Cost-Benefit Analysis Team (CoBA)
Cortona Meeting, November 24-26 2021

SCIENCE IMPACT FOR DIFFERENT MACRO-OPTIONS and GEOMETRY of ET

M. Branchesi on behalf of OSB

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S. Bagnasco, F. Legger, S. Vallero **et al.** (DIV3, DIV4, DIV6,DIV9)

Methodology to compare different scenarios

We evaluate the impact of the different ET macro-options and geometry using **basic metrics and different science cases:**

- **Population** of binary neutron stars (BNSs) and binary black holes (BBHs) → detection efficiency, SNR ditribution, and sky-localization capabilities for populations;
- **Primordial BH**
- **Horizon IMBH;**
- **NS physics;**
- **Stochastic background detection capabilities;**
- **Cosmology** (Michele's talk);
- **Modified gravity** (Michele's talk).

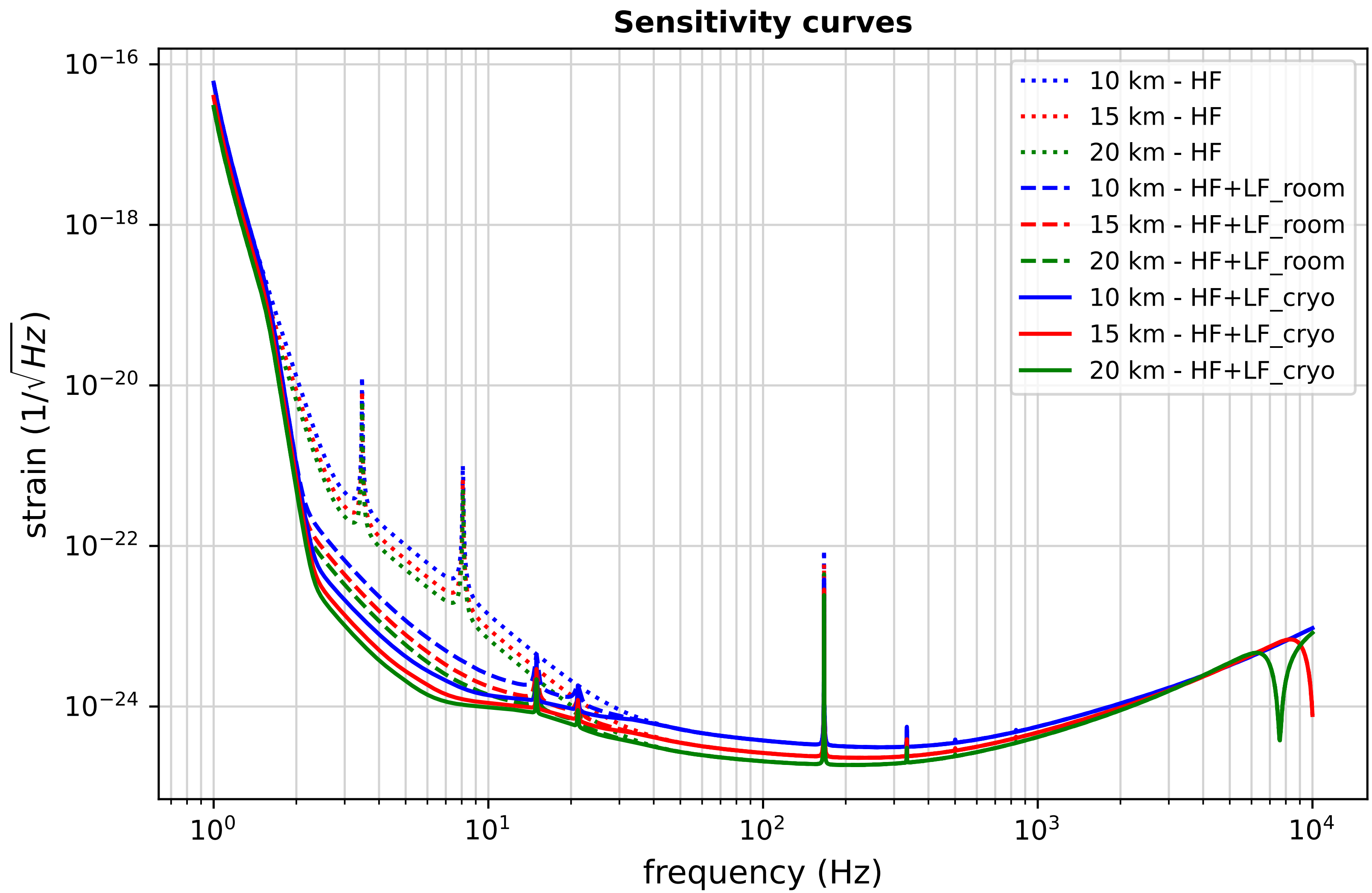
DIFFERENT MACRO-OPTIONS and GEOMETRY

Configuration	A) ET-HF	B) ET-LF cryo	C) ET –LF room temperature
ET Triangle 10 km arm (Design Study)			
ET Triangle 15 km arm			
Single L (HF) 15 km			
Single L (HF) 20 km			
Xylophone (HF+LF) 15 km			
Xylophone (HF+LF) 20 km			

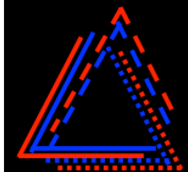
6 simulations for ET triangle
6 simulations for 2L **x 2** (aligned and misaligned of 45 deg)

+ we add also 6 simulation for 2L 10 km
9 simulation with CE 40 km

SENSITIVITY CURVES

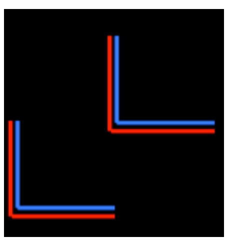


Triangle vs 2L network

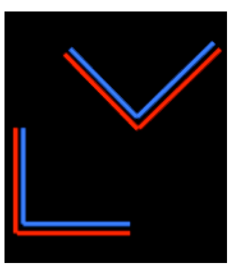


Two scenarios
- D of 10 km
- D of 15 km

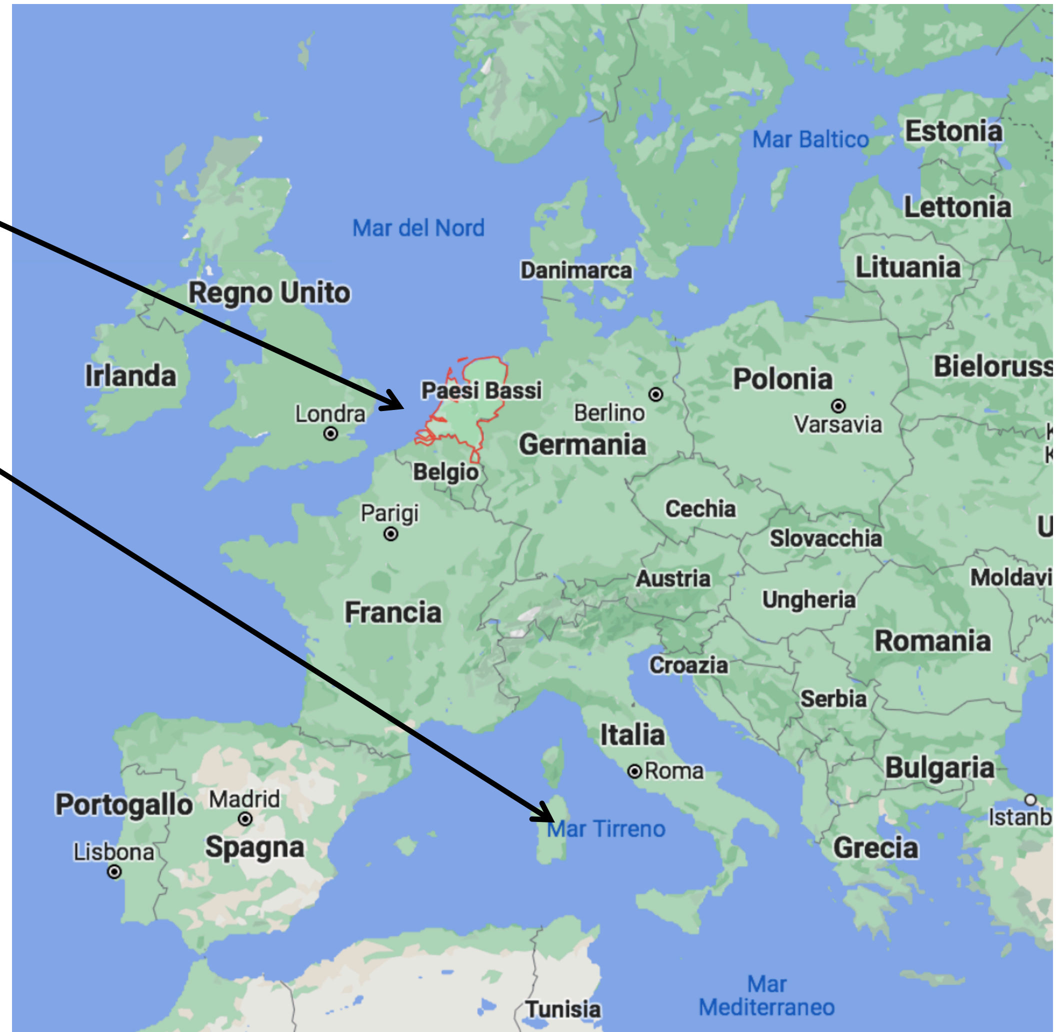
Three scenarios
- 2L of 10 km
- 2L of 15 km
- 2L of 20 km



2L aligned



2L misaligned of 45º



BNS and BBH population results

B.Banerjee, U.Dupletsa, M. Branchesi, J. Harms et al.

Simulation Methodology

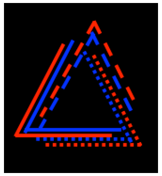
- Fisher matrix approach

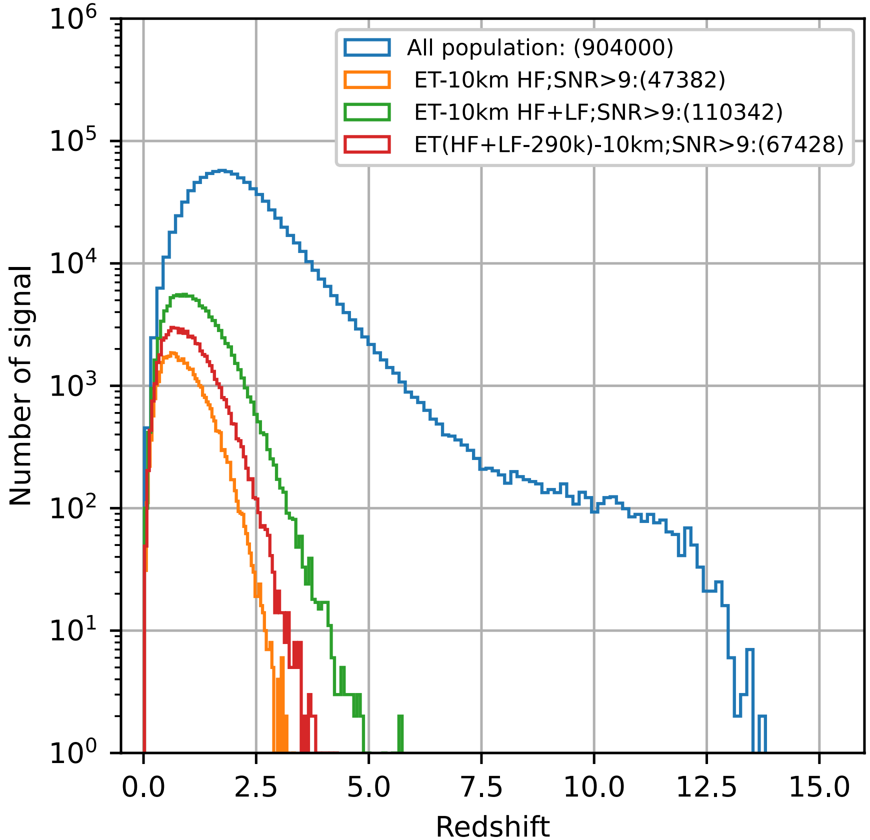
- **Astrophysical assumptions** (consistent with O3 LIGO and Virgo observations − GWTC-3):
  - BNS: rate distribution as function of z from last updates of Santoliquido et al. 2021, MNRAS (from M. Mapelli), **uniform mass distribution [1.0- 2.5] Msun**, no spin
  - BBH: rate distribution as function of z from (Regimbau et al. 2017, SF from Vangioni et al. 2015), **broken power-law mass distribution** consistent with O3a LIGO and Virgo observations (GWTC-2)

- For the injections we use TAYLORF2 waveforms

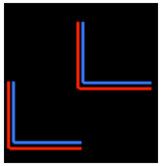
- 904000 BNS injections over the entire redshift range to determine the detection efficiency of each scenarios and 53000 injections for sky-localization $z < 0.8$

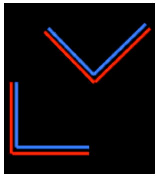
BNS: triangle (10 km)/2L(10 km)
HF, HF+LF_room, HF+LF_cryo



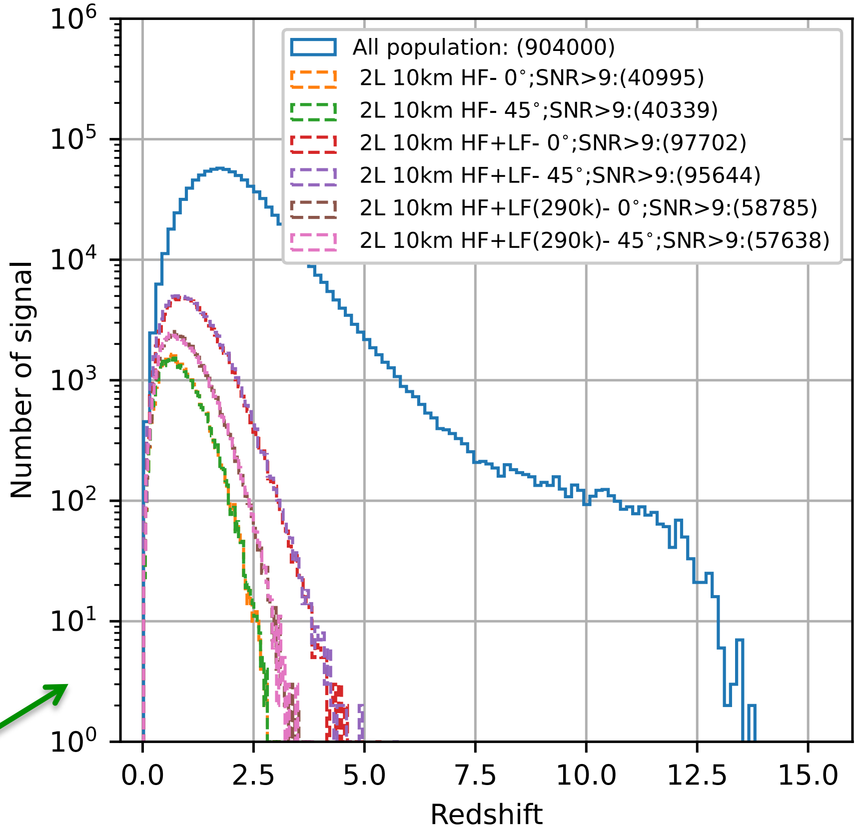


Detection efficiency





SNR > 9

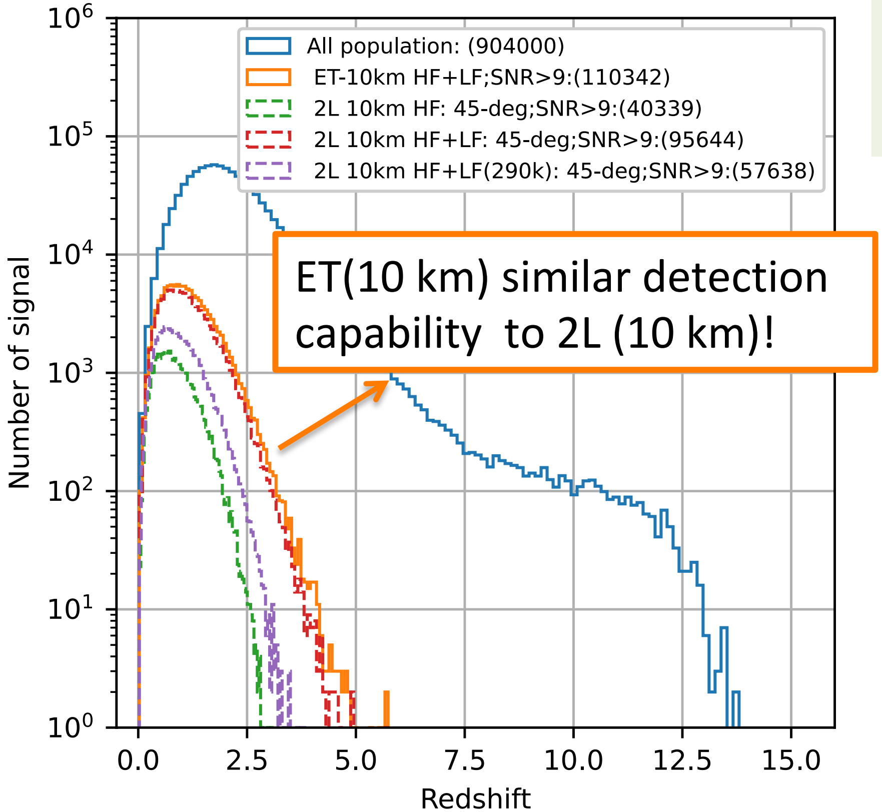


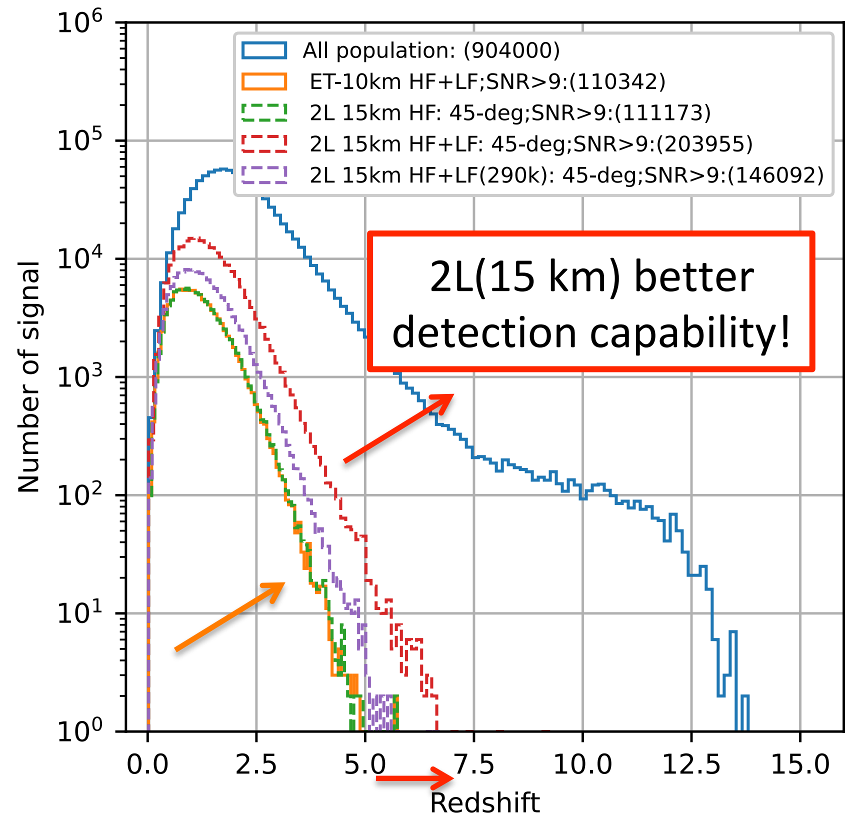
Detection efficiency → aligned and misaligned almost the same results!

