Gravitational waves: a new probe of the large scale structure

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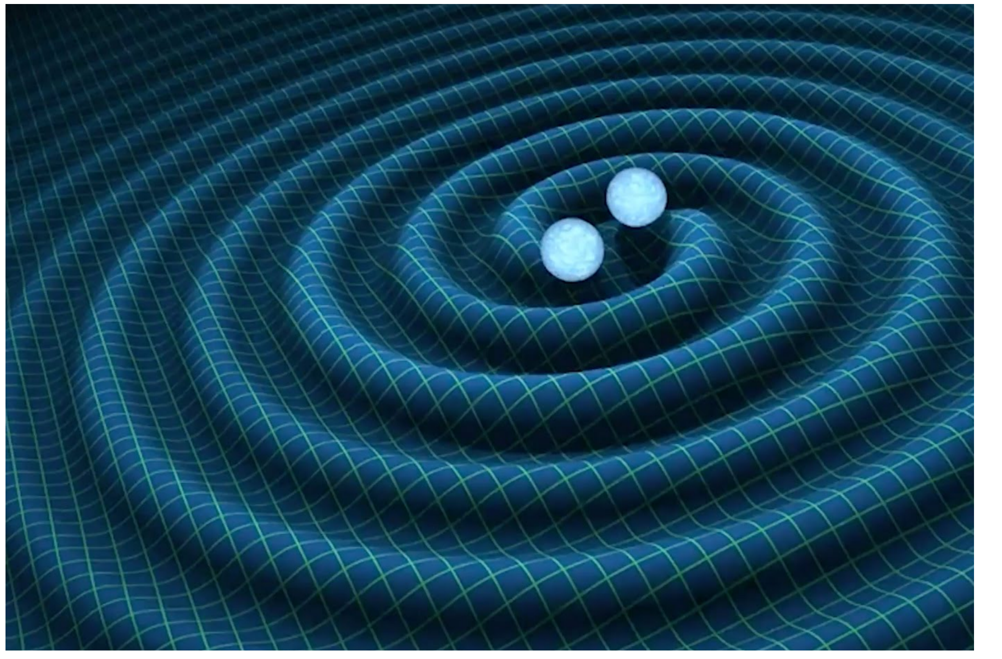
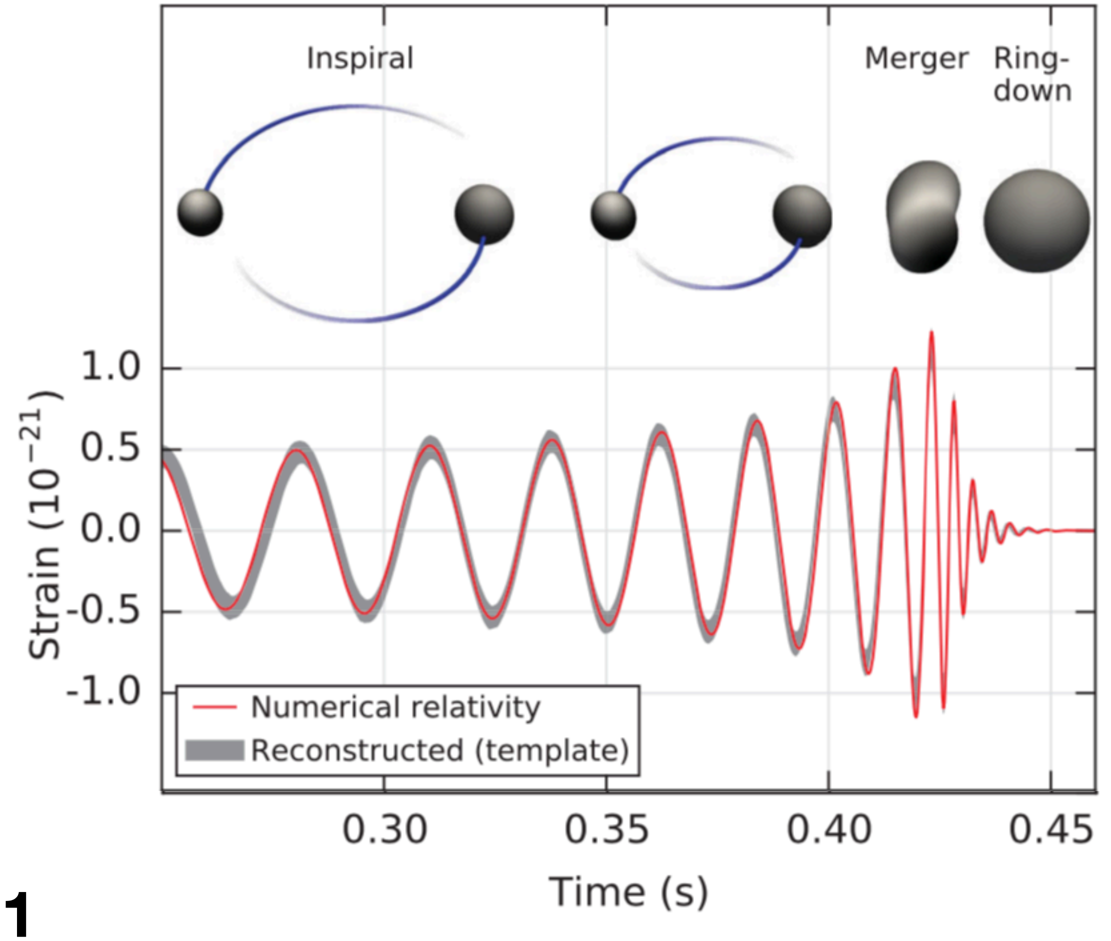
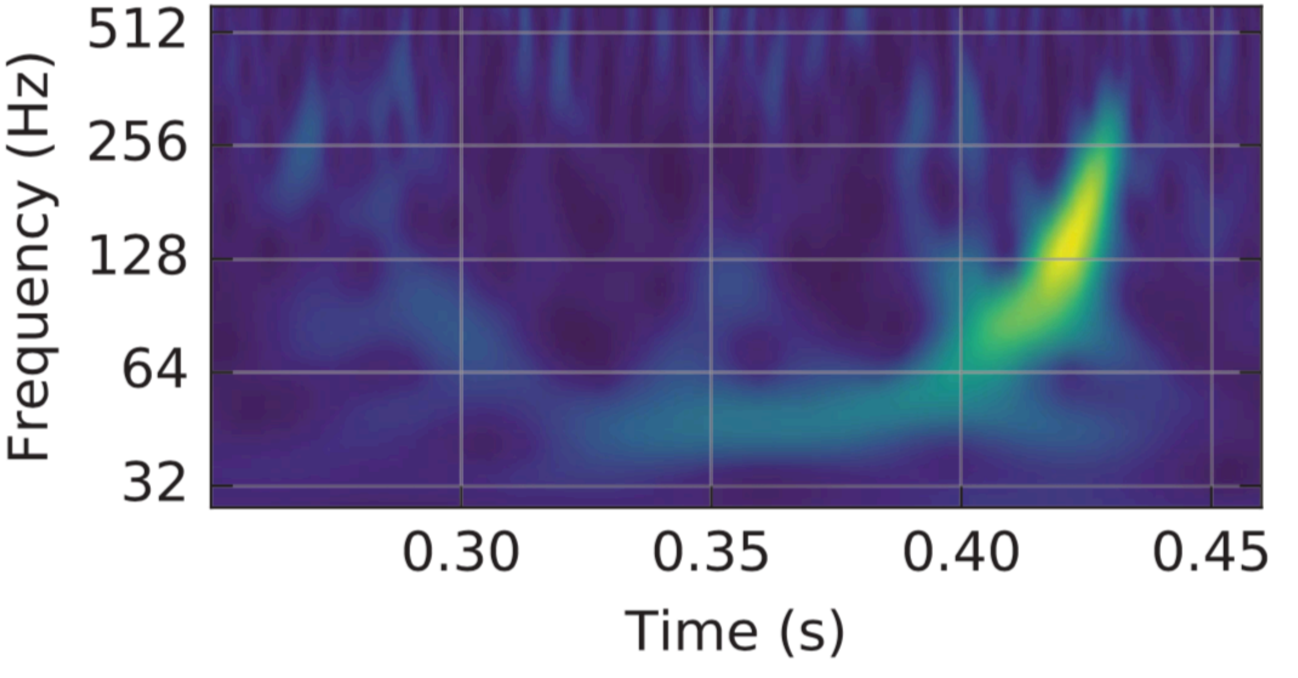
Gravitational waves: a new messenger

- GW: Metric perturbations, propagate with the speed of light
- Generated by time varying mass quadrupole



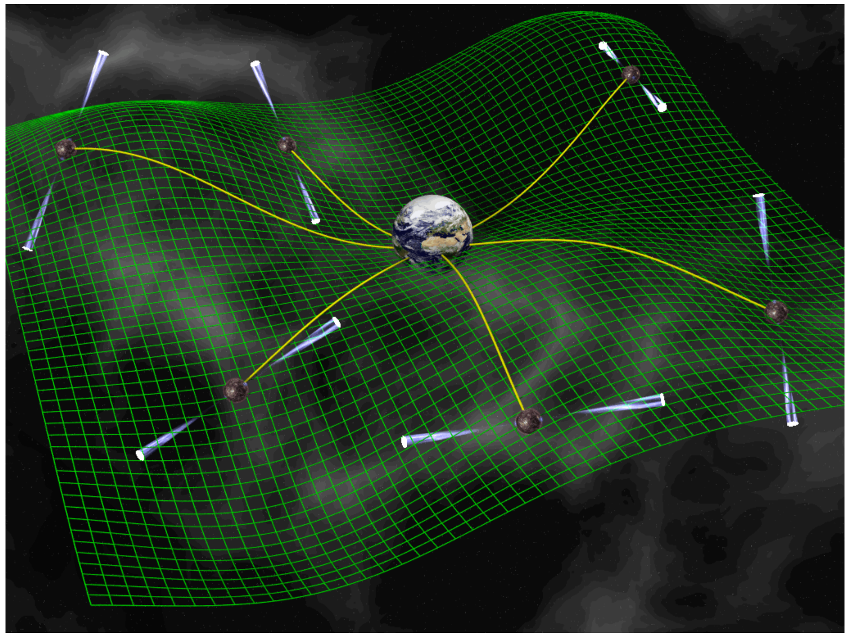
First detection! GW150914: a binary black hole.

