6^{5.3}_{0.04}$	$1.1^{21.3}_{0.03}$	$0.7^{5.9}_{0.04}$	$1.0^{15.0}_{0.04}$
	ET- Δ	ET-2V	ET-1V	ET-2L	ET-1L	ET- Δ + CE	ET-2V + CE	ET-1V + CE	ET-2L + CE	ET-1L + CE





Distance

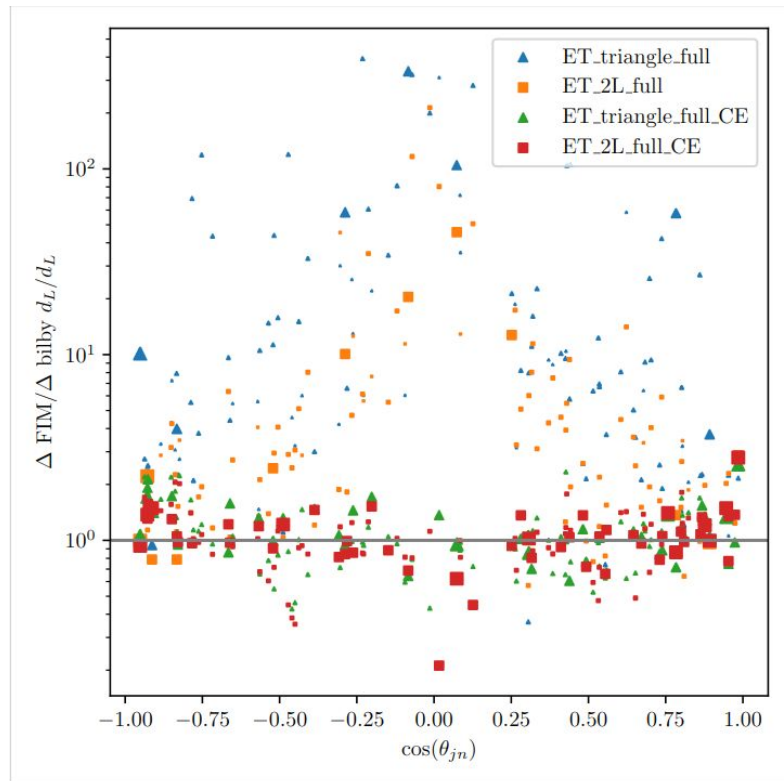
Accounting for
duty cycle





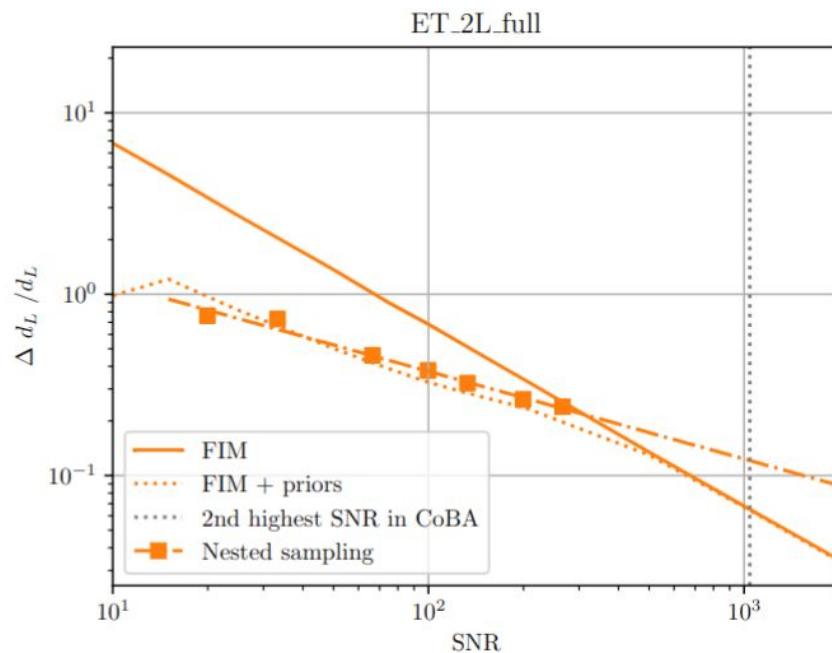
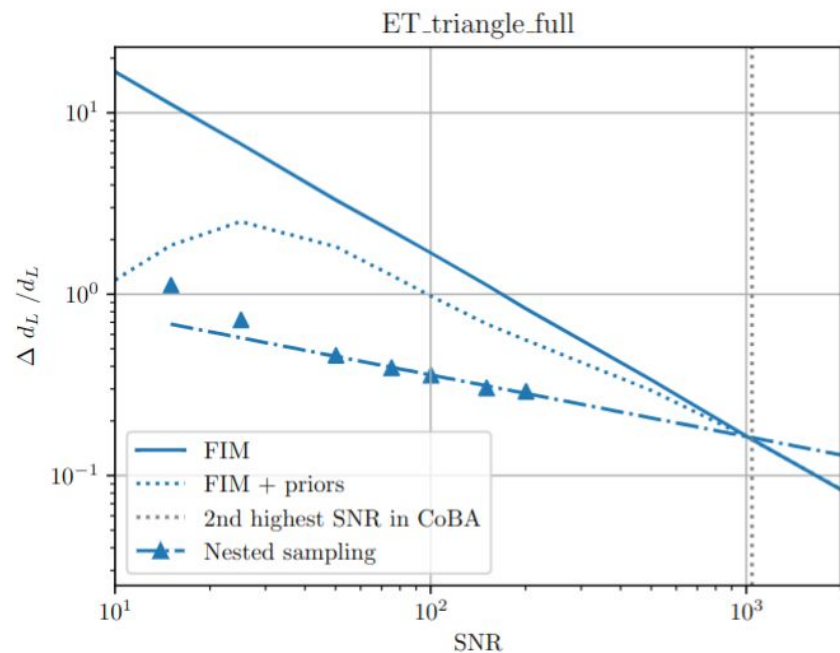
Distance bias driven by inclination angle and sky position

