Multi-Messenger Astrophysics with the Einstein Telescope

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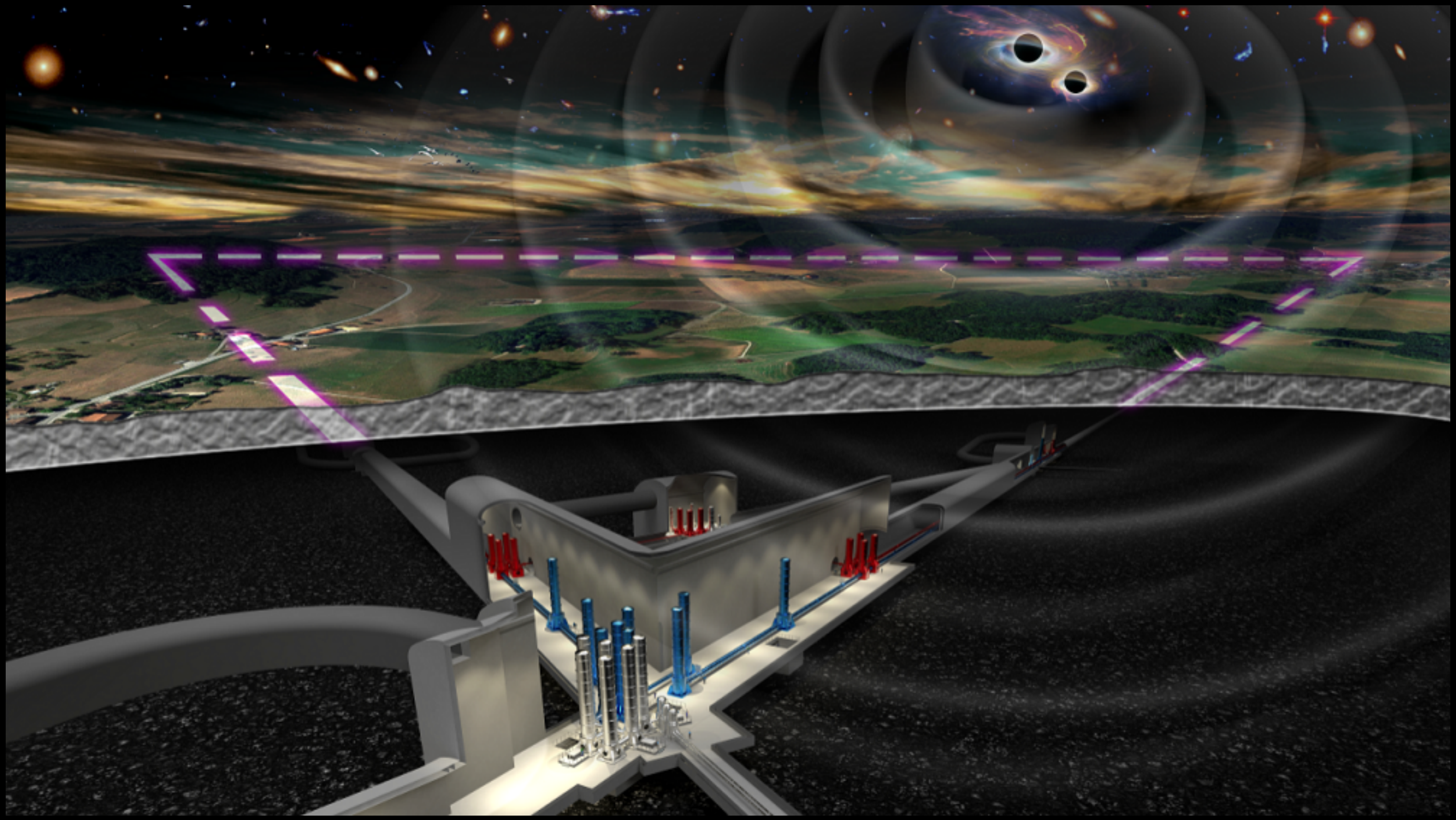
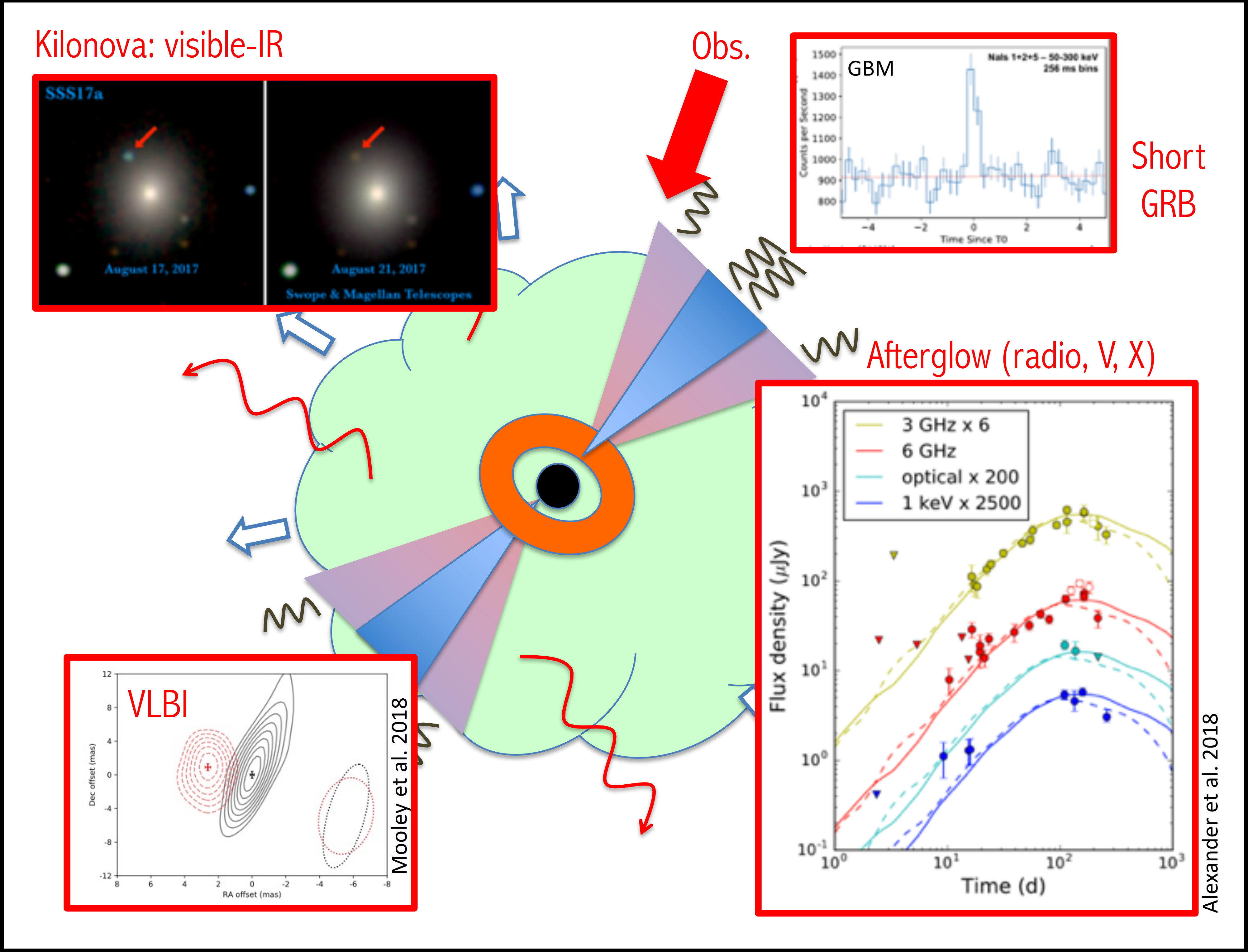


