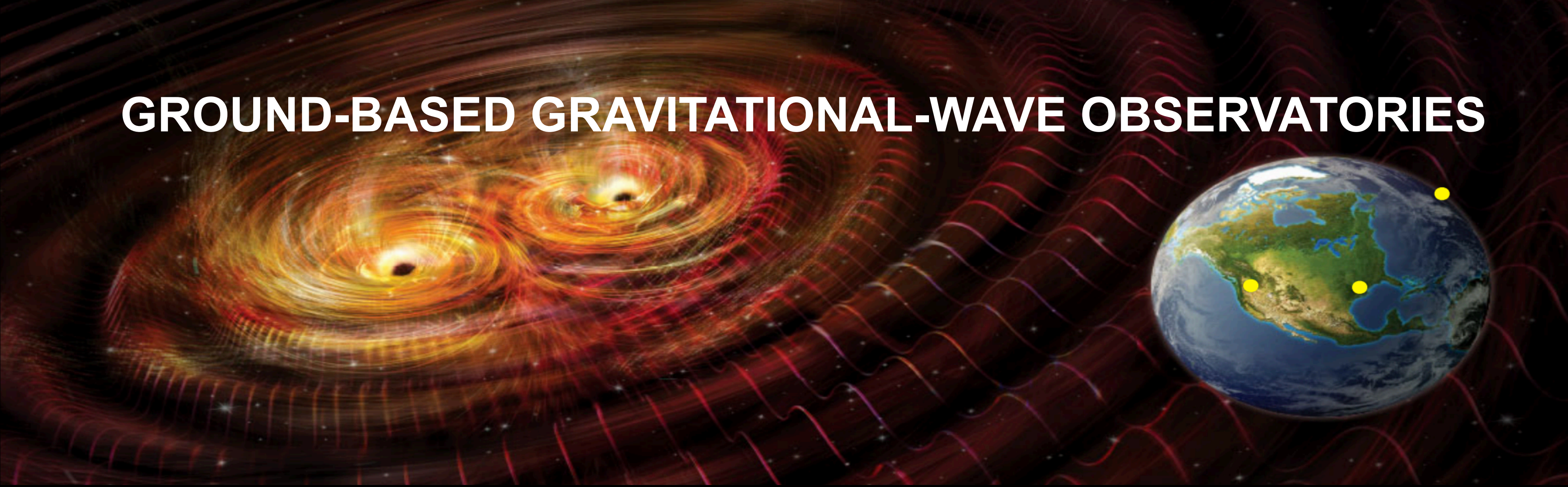
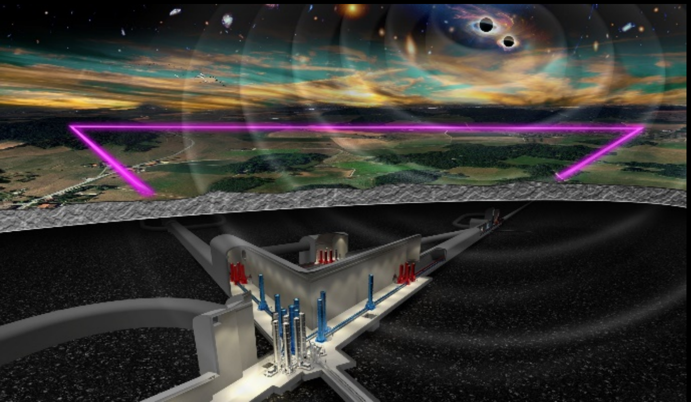
GROUND-BASED GRAVITATIONAL-WAVE OBSERVATORIES



M. Branchesi

Gran Sasso Science Institute
INFN/LNGS and INAF



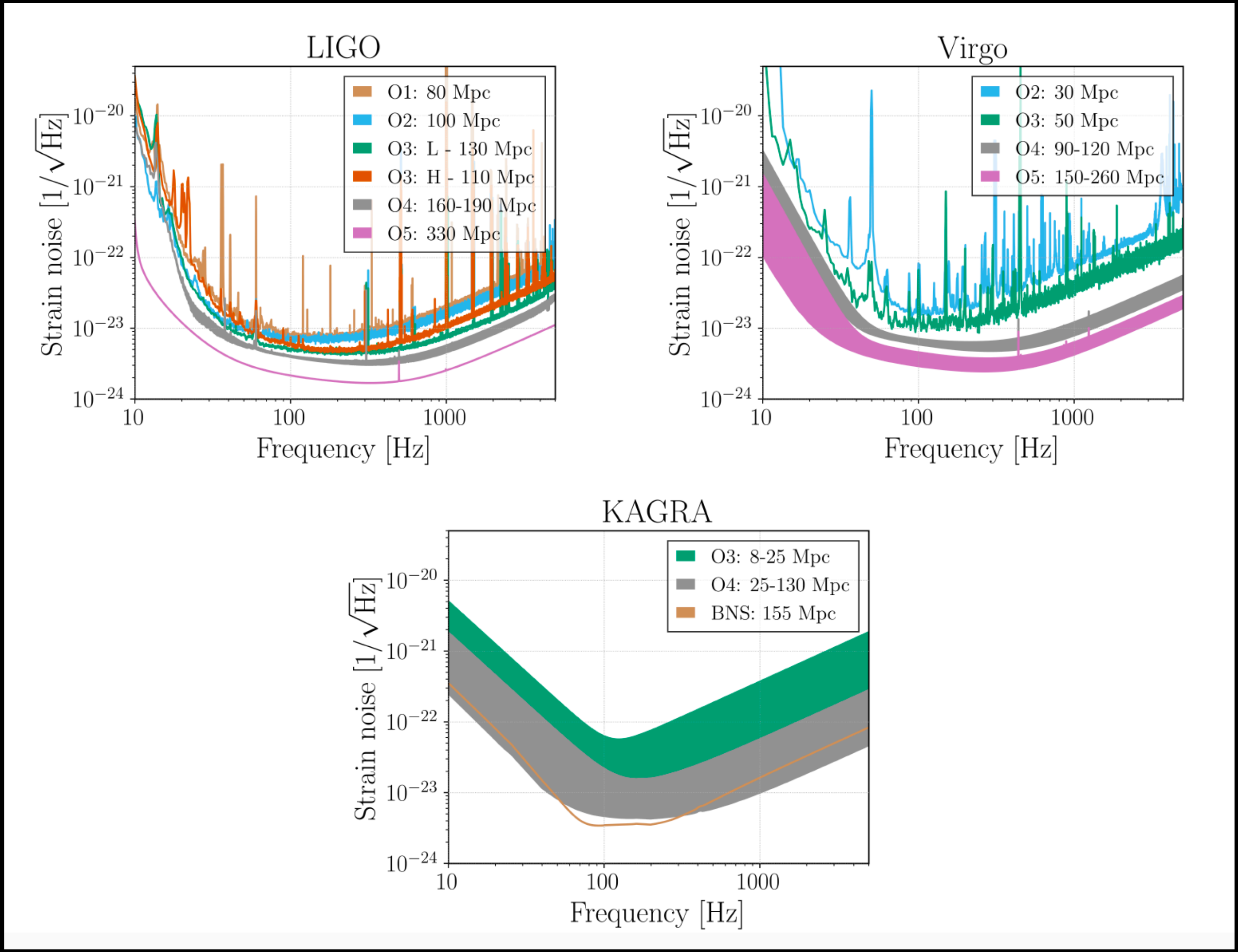
theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

A new window into the Universe

Credit: LIGO–Virgo

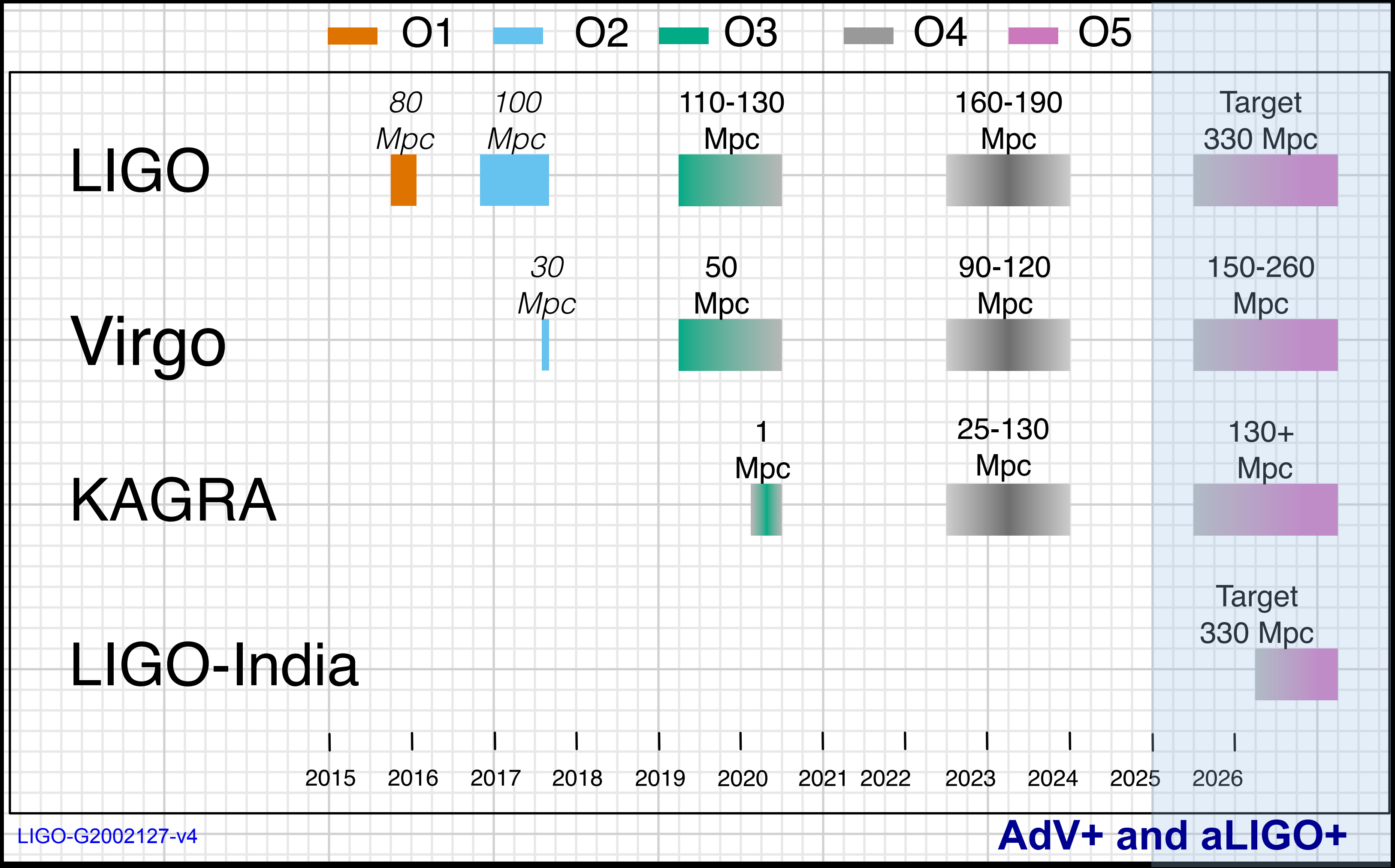
KAGRA, Japan

Strain sensitivities as a function of frequency



Abbott et al. 2020, LRR

Observing run timeline and BNS sensitivity evolution

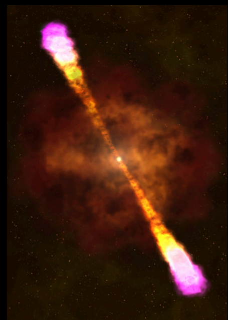


O5 volume = 15*O3 volume

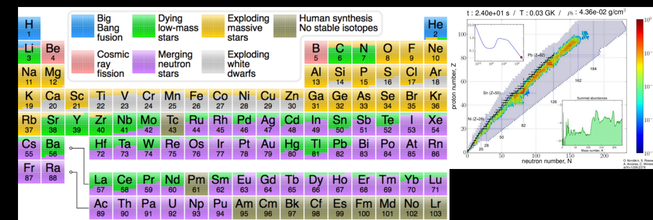
Abbott et al. 2020, LRR

Radioactively powered transients

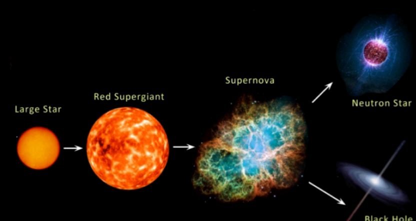
Relativistic astrophysics



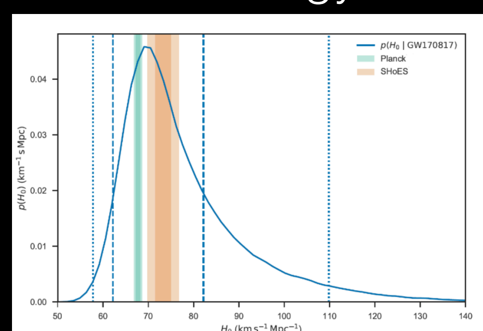
Nucleosynthesis and enrichment of the Universe



