Gravitational-wave standard siren cosmology

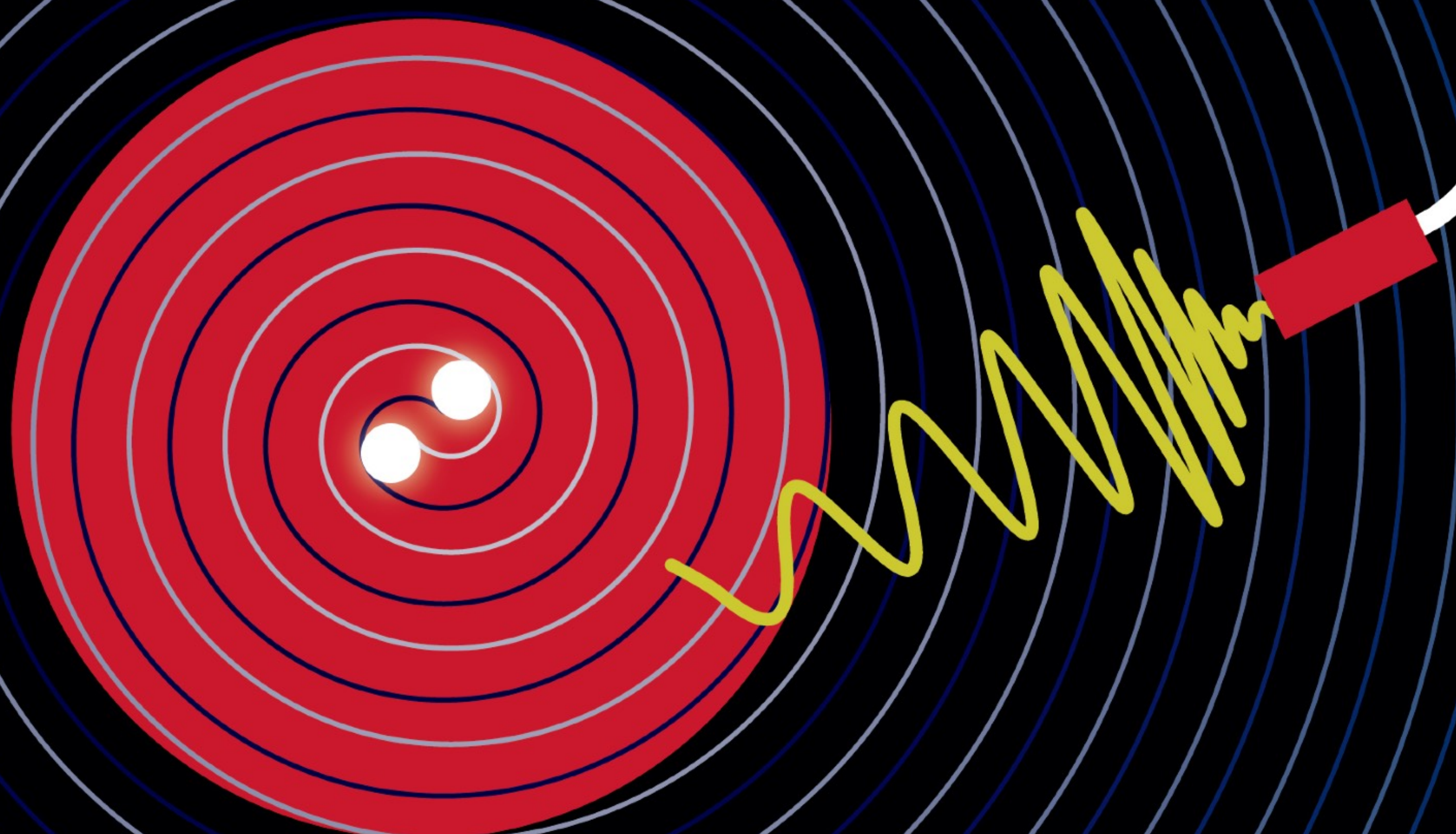
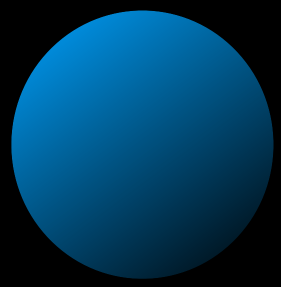


Image credit: S.W. Angela Chen

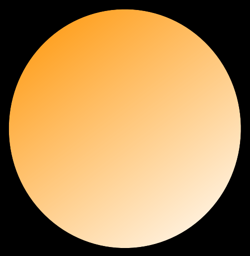
Hsin-Yu Chen

(NASA Einstein Fellow, MIT)

7th KAGRA International Workshop, December 2020

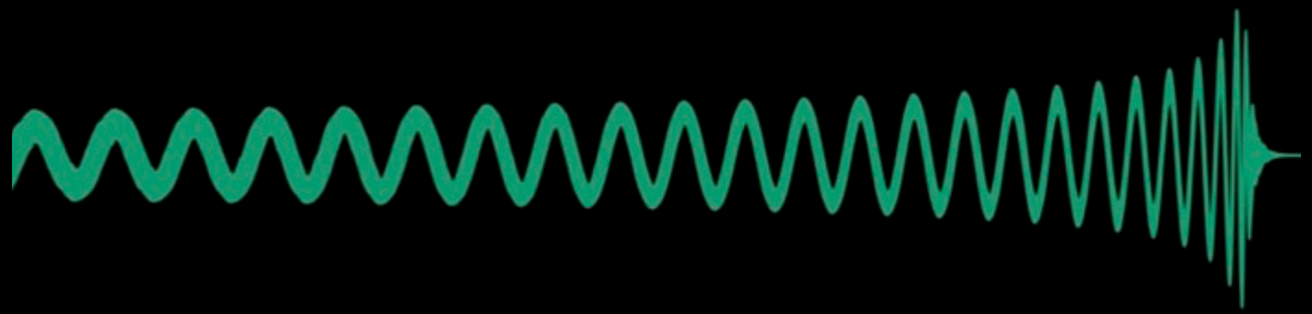


This is a black hole.



This is a neutron star.

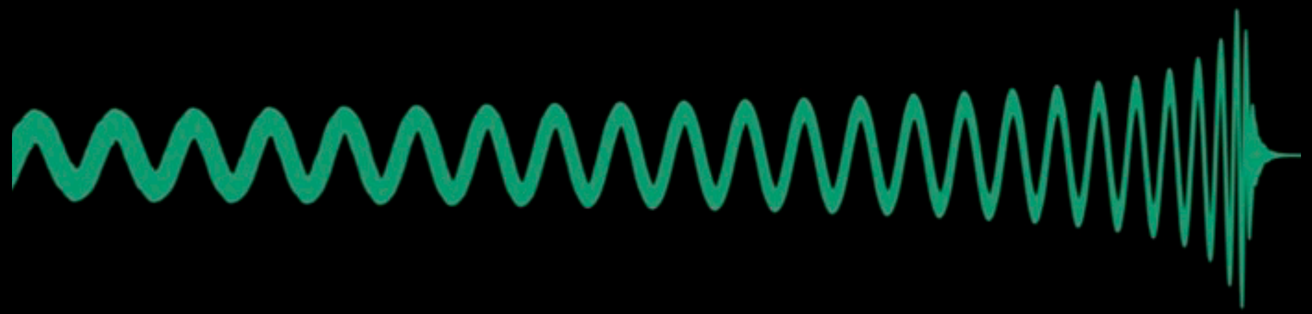
Direct measurement of the luminosity distance



Luminosity Distance ∝ 1/Amplitude

Schutz, Nature, 1986

Direct measurement of the luminosity distance

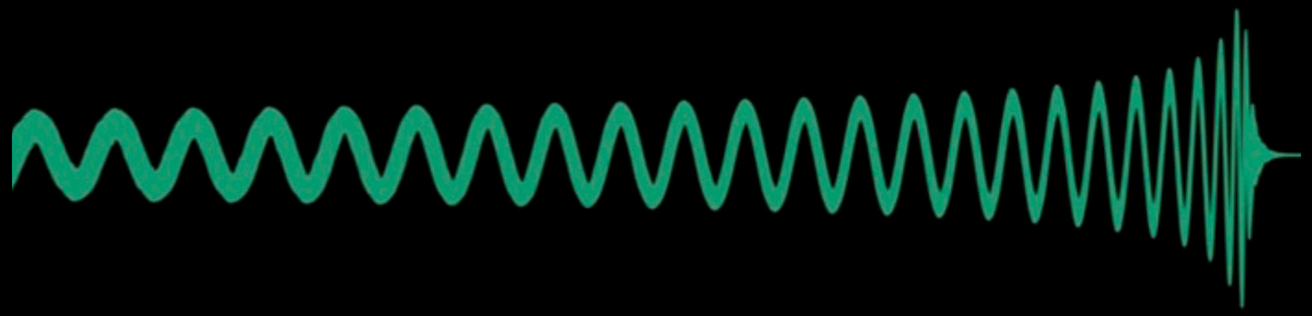


Luminosity Distance $\propto$ 1/Amplitude

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

Schutz, Nature, 1986

Direct measurement of the luminosity distance



Luminosity Distance ∝ 1/Amplitude

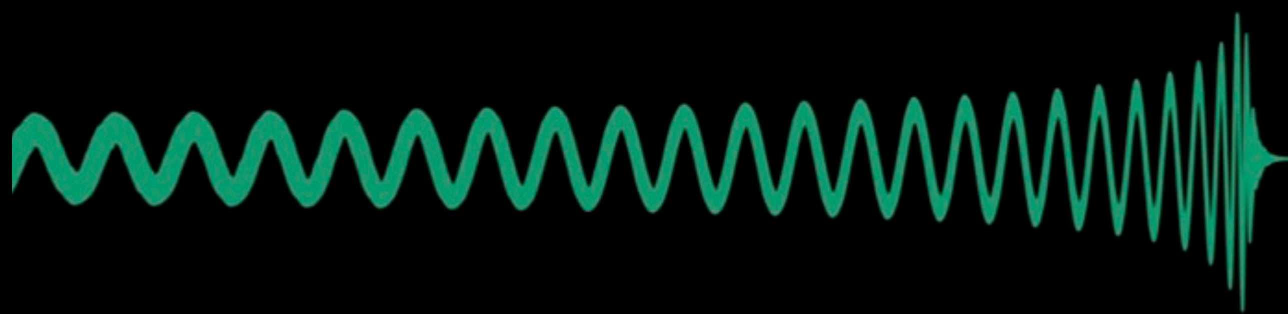
-Constrain the cosmological parameters with the redshift and luminosity distance:

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

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

Schutz, Nature, 1986

Direct measurement of the luminosity distance



Luminosity Distance ∝ 1/Amplitude

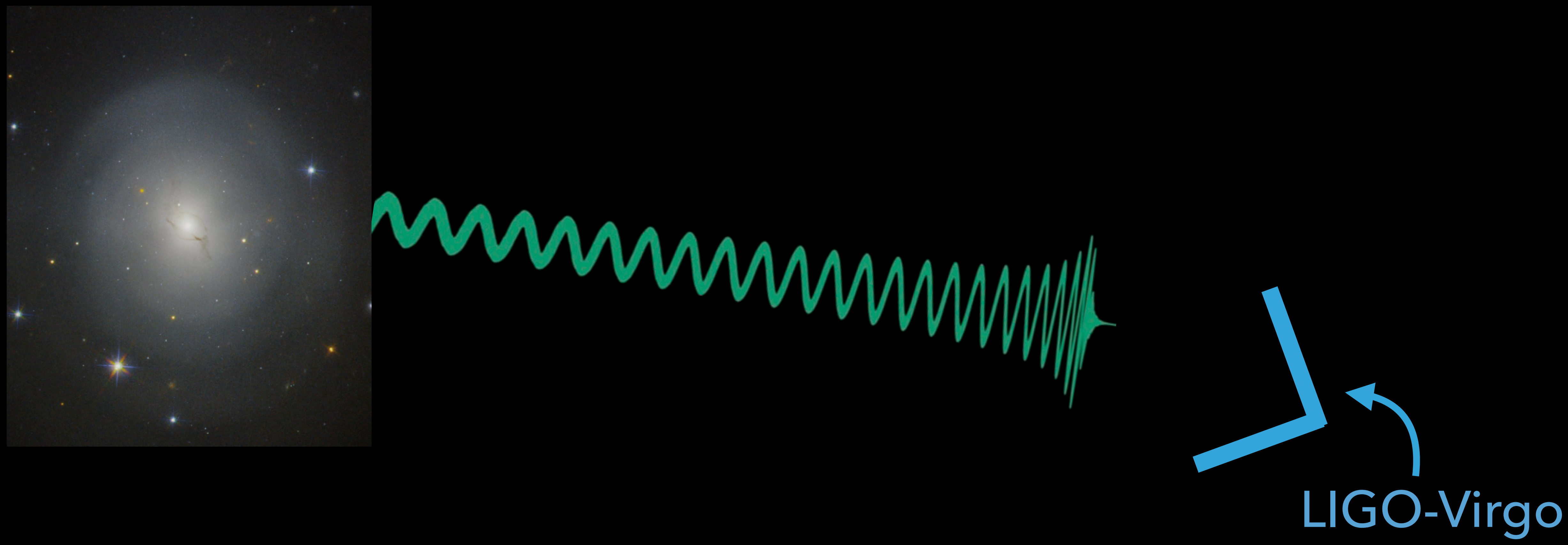
-Constrain the cosmological parameters with the redshift and luminosity distance:

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

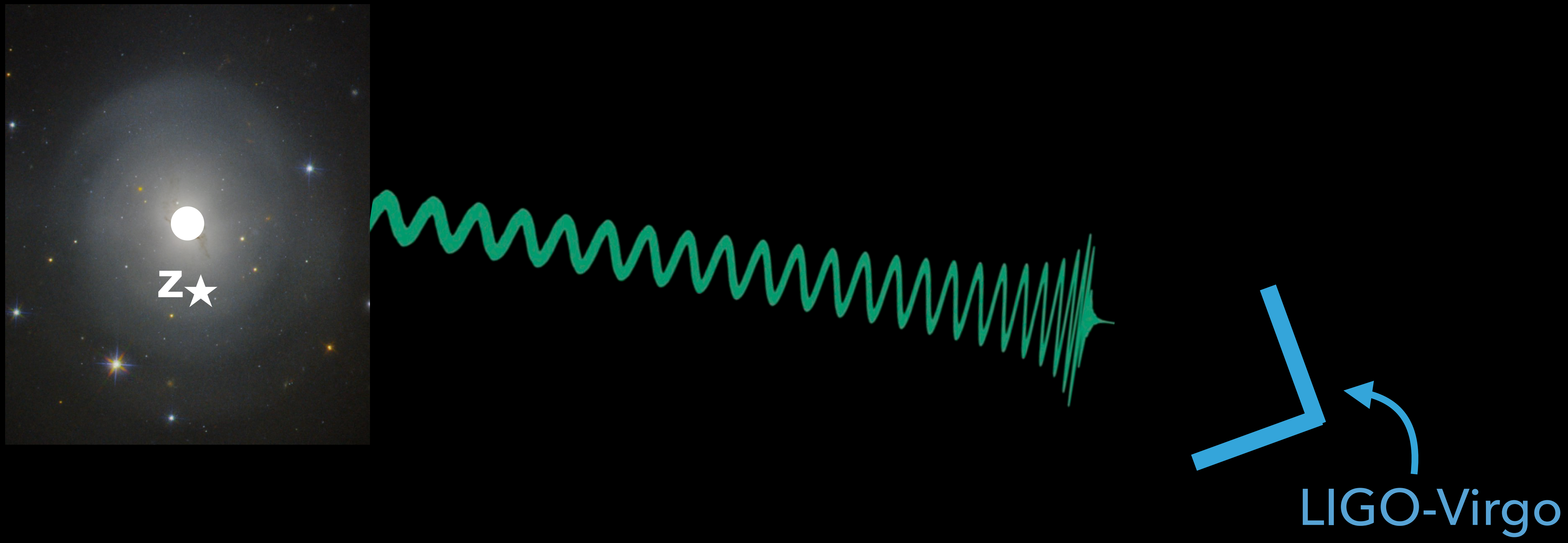
$$H(z) = H_0\sqrt{\Omega_{\mathrm{M}}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w_0+w_a)}e^{-3w_a z/(1+z)}}$$

