GraSP2024-Pisa

October 23rd, 2024

Forecasting detection & parameter estimation capabilities for the Einstein Telescope

Ulyana Dupletsa

on behalf of the **ET Collaboration**

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN

EINSTEIN TELESCOPE

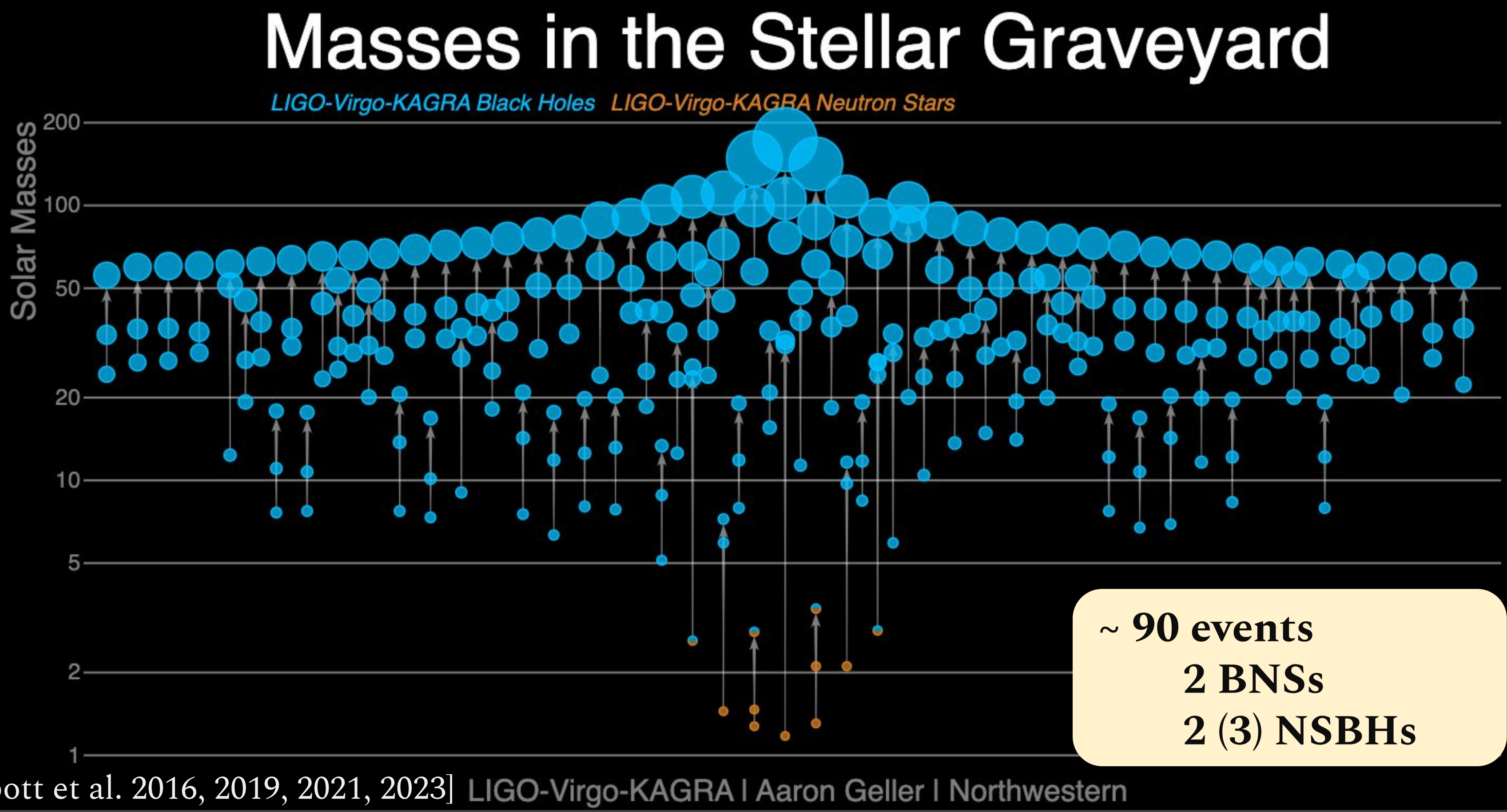
**Large fraction of slides adapted from Marica Branchesi

WHERE DO WE STAND?

TOWARDS NEXT-GENERATION

SCIENTIFIC TARGETS

2035-2040

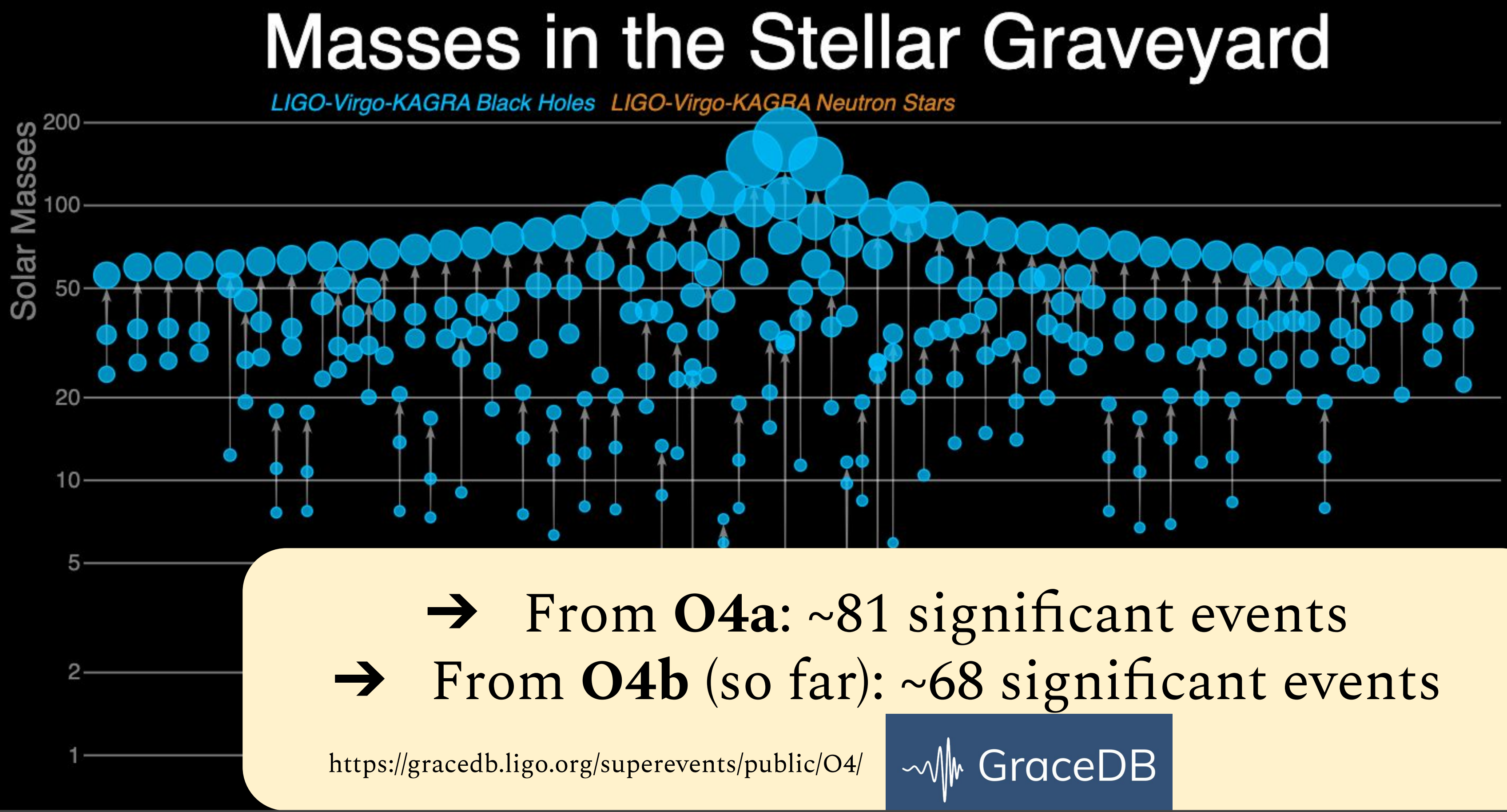


~ 90 events

2 BNSs

2 (3) NSBHs

[Abbott et al. 2016, 2019, 2021, 2023]

