Science potential of terrestrial GW detectors

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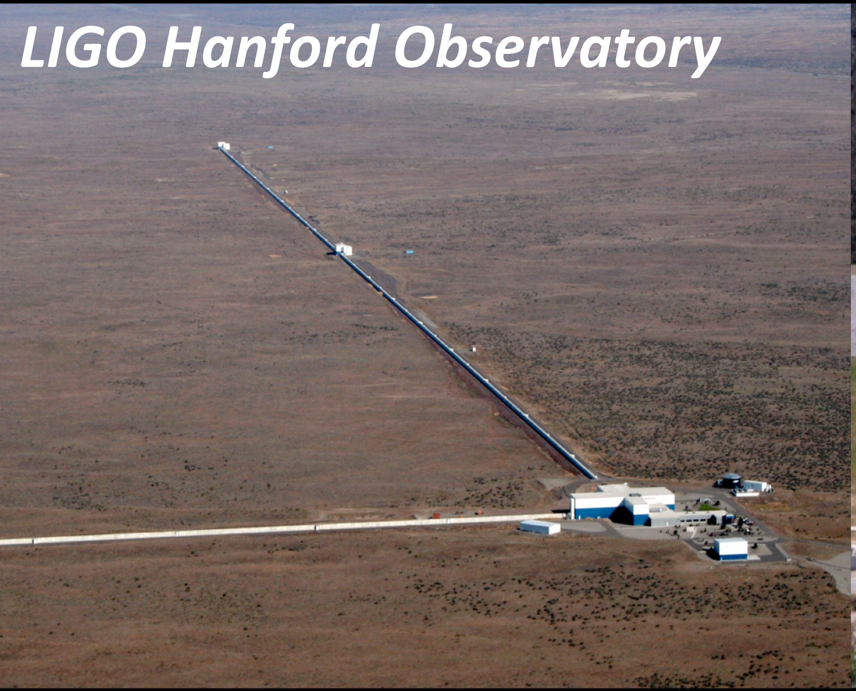
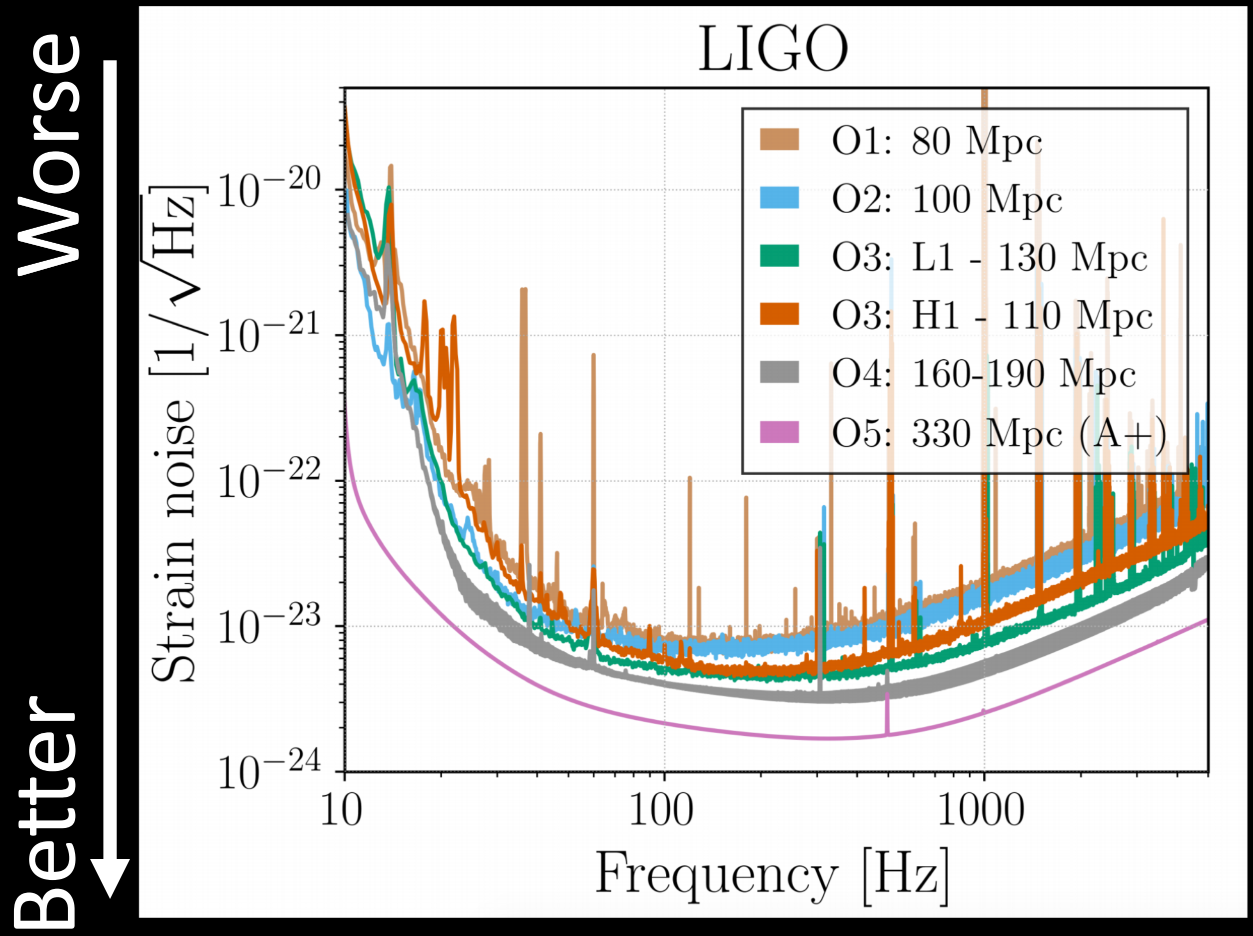
GravWaves at the Moon
Oct 14 2021

Ground based gravitational-wave detectors



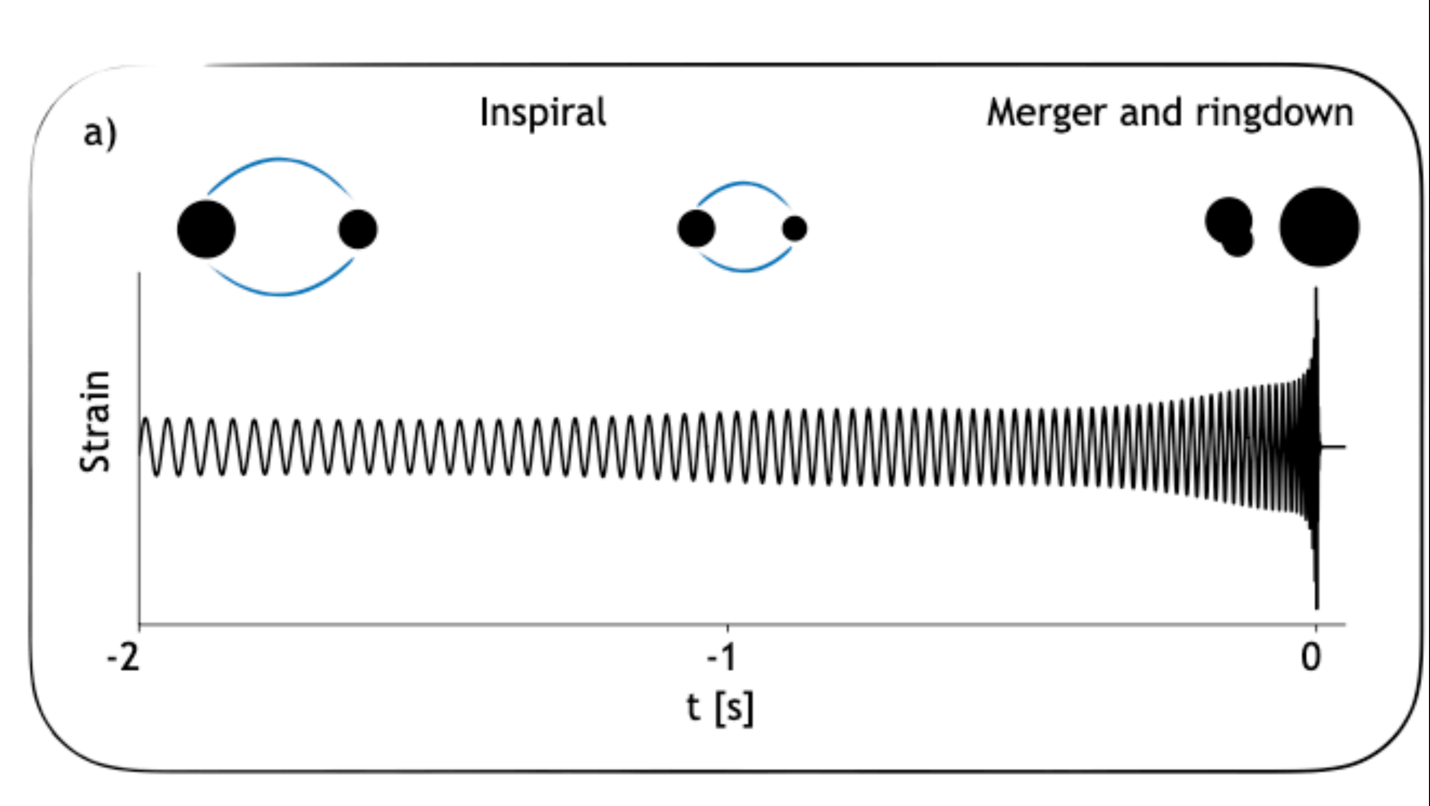
Where are we?