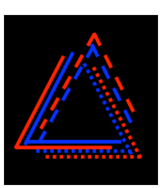
BNS: triangle (10 km), 2L(10 km), 2L(15 km) HF, HF+LF_room, HF+LF_cryo

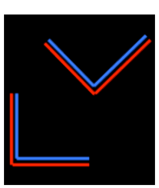
Detection efficiency

SNR > 9







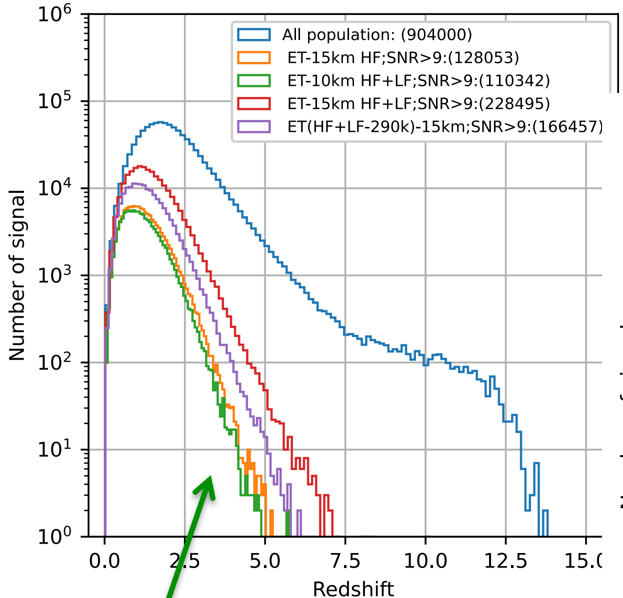


BNS: Triangle (15 km), 2L (10 km), 2L (15 km), 2L (20 km)

Detection efficiency

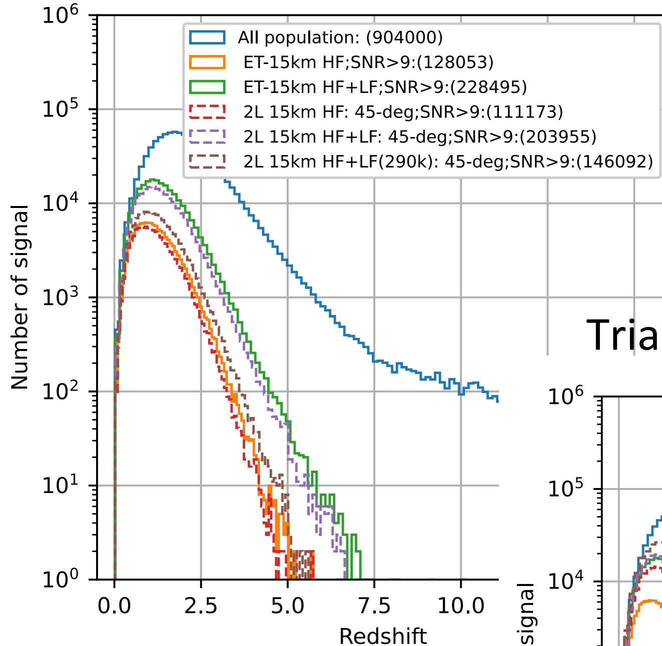
SNR > 9

Triangle (15 km) vs Triangle (10 km)



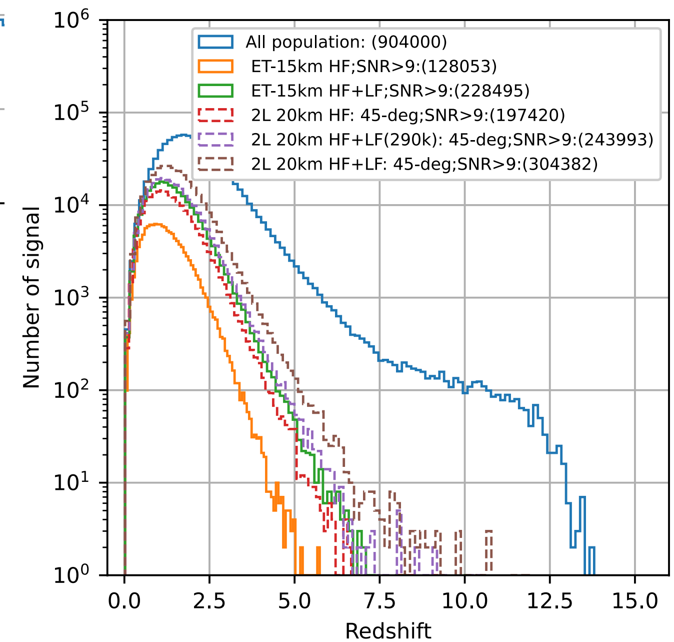
Detection efficiency
→ET(15) HF similar to
ET(10 km) HF+LF_cryo

Triangle (15 km) vs 2L (15 km)

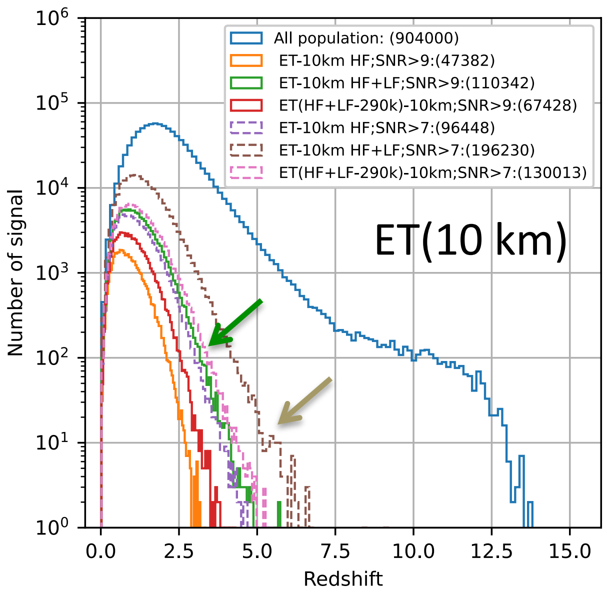


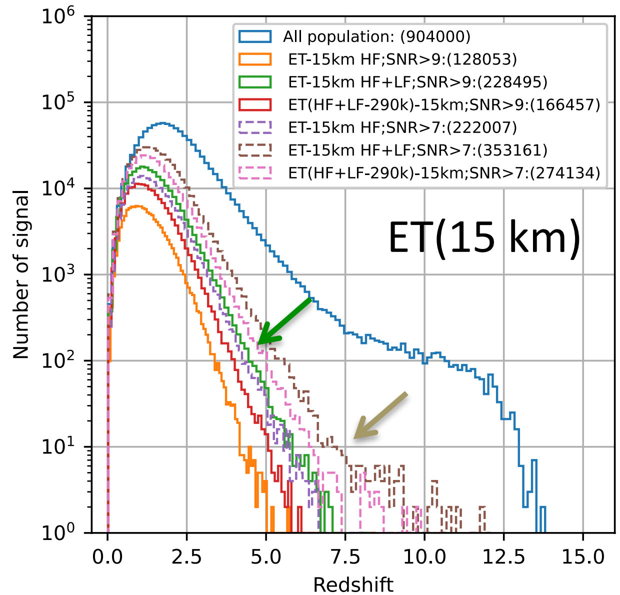
2L(20 km) better
detection capability!

Triangle (15 km) vs 2L (20 km)



BNS detection capability considering null stream veto

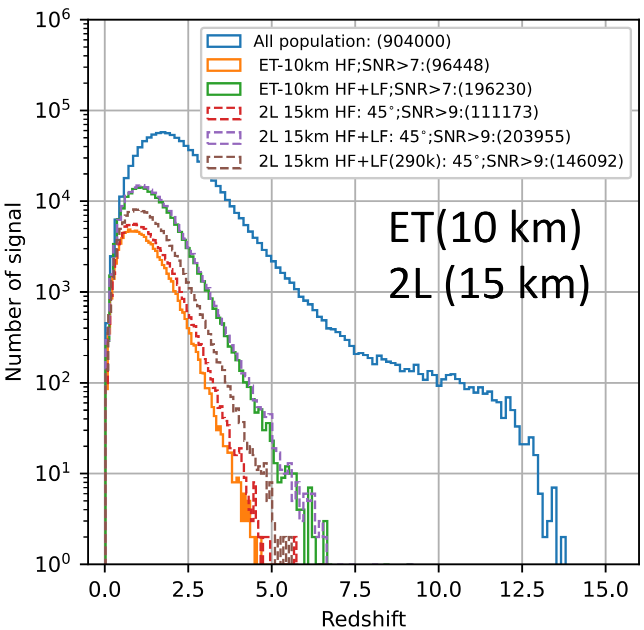


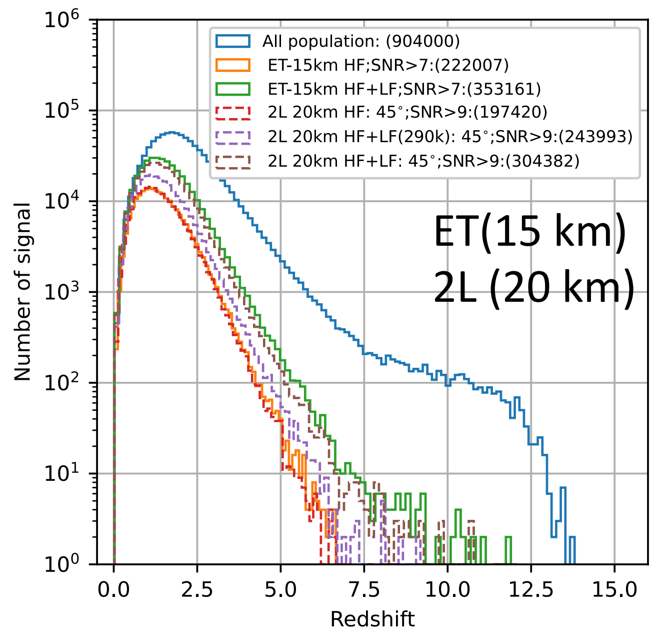


Detection efficiency

SNR > 9

SNR > 7 null stream veto





- ET(10 km) null stream veto similar to 2L(15 km)
- ET(15 km) null stream veto similar to 2L(20 km)

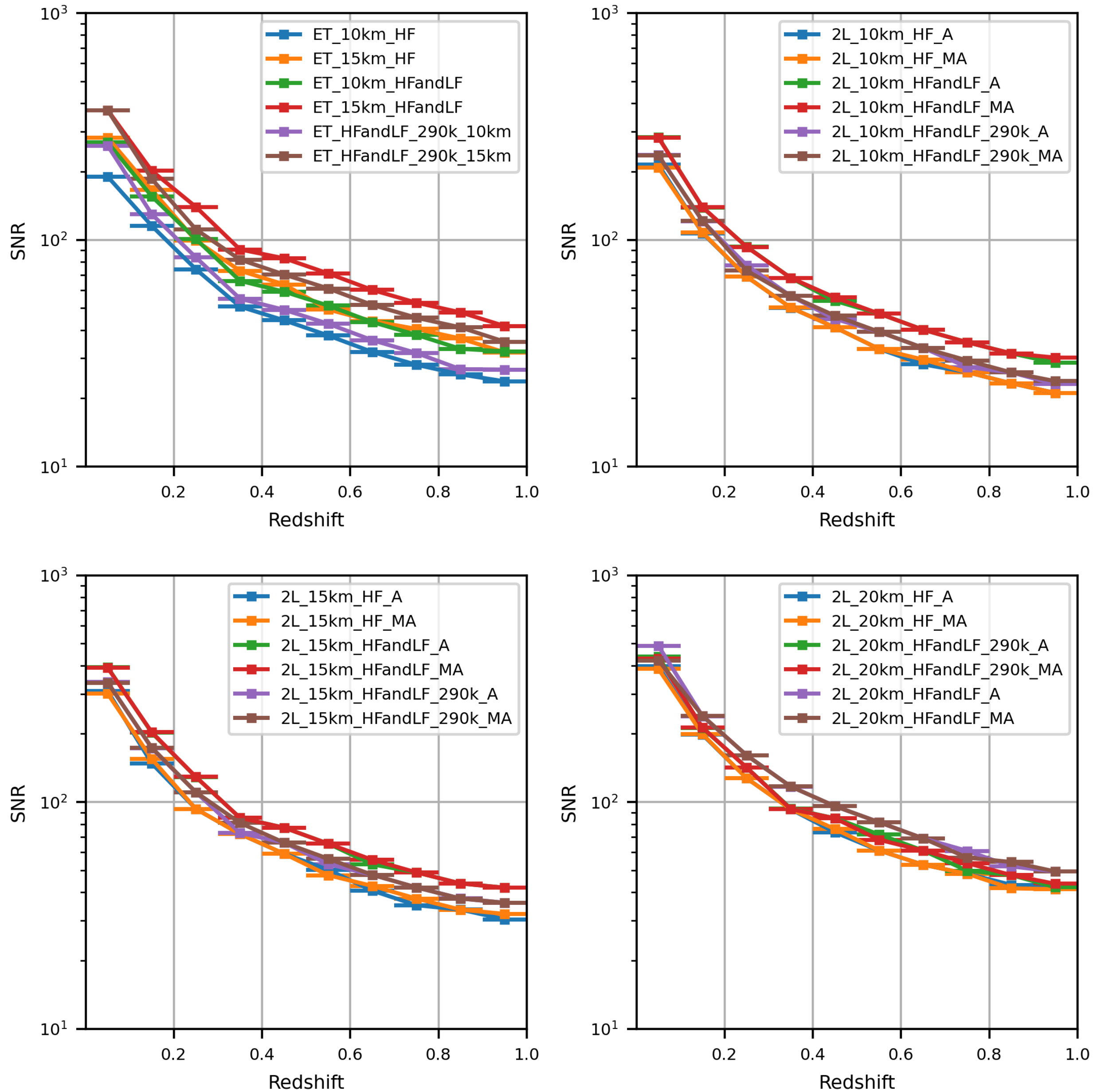
SNR > 9, merger rate per year $9x10^5$

Scenario	Detections per year HF	Detections per year HF+LF_room	Detections per year HF+LF_cryo
TRIANGLE (10 km)	47382	67428	110342
TRIANGLE (15 km)	128053	166457	228495
2L(10 km) aligned	40995	58785	97702
2L(10 km) misaligned	40339	58638	95644
2L(15 km) aligned	113502	149097	207355
2L(15 km) misaligned	111173	146092	203955
2L(20 km) aligned	200904	247299	305518
2L(20 km) misaligned	197420	243993	304382

