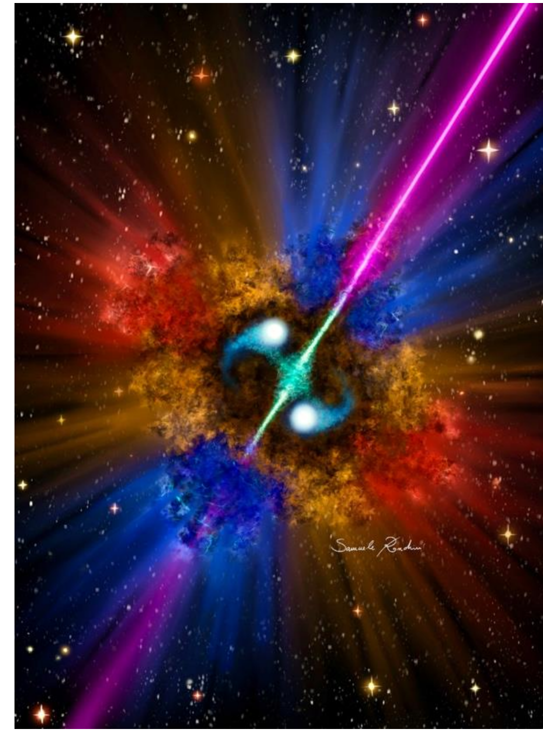
WST and Gravitational-Waves
Exploring the Era of Next-Generation Observatories



GSSI

M. Branchesi

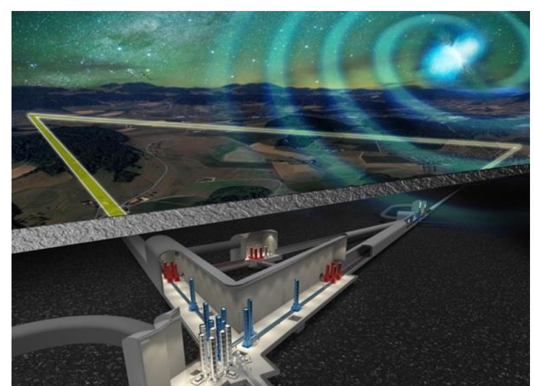
Gran Sasso Science Institute

INFN/INAF/ASI

ASI

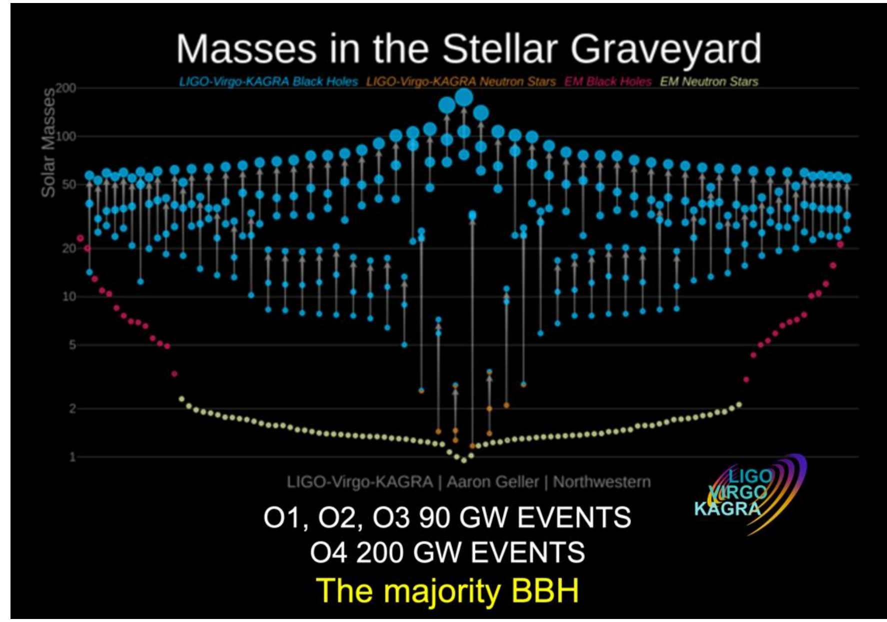
INFN
Istituto Nazionale di Fisica Nucleare

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

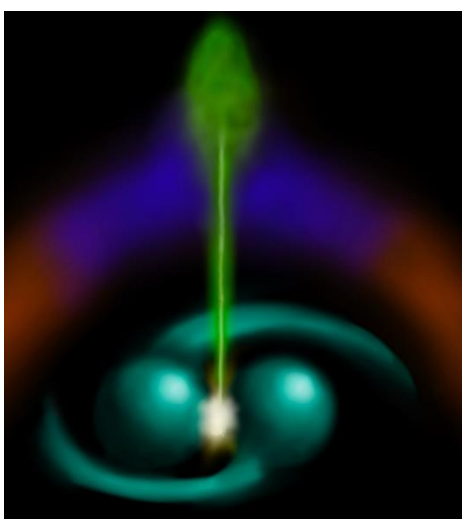


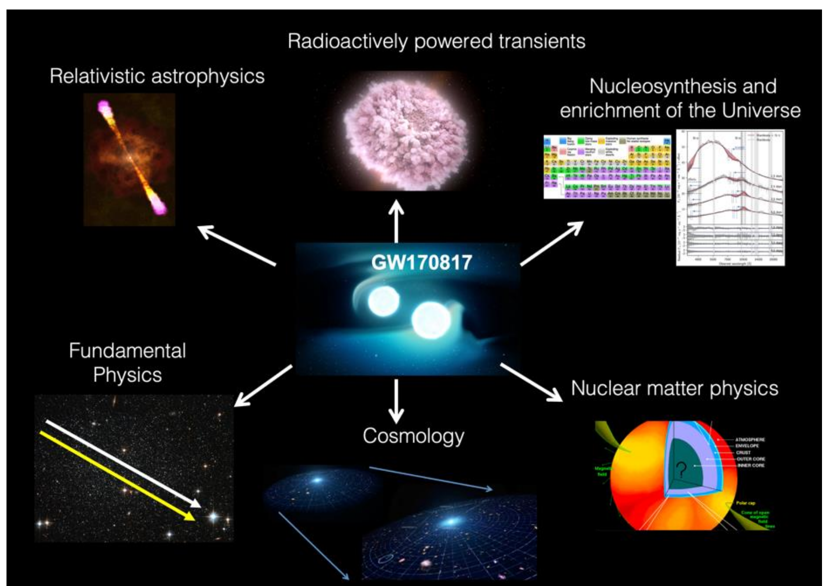
EINSTEIN TELESCOPE

GW astronomy so far..



GW170817



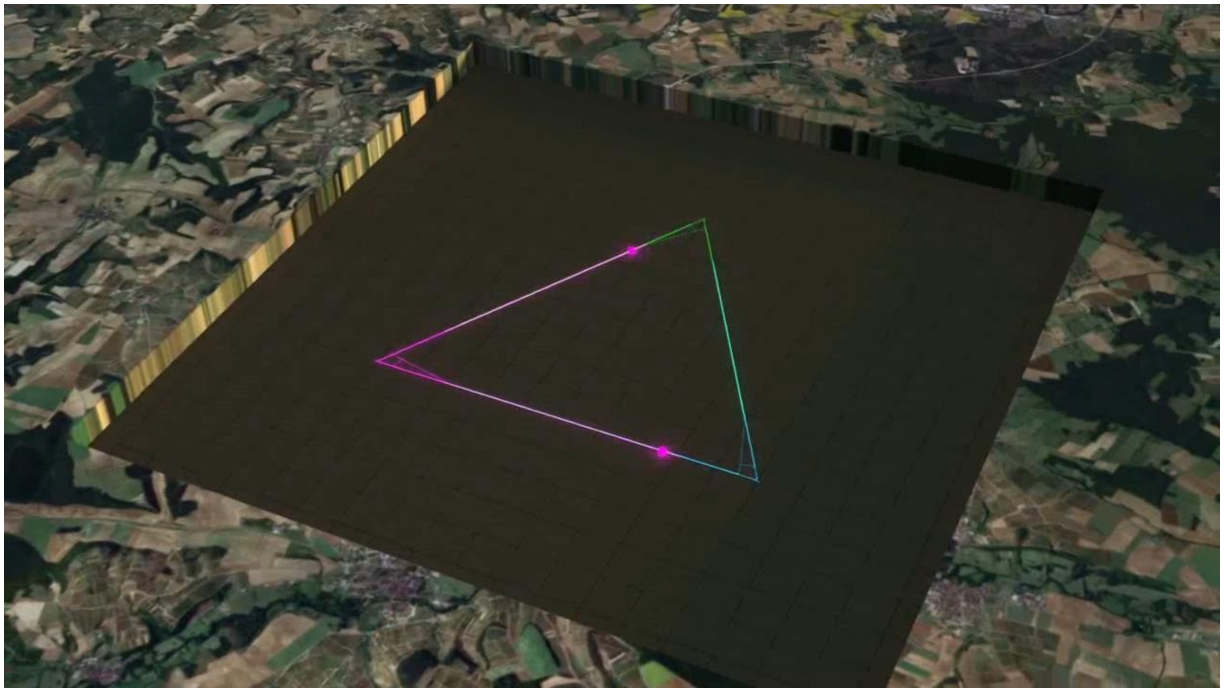


BNS mergers and MM events are rare!