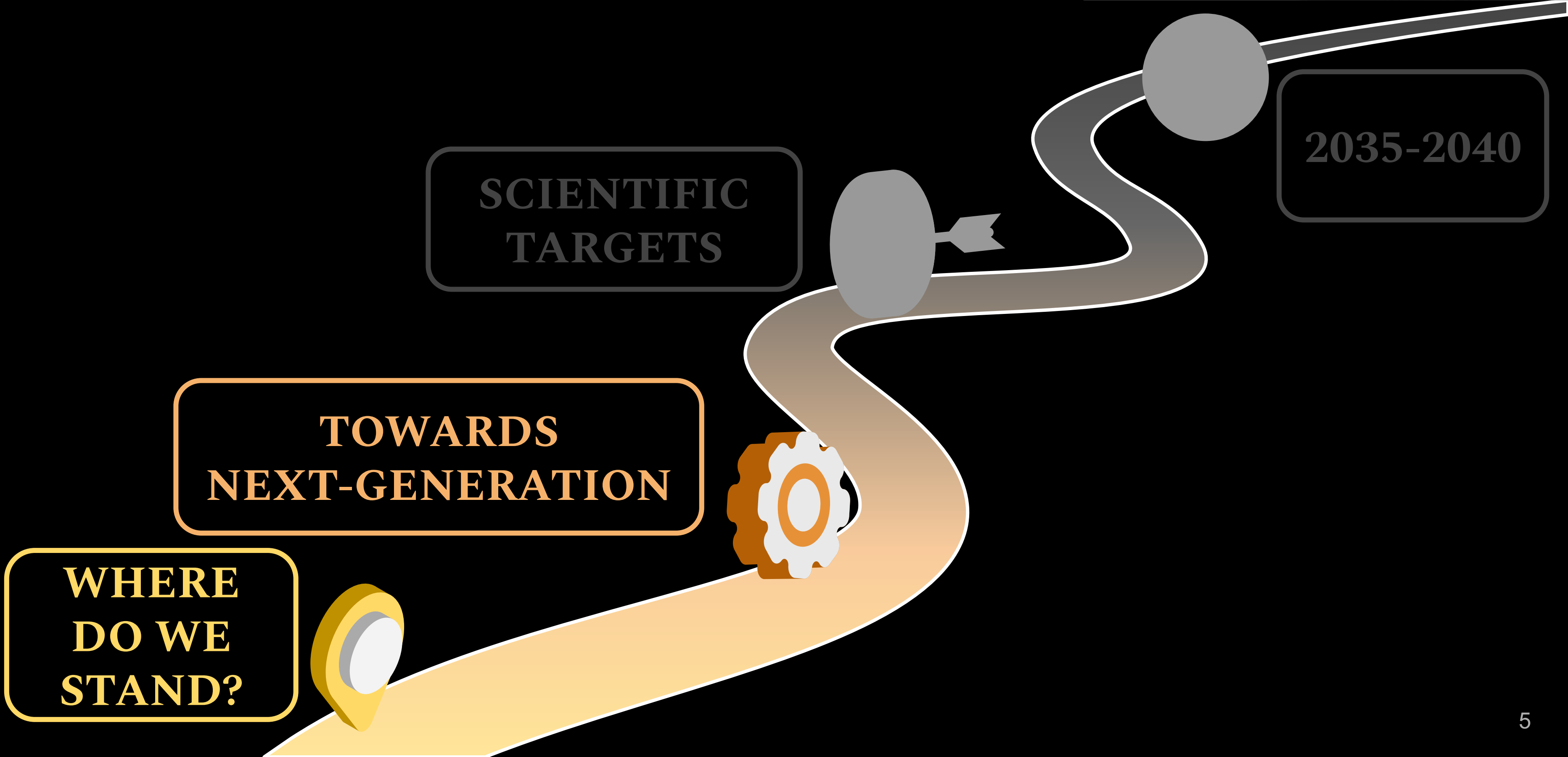


- ➔ From **O4a**: ~81 significant events
- ➔ From **O4b** (so far): ~68 significant events

https://gracedb.ligo.org/superevents/public/O4/

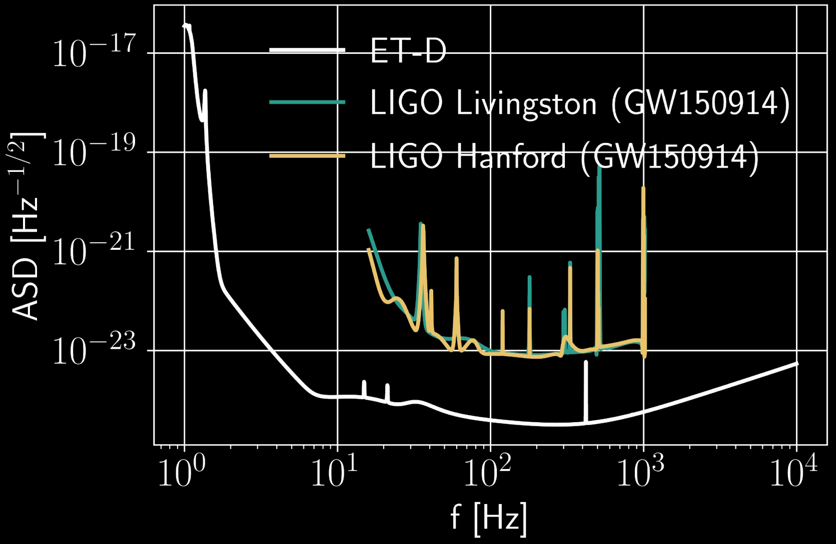
GraceDB

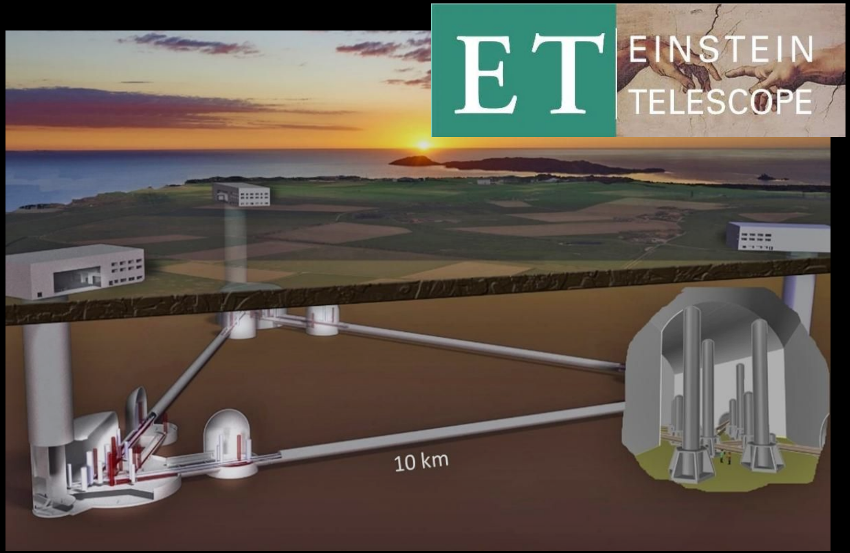
EINSTEIN TELESCOPE



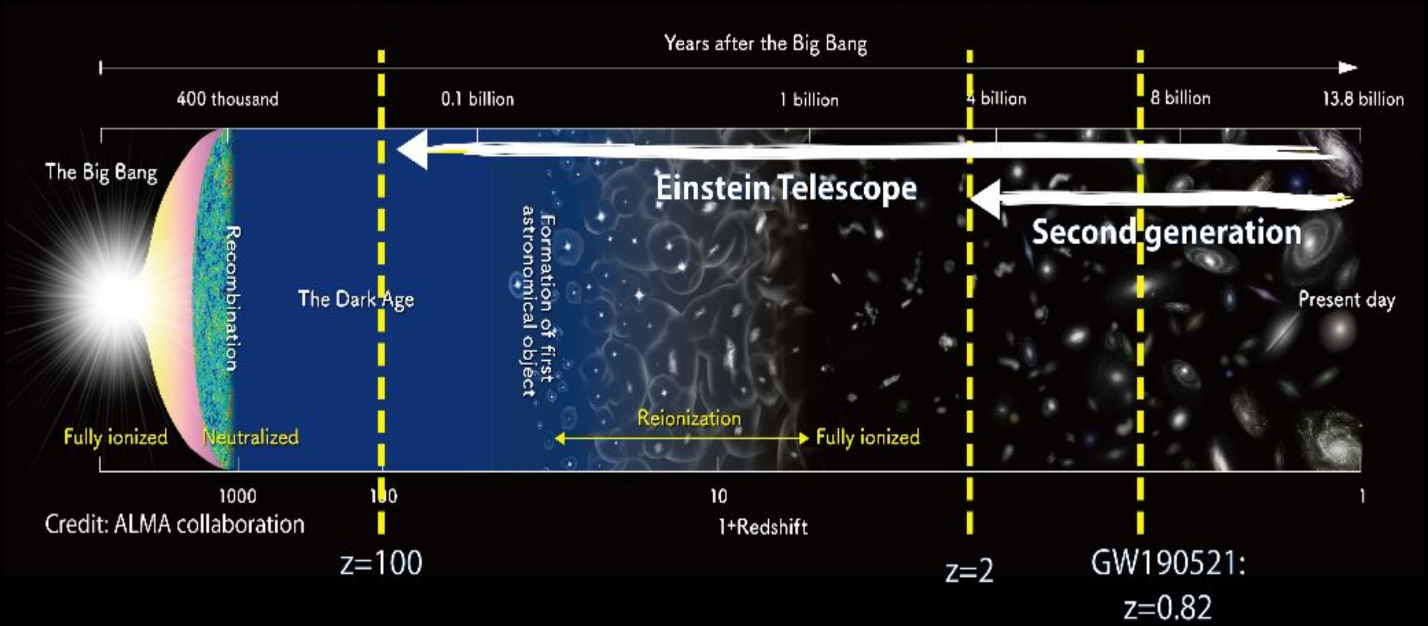
From current detectors to next-generation

[Hild et al. 2008]