SNR > 9, SNR>7 null stream veto, merger rate per year 9x10^5

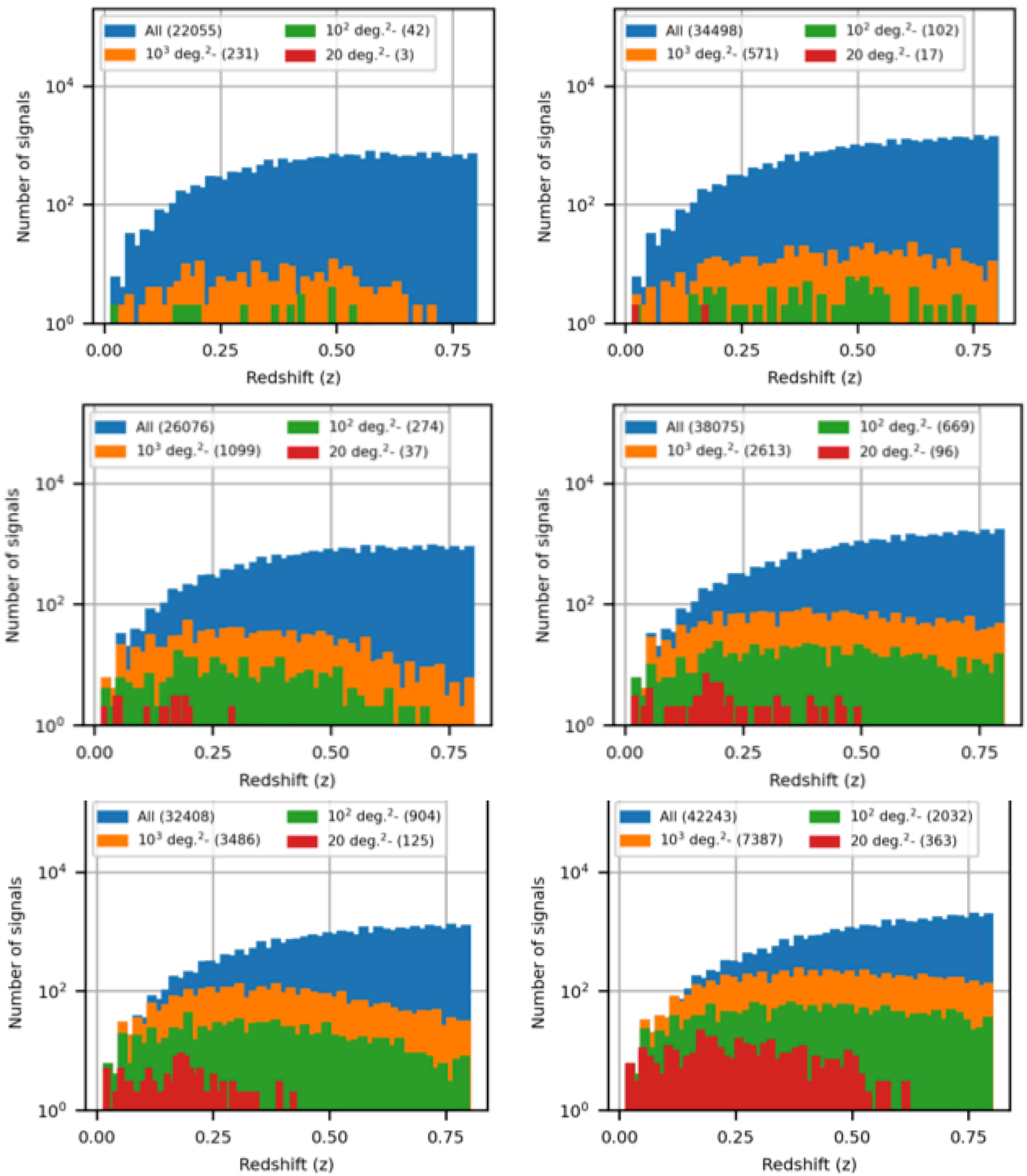
Scenario	Detections per year HF	Detections per year HF+LF_room	Detections per year HF+LF_cryo
TRIANGLE (10 km) SNR>7	47382 96448	67428 130013	110342 196230
TRIANGLE (15 km) SNR>7	128053 222007	166457 274131	228495 353161
2L(10 km) aligned	40995	58785	97702
2L(10 km) misaligned	40339	58638	95644
2L(15 km) aligned	113502	149097	207355
2L(15 km) misaligned	111173	146092	203955
2L(20 km) aligned	200904	247299	305518
2L(20 km) misaligned	197420	243993	304382

BNS SNR


ET_10km_HF
ET_15km_HF
ET_10km_HFandLF
ET_15km_HFandLF
ET_HFandLF_290k_10km
ET_HFandLF_290k_15km
2L_10km_HF_A
2L_10km_HF_MA
2L_10km_HFandLF_A
2L_10km_HFandLF_MA
2L_10km_HFandLF_290k_A
2L_10km_HFandLF_290k_MA
2L_15km_HF_A
2L_15km_HF_MA
2L_15km_HFandLF_A
2L_15km_HFandLF_MA
2L_15km_HFandLF_290k_A
2L_15km_HFandLF_290k_MA
2L_20km_HF_A
2L_20km_HF_MA
2L_20km_HFandLF_290k_A
2L_20km_HFandLF_290k_MA
2L_20km_HFandLF_A
2L_20km_HFandLF_MA
SNR
Redshift
10^1
10^2
10^3
0.2
0.4
0.6
0.8
1.0

BNS localization

Triangle(10 km) **Triangle(15 km)**



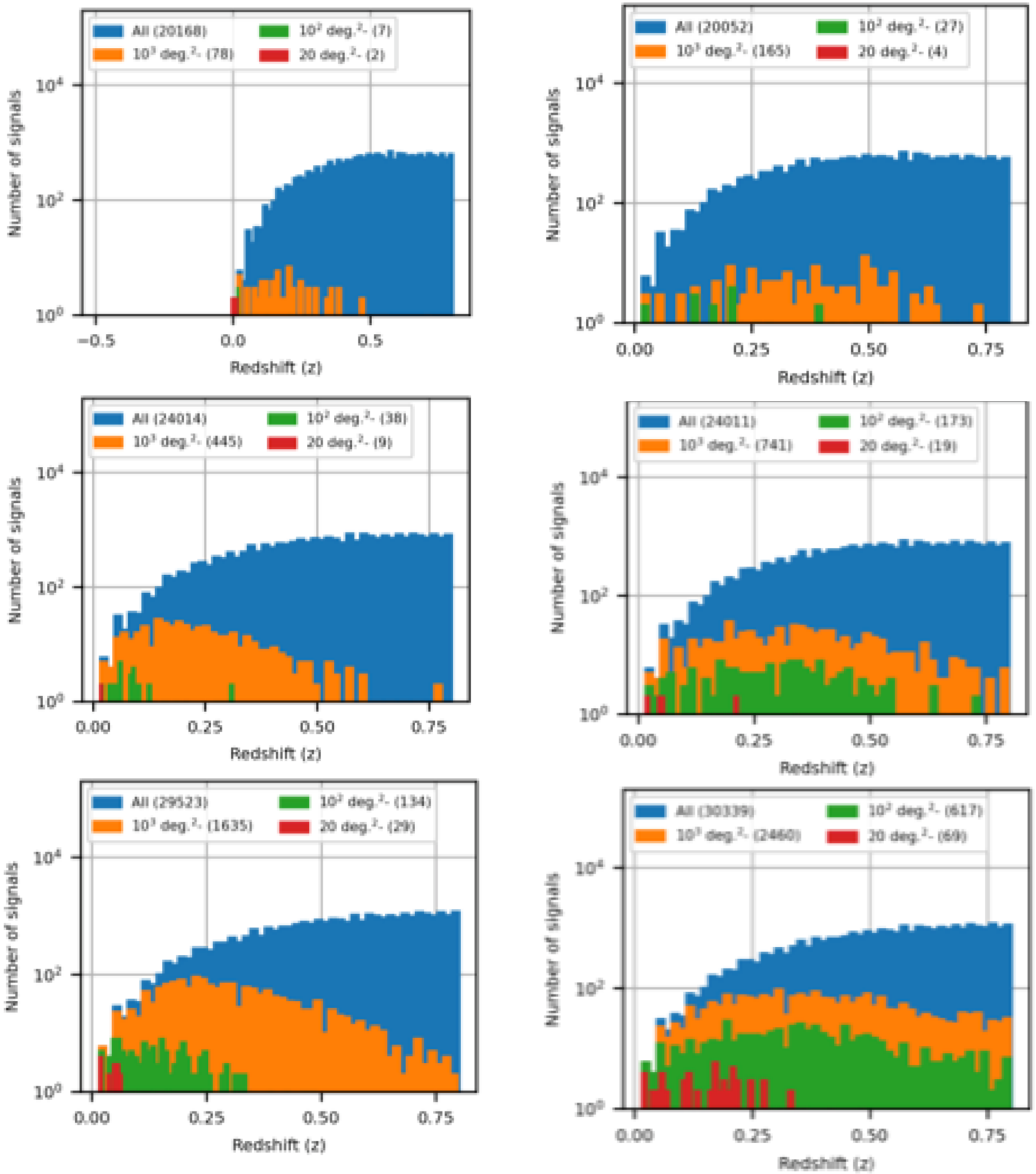
HF

HF+LF_room

HF+LF_cryo

BNS localization

2L(10 km) aligned | **2L (10 km) misaligned**



HF

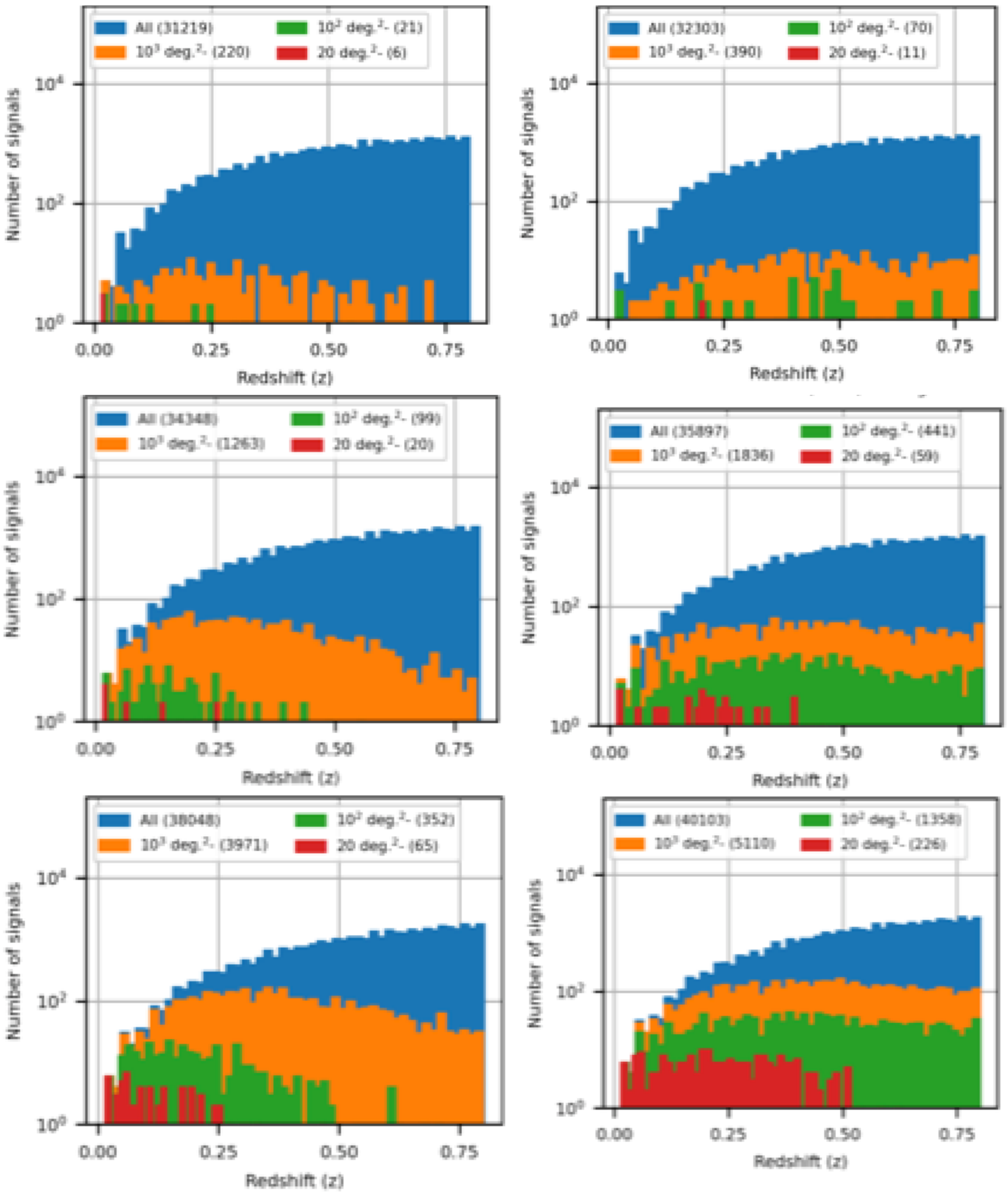
HF+LF_room

HF+LF_cryo

Misaligned better!
ET(10 km) better than 2L (10 km)!

BNS localization

2L(15 km) aligned **2L (15 km) misaligned**



HF

HF+LF_room

HF+LF_cryo

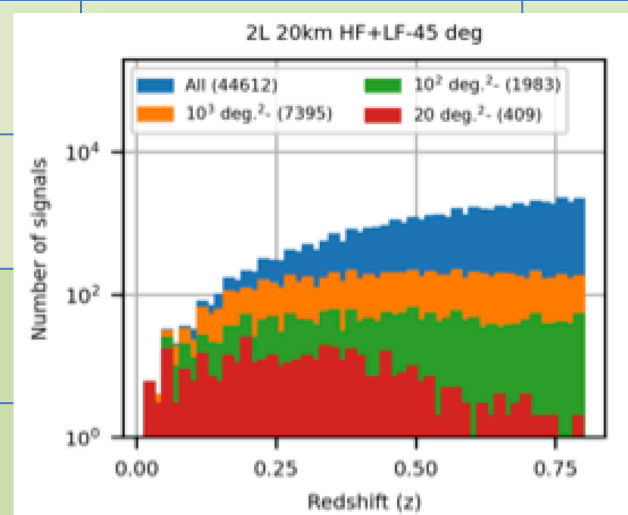
Misaligned better!
2L misaligned (15 km) is better than ET (10 km)!

SNR > 9, sky-localization < 20 deg^2, sky-localization <100 deg^2

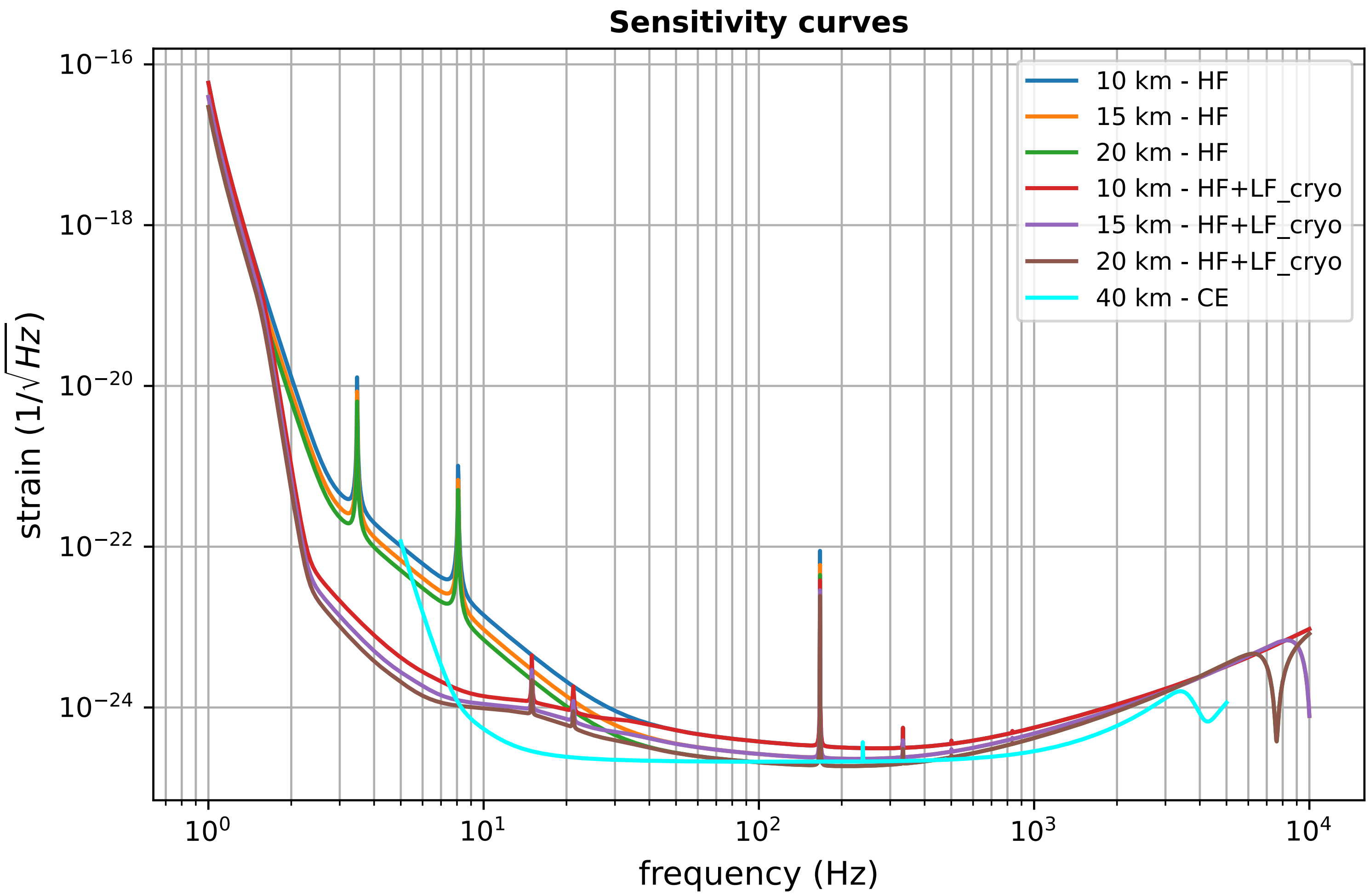
Scenario	Detections per year HF	Detections per year HF+LF_room	Detections per year HF+LF_cryo
TRIANGLE (10 km)	**3** 42	**37** 274	**125** 904
TRIANGLE (15 km)	**17** 102	**96** 669	**363** 2032
2L(10 km) aligned	**2** 7	**9** 38	**29** 134
2L(10 km) misaligned	**4** 27	**19** 173	**69** 117
2L(15 km) aligned	**6** 21	**20** 99	**65** 352
2L(15 km) misaligned	**11** 70	**59** 441	**226** 1358
2L(20 km) aligned	**10** 38	**36** 204	**117** 676
2L(20 km) misaligned	**15** 124	**137** 717	**409** 1983

SNR > 9, sky-localization < 20 deg^2, sky-localization <100 deg^2

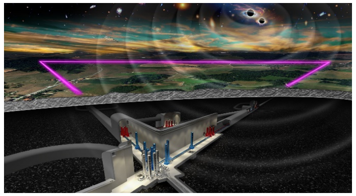
Scenario	Detections per year HF	Detections per year HF+LF_room	Detections per year HF+LF_cryo
TRIANGLE (10 km)	3 42	37 274	125 904
TRIANGLE (15 km)	17 102	96 669	363 2032
2L(10 km) aligned	2 7	9 38	29 134
2L(10 km) misaligned	4 27	19 173	69 117
2L(15 km) aligned	6 21		65 352
2L(15 km) misaligned	11 70		226 1358
2L(20 km) aligned	10 38		117 676
2L(20 km) misaligned	15 124		409 1983