Schutz, Nature, 1986

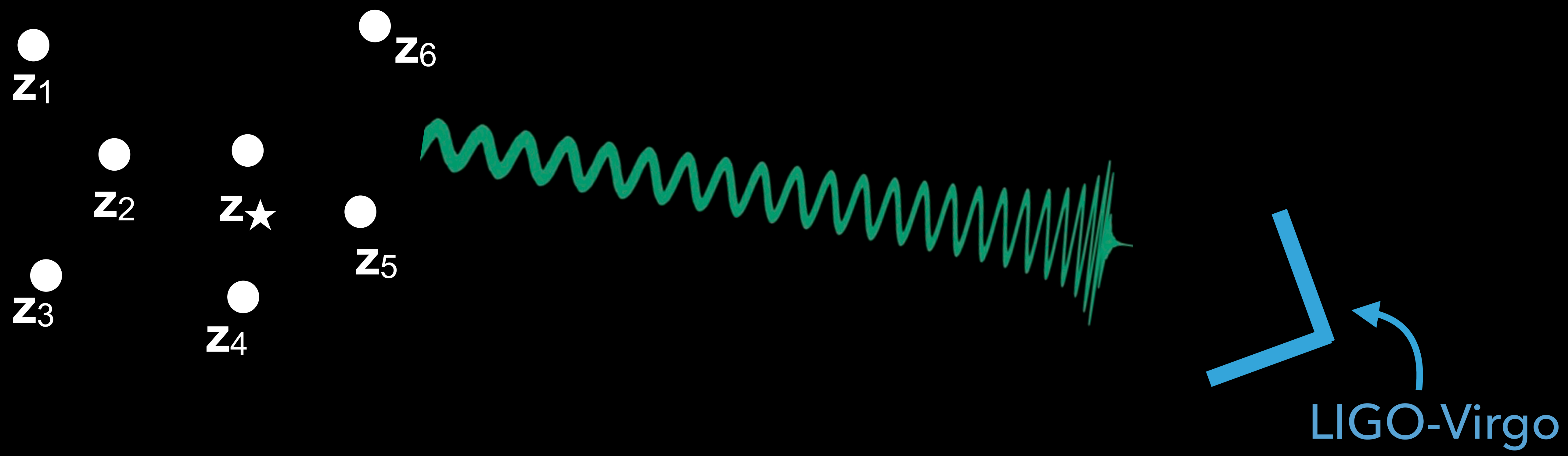
Determine the redshift of gravitational-wave source with the host galaxy



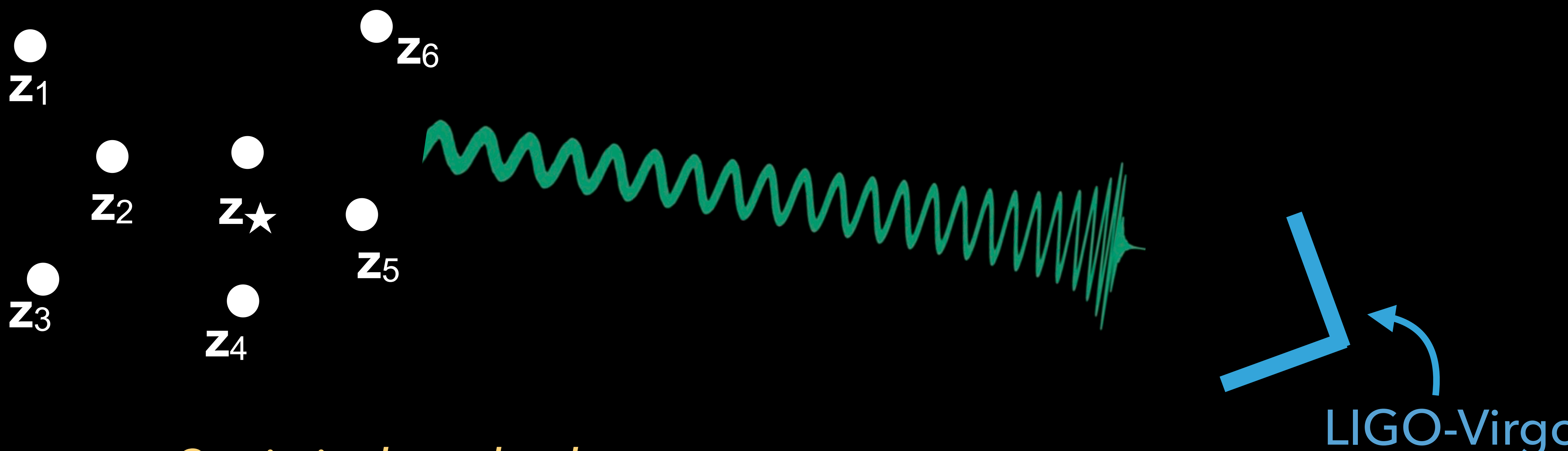
Determine the redshift of gravitational-wave source with the host galaxy



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



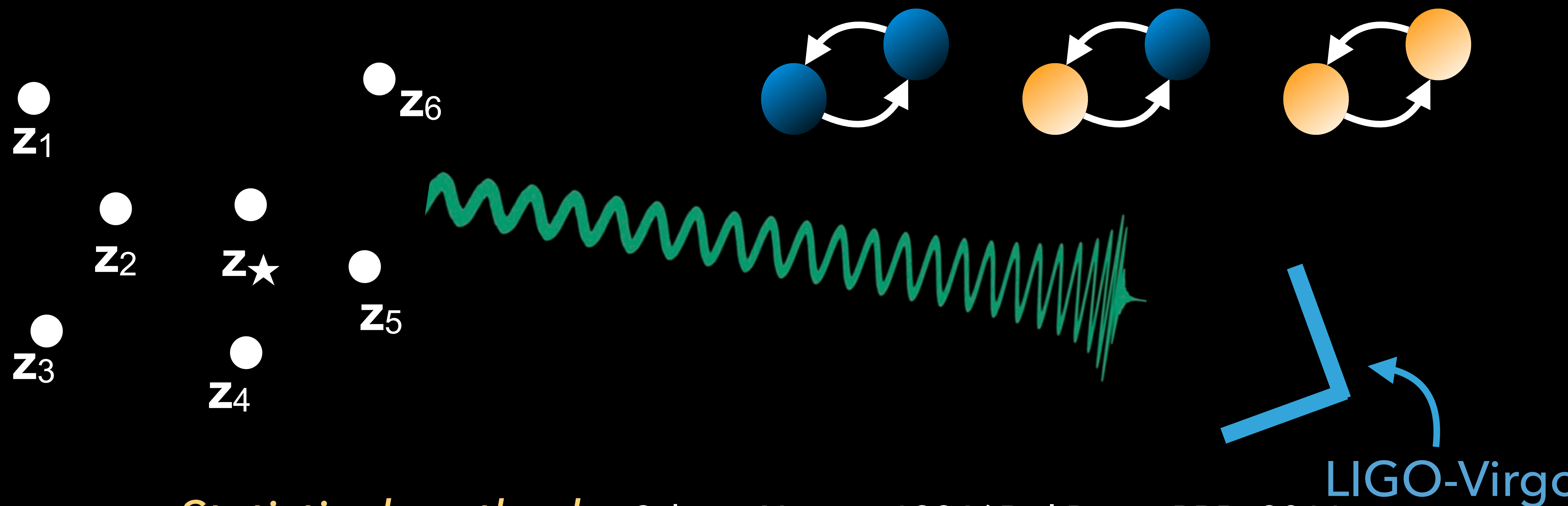
Determine the redshift of gravitational-wave source with the host galaxy



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

Combine the redshifts of all possible host galaxies.

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

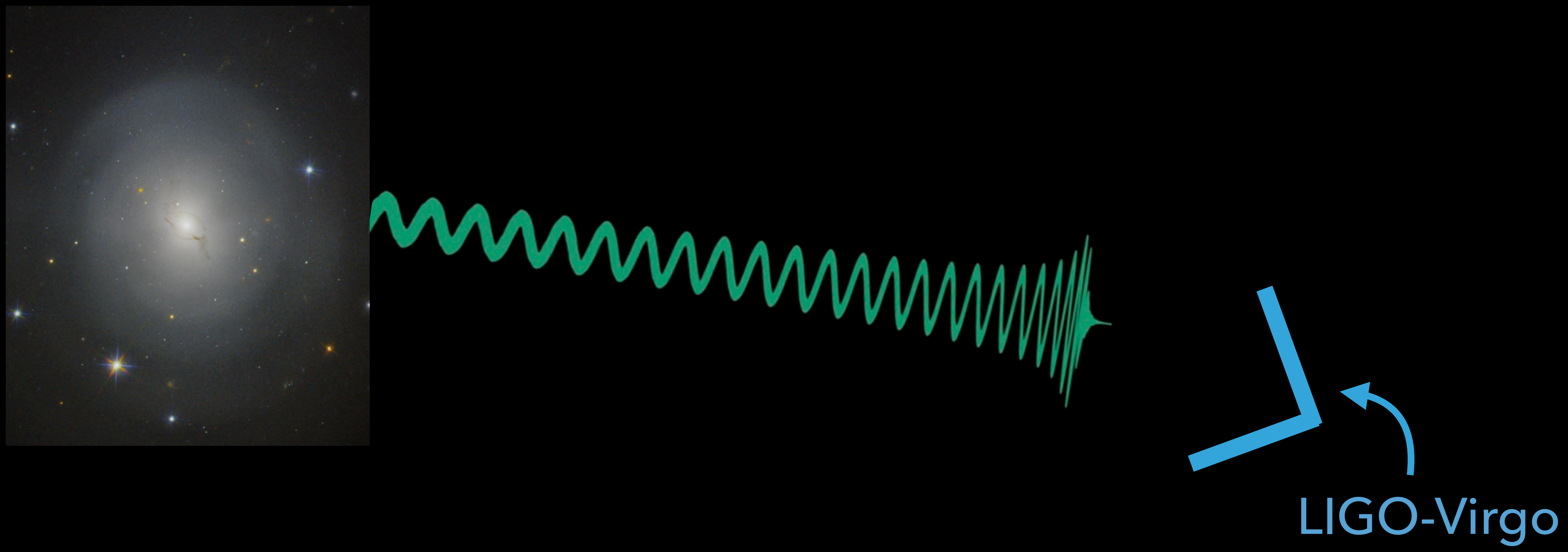
(Dark Energy Survey Year 3 data)

DES & LVC, 2019

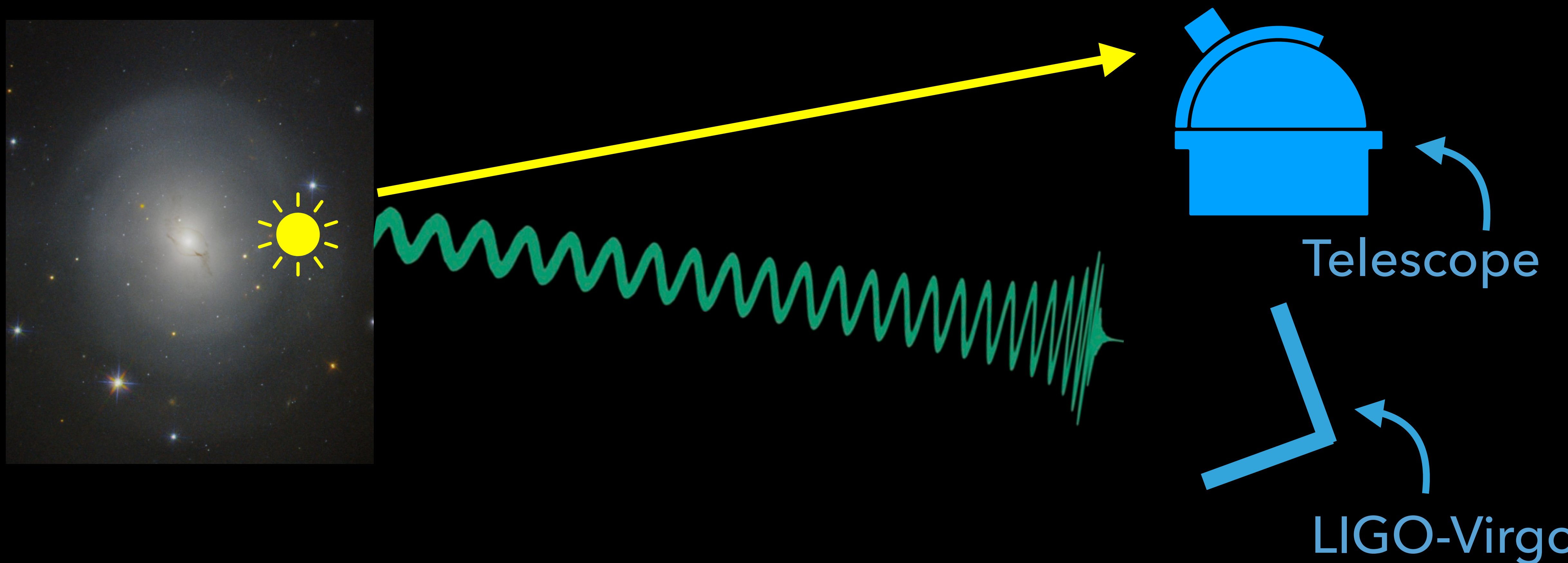
-GW170817: $H_0 = 76^{+48}_{-23}\,\mathrm{km/s/Mpc}$