LVC LRR 21 3

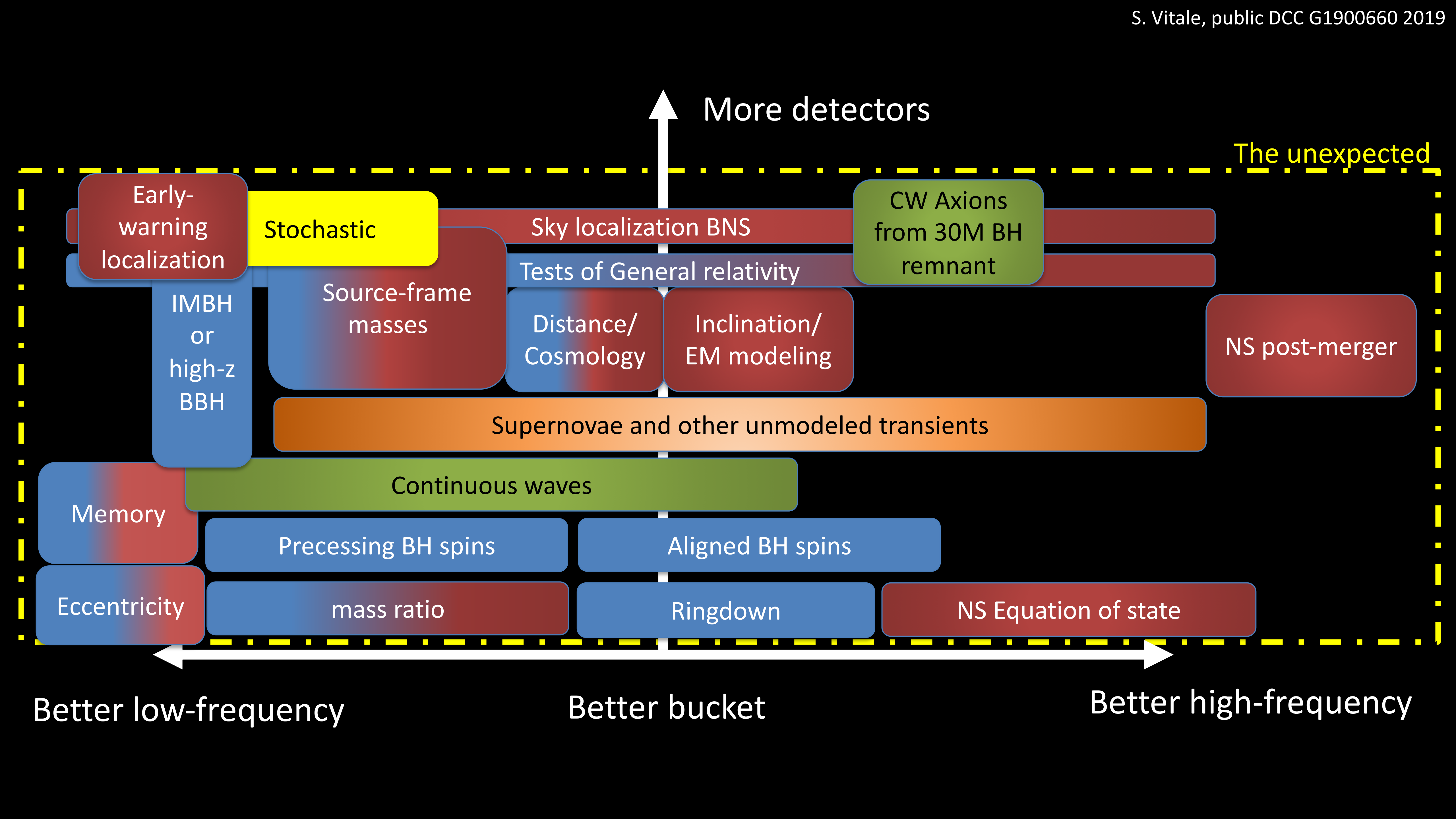
- Advanced LIGO detectors have run since 2015 (with Virgo since 2017)
- Three observing runs
- The third observing run lasted roughly one year

Compact binary anatomy



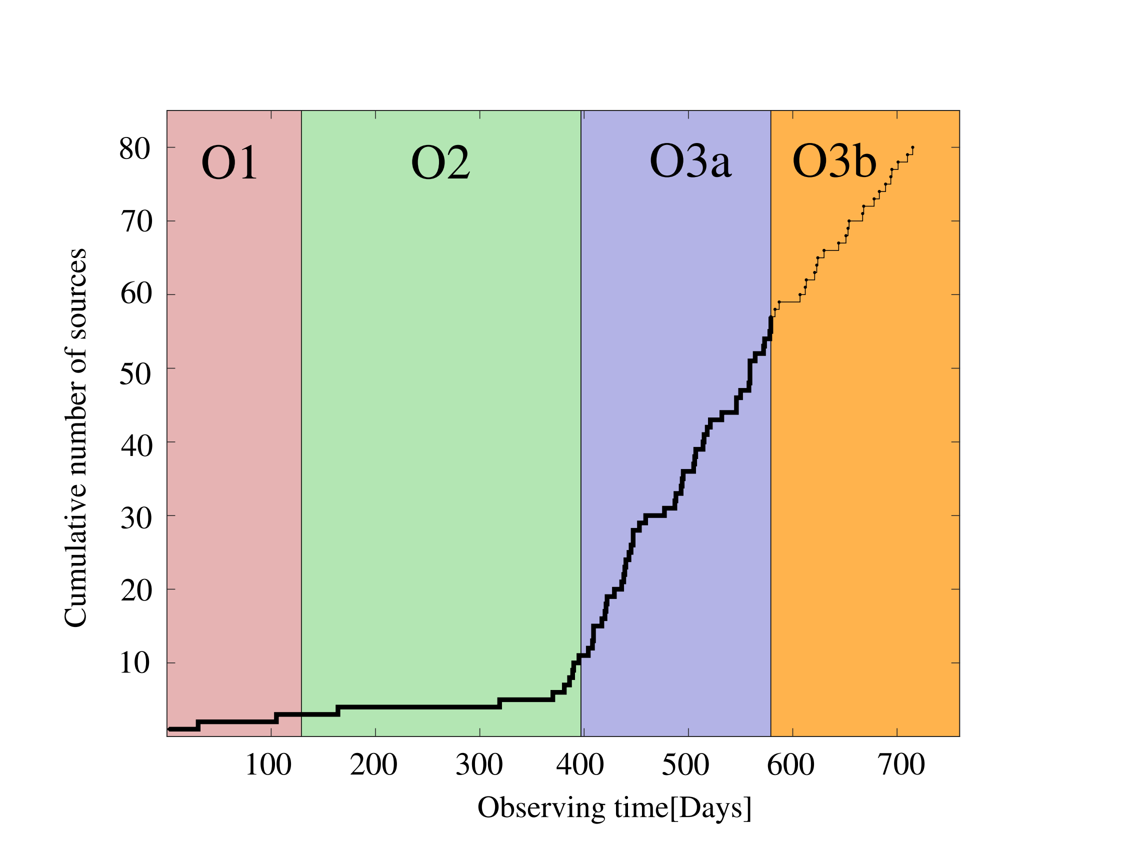
Vitale, Science 372, 6546

- Duration/Merger frequency: total mass, spins
- Phasing: chirp mass, mass ratio, spins
- Overall amplitude: distance, orbital inclination
- Amplitude modulation: spins angles
- Merger-ringdown: nature of the compact objects



S. Vitale, public DCC G1900660 2019
More detectors
The unexpected
Early-warning localization
Stochastic
Sky localization BNS
CW Axions from 30M BH remnant
Tests of General relativity
Source-frame masses
IMBH or high-z BBH
Distance/ Cosmology
Inclination/ EM modeling
NS post-merger
Supernovae and other unmodeled transients
Continuous waves
Memory
Precessing BH spins
Aligned BH spins
Eccentricity
mass ratio
Ringdown
NS Equation of state
Better low-frequency
Better bucket
Better high-frequency

Where are we?

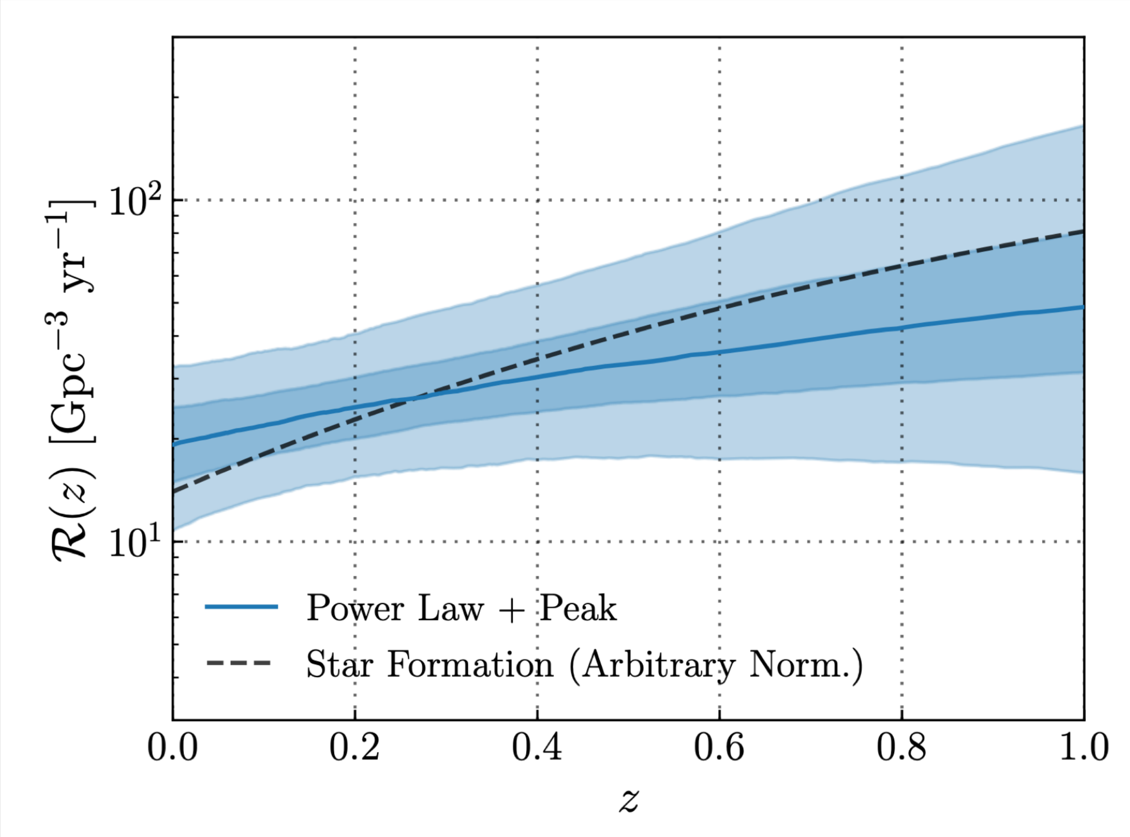


SV, Science 372, 6546, adapted from LVC public document G1901322

- Advanced LIGO detectors have run since 2015 (with Virgo since 2017)
- Three observing runs
- The third observing run lasted roughly one year
  - 56 candidate events made public (one per week!)
  - Two neutron star black hole mergers (LVK 2106.15163)
  - Tens of binary black holes!
  - LVC catalogs paper online: 2010.14527, 2010.14529, 2010.14533

Where are we?

- Even at design sensitivity, current detectors will be limited to
  - Local universe
  - ~100-200 sources (mostly BBH) per year
  - Low to moderate signal-to-noise ratio
  - Limited number of sources with EM counterparts



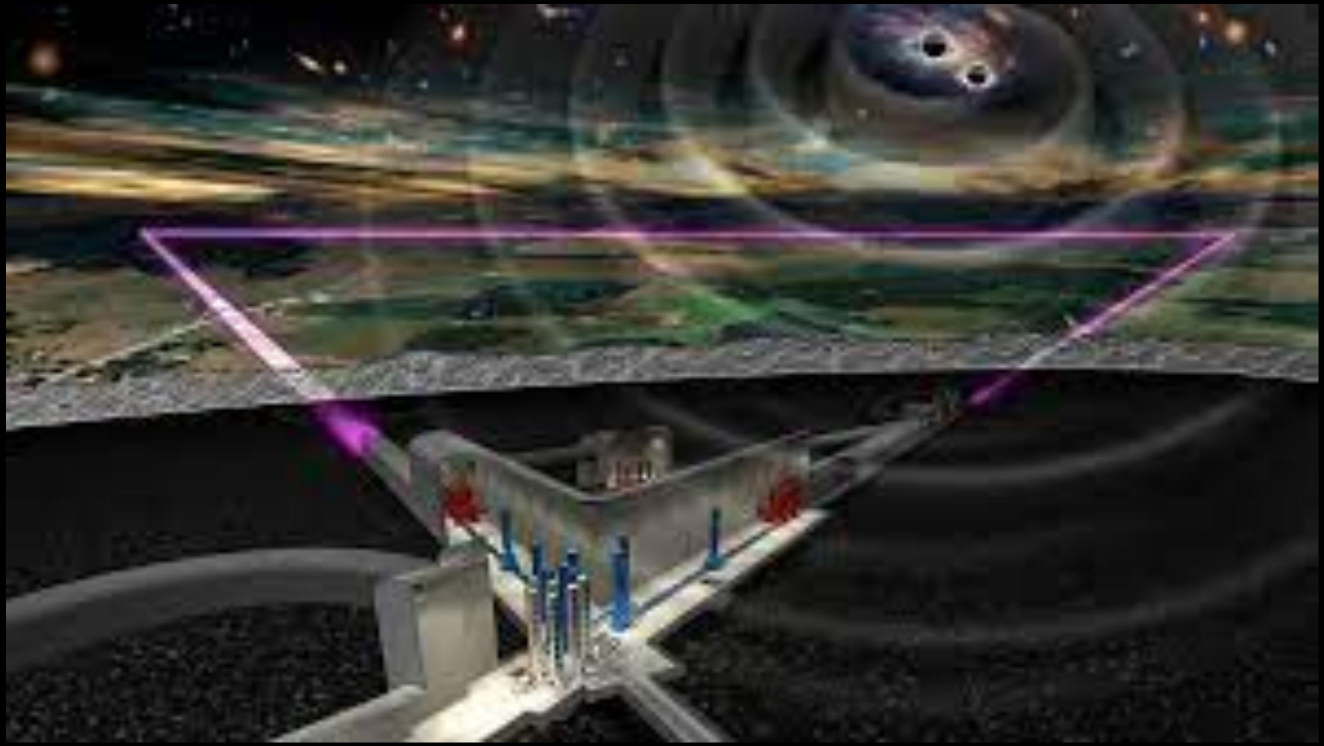
LVK ApJL 913 L7

Third-generation (3G) detectors

- To gain access to sources across the universe new facilities are required
- 3G detectors
  - Strain sensitivity 10x better than advanced detectors
  - Detect black hole binaries at large redshifts
  - High signal-to-noise ratios
  - Many 100K sources per year
- Targeting operation in the second half of 2030s