— — —





SNR dependency of the distance bias

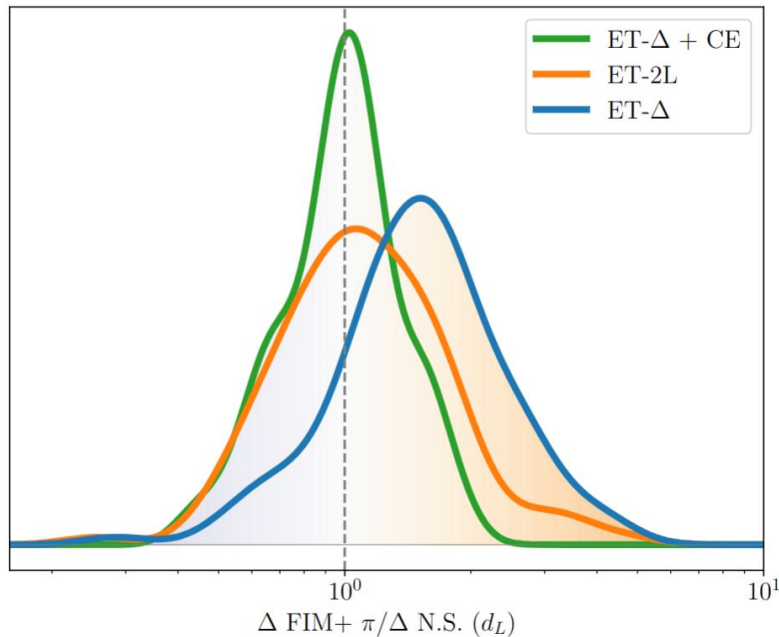




Priors help reduce a lot the bias, but it does not eliminate it

$\Delta \text{FIM} + \pi/\Delta \text{ N.S.}$

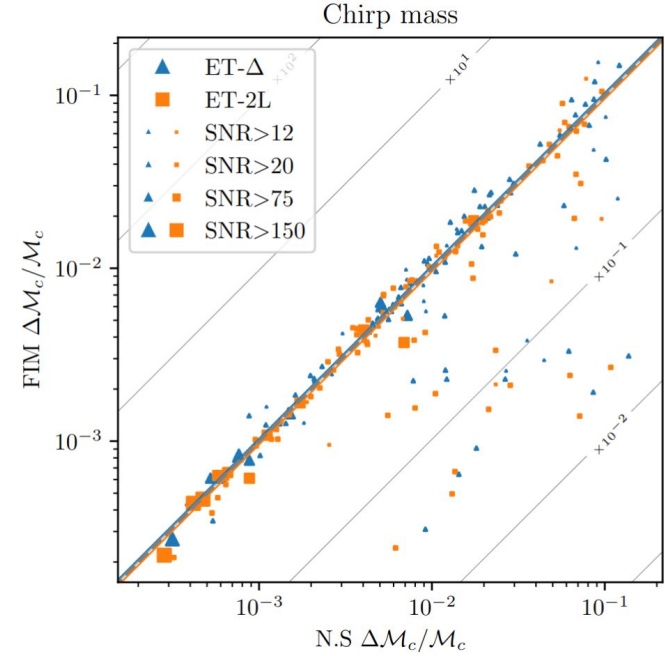
$\mathcal{M}_c$	1.0 ^{1.2} _{0.05}	0.9 ^{1.2} _{0.04}	1.0 ^{1.4} _{0.04}	0.9 ^{1.2} _{0.05}	1.0 ^{1.6} _{0.08}	0.9 ^{1.2} _{0.04}	0.9 ^{1.2} _{0.03}	0.9 ^{1.3} _{0.03}	0.9 ^{1.3} _{0.04}	0.9 ^{1.3} _{0.04}
q	1.2 ^{1.8} _{0.6}	1.1 ^{1.8} _{0.6}	1.3 ^{3.5} _{0.8}	1.1 ^{1.7} _{0.6}	1.3 ^{3.3} _{0.7}	0.9 ^{1.4} _{0.6}	0.9 ^{1.4} _{0.6}	0.9 ^{1.4} _{0.6}	0.9 ^{1.4} _{0.6}	1.0 ^{1.5} _{0.6}
χ_1	1.2 ^{3.0} _{0.4}	1.3 ^{3.2} _{0.5}	1.9 ^{5.7} _{0.5}	1.0 ^{2.6} _{0.3}	1.5 ^{4.8} _{0.4}	0.8 ^{1.9} _{0.2}	0.9 ^{1.9} _{0.2}	0.9 ^{2.1} _{0.2}	0.8 ^{1.8} _{0.2}	0.9 ^{2.0} _{0.2}
d_L	1.5 ^{3.1} _{0.7}	1.5 ^{3.2} _{0.6}	3.1 ^{1e+03} _{0.8}	1.1 ^{2.3} _{0.6}	6.9 ^{1e+03} _{0.8}	1.0 ^{1.6} _{0.6}	1.0 ^{1.6} _{0.5}	1.1 ^{2.6} _{0.4}	1.0 ^{1.5} _{0.5}	1.3 ^{2.7} _{0.6}
$\Omega_{90\%}$	0.3 ^{3.9} _{0.01}	0.3 ^{2.1} _{0.01}	1.2 ^{1e+05} _{0.01}	0.5 ^{3.9} _{0.05}	3.1 ^{2e+04} _{0.00}	1.0 ^{2.5} _{0.4}	1.0 ^{2.3} _{0.4}	0.8 ^{3.2} _{0.1}	1.0 ^{2.6} _{0.5}	1.0 ^{3.9} _{0.1}
	ET- Δ	ET-2V	ET-1V	ET-2L	ET-1L	ET- Δ + CE	ET-2V + CE	ET-1V + CE	ET-2L + CE	ET-1L + CE





