Science with the Einstein Telescope: a comparison of different designs

Michele Maggiore

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique théorique

XIII ET Symposium, Cagliari May 8-12, 2023 the `CoBA-Science' team, coordinated by M.Branchesi and MM

Science with the Einstein Telescope: a comparison of different designs

Marica Branchesi,[1,2] Michele Maggiore,[3,4] David Alonso,[5] Charles Badger,[6] Biswajit Banerjee,[1,2] Freija Beirnaert,[7] Swetha Bhagwat,[8,9] Guillaume Boileau,[10,11] Ssohrab Borhanian,[12] Daniel David Brown,[13] Man Leong Chan,[14] Giulia Cusin,[15,3,4] Stefan L. Danilishin,[16,17] Jerome Degallaix,[18] Valerio De Luca,[19] Arnab Dhani,[20] Tim Dietrich,[21,22] Ulyana Dupletsa,[1,2] Stefano Foffa,[3,4] Gabriele Franciolini,[8] Andreas Freise,[23,16] Gianluca Gemme,[24] Boris Goncharov,[1,2] Archisman Ghosh,[7] Francesca Gulminelli,[25] Ish Gupta,[20] Pawan Kumar Gupta,[16,26] Jan Harms,[1,2] Nandini Hazra,[1,2,27] Stefan Hild,[16,17] Tanja Hinderer,[28] Ik Siong Heng,[29] Francesco Iacovelli,[3,4] Justin Janquart,[16,26] Kamiel Janssens,[10,11] Alexander C. Jenkins,[30] Chinmay Kalaghatgi,[16,26,31] Xhesika Koroveshi,[32,33] Tjonnie G. F. Li,[34,35] Yufeng Li,[36] Eleonora Loffredo,[1,2] Elisa Maggio,[22] Michele Mancarella,[3,4,37,38] Michela Mapelli,[39,40,41] Katarina Martinovic,[6] Andrea Maselli,[1,2] Patrick Meyers,[42] Andrew L. Miller,[43,16,26] Chiranjib Mondal,[25] Niccolò Muttoni,[3,4] Harsh Narola,[16,26] Micaela Oertel,[44] Gor Oganesyan,[1,2] Costantino Pacilio,[8,37,38] Cristiano Palomba,[45] Paolo Pani,[8] Antonio Pasqualetti,[46] Albino Perego,[47,48] Carole Périgois,[39,40,41] Mauro Pieroni,[49,50] Ornella Juliana Piccinni,[51] Anna Puecher,[16,26] Paola Puppo,[45] Angelo Ricciardone,[52,39,40] Antonio Riotto,[3,4] Samuele Ronchini,[1,2] Mairi Sakellariadou,[6] Anuradha Samajdar,[21] Filippo Santoliquido,[39,40,41] B.S. Sathyaprakash,[20,53,54] Jessica Steinlechner,[16,17] Sebastian Steinlechner,[16,17] Andrei Utina,[16,17] Chris Van Den Broeck,[16,26] and Teng Zhang[9,17]

Motivations

The reference ET configuration:

- triangle, 10km arms
- 3 nested detectors in xylophone configuration (HF+LF cryo)

We want to evaluate the effect on the Science Case of

- changes in geometry: triangle vs 2L, and different arm-lengths
- role of low-frequency instrument

why now and not 10 yr ago?

when the basic layout of ET was first proposed (<2011) and until very recently, there were not even the elements for performing such a study

- only after GWTC-3 (+ recent theoretical population modeling) we have enough info on the coalescing binaries (redshift, mass distributions,...), so to optimize the ET design
- many of the most interesting specific Sciences Cases for 3G detectors have been developed only in recent years, in the flurry of activities after the first detection
- thanks to the OSB, we now have the large ET theoretical community needed to perform such a study (75 people involved)

now this study becomes possible and, therefore, mandatory

configurations studied

geometries:

- triangle, 10km arms (the current baseline ET geometry)
- 2L, 15km arms, parallel
- 2L, 15km arms at 45°

- triangle, 15km arms
- 2L, 20km arms, parallel
- 2L, 20km arms at 45°

NB. `parallel' with respect to the local North, not the great circle connecting them.
2.5° offset

what is a `fair comparison' in Δ vs. 2L is a delicate point

compare configurations with comparable costs?

detailed cost analysis not currently available, and well beyond the scope of this work

total linear arm length is not a good proxy for the cost: Δ10=30km, 2L15=60km, but

the two largest items of the cost are excavation and the vacuum pipes

- Δ10 and 2L15 have the same vacuum length: (`ETRAC' report)

  Δ10: 10km × 3 arms × 4 tubes = 120 km   2L15: 15km × 4 arms × 2 tubes = 120 km

- for triangle, larger tunnel diameter (d=8m vs 6.5m) $\Longrightarrow$ Δ10 and 2L15 have similar excavation volumes (but excavation costs rise more as d rather than d^2)
- costs and maintenance of 1 site and 6 instruments vs 2 sites and 4 instruments

furthermore two-site and one-site configurations might have different financial architectures

$\Longrightarrow$ our study is just a piece of the puzzle

structure of the work

Contents

Independently of the comparison between geometries, it is currently the most detailed study of the science that can be done with ET

presented first at ET Collaboration meeting, EGO, Nov. 2022
undergone a detailed ET internal review
now posted on the arxiv (submitted to JCAP)

coalescence of compact binaries (BBH,BNS)

we study detection rates, range and distribution in redshift, accuracy in the reconstruction of the source parameters

very general metrics that already provide a first solid understanding

first step (lasted several months):

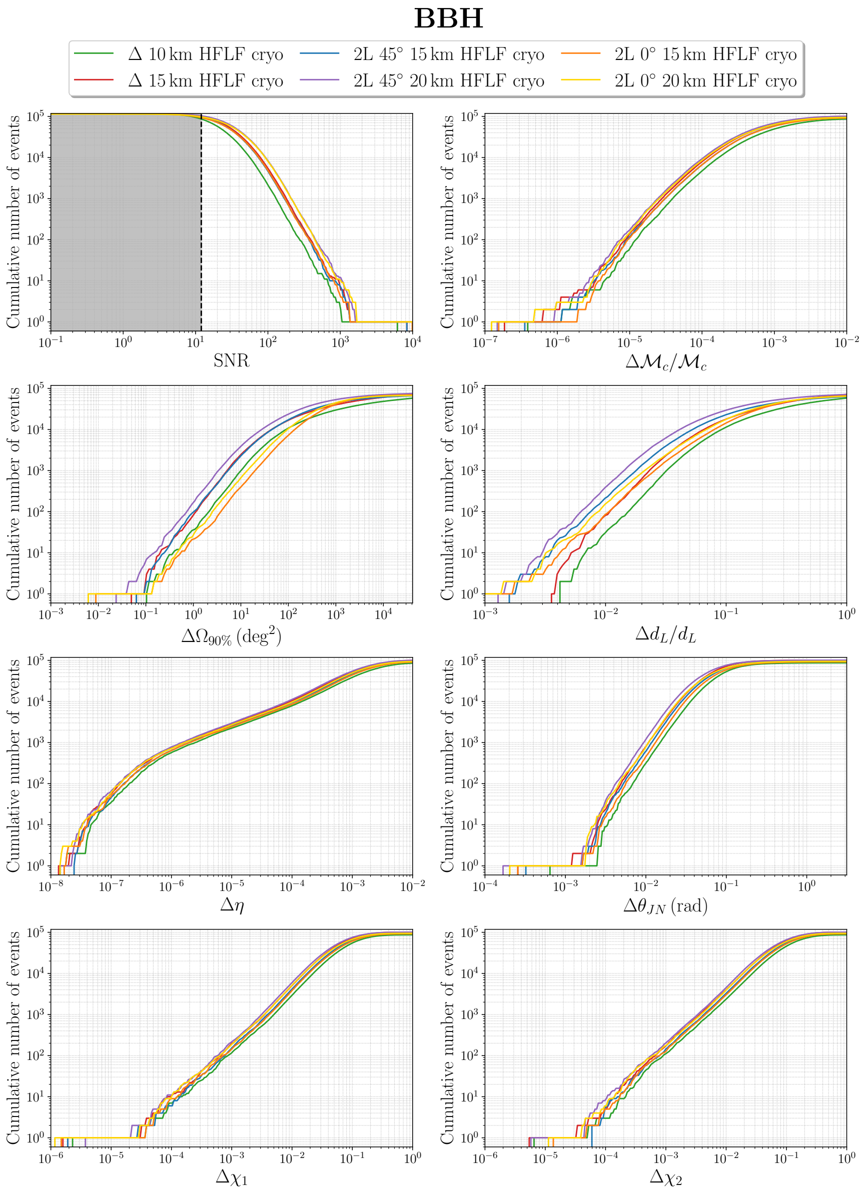
development and comparison of Fisher codes

- GWBENCH (Borhanian 2021, Borhanian and Sathyaprakash 2022)
- GWFISH (Harms, Dupletsa et al 2022, Ronchini et al 2022, GSSI group)
- GWFAST (Iacovelli, Mancarella, Foffa, MM 2022, Geneva Group)
- TiDoFM (Li, Heng, Chan et al 2022)
- (Pieroni, Ricciardone, Barausse 2022)

other technical details:

- state-of-the art population models (Santoliquido et al 2021)
- state-of-the art waveform models
  - IMRPhenomXPHM for BBHs (includes precessing spins and higher-order modes)
  - IMRPhenomD_NRTidalv2 for BNS (includes tidal effects)
- inference on a large parameter space

$$\{\mathcal{M}_c, \eta, d_L, \theta, \phi, \iota, \psi, t_c, \Phi_c, \chi_{1,x}, \chi_{2,x}, \chi_{1,y}, \chi_{2,y}, \chi_{1,z}, \chi_{2,z}, \Lambda_1, \Lambda_2\}$$



Configuration	SNR ≥ 8	SNR ≥ 12	SNR ≥ 50	SNR ≥ 100	SNR ≥ 200
Δ-10km-HFLF-Cryo	103 528	87 568	13 674	2298	282
Δ-15km-HFLF-Cryo	111 231	101 308	26 092	5730	759
2L-15km-45°-HFLF-Cryo	107 661	97 205	23 491	4933	644
2L-20km-45°-HFLF-Cryo	110 698	103 773	34 009	8828	1267
2L-15km-0°-HFLF-Cryo	104 935	94 015	24 088	5143	642
2L-20km-0°-HFLF-Cryo	106 417	98 274	32 915	8551	1246
LVK-O5	8603	2861	47	4	2

Configuration	$\Delta d_L/d_L \leq 0.1$	$\Delta d_L/d_L \leq 0.01$	$\Delta\Omega_{90\%} \leq 50\,\text{deg}^2$	$\Delta\Omega_{90\%} \leq 10\,\text{deg}^2$
Δ-10km-HFLF-Cryo	10 969	28	6064	914
Δ-15km-HFLF-Cryo	17 321	77	10 470	2273
2L-15km-45°-HFLF-Cryo	22 237	202	10 304	2124
2L-20km-45°-HFLF-Cryo	28 801	365	14 920	3648
2L-15km-0°-HFLF-Cryo	13 865	79	3030	374
2L-20km-0°-HFLF-Cryo	17 008	144	4706	608
LVK-O5	767	1	1607	599

Configuration	$\Delta\mathcal{M}_c/\mathcal{M}_c \leq 10^{-3}$	$\Delta\mathcal{M}_c/\mathcal{M}_c \leq 10^{-4}$	$\Delta\chi_1 \leq 0.05$	$\Delta\chi_1 \leq 0.01$
Δ-10km-HFLF-Cryo	48 922	4549	27 877	2811
Δ-15km-HFLF-Cryo	64 469	7703	41 612	4856
2L-15km-45°-HFLF-Cryo	58 371	6456	35 943	3958
2L-20km-45°-HFLF-Cryo	67 999	9073	45 666	5706
2L-15km-0°-HFLF-Cryo	57 330	6472	33 236	3653
2L-20km-0°-HFLF-Cryo	63 154	8279	40 068	4935

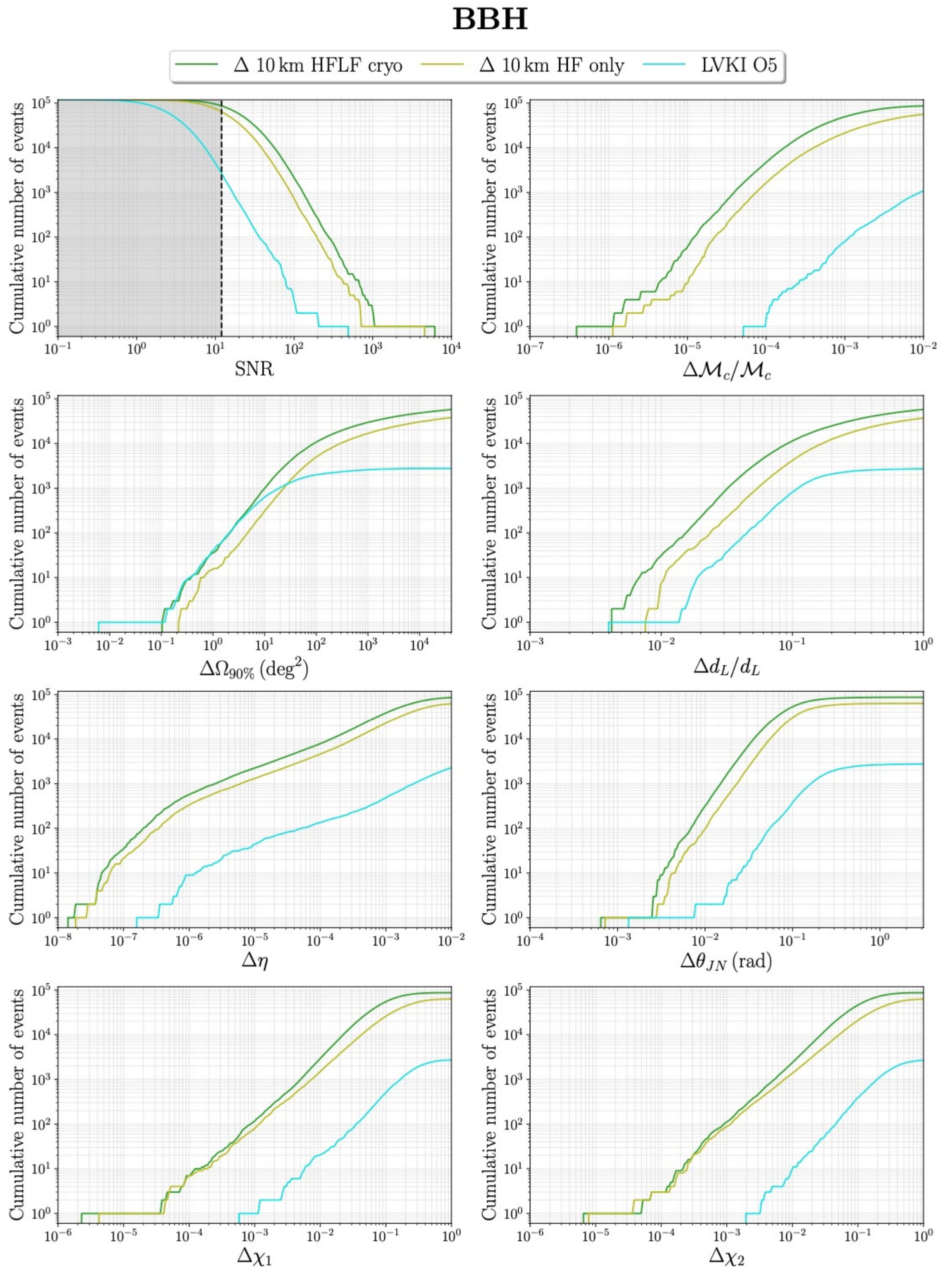
- the baseline 10km triangle has, by itself, fantastic performances, improving by several orders of magnitudes on 2G detectors