Einstein Telescope

- A proposed next-generation ground-based gravitational-wave detector
- Triangular-shaped, 10 Km arms
- Underground to access low (~Hz) frequency
- Mature design, design report published in 2011
- Recently included in the European Strategic Forum for Research Infrastructures (ESFRI) roadmap!

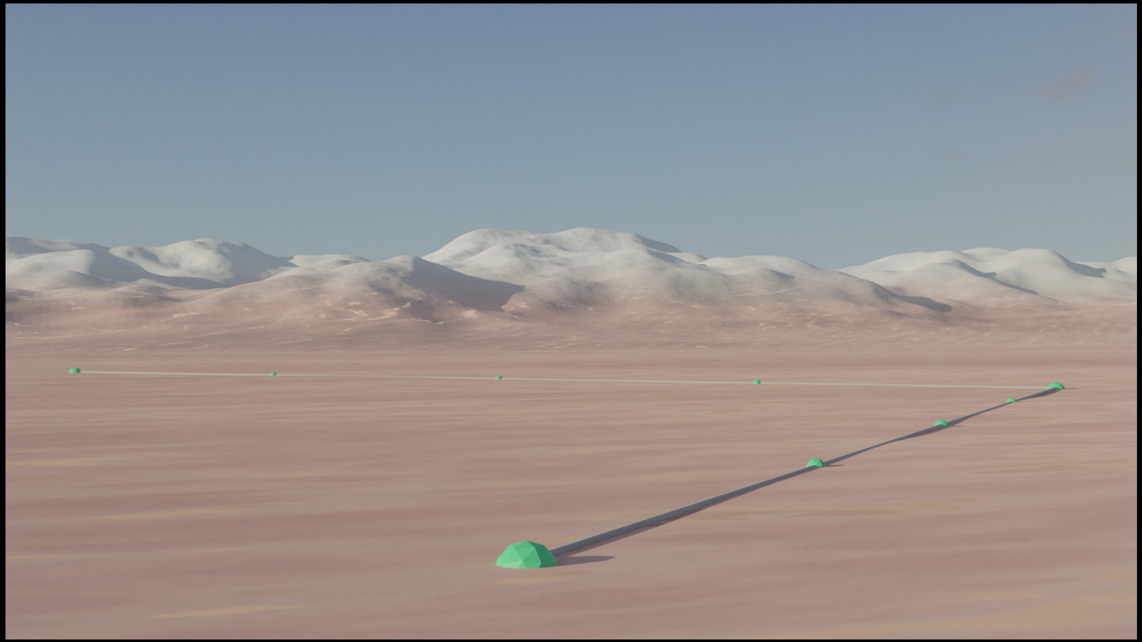


Credit: NIKHEF

Cosmic Explorer

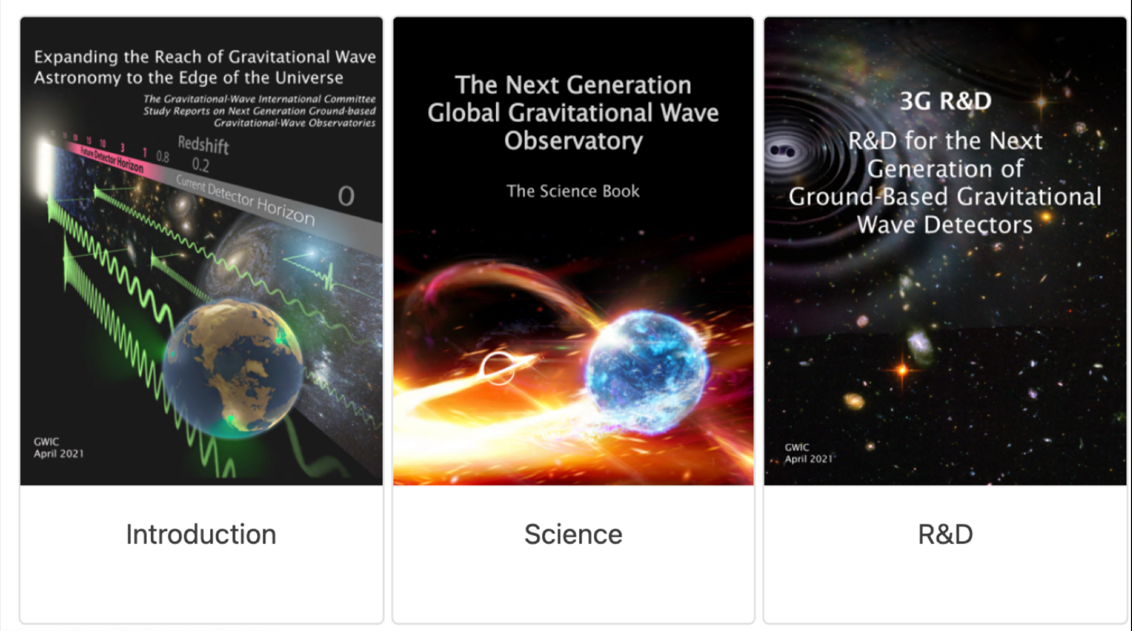
- A proposed next-generation ground-based gravitational-wave detector
- L-shaped like current detectors, but 40Km
- On the ground
- Can be optimized to target high-frequency (KHz) or medium-frequency (100s Hz) sources

Cosmic Explorer Horizon Study (CEHS) 2021



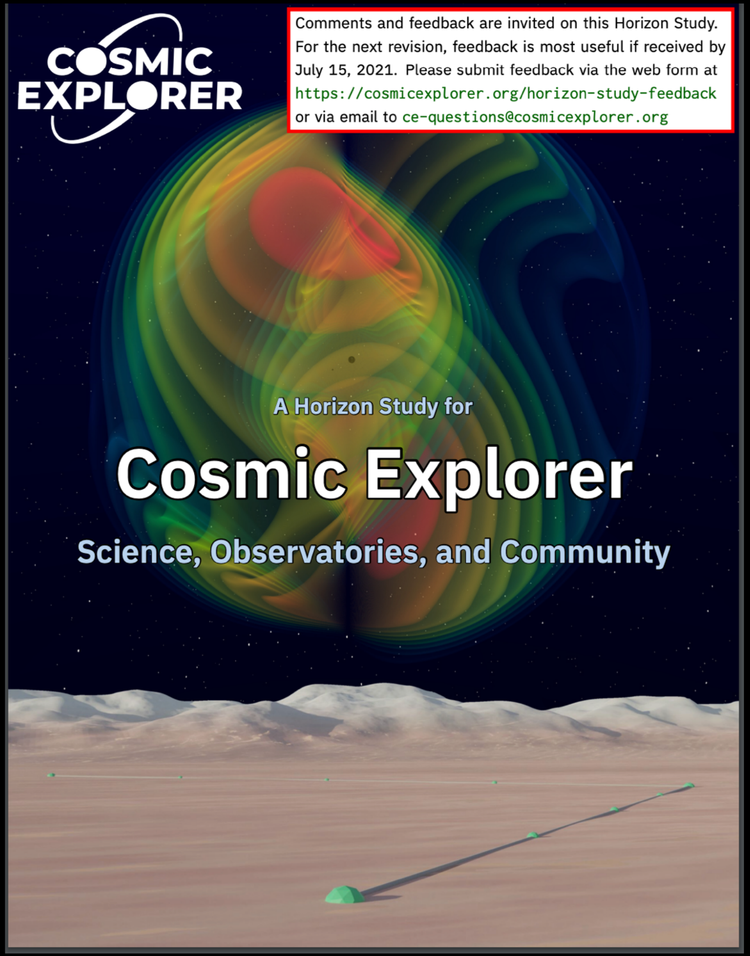
The Gravitational Wave International Committee and 3G

- To get the most out of 3G detectors, a network is required
- The GWIC has formed a committees focusing on 3G R&D, science, and global coordination
- Read more here: gwic.ligo.org/3Gsubcomm/
- Dozens of useful documents and links (includes Cosmic Explorer Horizon Study, Einstein Telescope Design report)



Cosmic Explorer Horizon Study

- NSF funded an Horizon Study (CEHS) to explore design options and scientific potential of ground-based next-generation detectors in the US
- The final draft can be read at https://cosmicexplorer.org/

