Nuclear Physics with ET: a comparison of different designs

UNIVERSITÉ DE GENÈVE

(lots of) work from:

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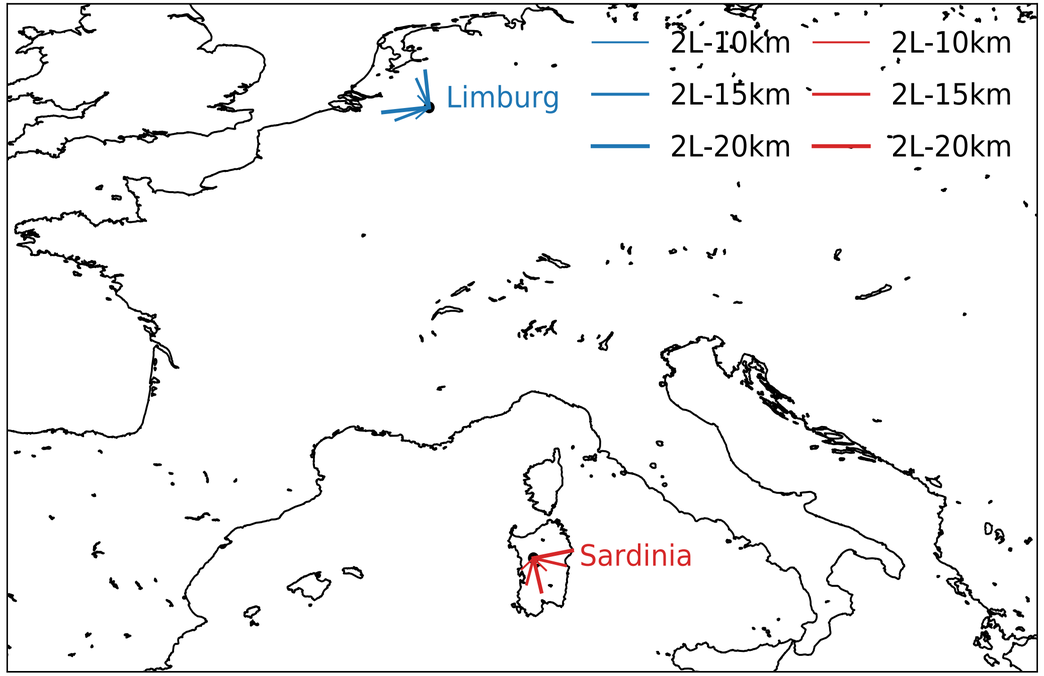
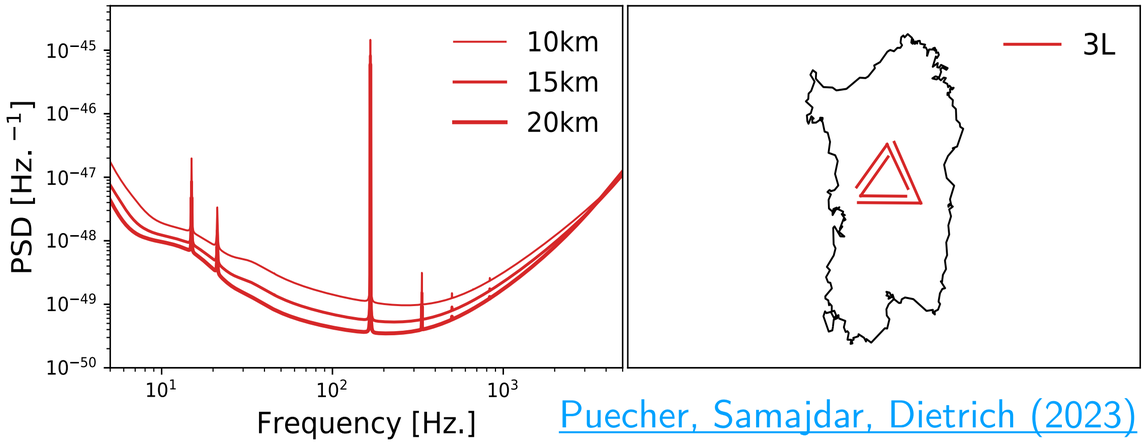
The “CoBA-science” study

Branchesi, Maggiore, et al.(2023)

ET has a reference design based on a triangular—shaped detector consisting of nested 60° interferometers, with each instrument featuring a “xylophone” configuration

In the “CoBA-science” paper we studied the scientific output of different possible designs, with a detailed evaluation of the science case





Puecher, Samajdar, Dietrich (2023)

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Science with the Einstein Telescope: a comparison of different designs

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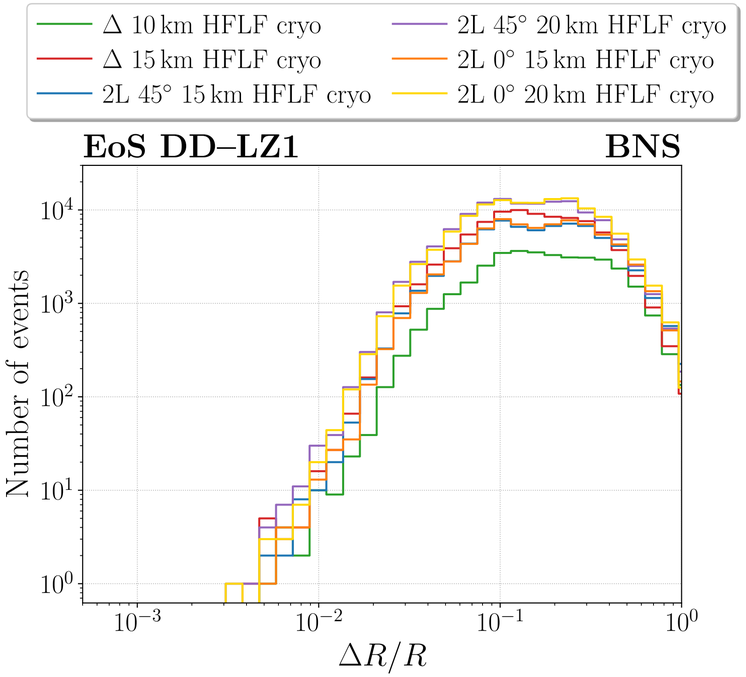
OSB Div 6 for “CoBA-science”: Fisher matrix

