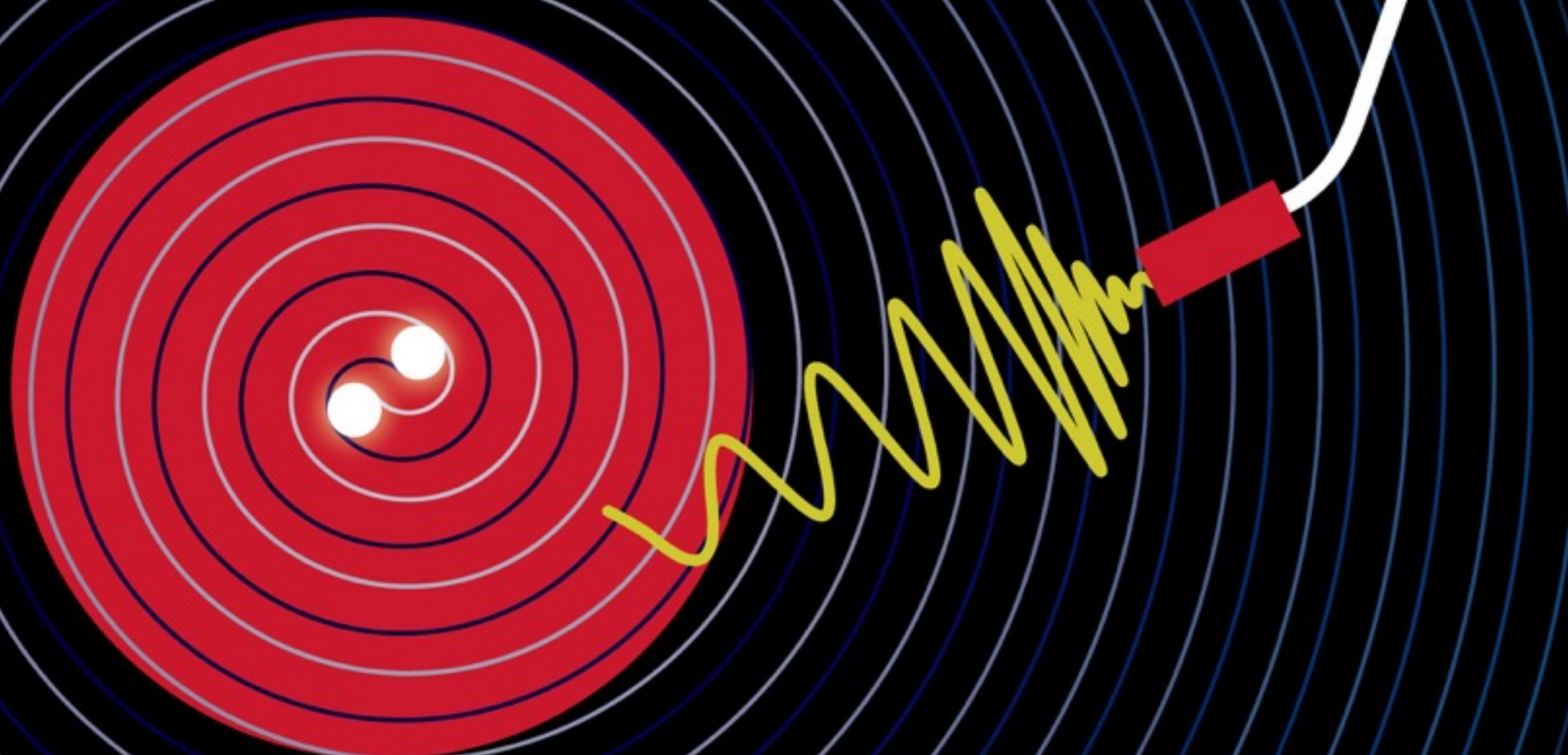
Image credit: S.W. Angela Chen

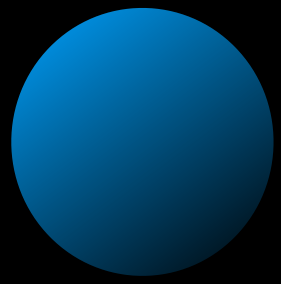
Listen to the Universe with gravitational-wave detections

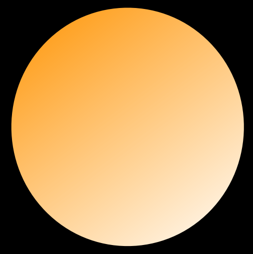


Hsin-Yu Chen

(Black Hole Initiative Fellow, Harvard University)

APCTP School on Gravitational-Wave Cosmology, Dec. 2 2019

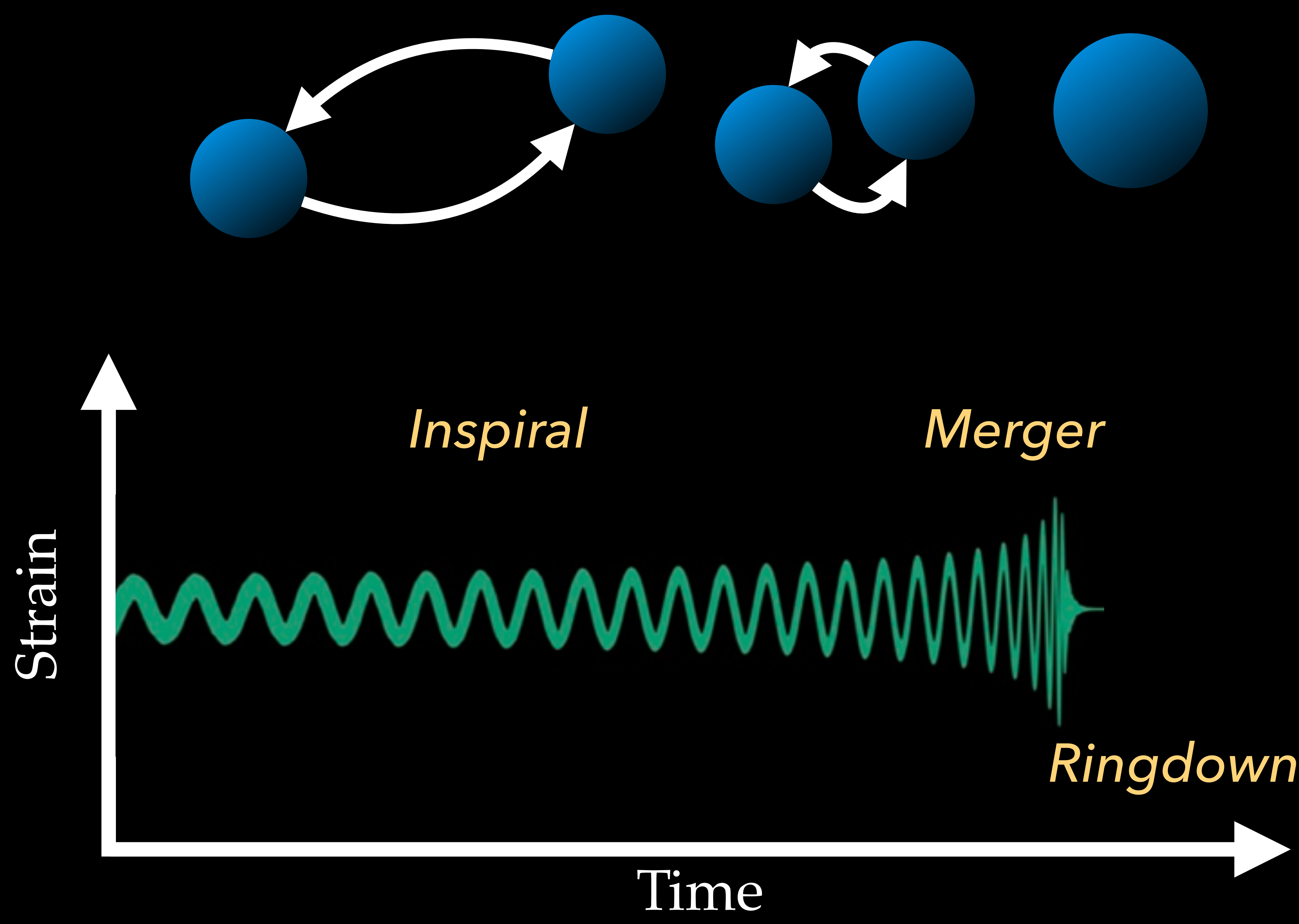




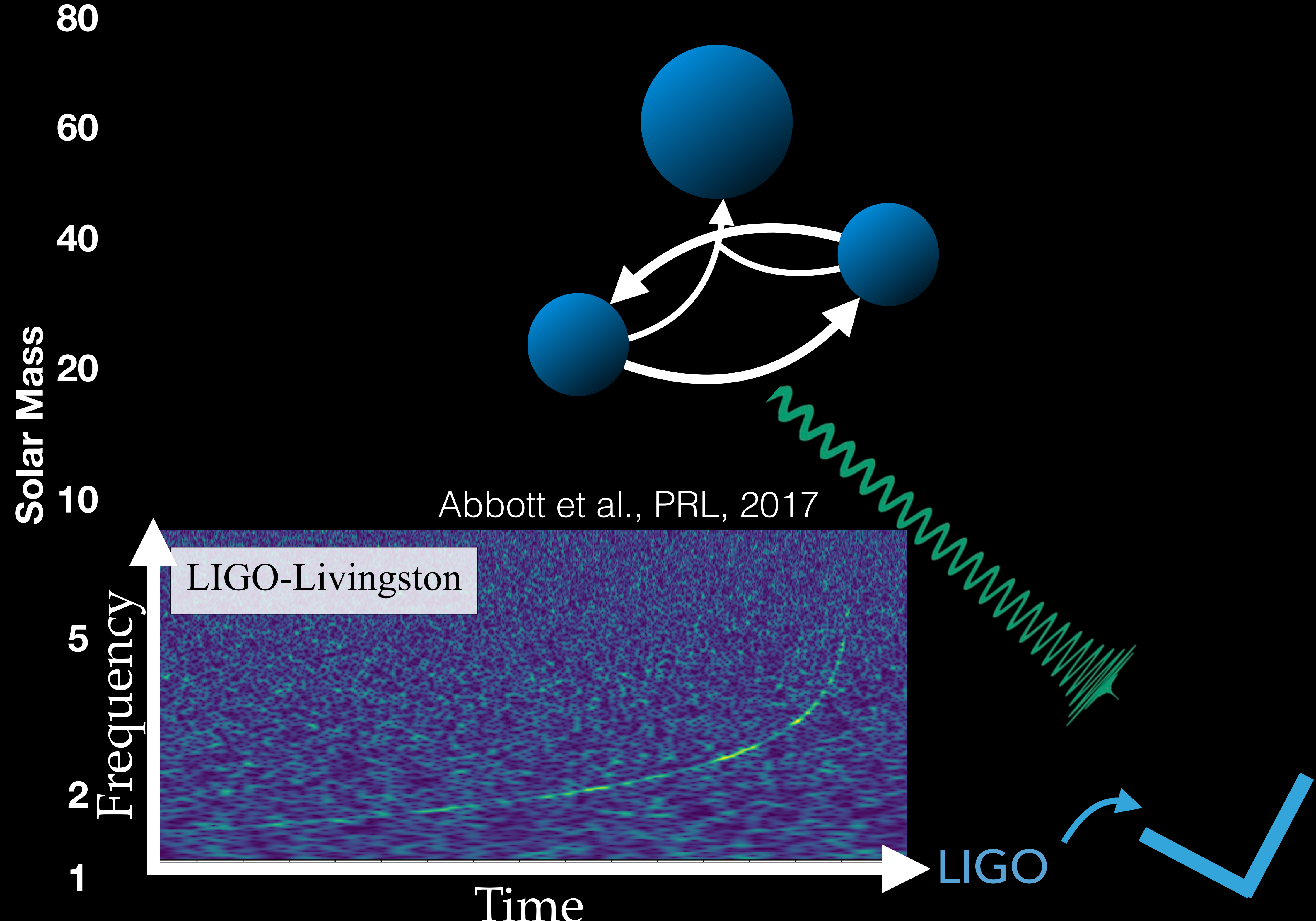
This is a black hole.

This is a neutron star.

