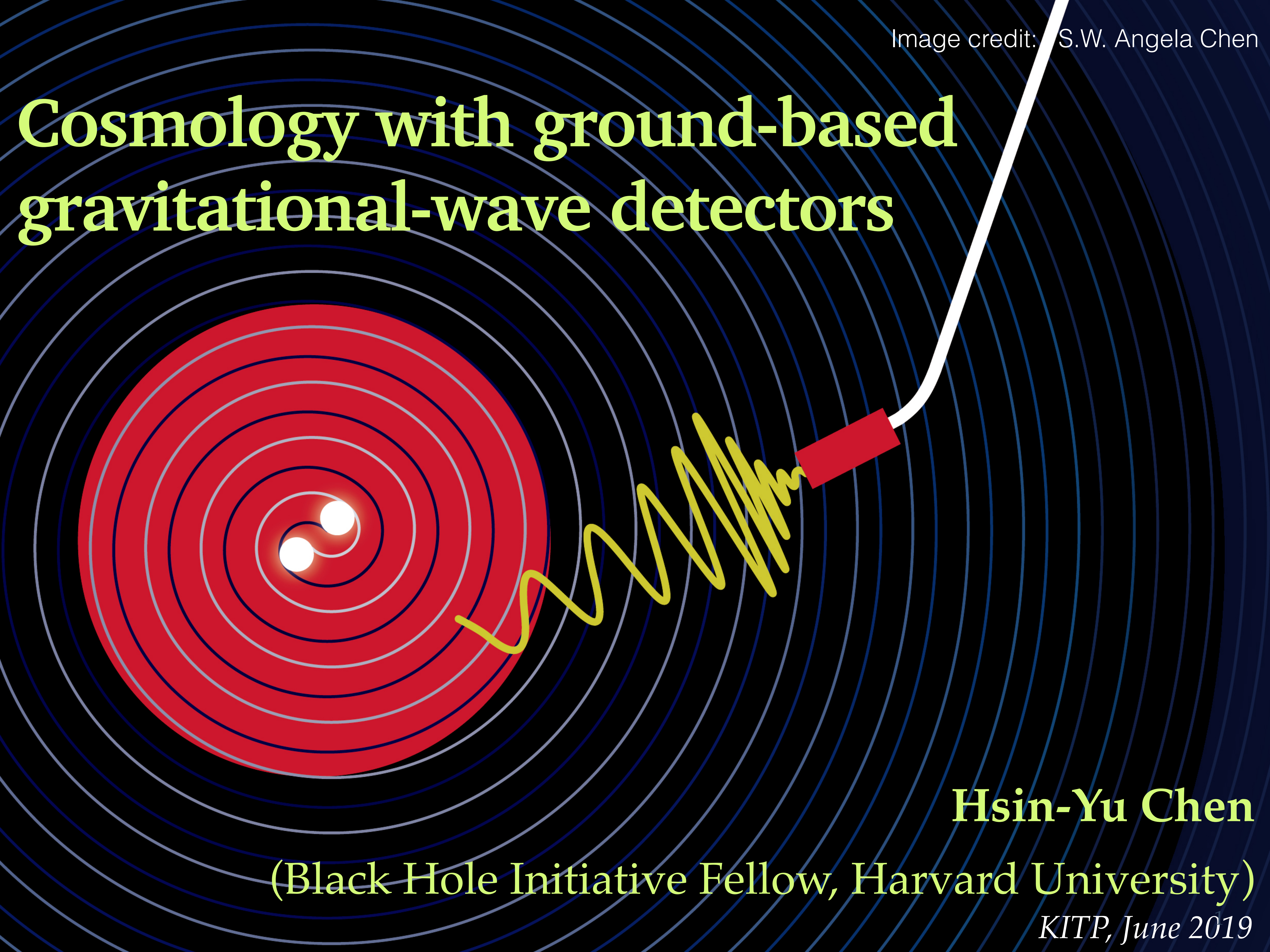


Image credit: S.W. Angela Chen

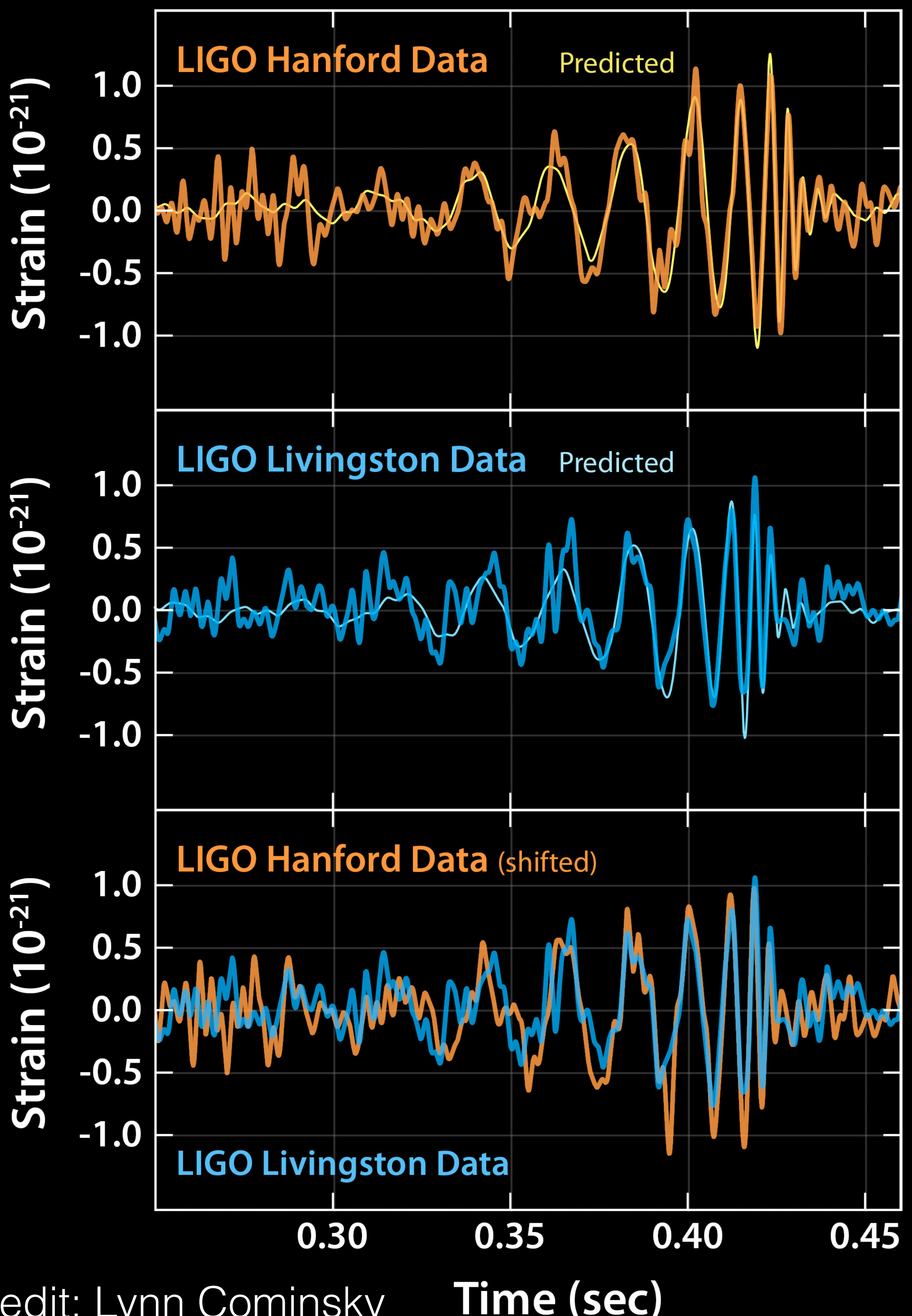
Cosmology with ground-based gravitational-wave detectors

Hsin-Yu Chen

(Black Hole Initiative Fellow, Harvard University)

KITP, June 2019

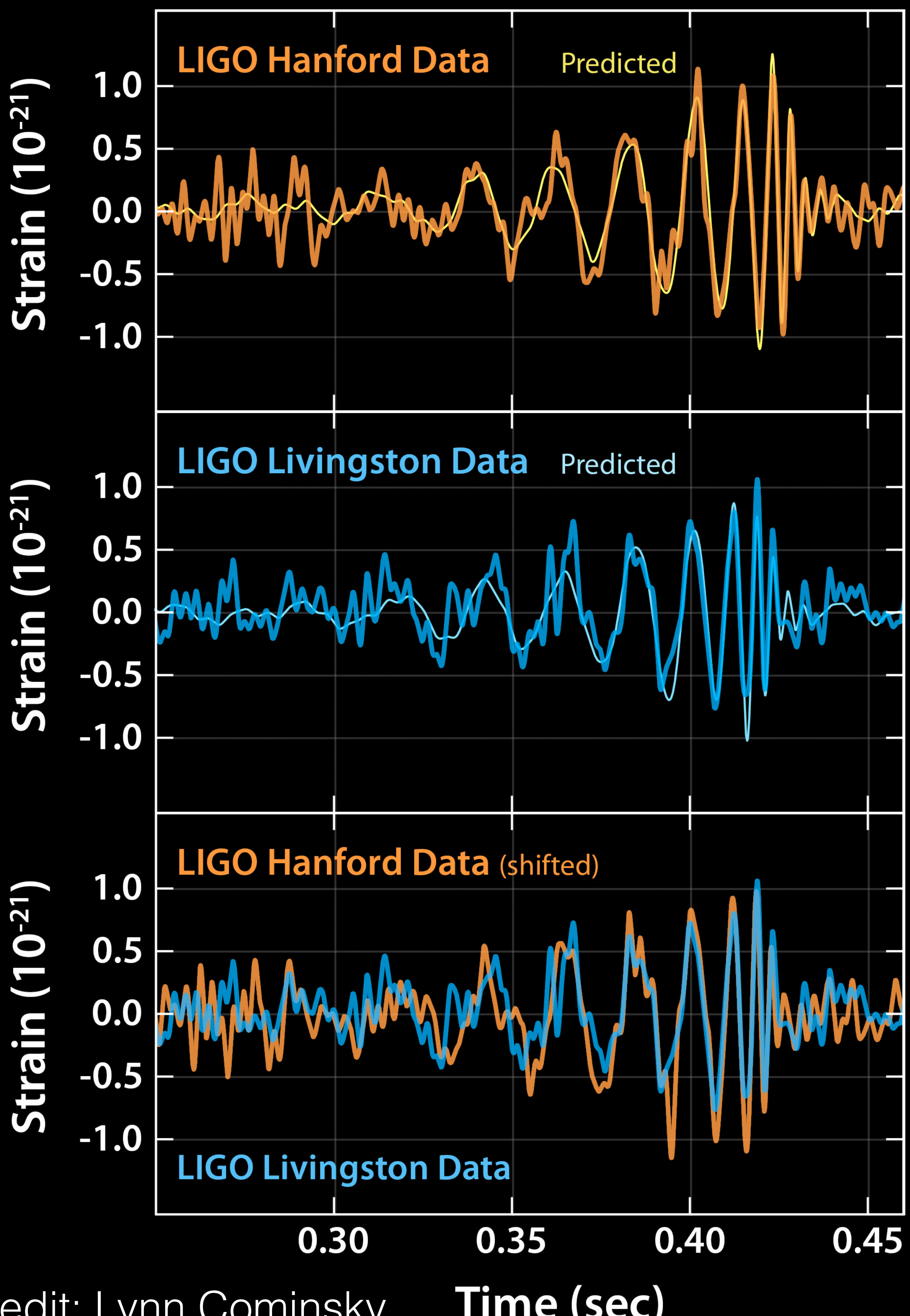
Direct measurement of the luminosity distance



Credit: Lynn Cominsky

Luminosity Distance $\propto$ 1/Amplitude

Direct measurement of the luminosity distance



Credit: Lynn Cominsky

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.

Direct measurement of the luminosity distance

Luminosity Distance ∝ 1/Amplitude

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

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

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

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Different methods for gravitational-wave cosmology

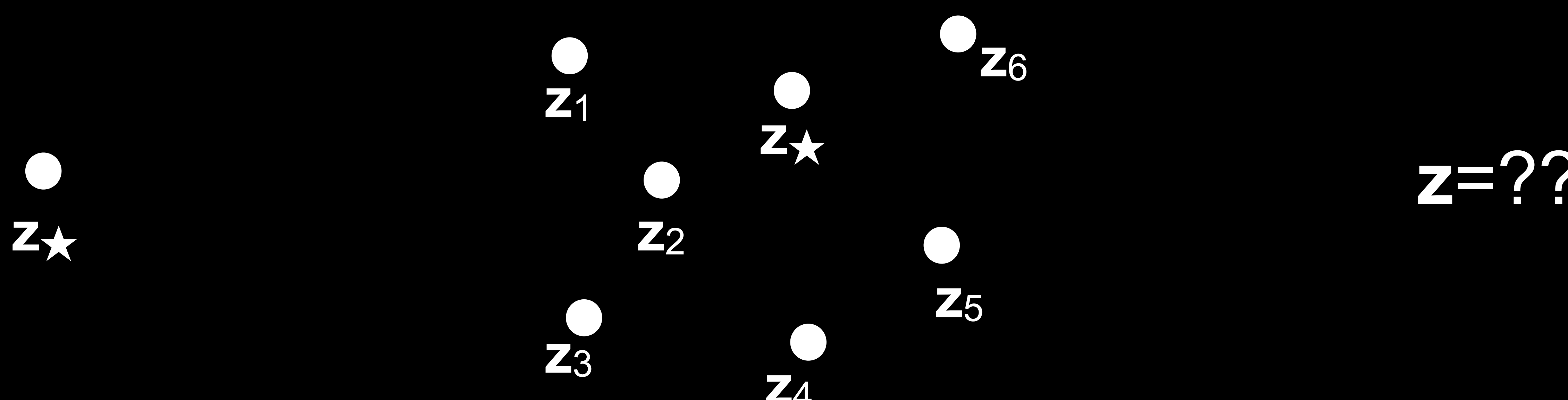
Electromagnetic counterpart

Without electromagnetic counterpart

Unique redshift

Multiple possible redshifts

No redshift



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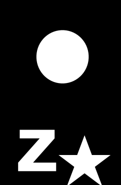

