GEMMA2 WORKSHOP - 16-19 SET 2024. LA SAPIENZA, ROME, ITALY

ENVISIONING TOMORROW: INAF PROSPECTS AND CHALLENGES FOR MULTI-MESSENGER ASTRONOMY IN THE ERA OF EINSTEIN TELESCOPE

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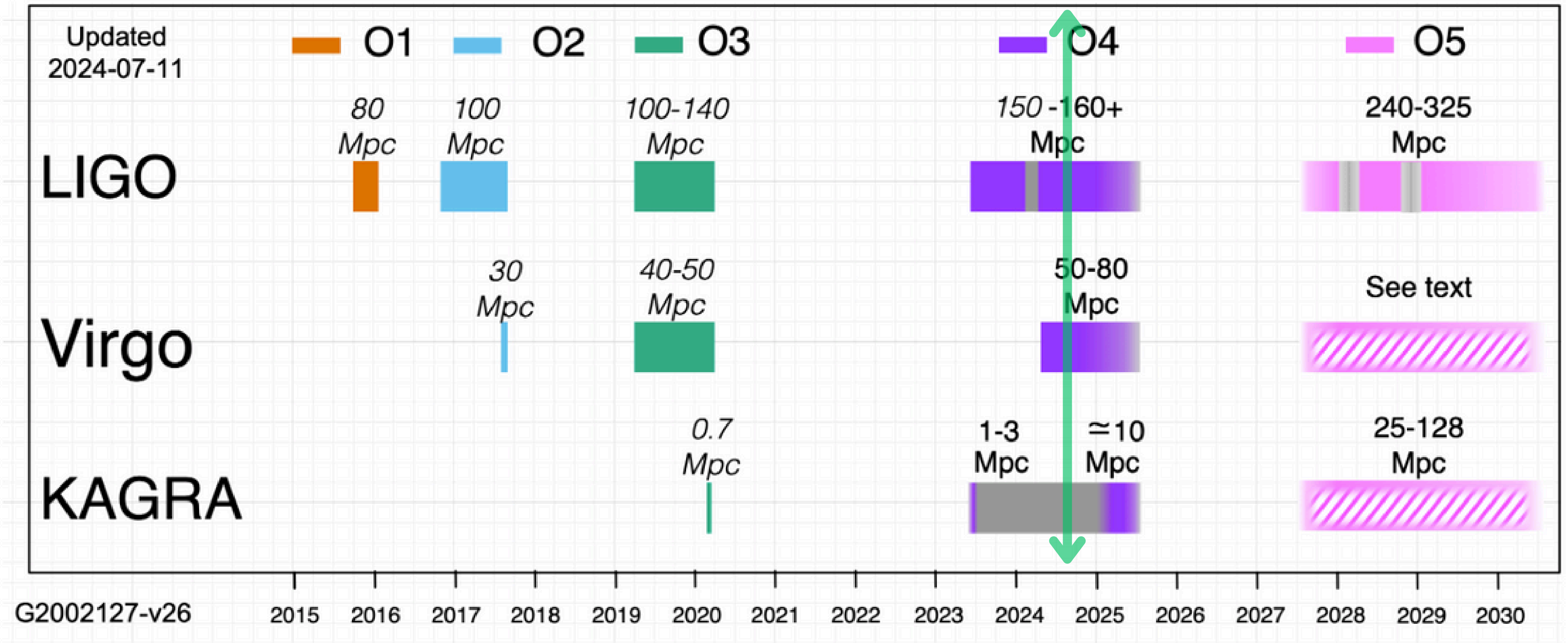
Istituto Nazionale di Astrofisica

Next LVK Observing runs

https://observing.docs.ligo.org/plan/



O4 volume = 3*O3 volume
O5 volume = 15*O3 volume

O4 LOCALIZATION: sky-area and volume

		BNS	NS-BH	BBH
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	270^{+34}_{-20}	330^{+24}_{-31}	280^{+30}_{-23}
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}
		Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.
O3	HLV	120^{+19}_{-24}	860^{+150}_{-150}	16000^{+2200}_{-2500}
O4	HLVK	52^{+10}_{-9}	430^{+100}_{-78}	7700^{+1500}_{-920}

Rates of BNS and NSBH detections still very uncertain

R_{BNS}= 110- 3840 Gpc^{-3} yr^{-1} R_{NSBH}= 0.6 - 1000 Gpc^{-3} yr^{-1} R_{BBH}= 25 - 109 Gpc^{-3} yr^{-1}

Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}

Abbott et al. 2020, LRR

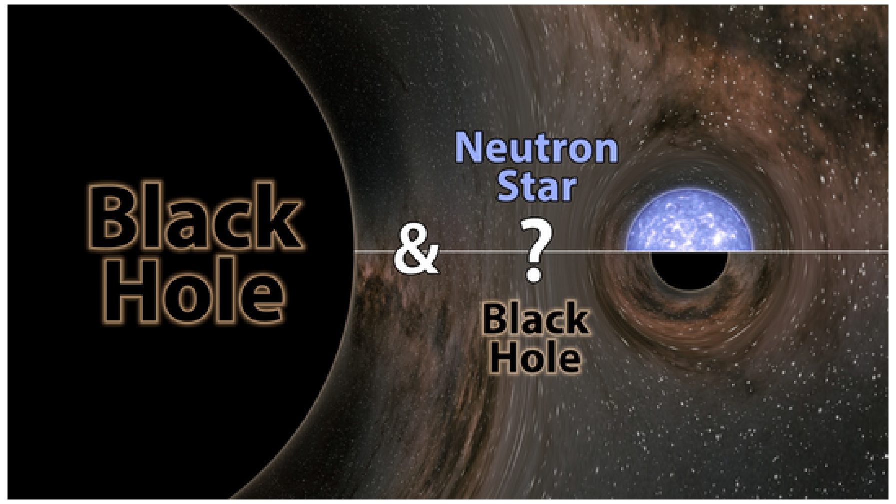
Notable Events Discovered after GW170817

The GW ERA

GW190814

Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object

Abbott et al. 2020, ApJL, 896



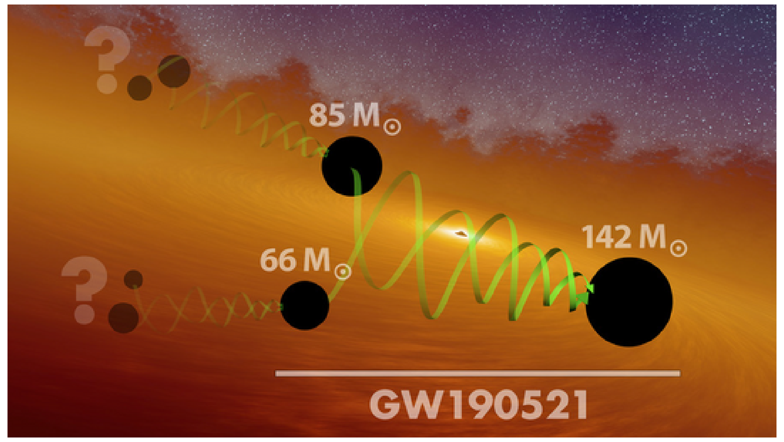
Sky localization of 18.5 deg^2
Luminosity distance 235 Mpc

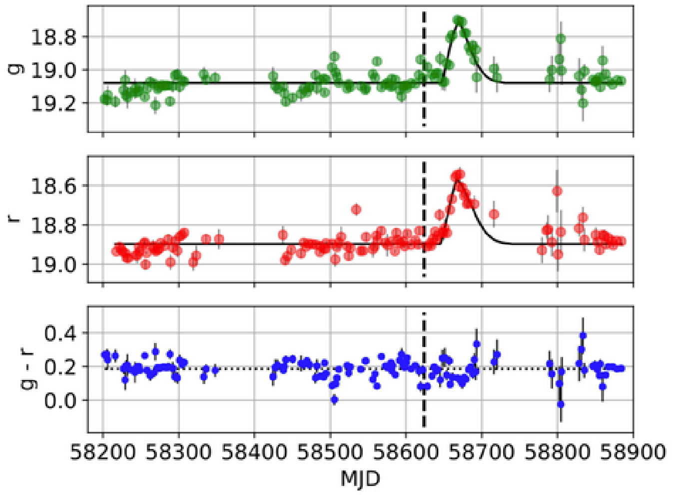
Consistent with both BBH and NSBH scenarios
In the NSBH, observation results can be explained by the large mass ratio

GW190521

A Binary Black Hole Merger with a Total Mass of 150 Msun

Abbott et al 2020, PRL, 125





Graham et al 2020, PRL 124

BBH in the accretion disk of a supermassive black hole?

ZTF detected a candidate counterpart(!?)

- EM flare close to AGN
  34 days after the GW event consistent with expectations for a kicked BBH merger in the accretion disk AGN
- 765 deg2 localization area
- ZTF observed 48% of the 765 deg^2 (90% c.r.)

GW190425

another BNS detection - Total mass larger than any known BNS (5σ from mean of Galactic BNS)

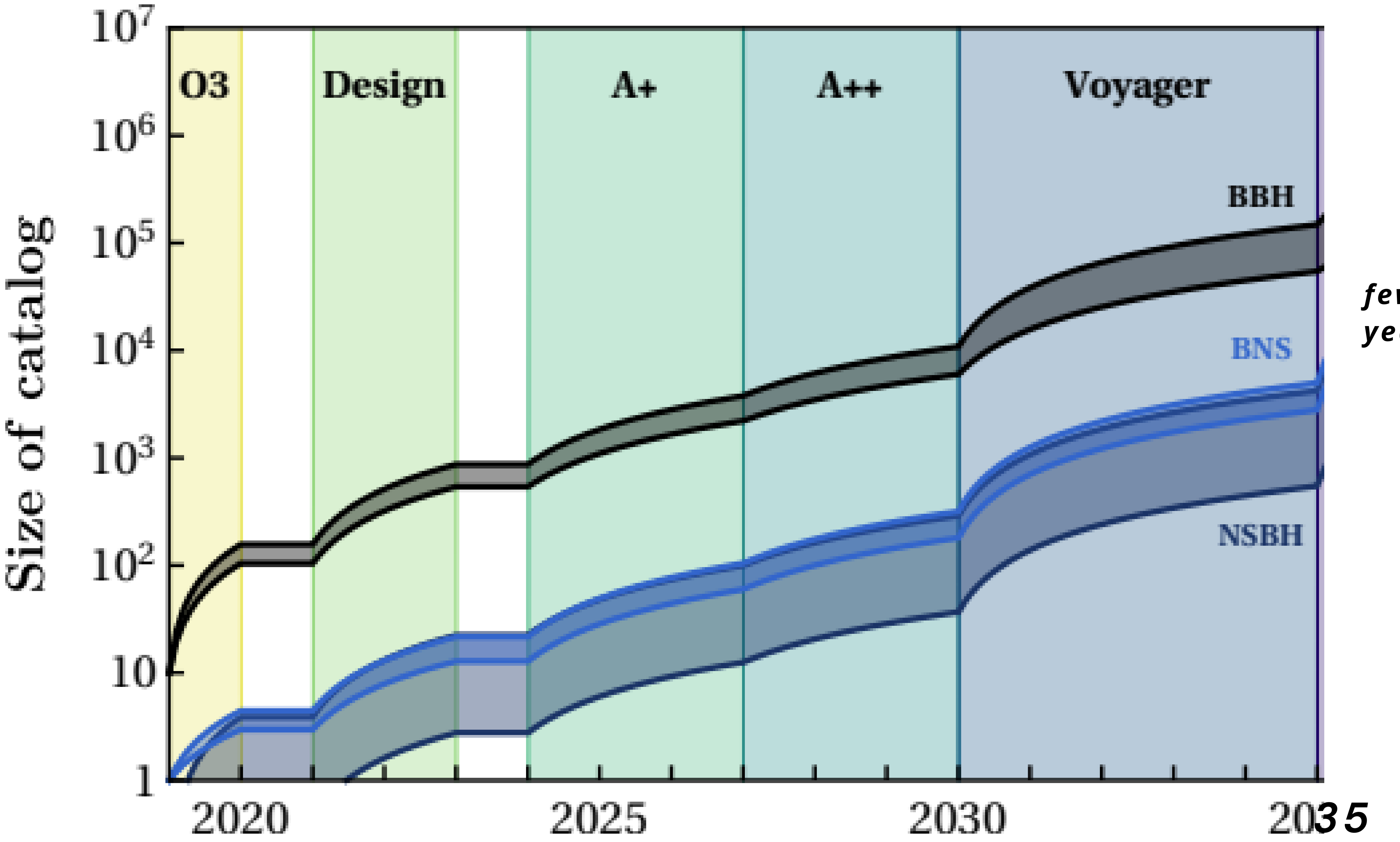
GW230529

Observation of Gravitational Waves from the Coalescence of a 2.5 - 4.5 M⊙ (mass gap) Compact Object and a Neutron Star
no EM couterpart: poor sky-localization