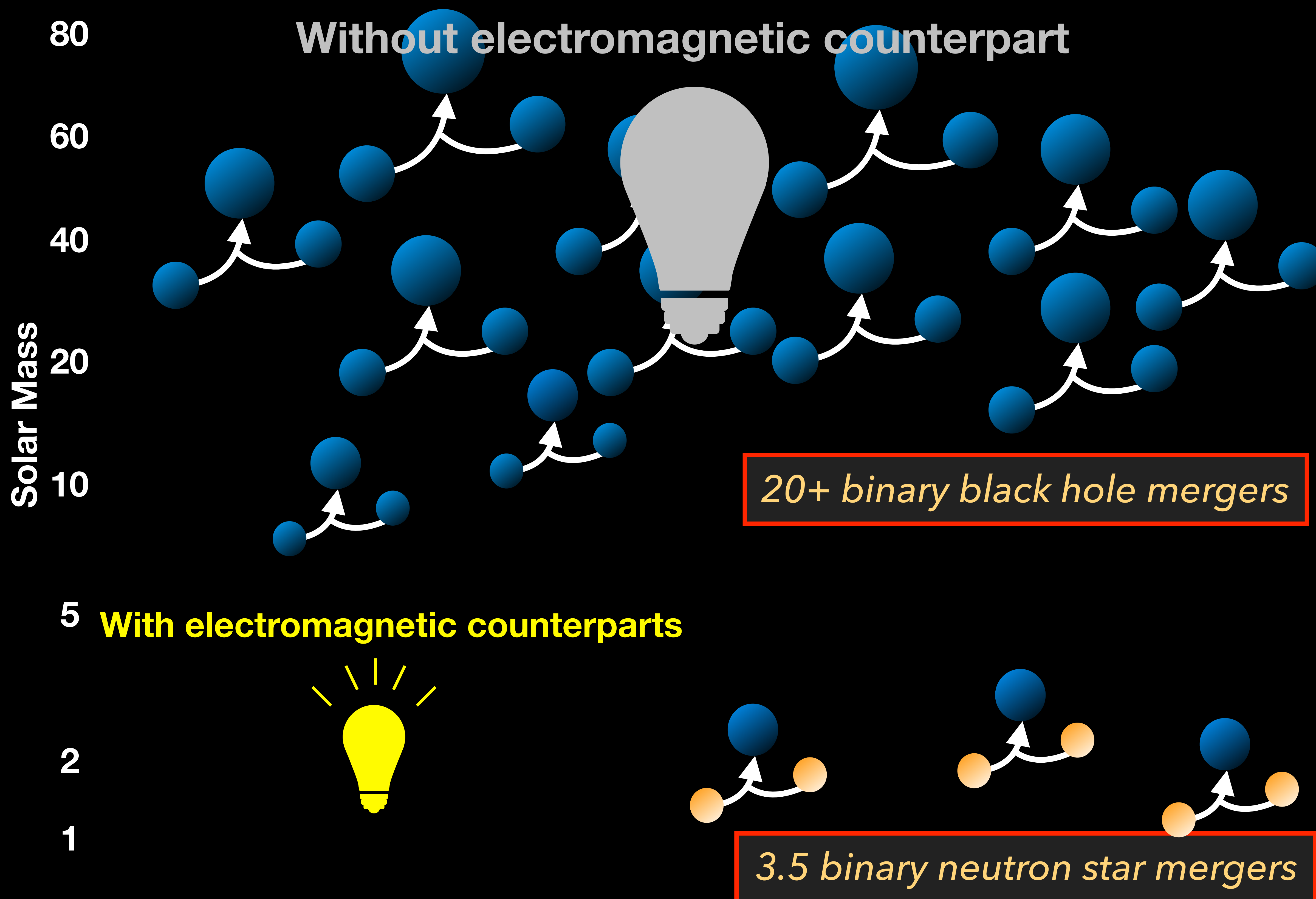
Information is encoded in the gravitational waveforms



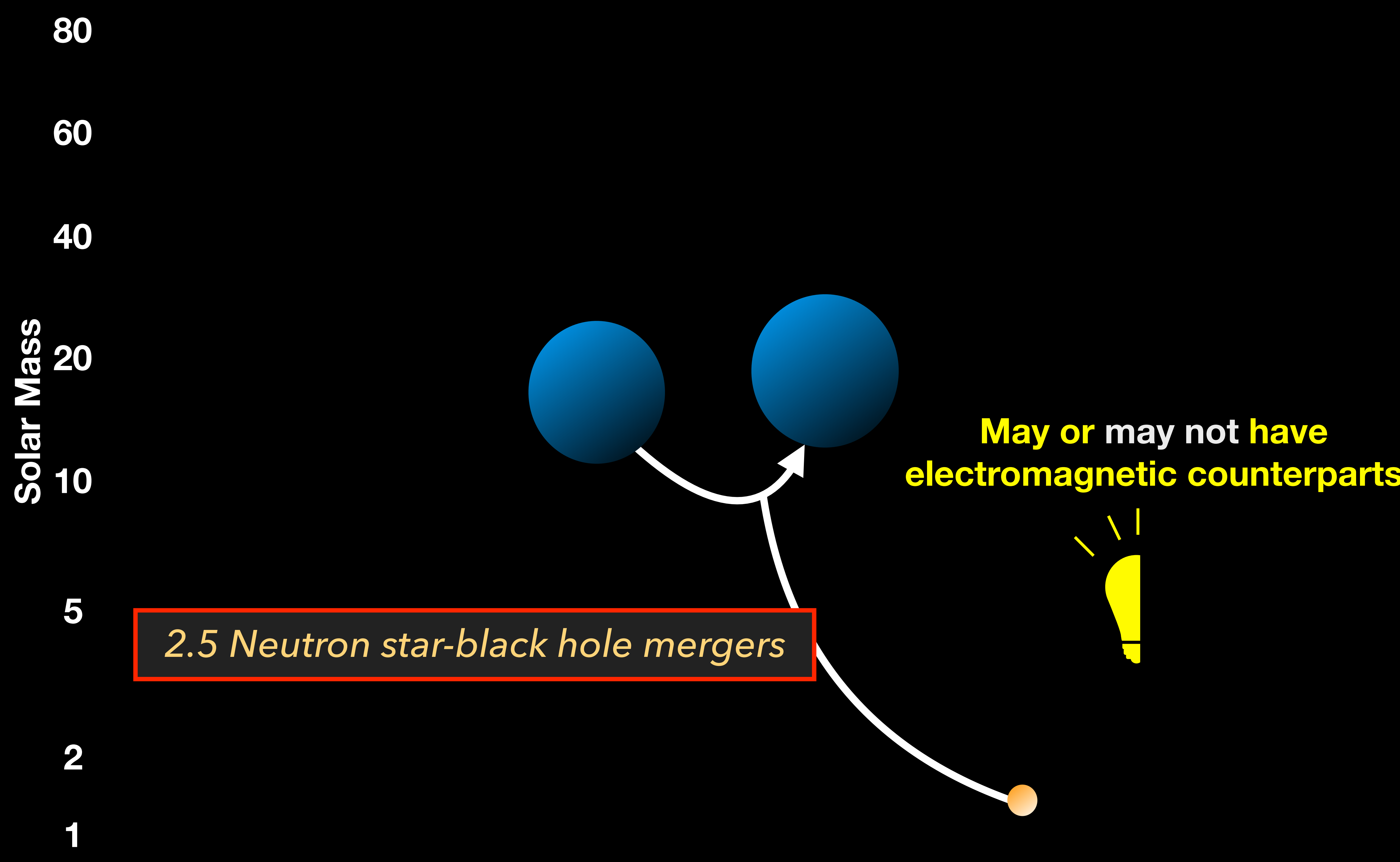
Gravitational-wave sources detected by LIGO-Virgo



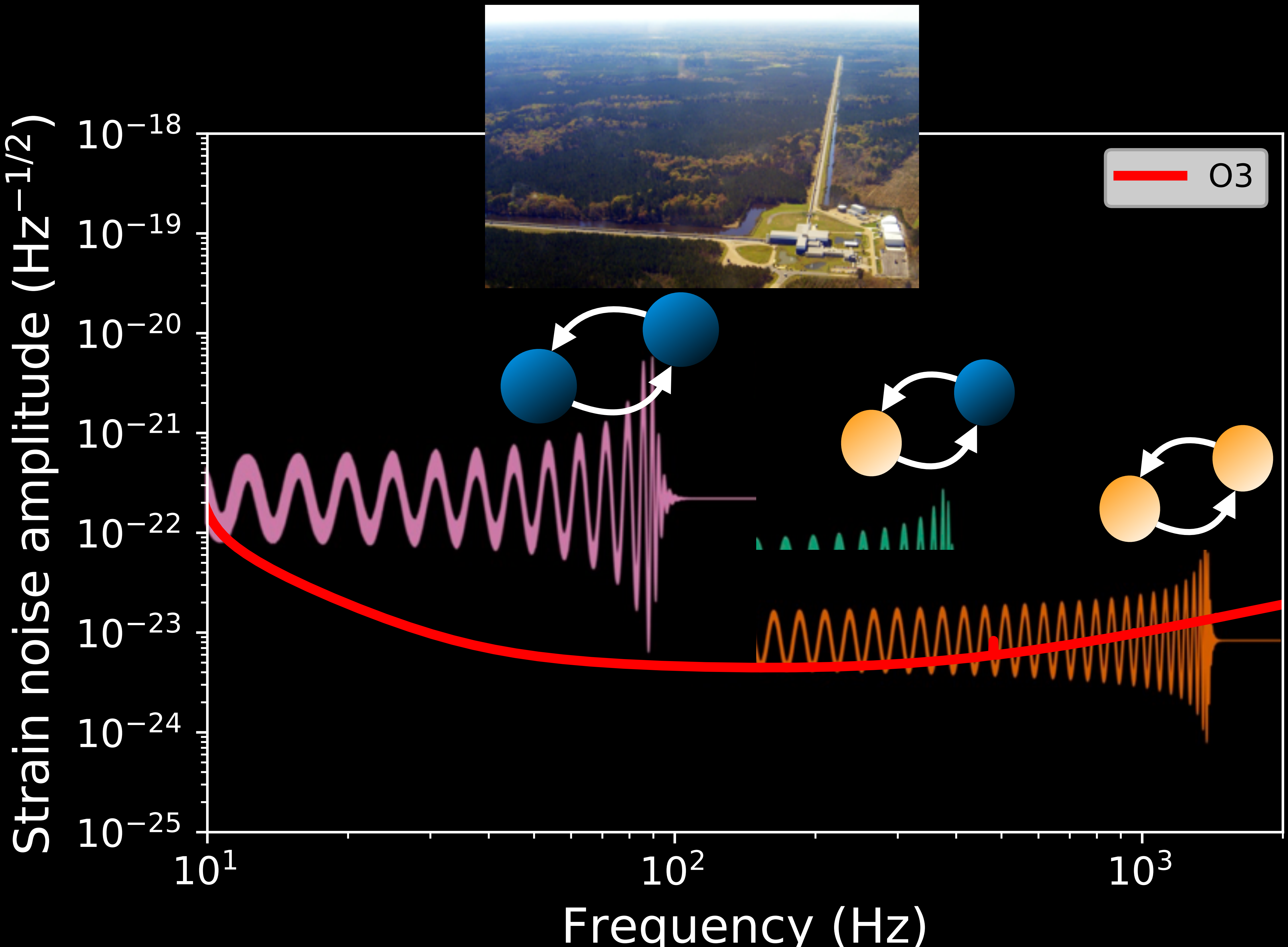
Gravitational-wave sources detected by LIGO-Virgo



