ET-OSB-Div5: Synergies with other GW observatories: 2G+ detectors, Cosmic Explorer, LISA, TianQin, PTA

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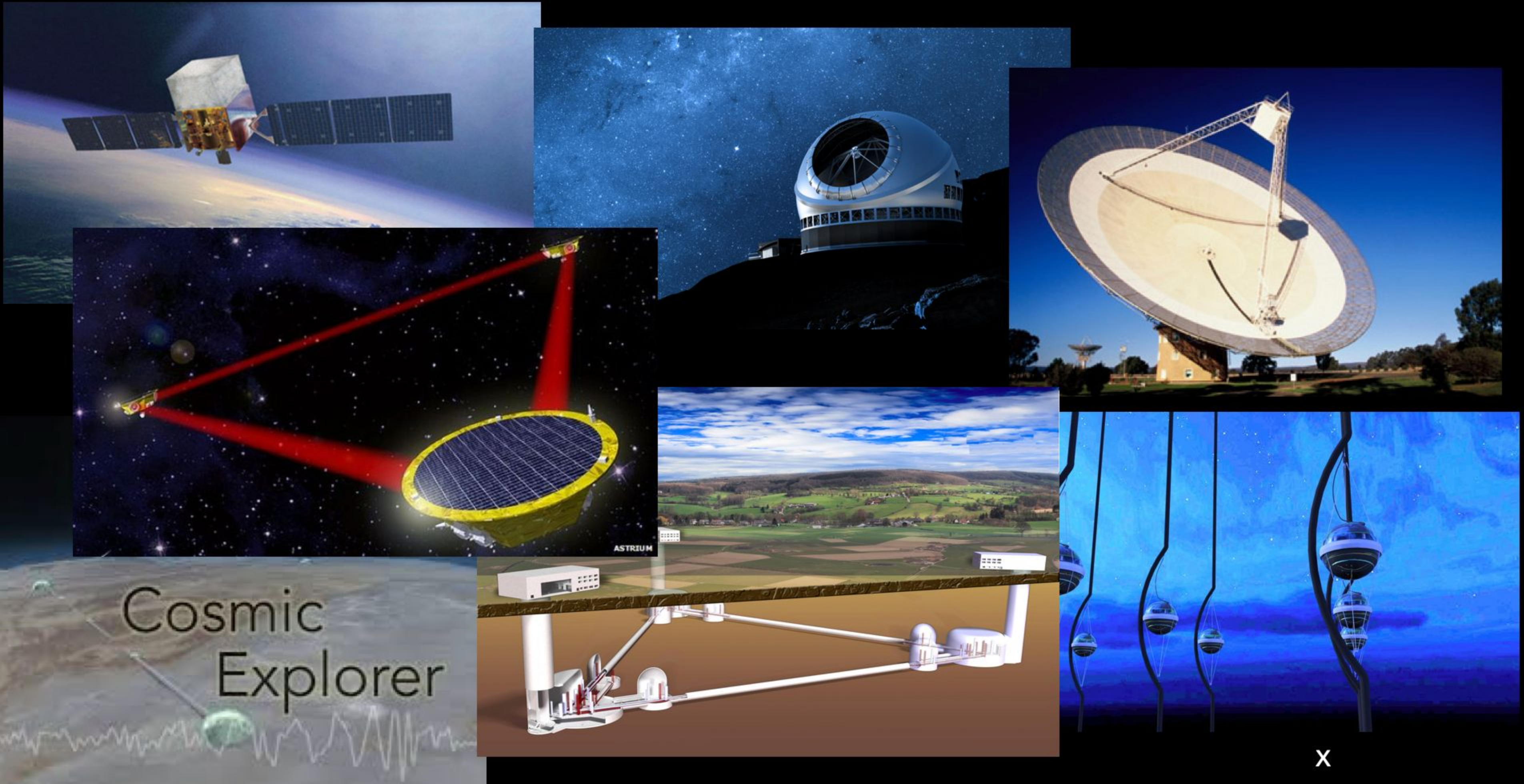
MULTIMESSENGER SCIENCE



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Plan of the presentation

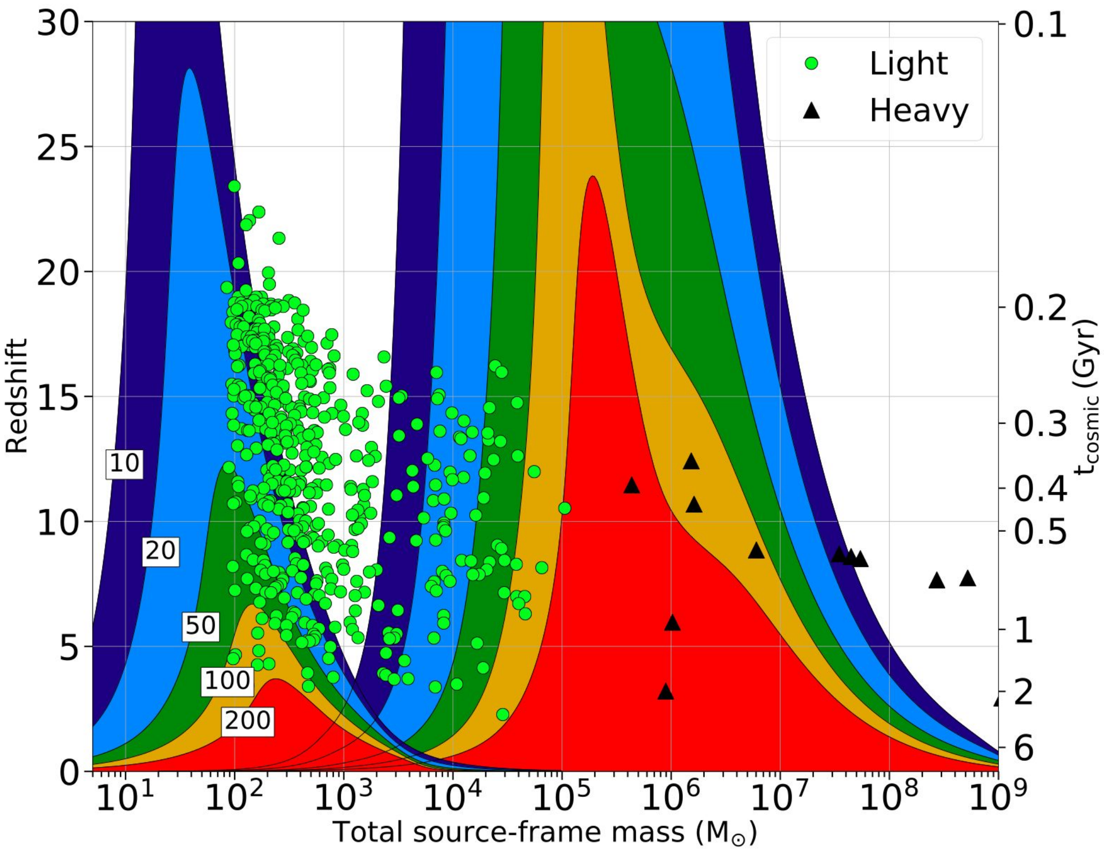
- **Facilities and their relevance**
  - Cosmic Explorer
  - LISA, TianQin
  - PTA, CMB

- **Work packages**
  - Fundamental Physics, Tests of GR and Dark Matter
  - Nuclear Physics, QCD phase transitions, Hot and Cold EOS of Neutron Stars, Kilonova and GRB Central Engine
  - Early Universe Cosmology and subtraction of foregrounds
  - Seed Black Holes, Hierarchical Mergers