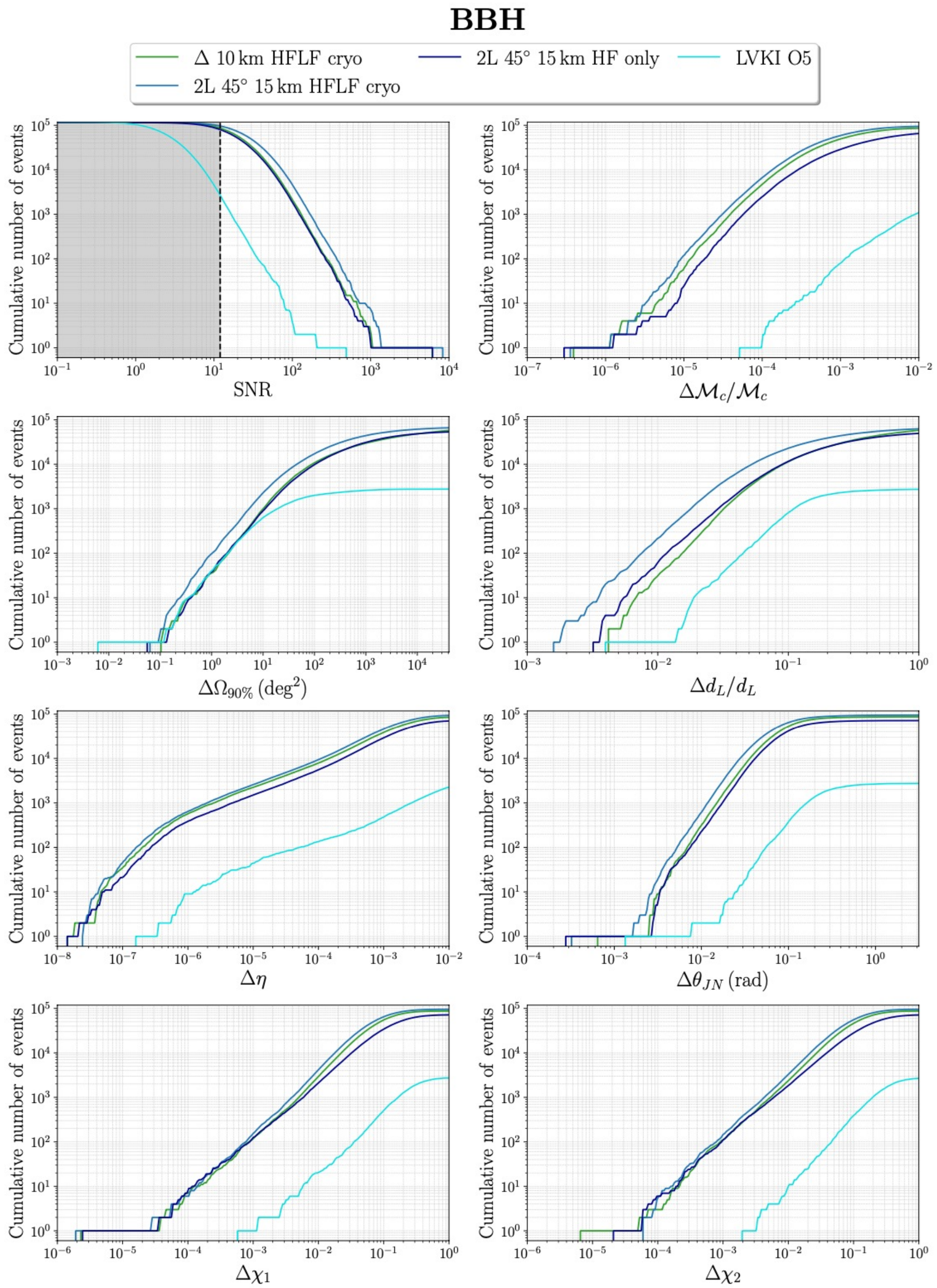
- for BBH, the 2L-15km-45° improves significantly on the 10 km triangle for d_L and angular localization, and is slightly better (~2) for the other parameters

  actually, 2L-15km-45° equal or better even than the 15 km triangle

- 2L with parallel arms quite disfavored, because of a comparatively poor angular localization capability triangle 10-km well superior to LVK-O5 even in HF-only configuration

(except angular localization)



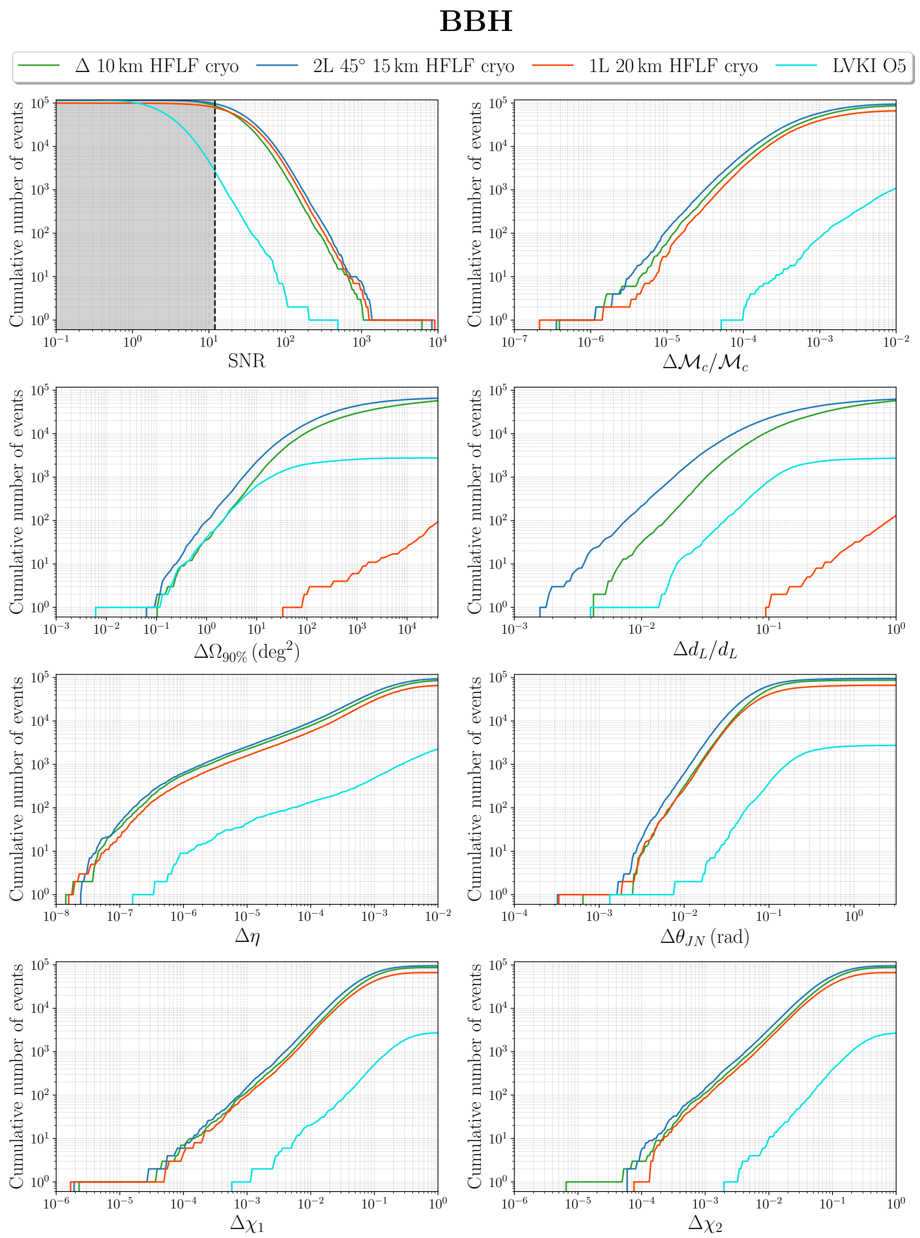


for BBH, the 2L-15km-45° HF-only is comparable or better than the 10km triangle at full sensitivity

Configuration	$\Delta d_L/d_L \leq 0.1$	$\Delta d_L/d_L \leq 0.01$	$\Delta\Omega_{90\%} \leq 50\,\mathrm{deg}^2$	$\Delta\Omega_{90\%} \leq 10\,\mathrm{deg}^2$
Δ-10km-HFLF-Cryo	10 969	28	6064	914
Δ-15km-HFLF-Cryo	17 321	77	10 470	2273
2L-15km-45°-HFLF-Cryo	22 237	202	10 304	2124
2L-20km-45°-HFLF-Cryo	28 801	365	14 920	3648
2L-15km-0°-HFLF-Cryo	13 865	79	3030	374
2L-20km-0°-HFLF-Cryo	17 008	144	4706	608
Δ-10km-HF	3919	6	2409	281
Δ-15km-HF	8083	26	5156	817
2L-15km-45°-HF	11 193	56	5263	835
2L-20km-45°-HF	16 155	113	8448	1566
2L-15km-0°-HF	4111	17	1054	120
2L-20km-0°-HF	9693	57	2936	362

a single L-shaped detector, not inserted in a global network, is basically useless for those aspects of the Science Case, such as multi-messenger astronomy or cosmology, that require accurate reconstruction of sky localization and distance of the sources

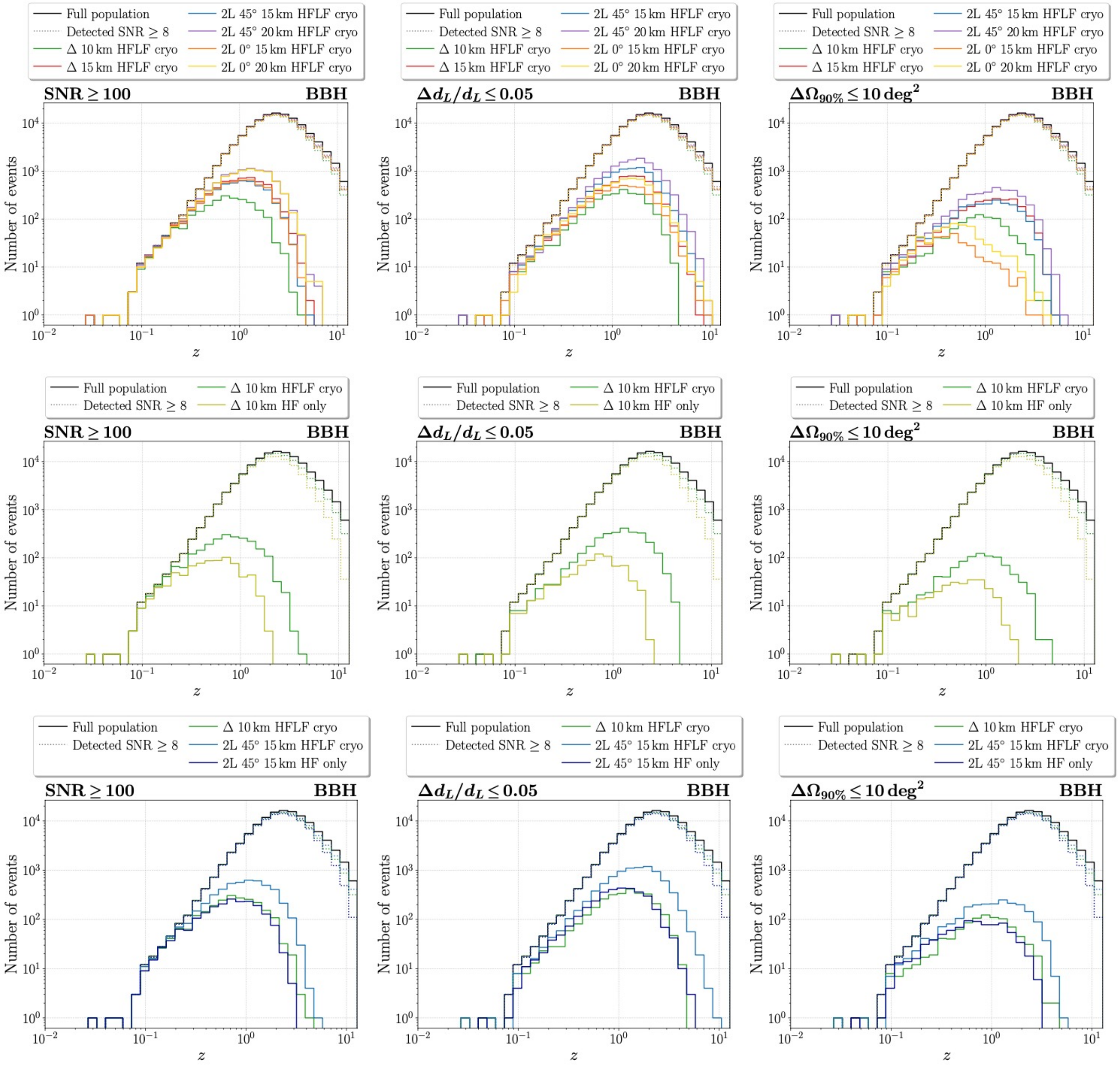
it is competitive on other parameters (assuming that glitches can be reliably vetoed)