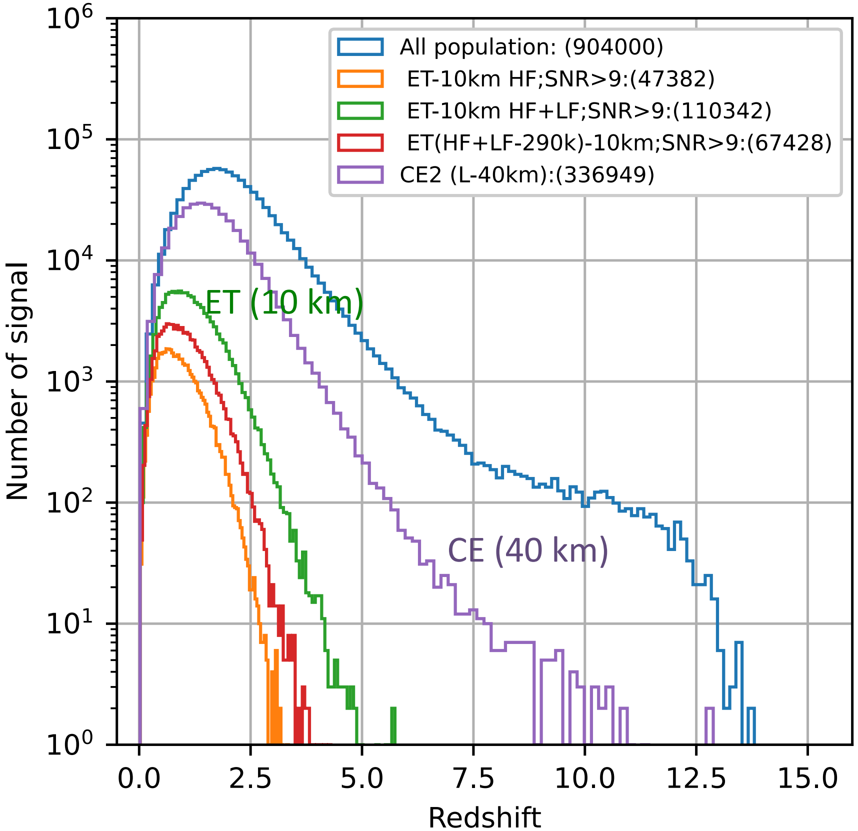


ET in the international context, ET+CE(40km)

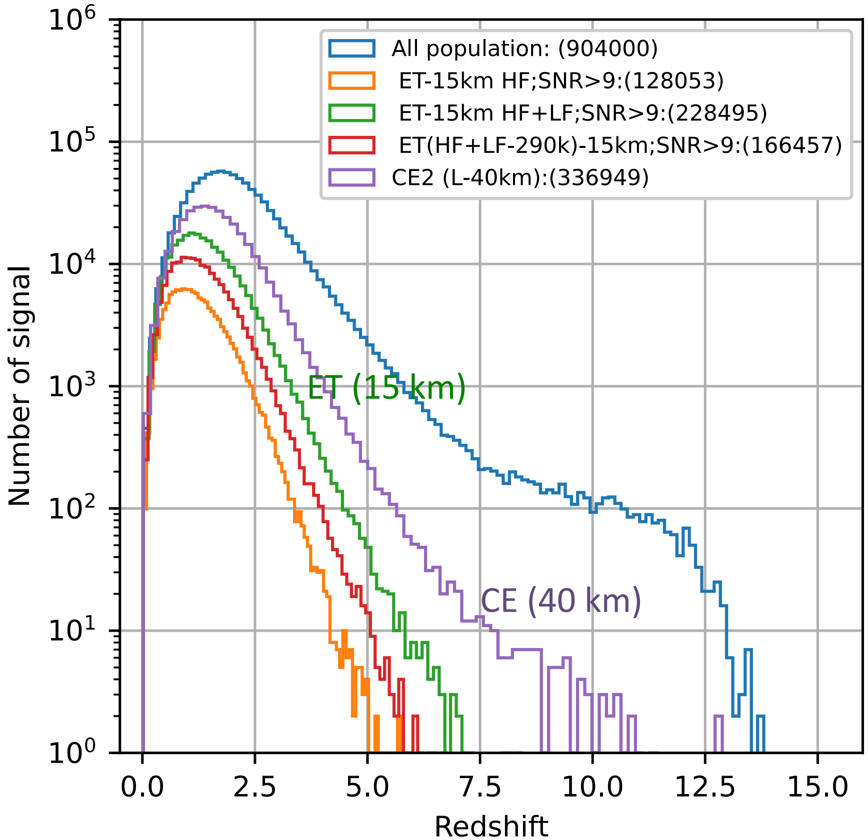


ET+CE(40km)



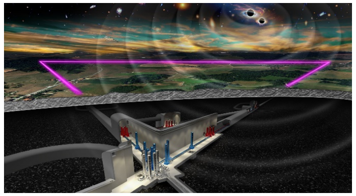


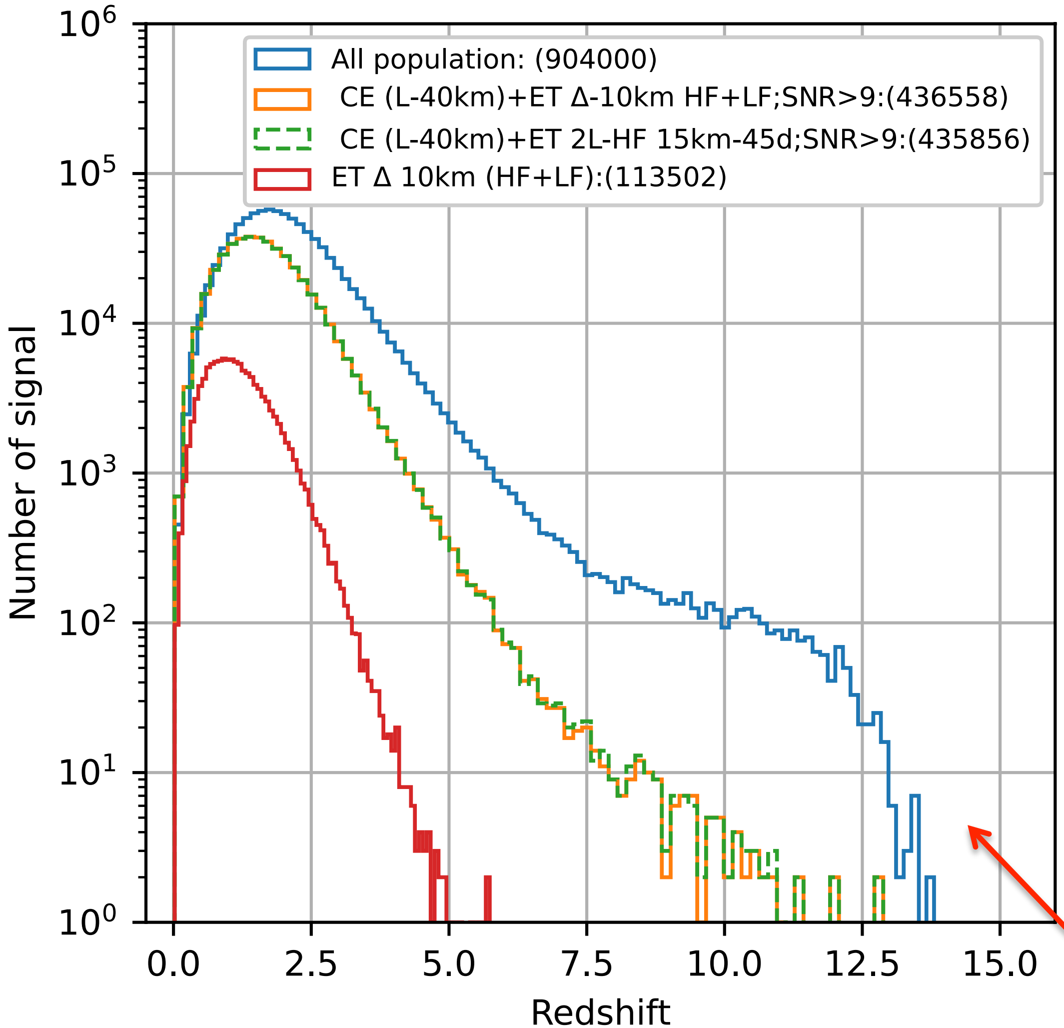
Number of signal
Redshift
All population: (904000)
ET-10km HF;SNR>9:(47382)
ET-10km HF+LF;SNR>9:(110342)
ET(HF+LF-290k)-10km;SNR>9:(67428)
CE2 (L-40km):(336949)
ET (10 km)
CE (40 km)



Number of signal
Redshift
All population: (904000)
ET-15km HF;SNR>9:(128053)
ET-15km HF+LF;SNR>9:(228495)
ET(HF+LF-290k)-15km;SNR>9:(166457)
CE2 (L-40km):(336949)
ET (15 km)
CE (40 km)

ET+CE(40km)



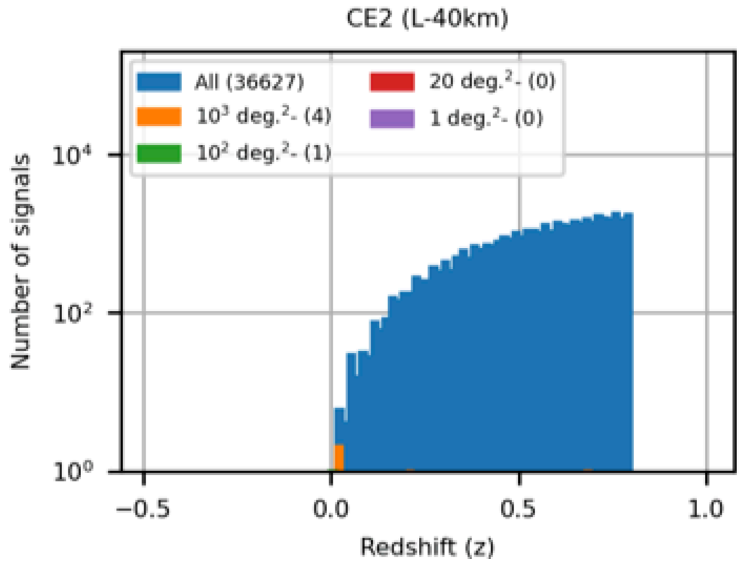


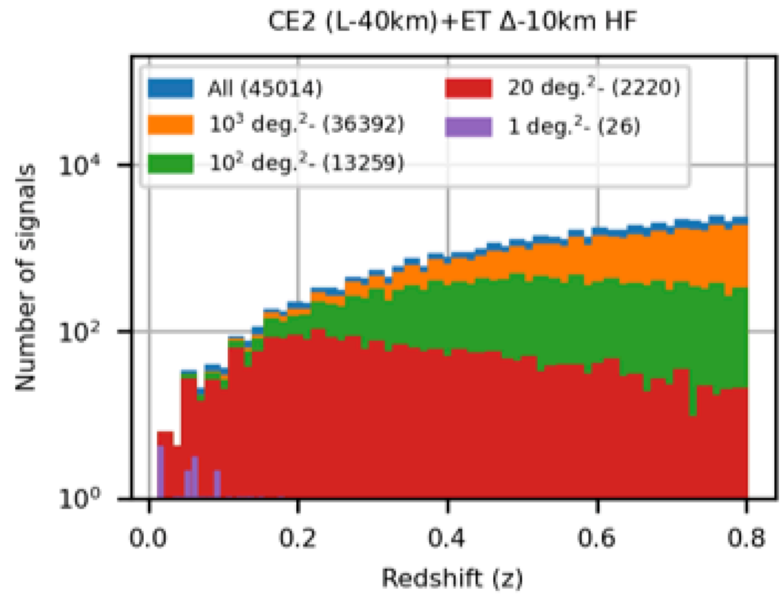
CE+ET(10 km) LF+HF_cryo similar to CE+2L(15 km) HF

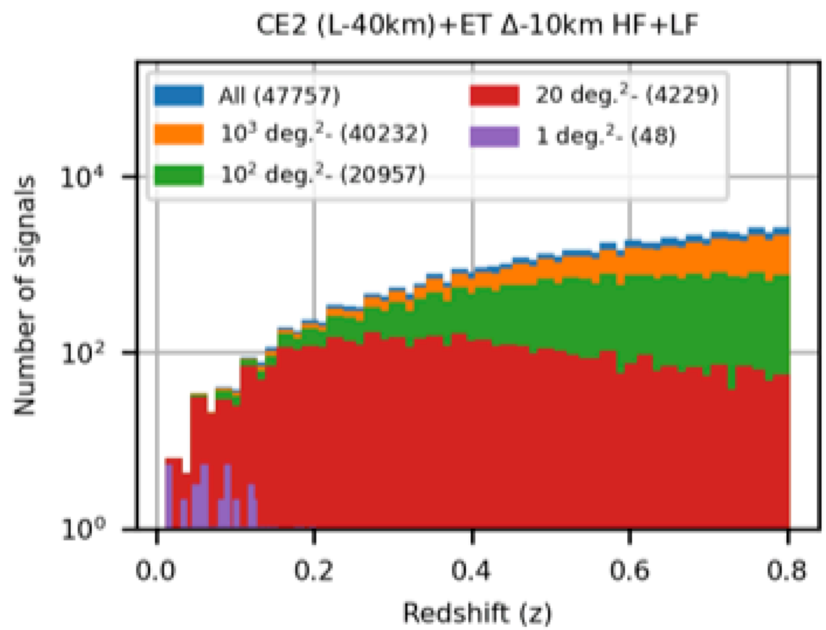
ET in the international context, ET+CE(40km)

Scenario	Detections per year SNR>9		
CE(40 km)	336949		
TRIANGLE (10 km) HF+CE(40 km)	392295		
TRIANGLE (10 km) HFLF_cryo+CE(40 km)	436558		
TRIANGLE (15 km) HF+CE(40 km)	448363		
TRIANGLE (15 km) HF+LF_cryo+CE(40 km)	510519		
2L(15 km)+CE (40 km) HF misaligned	435856		
2L(15 km)+CE (40 km) HF+LF_cryo misaligned	492885		
2L(20 km)+CE (40 km) HF misaligned	488974		
2L(20km)+CE (40 km) HF+LF_cryo misaligned	552415		

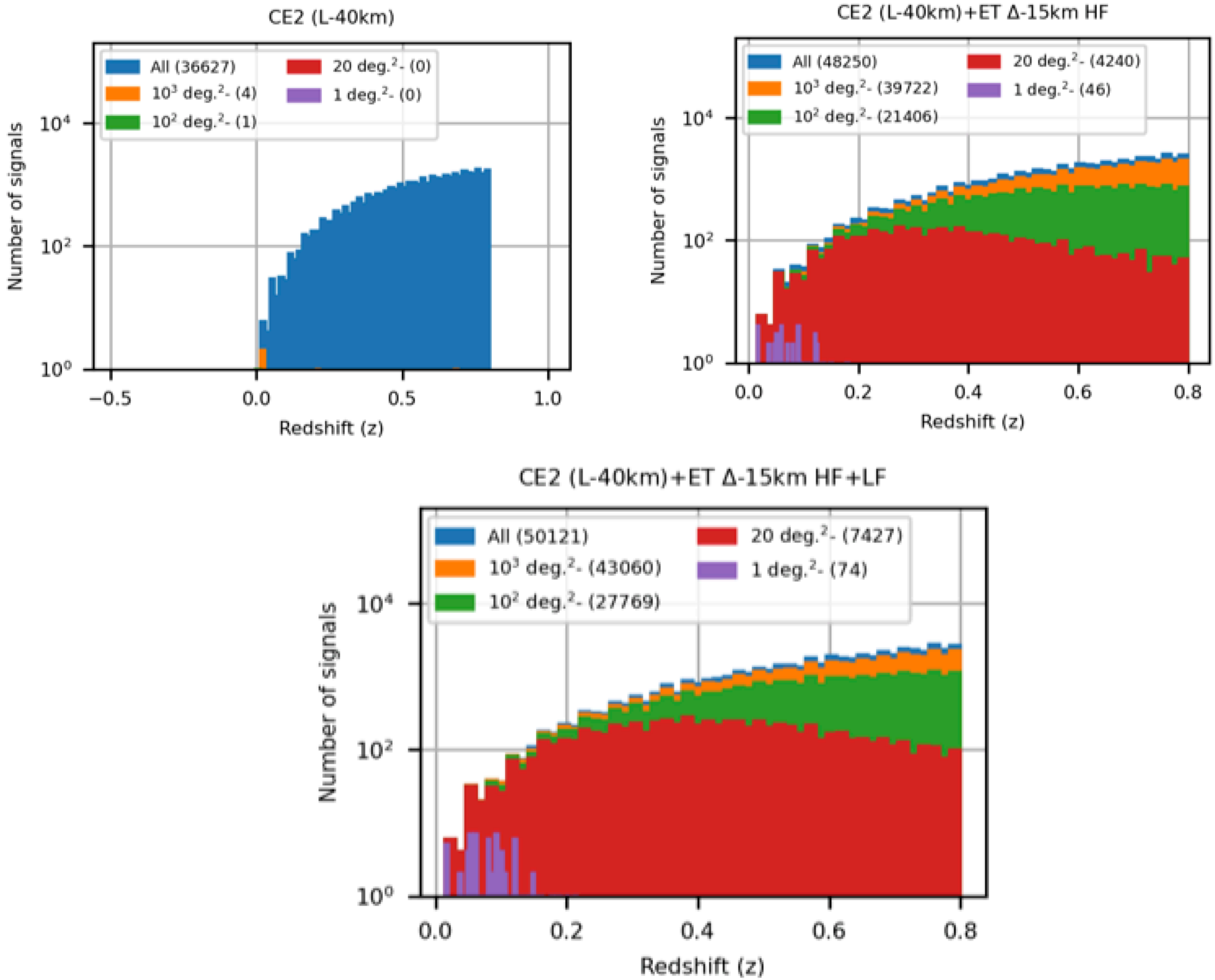
BNS localization: CE and CE+ET(10km)