Multi-Messenger Astrophysics with Gravitational Waves: Current Status

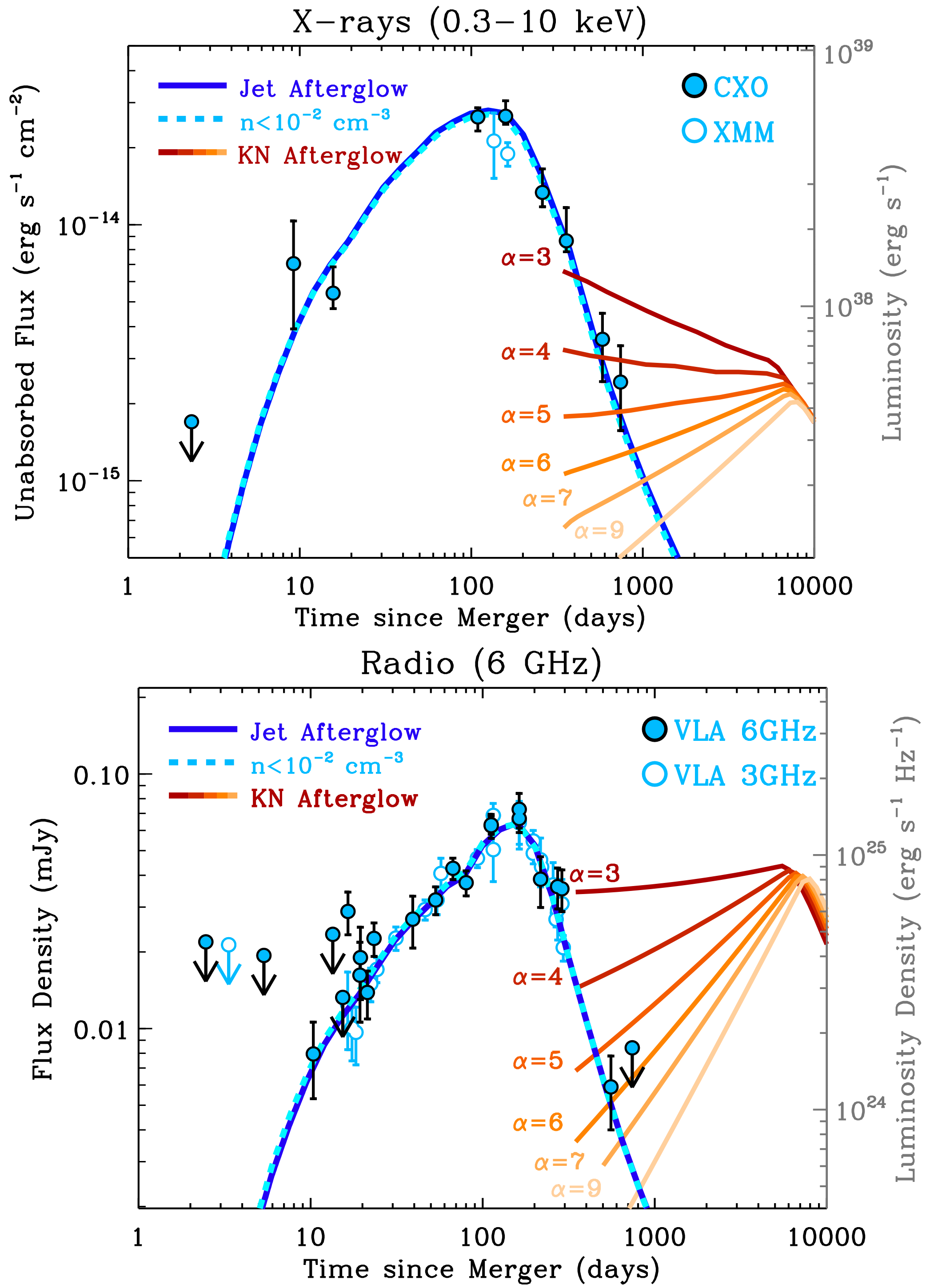
- **Simultaneous observation of the same phenomenon with several messengers:**
  - still only a single event: BNS merger GW170817
  - with an incredible set of observations:

GW: BNS inspiral - still missing: post-merger GW emission
EM: kilonova (V,IR) - still missing? kilonova afterglow
short GRB (gamma-rays) - afterglow (radio to X-rays + radio VLBI) - host galaxy