Multiband observations and science

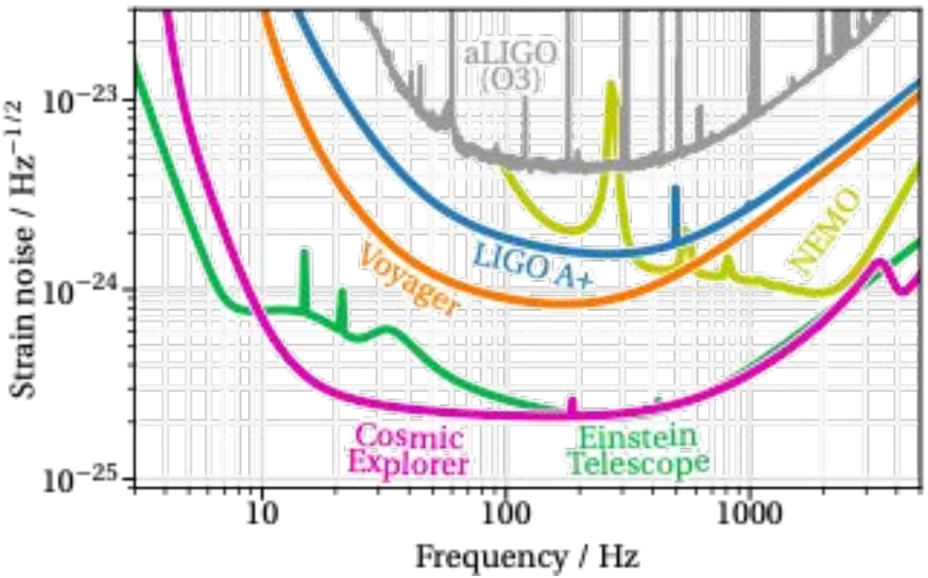
- Ultra-low frequency: Cosmic Microwave Background
  - Is the background (not) found in ET consistent with the CMB?
  - What are the implications of primordial backgrounds in ET on the index of fluctuation spectrum?
- Very-low frequency: Pulsar Timing Arrays
  - Seed black holes and their growth – connection between intermediate black holes and supermassive black holes
  - Tests of General Relativity – what do tests of GR carried out in the nano-Hertz range imply for tests of GR carried out in the kilohertz range
- Low-frequency: Laser Interferometer Space Antenna, TianQin, ...
  - Questions as in PTA plus: How can we improve tests of GR with multiband observations of sources
  - Implications on astrophysical models of observing sources with eccentricity, background
- Synergies with other observatories in the audio band
  - Cosmic Explorer, NEMO, 2G+ observatories operating in 2030s

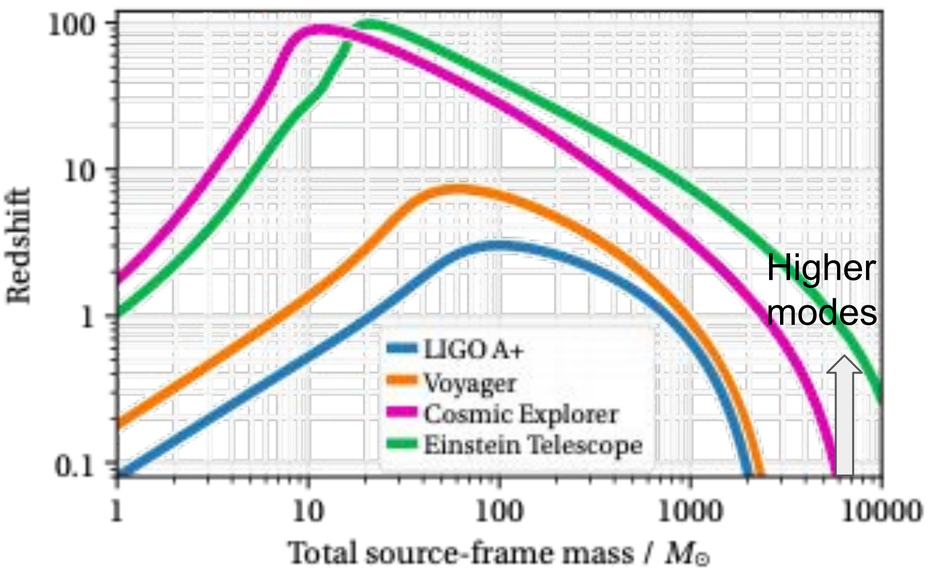
Complementarity of ET+LISA



GWIC-3G Science Book

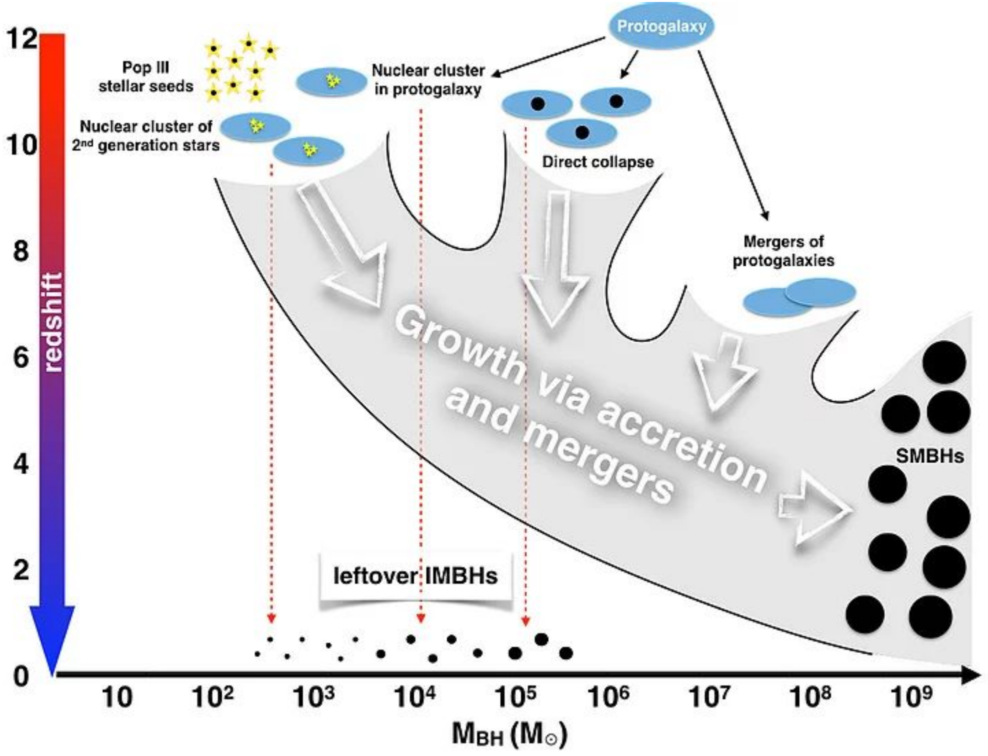
Complementarity of ET+Cosmic Explorer





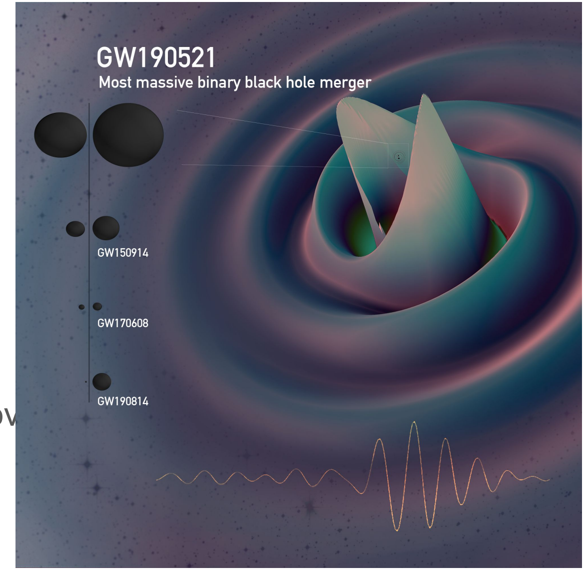
Cosmic Explorer Horizon Study Document

Seed black holes and Hierarchical Mergers: PTA, LISA, TianQin, Einstein Telescope, Cosmic Explorer



Credit: Mezcua (2017), International Journal of Modern Physics D, vol. 26, No 11.