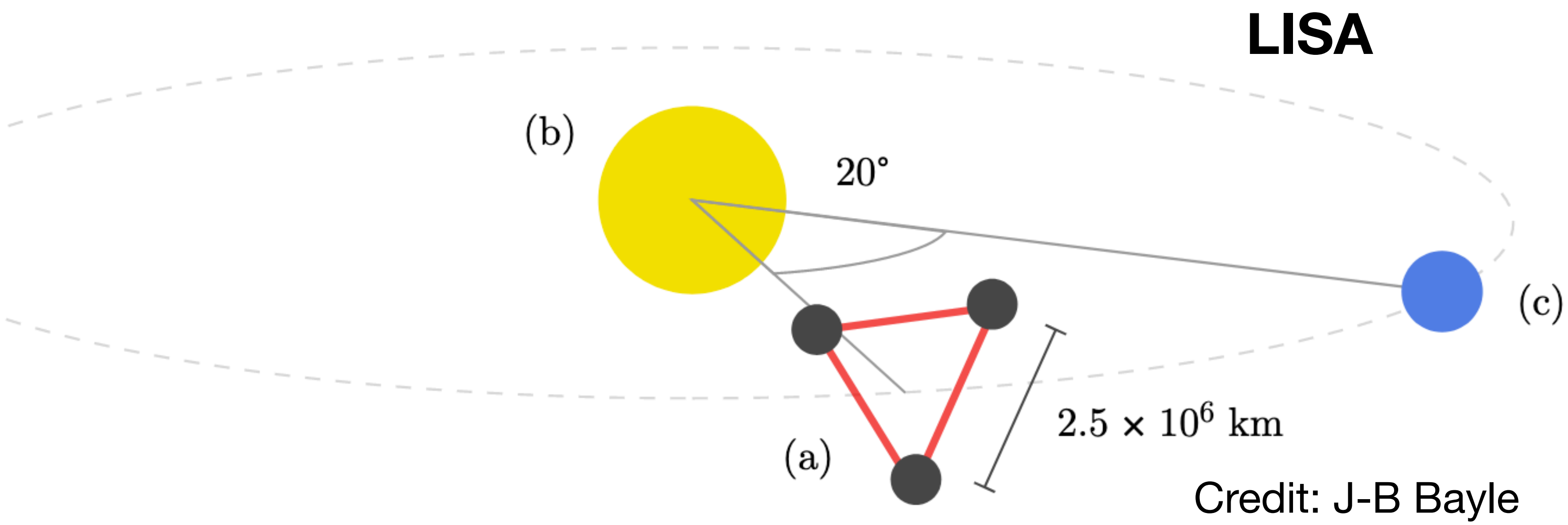




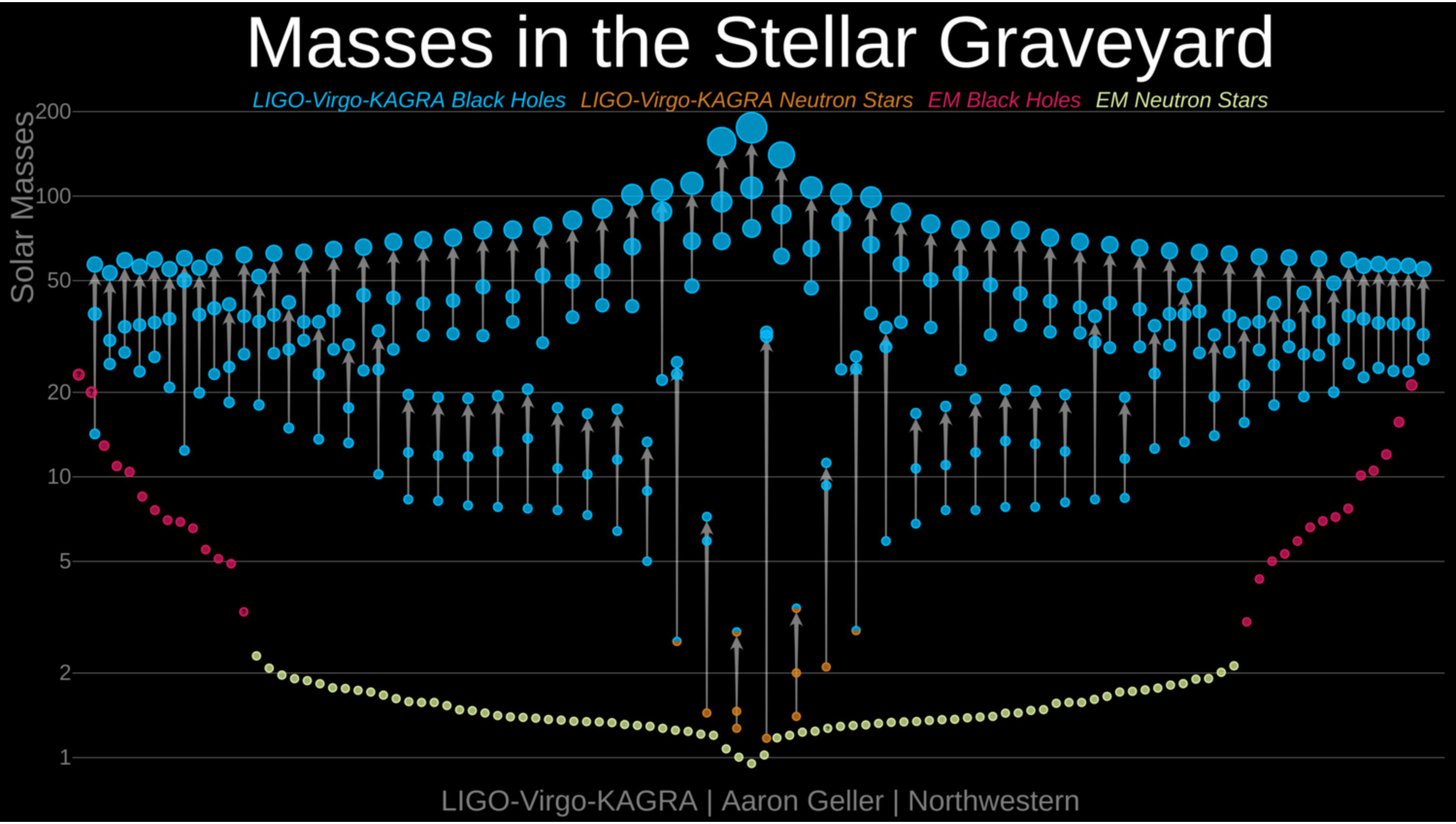
Gravitational-wave observatories

- **LIGO (Hanford+Livingston, USA)**
- **Virgo (Italy)**
- **Kagra (Japan)**
- *LIGO-India*
- *Einstein Telescope (Europe) / Cosmic Explorer (USA)*
- *LISA (space! ESA+NASA)*
- **Pulsar Timing Arrays (radio telescopes; Europe+USA+Australia)**

