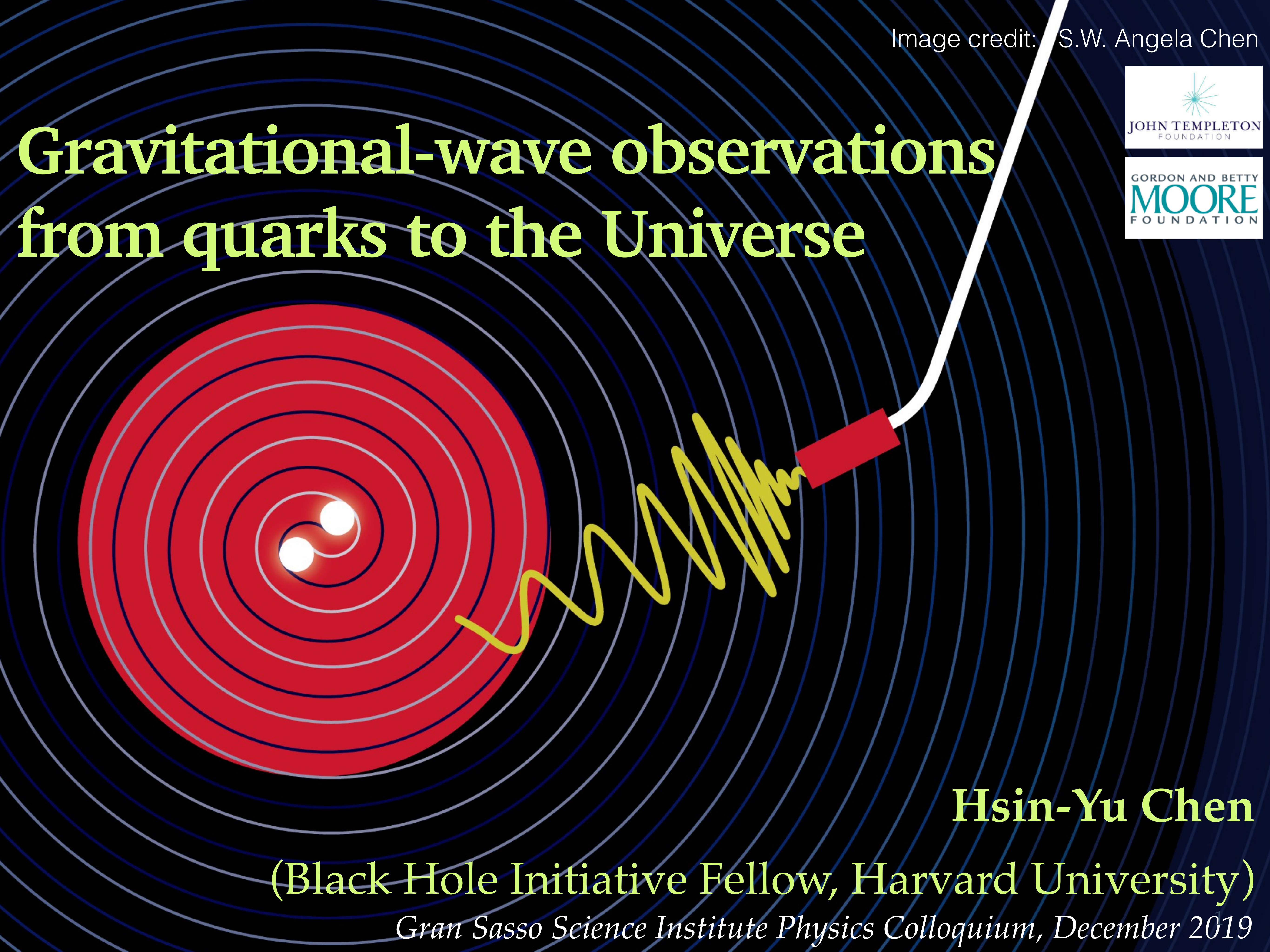


Image credit: S.W. Angela Chen

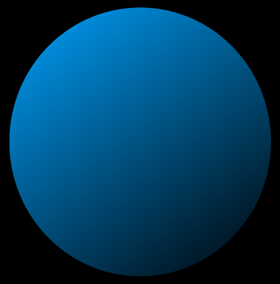
JOHN TEMPLETON FOUNDATION
GORDON AND BETTY MOORE FOUNDATION

Gravitational-wave observations from quarks to the Universe

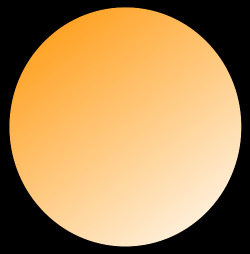
Hsin-Yu Chen

(Black Hole Initiative Fellow, Harvard University)

Gran Sasso Science Institute Physics Colloquium, December 2019

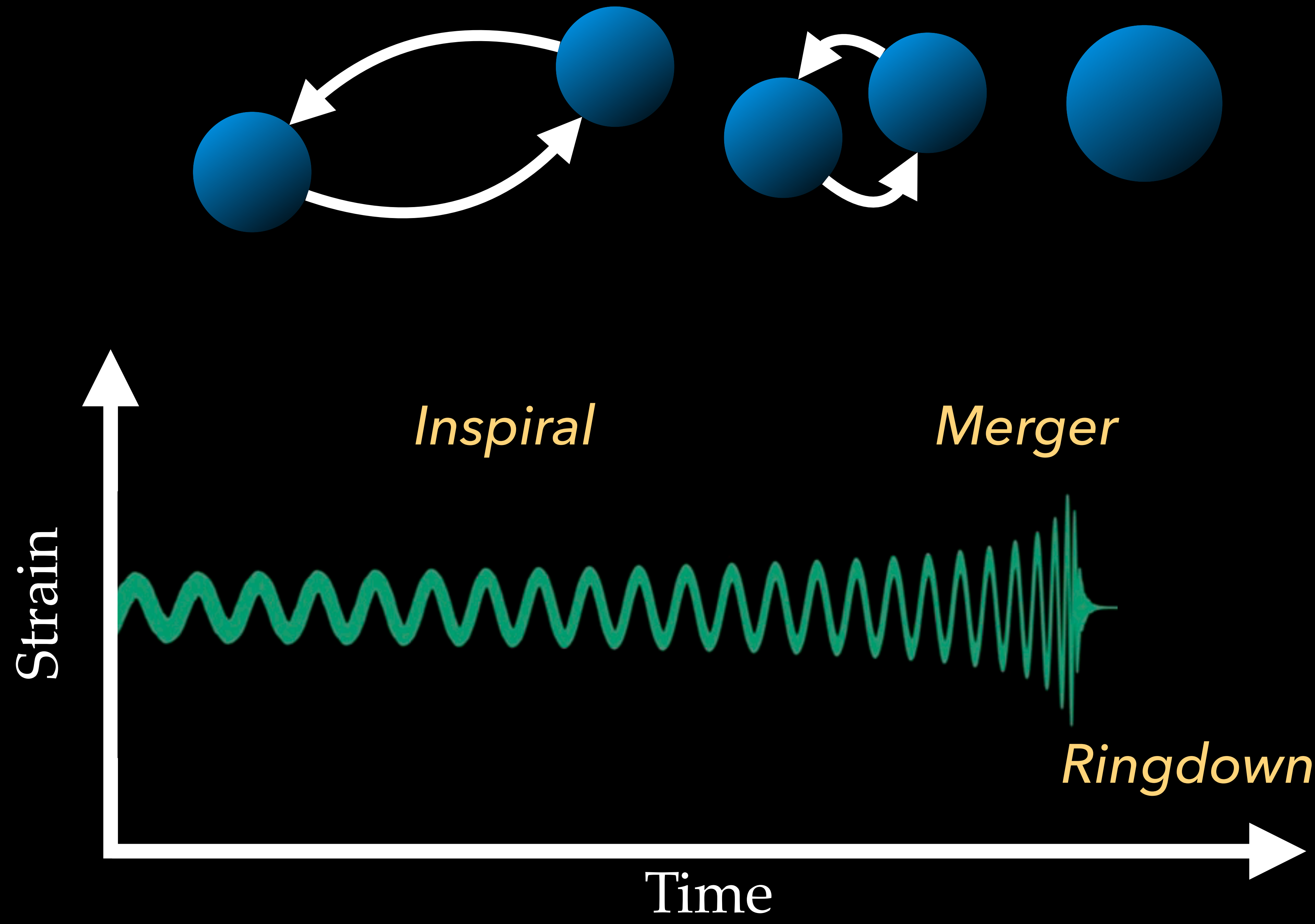


This is a black hole.

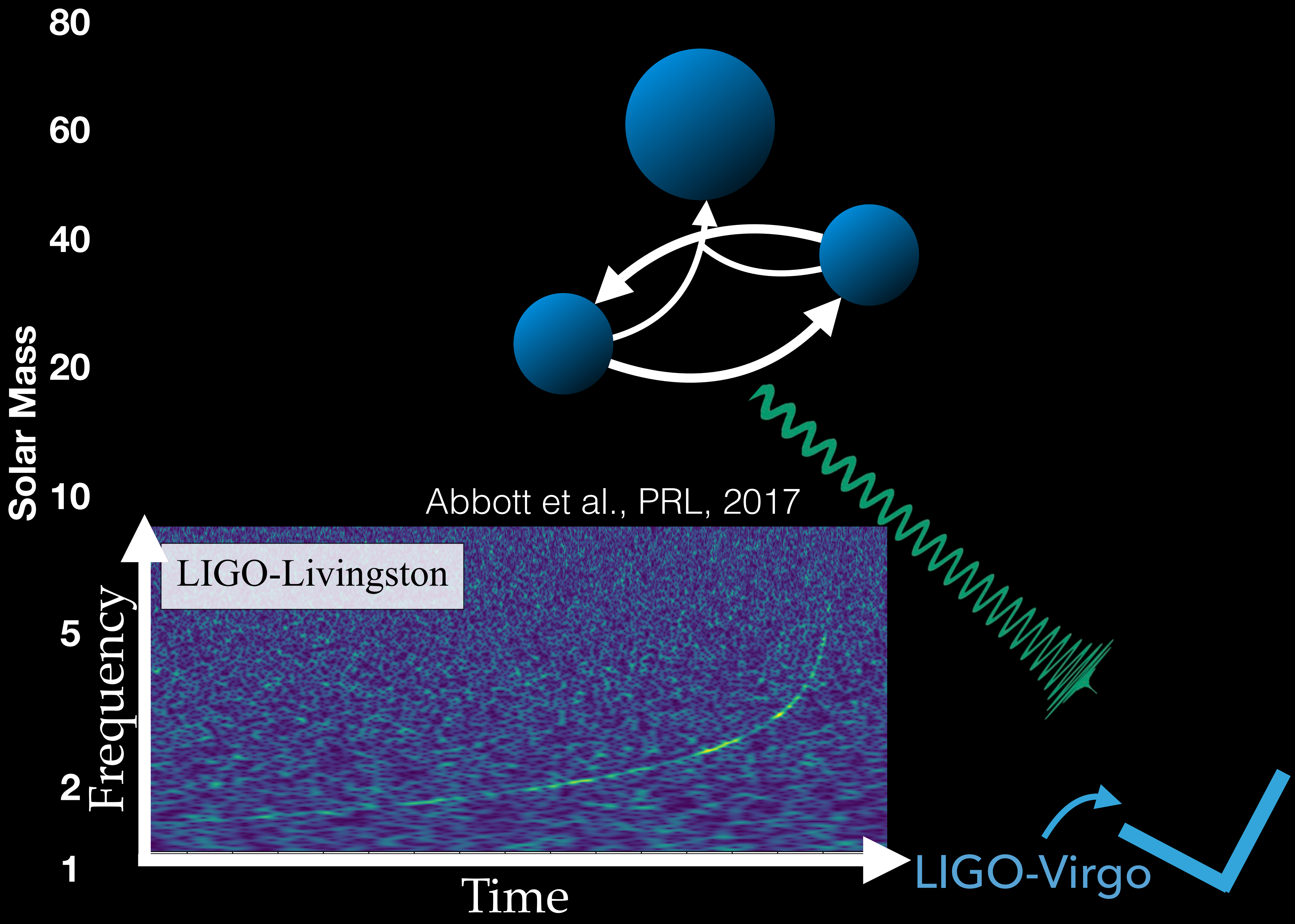


This is a neutron star.