GW190521 - Observation of the birth of an IMBH



GW signal is consistent with a BBH merger source, with total mass of 150 $M_{\odot}$.

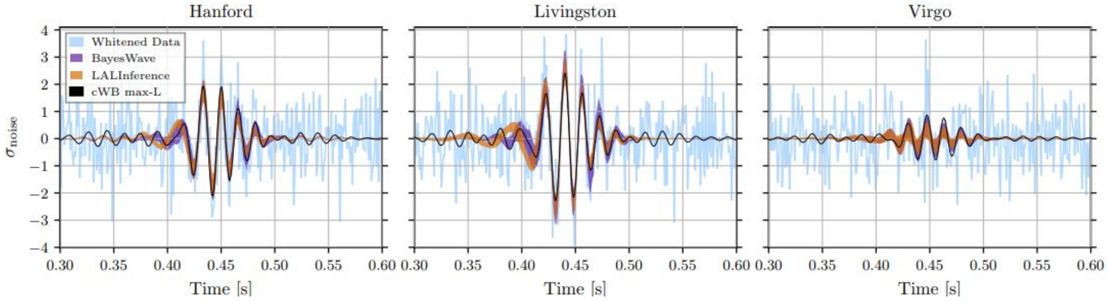
M1 ~ 85 $M_{\odot}$, M2 ~ 66 $M_{\odot}$, M_{final} ~ 142 $M_{\odot}$

5.3 Gpc, z ~ 0.82; age of universe was 6.7 Gyr

The final merged (remnant) black hole is an Intermediate Mass Black Hole (IMBH).

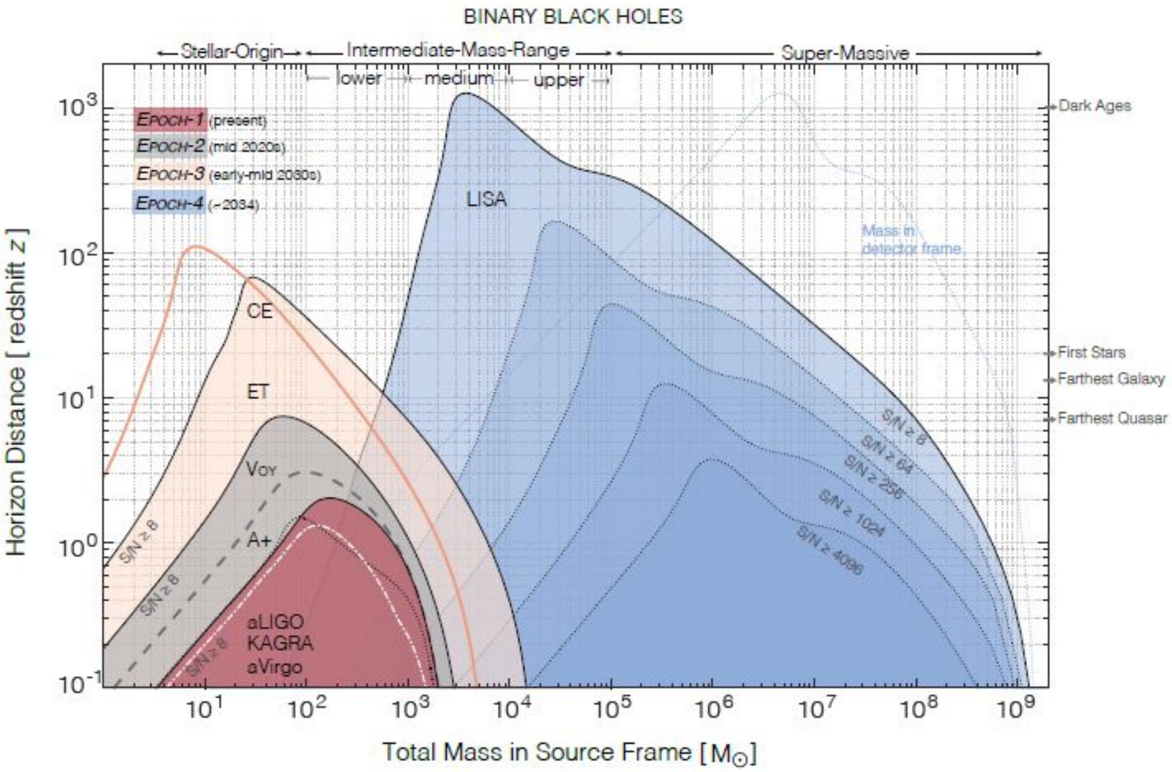
The more massive of the two BHs in binary is ~ 85 $M_{\odot}$,in the Pair Instability Supernov mass gap.

It may itself be the result of a previous BBH merger.



Detectability of IMBHs

Gravitational wave detectors will map out binary black hole systems as a function of redshift.



Jani, Shoemaker, Cutler. Nature Astron 2019

IMBH: Bridge from Stellar Mass to SMBH

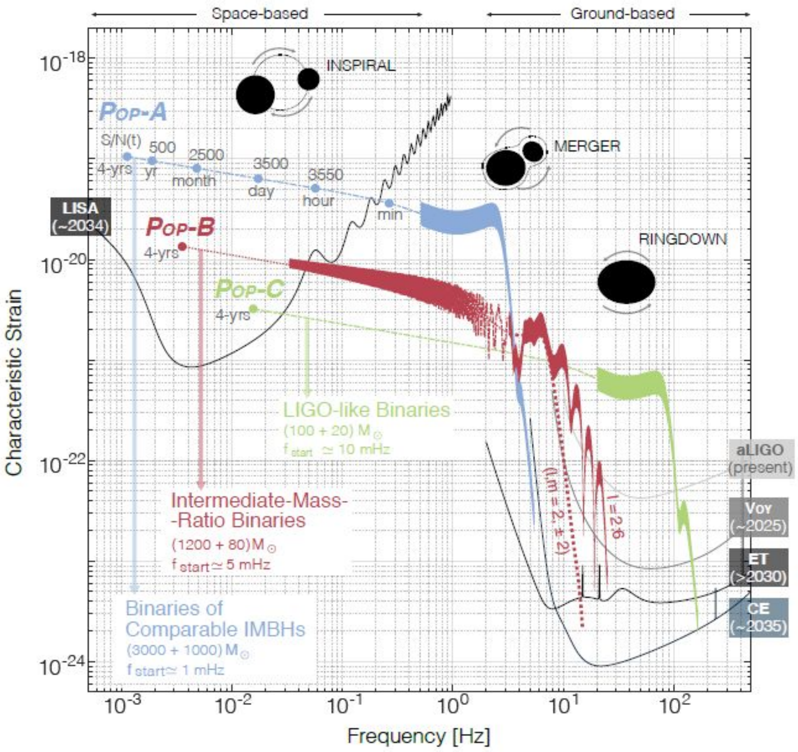
LIGO-Virgo, BBH systems with 100s of solar mass