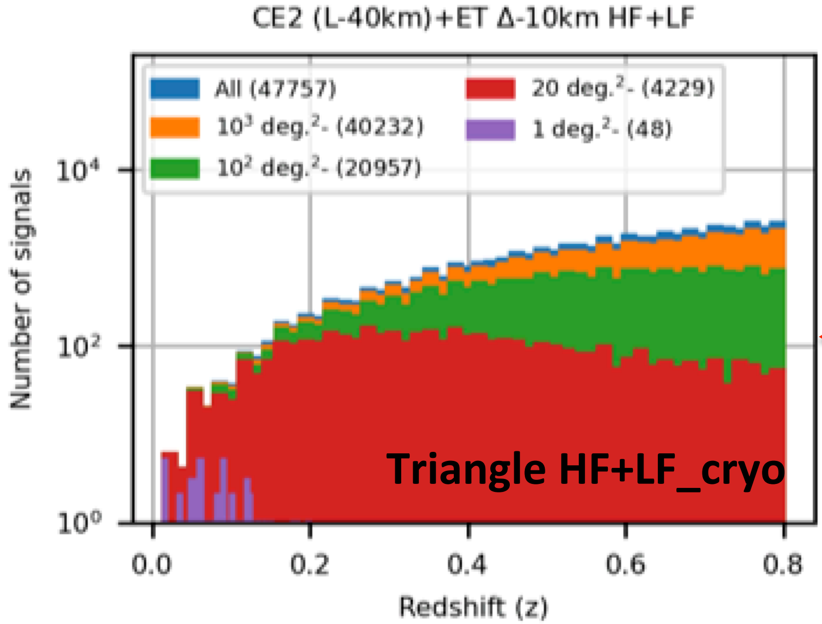




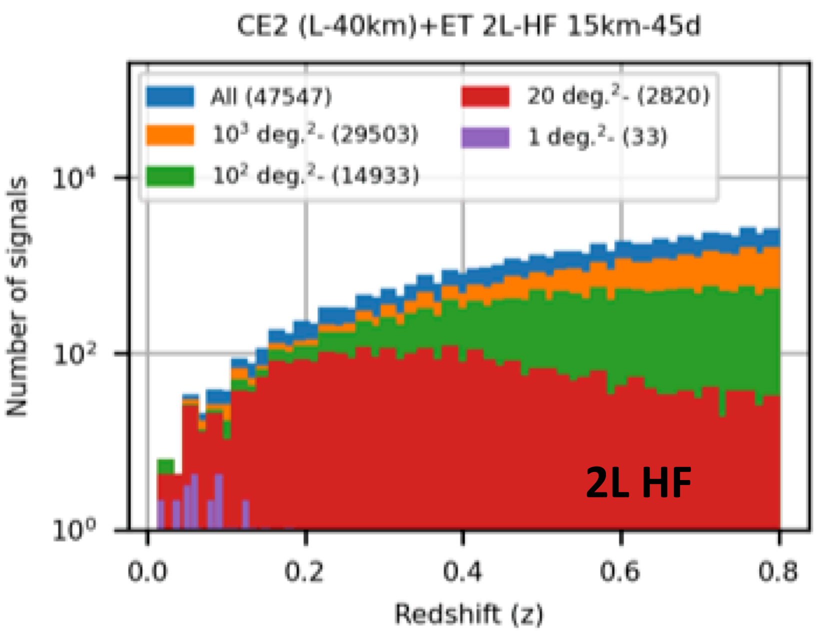
BNS localization: CE and CE+ET(15km)

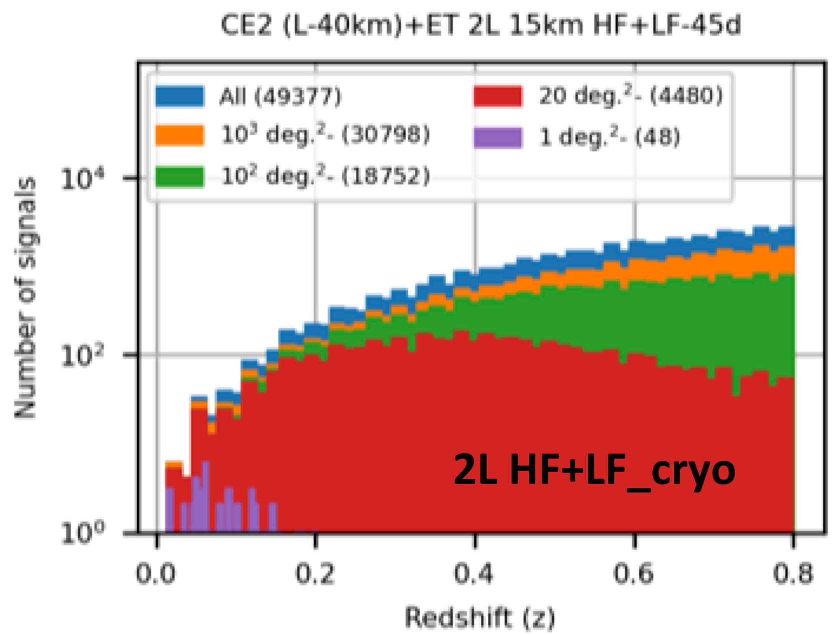


BNS localization: CE+ET(10km) and 2L (15 km)



CE+ET(10 km)
LF+HF_cryo
similar
to CE+2L(15 km)
LF+HF_cryo

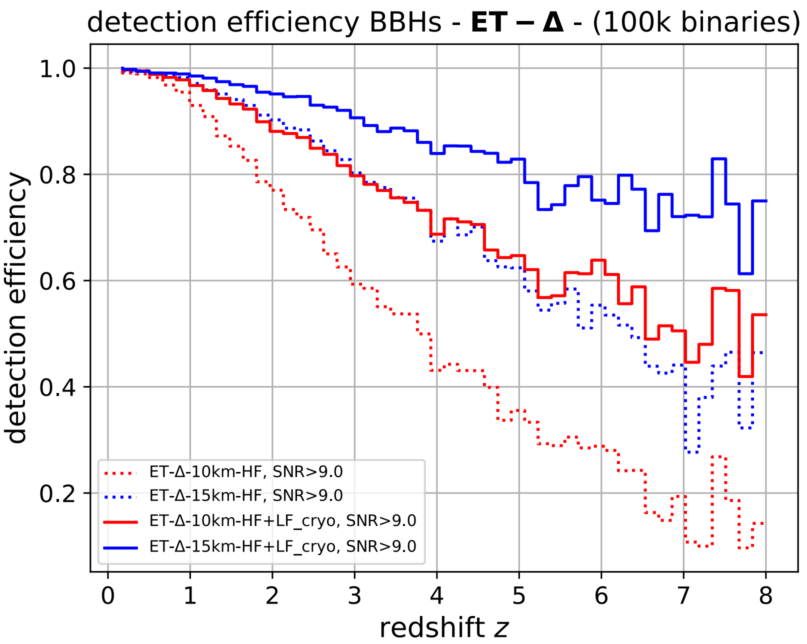


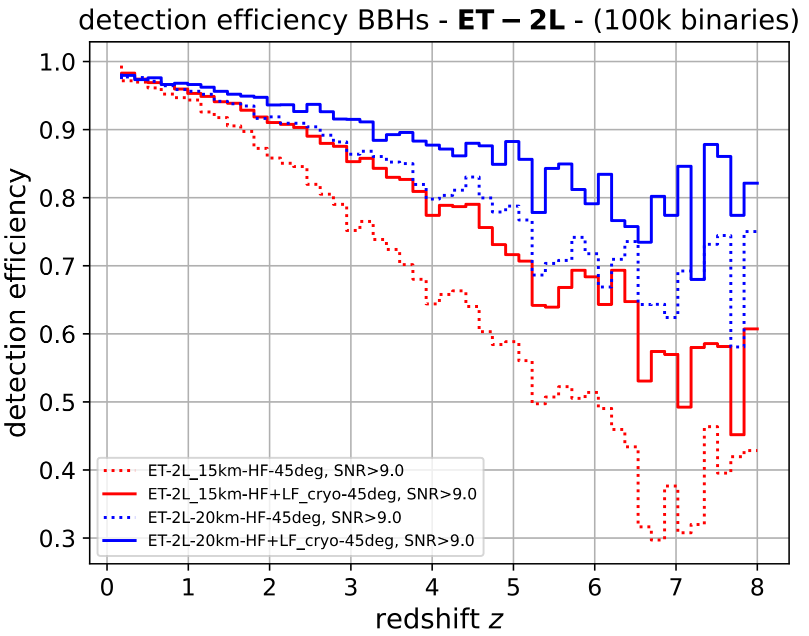


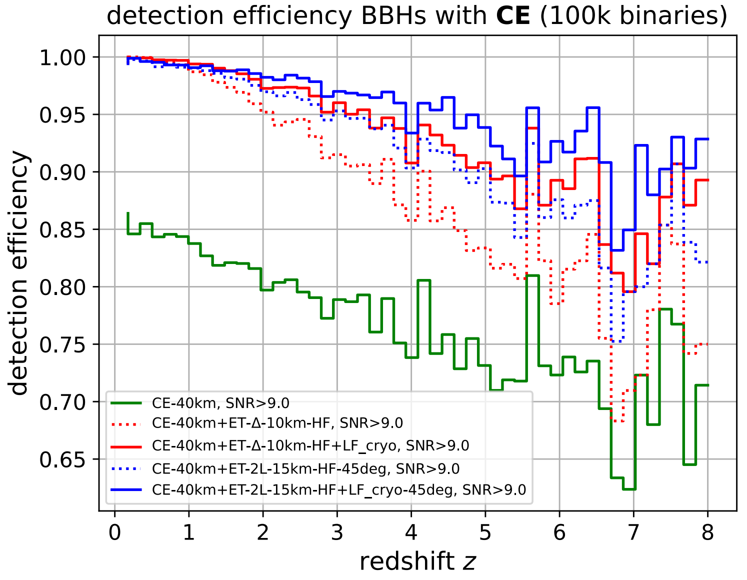
ET in the international context, ET+CE(40km)

Scenario	Detections per year SNR>9	Detections with sky-loc < 20 deg2	Detections with sky-loc < 100 deg2
CE(40 km)	336949	0	1
TRIANGLE (10 km) HF+CE(40 km)	392295	2220	13259
TRIANGLE (10 km) HFLF_cryo+CE(40 km)	436558	4229	20957
TRIANGLE (15 km) HF+CE(40 km)	448363	4240	21406
TRIANGLE (15 km) HF+LF_cryo+CE(40 km)	510519	7427	27769
2L(15 km)+CE (40 km) HF misaligned	435856	2820	14933
2L(15 km)+CE (40 km) HF+LF_cryo misaligned	492885	4480	18752
2L(20 km)+CE (40 km) HF misaligned	488974	5130	20013
2L(20km)+CE (40 km) HF+LF_cryo misaligned	552415	7383	23190

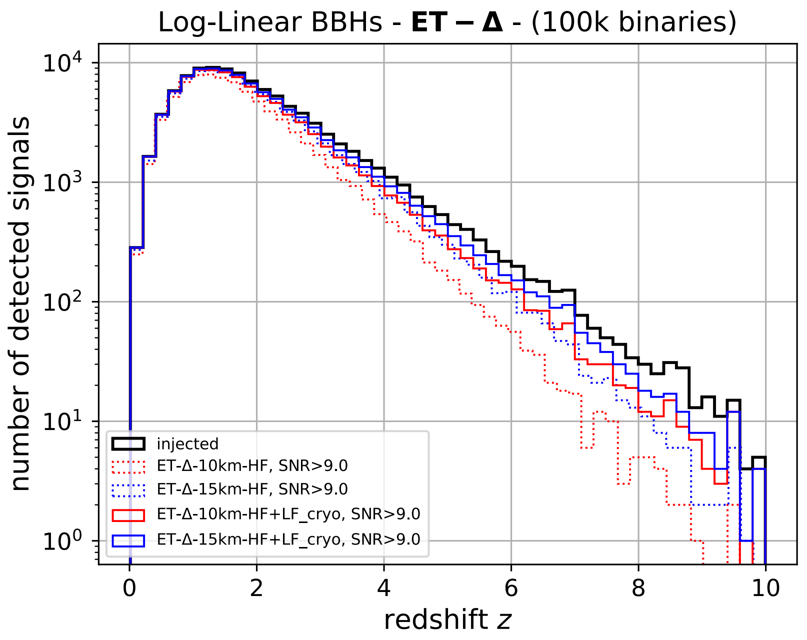
BBH simulations

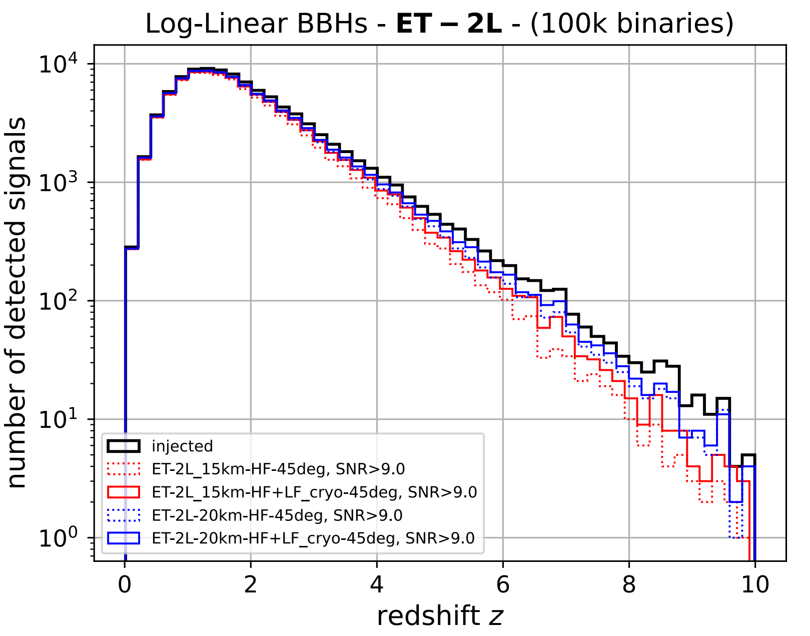


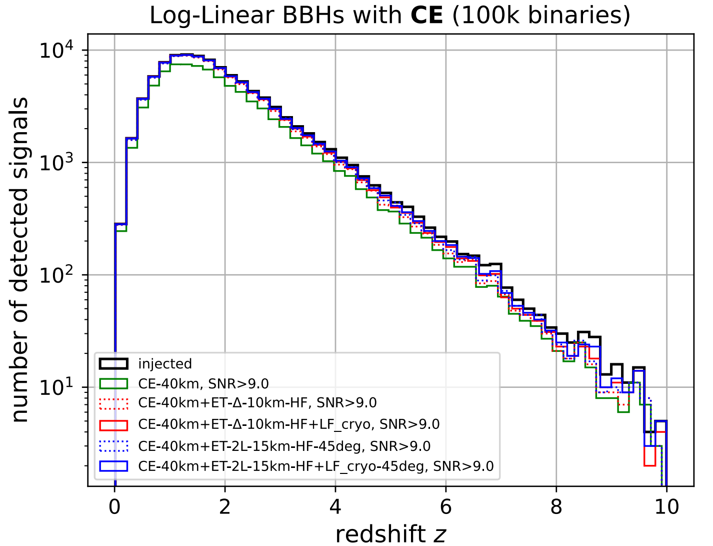


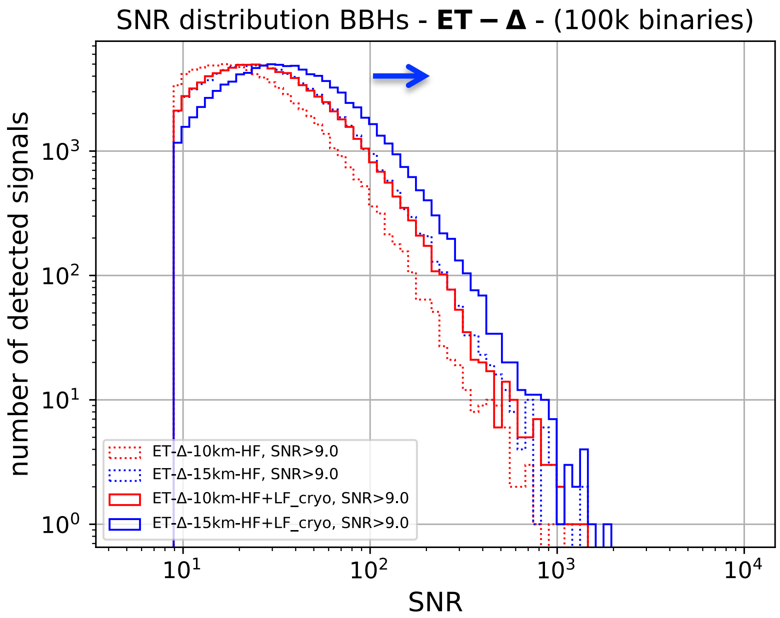


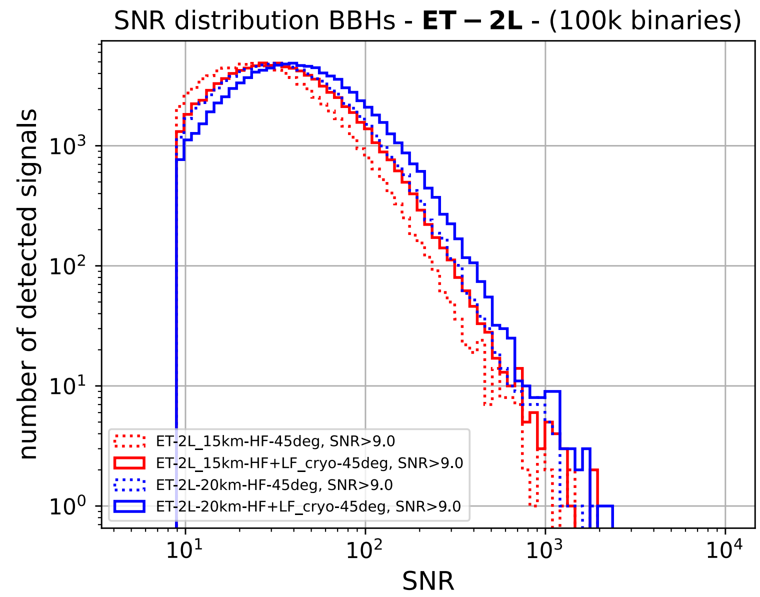
BBH simulations

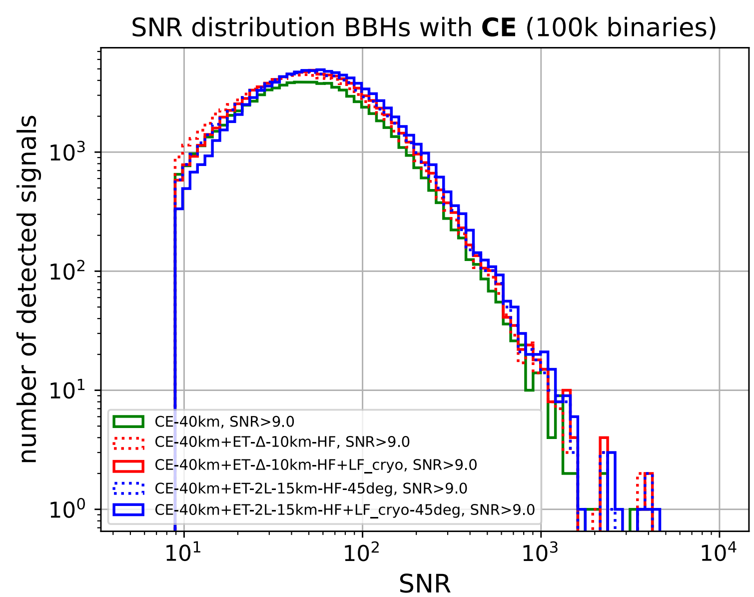







SNR distribution BBHs - **ET − Δ** - (100k binaries)
number of detected signals
SNR
ET-Δ-10km-HF, SNR>9.0
ET-Δ-15km-HF, SNR>9.0
ET-Δ-10km-HF+LF_cryo, SNR>9.0
ET-Δ-15km-HF+LF_cryo, SNR>9.0