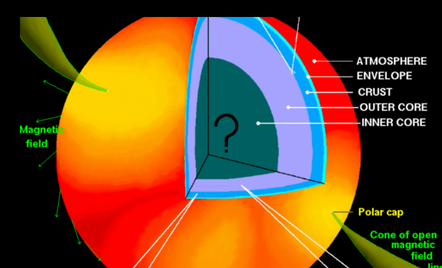
Compact object formation and evolution



Cosmology



Nuclear matter physics

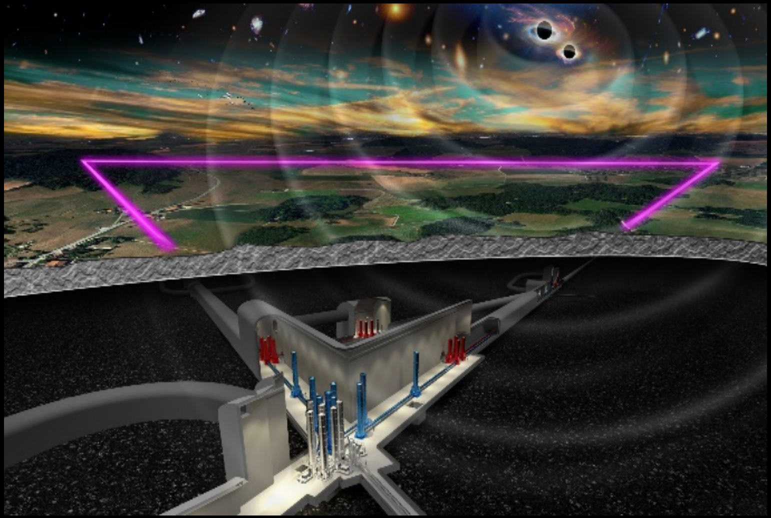


What is the future of the GW astrophysics?

The European 3G concept

Europe we developed the idea of a 3G GW observatory

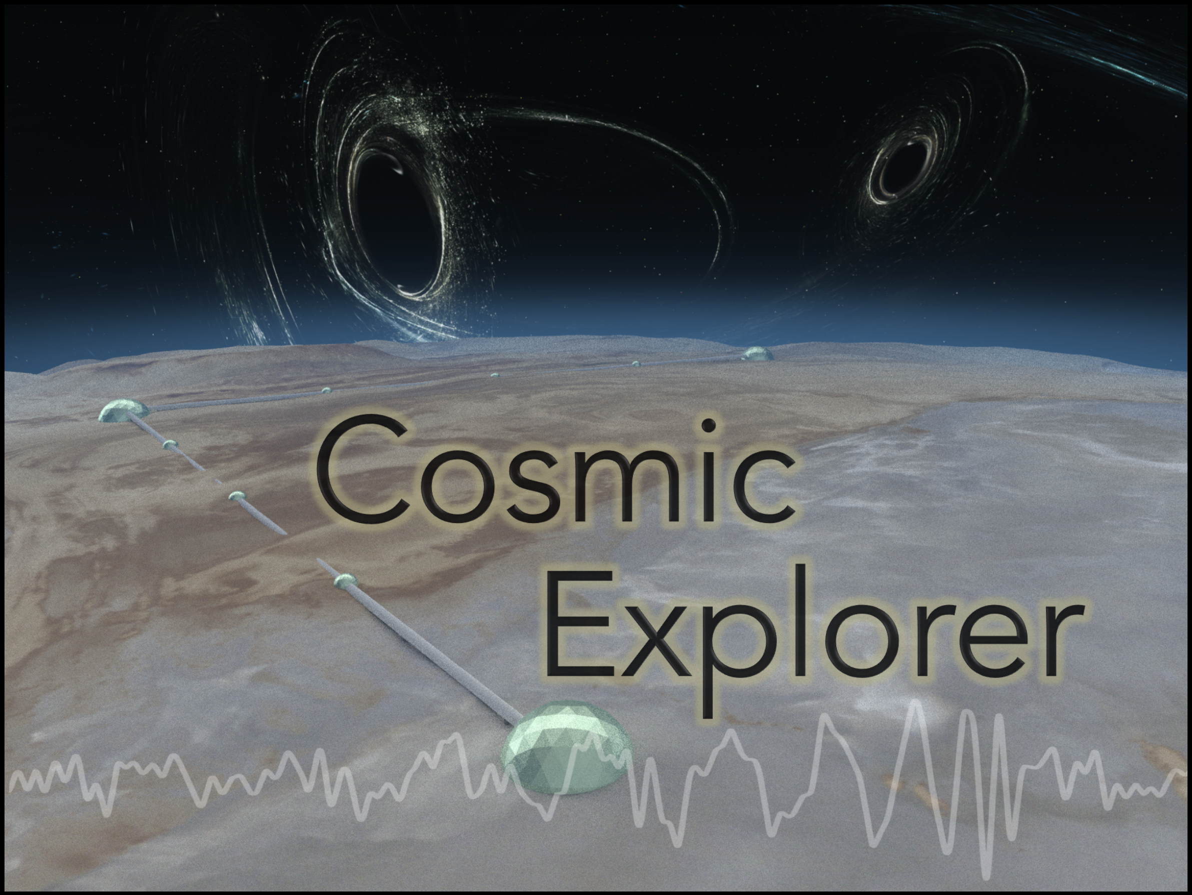
- Factor 10 better (x1000 Volume) than 2G detectors
- Wide frequency, with special attention to low frequency (few HZ)
- Capable to work alone (but aiming to be in a 3G network)
- 50-years lifetime of the infrastructure



Triangular shape
Arms: 3 → 10 km
Underground
Cryogenic
increase laser power
Xylophone
...

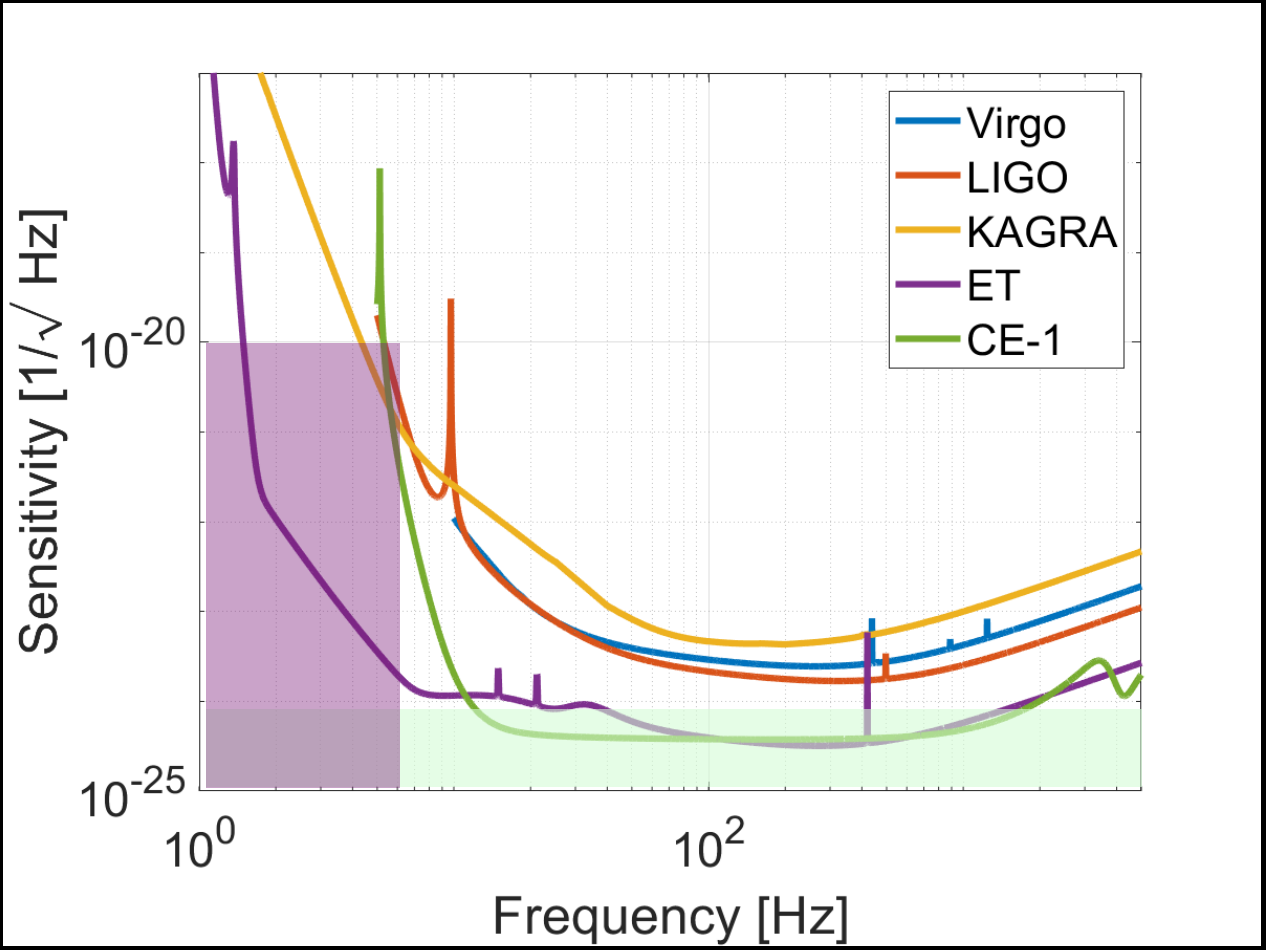
ESFRI proposal
submitted in September

3G effort worldwide



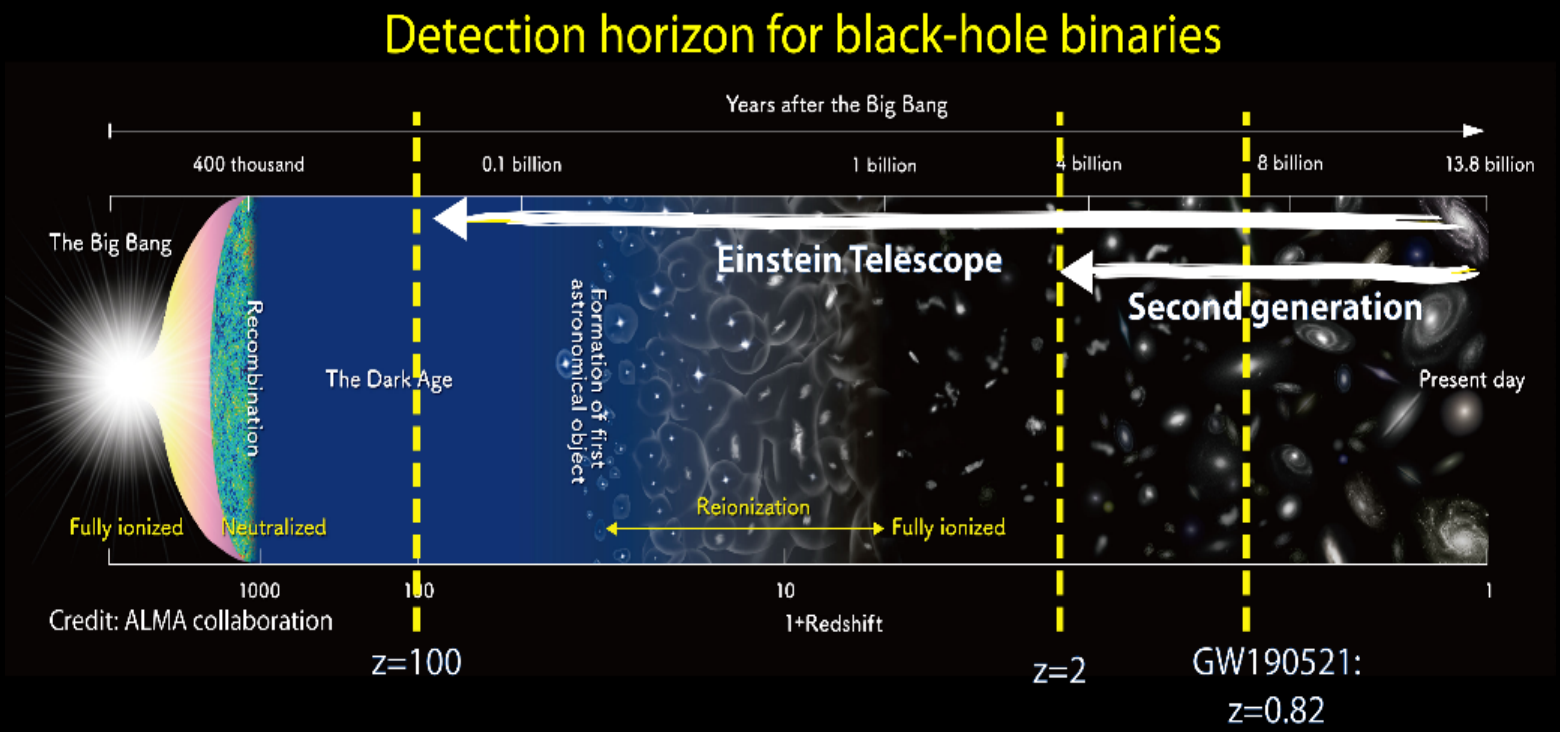
NSF funded in 2018 the Conceptual Design Study of a 3G facility: Cosmic Explorer: 40km – L shaped detector