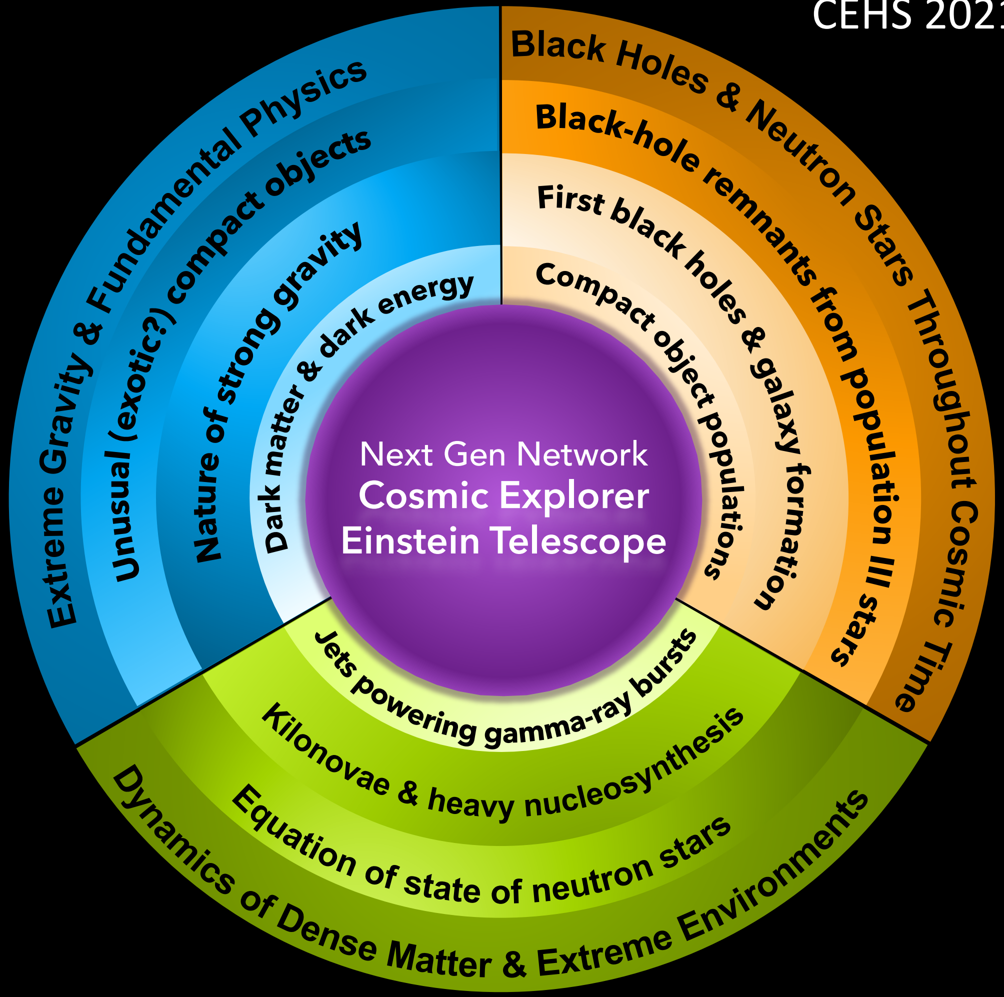


CEHS 2021

Cosmic Explorer Horizon Study

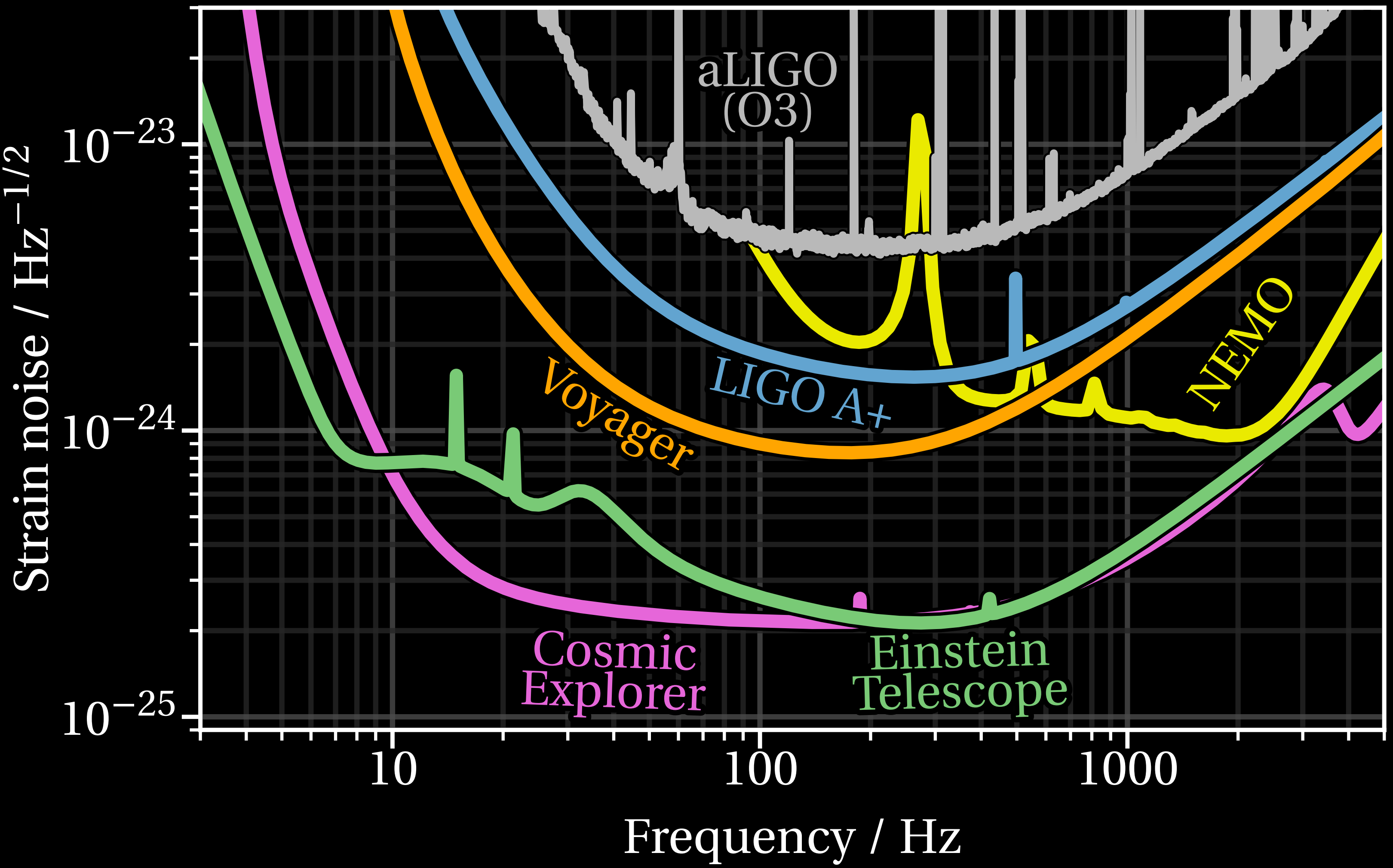
- The CE HS identifies key science outcomes that can be reached with 3G detectors
  - Black holes and neutron stars throughough cosmic time
  - Dynamics of dense matter & extreme environments
  - Extreme gravity & Fundamental Physics