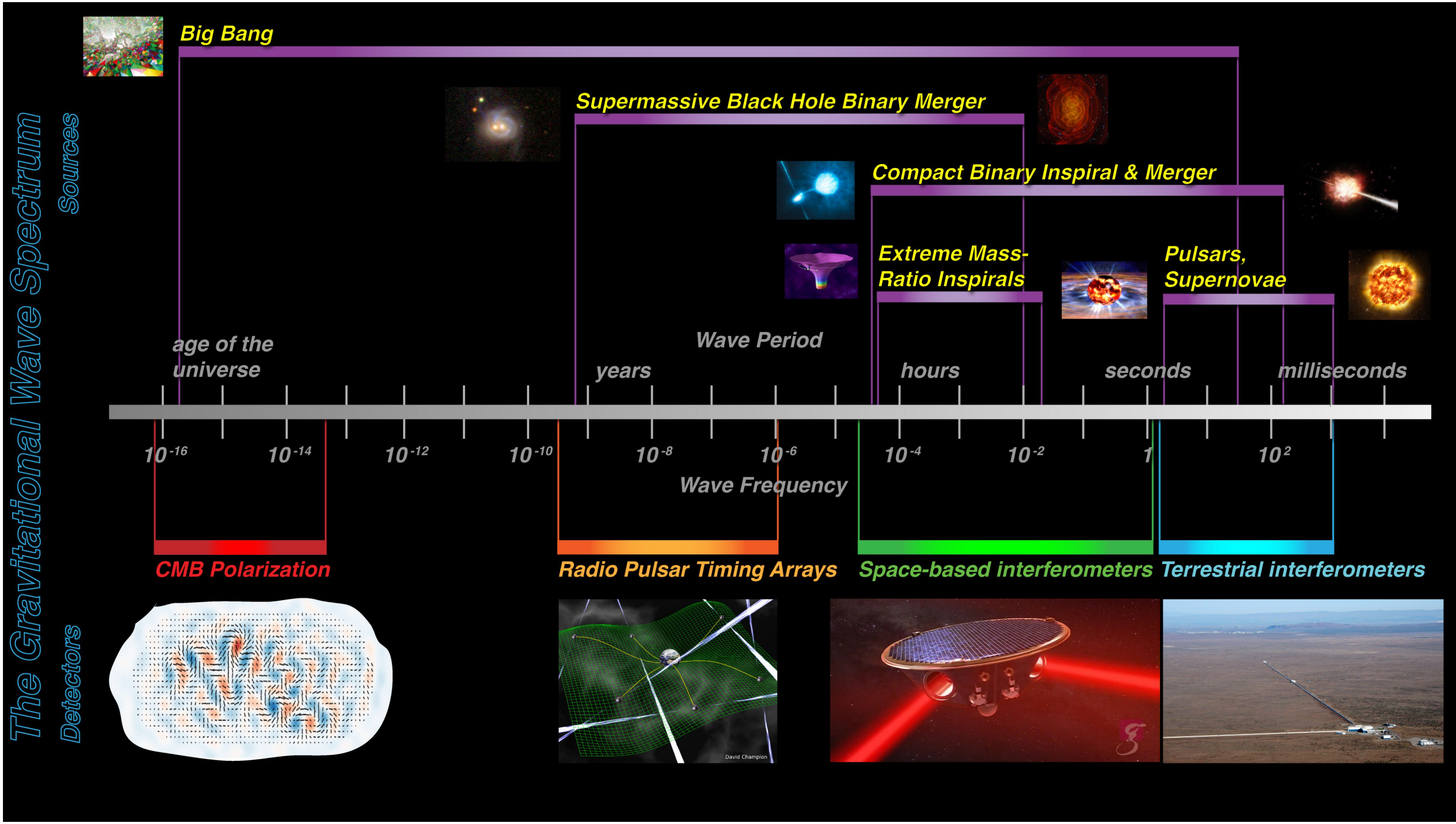


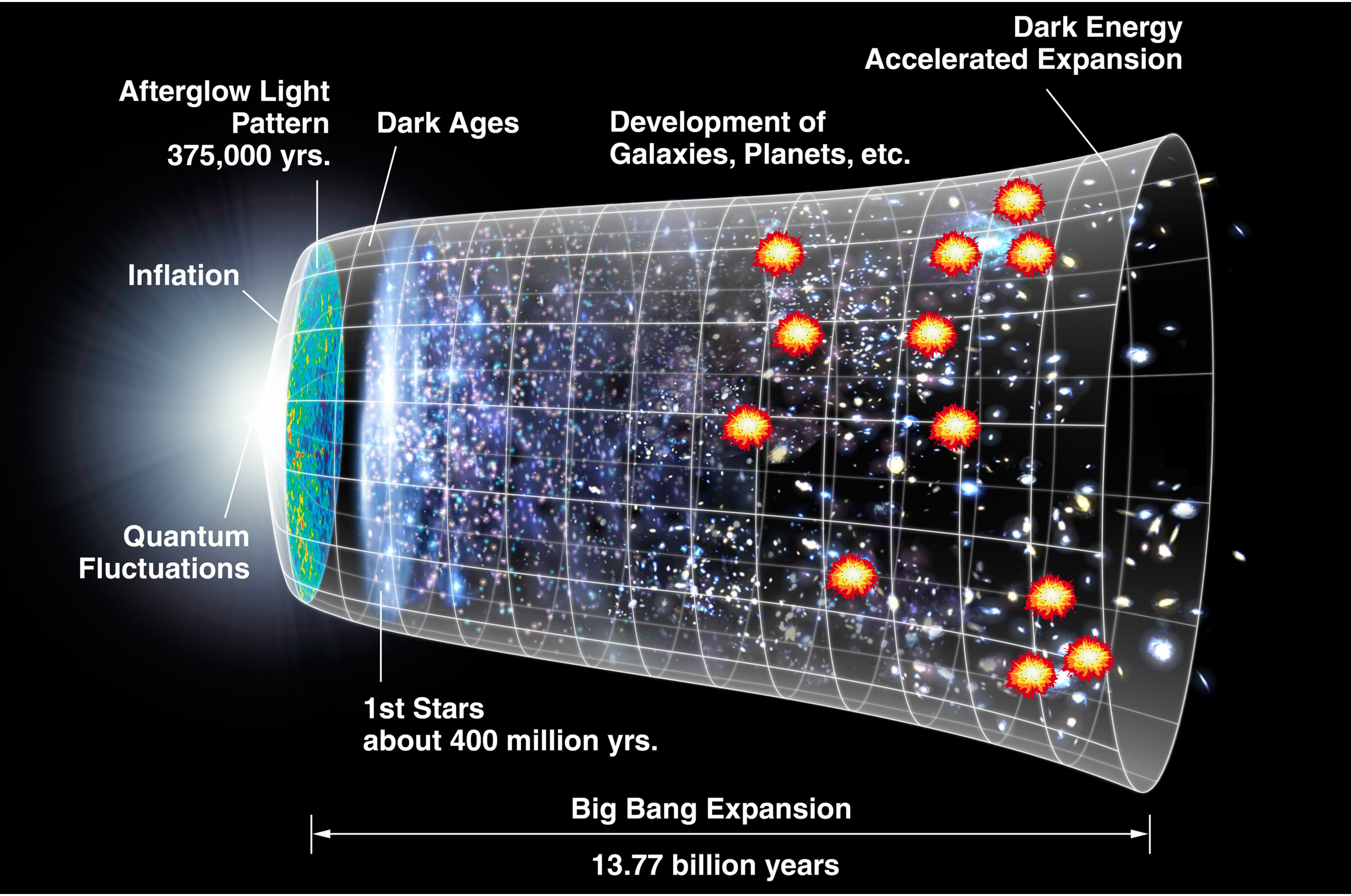


LIGO-Virgo GW transient catalogue



Overview of GW sources

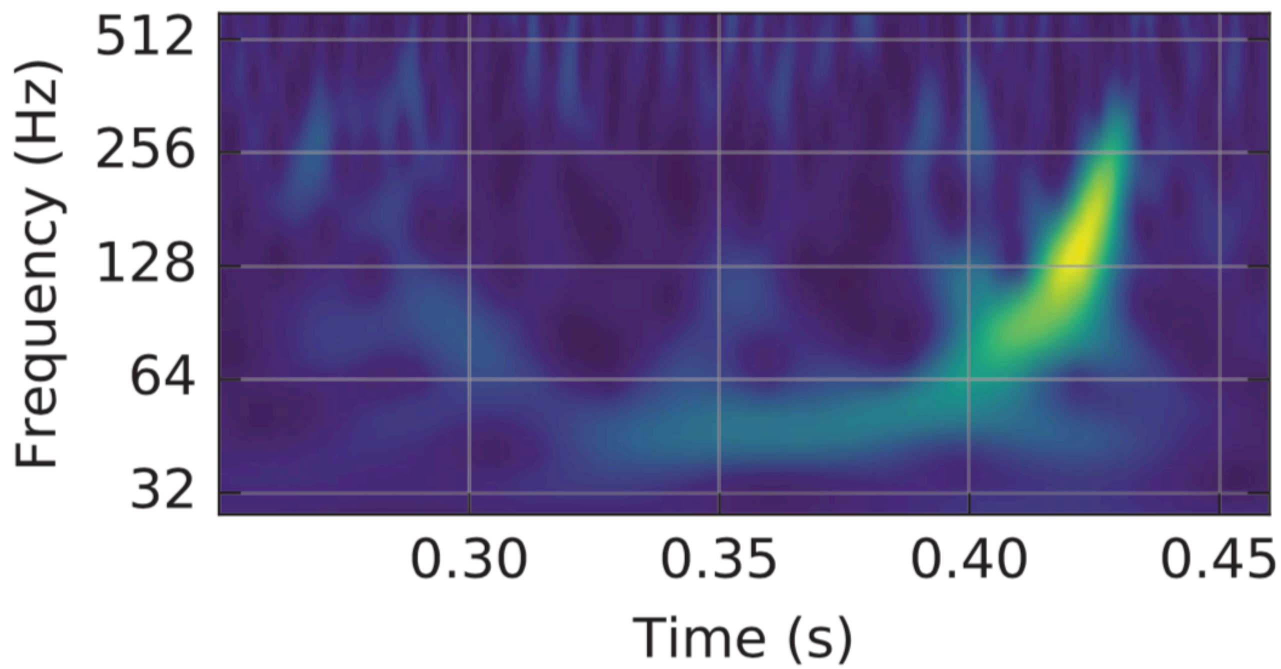



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Standard sirens

[Schutz (1986)]

$$\dot{f}_{obs} \propto \left(\frac{GM_c(z)}{c^3}\right)^{5/3} f_{obs}^{11/3}$$



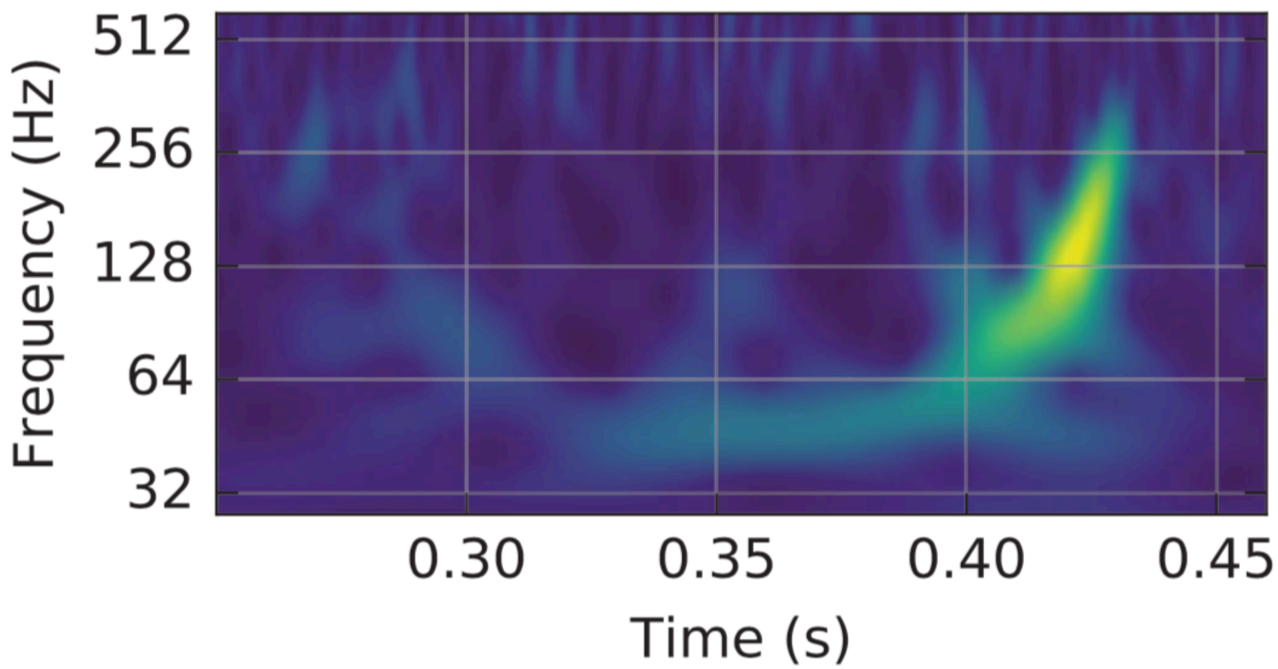
$$h \propto \frac{1}{d_L(z)} \left(\frac{GM_c(z)}{c^2}\right)^{5/3} \left(\frac{\pi f_{obs}}{c}\right)^{2/3}$$