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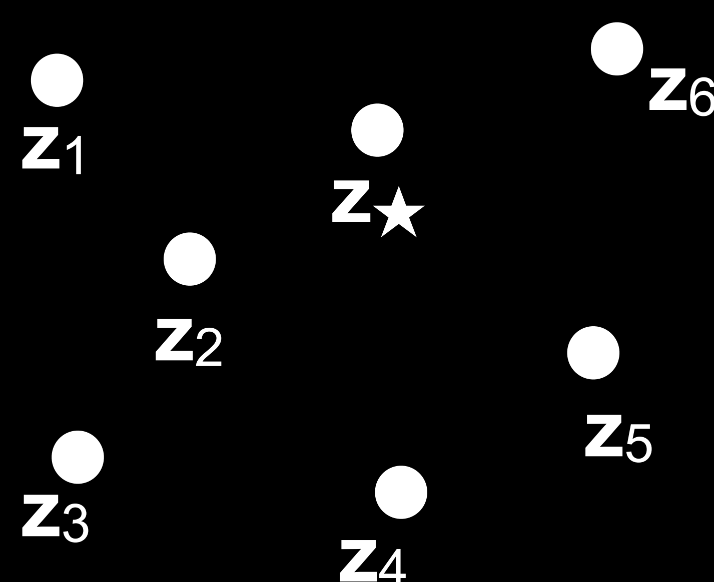
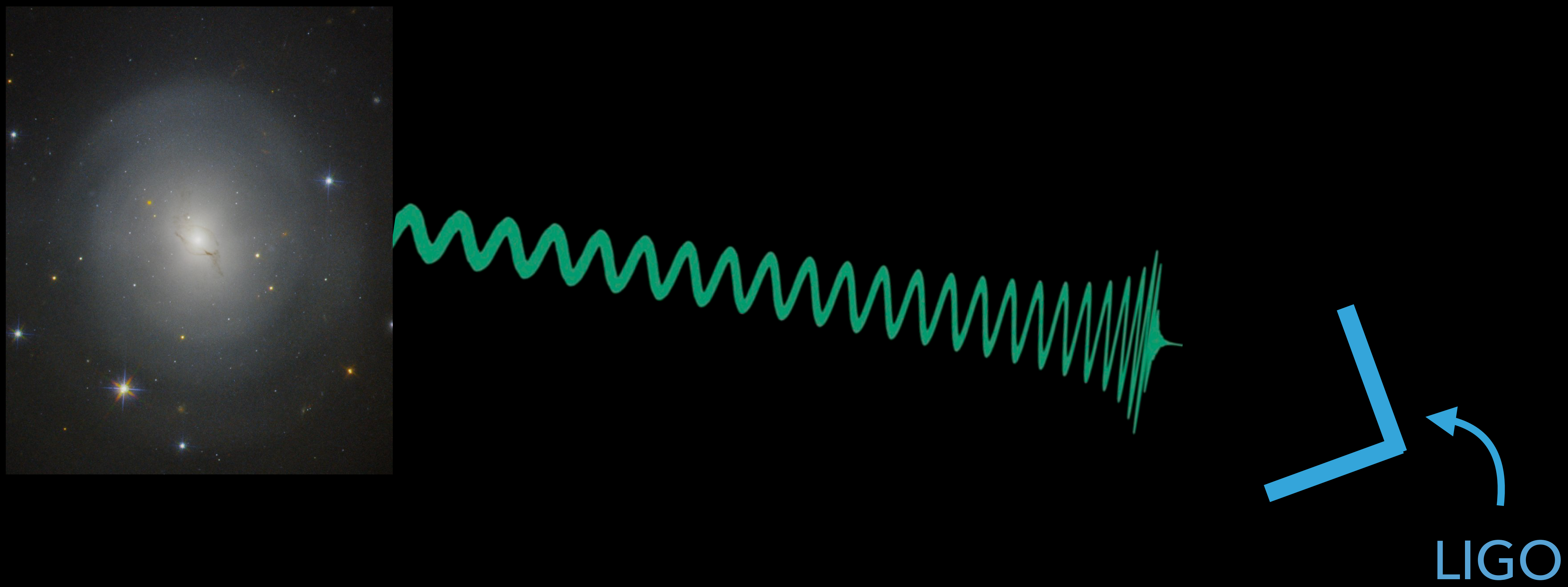


No redshift

z=??

Determine the redshift of gravitational-wave source with the host galaxy [“Standard Siren”]



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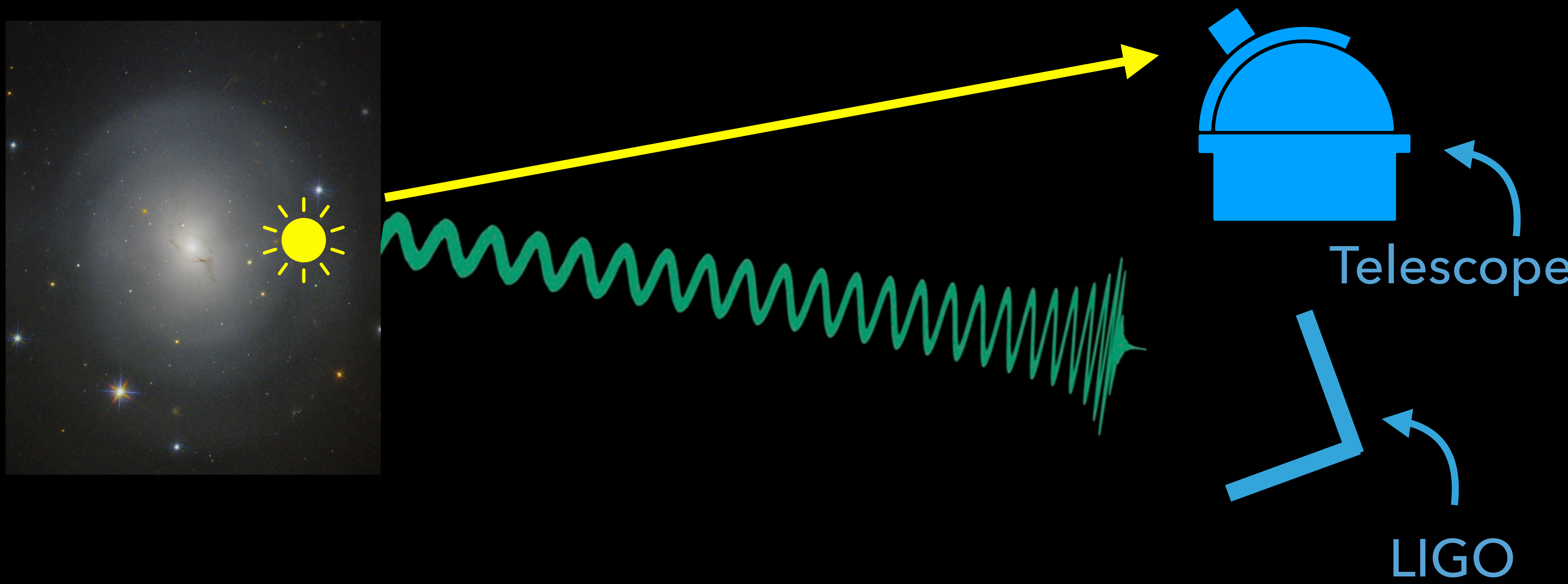
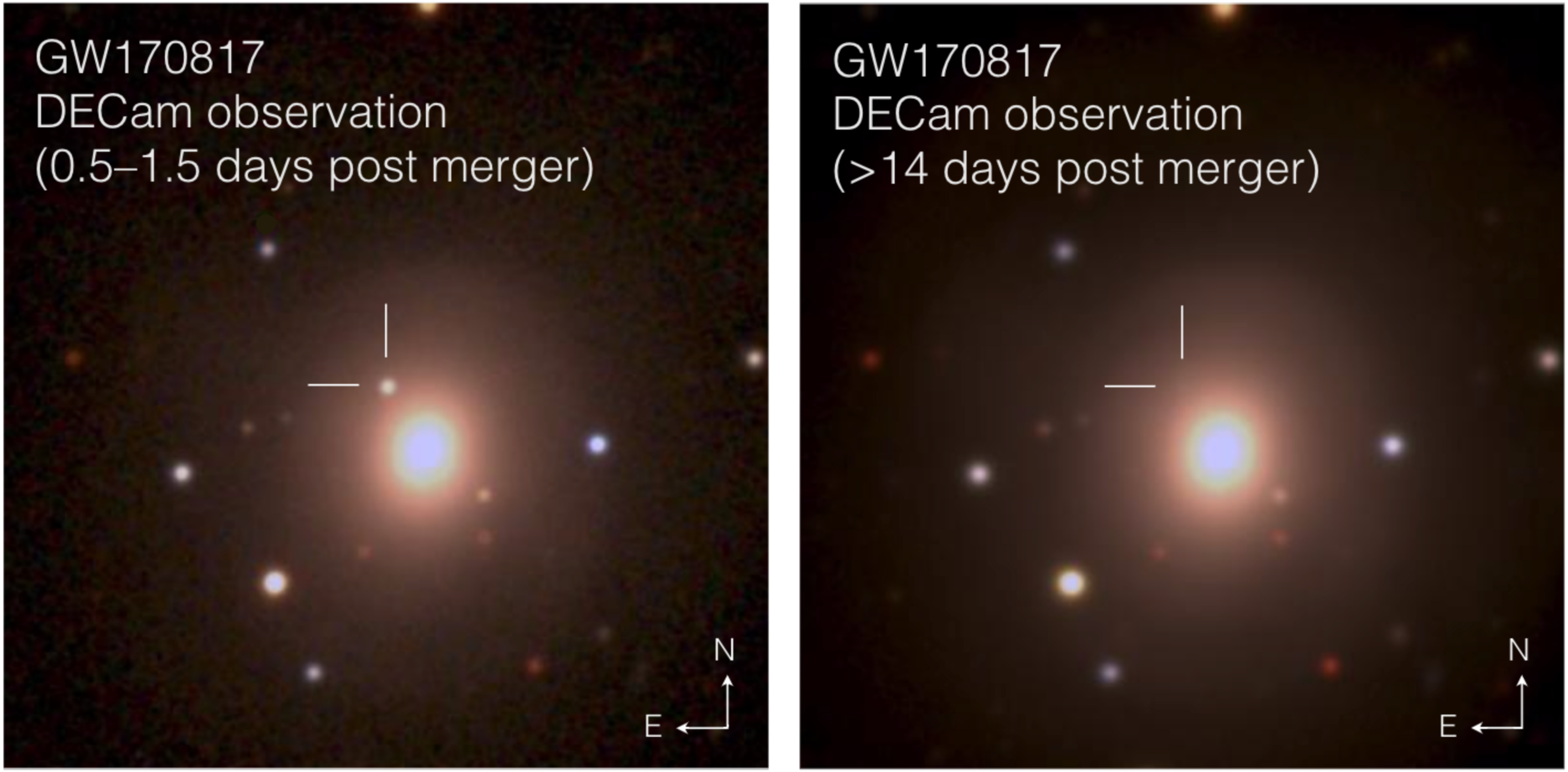


Counterpart method:
Find the host galaxy of the electromagnetic counterpart.

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

The first standard siren measurement with an electromagnetic counterpart



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

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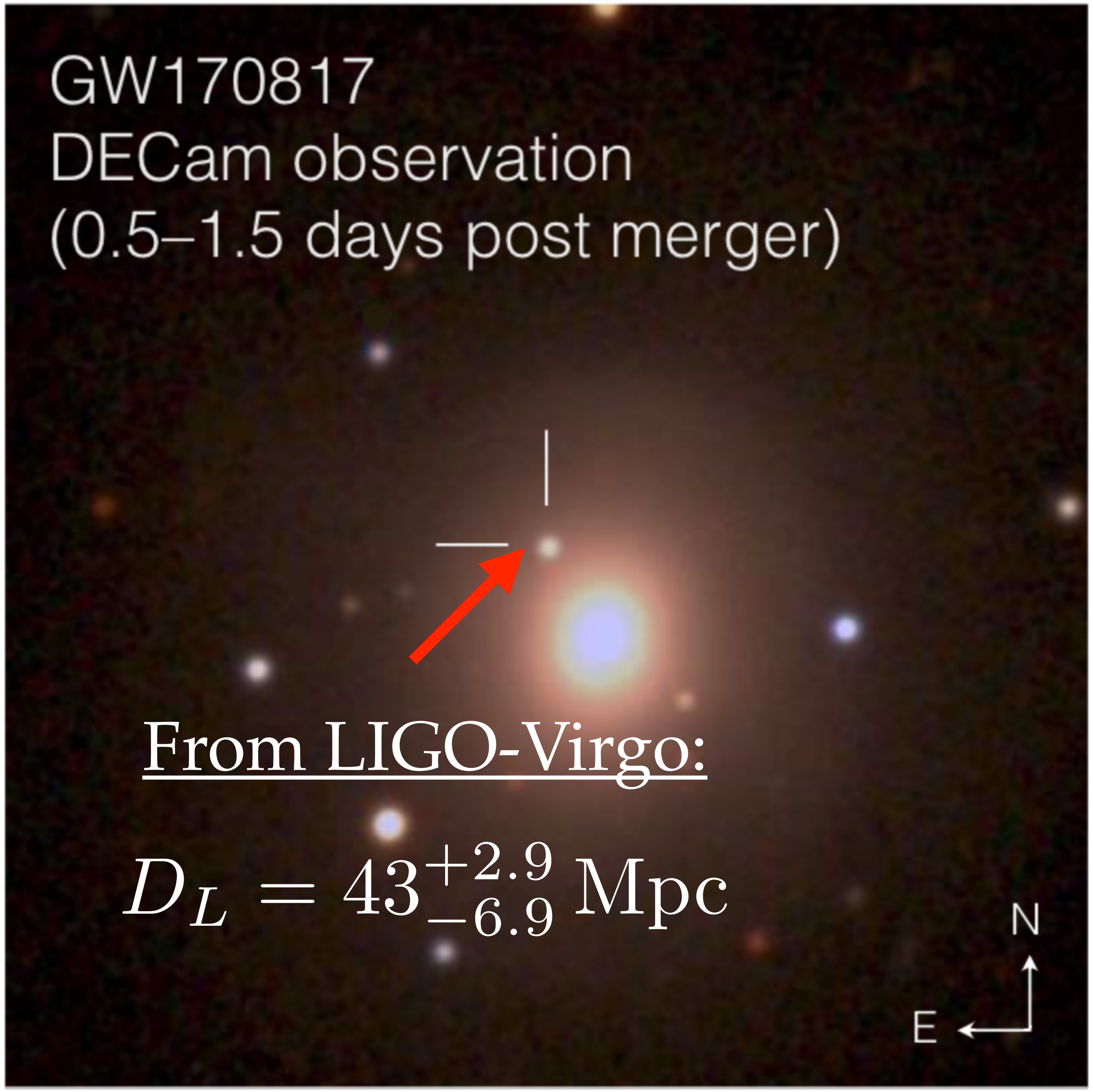