Fishbach, ~Chen et al., ApJL, 2019

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



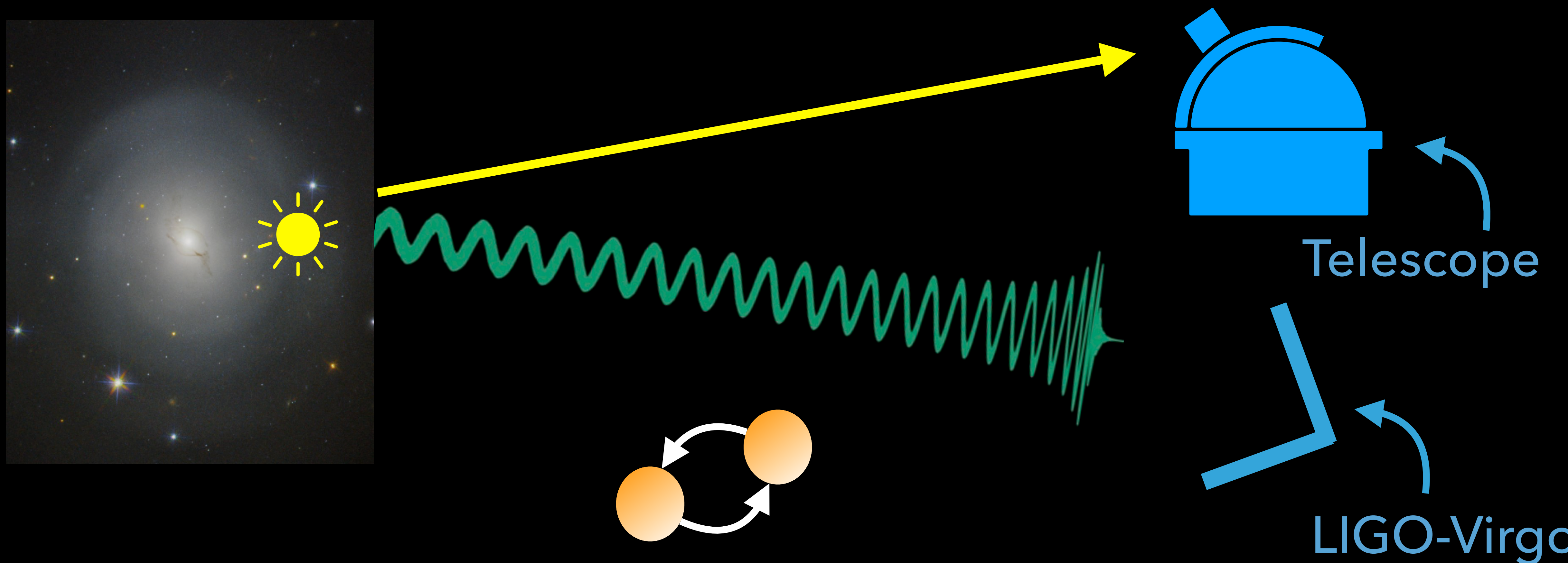
Determine the redshift of gravitational-wave source with the host galaxy



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

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

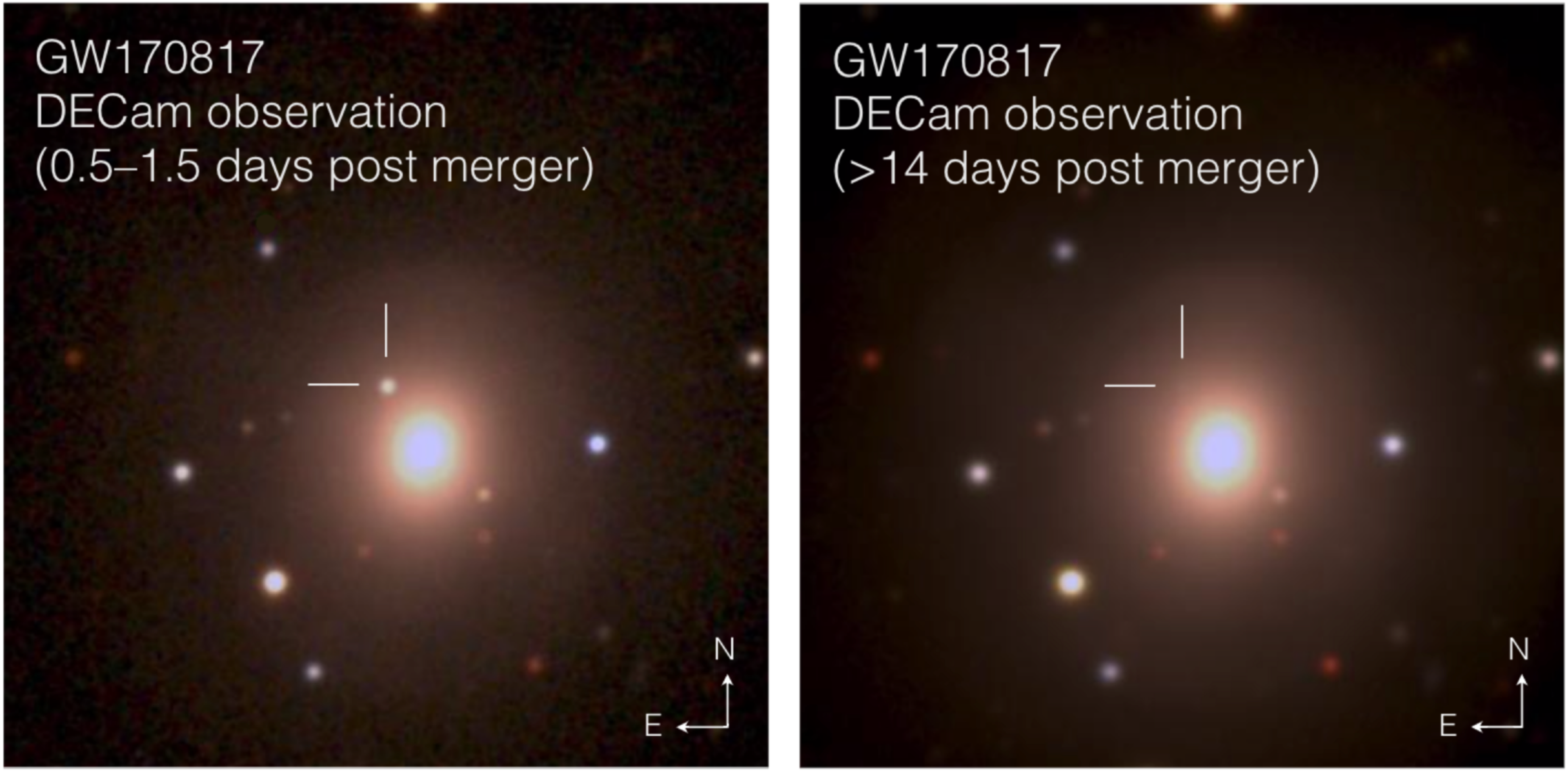
Determine the redshift of gravitational-wave source with the host galaxy



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

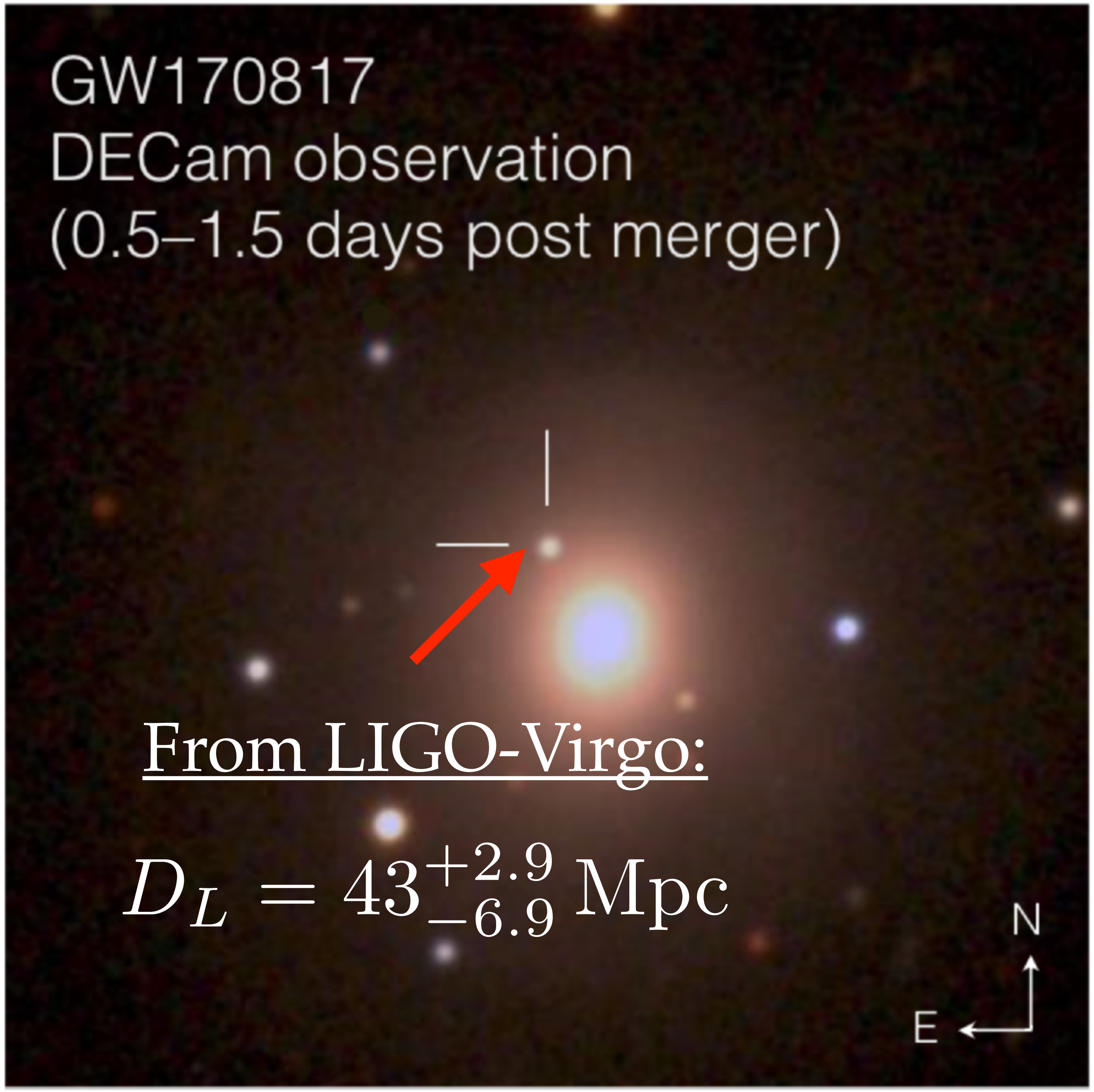
Schutz, Nature, 1986 / Holz & Hughes, ApJ, 2005

The first standard siren measurement with an electromagnetic counterpart



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

The first standard siren measurement with an electromagnetic counterpart

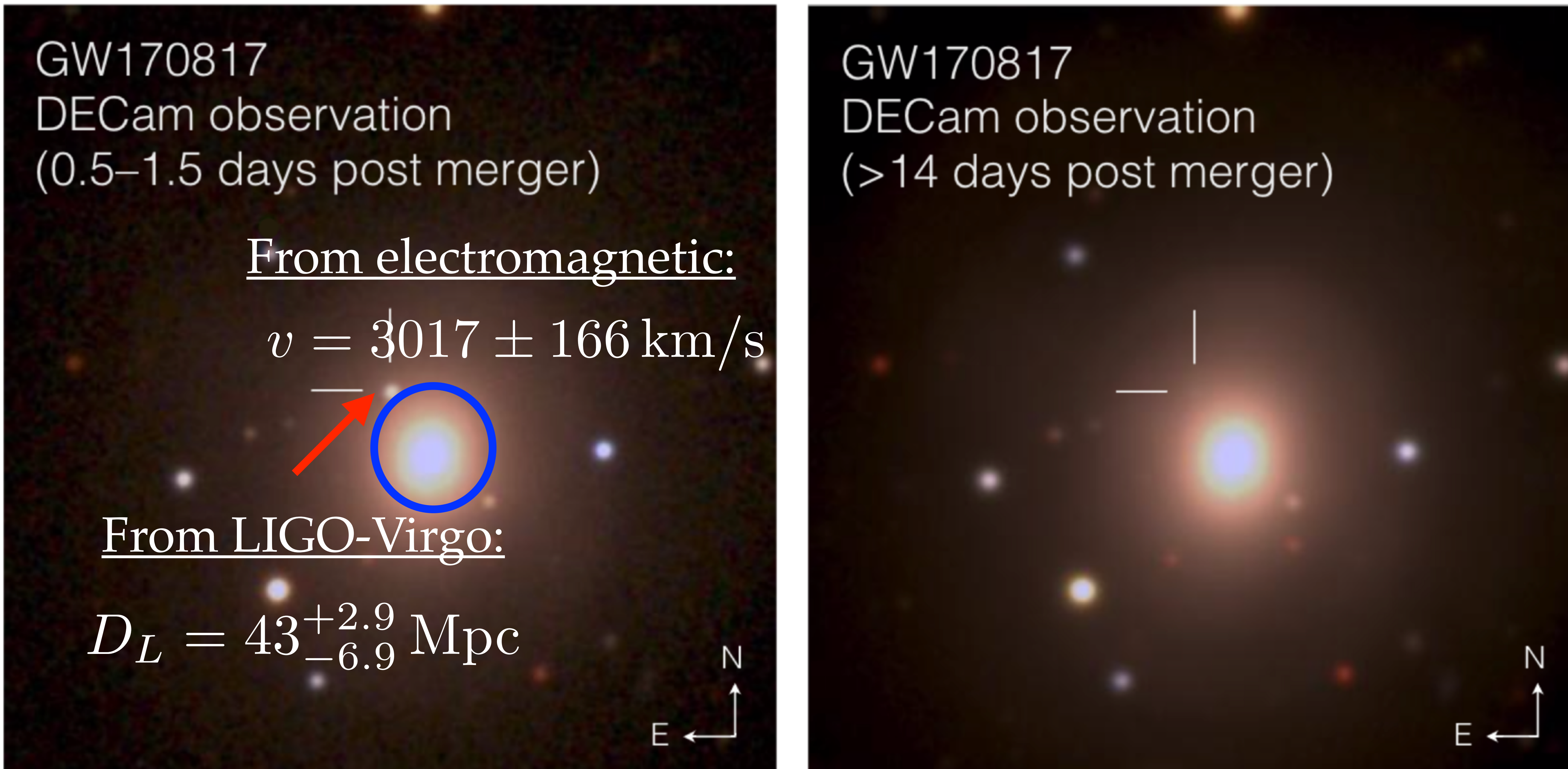


From LIGO-Virgo:

$$D_L = 43^{+2.9}_{-6.9}\,\mathrm{Mpc}$$

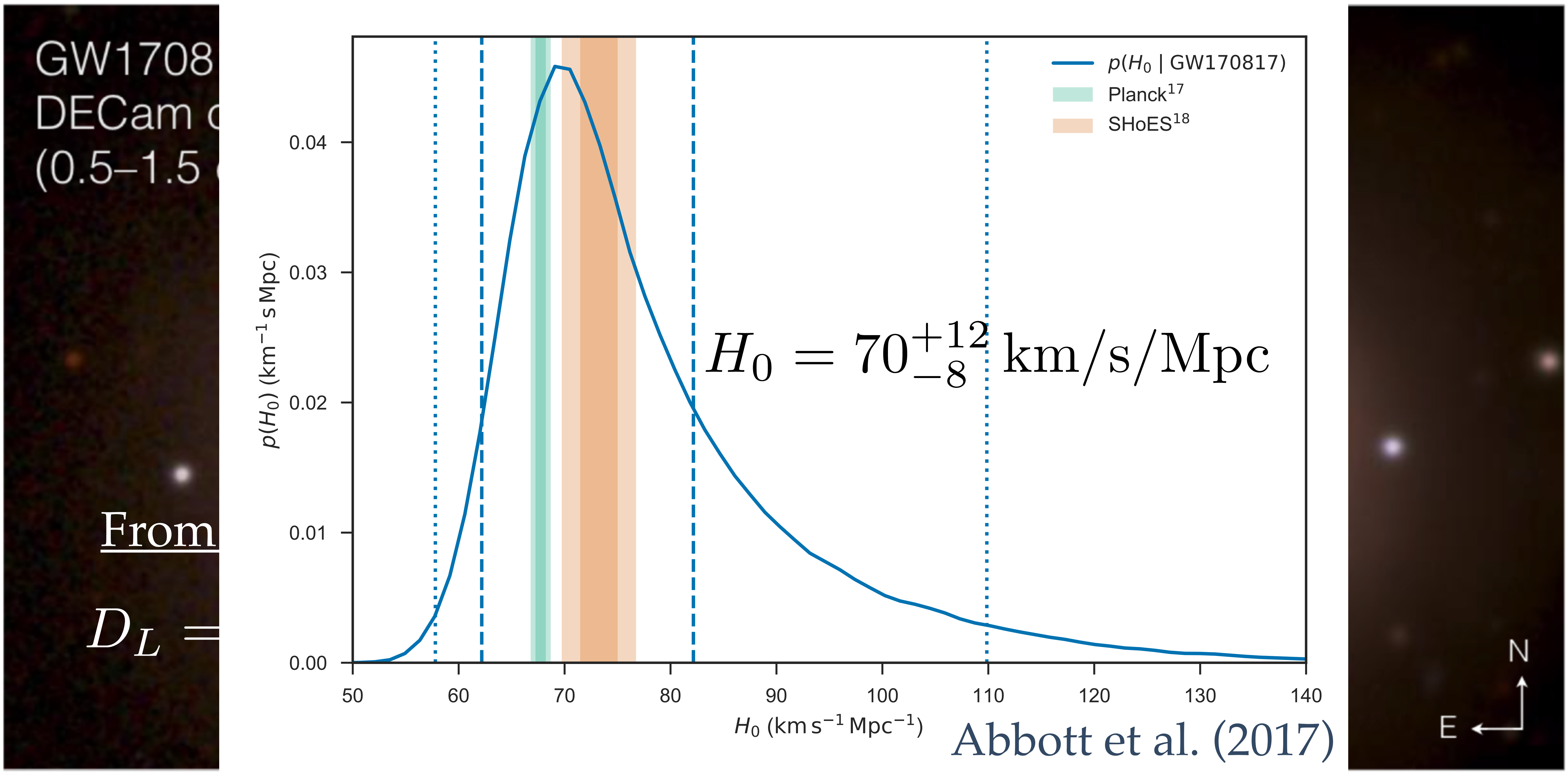
Soares-Santos, ~, Chen+, ApJL, 2017

The first standard siren measurement with an electromagnetic counterpart



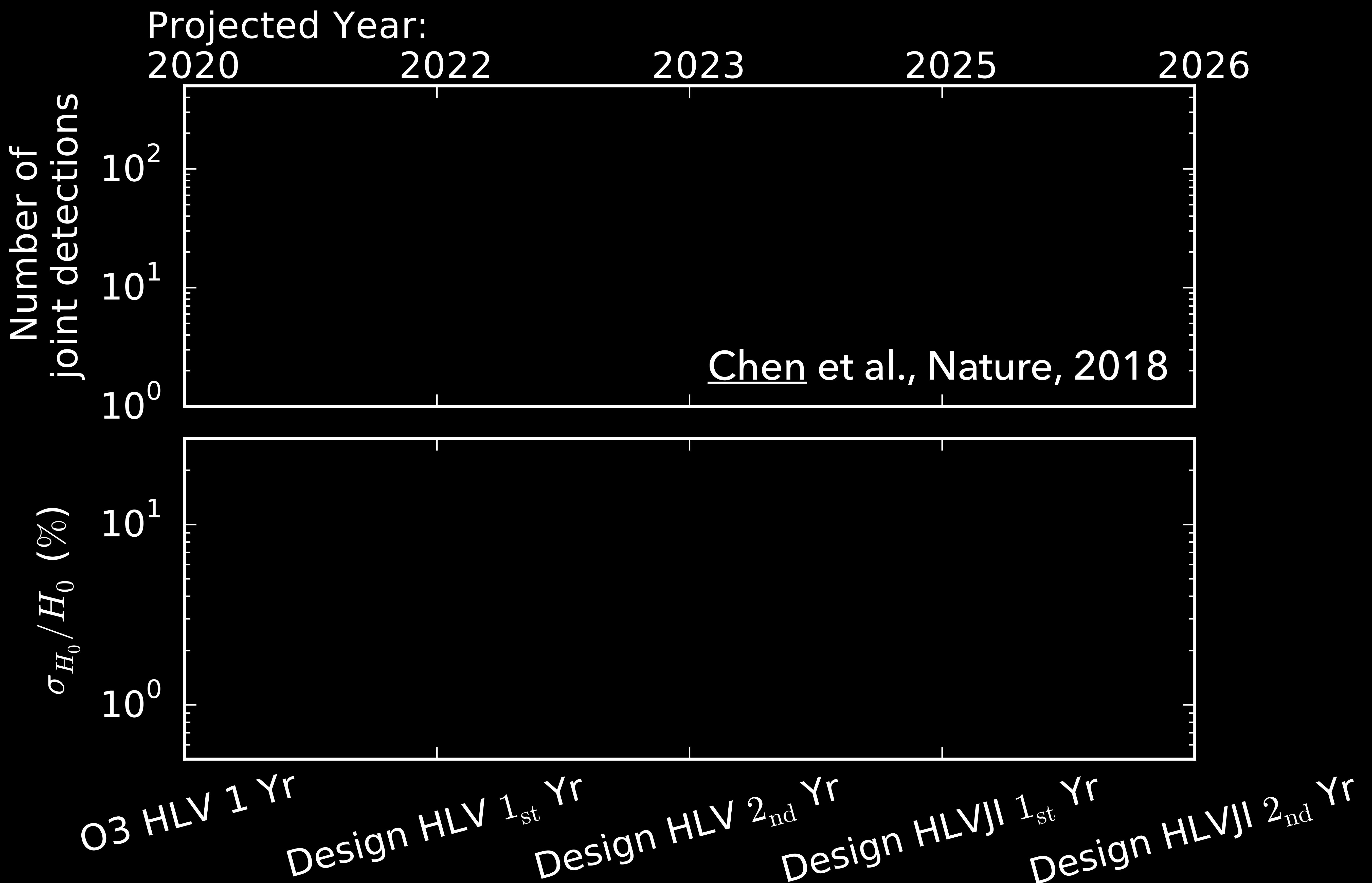
Soares-Santos, ~, Chen+, ApJL, 2017

The first standard siren measurement with an electromagnetic counterpart

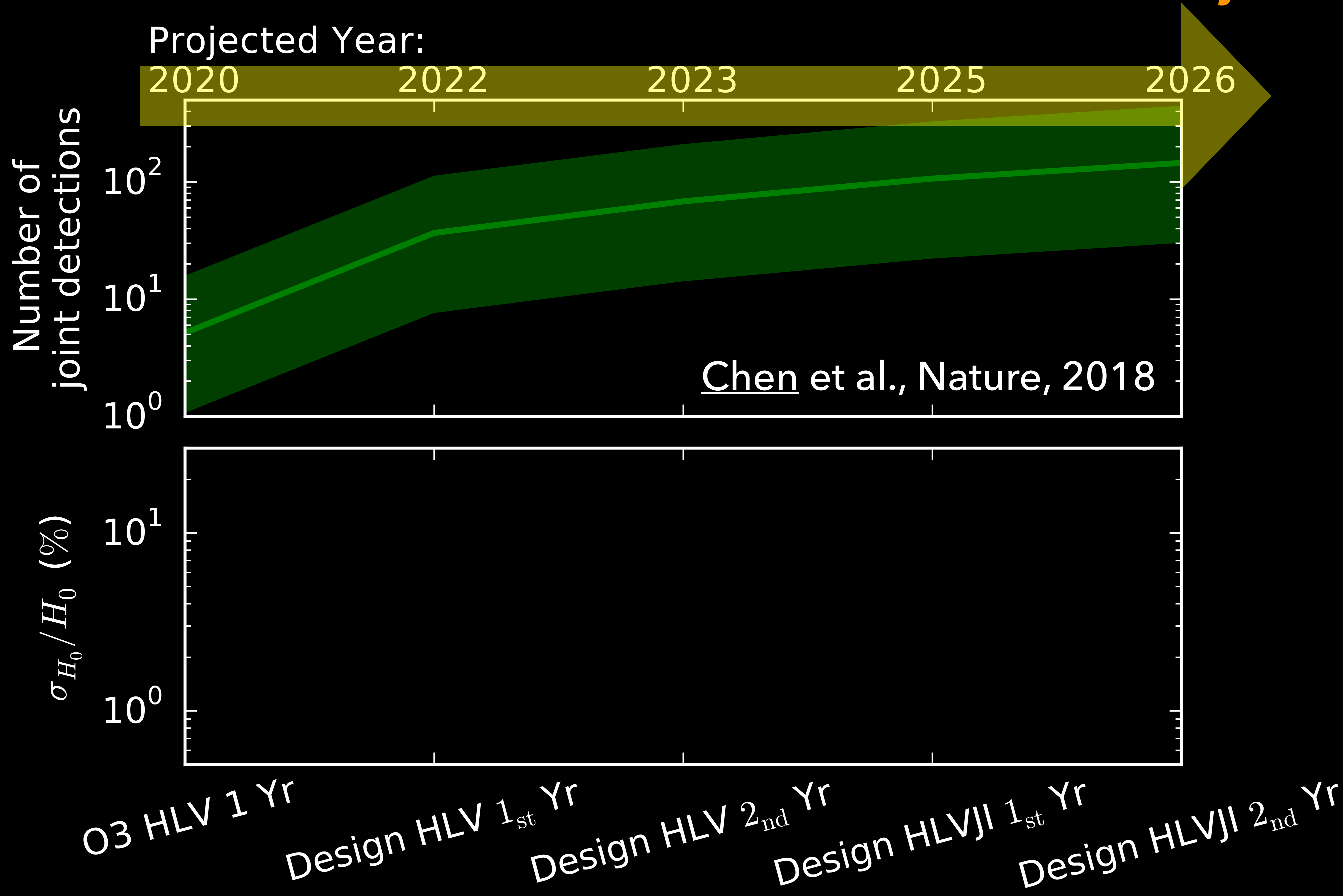


Soares-Santos, ~, Chen+, ApJL, 2017

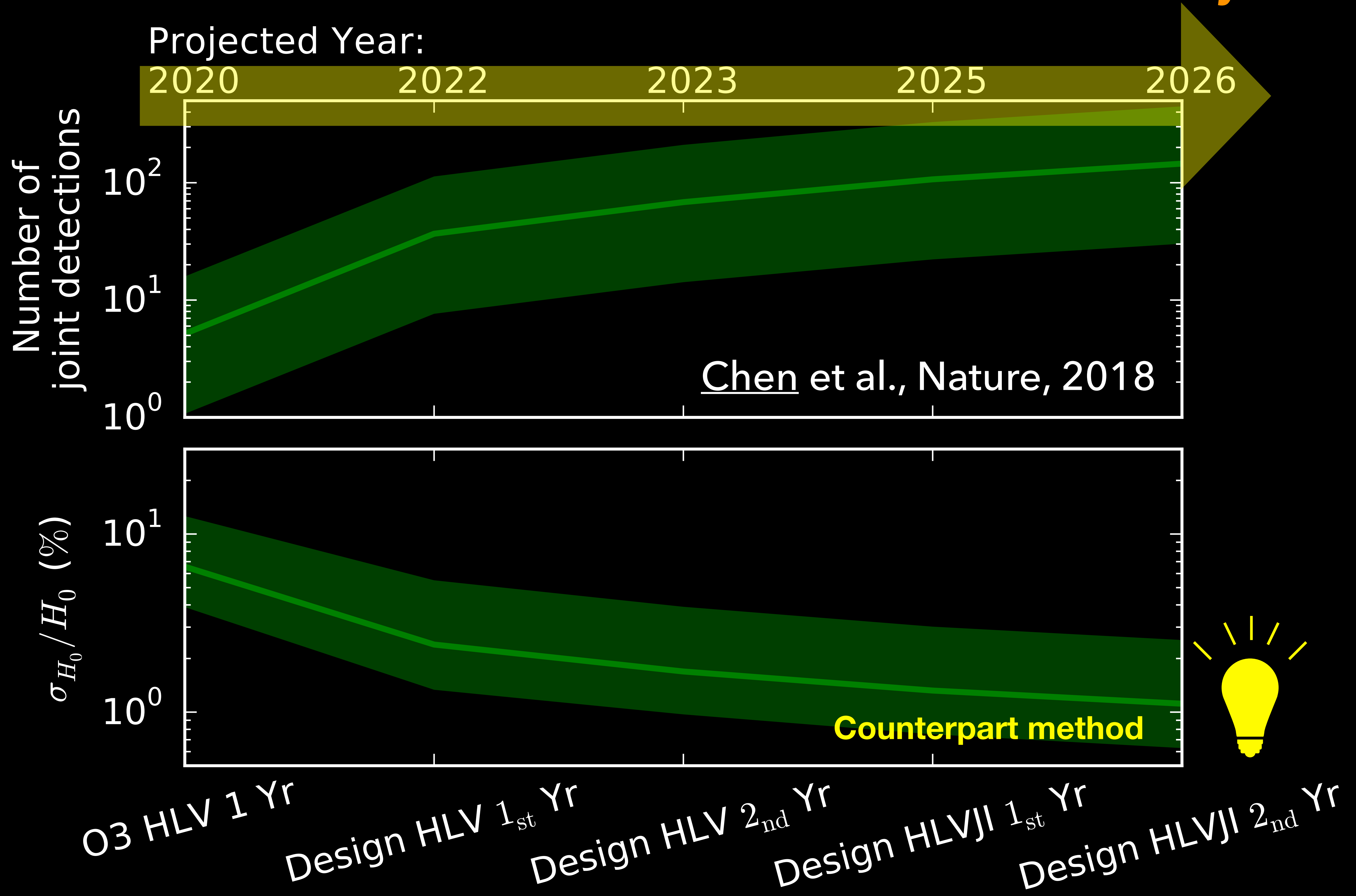
Percent-level Hubble constant measurement within a few years