Standard sirens

[Schutz (1986)]

$$\dot{f}_{obs} \propto \left(\frac{GM_c(z)}{c^3}\right)^{5/3} f_{obs}^{11/3} \longrightarrow$$

Measure chirp mass



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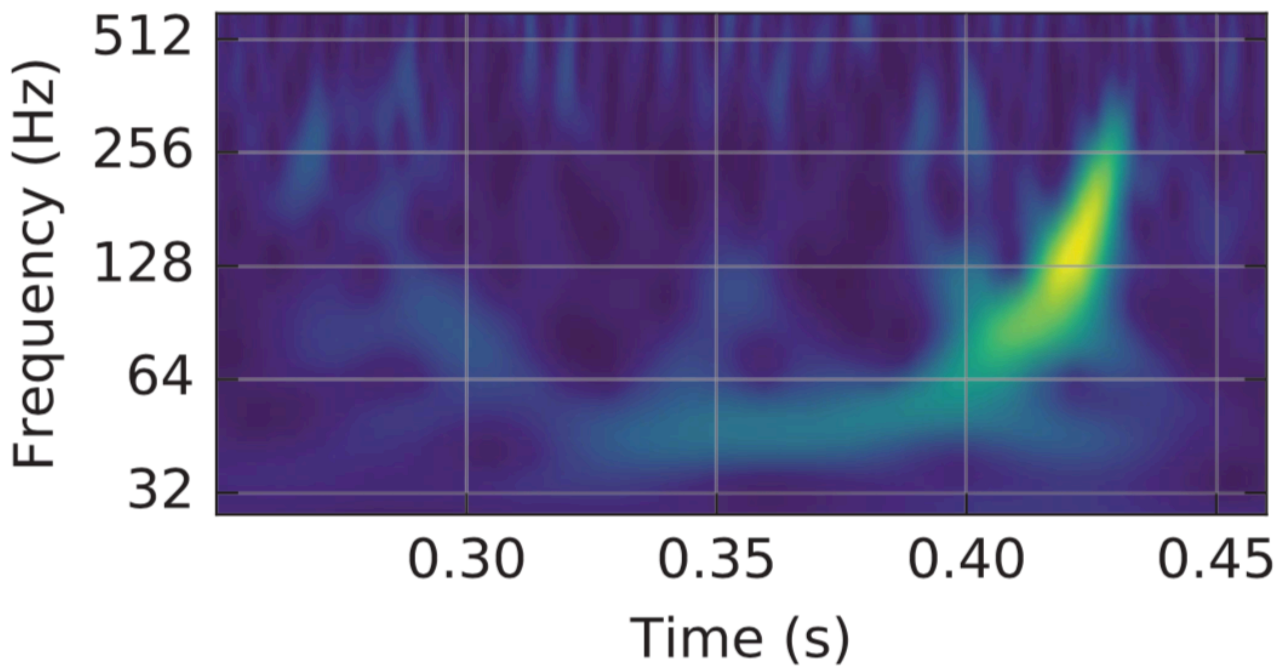
Standard sirens

[Schutz (1986)]

$$\dot{f}_{obs} \propto \left(\frac{GM_c(z)}{c^3}\right)^{5/3} f_{obs}^{11/3} \longrightarrow$$ Measure chirp mass



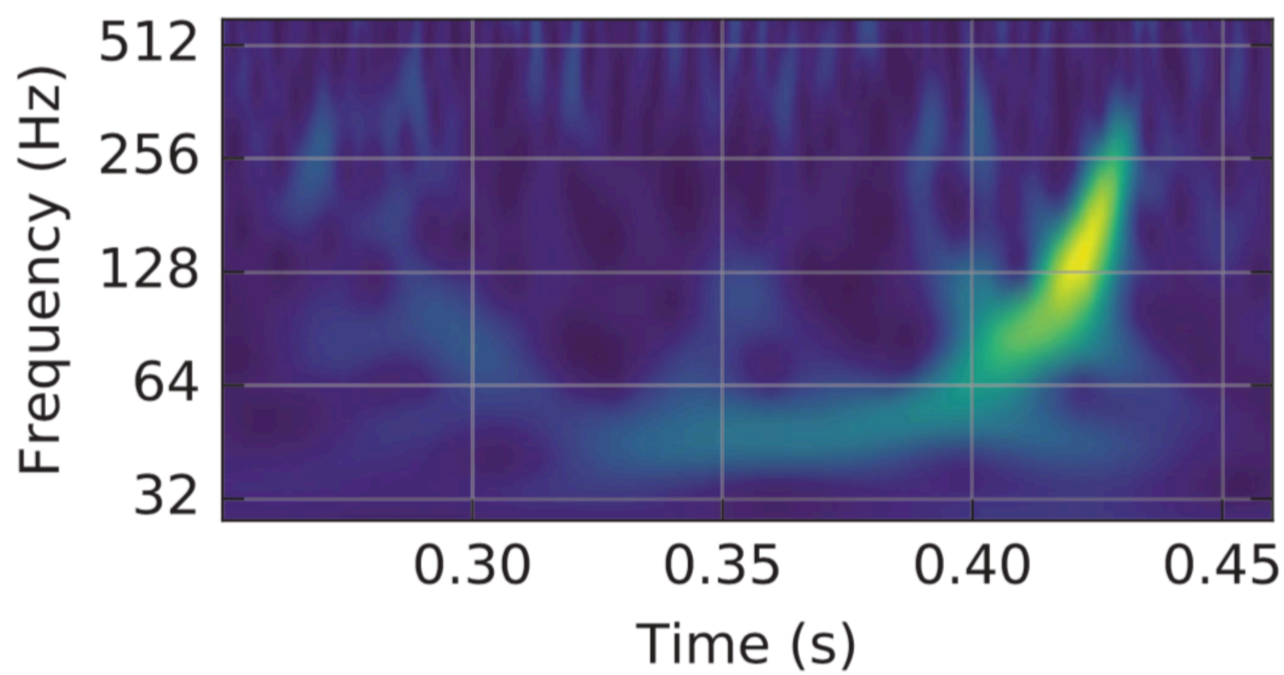
$$h \propto \frac{1}{d_L(z)} \left(\frac{GM_c(z)}{c^2}\right)^{5/3} \left(\frac{\pi f_{obs}}{c}\right)^{2/3} \longrightarrow$$ Measure luminosity distance

Standard sirens

[Schutz (1986)]

$$\dot{f}_{obs} \propto \left(\frac{GM_c(z)}{c^3}\right)^{5/3} f_{obs}^{11/3} \longrightarrow$$