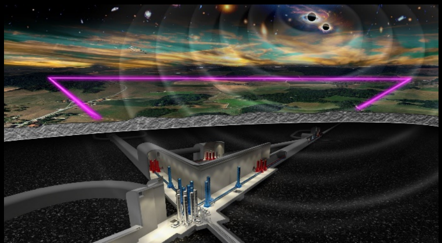
EXPECTED SENSITIVITY



The ET exquisite sensitivity and wide frequency band will make it possible:

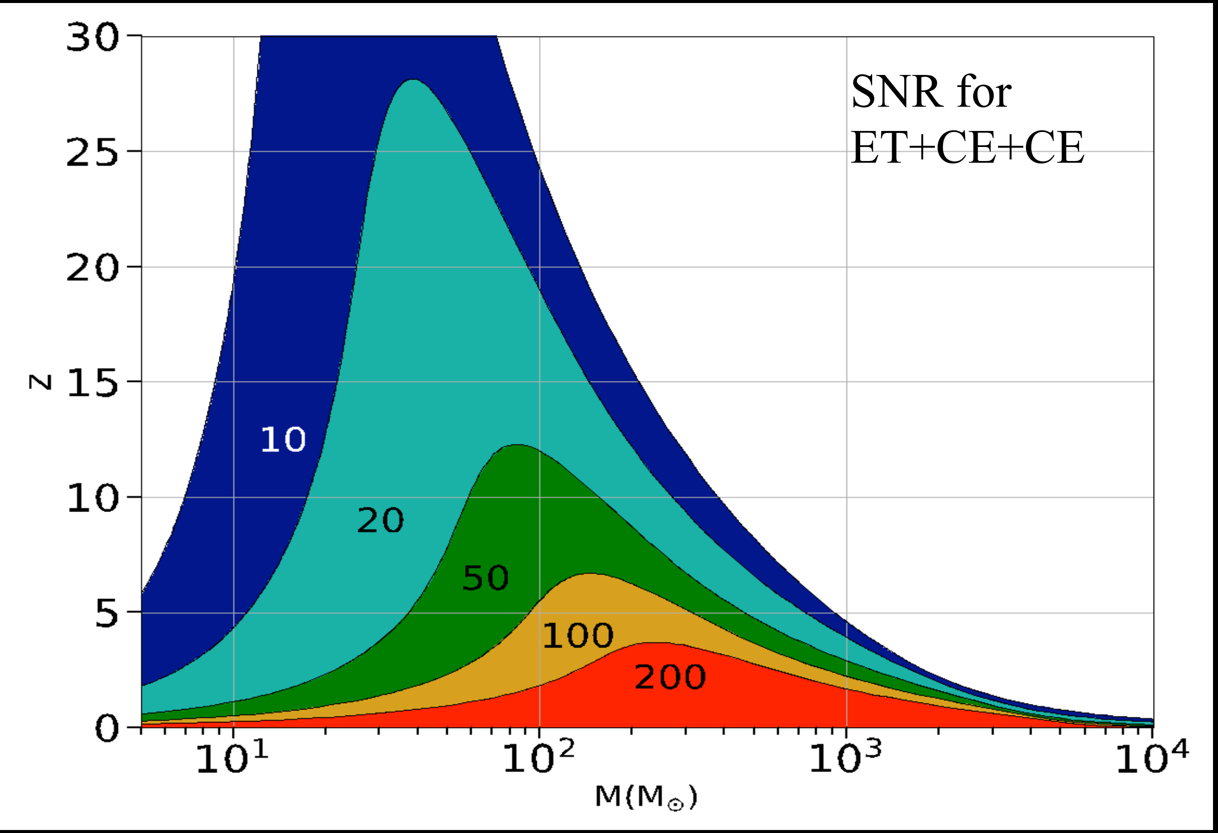
- Large distances back to the early Universe





The ET exquisite sensitivity and wide frequency band will make it possible:

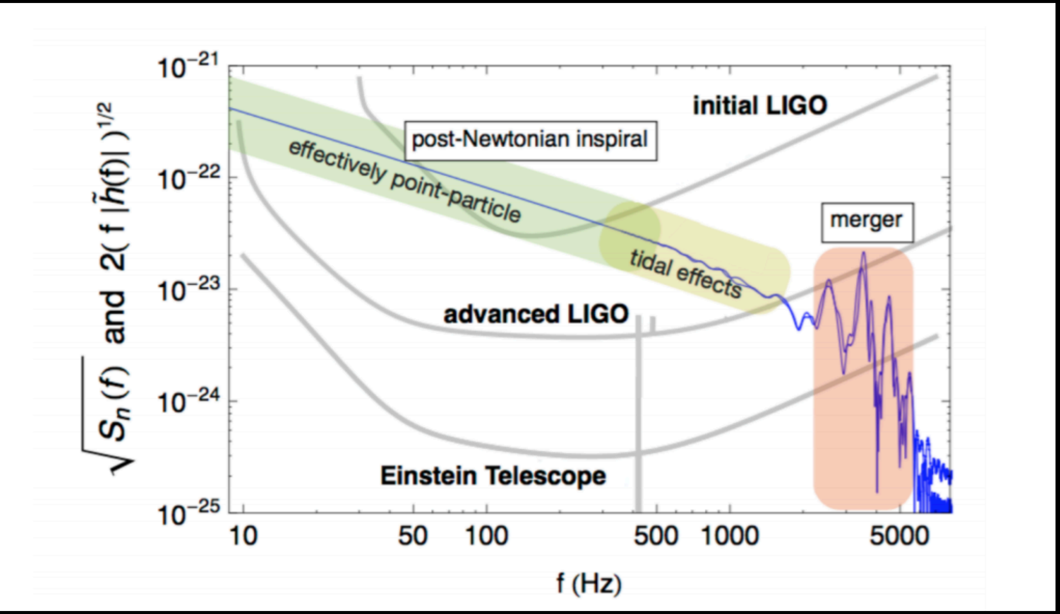
- Large distances back to the early Universe
- access unexplored mass up to 10^3 Mo



courtesy Colpi and Mangiagli

The ET exquisite sensitivity and wide frequency band will make it possible:

- Large distances back to the early Universe
- access unexplored mass up to 10^3 Mo
- benefit of exceptional parameter estimation accuracy for very high SNR events



3G Science case WP

ET will provide a wealth of data that have the potential of triggering revolutions in astrophysics, cosmology and fundamental physics

A summary of the Science of ET
(see Maggiore et al. 2020)

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

EINSTEIN TELESCOPE

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

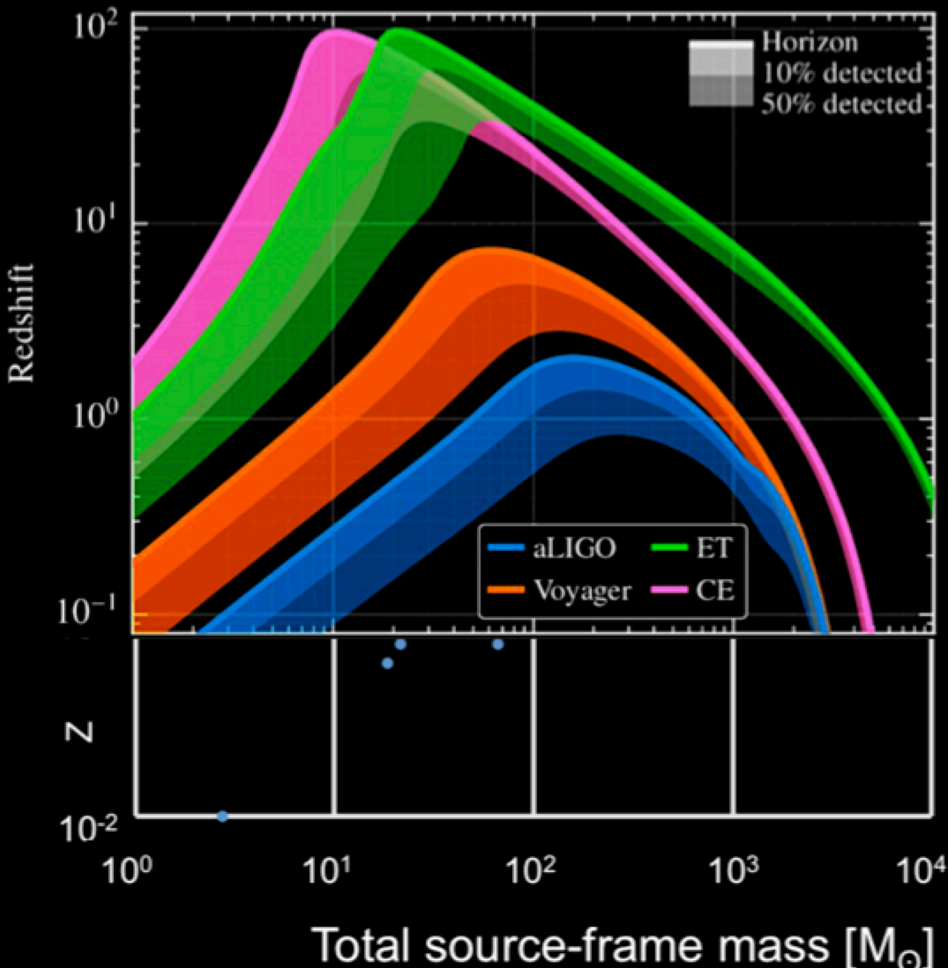
- Dark energy and modifications of gravity on cosmological scales
  - DE equation of state
  - modified GW propagation

- Stochastic backgrounds of cosmological origin

THE UNEXPECTED…ET will be a “discovery observatory”!

Multi-messenger in the ET era

Binary systems of Compact Objects



Kilonova/GW - EOS constraints

Kilonova/GW - Nucleosynthesis

GRBs – BNS/NSBH merger up to high z

Relativistic jet properties

Jet-less/jet GRBs

GRB/stable NS remnant

Link to Star Formation History

Emission mechanism

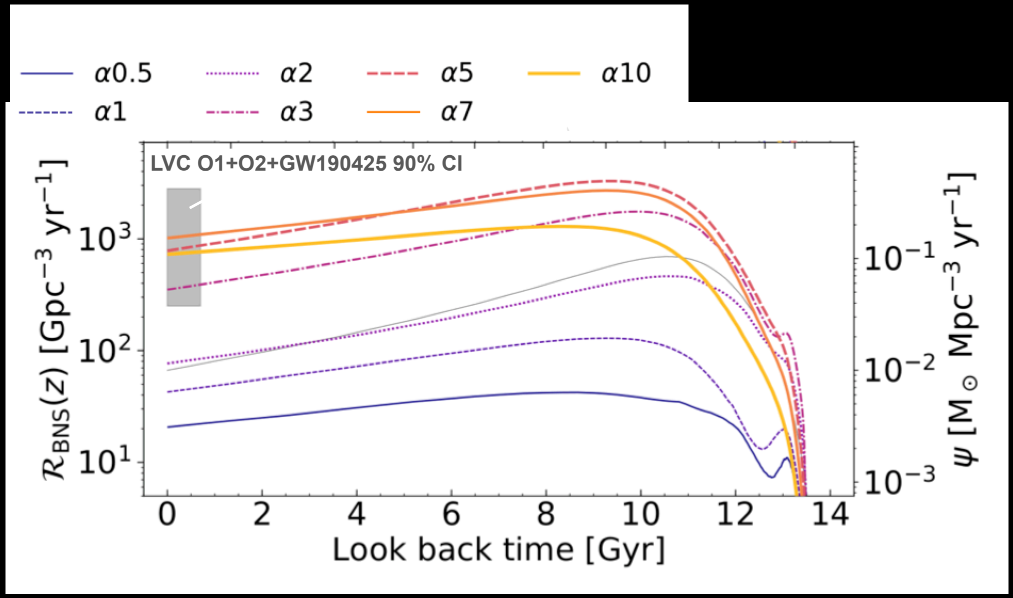
Cosmology

- Study BNS/NSBH along the cosmic history
- Large increase of detection rate
- Better parameter estimation

