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Forecasting the Detection and Parameter Estimation Capabilities for different ET Designs

Ulyana Dupletsa
on behalf of
Branchesi, Maggiore et al. (arXiv:2303.15923)

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Science with the Einstein Telescope: a comparison of different designs

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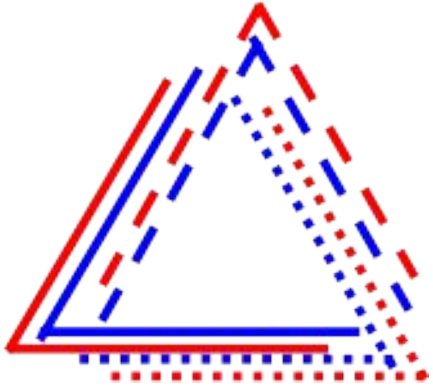
Science Reference Paper for the **CoBA study**

Work coordinated by **Marica Branchesi** and **Michele Maggiore**

submitted to JCAP

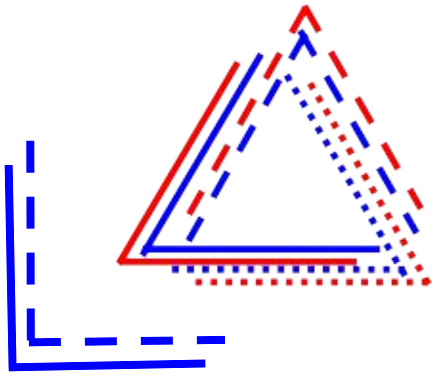
Reference Design of ET



The reference ET configuration consists of:

- **Triangular** shape
- **10 km** arms
- 3 nested detectors in xylophone configuration: **HF + LF** (cryogenic)

Different Configurations



We want to evaluate the effect on the **Science Case** of:

- Changes in geometry: triangle vs 2L, different arm lengths
- Role of the low frequency instrument: what happens if we have only the HF part?

- Triangle, 10 km arms **(reference design)**
- 2L, 15 km arms, parallel
- 2L, 15 km arms, at 45º
- Triangle, 15 km arms
- 2L, 20 km arms, parallel
- 2L, 20 km arms, at 45º

Fisher Matrix Analysis

gwFAst

gwbench

S. Borhanian, 2021, *Class.Quant.Grav.*

GitLab link

GWFAST

F. Iacovelli,
M. Mancarella, et al.
2022, *Astrophys.J.*

GitHub link

TiDoFM

Li et al.
2022, *Phys. Rev. D*

GWFISH

GWFish

U. Dupletsa, J. Harms,
et al.
2023, *Astronomy and Computing*

GitHub link

Starting Assumptions

- We use waveform including higher order modes and tidal deformability parameters (for BNSs): **IMRPhenomXPHM** and **IMRPhenomD_NRTidalv2**
- The parameters of the waveform are:

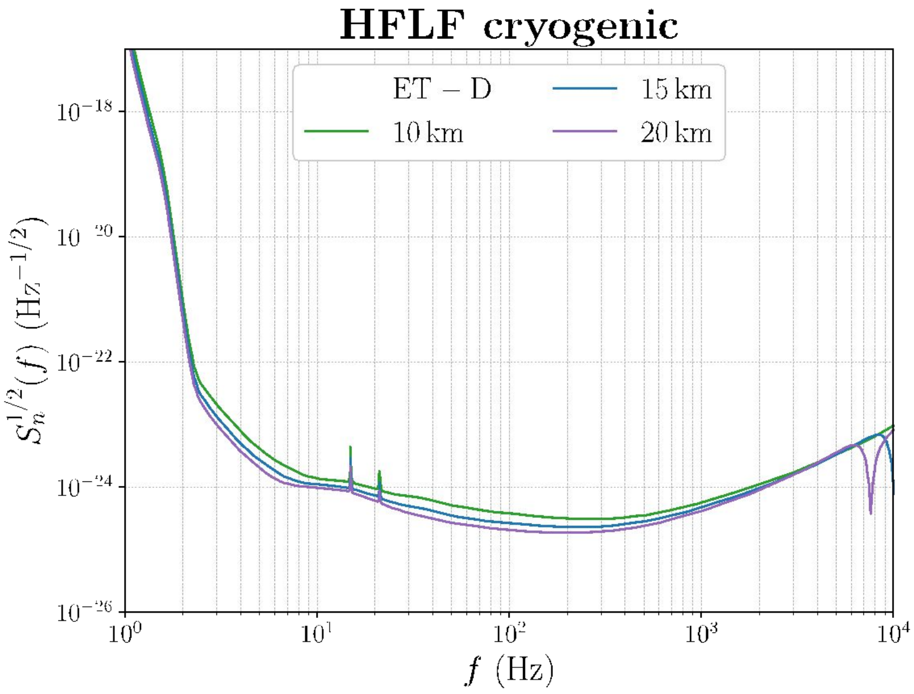
$$\{\mathcal{M}_c, \eta, d_L, \underbrace{\boxed{\theta, \phi}}_{\text{sky position}}, \iota, \psi, t_c, \Phi_c, \underbrace{\boxed{\chi_{1,x}, \chi_{2,x}, \chi_{1,y}, \chi_{2,y}, \chi_{1,z}, \chi_{2,z}}}_{\text{spin parameters}}, \boxed{\Lambda_1, \Lambda_2}\}$$

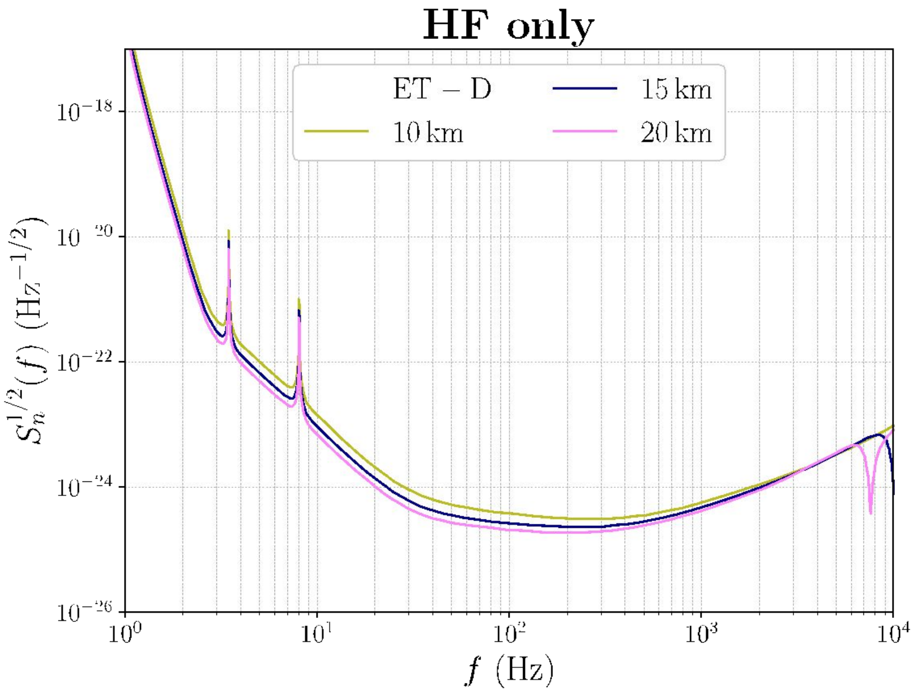
tidal polarizability (for BNSs only)

- The BNS population was obtained using **MOBSE** (isolated binaries) with a local merger rate of 250 Gpc^{-3} yr^{-1} (to compare to the LVK result of 10-1700 Gpc^{-3} yr^{-1}
- The BBH population was obtained using **FASTCLUSTER** (isolated evolution + dynamical formation channel)

Sensitivity Curves (provided by the ISB)

Actual curves are still evolving!