CEHS 2021

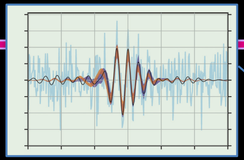


Detector sensitivity

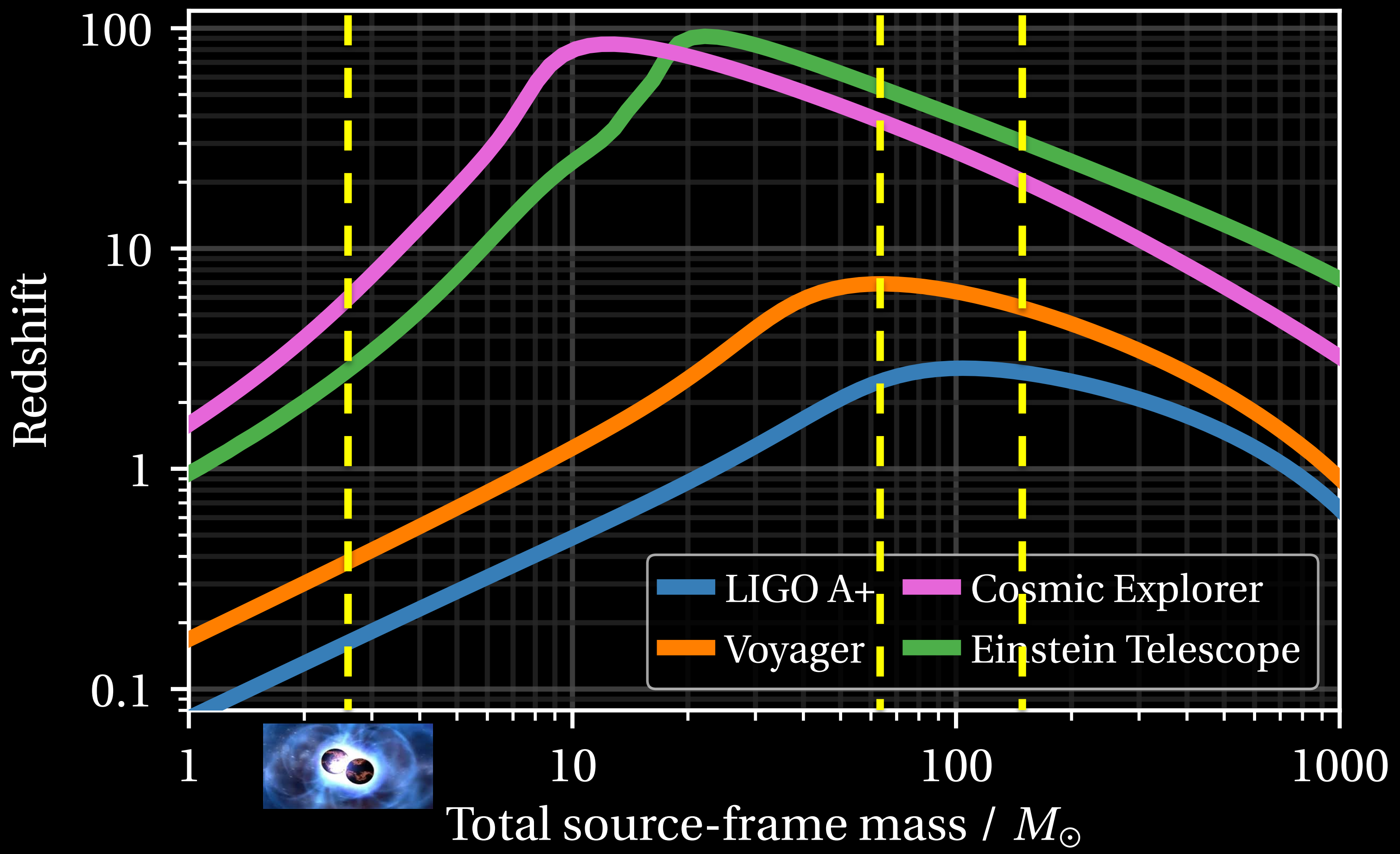
CEHS 2021



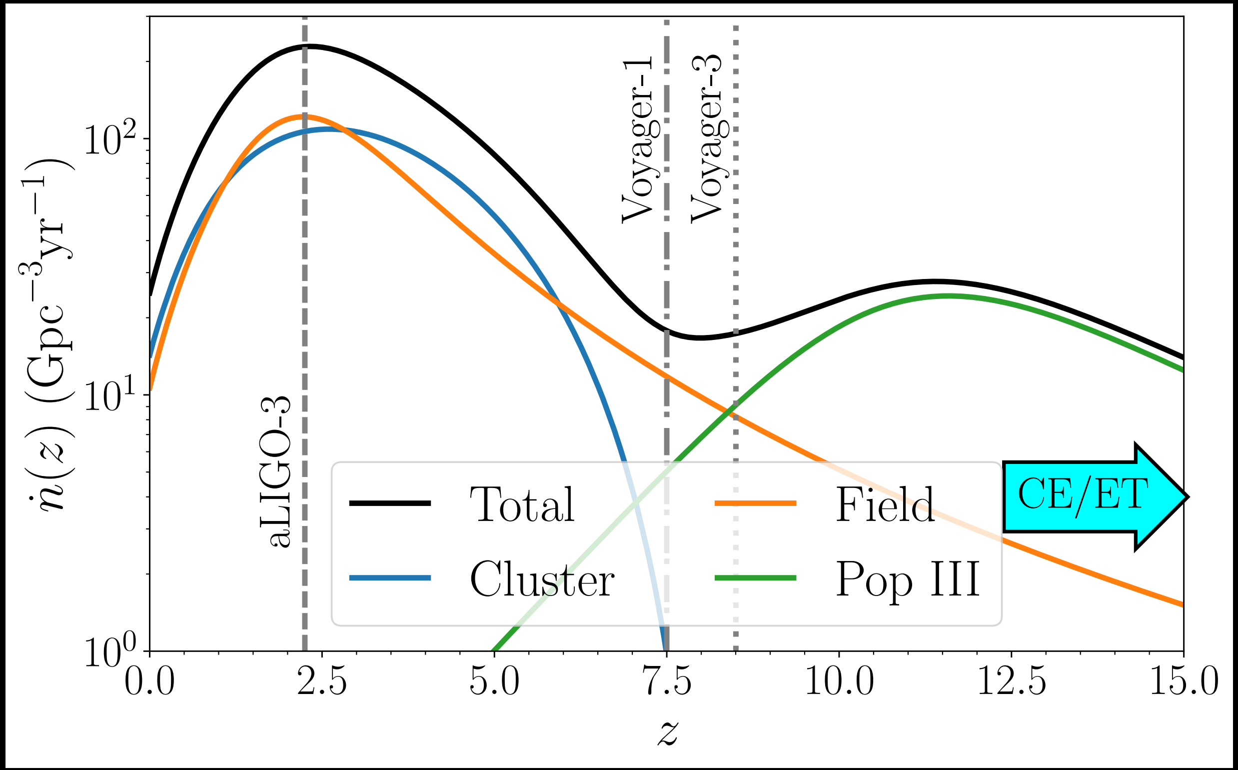
Listening to the Universe



CEHS 2021



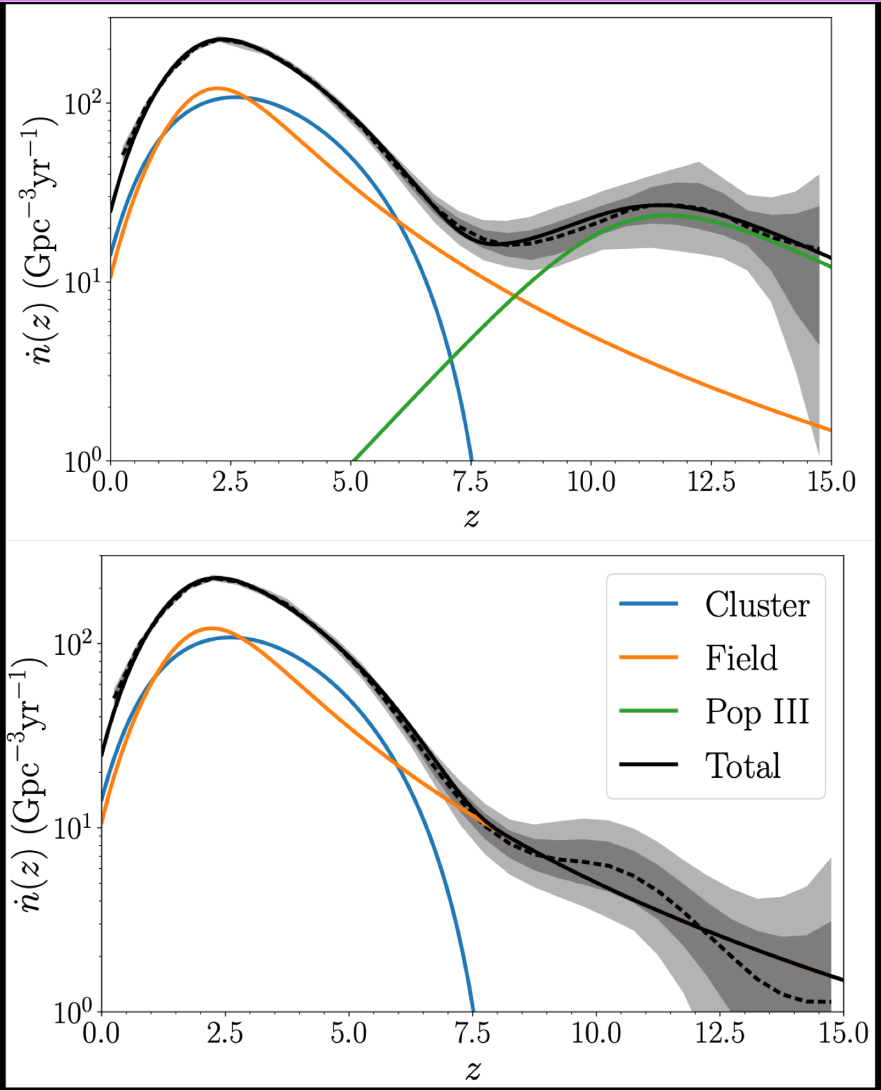
Populations of binaries



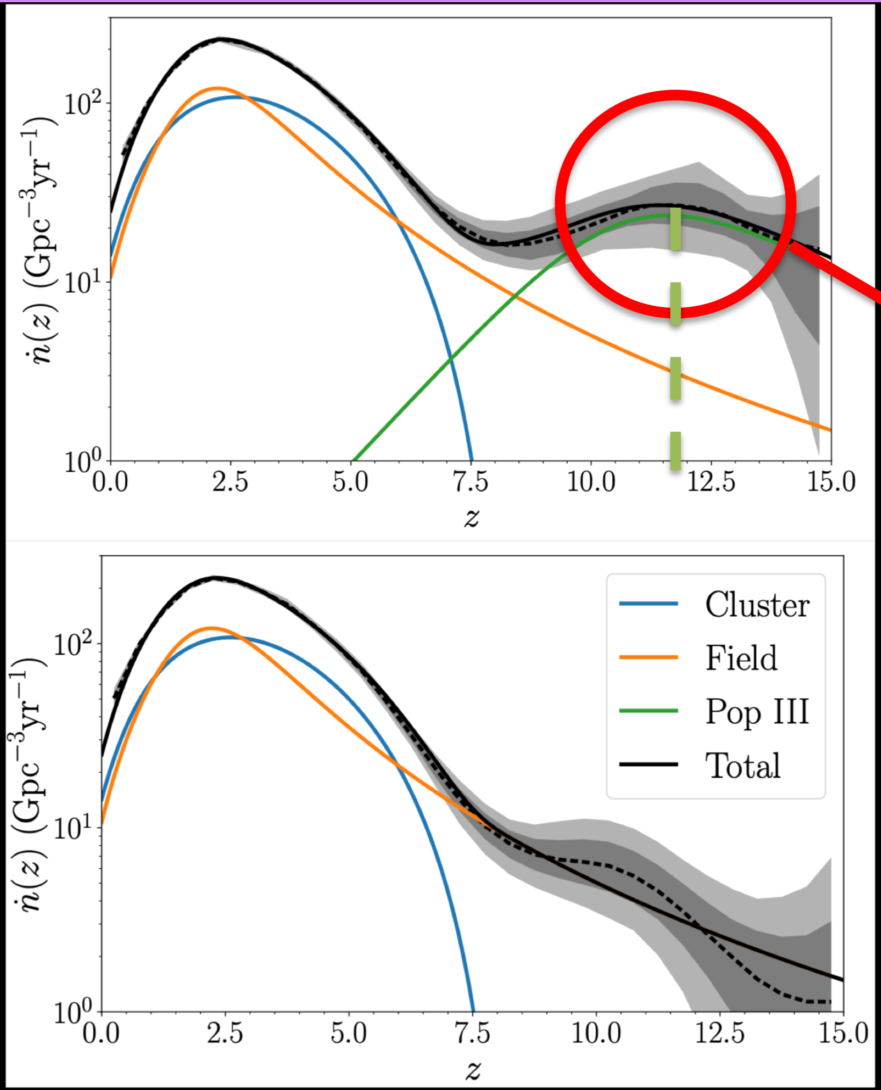
Ng+ ApJL 913 L5

- Can detect black holes from populations which are currently unaccessible
- It is important to have a network, to measure distance well, and hence source-frame mass

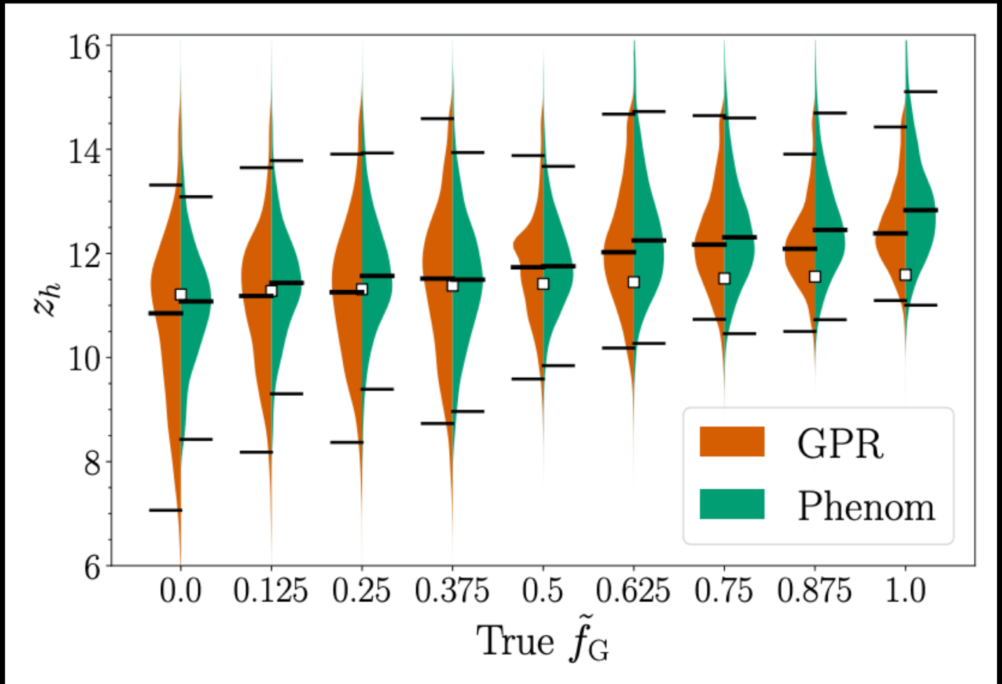
Detecting Pop III BH mergers



Detecting Pop III BH mergers



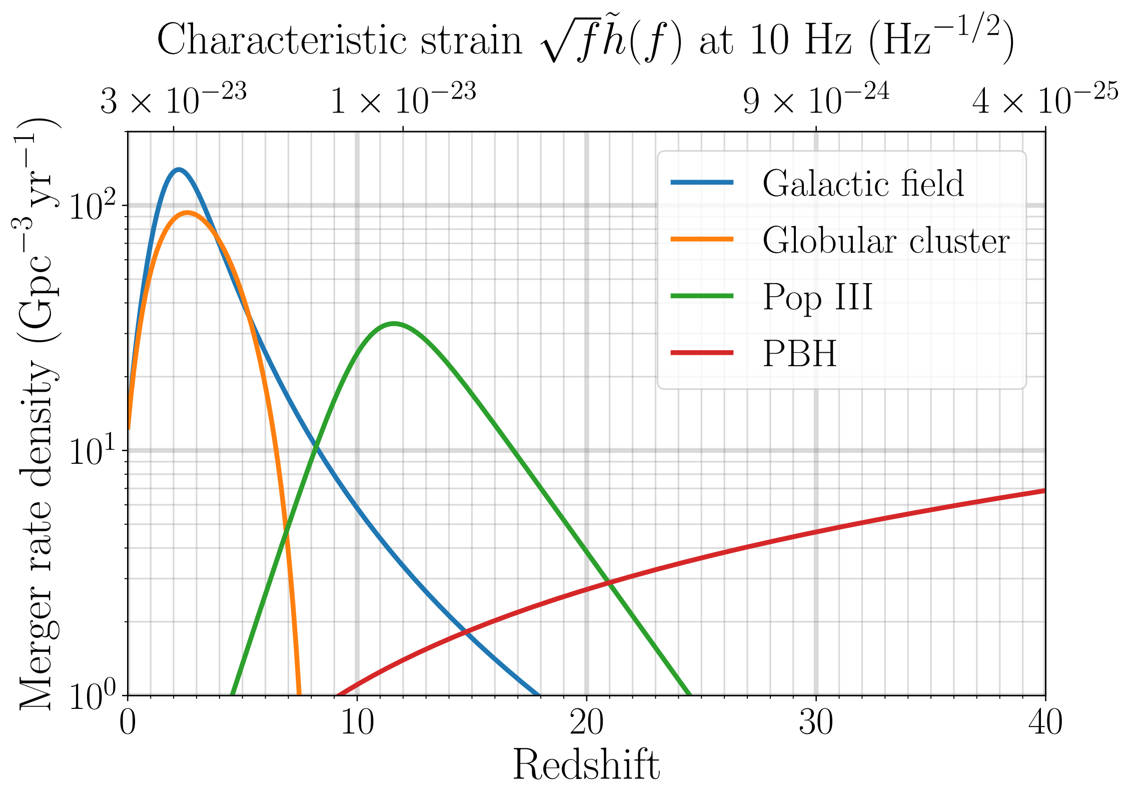
Can measure the location of high-z peak with a few months worth of data and no modeling!



