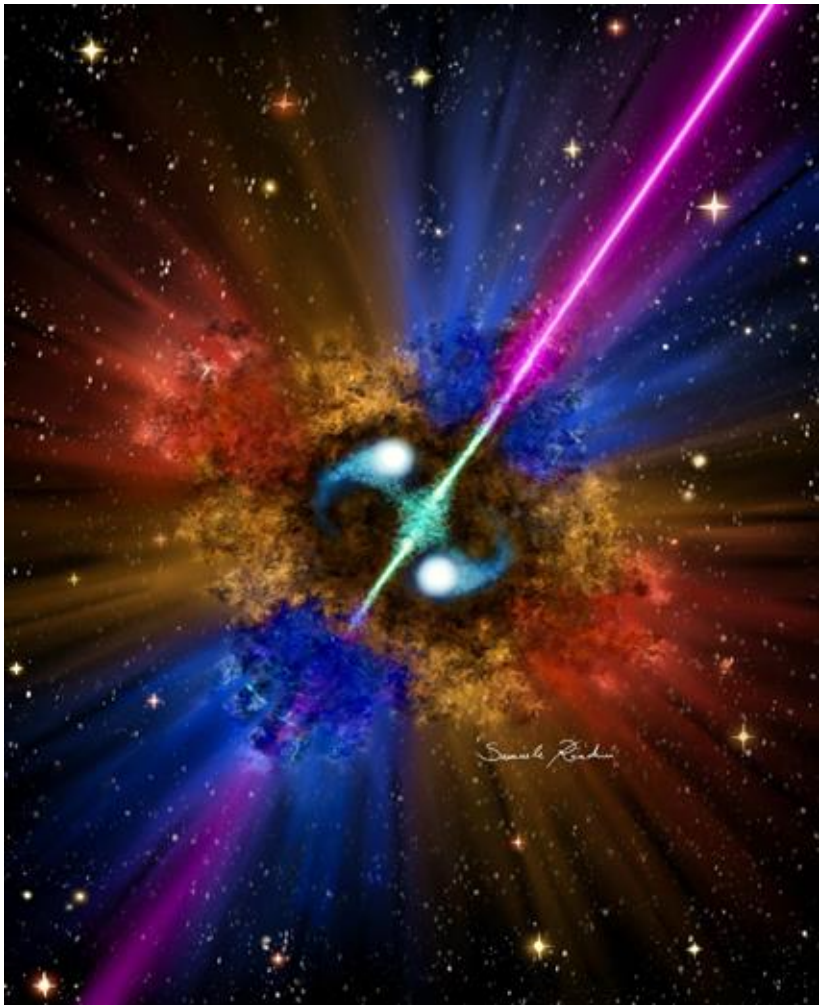
Einstein Telescope status and prospects

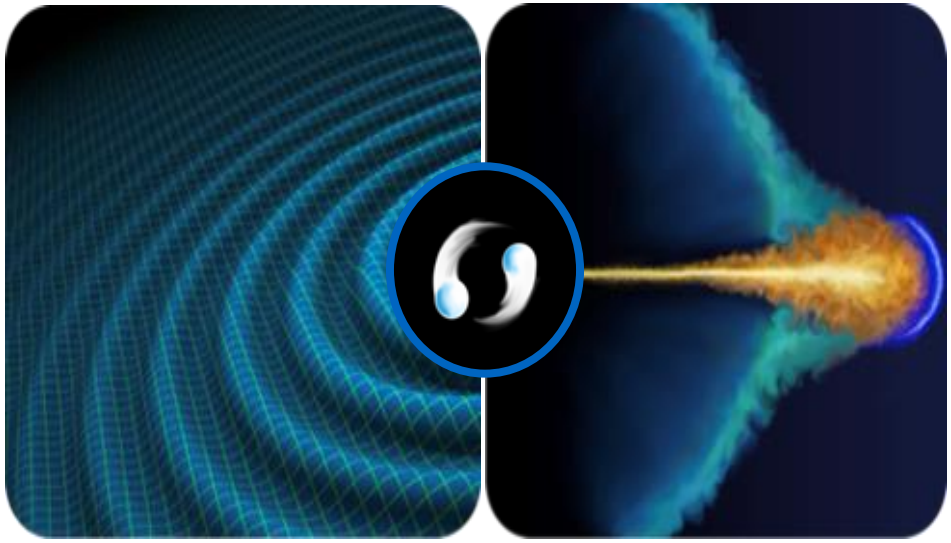
Some results of the PRIN project:
Multimessenger astronomy in the Einstein Telescope Era (METE)



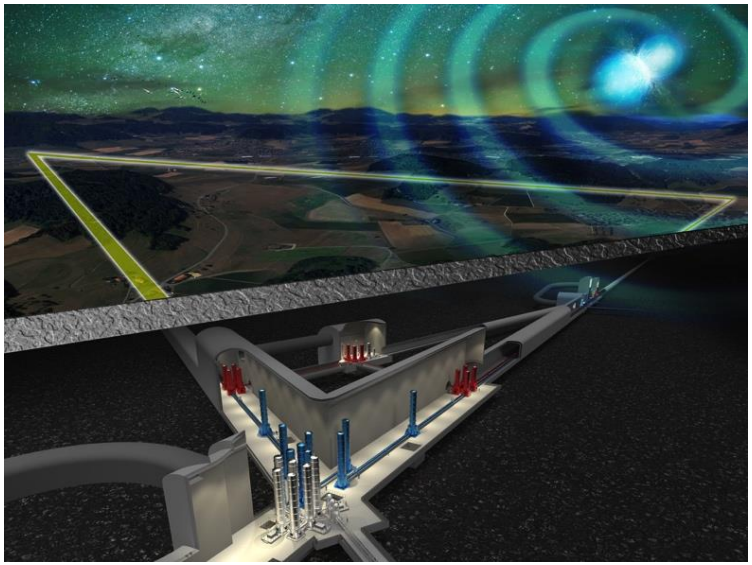
M. Branchesi

Gran Sasso Science Institute

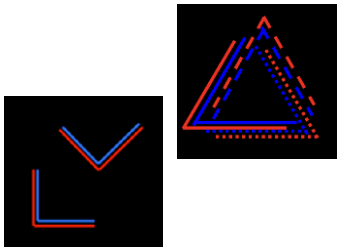
INFN/INAF/ASI



Einstein Telescope: the European next generation GW observatory



Triangular (10 km arms)
or 2L shape (15 km arms) misaligned
Underground
Cryogenic
Xylophone
…



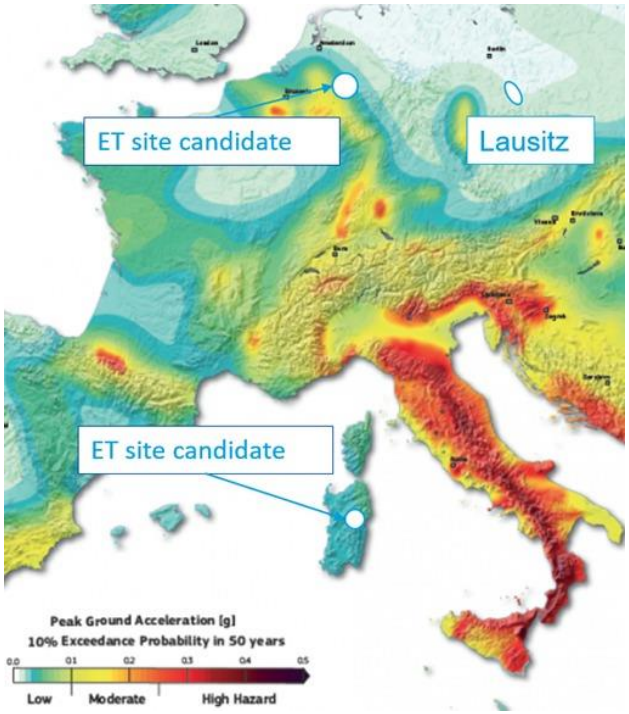
ESFRI ROADMAP 2021
ET collaboration around 2000 members

Science design comparison in
Branchesi, Maggiore et al. 2024 JCAP

MAIN RESULTS:

- For compact binary coalescences, the 2L enables gains of at least a factor of 2–3 in both detection rates and the accuracy of parameter reconstruction with respect to ET-triangle
- This improvement is critical for exploratory science: early Universe, IMBHs, high-SNR "golden events" for precision tests of gravity, very well-localized sources
- For several science cases (including joint GW/GRB observations) the 2L only on the high-frequency IFOs allows to reach goals that would require high- and low-frequency IFOs in ET-triangle.

ETO+ETC: geometry comparison
science+risk, cost, governace, socio-economic impact



Three candidate sites candidates to host ET:
EMR, **Sardegna**, and **Lusastia**

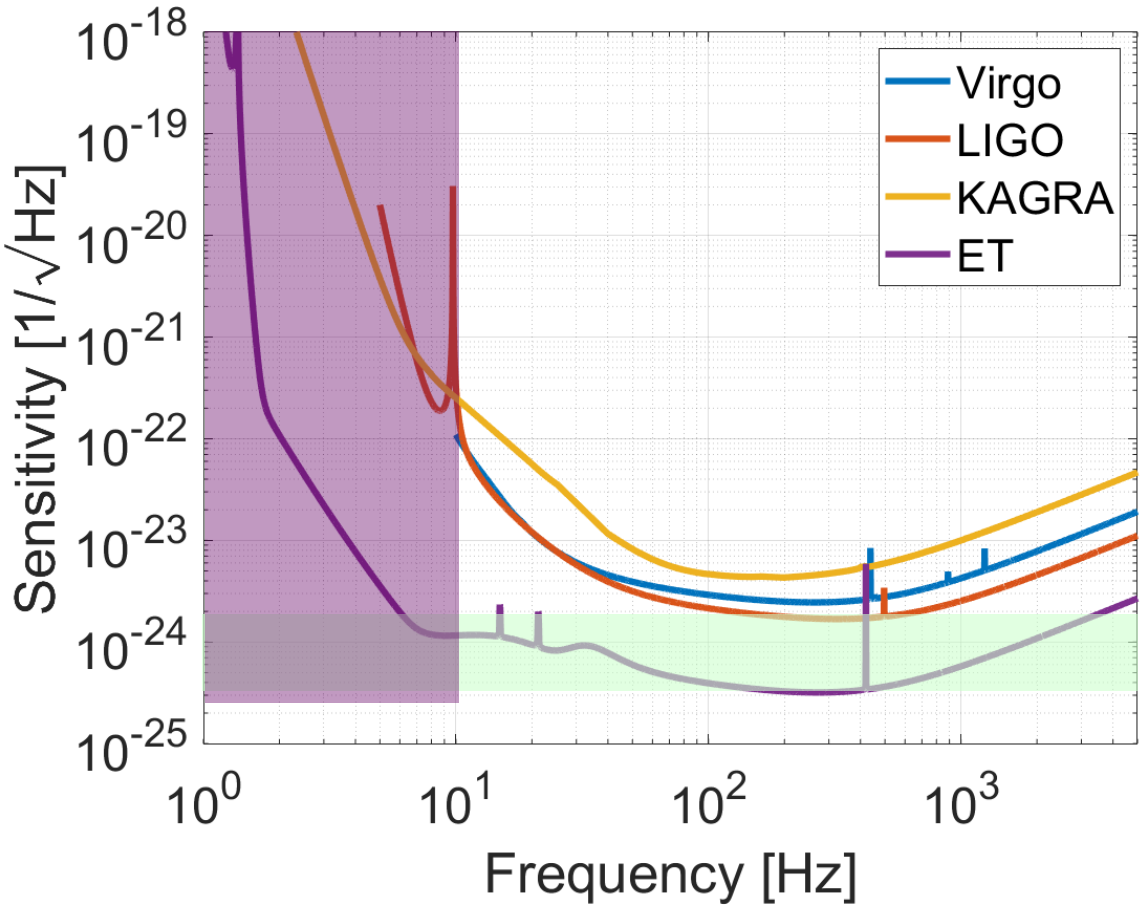
Italy and the Netherlands have pledged to cover nearly half of the cost if their proposed sites are selected.