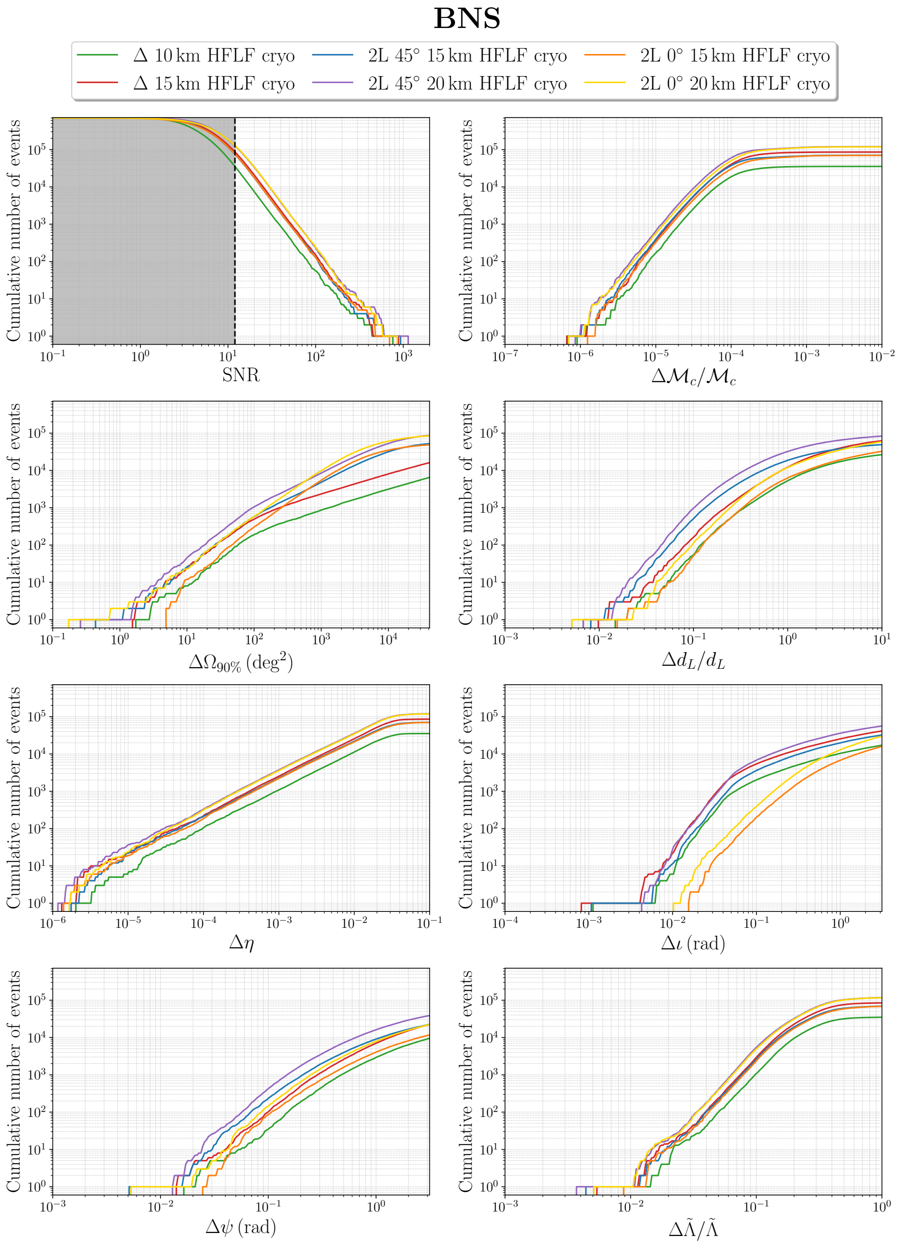


BBH `golden' events

the 2L-45° and Δ–15km give the best compromise between detecting many of them, up to large redshift, and localizing them.

2L-15km-45°, even with HF-only, is comparable to Δ–10km with full HFLF-cryo sensitivity





BNS

for the full HFLF-cryo configuration, BNSs confirm the basic message from BBHs

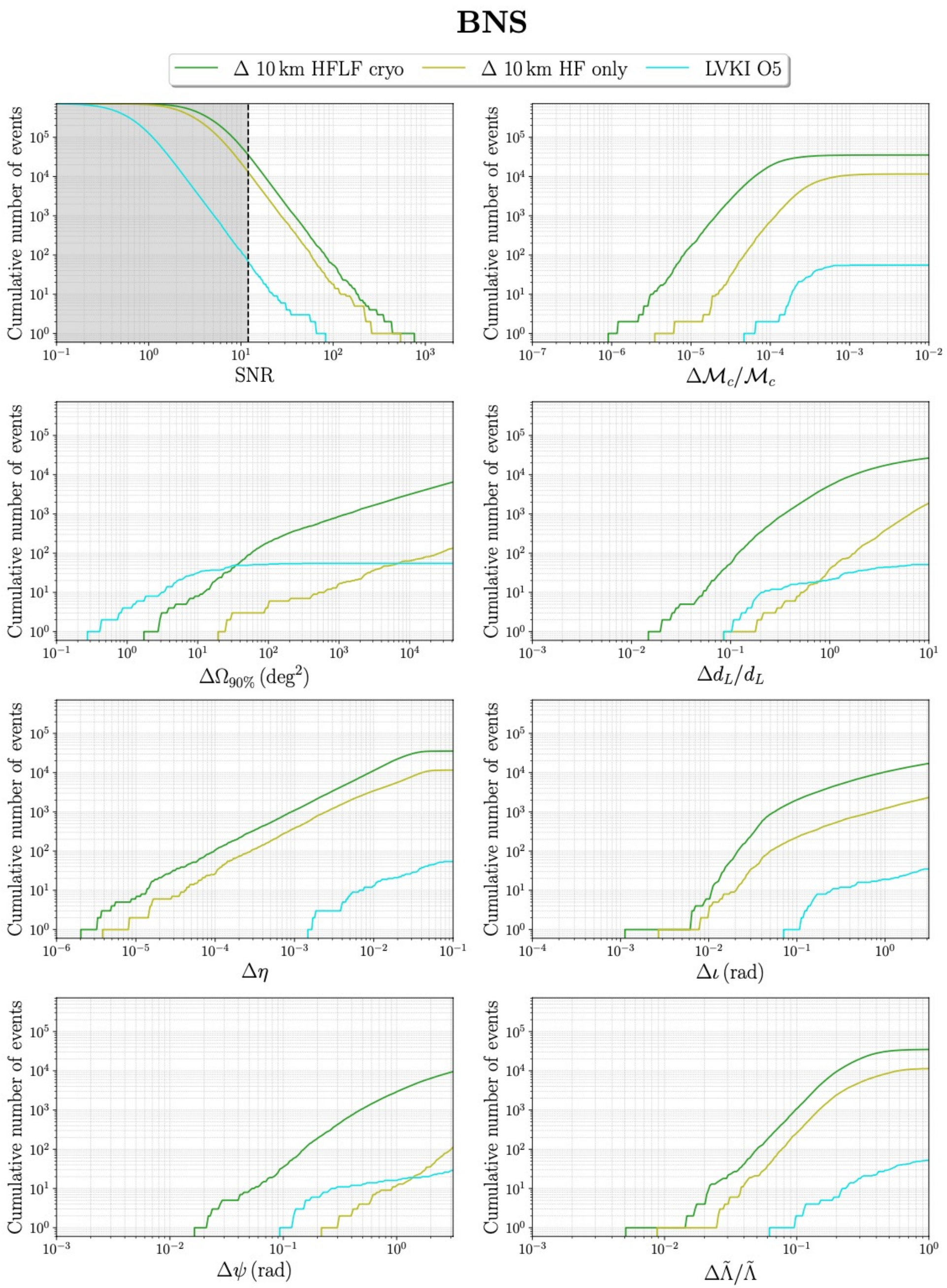
the baseline 10km triangle has remarkable performances, improving by orders of magnitude wrt 2G

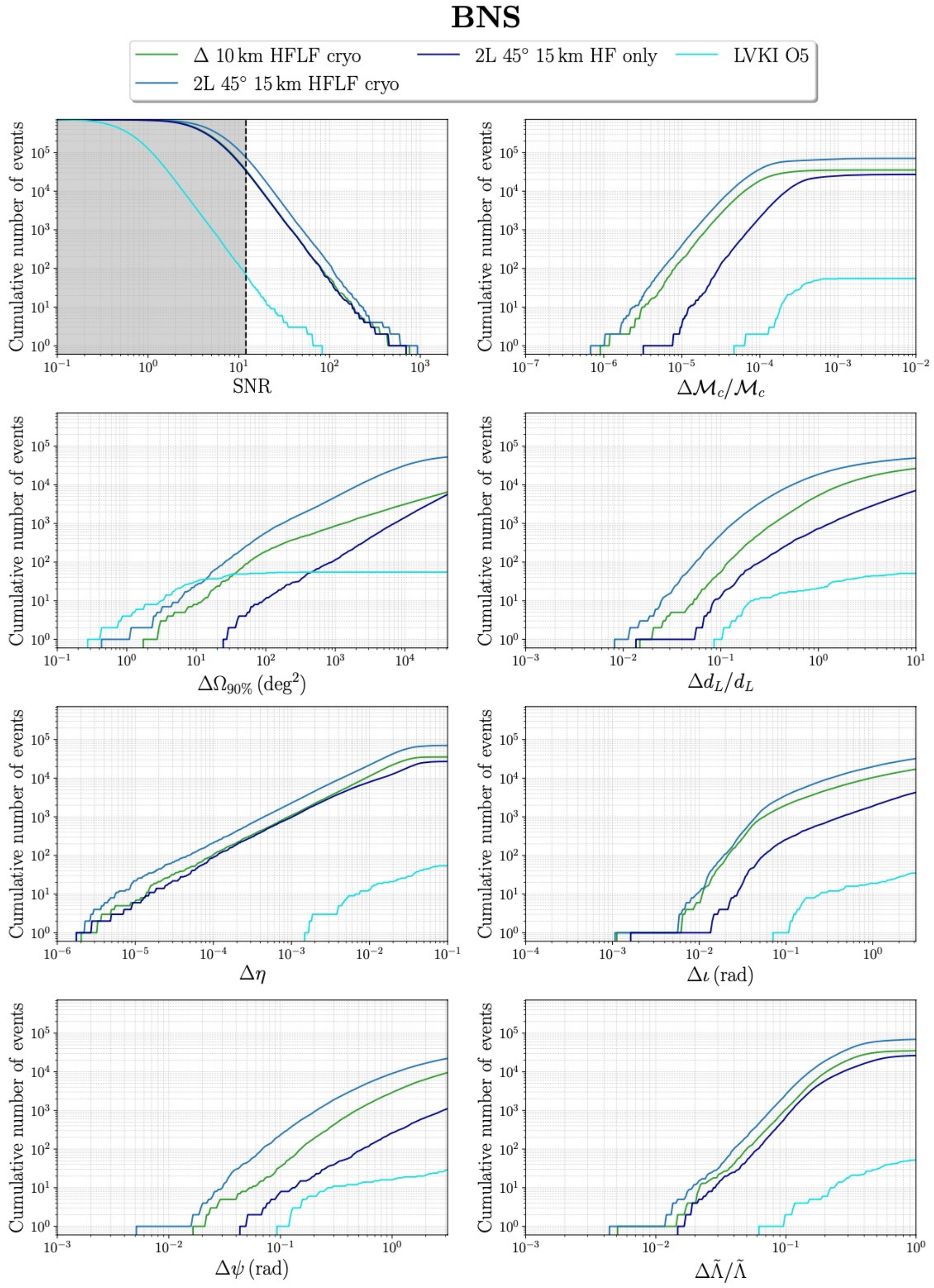
the 2L-15km-45° improves by a further factor 2-3

2L-15km-0° disfavored

Losing the LF in the 10km triangle:

LF sensitivity particularly important for BNS (long time in bandwidth)



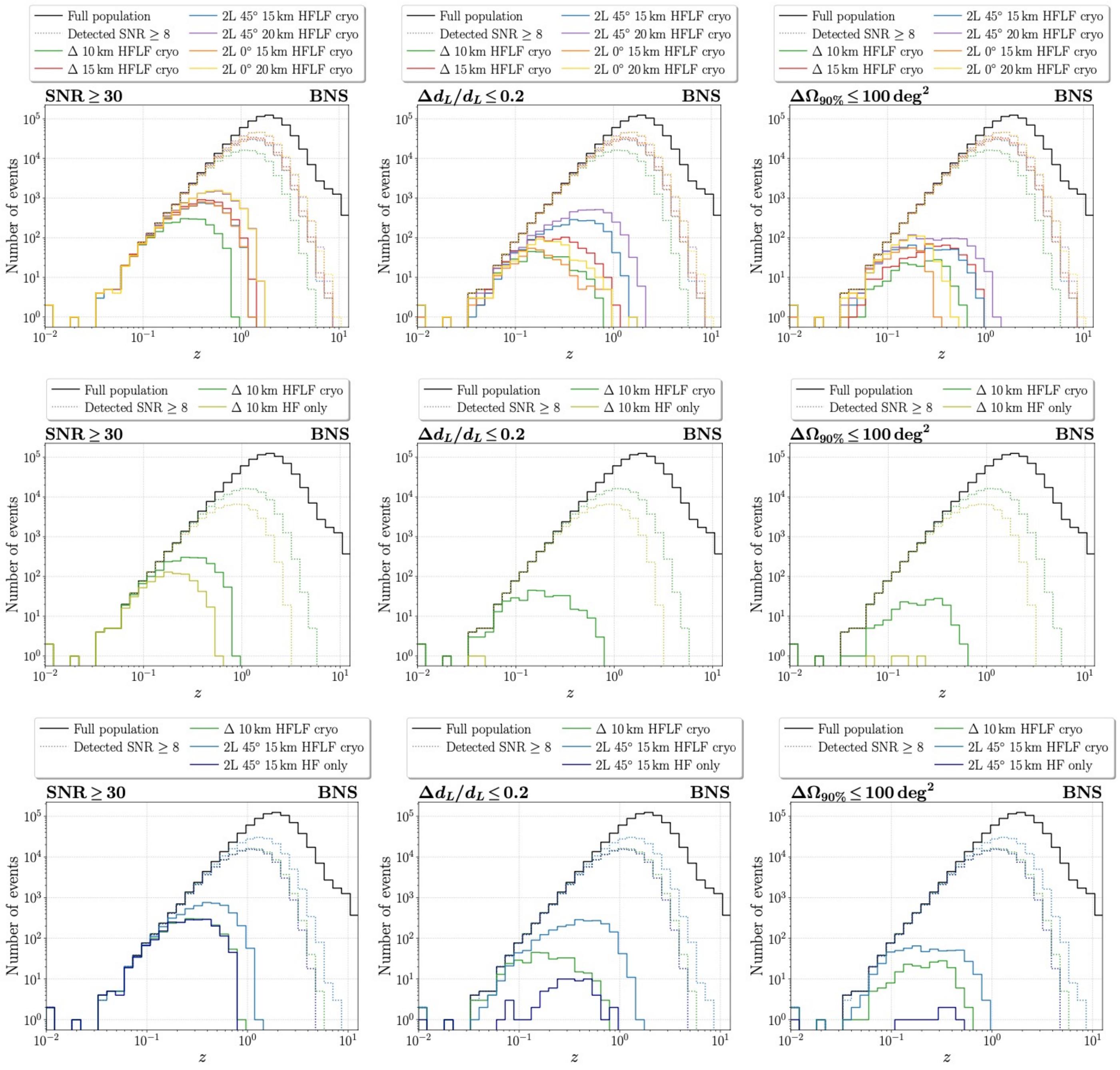


The 2L-15km-45° improves on the 10-km triangle

but now, 2L-15km-45° -HFonly is sensibly worse than triangle 10km full HFLF-cryo

again, LF especially important for BNS

BNS `golden' events



ET in a network with 1CE (40km) or 2CE (40km + 20km)