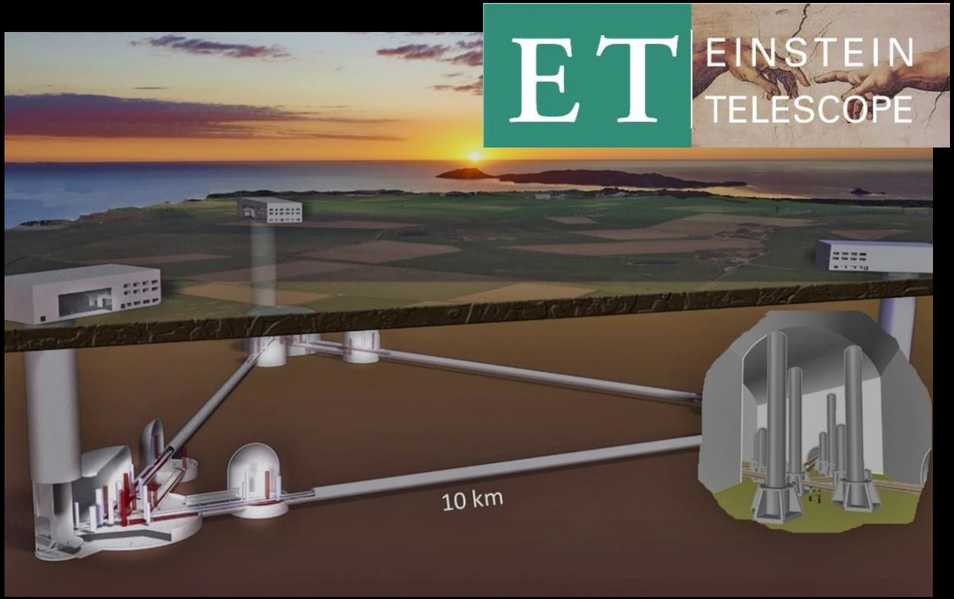




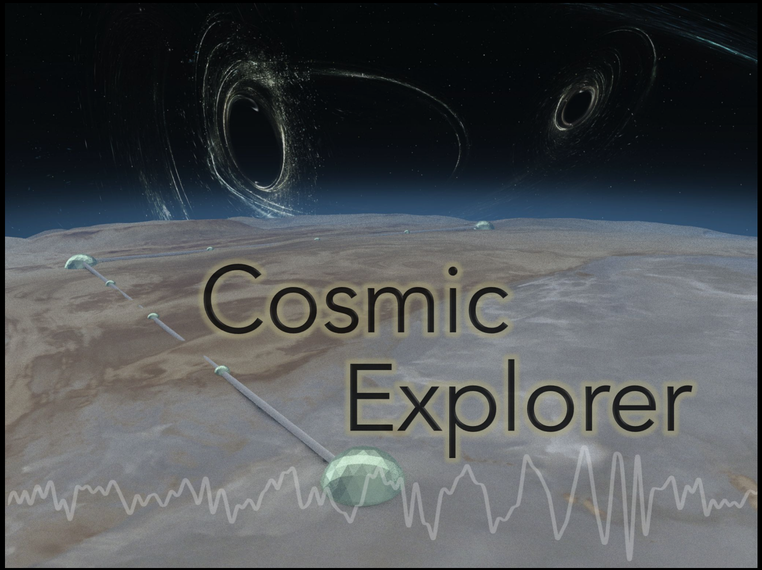
Detection horizon for black-hole binaries



Next-generation ground-based GW detectors

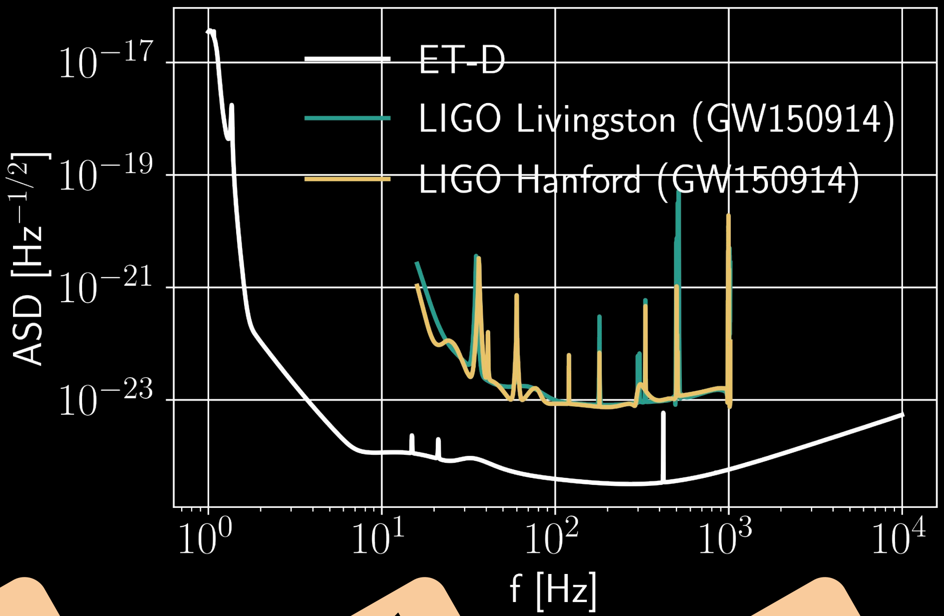


[Hild et al. 2008, Punturo et al. 2010, Maggiore et al. 2020, Branchesi et al. 2023]



[Reitze et al. 2019, Evans et al. 2010]

- ➔ **Number** of detections
- ➔ Detection with very **high SNR**

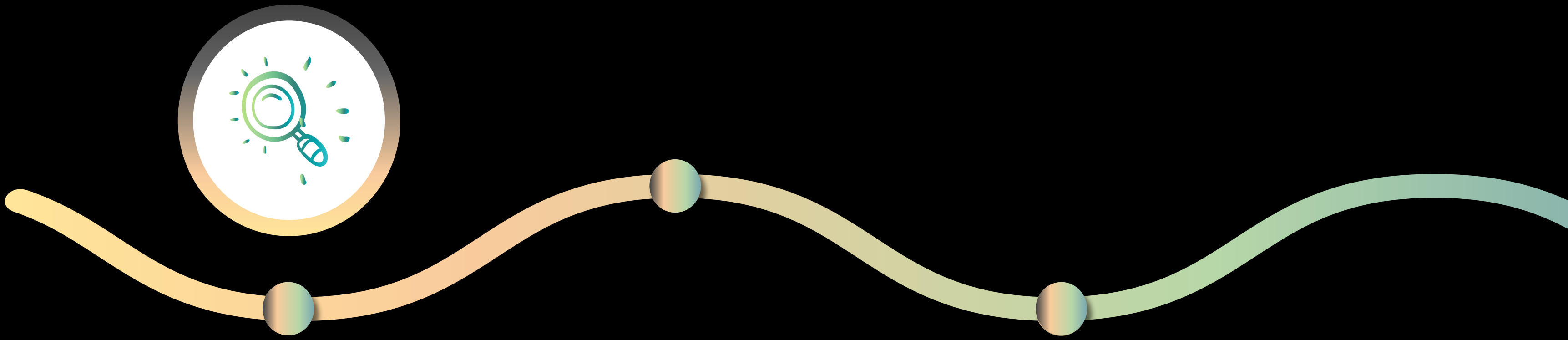


Astrophysics

Nuclear Physics

Fundamental Physics

Cosmology



2011

First ET Conceptual Design Report

2011

First ET Conceptual Design Report

2020

ET in the ESFRI Roadmap

2011

First ET Conceptual Design Report

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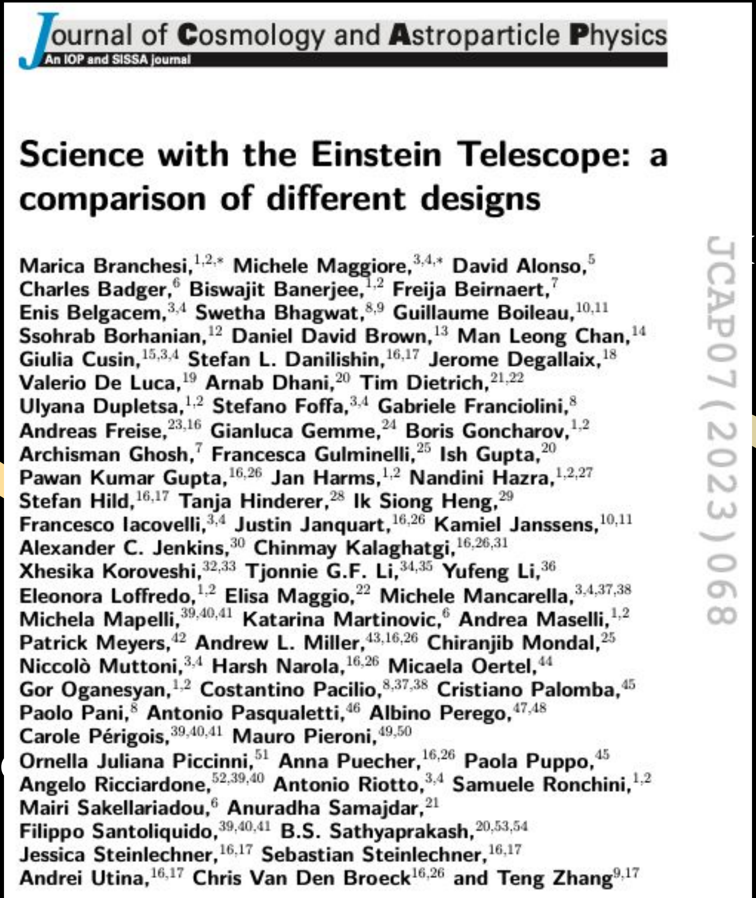
ET in the ESFRI Roadmap