Recently, Sardinia and Saxony have signed a declaration of intents to strenghten scientific collaboration and to support the “2L” solution

Geometry and site selection expected by 2027

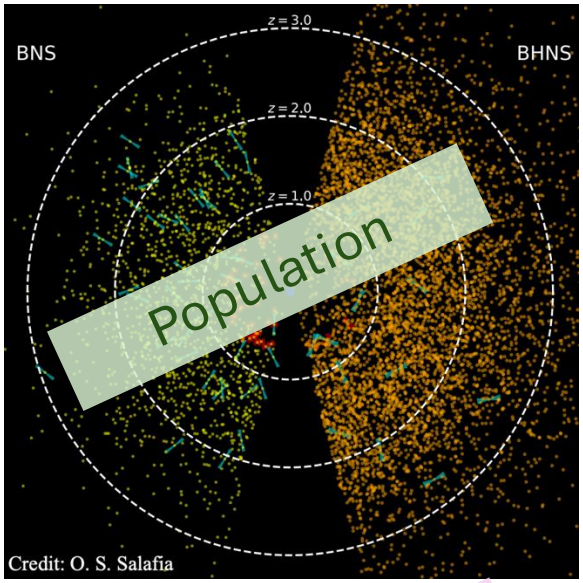
Operations by 2040

EXPECTED SENSITIVITY



arXiv:2503.12263

ET Science in a nutshell

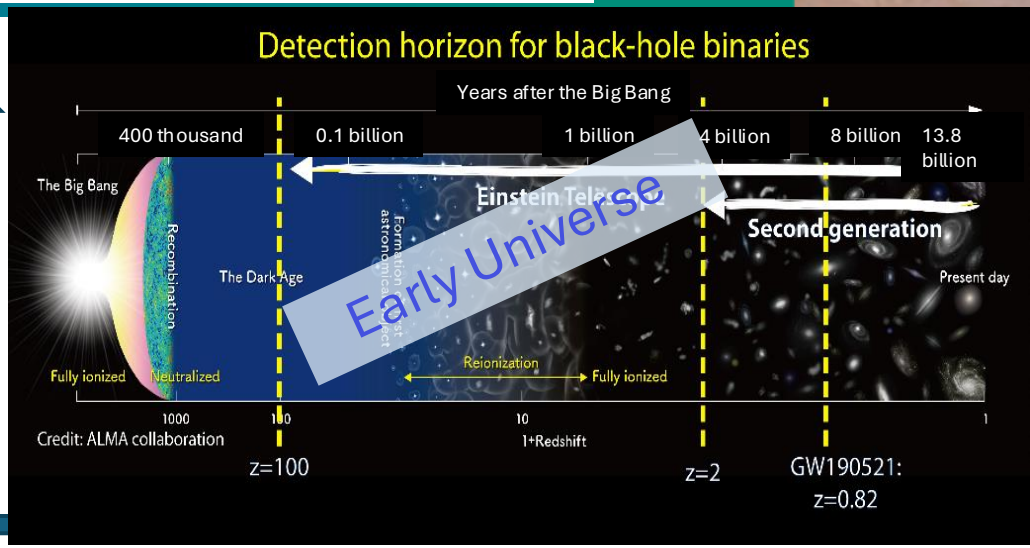


Population

Precise GW astronomy

Remote Universe

Closer Universe



Early Universe

ET science book

Combination of:

- Larger distances
- Increased number of detections
- Detections with very high SNR

ET science book, Abac et al. arXiv:2503.12263

ET Science in a nutshell

ASTROPHYSICS

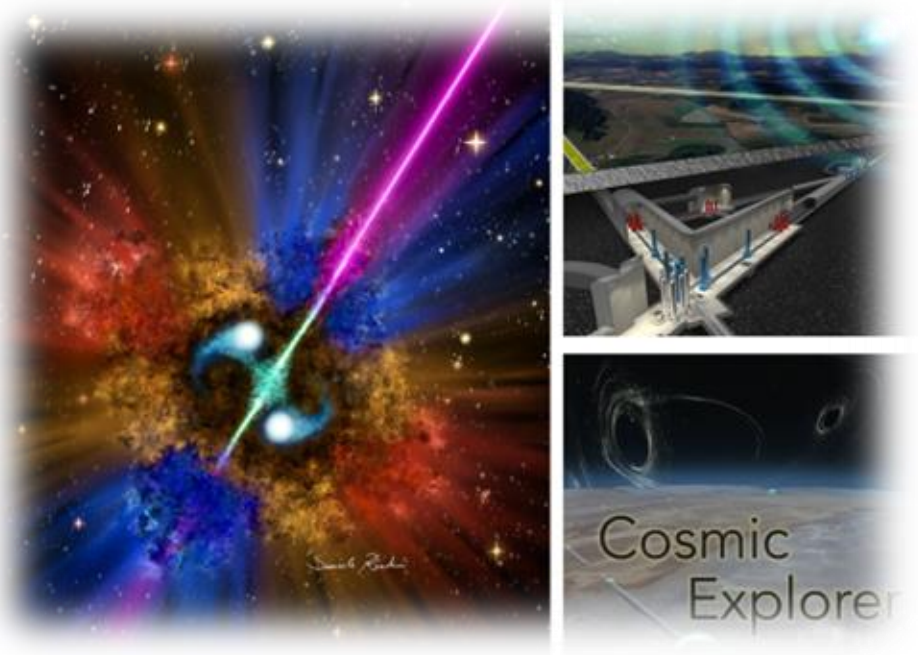
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

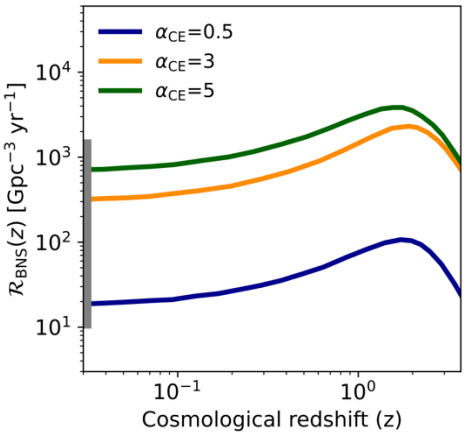
ET science book, Abac et al. arXiv:2503.12263

Multi-messenger in the ET era



Forecasting detection and parameter estimation capabilities

CBC populations



GWFISH

G S
S I

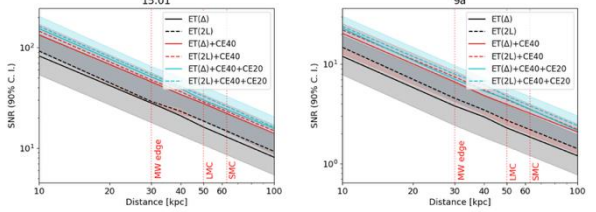
Dupletsa et al. 2023 A&C
Dupletsa et al. 2025 PRD

https://github. com/janosch314/GWFish
PRIN METE
PERIODIC ACME TUTORIAL

Python Fisher-Matrix code/package

+GW waveforms

ET science book

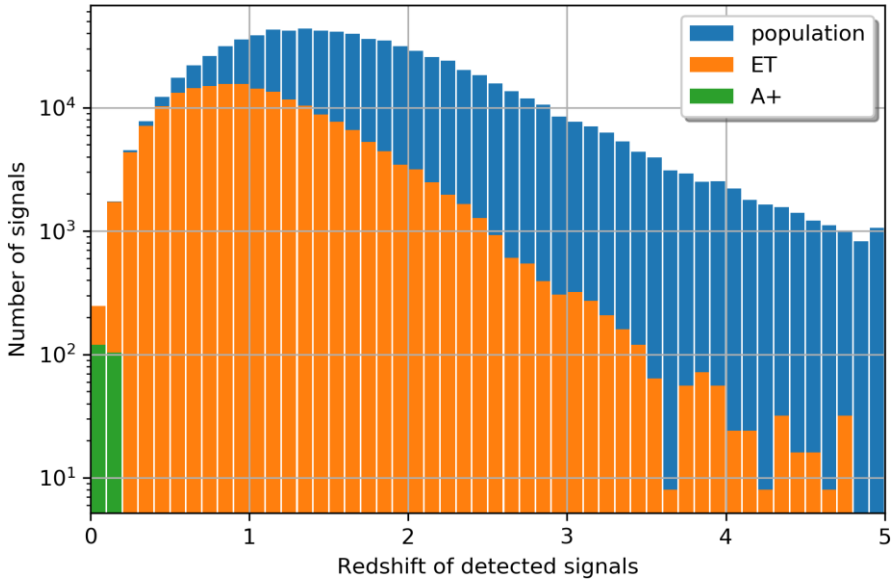


- It implements SNR and horizon estimate for SNe
- Beyond long-wavelength approximation for kHz studies (see for example Arnab et al. arXiv:2507.14071 on direct measurement of the accretion disk mass)
- It is use for ET, LGWA and multi-band studies (see for example Benetti et al. 2026, A&A for WD-WD)

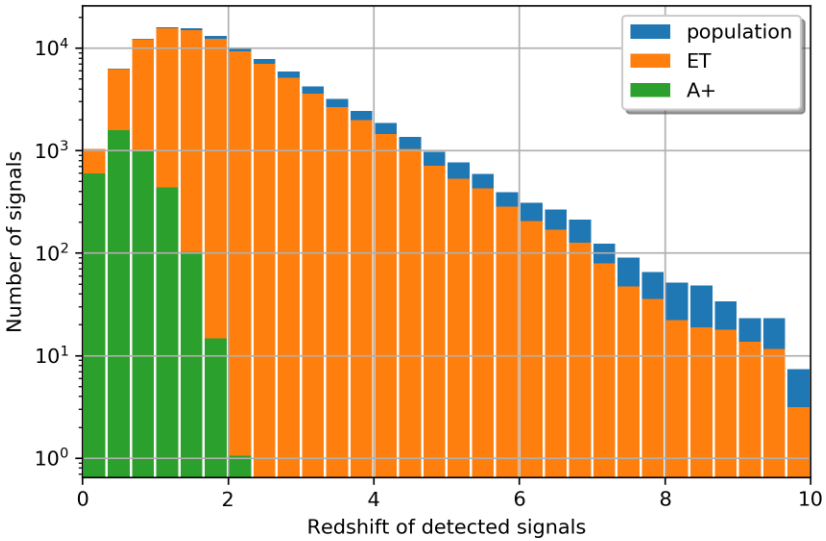
COMPACT OBJECT BINARY POPULATIONS

EINSTEIN TELESCOPE

BINARY NEUTRON-STAR MERGERS



BINARY BLACK-HOLE MERGERS

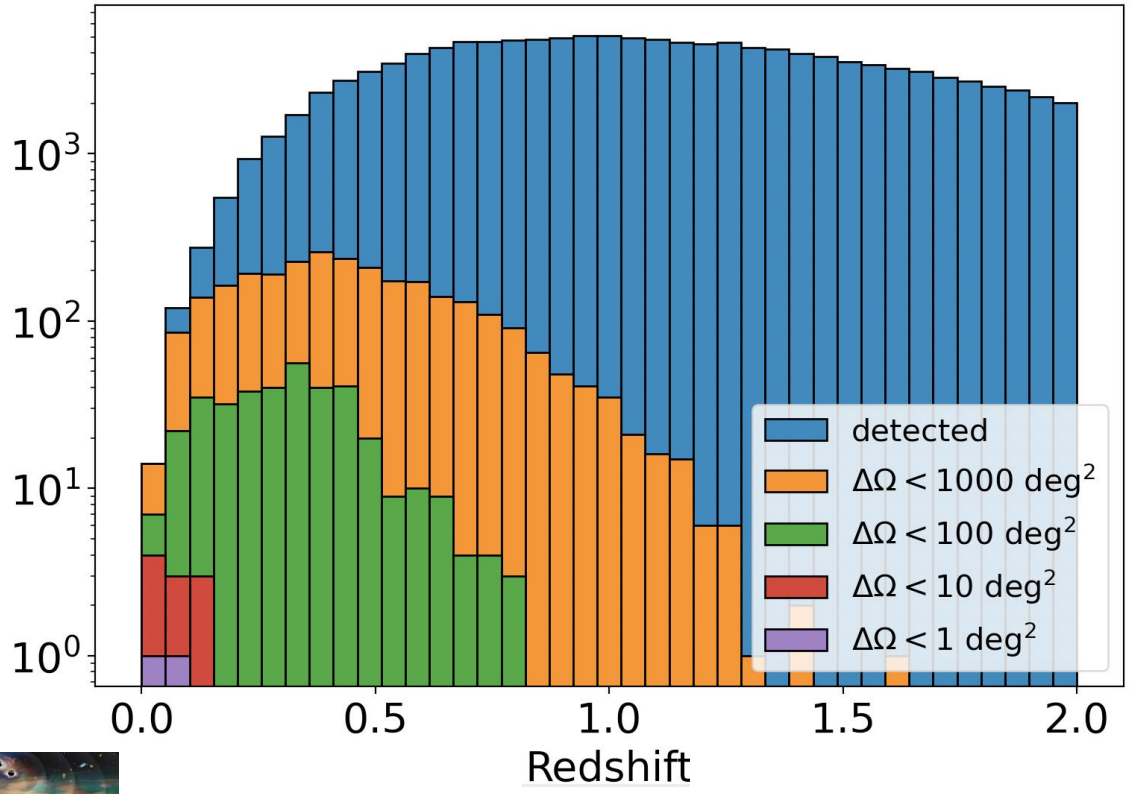


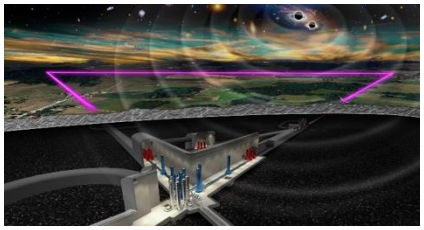
Sampling **astrophysical populations** of binary system of compact objects along the cosmic history of the Universe