Measure chirp mass

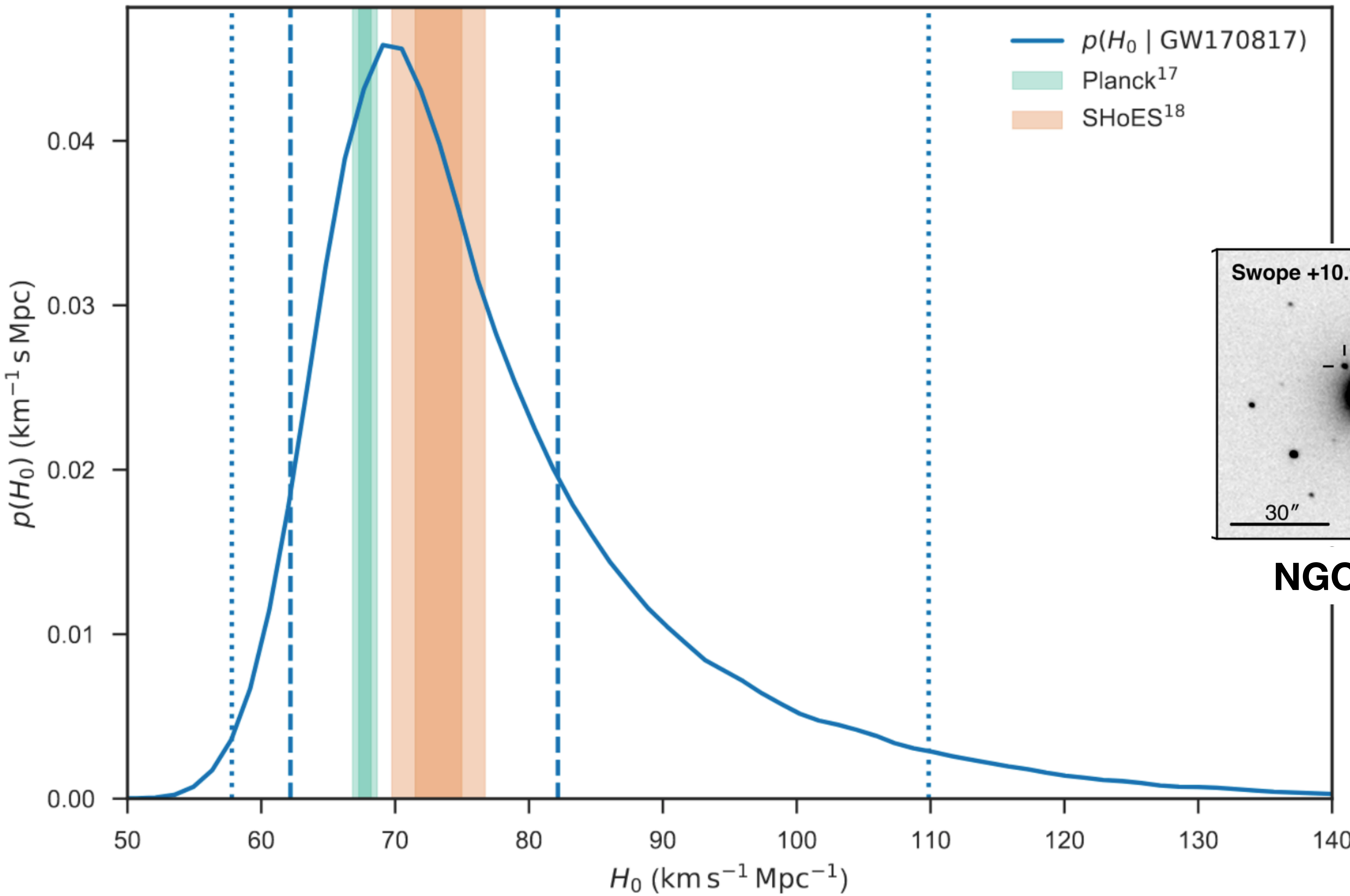


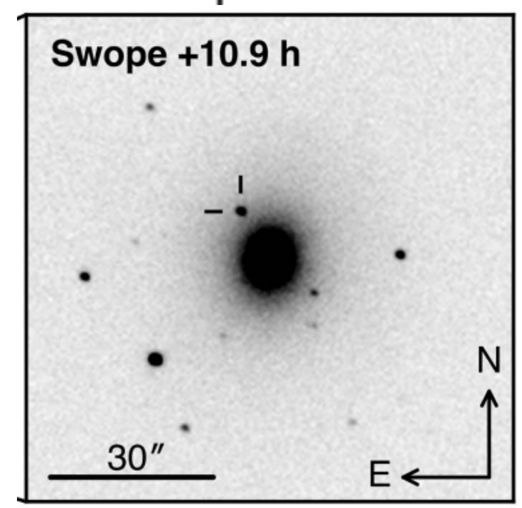
$$h \propto \frac{1}{d_L(z)} \left(\frac{GM_c(z)}{c^2}\right)^{5/3} \left(\frac{\pi f_{obs}}{c}\right)^{2/3} \longrightarrow$$

Measure luminosity distance

If redshift known (for example host galaxy identified) ⟶ **$d_L(z)$ vs. z**

Binary neutron star merger: GW and optical counterpart

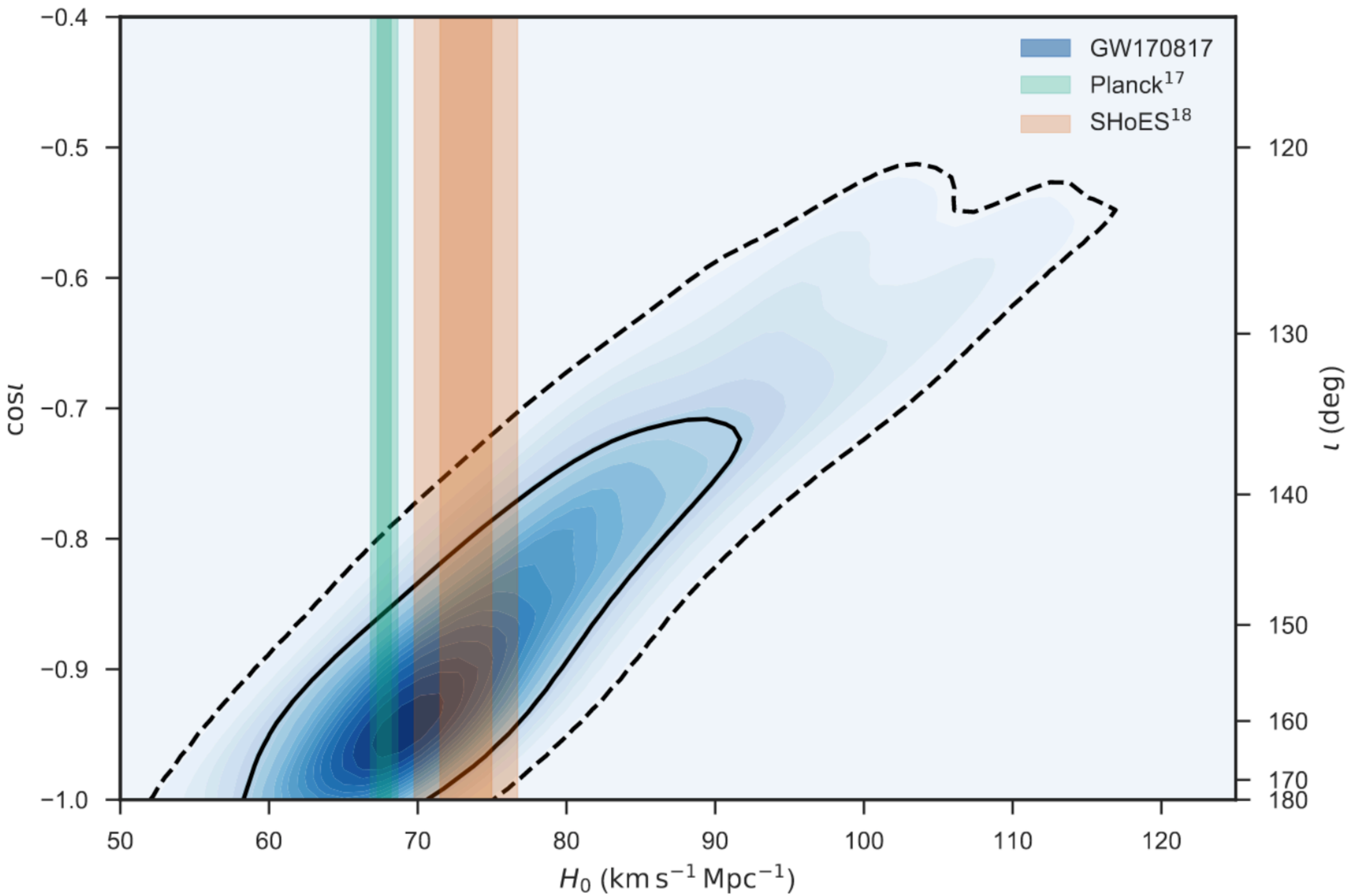




NGC 4993

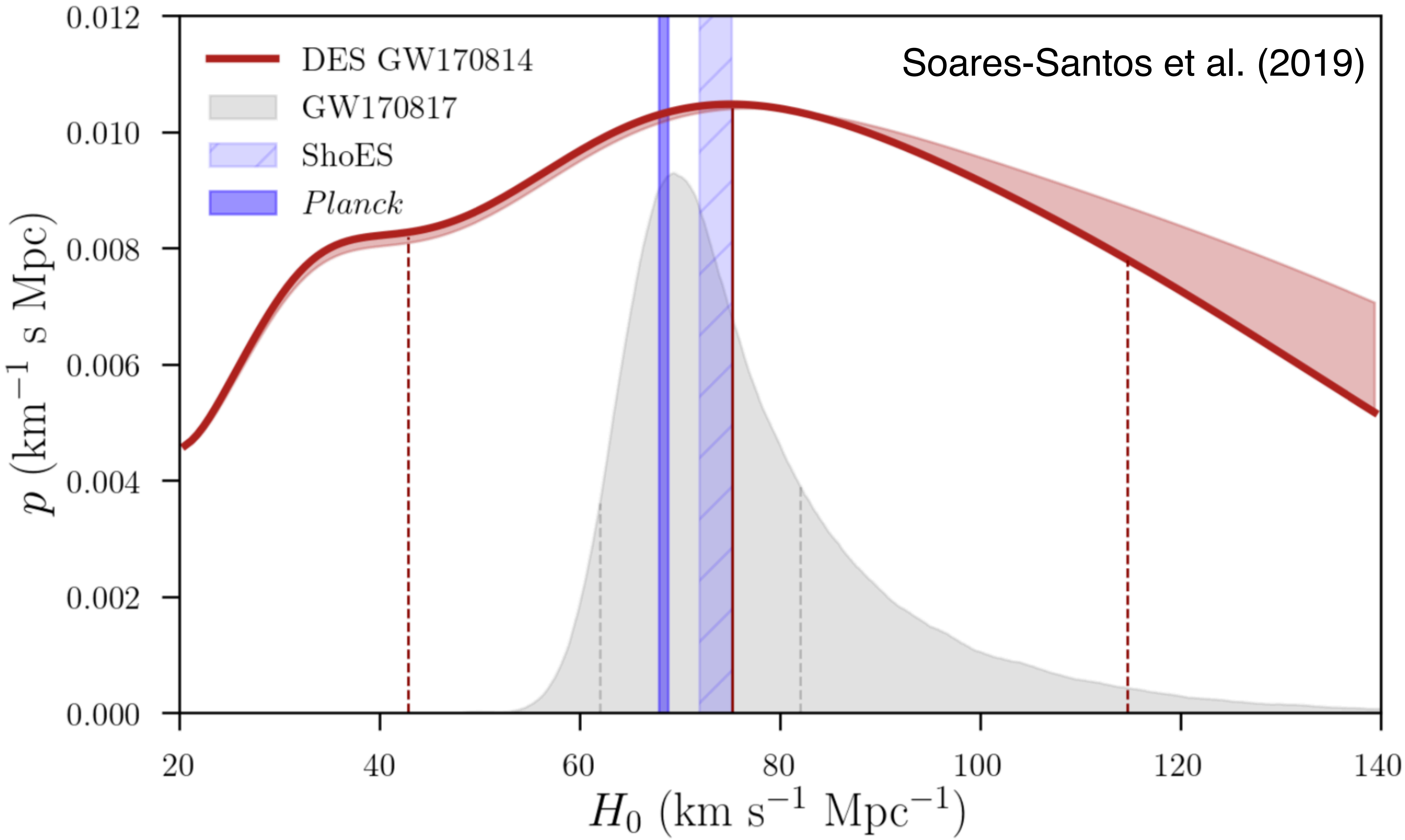
[Abbott+2017]