2023

Science with the Einstein Telescope



Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Science with the Einstein Telescope: a comparison of different designs

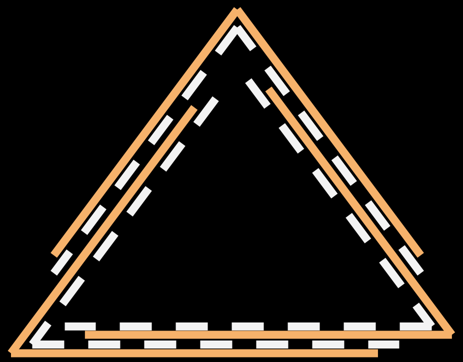
Marica Branchesi,[1,2,*] Michele Maggiore,[3,4,*] David Alonso,[5] Charles Badger,[6] Biswajit Banerjee,[1,2] Freija Beirnaert,[7] Enis Belgacem,[3,4] Swetha Bhagwat,[8,9] Guillaume Boileau,[10,11] Ssohrab Borhanian,[12] Daniel David Brown,[13] Man Leong Chan,[14] Giulia Cusin,[15,3,4] Stefan L. Danilishin,[16,17] 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]

JCAP07(2023)068

2023

Science with the Einstein Telescope

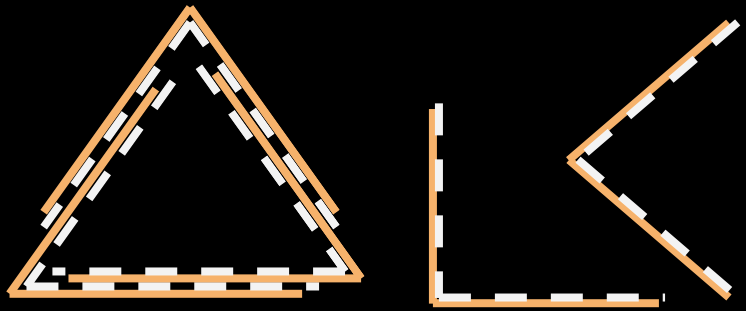
Reference Design of ET



The reference ET configuration consists of:

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

Different Configurations

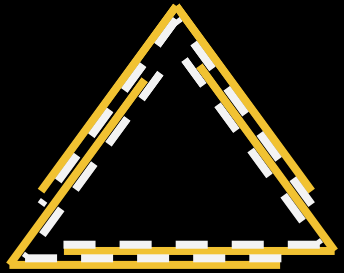


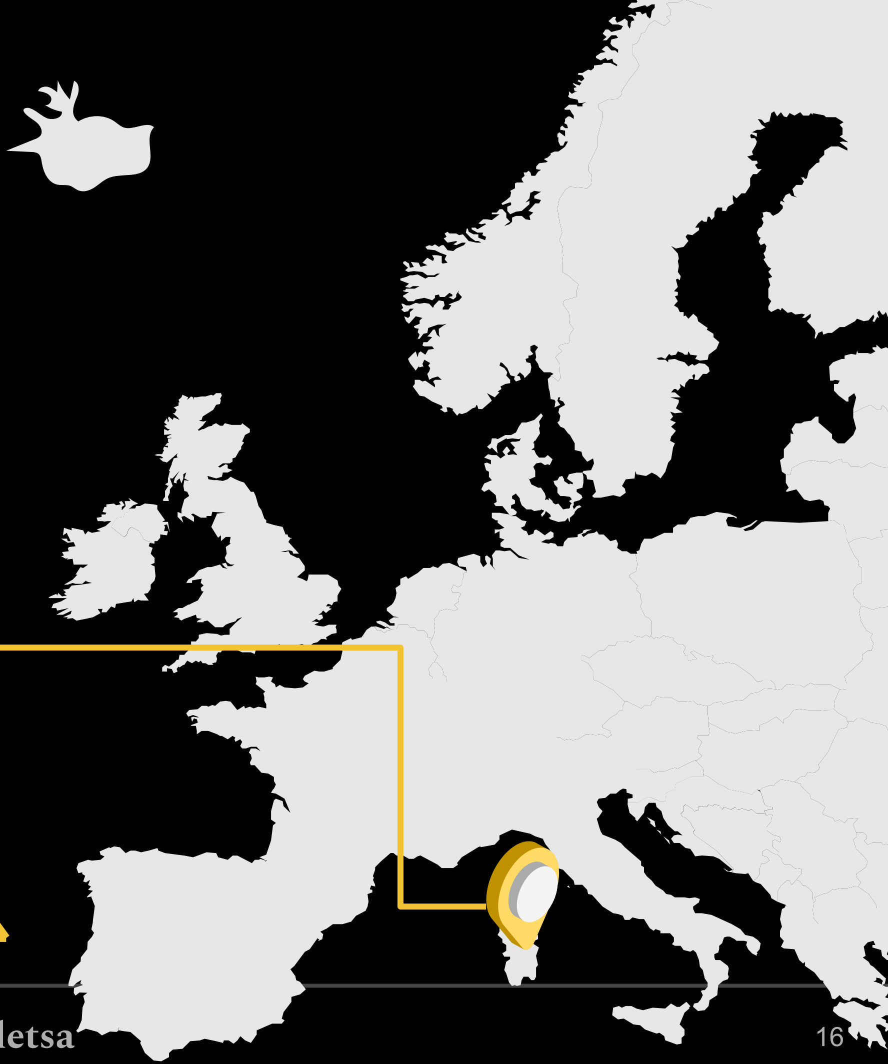
- Changes in geometry: triangle vs 2L, different arm lengths