Ng+ ApJL 913 L5

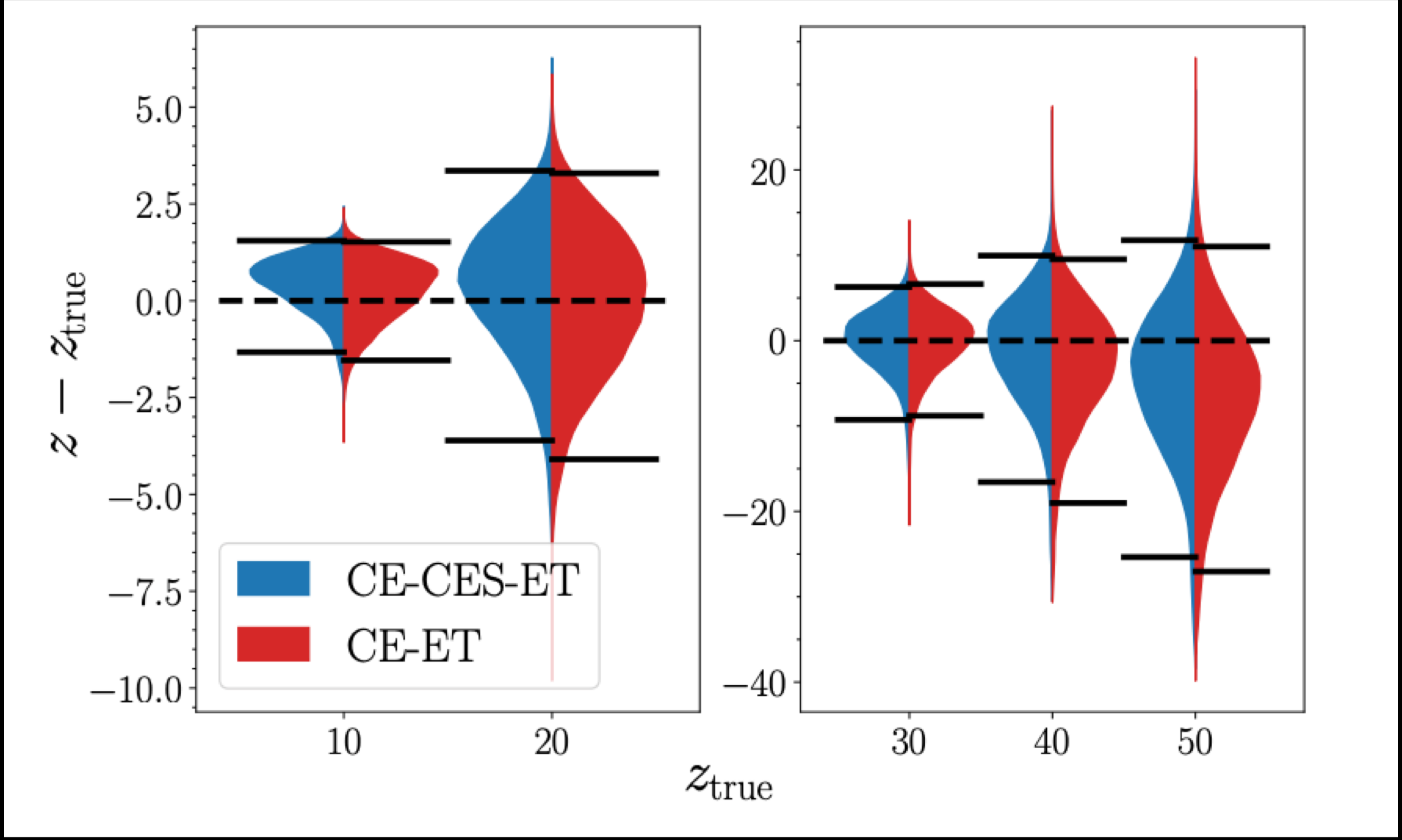
Detecting PBHs mergers

- Primordial black holes mergers might be recognizable because of
  - Mass and spins spectrum
  - Eccentricity at merger
  - Extemely high redshift
- Of these, the high redshift seems like the most uncontroversial tracer