BNS

Configuration	$\Delta d_L/d_L \leq 0.3$	$\Delta d_L/d_L \leq 0.1$	$\Delta\Omega_{90\%} \leq 100\,\text{deg}^2$	$\Delta\Omega_{90\%} \leq 10\,\text{deg}^2$
Δ-10km-HFLF-Cryo+CE-40km	32 053	4100	54 994	2427
2L-15km-45°-HFLF-Cryo+CE-40km	45 252	7949	75 828	3838
2L-15km-0°-HFLF-Cryo+CE-40km	16 999	2079	29 821	1515
Δ-10km-HFLF-Cryo+2CE	72 335	13 630	112 705	6570
2L-15km-45°-HFLF-Cryo+2CE	89 877	19 129	145 272	9841
2L-15km-0°-HFLF-Cryo+2CE	78 798	14 909	125 640	7592

differences are smaller but still significant, especially with 1 CE

Multi-messenger Astrophysics with ET

Key parameters:

- *Ability to localize the source*
- *Accessible Universe in terms of achieved z*
- *Pre-merger detection and PE*

For the MM studies we use an SNR detection threshold of 8
We consider only 2L misaligned configurations

On-axis events

Full (HFLF cryo) sensitivity detectors

$\Delta\Omega_{90\%}(\text{deg}^2)$	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

2L with 15 km misaligned arms
- comparable to 15 km triangle
- better than 10 km triangle

Without low-frequency

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
- decrease of well-localized events more severe for the triangle configurations
- a large fraction of well-localized events already missed at small z
- on-axis events, decrease of well-localized events but in a smaller percentage than events randomly oriented

Pre-merger detections

Full (HFLF cryo) sensitivity detectors							
Configuration	$\Delta\Omega_{90\%}$	All orientation BNSs			BNSs with $\Theta_v < 15°$		
	[deg^2]	30 min	10 min	1 min	30 min	10 min	1 min
Δ10km	10	0	1	5	0	0	0
	100	10	39	113	2	8	20
	1000	85	293	819	10	34	10
	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

Critical to detect the prompt/early multi-wavelength emission

- to probe the central engine of GRBs, particularly to understand the jet composition, the particle acceleration mechanism, the radiation and energy dissipation mechanisms (e.g. VHE prompt CTA/ET synergy)
- to probe the structure of the outer sub-relativistic ejecta, early UV emission (e.g. ULTRASAT/UVEX/DORADO synergy)

Without low-frequency

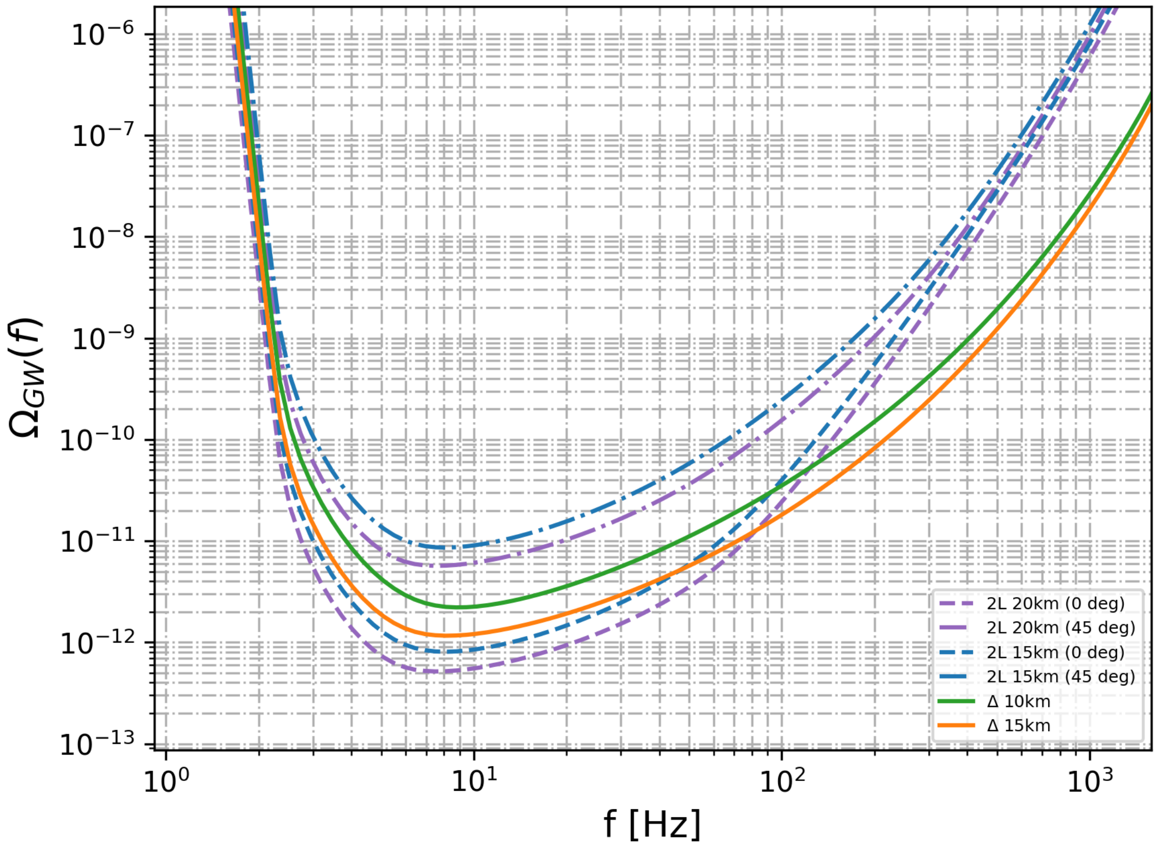
HF sensitivity detectors

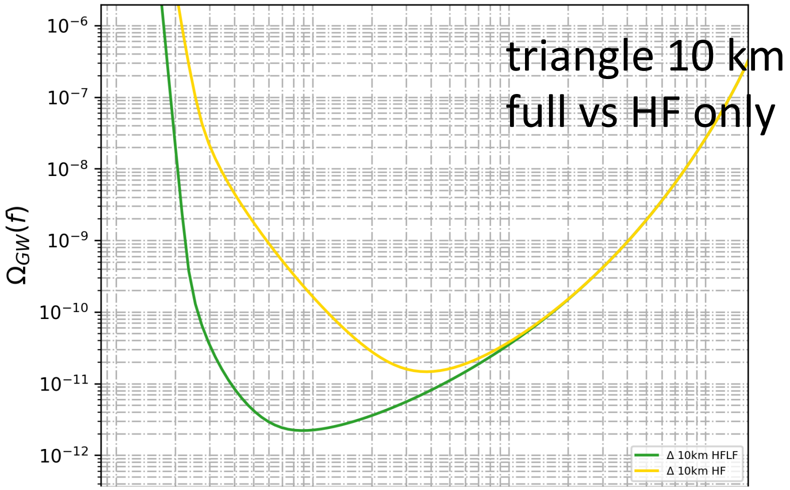
Configuration	$\Delta\Omega_{90\%}$ [deg^2]	All orientation BNSs 30 min	All orientation BNSs 10 min	All orientation BNSs 1 min	BNSs with $\Theta_v < 15°$ 30 min	BNSs with $\Theta_v < 15°$ 10 min	BNSs with $\Theta_v < 15°$ 1 min
Δ10km	100	0	0	0	0	0	0
	1000	0	0	4	0	0	1
	All detected	0	3	317	0	0	26
Δ15km	100	0	0	2	0	0	0
	1000	0	0	10	0	0	4
	All detected	2	8	891	0	0	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

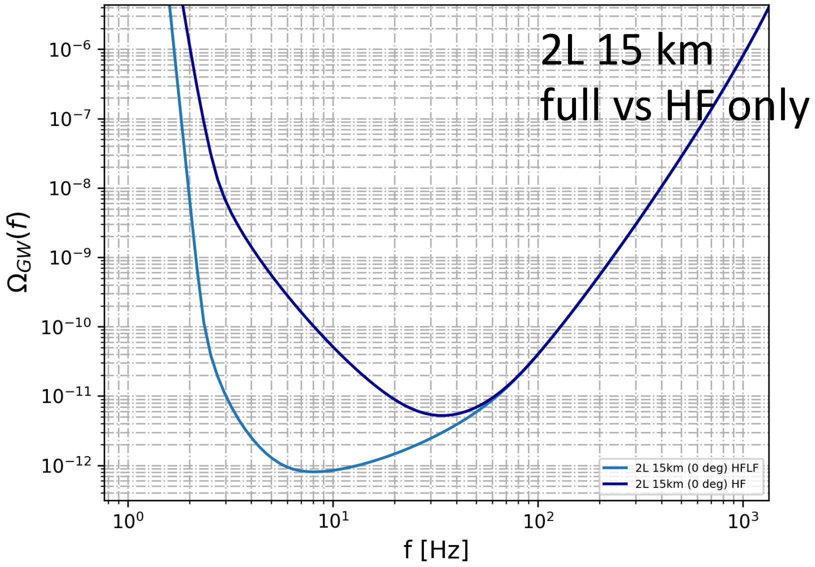
NO localized pre-merger detections!

Detections within z=1.5

stochastic backgrounds

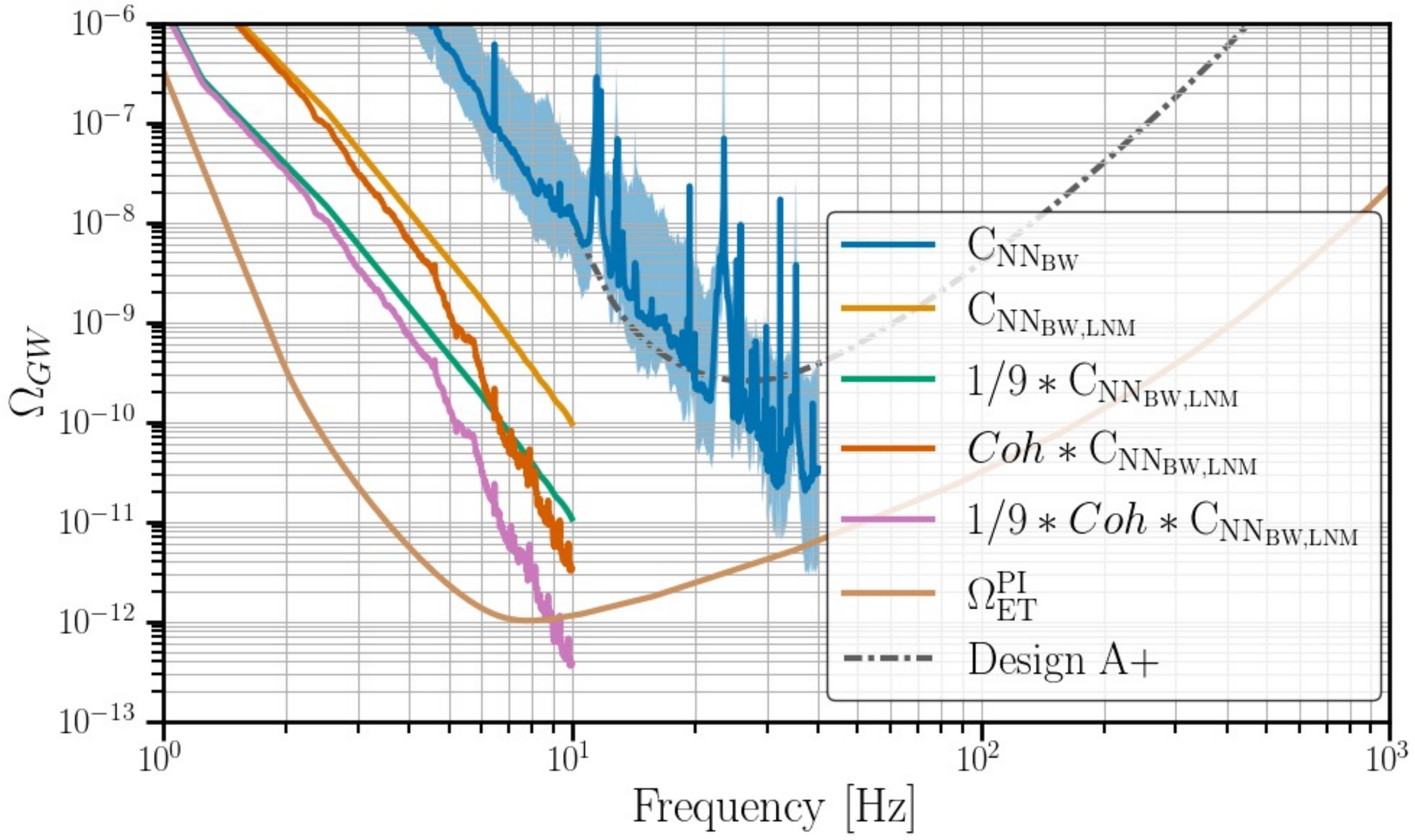






note: alignment angle defined wrt to North at one site: equivalent to 2.5 deg misalignment with angles defined with respect to great circle joining the detectors

correlated Netwonian, seismic and magnetic noise. A threat for the triangle?