Einstein Telescope and Cosmic Explorer, BBH systems with 1000s of solar mass

LISA, BBH systems with millions of solar mass

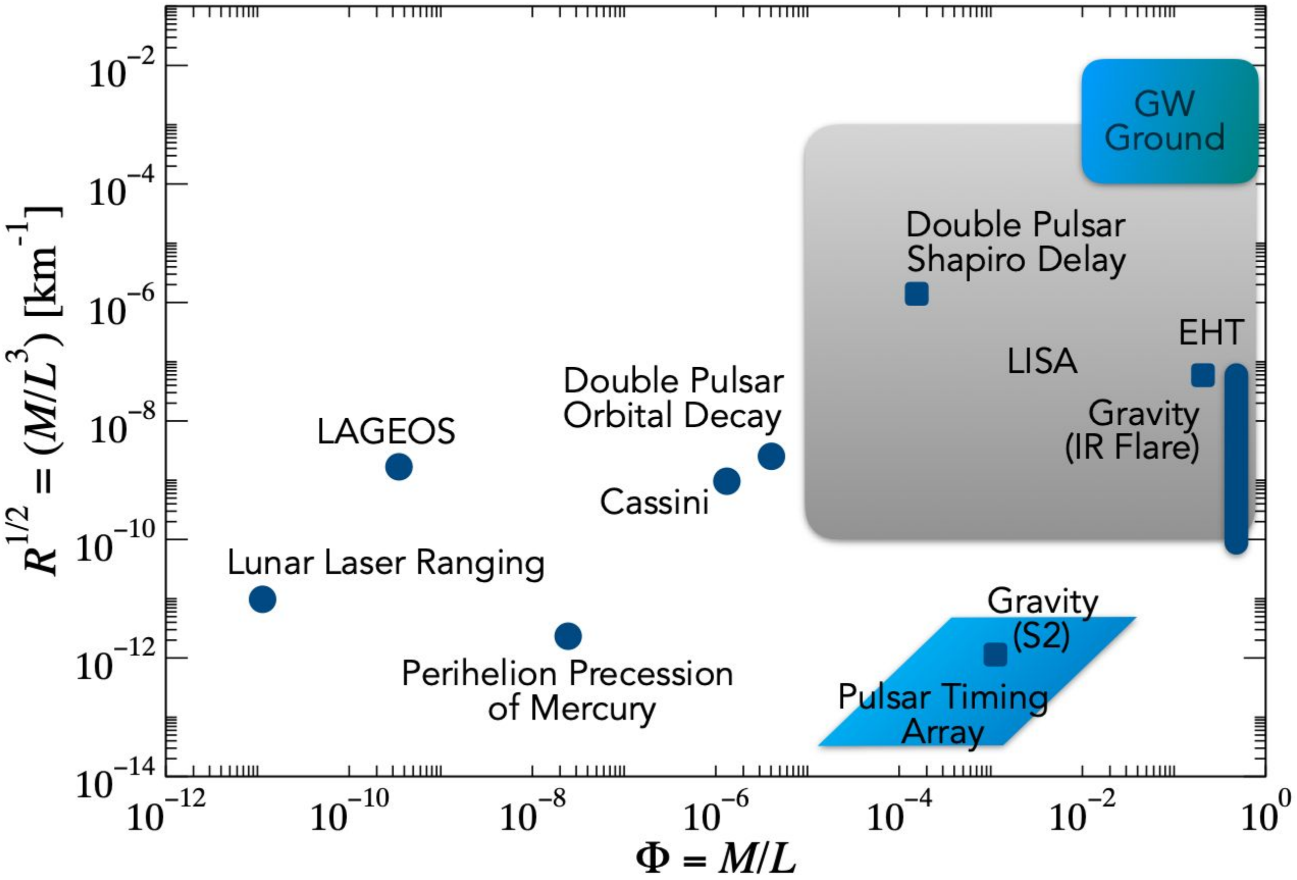
A tremendous opportunity to measure the BBH systems from stellar mass to SMBH

This can only be done with gravitational wave observations!

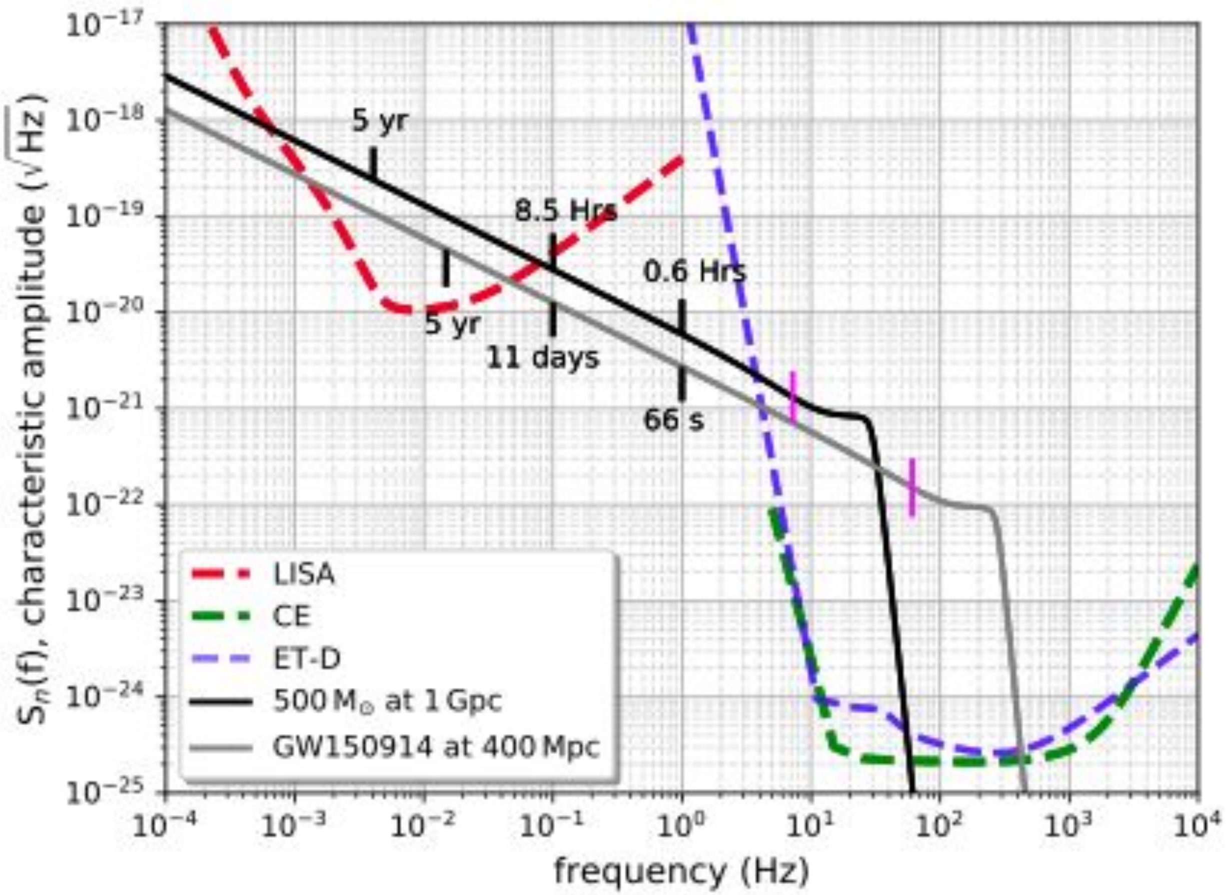


Examples of binaries with IMBHs in multiband gravitational wave spectrum. Jani, Shoemaker, Cutler. Nature Astron 2019