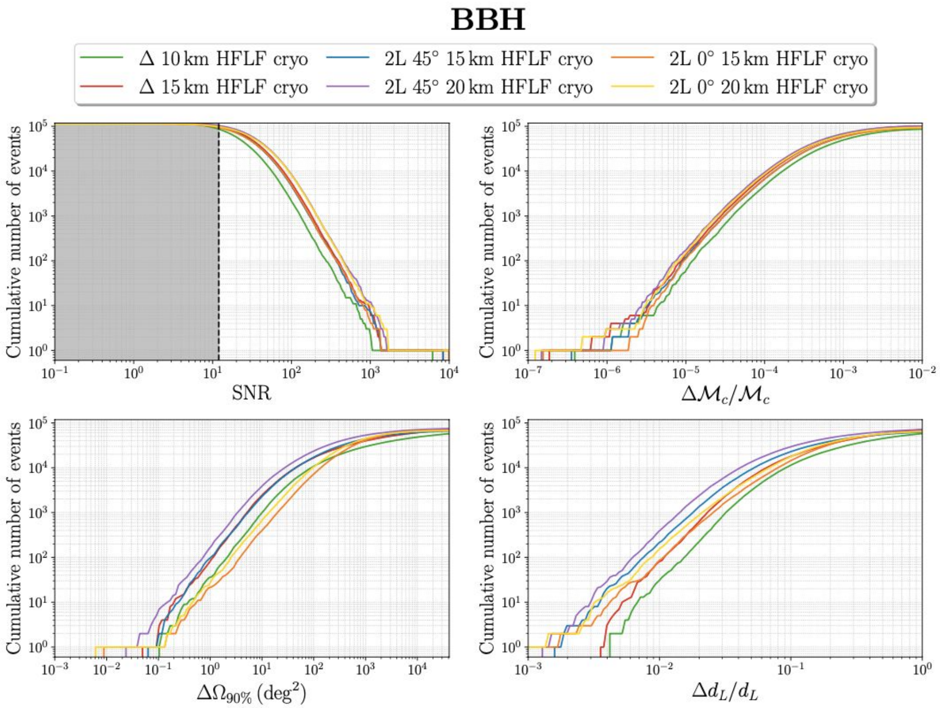


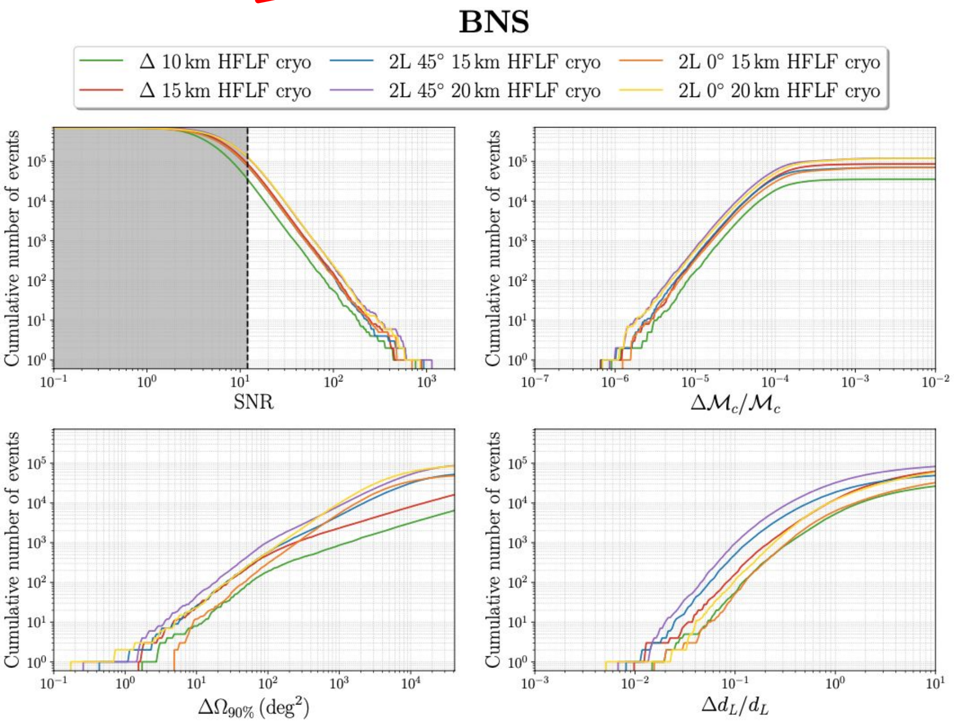
Structure of the Work

Contents

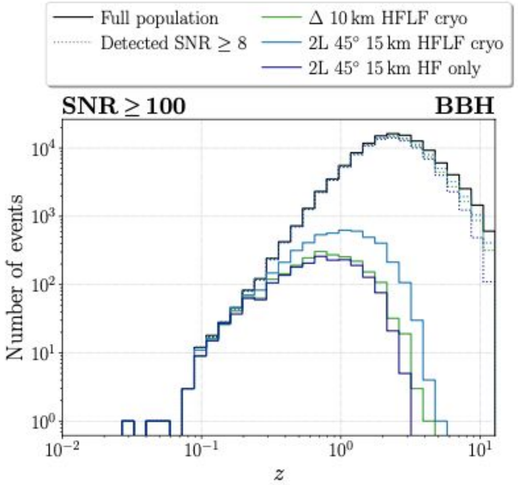
Coalescence of Compact Binaries

1 year of observations!

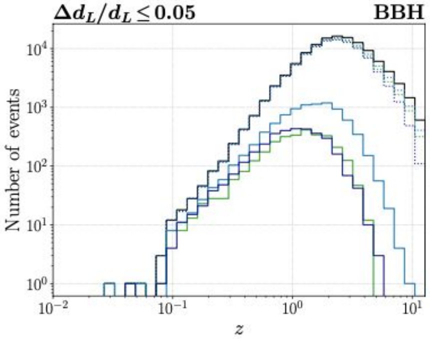


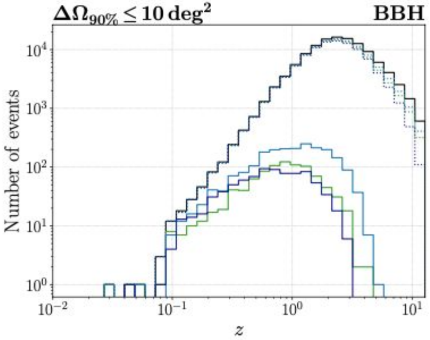


Coalescence of Compact Binaries: Golden Events



Configuration	SNR ≥ 100
Δ-10km-HFLF-Cryo	2298
Δ-15km-HFLF-Cryo	5730
2L-15km-45°-HFLF-Cryo	4933
2L-20km-45°-HFLF-Cryo	8828
2L-15km-0°-HFLF-Cryo	5143
2L-20km-0°-HFLF-Cryo	8551
2L-15km-45°-HF	1987