ET alone → 10^5 BNS per per year
10^5 BBH per year

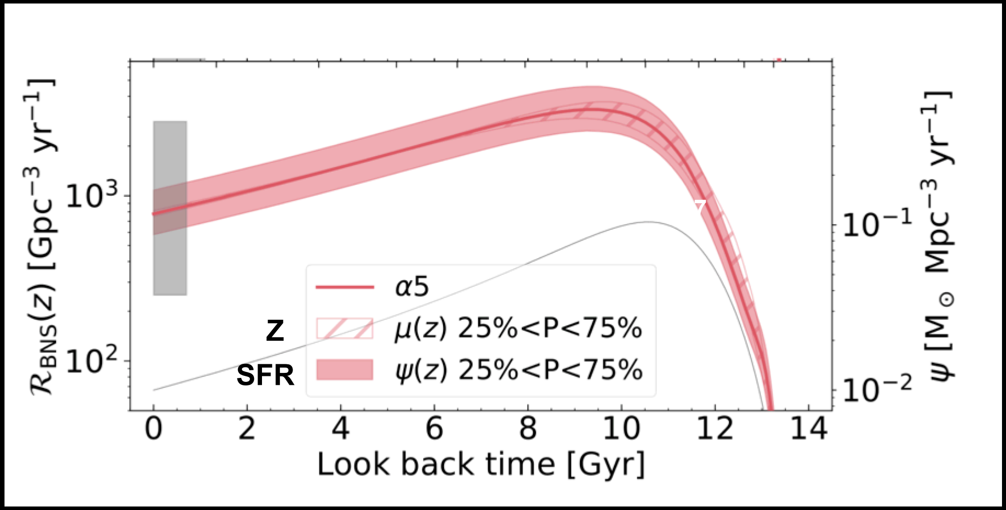
ET capabilities

Astrophysical simulations for BNS from population synthesys code



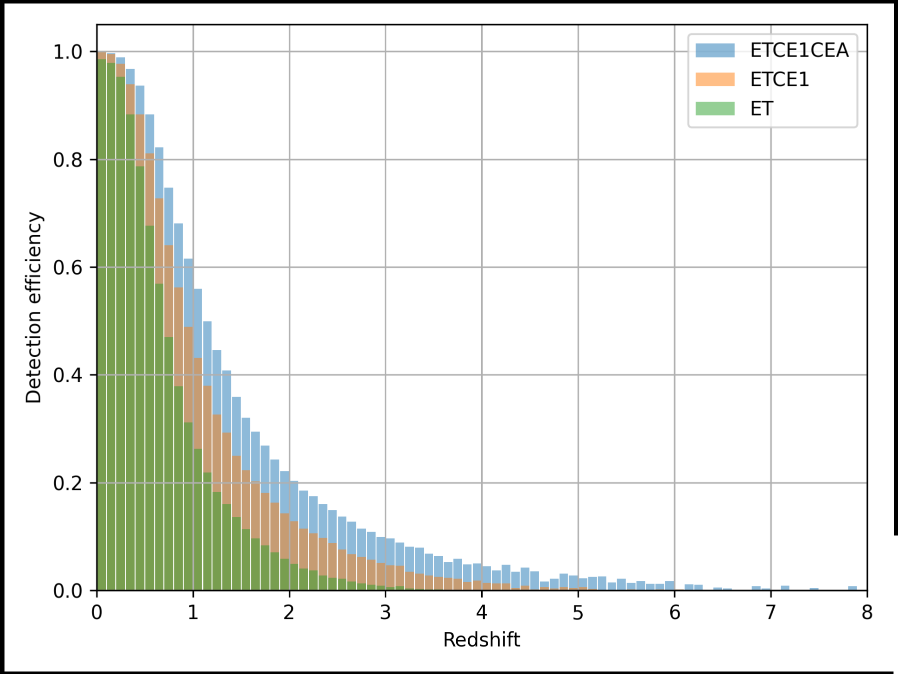
MERGER RATE EVOLUTION
impact of common envelope

MERGER RATE EVOLUTION
impact of SFR and metallicity uncertainty



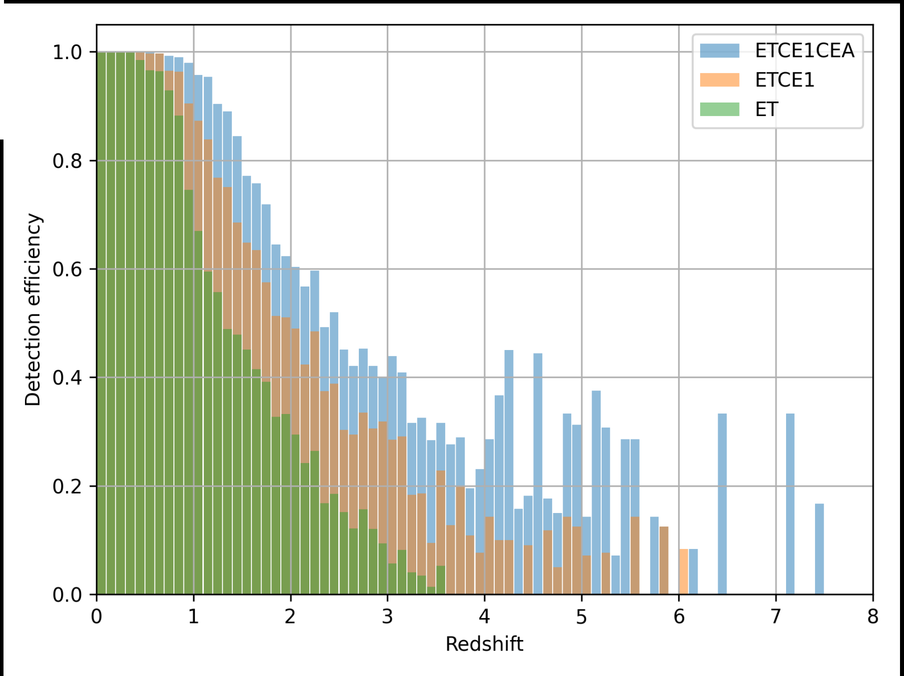
Santoliquido et al. 2020,

ET DETECTION EFFICIENCY



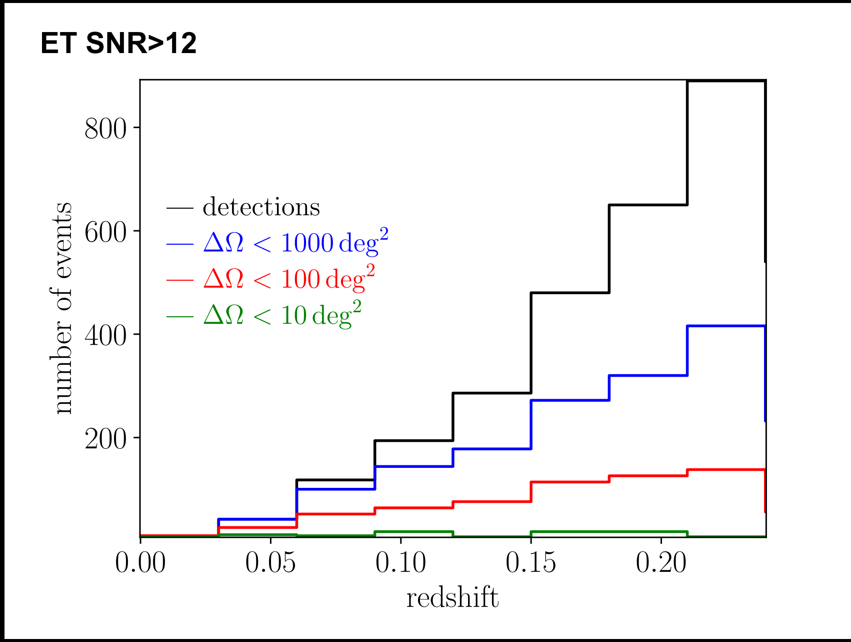
ALL ORIENTATION

Viewing angle < 10 deg

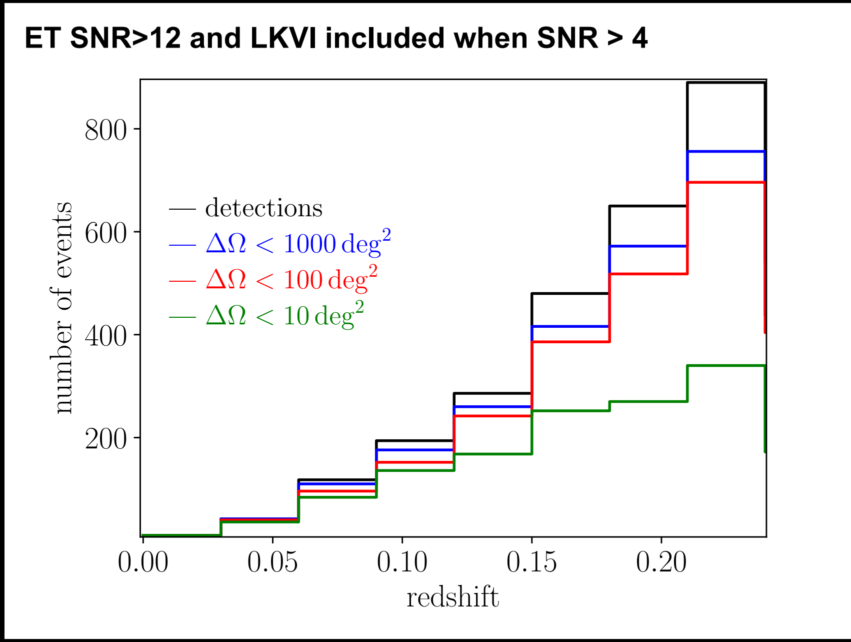


EINSTEIN TELESCOPE DETECTION/SKY LOCALIZATION
up to z=0.26

ET



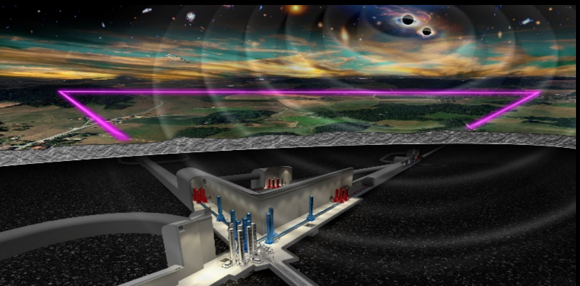
ET+LIGO/Virgo/KAGRA/LIGOindia



1 year of observations

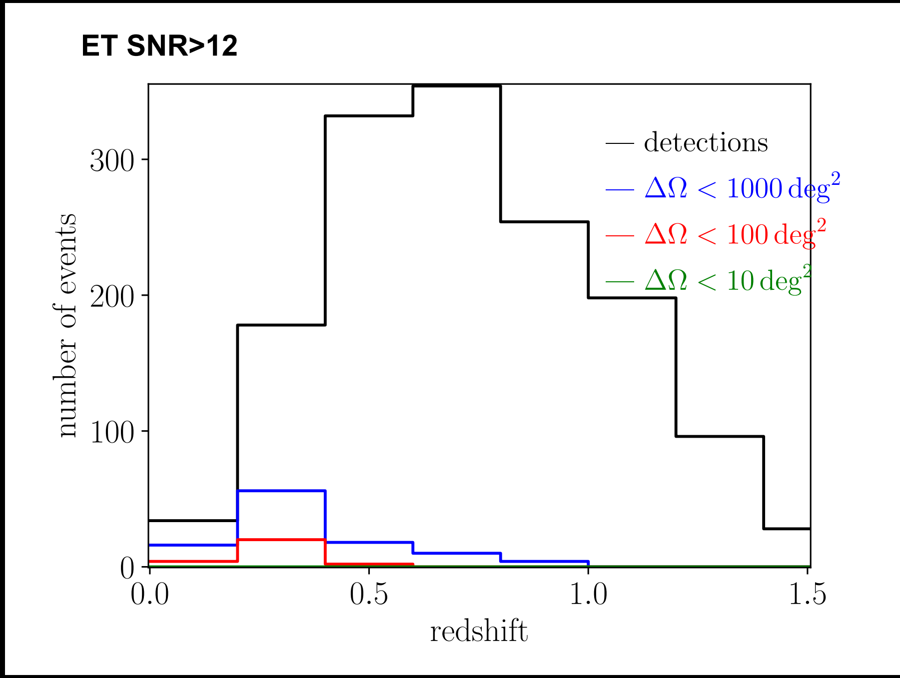
Up to z=0.26

- Among ~4000 mergers per year detected 3000 per year
- For ET 100 per year have sky loc < 10 sq. degrees
- For ET+LVKI 1000 per year have sky loc < 10 sq. degrees
- For ET+LVKI 100 per year have sky loc < 1 sq. degrees