Chirp mass

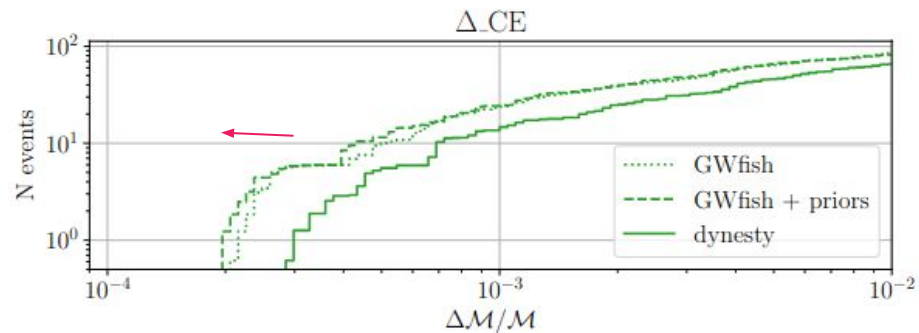
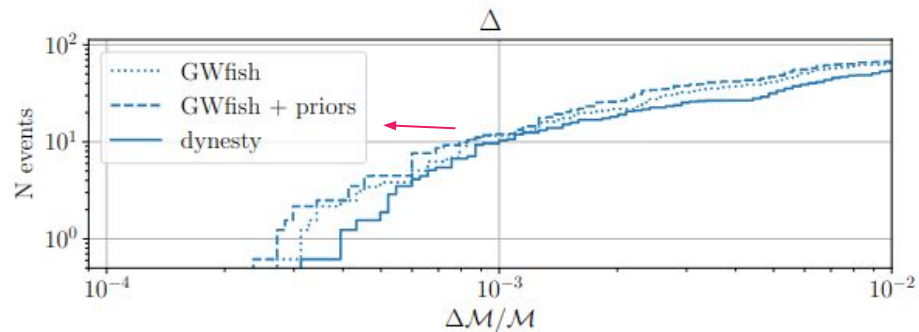
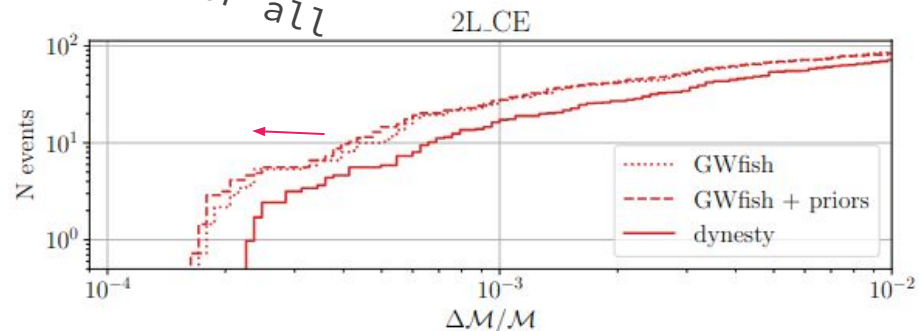
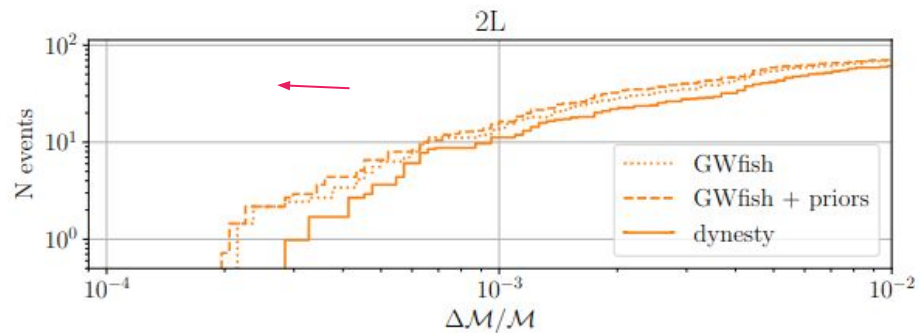
	$\Delta \text{FIM}/\Delta \text{bilby}$									
$\mathcal{M}_c$	$1.0^{1.4}_{0.06}$	$1.0^{1.5}_{0.06}$	$1.1^{3.7}_{0.05}$	$1.0^{1.3}_{0.06}$	$1.1^{3.6}_{0.09}$	$1.0^{1.2}_{0.04}$	$0.9^{1.3}_{0.03}$	$1.0^{1.3}_{0.03}$	$0.9^{1.3}_{0.04}$	$0.9^{1.3}_{0.04}$
q	$1.7^{3.3}_{0.7}$	$1.6^{3.8}_{0.7}$	$2.0^{4.2}_{0.9}$	$1.4^{2.6}_{0.8}$	$1.7^{4.0}_{0.9}$	$1.1^{1.9}_{0.7}$	$1.1^{2.0}_{0.7}$	$1.2^{2.1}_{0.7}$	$1.1^{1.9}_{0.7}$	$1.2^{1.9}_{0.7}$
χ_1	$1.5^{6.9}_{0.4}$	$1.7^{8.0}_{0.5}$	$2.2^{8.8}_{0.6}$	$1.1^{4.8}_{0.3}$	$1.9^{7.9}_{0.4}$	$0.9^{2.1}_{0.2}$	$1.0^{2.3}_{0.2}$	$1.1^{2.9}_{0.3}$	$0.8^{2.0}_{0.2}$	$1.0^{2.5}_{0.3}$
d_L	$6.7^{151.7}_{1.2}$	$8.2^{212.2}_{1.2}$	$168^{2e+03}_{3.3}$	$2.6^{45.1}_{0.8}$	$158^{2e+03}_{3.7}$	$1.0^{2.0}_{0.6}$	$1.0^{1.9}_{0.5}$	$1.5^{12.7}_{0.7}$	$1.0^{1.6}_{0.5}$	$1.8^{21.4}_{0.7}$
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	ET- Δ	ET-2V	ET-IV	ET-2L	ET-1L	ET- Δ + CE	ET-2V + CE	ET-IV + CE	ET-2L + CE	ET-1L + CE