Binary neutron star merger: orbital plane inclination uncertainty



[Abbott+2017]

Dark sirens: no optical counterpart

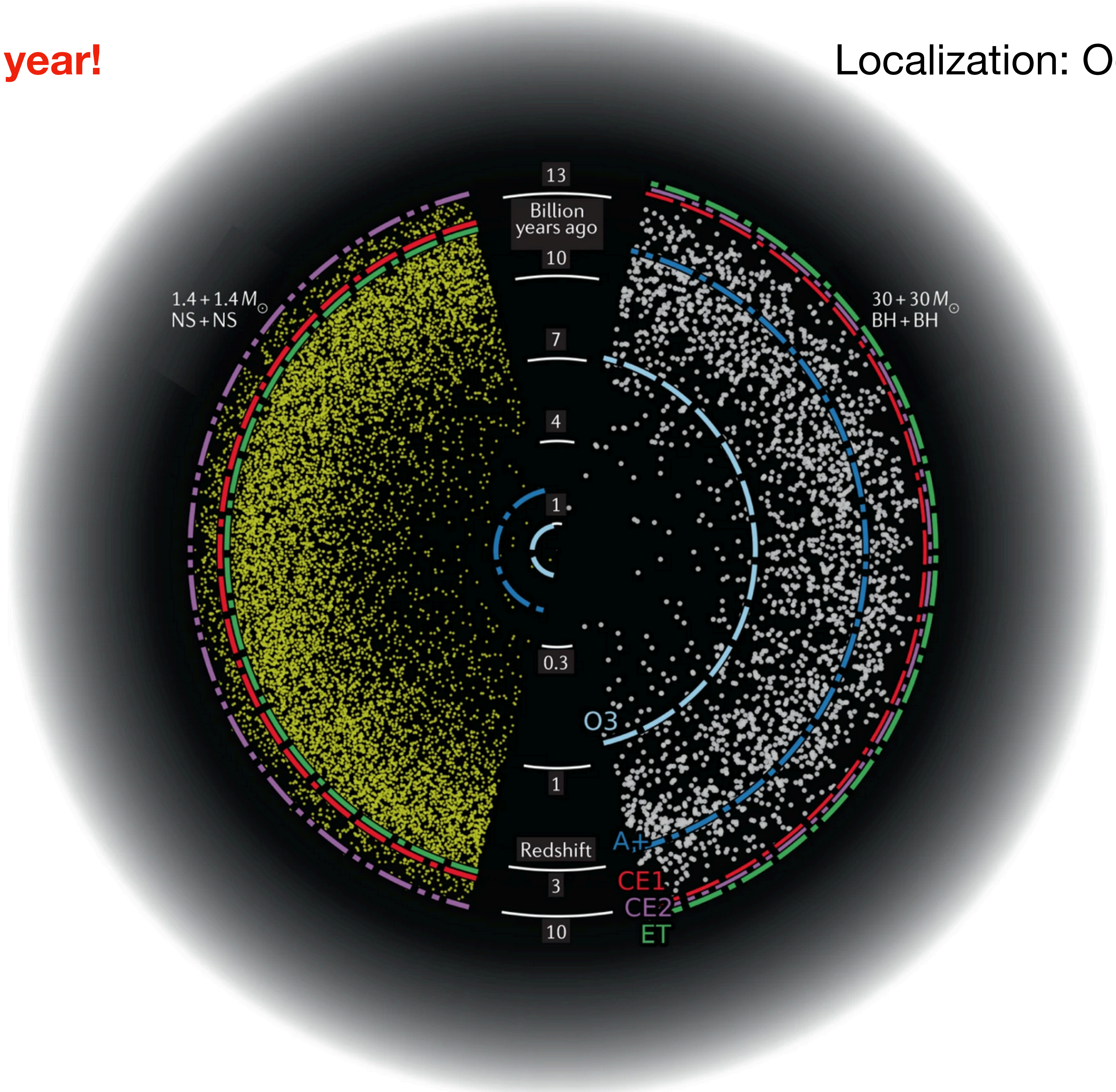


See also [Chen+2018; Mukherjee+2021; de Sousa+2022…]

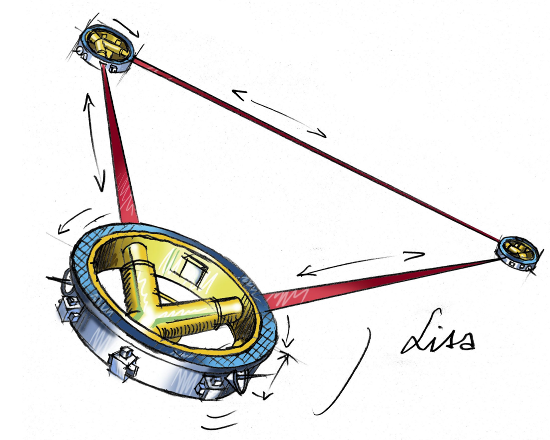
Third generation detectors: Einstein Telescope and Cosmic Explorer

10^5 events per year!

Localization: O(10)-O(100) deg^2



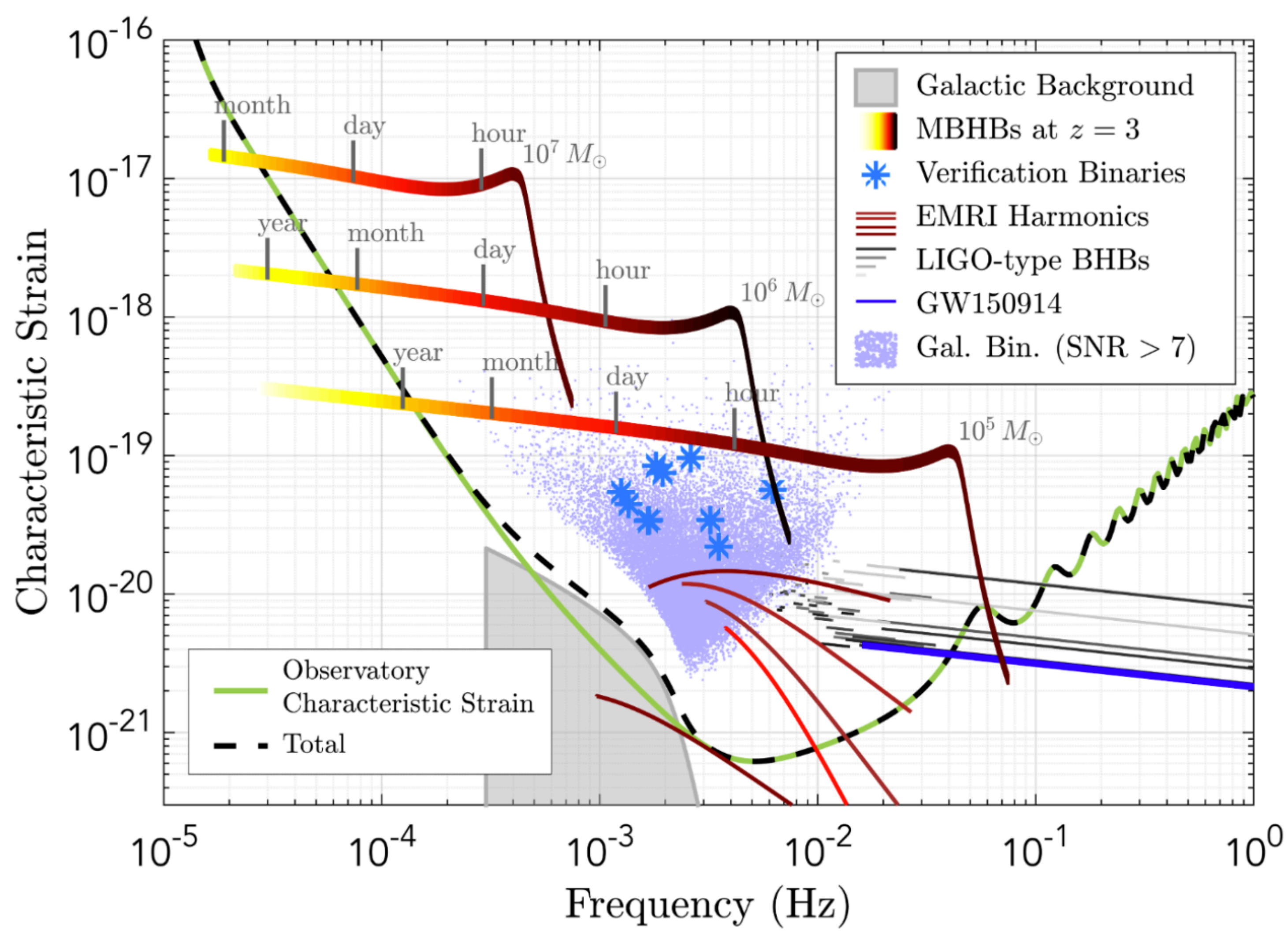
A variety of GW sources with LISA



- LISA will detect new types of sources
  - Stellar-mass binaries
  - Massive black hole binaries
  - Extreme mass-ration inspirals
- Hubble diagram out to higher redshifts

Astrophysics with LISA [2203.06016]