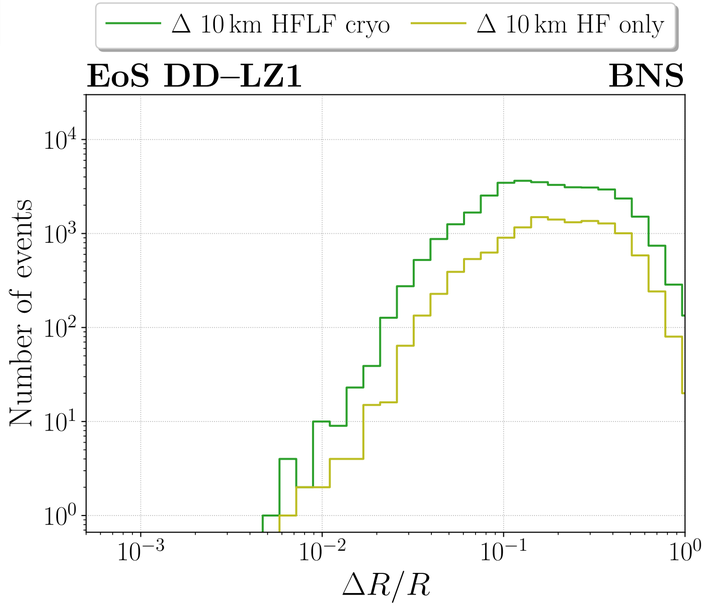
We used a synthetic population of BNS mergers to predict the accuracy in the reconstruction of the tidal parameter $\tilde{\Lambda}$ and the NS radius using the Fisher matrix approach

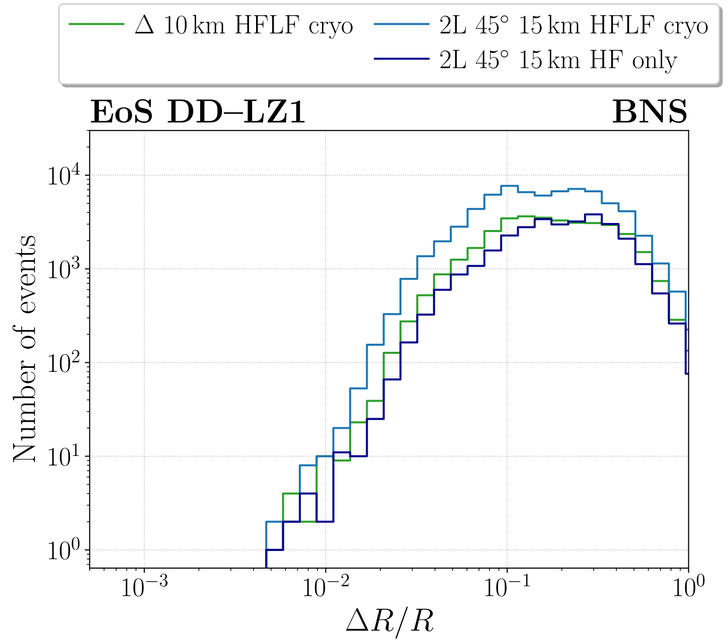
$$\eta = \frac{m_1 m_2}{(m_1 + m_2)^2}$$

$$\tilde{\Lambda} = \frac{8}{13}\left[(1 + 7\eta - 31\eta^2)(\Lambda_1 + \Lambda_2) + \sqrt{1 - 4\eta}(1 + 9\eta - 11\eta^2)(\Lambda_1 - \Lambda_2)\right]$$

$$\tilde{\Lambda} \propto R^6 \implies \frac{\Delta R}{R} = \frac{\Delta\tilde{\Lambda}}{\tilde{\Lambda}}$$







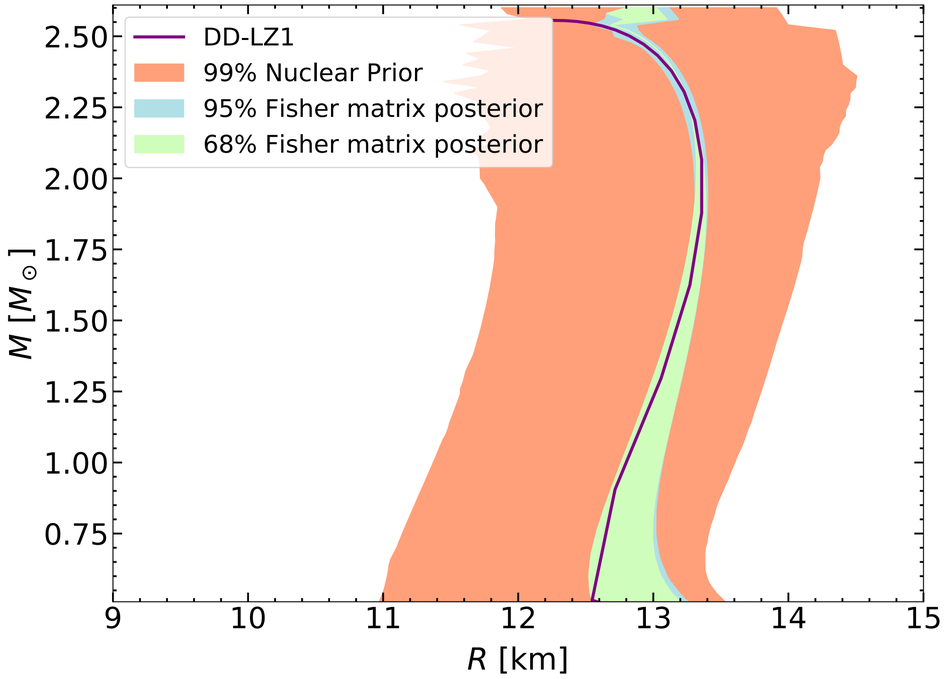
OSB Div 6 for “CoBA-science”: Fisher matrix

We used these Fisher results to get predictions for the reconstruction of the NS mass-radius relation at ET

N_{det}	$R_{1.4M_\odot}{}^{+\Delta R_+}_{-\Delta R_-}$ [km]	$R_{2.0M_\odot}{}^{+\Delta R_+}_{-\Delta R_-}$ [km]
Prior	$12.983^{+0.420}_{-0.420}$	$13.156^{+0.447}_{-0.454}$
54	$13.163^{+0.221}_{-0.227}$	$13.358^{+0.234}_{-0.242}$
592	$13.146^{+0.122}_{-0.136}$	$13.355^{+0.099}_{-0.083}$
5970	$13.107^{+0.148}_{-0.037}$	$13.332^{+0.050}_{-0.013}$

This is done by MC sampling a large set of 10 independent, uniformly distributed empirical parameters characterising the density dependence of the energy in the symmetric matter and of the symmetry energy

Different configurations do not make any significant difference in the outcome!