CEHS 2021

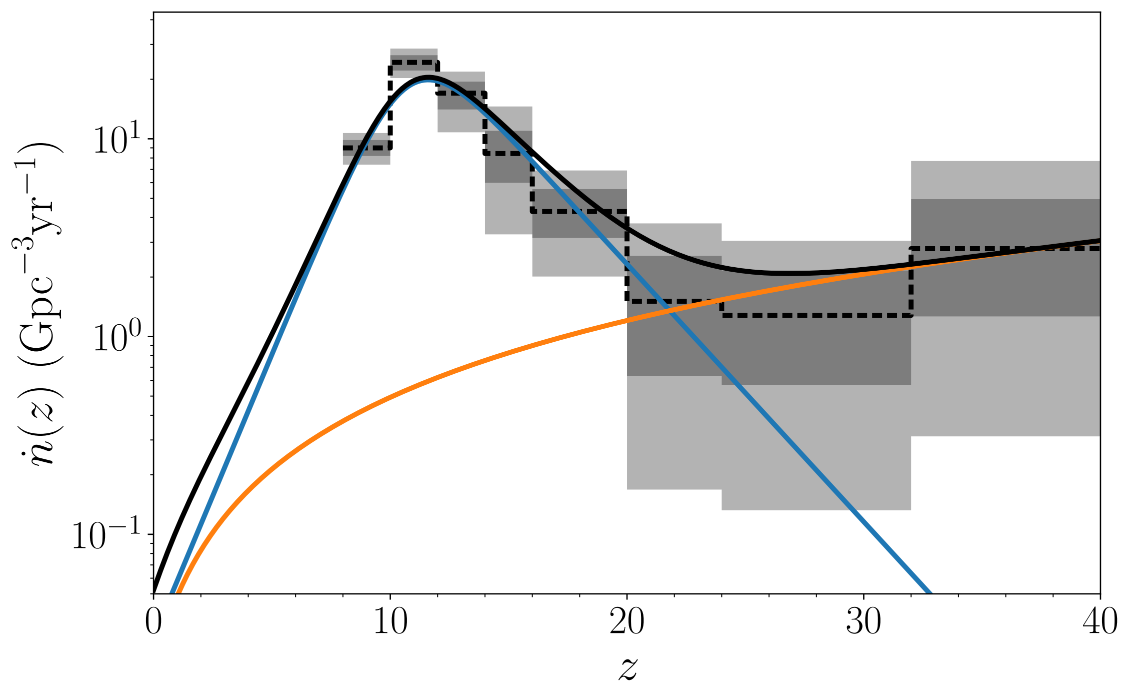
Pinning down a single PBH



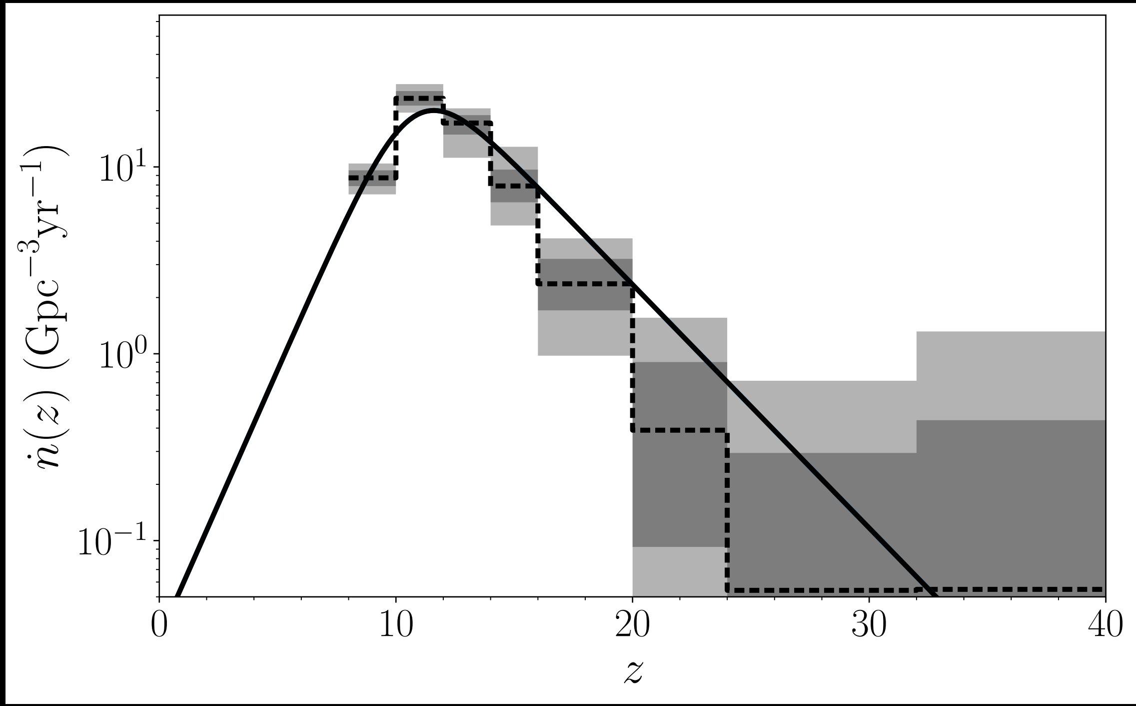
Ng+, 2108.07276

Detecting PBHs mergers

$N_{PBH} = 1/8\ N_{Pop\ III}$



$N_{PBH} = 0$

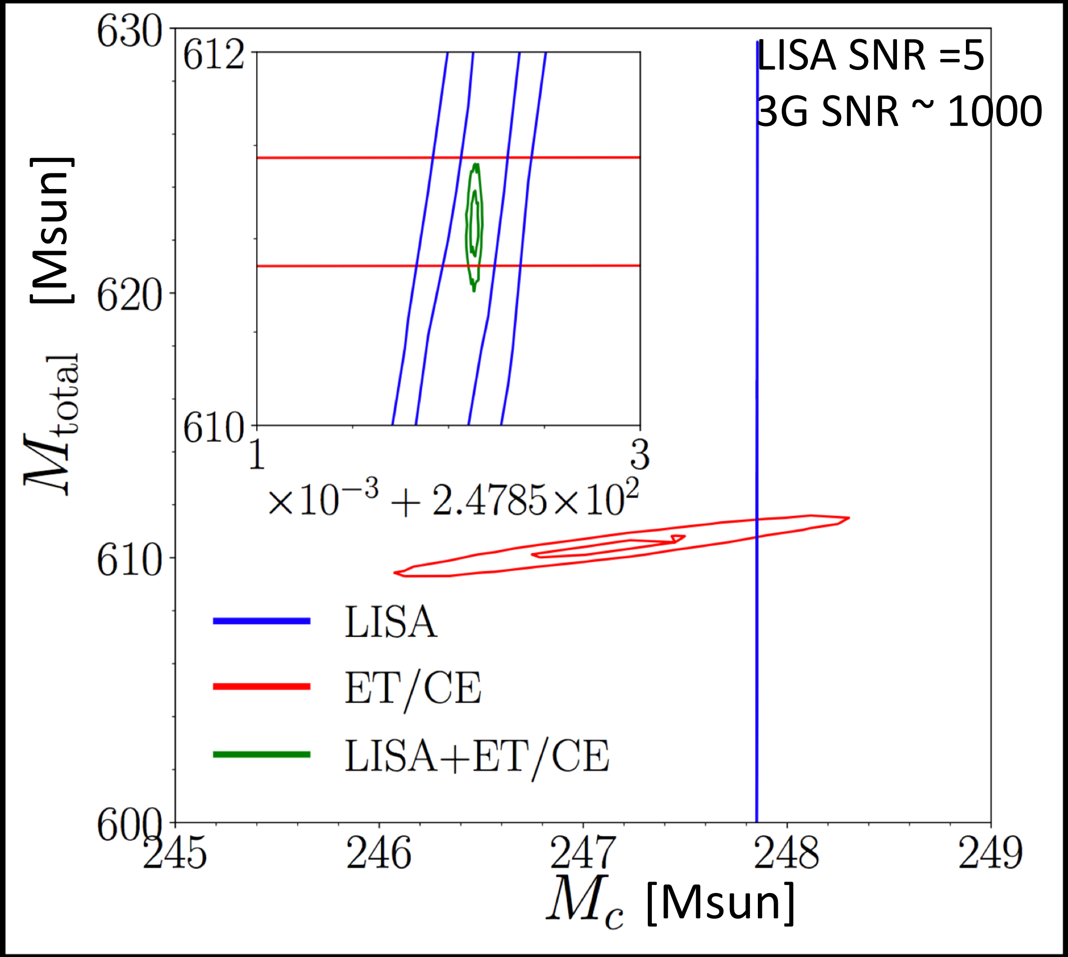


Ng+ in prep

Multibanding

- LISA can observe heavy BBH and intermediate-mass BBH
- Some of those signals will also be visible from the ground (years later)
- Complementary information! (Sesana PRL 116, 231102; Vitale PRL 117, 051102; Barausse+ PRL 116, 241104)
- For nearby IMBH, LISA might provide Mchirp info, but not for z>~0.3

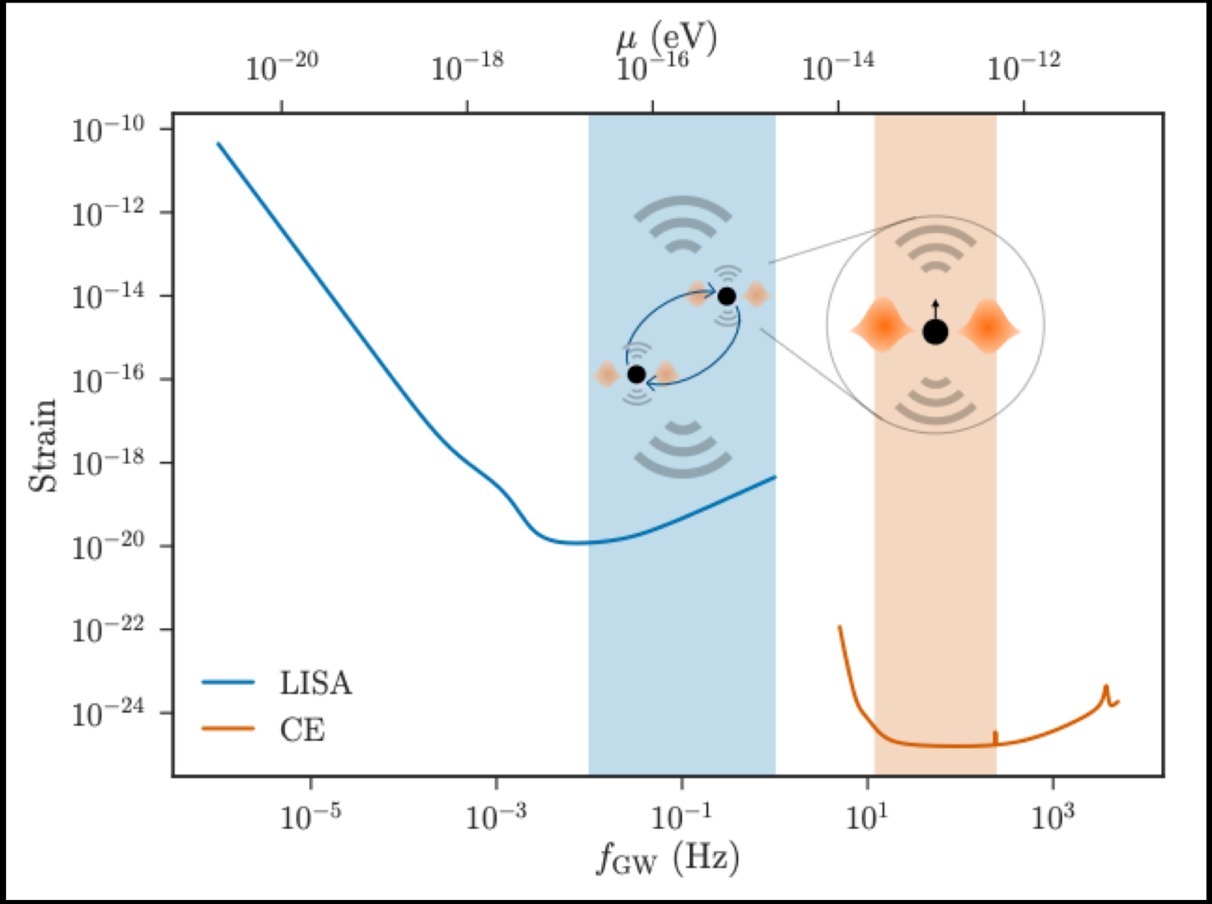
Cutler+, 1903.04069



Multibanding

Ng+ PRD 102, 083020

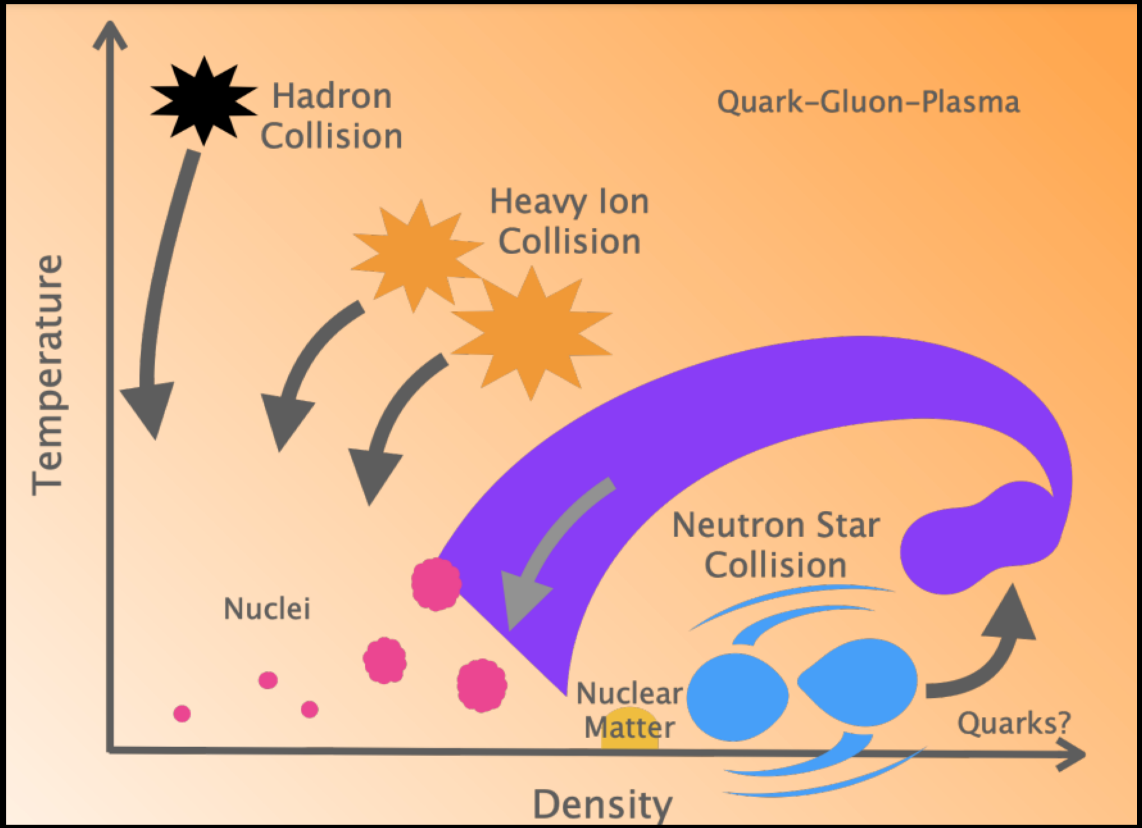
- Black holes will form clouds of ultralight bosons (if such particles exist)
  - The bosons cloud emits nearly monochromatic GWs
- LISA could detect the GWs from the inspiral while 3G detectors could *simultaneously* detect the GWs from the axion clouds



Neutron star physics

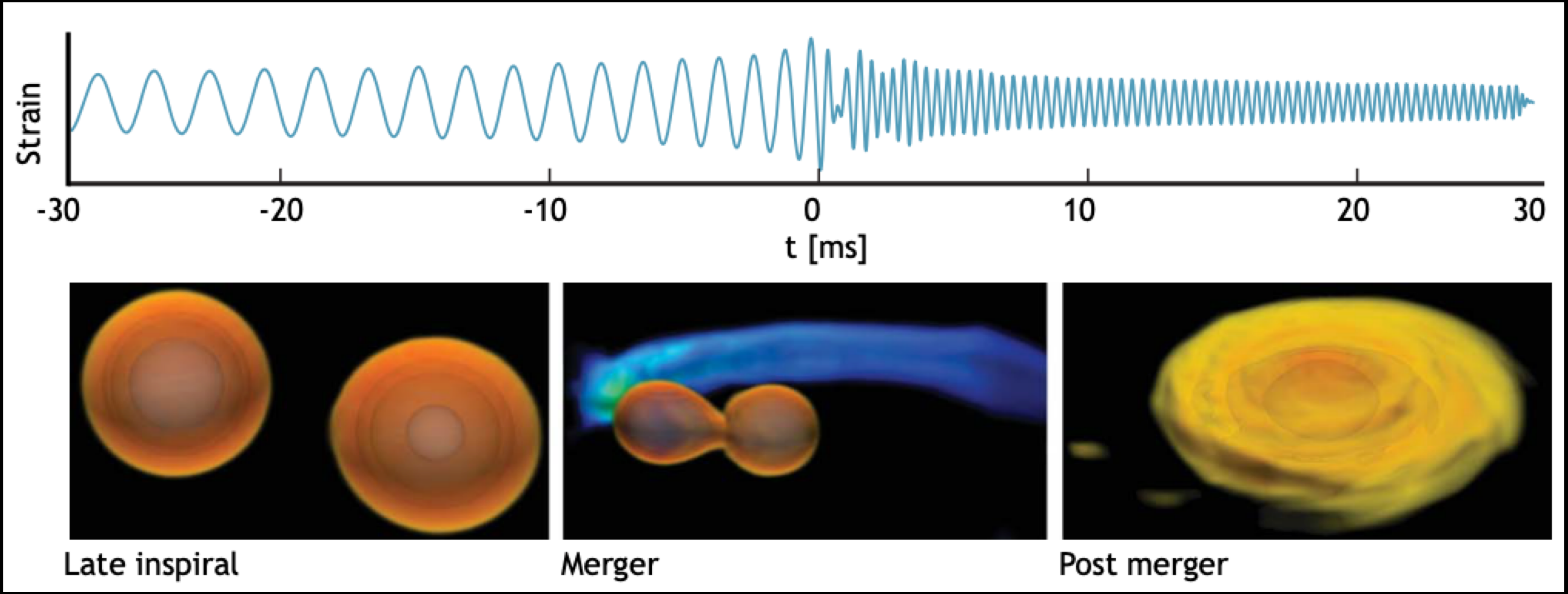
CEHS 2021

- Matter in neutron stars experiences the most extreme conditions in the visible universe
- Can explore regions of the QCD phase diagram which are not accessible at Earth
  - Determine internal structure of neutron star
  - Equation of state