Information is encoded in the gravitational waveforms

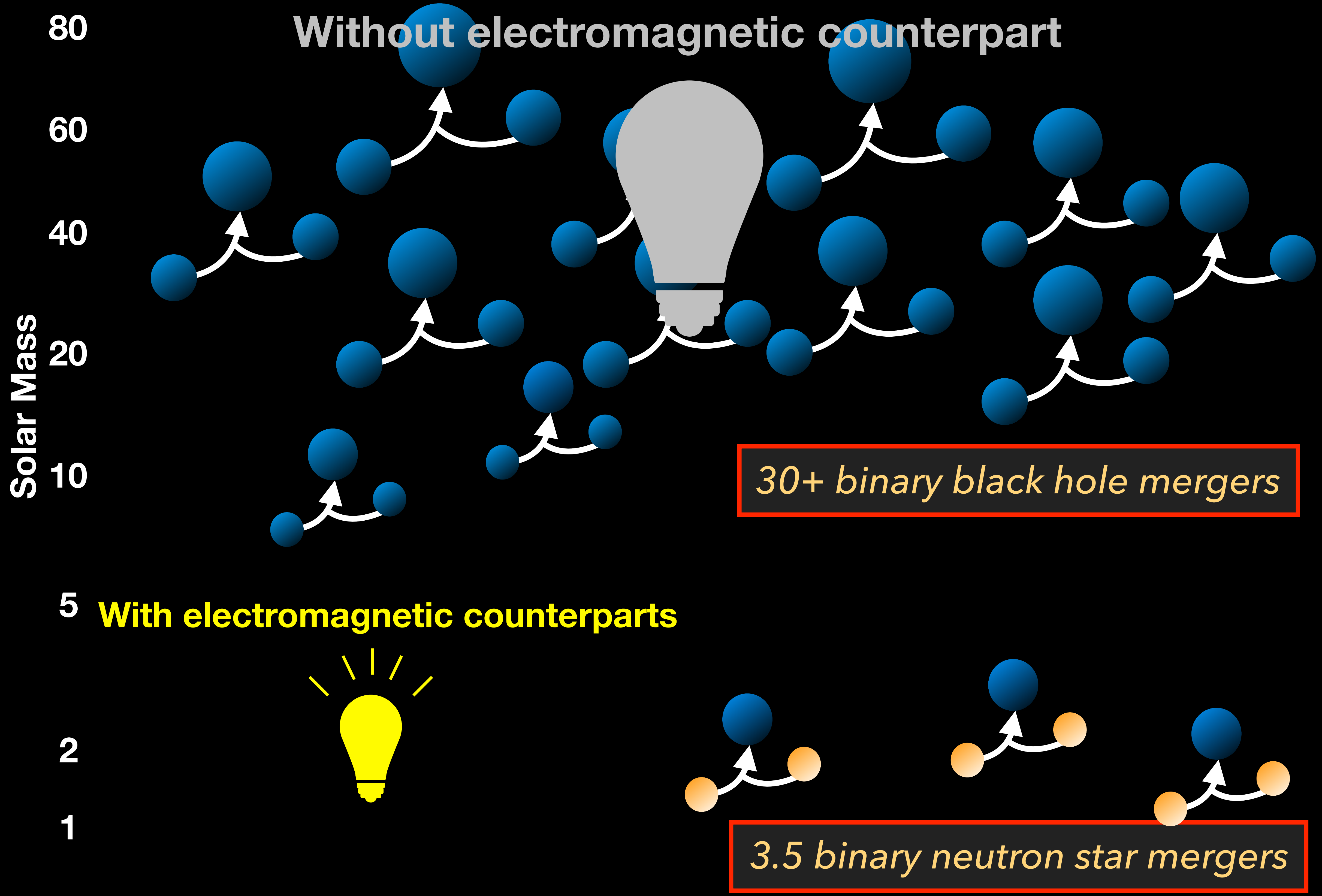


Gravitational-wave sources detected by LIGO-Virgo



Abbott et al., PRL, 2017

Gravitational-wave sources detected by LIGO-Virgo



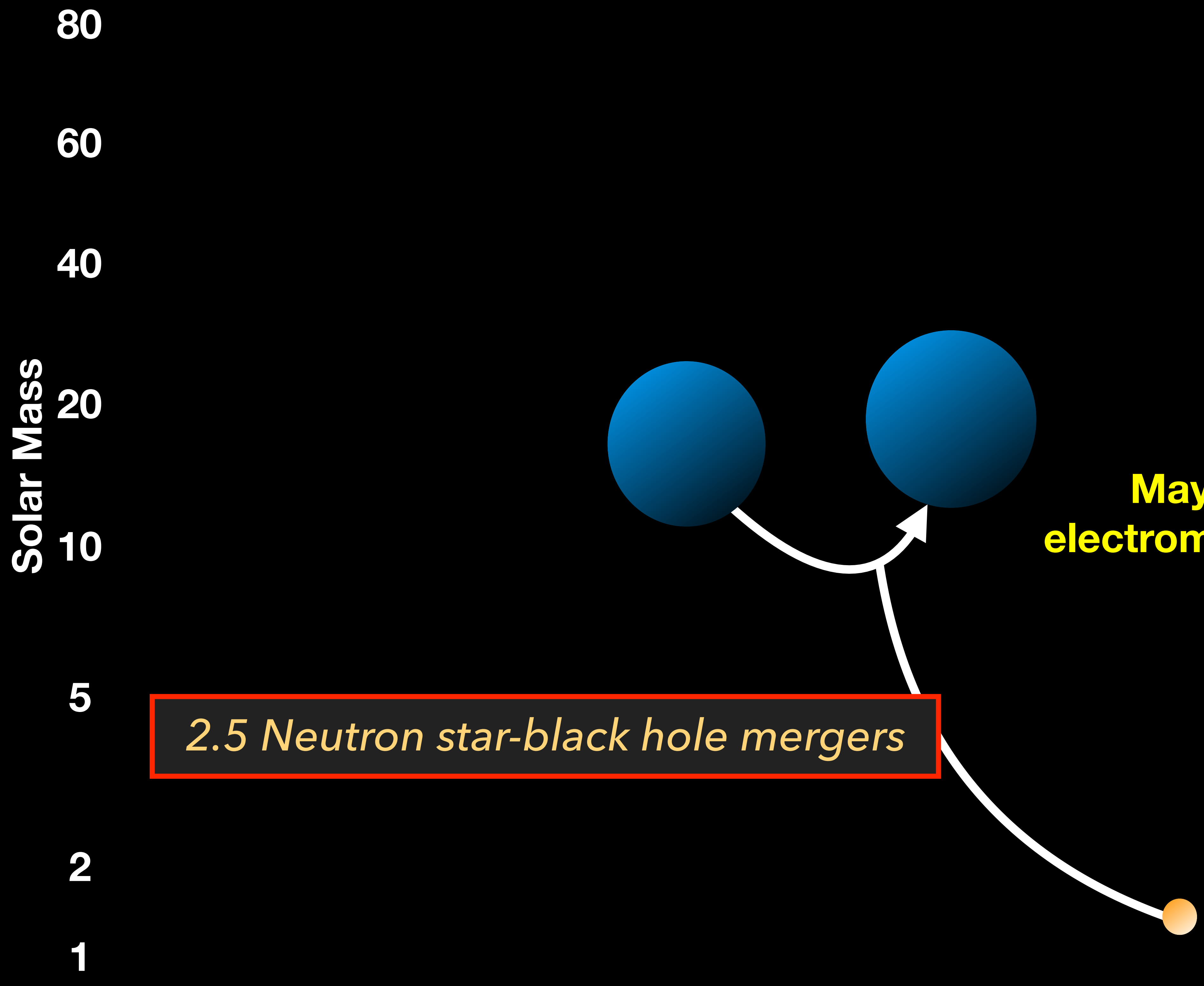
Without electromagnetic counterpart

30+ binary black hole mergers

With electromagnetic counterparts

3.5 binary neutron star mergers

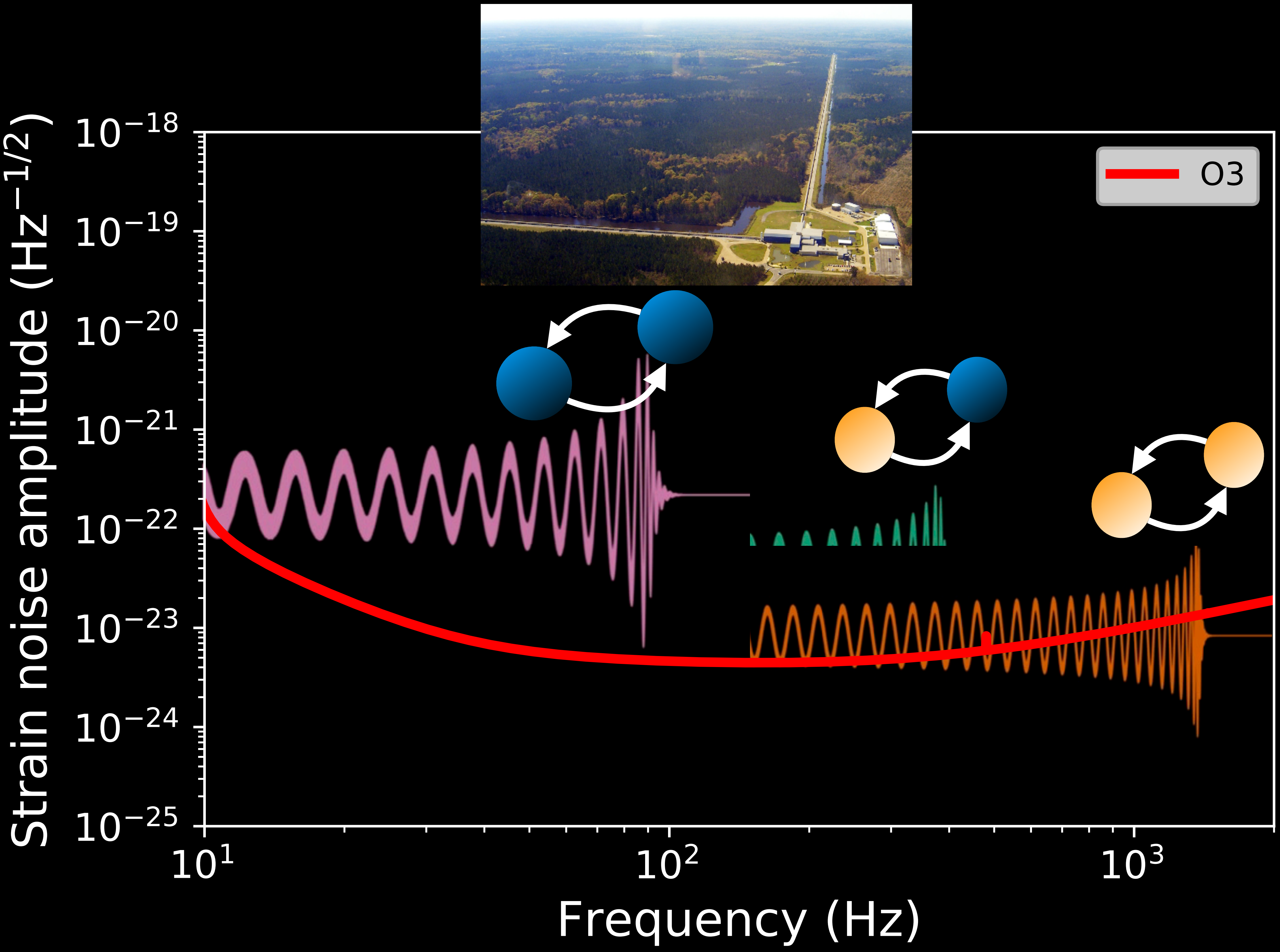
Gravitational-wave sources detected by LIGO-Virgo



2.5 Neutron star-black hole mergers

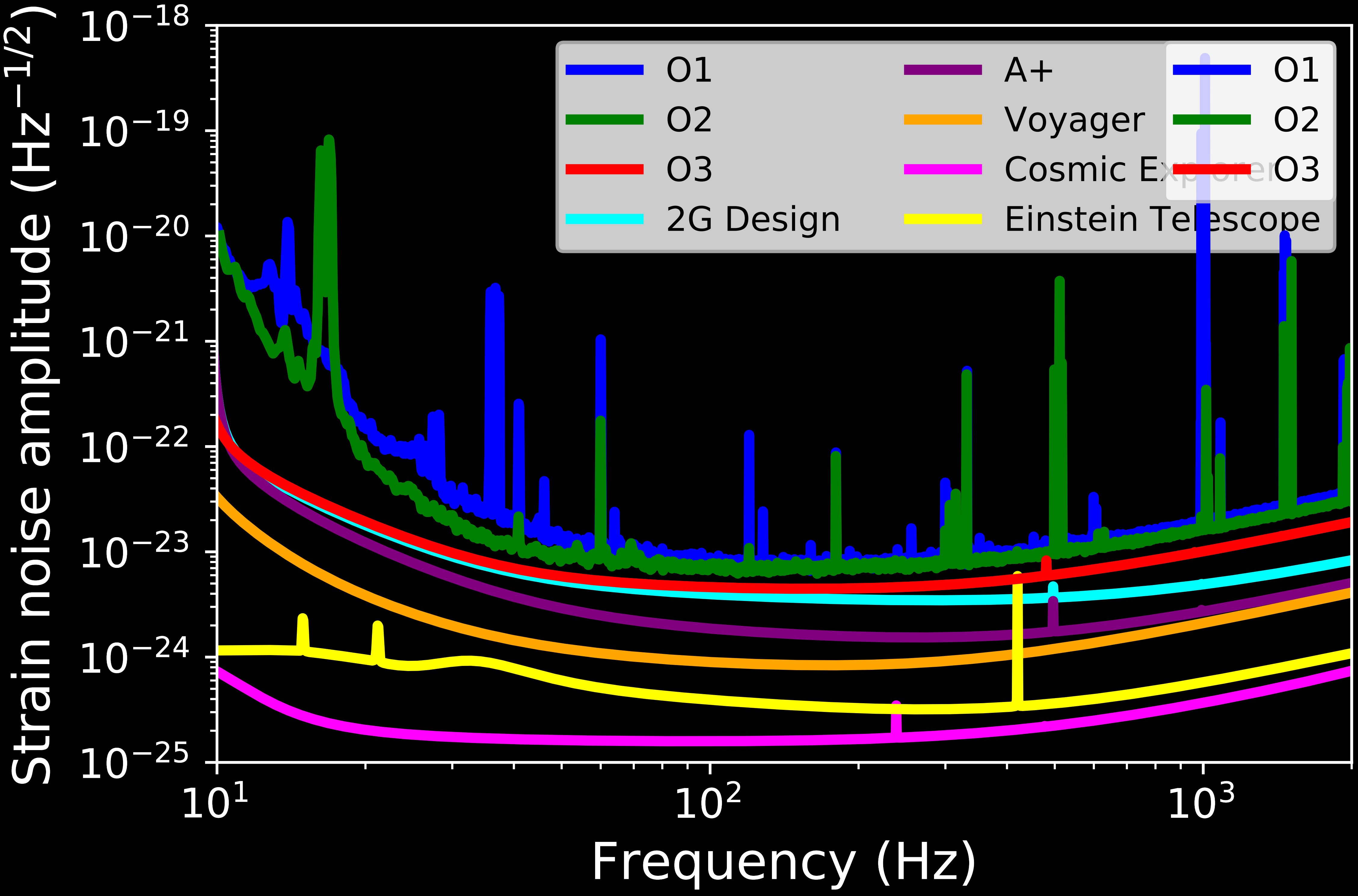
May or may not have electromagnetic counterparts

Gravitational-wave detector sensitivities



LIGO Lab/LIGO Document T1500293

Gravitational-wave detector sensitivities



Upgrade of gravitational-wave detector

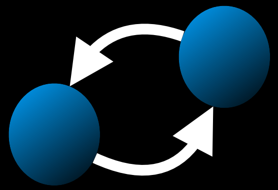
2G 3G

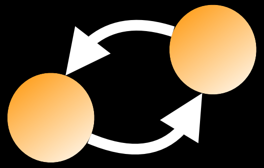
2019 2022 2026 2030

O3 A+ Voyager CE/ET

Number of detections a year:

BH-BH	O(10)	O(1000)	O(100,000)	O(100,000)
NS-NS	O(1)	O(100)	O(1000)	O(1,000,000)

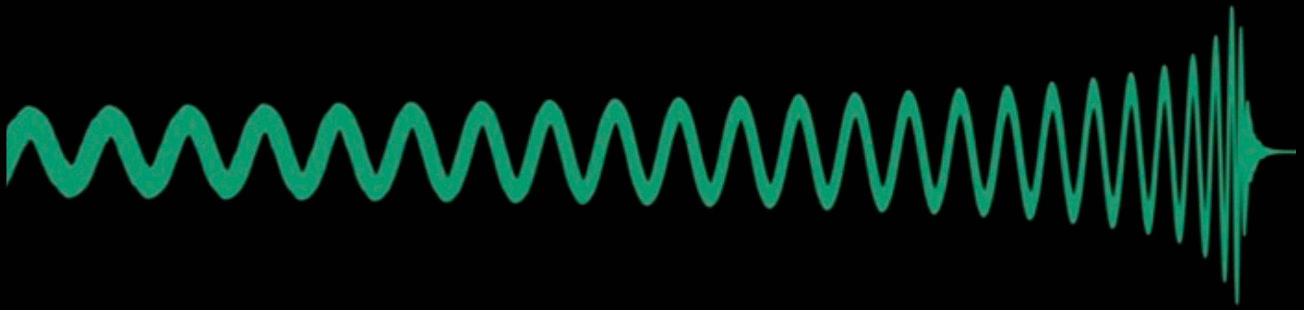




http://gwc.rcc.uchicago.edu Chen et al, 2017

Gravitational-wave cosmology with the standard sirens

Direct measurement of the luminosity distance



Luminosity Distance∝1/Amplitude

-Constrain the cosmological parameters with the redshift and luminosity distance:

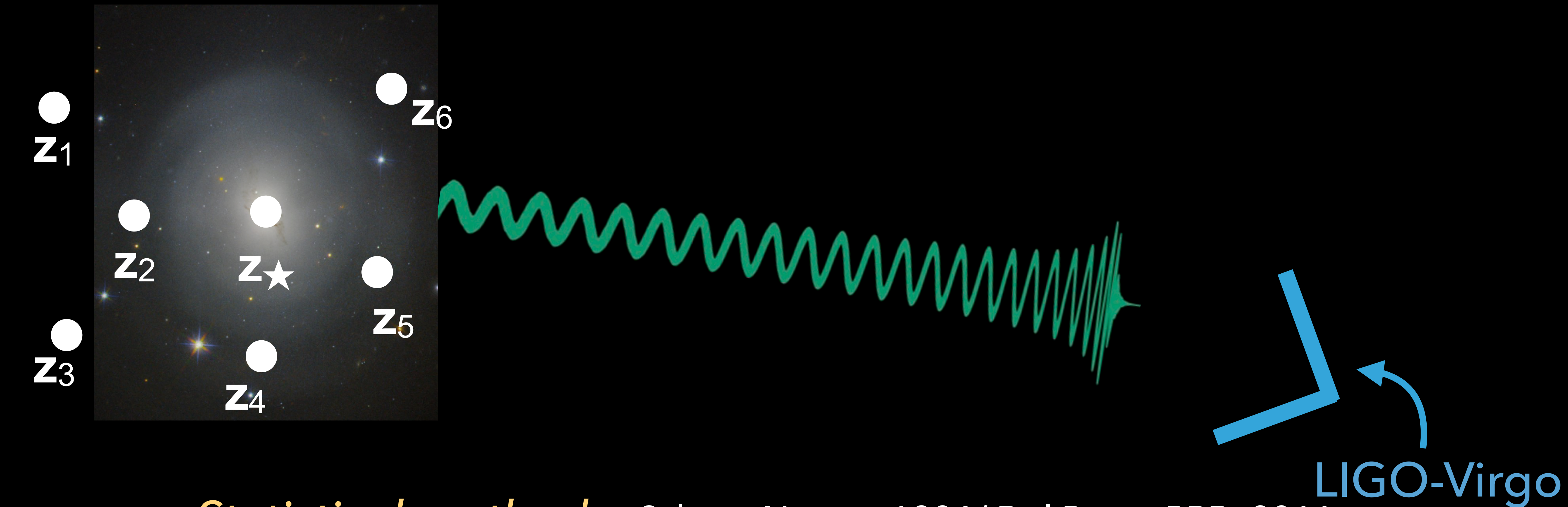
$$D_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

$$H(z) = H_0\sqrt{\Omega_{\rm M}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w_0+w_a)}e^{-3w_a z/(1+z)}}$$

-Mass, sky location, and binary orientation also affect the amplitude, however these parameters can either be determined independently or marginalized out.

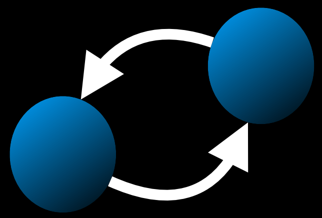
Schutz, Nature, 1986

Determine the redshift of gravitational-wave source with the host galaxy



Statistical method: Schutz, Nature, 1986/ Del Pozzo,PRD, 2011

Combine the redshifts of all possible host galaxies.