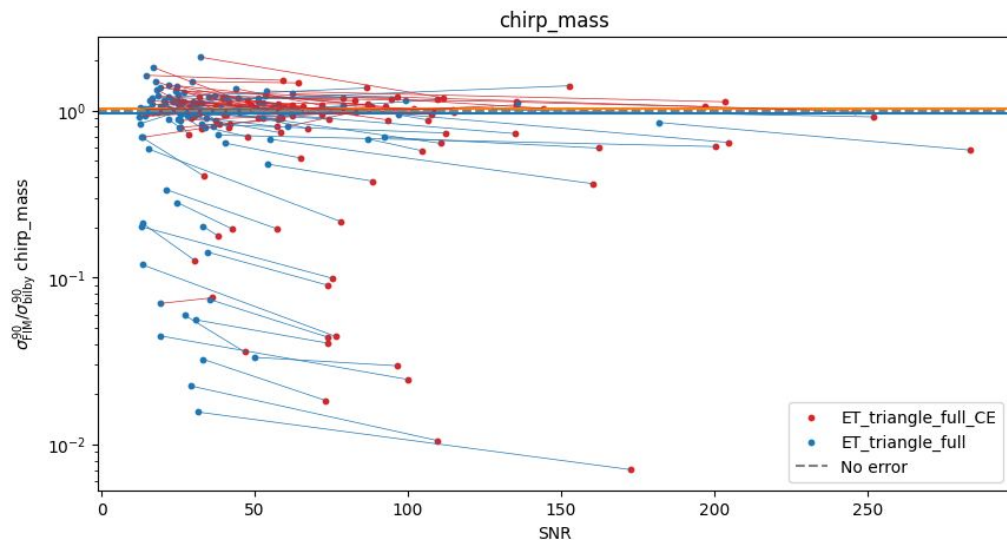
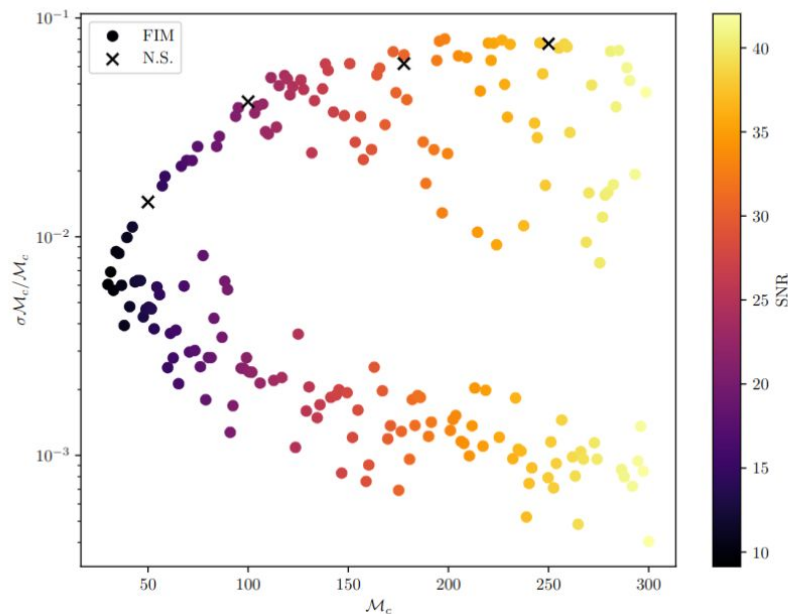
Chirp mass

Uncertainties
underestimated for all
networks





Chirp mass



$$\Gamma_{ij} = \langle \dot{h}_i | \dot{h}_j \rangle$$

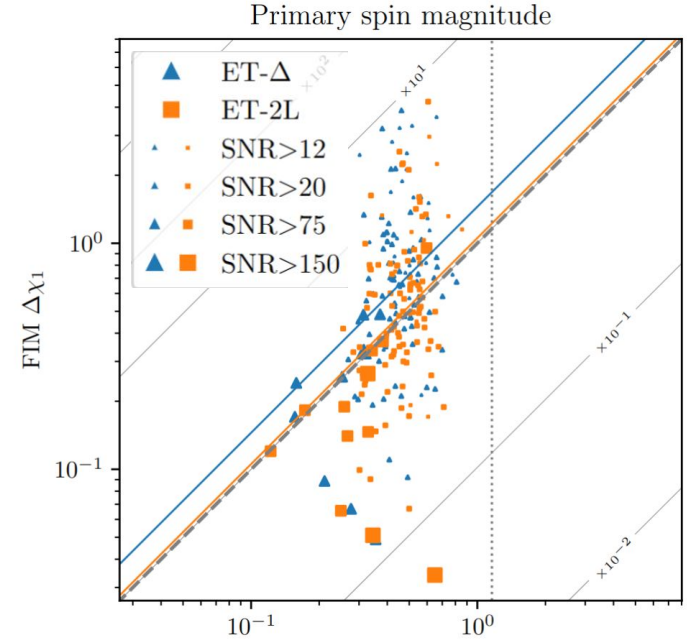
Derivative can be quite noisy when
signal is merger-dominated