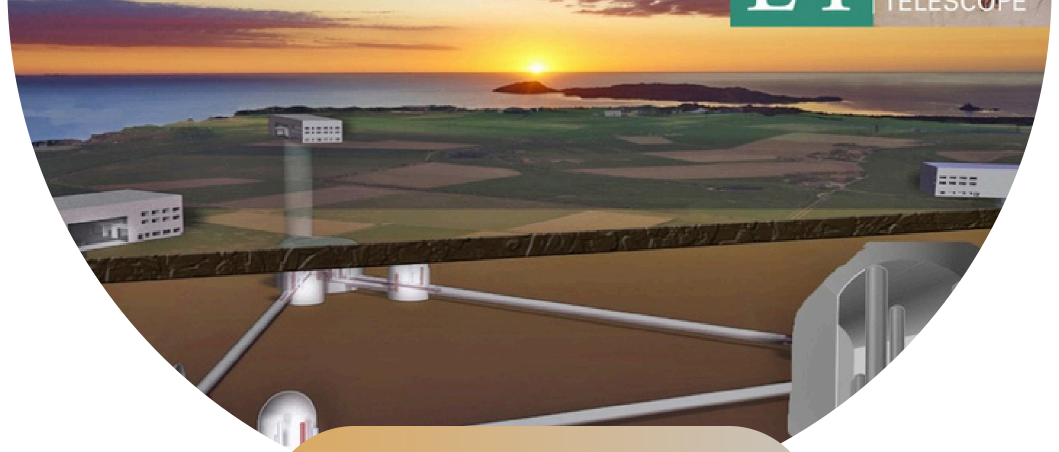
https://arxiv.org/abs/2404.04248

Next LVK Observing runs

... the number of detections is expected to quickly raise



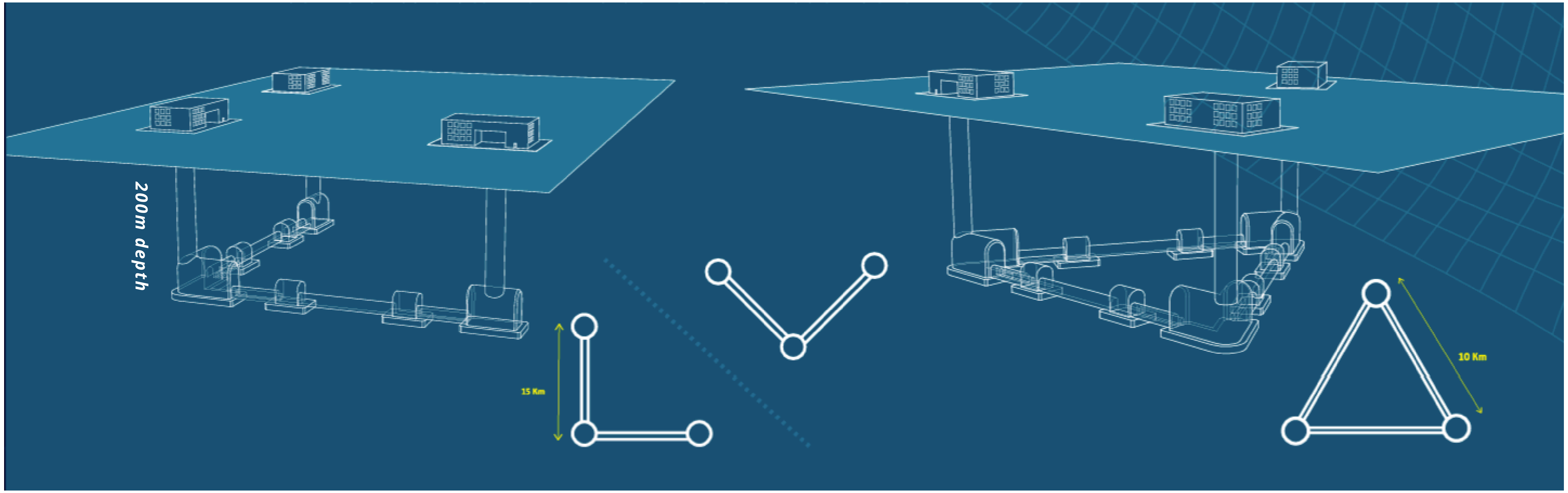
few hundred of BNS detections per year are expected with current GW detectors up to z = 0.2



EINSTEIN TELESCOPE

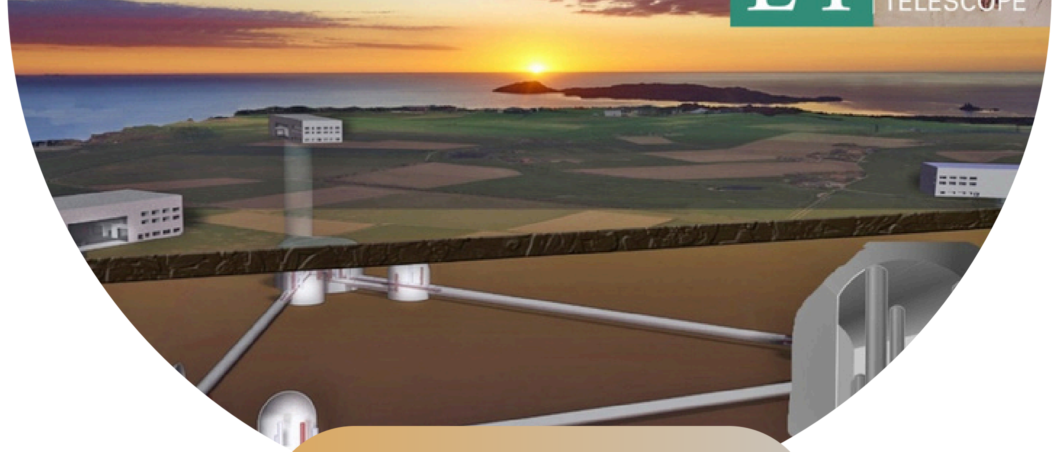
3G detectors: ET

- new infrastructure capable to host future upgrades
- large improvement in sensitivity
- extended frequency, especially below 10Hz



ET collaboration with > 1600 scientists

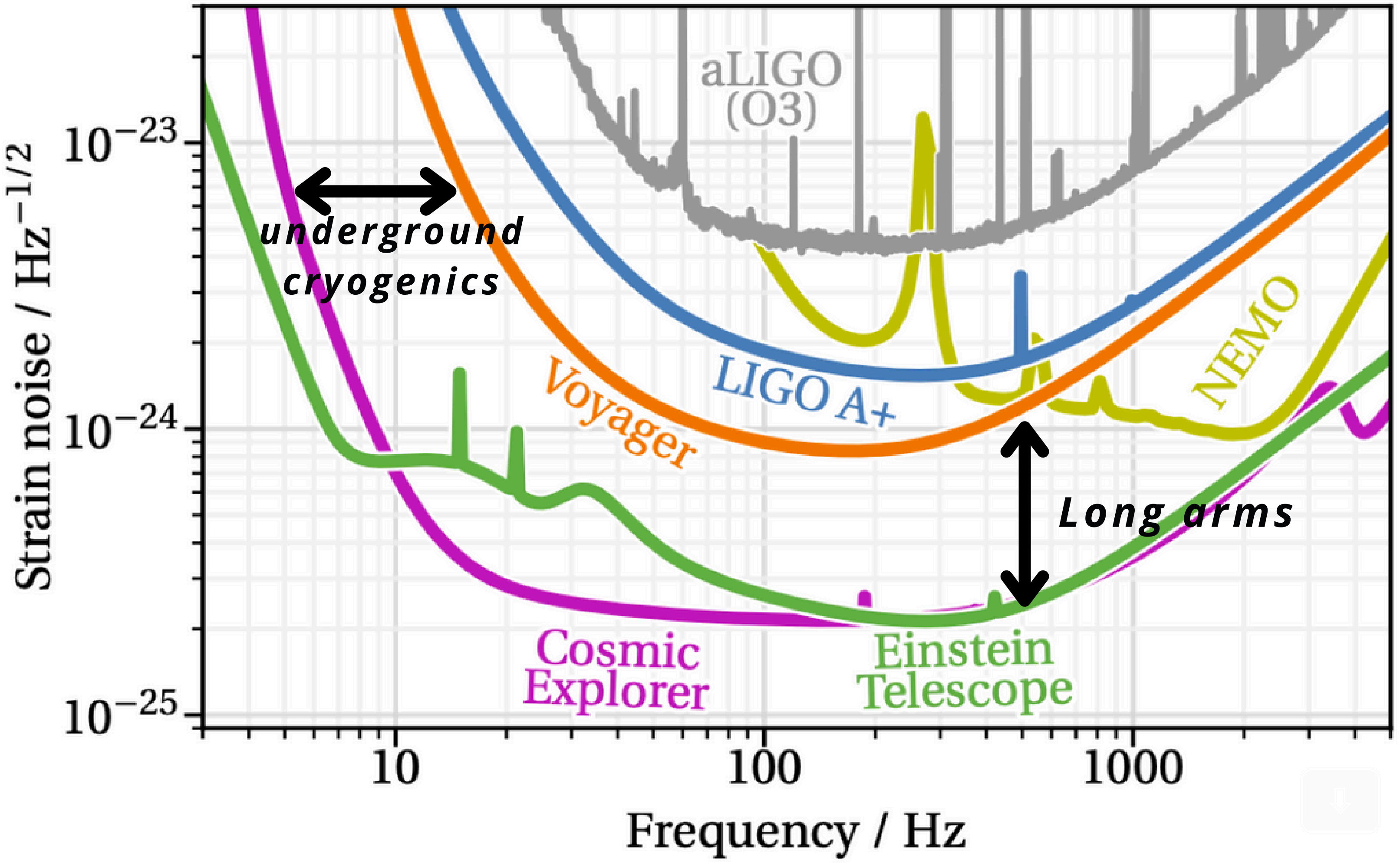
Proposed more than 10 years ago (Punturo et al. (2010)) and included in ESFRI roadmap in 2021.
Science case in Maggiore et al. (2020)



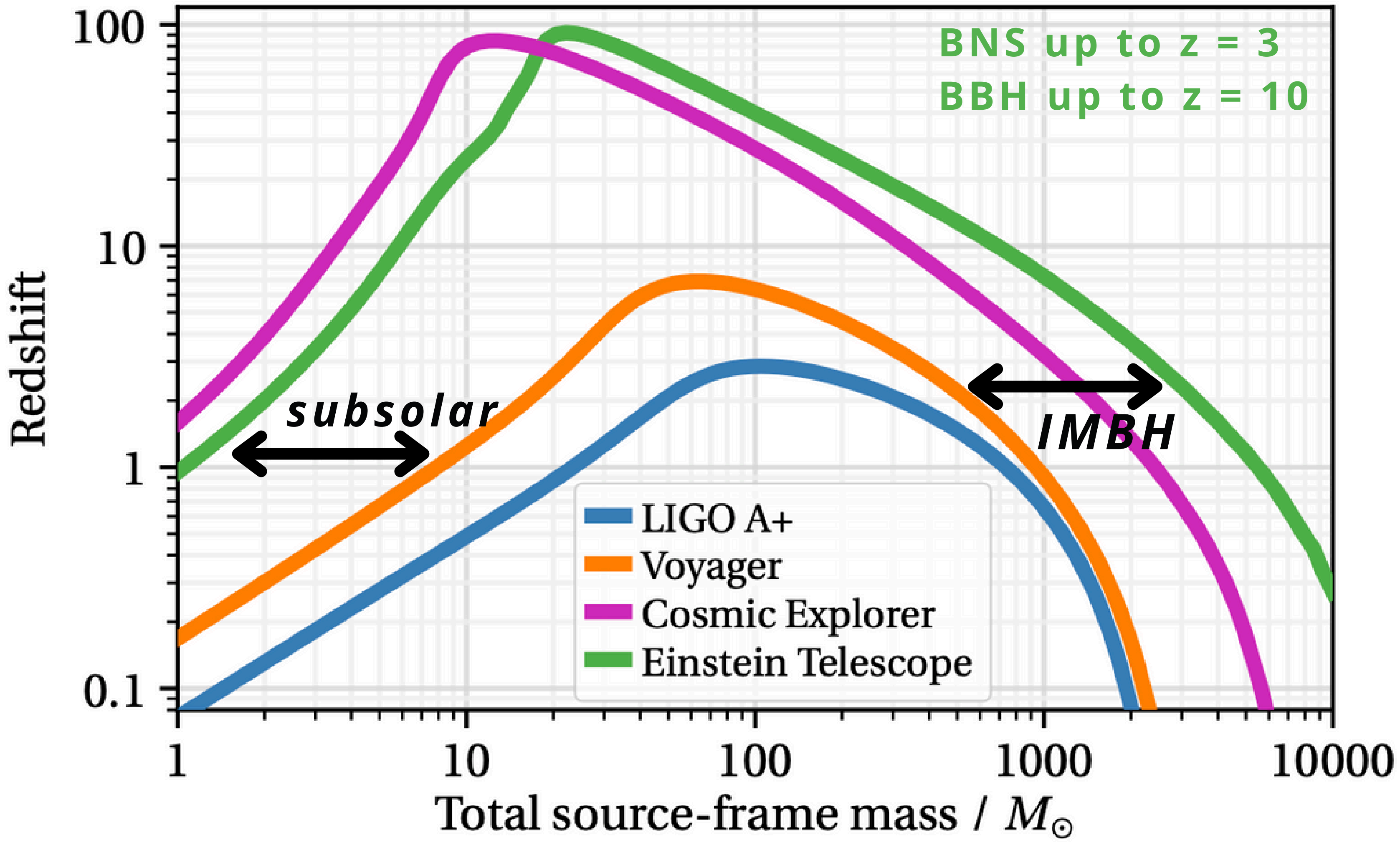
3G detectors: ET

How much do we gain?

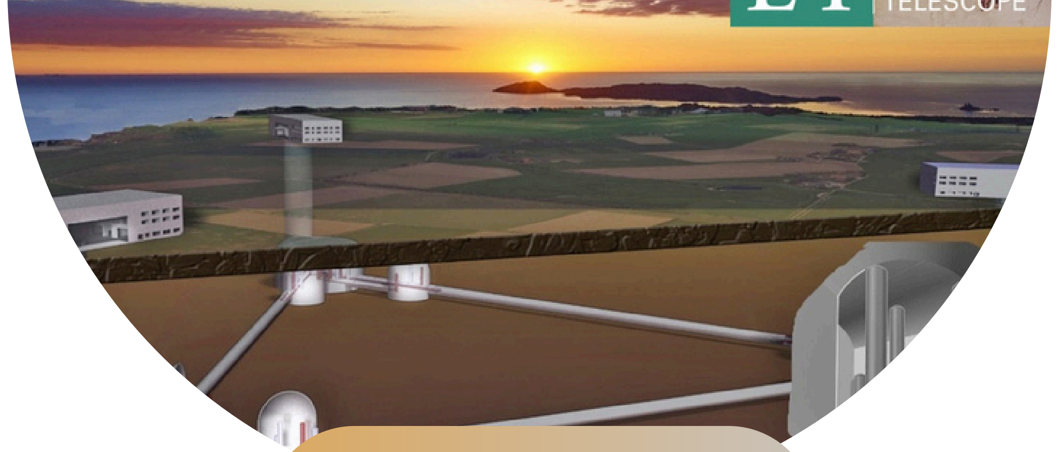
Sensitivities will improved more than 10 times compared to LVK!