-GW170814: $H_0 = 75.2^{+39.5}_{-32.4}\,\mathrm{km/s/Mpc}$

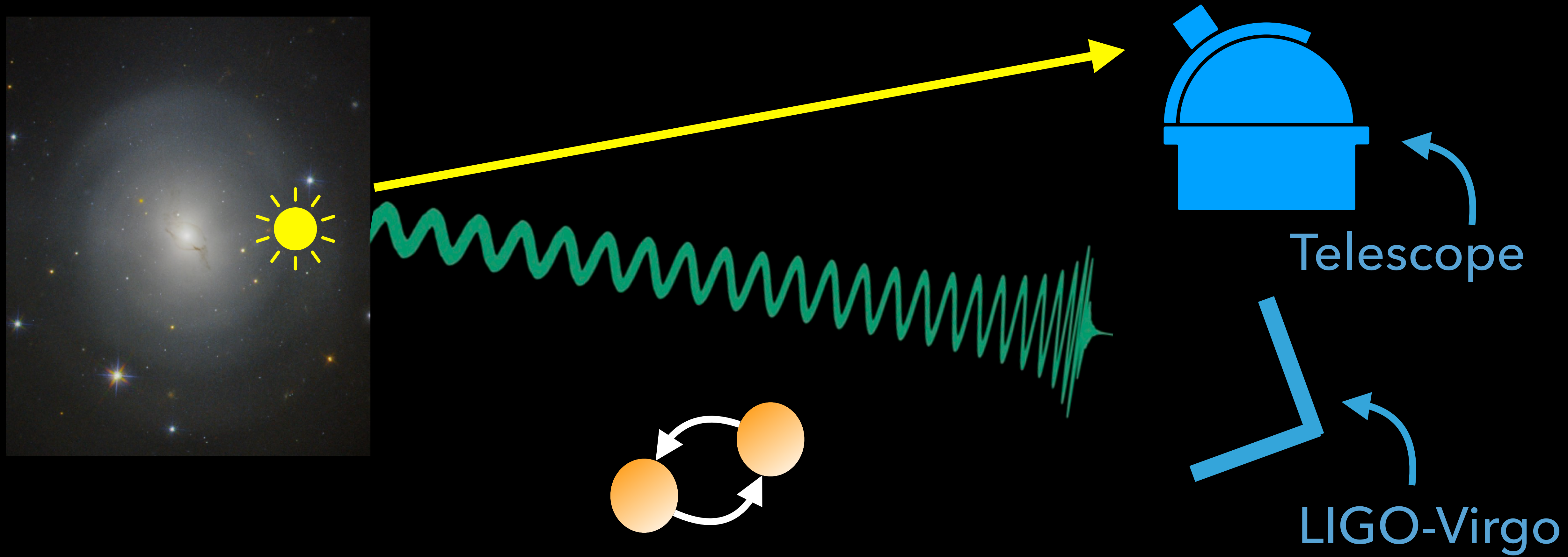
(Dark Energy Survey Year 3 data)

DES & LVC, 2019

-GW170817: $H_0 = 76^{+48}_{-23}\,\mathrm{km/s/Mpc}$

Fishbach, ~Chen et al., ApJL, 2019

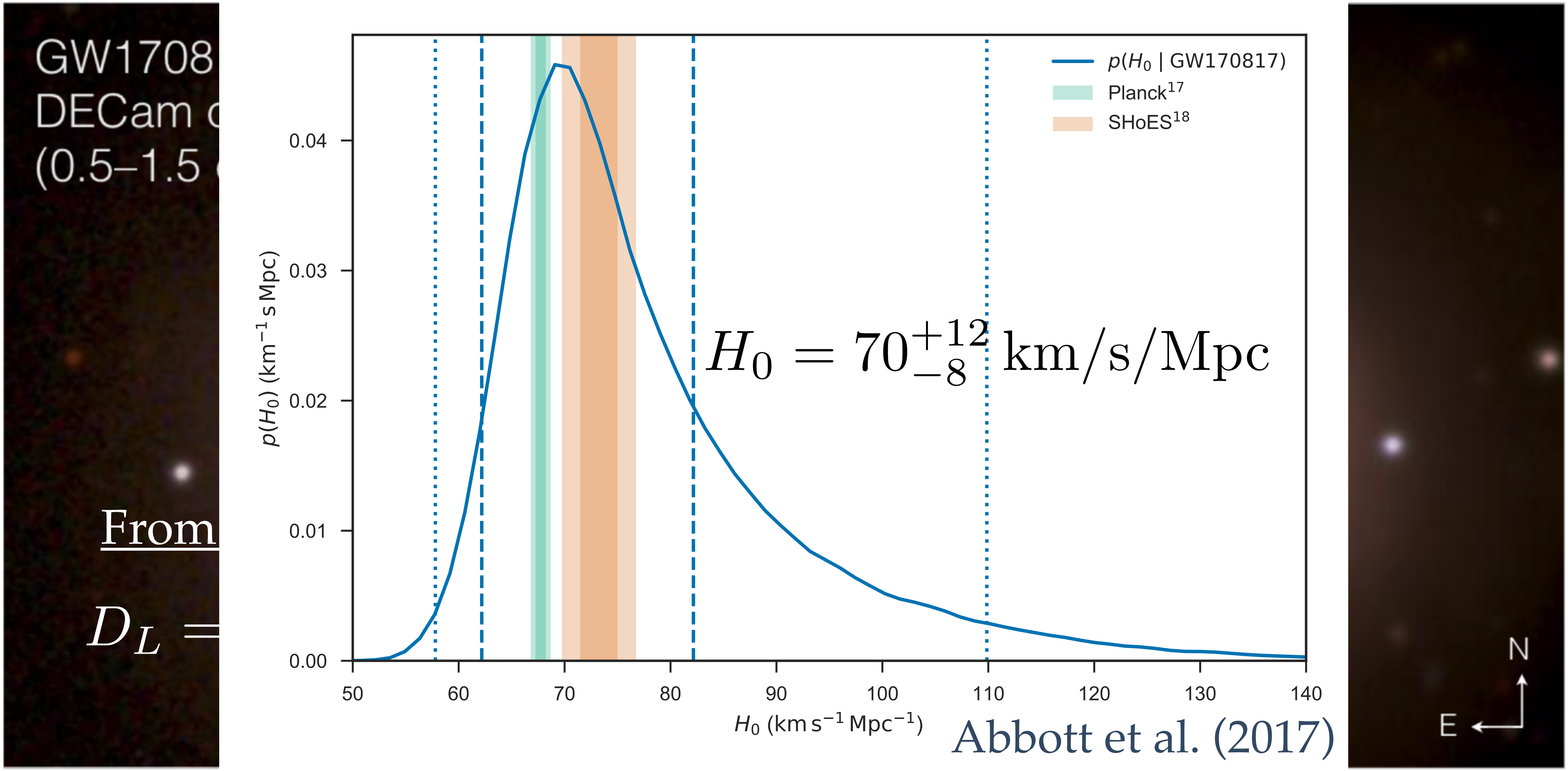
Determine the redshift of gravitational-wave source with the host galaxy



Counterpart method:
Find the host galaxy of the electromagnetic counterpart.

Schutz, Nature, 1986 / Holz & Hughes, ApJ, 2005

The first standard siren measurement with an electromagnetic counterpart

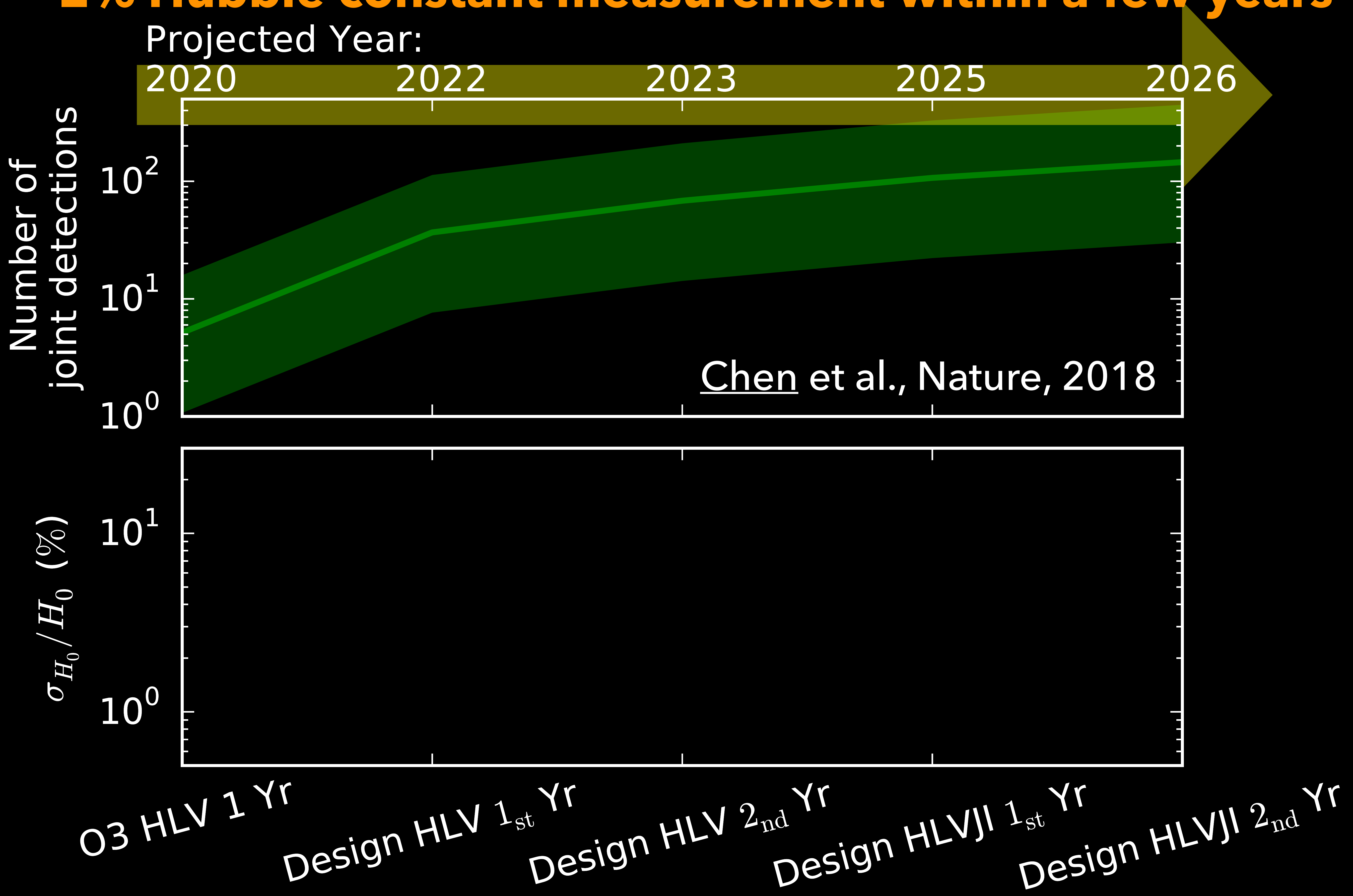


$$H_0 = 70^{+12}_{-8}\ \mathrm{km/s/Mpc}$$

Abbott et al. (2017)

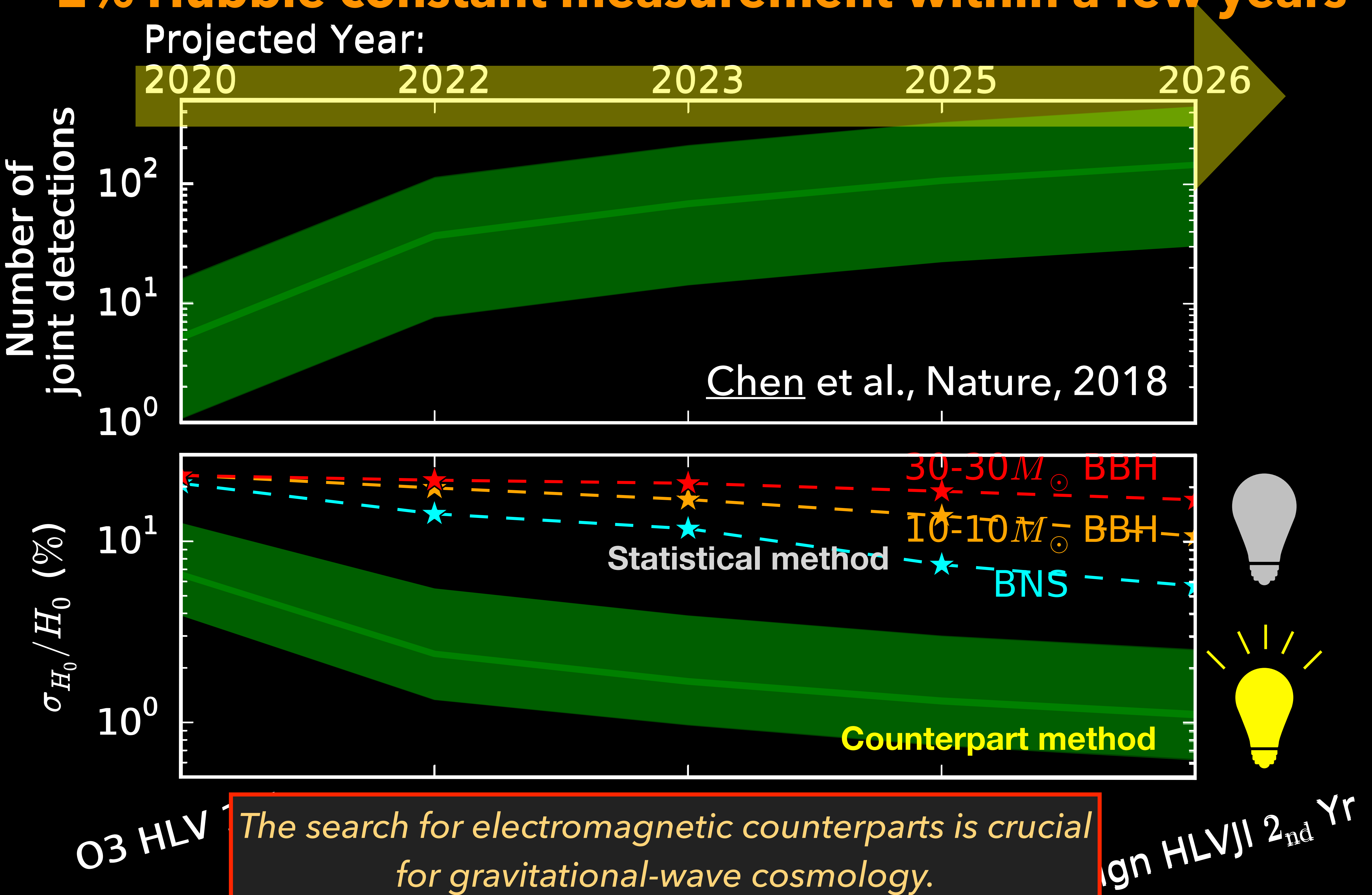
Soares-Santos, ~, Chen+, ApJL, 2017

2% Hubble constant measurement within a few years



Chen et al., Nature, 2018

2% Hubble constant measurement within a few years



The search for electromagnetic counterparts is crucial for gravitational-wave cosmology.

Why is it difficult to find the electromagnetic counterpart?

-We don’t know where it is on the sky.

-The counterpart emissions fade away.

-Rapid sky localization.