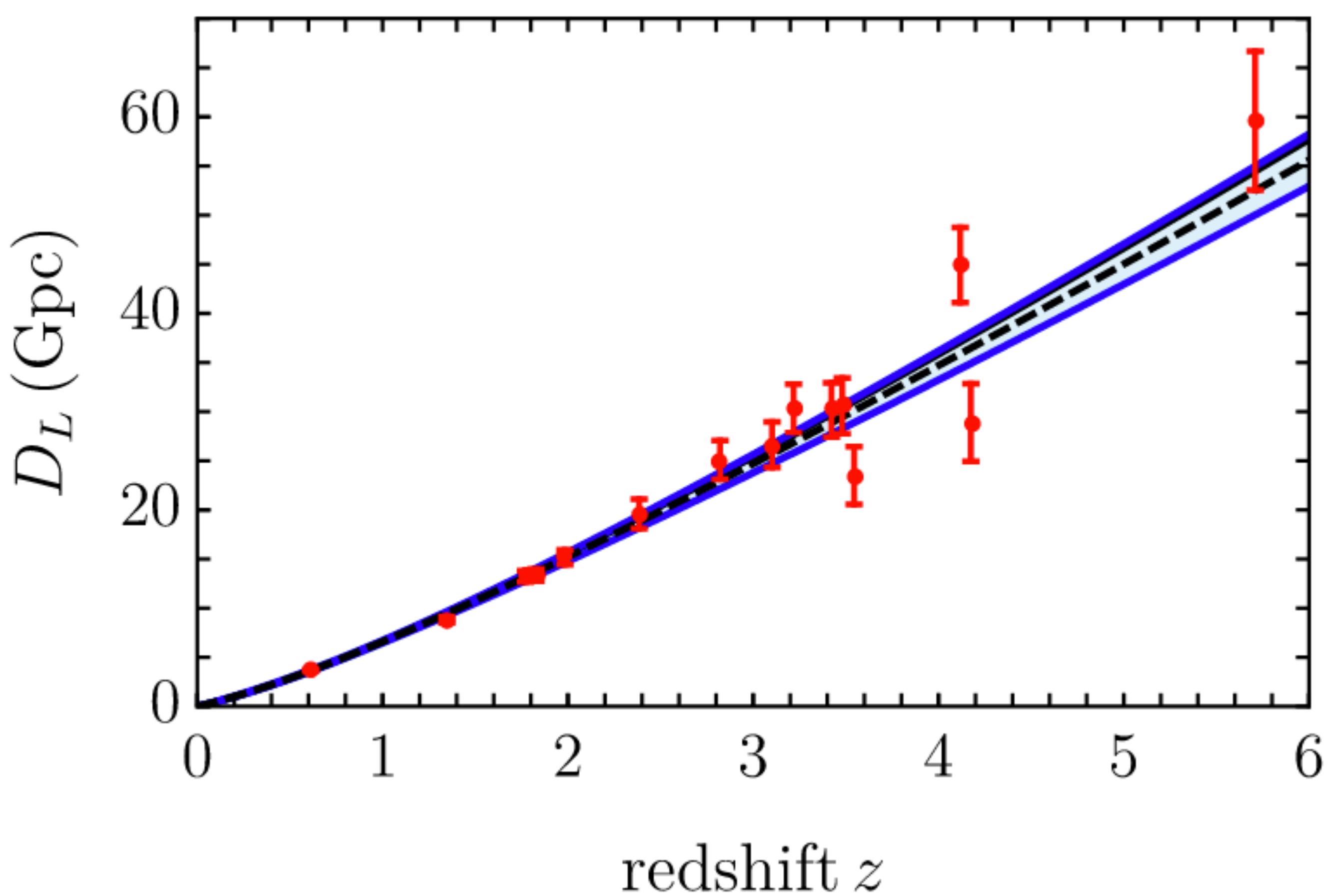
Cosmology with LISA [2204.05434]

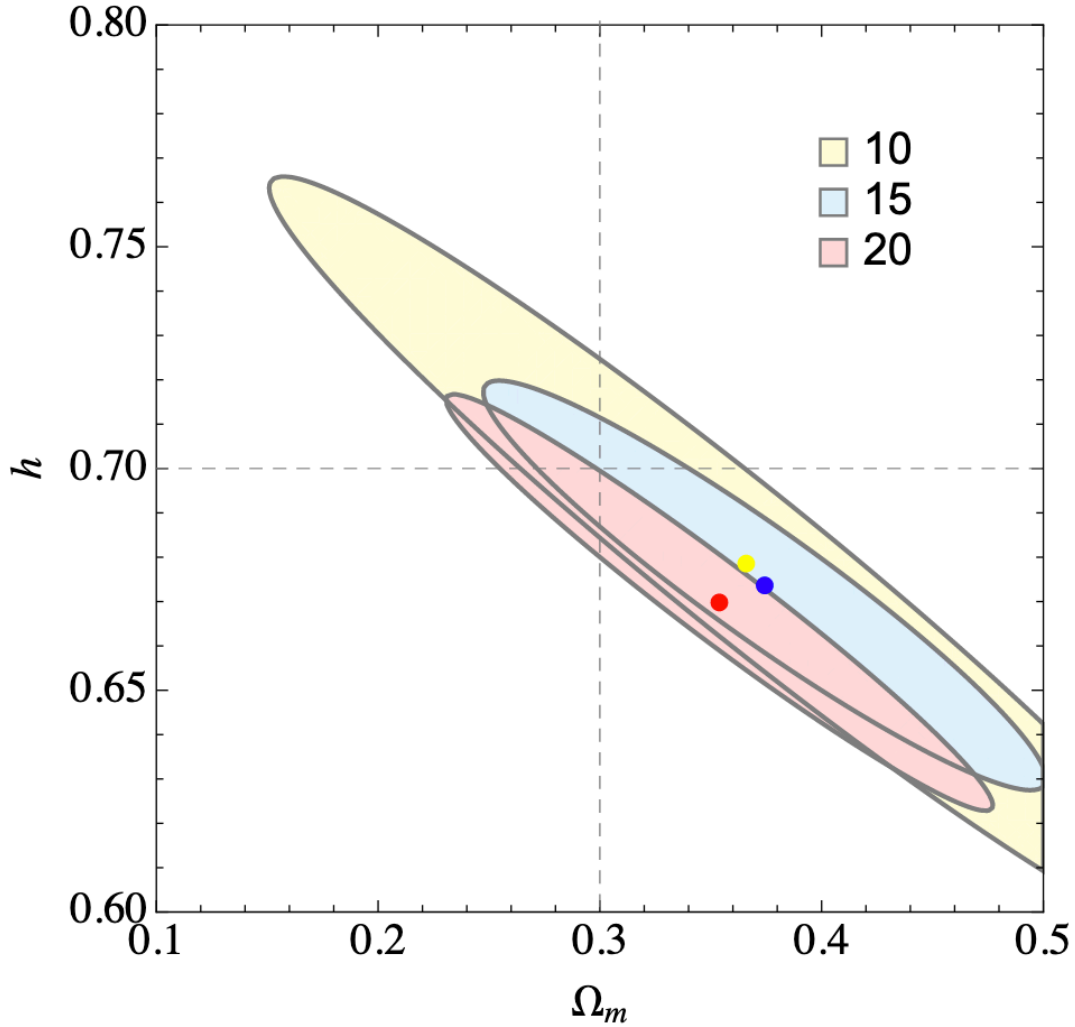


Massive black hole binaries

- Expected merger rates $10 - 100\ yr^{-1}$ [e.g. Dayal+2019; Katz+2019; Barausse, **ID**+ 2020 …]
- EM signal? $O(1)\ yr^{-1}$ [e.g. Kocsis+2006; De Rosa+2020; Mangiagli+2022 …]

[Speri+2020]



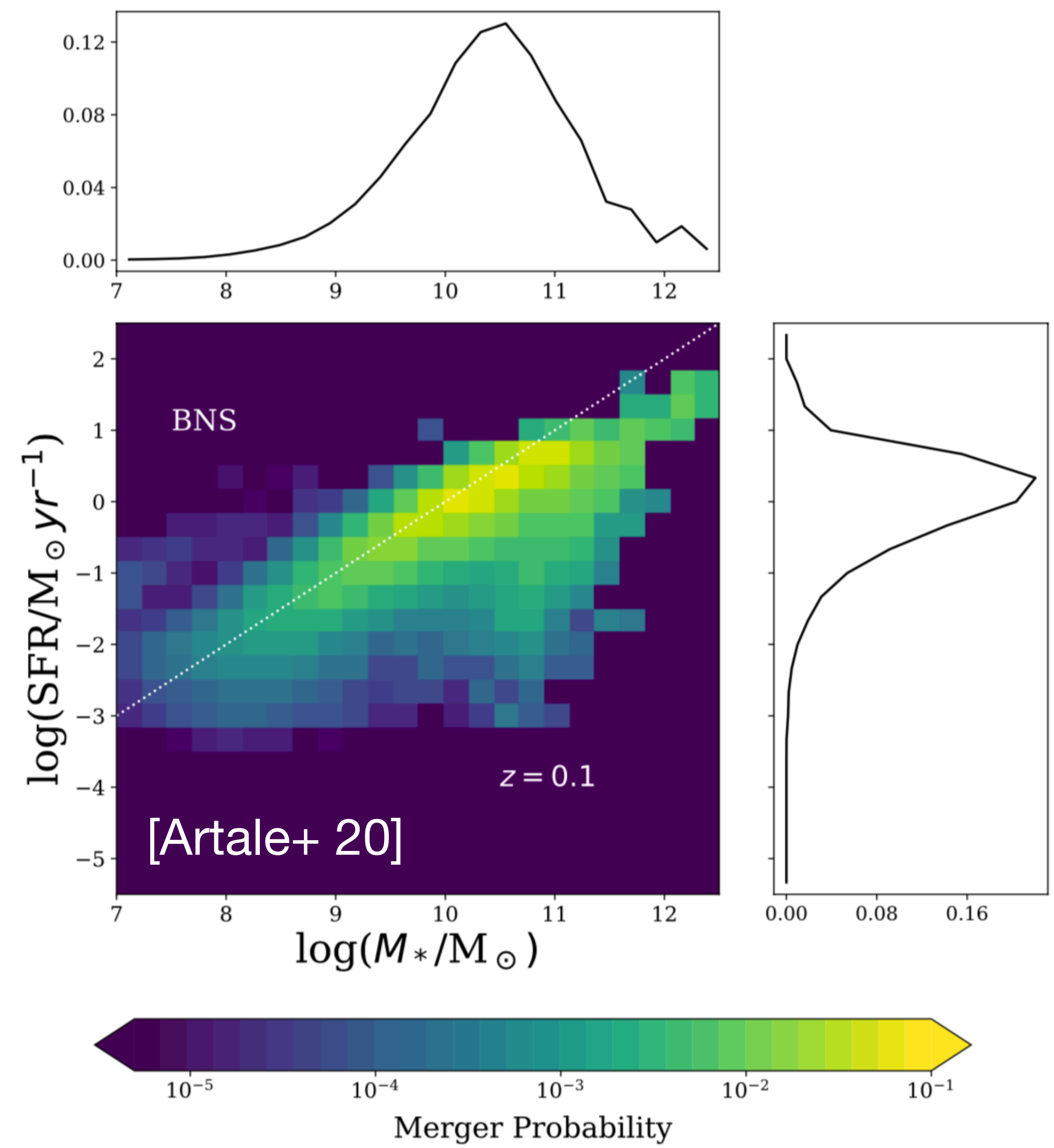


See also [Tamanini+2016; Laghi +2021; Muttoni+2022…]

How do stellar-mass compact binaries form?