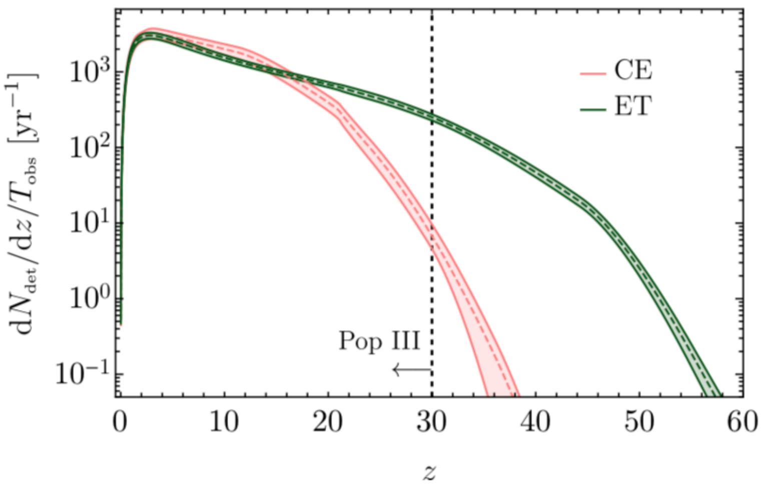

SNR distribution BBHs - **ET − 2L** - (100k binaries)
number of detected signals
SNR
ET-2L_15km-HF-45deg, SNR>9.0
ET-2L_15km-HF+LF_cryo-45deg, SNR>9.0
ET-2L-20km-HF-45deg, SNR>9.0
ET-2L-20km-HF+LF_cryo-45deg, SNR>9.0

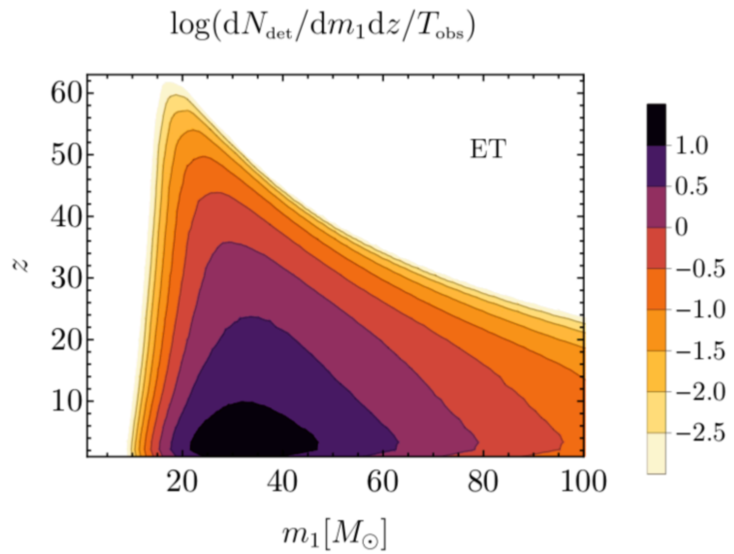

SNR distribution BBHs with **CE** (100k binaries)
number of detected signals
SNR
CE-40km, SNR>9.0
CE-40km+ET-Δ-10km-HF, SNR>9.0
CE-40km+ET-Δ-10km-HF+LF_cryo, SNR>9.0
CE-40km+ET-2L-15km-HF-45deg, SNR>9.0
CE-40km+ET-2L-15km-HF+LF_cryo-45deg, SNR>9.0

Primordial BH

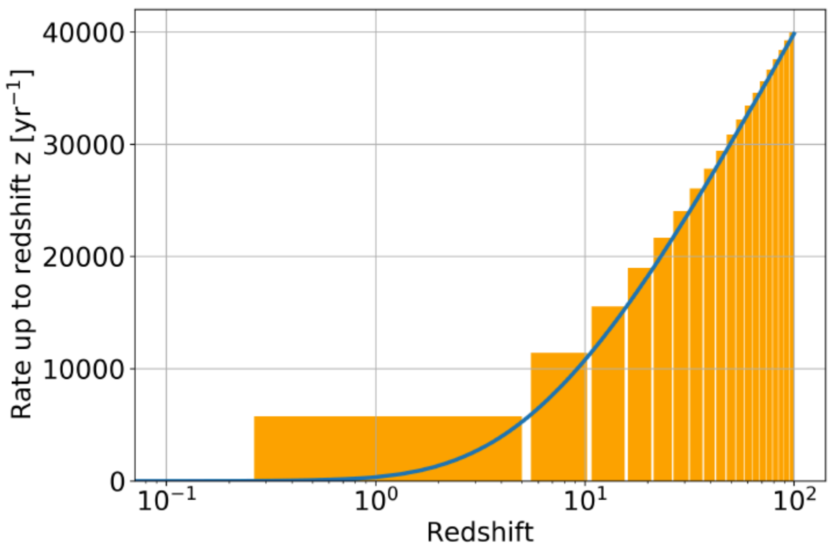
U.Dupletsa, M. Branchesi, J. Harms

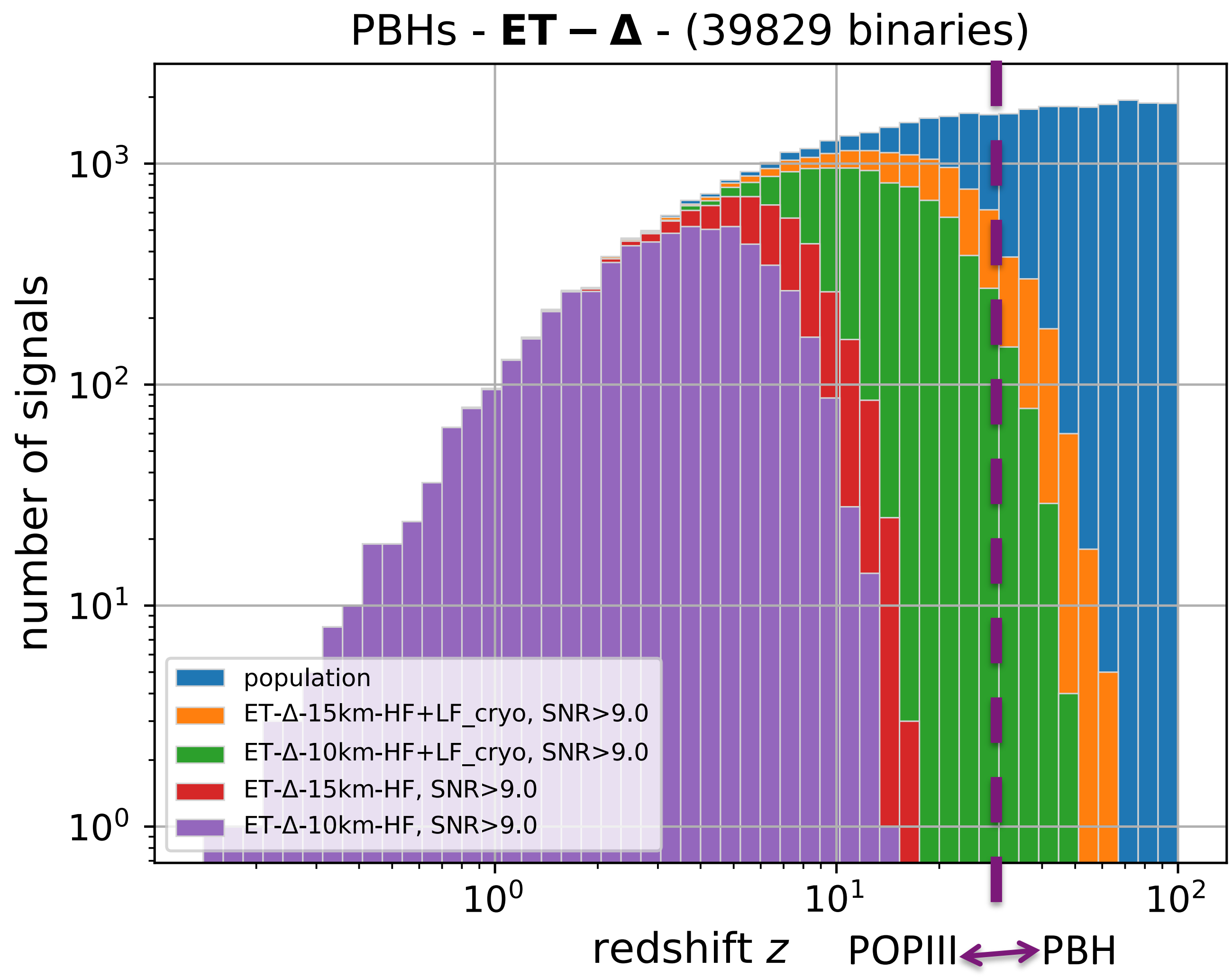
PBH rate evolution and mass distribution by Toni Riotto (DIV3)



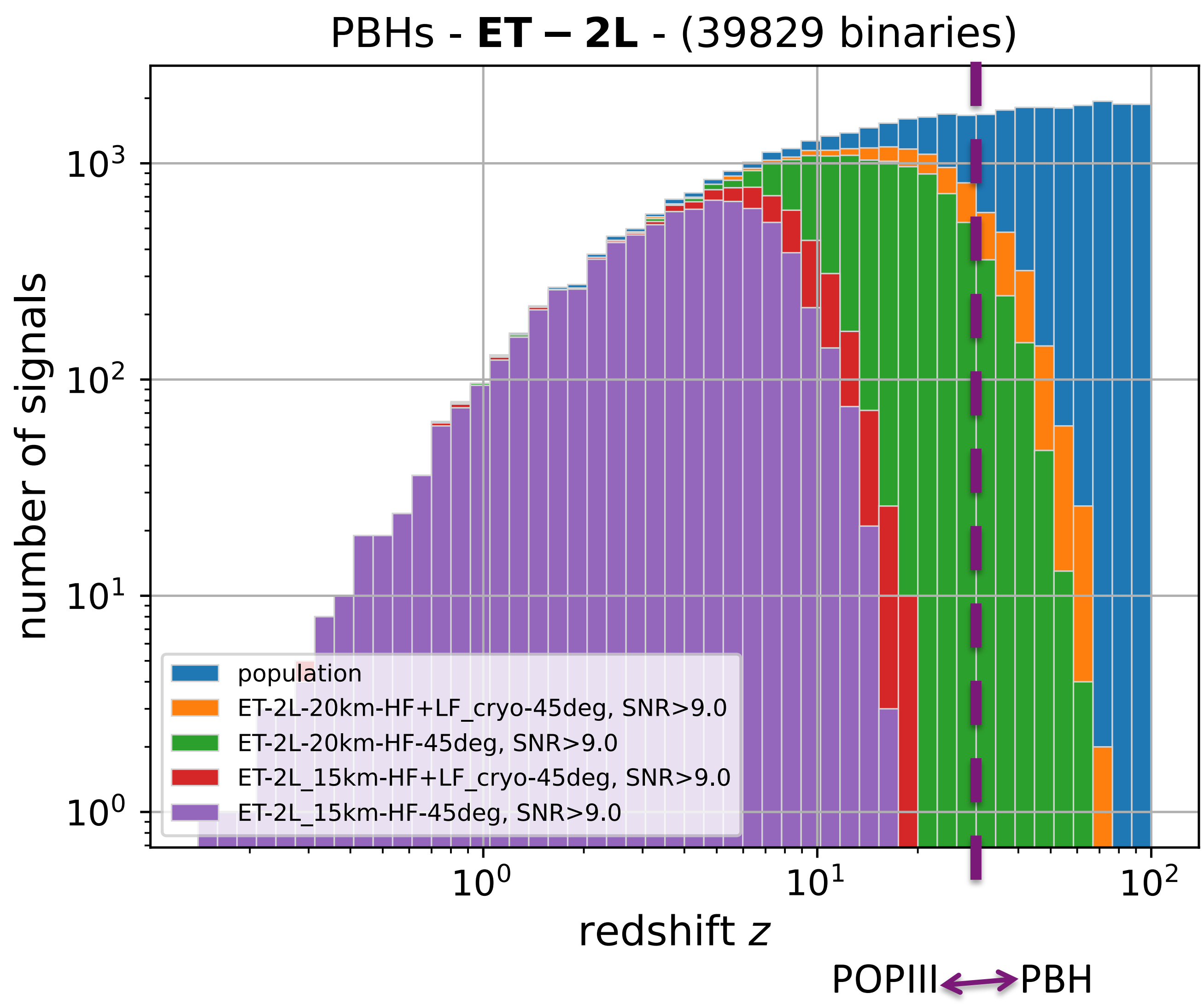


(De Luca et al. 2102.03809)





About 40k binaries injections

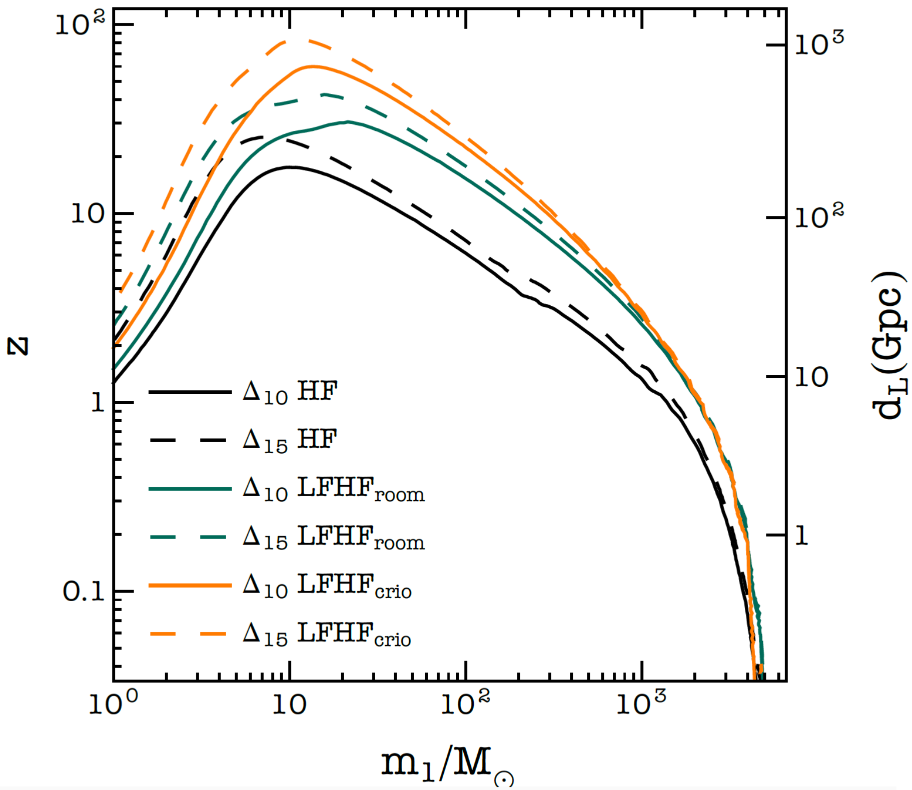


PBHs - **ET − 2L** - (39829 binaries)
number of signals
redshift z
population
ET-2L-20km-HF+LF_cryo-45deg, SNR>9.0
ET-2L-20km-HF-45deg, SNR>9.0
ET-2L_15km-HF+LF_cryo-45deg, SNR>9.0
ET-2L_15km-HF-45deg, SNR>9.0
POPIII
PBH