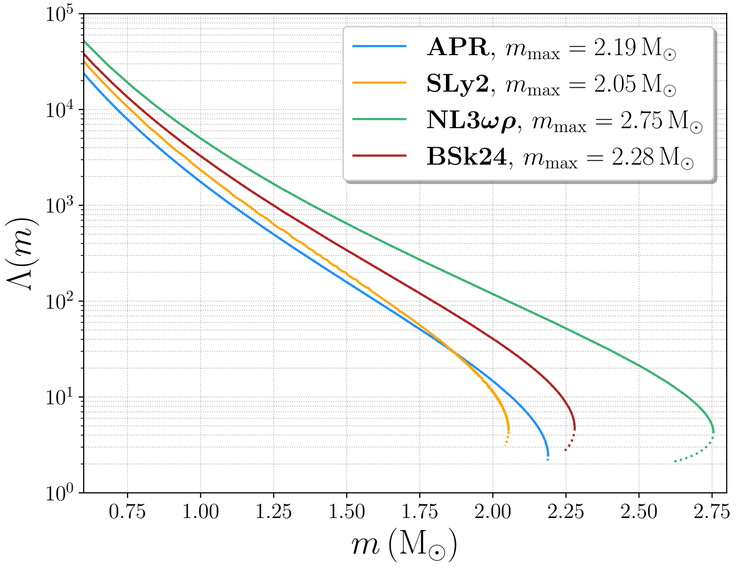


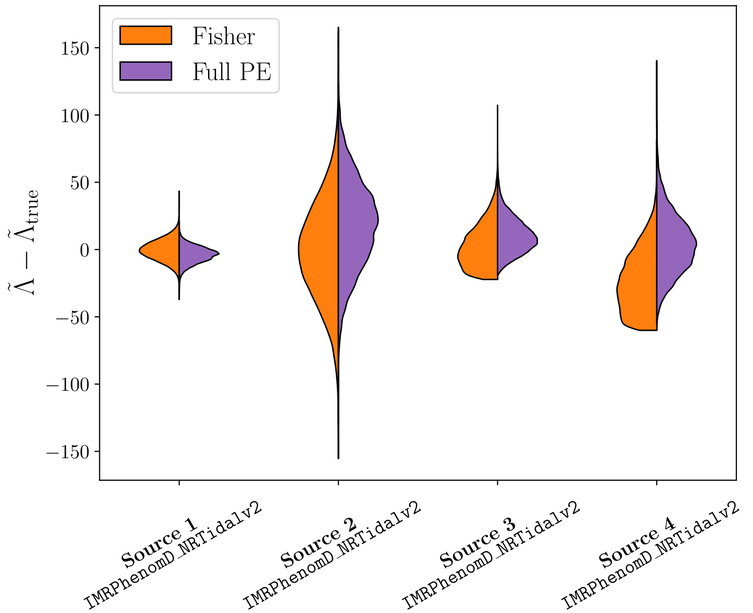
OSB Div 6 for “CoBA-science”: Fisher matrix

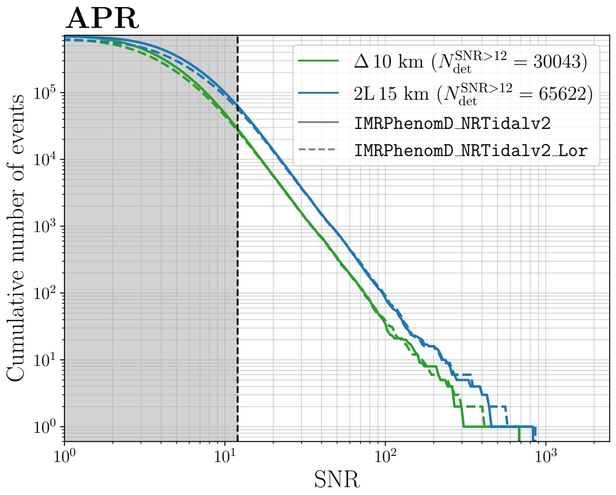
We are further checking the adherence of the Fisher approach with full PE runs, and also considering different waveforms and EoSs to see their impact on the population estimates NS mass-radius relation reconstruction

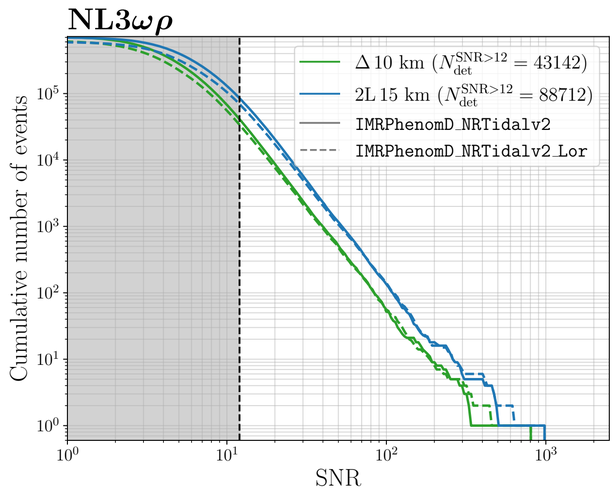
(Still work in progress, Dietrich et al., in preparation)

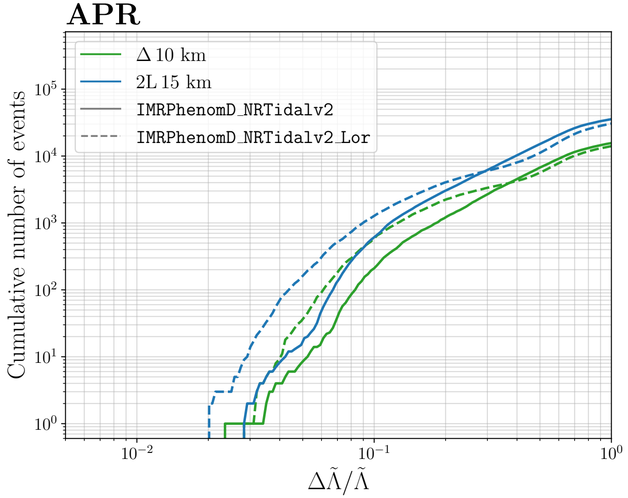
Puecher, et al. (2022)