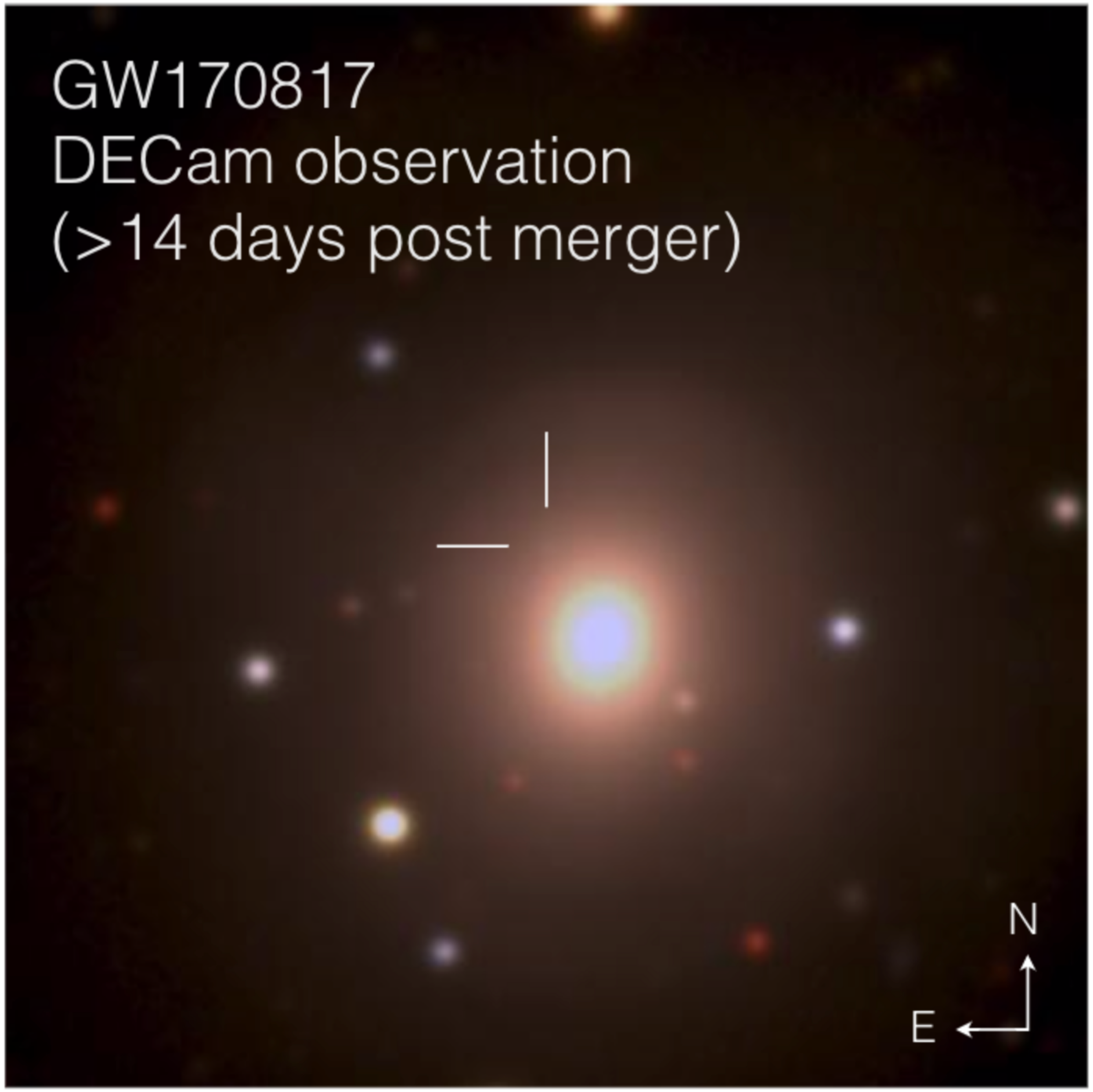

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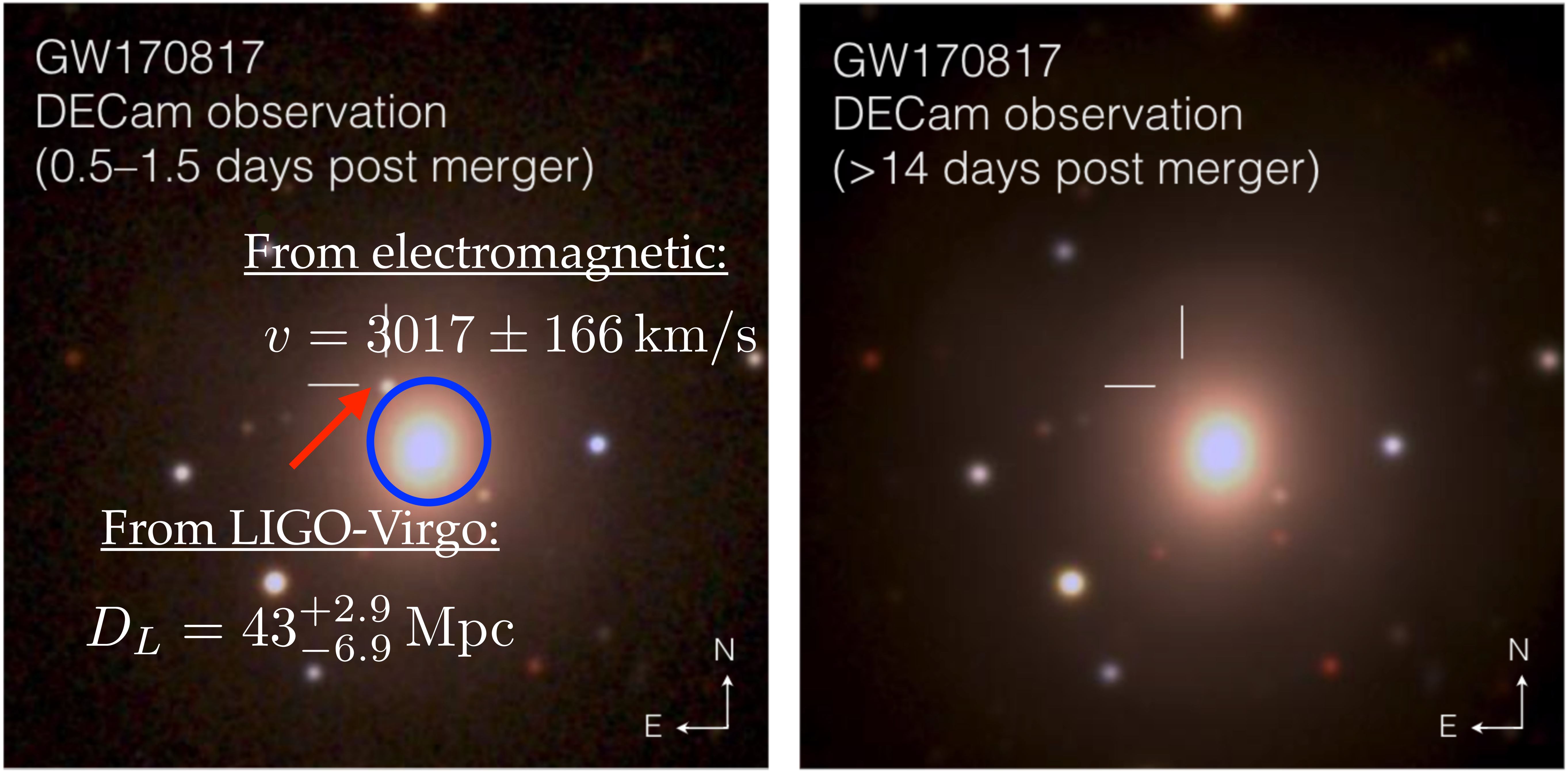

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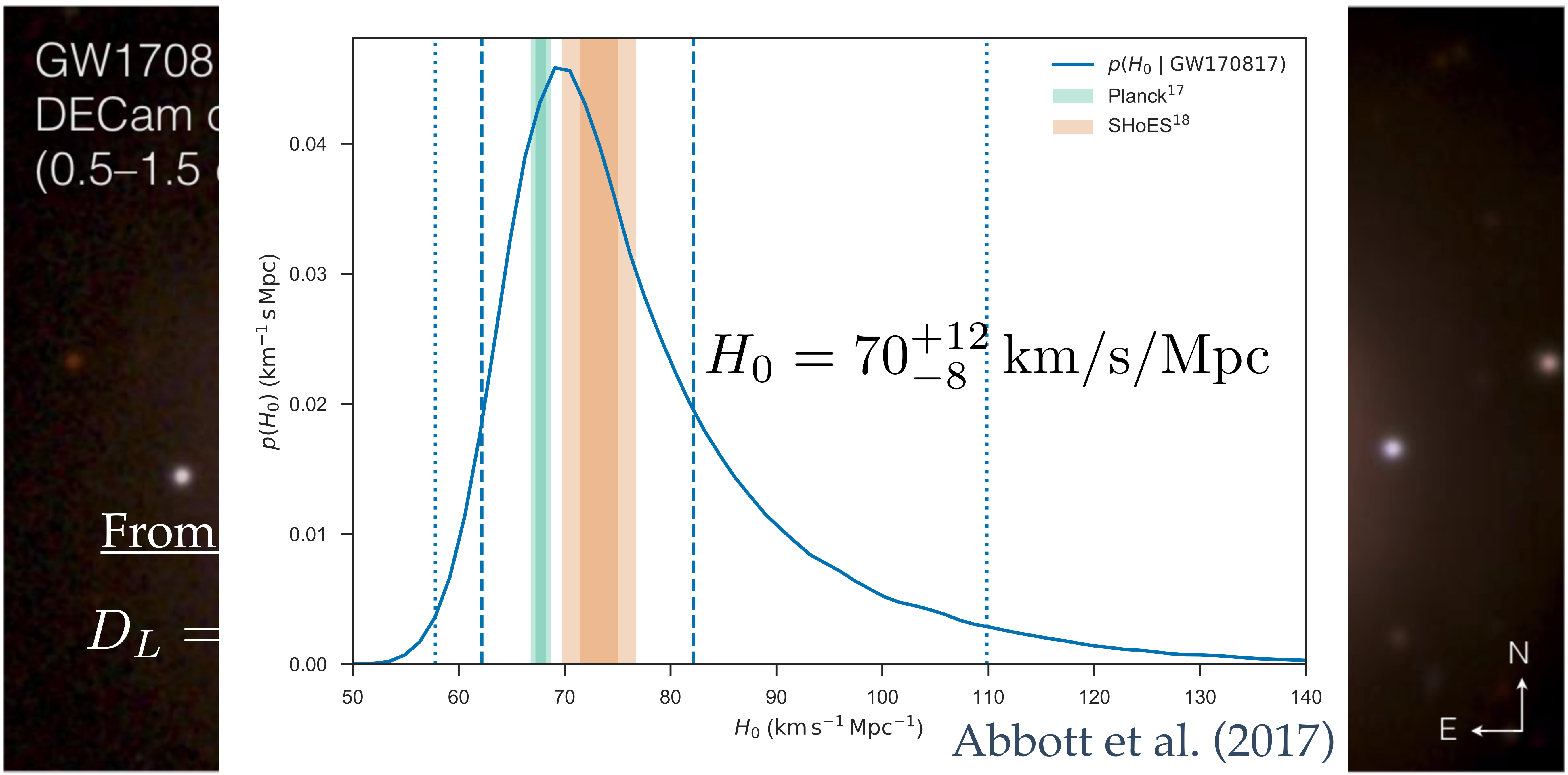
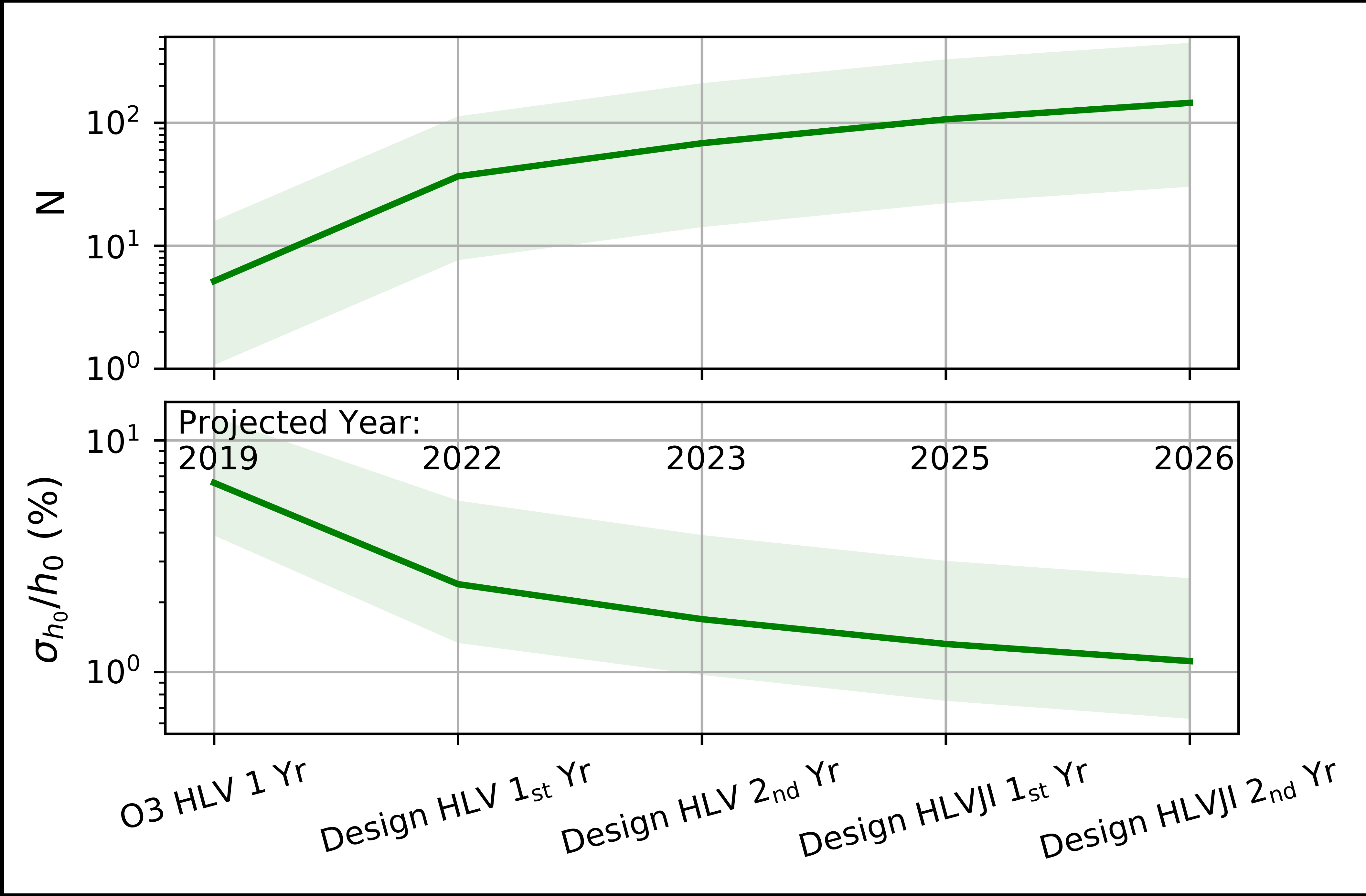