IMBH: horizon as function of z

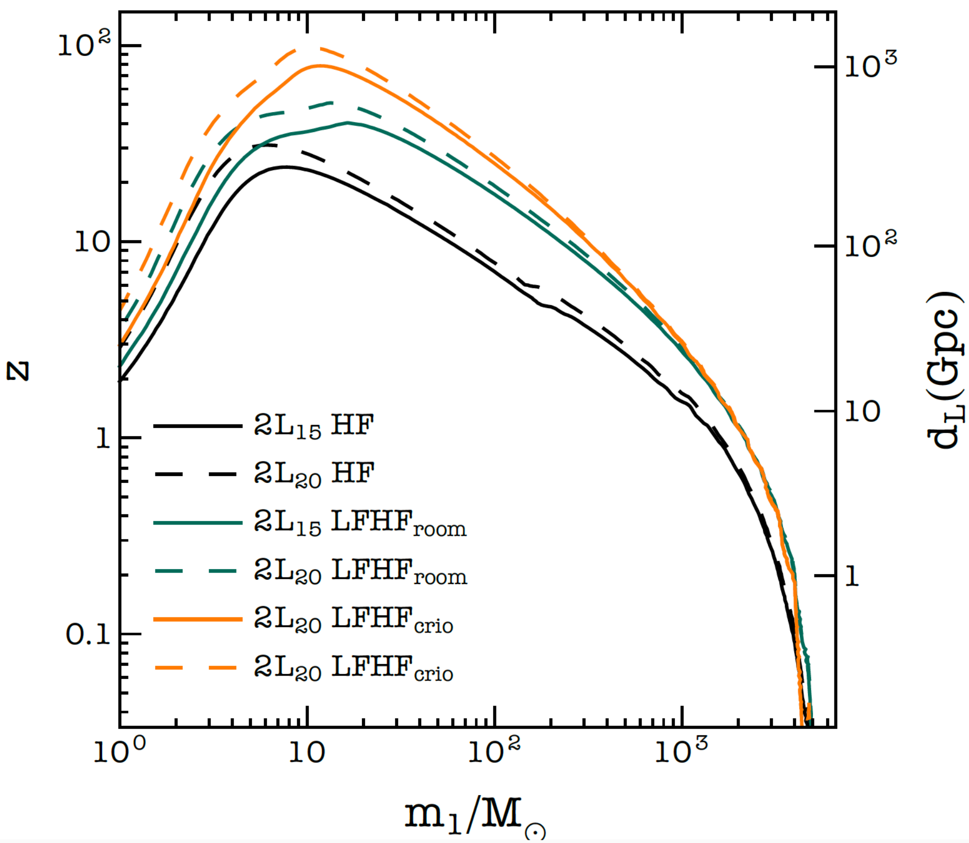
A .Maselli, M. Branchesi, J. Harms

Horizon as a function of z

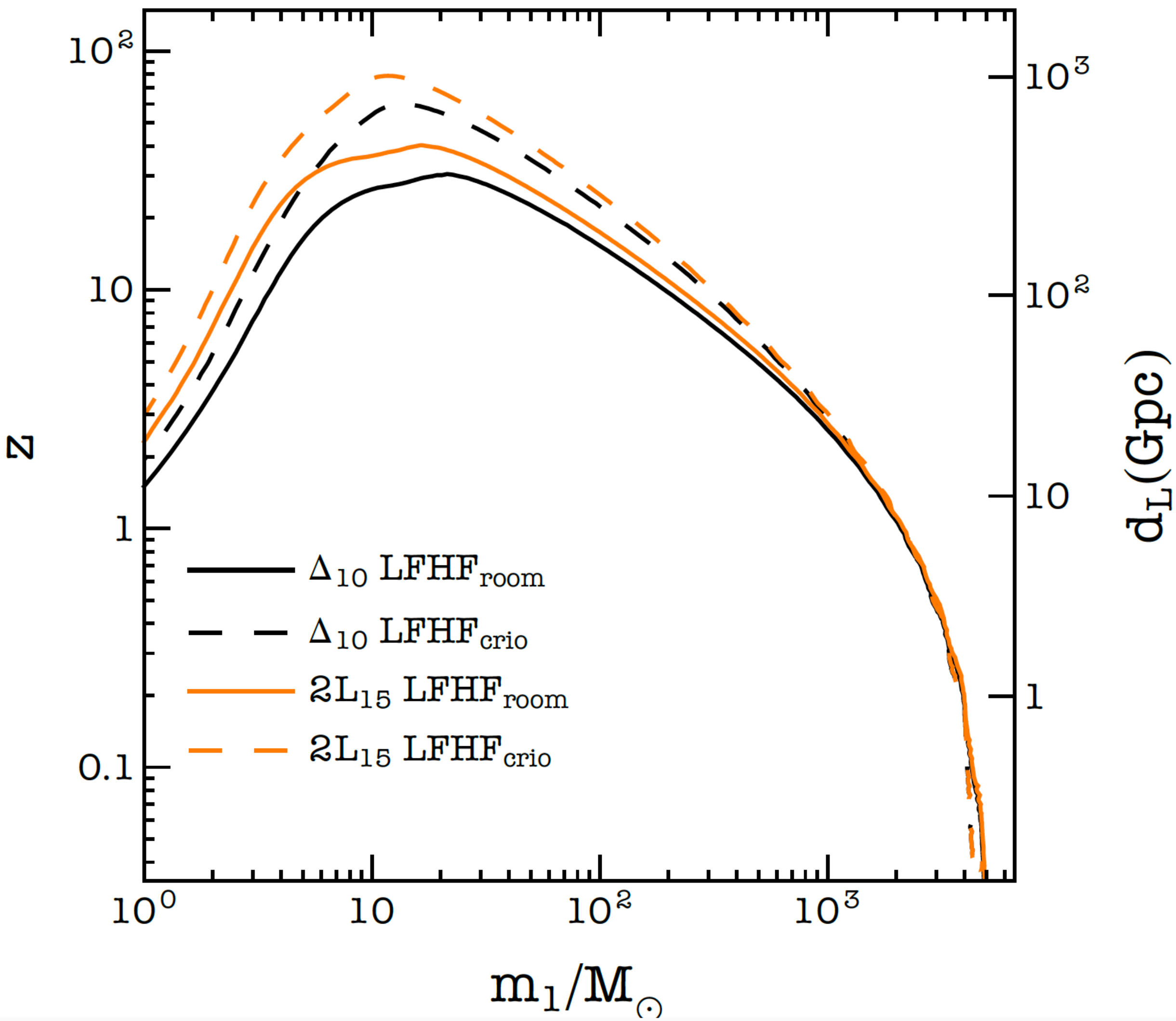


Warning:
- No higher mode
- No Earth rotation

m = rest frame mass
mass ratio=1



Horizon as a function of z



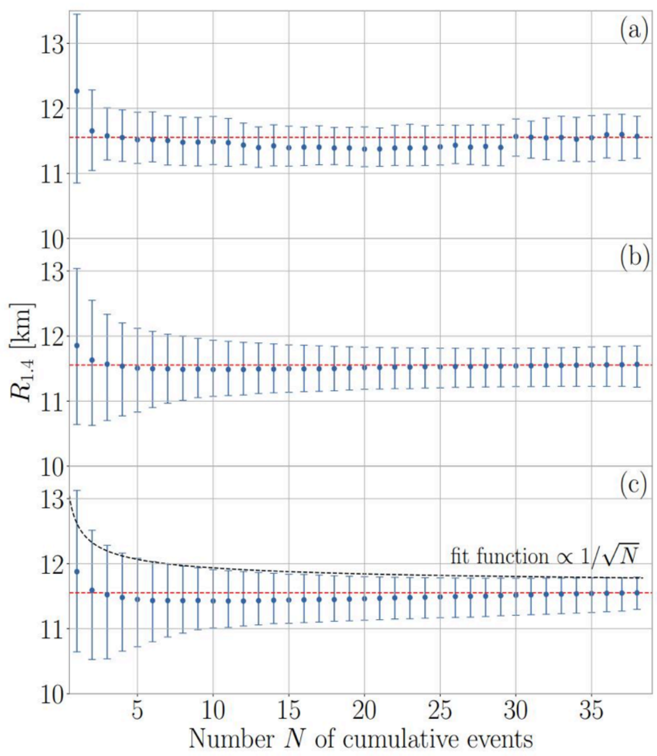
m = rest frame mass
mass ratio=1

NS Physics

DIV 6
T. Dietrich, T. Hinderer, M. Oertel
and Gulminelli,, C. Kalaghatgi, N.Kunert,
C. Mondal, P. Pang, A. Pucher

1. Estimating the statistical radius uncertainty

estimates based on Kunert et al.,
arXiv: 2110.11835, [astro-ph.HE]



point of contact: T.Dietrich, N.Kunert, P.Pang

→ It was shown that a 1/sqrt{N} scaling can be achieved for large number of detections.

→ We use the estimated error for an error obtained from an injection of 30 events (using advanced LIGO PSD) and extrapolate to obtain an idea about the statistical uncertainty (starting point 570.5m for 30 detections with SNR>9)

→ The study of Kunert et al., includes information from chiral EFT, hence a more agnostic approach would likely lead to larger uncertainties, hence, we consider this as an optimistic estimate

→ We assume that waveform systematics and other systematic effects will contribute with an uncertainty of at least 20 meters (current systematic uncertainties ~250-500m)

Estimate of statistical radius uncertainty

Configuration	**Number of Detections**	**Statistical Radius uncertainty for a 1.4Msun star [meter]**
ET 10km HF	47382	14.4
ET(HF+LF-290k)-10km	67428	12.0
ET(HF+LF)-10km	110342	9.4
ET 15km HF	128053	8.7
ET(HF+LF-290k)-15km	166457	7.7
ET(HF+LF)-15km	228495	6.6

From GSSI simulation

Estimate of statistical radius uncertainty

Configuration	**Number of Detections**	**Statistical Radius uncertainty for a 1.4Msun star [meter]**
2L 10km HF 0-deg	40995	15.4
2L 10km HF 45-deg	40339	15.6
2L 10km HF+LF (290K) 0-deg	58785	12.9
2L 10km HF+LF (290K) 45-deg	57638	13.0
2L 10km HF+LF 0-deg	97702	10.0
2L 10km HF+LF 45-deg	95644	10.1

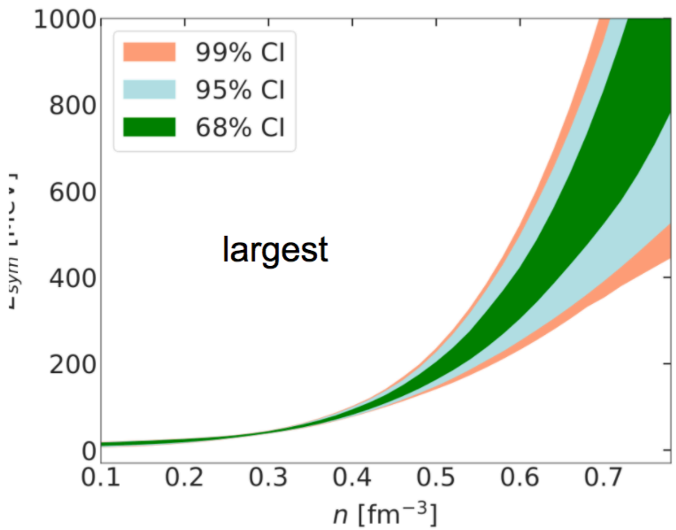
Estimate of statistical radius uncertainty

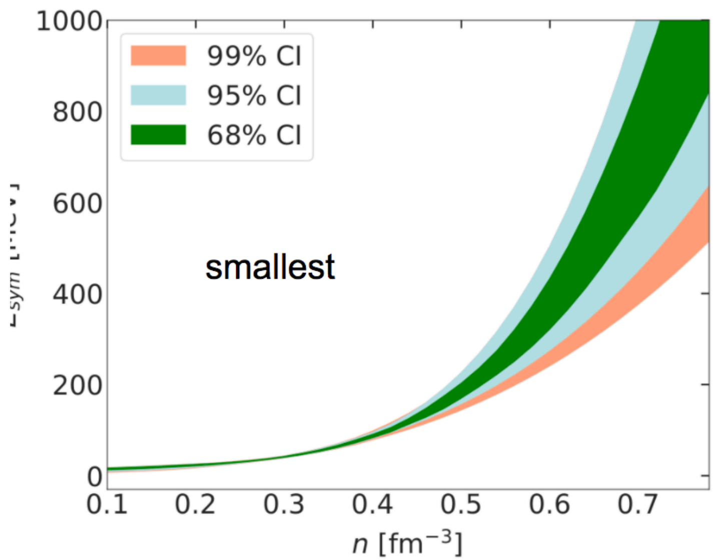
Configuration	Number of Detections	Statistical Radius uncertainty for a 1.4Msun star [meter]
2L 15km HF 0-deg	113502	9.3
2L 15km HF 45-deg	111173	9.4
2L 15km HF+LF (290K) 0-deg	149097	8.1
2L 15km HF+LF (290K) 45-deg	146092	8.2
2L 15km HF+LF 0-deg	207355	6.9
2L 15km HF+LF 45-deg	203955	6.9

Estimate of statistical radius uncertainty

Configuration	**Number of Detections**	**Statistical Radius uncertainty for a 1.4Msun star [meter]**
2L 20km HF 0-deg	200904	6.9
2L 20km HF 45-deg	197420	7.0
2L 20km HF+LF (290K) 0-deg	247299	6.3
2L 20km HF+LF (290K) 45-deg	243993	6.4
2L 20km HF+LF 0-deg	305518	5.7
2L 20km HF+LF 45-deg	304382	5.7

2.) Connected uncertainty of nuclear-physics parameters





Measurements of tidal parameters and corresponding masses
-> translate into information on the underlying nuclear equation of state and nuclear matter parameters

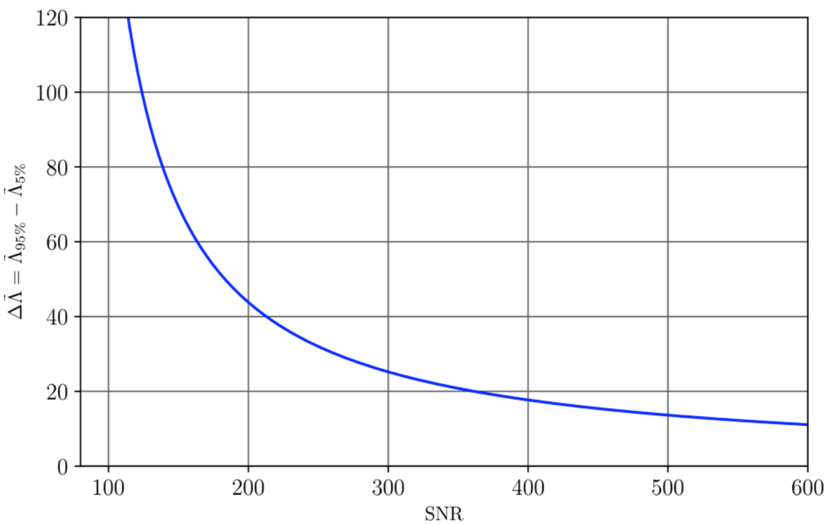
Example: nuclear symmetry energy from nuclear meta model, minimal priors (stability conditions, causality, measured nuclear masses) taking M-R values as before
Compare smallest **(2L 20km HF+LF cryogenic)** statistical and waveform uncertainty with largest **(2L 10km HF)** uncertainty

At nuclear saturation density:
L_{sym} = 38.68 + 7.32 - 7.68 MeV (largest)
L_{sym} = 37.29 + 6.71 - 6.29 MeV (smallest)

Based on Mondal& Gulminelli, arXiv: 2111.04520

point of contact: M. Oertel, C. Mondal, F. Gulminelli

3.) Estimating the uncertainty from a single measurement



estimates based on Gamba et al., 2021 Phys.Rev.D 103 (2021) 12, 124015

→ We use the provided fit formula (Eq. (32) of PRD 103 124015) from Gamba et al.

$$\Delta\tilde{\Lambda} = \tilde{\Lambda}_{95\%} - \tilde{\Lambda}_{5\%} = \frac{c_0}{SNR - c_1}$$

→ We use the fitting parameters for TaylorF2 and IMRPhenomPv2NRTidal and average over the obtained uncertainty as outlined in Gamba et al.

→ The loudest SNR that we use for our estimate is based on the result provides by M. Branchesi and B. Banerjee

→A measurement at one given mass does not impact considerably nuclear physics parameters (need EoS(density))

point of contact: T.Dietrich

Estimate of uncertainty in lambda from loudest event

Configuration	**Loudest SNR**	**Uncertainty in Lambda**
ET 10km HF	190.009	47.3
ET(HF+LF-290k)-10km	260.322	30.3
ET(HF+LF)-10km	269.155	29.0
ET 15km HF	282.215	27.3
ET(HF+LF-290k)-15km	372.464	19.3
ET(HF+LF)-15km	373.438	19.2

From GSSI simulation

Estimate of uncertainty in lambda from loudest event

Configuration	**Loudest SNR**	**Uncertainty in Lambda**
2L 10km HF 0-deg	214.388	39.6
2L 10km HF 45-deg	208.698	41.2
2L 10km HF+LF (290K) 0-deg	236.369	34.5
2L 10km HF+LF (290K) 45-deg	235.035	34.8
2L 10km HF+LF 0-deg	283.398	27.1
2L 10km HF+LF 45-deg	282.036	23.3

Estimate of uncertainty in lambda from loudest event

Configuration	Loudest SNR	Uncertainty in Lambda
2L 15km HF 0-deg	308.656	24.3
2L 15km HF 45-deg	300.517	25.1
2L 15km HF+LF (290K) 0-deg	338.189	21.7
2L 15km HF+LF (290K) 45-deg	336.285	21.8
2L 15km HF+LF 0-deg	392.665	18.1
2L 15km HF+LF 45-deg	390.813	18.2

Estimate of uncertainty in lambda from loudest event

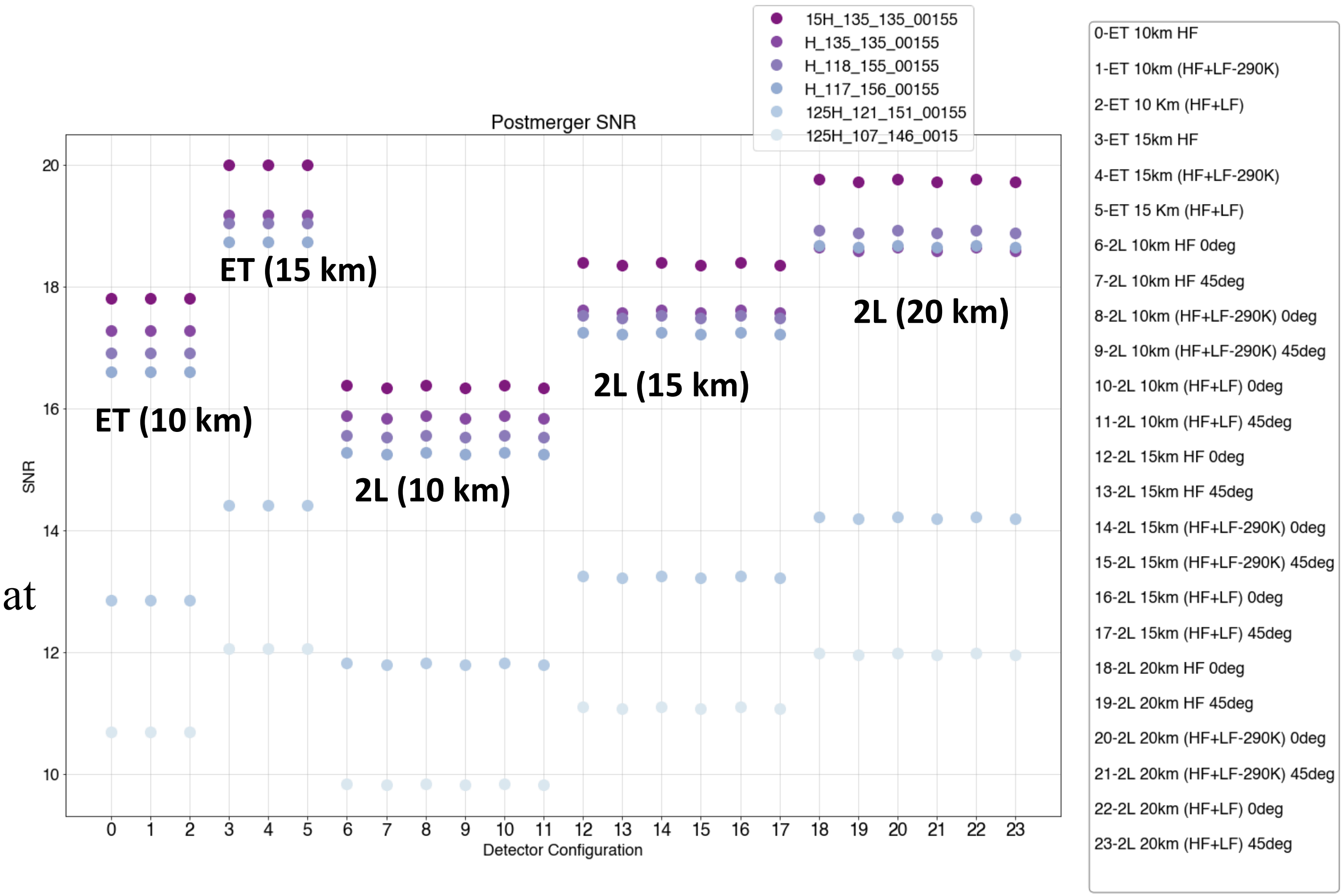
Configuration	Loudest SNR	Uncertainty in Lambda
2L 20km HF 0-deg	396.836	17.9
2L 20km HF 45-deg	386.431	18.4
2L 20km HF+LF (290K) 0-deg	437.597	15.9
2L 20km HF+LF (290K) 45-deg	430.521	16.2
2L 20km HF+LF 0-deg	488.337	14.0
2L 20km HF+LF 45-deg	421.688	16.6

4.) Postmerger Detectibility

→ We compute the postmerger SNR of five different numerical-relativity simulations.