10^5 BNS detections per year

10^5 BBH detections per year

ET sky-localization capabilities

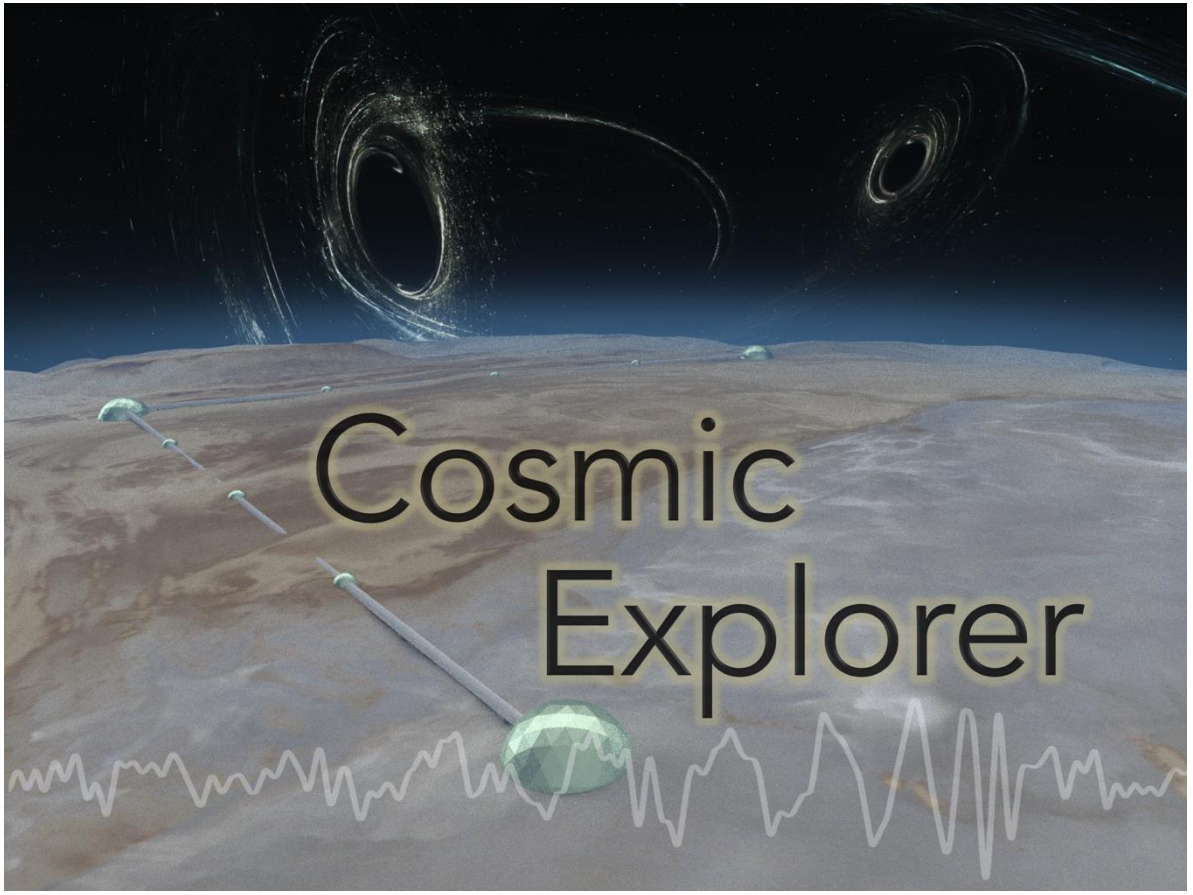




ET low frequency sensitivity make it possibile
To localize BNS!

- O(100) detections per year with sky-localization (90% c.r.) < 100 sq. deg
- Early warning alerts!

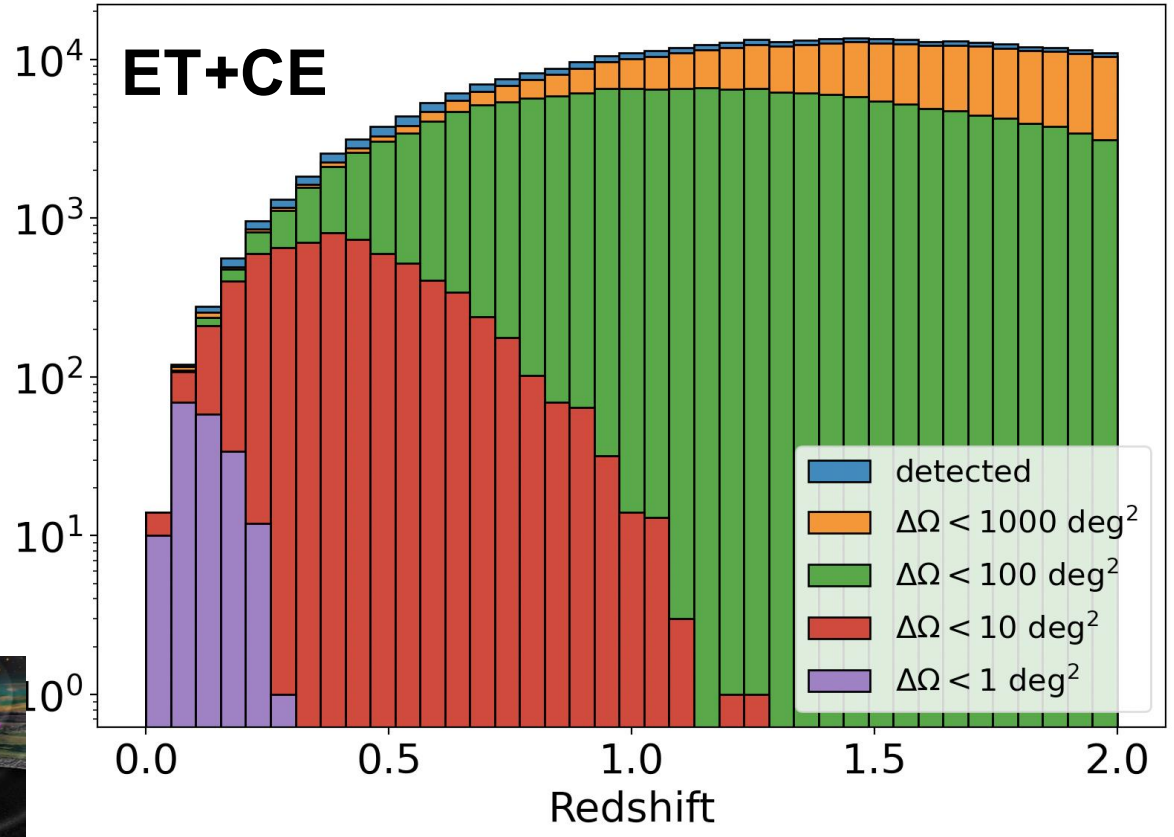
Next generation GW effort worldwide

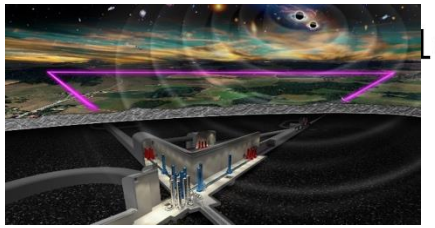


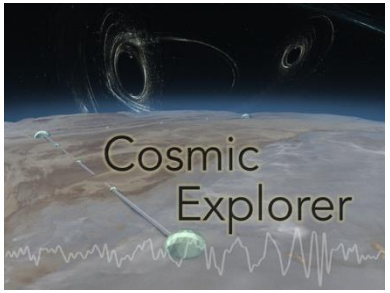
Cosmic Explorer: L shaped detectors, two sites (40km, 20 km [option])

Evans et al. 2021, 2023; Gupta et al. 2023

Network sky-localization capabilities





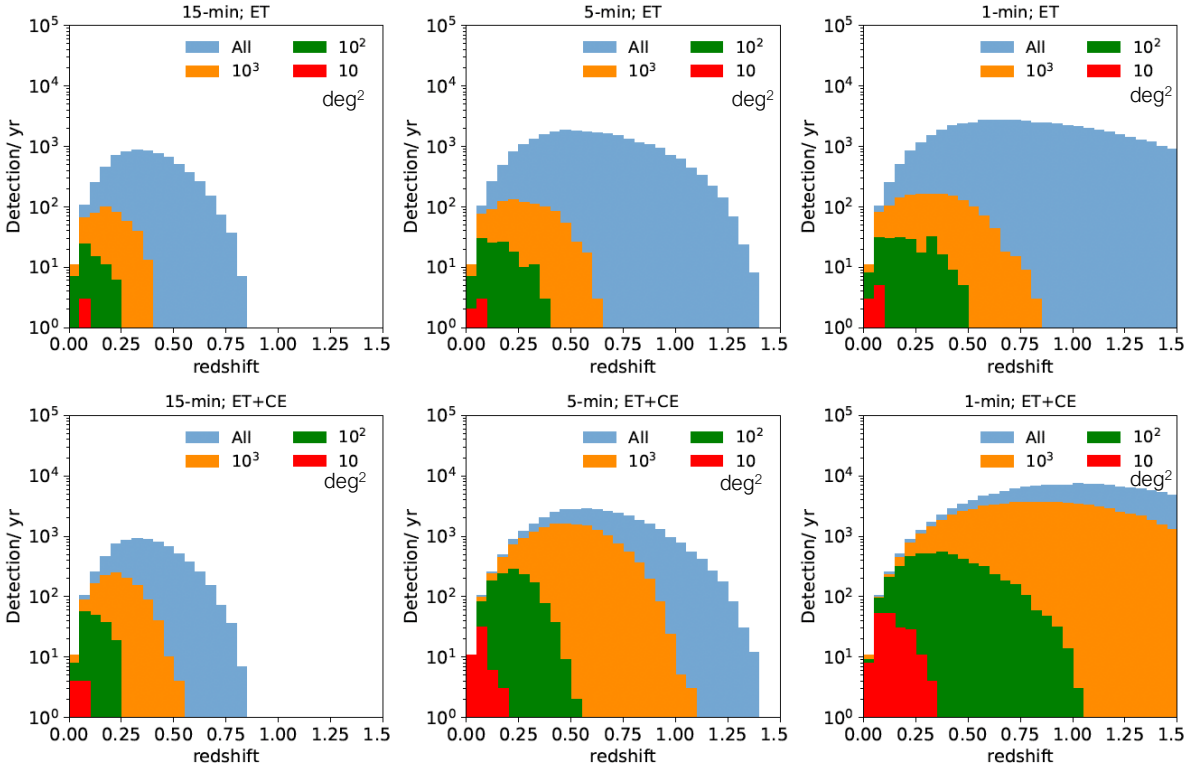


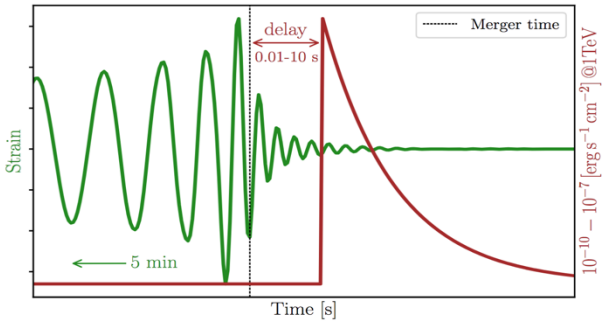
- O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg

Branchesi et al. 2023, Dupletsa et al. 2023, Ronchini et al. 2022

GWFISH

Pre-merger detections





Five minutes before the merger:

- ET → O(10) detections with sky-localization < 30 deg^2
- ET+CE → O(100) detections with sky-localization < 30 deg^2

Banerjee et al. 2023, A&A
Branchesi et al. 2023, JCAP

Getting closer to the merger time:

- improvement in sky localization capabilities
- more distant events can be localized