Soares-Santos, ~, Chen+, ApJL, 2017

2% Hubble constant measurement within five years



Chen, Fishbach, Holz , Nature, 2018

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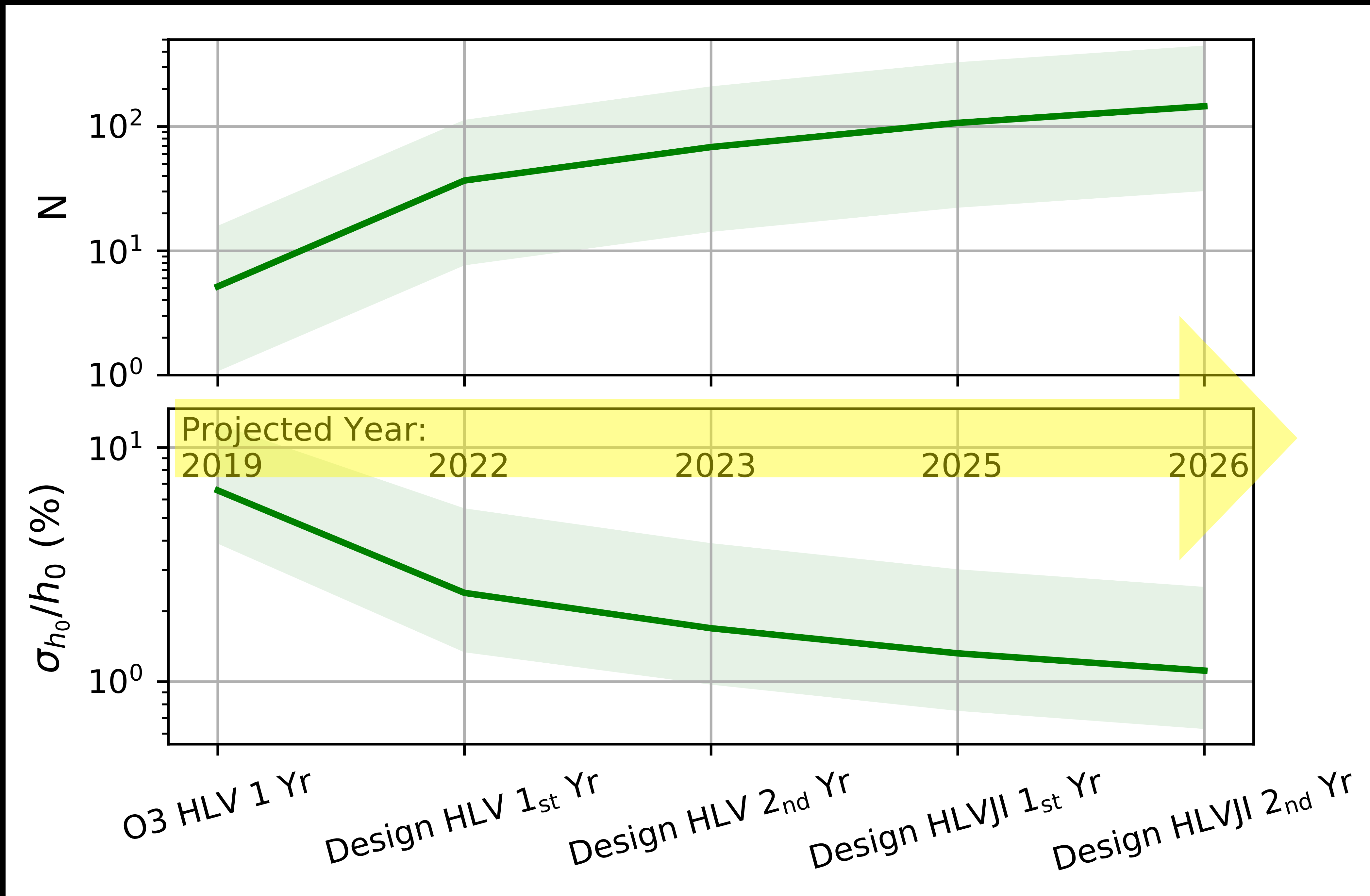

<u>Chen</u>, Fishbach, Holz , Nature, 2018

Chen, Fishbach, Holz , Nature, 2018

2% in five years

- Realistic distance posteriors were used.

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

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

Chen, Fishbach, Holz , Nature, 2018

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- BNS astrophysical rate is the major source of the uncertainty.

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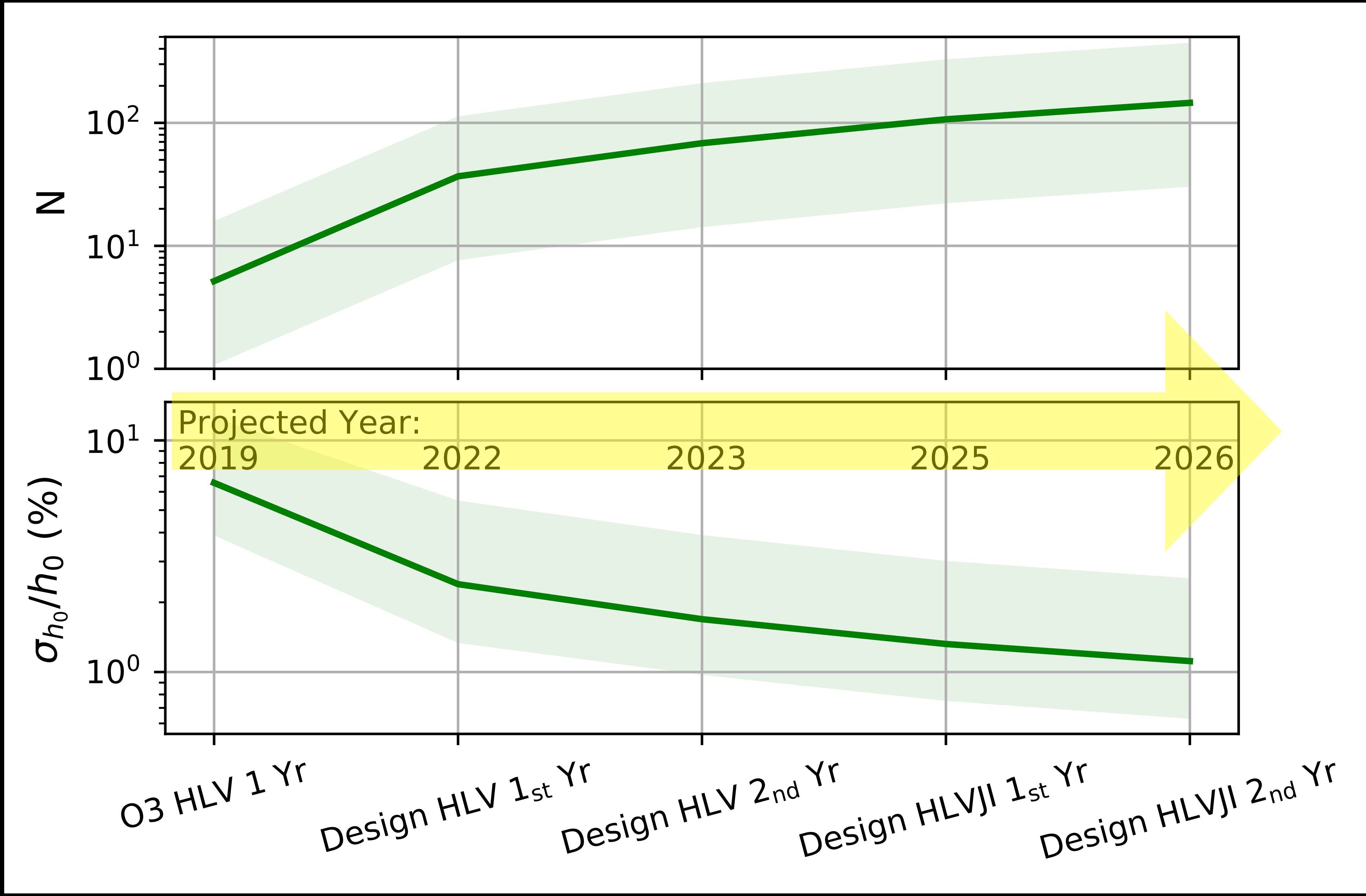

Chen, Fishbach, Holz , Nature, 2018

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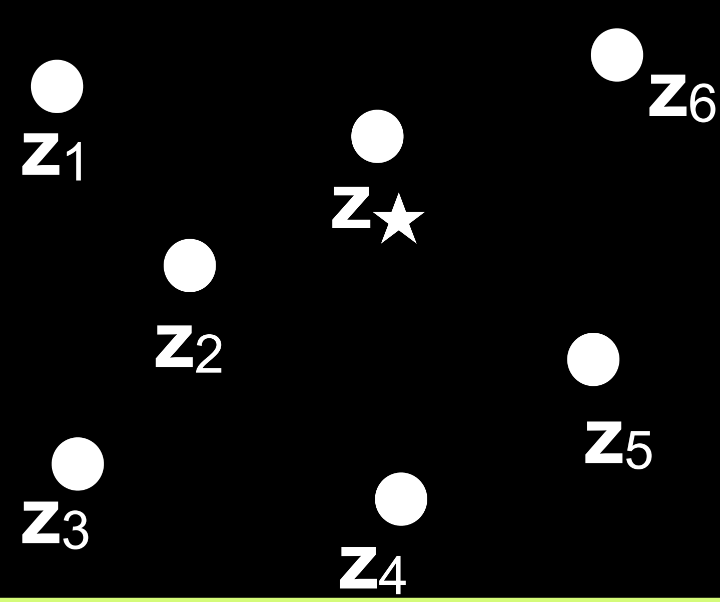

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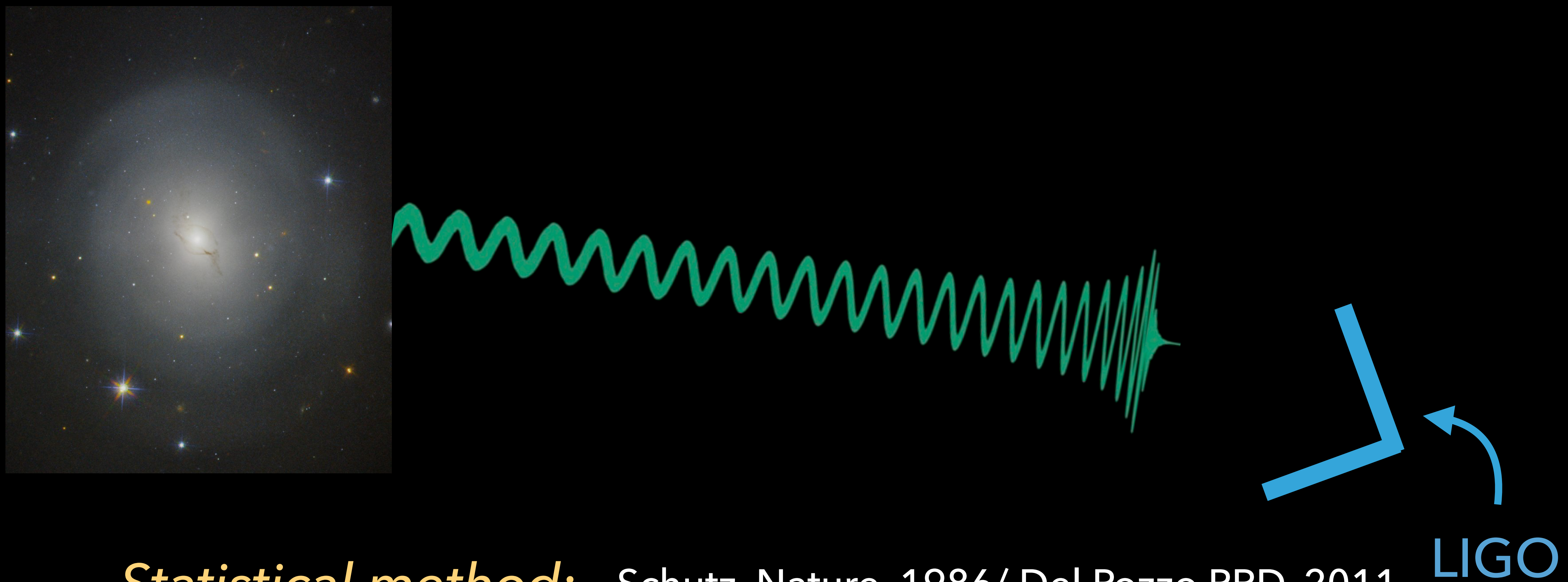
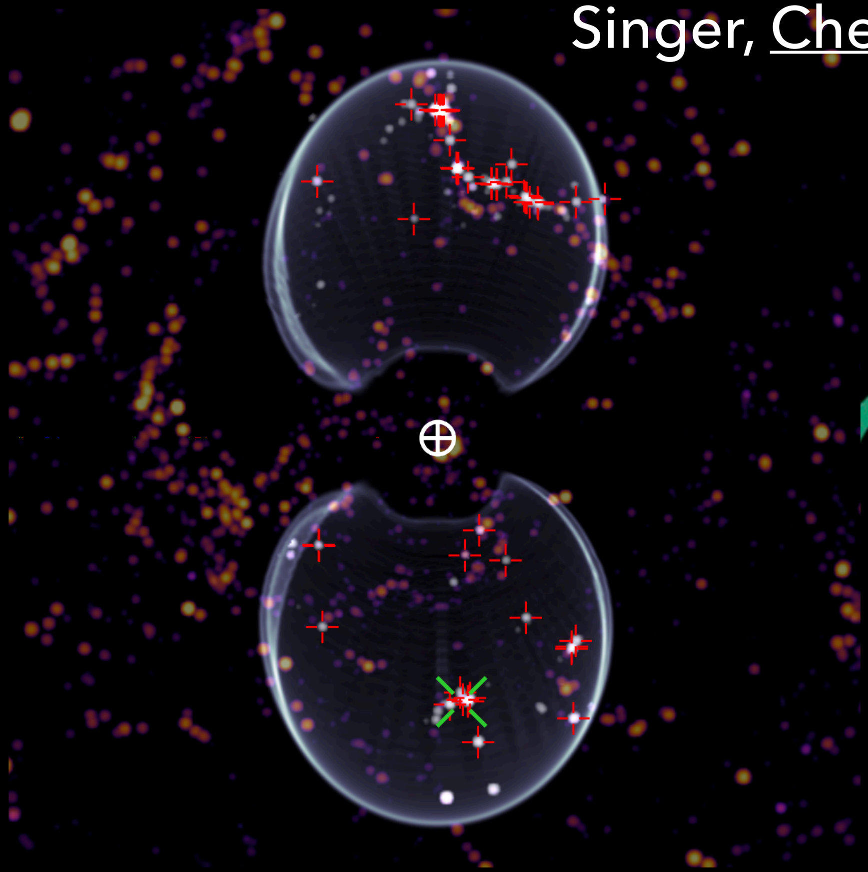