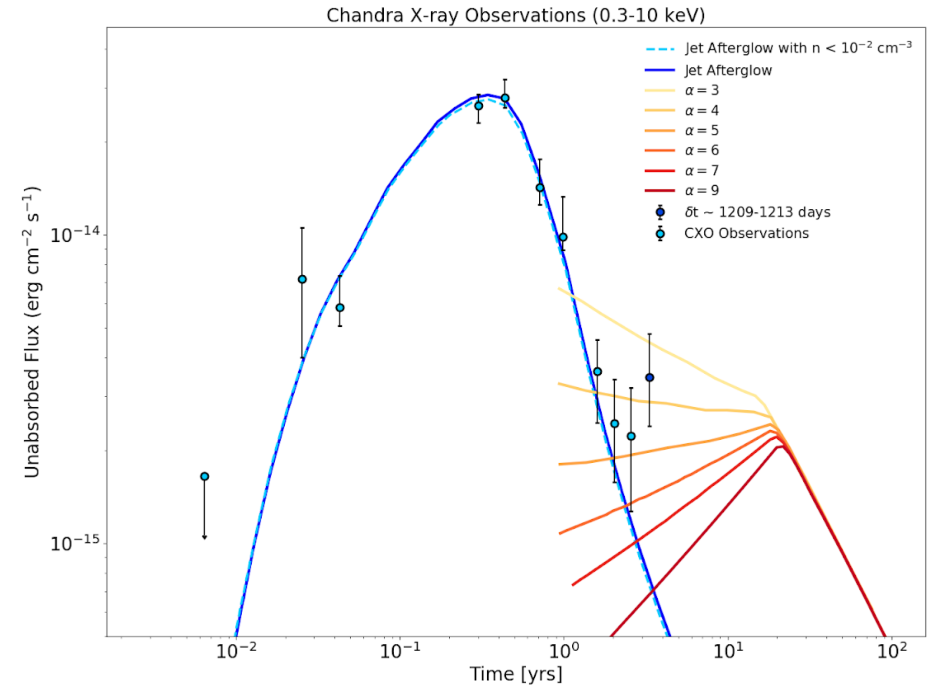
GW170817 electromagnetic counterparts



GW170817 electromagnetic counterparts
Late afterglow



Hajela et al. 2019



Update @ 3.3 yr (Hajela, GCN#29055)

KN afterglow?

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  - and an incredible list of major results:

  association of a short GRB with a BNS - first detection of a KN, evidence for r process - first off axis observation of a GRB relativistic jet, etc.

  New constraints on NS EOS - Hubble Constant - Test of GR - Constraints on new theories of gravity, etc.

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- but also a long list of open questions:

e.g. (focussing only on astrophysical questions):
Origin of the short GRB, connection to the cosmic population?
Post-merger evolution?
Nature of the central source (intermediate state with a massive NS?)?
Mechanisms for the various ejecta?
Origin of the structure of the relativistic jet? etc.
Contribution of BNS to the production of heavy elements? etc.

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- **O3: at least two BNS, possible NSBH, no em counterparts**

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- **Multi-Messenger Astrophysics is not limited to simultaneous observations:**

  e.g.
  - evolution of massive stars in binary systems
  - origin of heavy elements in the Universe
  - constraints on the EOS of ultra-dense matter
  etc.

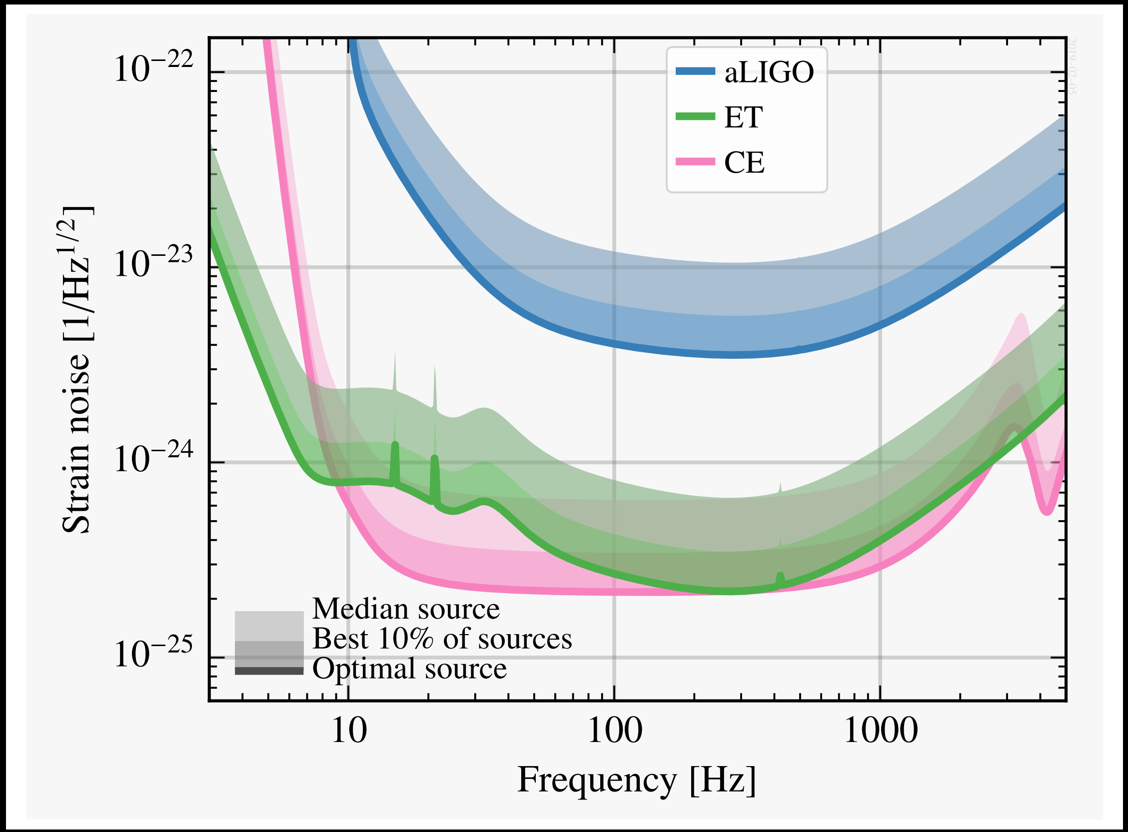
  GW merger detections complement very well standard em observations

  (see this morning's presentations)