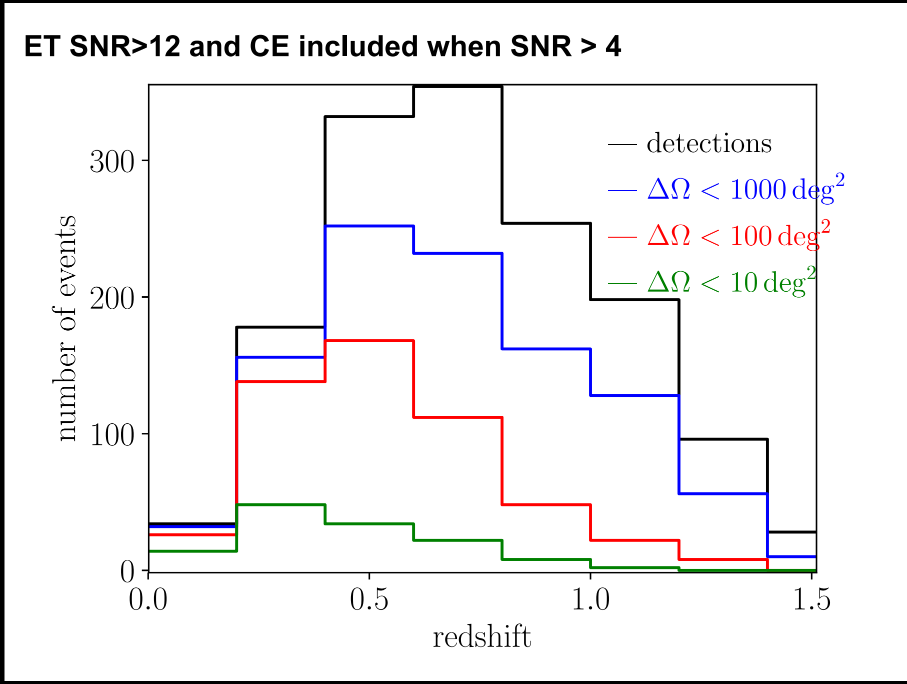


EINSTEIN TELESCOPEDETECTION/SKY LOCALIZATION up to z=1.8

ET

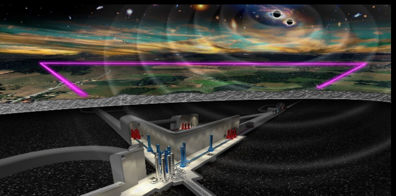


ET+CE

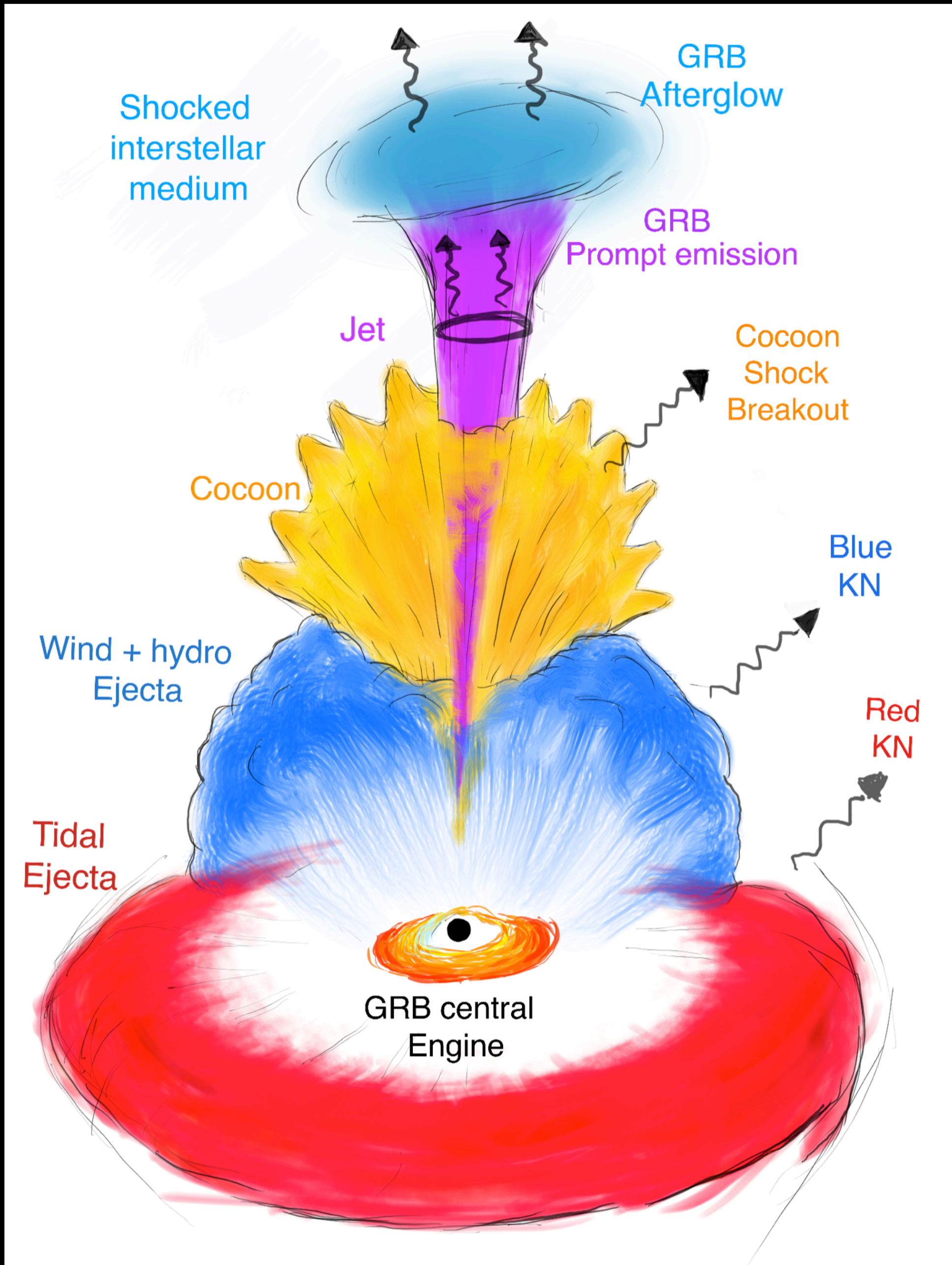


1 week of observations

- For ET+ CE 100 per week have sky loc < 10 sq. degrees

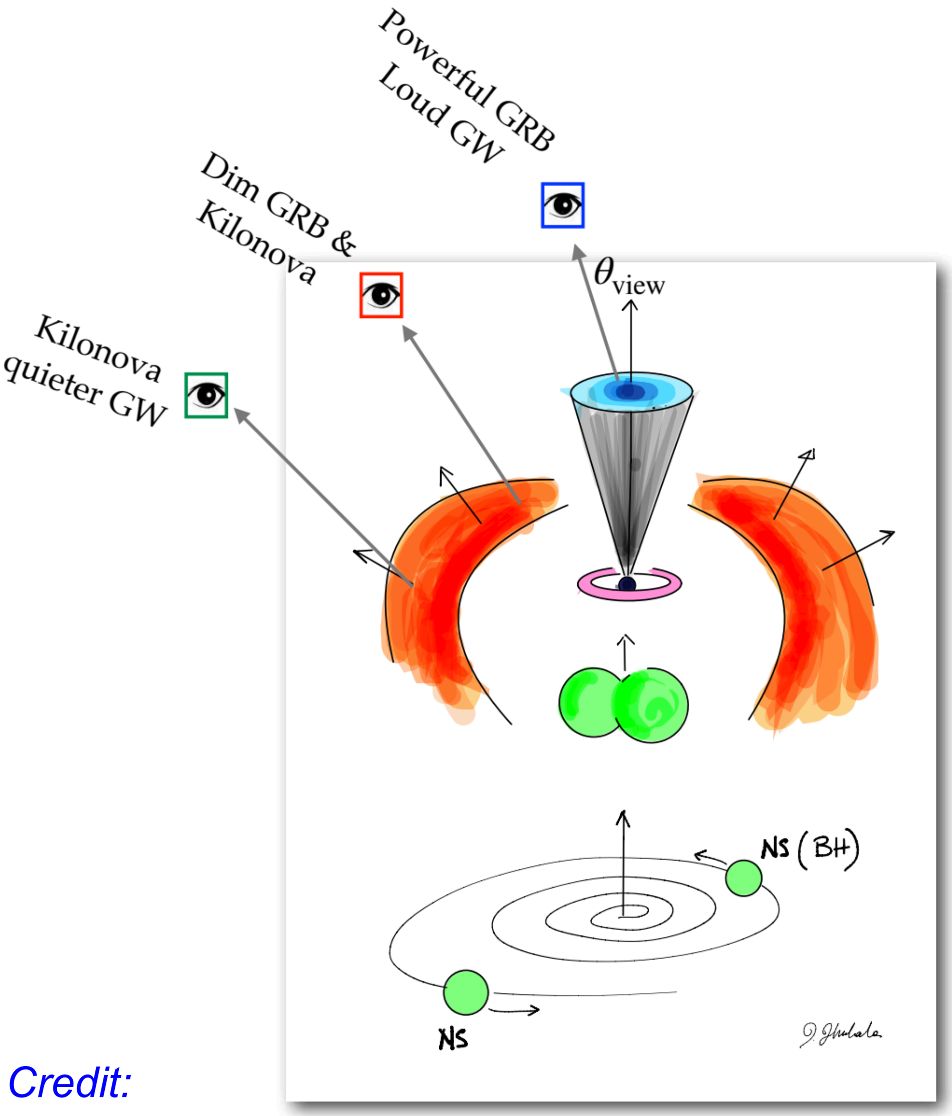


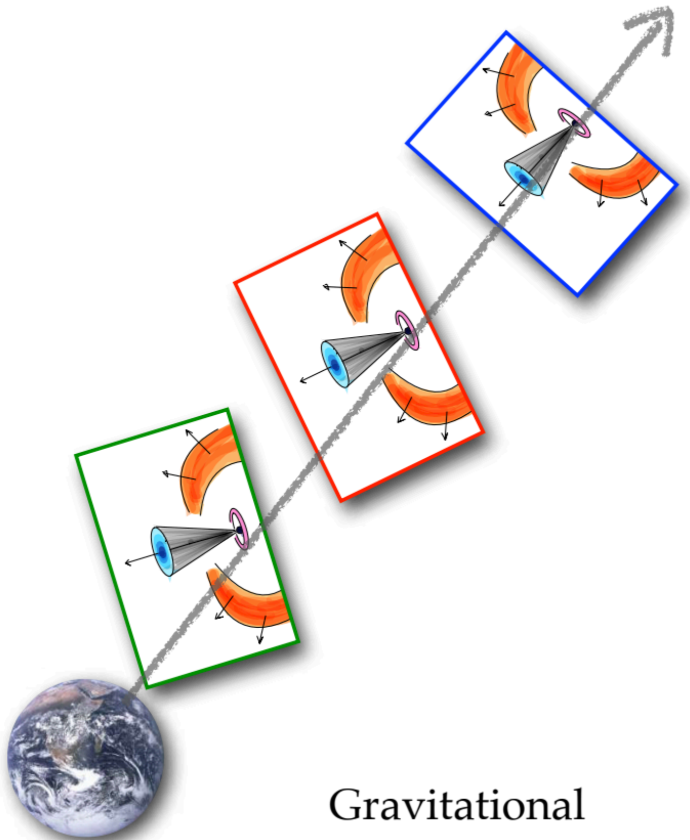
At z larger than 0.2 sky-localization from GRBs!