Gravitational-wave sources detected by LIGO-Virgo

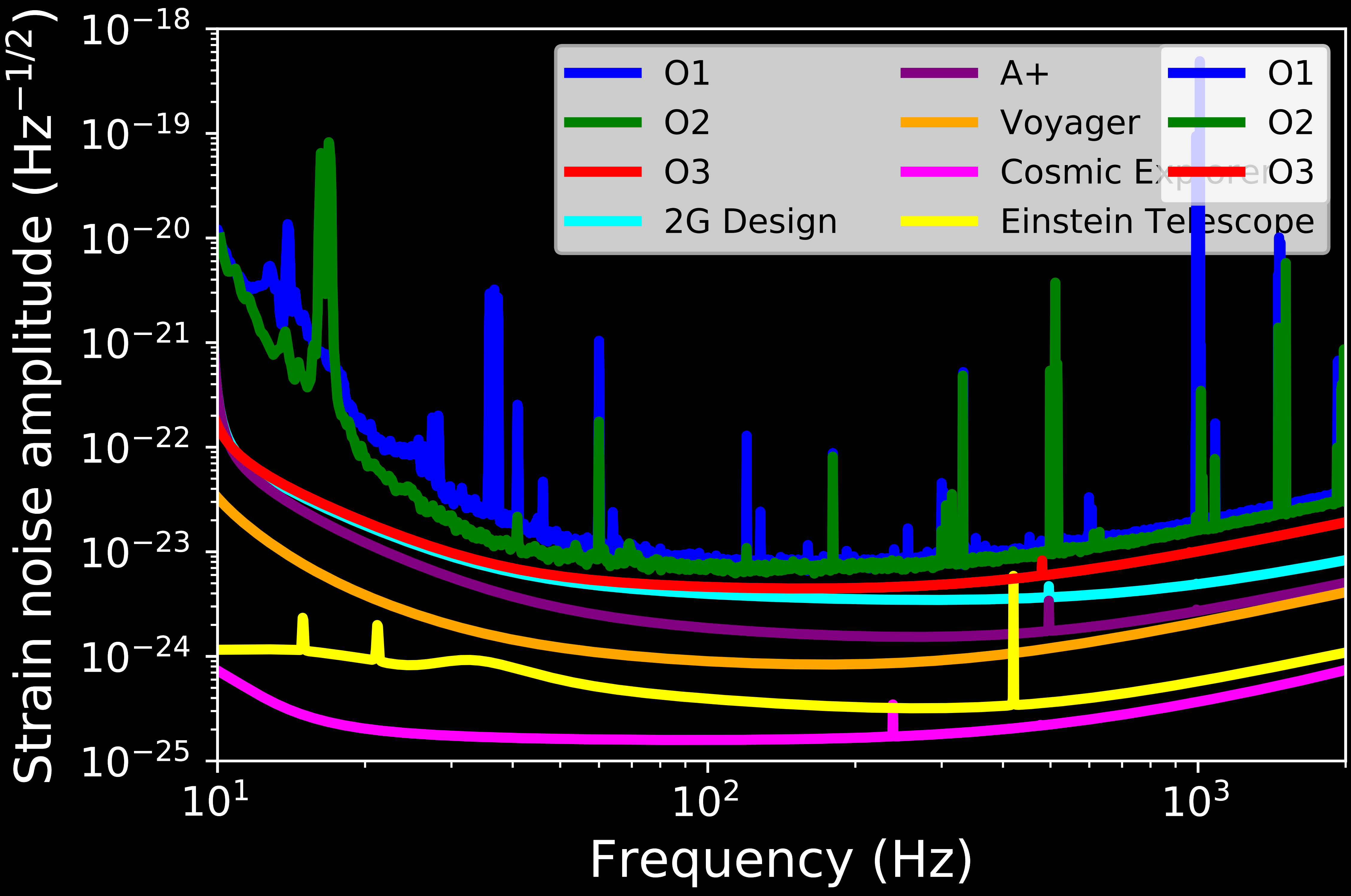


Gravitational-wave detector sensitivities



LIGO Lab/LIGO Document T1500293

Gravitational-wave detector sensitivities

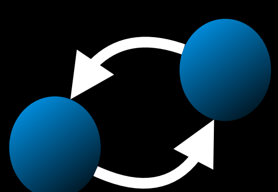


Upgrade of gravitational-wave detector

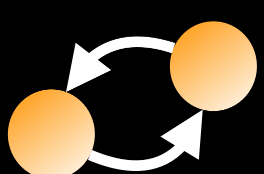
	2G		3G	
	2019	2022	2026	2030
	O3	A+	Voyager	CE/ET

Number of detections a year:

BH-BH



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



NS-NS

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

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APS NEWS

May 2018 (Volume 27, Number 5)

Hubble Trouble: A Crisis in Cosmology?

By Sophia Chen

2018 APS April Meeting, Columbus, Ohio — In 2013, the European Space Agency's Planck Observatory released a map of the cosmic microwave background (CMB) — with the highest resolution to date.

That's when the trouble started.

Applying the standard model of cosmology — the Lambda Cold Dark Matter (λCDM) model — researchers use the CMB map to calculate the Hubble constant, a number that describes how quickly the universe is expanding. But that number disagreed with calculations based on telescope observations of supernovae and pulsating star

ae versions by more tha

e constant differs

The New York Times https://nyti.ms/2m1HsmF

Cosmos Controversy: The Universe Is Expanding, but How Fast?

A small

long-sought number has fostered a debate

about just how well we know the cosmos.

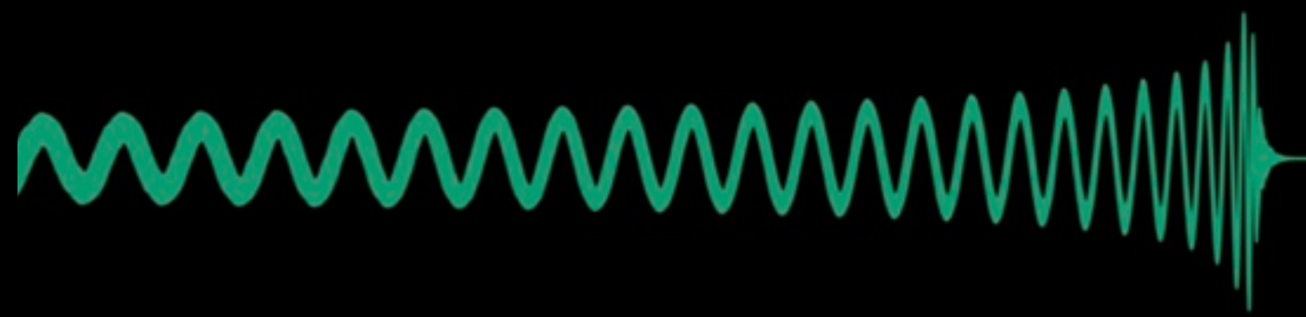
Dennis Overbye

OUT THERE FEB. 20, 2017

Gravitational Waves can possible provide an independent measurement of the Hubble constant.

Gravitational-wave cosmology with the standard sirens

Direct measurement of the luminosity distance



Luminosity Distance ∝ 1/Amplitude

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

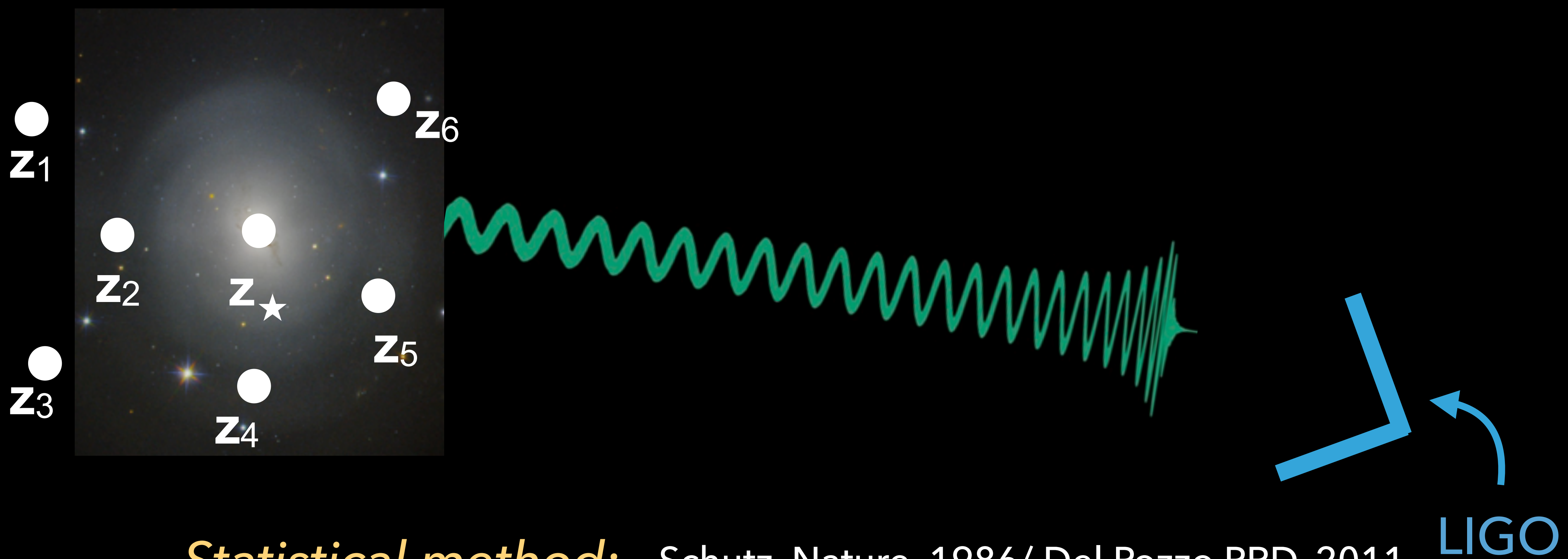
-Constrains the cosmological parameters with the redshift and luminosity distance:

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

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

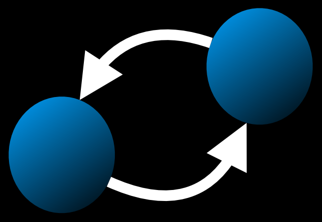
Schutz, Nature, 1986

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

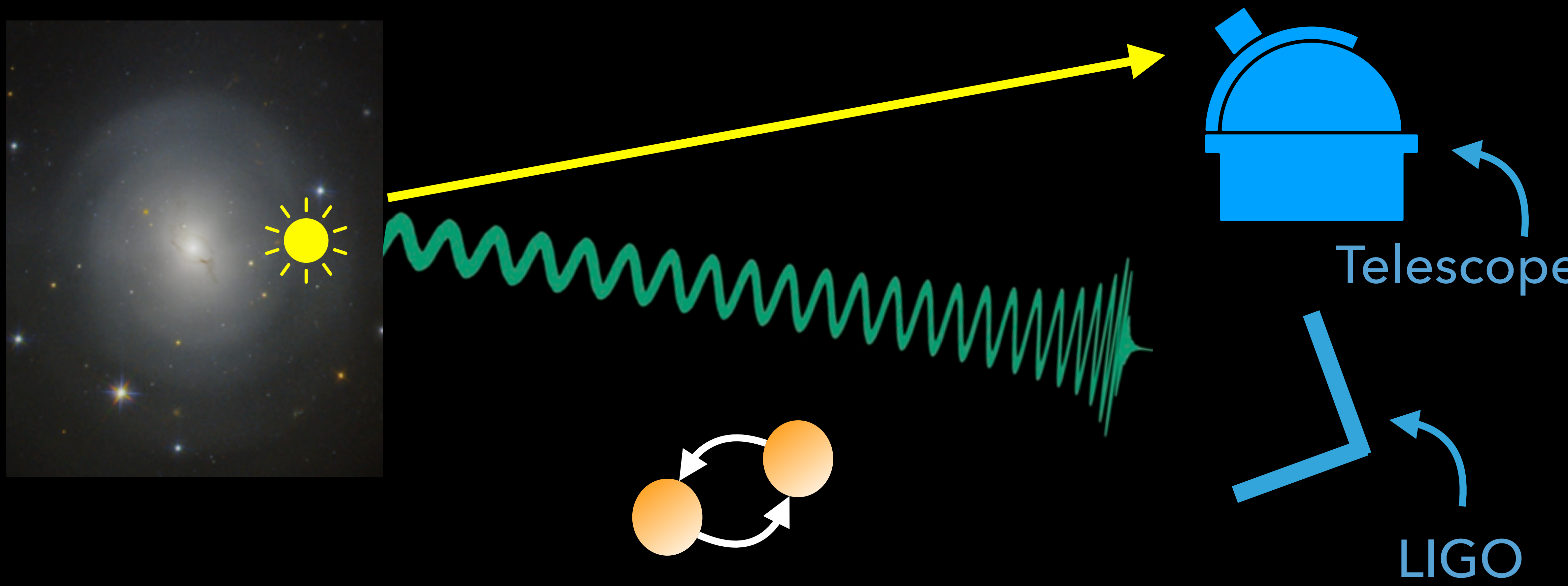
(Dark Energy Survey Year 3 data)