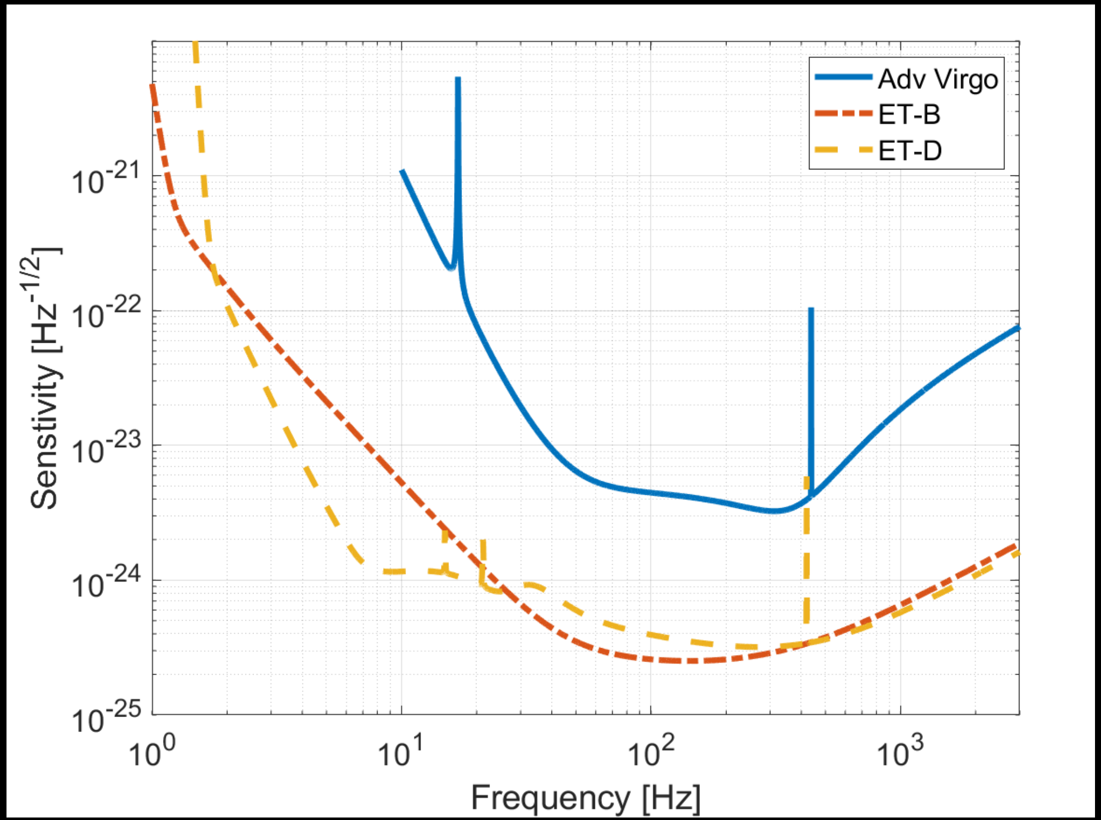
Multi-Messenger Astrophysics with Gravitational Waves: Requirements for the next generation of GW detectors

- **Better sensitivity: Einstein Telescope: about one order of magnitude better**

GW international committee:
3G observatory science case



ET Science Case, Maggiore et al. (arXiv: 1912.02622)



A better sensitivity offers the possibility to detect new classes of sources

For know sources: a major challenge = connecting the local BNS merger population with the cosmic population of short GRBs.

[on the em side: an adapted new generation of instruments with a better sensitivity should be available: e.g. ngVLA or SKA in radio; THESEUS in gamma-rays, etc.]

Multi-Messenger Astrophysics with Gravitational Waves: Requirements for the next generation of GW detectors

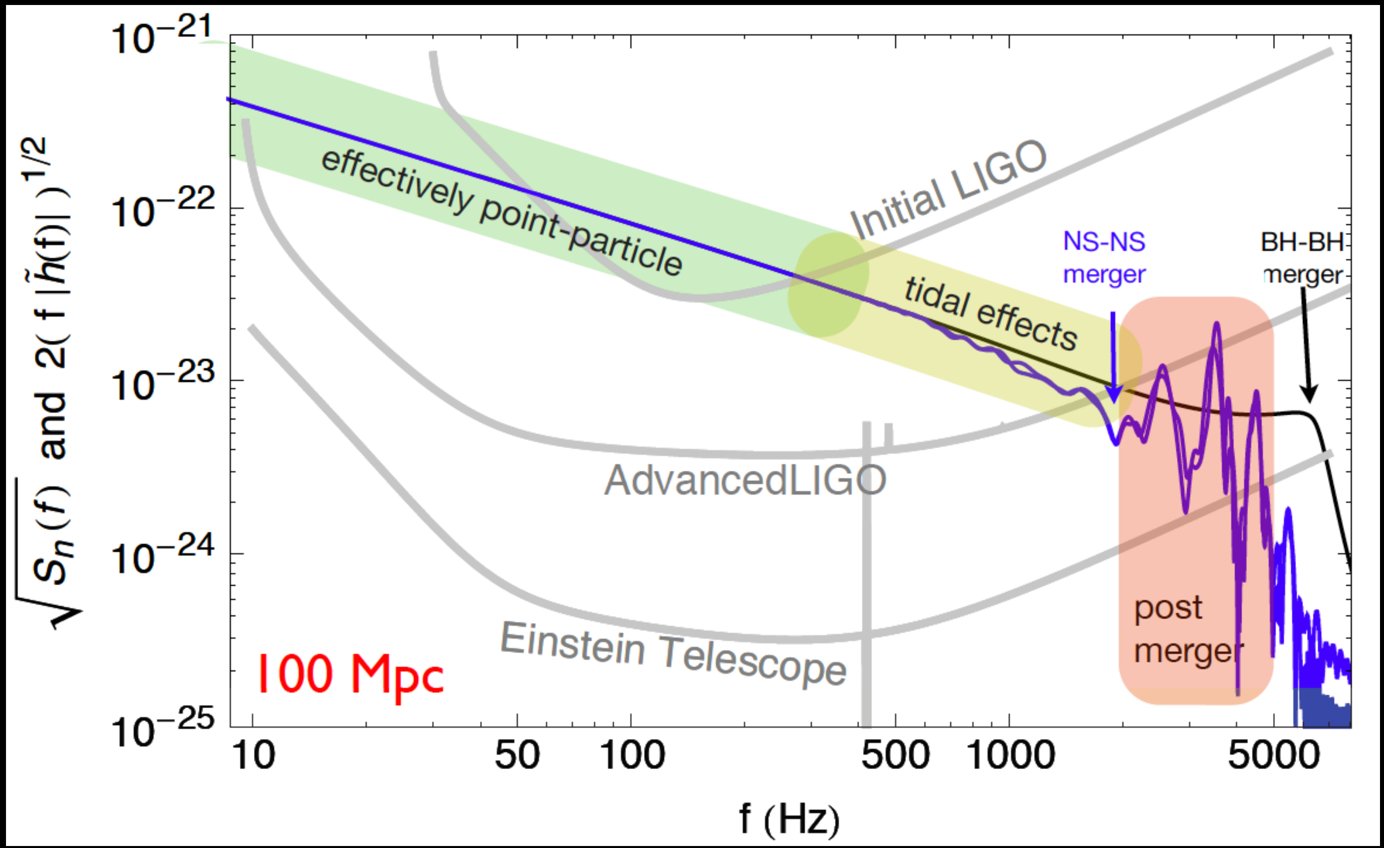
- **Better sensitivity: Einstein Telescope: about one order of magnitude better**

- **Broader range of accessible frequency:**

Einstein Telescope: extends to lower frequency (LISA: even lower frequencies)

A major challenge: detecting the post-merger GW signal of a BNS (then improved sensitivity at high frequency is also very important)

[Interesting synergy ET-LISA not discussed here: multi-band GW observations of some sources?]