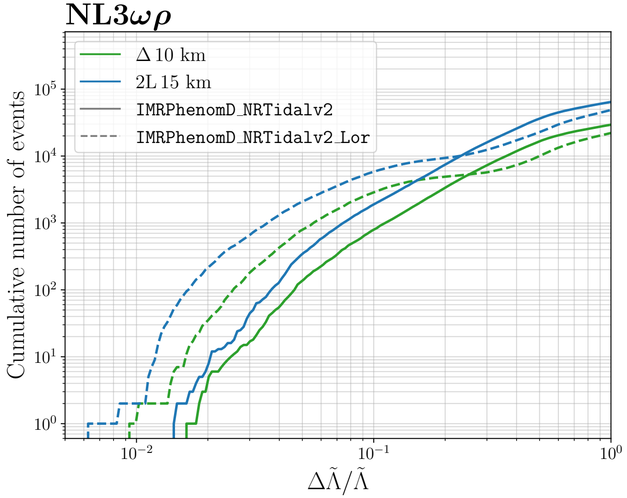








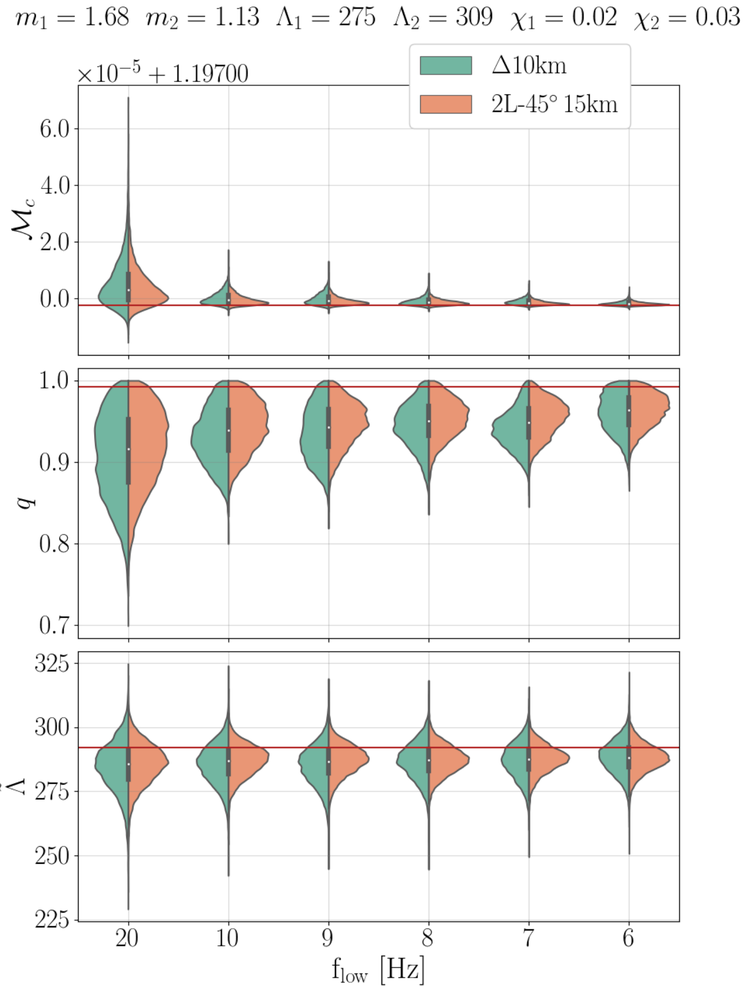


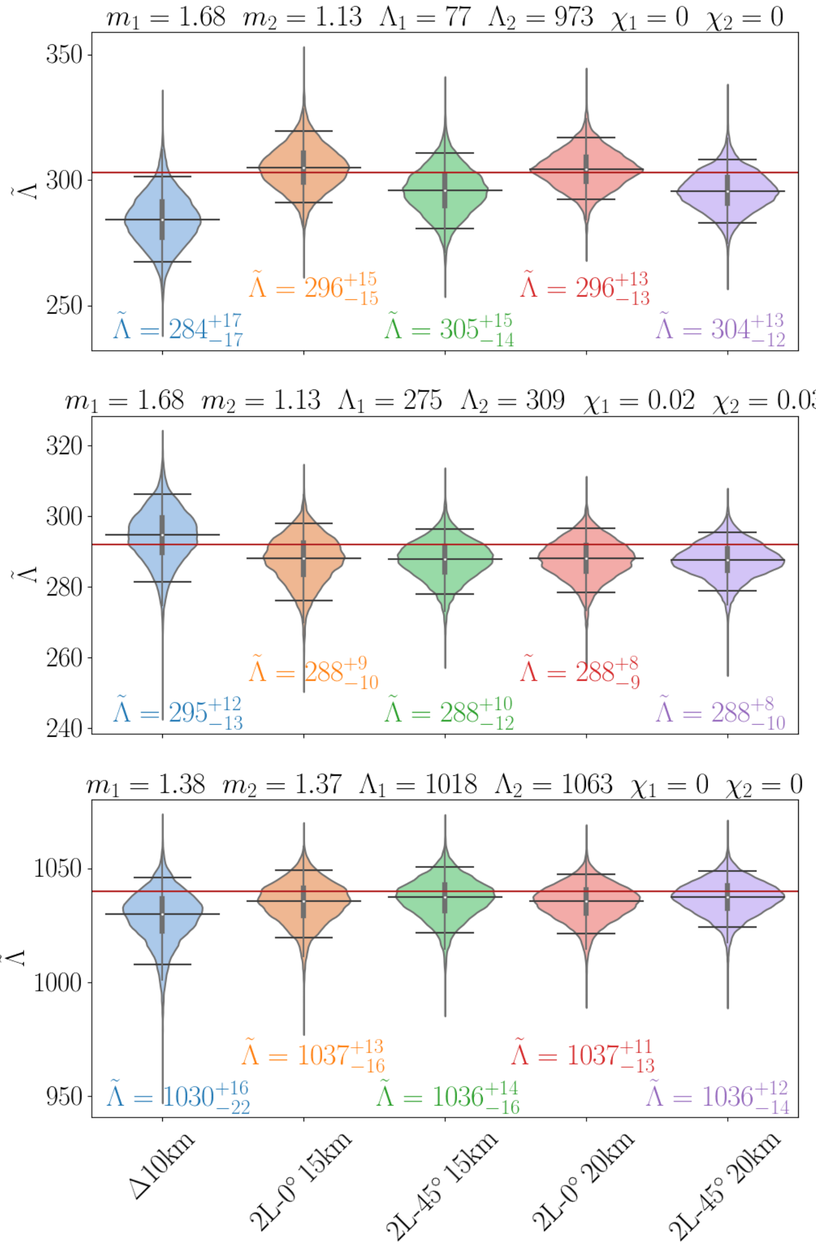


OSB Div 6 for “CoBA-science”: PE runs

We also performed a full Bayesian parameter estimation using ***bilby*** for a small set of selected events with different equations of state (APR4 and H4)