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

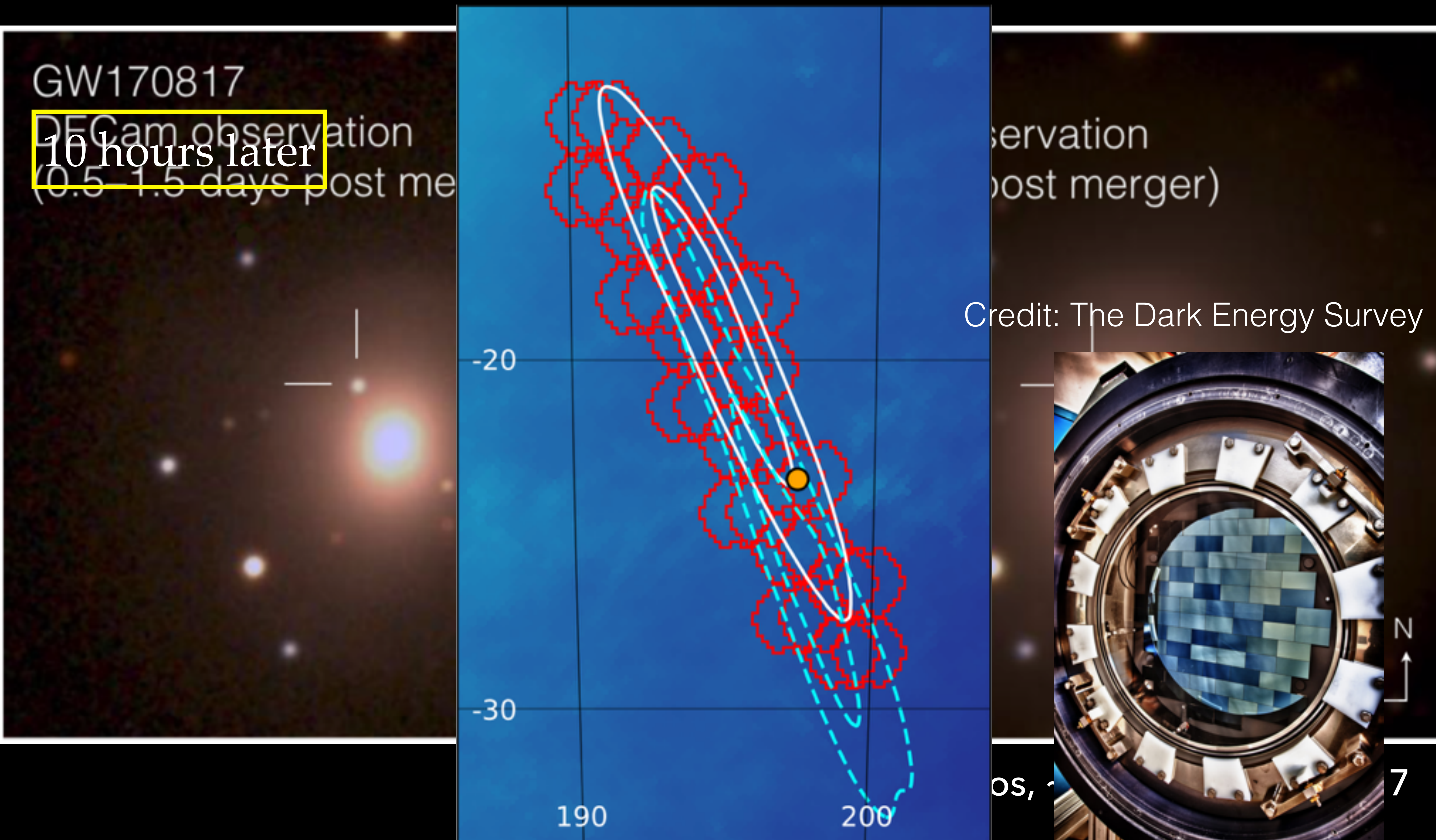


Counterpart method:

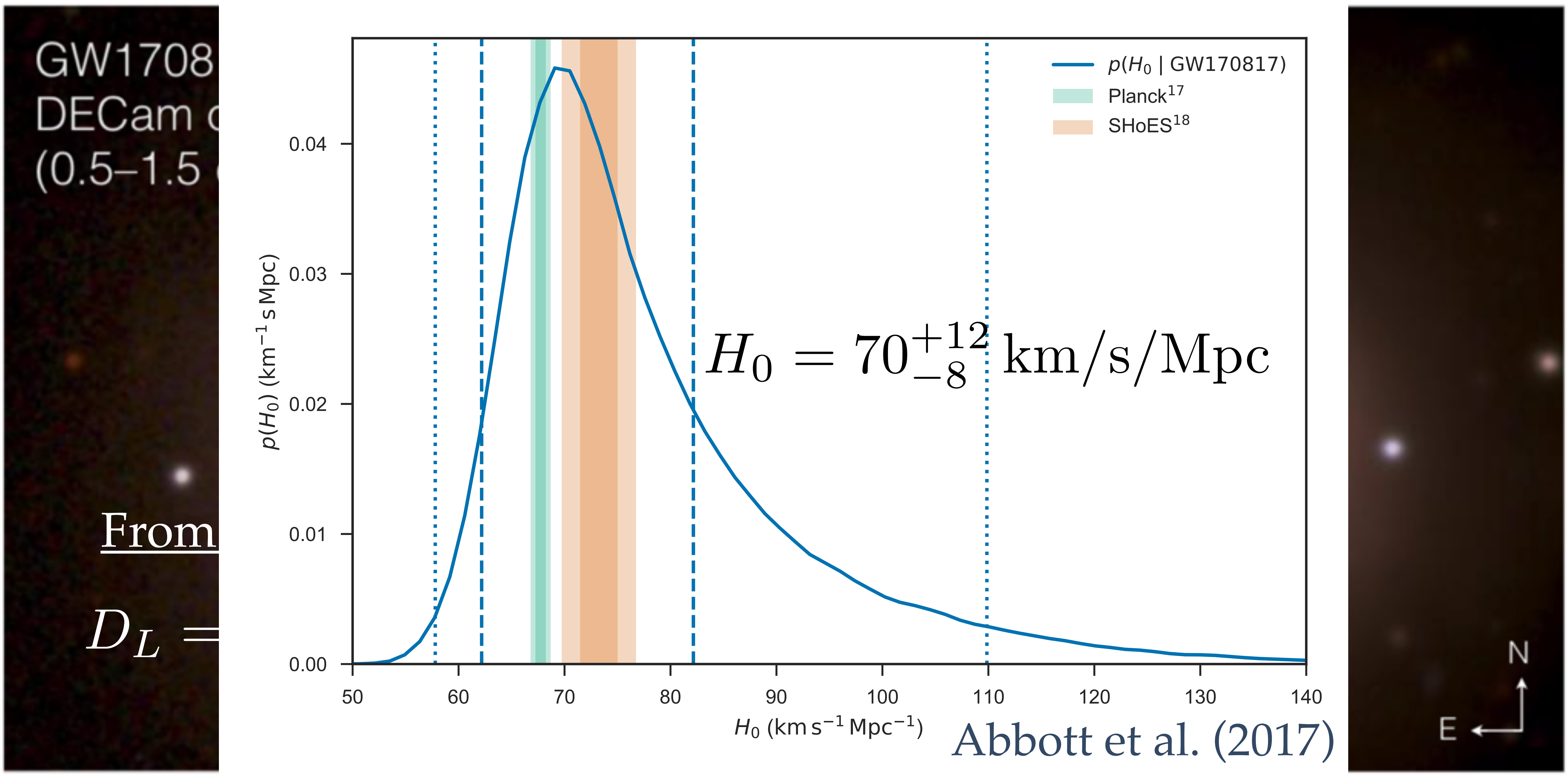
Find the host galaxy of the electromagnetic counterpart.