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- **Better localization:**

  BNS: Einstein Telescope alone: hundreds of deg^2?
  ET + aLIGO/aVirgo/…: a few deg^2/tens of deg^2 (but for nearby events)?
  a network or three 3G-observatories: thousands of BNS within a few square deg^2?

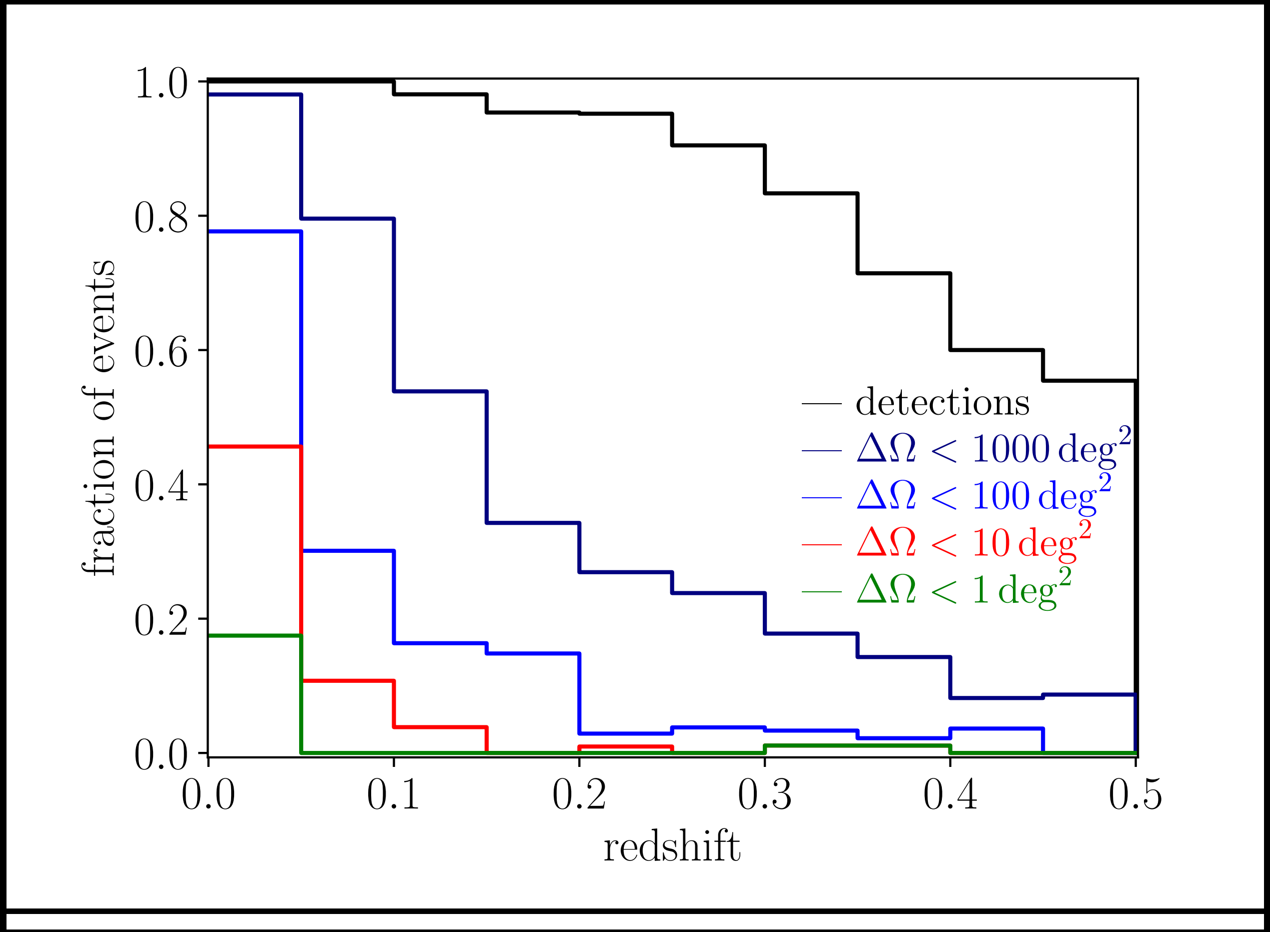
  Strong impact on the capacity to detect em counterparts.

  [on the em side: the efficiency of the follow-up can still be improved and new instruments are coming (LSST, SVOM, CTA, …]: let's wait for the run O4.]