Thermal and non thermal emission components associated with BNS and NSBH merger

Ascenzi et al. 2020 arXiv:2011.04001



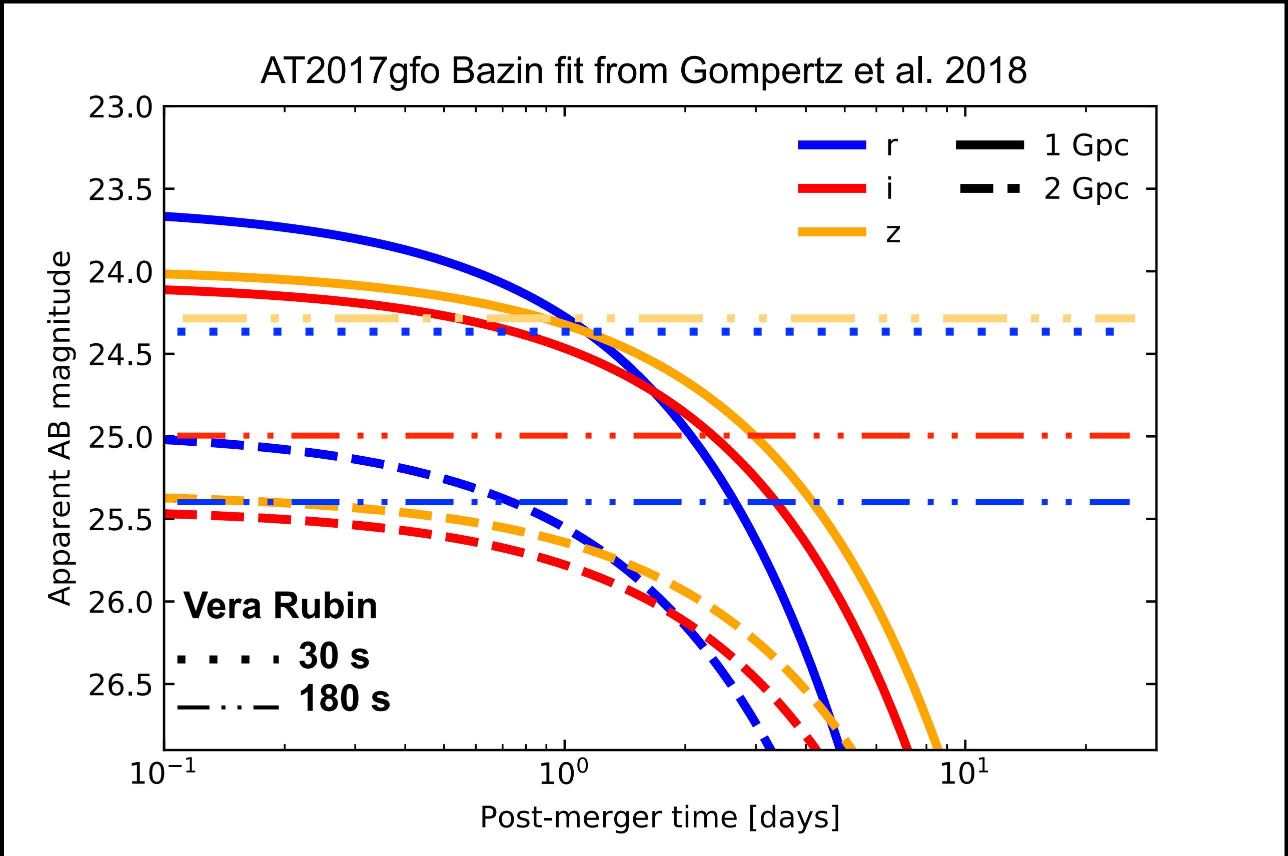


Gravitational
&
Electromagnetic
ranges

Credit: Ghirlanda

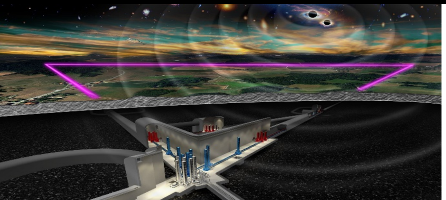
THERMAL EMISSION - KILONOVAE

OPTICAL BAND

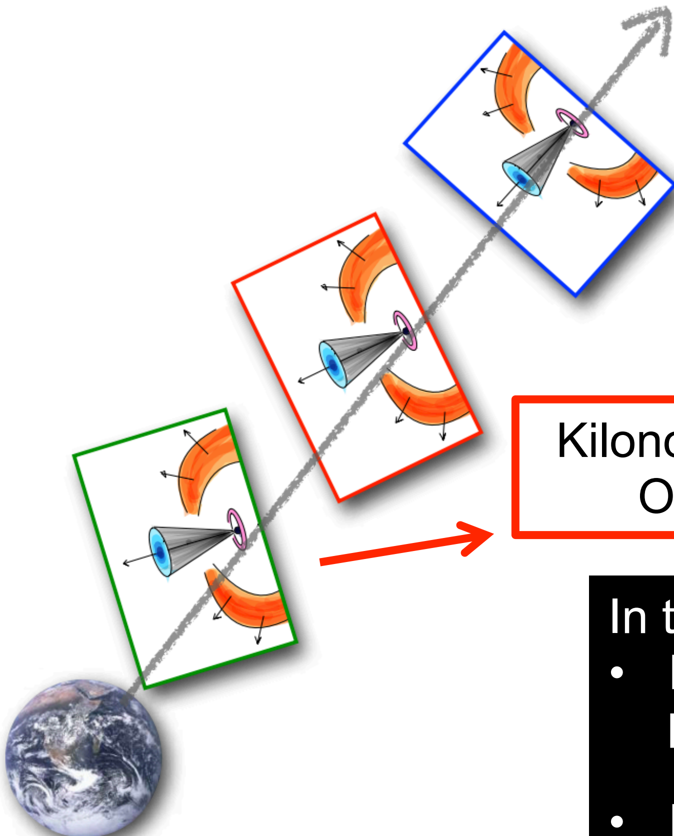


☹

- Too faint counterpart
- Large sky-localization/many contaminants



Joint detections for ET limited by optical instruments capabilities!!

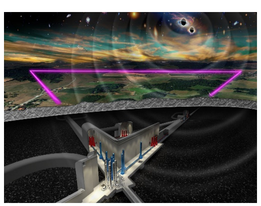


Kilonovae detectable by the Vera Rubin Observatory survey up to 1 Gpc

In this volume

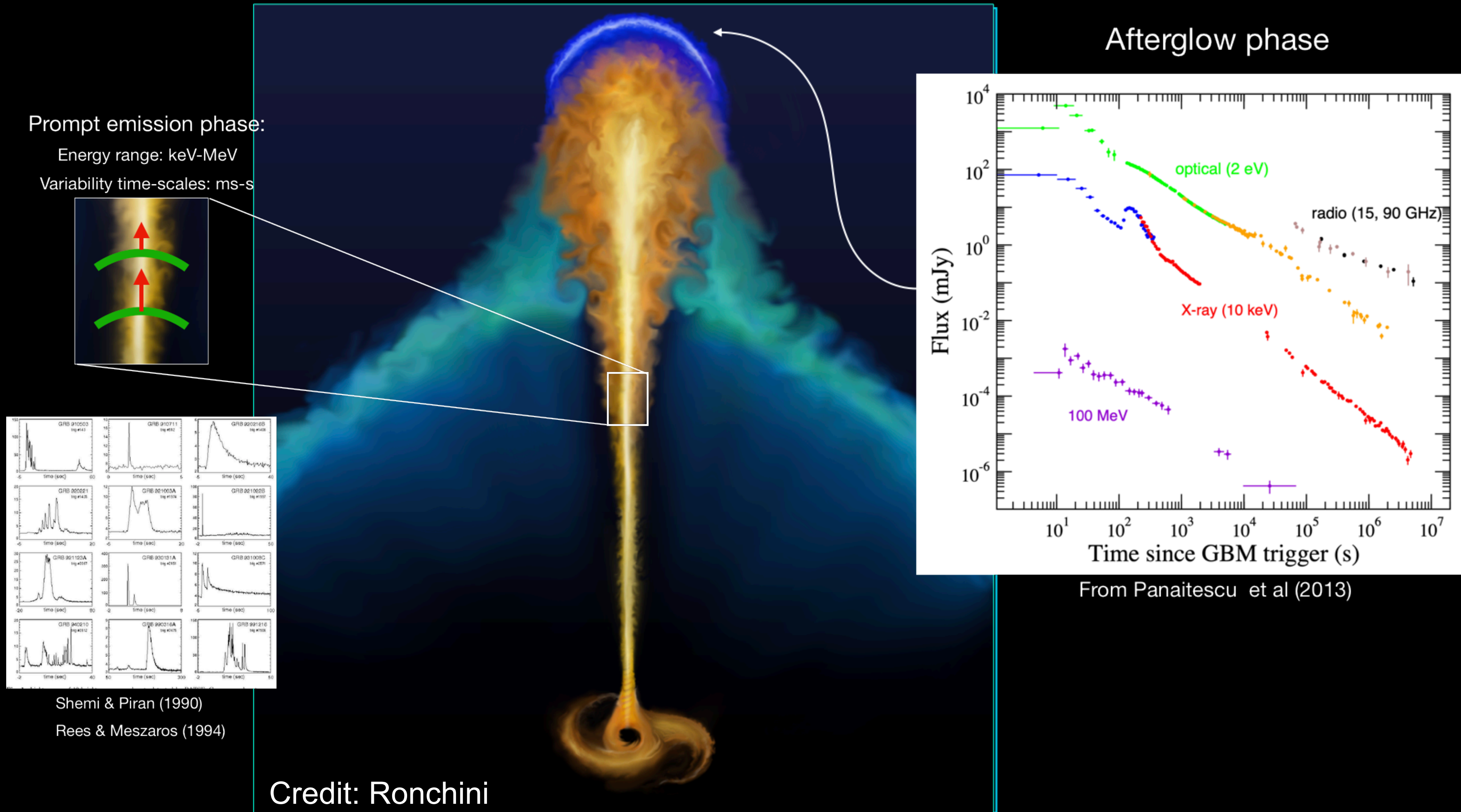
- ET about 100 event per year have sky loc < 10 sq. degrees
- For ET+LVKI 10^3 per year have sky loc < 10 sq. degrees

A few tens to a few hundreds joint detections!

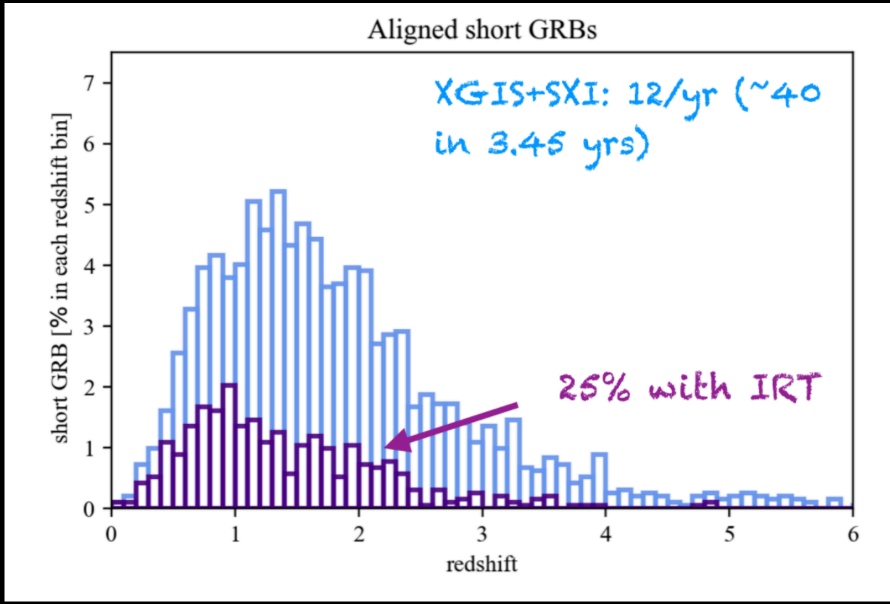


Three epochs of VRO 300s ToO observations in two filters (as in Chen et al. 2020)

HIGH-ENERGY



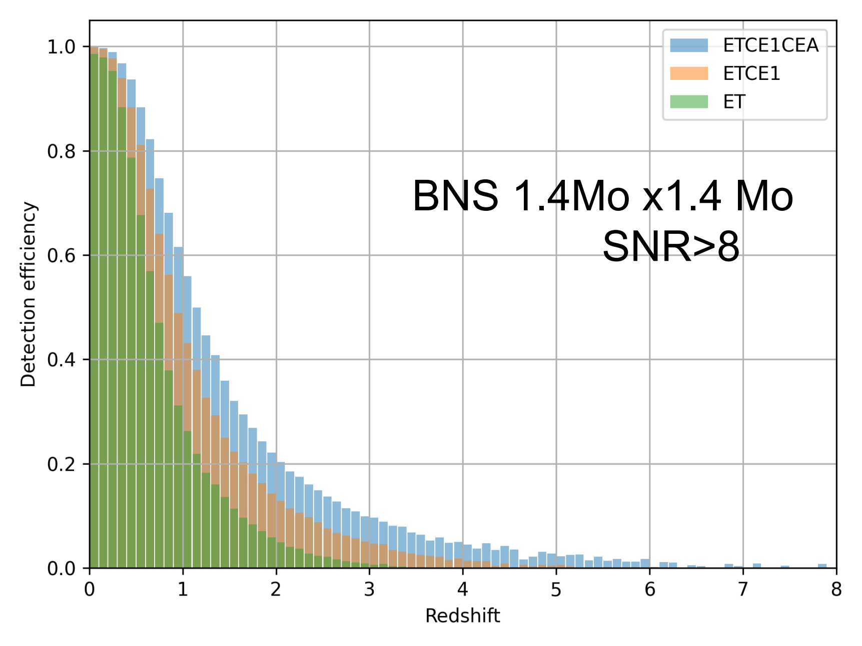
- GRB detectable up to high z
- Small number of contaminants
- Promising wide FoV hard-soft Xray instruments
- Good sky localization to drive a prompt EM follow-up