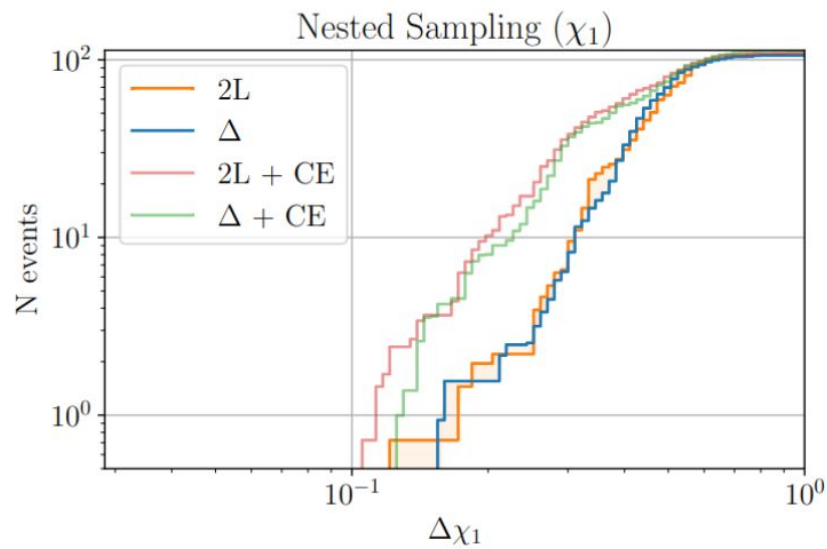
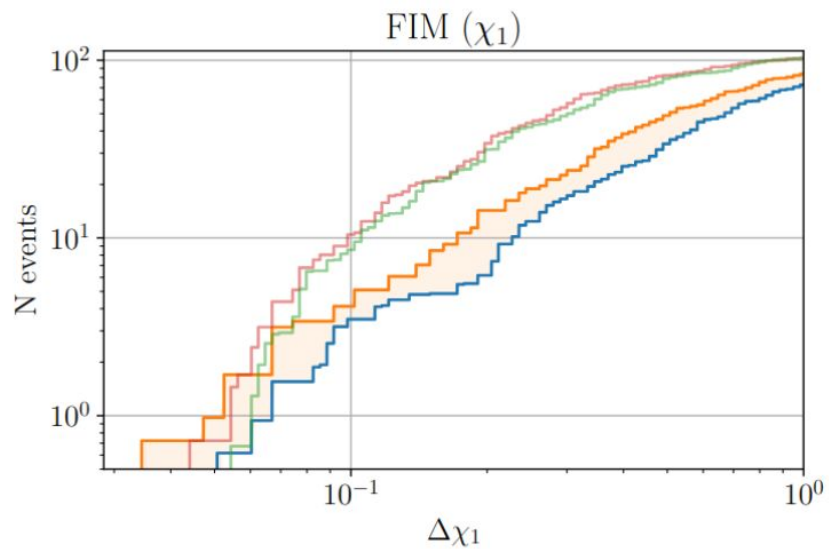
Spins

$\Delta \text{FIM} / \Delta \text{bilby}$

$\mathcal{M}_c$	1.0 ^{1.4} _{0.06}	1.0 ^{1.5} _{0.06}	1.1 ^{3.7} _{0.05}	1.0 ^{1.3} _{0.06}	1.1 ^{3.6} _{0.09}	1.0 ^{1.2} _{0.04}	0.9 ^{1.3} _{0.03}	1.0 ^{1.3} _{0.03}	0.9 ^{1.3} _{0.04}	0.9 ^{1.3} _{0.04}
q	1.7 ^{3.3} _{0.7}	1.6 ^{3.8} _{0.7}	2.0 ^{4.2} _{0.9}	1.4 ^{2.6} _{0.8}	1.7 ^{4.0} _{0.9}	1.1 ^{1.9} _{0.7}	1.1 ^{2.0} _{0.7}	1.2 ^{2.1} _{0.7}	1.1 ^{1.9} _{0.7}	1.2 ^{1.9} _{0.7}
χ_1	1.5 ^{6.9} _{0.4}	1.7 ^{8.0} _{0.5}	2.2 ^{8.8} _{0.6}	1.1 ^{4.8} _{0.3}	1.9 ^{7.9} _{0.4}	0.9 ^{2.1} _{0.2}	1.0 ^{2.3} _{0.2}	1.1 ^{2.9} _{0.3}	0.8 ^{2.0} _{0.2}	1.0 ^{2.5} _{0.3}
d_L	6.7 ^{151.7} _{1.2}	8.2 ^{212.2} _{1.2}	168 ^{2e+03} _{3.3}	2.6 ^{45.1} _{0.8}	158 ^{2e+03} _{3.7}	1.0 ^{2.0} _{0.6}	1.0 ^{1.9} _{0.5}	1.5 ^{12.7} _{0.7}	1.0 ^{1.6} _{0.5}	1.8 ^{21.4} _{0.7}
$\Omega_{90\%}$	2.7 ^{2e+04} _{0.01}	2.4 ^{2e+04} _{0.01}	299 ^{3e+05} _{0.1}	1.4 ^{51.9} _{0.02}	212 ^{7e+04} _{0.06}	0.7 ^{4.8} _{0.04}	0.6 ^{5.3} _{0.04}	1.1 ^{21.3} _{0.03}	0.7 ^{5.9} _{0.04}	1.0 ^{15.0} _{0.04}
	ET- Δ	ET-2V	ET-1V	ET-2L	ET-1L	ET- Δ + CE	ET-2V + CE	ET-1V + CE	ET-2L + CE	ET-1L + CE