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

The first standard siren measurement with an electromagnetic counterpart

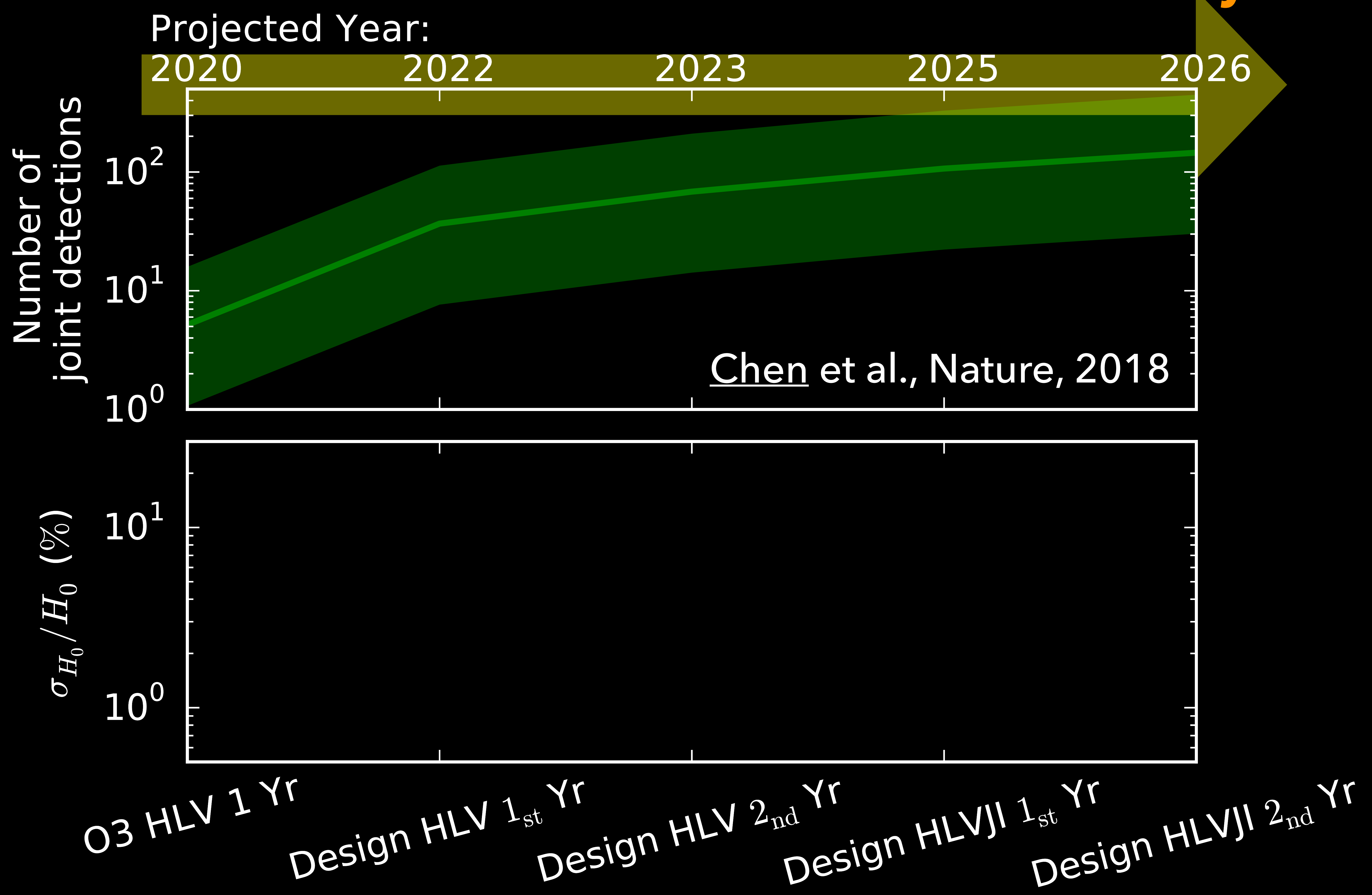


The first standard siren measurement with an electromagnetic counterpart

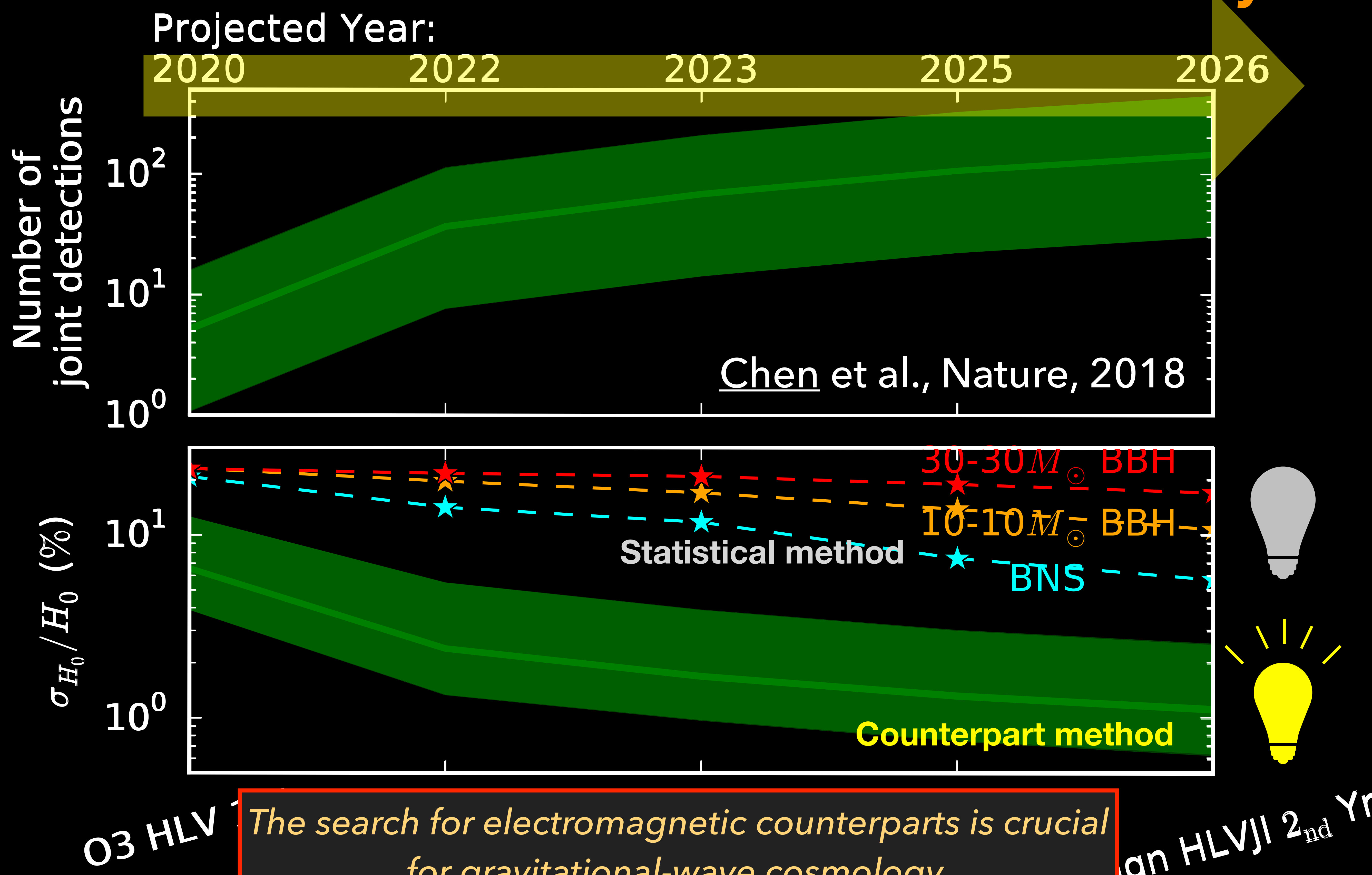


Soares-Santos, ~, Chen+, ApJL, 2017

2% Hubble constant measurement within a few years



2% Hubble constant measurement within a few years



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

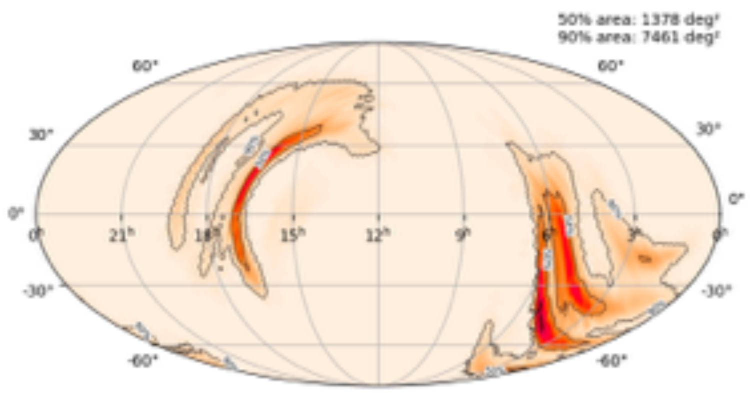
Why is it difficult to find the electromagnetic counterpart?

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

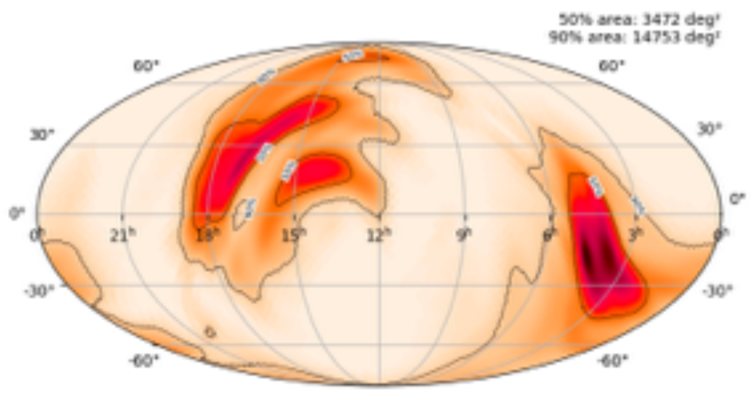
-The counterpart emissions fade away.

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

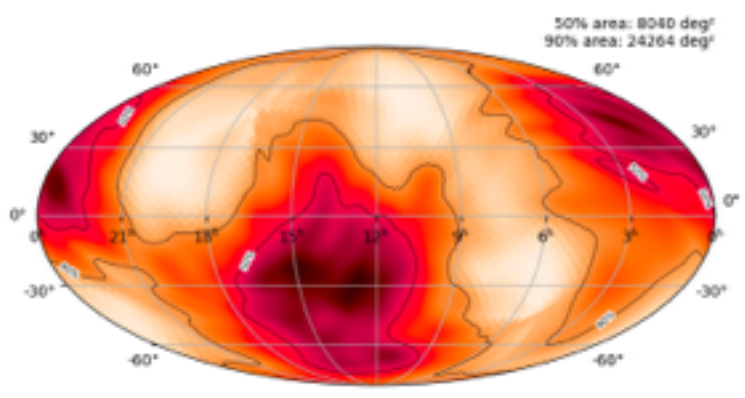
- The binary neutron star mergers in O3a were only detected by LIGO-Livingston (+Virgo).



S190425z [L,V]



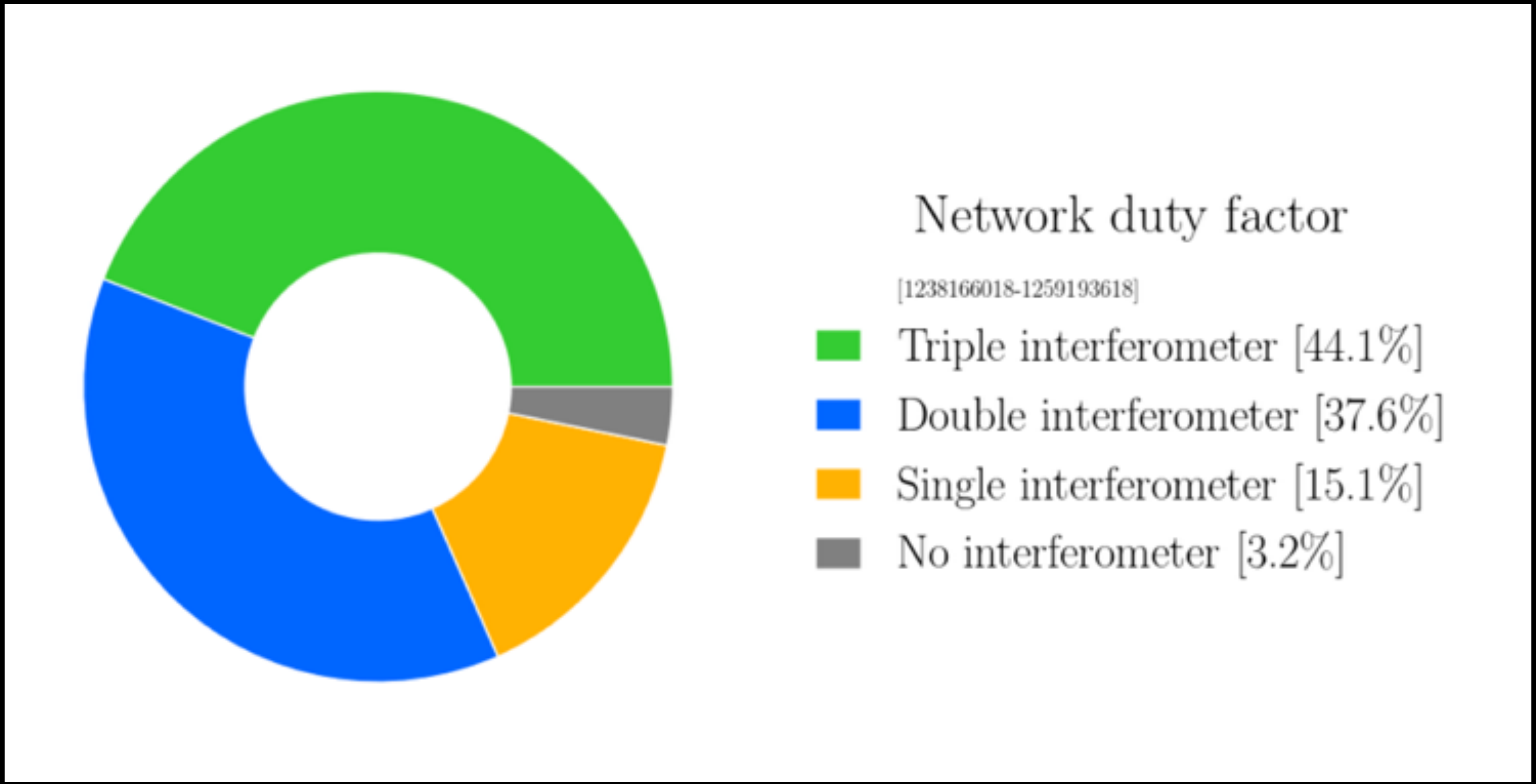
S190901ap [L,V]



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☉ for all BNSs detected so far, the BNS astrophysical rate is ~30% higher than the O1-O2 estimation from GW170817.

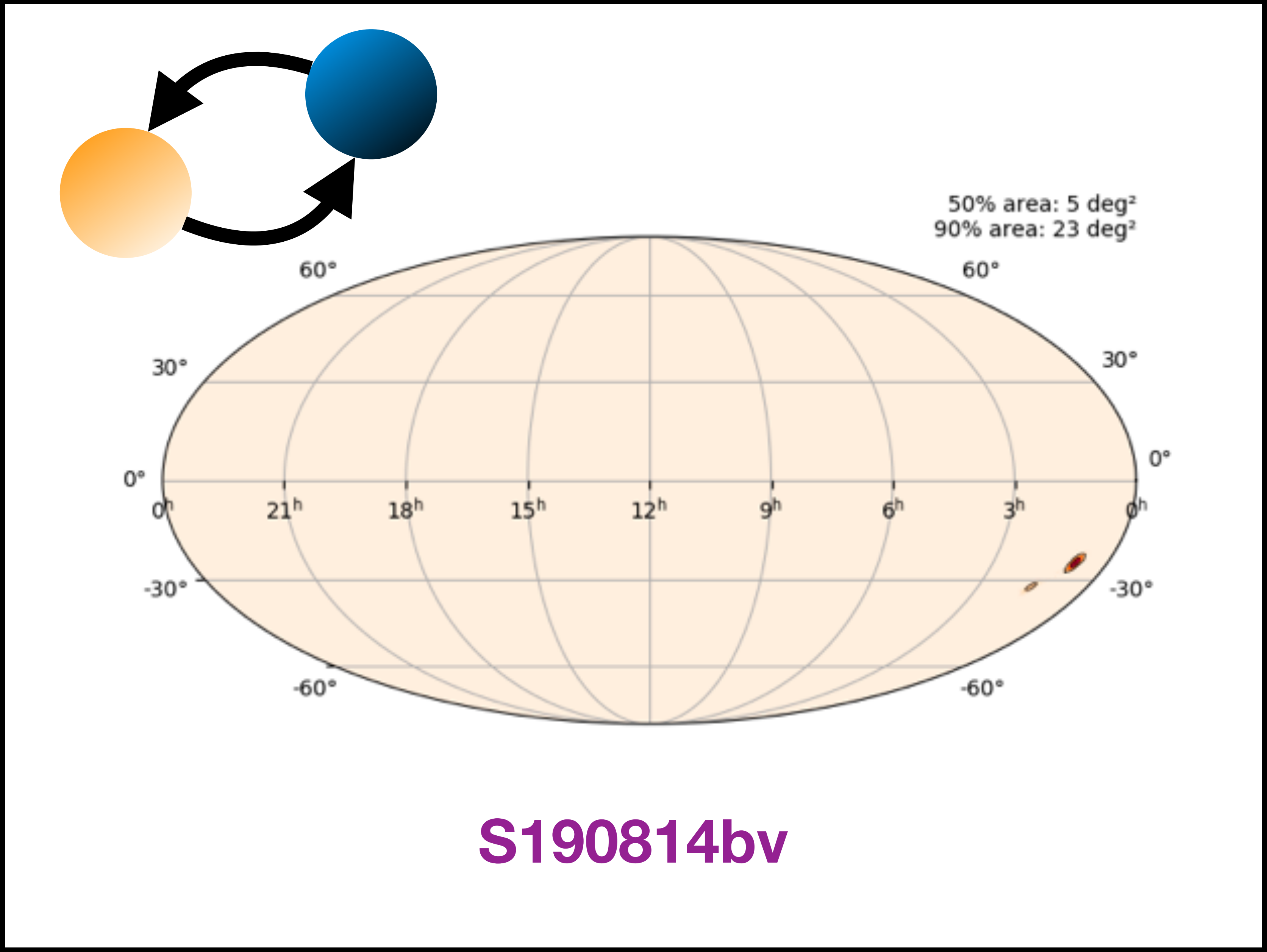
We still have only one binary neutron star with electromagnetic counterparts. Why?