- Isolated massive stellar binaries
- Hierarchical formation in dense stellar systems
- AGN disks
- Primordial black holes
- …

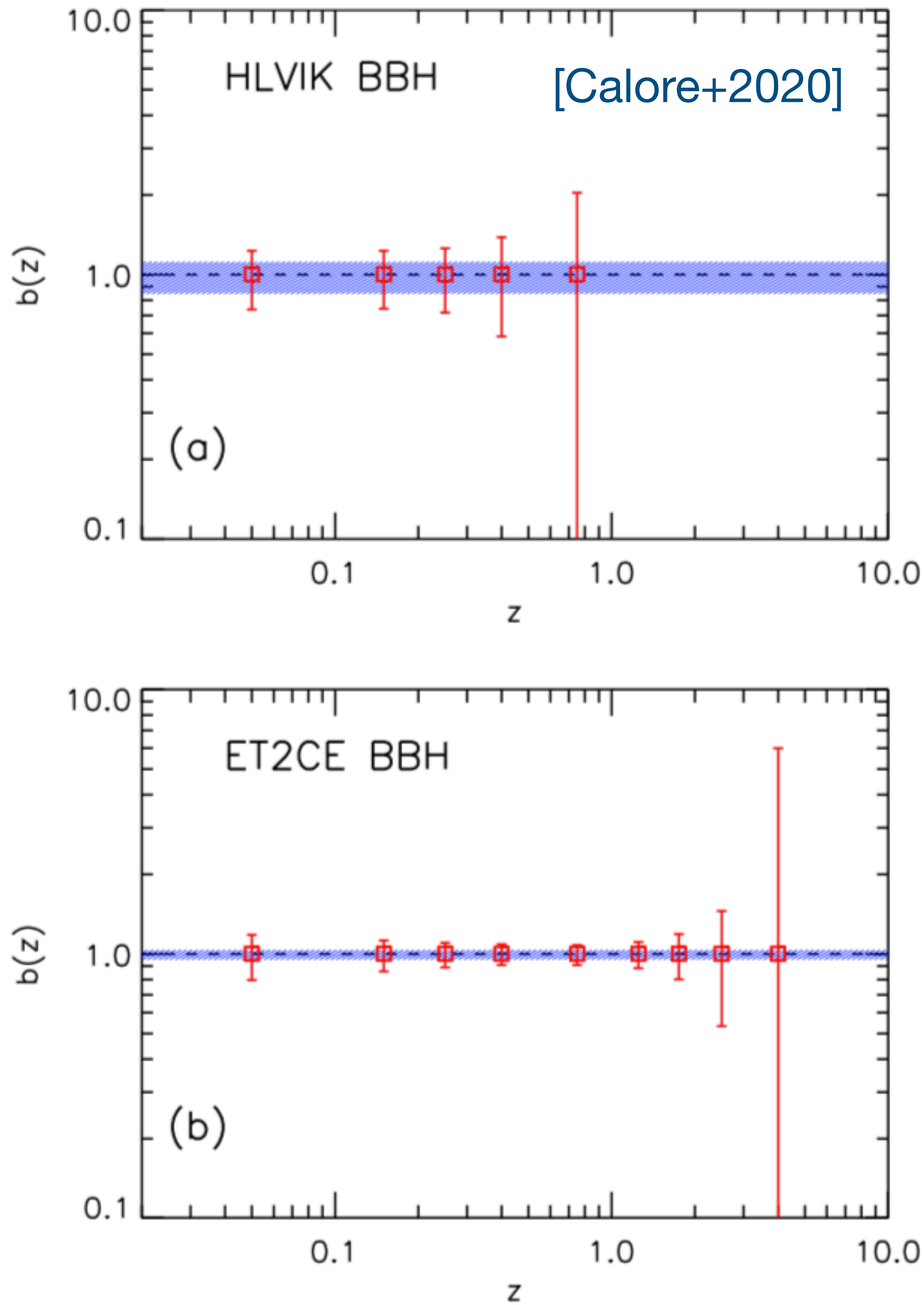
- Mass distribution
- Redshifts
- **Host galaxies**
- EM signal?



Cross-correlating GW and galaxy counts

- Stellar-mass black hole binaries: biased tracer of the galaxy distribution
- Cross-correlate the distribution of GW events and the sky-projected spatial distribution of galaxies
- Assume galaxy bias is known
- Constrain the bias of GW events

See also [Scelfo+2020, Libanore+2021, Mukherjee+2021]



A variety of new methods to study GW and LSS

- H0 determination using the spectrum of merging black holes ('spectral sirens')

$$M_c(z) = (1 + z)M_c$$ [Mastrogiovanni+2021; Ezquiaga&Holz 2022]

- Weak lensing of GW sources

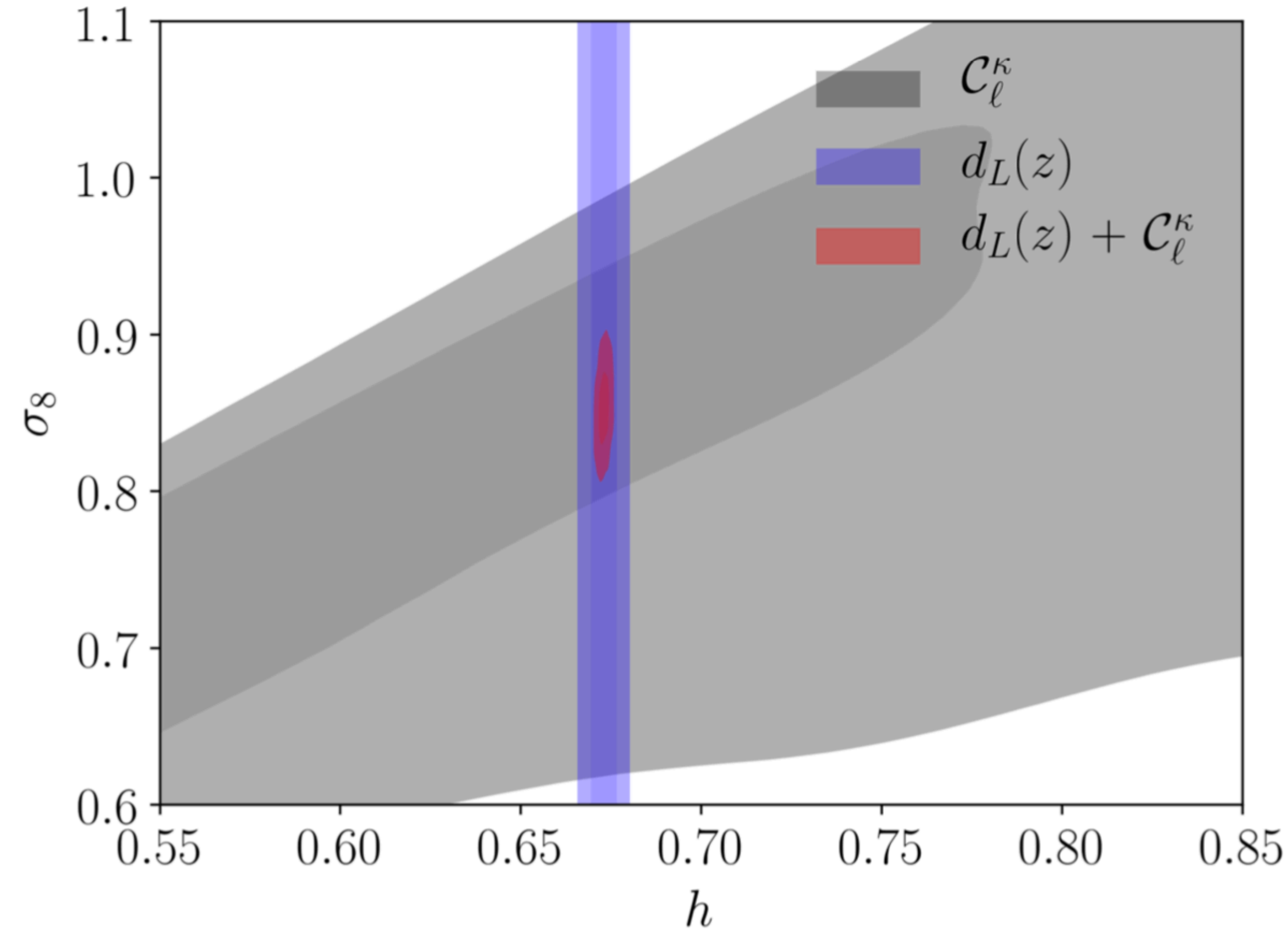
[Congedo&Taylor 2018; Balaudo+2022]

- BAO with neutron star mergers (with ET)

[Kumar+2022]

- Anisotropic stochastic backgrounds

[e.g. Bartolo+2019; Cusin, **ID**, Pitrou, Uzan 2019; Jenkins+2019; Bertacca+2020; Ricciardone+2021; Bellomo+21…]



From White Paper for Voyage2050 "High Angular Resolution GW Astronomy"

Conclusions

- New interesting science to be done with GW!
- Standard sirens can be used to constrain cosmological parameters.

  Caveat: expect few EM counterparts, will need to rely on dark sirens.
- GW sources are a new biased tracer of the galaxy distribution.
- Synergy between GW and EM observatories is crucial