MM change of paradigm

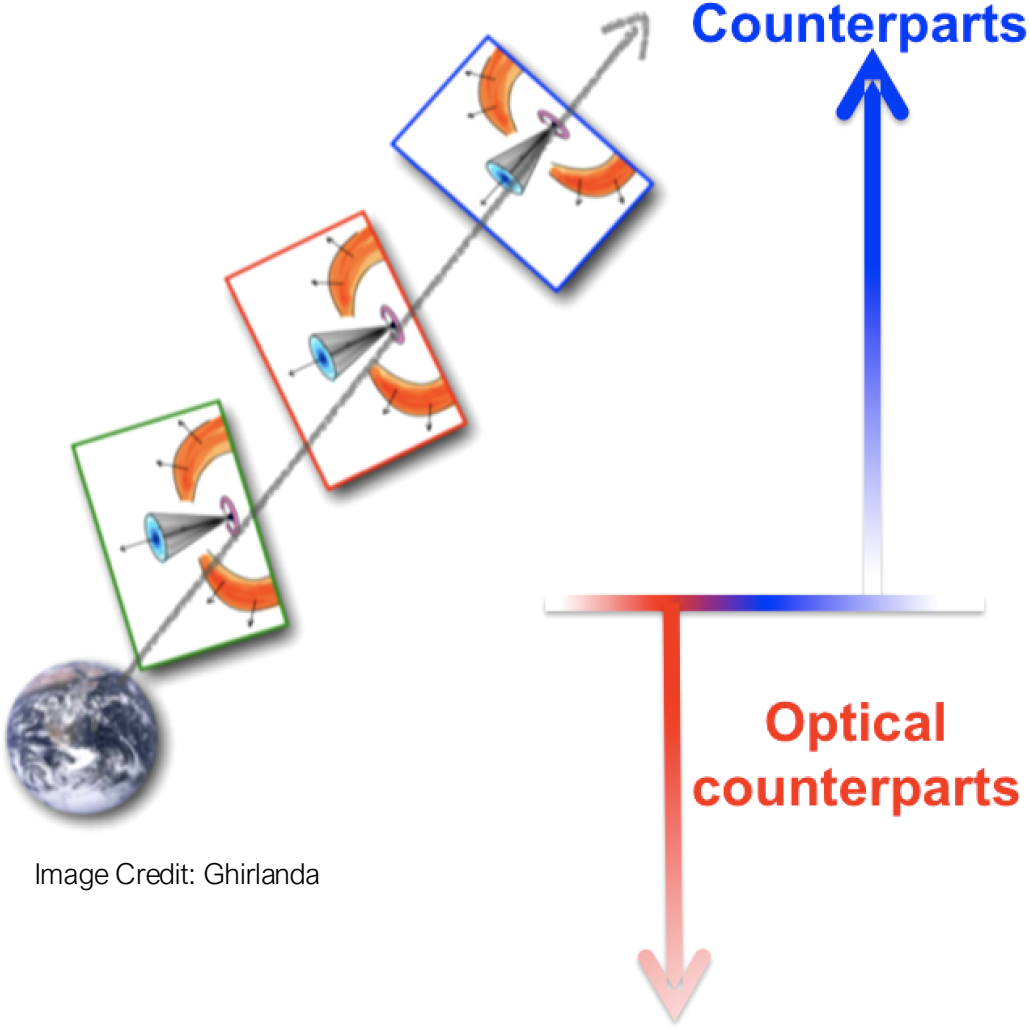
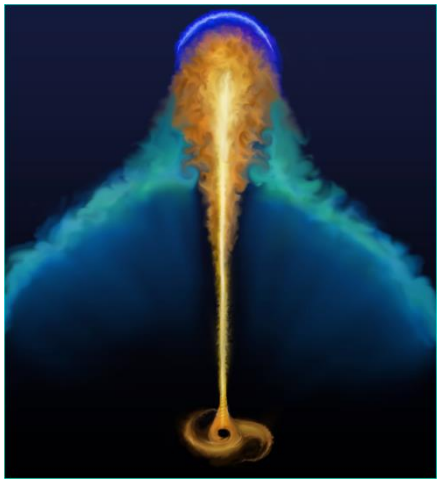


Image Credit: Ghirlanda

RELATIVISTIC JET PHYSICS,
GRB EMISSION MECHANISMS,
COSMOLOGY and MODIFIED GRAVITY

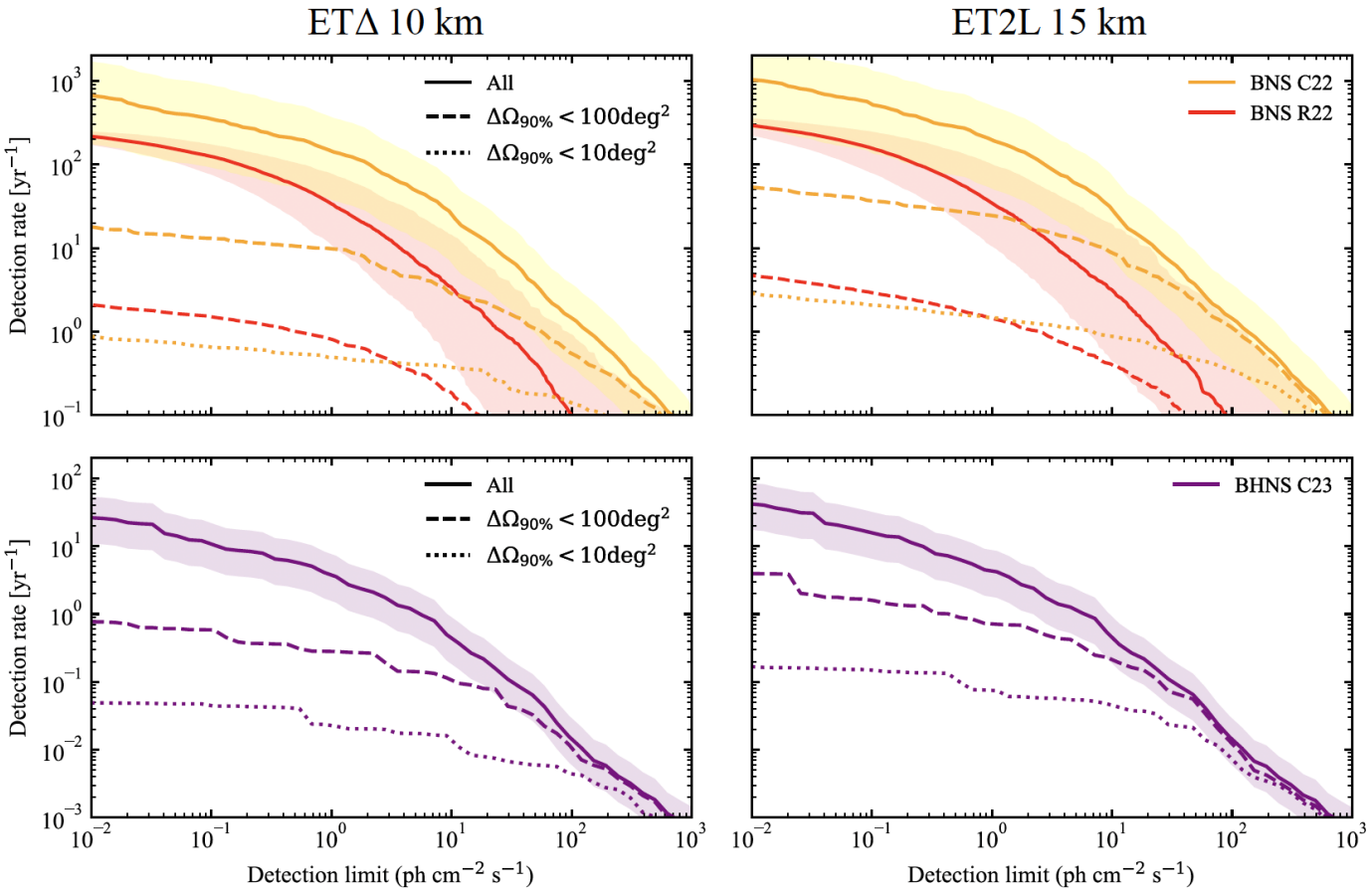


KILONOVA PHYSICS,
NUCLEOSYNTHESIS,
NUCLEAR PHYISCS
and H0 ESTIMATE

HIGH-ENERGY

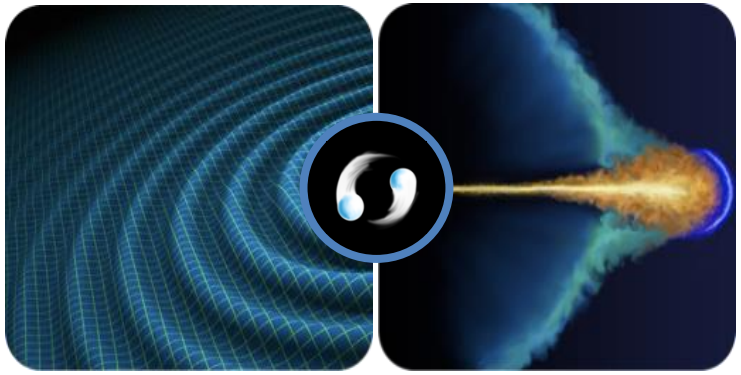
RELATIVISTIC JET PHYSICS,
GRB EMISSION MECHANISMS,
COSMOLOGY and MODIFIED GRAVITY

GW/Short GRB prompt emission



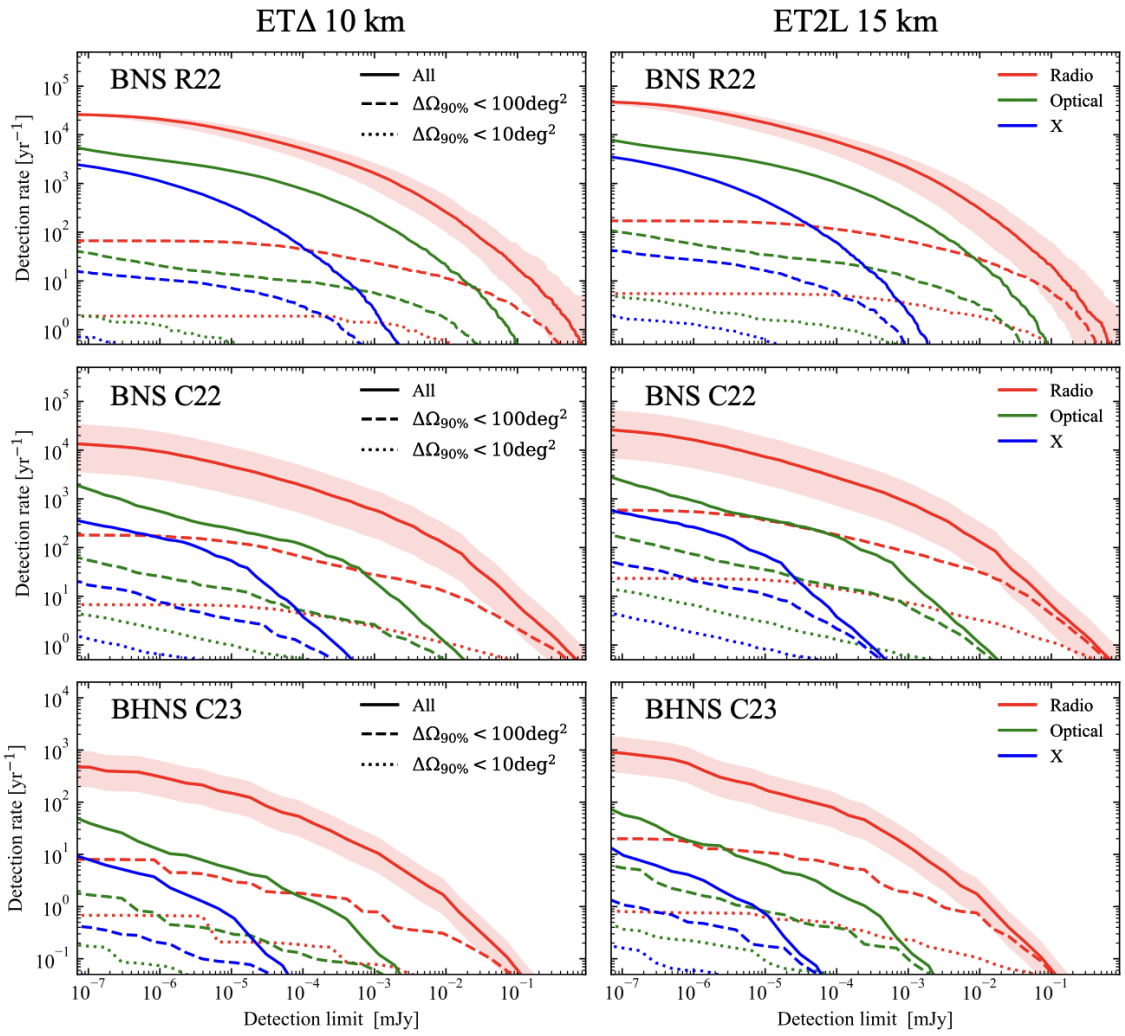
ET science book

Almost all detected short GRBs will have a GW counterpart



*See Ronchini, **MB** et al. A&A **2022***
Colombo et al. A&A 2025

AFTERGLOW EMISSION



*See Ronchini, **MB** et al. A&A **2022***
Colombo et al. A&A 2025

ET science book

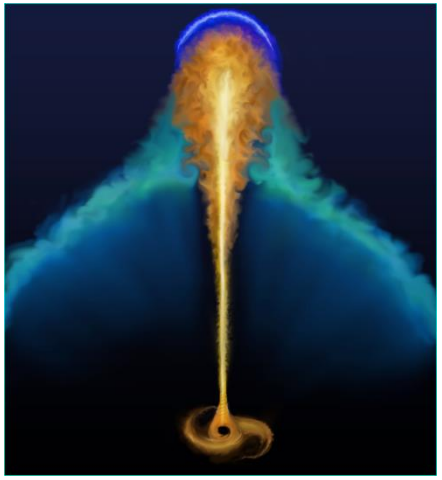
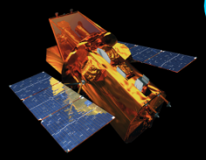