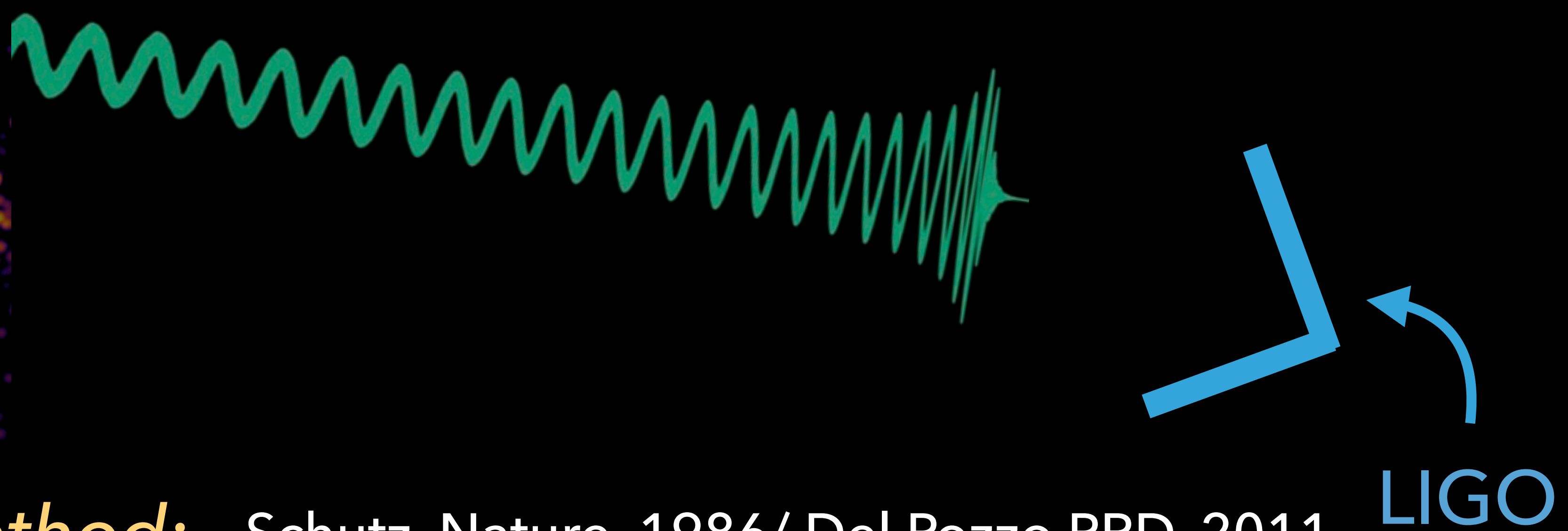
Statistical method: Schutz, Nature, 1986/ Del Pozzo,PRD, 2011

Combine the redshifts of all possible host galaxies.

Determine the redshift of gravitational-wave source with the host galaxy ["Standard Siren"]

Singer, Chen+, ApJL, 2016





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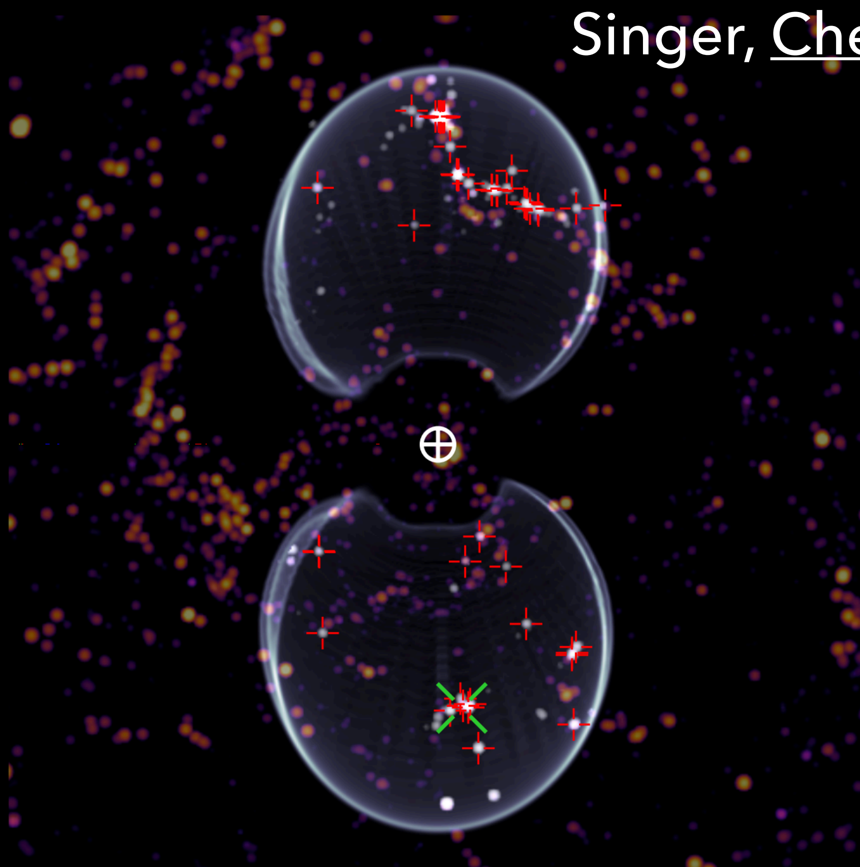

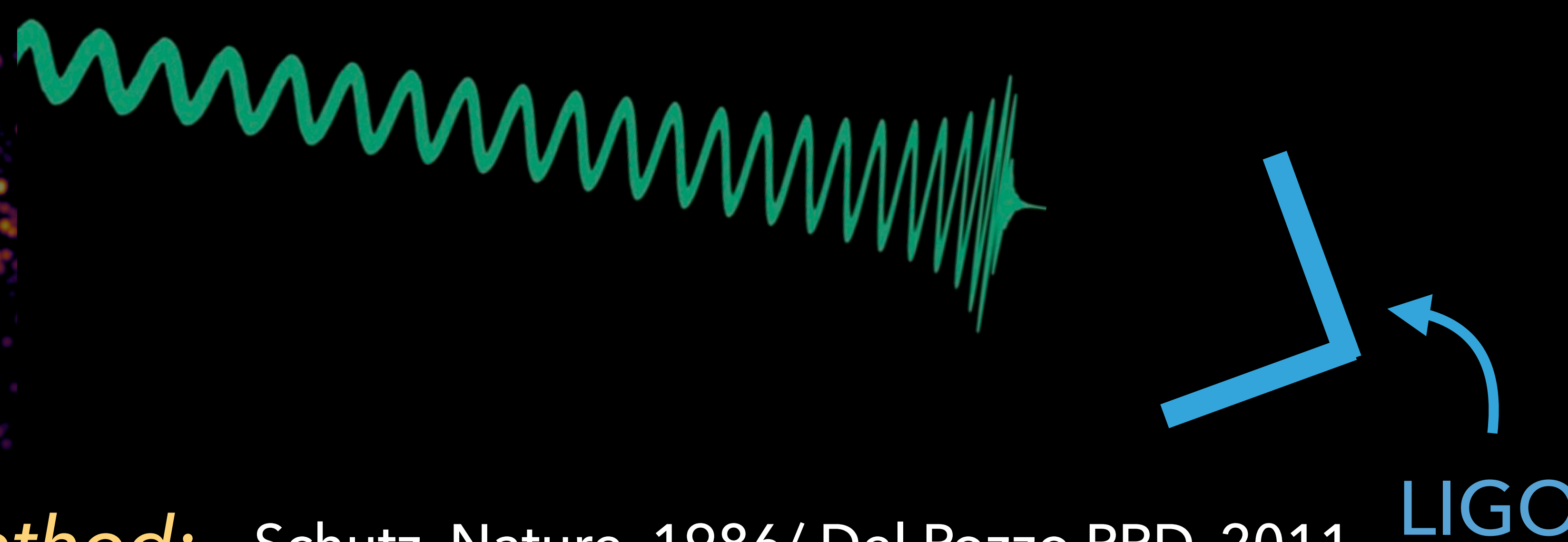

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-GW170814: $H_0 = 75.2^{+39.5}_{-32.4}\,\mathrm{km/s/Mpc}$

(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

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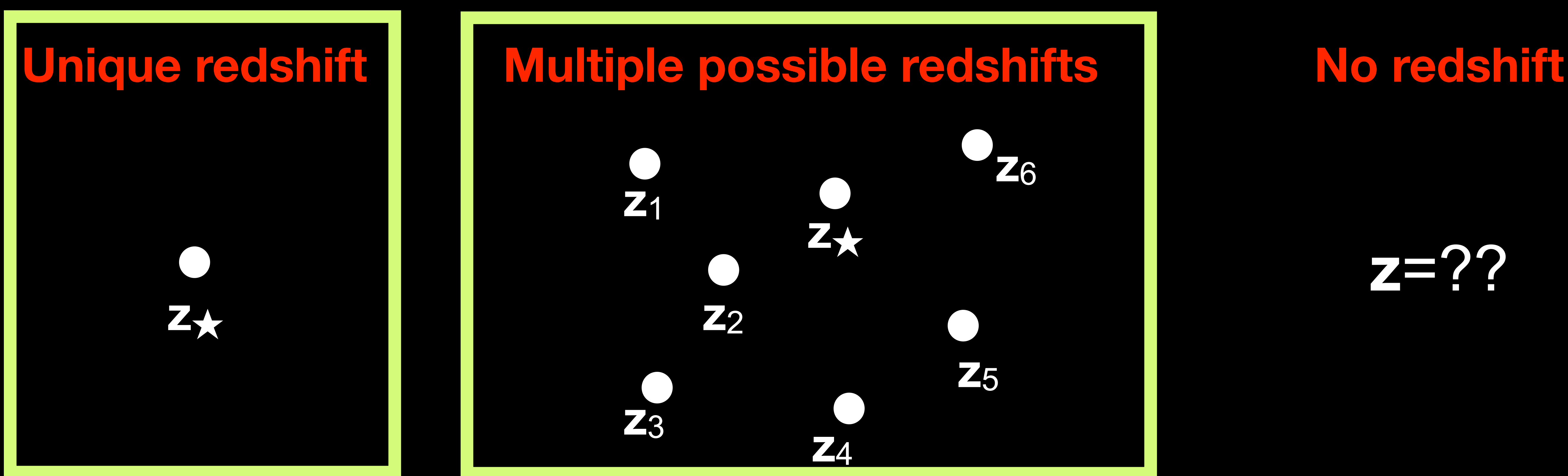
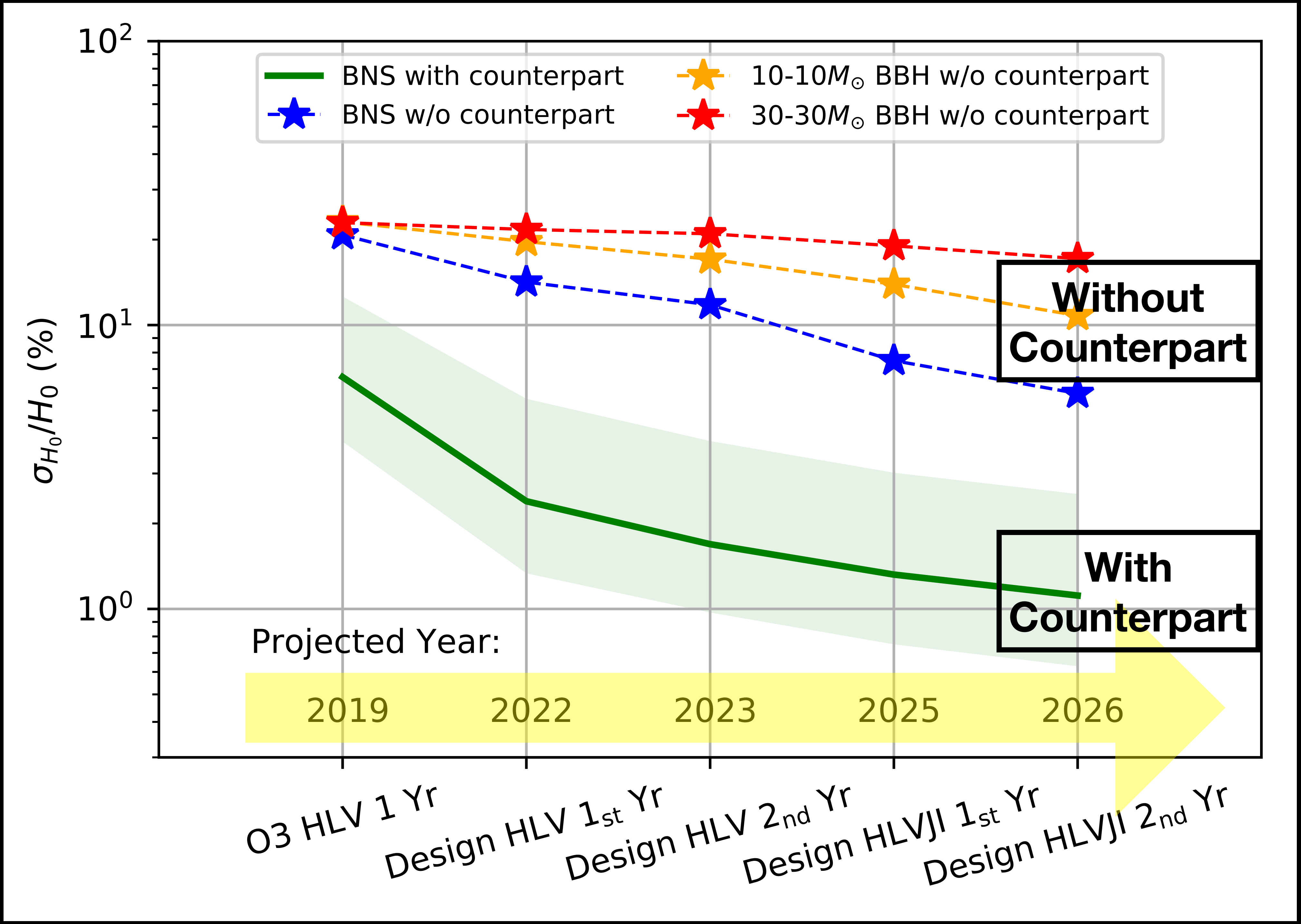