impacts stochastic backgrounds searches but possibly also CBC and unmodeled bursts

Impacts on specific science cases

(a selection of the examples worked out)

Physics near BH horizon

$SNR_{GW150914}$	HFLF-cryo	HF-only
Δ-10 km	141	141
Δ-15 km	190	190
2L-15 km-0°	196	196
2L-15 km-45°	192	192
2L-20 km-0°	240	240
2L-20 km-45°	235	235

Ringdown SNR of GW150914-like event

$$\frac{\Delta f_{220}}{f_{220}} \sim 0.2\% \left(\frac{100}{\mathrm{SNR}}\right), \qquad \frac{\Delta \tau_{220}}{\tau_{220}} \sim 2\% \left(\frac{100}{\mathrm{SNR}}\right)$$

	$N_{\rm det}(\mathrm{SNR} \geq 12)$	$N_{\rm det}(\mathrm{SNR} \geq 50)$	$N_{\rm det}(\mathrm{SNR} \geq 100)$	max(SNR)
LVKI-O5	22	0	0	34
ET				
Δ-10 km	5272	41	4	255
Δ-15 km	12916	139	15	312
2L-15 km-0°	11602	109	11	265
2L-15 km-45°	11277	110	10	323
2L-20 km-0°	19081	248	22	309
2L-20 km-45°	18695	252	21	376

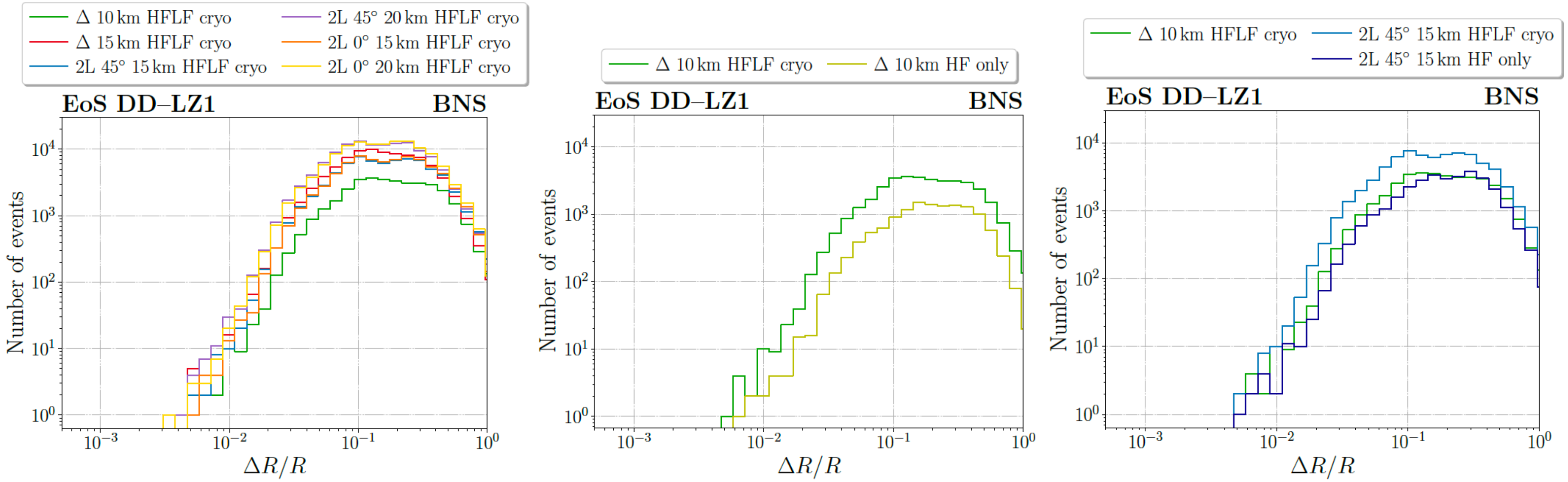
Ringdown detections per year

ET (+1CE)	$N_{det}(SNR \geq 12)$	$N_{det}(SNR \geq 50)$	$N_{det}(SNR \geq 100)$	max(SNR)
Δ-10 km	17690	202	17	296
Δ-15 km	24495	335	32	346
2L-15 km-0°	23202	311	29	304
2L-15 km-45°	23125	308	30	356
2L-20 km-0°	29278	490	45	343
2L-20 km-45°	29298	482	42	405
ET (+2CE)				
Δ-10 km	22056	290	26	302
Δ-15 km	28498	424	40	351
2L-15 km-0°	27146	408	39	311
2L-15 km-45°	27134	396	38	362
2L-20 km-0°	32796	606	54	348
2L-20 km-45°	33006	593	53	409

Differences remain significant also with 1 or 2 CE

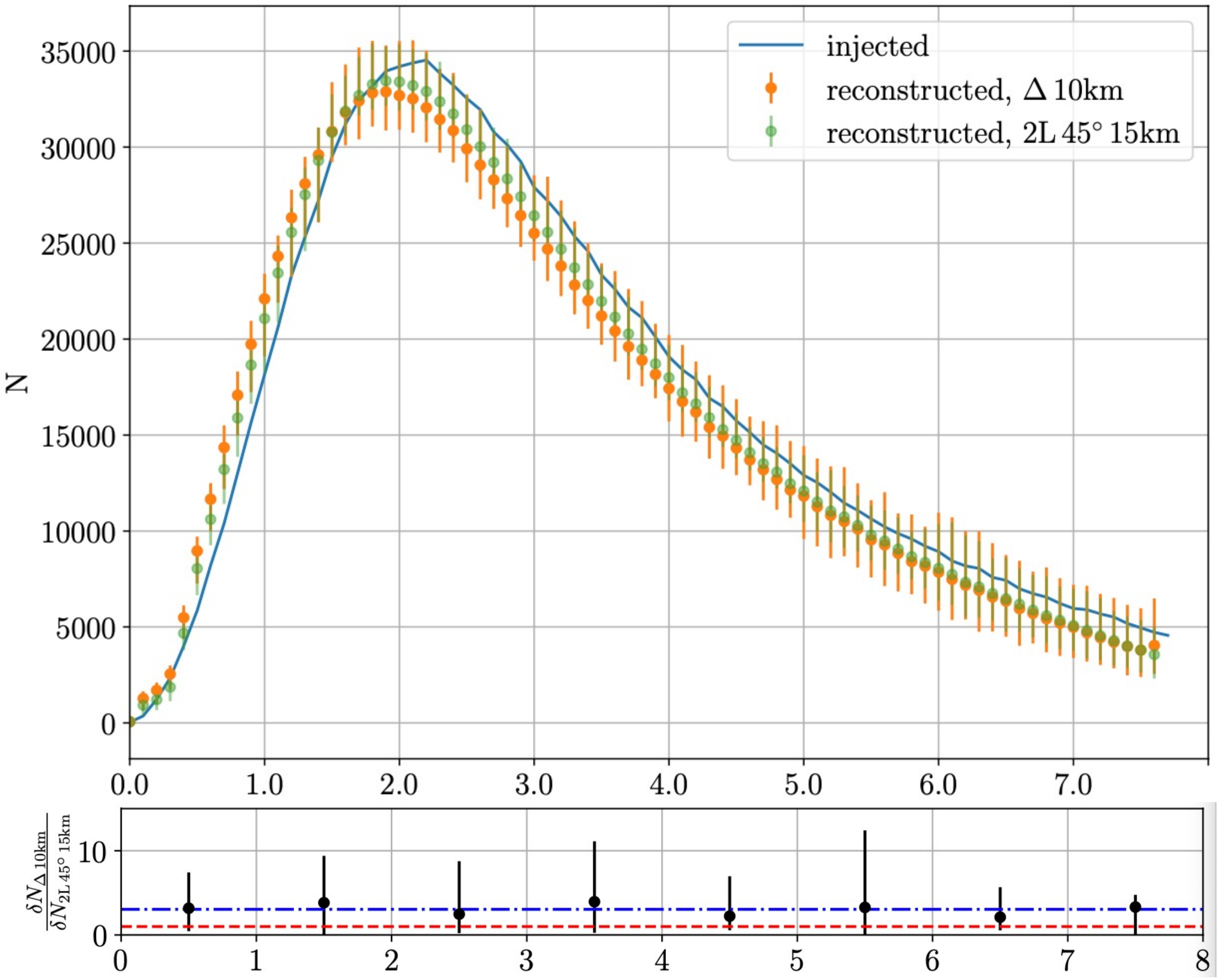
Nuclear Physics

one example:



2L-15 HF-only is as good as full 10km triangle

Population studies



Merger rate reconstruction

both 10km triangle and
2L-15km-45° reconstruct it correctly,
but 2L-15km-45° is better by a factor 2-3

primordial BHs

Detections at z> 30 are a smoking-gun signature

Configuration	$N_{\text{det}}(z>10)$ [1/yr]	$N_{\text{det}}(z>30)$ [1/yr]	$f_{\text{PBH}}^{\text{constrained}}$ [$\times 10^{-5}$]
Δ-10km	**1140.01**	**76.81**	**2.61**
Δ-15km	1763.87	260.65	1.42
2L-15km-0°	1596.61	238.16	1.48
2L-15km-45°	1650.87	220.86	1.54
2L-20km-0°	1983.97	433.82	1.10
2L-20km-45°	2080.13	415.80	1.12

(based on a PBH population model fitted to GWTC-3)

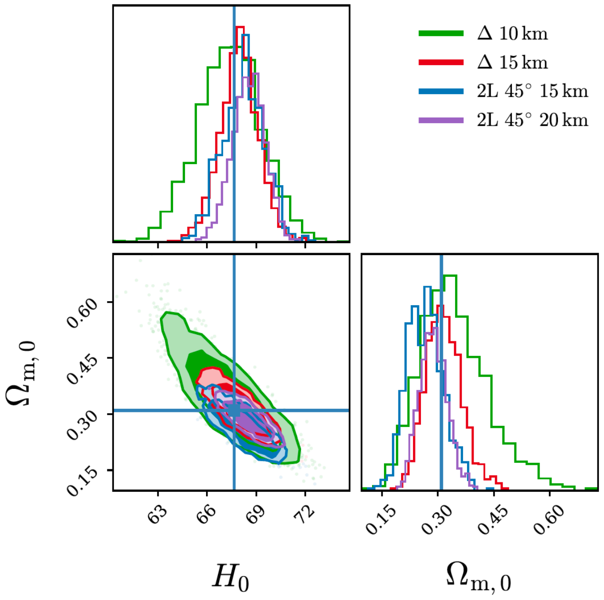
LF crucial: N(z>30) =0 otherwise !

Configuration	$N_{\text{det}}(z>10)$ [1/yr]	$N_{\text{det}}(z>30)$ [1/yr]	$f_{\text{PBH}}^{\text{constrained}}$ [$\times 10^{-5}$]
CE40km	1373.48	47.07	3.34
Δ-10km + CE40km	1940.35	180.08	1.71
Δ-15km + CE40km	2275.96	372.14	1.19
2L-15km-45° + CE40km	2210.49	332.89	1.26
2L-20km-45° + CE40km	2476.43	522.32	1.00

significant differences
also in a network with 1CE

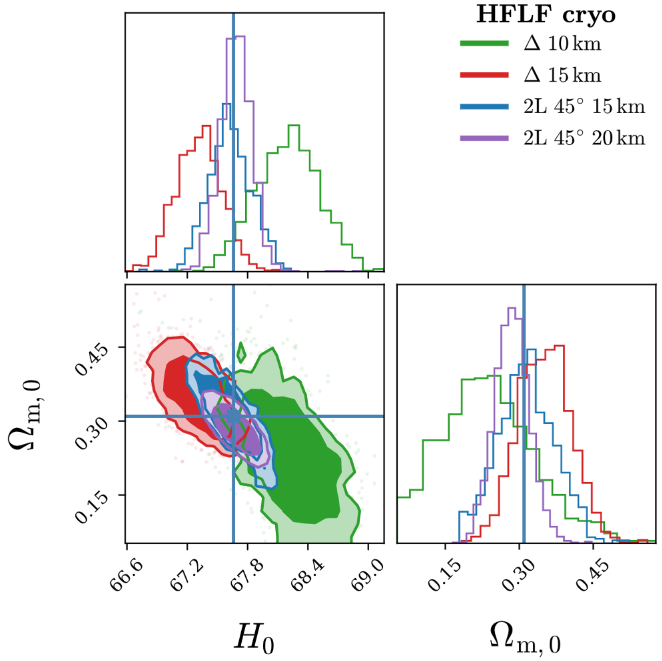
Cosmology

Joint GW-GRB detections, ET+THESEUS



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

Joint GW-kilonova detections, ET+VRO



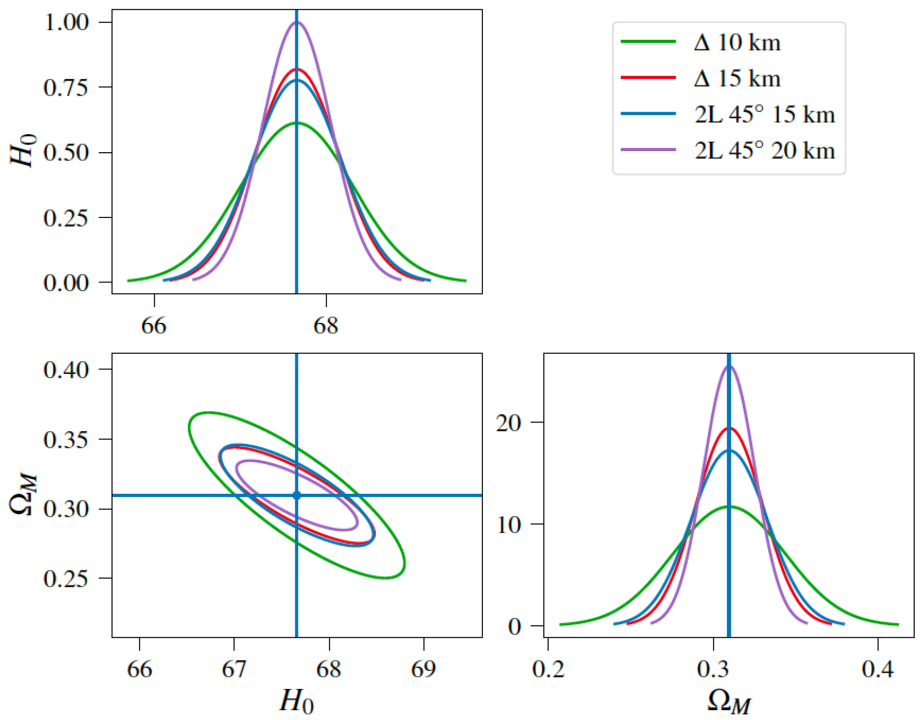
HFLF cryogenic		
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.009	0.832
Δ-15km	0.007	0.303
2L-15km-45°	0.006	0.370
2L-20km-45°	0.004	0.243

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

Note: the bounds becomes stronger using the Planck prior on Ω_M

See the paper for DE EoS and modified GW propagation

NS source-frame mass (and then z) determined from tidal deformability of NS



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}

Summing up....