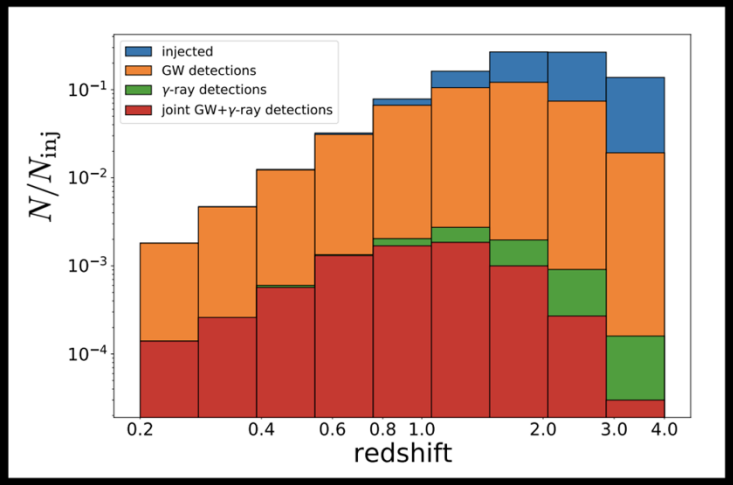
Image Credit: Ronchini

GW + γ-ray joint detections per year

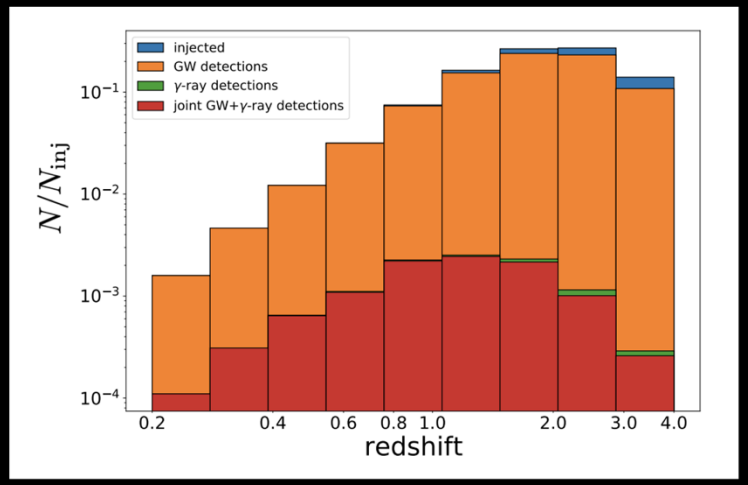
SURVEY MODE



Fermi-GBM+ET



Fermi-GBM+(ET+CE)



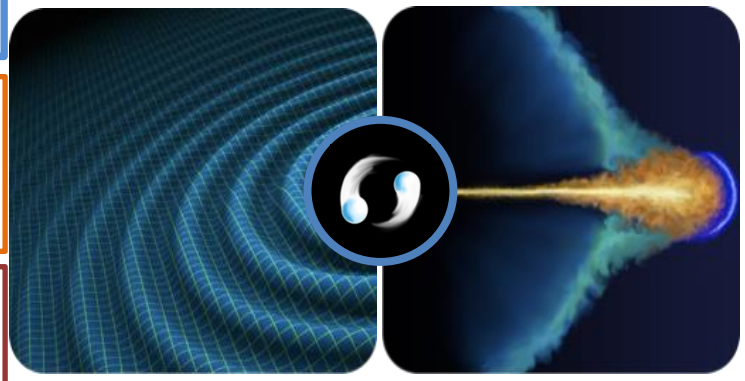
Depending on the satellites, we will have
tens (e.g. THESEUS) to **hundreds (e.g HERMES)** of detections per year

Crucial instruments able to localize at arcmin-arcsec level to drive the ground-based follow-up

AFTERGLOW: Wide FoV X-ray telescopes
(EP, THESEUS-SXI) increases the number of joint detections inlcuding off-axis GRB afterglow

Sensitive X-ray instruments such as **newATHENA** are required for the characterization

*Ronchini, **MB** et al. A&A **2022***



Implementation of the theoretical framework developed by Ronchini et al. 2022 used for THESEUS and GRINTA proposals

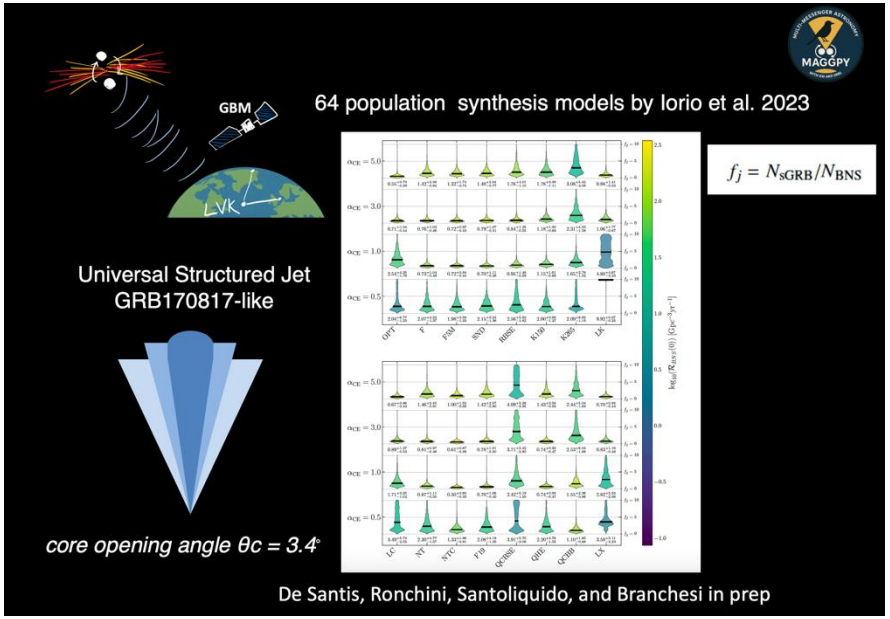
A new fast code almost ready to be released

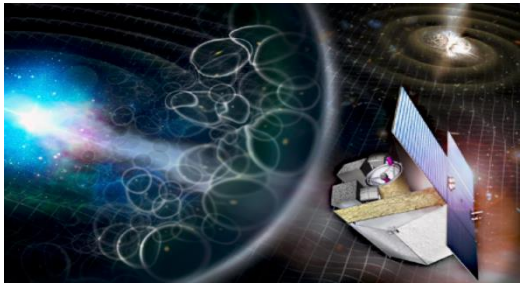
MAGGPY

Provided the BNS GW observations, is there a tension among BNS merger populations and short GRBs?

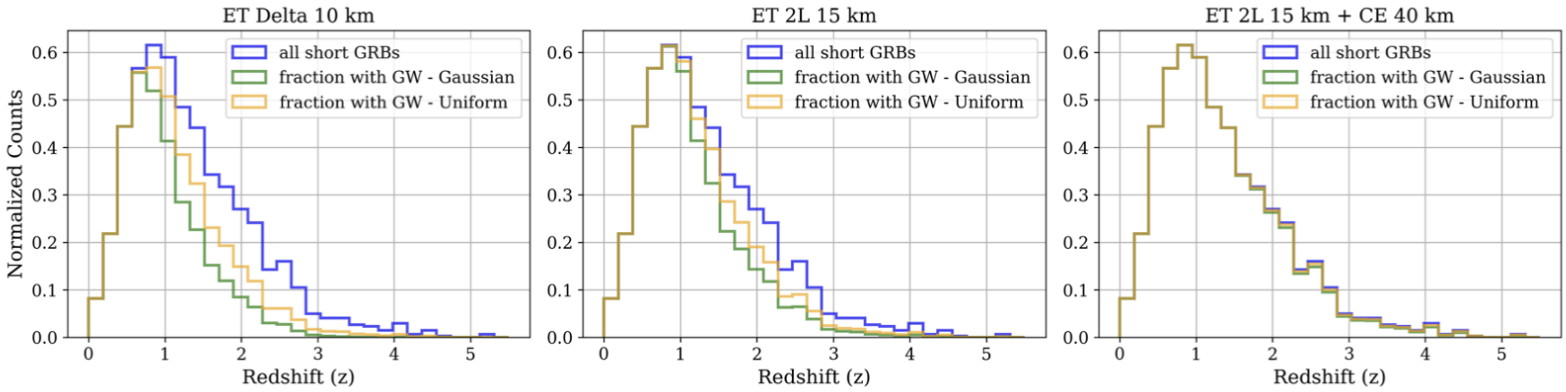
Constraining BNS populations using Short GRB Observations+

De Santis, Ronchini, Santoliquido, Branchesi 2026 ready to be submitted to A&A



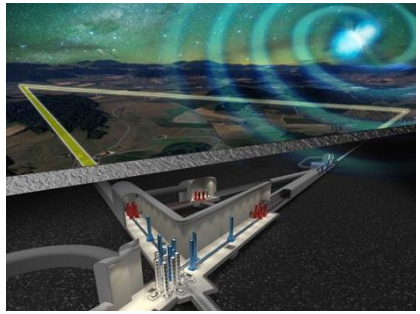


THESEUS and ET



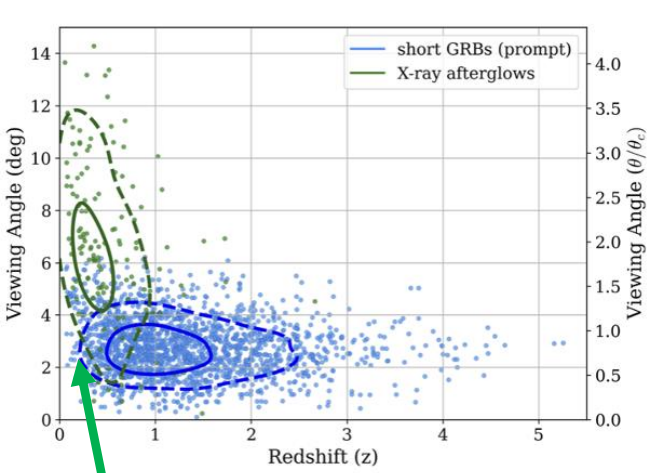
GW observatories	Prompt
ET Δ 10 km	27 – 33
ET 2L 15 km	34 – 38
ET 2L 15 km + CE L 40 km	43 – 44

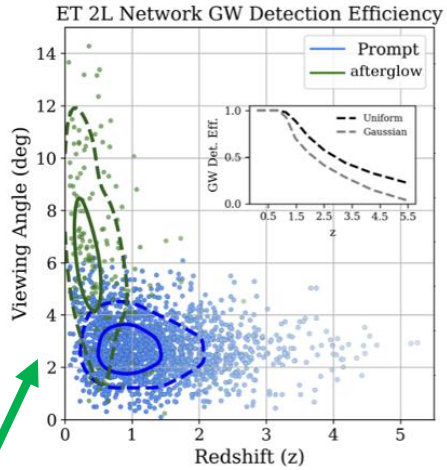
Expected number of well-localized THESEUS short GRBs with a joint GW detection over the nominal mission science time

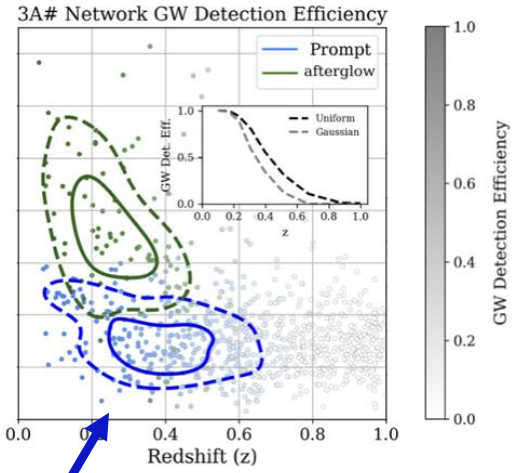


THESEUS Yellow Book, De Santis, Ronchini

Viewing angle vs. redshift distributions of THESEUS prompt and "orphan" afterglow detections







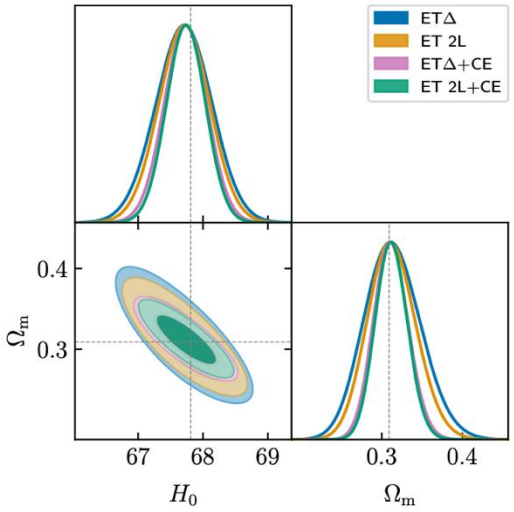
Afterglow-only cases up to viewing angle of ~14 deg are limited to z<1 → 3-4 other detections
Unprecedented precise parameter estimation from the GW