We find the main improvement in the estimation of $\tilde{\Lambda}$ to come from the length of the arms, and the presence of the LF instrument to be preferable





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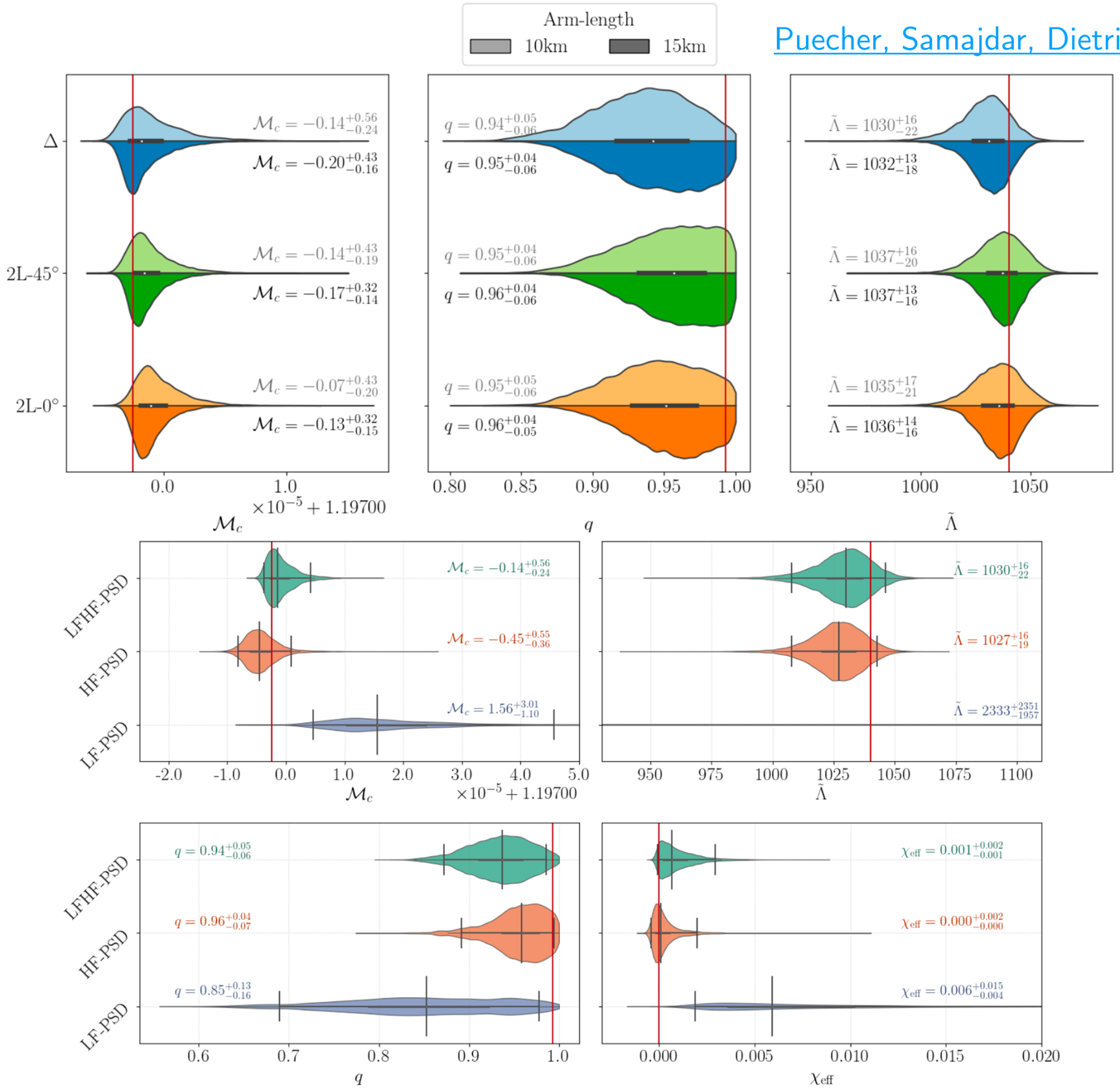
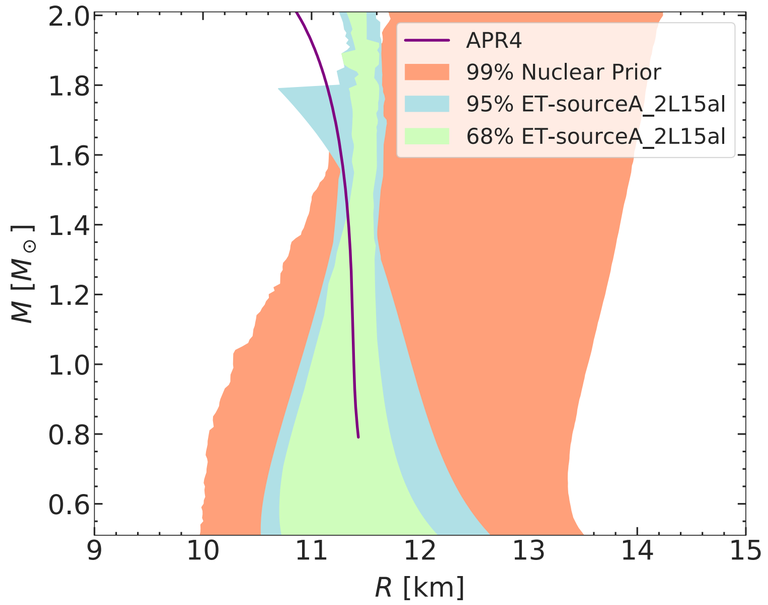
[Puecher, Samajdar, Dietrich (2023)]