Finding the electromagnetic counterpart is critical



Chen, Fishbach, Holz , Nature, 2018

Chen et al., Nature, 2018

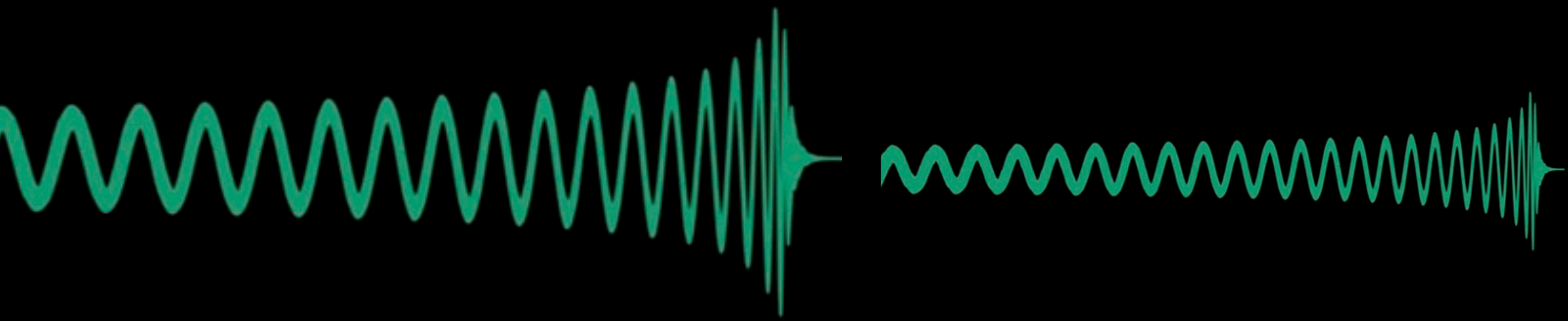
Statistical Method

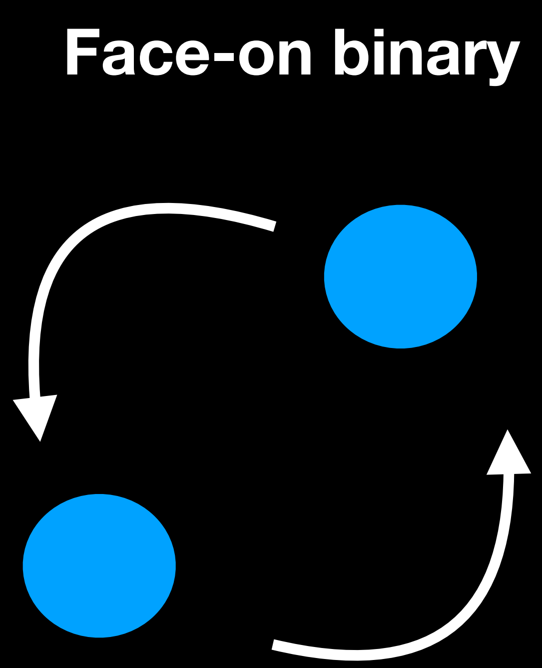
- Most of the BBHs can not be localized well.
  - *They do not contribute to the H0 measurement.*

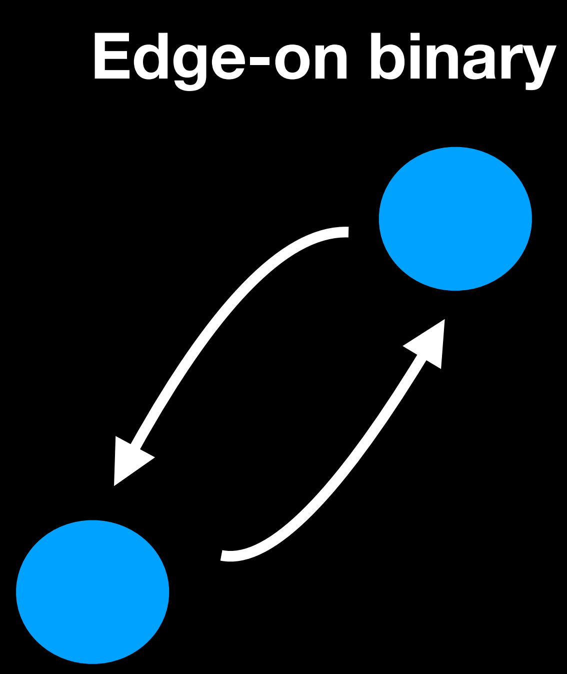
- Complete galaxy catalog was assumed.
  - *This is not true for most of the cases.*

Improve the H_0 measurement precision:

Break the distance-inclination degeneracy







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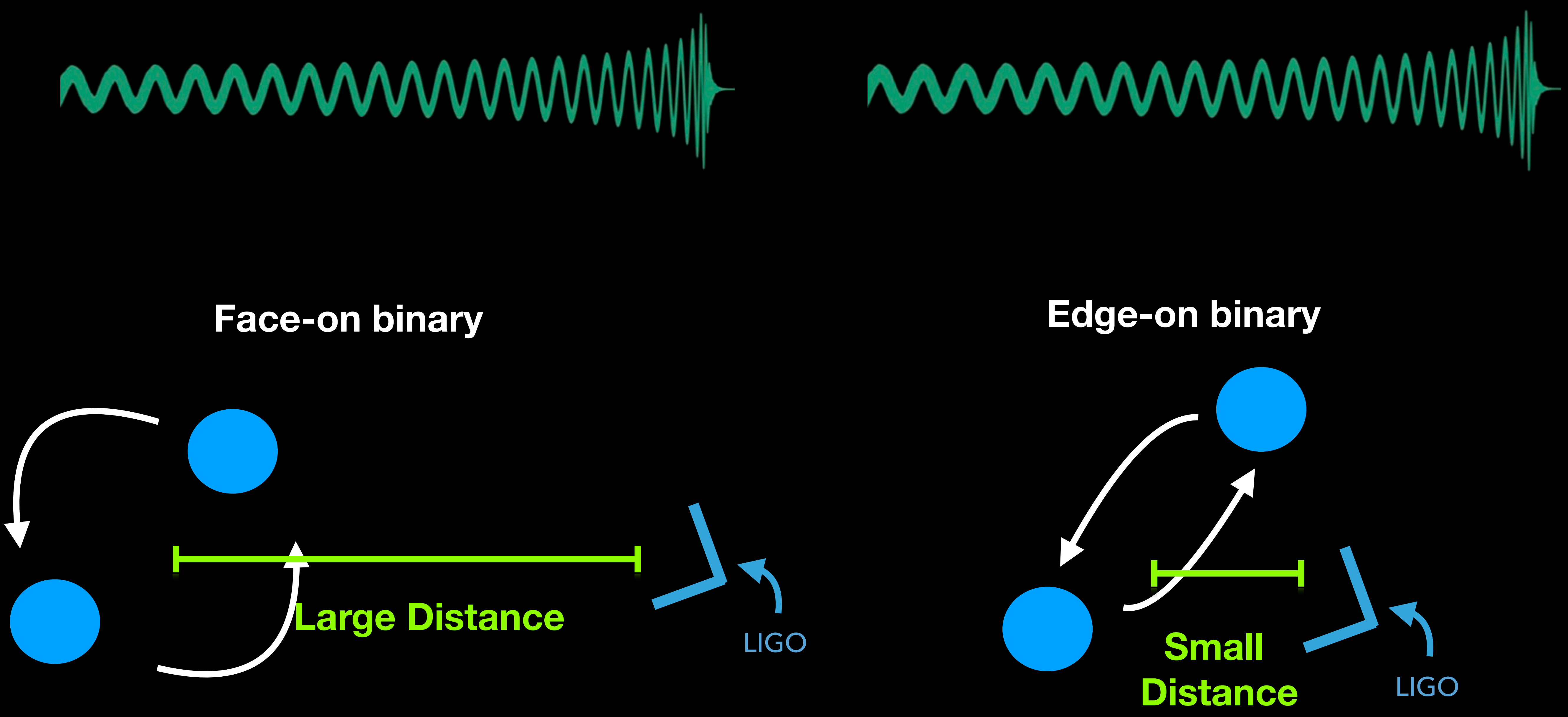

Improve the H_0 measurement precision:

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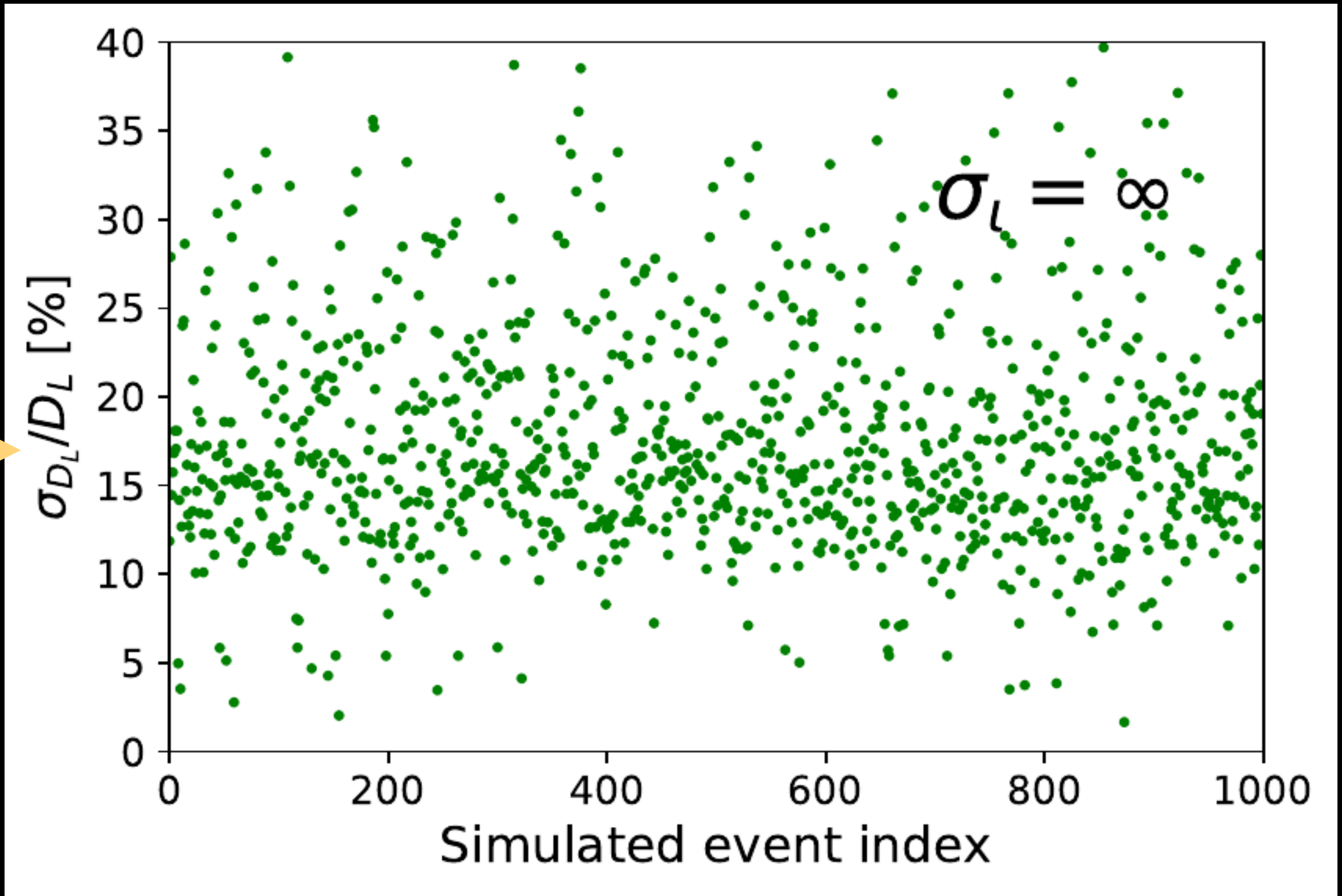
*-Neutron star mergers with **viewing angles constrained by electromagnetic emission**.*

Can be viewed as **H0 uncertainty**



Chen, Vitale, Narayan, 2018

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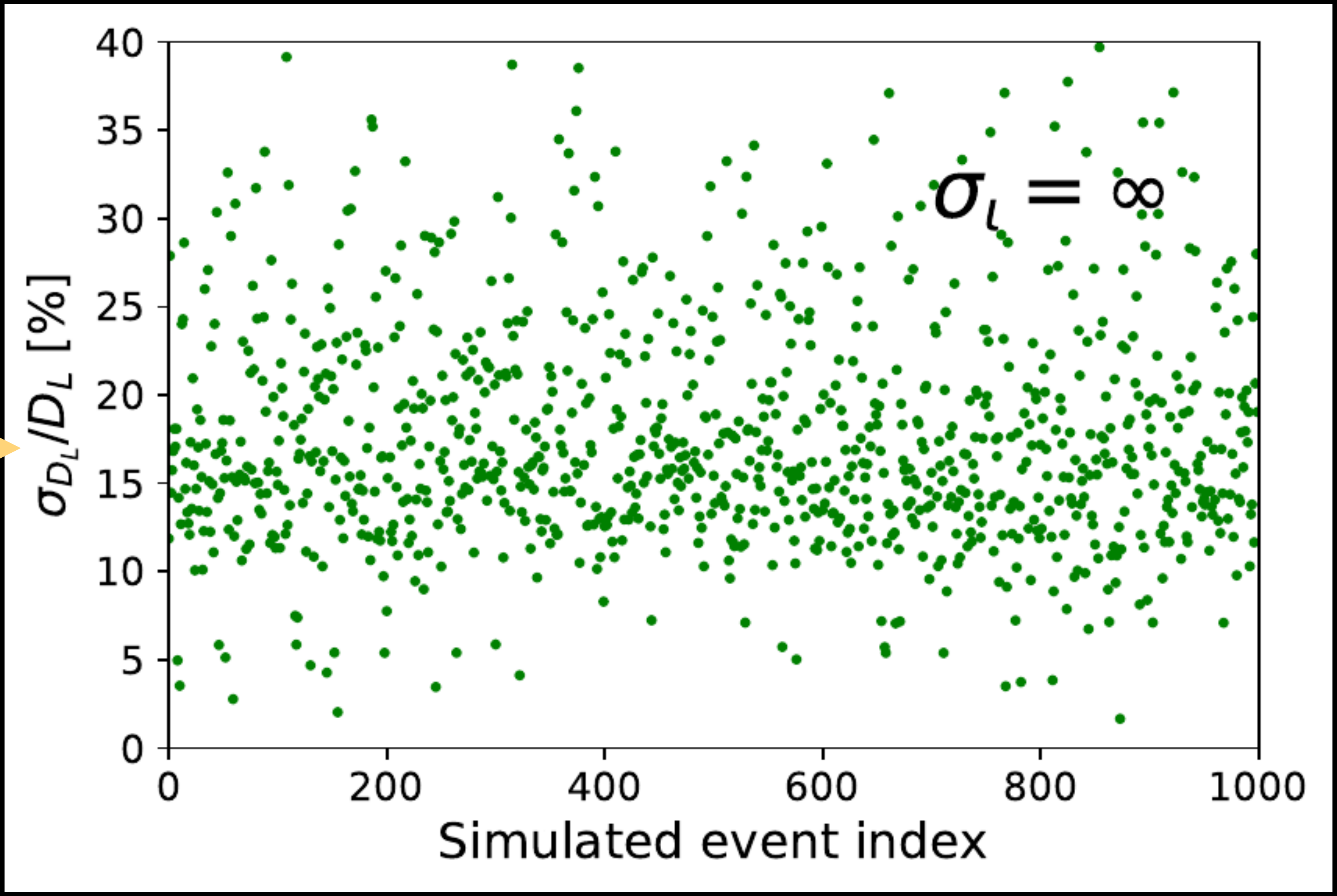