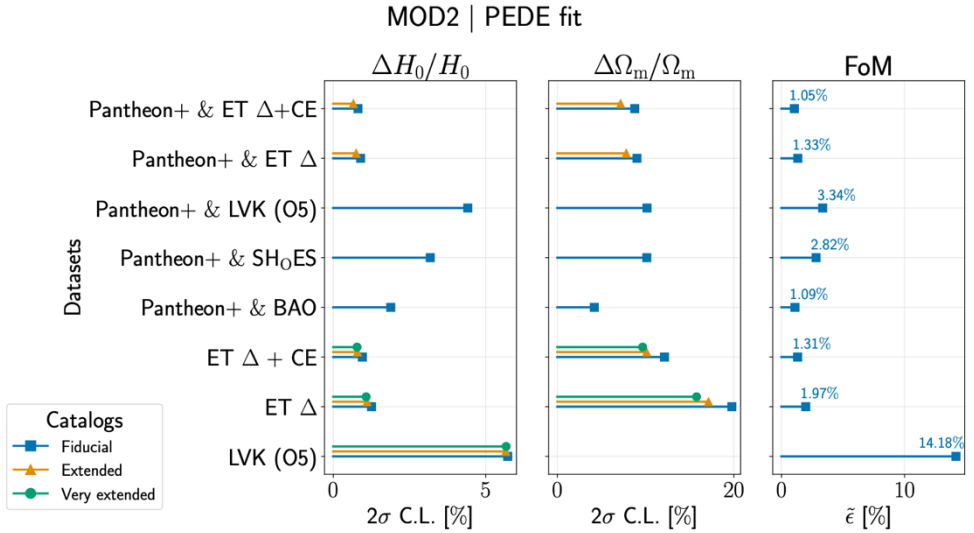
Post-O5 scenario 3A#
4-6 joint THESEUS+GW detections

Cosmology with joint observations of GWs and GRBs

- Mock MM data based on short GRB observed by Swift and Fermi
- Fisher matrix + agnostic reconstruction of the DE phenomenology (ML)

*See Cozzumbo et al. JCAP **2025***



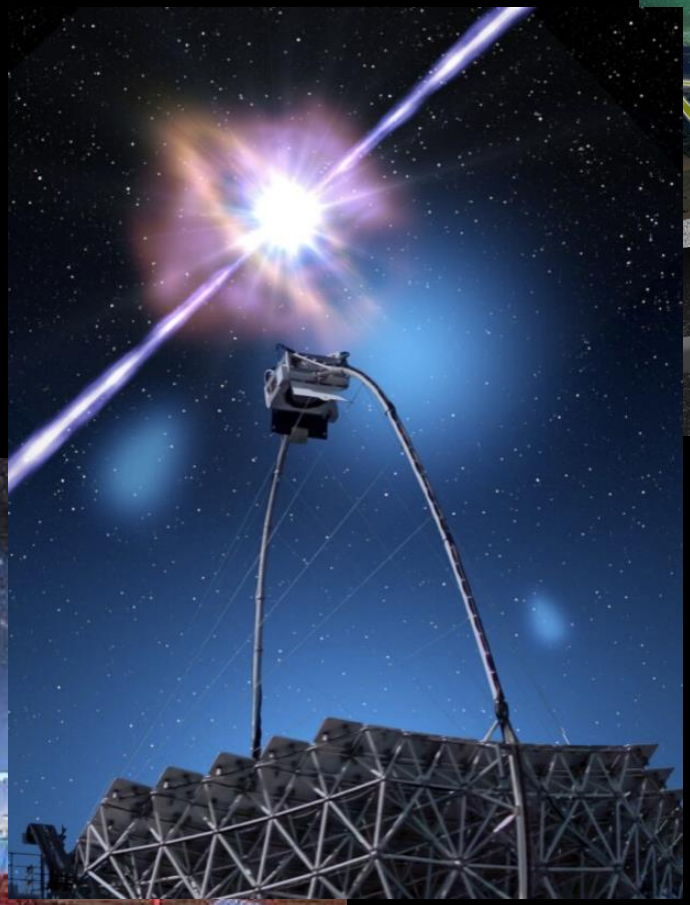


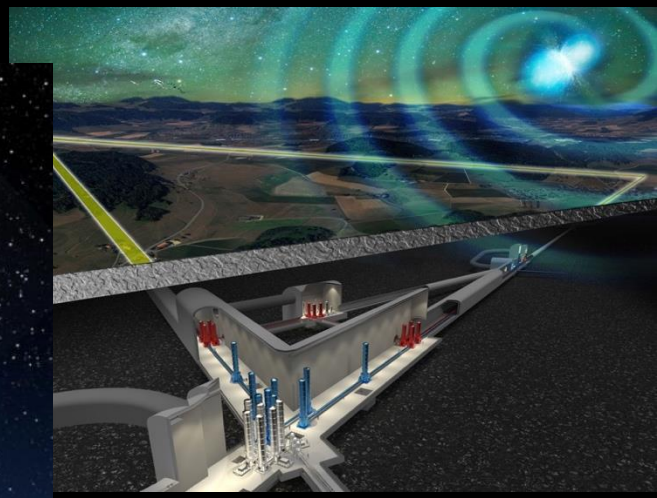
HIGHLIGHTS:

- in combination with forthcoming cosmological surveys, around **40 GW-GRB detections** → unprecedented precision on H_0 and Ω_m, and DE density evolution
- required observatories capable of detecting GRBs and identifying their redshift.

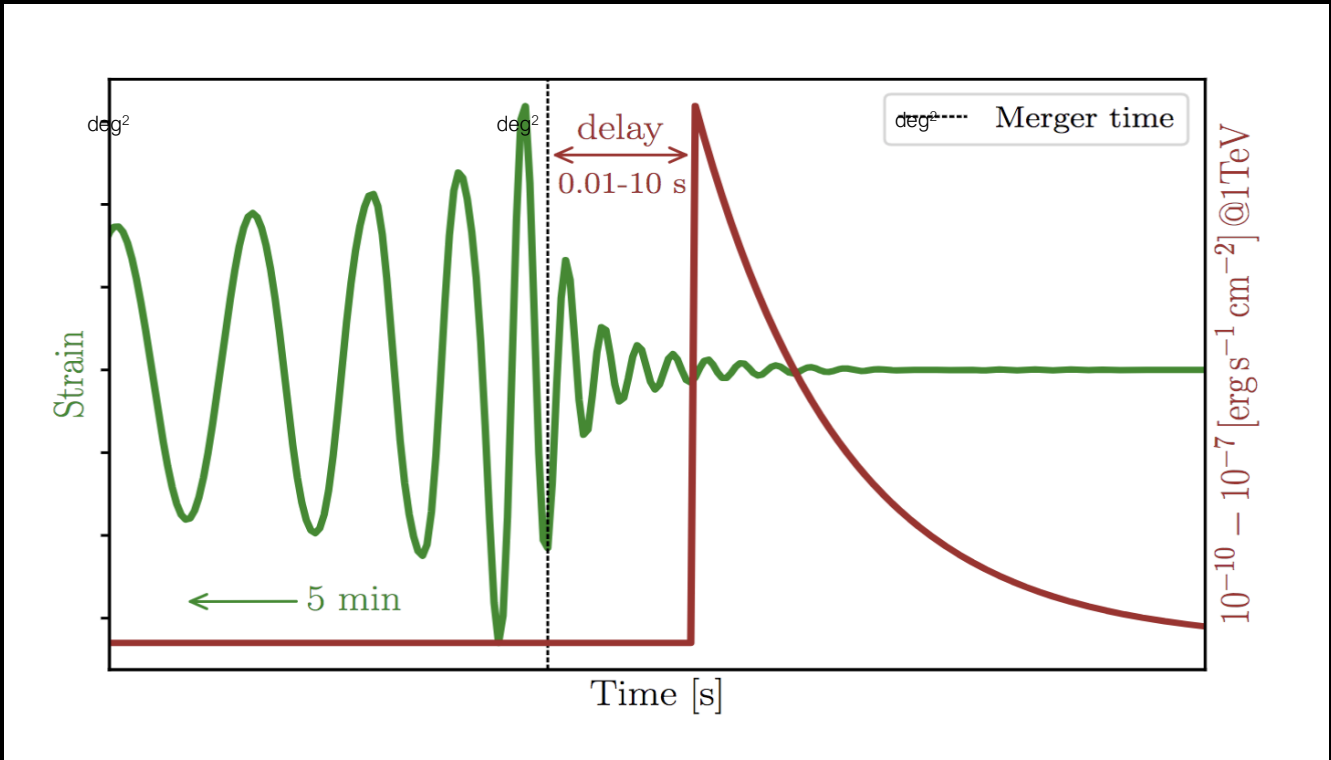
.

CTAO and GW DETECTOR synergies

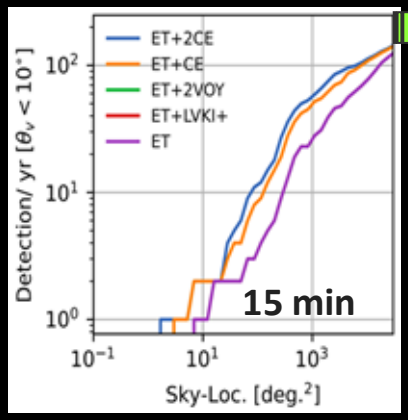


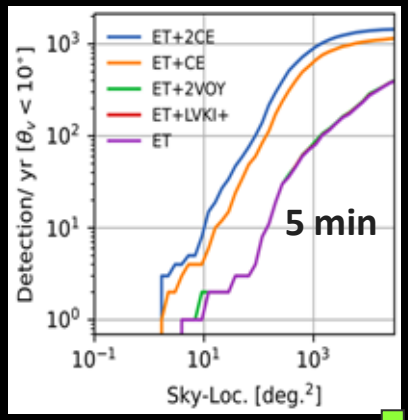


Pre-merger detections

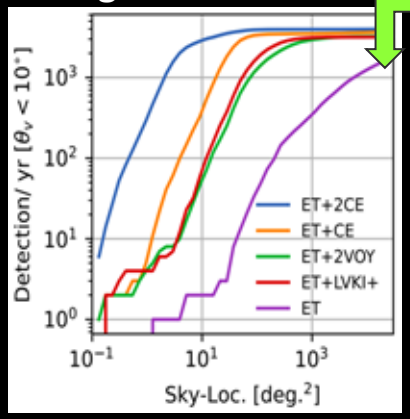


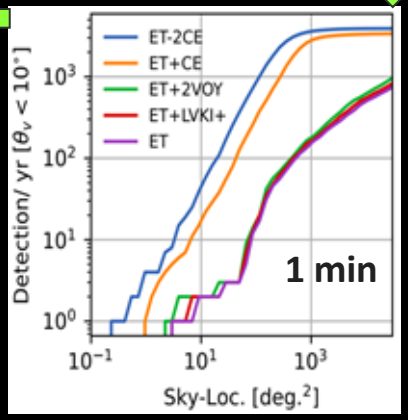
Sky-localization capability:





Merger





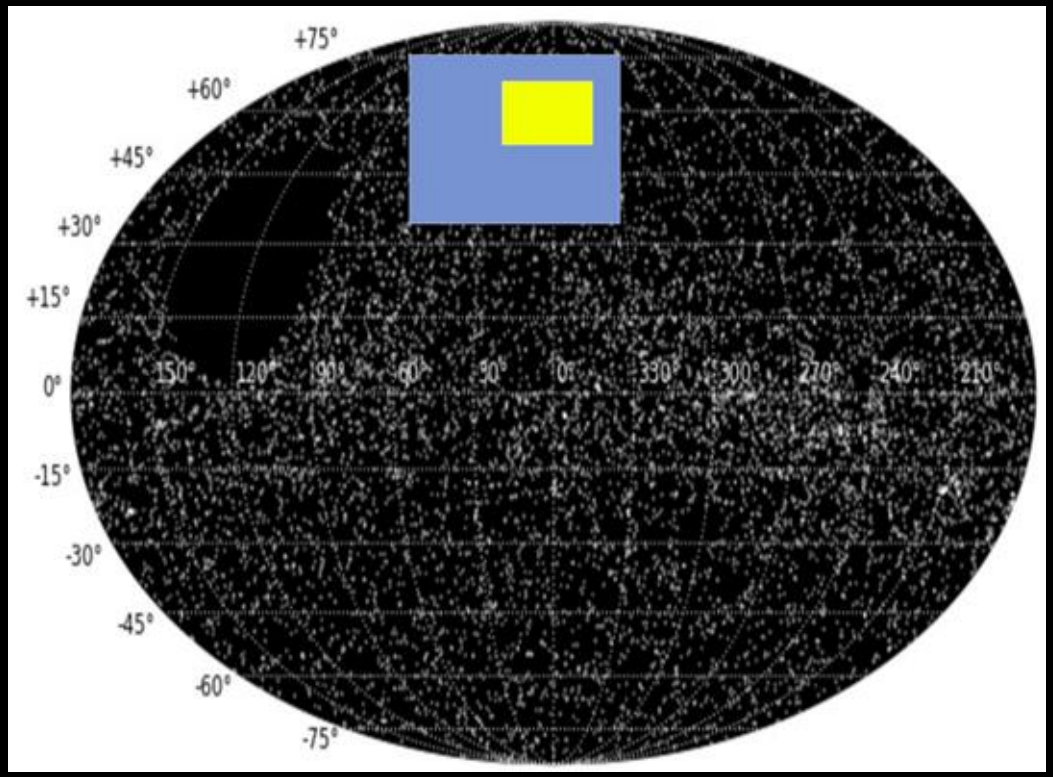
Events per year

Detector	Ω [deg^2]	All orientations			
		15 min	5 min	1 min	0 min
ET + CE	**100**	**442**	**1325**	**5075**	**123303**
ET	**100**	**90**	**130**	**208**	**436**