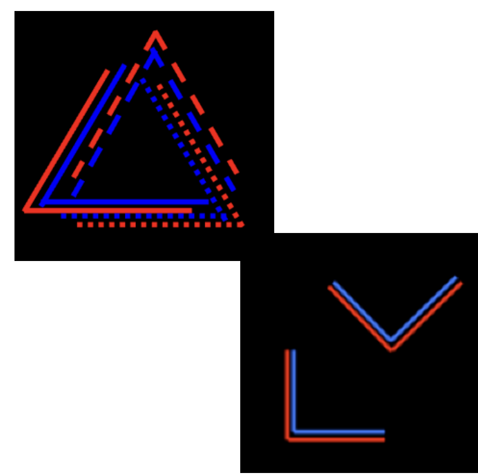
Next generation gravitational-wave and multi-messenger astronomy

See Bailes et al. 2021, Nature Reviews Physics;
Maggiore et al 2020, JCAP; Evans et al. 2021 arXiv:2109.09882;
Branchesi et al. 2023, JCAP, ET blue-book 2025

ET: the European next generation GW observatory



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



ET Science in a nutshell

EINSTEIN TELESCOPE

ASTROPHYSICS

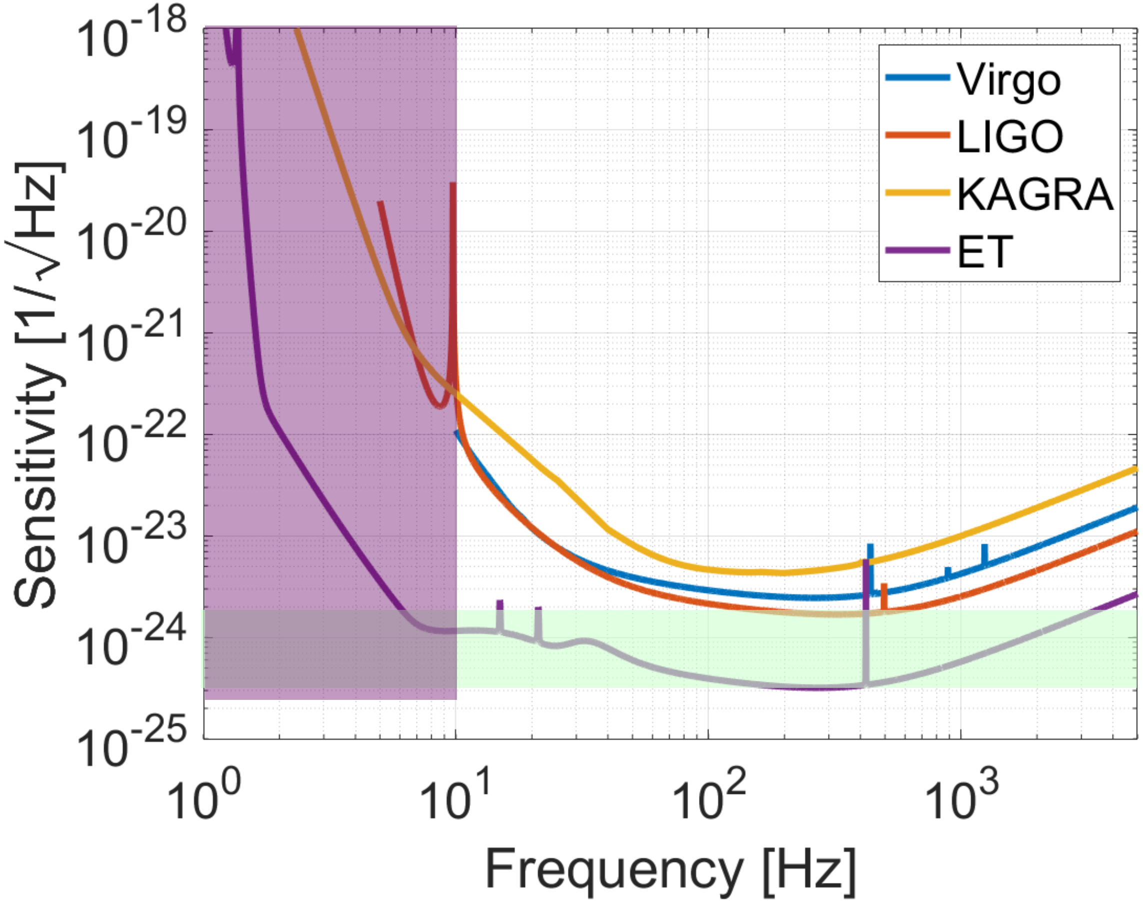
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - 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

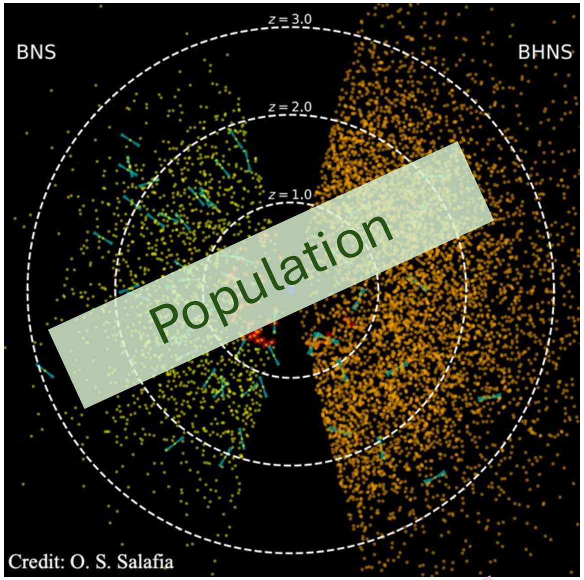
ET blue-book, soon in arXiv

EXPECTED SENSITIVITY



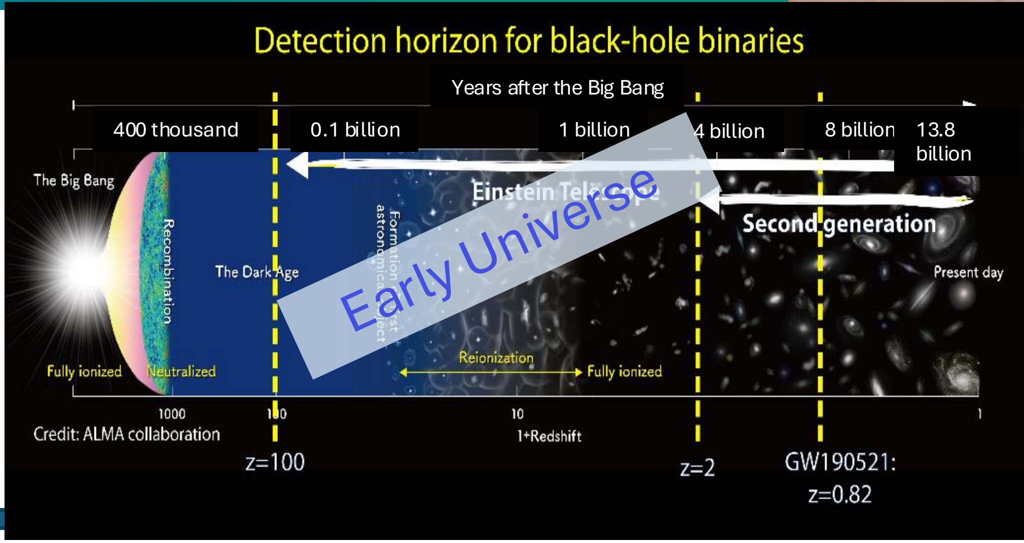
ET Science in a nutshell

EINSTEIN TELESCOPE



Remote Universe

Closer Universe



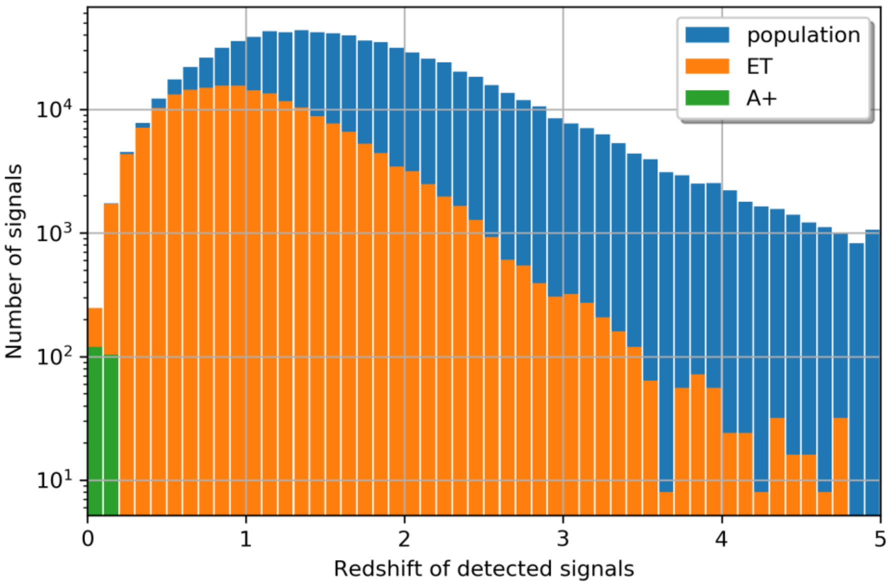
Combination of:

- Larger distances and broader masses explored
- Increased number of detections
- Detections with very high SNR