Access UNEXPLORED MASS up to 10^3 Mo



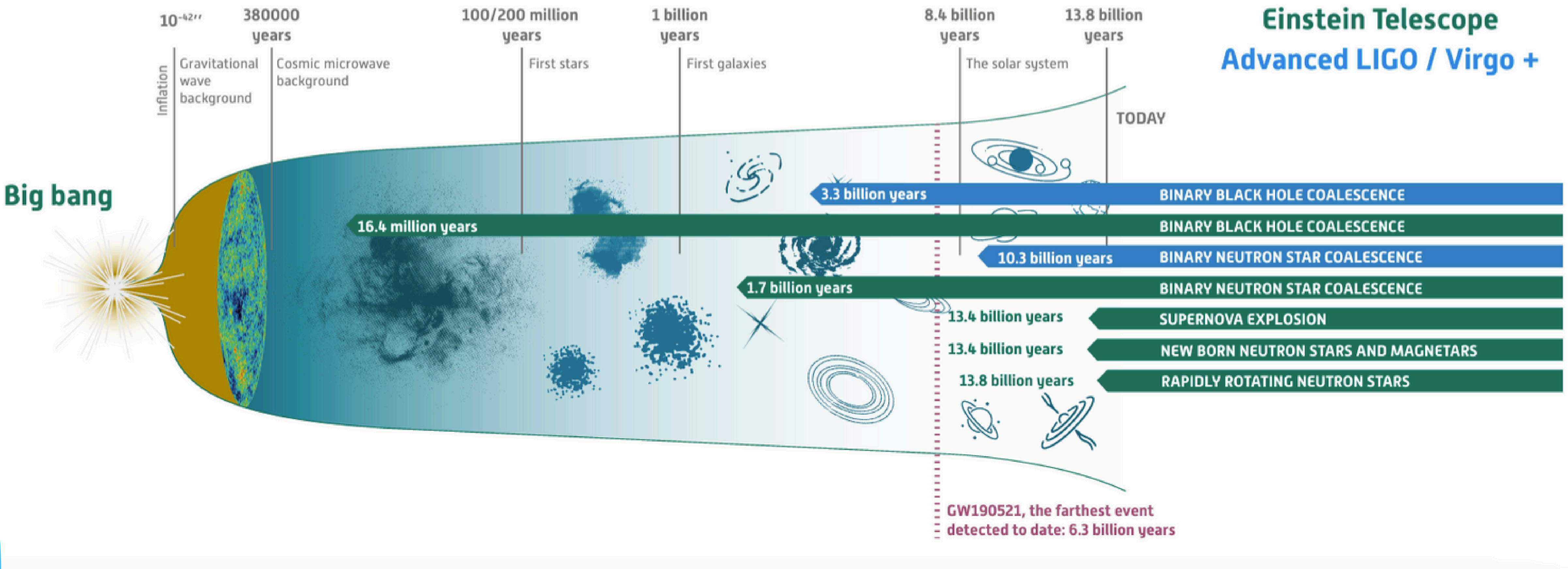
Gossan, Sarah & Hall, Evan & Nissanke, Samaya et al 2022
https://cosmicexplorer.org/sensitivity.html

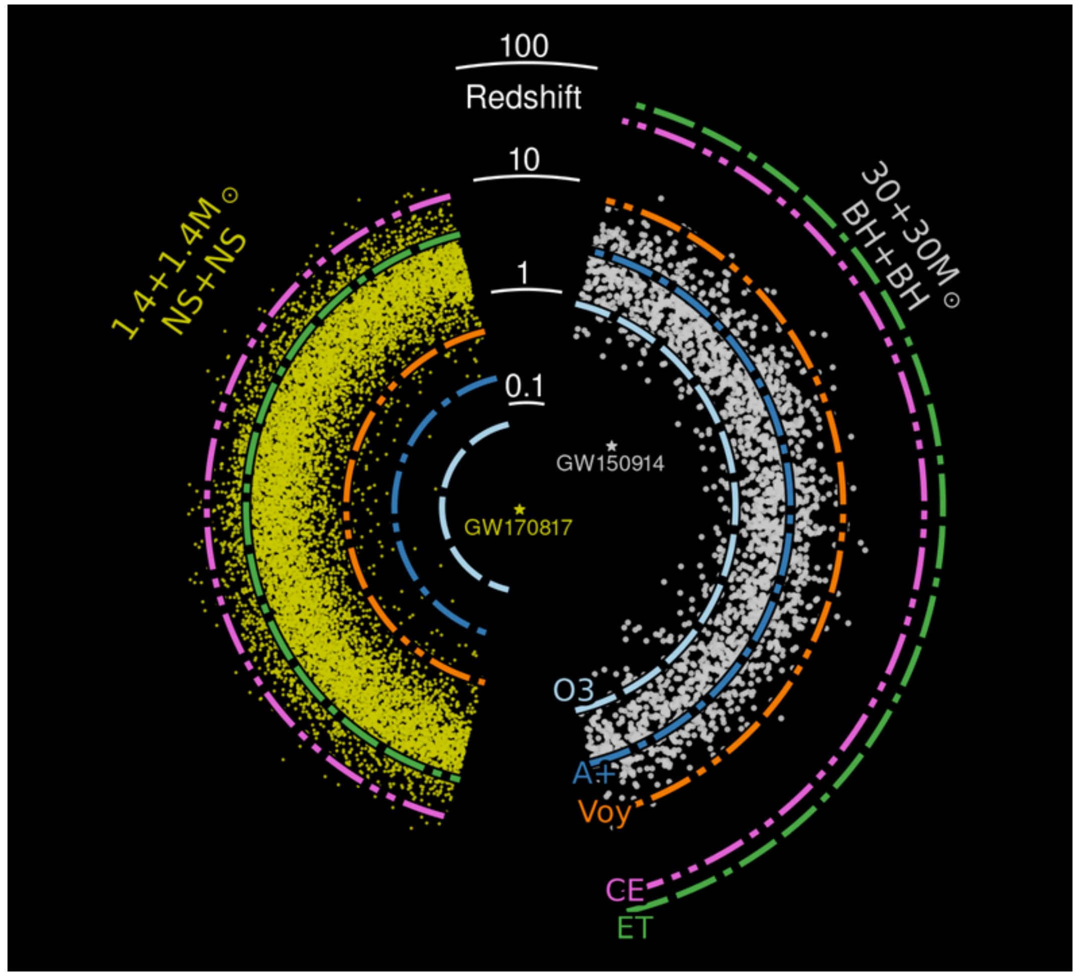


3G detectors: ET

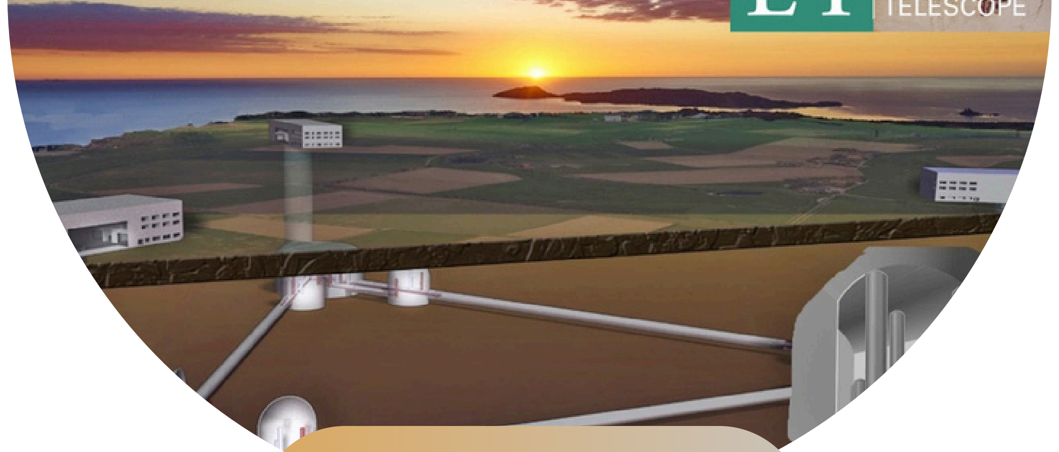
Why do we need it?

EARLY UNIVERSE





https://www.einstein-telescope.it
https://dcc.cosmicexplorer.org/public/0163/P2100003/007/ce-horizon-study.pdf



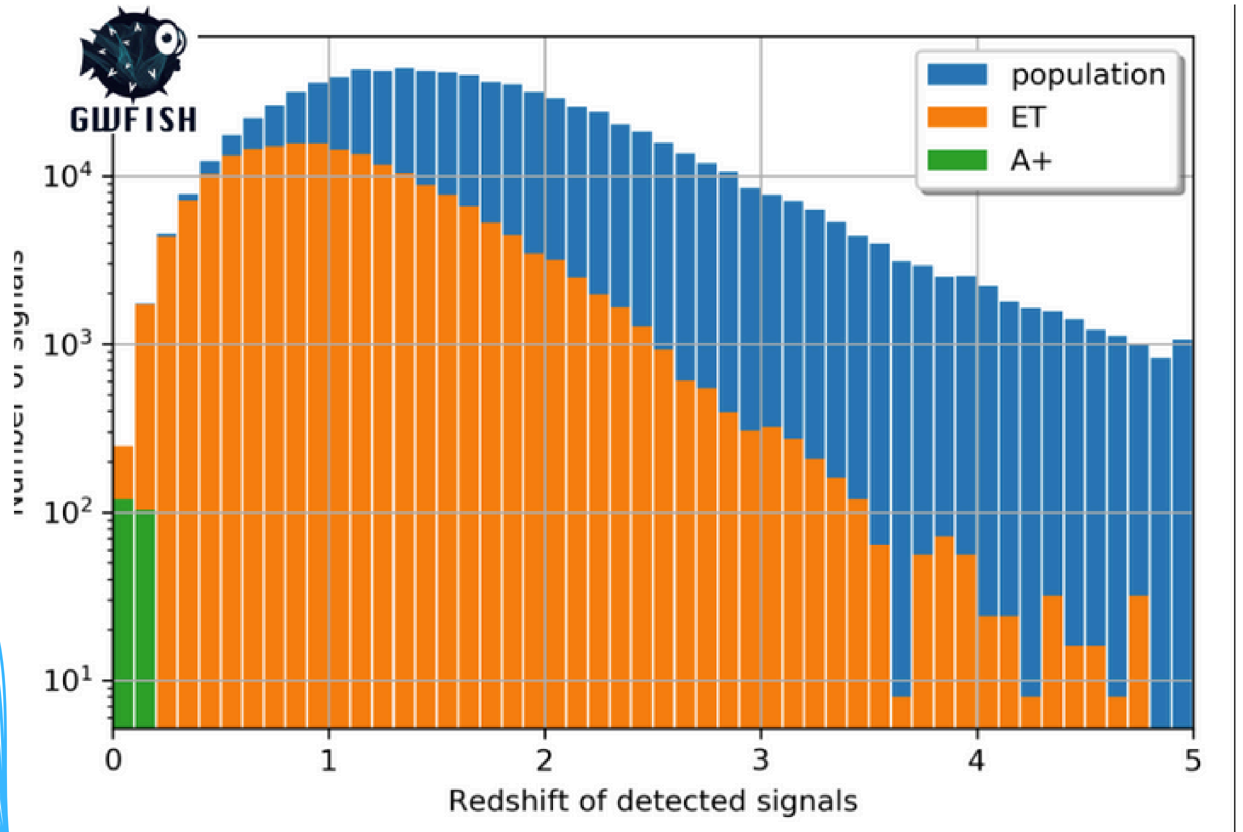
Why do we need it?

3G detectors: ET

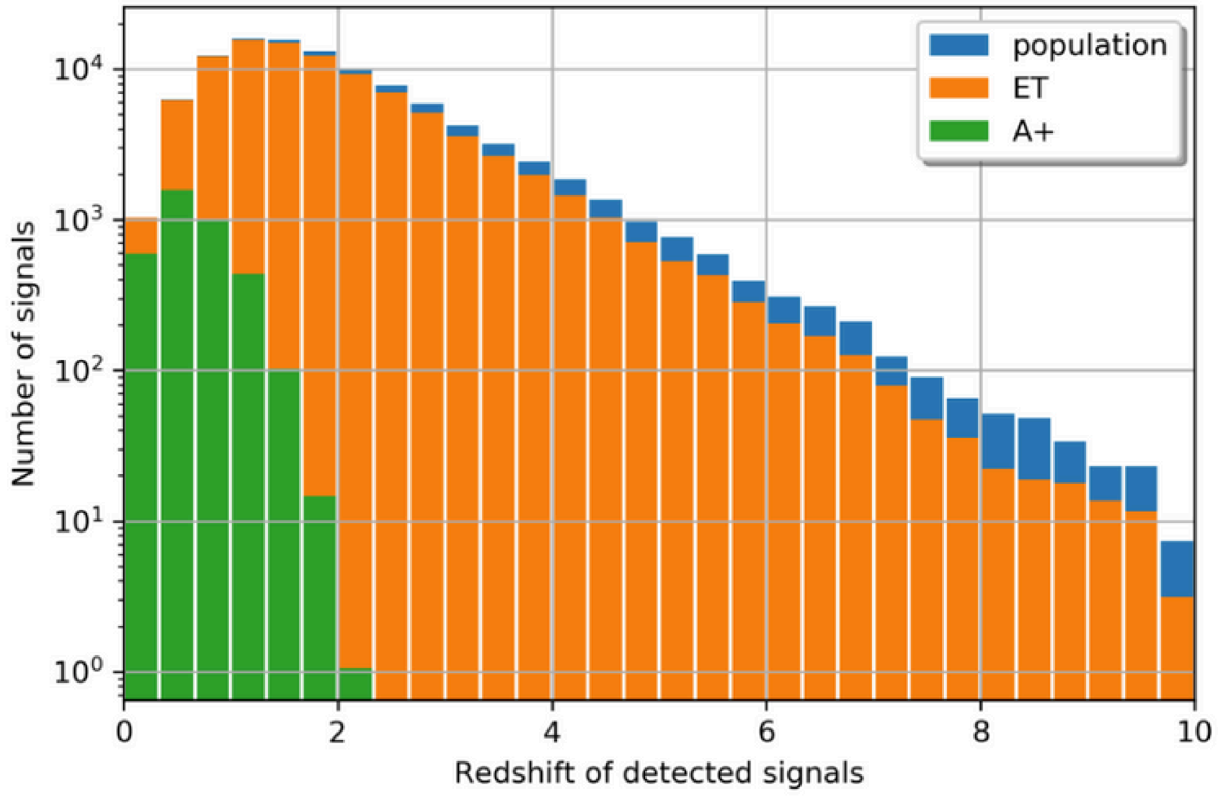
POPULATION

Sampling astrophysical populations of binary system of compact objects along the cosmic history of the Universe

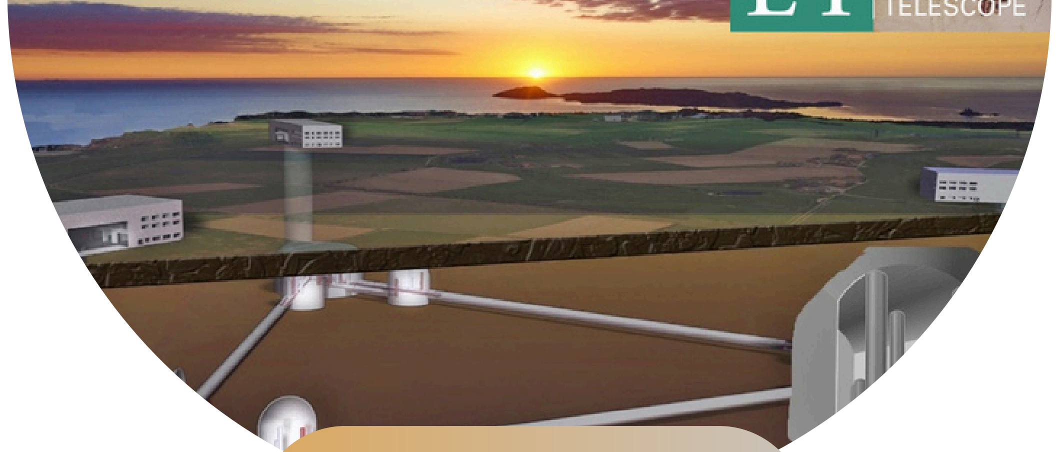
BINARY NEUTRON-STAR MERGERS



BINARY BLACK-HOLE MERGERS



10^5 BNS detections per year
10^5 BBH detections per year



Why do we need it?