OSB Div 6 for “CoBA-science”: PE runs

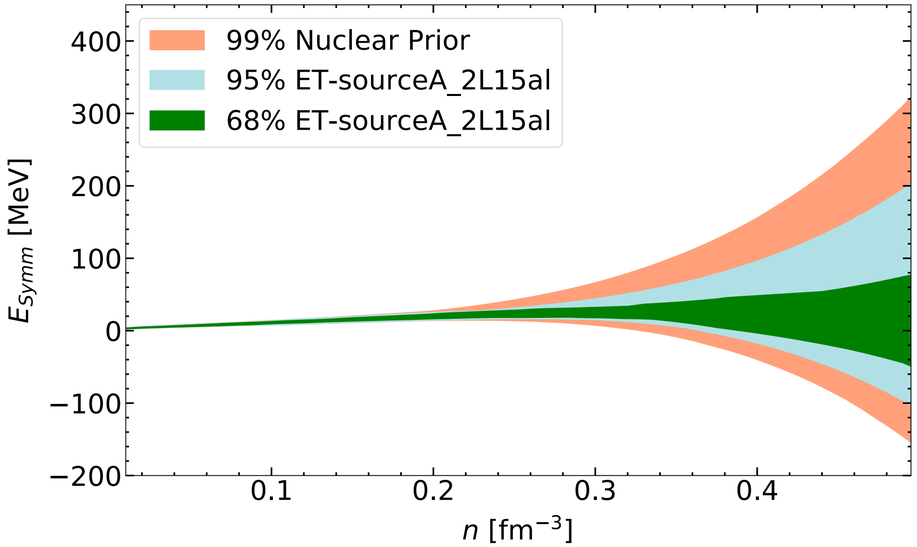
Also for these sources we used the MC sampling to get estimations of the reconstruction of the NS mass-radius relation

(APR4 shows differences because of the adopted nuclear physics prior)



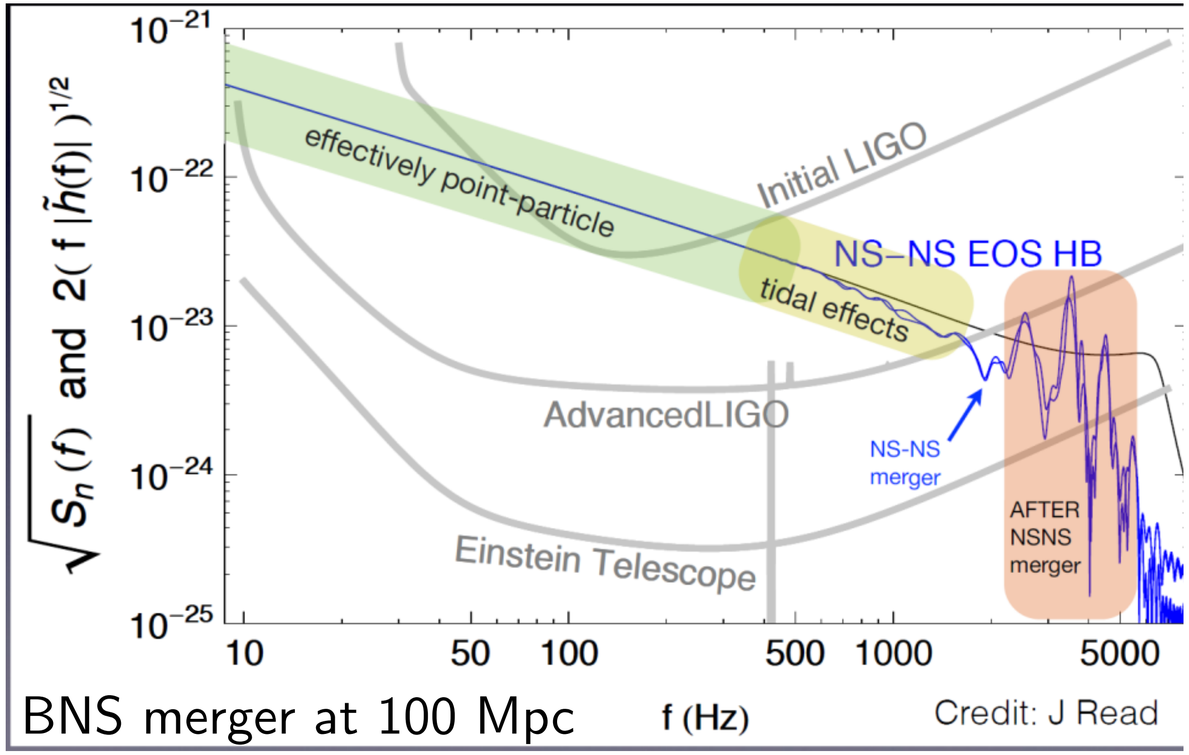
source	Geometry	$R_{1.4M_\odot}$ [km]
source-A	2L 20km 0°	$11.44^{+0.13}_{-0.13}$
	Δ 10km	$11.34^{+0.15}_{-0.15}$
source-B	2L 20km 0°	$11.30^{+0.19}_{-0.21}$
	Δ 10km	$11.32^{+0.20}_{-0.20}$
source-C	2L 20km 0°	$13.69^{+0.07}_{-0.06}$
	Δ 10 km	$13.68^{+0.06}_{-0.07}$