Tests of general relativity and alternative gravity theories



Multiband Tests of General Relativity: LISA, TianQin



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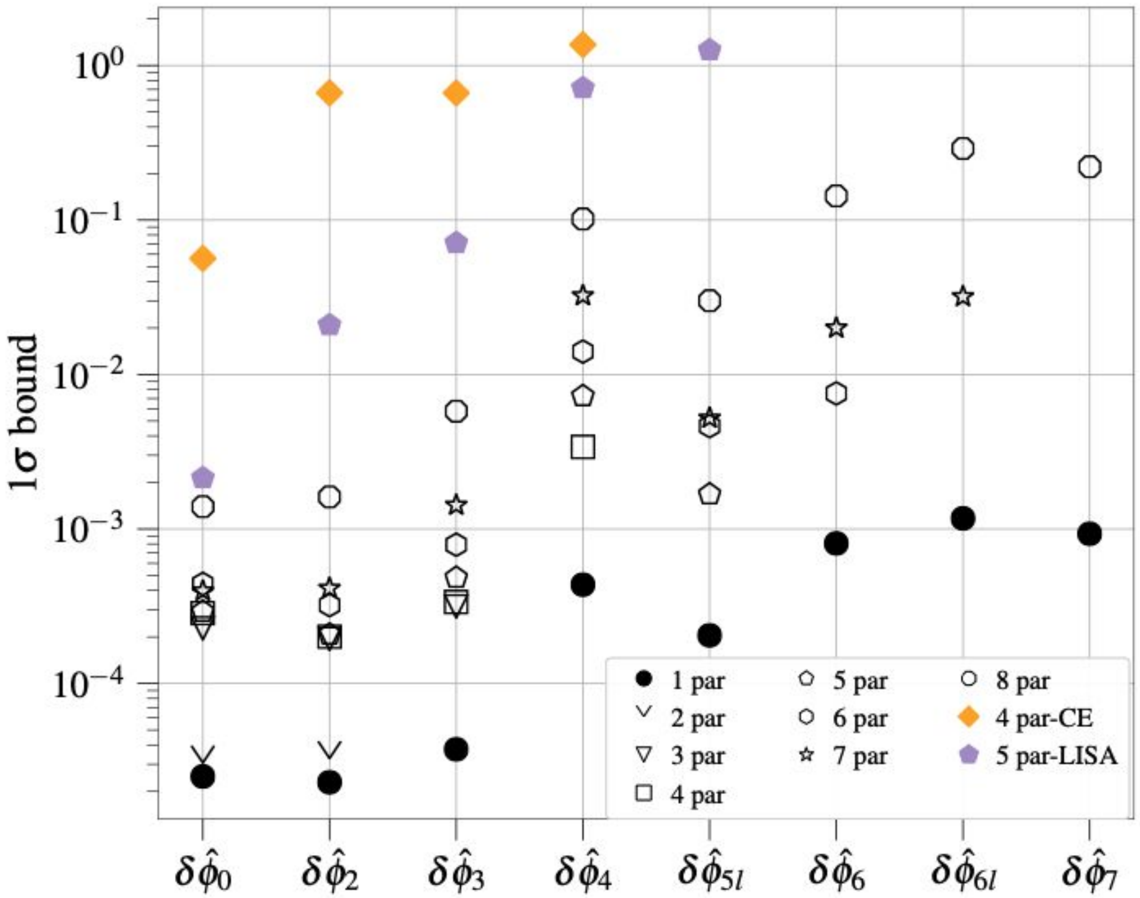
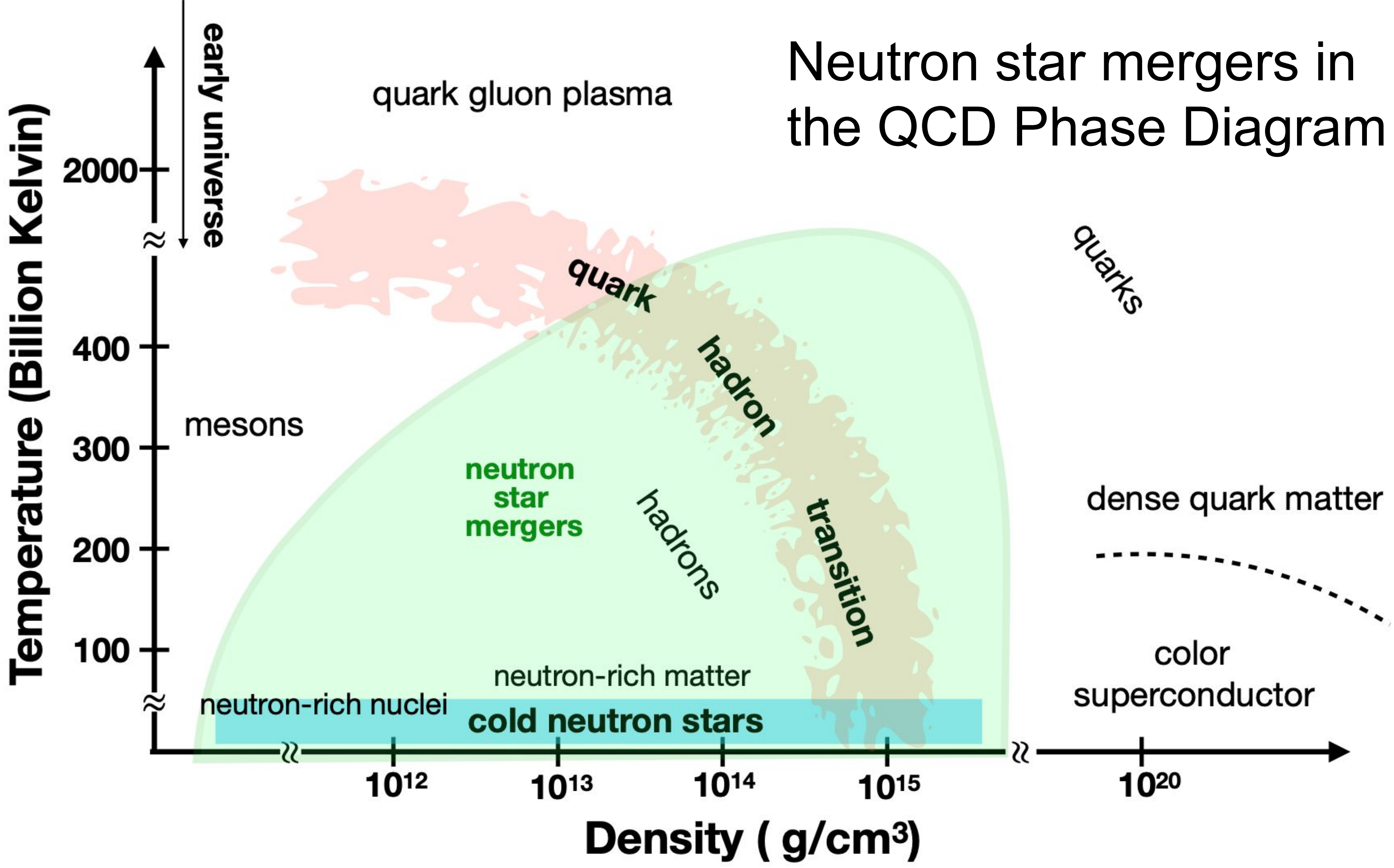