Spins

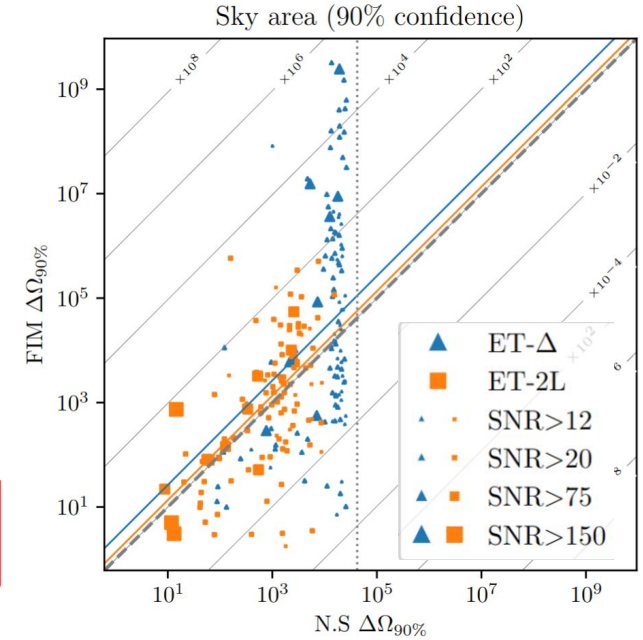




Sky area

$\Delta \text{FIM} / \Delta \text{bilby}$

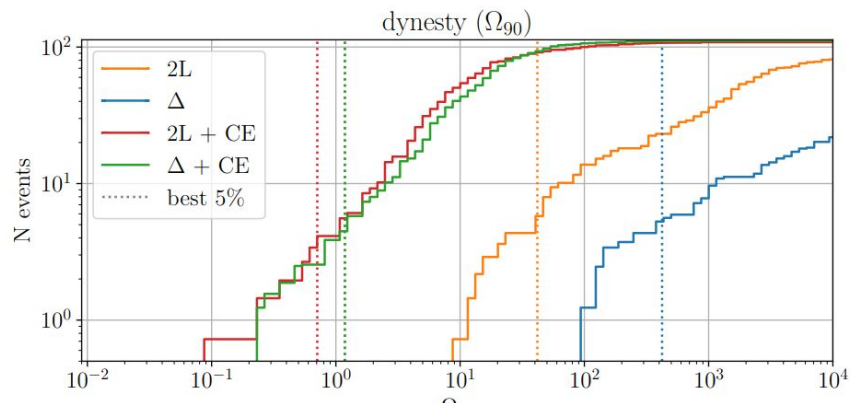
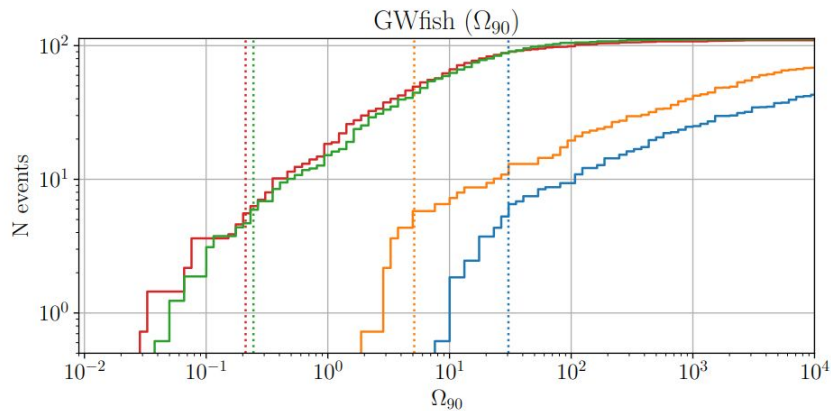
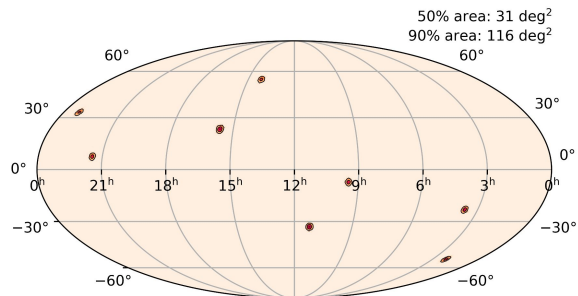
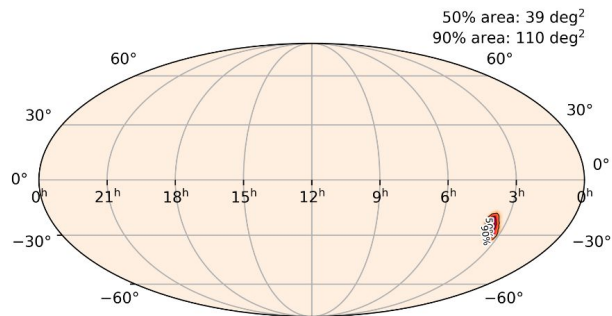
$\mathcal{M}_c$	1.0 ^{1.4} _{0.06}	1.0 ^{1.5} _{0.06}	1.1 ^{3.7} _{0.05}	1.0 ^{1.3} _{0.06}	1.1 ^{3.6} _{0.09}	1.0 ^{1.2} _{0.04}	0.9 ^{1.3} _{0.03}	1.0 ^{1.3} _{0.03}	0.9 ^{1.3} _{0.04}	0.9 ^{1.3} _{0.04}
q	1.7 ^{3.3} _{0.7}	1.6 ^{3.8} _{0.7}	2.0 ^{4.2} _{0.9}	1.4 ^{2.6} _{0.8}	1.7 ^{4.0} _{0.9}	1.1 ^{1.9} _{0.7}	1.1 ^{2.0} _{0.7}	1.2 ^{2.1} _{0.7}	1.1 ^{1.9} _{0.7}	1.2 ^{1.9} _{0.7}
χ_1	1.5 ^{6.9} _{0.4}	1.7 ^{8.0} _{0.5}	2.2 ^{8.8} _{0.6}	1.1 ^{4.8} _{0.3}	1.9 ^{7.9} _{0.4}	0.9 ^{2.1} _{0.2}	1.0 ^{2.3} _{0.2}	1.1 ^{2.9} _{0.3}	0.8 ^{2.0} _{0.2}	1.0 ^{2.5} _{0.3}
d_L	6.7 ^{151.7} _{1.2}	8.2 ^{212.2} _{1.2}	168 ^{2e+03} _{3.3}	2.6 ^{45.1} _{0.8}	158 ^{2e+03} _{3.7}	1.0 ^{2.0} _{0.6}	1.0 ^{1.9} _{0.5}	1.5 ^{12.7} _{0.7}	1.0 ^{1.6} _{0.5}	1.8 ^{21.4} _{0.7}
$\Omega_{90\%}$	2.7 ^{2e+04} _{0.01}	2.4 ^{2e+04} _{0.01}	299 ^{3e+05} _{0.1}	1.4 ^{51.9} _{0.02}	212 ^{7e+04} _{0.06}	0.7 ^{4.8} _{0.04}	0.6 ^{5.3} _{0.04}	1.1 ^{21.3} _{0.03}	0.7 ^{5.9} _{0.04}	1.0 ^{15.0} _{0.04}
	ET- Δ	ET-2V	ET-IV	ET-2L	ET-1L	ET- Δ + CE	ET-2V + CE	ET-IV + CE	ET-2L + CE	ET-1L + CE