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

SARDINIA

Sos Enattos site



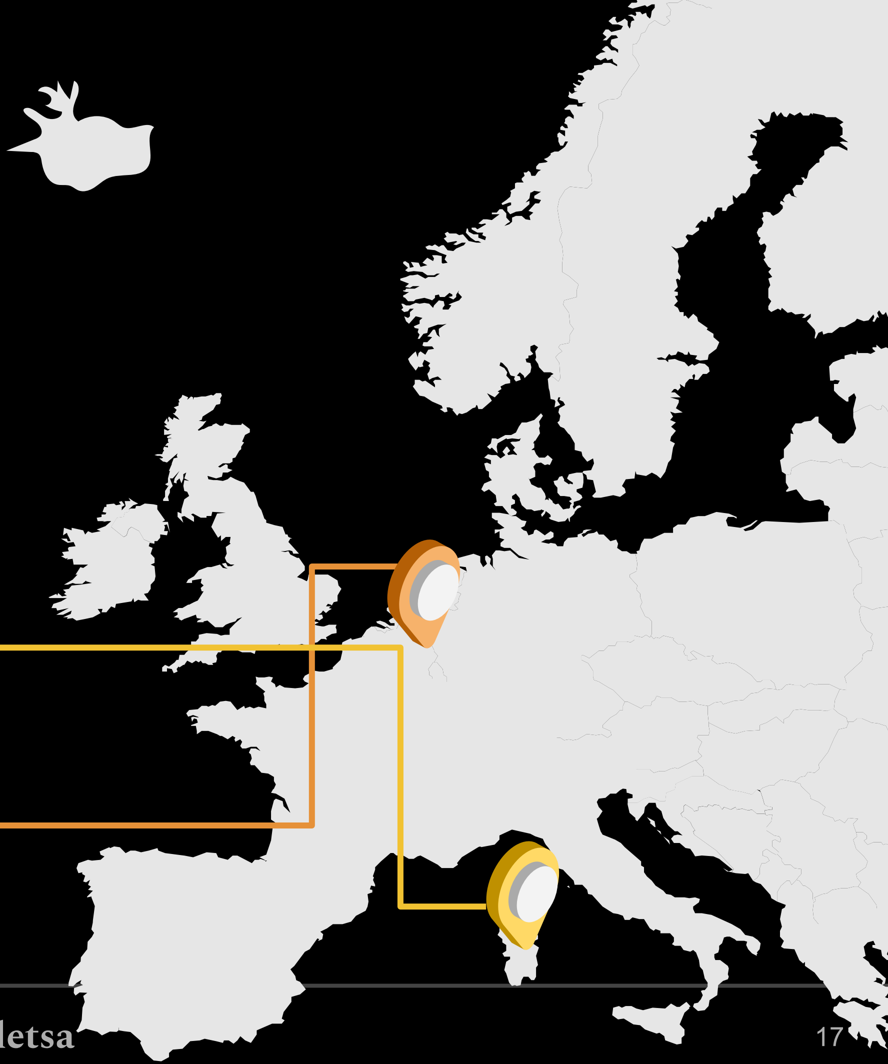


SARDINIA

Sos Enattos site

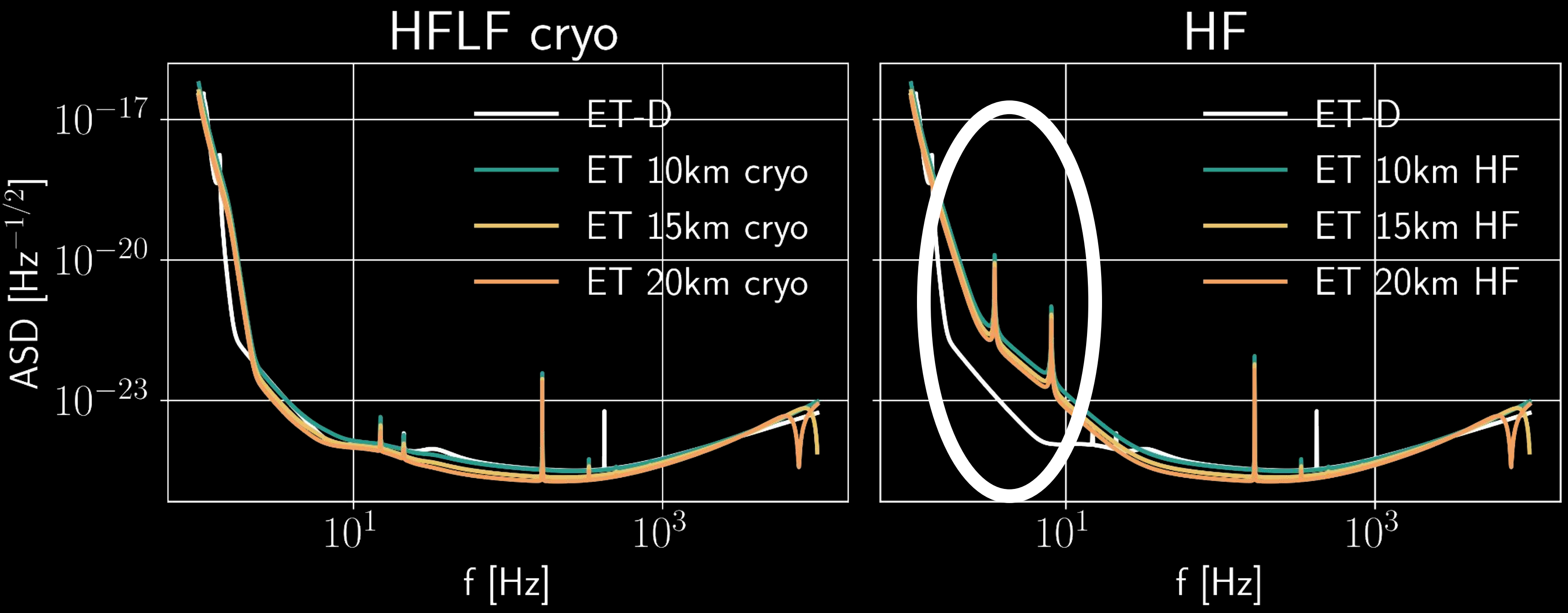
MEUSE-RHINE

Three-border region across Belgium, Germany and the Netherlands



Role of the low frequency instrument:

What happens if we have only the HF part?



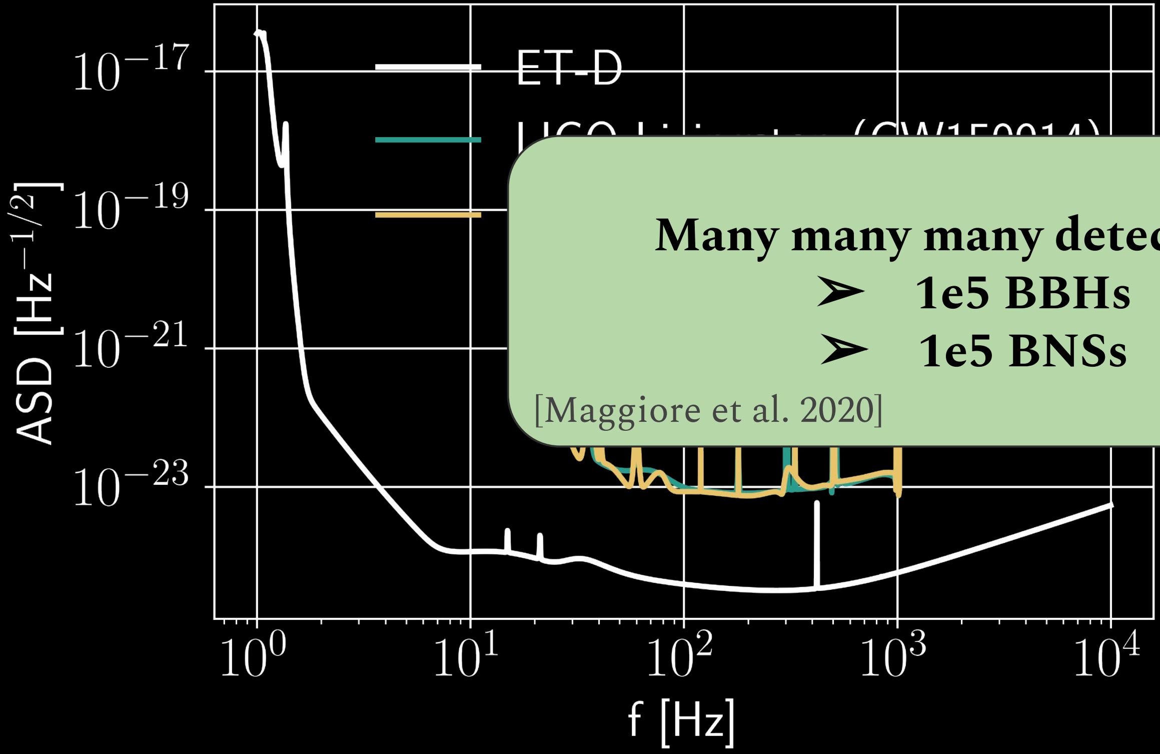
2035-2040

SCIENTIFIC TARGETS

TOWARDS NEXT-GENERATION

WHERE DO WE STAND?

From current detectors to next-generation



Many many many detections!

- ➢ **1e5 BBHs**
- ➢ **1e5 BNSs**

[Maggiore et al. 2020]

Increased detection rate for 3G detectors

Full Bayesian PE software is too expensive

Increased detection rate for 3G detectors

Full Bayesian PE software is too expensive

[Ashton et al. 2018]

From signals to parameters

Increased detection rate for 3G detectors

Full Bayesian PE software is too expensive

$$d = n + h(\vec{\theta}_{\text{true}})$$

$$p(\vec{\theta}|d) \propto \mathcal{L}(\vec{\theta}|d)\pi(\vec{\theta})$$

$$\mathcal{L}(d|\vec{\theta}) \propto \exp\left[-\frac{1}{2}\langle d - h(\vec{\theta})|d - h(\vec{\theta})\rangle\right]$$

[Ashton et al. 2018]

matched-filtering

templates bank

Increased detection rate for 3G detectors

Full Bayesian PE software is too expensive

Fisher matrix approximation

$$\mathcal{L}(d|\vec{\theta}) \propto \exp\left[-\frac{1}{2}\langle d - h(\vec{\theta})|d - h(\vec{\theta})\rangle\right]$$

$$h(\vec{\theta}) = h_0 + \Delta\theta^i h_i$$

Linear signal approximation

$$\mathcal{L}(d|\vec{\theta}) = \exp\left[-\frac{1}{2}\Delta\theta^i \langle h_i|h_j\rangle \Delta\theta^j\right]$$

Gaussian Likelihood

$$\Delta\theta^i = \theta^i - \theta^i_{\text{inj}}$$

Fisher matrix approximation

[Cutler & Flanagan 1994, Vallisneri et al. 2008, Rodriguez et al. 2013]

$$\mathcal{L}(d|\vec{\theta}) \propto \exp\left[-\frac{1}{2}\langle d - h(\vec{\theta})|d - h(\vec{\theta})\rangle\right]$$

Computationally fast!

$$h(\vec{\theta}) = h_0 + \Delta\theta^i h_i$$

Linear signal approximation

$$\mathcal{L}(d|\vec{\theta}) = \exp\left[-\frac{1}{2}\Delta\theta^i \langle h_i|h_j\rangle \Delta\theta^j\right]$$

Gaussian Likelihood

$$\Delta\theta^i = \theta^i - \theta^i_{\text{inj}}$$

Fisher matrix approximation

[Cutler & Flanagan 1994, Vallisneri et al. 2008, Rodriguez et al. 2013]

Cross-checked inside the OSB9 division of ET!

gwbench

S. Borhanian,
2021

GitLab link

TiDoFM

Li et al.
2022

GitHub link

GWFAST

F. Iacovelli,
M. Mancarella, et al.
2022

GitHub link

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GWFISH

and more …

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JCAP07(2023)068

Science Reference Paper for the **CoBA study**

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

(arXiv:2303.15923)

G S
S I

JCAP 07 (2023) 068

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Coalescence of compact binaries

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Multi-messenger astrophysics