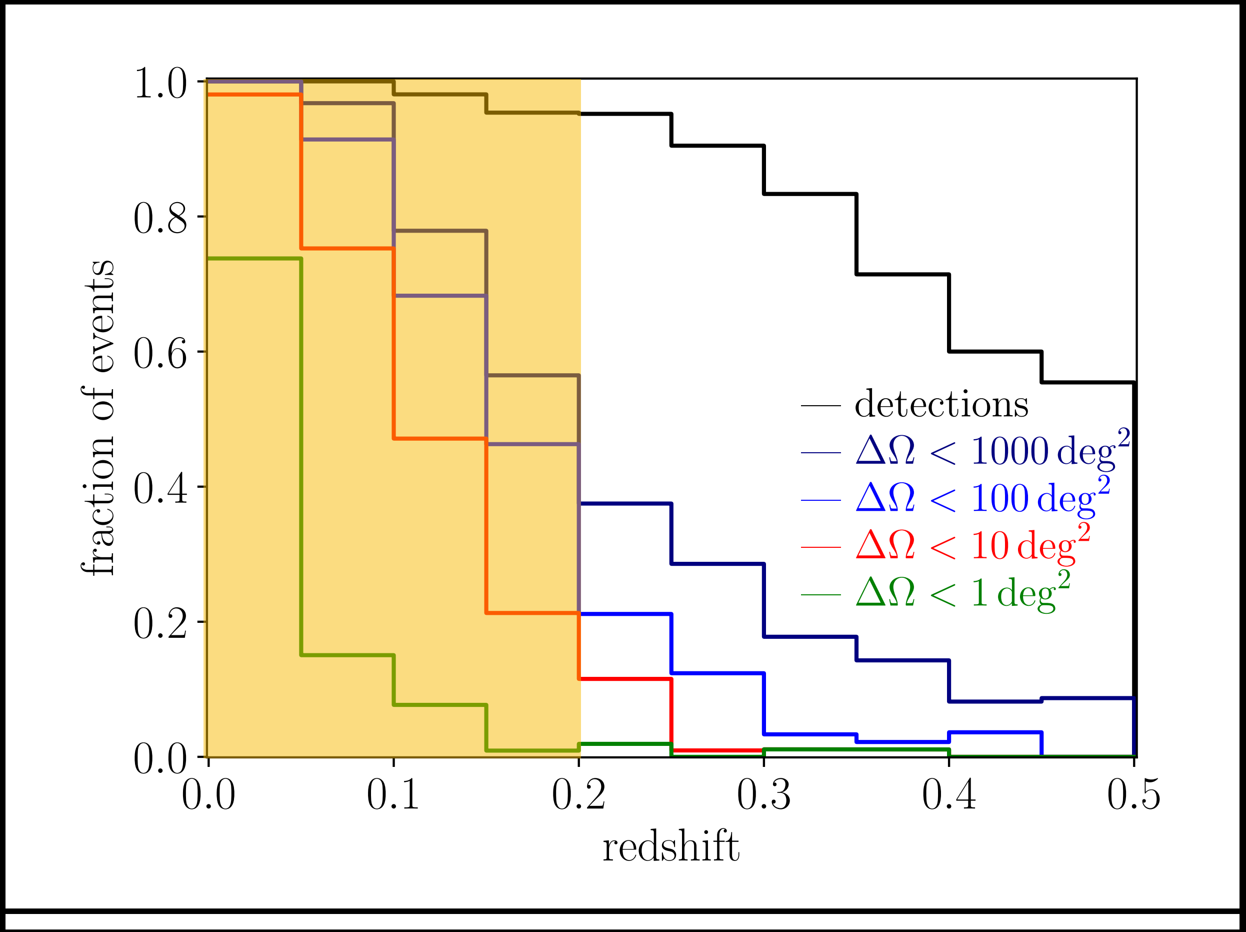
Multi-Messenger Astrophysics with Gravitational Waves: Requirements for the next generation of GW detectors

Localization of BNS:

ET alone



ET + 2G network



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- **Better duty cycle:**

  Einstein Telescope: ?

  It is a major challenge for rare events such as short GRBs,
  or the Holy Grail: the next Galactic core-collapse supernova

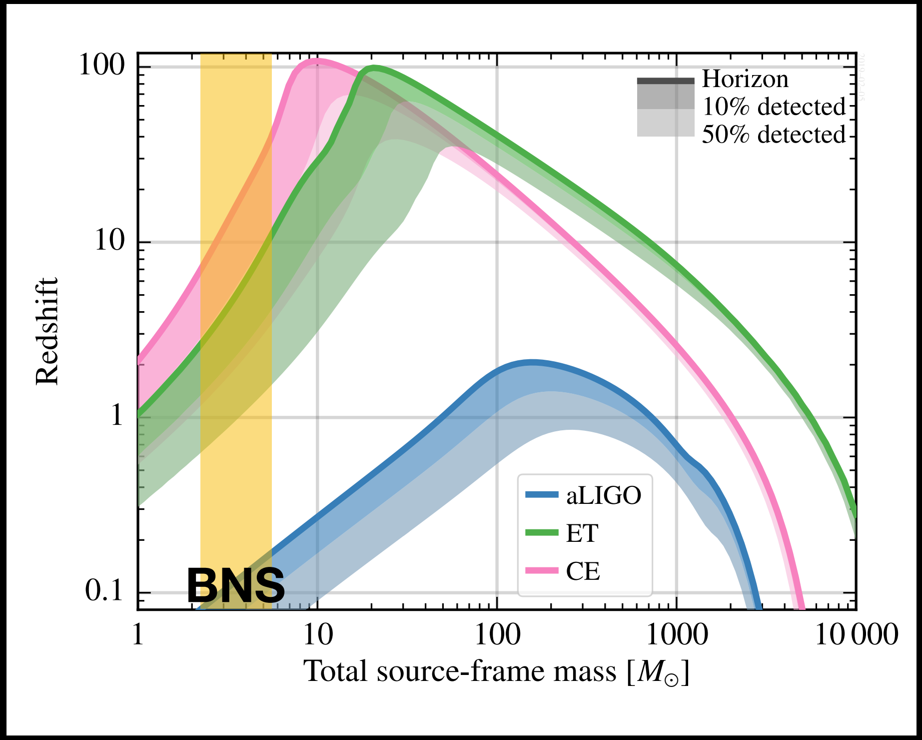
Multi-Messenger Astrophysics with the Einstein Telescope
Mergers

- **Much more BNS/NSBH!**
  7x10^4 BNS/yr ?

- **Maximum redshift for BNS ~2-3**
  (170817: 40 Mpc; aLIGO/aVirgo: 0.2)