Comparison between geometries

- for BBH parameter estimation:
  - the 2L-15km-45° improves significantly on the 10 km triangle for d_L and angular localization, and is slightly better (~2) for the other parameters,
  - is equal or better even than the 15 km triangle
  - in a network with 1 or 2CE the differences are still significant

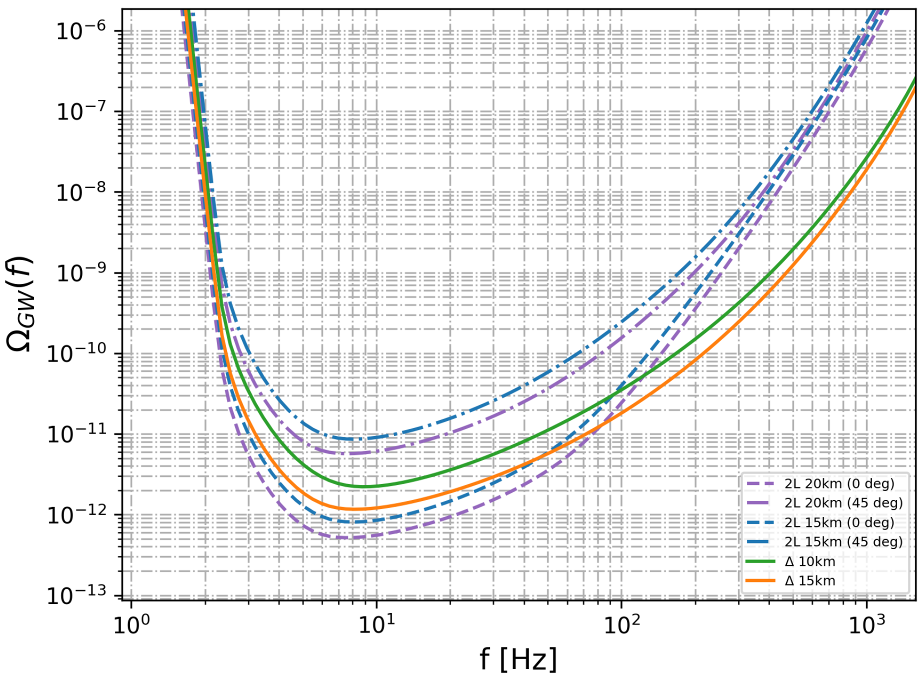
- for BNS, the effect is even larger

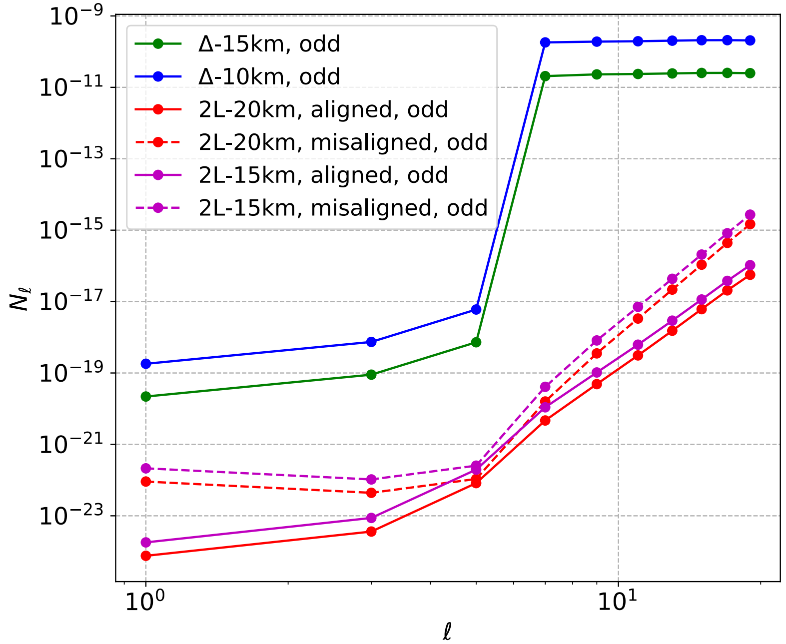
Configuration	$\Delta d_L/d_L \leq 0.3$	$\Delta d_L/d_L \leq 0.1$	$\Delta\Omega_{90\%} \leq 100\,\text{deg}^2$	$\Delta\Omega_{90\%} \leq 10\,\text{deg}^2$
Δ-10km-HFLF-Cryo	748	52	184	8
Δ-15km-HFLF-Cryo	1756	153	479	23
2L-15km-45°-HFLF-Cryo	4328	479	559	25
2L-20km-45°-HFLF-Cryo	7821	919	1028	43
2L-15km-0°-HFLF-Cryo	774	48	293	12
2L-20km-0°-HFLF-Cryo	1499	104	565	23

For multi-messenger astronomy:

- 2L-15km-45° better than 10 km triangle (and comparable to 15 km triangle) enabling observation of a larger number of well-localized events up to a larger redshift
- number of short GRBs with an associated GW signal increases by about 30%, and the number of expected kilonovae counterparts increases by a factor of 2
- pre-merger alerts for on-axis events localized within 10^3 deg^2 increase by a factor of 2

- for stochastic backgrounds

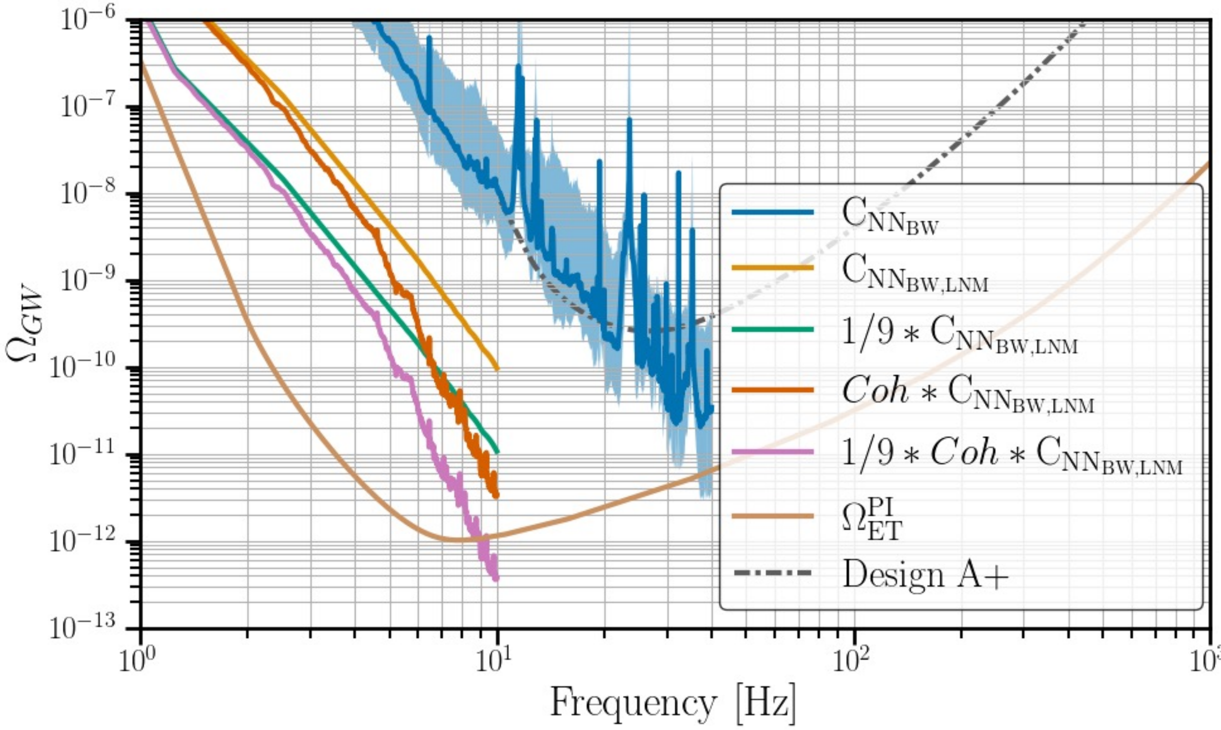




for the isotropic sensitivity:
2L at 45° the less good
2L parallel the best below 100 Hz
triangle the best above 100Hz

For angular resolution:
2L better than triangle

- correlated Newtonian and seismic noise



a potential treath for the triangle

also, correlated magnetic noise
and lightening strikes

individual science case typically show an improvement by a factor 2-3 from the 10km triangle to 2L-15km-45°

- tests of GR:

$\mathrm{SNR}_{\mathrm{GW150914}}$	HFLF-cryo
Δ-10 km	141
Δ-15 km	190
2L-15 km-0°	196
2L-15 km-45°	192

ringwdown SNR

	$N_{\mathrm{det}}(\mathrm{SNR} \geq 12)$	$N_{\mathrm{det}}(\mathrm{SNR} \geq 50)$	$N_{\mathrm{det}}(\mathrm{SNR} \geq 100)$	max(SNR)
LVKI-O5	22	0	0	34
ET				
Δ-10 km	5272	41	4	255
Δ-15 km	12916	139	15	312
2L-15 km-0°	11602	109	11	265
2L-15 km-45°	11277	110	10	323

- nuclear physics: minor differences (ΔR from 10.0m to 6.4m)
- merger rate reconstruction; improvement by a factor ~3
- PBH: improvement by a factor ~3 for events at z>30
- cosmology: improvements ~1.5 on H_0, w_0, Ξ_0

In general, results for 2L-15km-45° quite comparable to 15-km triangle

The role of the LF instrument

For BNS, catastrophic degradation on sky localization and luminosity distance (LF allows BNS to stay a longtime in the bandwidth)

Configuration	$\Delta d_L/d_L \leq 0.3$	$\Delta d_L/d_L \leq 0.1$	$\Delta\Omega_{90\%} \leq 100\,\mathrm{deg}^2$	$\Delta\Omega_{90\%} \leq 10\,\mathrm{deg}^2$
Δ-10km-HFLF-Cryo	748	52	184	8
Δ-15km-HFLF-Cryo	1756	153	479	23
2L-15km-45°-HFLF-Cryo	4328	479	559	25
2L-20km-45°-HFLF-Cryo	7821	919	1028	43
2L-15km-0°-HFLF-Cryo	774	48	293	12
2L-20km-0°-HFLF-Cryo	1499	104	565	23
Δ-10km-HF	4	1	4	0
Δ-15km-HF	7	1	11	1
2L-15km-45°-HF	126	12	11	0
2L-20km-45°-HF	262	22	24	1
2L-15km-0°-HF	20	1	11	1
2L-20km-0°-HF	28	2	24	1

$\Longrightarrow$ no MMO, no standard sirens cosmology

- premerger alerts impossible without the LF instrument

Full (HFLF cryo) sensitivity detectors

Configuration	$\Delta\Omega_{90\%}$	All orientation BNSs			BNSs with $\Theta_v < 15°$		
	[deg^2]	30 min	10 min	1 min	30 min	10 min	1 min
Δ10km	10	0	1	5	0	0	0
	100	10	39	113	2	8	20
	1000	85	293	819	10	34	10
	All detected	905	4343	23597	81	393	2312
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

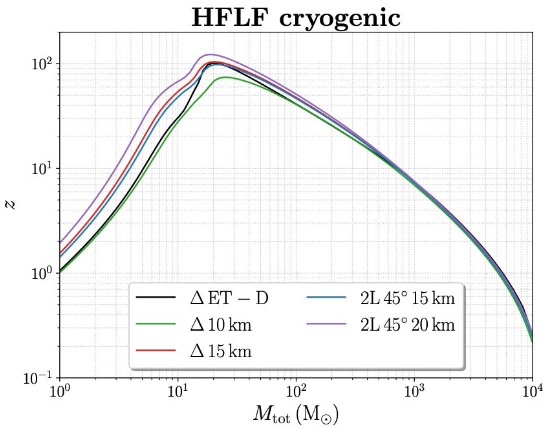
HF sensitivity detectors

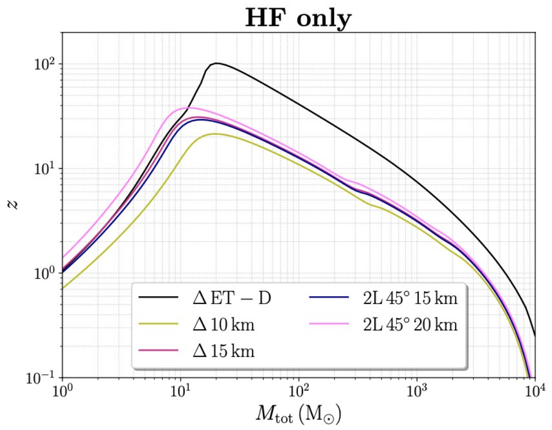
Configuration	$\Delta\Omega_{90\%}$	All orientation BNSs			BNSs with $\Theta_v < 15°$		
	[deg^2]	30 min	10 min	1 min	30 min	10 min	1 min
Δ10km	100	0	0	0	0	0	0
	1000	0	0	4	0	0	1
	All detected	0	3	317	0	0	26
2L 15 km misaligned	100	0	0	0	0	0	0
	1000	0	0	7	0	0	3
	All detected	0	7	743	0	1	69

dramatic impact on the possibility of detecting precursor and probe prompt/early counterpart $\Longrightarrow$ miss the info on GRB engine, jet launch, kilonova ejecta

- joint GW-GRB detections decrease by 40% (10km triangle) or 30% (2L-15km)

- HF-only has a significantly smaller reach in distance





- for BNS: from z≃4 to z≃2 (triangle 10km) or from z≃6 to z≃3 (2L-15km)

Δ10 misses the peak of the star formation rate

- for PBH: impossible to identify them on the basis of z>30

Configuration	$N_{\rm det}(z>10)$ [1/yr]	$N_{\rm det}(z>30)$ [1/yr]	$f_{\rm PBH}^{\rm constrained}$ [$\times 10^{-5}$]
Δ-10km	**1140.01**	**76.81**	**2.61**
Δ-15km	1763.87	260.65	1.42
2L-15km-0°	1596.61	238.16	1.48
2L-15km-45°	1650.87	220.86	1.54
2L-20km-0°	1983.97	433.82	1.10
2L-20km-45°	2080.13	415.80	1.12

Configuration	$N_{\rm det}(z>10)$ [1/yr]	$N_{\rm det}(z>30)$ [1/yr]	$f_{\rm PBH}^{\rm constrained}$ [$\times 10^{-5}$]
Δ-10km-HF	15.47	0.00	-
Δ-15km-HF	84.91	0.00	-
2L-15km-0°-HF	75.08	0.00	-
2L-15km-45°-HF	69.48	0.00	-
2L-20km-0°-HF	177.84	0.00	-
2L-20km-45°-HF	169.81	0.00	-

- IMBH: reduction by a factor ∼ 5 in comoving volume explored

Summary

1. All the triangular and 2L geometries that we have investigated can be the baseline for a superb 3G detector, that will allow us to improve by orders of magnitudes compared to 2G detectors, and allow us to penetrate deeply into unknown territories.