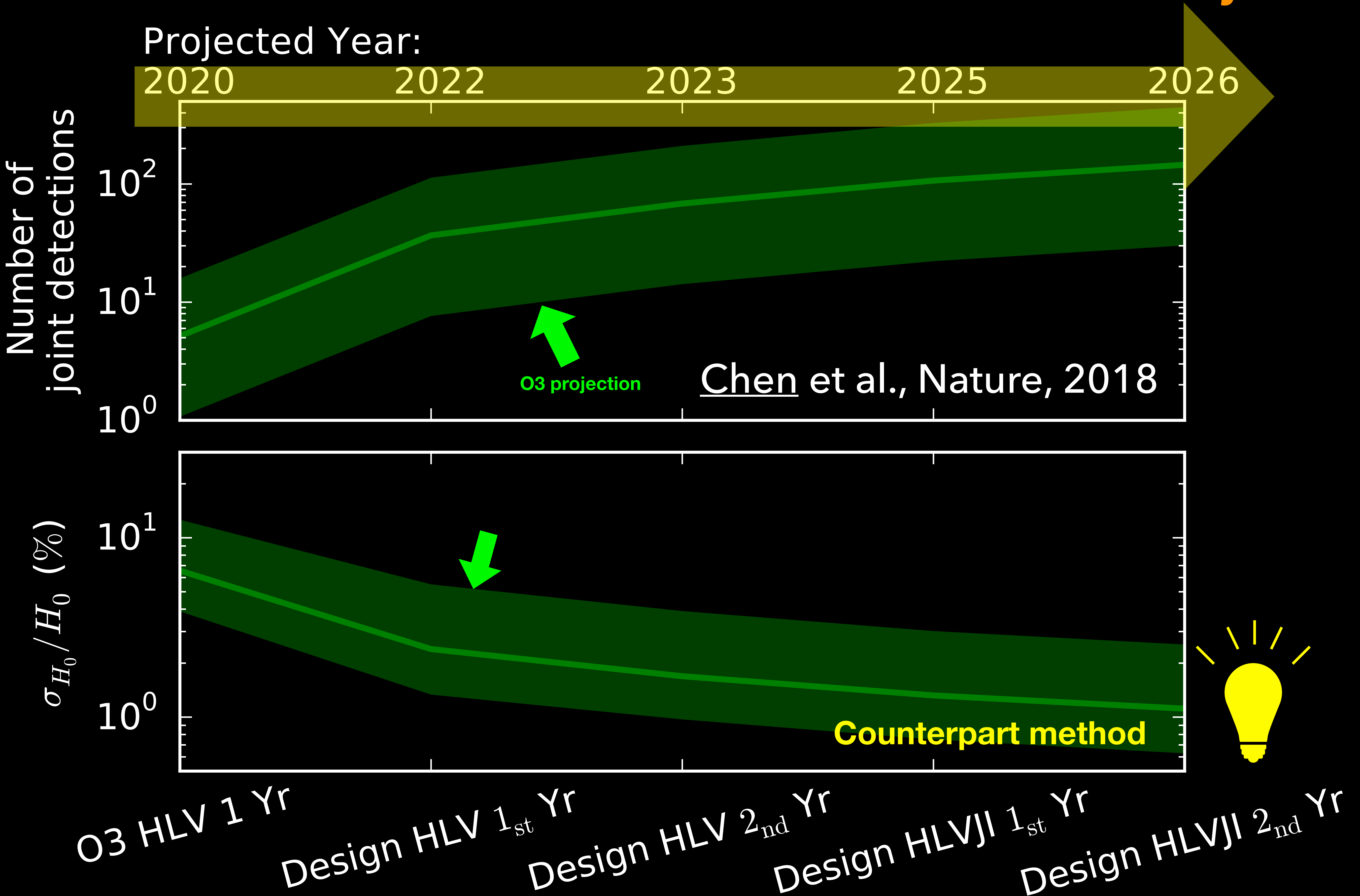
Percent-level Hubble constant measurement within a few years



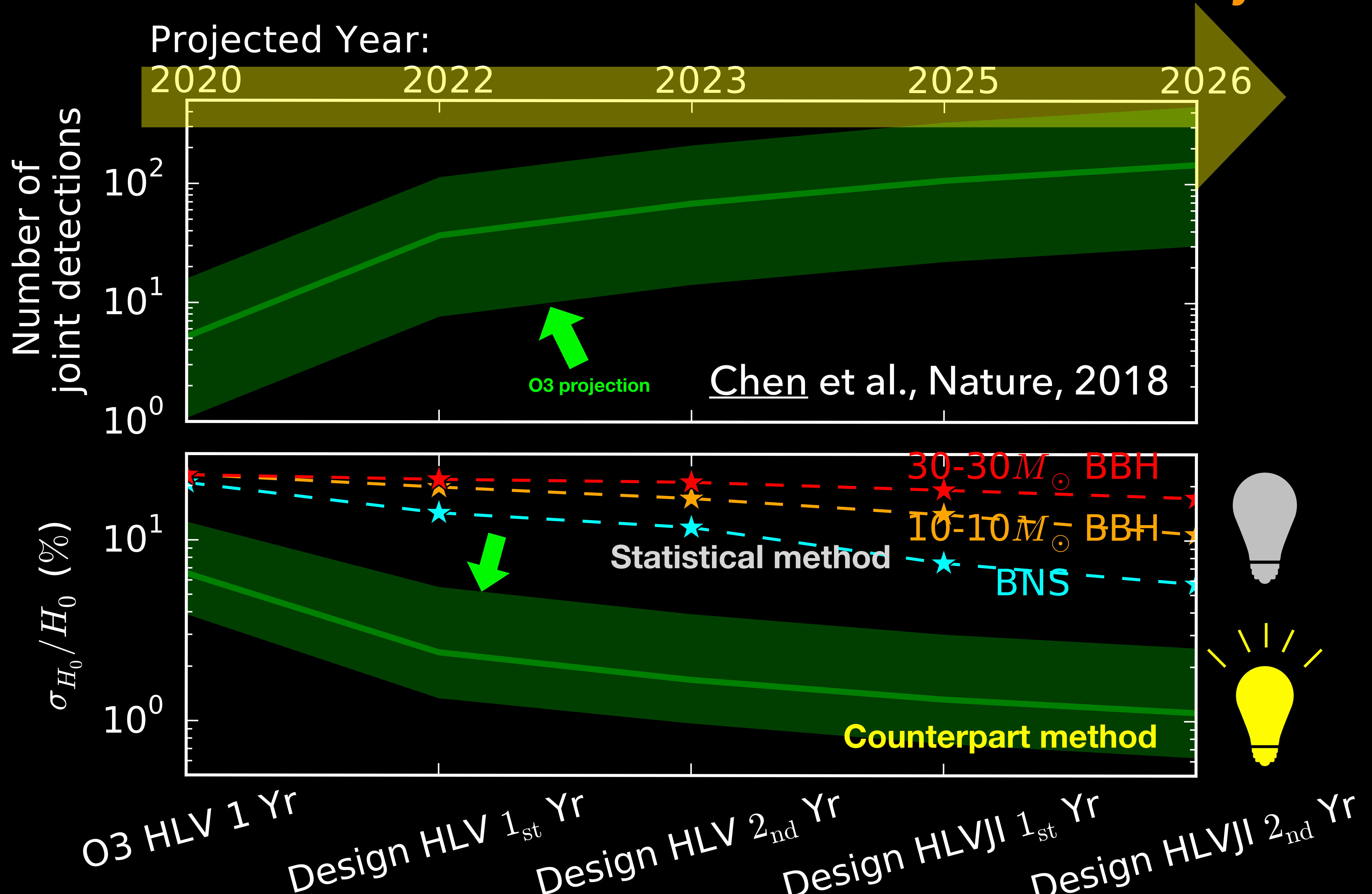
Percent-level Hubble constant measurement within a few years



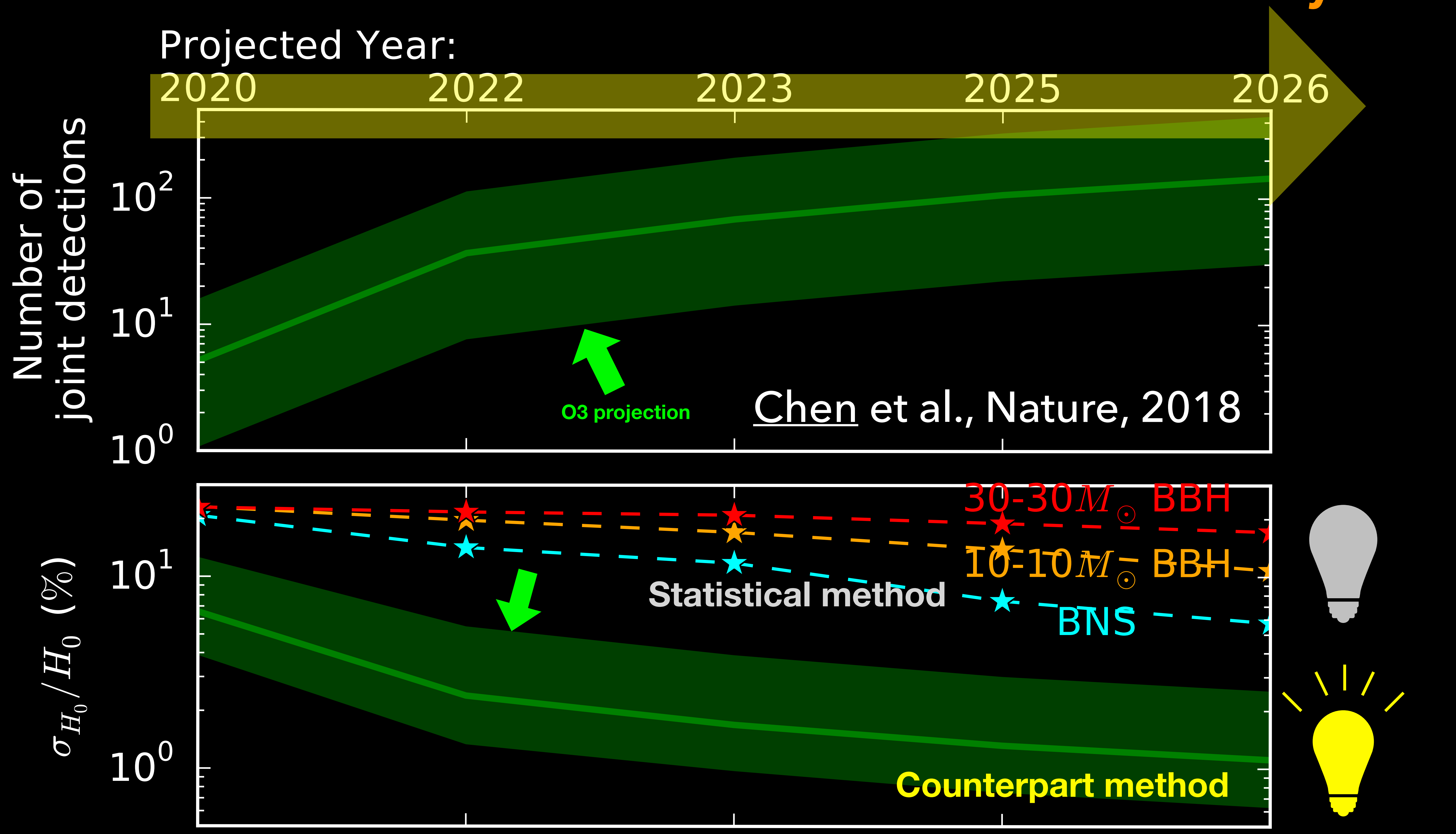
Percent-level Hubble constant measurement within a few years



Percent-level Hubble constant measurement within a few years



Percent-level Hubble constant measurement within a few years

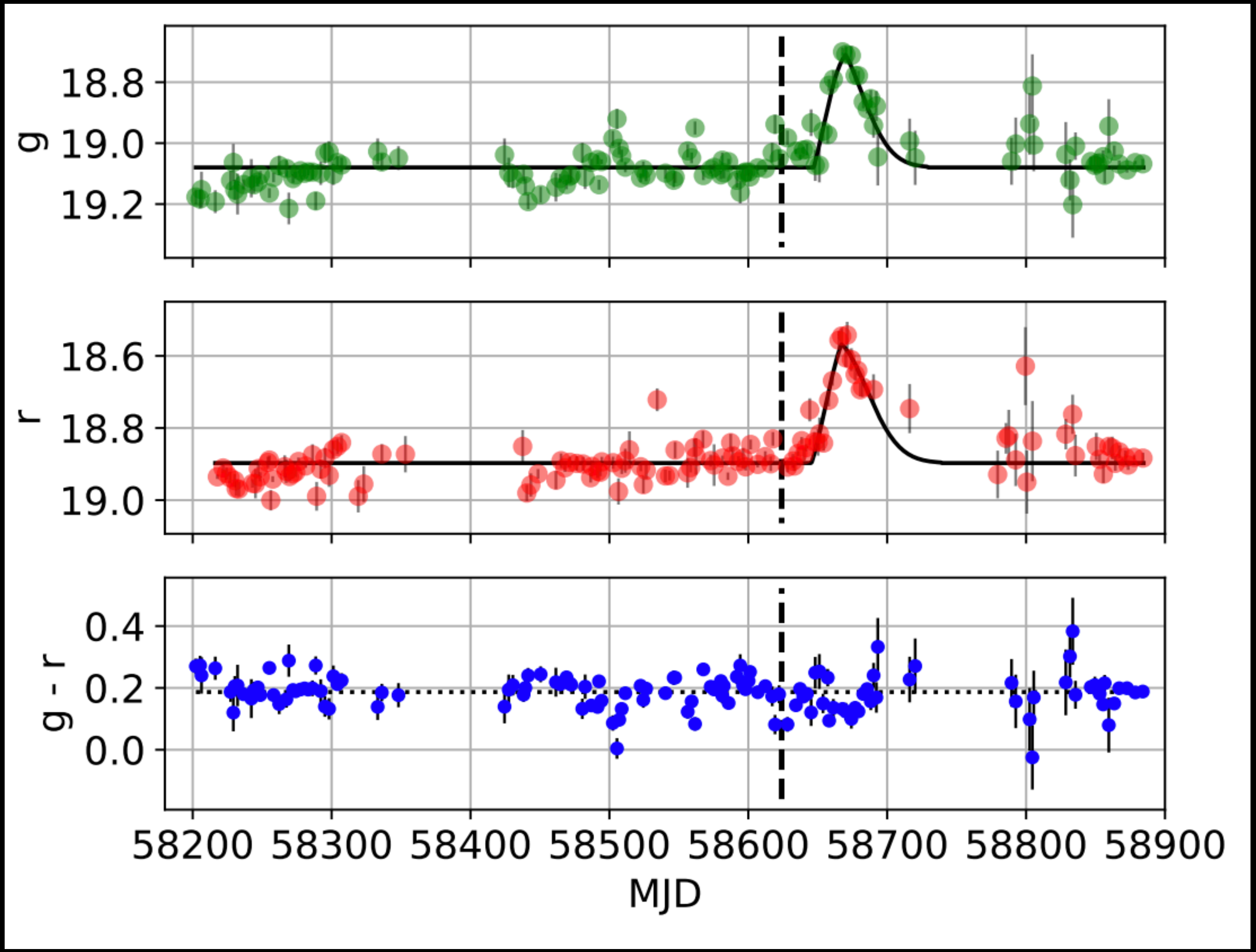


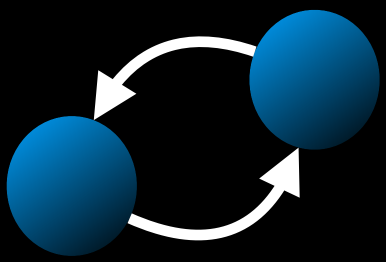
The search for electromagnetic counterparts is crucial for gravitational-wave cosmology.