→ SNR is computed between the merger frequency and 4096Hz.

→ We place our sources at a distance of 50Mpc



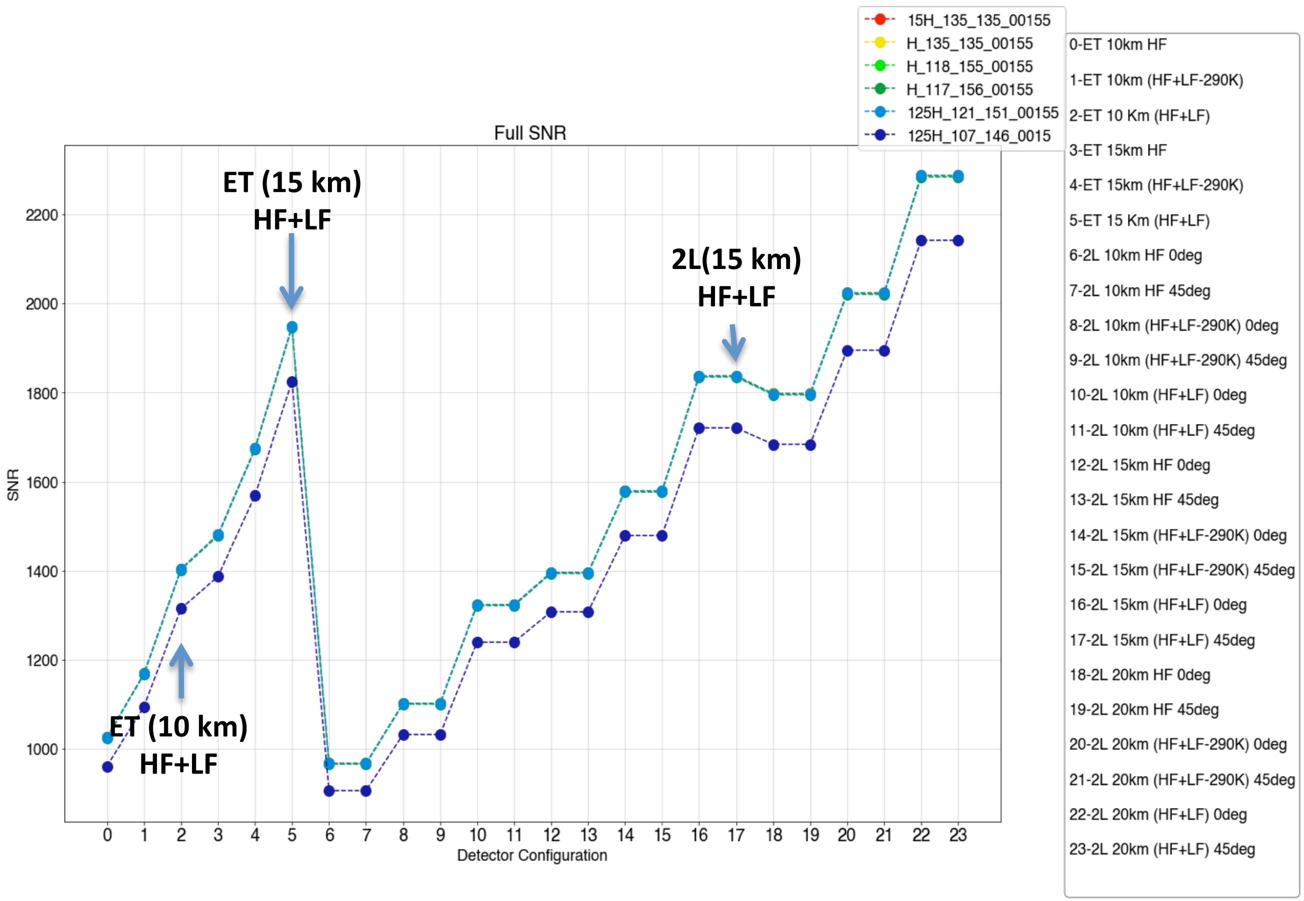
point of contact: C. Kalaghatgi, A. Pucher, T. Dietrich

5.) Accumulated SNR during the inspiral

→ We use the same 5 setups as in (4), but compute now the SNR during the inspiral

→ We keep the distance of 50Mpc

Warning: the code does not include Earth rotation!

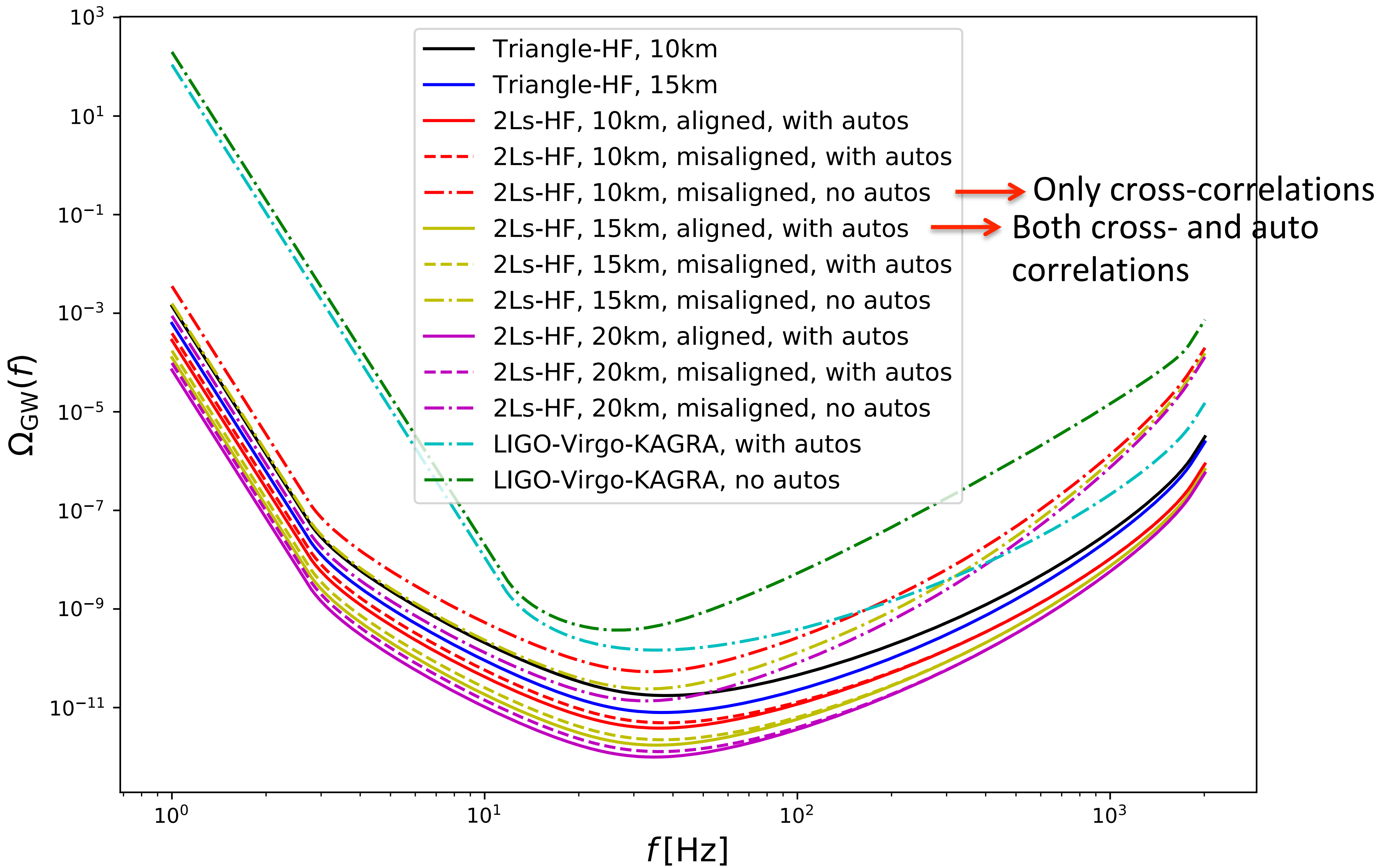


point of contact: C. Kalaghatgi, A. Pucher, T. Dietrich

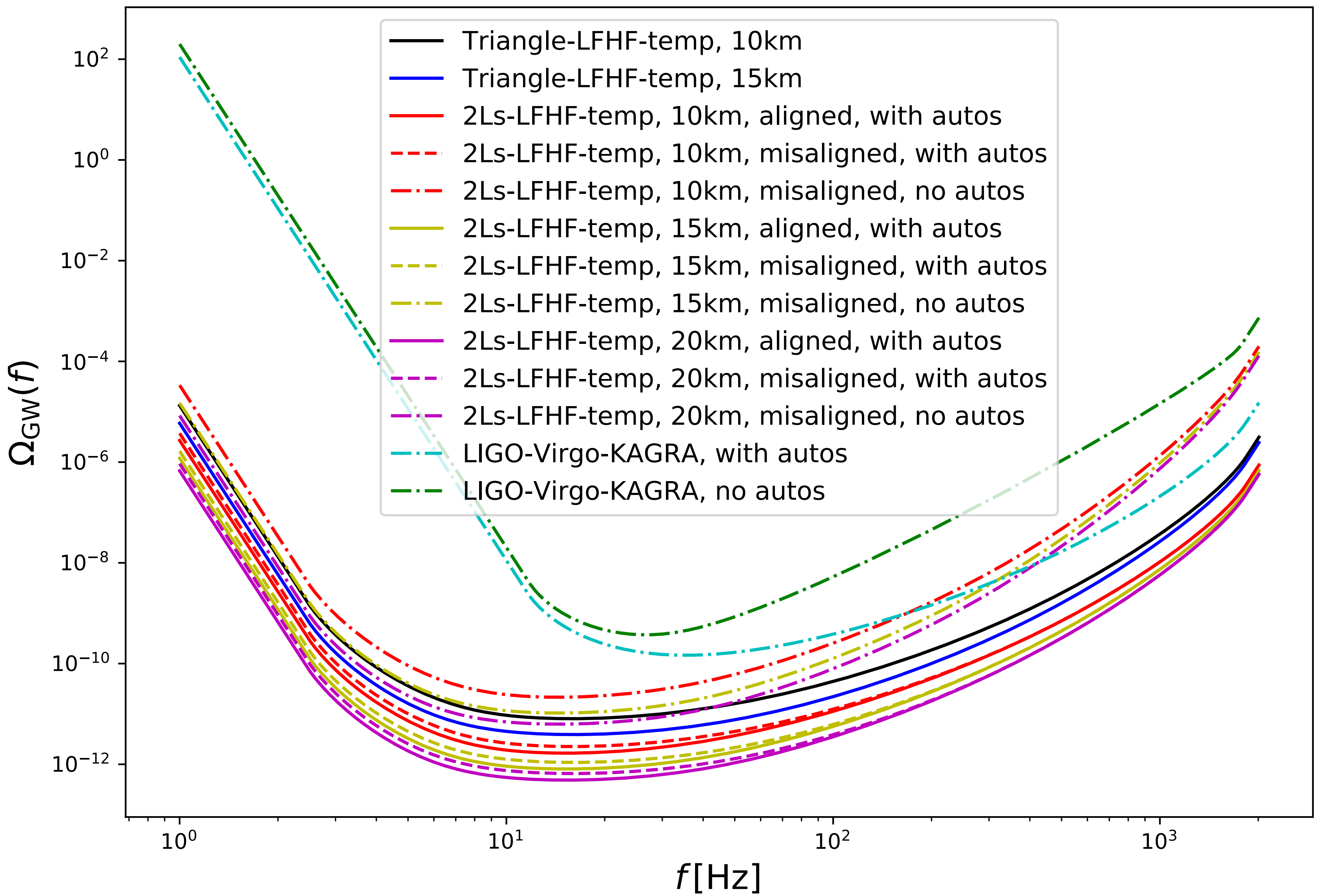
Stochastic Background

D.Alonso and G.Cusin

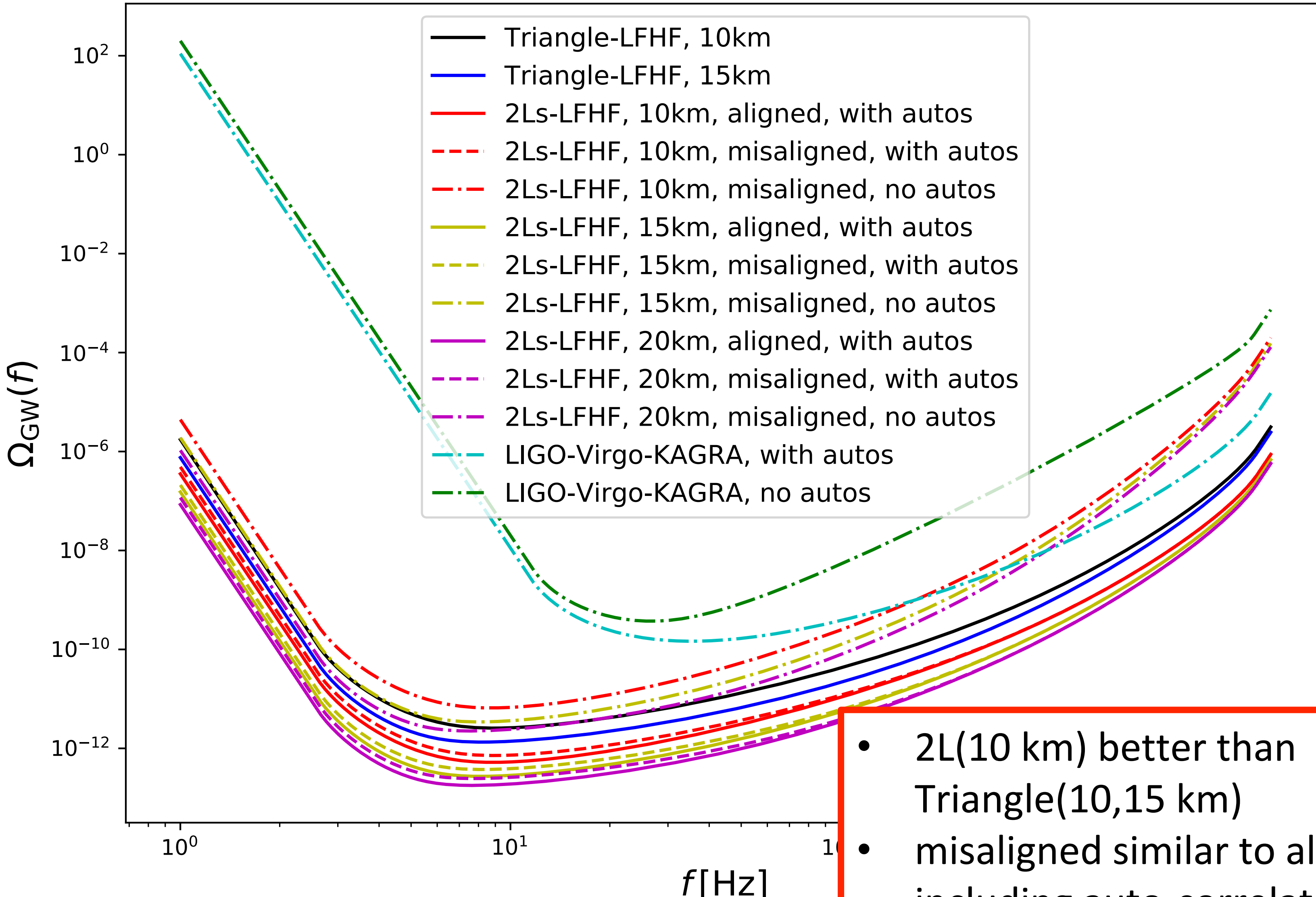
Power-law integrated sensitivity curves for 1 year



Power-law integrated sensitivity curves for 1 year



Power-law integrated sensitivity curves for 1 year



- 2L(10 km) better than Triangle(10,15 km)
- misaligned similar to aligned including auto-correlations (but hard to precisely model noise auto-correlation!)