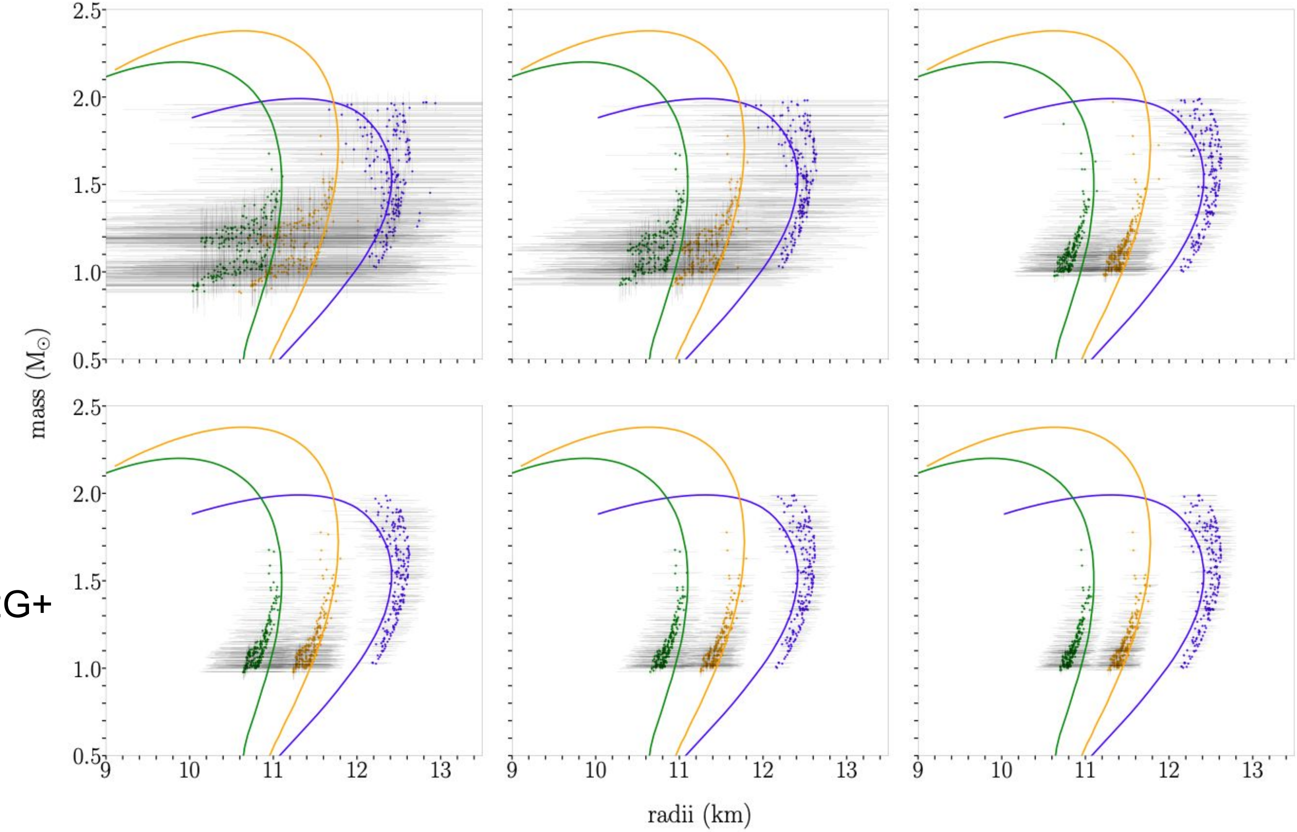
Neutron star mergers in the QCD Phase Diagram



Neutron Star Mass-Radius Curve: ET with 2G+, Cosmic Explorer

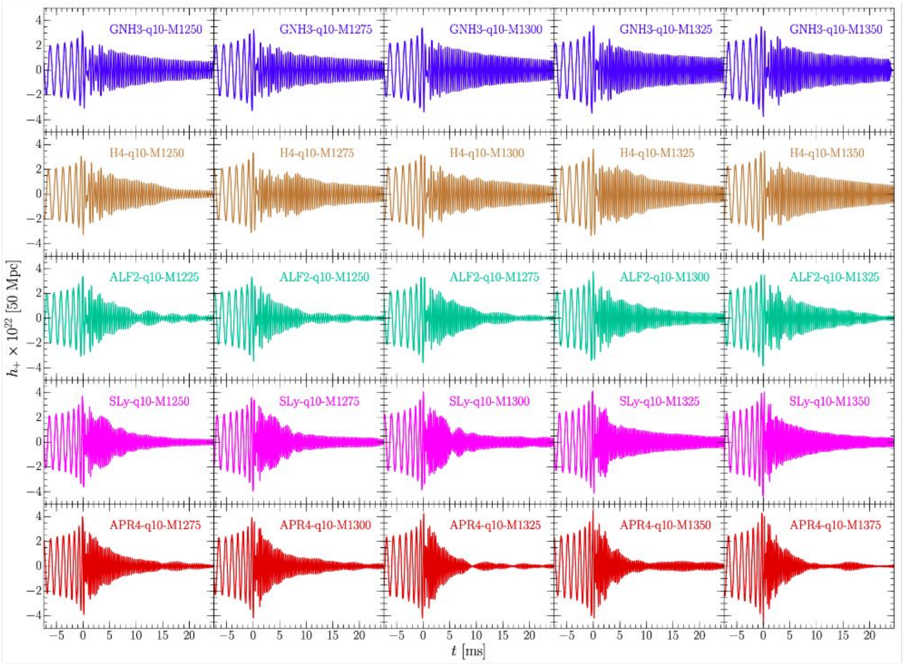
top panels: A+ networks and Voyager

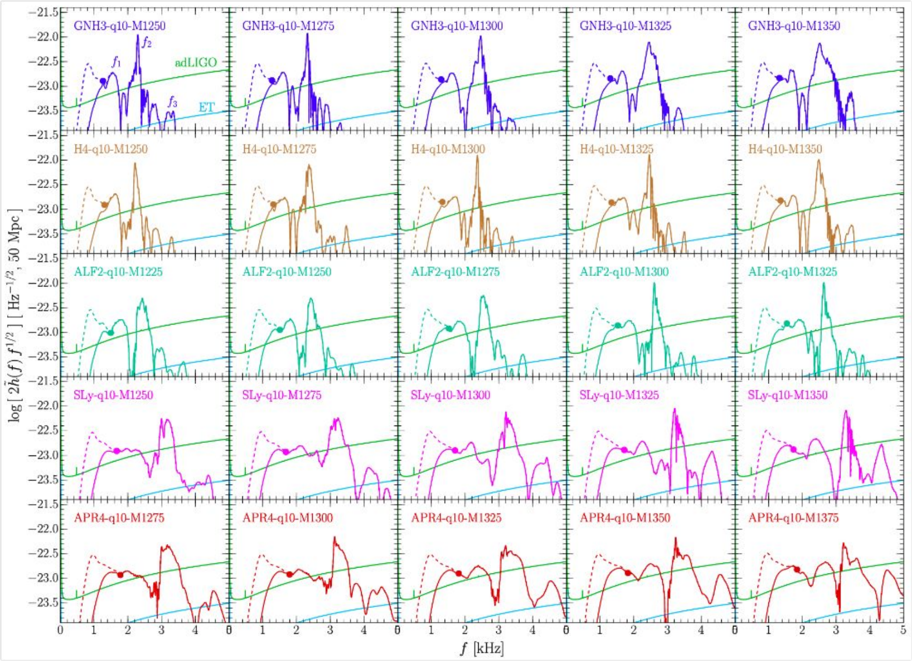
bottom panels: ET or CE with 2G+ and ET+CE