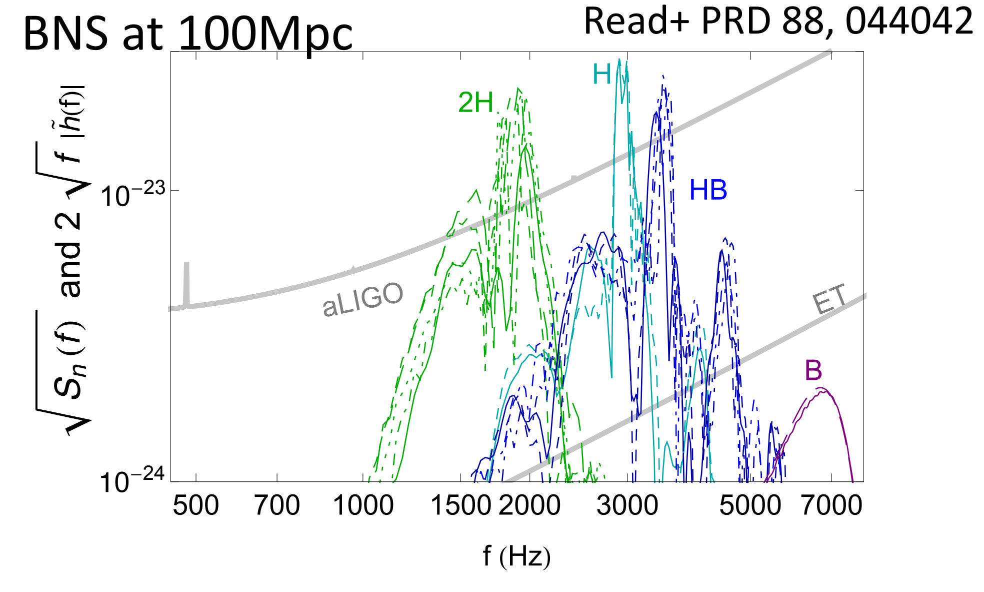
Binary neutron stars

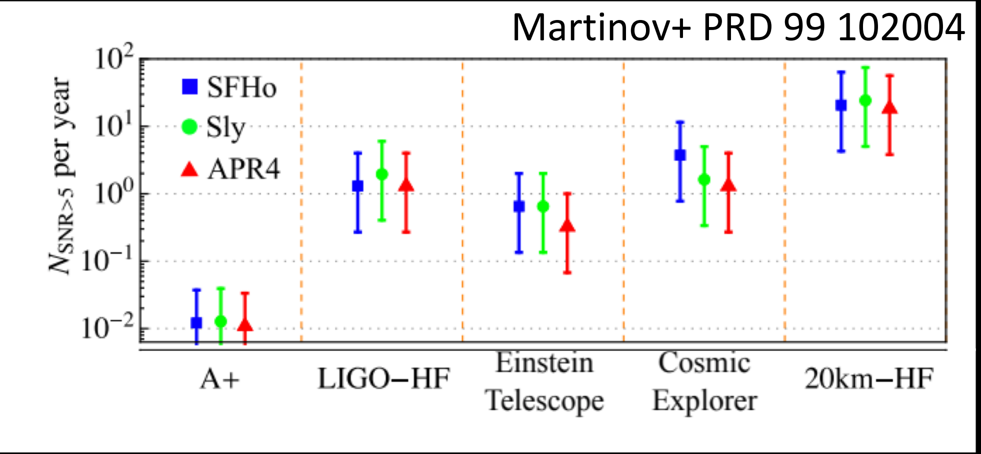
Credit: T. Dietrich



Binary neutron stars - Equation of state

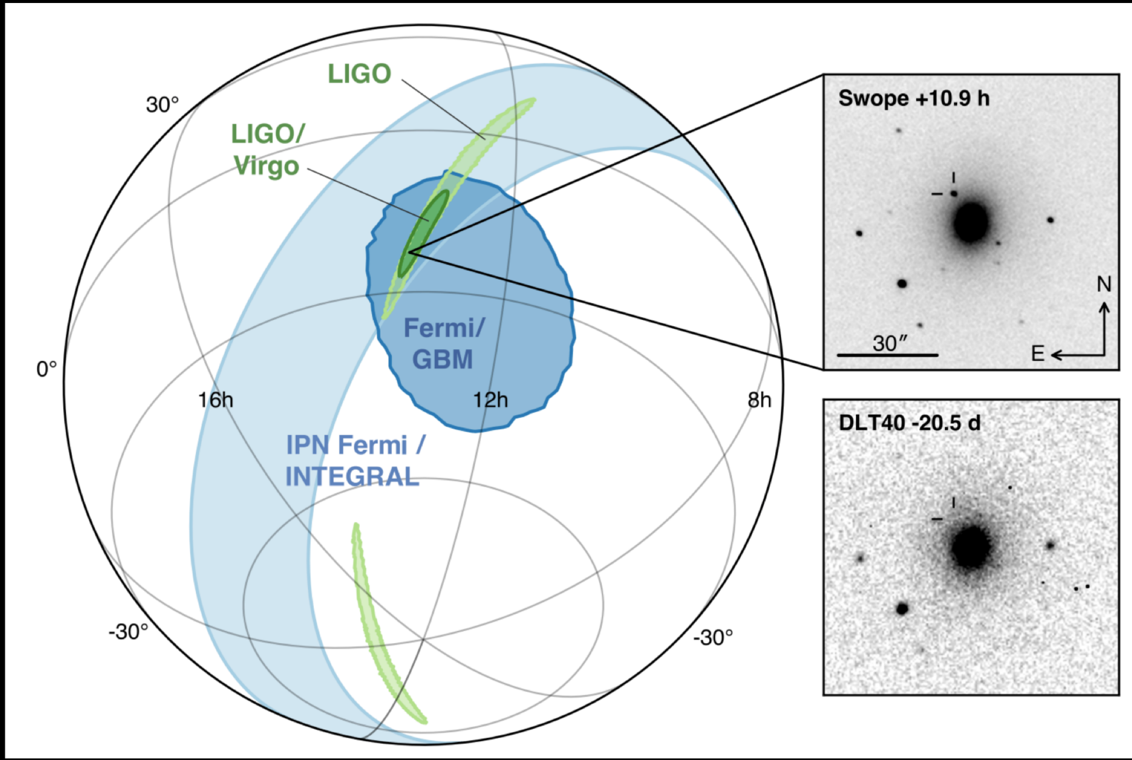
- Advanced detectors will start measuring the equation of state of neutron stars
  - Most likely from the inspiral phase
  - With a bit of luck, hints of postmerger physics
- 3G detectors will easily measure the EOS from both inspiral and post-inspiral





Multimessenger astrophysics - now

- The binary neutron star GW170817 was detected both in the GW and electromagnetic (EM) band
  - Detection at all frequencies, from gamma rays to radio waves
  - Proved BNS are progenitors of (at least some) short gamma ray bursts
  - Proved BNS produce kilonovae emission, and heavy metals
  - Allowed for a measurement of the local Hubble parameter (LVC Nature 551, 85–88)

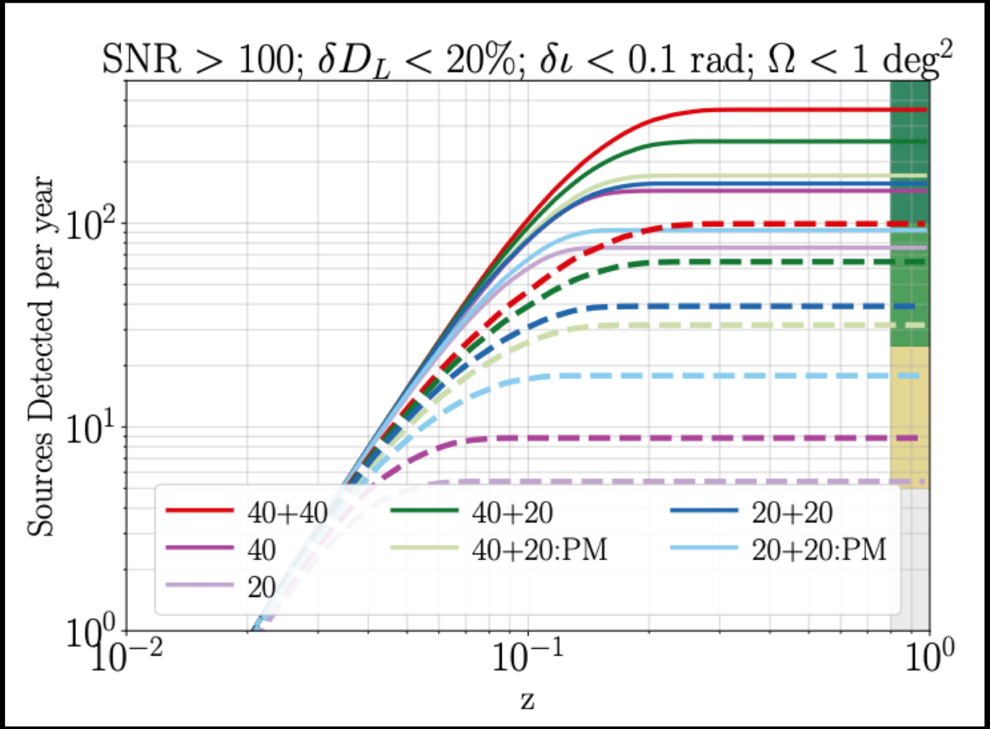


LVC and friends, ApJL, 848:L12, 2017

Multimessenger astrophysics - 3G

- With a network of 3G detectors we will be able to access hundreds of well-characterized BNSs per year
  - For many of them, the source can be localized even *before* the merger happens
  - Variety of system parameters, their effect on the EM emission and its energetics

CEHS 2021



Conclusions

- Advanced detectors will explore the local universe (z ~ 1)
- A new generation is required to detect sources everywhere in the universe
  - Characterization of BH masses and spins, formation channels, evolution,…
  - Thousands of neutron stars, EOS, cosmology,...
  - Precise tests of general relativity
  - Access to sources throughout cosmic history
- Get involved! Numerous opportunities to play role in CE and ET