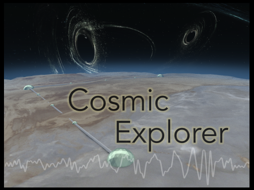


See Giulia Stratta talk

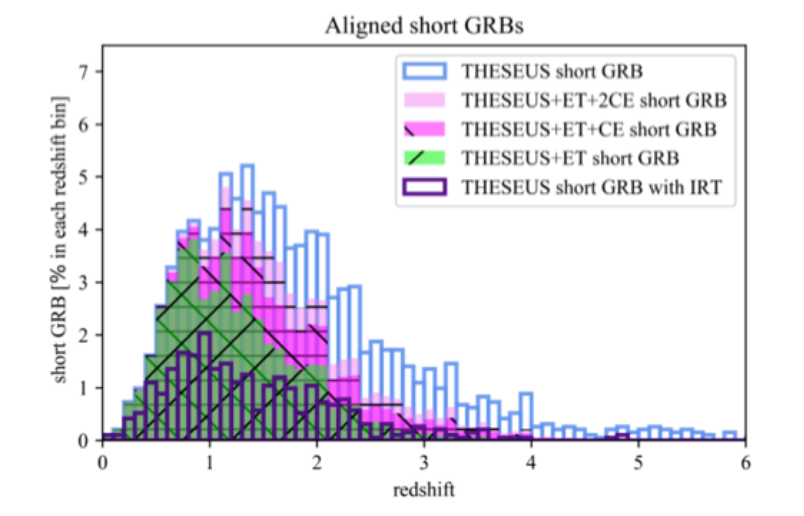
+

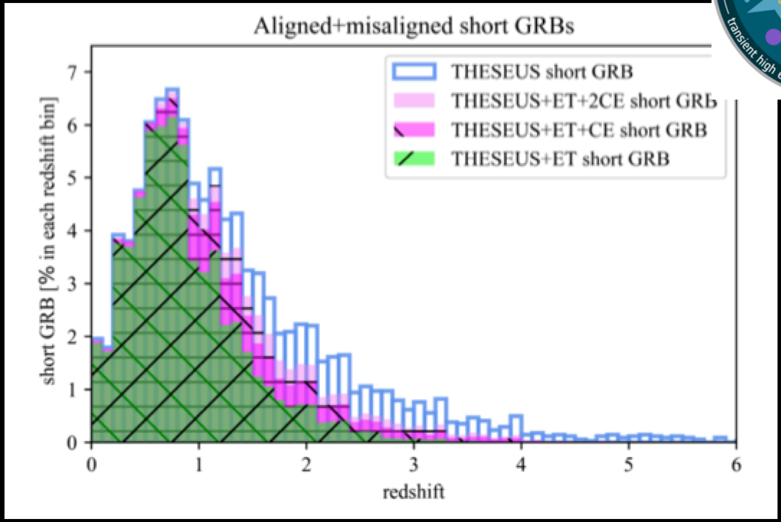
ET, ET+CE, ET+CE+CE





THESEUS in Multi-Messeger context

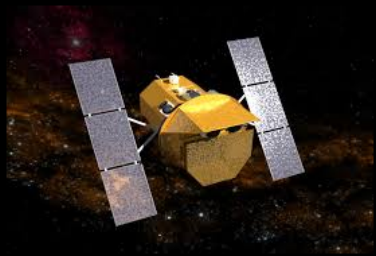


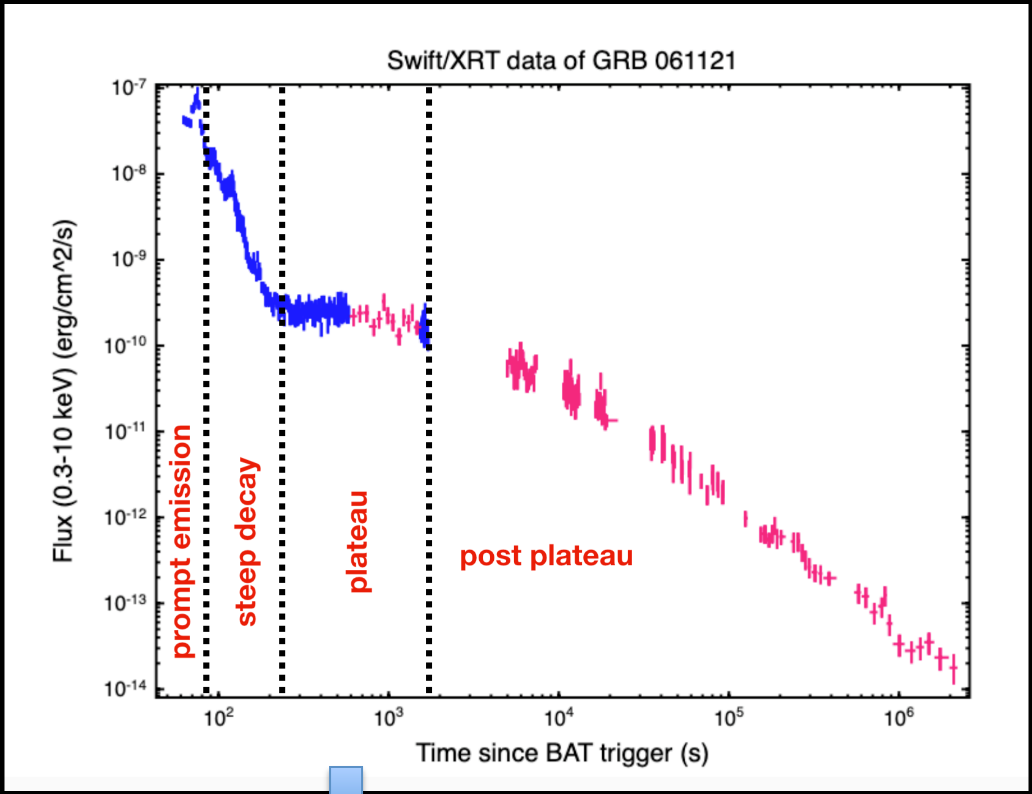


GW detectors	THESEUS+GW detectors plausible joint observation time	aligned short GRB+GW detections	aligned & misaligned short GRB+GW detections
2G network z<0.107 (500 Mpc)	3.45 yr	~0.04	1.8
ET	1 yr (3.45 yr)	5.6 (19.2)	13 (46)
ET+CE	1 yr (3.45 yr)	7.4 (25.7)	16 (55)
ET+2CE	1 yr (3.45 yr)	8.7 (30.1)	18 (61)

Credit THESEUS Yellow Book

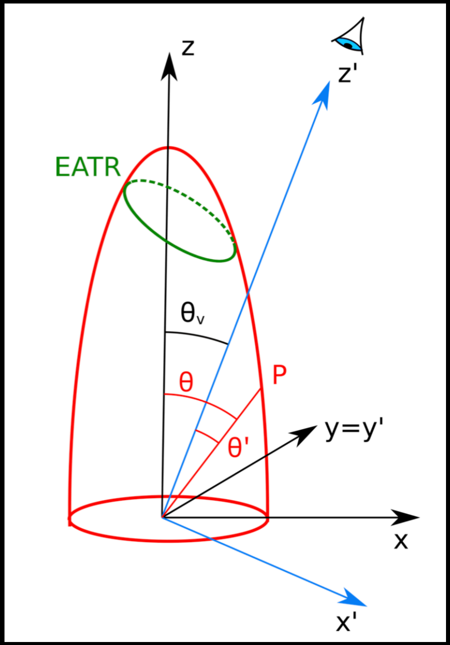
OTHER PROMISING HIGH-ENERGY COUNTERPARTS for SXI (0.5- 5 KeV sky loc < 1-2’

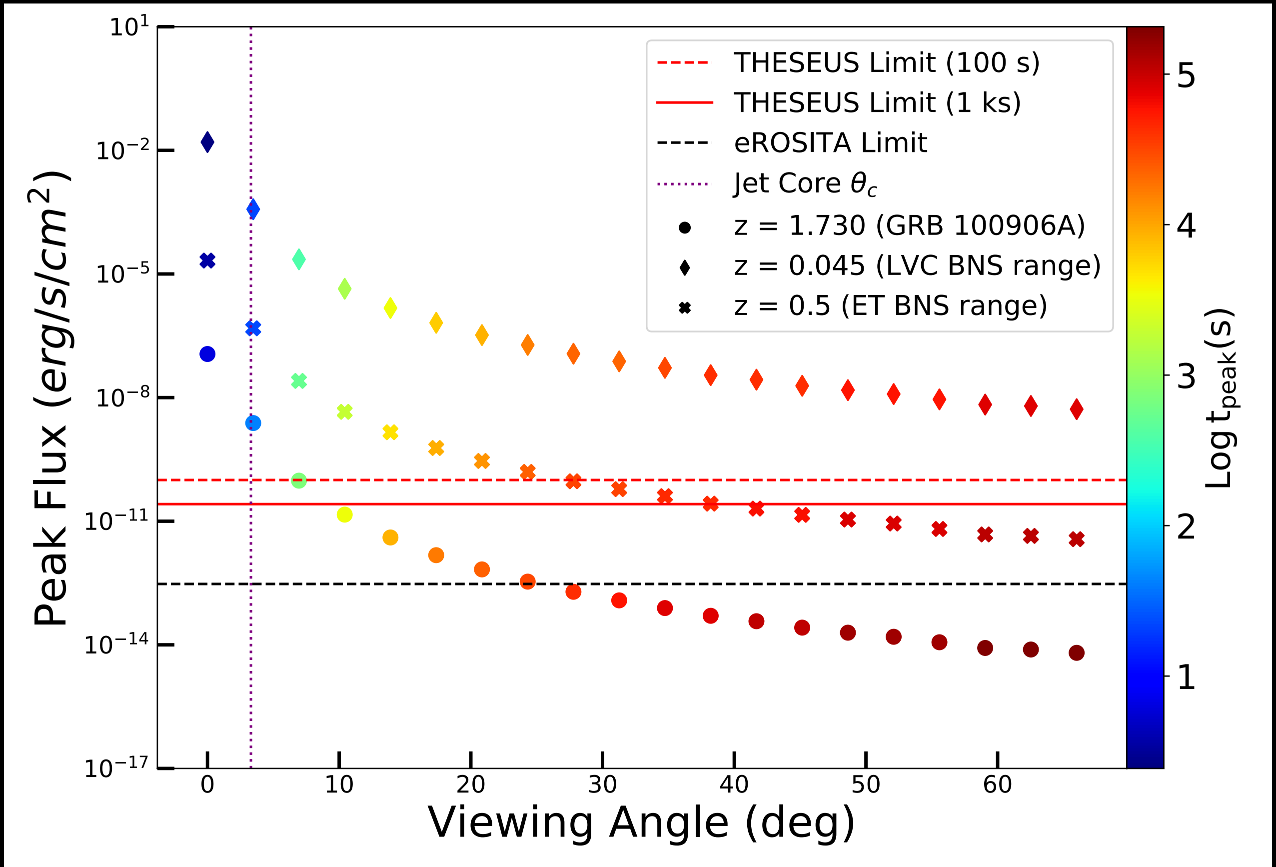




Magnetar? or High latitude emission from structured jet?

What happen off-axis?



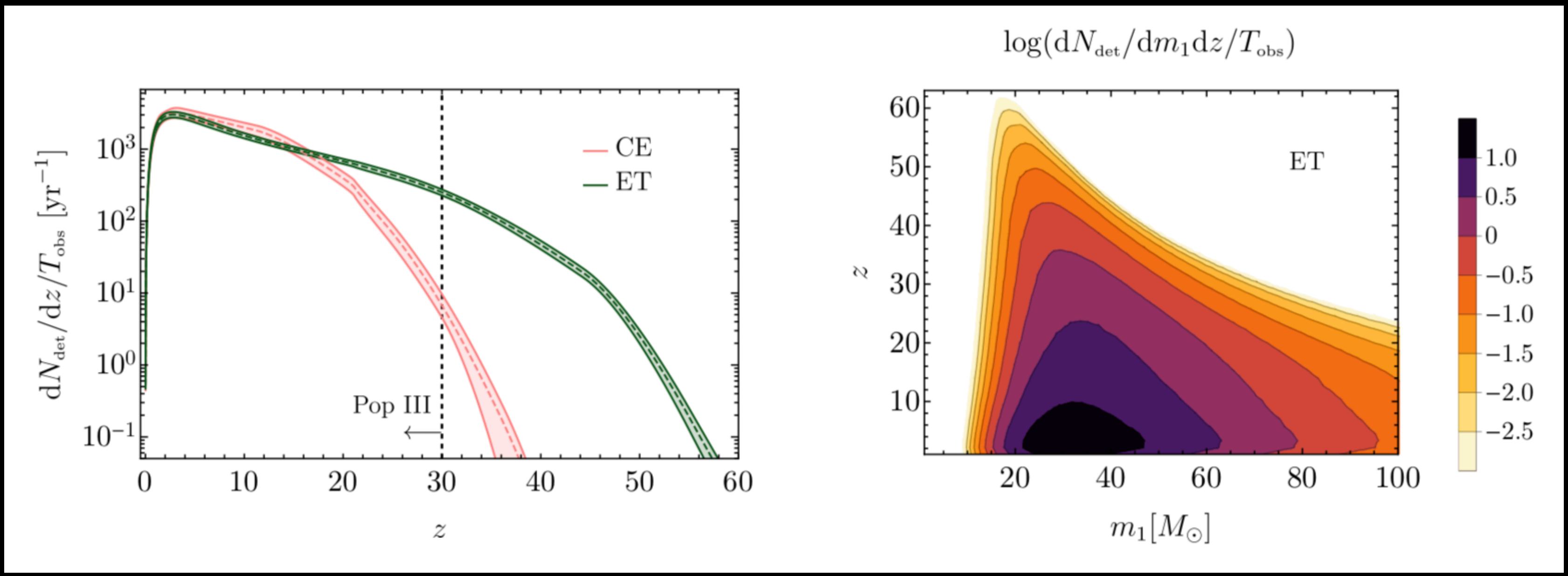


Ascenzi et al. 2020 A&A

Promising X-ray couterparts!