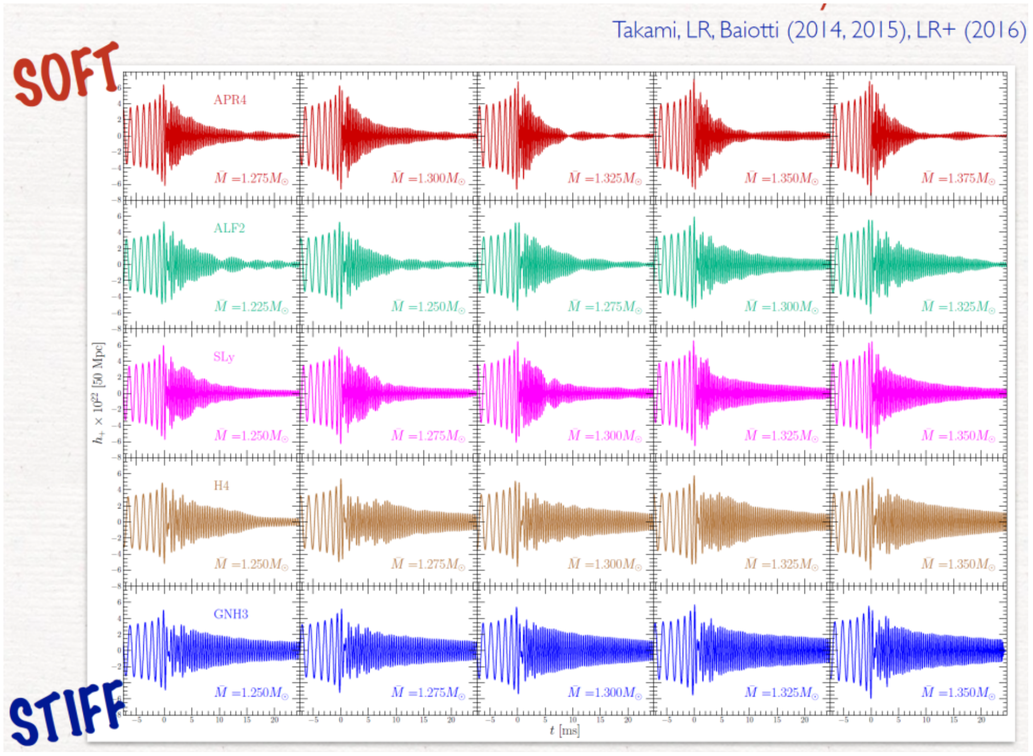
source	Geometry	n_{sat}	E_{sat}	K_{sat}	E_{sym}	L_{sym}	K_{sym}
source-A	2L 20km 0°	$0.164^{+0.005}_{-0.004}$	$-16.18^{+0.41}_{-0.40}$	228^{+34}_{-24}	$31.65^{+2.85}_{-2.15}$	$40.9^{+9.1}_{-13.9}$	-262^{+61}_{-70}
	Δ 10km	0.164^{+005}_{-007}	$-16.14^{+0.44}_{-0.42}$	229^{+27}_{-25}	$31.59^{+3.41}_{-2.99}$	$40.1^{+14.8}_{-15.1}$	-269^{+83}_{-70}
source-B	2L 20km 0°	$0.162^{+0.007}_{-0.007}$	$-16.06^{+0.54}_{-0.47}$	227^{+29}_{-27}	$30.91^{+2.69}_{-2.81}$	$42.0^{+21.9}_{-19.0}$	-197^{+155}_{-141}
	Δ 10km	$0.163^{+0.006}_{-0.007}$	$-16.05^{+0.53}_{-0.49}$	227^{+27}_{-26}	$30.86^{+3.34}_{-2.86}$	$40.9^{+17.1}_{-18.9}$	-208^{+165}_{-137}
source-C	2L 20km 0°	$0.155^{+0.005}_{-0.004}$	$-15.94^{+0.44}_{-0.56}$	236^{+21}_{-17}	$30.96^{+1.54}_{-2.06}$	$70.3^{+11.7}_{-10.3}$	74^{+78}_{-87}
	Δ 10km	$0.156^{+0.004}_{-0.005}$	$-15.92^{+0.47}_{-0.49}$	236^{+23}_{-19}	$30.92^{+1.58}_{-2.02}$	$70.8^{+11.2}_{-11.8}$	74^{+78}_{-87}



OSB Div 6 for “CoBA-science”: post merger

At 2G detectors we do not expect to be able to detect the post merger phase of BNS mergers ($f \gtrsim 1\,\mathrm{kHz}$) but this can carry invaluable information on BNS physics, and 3G detectors can observe it!