Because we used up our luck in O1 and O2.

☹️

O3b is running!

Statistical method with neutron star-black hole merger?

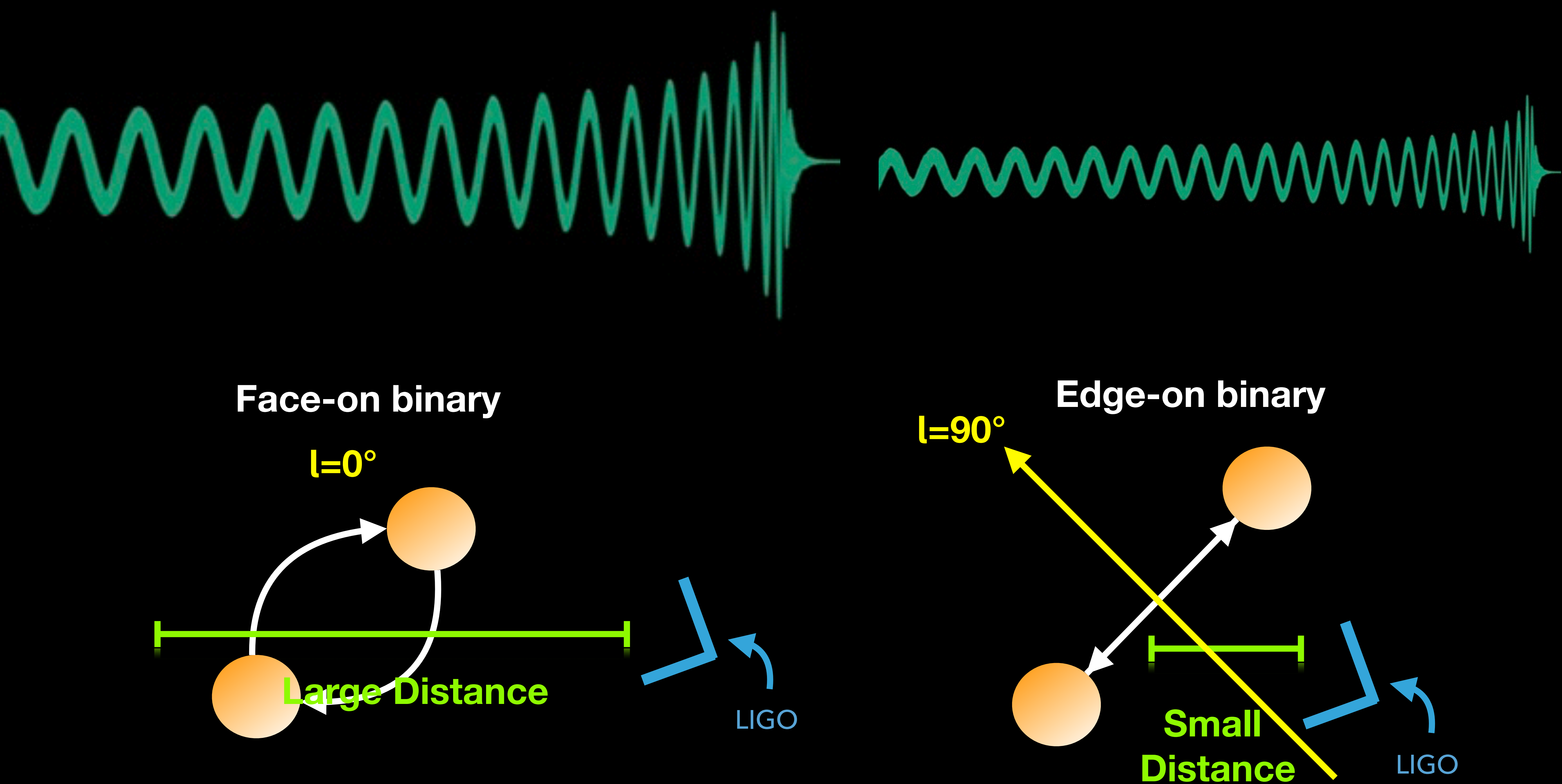


- The localization is good. The rate is not low.

Improve the precision of standard sirens

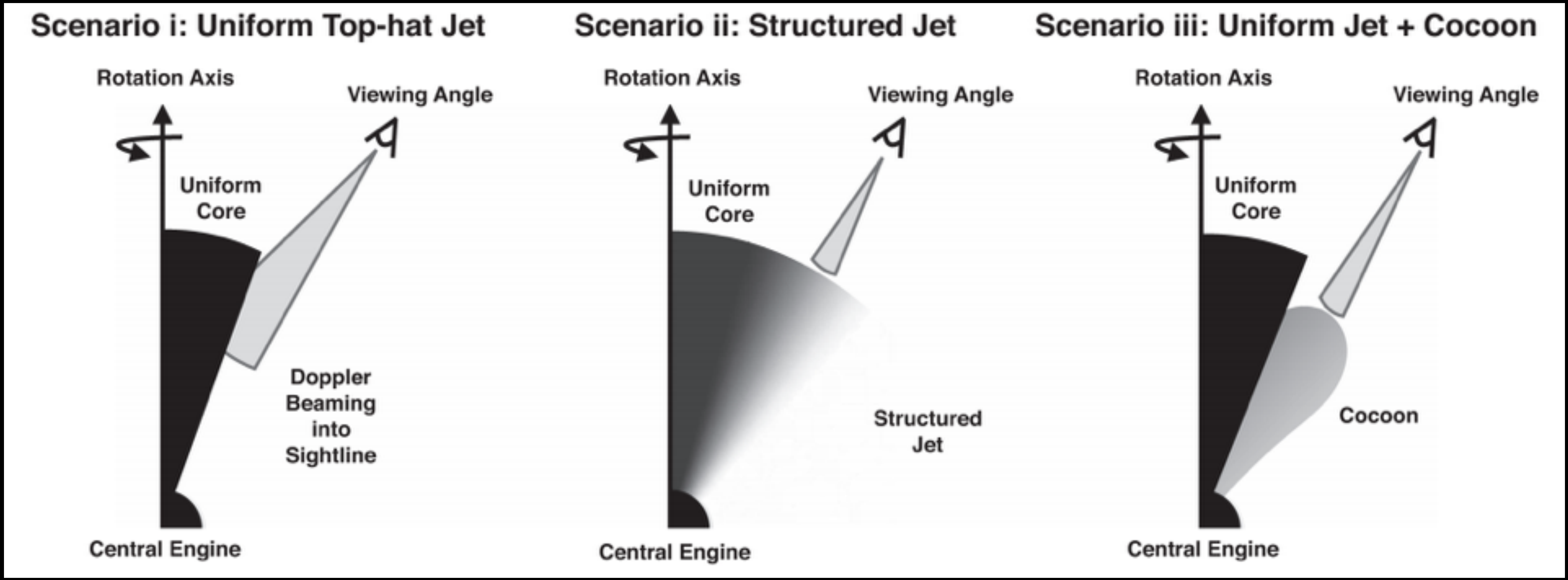
-Break the distance-inclination degeneracy.

Distance-inclination degeneracy



Different viewing angles lead to different electromagnetic signatures

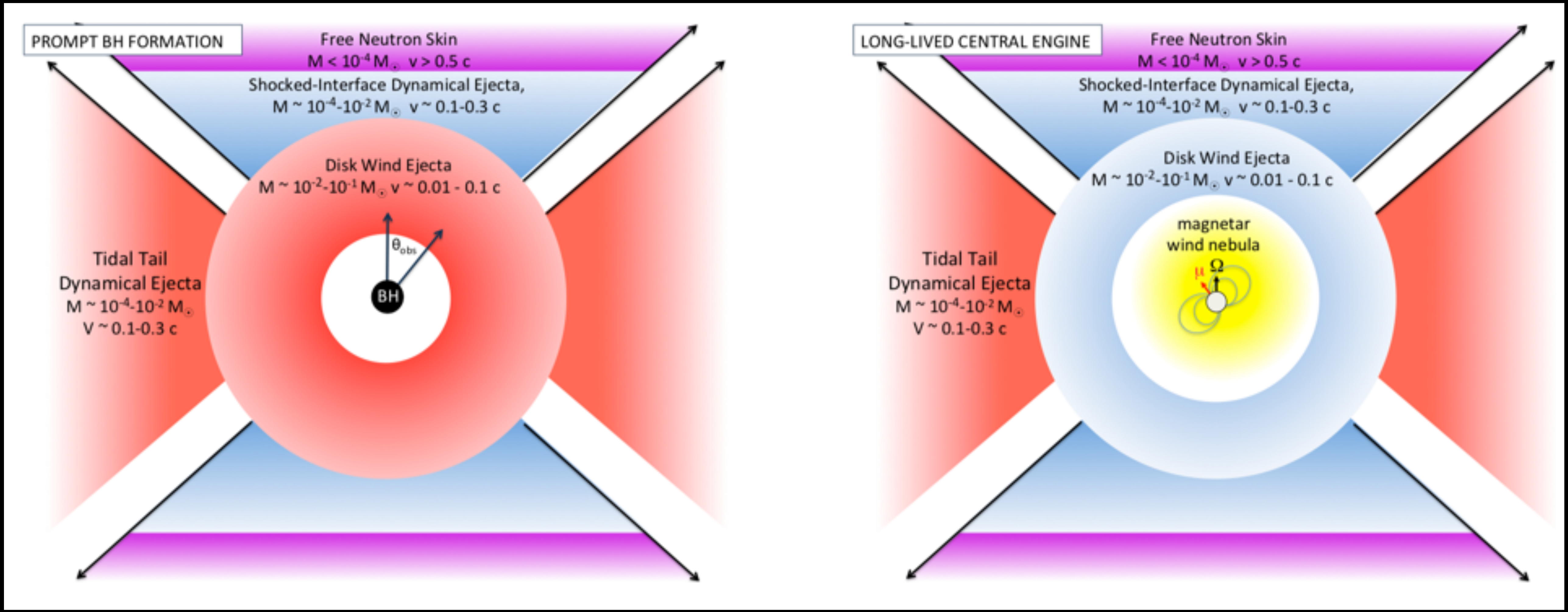
Short gamma-ray burst:



LIGO, Virgo, Fermi, INTEGRAL, 2017

Different viewing angles lead to different electromagnetic signatures

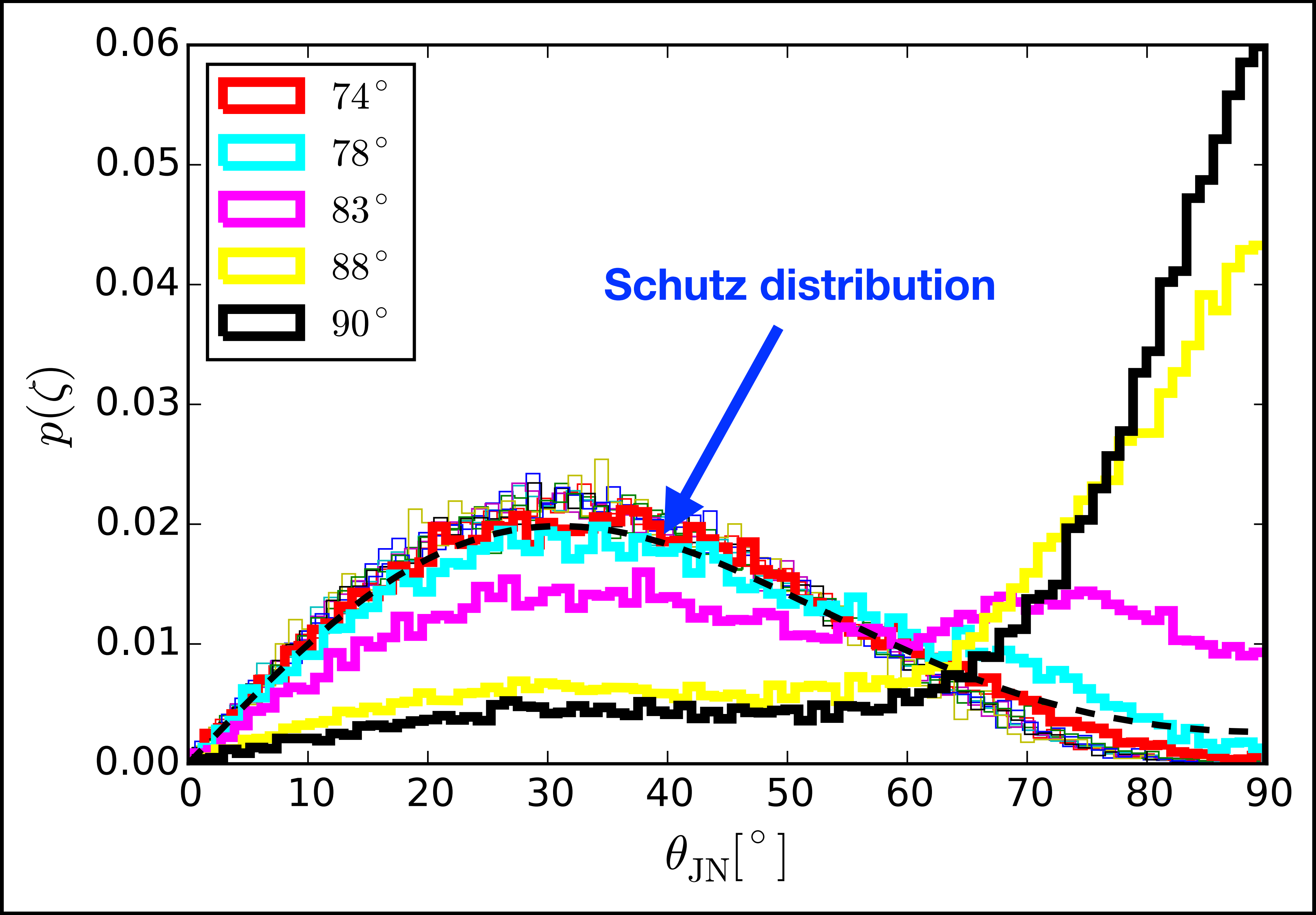
Kilonova:



Metzger, 2017

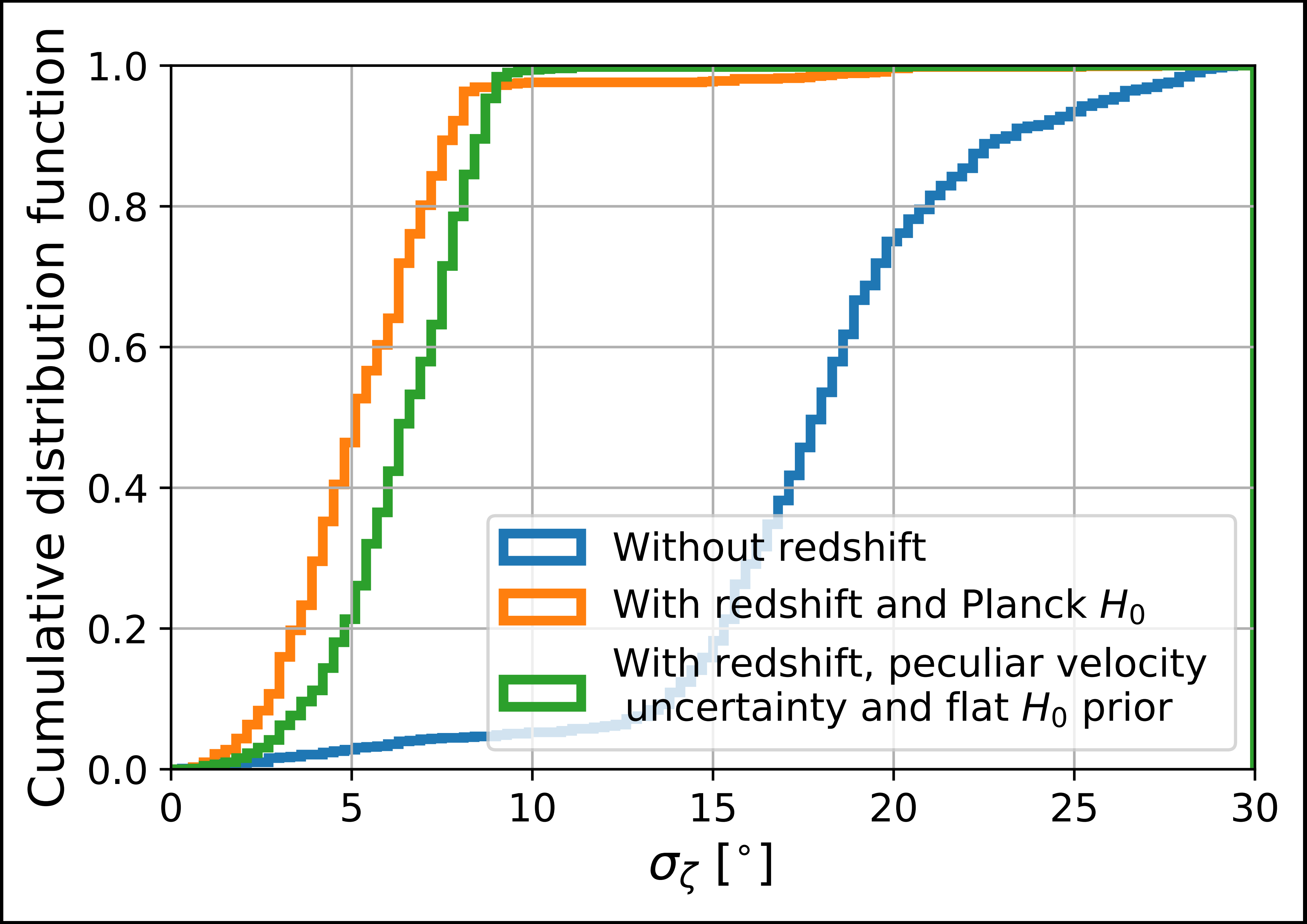
How do we infer the inclination angle?

Signal-to-noise ratio + phase and arrival time



Schutz 2011, Chen et al. PRX 2019

How well can we constrain the inclination angle?



Chen et al., PRX, 2019

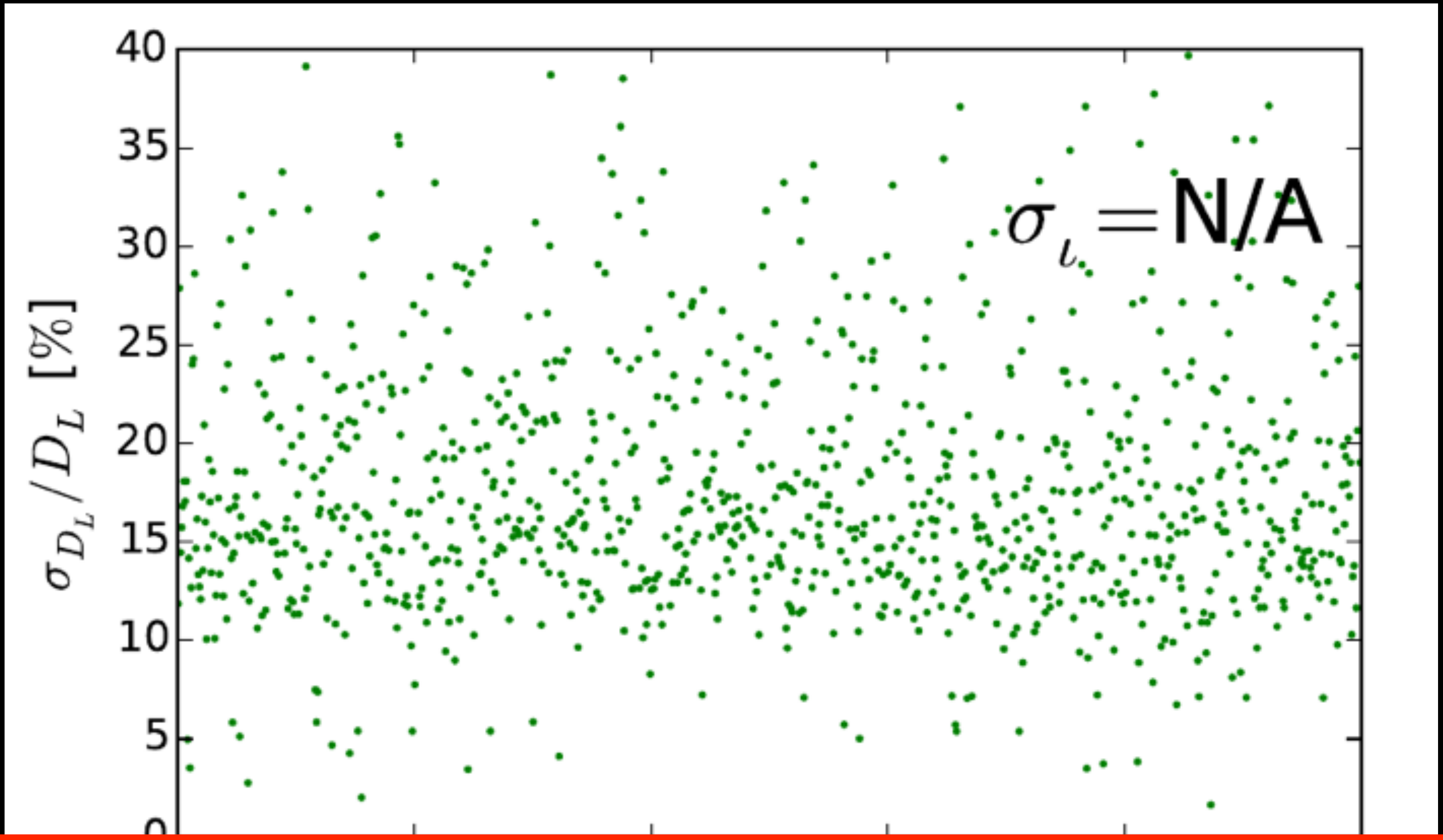
Break the distance-inclination degeneracy

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

Chen et al., PRX, 2019

Can be viewed as → **H₀ uncertainty**

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



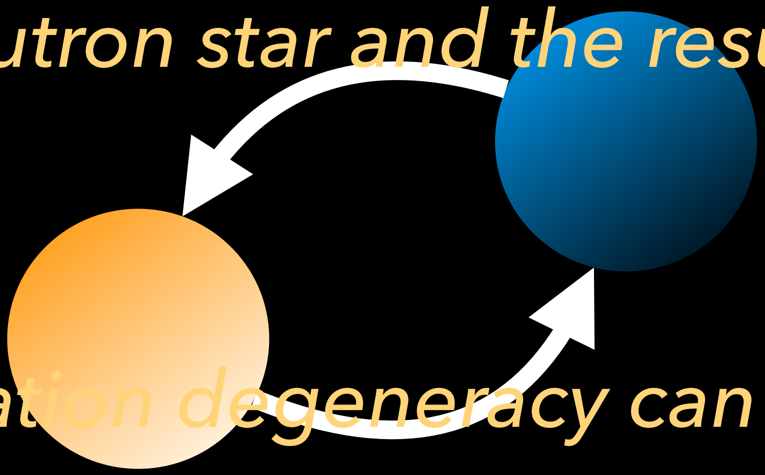
A factor of 5 to10 fewer events are required to reach the same Hubble Constant precision if the viewing angle is constrained.