Singer et al, ApJ, 2014
Singer, Chen et al, ApJL, 2016
Chen and Holz, ApJ, 2017
Chen and Holz, 2016

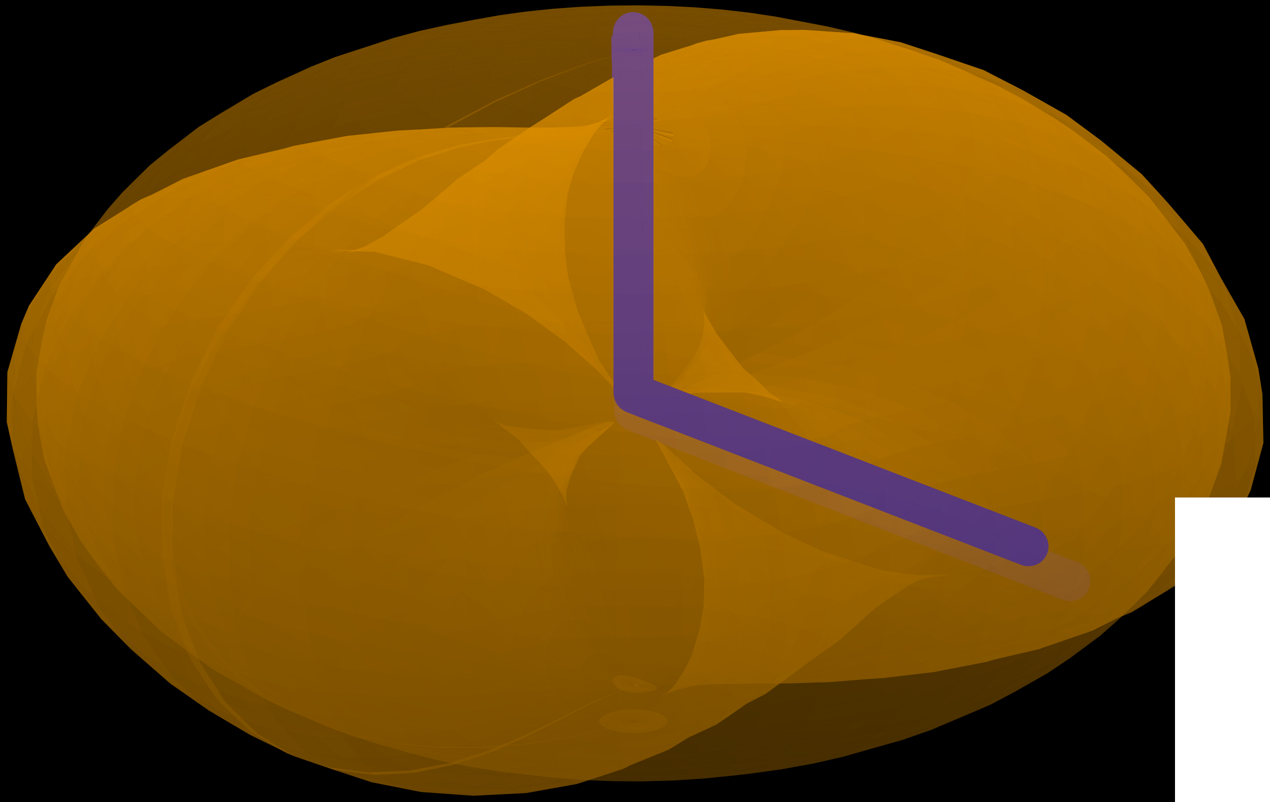
Gravitational-wave weather forecast

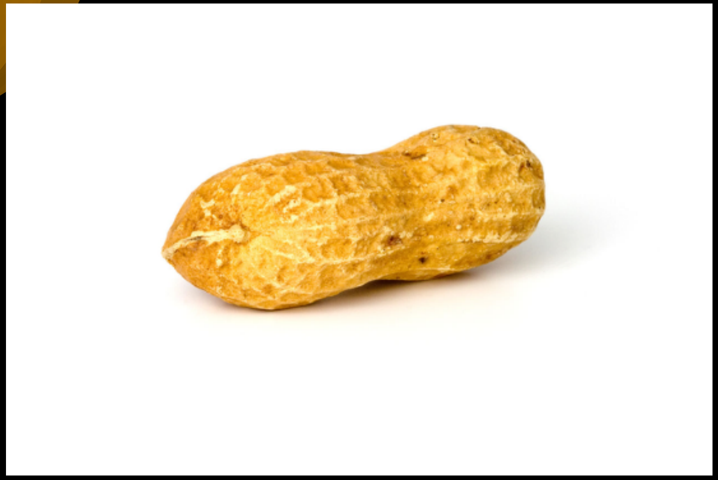
We can anticipate ***from where on the sky*** *the events will most likely come* ***at a given time****.*

Chen, Essick et al., ApJ, 2017

Gravitational-wave weather forecast

-Spatial selection effect: Antenna Patterns

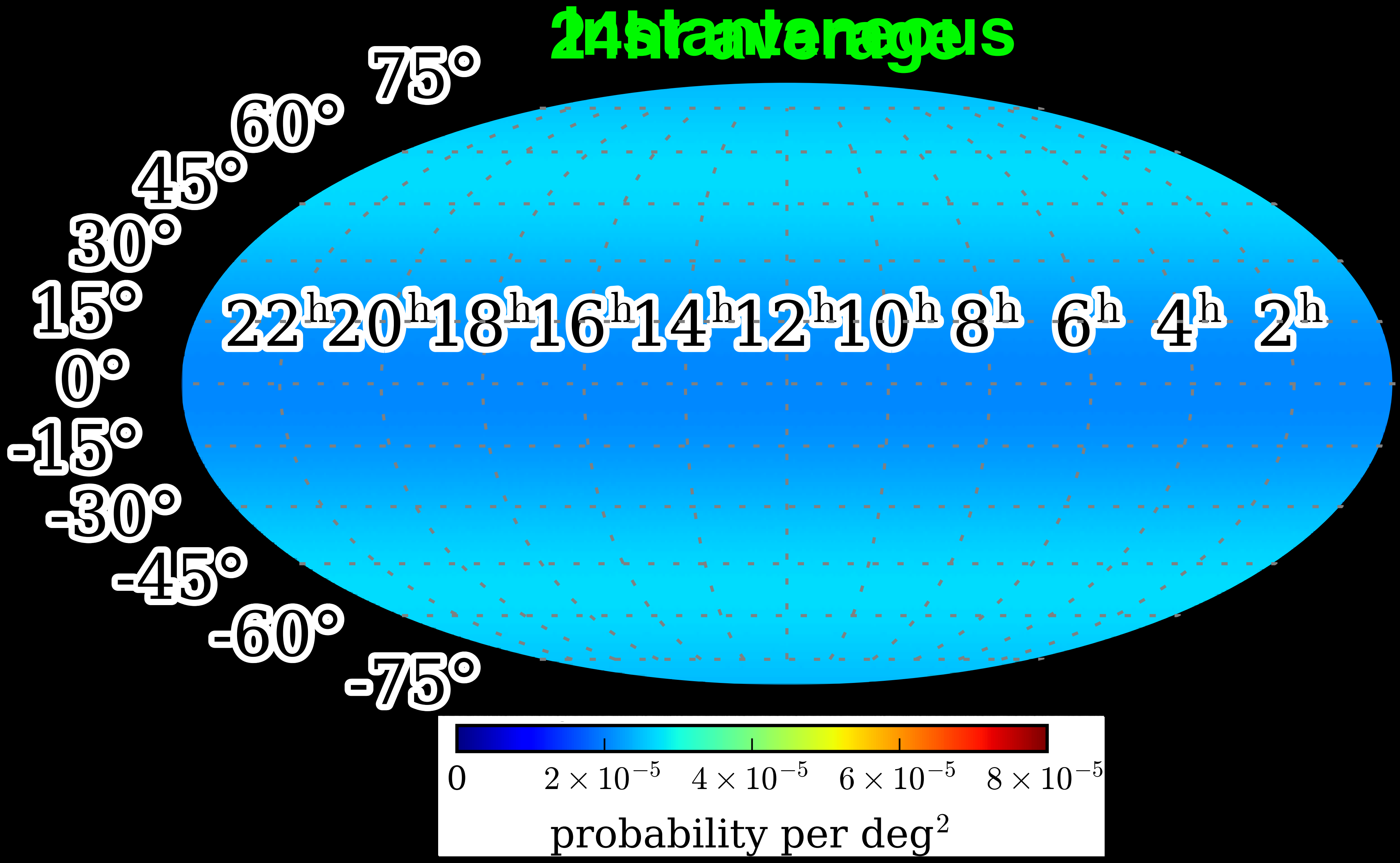




<u>Chen</u>, Essick et al., ApJ, 2017

Gravitational-wave weather forecast

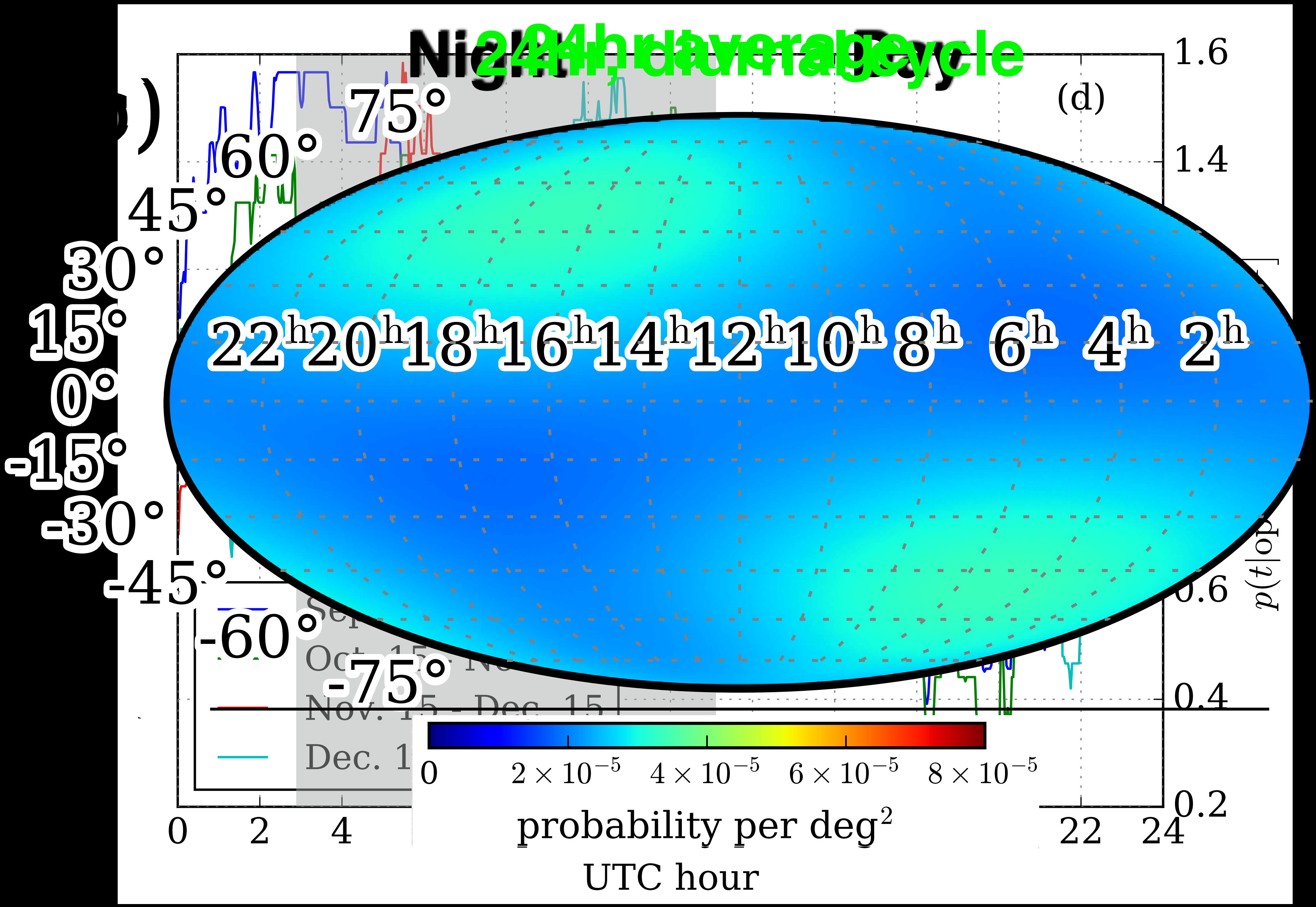
-Spatial selection effects: Antenna Patterns



Chen, Essick et al., ApJ, 2017

Gravitational-wave weather forecast

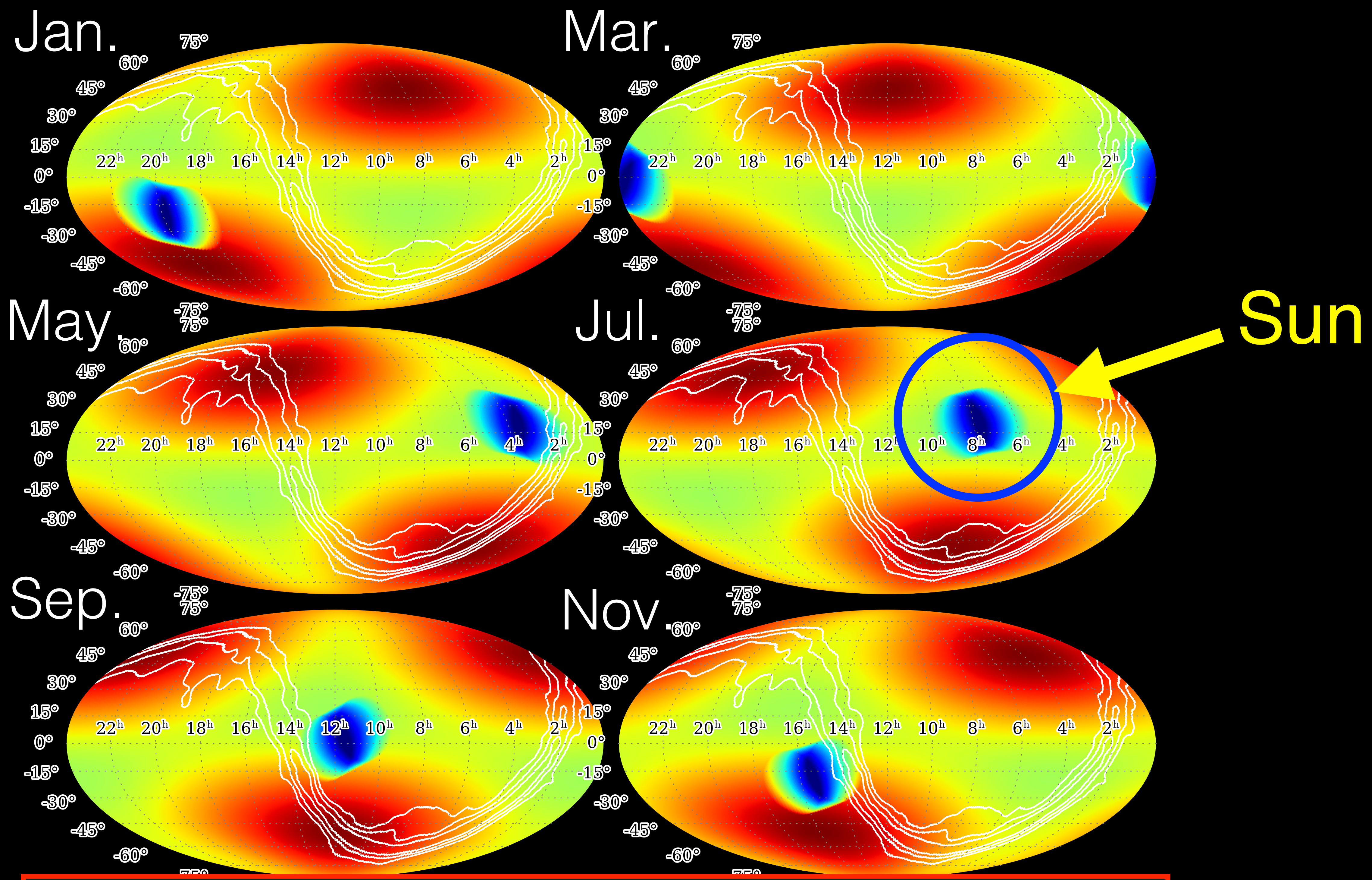
-Temporal selection effect: Diurnal cycle



Chen, Essick et al., ApJ, 2017

Chen, Essick et al., ApJ, 2017

Gravitational-wave weather forecast



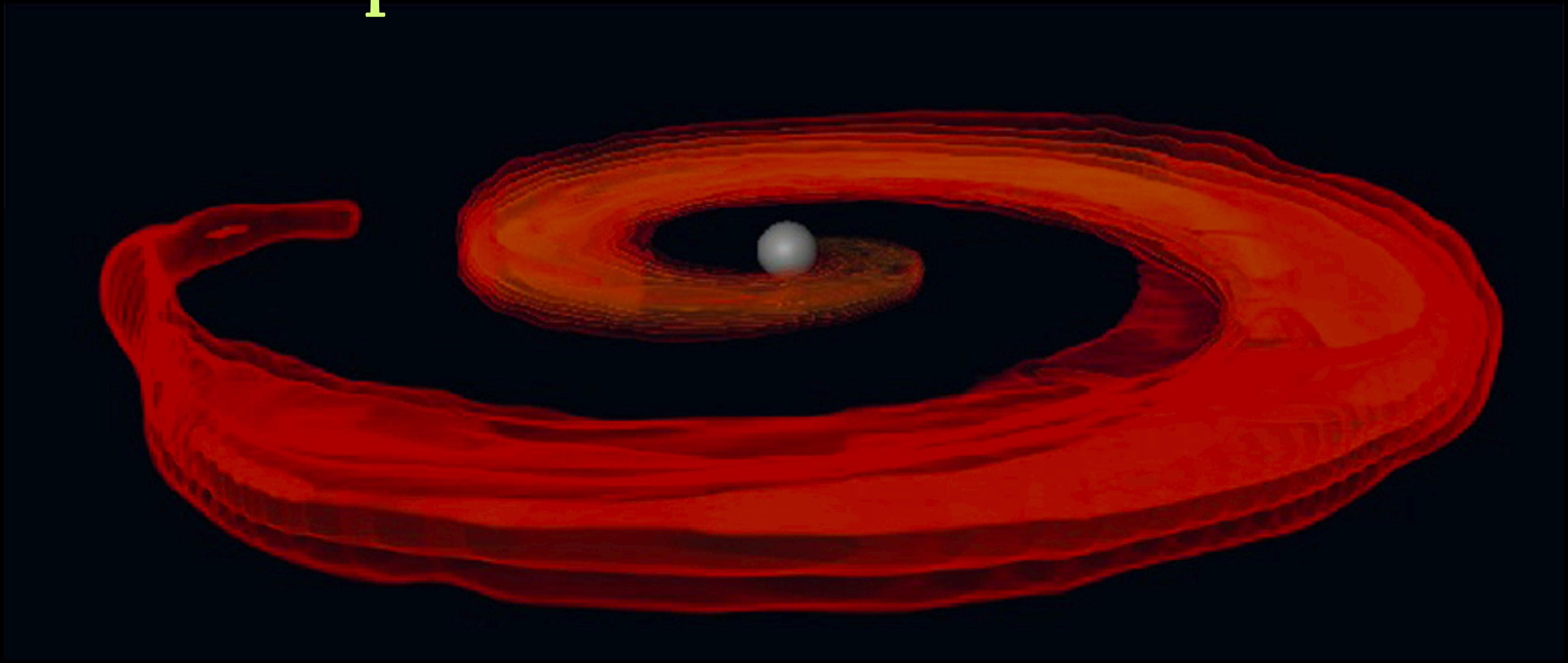
Sun

This method has already been implemented on the Swift Gamma-Ray Burst satellite observatory.