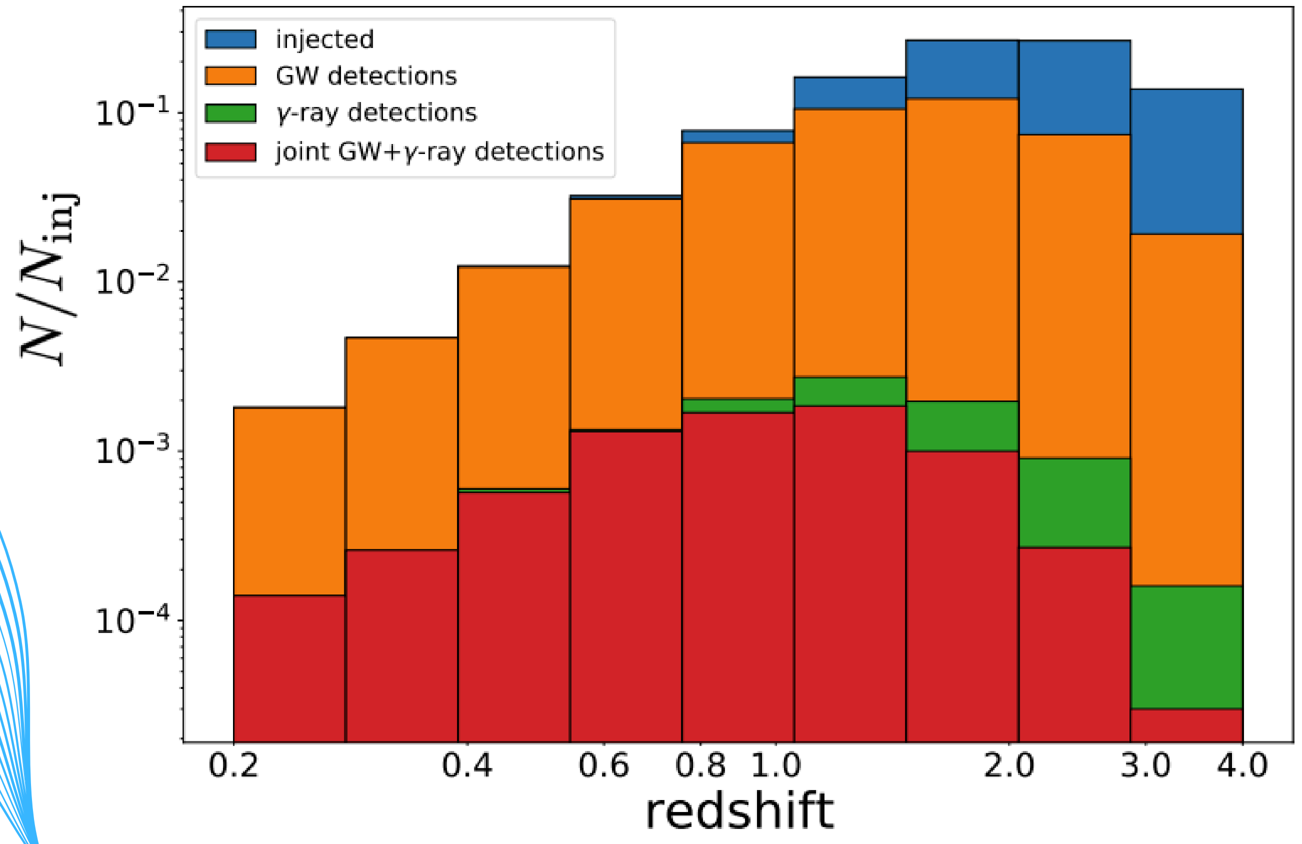
3G detectors: ET

POPULATION

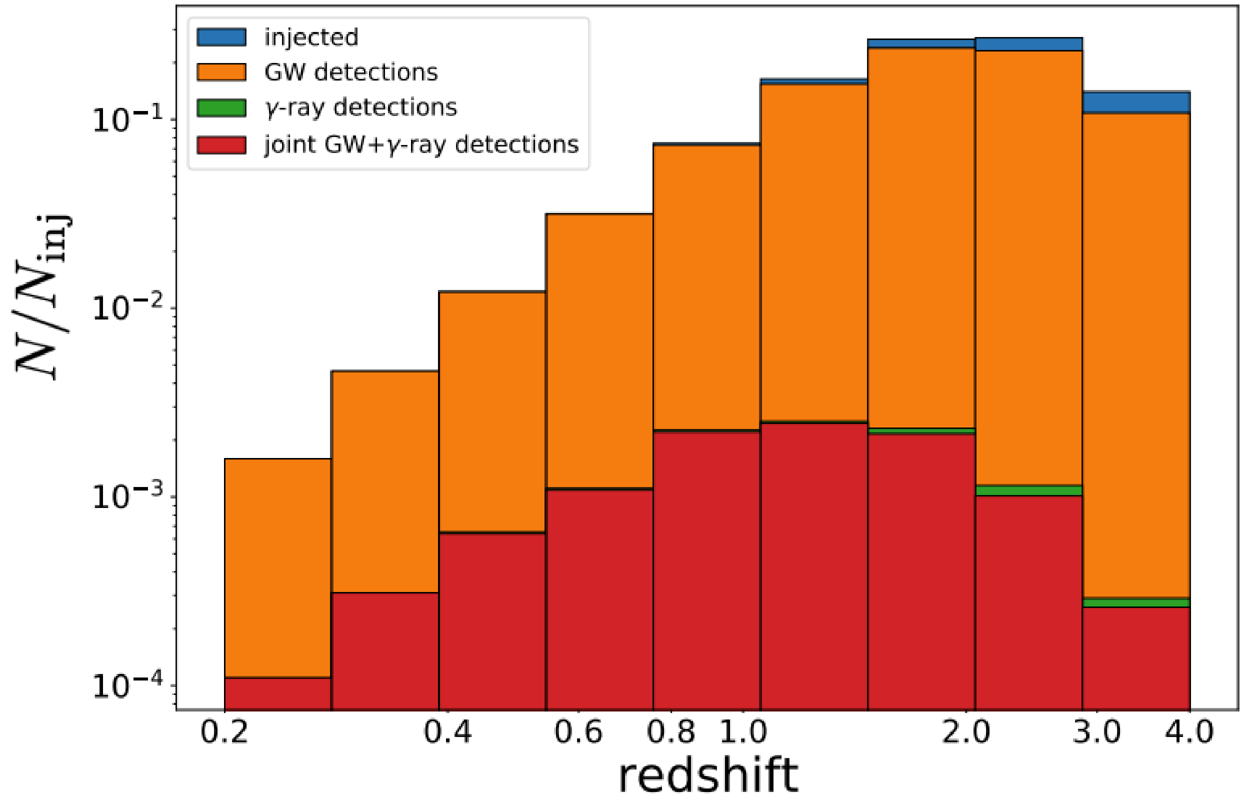
BINARY NEUTRON-STAR MERGERS

GW + γ-ray joint detections per year

Fermi-GBM+ET

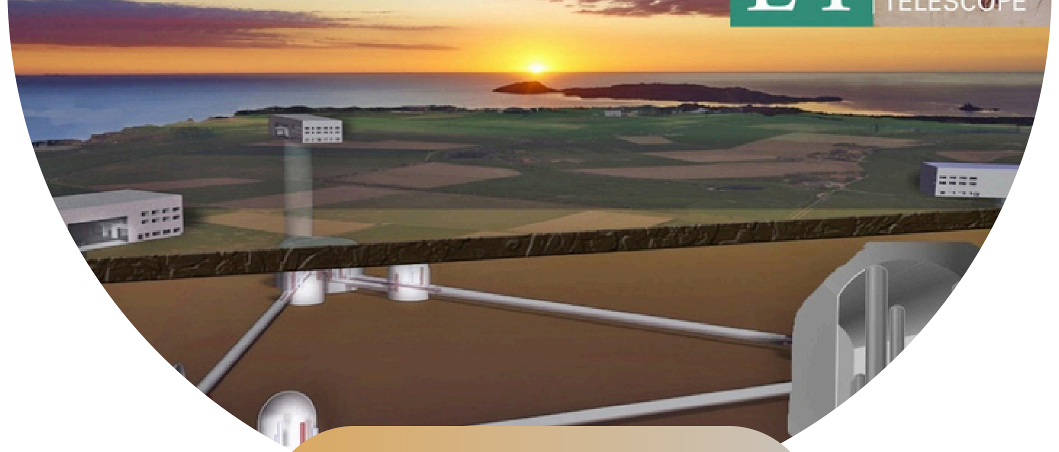


Fermi-GBM+(ET+CE)



Almost all detected short GRB will have a GW counterpart

Ronchini et al 2022

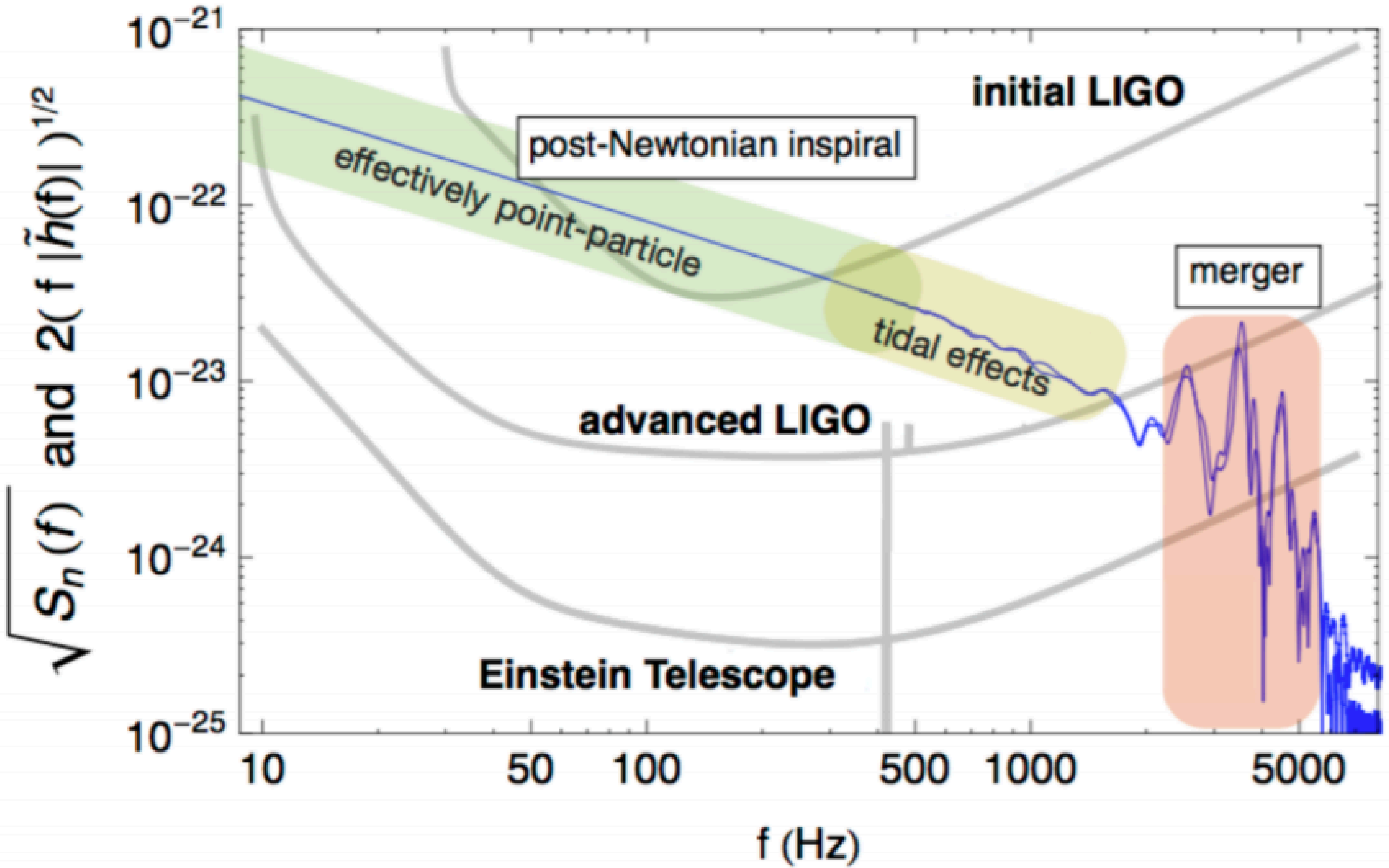


3G detectors: ET

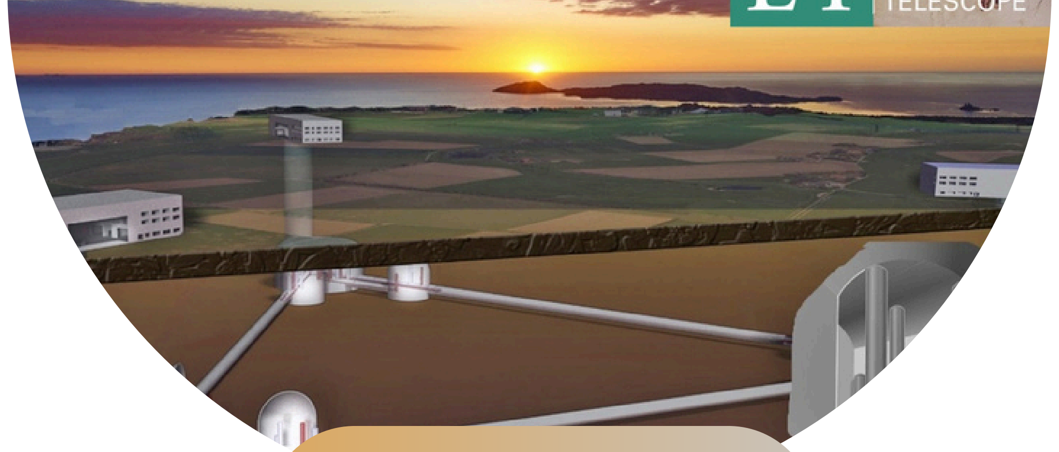
Why do we need it?