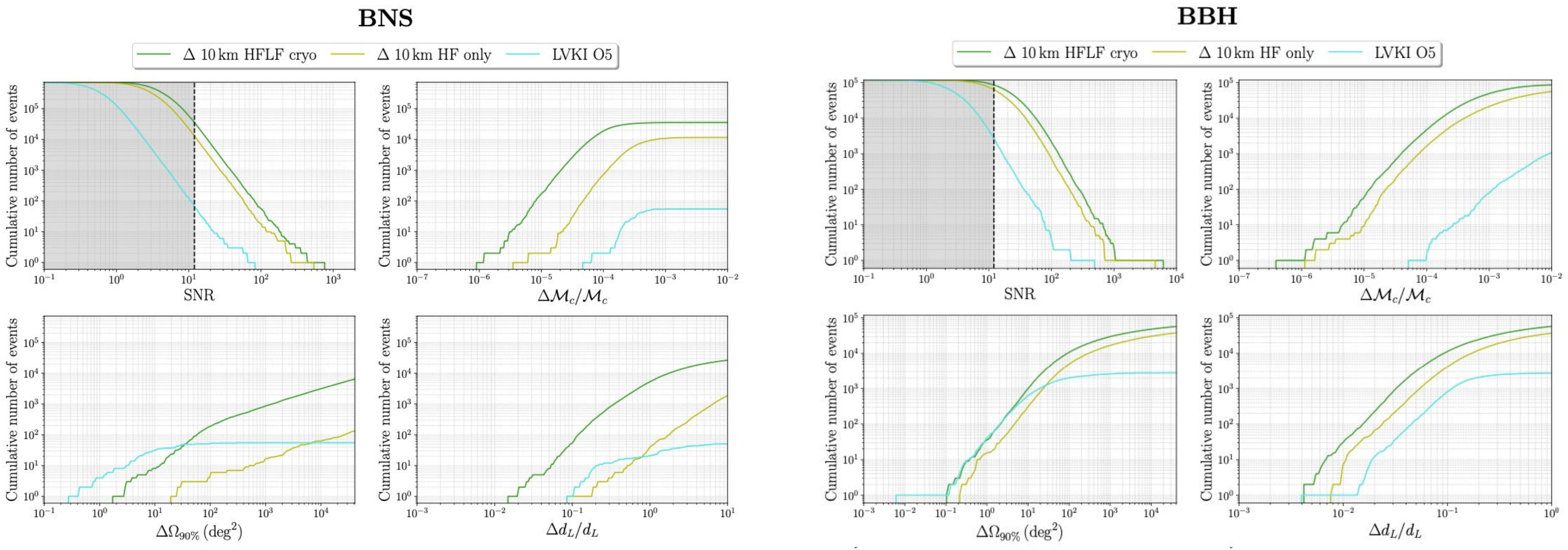


The full population contains 1.2×10^5 BBH events!

Coalescence of Compact Binaries

- The reference design of 10 km has remarkable performance, improving by orders of magnitude with respect to 2G
- The 2L-15 km-45º configuration improves by a further factor of 2-3, especially for distance and sky localization
- The 2L-15km-0º configuration is disfavored, because of the poor angular localization capabilities

Coalescence of Compact Binaries: losing LF

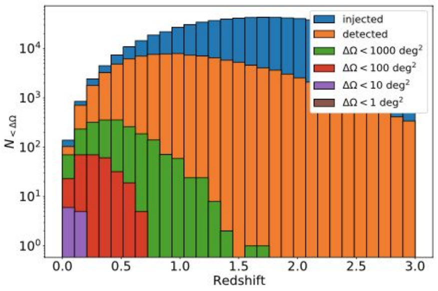


- LF sensitivity is particularly important for BNSs as they stay for a longer time in bandwidth
- The reference triangle-10 km design is well superior LVK-O5 even if we have only HF sensitivity, except for angular localization

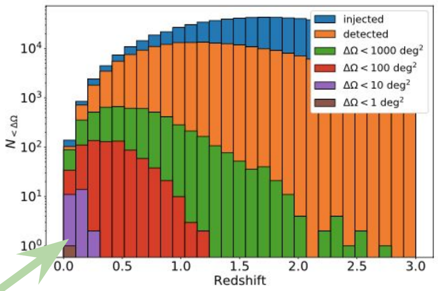
Multi-Messenger Astronomy

The key parameters to take into account are:

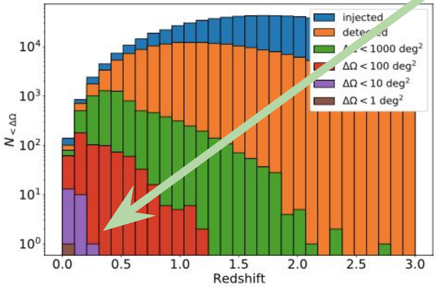
- Ability to localize the source
- Number of joint detections (SNR > 8)
- Reached redshift
- Pre-merger detection and parameter estimation