2a. The 2L-15km-45° configuration in general offers better scientific return with respect to the 10 km triangle, improving on most figures of merits and scientific cases, by factors typically of order 2-3 on the errors of the relevant parameters.

2b. The 2L-15km-45° configuration has a scientific output very similar to that of the 15 km triangle

3. A single L-shaped detector is not a viable alternative, independently of arm length. If a single site solution should be preferred for ET, the detector must necessarily have the triangular geometry.

4. The low-frequency sensitivity is crucial for exploiting the full scientific potential of ET. In the HF-only configuration, independently of the geometry chosen, several crucial scientific targets of the science case would be lost or significantly diminished.

5. There are some very interesting targets of the Science Case that depend only on the HF sensitivity, and that could be fully reached with an HF-only instrument.

6. For several important aspects of the Science Case, the 2L with 15 km arms at 45°, already in the HF-only configuration, is comparable the 10 km triangle in a full HFLF-cryo configuration.

Inputs for further studies

- The 2L-15km-45^o appears to give a better possibility of going through staging:

  - commission first HF (already important results will be obtained)

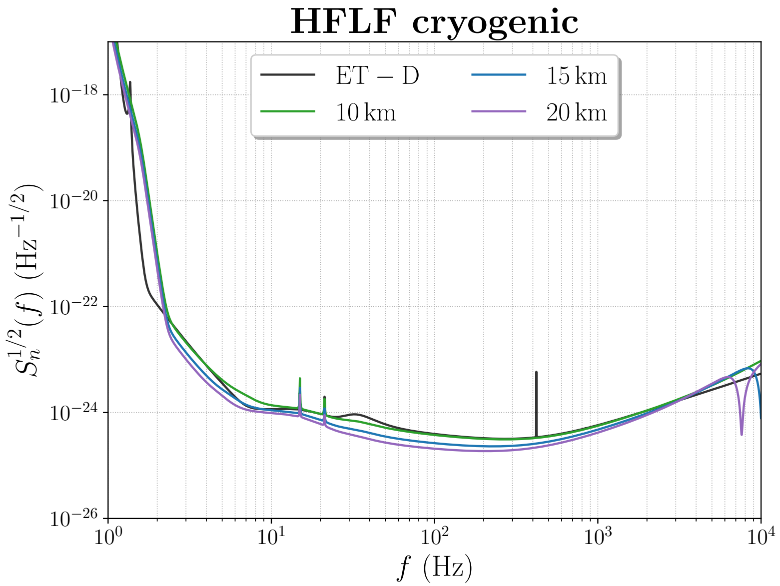
  - move toward full HFLF-cryo sensitivity, maybe through intermediate HFLF-room sensitivity ⟹ input to the ISB

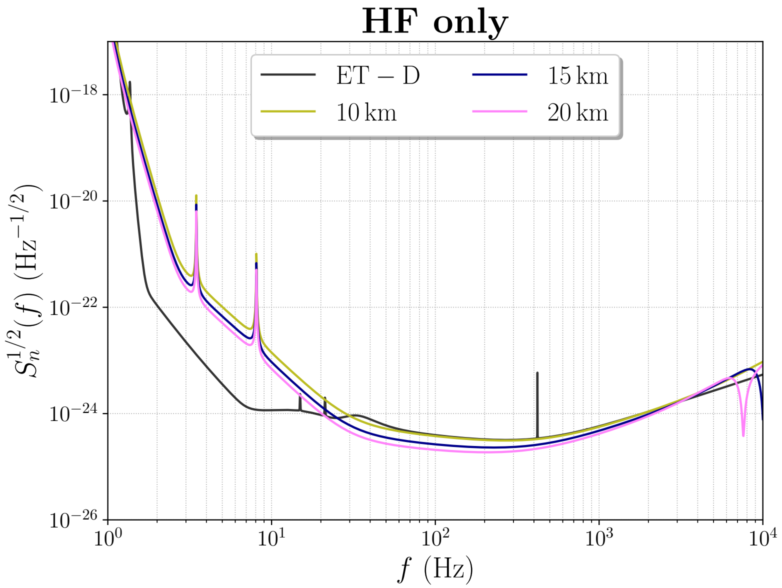
- need a detailed analysis of the costs of different configurations

thanks!

bkup slides

amplitude spectral density (ASD)





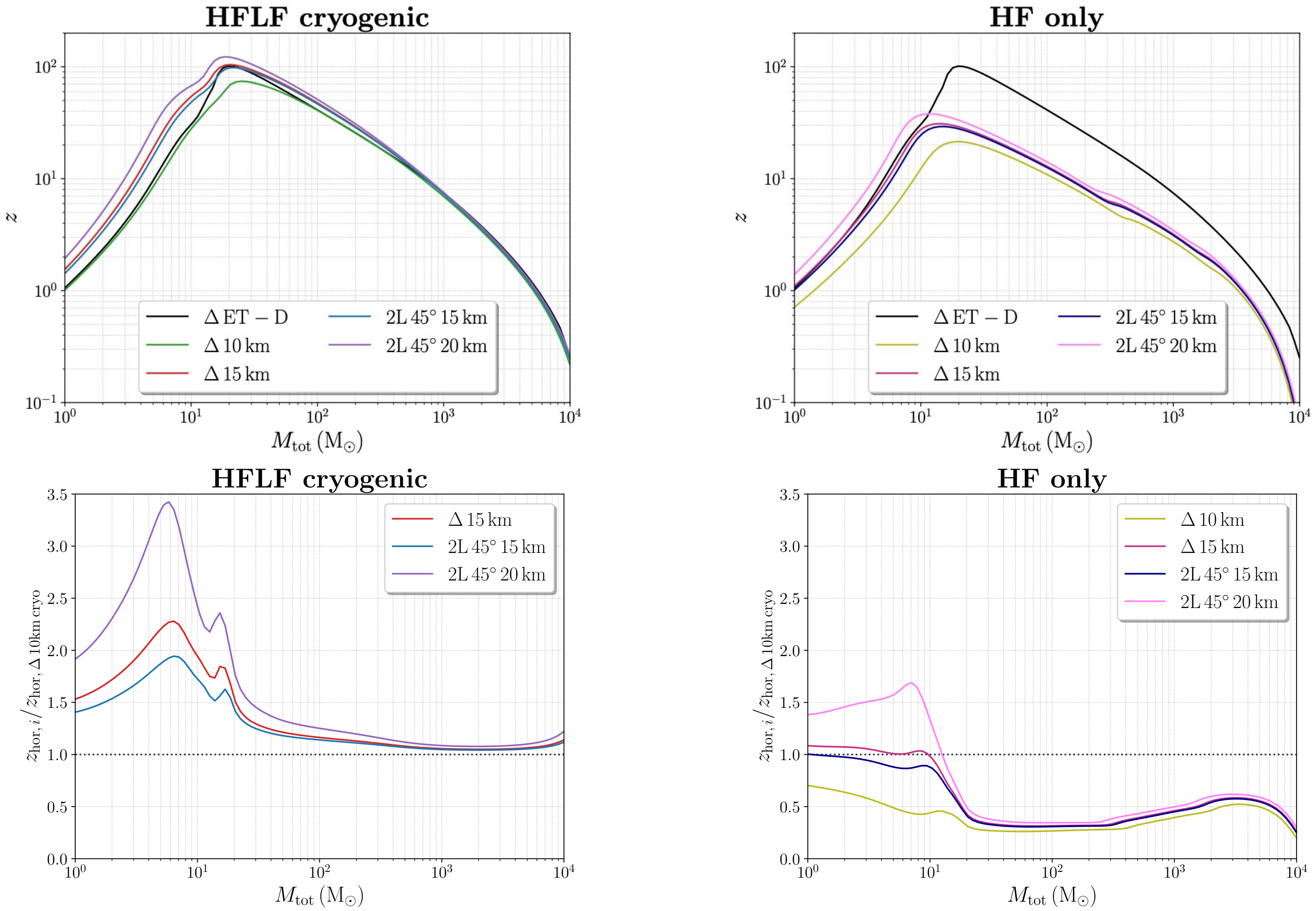
- full HFLF cryo, or HF instrument only

sensitivity curves provided by the ISB

the HFLF cryo curve used updates the ET-D curve.

note: actual curves still evolving

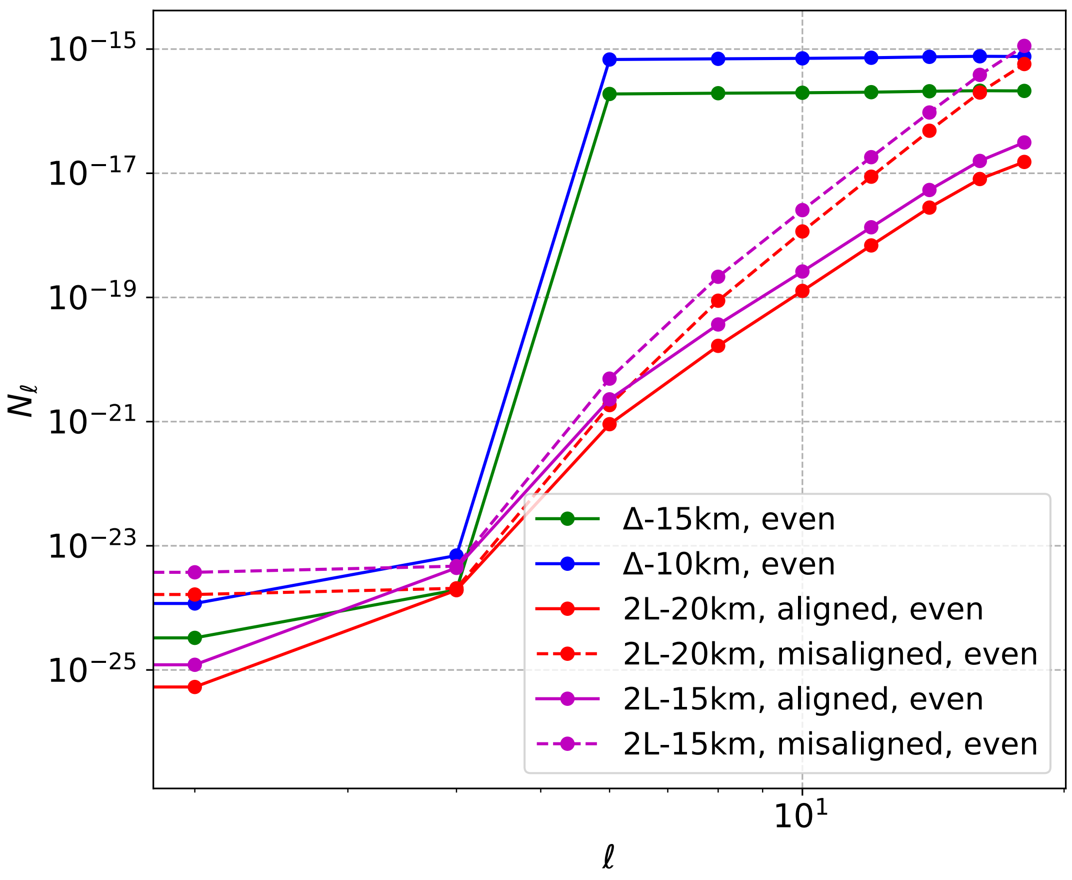
horizon distance for equal mass binaries