PRECISE GW ASTRONOMY

Exceptional parameter estimation accuracy for very high SNR events



Courtesy of Branchesi



3G detectors: ET

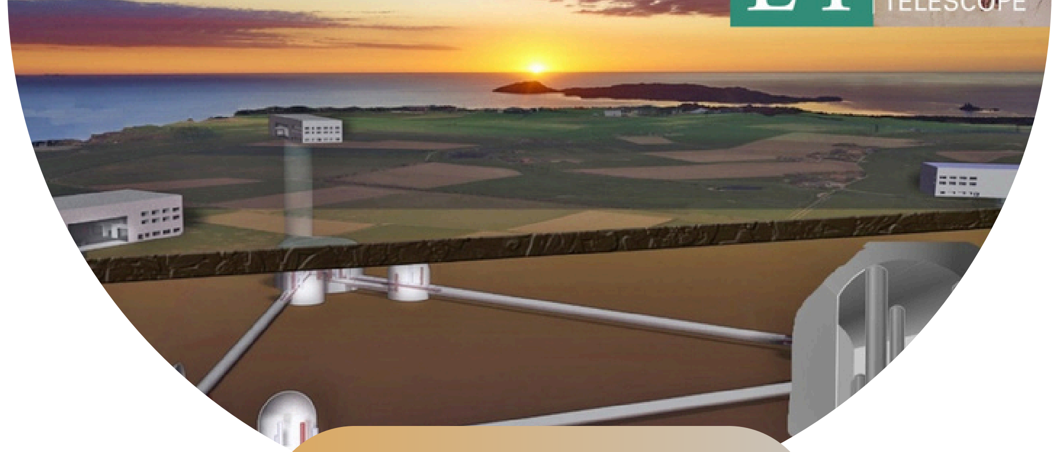
Why do we need it?

PRE-MERGER DETECTIONS

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
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

Number of BNS mergers per year detected (SNR ≥ 8) before the merger within z = 1.5 for the different full sensitivity ET configurations.

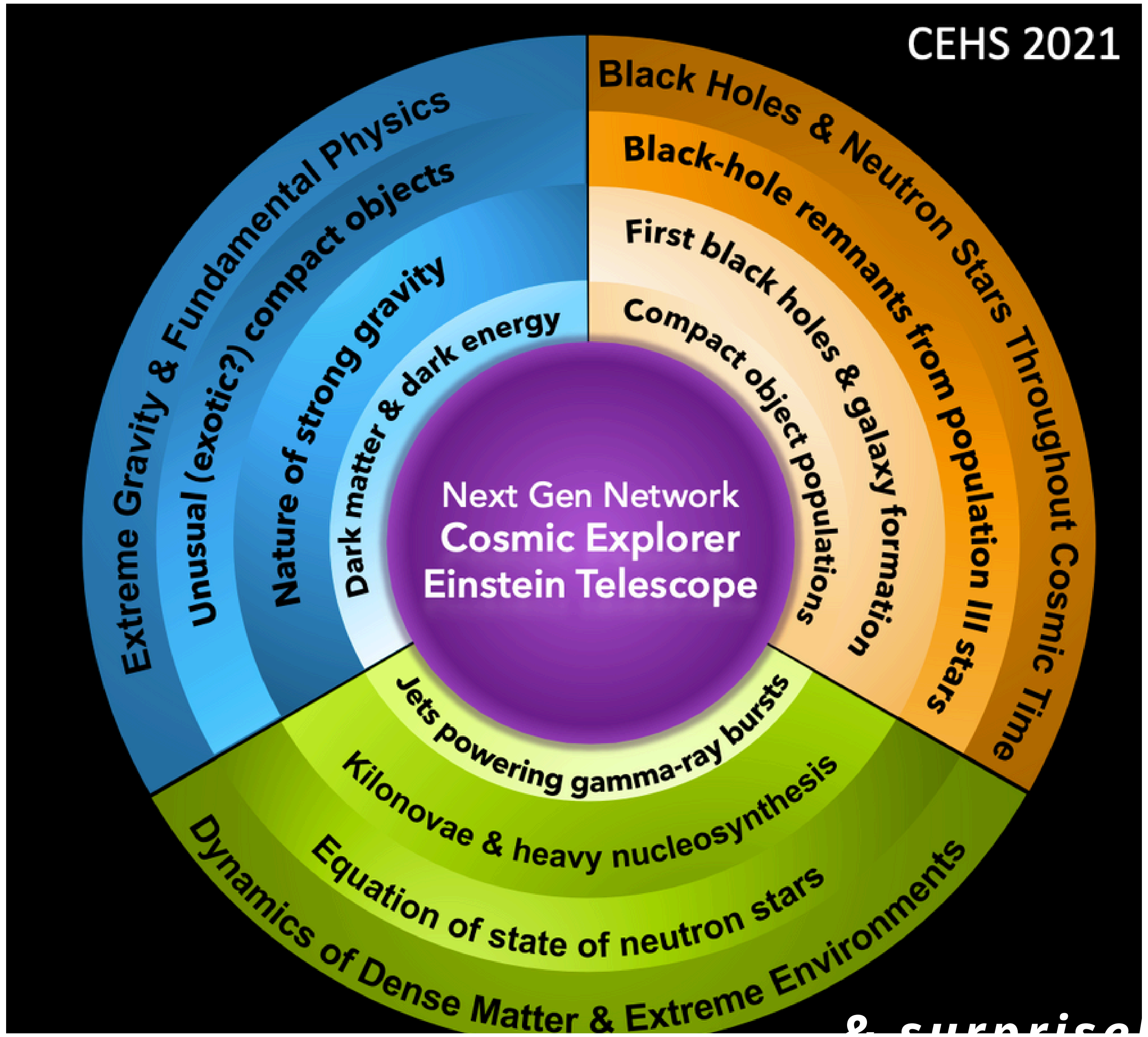
Branchesi, Maggiore et al. 2023, JCAP



3G detectors: ET

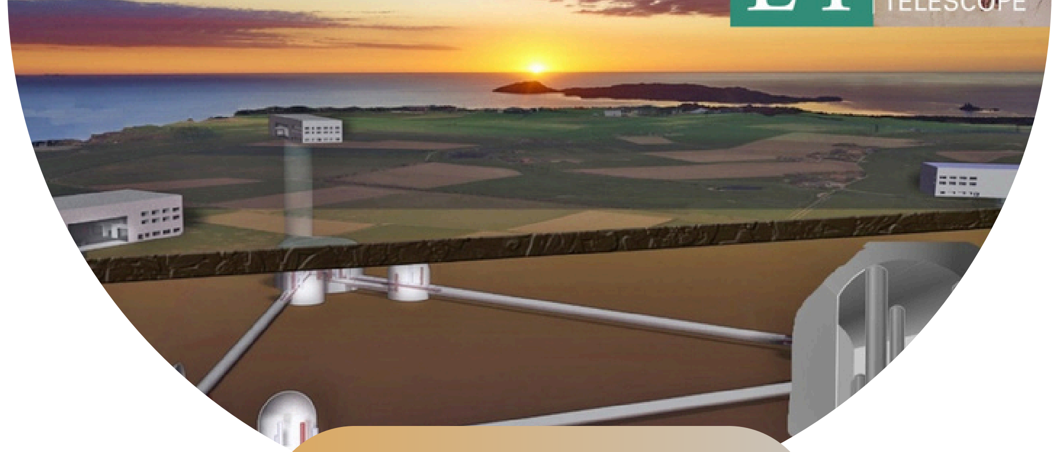
Why do we need it?

SCIENTIFIC OUTPUT



& surprise

GW sources produce signals in different GW ranges: the larger the frequency band and the more sensitive the detector, the higher the scientific output



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ISTITUTO NAZIONALE DI ASTROFISICA

3G detectors: ET

A summary of the Science of ET Astrophysics

- **Black hole properties**
  – origin (stellar vs. primordial)
  – evolution, demography

- **Neutron star properties**
  – demography, equation of state

- **Multi-messenger astronomy**
  – joint GW/EM observations
  – multiband GW detection
  – neutrinos

- **Detection of new astrophysical sources**
  – core collapse supernovae
  – isolated neutron stars
  – stochastic background of astrophysical origin

Maggiore et al. ``Science Case for the Einstein Telescope",

ET's impact on astrophysics and multimessenger astronomy

- What is the mass function of BHs and NSs and their redshift distribution?
- What are the progenitors of gamma-ray bursts?
- How do compact binaries form and evolve?
- What is the physical mechanism behind supernovae and how asymmetric is the gravitational collapse that ensues?
- Do relativistic instabilities occur in young NSs and if so what is their role in the evolution of NSs?
- Why are spin frequencies of NSs in low-mass X-ray binaries bounded?
- What is the nature of the NS crust and its interaction with the core?
- What is the population of GW sources at high redshifts?

Sathyaprakash et al. "SCIENTIFIC POTENTIAL OF EINSTEIN TELESCOPE",

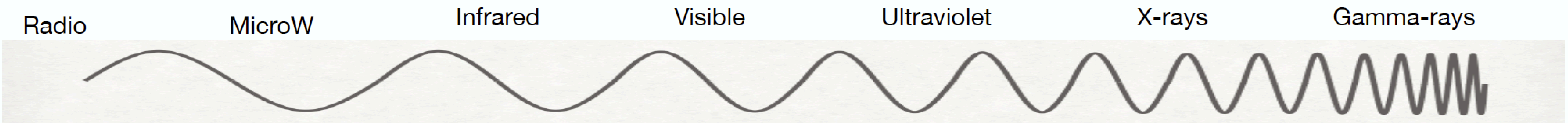
EXCELLENCE IN MULTIMESSENGER ASTRONOMY @ INAF

GraWITA

~ 100 scientists (P.I. E. Brocato) from 21 Institutes (INAF+Uni), since O1
Coord: with AGILE, Fermi, INTEGRAL, Swift teams, since O3

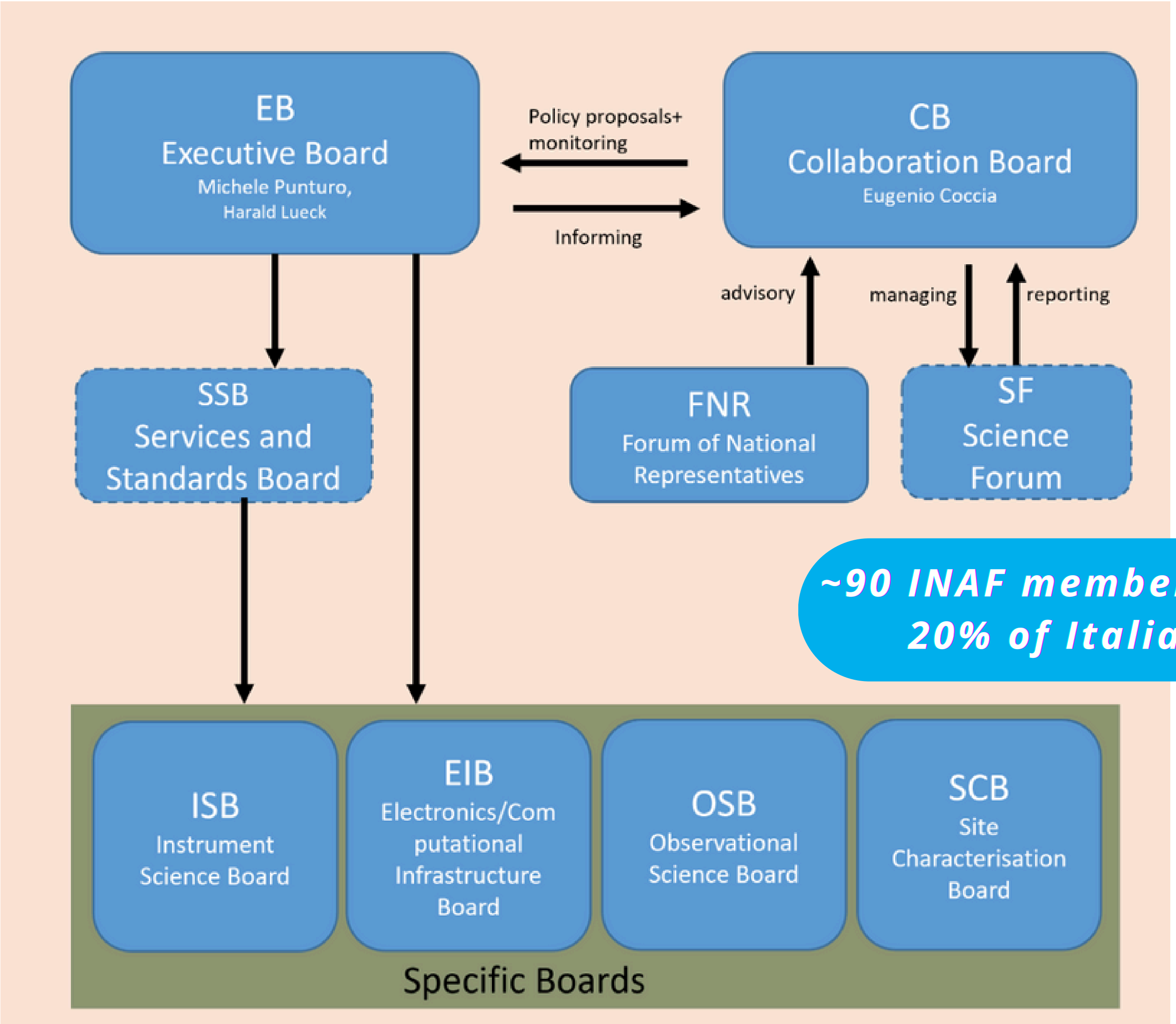
ENGRAVE

~ 250 scientists, since O3 (EM search and follow up | VLT+ALMA+HST+JWST)