Huxford+2021

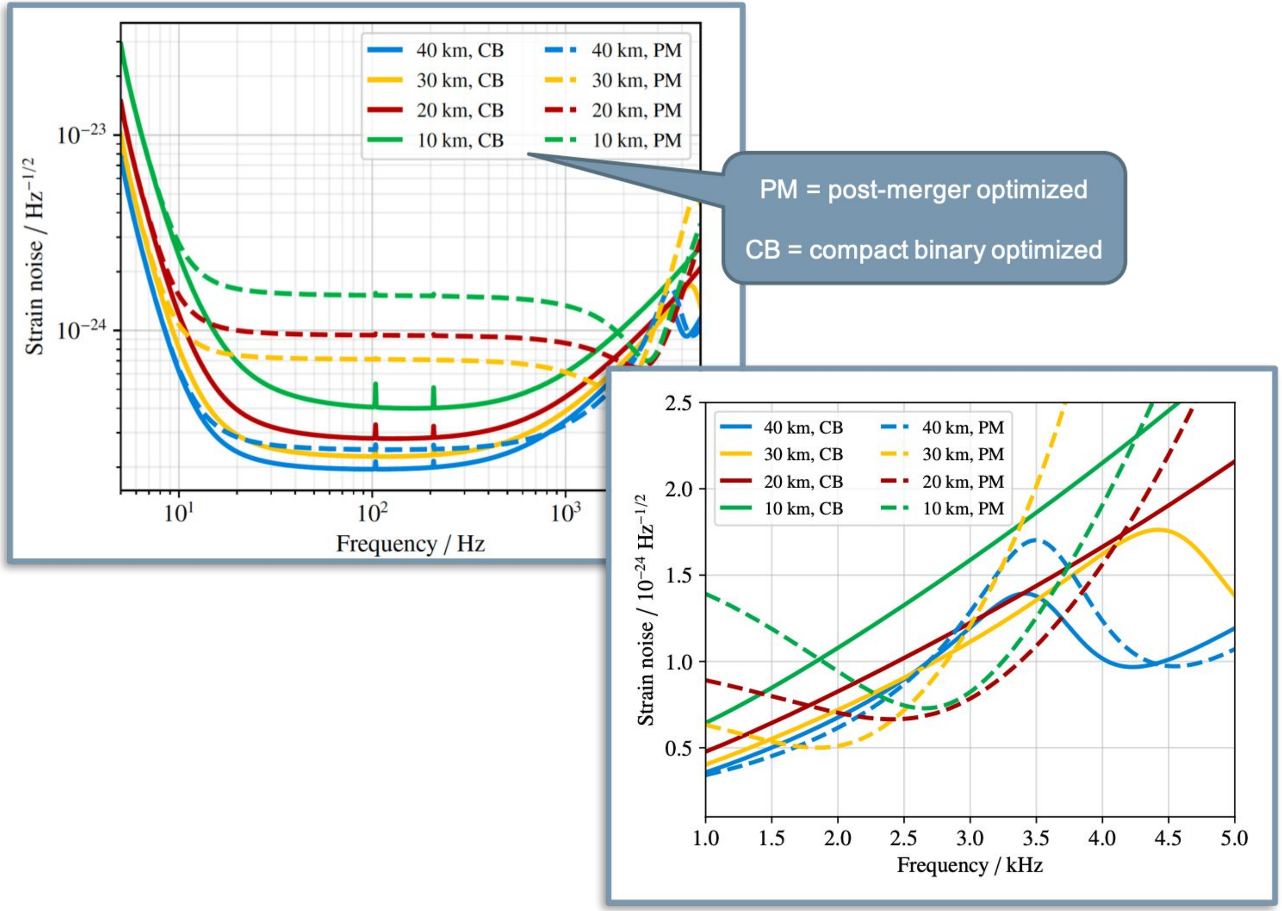
Post-merger oscillations





Takami, Rezzolla, Baiotti, 2014

Post-merger oscillations



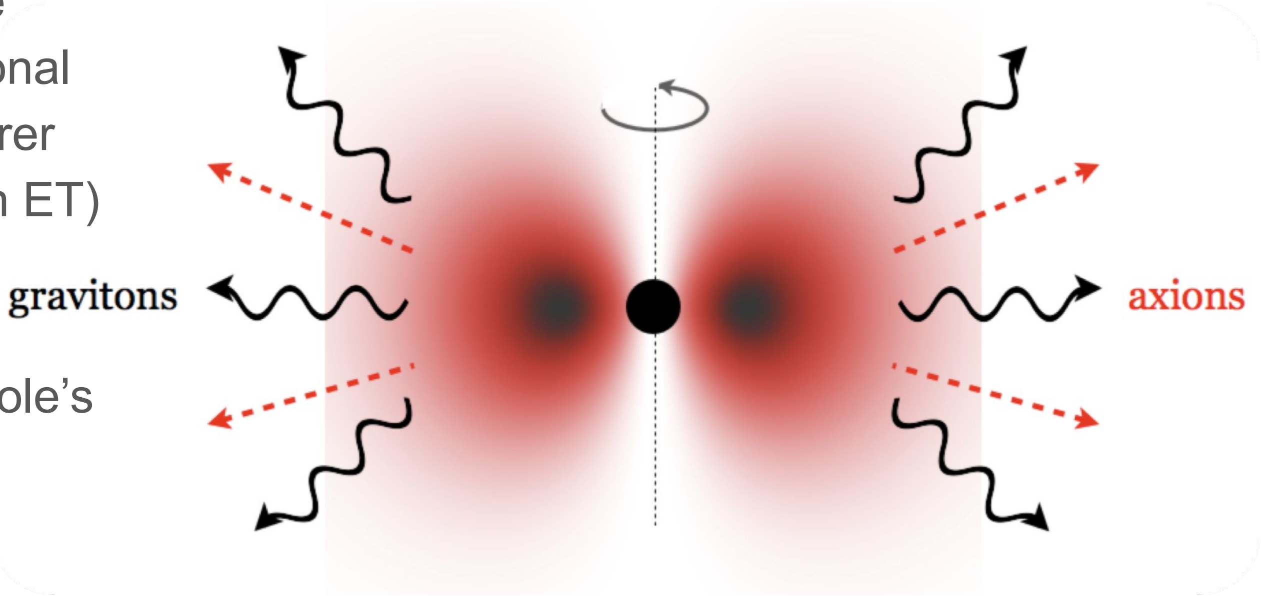
What are the options for tuning Einstein Telescope in the kilohertz range?

Shorter arm detectors (10 km and 20 km) are more sensitive than 30 km or 40 km arm detectors

Dark Matter Searches: LISA, TianQin, Cosmic Explorer

- axionic fields of Compton wavelength ~ black hole horizon form a gravitational atom (LISA would explorer lighter DM particles than ET)

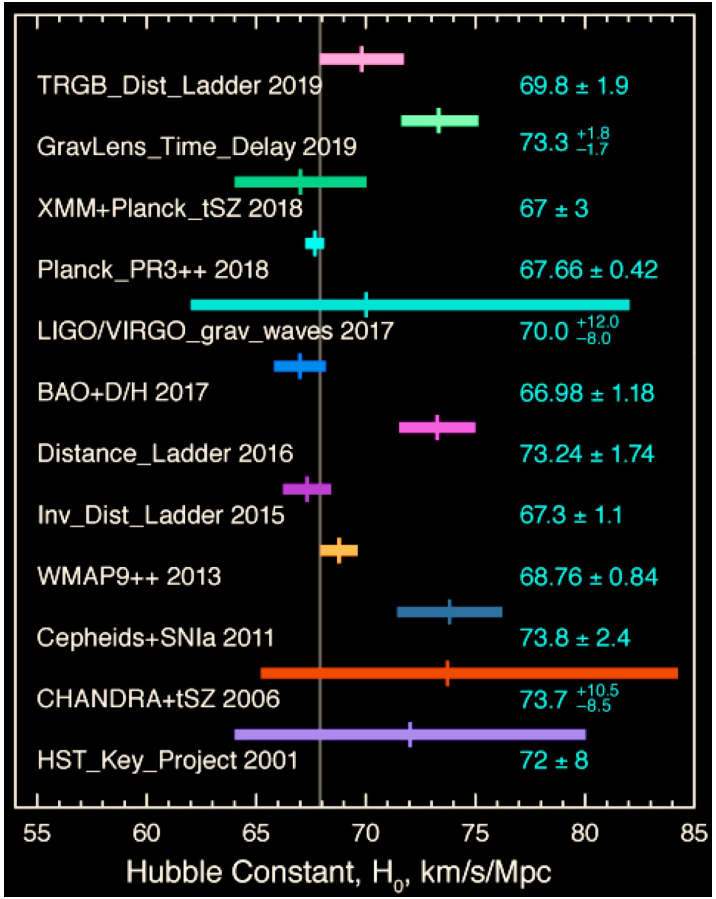
- they can extract black hole’s angular momentum via superradiance



Arvanitaki+ Phys. Rev. D83 (2011)