  Rates, evolution,
  distribution of merger times, …

  Impact
  on stellar evolution in binaries,
  on chemical evolution,
  etc



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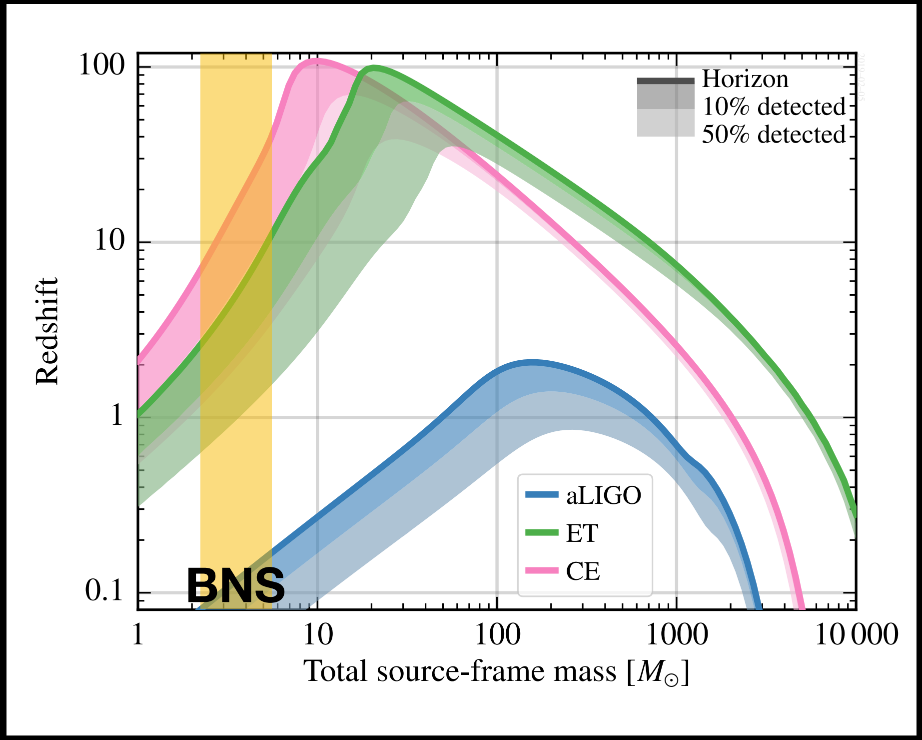

- **Major challenge: electromagnetic counterparts**

  (1) short GRB: a major goal = connecting the BNS population revealed by GW with the standard population of short GRBs

  No follow-up/Needs gamma-ray satellites with large field of view alla Swift/Fermi/SVC
  (e.g. THESEUS proposed to ESA)

  Except at very low distance (e.g. 170817): on-axis events

  Before ET: very difficult (mean short GRB redshift ~0.5)

Multi-Messenger Astrophysics with the Einstein Telescope Mergers

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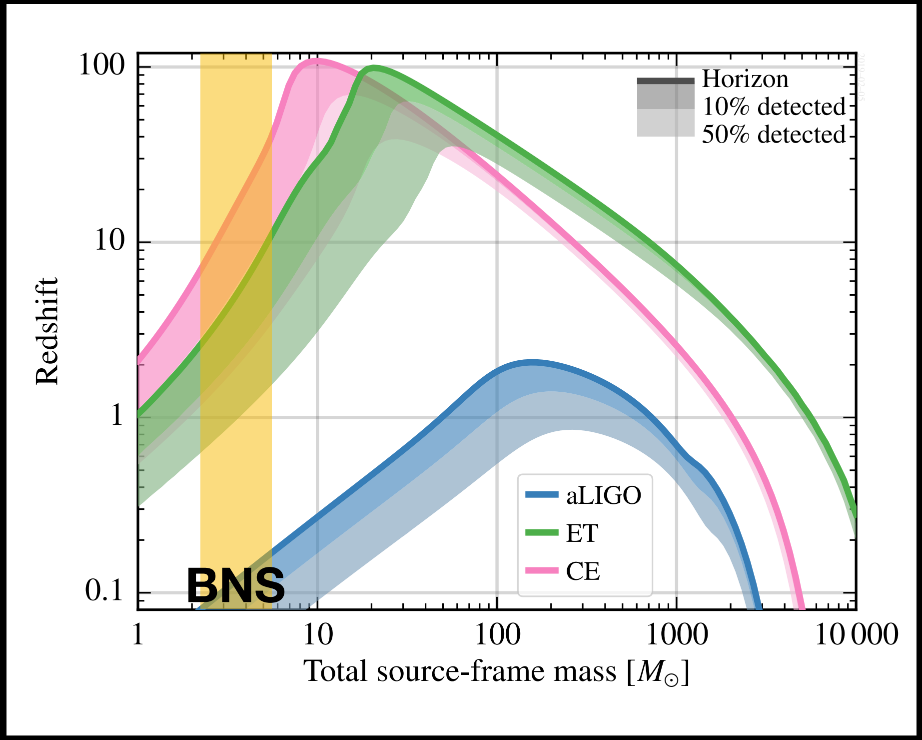

- **Major challenge: electromagnetic counterparts**

  (2) other counterparts: kilonova+host galaxy, afterglow

  Kilonova (V,IR): in principle the easiest to catch (~isotropic emission)
  Afterglow (X,radio): strong dependency on the viewing angle
  (VLBI: only a low distance)

  Depends strongly on localization+efficiency of the follow-up

Multi-Messenger Astrophysics with the Einstein Telescope
Mergers

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  $7x10^4$ BNS/yr ?

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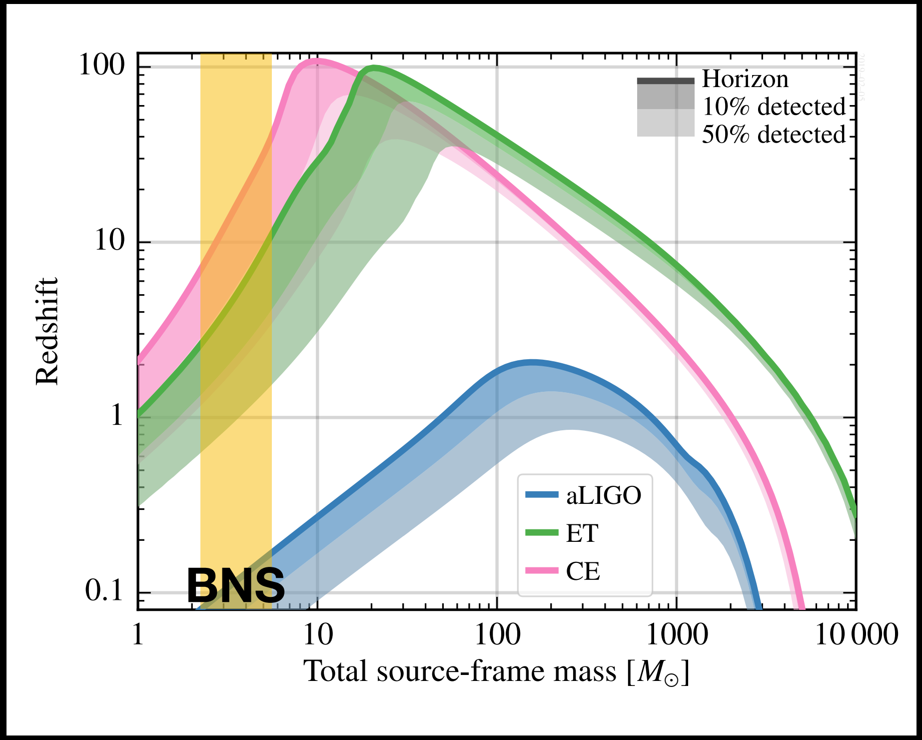