Detector	Ω [deg^2]	Viewing angle (<10^0)			
		15 min	5 min	1 min	0 min
ET + CE	**100**	**21**	**71**	**314**	**3376**
ET	**100**	**3**	**6**	**13**	**40**

Banerjee, Oganesyan, Branchesi et al 2023, A&A

Observation strategy:

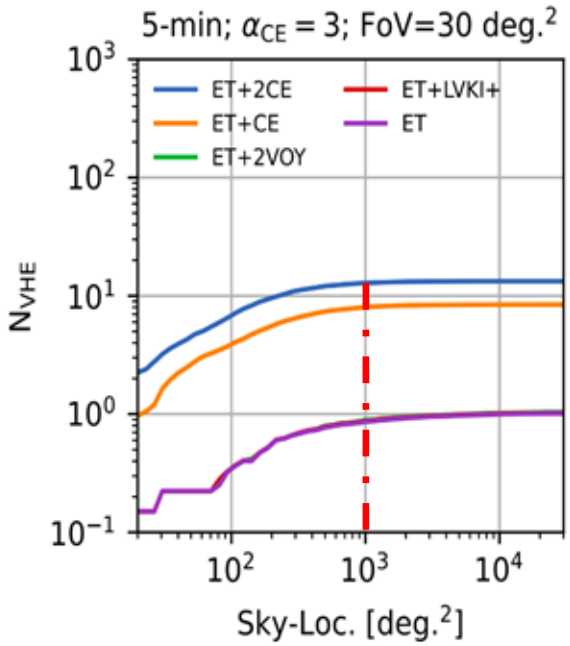


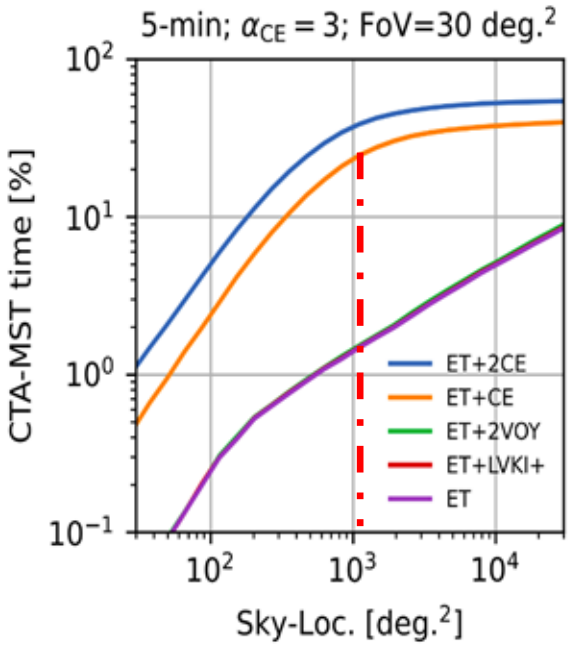
Follow-up pre-merger alerts with CTA

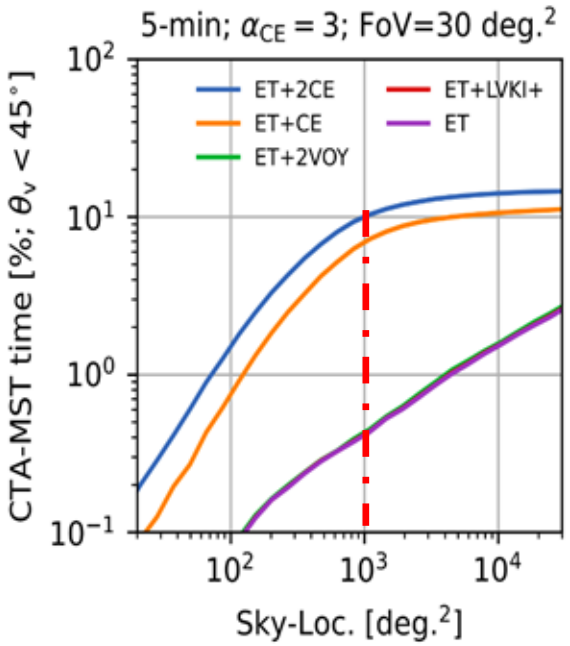
- Follow-up well localized sources (< FoV)
- Single shot observation
- Mosaic strategy
- Divergent pointing

Banerjee, Oganesyan, Branchesi et al 2023, A&A

Observation strategy: MST – one shot







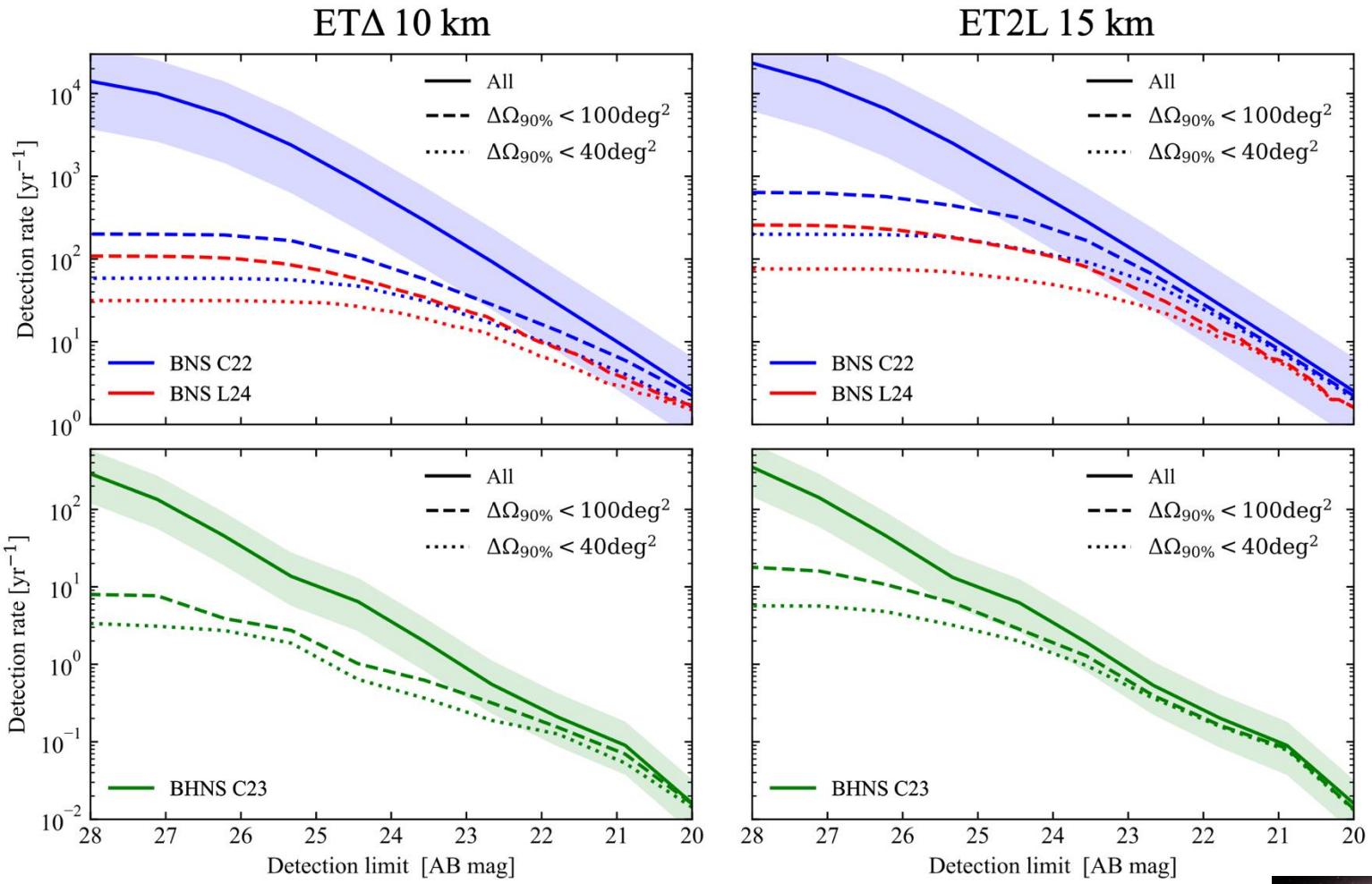
ET+CE: around ten VHE counterparts can potentially be detected using 10% of the CTA time

Banerjee, Oganesyan, Branchesi et al 2022, A&A

THERMAL EMISSION - KILONOVAE

KILONOVA PHYSICS, NUCLEOSYNTHESIS, NUCLEAR PHYISCS and COSMOLOGY

Kilonova emission



ET science book

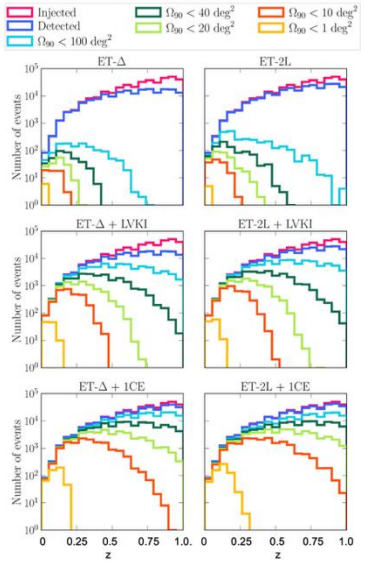
See Loffredo, Hazra, Dupletsa, MB et al. 2025, A&A
Colombo et al. A&A 2025

Einstein Telescope and Vera Rubin Observatory

64 simulations (release in zenodo Dupletsa et al. 2024)

- *Two BNS merger populations (10 years)*
- *NS mass distribution: Gaussian and uniform*
- *EoSs: BLh and APR4*
- *Several network of detectors*

GWFISH

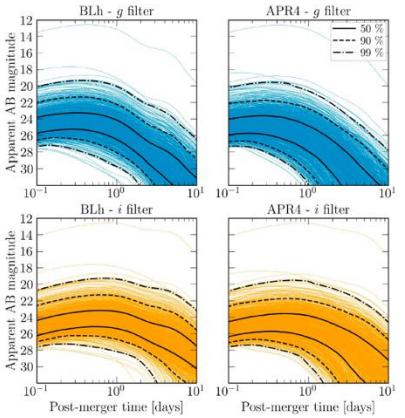


Population KN light-curves

- *Multi-component ejecta: dynamical + spiral wind + secular*
- *KNe ejecta through numerical-relativity informed fits*
- *Calibrated for **GW170817** and **GW190425***
- *Including **prompt collapse** of the remnant to black hole*