Image credit: A. Tonita, L. Rezzolla, F. Pannarale

Electromagnetic Follow-up

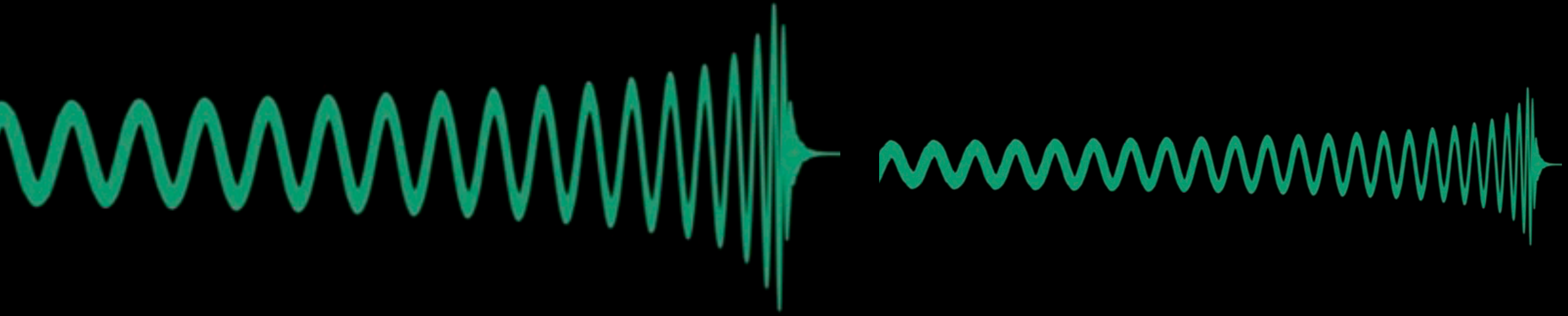
- Combine the detector characteristics, source properties and electromagnetic emission modeling to maximize the probability of successful follow-up.



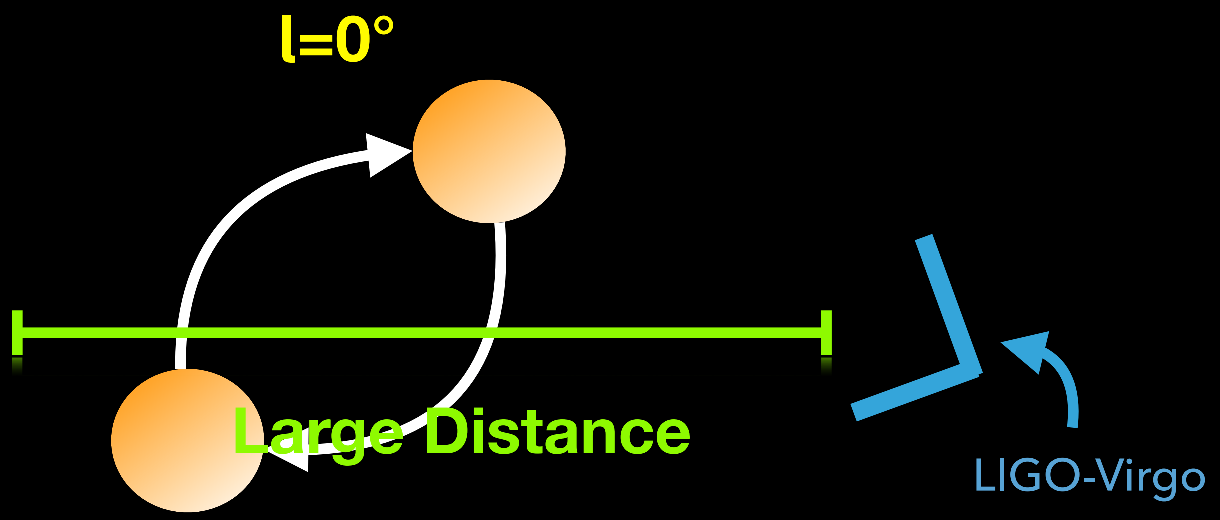
Improve the precision of standard sirens

-Break the distance-inclination degeneracy.

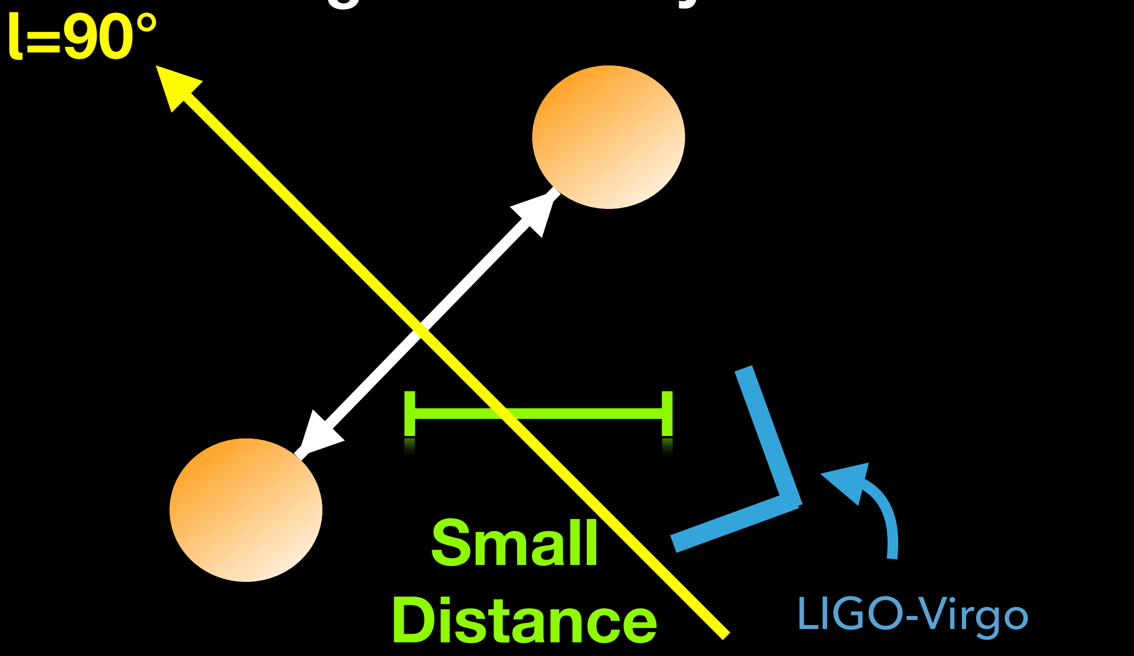
Distance-inclination degeneracy



Face-on binary



Edge-on binary



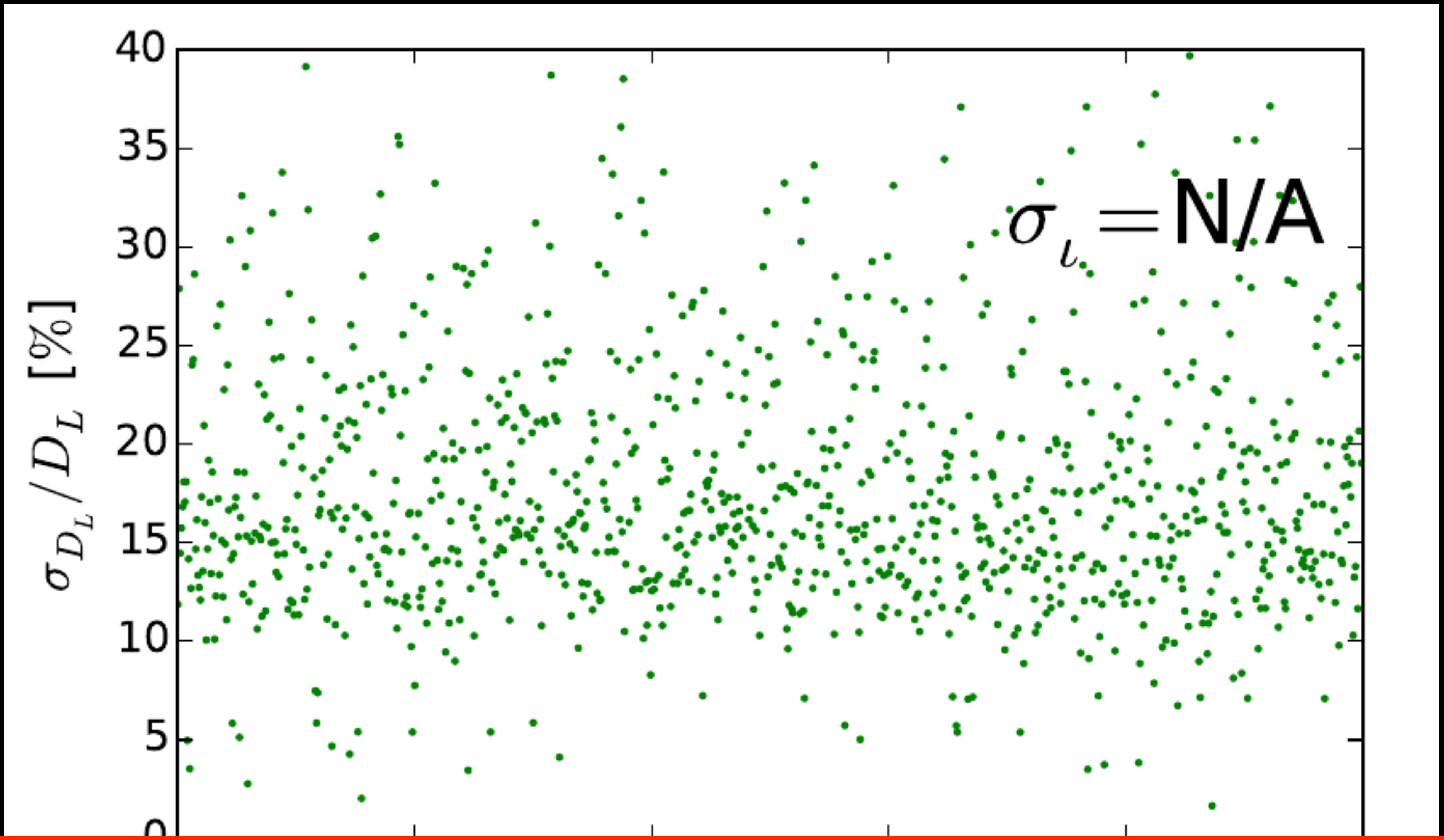
Break the distance-inclination degeneracy

*A) Neutron star mergers with **viewing angles constrained by electromagnetic emission**.*

Chen et al., PRX, 2019

Can be viewed as → **H₀ uncertainty**

$$\sigma_{H_0} \propto \frac{1}{\sqrt{N}}$$



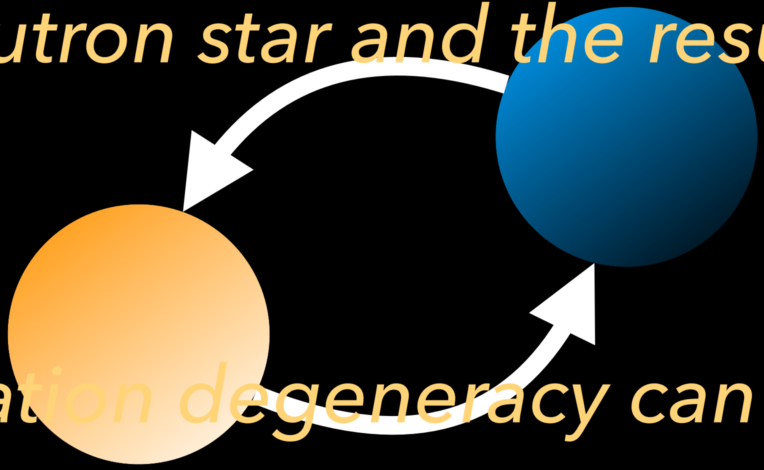
A factor of 5 to10 fewer events are required to reach the same Hubble Constant precision if the viewing angle is constrained.

Break the distance-inclination degeneracy

B) ***Neutron star-black hole*** *mergers with precession.*

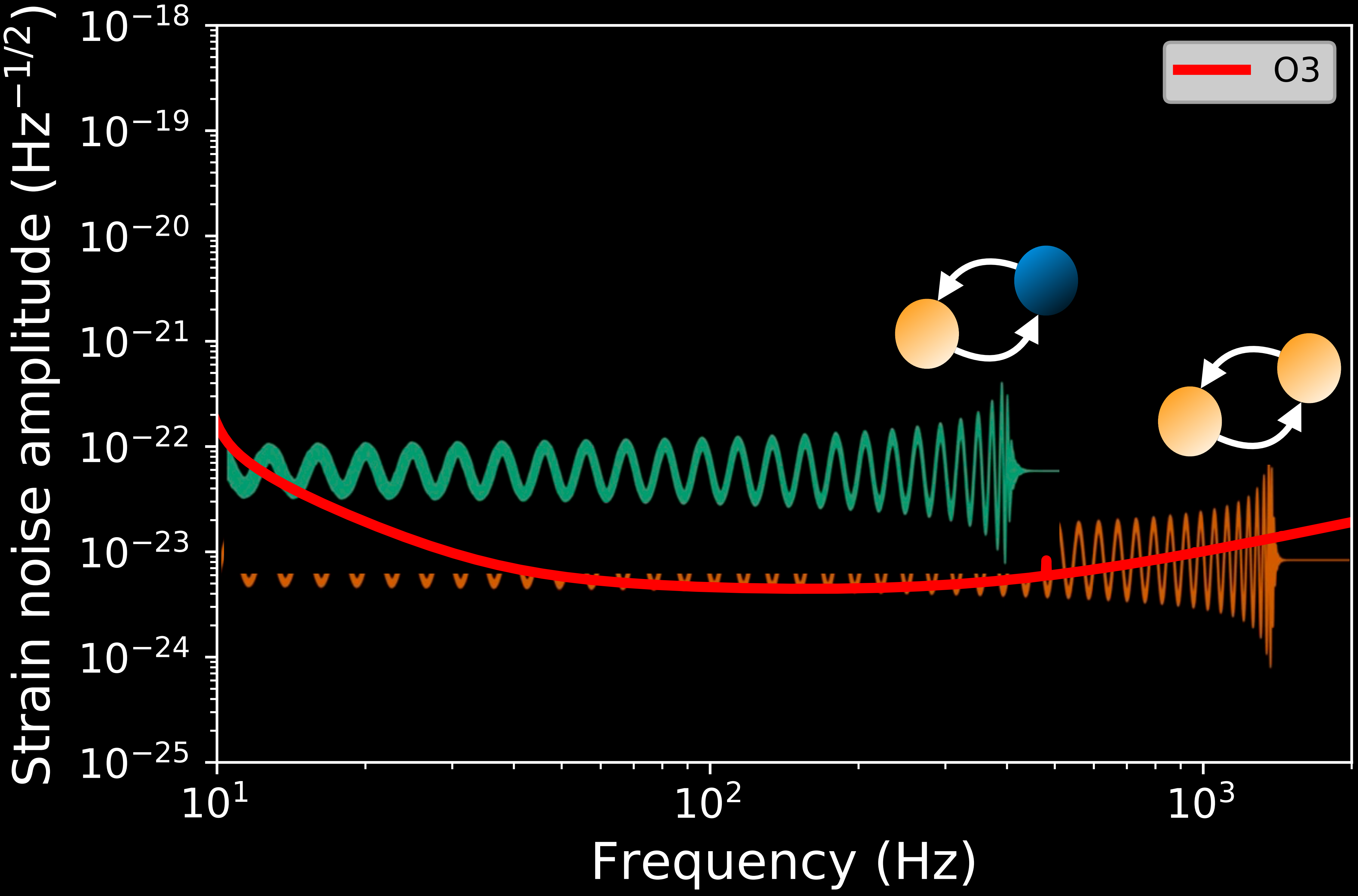
Vitale & Chen, PRL, 2018

-Electromagnetic emissions could be powered by tidal disruption of the neutron star and the resulting accretion disk.