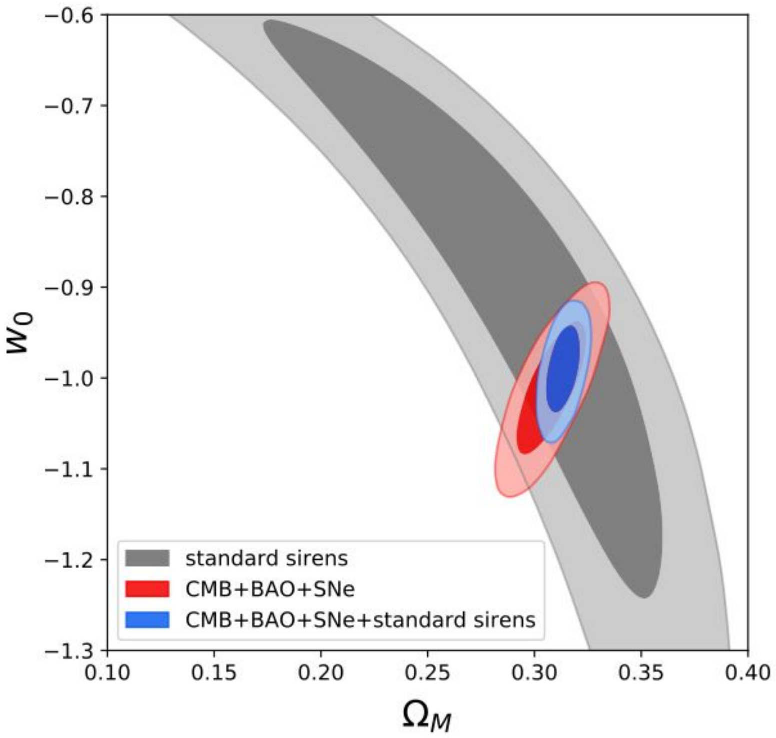
Hubble parameter: LISA, TianQin, Cosmic Explorer

- What is the role of ET in accurately measuring the Hubble parameter by 2035?
  - How does that accuracy compare with LISA and TianQin (using EMRIs, for example)
- Most likely 2G+ detectors would have made an independent measurement of H0 to a few percent by 2035
- However, ET will likely improve the accuracy by an order of magnitude beyond standard candles
  - How best to exploit this measurement for other applications? (say, cosmography)
  - Calibrate other distance measures in the distance ladder?

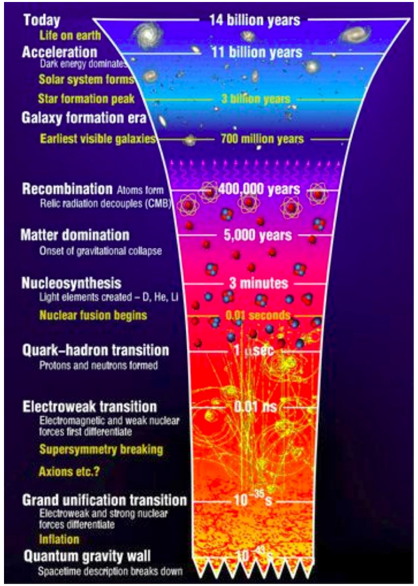


Cosmography: LISA, TianQin, 2G+, Cosmic Explorer

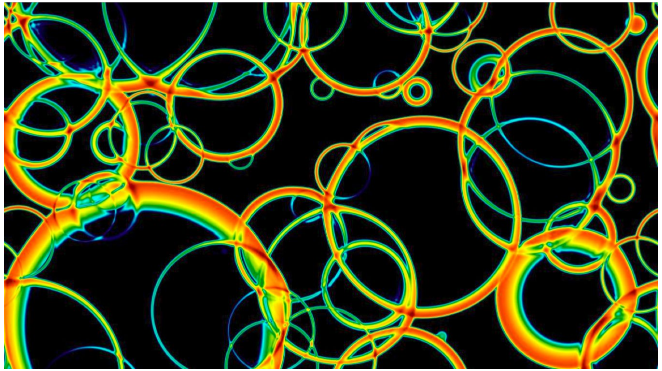
- Space observatories have the capability to measure dark matter and dark energy densities provided the event rate is large and nearby
- What is the best way to make use of data from space observatories with ET?
- ET and Cosmic Explorer together can better localize sources and measure distances
  - how does that compare with ET and 2G+ detectors?
- Hubble constant is greatly degenerate with other cosmological parameters
  - Exploit close universe measurement of H0 in measuring dark matter and dark energy density parameters and possibly w



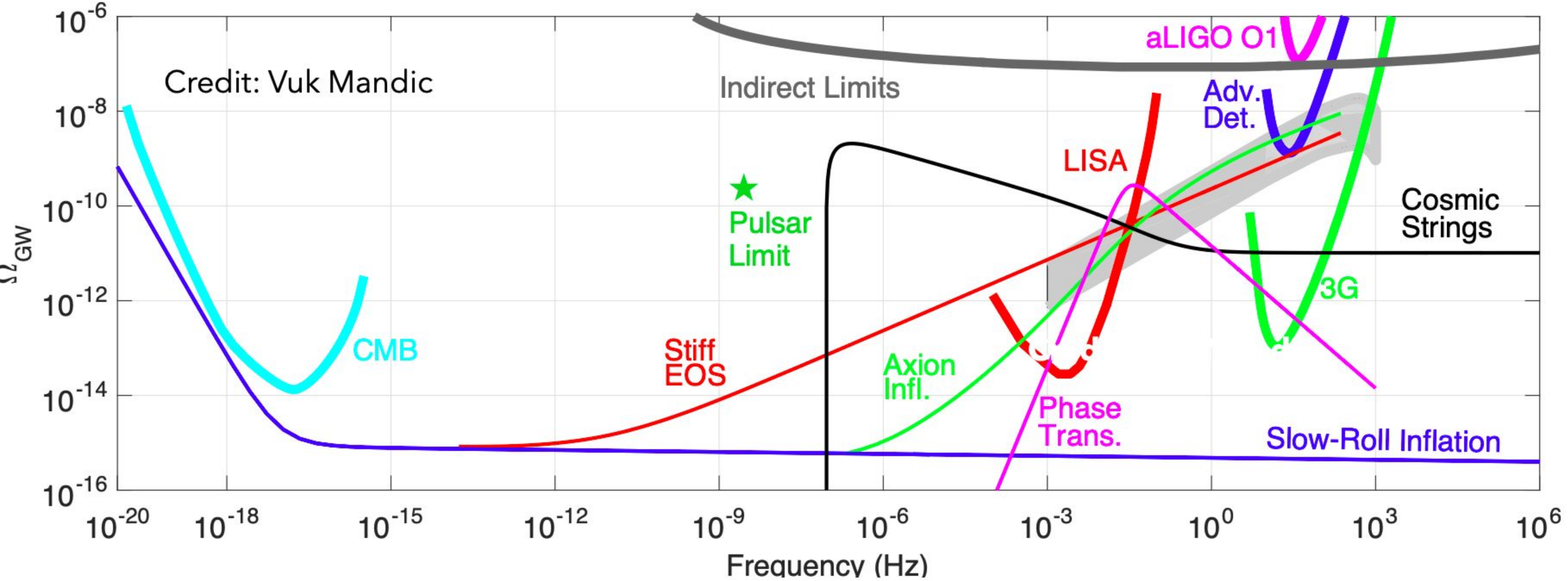
Primordial and Astrophysical Backgrounds: LISA, TianQin, Cosmic Explorer



- bubble collisions during phase transitions could produce observable gravitational waves
  - energy scale determines the frequency at which they might appear
- beyond standard model physics
  - mass-gap between BSM particles and EW scale
    - e.g. SUSY phase transitions
  - is the Universe natural?
  - what order is the EW phase transition?
  - first order phase transitions in the Higgs condensate
    - presence of new physics could alter the thermal history of the EW symmetry breaking
    - to what extent do future GW observatories probe EW phase transitions?
- slow roll inflation produces primordial stochastic background
  - observable in CMB B-modes



STOCHASTIC BACKGROUND LANDSCAPE



- slow-roll inflation
- stiff equation of state
- axion inflation
- early universe phase transitions
- cosmic strings

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