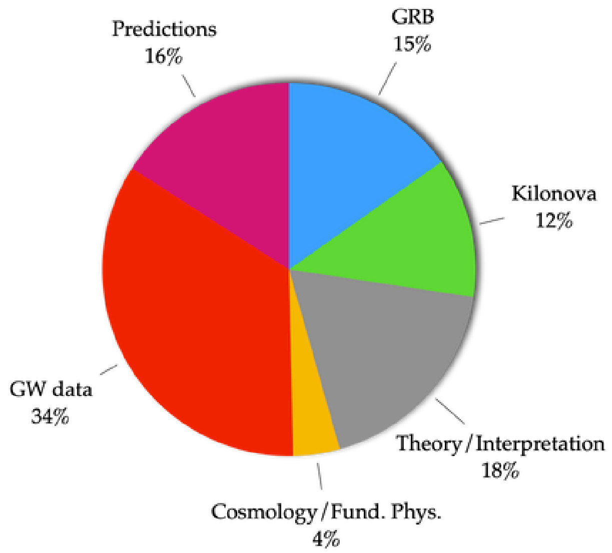


credits: G. Ghirlanda

ET COLLABORATION & INAF

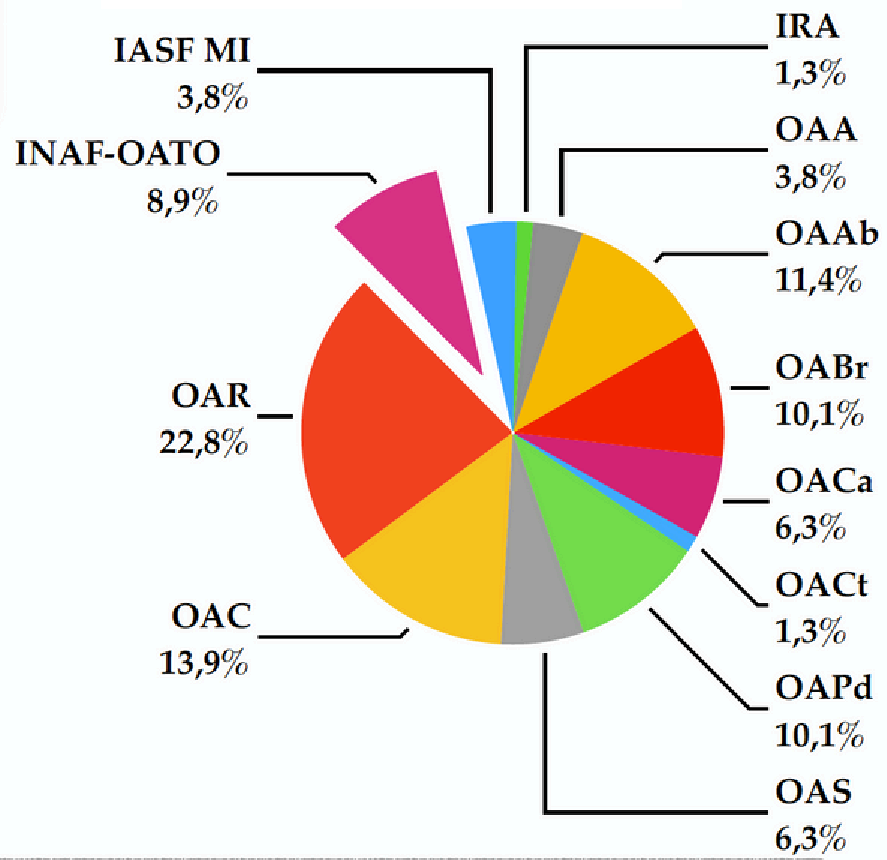


~90 INAF members (6.5% of total
20% of Italian members)



INAF Research Units:

1. *E. Brocato*
2. *M. Crosta*



SSB ***Editorial Committee (EC) S. Piranomonte***

ISB ***Pipe Arm Vacuum: A.Grado***

OSB

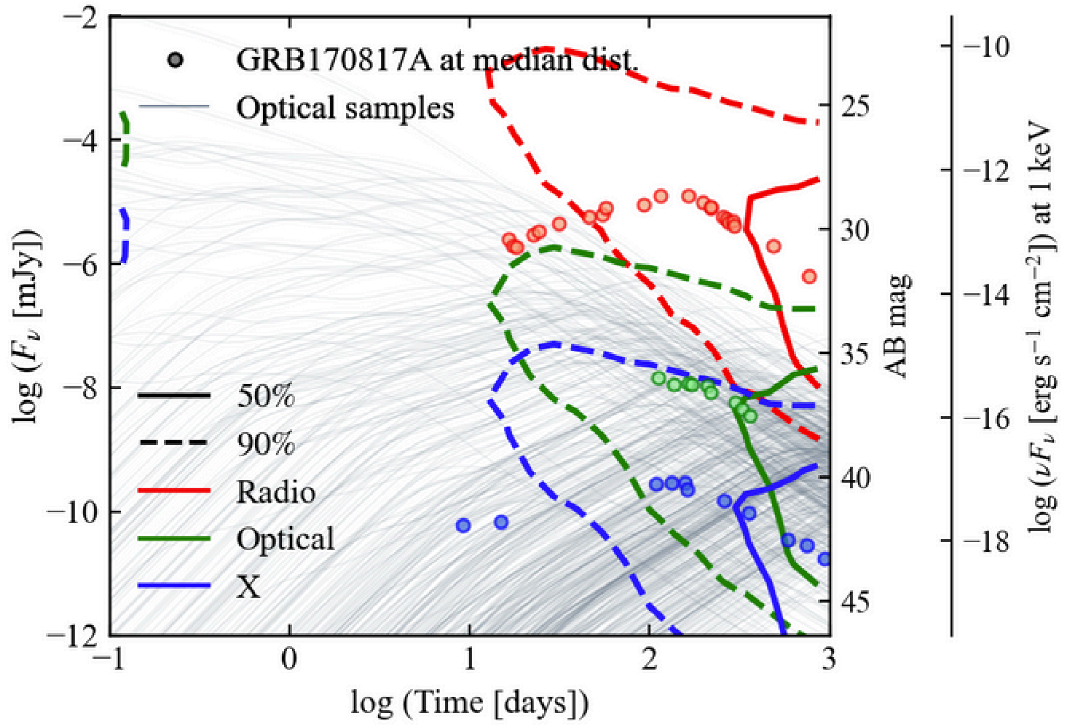
1. ***Fundamental Physics***
2. ***Cosmology***
3. ***Population Studies***
4. ***Multimessenger observations : G. Ghirlanda***
5. ***Synergies with other GW observatories***
6. ***Nuclear Physics***
7. ***Stellar collapse and isolated neutron stars: M. Limongi***
8. ***Waveforms***
9. ***Common Tools***
10. ***Data analysis platform***

Div S: future EM and neutrino experiments

https://www.et-gw.eu/index.php/the-et-collaboration

Light blue names = INAF

ET: INAF SCIENTIFIC CONTRIBUTIONS



OSB - Div4 (Ghirlanda, Levan, Vergani)

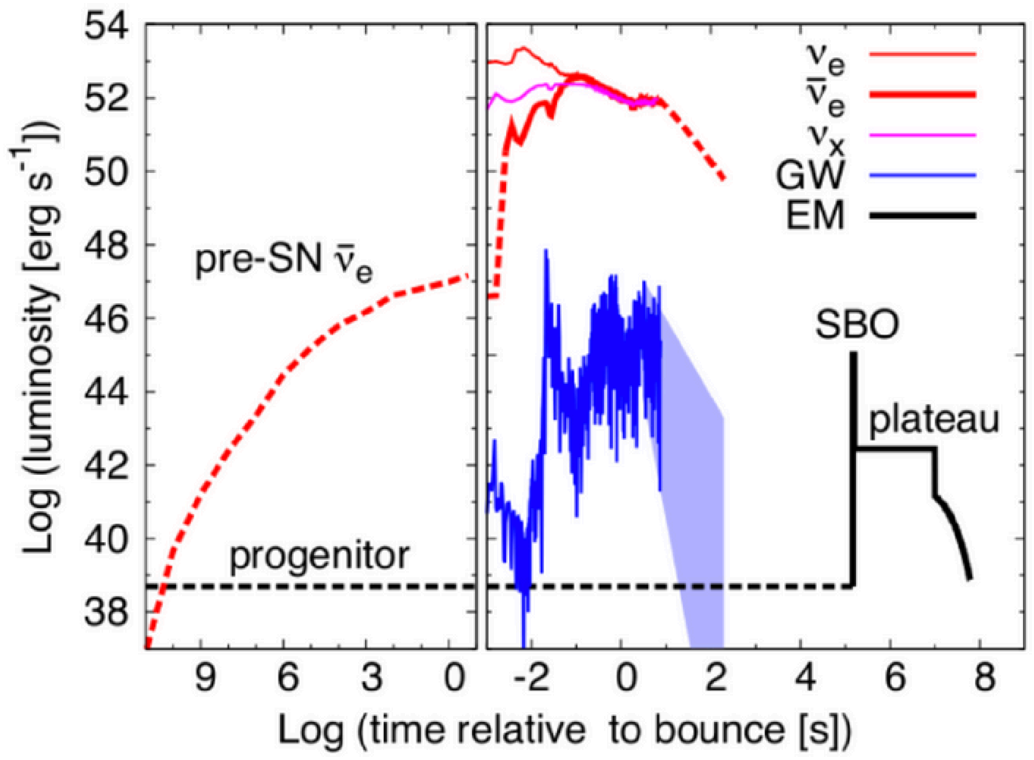
Multi Messenger Observations
•Simulation of EM signals (from CB mergers)
•How to catch and study them (facilities/strategies)
BLUE BOOK - DIV4

OSB - Div7 (Limongi, Palomba, Heng)

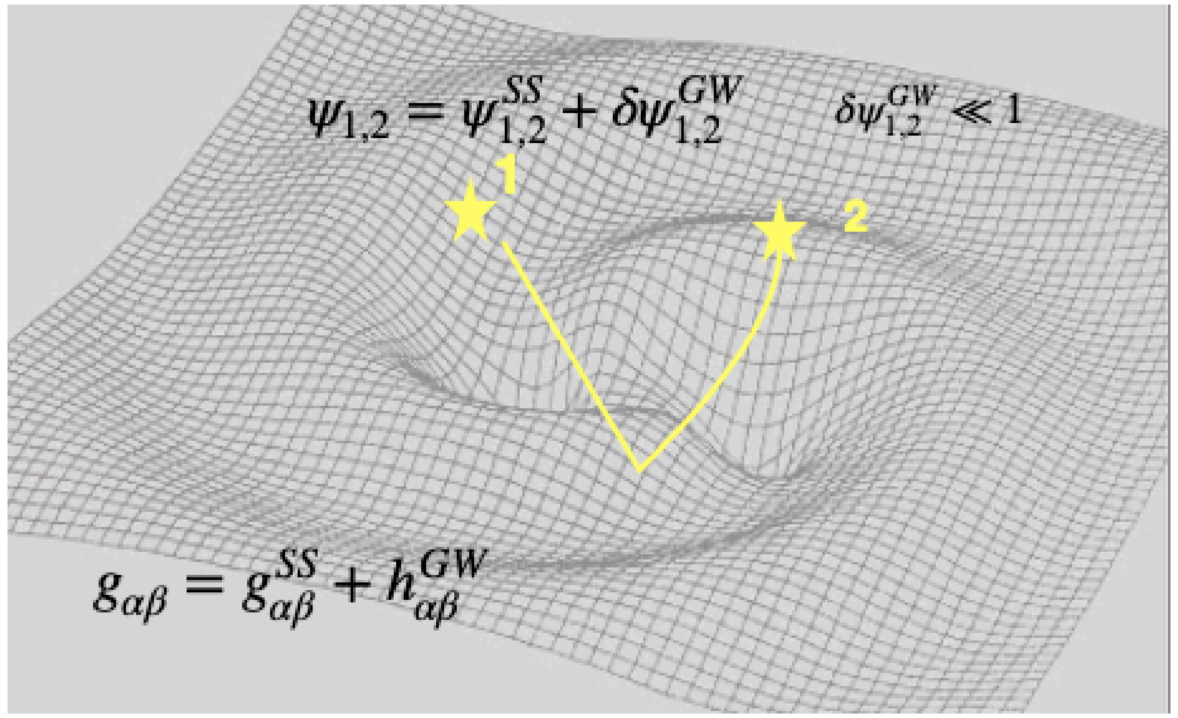
Stellar Collapse and Isolated Neutron Stars
- *Theoretical Models*
- *Data analysis*
- *MM Observational strategies*