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Stochastic backgrounds

· 05 ·

Impacts of detector designs on specific science case

· 06 ·

The role of the null stream in the triangle-2L comparison

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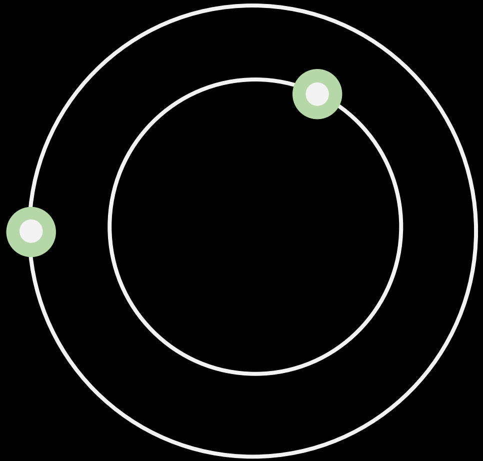
~ 720 000

1 year of BNS events



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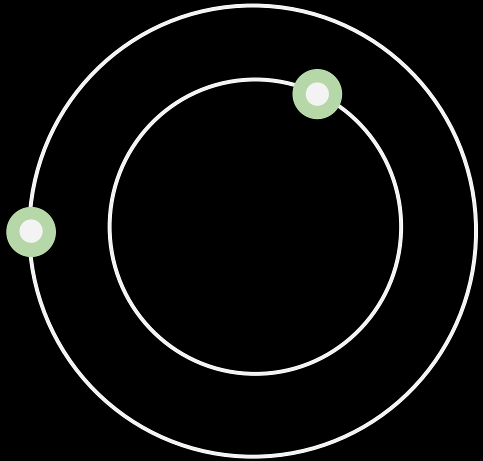


IMRPhenomD_NRTidalv2

KNe

Low redshift (~0.3=0.4)

GRBs

High redshift

1

Ability to localize the source

1

Ability to localize the source

2

Achievable redshift

1

Ability to localize the source

2

Achievable redshift

3

Pre-merger detection

1

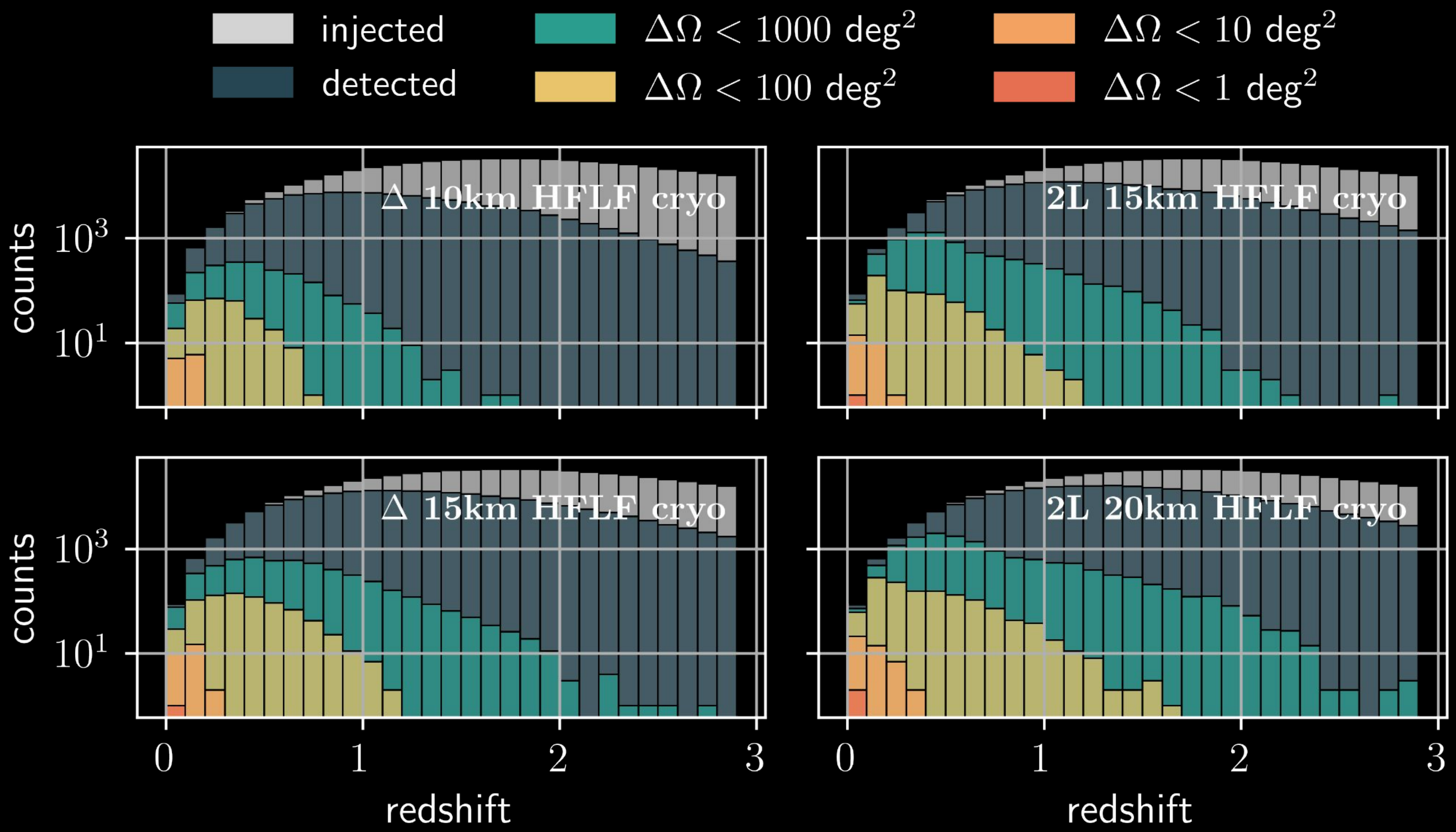
Ability to localize the source

2

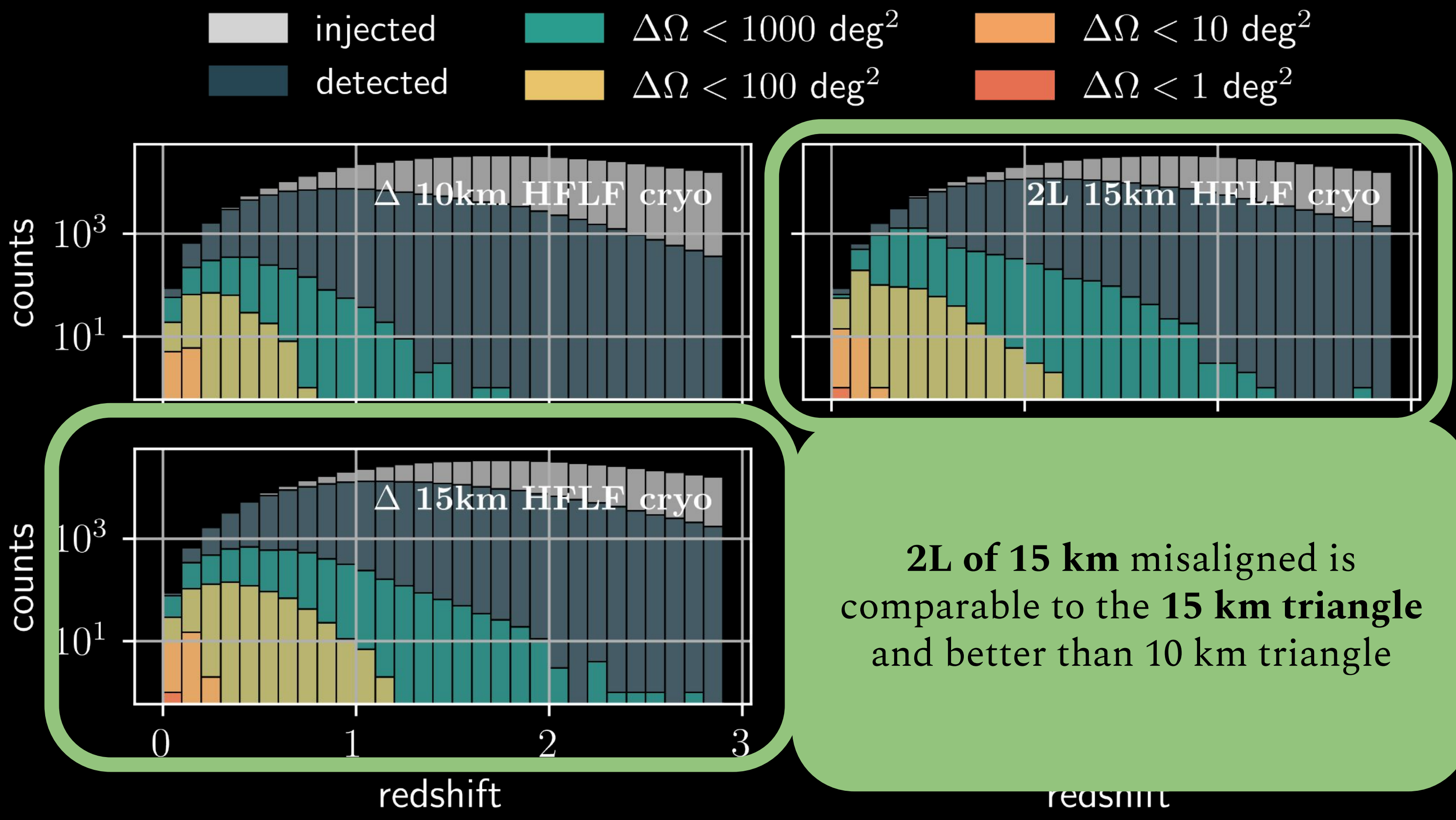
Achievable redshift

3

Pre-merger detection



injected
detected
$\Delta\Omega < 1000$ deg^2
$\Delta\Omega < 100$ deg^2
$\Delta\Omega < 10$ deg^2
$\Delta\Omega < 1$ deg^2
Δ 10km HFLF cryo
2L 15km HFLF cryo
Δ 15km HFLF cryo
2L 20km HFLF cryo
counts
10^3
10^1
0
1
2
3
redshift