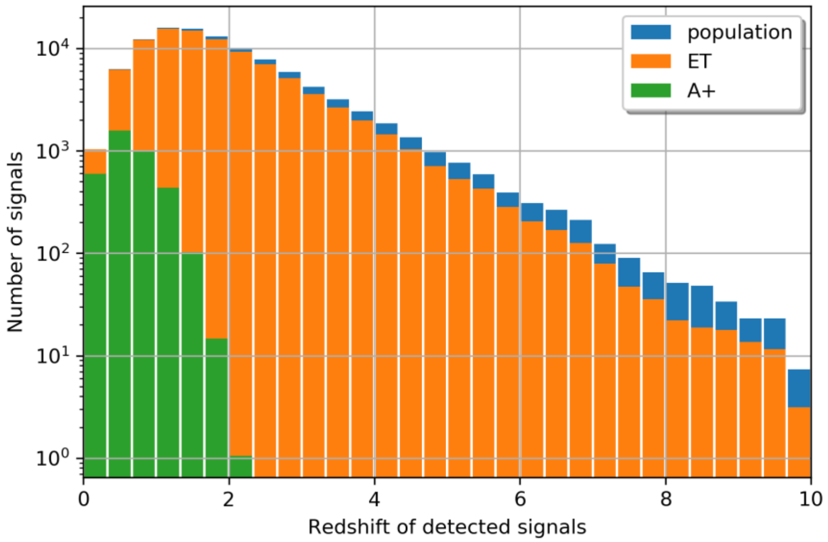
COMPACT OBJECT BINARY POPULATIONS

EINSTEIN TELESCOPE

BINARY NEUTRON-STAR MERGERS



BINARY BLACK-HOLE MERGERS

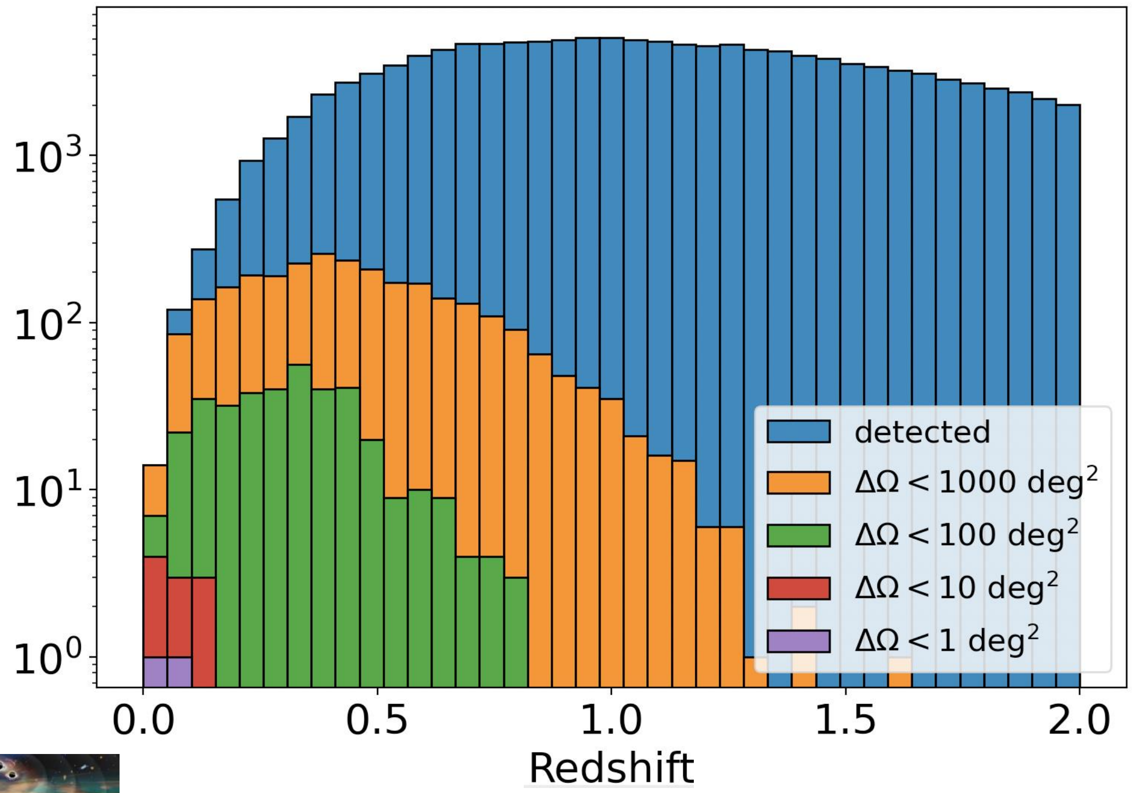


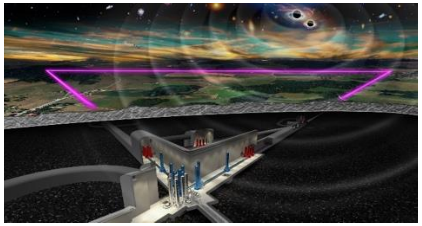
Sampling **astrophysical populations** of binary system of compact objects along the cosmic history of the Universe

10^5 BNS detections per year

10^5 BBH detections per year

ET sky-localization capabilities

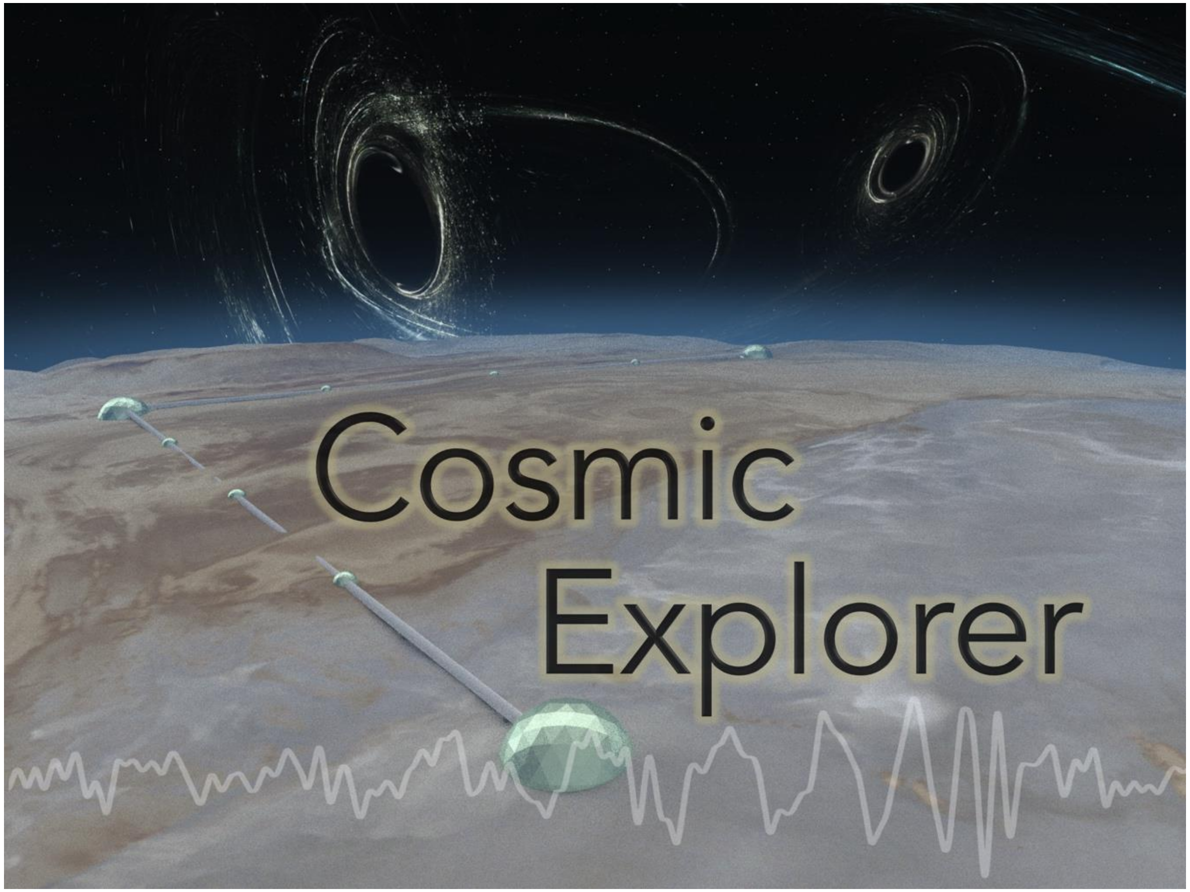




ET low frequency sensitivity make it possibile
To localize BNS!