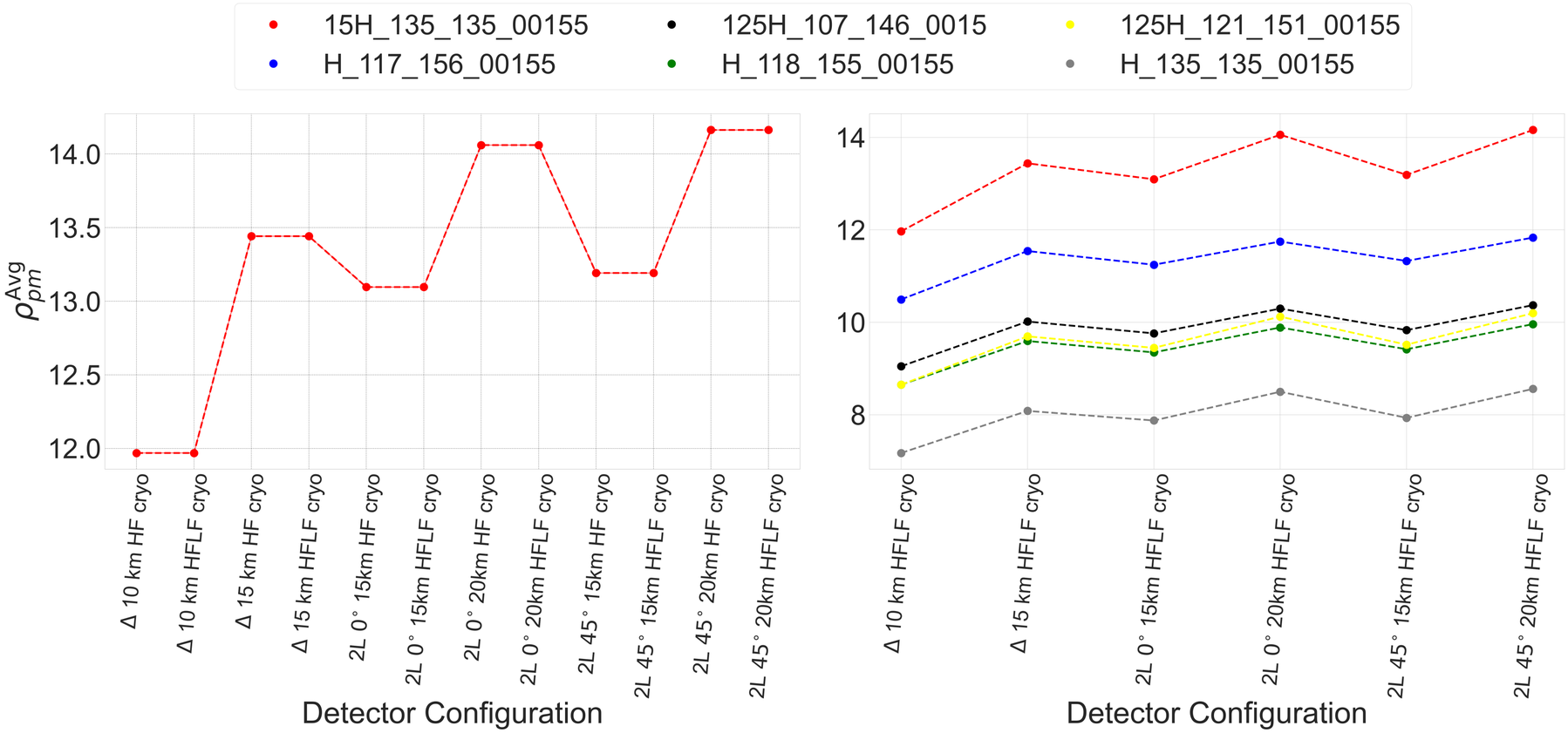




OSB Div 6 for “CoBA-science”: post merger

We used a set of 6 numerical relativity simulations (*SACRA*) to compute the SNRs only in the BNS post merger phase attainable at ET (we also average over the sky position angles and polarisation)

Configuration name	mass1	mass2	Λ_1	Λ_2
15H_135_135_00155	1.35	1.35	1211	1211
125H_107_146_0015	1.07	1.46	3196	535
H_117_156_00155	1.17	1.56	1415	238
H_135_135_00155	1.35	1.35	607	607
125H_121_151_00155	1.21	1.51	1621	435
H_118_155_00155	1.18	1.55	1354	249

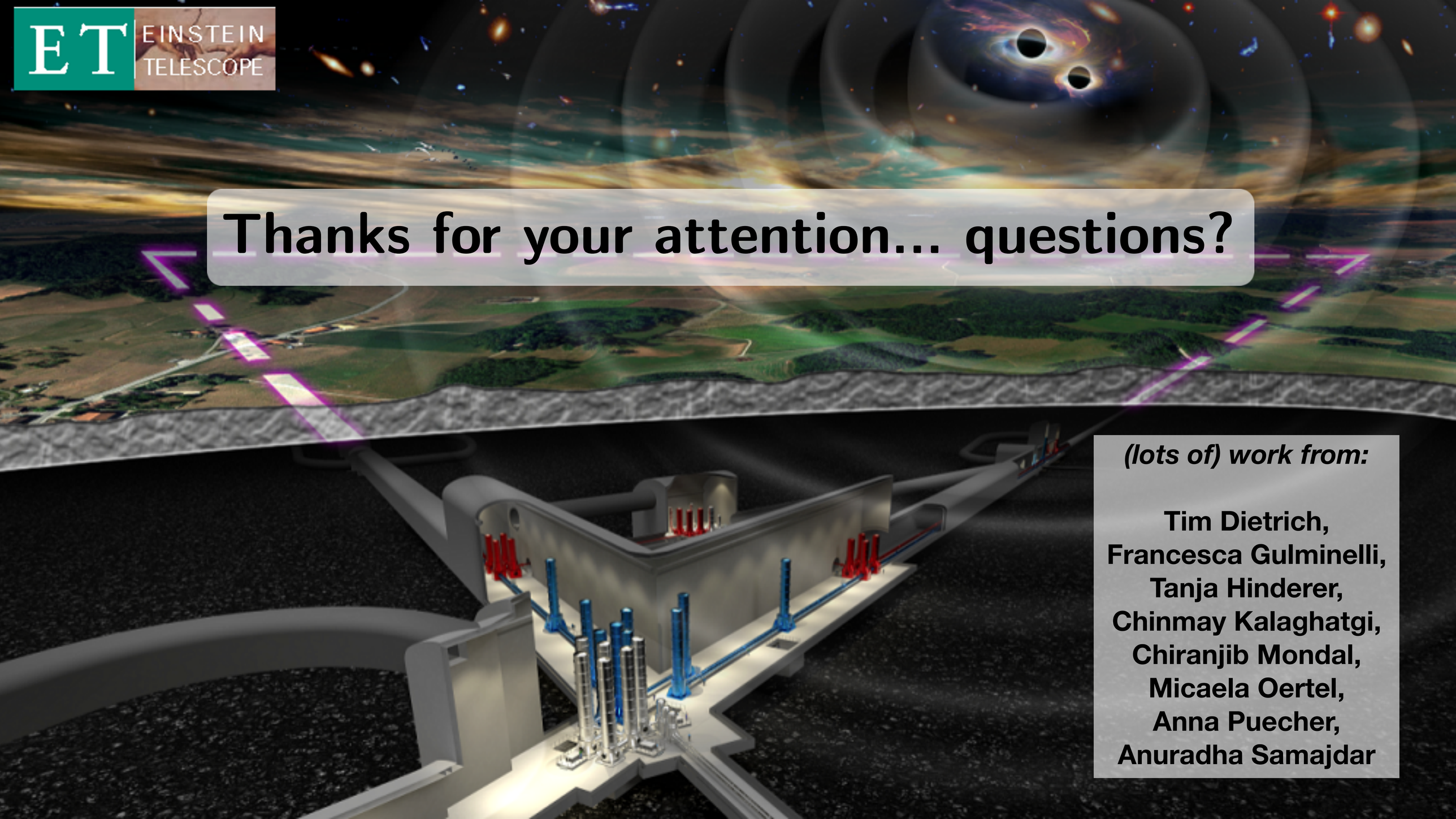


OSB Div 6 for “CoBA-science”: conclusions

- ET will significantly advance our ability to constrain fundamental nuclear physics properties

- ET, will be able to determine NS radii with sub-percent precision due to the immense statistics (10^5 ev/yr) and accuracy, and will also be able observe the post merger phase

- there is no significant difference between the different detector configurations, with longer arm-lengths leading to slightly better results



Thanks for your attention... questions?

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