Break the distance-inclination degeneracy

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

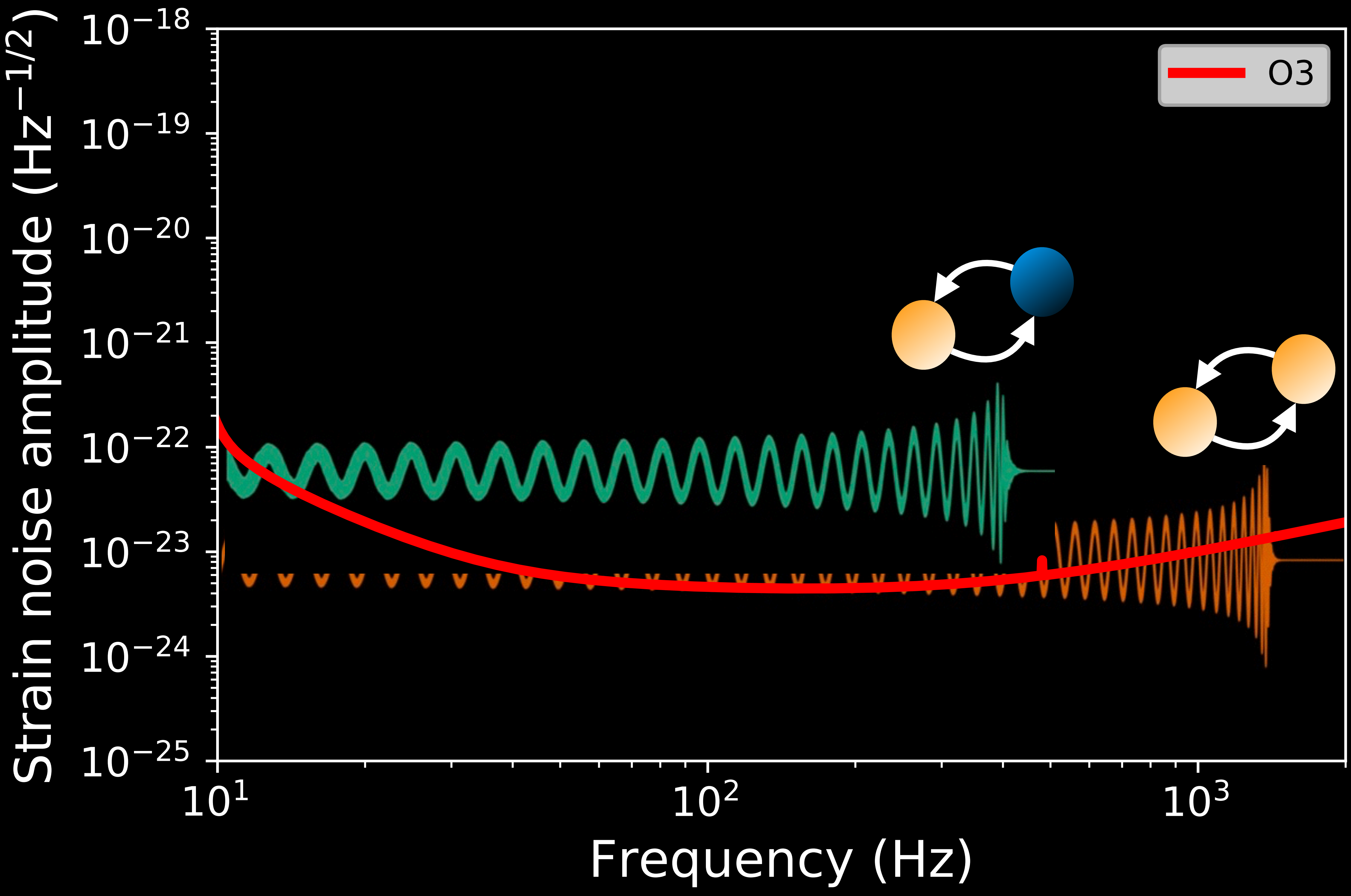
Vitale & Chen, PRL, 2018

-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

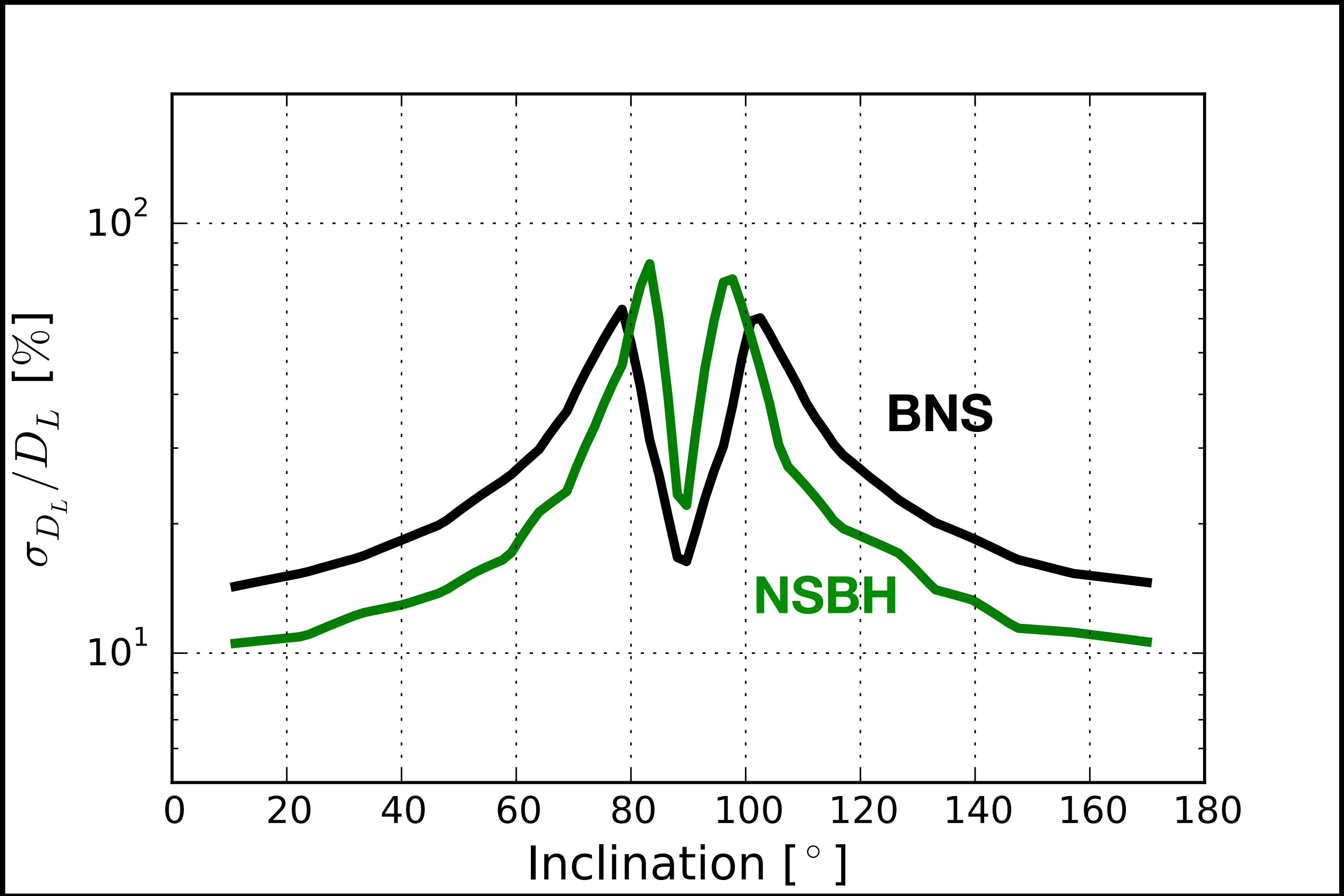


Break the distance-inclination degeneracy

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

Vitale & Chen, PRL, 2018

Can be viewed as **H0 uncertainty**

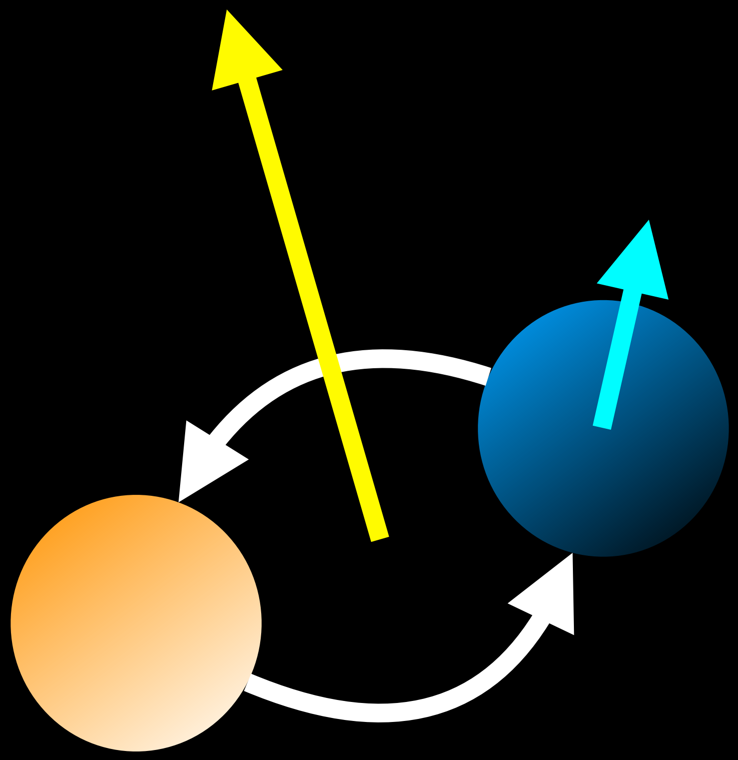


The difference between BNS and NSBH is mainly due to the observation of merger-ringdown.

Break the distance-inclination degeneracy

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

Vitale & Chen, PRL, 2018



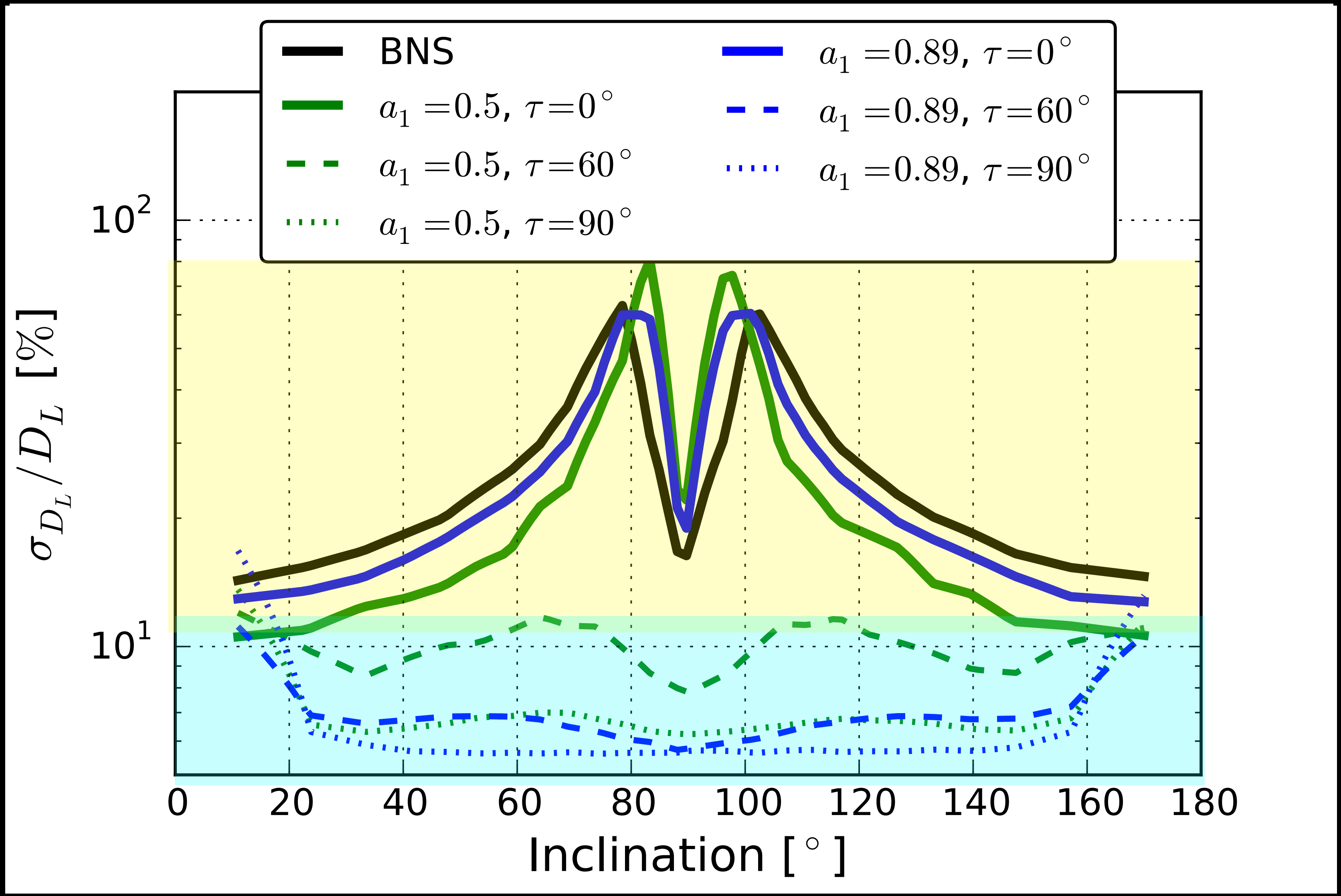
Break the distance-inclination degeneracy

*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.

Summary

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

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

Systematic uncertainties

- Luminosity distance:
  calibration, waveform, viewing angle
- Redshift:
  peculiar velocity, host galaxy type,
  misidentification of electromagnetic counterparts