- **Major challenge: electromagnetic counterparts**

  What is expected? GW+EM observations of BNS/NSBH can address several fundamental questions in astrophysics (and also in cosmology: see D. Steer's talk)

  - better understanding of the post-merger evolution from GW in association with the electromagnetic signal associated to various ejecta
  - exploring diversity: intrinsic (NSBH vs BNS, …) and extrinsic (viewing angle)
  - understanding the physics of the kilonova and the origin of heavy elements
  - constraints on stellar evolution in binaries (via host galaxy + rate + mass distrib. + …)
  - understanding the physics of extreme relativistic jets (sampling the viewing angle is important)
  - etc.

Multi-Messenger Astrophysics with the Einstein Telescope
Core-collapse supernovae

- **2G: our Galaxy**
  low rate o(1/century)
- **ET: ~100 kpc (a new SN1987A?)**

A three-messenger detection?

GW+neutrinos: a direct probe
of the core collapse and formation
of a compact object

GW: proto-NS, rotation, asymetry, …

EM: the explosion of the enveloppe

Be ready for the next Galactic SN
(warning: duty cycle)

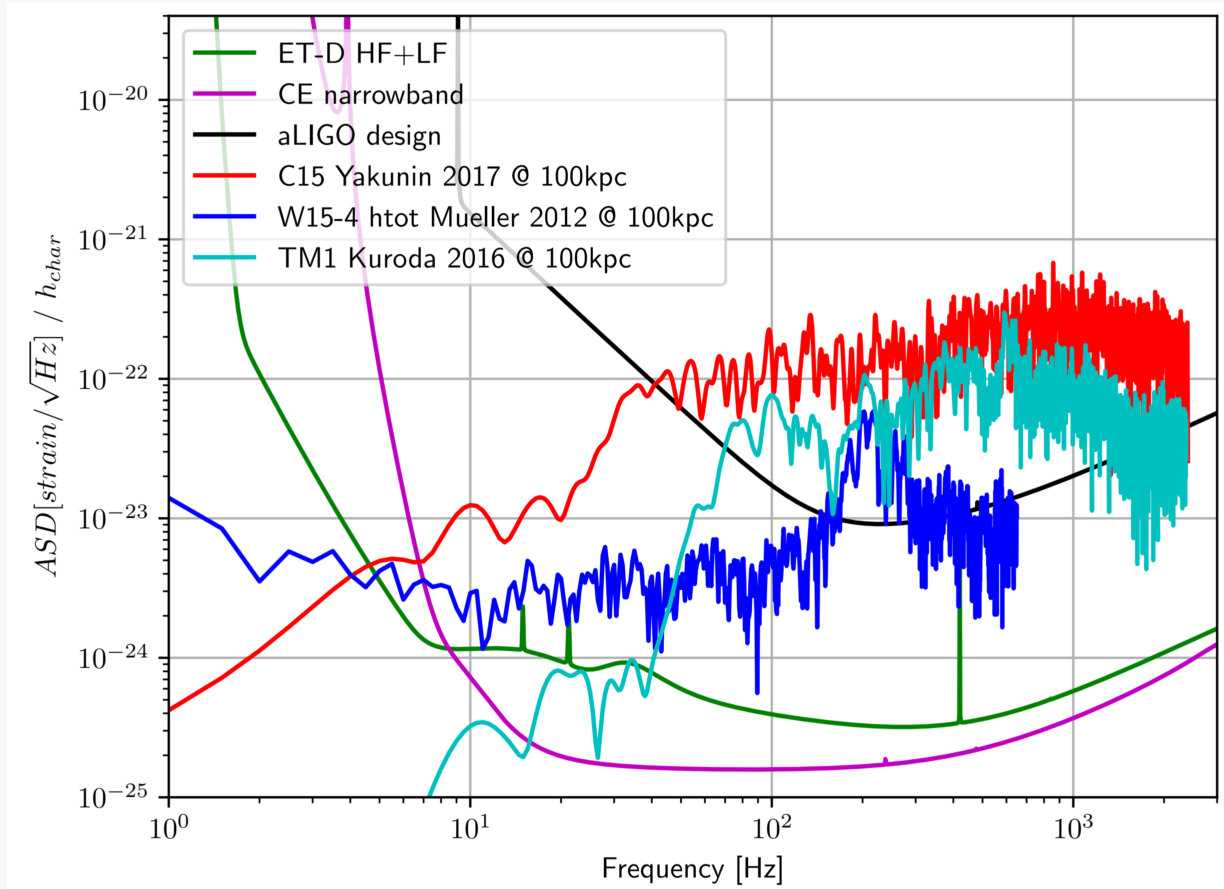

Figure 4.1: Characteristic strain vs. frequency of three typical 3D core collapse SN simulations: C15 [371], W15-4 [342], and TM1 [352]. The Einstein Telescope in xylophone D (ET-D) configuration [372], the Cosmic Explorer (CE) [373], and the Advanced LIGO design [213] also shown.

GW international committee:
3G observatory science case

Multi-Messenger Astrophysics with the Einstein Telescope
Backgrounds

- New generation of neutrino detectors (e.g. HyperKamiokande) should detect the neutrino background of stellar origin (main source: SNae)

- The detection of the GW background of stellar origin (main source: binaries) would complement nicely this observation

A new look on the formation of large structures, on the star formation history, on stellar evolution, etc.

Multi-Messenger Astrophysics with the Einstein Telescope
Other sources

- **Continuous emission from spinning NS**
- **Bursts from magnetars**
- **etc.**

Not discussed here

Multi-Messenger Astrophysics with the Einstein Telescope
Conclusion

- **ET: an impressive scientific potential for astrophysics+cosmology+physics (mergers, new sources?)**

- **ET alone can already bring a lot of progress thanks to a better sensitivity/ frequency range**
  (rates, evolution, post-merger physics, connection to short GRBs, etc.)

- **To exploit the full potential for multi-messenger astrophysics: two additional strong requirements**

  - localisation (ET + 2G network is already much better)
  - duty cycle
  (but I don't know when the next Galactic core-collapse supernova will explode)