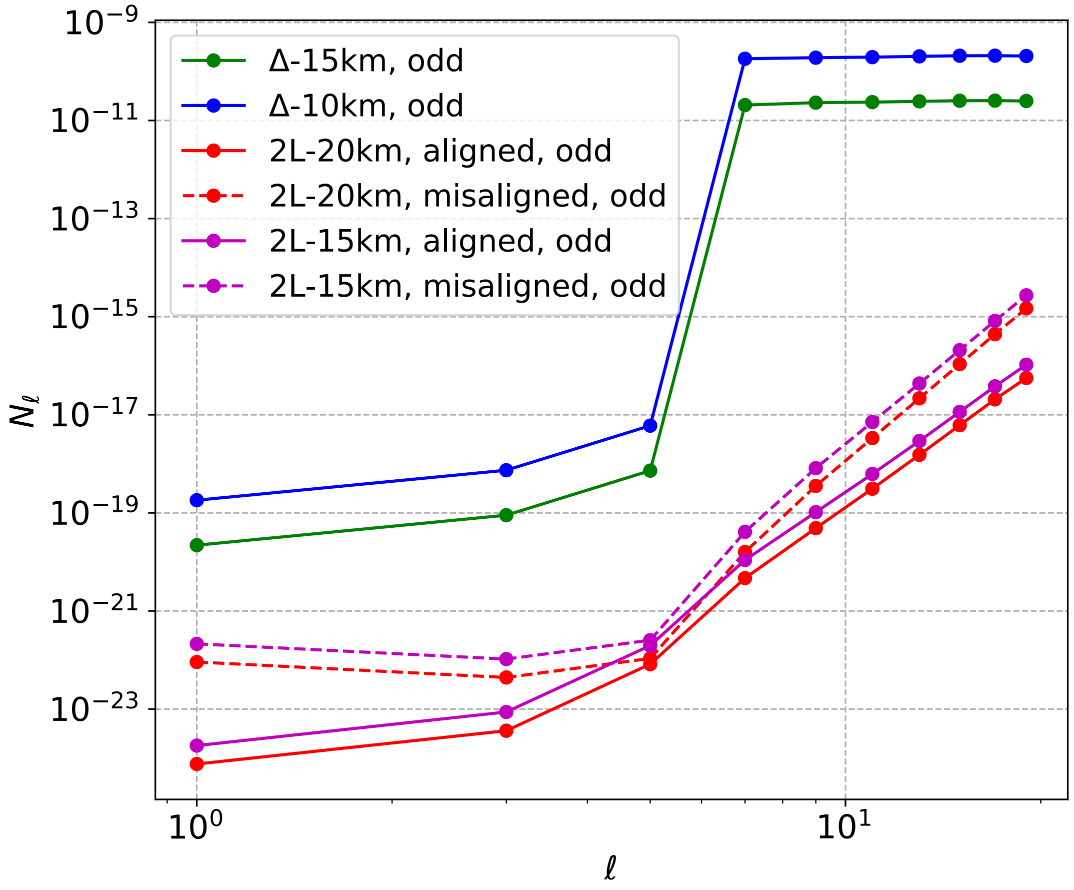


horizon distances

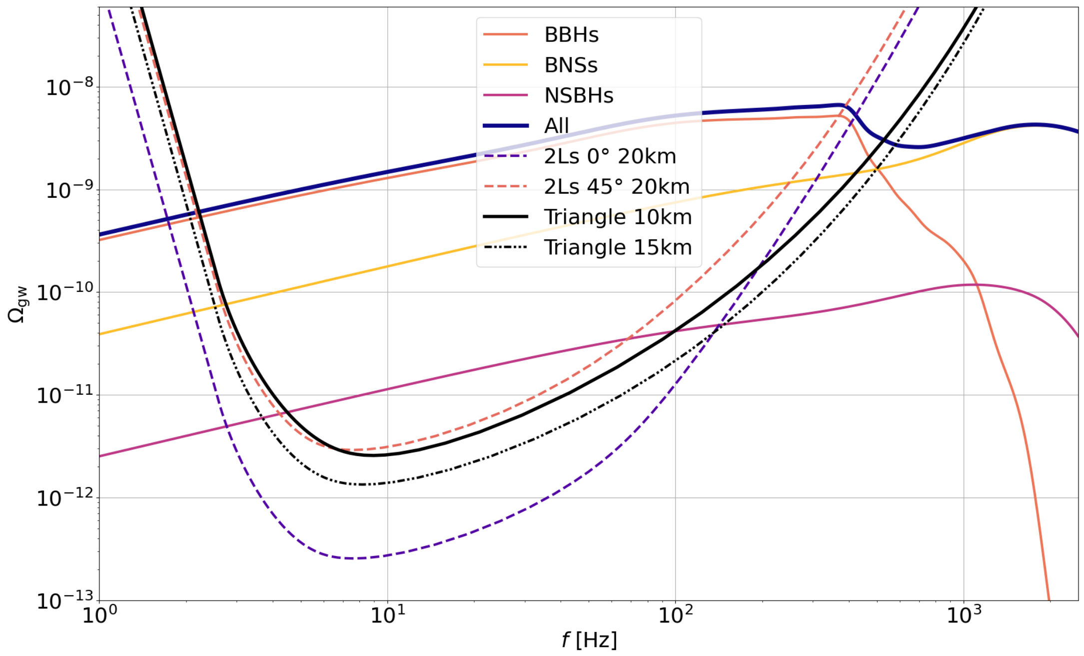
relative differences in horizon, wrt the full (HFLF-cryo) 10km triangle

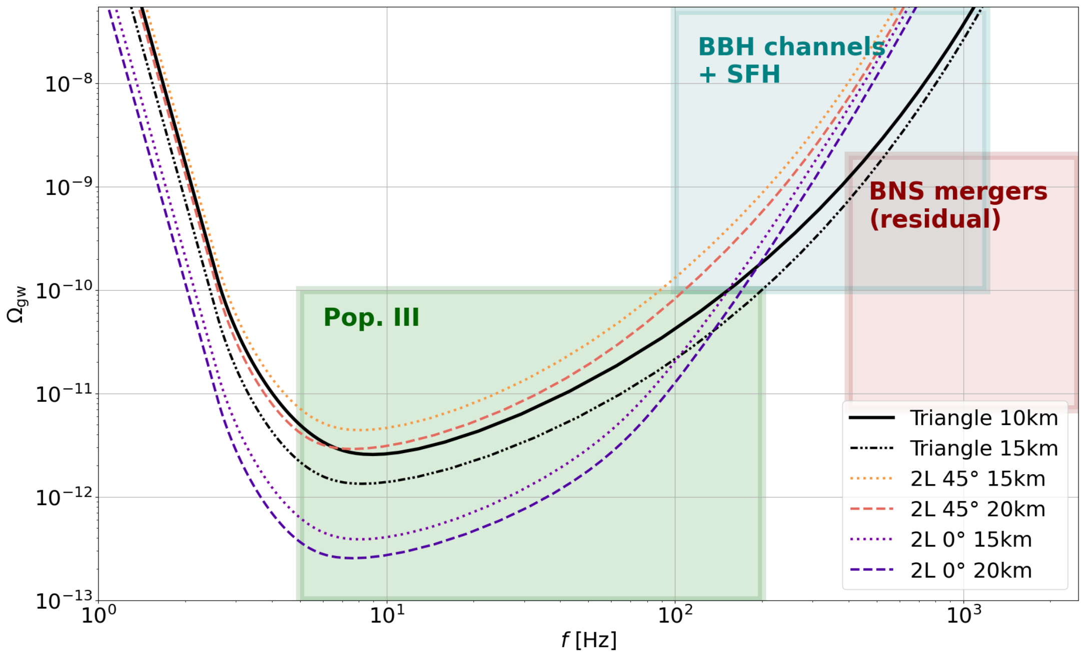
multipole decomposition of the stochastic background





astrophysical signatures in stochastic bkgd





signatures inprinted in deviations from $f^{2/3}$

The role of the Null Stream

- some qualifications on the use of the null stream:

coherent inference with the three interferometers already uses all the information.
The null stream cannot be used to further lower the SNR detection threshold
(it is just a change of basis)

the issue can actually be more complicated since the detection threshold depends on the FAR, the SNR is only a proxy.

- having 3 ifos should allow to lower the FAR, compared to 2L
- on the other hand, the ifos are colocated: glitches in different ifos can then have a common cause and similar morphology, and evade the null stream veto

- null stream removes the non-Gaussian component of the background However, the current non-Gaussian background in LIGO-Virgo is small. ET might have a different non-Gaussian background, but there is no way to know its contribution before ET is operational

- null stream only relevant when all three interferometers are up
  - if we assume independent duty cycle of 80%, this means 51% of the time
  - if we take all 6 instruments with independent duty cycle, becomes 26%

the (established) virtues of the null stream

- estimation of the noise, unbiased by the confusion noise from unresolved GW signals

it assumes that noise are incoherent among detectors. Then,

$$d_{null}=d_1+d_2+d_3 \quad \Rightarrow \quad S_{n,i} = \langle d_{null} , d_i^{*} \rangle$$

caveat:

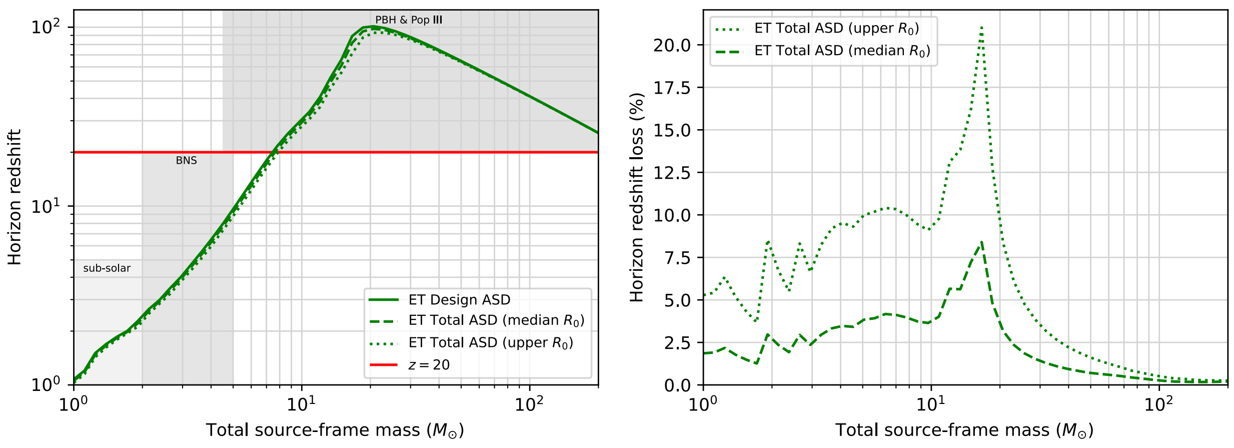
there can be coherent noise: eg lightning, magnetic noise, seismic gravity fluctuations (however, the problem is possibly mitigated by witness sensors)

benefits of an unbaised noise estimate:

1. stochastic backgrounds

caveat: the dominant error might come from imperfect subtraction of resolvable astrophysical signals

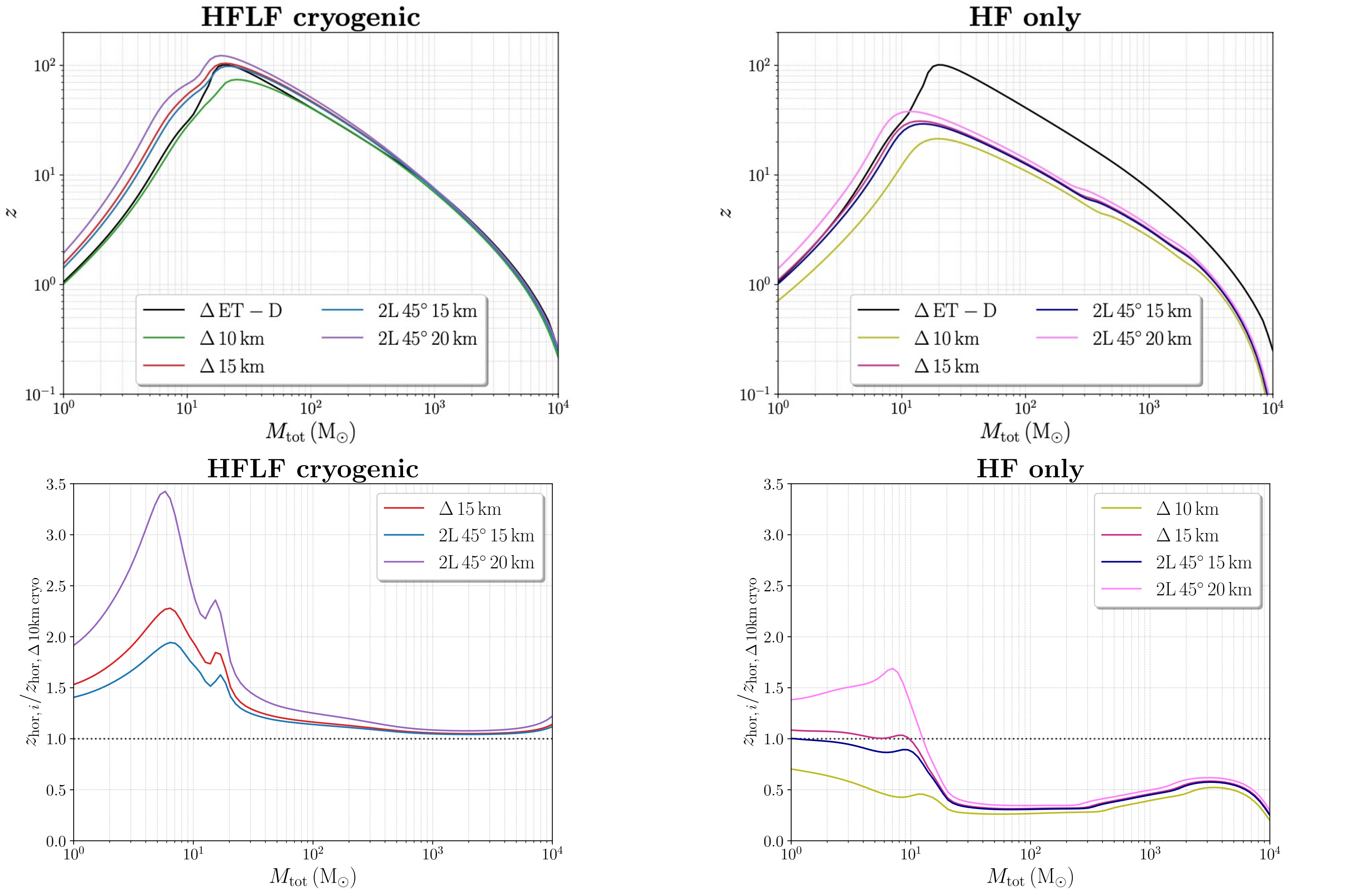
2. for CBC, biased estimate of the noise produces loss of matched filtering SNR



increase the horizon by (2-5)%

Note however that 2L15km increase the horizon, with respect to Δ-10km, by (50-150)%

horizon distance for equal mass binaries



horizon distances

relative differences in horizon, wrt the full (HFLF-cryo) 10km triangle

3. Mitigation of transient detector glitches

glitches appear as non-Gaussian outliers in the null stream. It is possible to eliminate them and end up with a clean Gaussian background, in the limit where the 3 ET components have exactly the same sensitivity

⇒ benefit for high-mass BBH and unmodeled bursts

4. Improvement in calibration errors

my take on this part: null stream very valuable if we have a triangle, but there are many caveats, and is not a golden bullet