Sky area

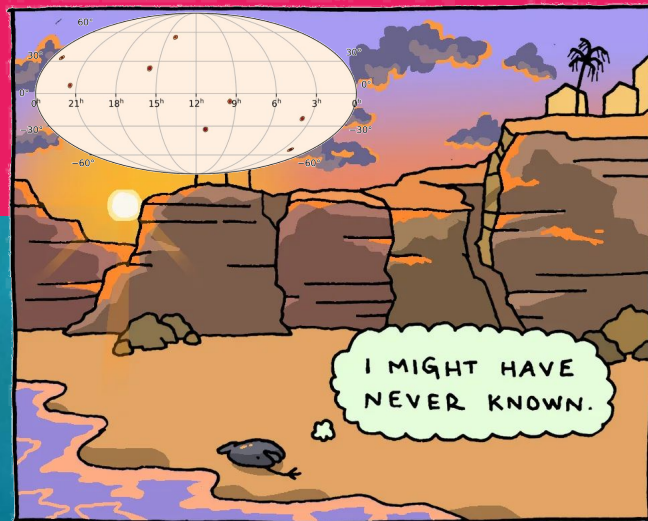
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Conclusions

- Fisher can introduce artificial biases when comparing detector designs
- Fisher tends to **exaggerate** the difference between networks, **overshooting** the uncertainties for networks with **lower-SNRs and shorter baselines**.
- The high-SNR limit is not guaranteed for **all but 1 signals in the CoBA dataset**



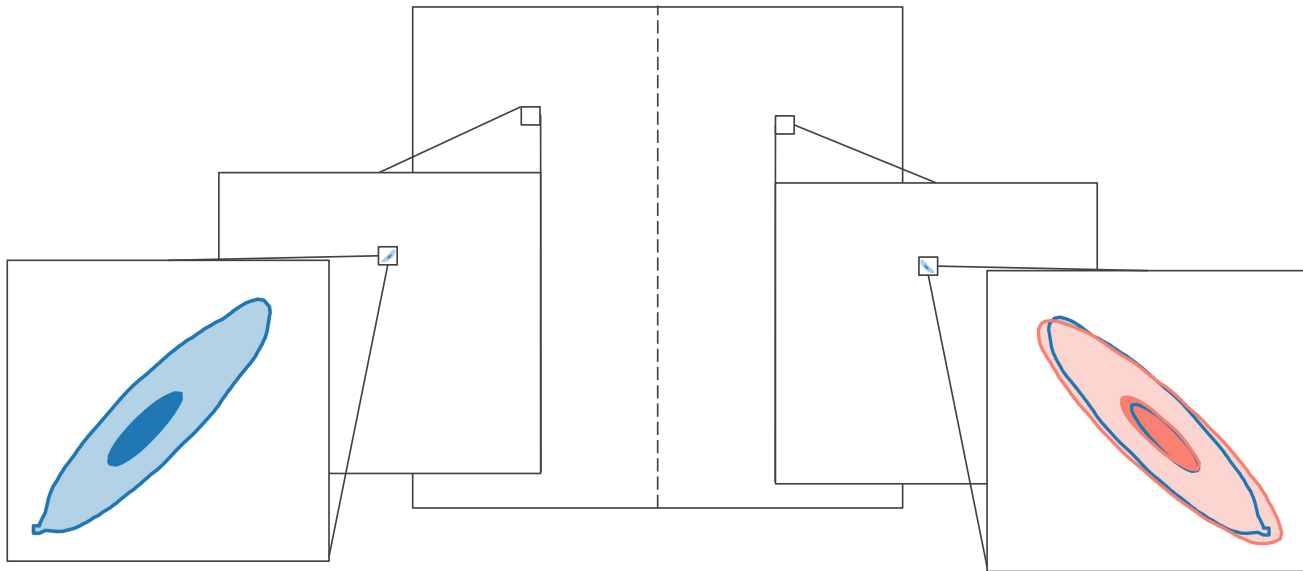


The posterior is (not) concentrated around true values

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Meaning : assume Posterior is unimodal.

If posterior is multimodal (eg., symmetries in the problem) Fisher will fail!

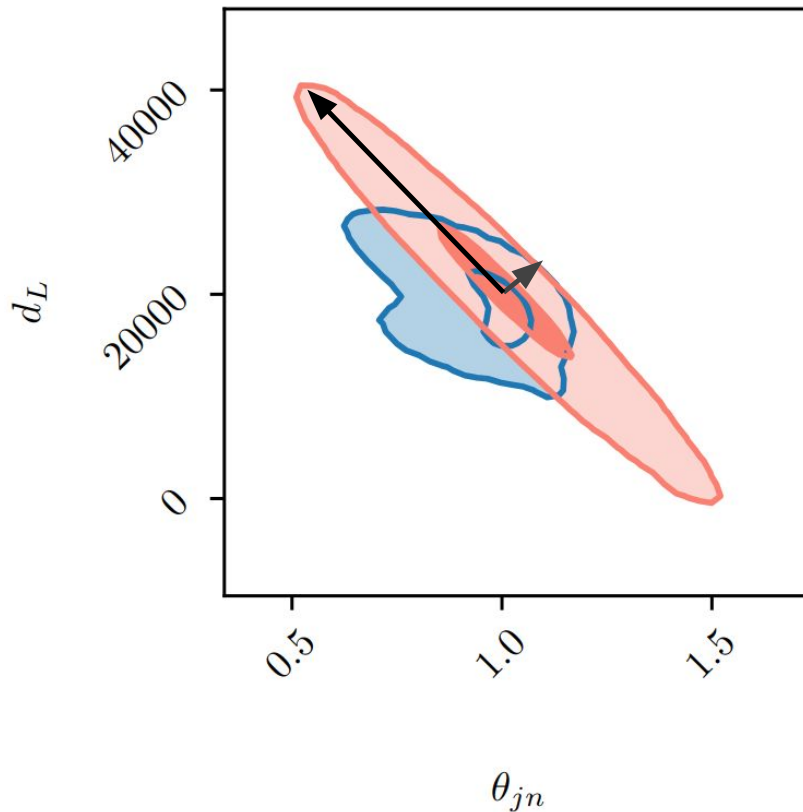




The response is (not) linear

Fisher is equivalent to and expansion of 1st order in $1/\text{SNR}$ of the Bayesian posterior