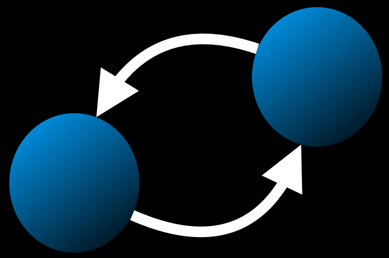
Could binary black hole or neutron star-black hole mergers have electromagnetic counterparts?

Binary black hole merger GW190521 and its potential electromagnetic counterpart

-Kicked black hole merger in the accretion disk of an Active Galactic Nuclei



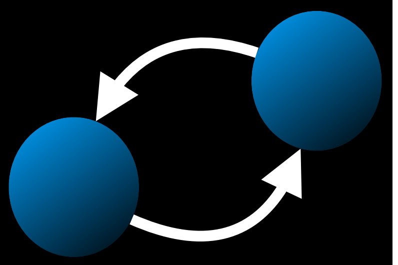


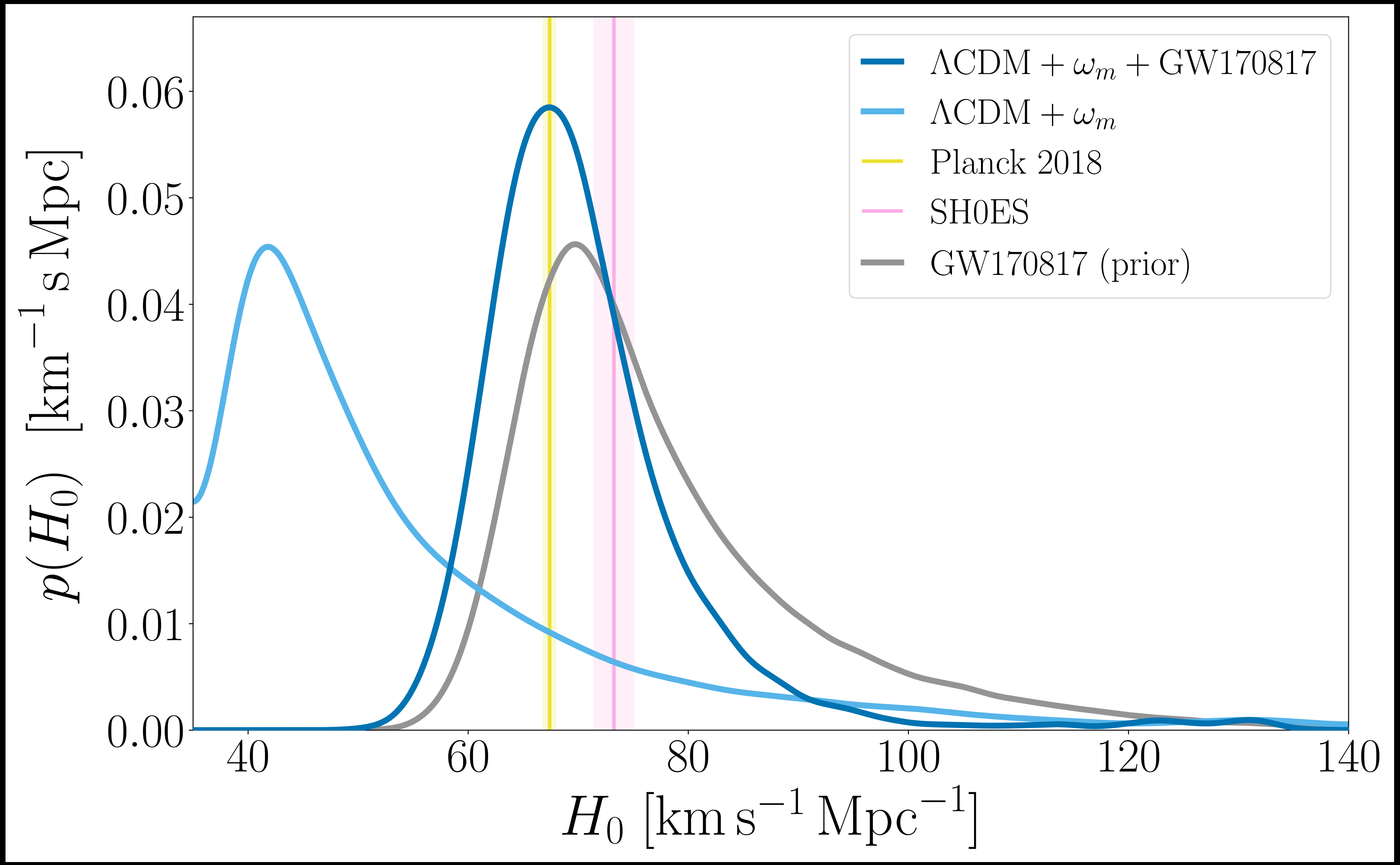


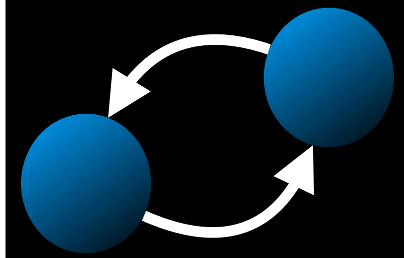
Graham et al., PRL, 2020

Binary black hole merger GW190521 and its potential electromagnetic counterpart

-The uncertainty of H_0 improved from 15% to 10%.







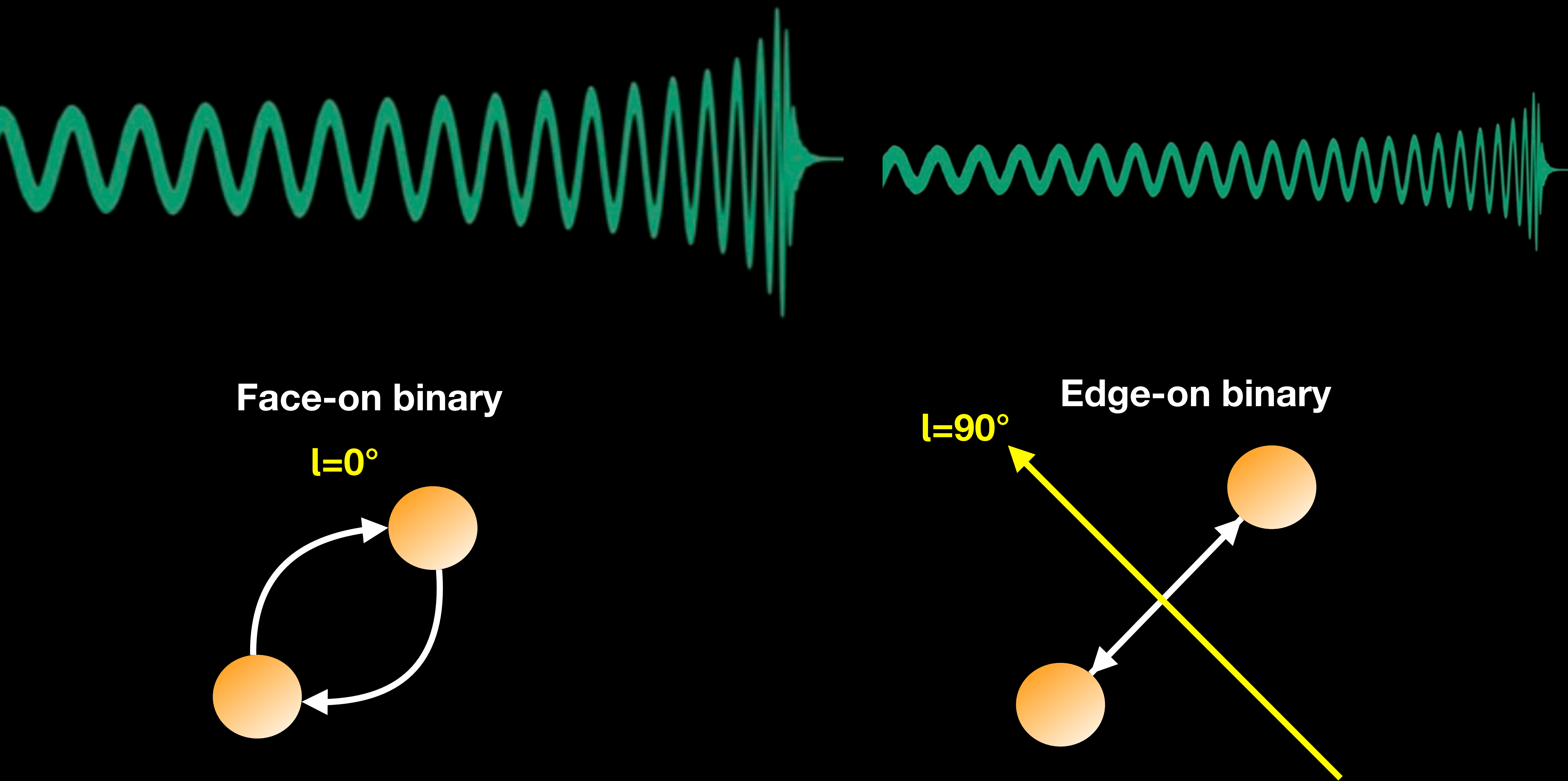
Chen et al., arXiv: 2009.14057

Improve the precision of standard sirens

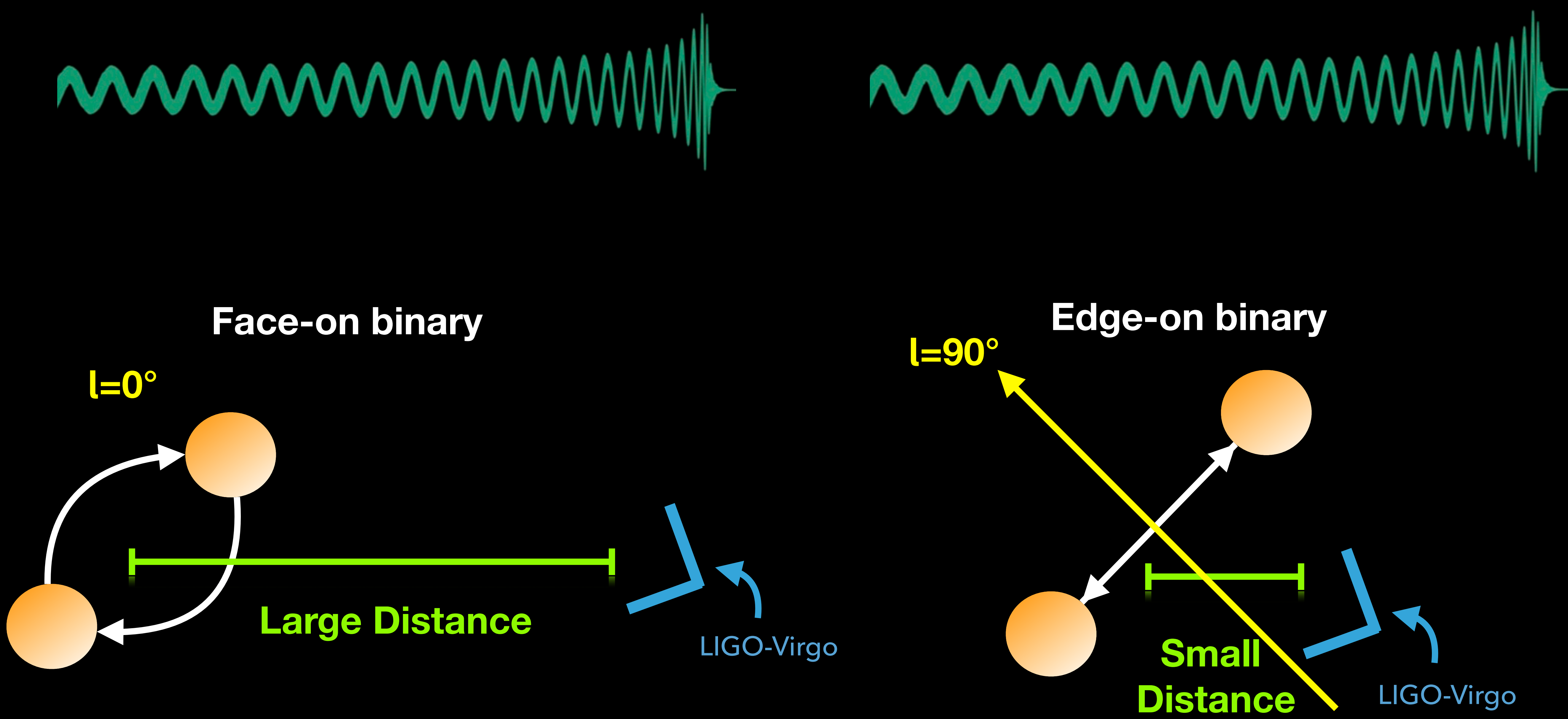
Improve the precision of standard sirens

-Break the distance-inclination degeneracy.