-The distance-inclination degeneracy can be broken by the observation of ***merger-ringdown*** *and* ***precession****.*

Gravitational-wave detector sensitivities

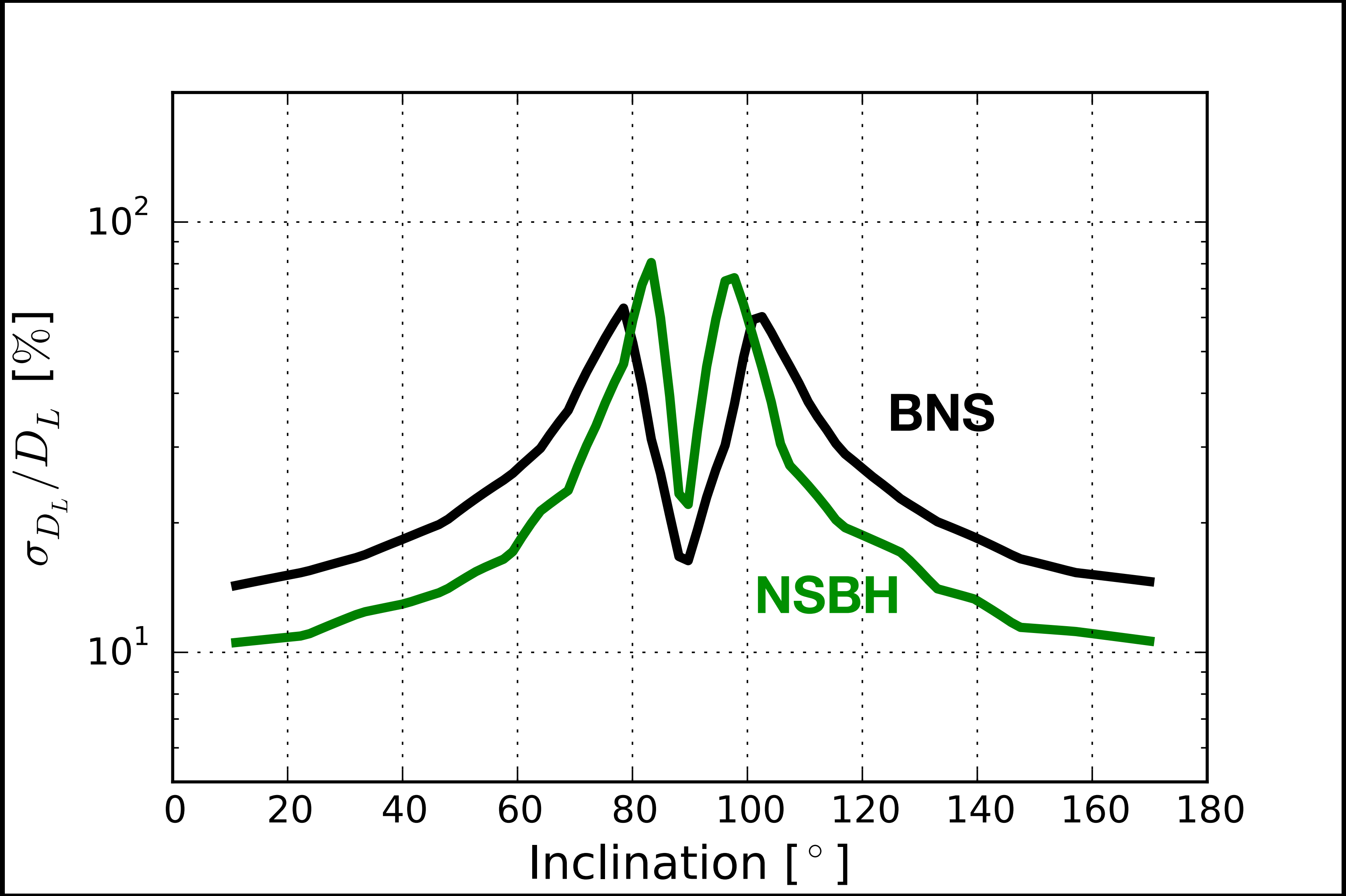


Break the distance-inclination degeneracy

B) ***Neutron star-black hole*** *mergers with precession.*

Vitale & Chen, PRL, 2018

Can be viewed as → **H0 uncertainty**

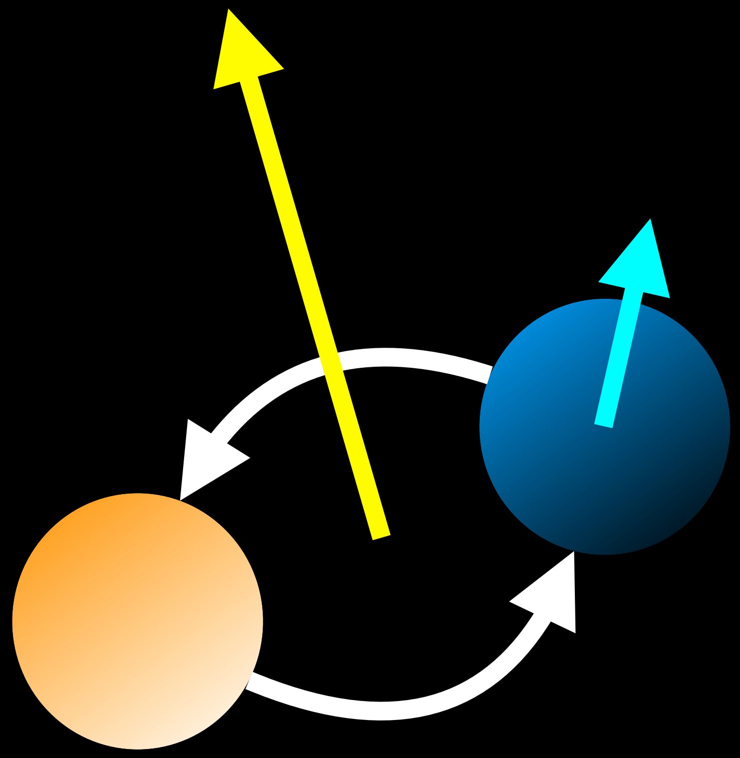


The difference between BNS and NSBH is mainly due to the observation of merger-ringdown.

Break the distance-inclination degeneracy

2. Neutron star-black hole mergers with ***precession****.*

Vitale & Chen, PRL, 2018



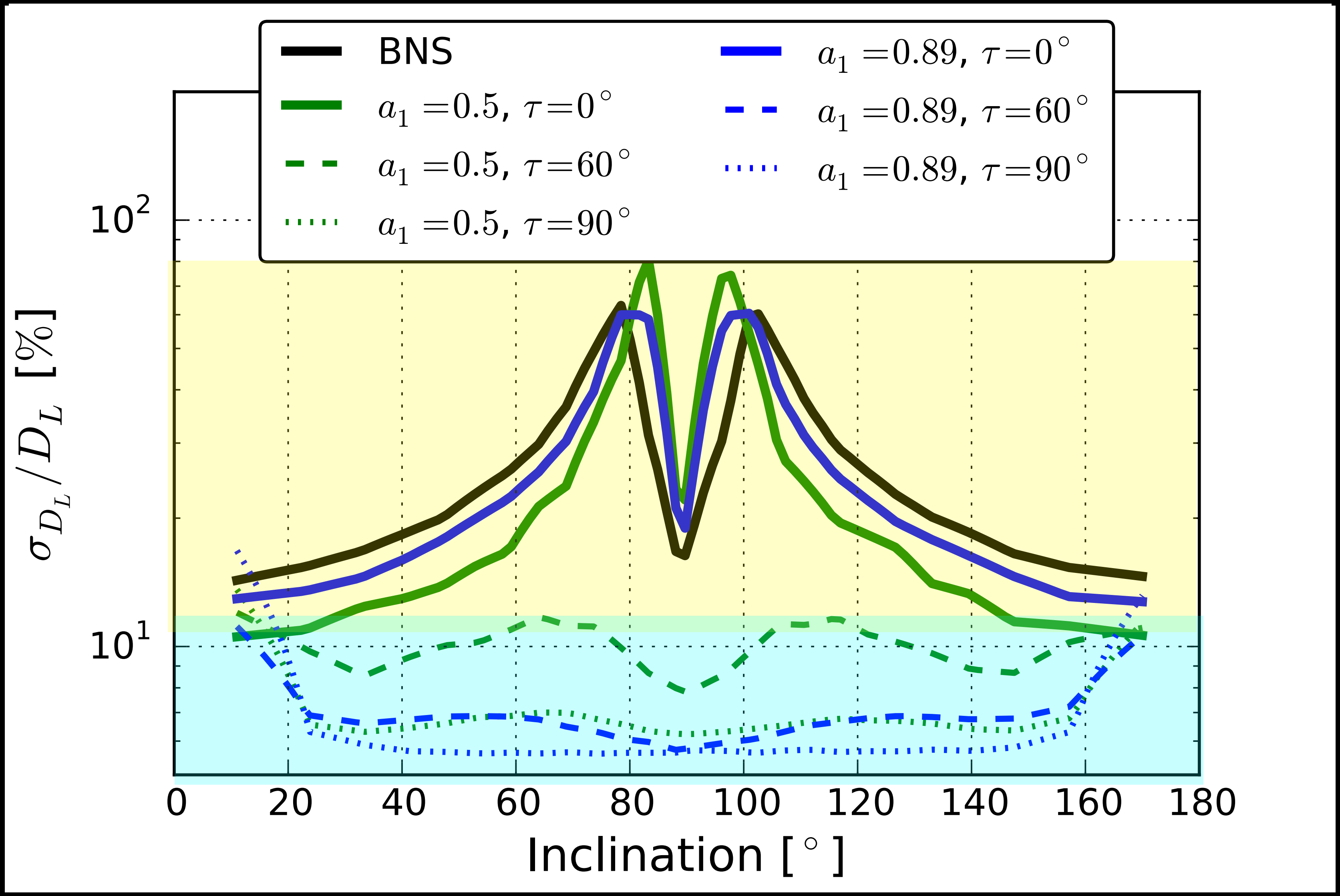
Break the distance-inclination degeneracy

2. Neutron star-black hole mergers with ***precession****.*

Vitale & Chen, PRL, 2018

Can be viewed as → **H0 uncertainty**

$$\sigma_{H_0} \propto \frac{1}{\sqrt{N}}$$



Without Precession

With Precession

A large and misaligned black hole spins results in a significant waveform amplitude modulation, which entirely breaks the degeneracy.

Gravitational-Wave Cosmology

- Combine and compare to other cosmological measurements.

- Electromagnetic emission modelings, instrumental calibration, waveform modeling, weak lensing etc. can all lead to systematics. How much will them affect the accuracy of cosmological measurement? What are possible methods to eliminate them?

- Application to 3G ground-based detectors and the space-based detector—LISA.

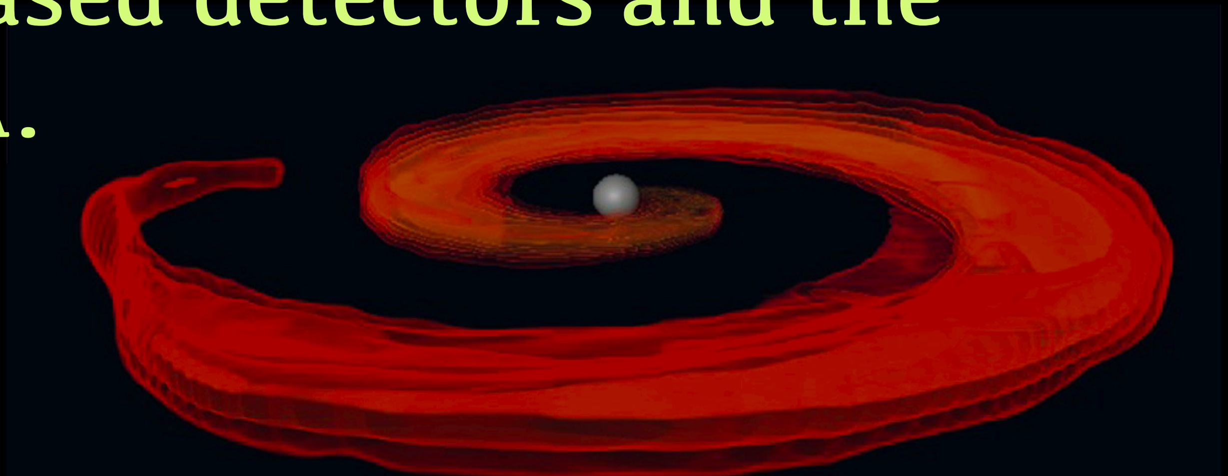
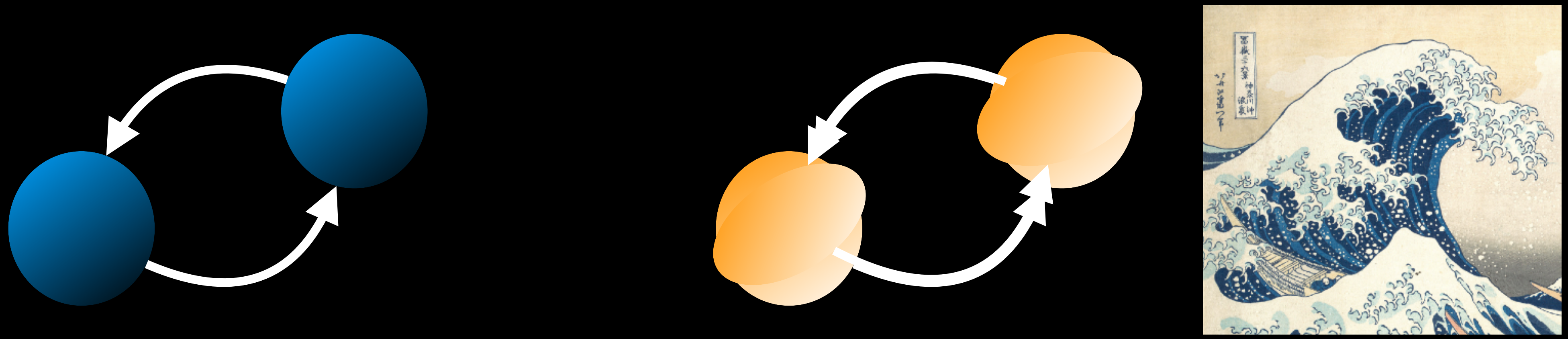


Image credit: A. Tonita, L. Rezzolla, F. Pannarale

Tidal deformation of neutron stars

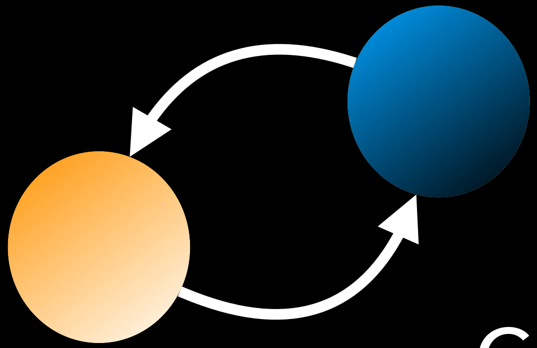


-Neutron star equation-of-state.