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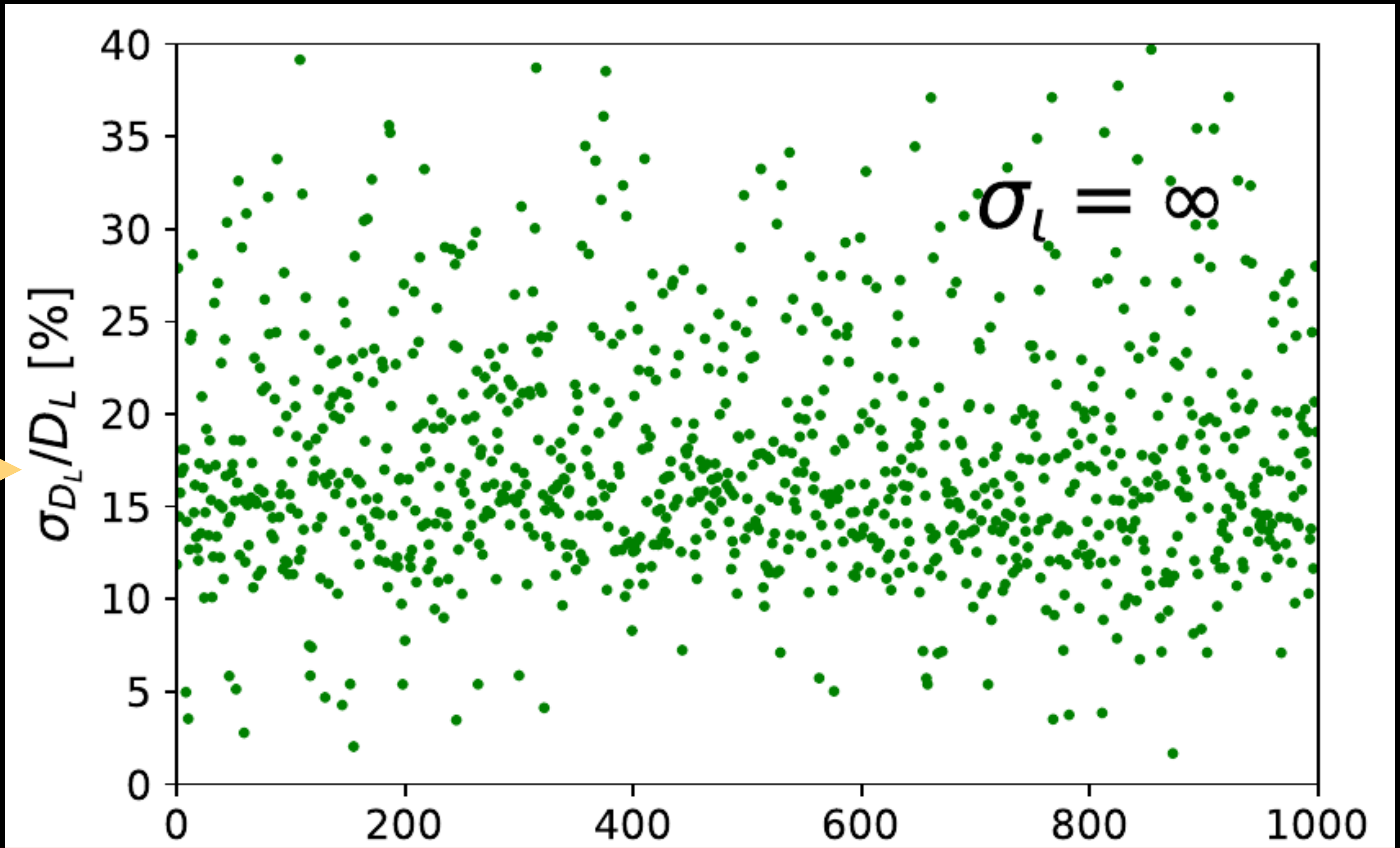
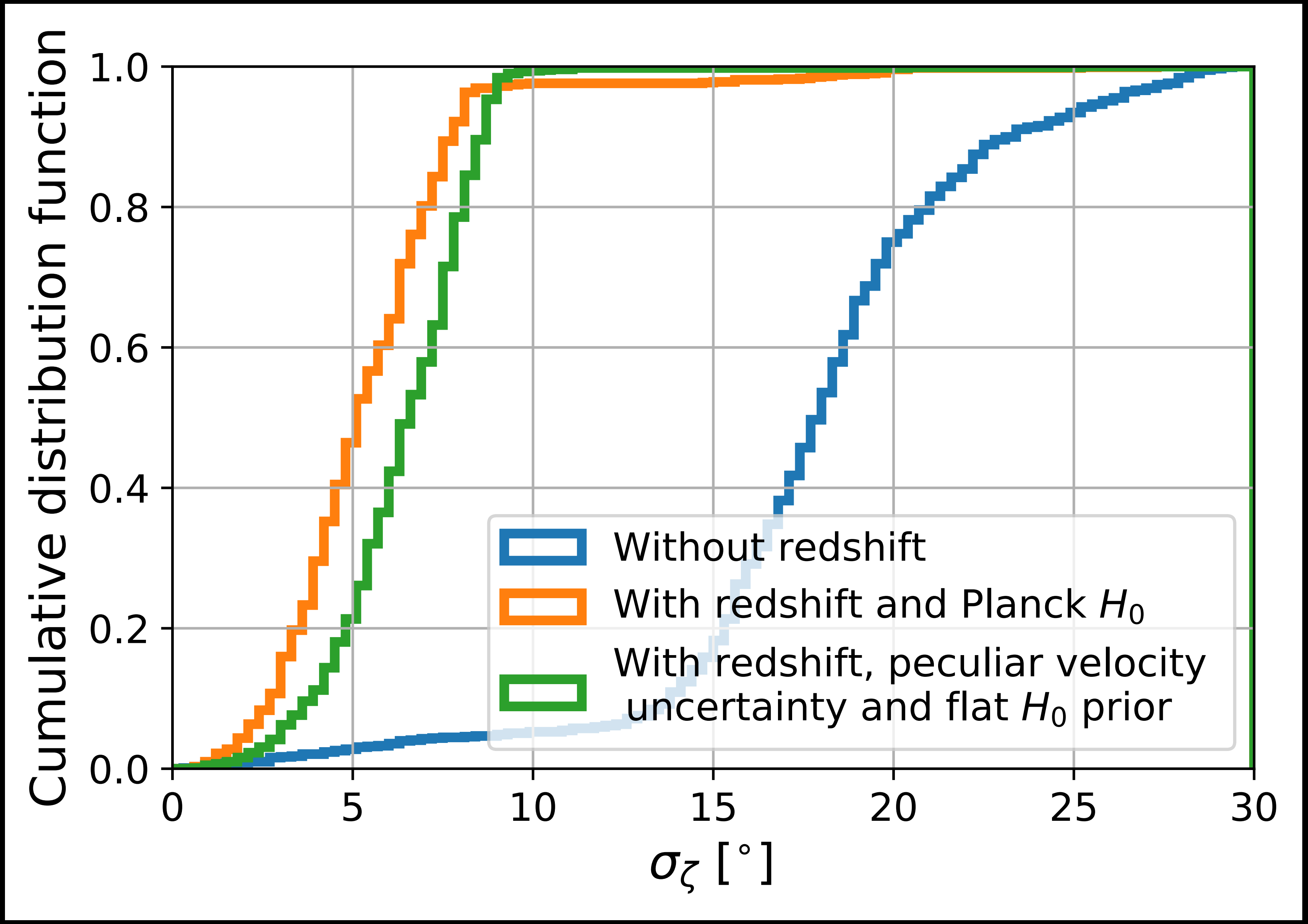


A factor of 5 to10 fewer events are required to reach the same Hubble Constant precision if the viewing angle is constrained.

How well can GW detectors constrain the viewing angle?

-HLV at design sensitivity. O3 is ~10% worse. Five detectors at design sensitivity is ~10% better.



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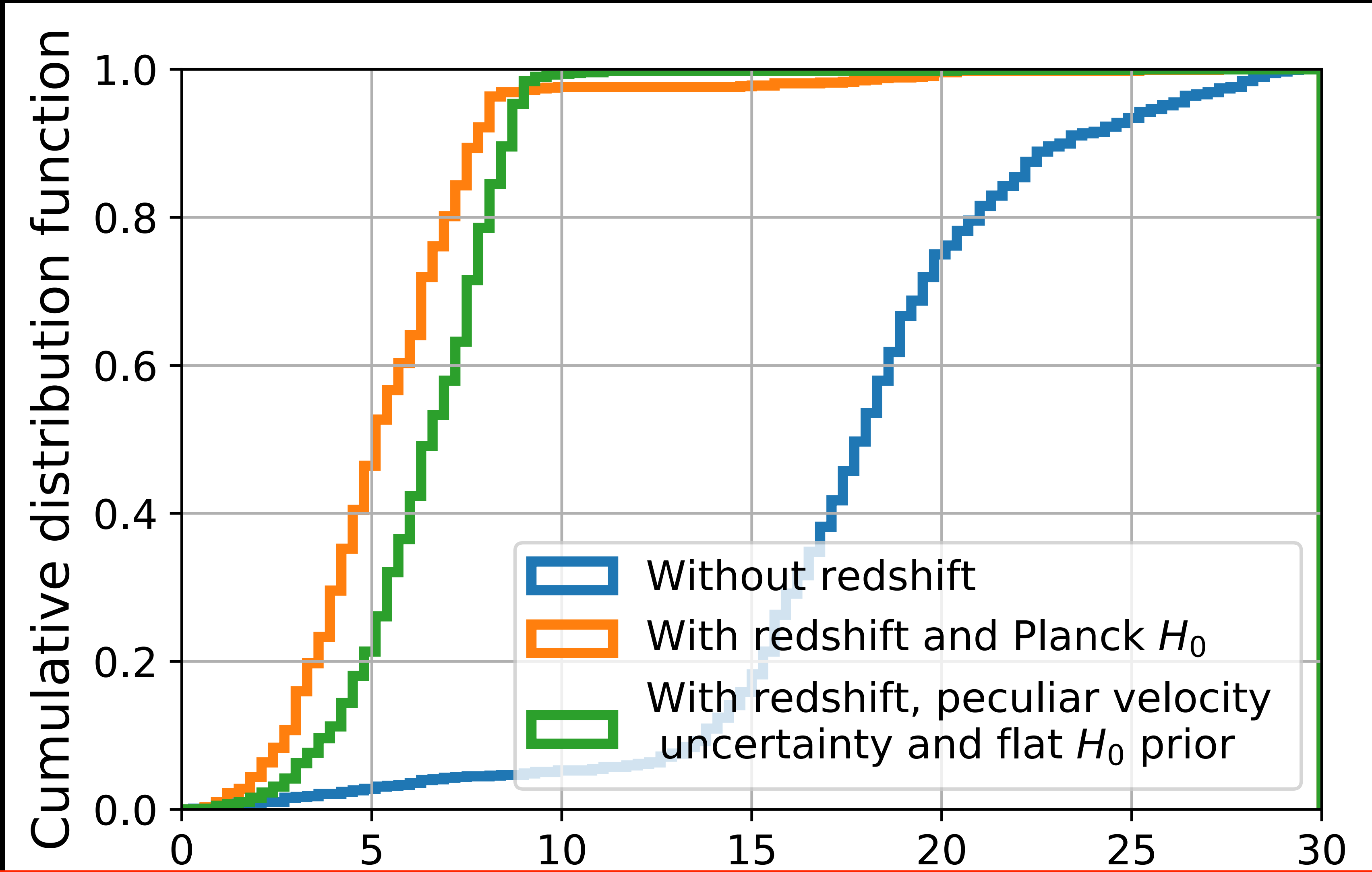

Redshift measurement makes a factor of ~3 difference.

Chen, Vitale, Narayan, 2018

What is special about neutron star-black hole merger?