2L of 15 km misaligned is comparable to the **15 km triangle** and better than 10 km triangle

Full (HFLF cryo) sensitivity detectors								
$\Delta\Omega_{90\%}$ [deg^2]	All orientation BNSs				BNSs with Θ_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
10000	2112	5441	7478	13482	272	632	1045	1725

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HF sensitivity detectors

$\Delta\Omega_{90\%}$ [deg^2]	All orientation BNSs				BNSs with $\Theta_v < 15°$			
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40	4	10	20	47	0	5	6	17
100	14	53	76	144	7	33	35	64
10000	145	548	1662	3378	80	336	672	1302

Significantly smaller number of well-localized events

Full (HFLF cryo) sen								
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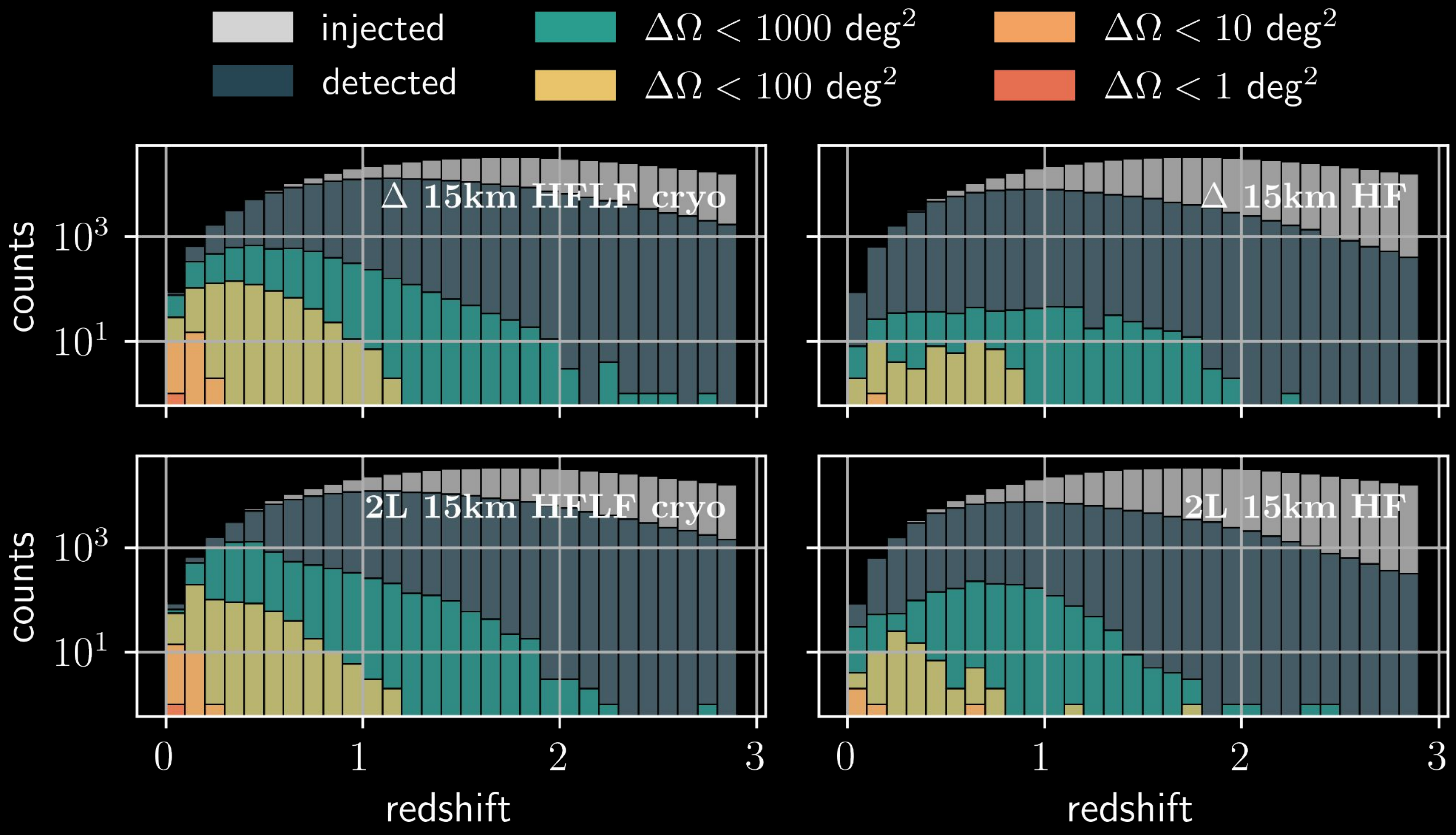
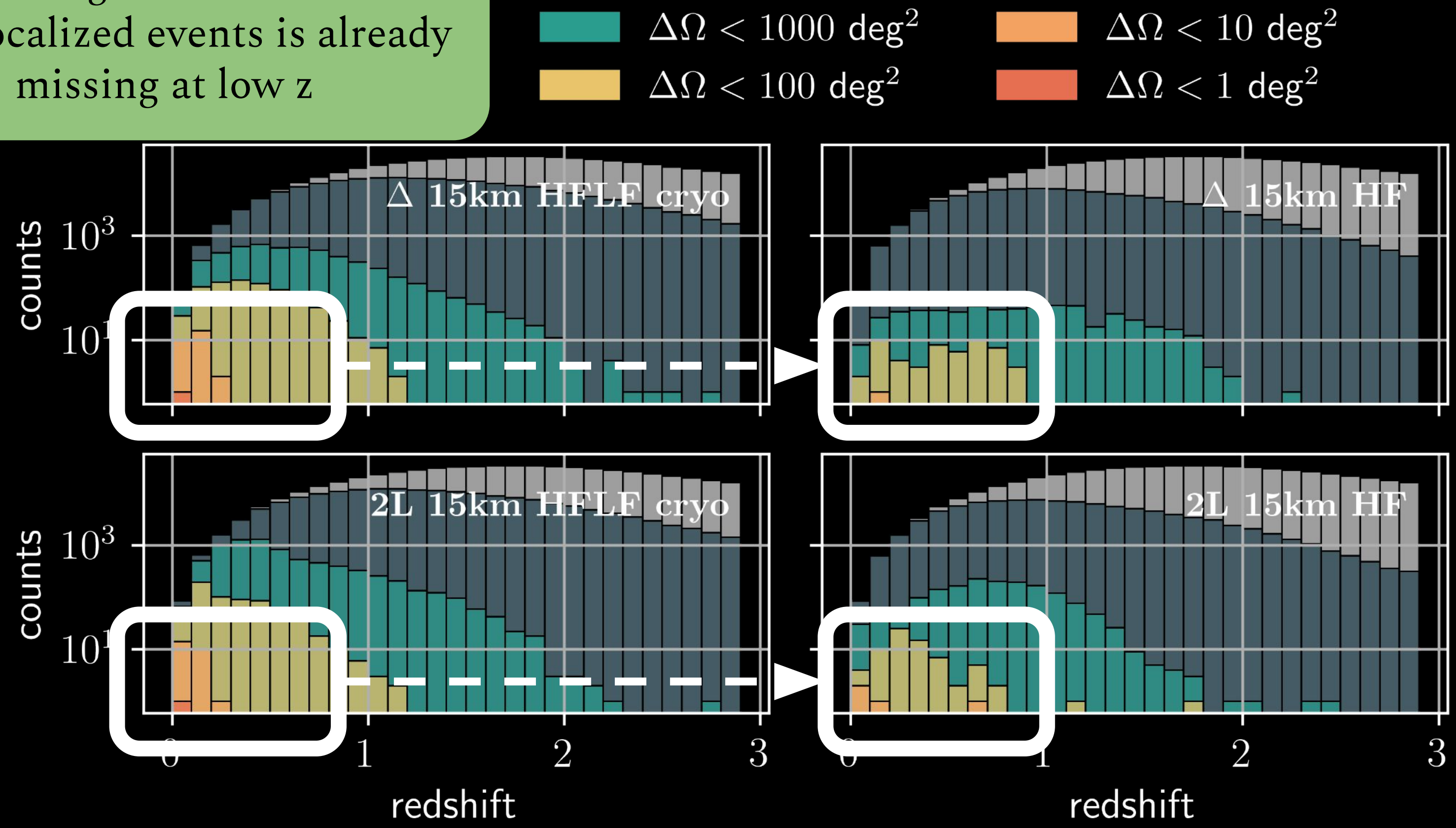


injected
detected
ΔΩ < 1000 deg²
ΔΩ < 100 deg²
ΔΩ < 10 deg²
ΔΩ < 1 deg²
Δ 15km HFLF cryo
Δ 15km HF
2L 15km HFLF cryo
2L 15km HF
counts
10³
10¹
0
1
2
3
redshift