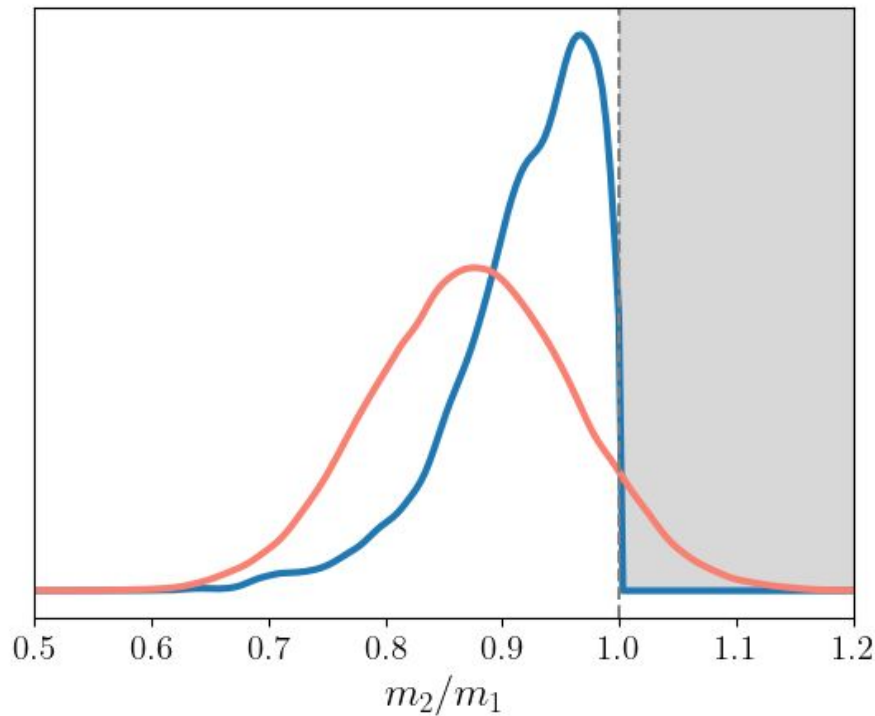
Higher modes might be relevant





The prior information is (not) negligible

If injection lies next to
the prior bound,
**Fisher could predict
unphysical values**

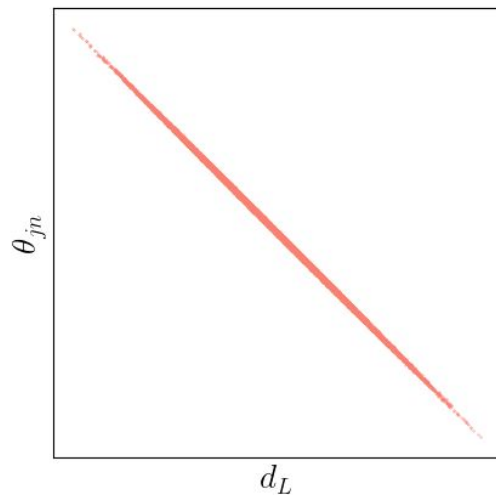




The numerical precision is (not) unlimited

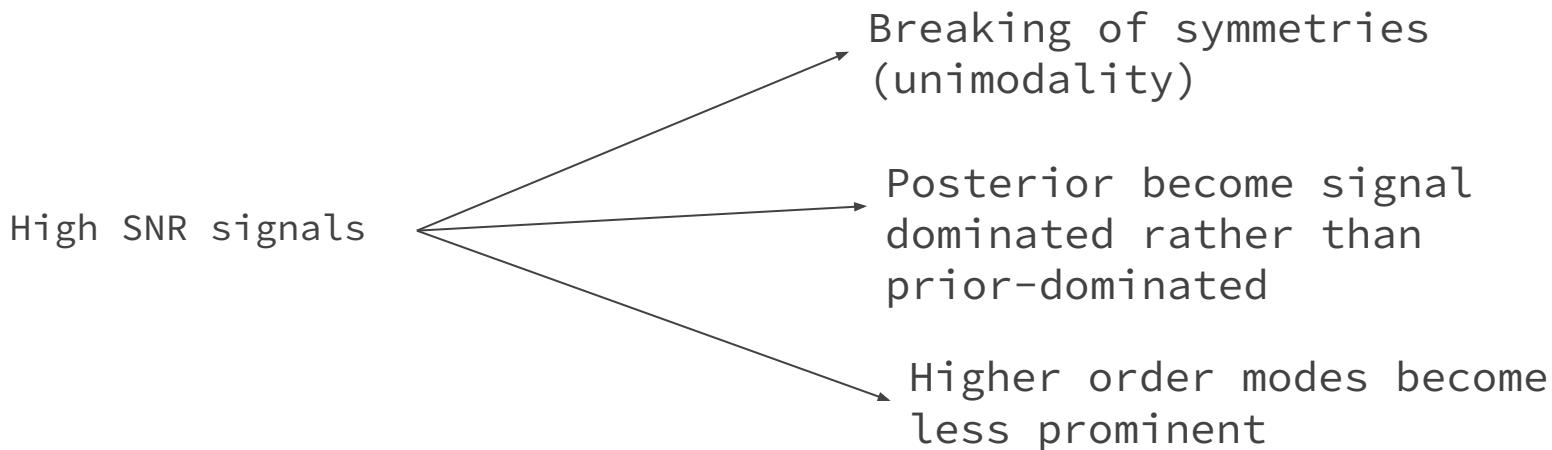
- Noisy likelihood leads to noisy finite differencing.
- Matrix inversion can introduce noise due to numerical precision if the dynamic range of the eigenvalues is too large.

$$\Gamma_{ij} = \langle h_i | h_j \rangle$$





Do the assumption hold for ET?



Numerical instabilities can easily be caught and results thrown away