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

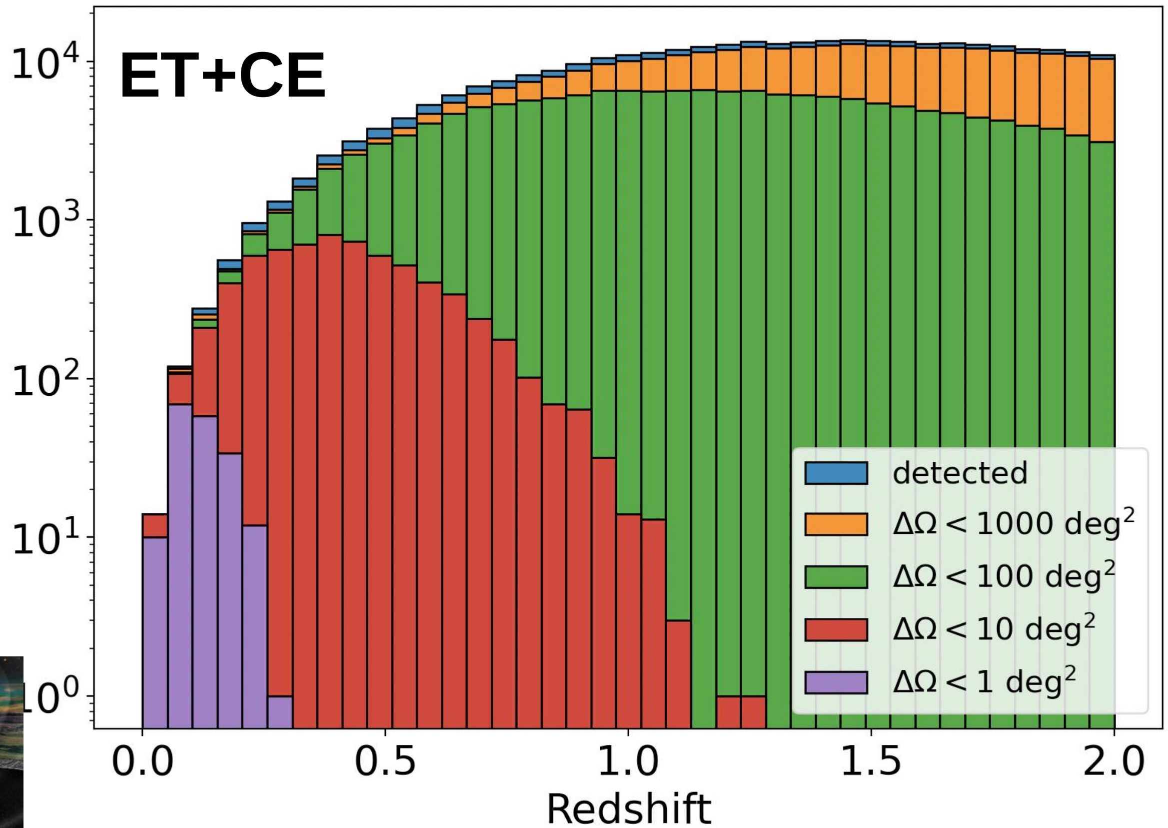
Next generation GW effort worldwide

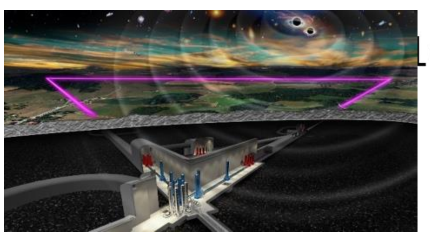


Cosmic Explorer: L shaped detectors, two sites
(40km, 20 km [option])

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

Network sky-localization capabilities



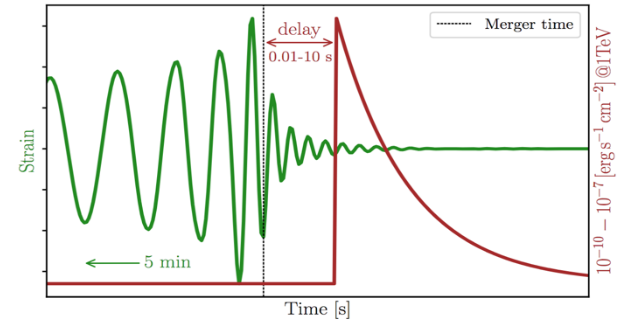


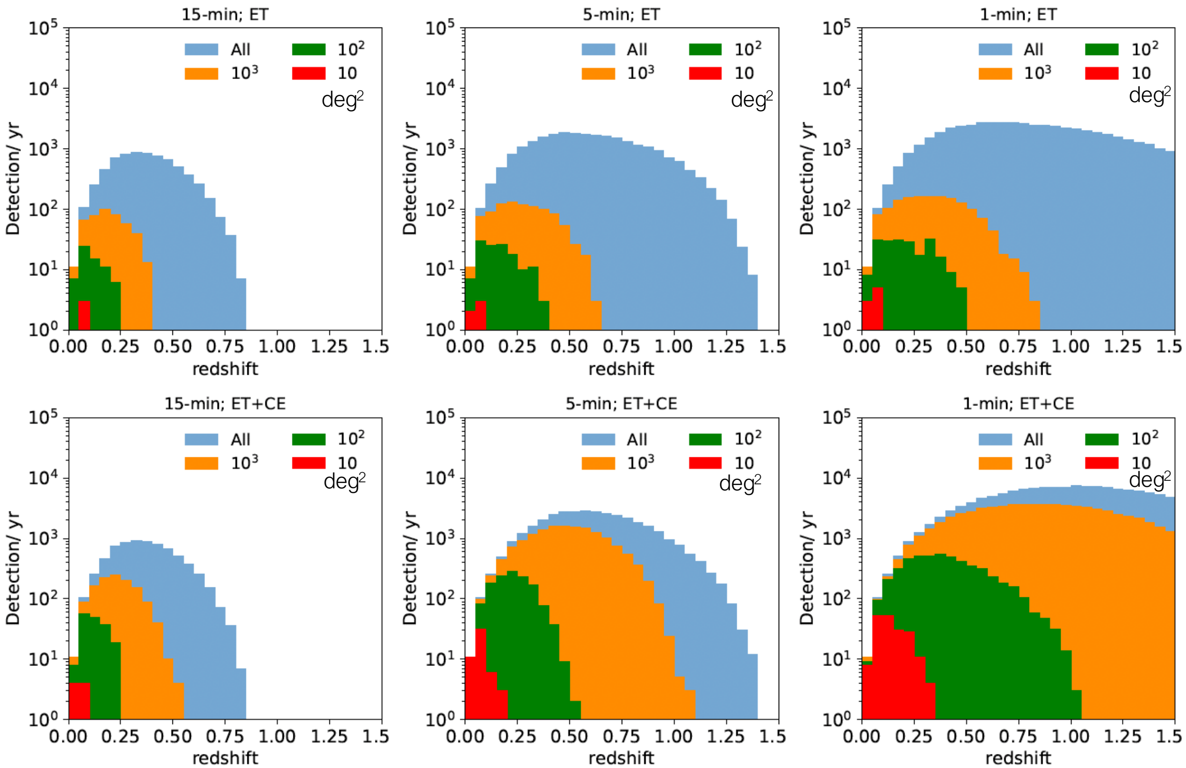
- O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg

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

GWFISH

Pre-merger detections





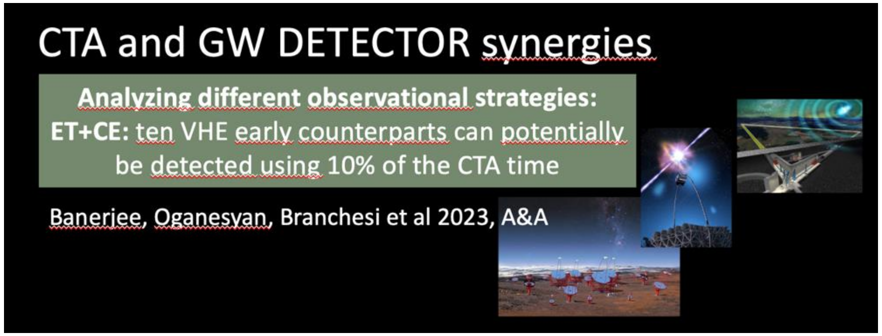
Five minutes before the merger:

- 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



Prioritization of triggers

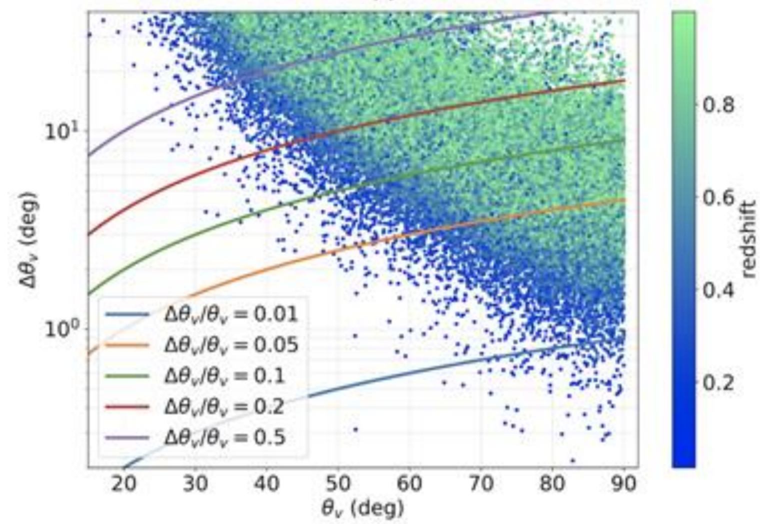
Sky-localization

	ET	ET+CE	ET+2CE
$N_{\rm det}$	143970	458801	592565
$N_{\rm det}(\Delta\Omega < 1\ {\rm deg}^2)$	2	184	5009
$N_{\rm det}(\Delta\Omega < 10\ {\rm deg}^2)$	10	6797	154167
$N_{\rm det}(\Delta\Omega < 100\ {\rm deg}^2)$	370	192468	493819
$N_{\rm det}(\Delta\Omega < 1000\ {\rm deg}^2)$	2791	428484	585317

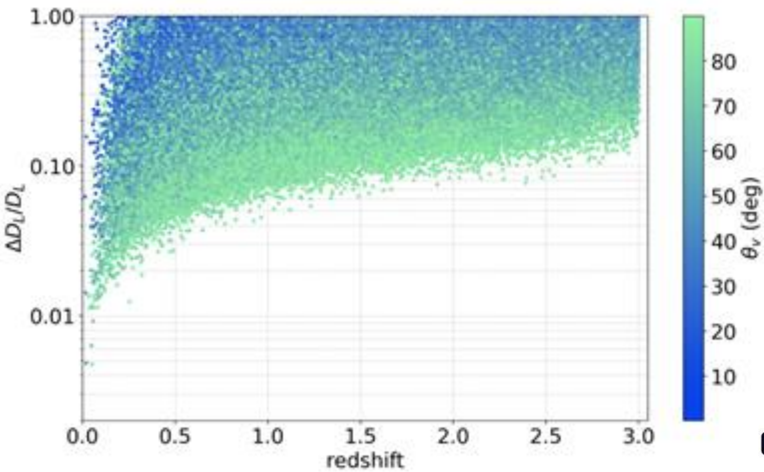
Ronchini et al. 2022, A&A

Too large numbers of triggers well localized to be followed-up

Viewing angle



Distance



- Send in low-latency source parameters and continuous updates
- Science-case dependent prioritization
- ET will become a trigger listener