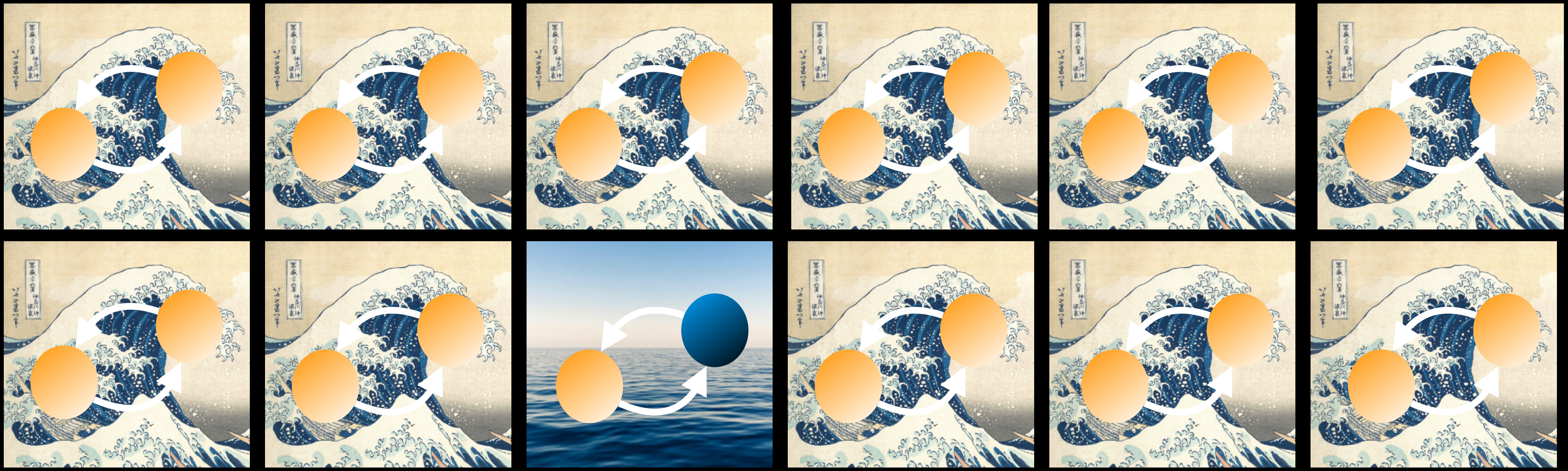
GW170817 Equation-of-state
(Abbott et al., PRX 2019)

Were they really binary neutron stars?
Could they be…

A) Neutron star-black hole mergers

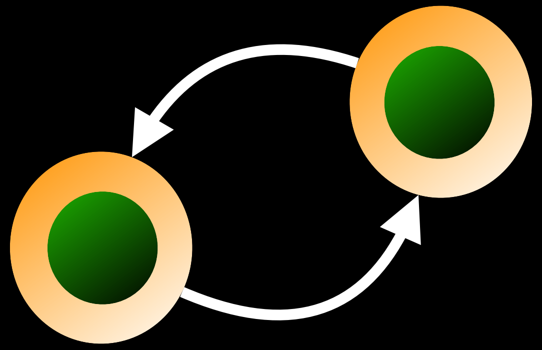


Chen & Chatziioannou, 2019

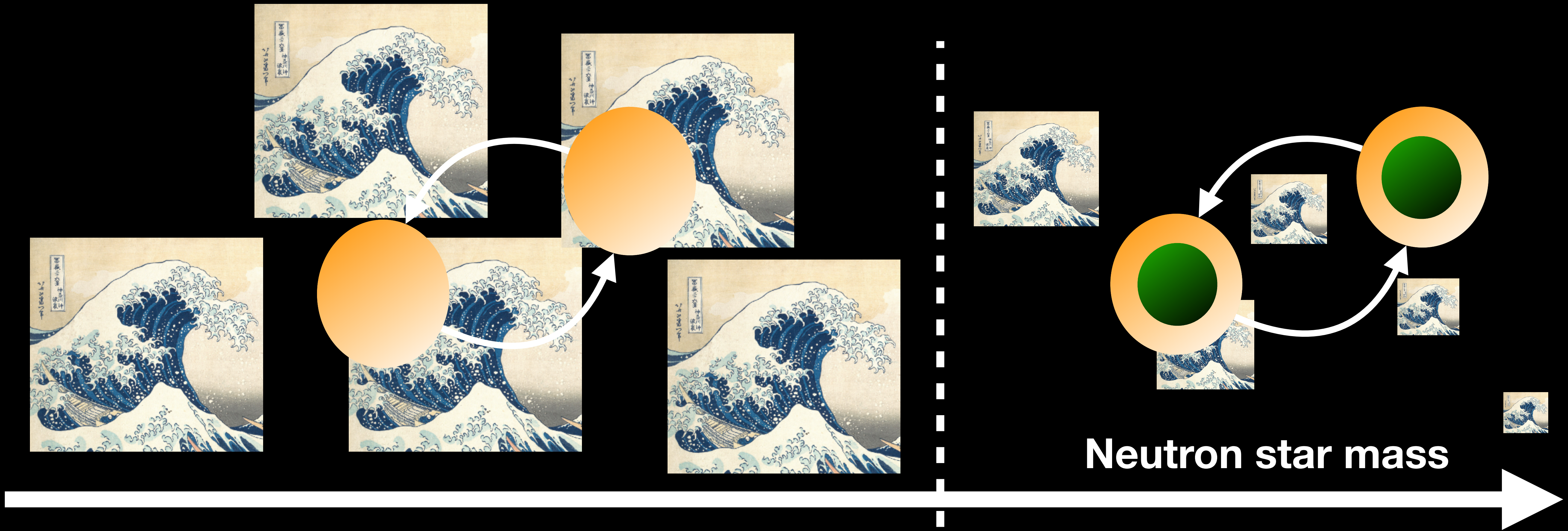


Were they really binary neutron stars?
Could they be…

B) Hybrid star mergers (Quark matter core)



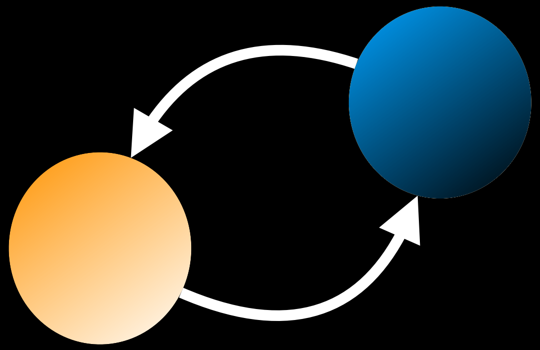
Chen et al., 2019



Were they really binary neutron stars?
Could they be…

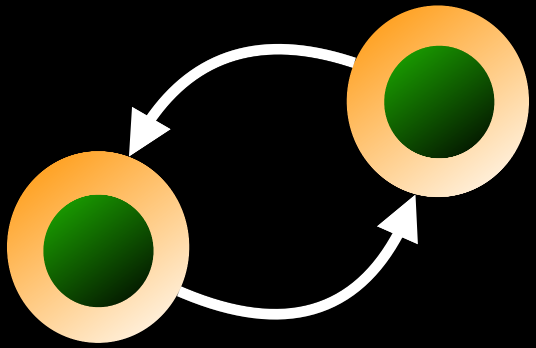
A) Neutron star-black hole mergers

Chen & Chatziioannou, 2019



B) Hybrid star mergers (Quark matter core)

Chen et al., 2019

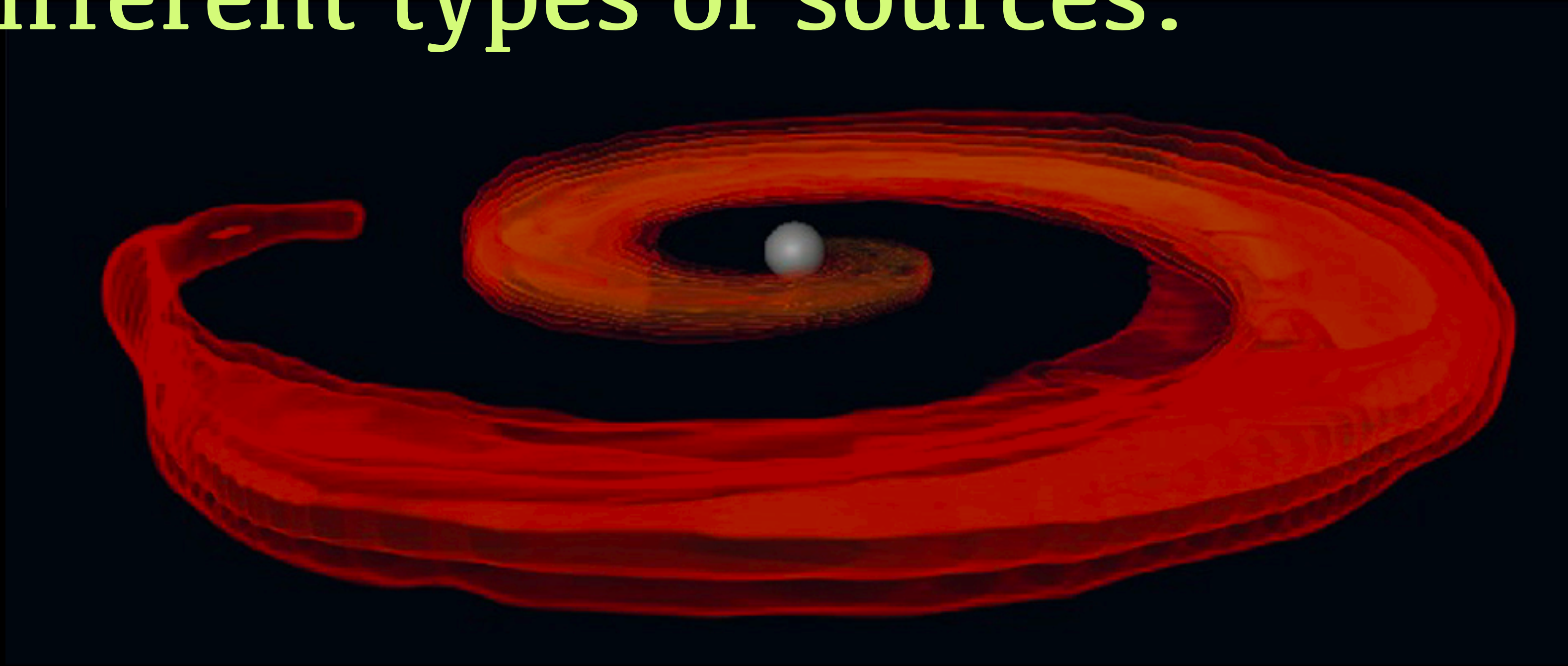


Combining O(10) to O(100) detections will verify/exclude these scenarios.

Image credit: A. Tonita, L. Rezzolla, F. Pannarale

Extreme Matter Equation-of-State

- Make use of the better-measured mass distribution and improved waveform modeling.
- Develop pipelines to optimize the identification of different types of sources.



Summary

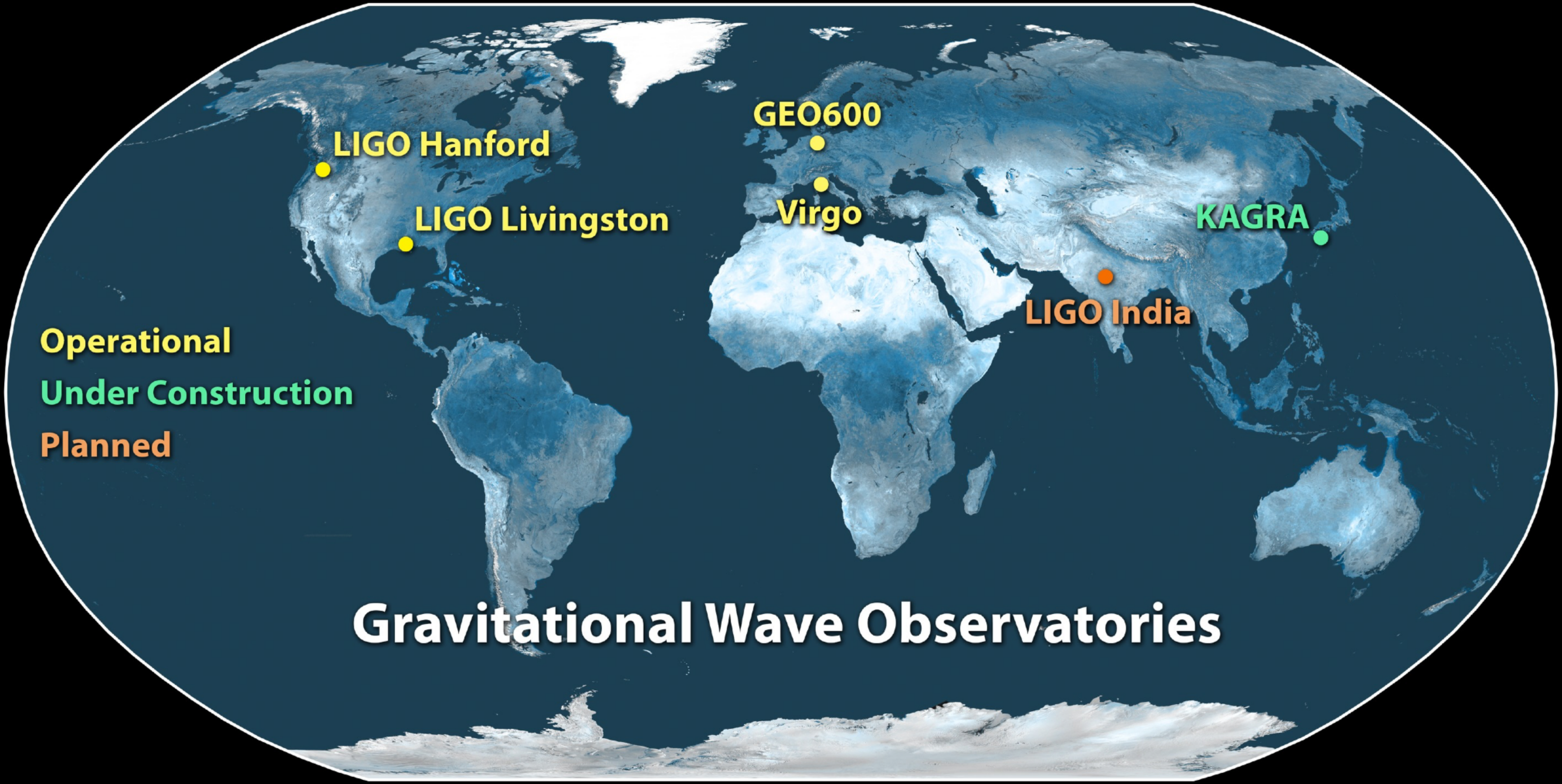
-Gravitational waves can serve as an independent probe to the Universe.

-The electromagnetic counterpart observations are crucial for gravitational-wave cosmology.

-More detections will shed light on the high-density low-temperature nuclear matter equation-of-state

Thank you!

Gravitational-Wave Observatories Across the Globe



Chen et al., Nature, 2018

2% in five years

- Realistic distance posteriors were used.

  Chen & Holz (2016) / Chen et al. (2018)

- 200 km/s peculiar velocities.
  – *BNSs at 40-80 Mpc give smallest H0 uncertainty.*

- 50% duty cycle for 3 detectors, 30% duty cycle for 5 detectors.
  – *s190425z (no EM counterpart)-like events were **not** included.*

- BNS astrophysical rate is the major uncertainty.

Chen et al., Nature, 2018

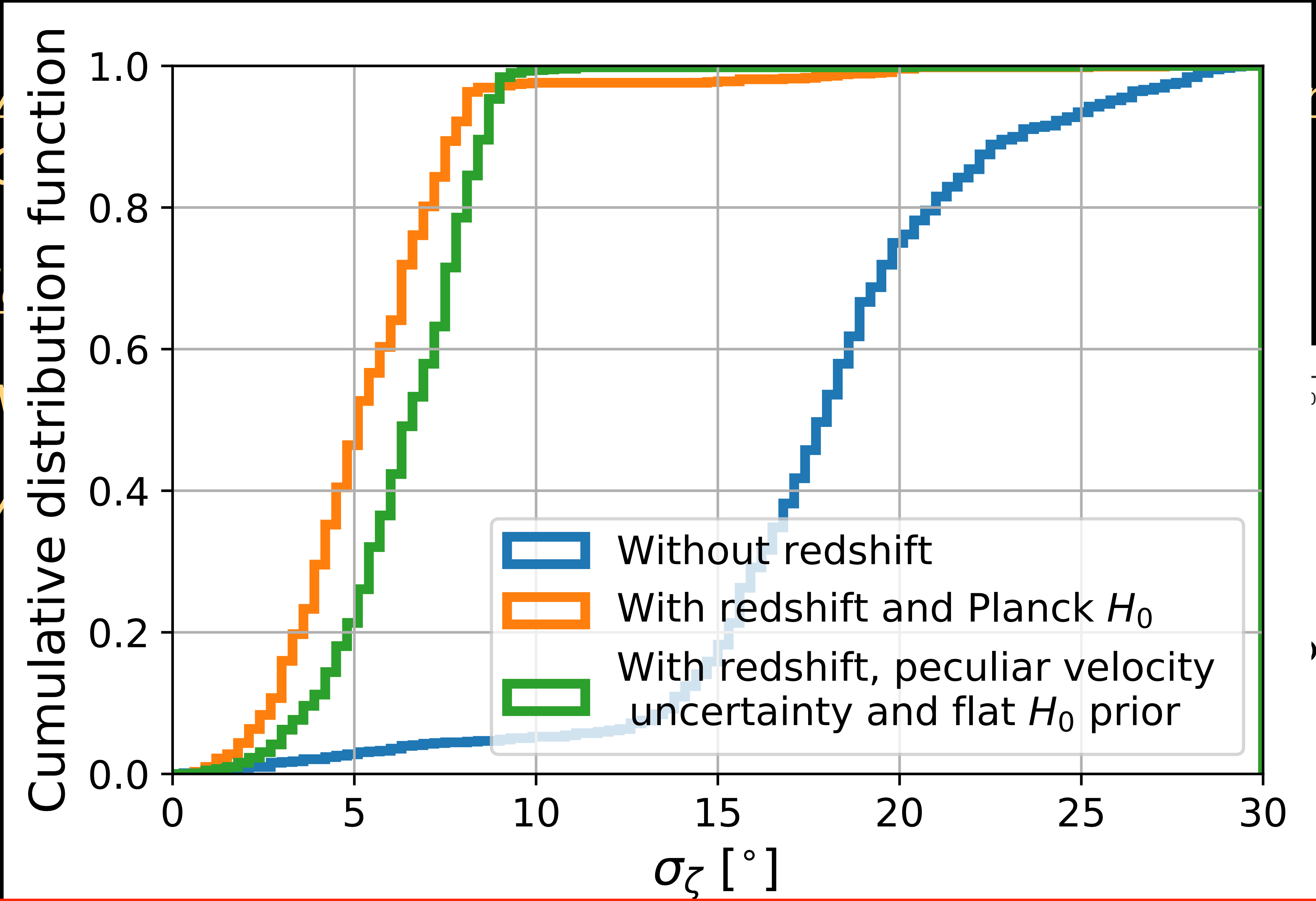
Statistical Method

- Complete galaxy catalog was assumed.
  - *This is not true for most of the cases.*

- Most of the BBHs can not be localized well.
  - *They do not contribute to the H0 measurement.*

What has not been discussed?