+ sGRB afterglow

Gaussian NS mass distribution

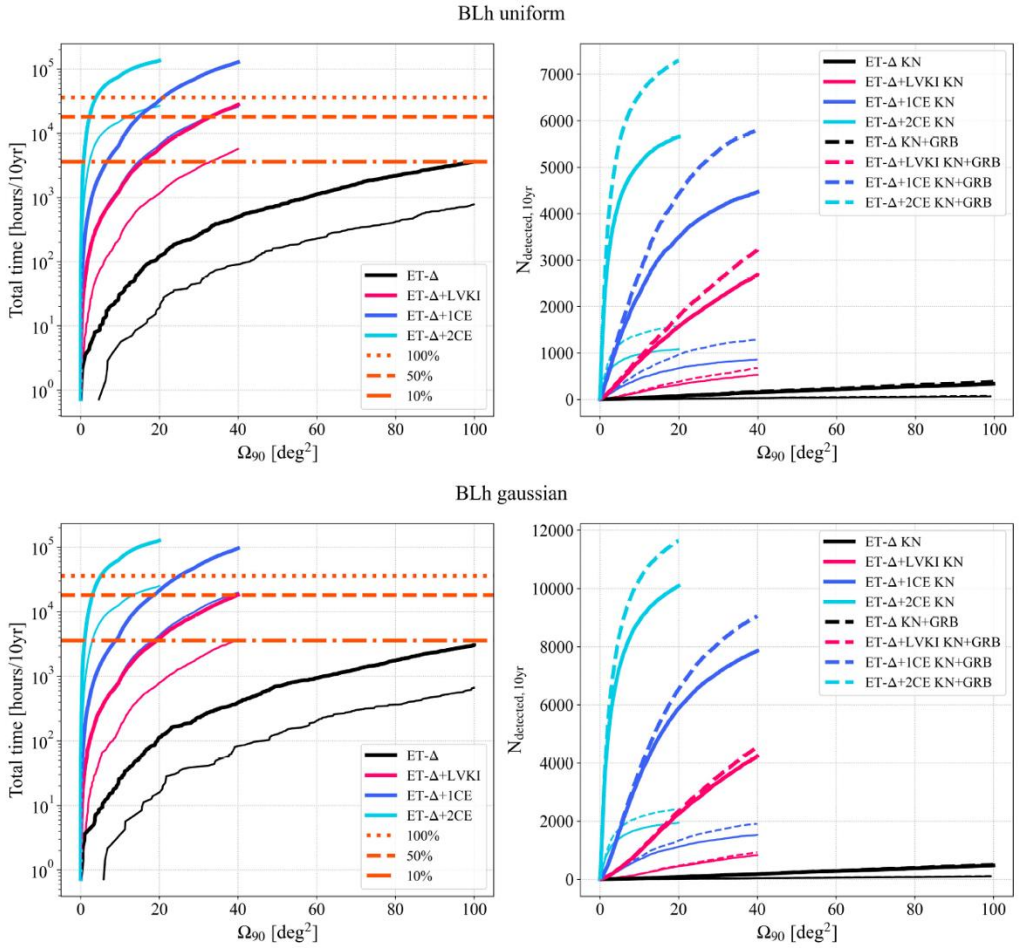


Realistic Observational strategy

- *multi-epochs (2 nights)*
- *multi-filters (i and g)*
- *ToO observations, exposure = 600 s*
- *mosaic to cover the GW sky-loc*

Loffredo, Hazra, Dupletsa, MB et al. 2025 A&A

Einstein Telescope and Vera Rubin Observatory



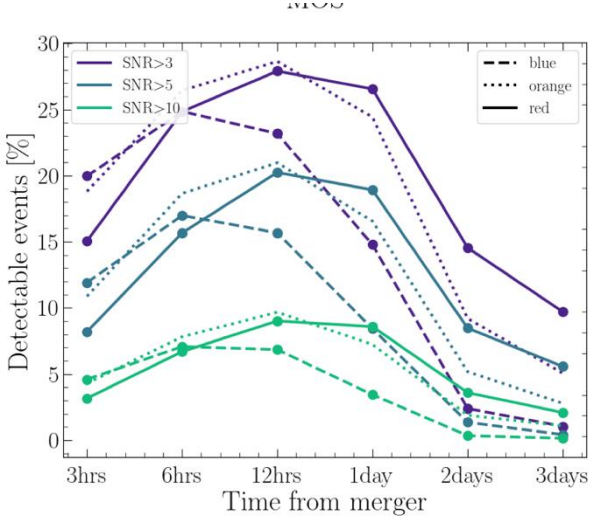
- *multi-epochs (2 nights)*
- *multi-filters (i and g)*
- *ToO observations, exposure = 600 s*
- *mosaic to cover the GW sky-loc*

- ET → Rubin 10 –100 KNe per year
- ET-LVKI → Rubin detection increase by an order of magnitude wrt ET
- ET-CE → Rubin detection increase by 3 wrt ET+LVKI (not correspond to the increase of well-localised events because KN limited by Rubin detection efficiency)

Loffredo, Hazra, Dupletsa, MB et al. A&A

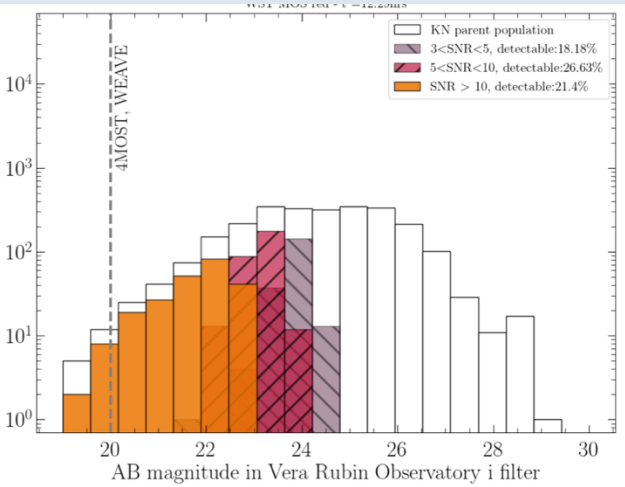
Einstein Telescope and wide-field, high-multiplex spectroscopic facilities (WST)

WST-MOS Detectable KN as a function of time for ET 2L

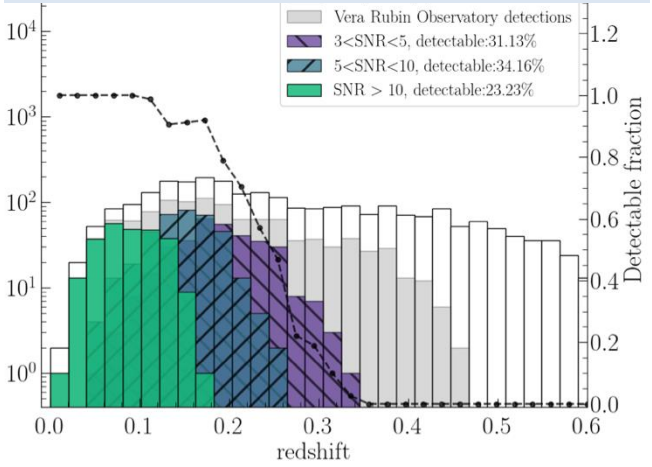


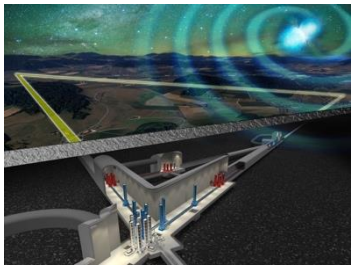
BNS detected by ET in 10 yrs up to z=1 with sky-loc < 100 deg^2

KN-magnitude at 12 hrs after the merger



Redshift distribution





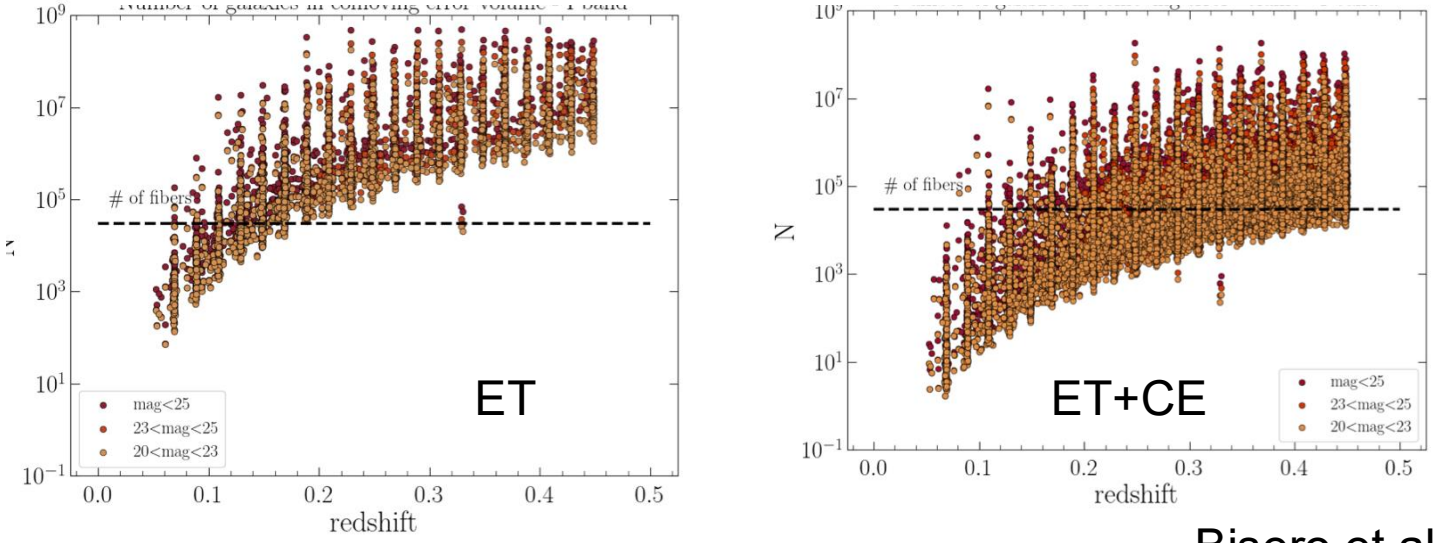
Bisero et al. A&A 2026

Einstein Telescope and wide-field, high-multiplex spectroscopic facilities (WST)

Two strategies:

- WST alone performing a galaxy targeted research (peak of the probability regions with the IFS and the remaining area with MOS fibres) The second strategy that we consider
- WST in synergy with optical-NIR pho- tometric observations - VRO

Number of galaxies in the comoving error volume of BNS



Bisero et al. A&A 2026

***Golden* events for WST follow- up:**

- BNS with redshifts $z < 0.3$ and that have sky loc. < 10 deg^2
- WST able to cover all the galaxies in the error volume with a limited number of exposures
- ~ 10 (ET-alone) to hundreds per year (ET+CE)

SUMMARY

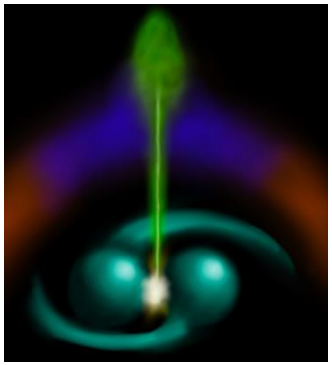
In the ET era MM astronomy will become a routine

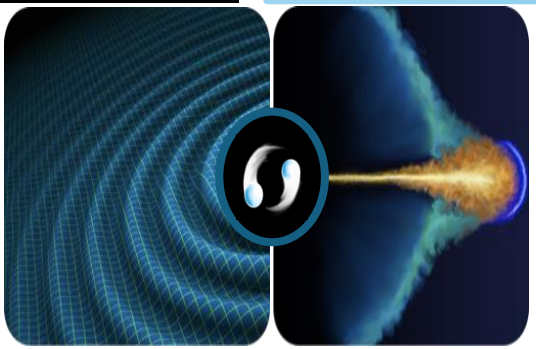
- Kilonovae will be detectable up to z = 0.3-0.4

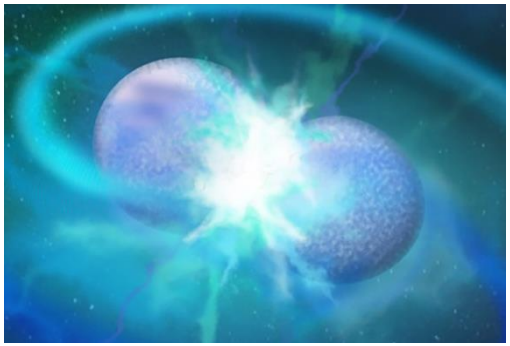
  [see Loffredo et al. 2025, Bisero et al. 2026, Colombo et al. 2025 Branchesi et al. 2024, Abac et al. 2026]

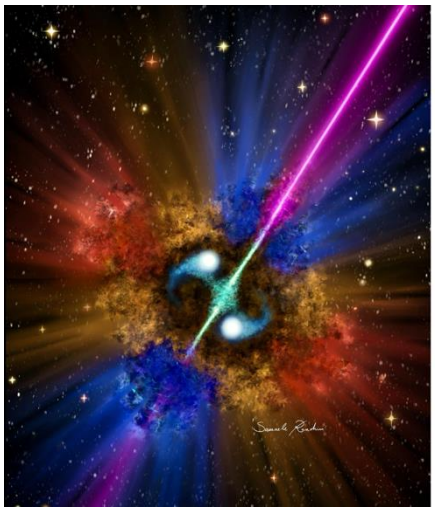
- GRBs will be the only counterparts detectable at high z
- Almost each detected GRB will have a GW counterpart GRB localization will be crucial to drive the follow-up by ground [see Ronchini et al. 2022, Colombo et al. 2025, Branchesi et al. 2024, Abac et al. 2026]

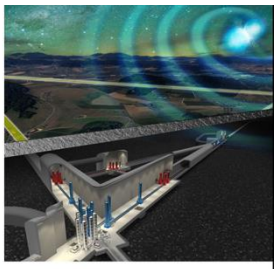
Early warning alerts critical to detect the prompt/early emission [see Banrjee et al. 2022, Branchesi et al. 2024, Abac et al. 2026]











Presented papers and coded were developed within the PRIN METE