THESEUS AND ET as multi-probes of the early Universe

Disentangle astrophysical PoPIII from primordial BHs



De Luca et al. 2102.03809

Any BBH merger at z>30 will be of primordial origin

- Difference between ET and CE due to the better ET sensitivity at low frequencies
- Note: accurate measurement of z is also needed !

Cosmology and dark energy with ET

Modified GW propagation

Coalescing binaries measure a ``GW luminosity distance" different from the standard (electromagnetic) luminosity distance !

PARAMETRIZATION OF MODIFIED GW PROPAGATION

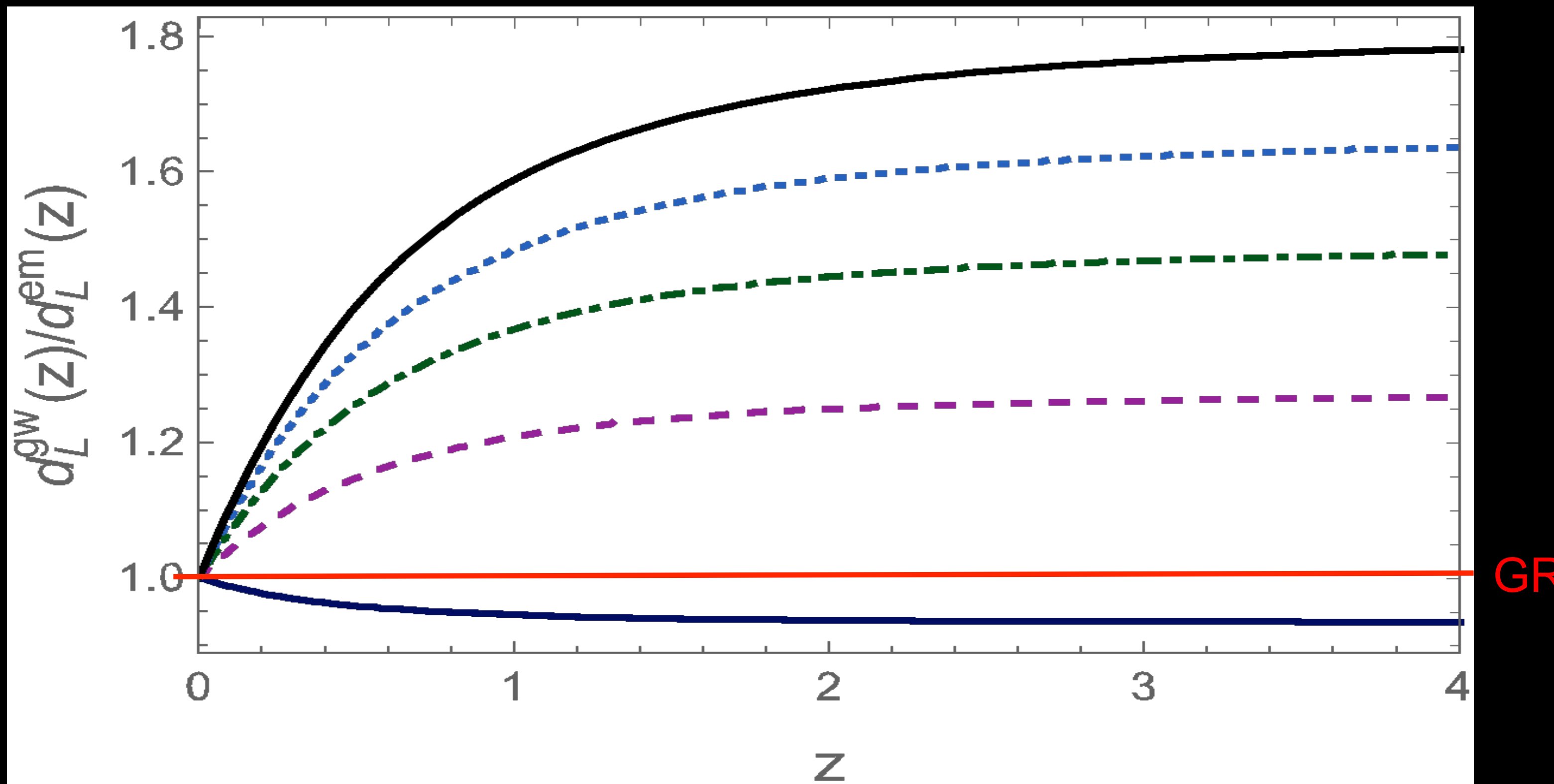
$$\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

This parametrization is very natural, and fits the result of (almost) all modified gravity models

Belgacem et al.
PRD 2018, 1712.08108
PRD 2018, 1805.08731
JCAP 2019, 1907.02047

- Standard sirens in Giulia Stratta talk

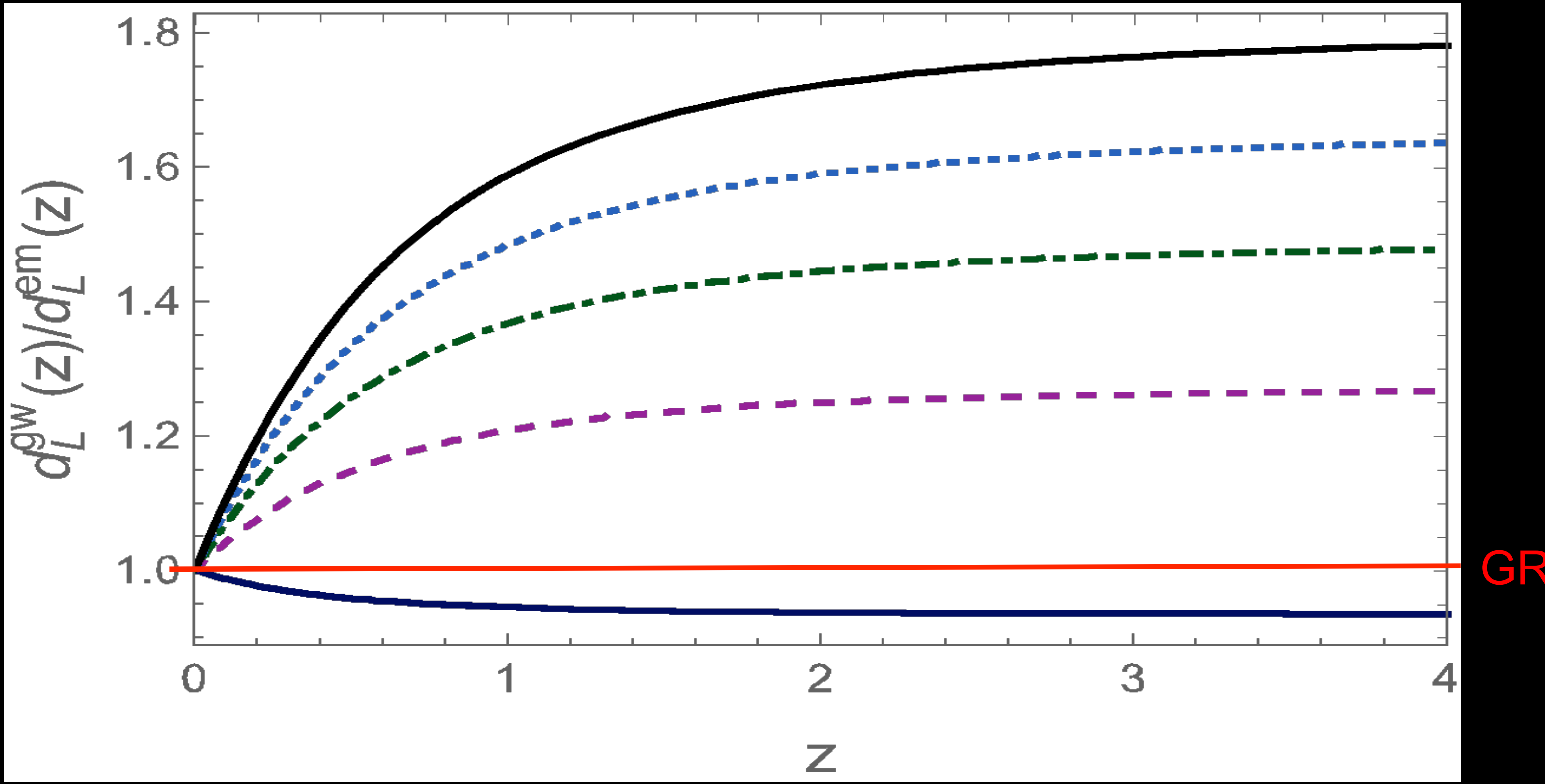
Ratio of the gravitational to electromagnetic luminosity distance in a modified gravity model



Modified gravity models: the counterpart could be at a different distance with respect to luminosity distance from the GWs!

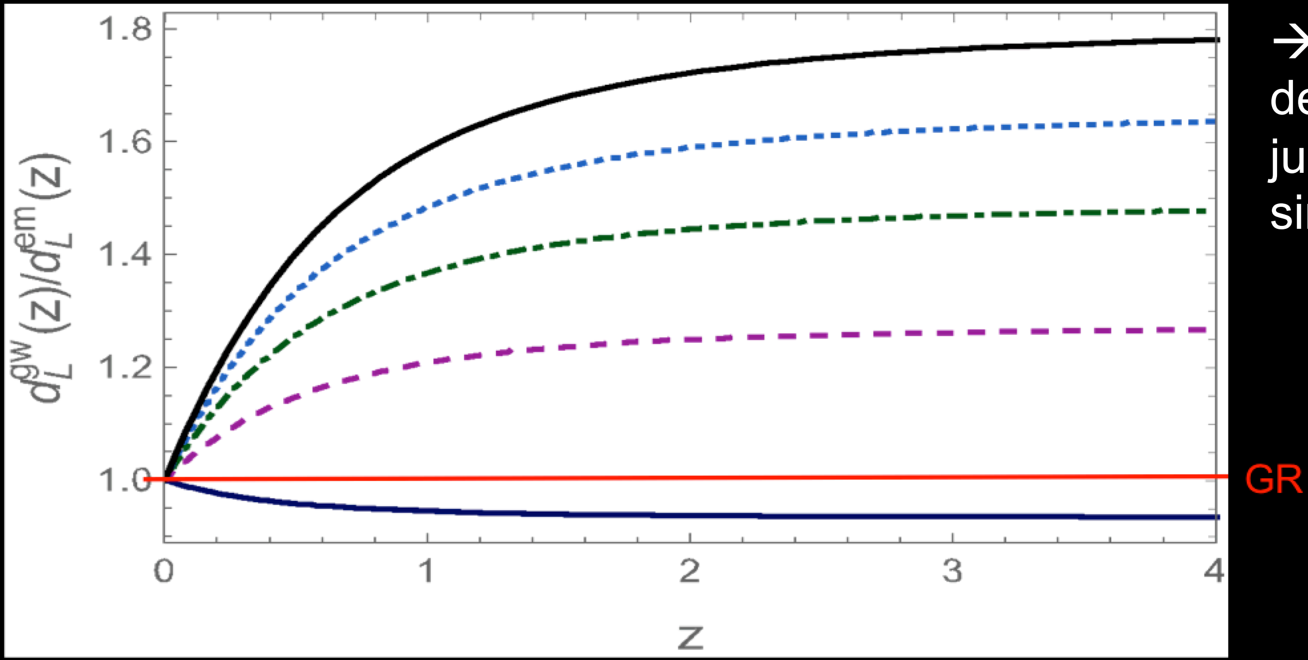
GW/EM the same travel time → temporal EM/GW coincidence

Belgacem et al. JCAP 2019, 1907.02047



- JOINT GW/GRB detections
- Small error in dL^{GW}
- High z

Belgacem et al. JCAP 2019, 1907.02047



→ Large effect could be detectable even with just a single standard siren at ET

↓

Few hundreds of joint GW-GRB detection → $\Delta\Xi_0/\Xi_0 \simeq 1\%$ or better

EINSTEIN TELESCOPE

theseus

⟹ GWs could become the best experiments for studying dark energy!

theseus

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

+

ET EINSTEIN TELESCOPE

Expected brilliant synergy!