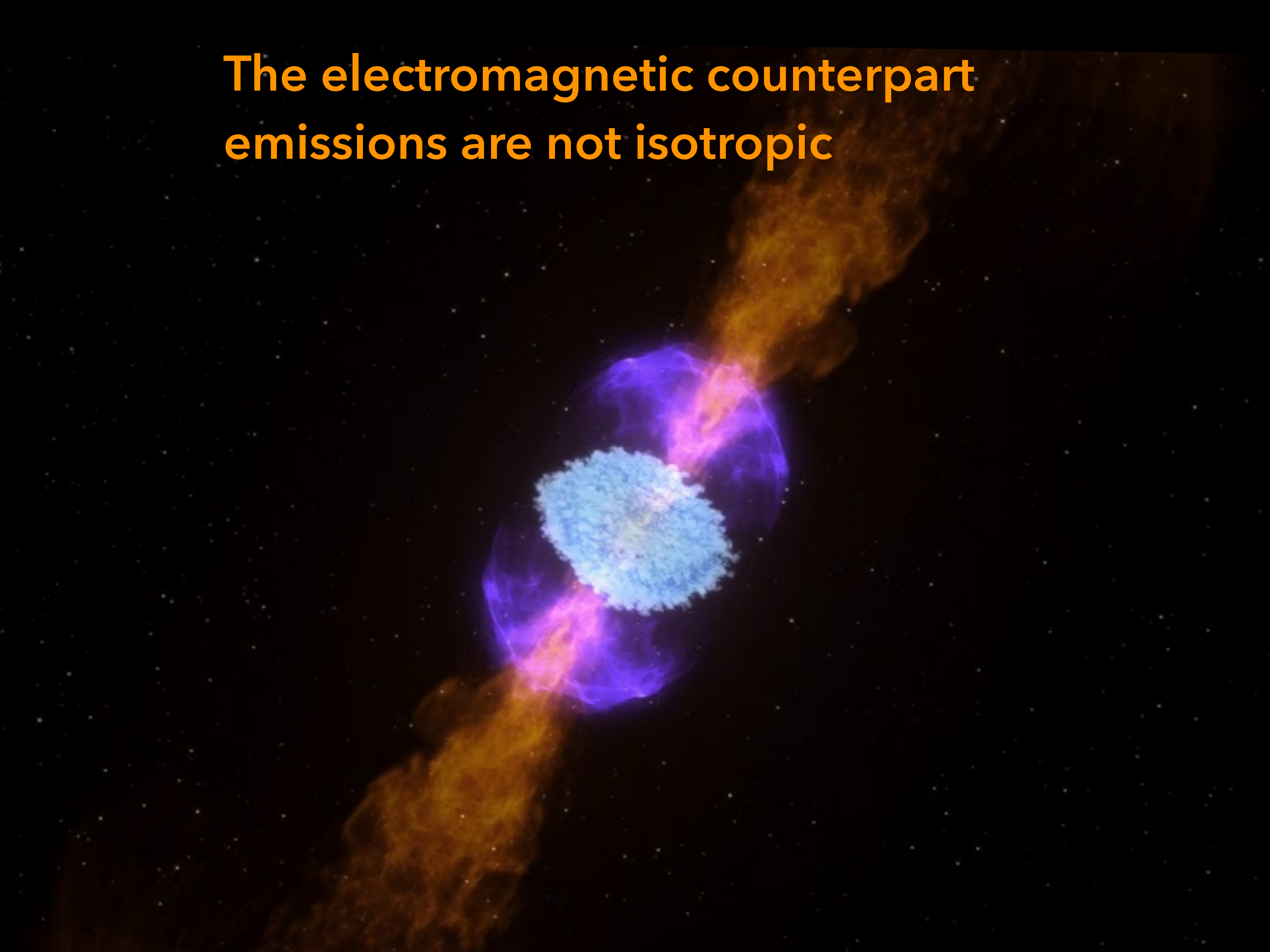
Distance-inclination degeneracy



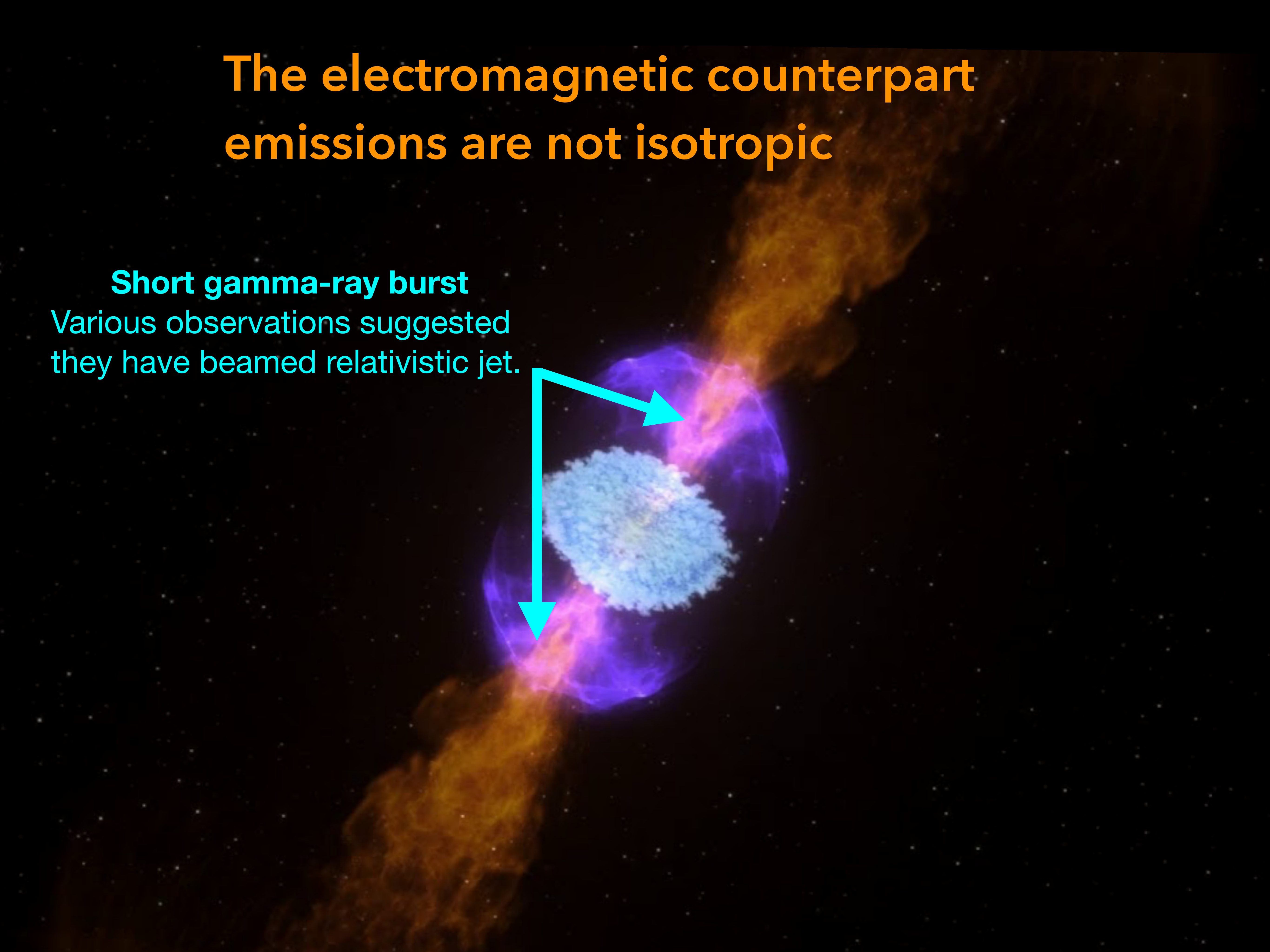
Distance-inclination degeneracy



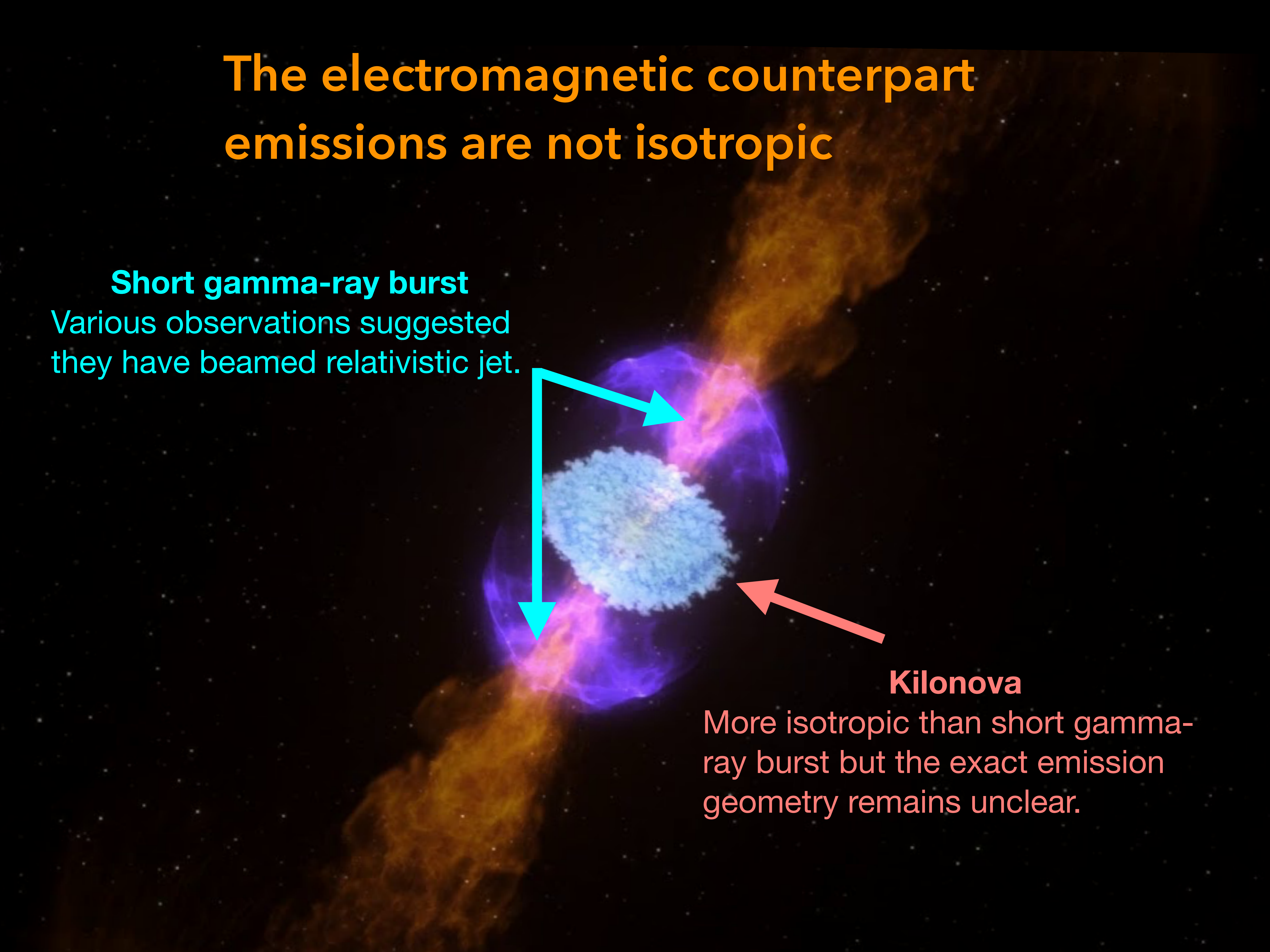
The electromagnetic counterpart emissions are not isotropic



The electromagnetic counterpart emissions are not isotropic



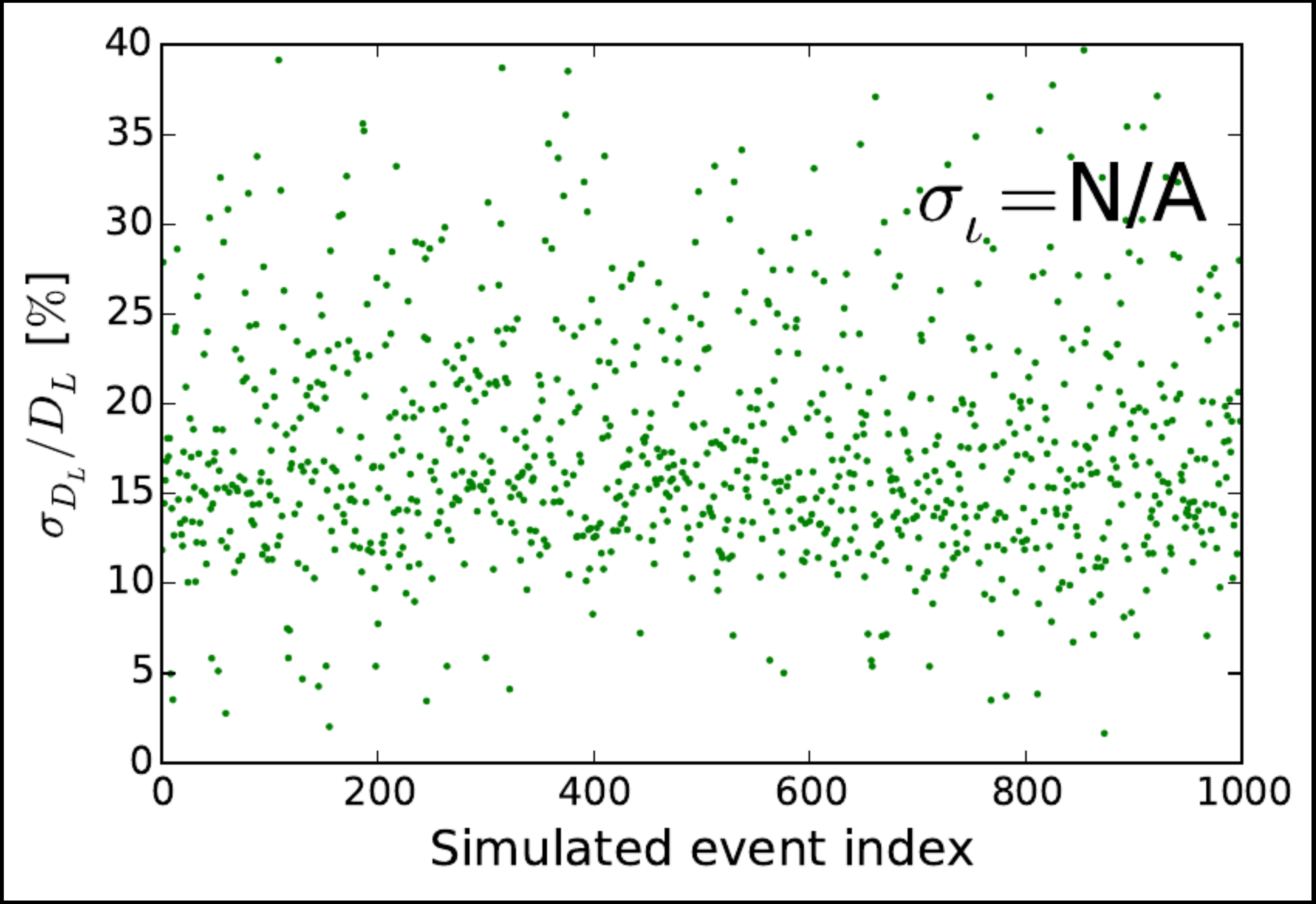
The electromagnetic counterpart emissions are not isotropic