BLUE BOOK - DIV7

K. Nakamura et al., MNRAS 2016

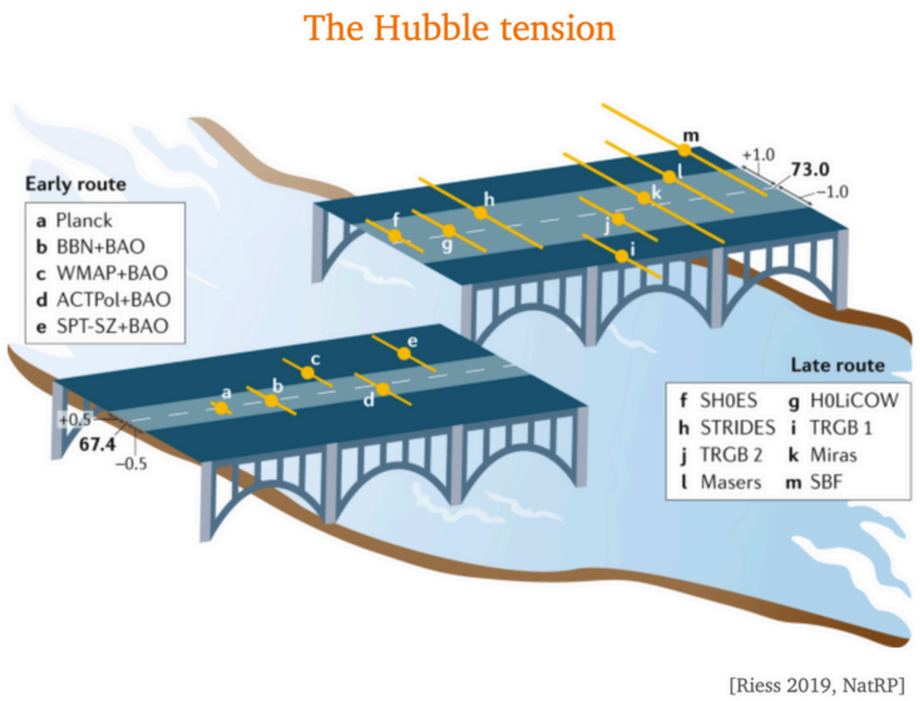


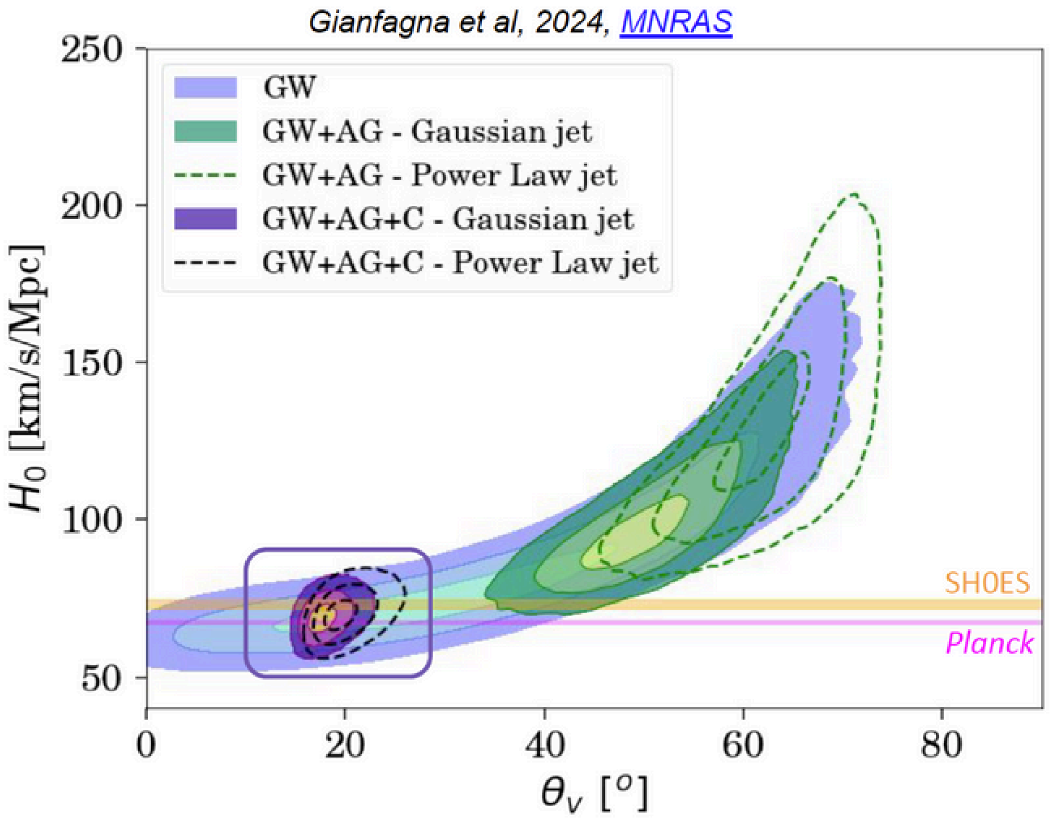
ET: INAF SCIENTIFIC CONTRIBUTIONS



***ASTROmetric GRAvitational Wave ANTenna* (RU2 INAF Torino - Crosta)**
GAIA —> complement ET
Study of possible auxiliary space/ground based observatories to complement ET (GW sentinel)

Cosmological constraints (Cantiello et al., Gianfagna et al.)
- *Methods (SBF, GW170717)*
- *Precision*
- *Complementarity*





ET: INAF SCIENTIFIC CONTRIBUTIONS

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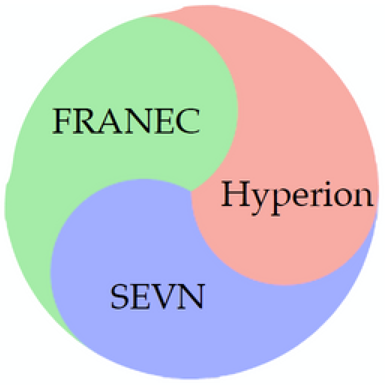
Envisioning Tomorrow: prospects and challenges for multi-messenger astronomy in the era of Rubin and Einstein Telescope



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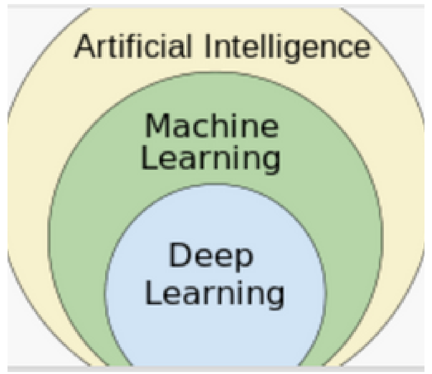


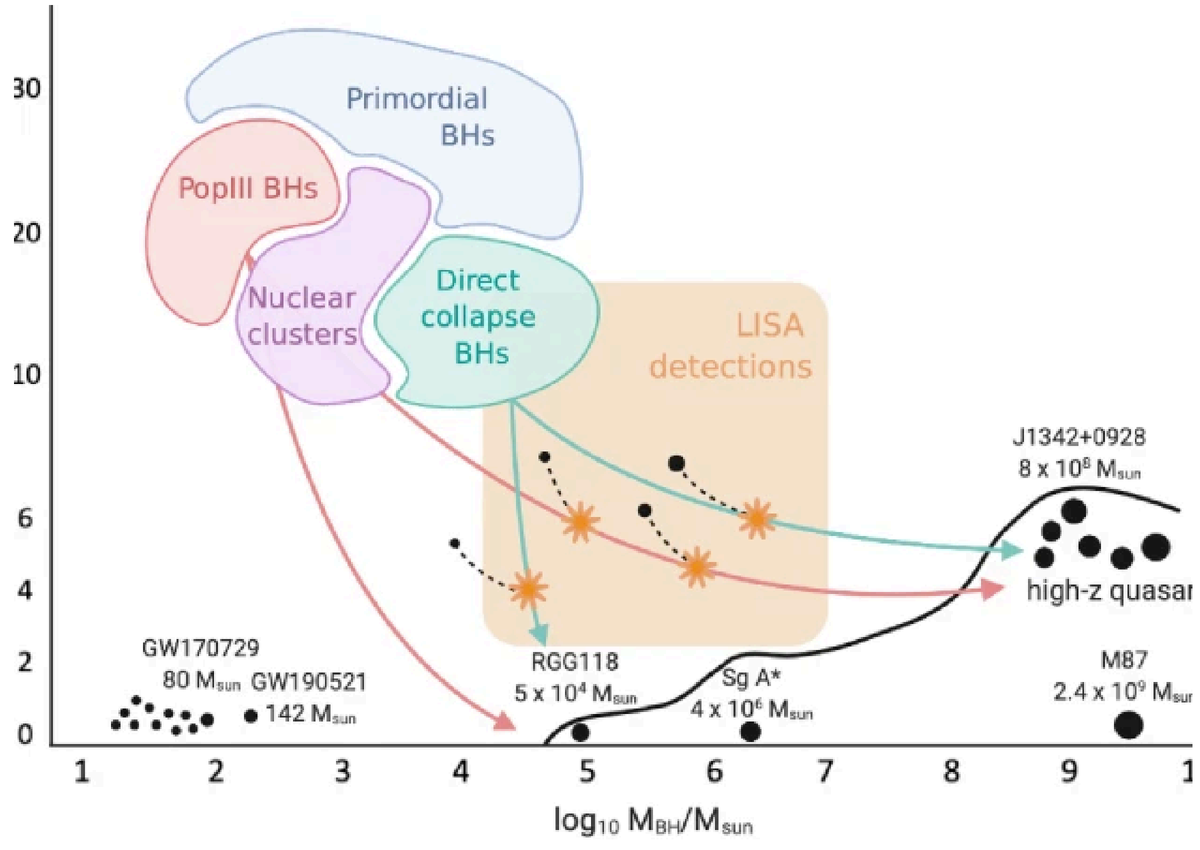
INAF LARGE GRANT (submitted in 2024) - Piranomonte, Melandri, Limongi, Spera, Brocato, Cristallo, Onori, Ragosta

- *Models for evolution (FRANEC) + explosion (Hyperion) of intermediate mass stars within population synthesis codes (SEVN)*
- *Predictions*
- *MM synergies*
- *Data analysis*

- *formation and evolutionary pathways of compact binary coalescences;*
- *observational strategy leveraging machine learning (ML) algorithms to effectively handle large datasets.*

in collab with: DIV 3 + DIV 4 + DiIV 7

SMBH formation channels - a Multi-messenger approach
(Mannucci et al.)
EM (IR/X-ray) probe accretion physics of the parent population



ET: INAF TECHNOLOGICAL CONTRIBUTIONS

ETIC (PNRR)

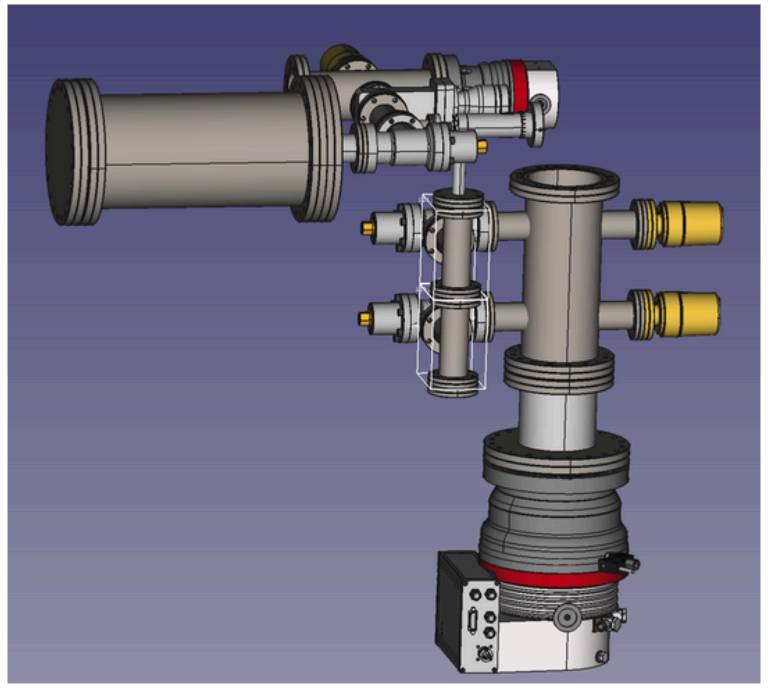
ETIC project: Study of hydrocarbon contamination on surfaces in UHV systems

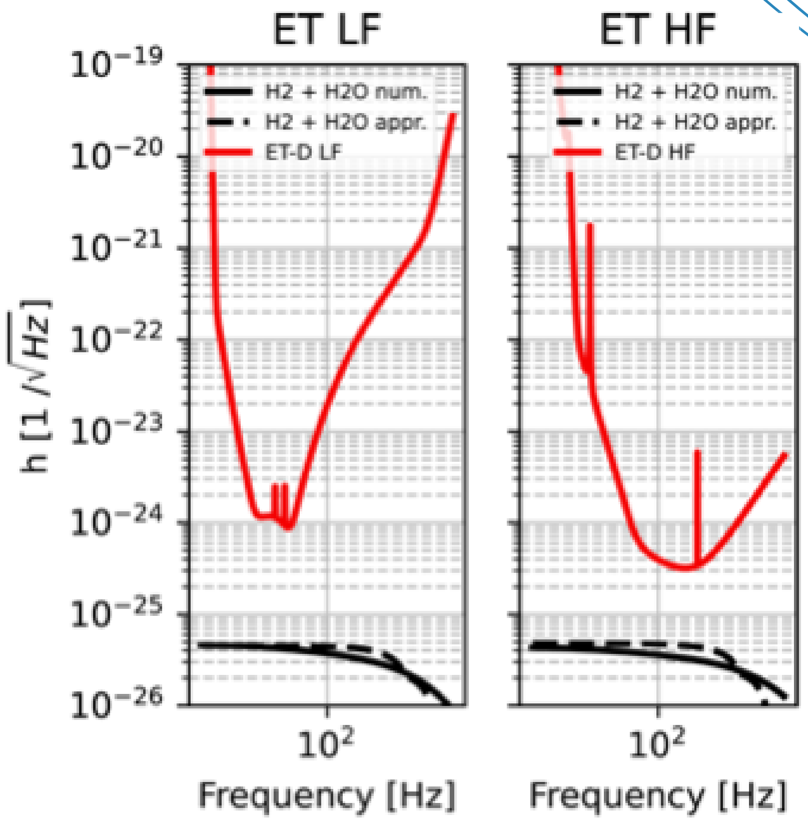
[E.Cappellaro]

•ADONI (Esposito)

•IdroC cont. (Mennella)

•Vacuum pipe material (Grado)





WP 2.43-45 - Simone Esposito
Laboratory for testing adaptive mirror control techniques.
WP 3-45 - Vito Mennella
Cryostat for checking hydrocarbon contamination in Ultra-high vacuum

ETIC funds: 407 kEuro

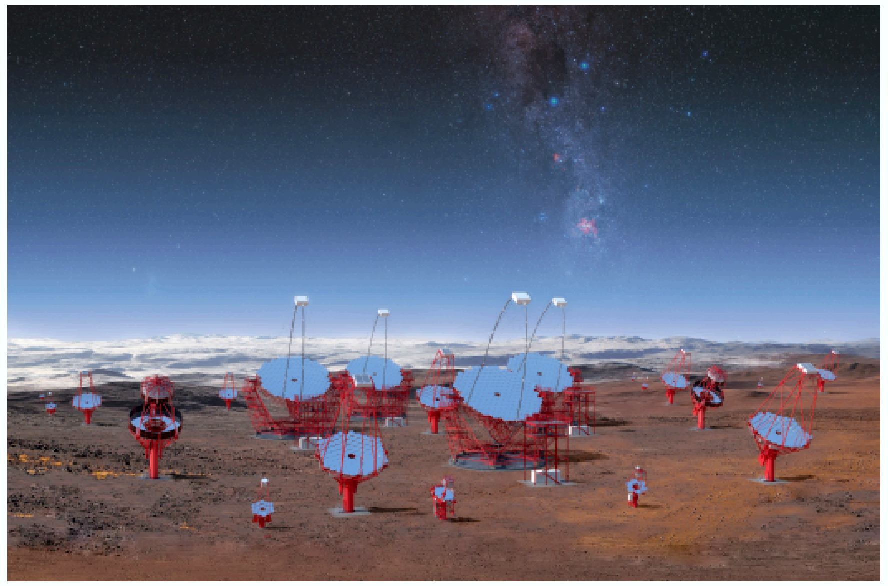
Set up of a degassing station at the INAF OAC (Naples) to study materials for the beampipe
– A. Grado, V. Mennella, F. Cozzolino, L. Limatola, F. Getman, E. Zona