GWFISH

MM change of paradigm

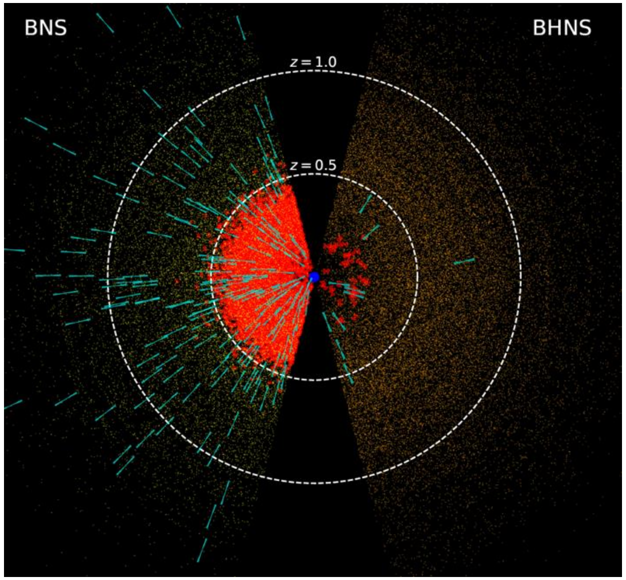
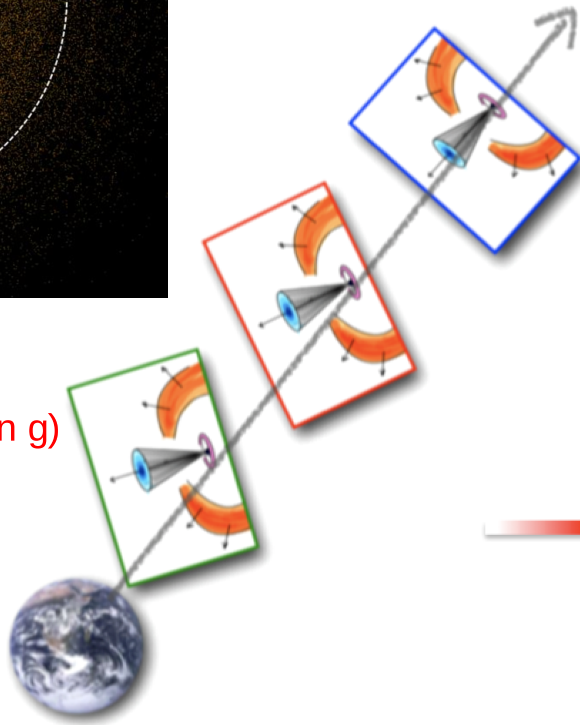


Image Credit: ET blue-book

Detectable GRBs

Detectable KN (< 26 mag in g)



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

High-energy Counterparts

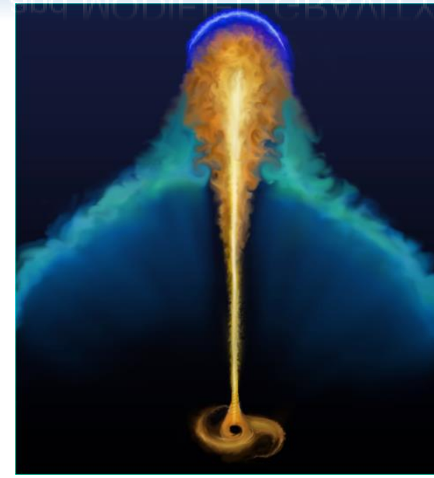


Image Credit: Ronchini

Optical counterparts

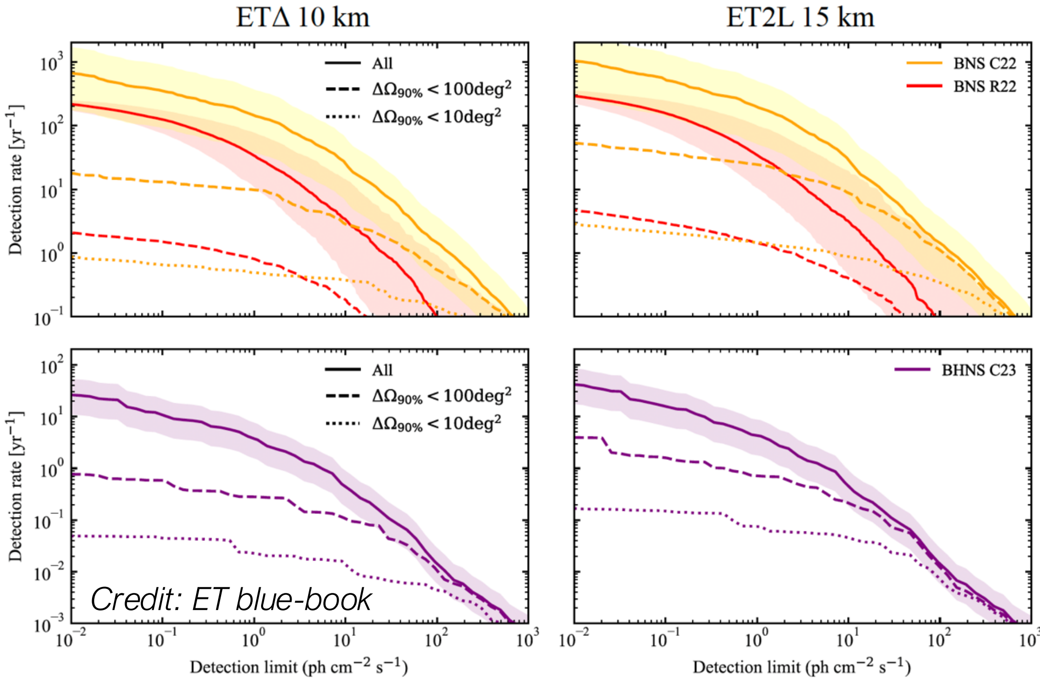
KILONOVA PHYSICS,
NUCLEOSYNTHESIS,
NUCLEAR PHYISCS
and H0 ESTIMATE

Image credit: NASA

HIGH-ENERGY

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

GW/Short GRB prompt emission



Almost all detected short GRBs will have a GW counterpart

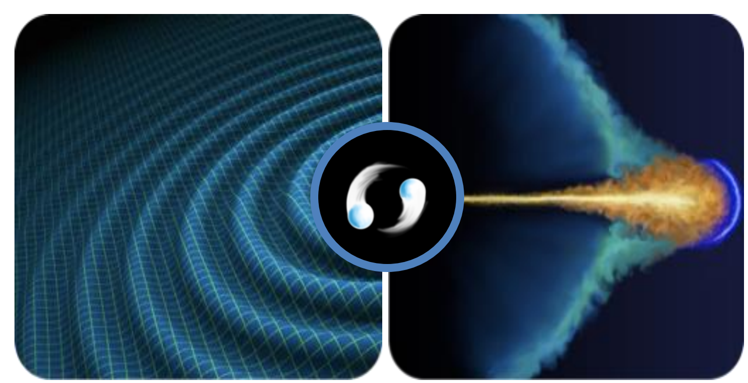
*See Ronchini, **MB** et al. 2022*
Colombo et al. 2025

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

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

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 ATHENA, AXIS require for the characterization

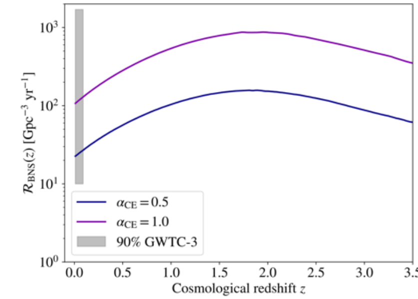


THERMAL EMISSION - KILONOVAE

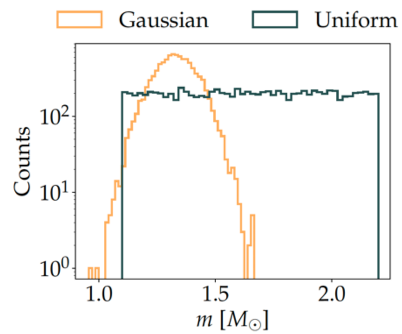
KILONOVA PHYSICS, NUCLEOSYNTHESIS, NUCLEAR PHYISCS and COSMOLOGY

Prospects for optical detections from BNS mergers with the next-generation MM observatories

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



- **Two BNS merger populations** consistent with O1, O2, O3 and current LVK observations



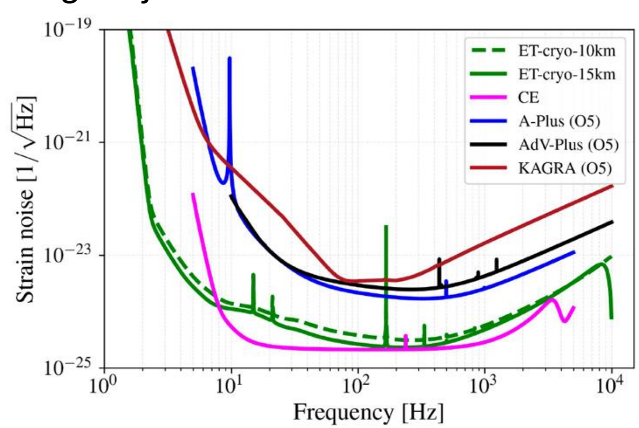
- **NS mass**:
  Gaussian and uniform mass distributions