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

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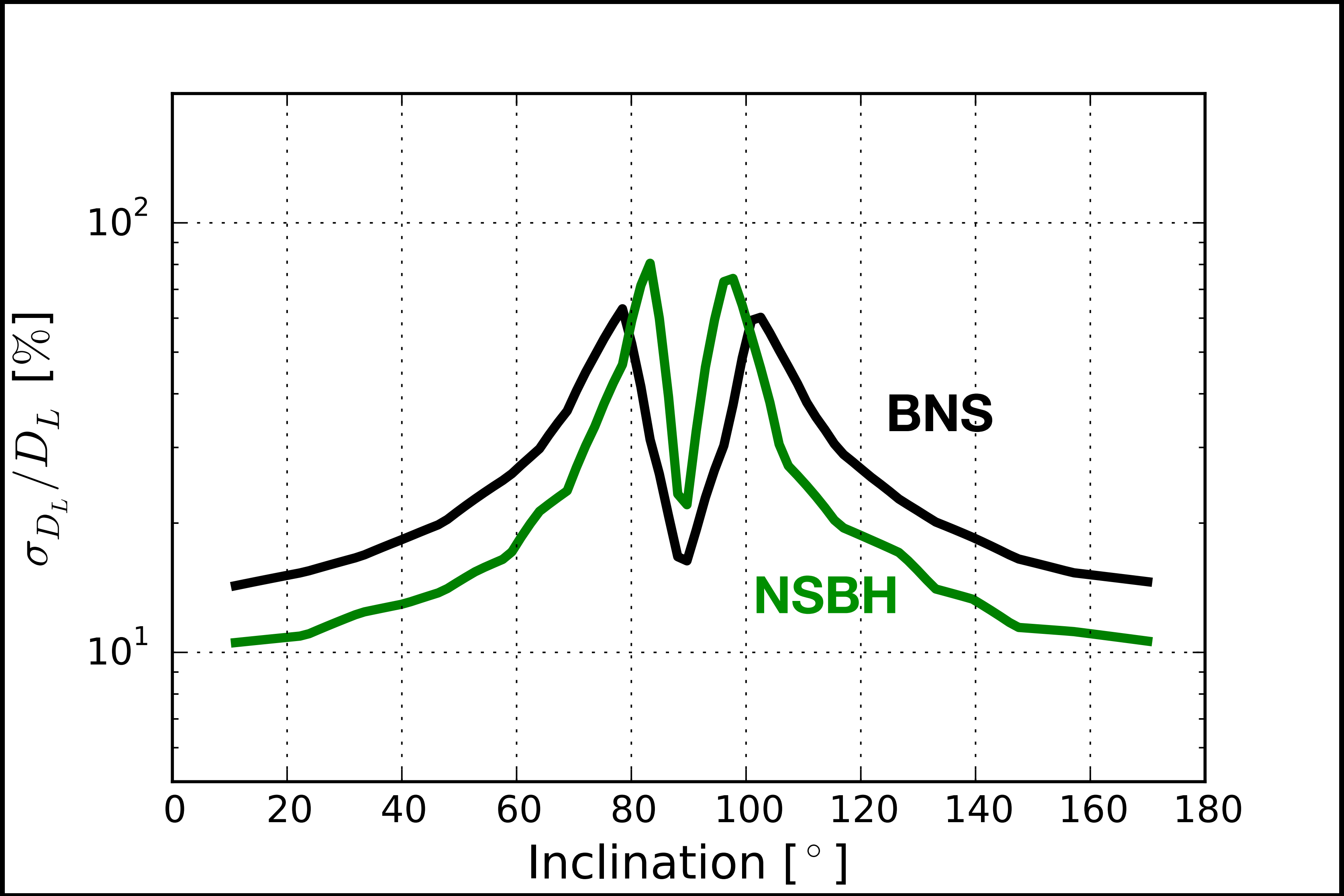
-The distance-inclination degeneracy can be broken by the observation of merger-ringdown and precession.

Improve the H_0 measurement precision:

Break the distance-inclination degeneracy

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.

Improve the H_0 measurement precision:

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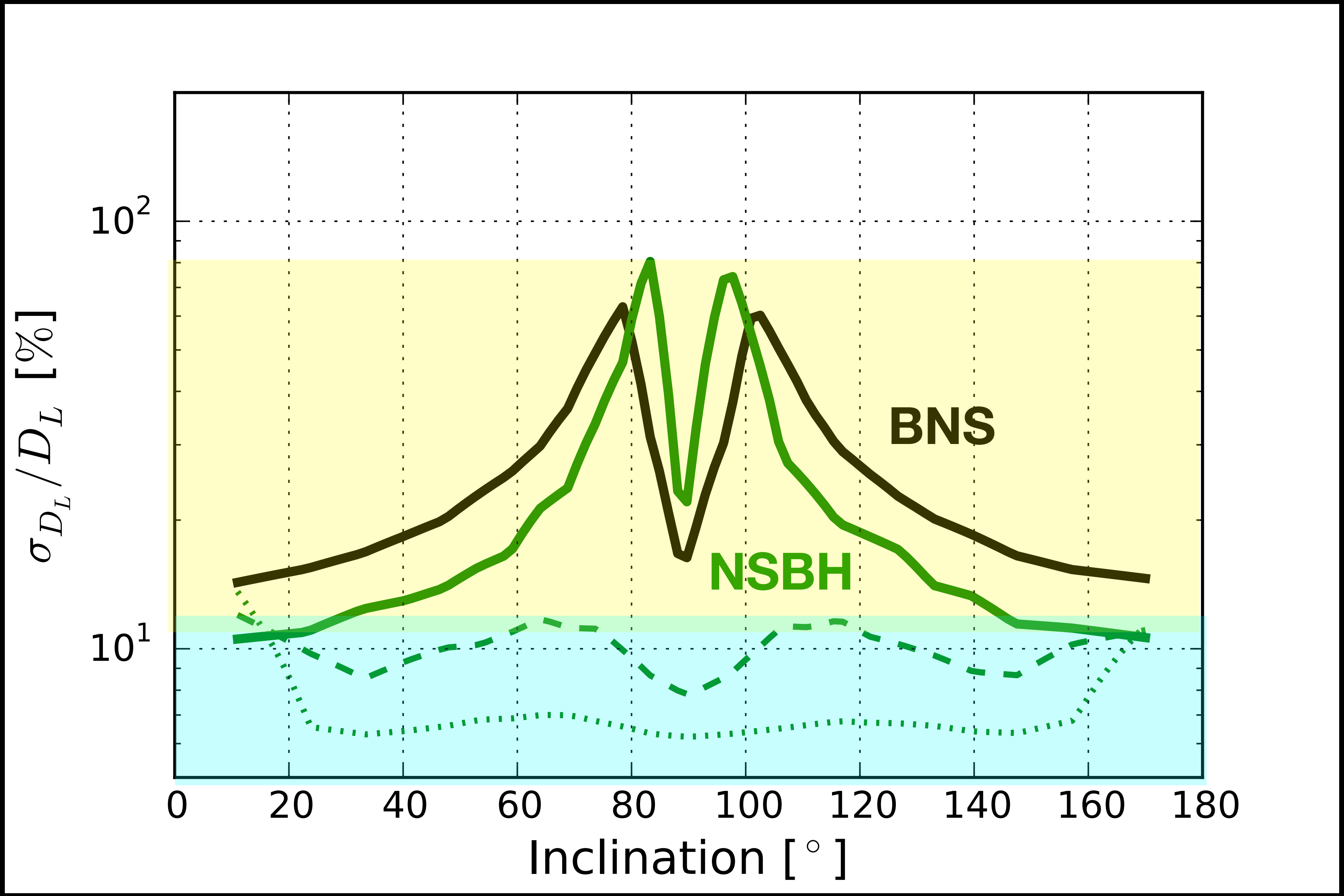
Vitale & Chen, PRL, 2018

Can be viewed as **H0 uncertainty** →



Without Precession

With Precession

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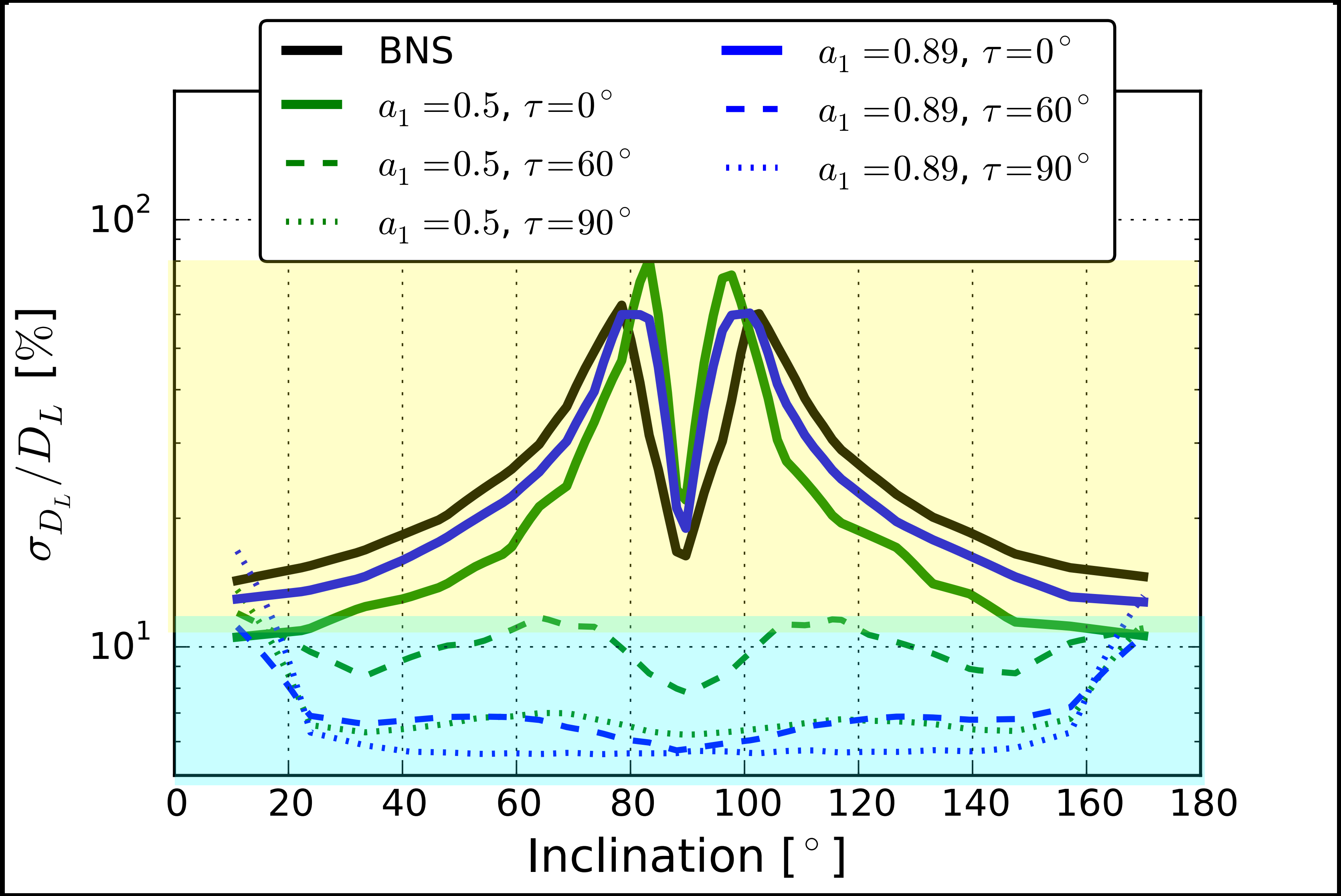

Without Precession

With Precession

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

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Vitale & Chen, PRL, 2018

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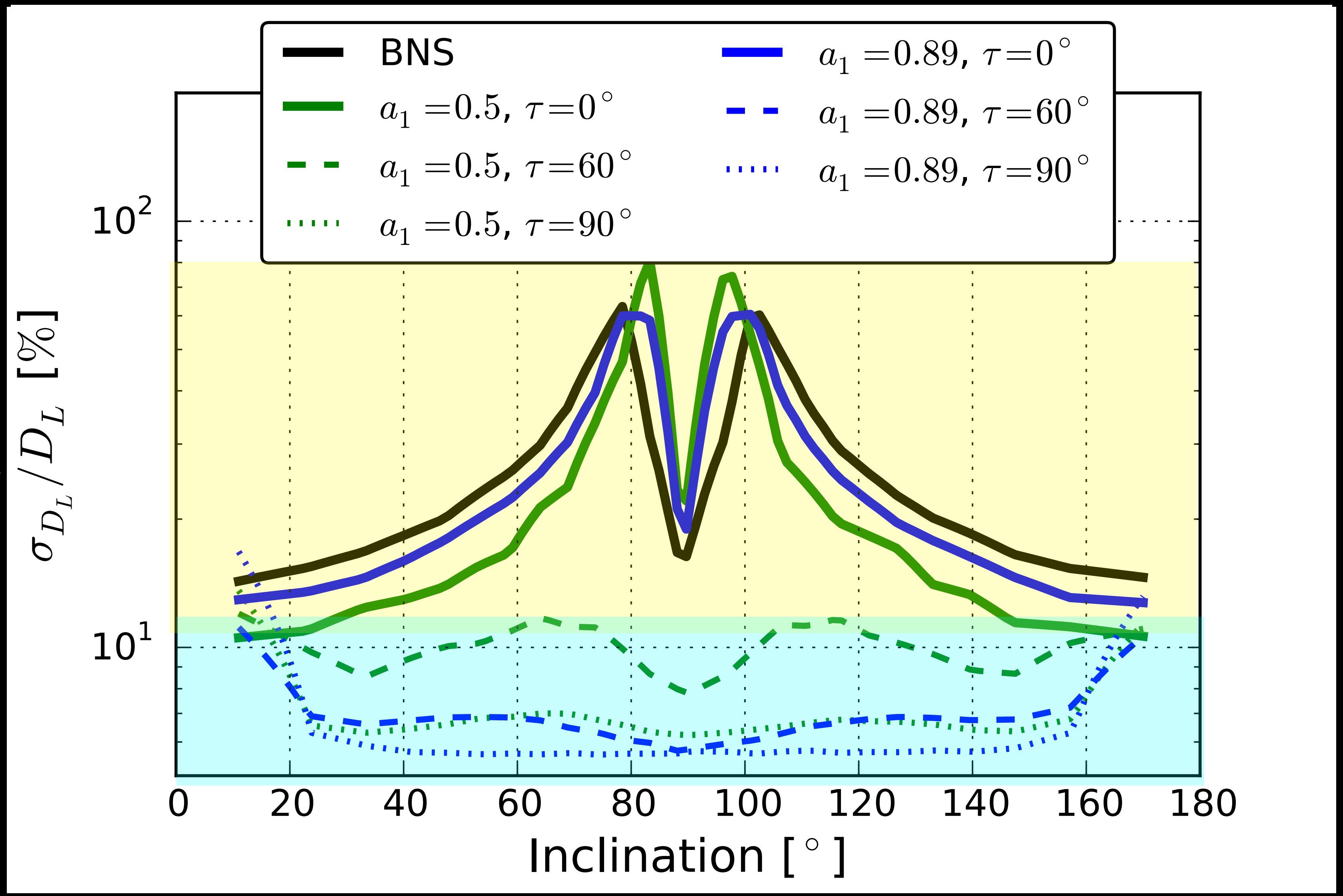

NSBHs can provide more precise Hubble Constant measurement if its astrophysical rate is larger than 1/10 of binary neutron star mergers.

What has not been discussed?

Systematics error of gravitational wave distance measurement

- Calibration errors, waveform

Electromagnetic observation selection effects

- Mass, spin

-Viewing angle

Beyond 2G, beyond H_0

LVC+1M2H+DECam+DLT40+Las Cumbres+VINROUGE+MASTER , Nature (2017)

Summary

-Gravitational waves can serve as an independent probe to the Universe. The Hubble constant uncertainty is expected to reduce to two percent in five years.

-In addition to capturing the EM counterpart, we also need to address various possible systematics and selection effects carefully to ensure an accurate H0 measurement.