ET: INAF PROJECTS RELEVANT FOR ET

γ-rays

Cherenkov Telescope Array

4 Large (+2 INAF) (23m)
25 medium (12m)
37 small (5m)



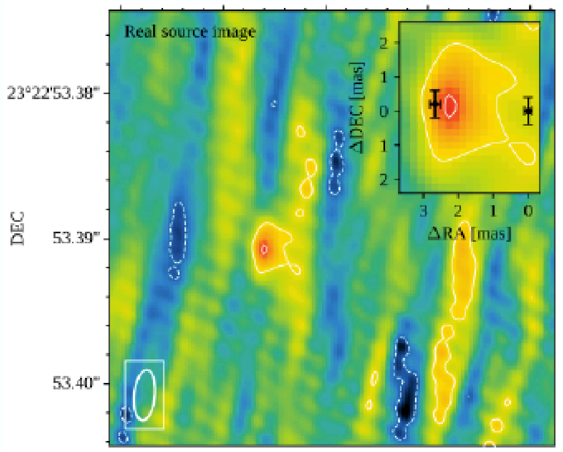
ASTRI Mini-Array

Unique search capabilities
Unique characterisation

Benefit of ET pre-merger alerts

Radio

Square Kilometer Array

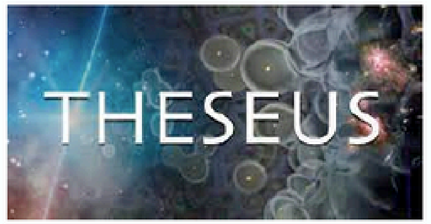


INAF radio telescopes

credits: G. Ghirlanda

ET: INAF PROJECTS RELEVANT FOR ET

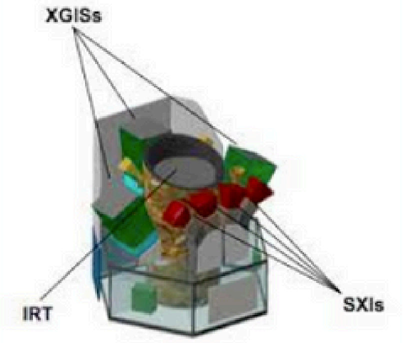
X-γ-rays (space)



ESA M7 (+ASI) (INAF P.I. L. Amati)

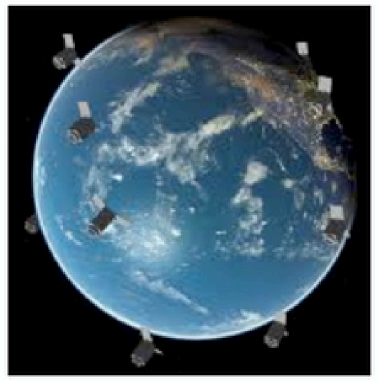
INAF PI/Co-ship of 2/3 detectors

Discovery & localisation of X/gamma ray counterparts + KN studies



HERMES
(INAF P.I. F. Fiore)

"Distributed architecture"



Search machine

Optical/NIR

ELT (Extremely Large Telescope)

>2027

ø=39m

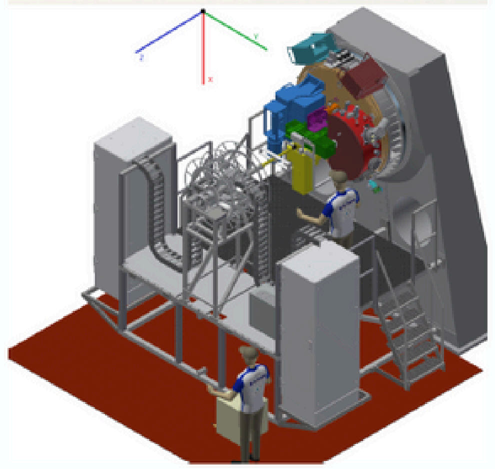
MAORY (INAF)

HIRES (INAF)

>100 GTO nights @ INAF

Rubin Telescope (VRO)
a lot of INAF MMA people involved
(i.e.:GuRu Project (Piranomonte),
SBF methods (Cantiello))

SoXS (Campana, S.)



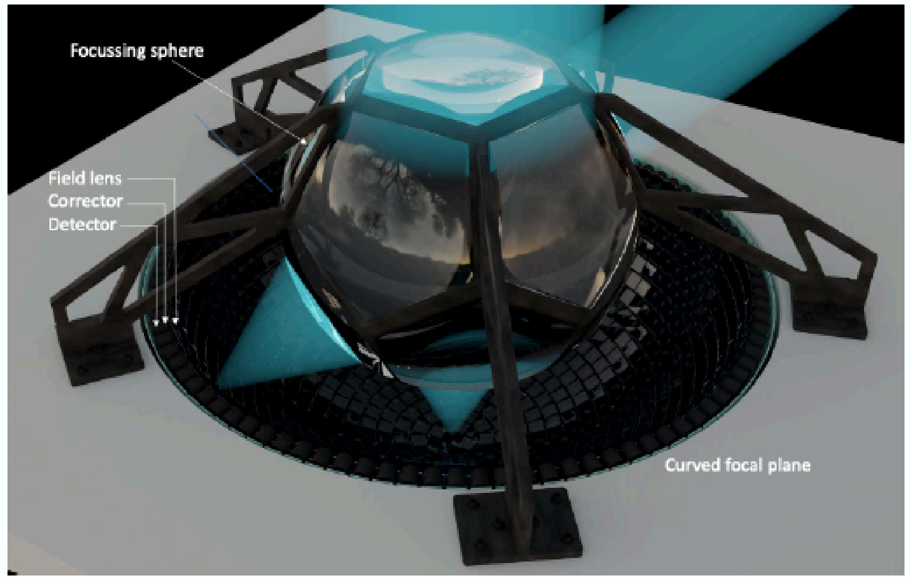
credits: G. Ghirlanda

ET: INAF … THINKING TANK

INAF ISTITUTO NAZIONALE DI ASTROFISICA

MezzoCielo (INAF - R. Ragazzoni)

FoW ~ 20.000 deg^2 sampling 1 arcsec
4000 cameras with a 8k x 8k detectors



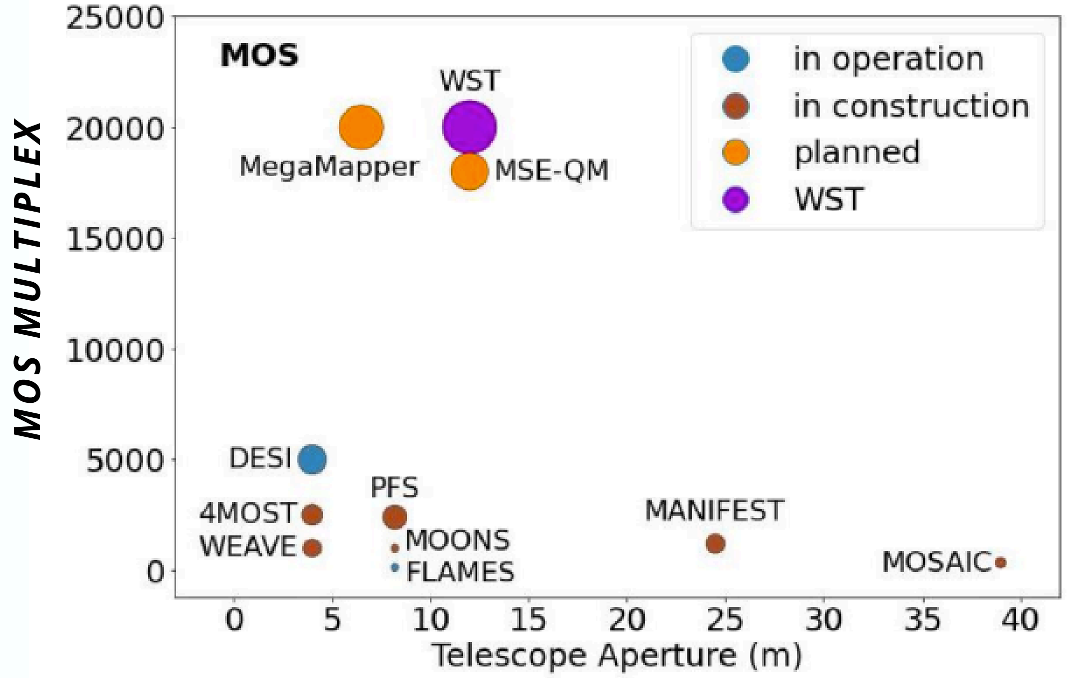
WST

https://www.wstelescope.com

HUGO (High-z Universe Grb Observatory) (INAF - S. Campana)

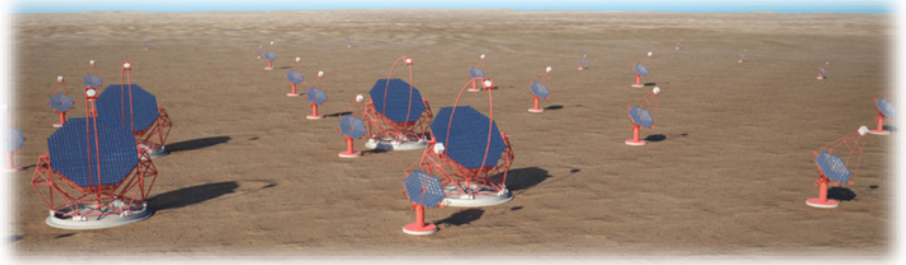
VRO

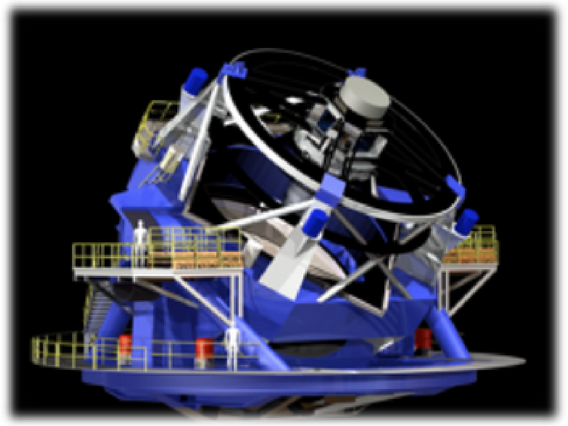
INAF - Randich, Schipani, Garilli, …



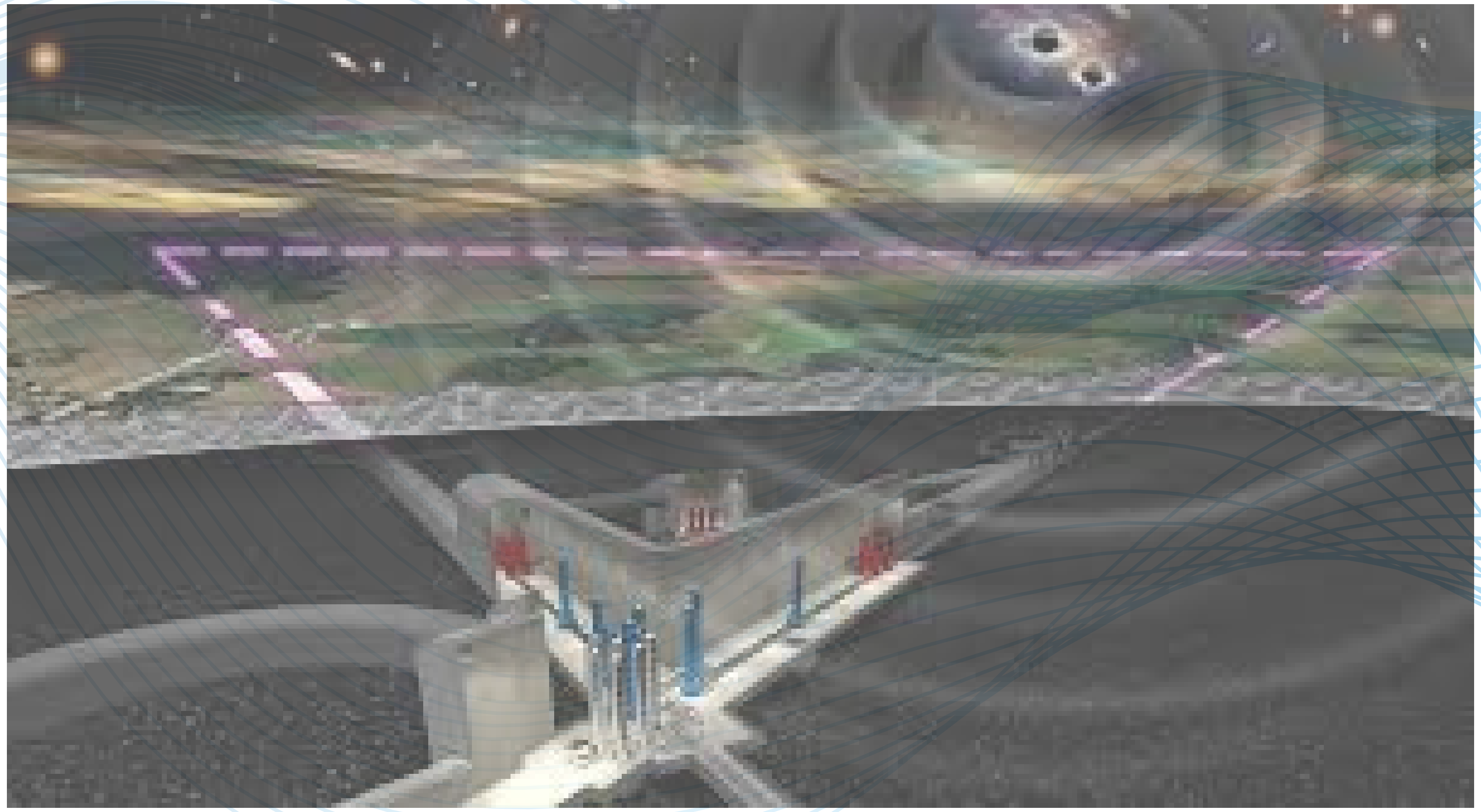
credits: G. Ghirlanda

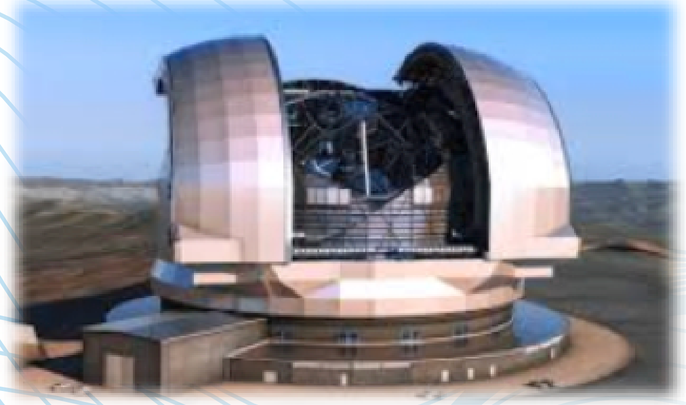
Conclusions





Einstein Telescope: Numbers, Distance, Surprises





HermeS

theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

WST

***INAF** : Astrophysics (Science, Technology, Education, Training …)*

The best is yet to come!!