- Two **EoSs**: BLh and APR4

with BLh producing less compact NSs and typically with larger ejecta

- **8 network of ET**

ET-Δ	ET-2L
ET-Δ + LVKI	ET-2L + LVKI
ET-Δ + 1CE	ET-2L + 1CE
ET-Δ + 2CE	ET-2L + 2CE

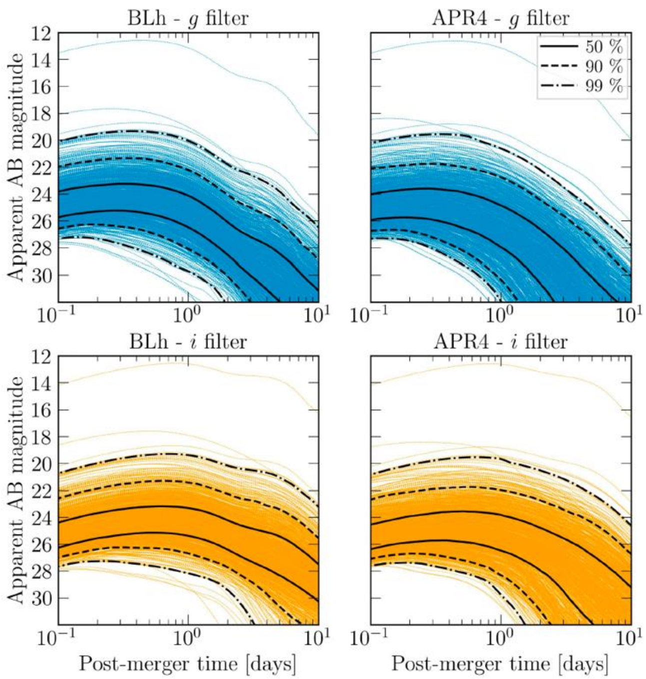


Loffredo, Hazra, Dupletsa, MB et al. arXiv:2212.14007

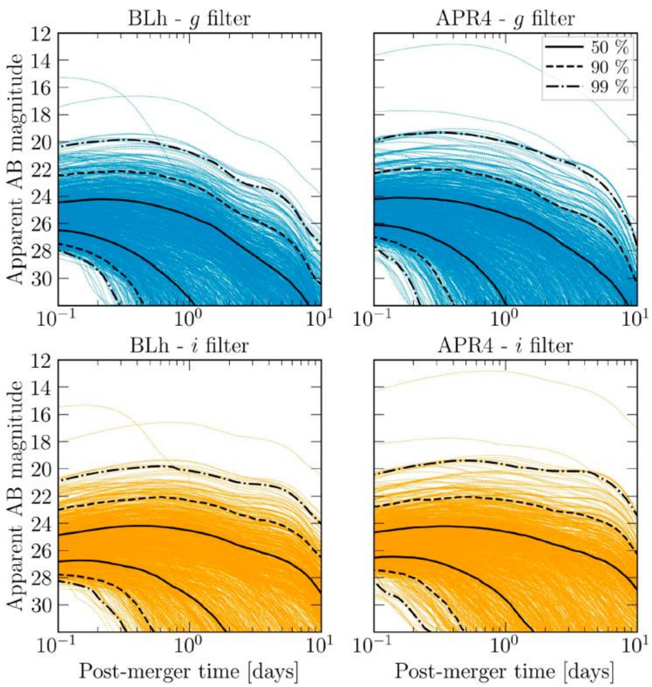
Population KN light-curves (LC)

- *KNe ejecta through numerical-relativity informed fits*
- *Fitting formulas for **GW170817** and more massive BNS systems, like **GW190425***
- *Including **prompt collapse** of the remnant to black hole*
- *Multi-component ejecta: dynamical + spiral wind + secular*

Gaussian NS mass distribution



Uniform NS mass distribution



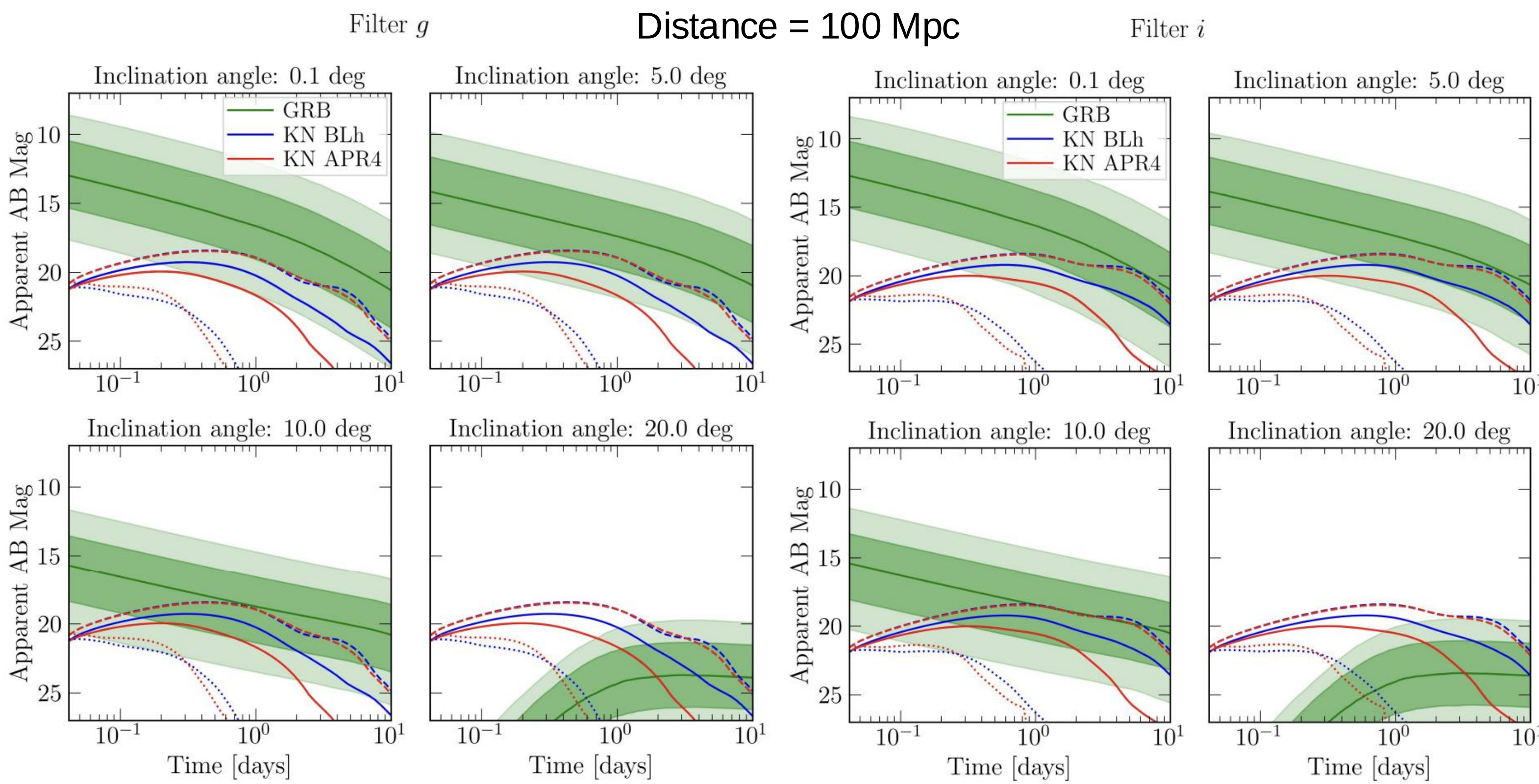
- BLh EOS → at the peak LC brighter by half to one magnitude and evolving more slowly than APR4
- Uniform NS mass distribution → high mass system, prompt collapse, fainter light curves than Gaussian

Loffredo, Hazra, Dupletsa, MB et al. arXiv:2212.14007

Adding GRB optical afterglows

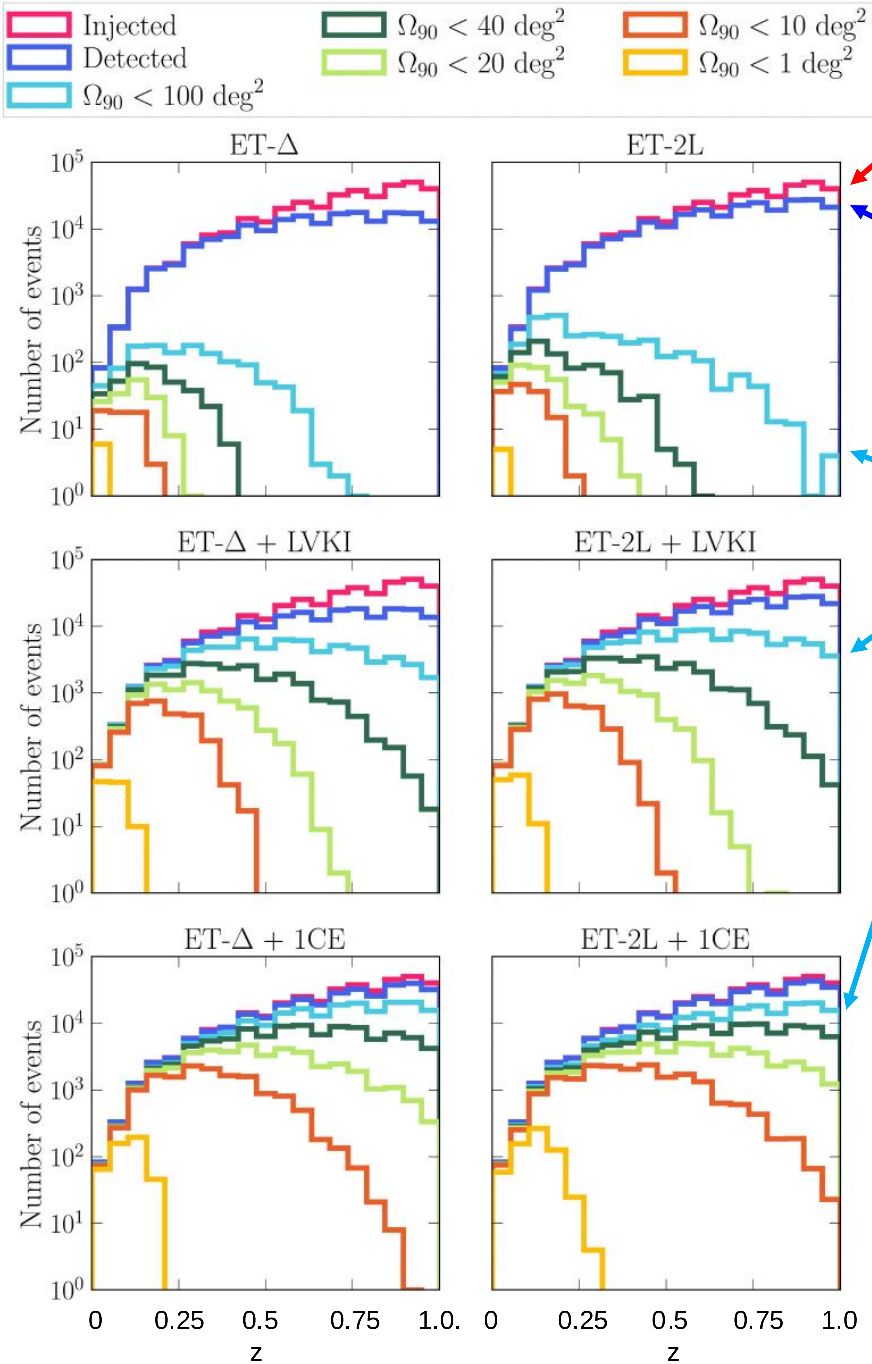
- On-axis consistent with observed optical afterglows of short GRBs
- Number of BNS producing a jet calibrated on sample of observed short GRBs