A large fraction of well-localized events is already missing at low z



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40	4	10	20	47	0	0	2	2
100	14	53	76	144	0	5	6	17
10000	145	548	1662	3378	7	33	35	64

Decrease of well-localized events is more severe for the triangular configurations

For the **on-axis** events the **percentage decrease** of well-localized events is **smaller** than for the randomly oriented ones

Full (HFLF cryo) sensitivity detectors

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40	**78**	215	162	350
100	**280**	764	644	1282
10000	**2112**	5441	7478	13482

2L of 15 km HF and 2L 20 km HF are worse than the **10 km triangle** for **randomly oriented** systems

HF sensitivity detectors								
$\Delta\Omega_{90\%}$ [deg^2]	All orientation BNSs				BNSs with $\Theta_v < 15°$			
	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
10000	145	548	**1662**	**3378**	80	336	672	1302

Full (HFLF cryo) sensitivity detectors								
$\Delta\Omega_{90\%}$ [deg^2]	All orientation BNSs				BNSs with Θ_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
10000	2112	5441	7478	13482	**272**	632	1045	1725

…nsitivity detectors								
	…BNSs				BNSs with Θ_v < 15°			
				2L 20	Δ10	Δ15	**2L 15**	**2L 20**
				5	0	0	**2**	**2**
				47	0	5	**6**	**17**
				144	7	33	**35**	**64**
				3378	80	336	**672**	**1302**

2L of 15 km HF only is comparable to the **full 10 km triangle** for **on-axis** events

1

Ability to localize the source

2

Achievable redshift

3

Pre-merger detection

The importance of pre-merger alerts

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)
- To probe the structure of the outer sub-relativistic ejecta, early UV emission

[**B. Banerjee** et al., *Astronomy&Astrophysics* 678 (2023) A126]

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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**
Δ10 km	**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
Δ15 km	**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	**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	**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

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2L 15 km better than **10 km triangle**

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15 km triangle better than **10 km triangle** and **2L 15 km**, comparable to **2L 20 km**

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Similar performances for **on-axis** events

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**
Δ10 km	**100**	0	0	0	0	0	0
	1000	0	0	4	0	0	1
	All detected	0	3	317	0	0	26
Δ15 km	**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	**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	**100**	0	0	3	0	0	0
	1000	0	0	13	0	0	6
	All detected	2	11	1535	0	1	146

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HF sensitivity detectors

Configuration	$\Delta\Omega_{90\%}$ [deg²]	All orientation BNSs			BNSs with $\Theta_v < 15°$		
		30 min	10 min	1 min	30 min	10 min	1 min
Δ10 km	100	0	0	0	0	0	0
	1000	0	0	4	0	0	1
	All detected	0	3	317	0	0	26
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NO localized
pre-merger detections!

Dramatic **decrease** of
pre-merger alerts

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

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- **Data analysis** for the next-generation poses a great **challenge**

ulyana.dupletsa@gssi.it

G S
S I

EINSTEIN TELESCOPE

2035-2040

SCIENTIFIC TARGETS

TOWARDS NEXT-GENERATION

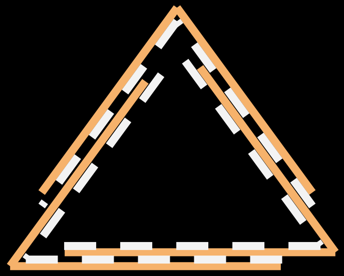
WHERE DO WE STAND?

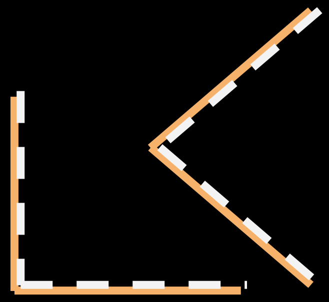
Thank You!

Backup

What is a fair comparison?

10 km





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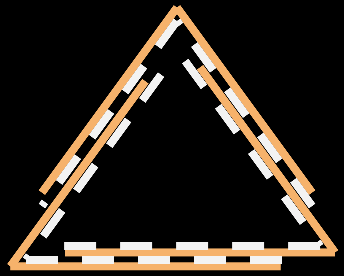

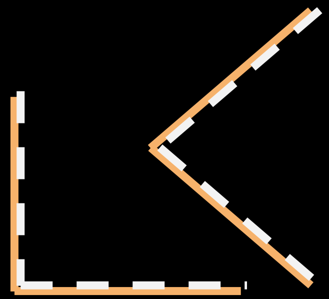

1

Vacuum length

Δ: 4x3x10km = 120km
2L: 4x2x15km = 120km

What is a fair comparison?

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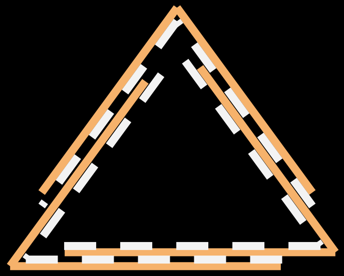

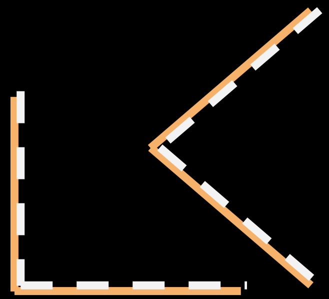

15 km

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2

Excavation volume

For triangle larger tunnel diameter, but similar excavation volumes

What is a fair comparison?

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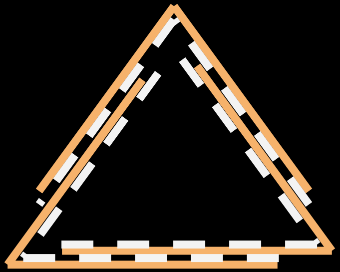

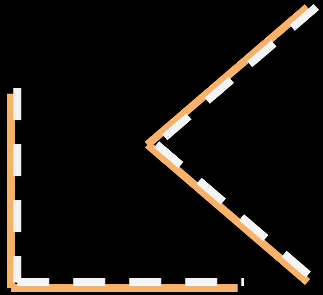

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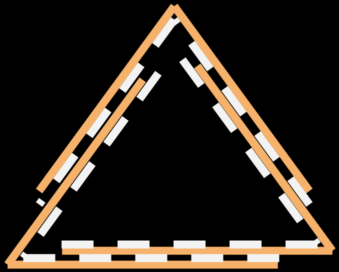
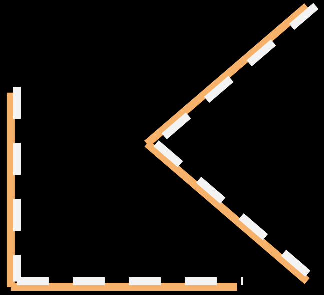
Cost & maintenance

1 site and 6 instruments vs 2 sites and 4 instruments

What is a fair comparison?

10 km





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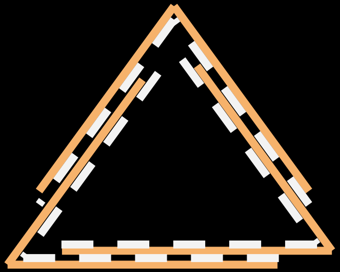

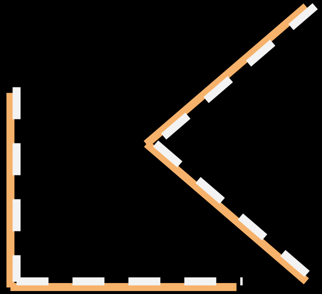

15 km

1. Vacuum length
2. Excavation volume
3. Cost & maintenance

2L of 15 km and triangle of 10 km are comparable!

Starting Assumptions

BNSs

- **IMRPhenomD_NRTidalv2 (tidal effects)**
- **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}**
- **1 year of observations**

BBHs

- **IMRPhenomXPHM (precessing spins and higher order modes)**
- **Mixing of isolated evolution and dynamical evolution channels using the code FASTCLUSTER**
- **1 year of observations**

Populations as in Santoliquido et al 2021, Mapelli et al. 2022

Cosmology: ET + VRO

- Joint GW-kilonova detections!
- 1 year of observations
- 115 joint detections for 2L-20km-cryo
- Dependence on BNS merger rate normalization

Cosmology: ET + VRO

HFLF cryogenic		
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ10 km	0.009	0.832
Δ15 km	0.007	0.303
2L 15 km	0.006	0.370
2L 20 km	0.004	0.243

HF only		
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ10 km	0.065	1.23
Δ15 km	0.057	1.86
2L 15 km	0.066	1.31
2L 20 km	0.031	1.22

Cosmology: ET + VRO

Dramatic reduction of joint detections without LF in both cases!

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