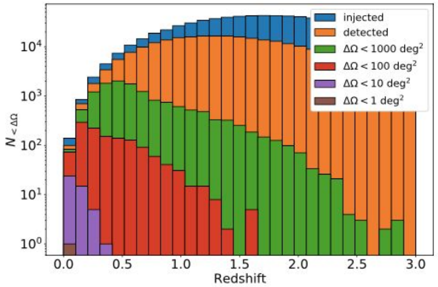
(a) Δ 10 km HFLF cryo



(b) Δ 15 km HFLF cryo



(d) 2L 15 km HFLF cryo



(e) 2L 20 km HFLF cryo

The 2L-15km-45º is comparable to Δ-15km and is better than Δ-10km

Multi-Messenger Astronomy: HF only

on-axis events

Full (HFLF cryo) sensitivity detectors

$\Delta\Omega_{90\%}(\mathrm{deg}^2)$	All orientation BNSs				BNSs with viewing angle $\Theta_v < 15°$			
	Δ10	Δ15	2L 15	2L 20	Δ10	Δ15	2L 15	2L 20
10	11	27	24	45	0	1	2	5
40	78	215	162	350	8	22	20	33
100	280	764	644	1282	26	74	68	133
1000	2112	5441	7478	13482	272	632	1045	1725

HF sensitivity detectors

$\Delta\Omega_{90\%}(\mathrm{deg}^2)$	All orientation BNSs				BNSs with viewing angle $\Theta_v < 15°$			
	Δ10	Δ15	2L 15	2L 20	Δ10	Δ15	2L 15	2L 20
10	0	1	5	5	0	0	2	2
40	4	10	20	47	0	5	6	17
100	14	53	76	144	7	33	35	64
1000	145	548	1662	3378	80	336	672	1302

- Significantly smaller number of well-localized events (<100deg²), especially for the Δ-configurations
- For the on-axis events the percentage decrease of well-localized events is smaller than that for randomly oriented events
- 2L-15km-HF and 2L-20km-HF are worse than Δ-10km-cryo for randomly oriented systems
- 2L-15km-HF is comparable to the full Δ-10km-cryo for on-axis events

Multi-Messenger Astronomy: Pre-Merger Detections

Full (HFLF cryo) sensitivity detectors

Configuration	$\Delta\Omega_{90\%}$ [deg^2]	All orientation BNSs 30 min	All orientation BNSs 10 min	All orientation BNSs 1 min	BNSs with $\Theta_v < 15°$ 30 min	BNSs with $\Theta_v < 15°$ 10 min	BNSs with $\Theta_v < 15°$ 1 min
Δ10km	10	0	1	5	0	0	0
	100	10	39	113	2	8	20
	1000	85	293	819	10	34	132
	All detected	905	4343	23597	81	393	2312
Δ15km	10	1	5	11	0	1	1
	100	41	109	281	6	14	36
	1000	279	806	2007	33	102	295
	All detected	2489	11303	48127	221	1009	4024
2L 15 km misaligned	10	0	1	8	0	0	0
	100	20	54	169	2	7	26
	1000	194	565	1399	23	73	199
	All detected	2172	9598	39499	198	863	3432
2L 20 km misaligned	10	2	4	15	1	1	2
	100	39	118	288	7	19	47
	1000	403	1040	2427	47	128	346
	All detected	4125	17294	56611	363	1588	4377

Detections within z=1.5

Pre-merger detections are critical to detect the prompt/early multi-wavelength emission in order to:

- Probe the central engine of GRBs, and in particular to understand the jet composition, the particle acceleration mechanism, the radiation and energy dissipation mechanisms (VHE prompt CTA/ET synergy - see **Banerjee et al., 2023**)
- To probe the structure of the outer sub-relativistic ejecta, early UV emission (ULTRASAT/UVEX/DORADO synergy)

Similar performances for on-axis events!