Distance = 100 Mpc



- *The afterglows outshine faintest KNe for viewing angles < 15 deg*
- *KNe dominate early emissions at viewing angle ≥ 20 deg*
- *Brightest KNe overcome a non-negligible portion of the afterglows at any angle a few hours after the merger*

Loffredo, Hazra, Dupletsa, MB et al. arXiv:2212.14007



Injected/detected

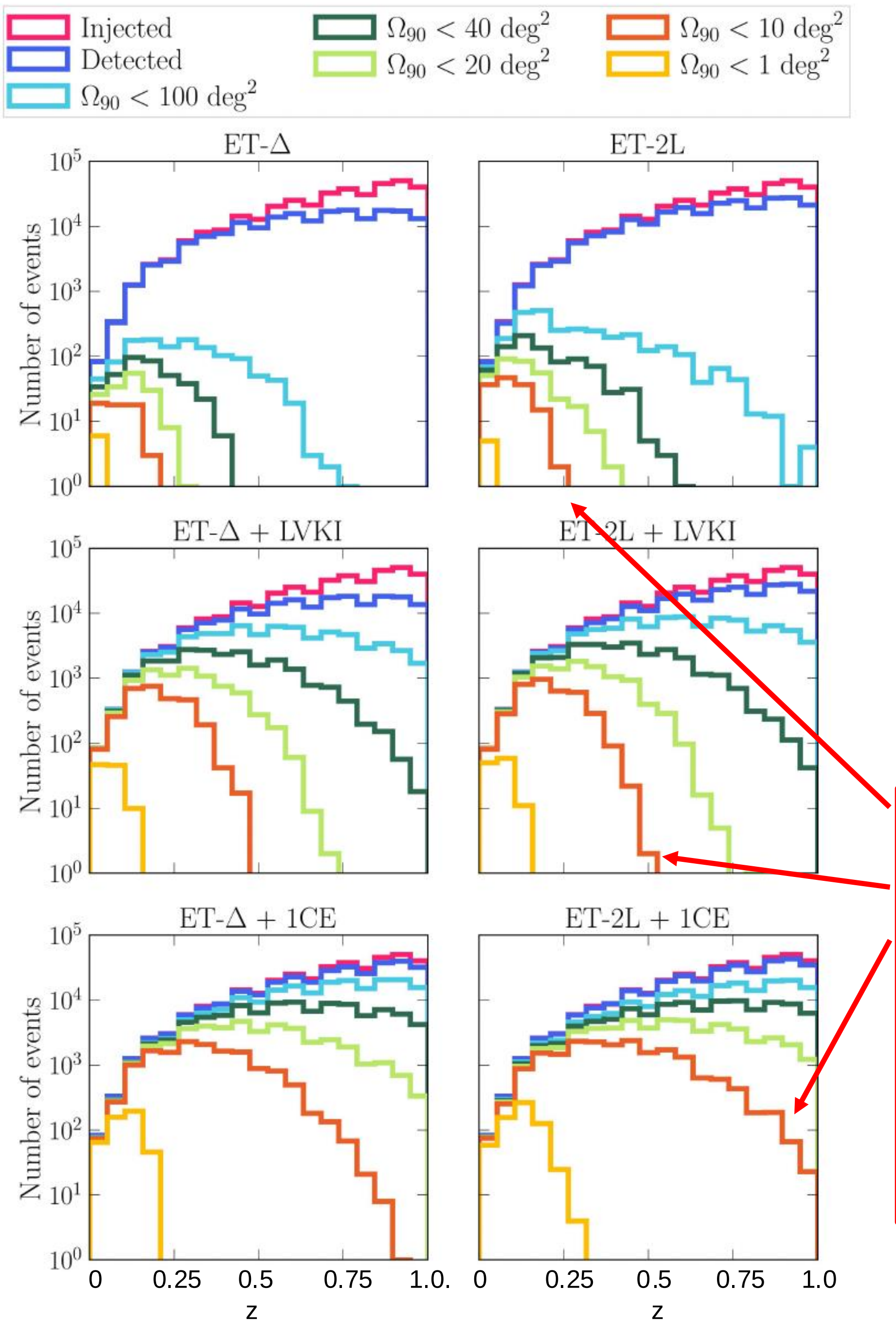
- ET-2L 30% more detections wrt ET-triangle
- ET+LVKI negligible increase of detections wrt ET
- ET+CE about a factor 2 increase of detections wrt ET

Relatively well-localized events (sky-loc < 100 deg^2)

- ET-2L twice detections wrt ET-triangle
- O(100) per year by ET
- O(10^3) per year ET+LVKI
- O(10^4) for ET+CE

Plots show 10 years of observations

Loffredo, Hazra, Dupletsa, MB et al. arXiv:2212.14007



Injected/detected

- ET-2L 30% more detections wrt ET-triangle
- ET+LVKI negligible increase of detections wrt ET
- ET+CE about a factor 2 increase of detections wrt ET

Relatively well-localized events (sky-loc < 100 deg^2)

- ET-2L twice detections wrt ET-triangle
- O(100) per year by ET
- O(10^3) per year ET+LVKI
- O(10^4) for ET+CE

Well-localized events (sky-loc < 10 deg^2)

- ET-2L three times detections wrt ET-triangle
- more detections than the ET triangl
- a few per year by ET
- O(100) per year ET+LVKI
- O(10^3) for ET+CE

Networks enable to localize events up to higher z

Loffredo, Hazra, Dupletsa, MB et al. arXiv:2212.14007

Next-generation MM astronomy in the optical band

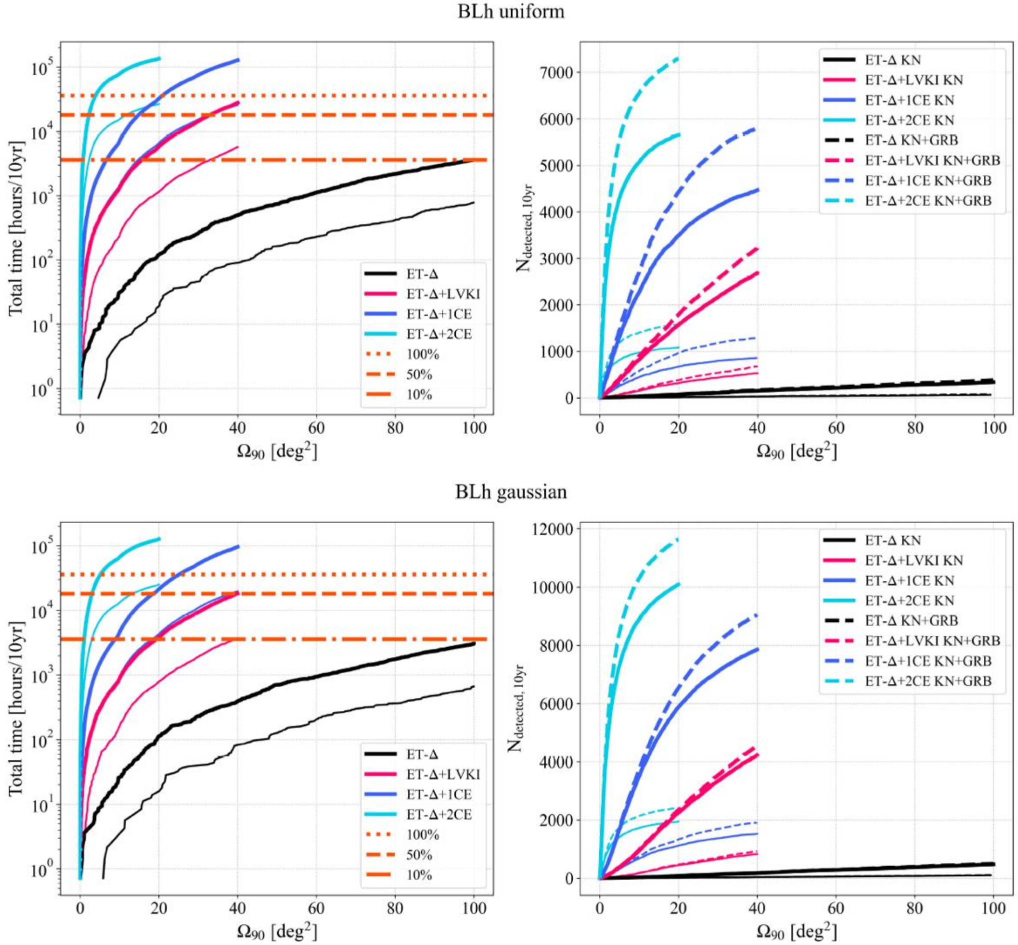
Faint KNe
+
Large GW Sky-Localization

Requirements:

1) Large (sensitive) FoV optical instruments for the counterpart search;

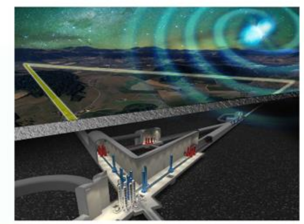
2) Large (sensitive) facilities for characterize the counterparts (imaging/spectroscopy).