Chen et al., 2018



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With the redshift from electromagnetic wave observations, the constraint of viewing angle can be interesting.

(2017)

Determine the redshift of gravitational-wave source with the <u>source frame mass</u>

$(1 + z_1)M_1$

Identical si

Significant number of detections are needed.

-<u>Mass distribution</u>: Understand the mass distribution and compare it to the detected populations.

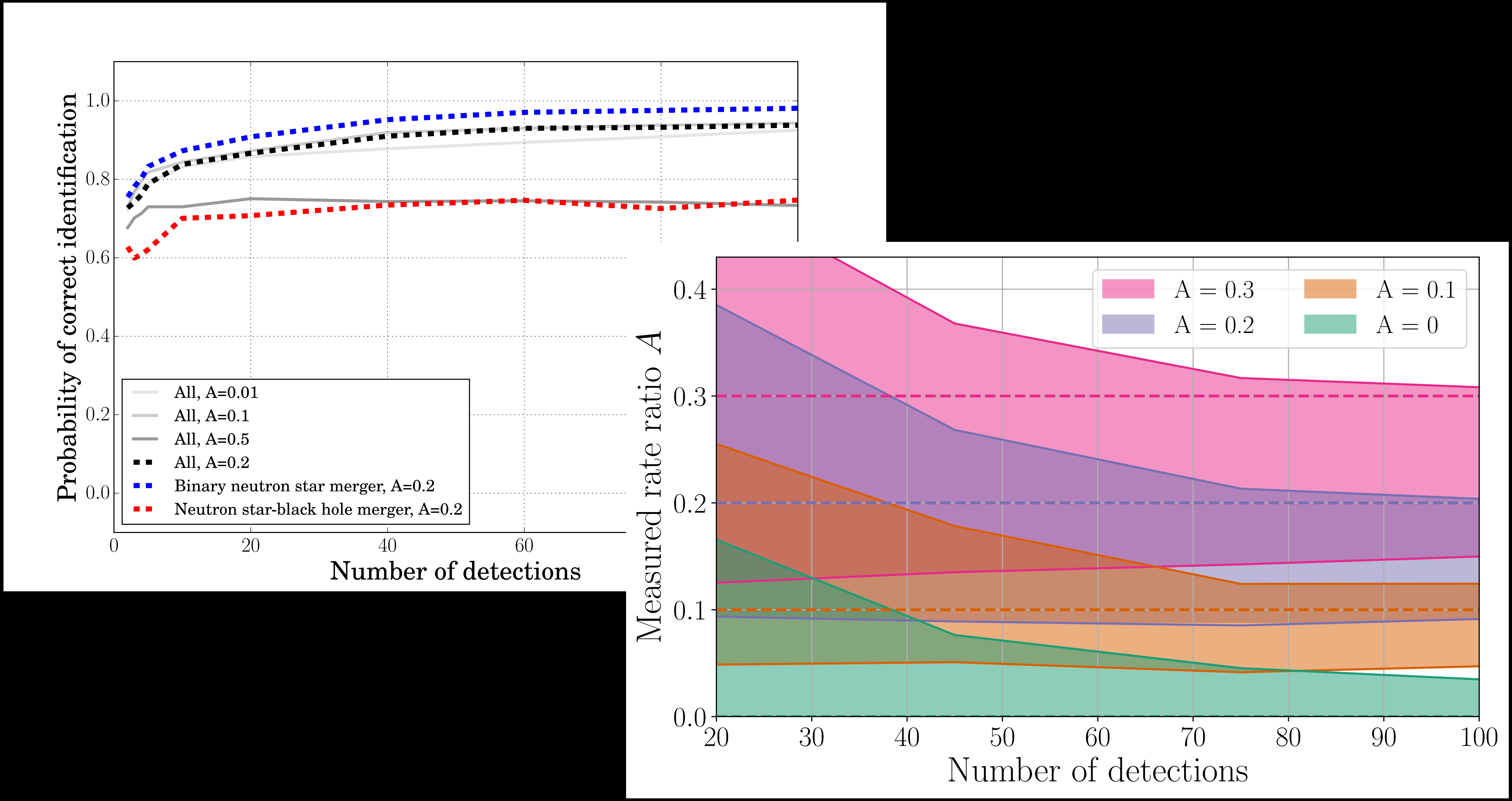
Taylor+, PRD, 2012

-<u>Neutron star mergers tidal effect</u>: Understand the neutron star equation-of-state and measure the mass from the tidal effect presented in the gravitational-wave signals.

Messenger & Read, PRL, 2012

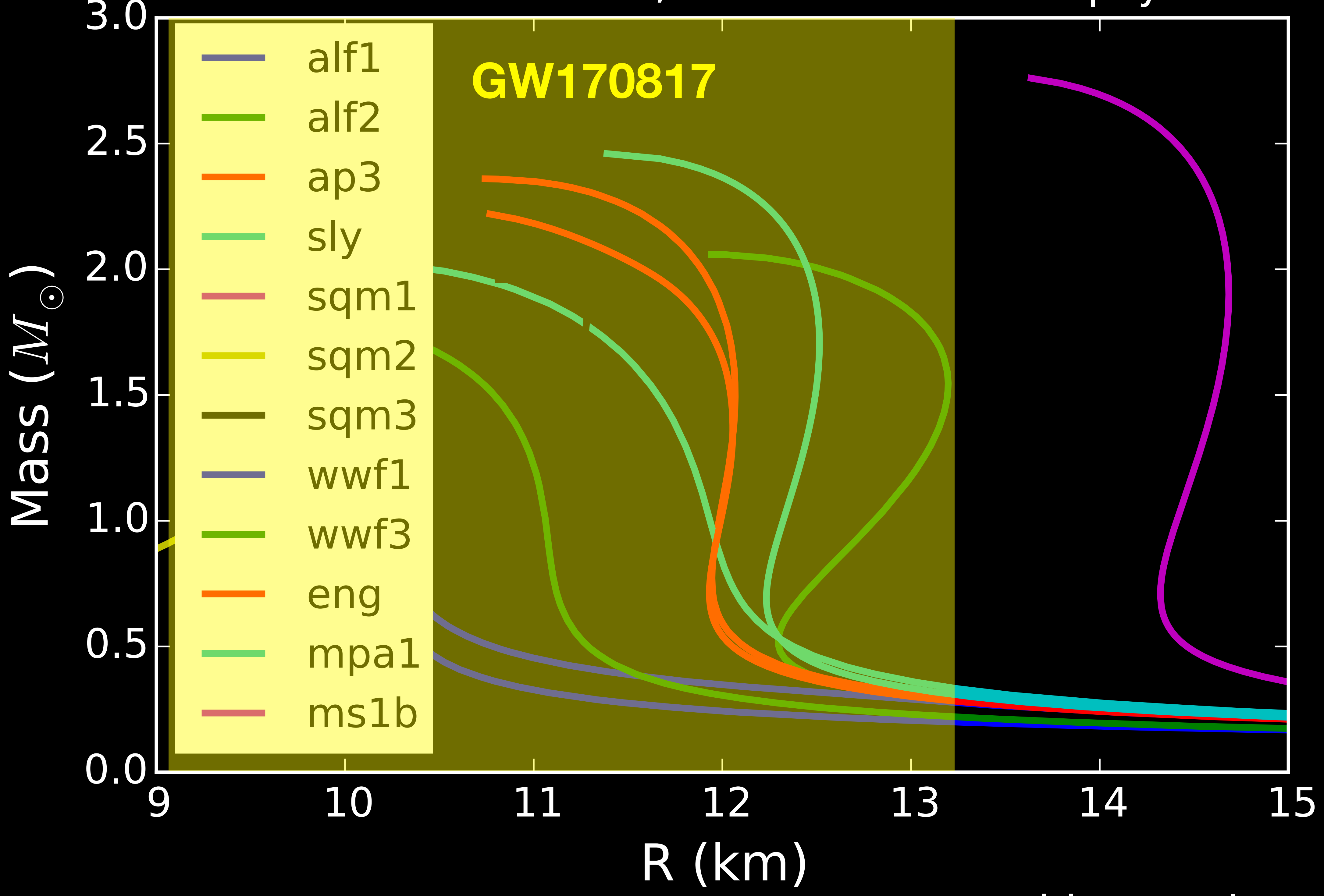
Distinguishing binary neutron star from neutron star-black hole mergers with gravitational waves

Chen & Chatziioannou, arXiv: 1903.11197



Neutron star mass-radius relation

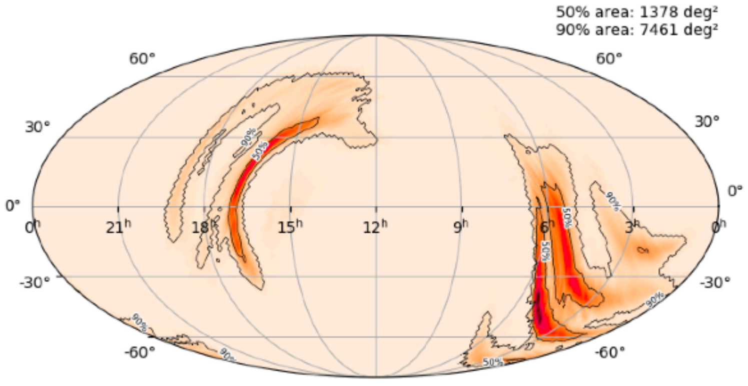
Ozel et al., Ann.Rev.Astron.Astrophys 2016



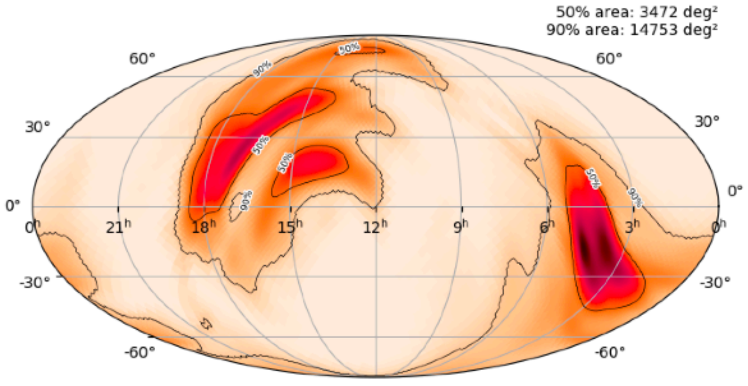
Abbott et al., PRX 2019

We still have only one binary neutron star with electromagnetic counterparts. Why?

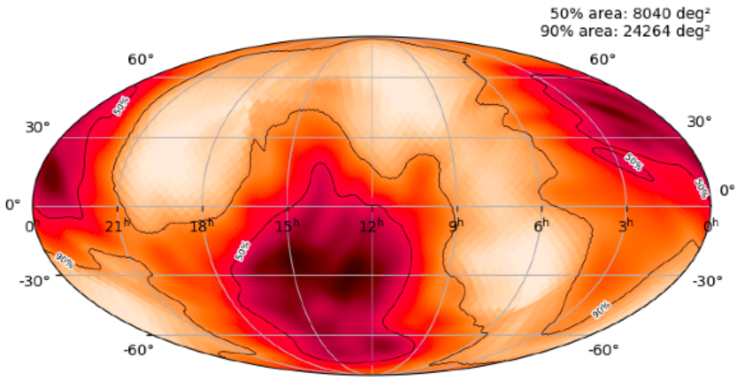
- The binary neutron star mergers in O3a were only detected by LIGO-Livingston (+Virgo).



S190425z [L,V]



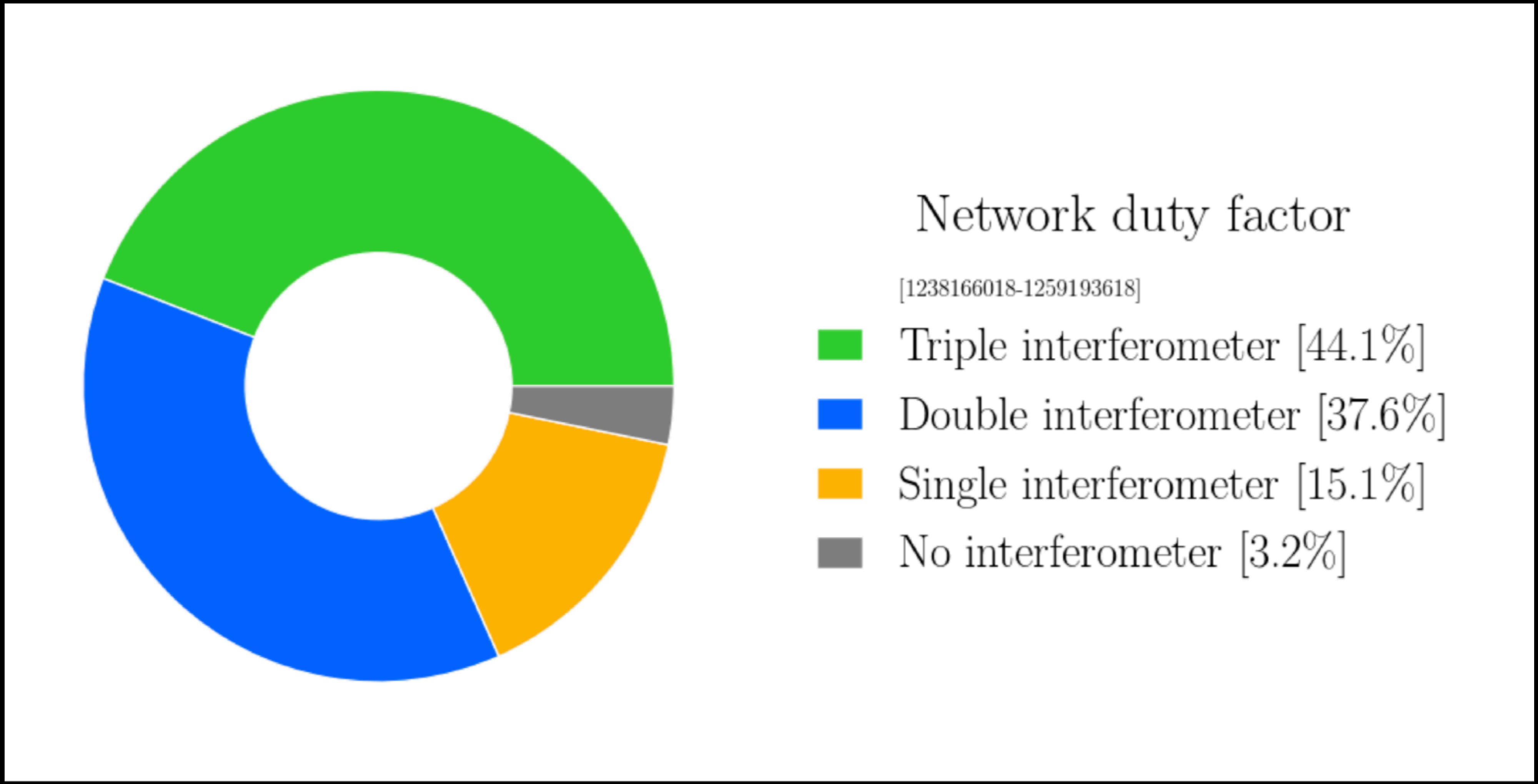
S190901ap [L,V]



S190910h [L]

We still have only one binary neutron star with electromagnetic counterparts. Why?

- The detector network duty factor is similar as before.



We still have only one binary neutron star with electromagnetic counterparts. Why?

- Is the binary neutron star merger rate too low?

  No. If we assume 1.4-1.4 $M_\odot$ for all BNSs detected so far, the BNS astrophysical rate is ~30% higher than the O1-O2 estimation from GW170817.

We still have only one binary neutron star with electromagnetic counterparts. Why?

Because we used up our luck in O1 and O2.

🙁

O3b is running!