Without LF

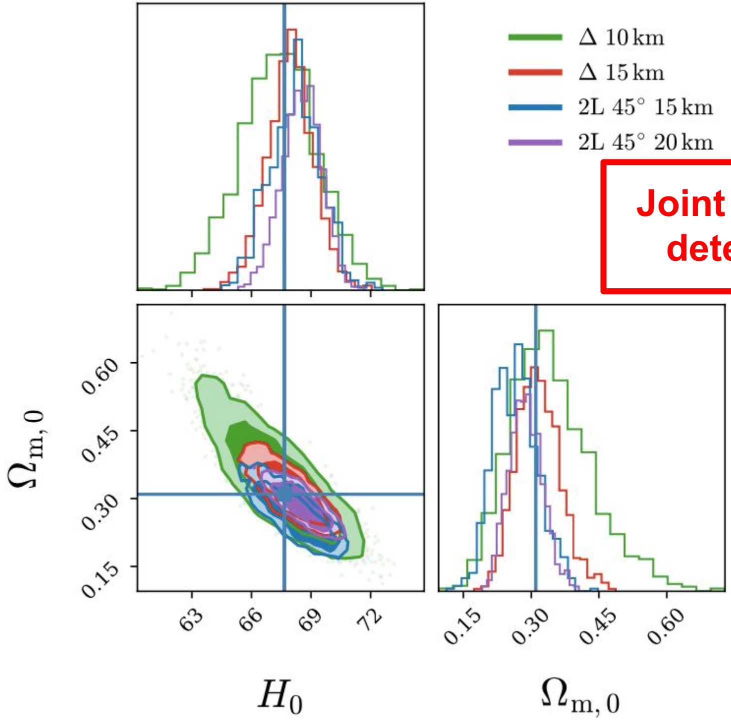
HF sensitivity detectors

Configuration	$\Delta\Omega_{90\%}$ [deg^2]	All orientation BNSs			BNSs with $\Theta_v < 15°$		
		30 min	10 min	1 min	30 min	10 min	1 min
Δ10km	100	0	0	0	0	0	0
	1000	0	0	4	0	0	1
	All detected	0	3	317	0	0	26
Δ15km	100	0	0	2	0	0	0
	1000	0	0	10	0	0	4
	All detected	2	8	891	0	1	84
2L 15 km misaligned	100	0	0	0	0	0	0
	1000	0	0	7	0	0	3
	All detected	0	7	743	0	1	69
2L 20 km misaligned	100	0	0	3	0	0	0
	1000	0	0	13	0	0	6
	All detected	2	11	1535	0	1	146

Detections within z=1.5

No localized pre-merger detections!

Cosmology: ET + THESEUS



Joint GW-GRB detections!

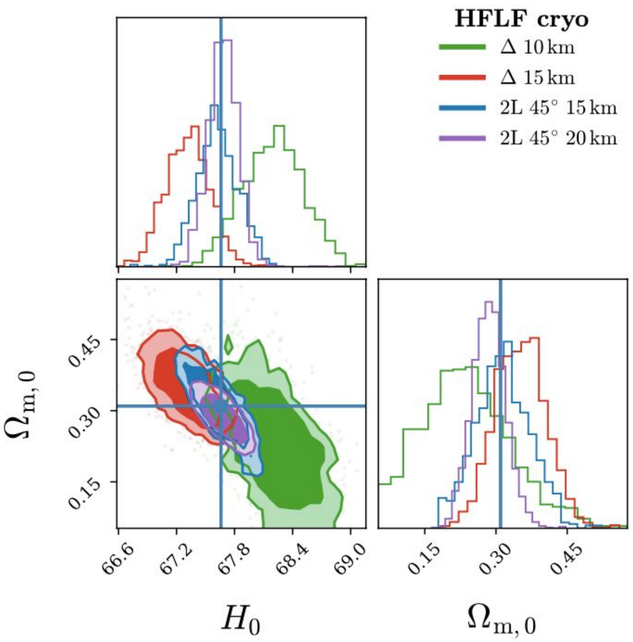
- 5 years of observations
- **75 joint detections** in the configuration 2L-20km-cryo
- Solid and conservative results based on prompt GRB observations

Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.057	0.546
Δ-15km	0.035	0.290
2L-15km-45°	0.040	0.370
2L-20km-45°	0.029	0.276

Cosmology: ET + VRO

Joint GW-kilonova detections

- 1 year of observations (larger number of joint detections expected)
- **115 joint detections** for 2L-20km-cryo
- Dependence on BNS merger rate normalization

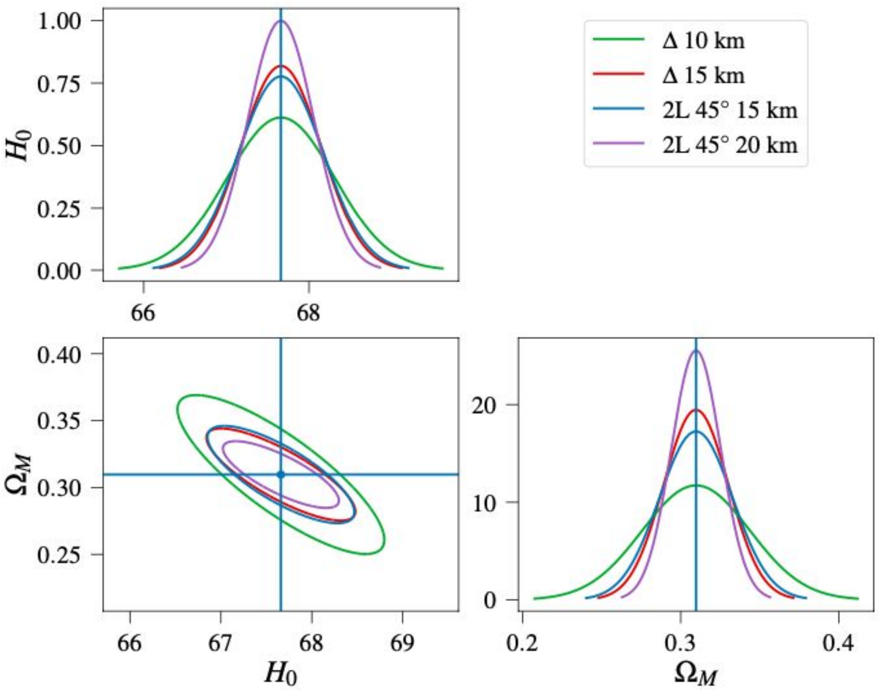


HFLF cryogenic		
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.009	0.832
Δ-15km	0.007	0.303
2L-15km-45°	0.006	0.370
2L-20km-45°	0.004	0.243

HF only		
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.065	1.23
Δ-15km	0.057	1.86
2L-15km-45°	0.066	1.31
2L-20km-45°	0.031	1.22

Dramatic reduction of joint detections without LF in both cases!

Cosmology from BNS Tidal Deformability



- Assuming that the nuclear EOS is known
- The source-frame mass can be determined from the measurement of tidal deformability
- Direct measurement of z from the GW signal
- Sub-percent error on H_0 with a single year of observing run with ET alone

Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	9.63×10^{-3}	1.10×10^{-1}
Δ-15km	7.20×10^{-3}	6.62×10^{-2}
2L-15km-45°	7.59×10^{-3}	7.47×10^{-2}
2L-20km-45°	5.90×10^{-3}	5.04×10^{-2}

CoBA Conclusions

- All the triangular and 2L geometries that have been investigated can be the baseline of a **superb 3G detector**, that will allow to improve by orders of magnitude compared to 2G detectors
- The **2L-15km-45º configuration** in general offer a better scientific return with respect to the **Δ**-10km, and has a similar performance on all parameters (for both BBHs and BNSs) to the **Δ-15km**
- The **low frequency sensitivity** is crucial for exploiting the full potential of ET. In the HF-configuration only, independently of the chosen geometry, several scientific targets would be lost or significantly diminished

Thank you!