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*

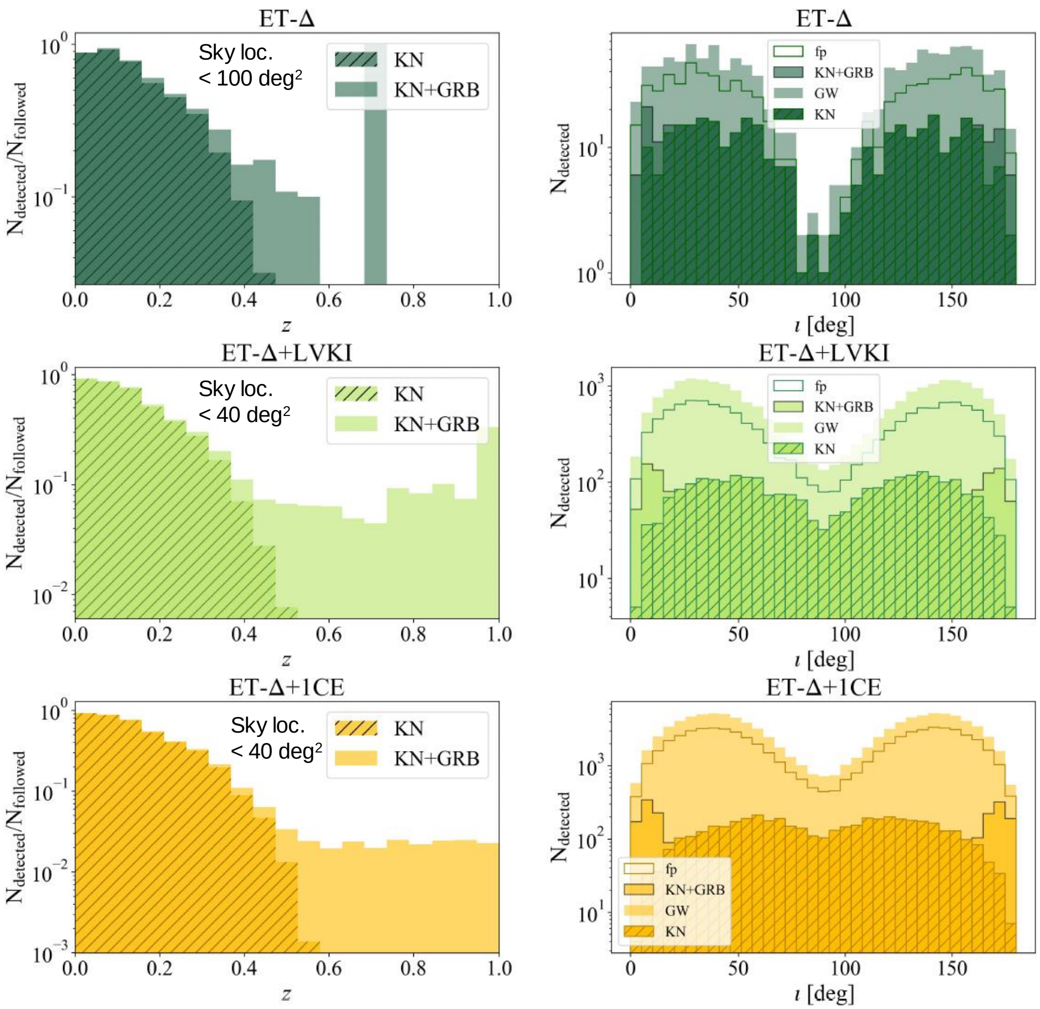
VERA C. RUBIN OBSERVATORY



- 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)

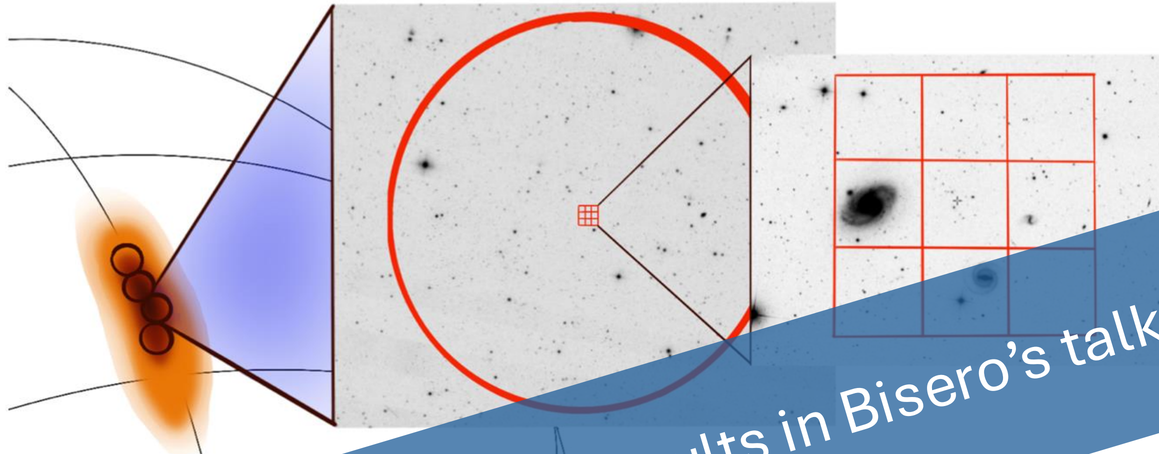
Loffredo, Hazra, Dupletsa, MB et al. arXiv:2212.14007

Joint detection efficiency



Efficiency drops to 50% already at redshift ~ 0.3

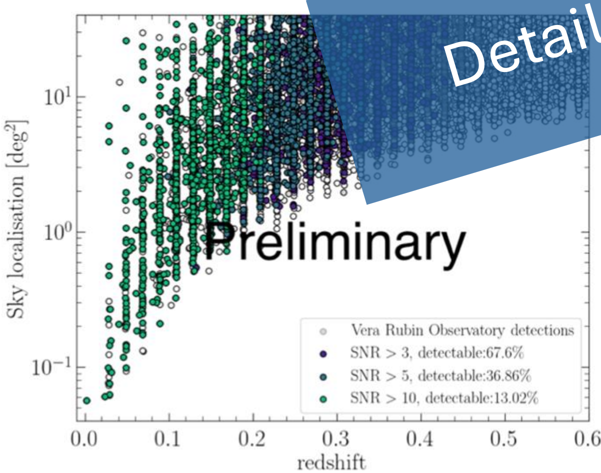
Einstein Telescope and WST



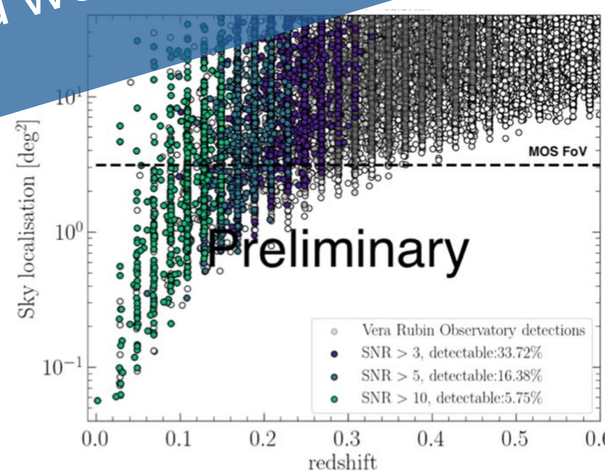
Detailed work and results in Bisero's talk

WST science white paper

WST IFS blue 12.3 hrs

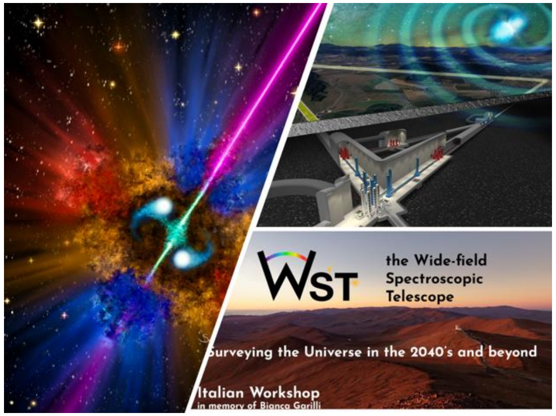


WST MOS blue 12.3 hrs



- **Synergy with optical-NIR photometric observations**: targeting Rubin candidates
- **Stendalone-scenario**: galaxies's distance consistent with GW

WST will characterize (SNR> 10) on the order of 100 events per year



SUMMARY

ET working in synergy with electromagnetic observatories will **revolutionize MM astronomy**, transforming today's rare detections into hundreds of detections per year, significantly **advancing our understanding of extreme events in the Universe**

ET 2L perform better than ET triangle increasing of factor 2-3 the number of events and the accuracy of the parameter estimation
(see Branchesi et al. 2023)

ET with instrument such the **Rubin Observatory** and **WST** will probe ejected matter and KN emission **advancing our knowledge in nucleosynthesis, nuclear physics** and **cosmology**