Break the distance-inclination degeneracy

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

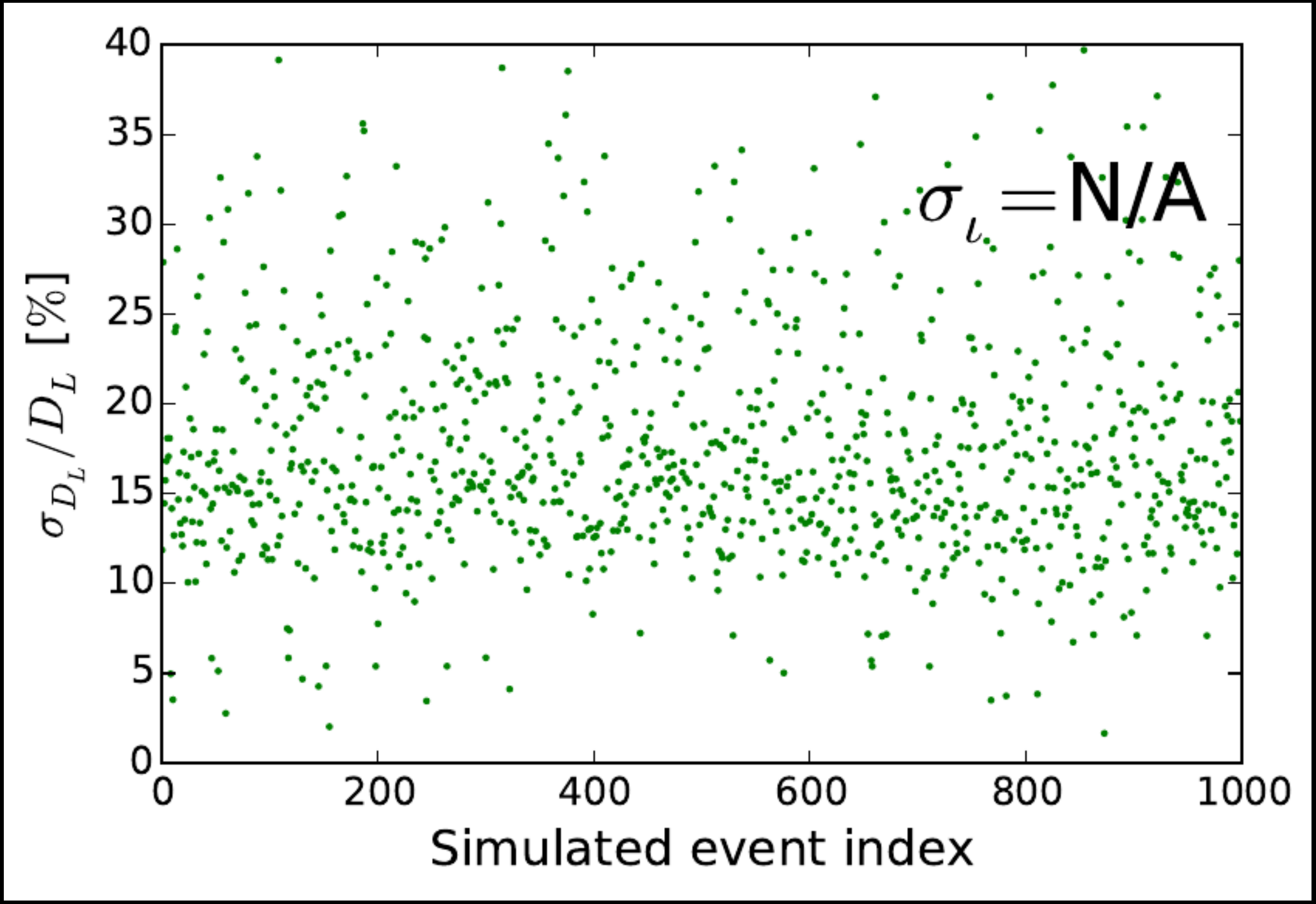
Chen, Vitale & Narayan, PRX, 2019



Break the distance-inclination degeneracy

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

Chen, Vitale & Narayan, PRX, 2019

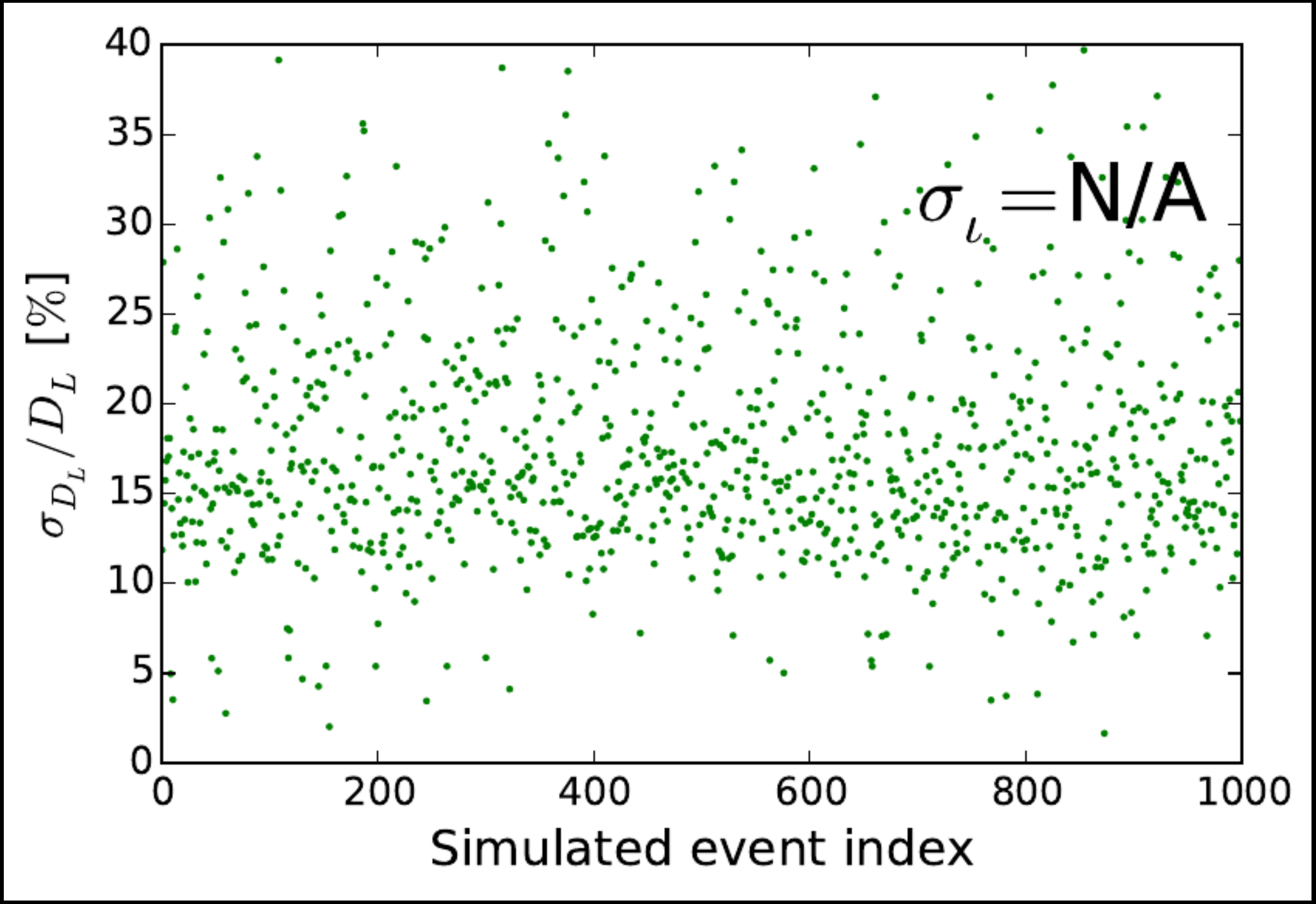


Break the distance-inclination degeneracy

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

<u>Chen</u>, Vitale & Narayan, PRX, 2019

Can be viewed as → **<u>H_0 uncertainty</u>**



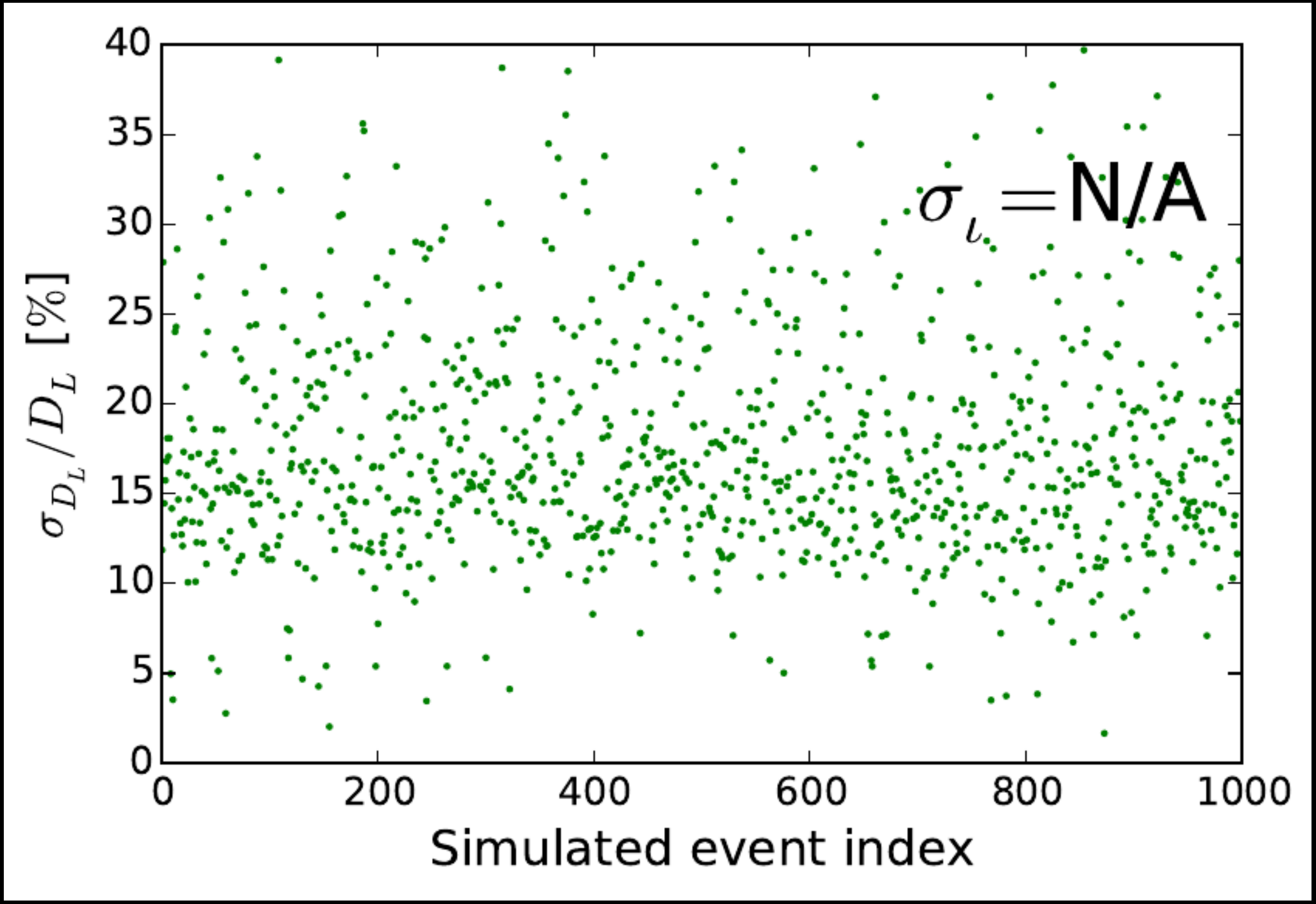
Break the distance-inclination degeneracy

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

Chen, Vitale & Narayan, PRX, 2019

Can be viewed as → ***H₀ uncertainty***

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



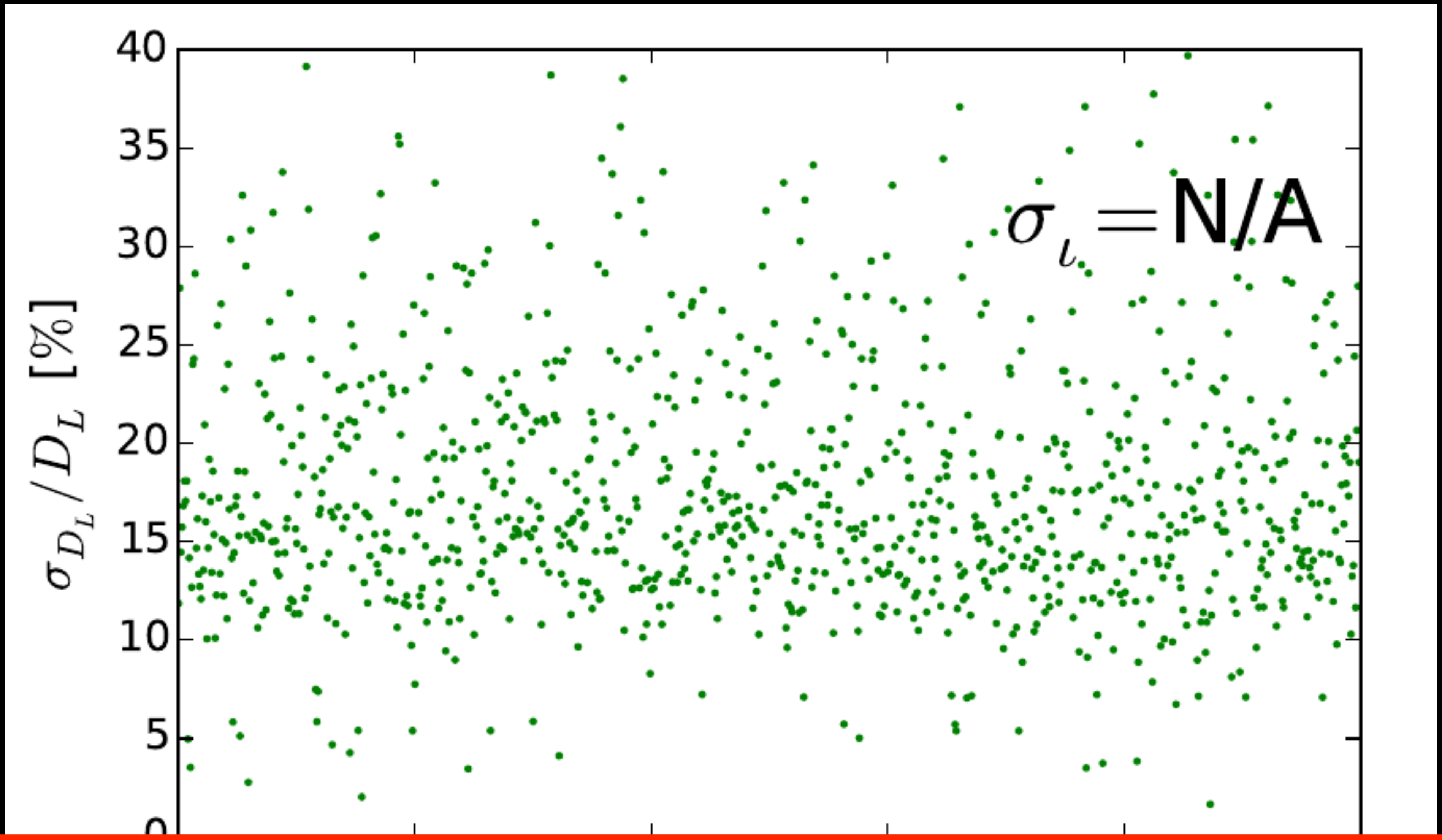
Break the distance-inclination degeneracy

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

Chen, Vitale & Narayan, PRX, 2019

Can be viewed as → ***H₀ uncertainty***

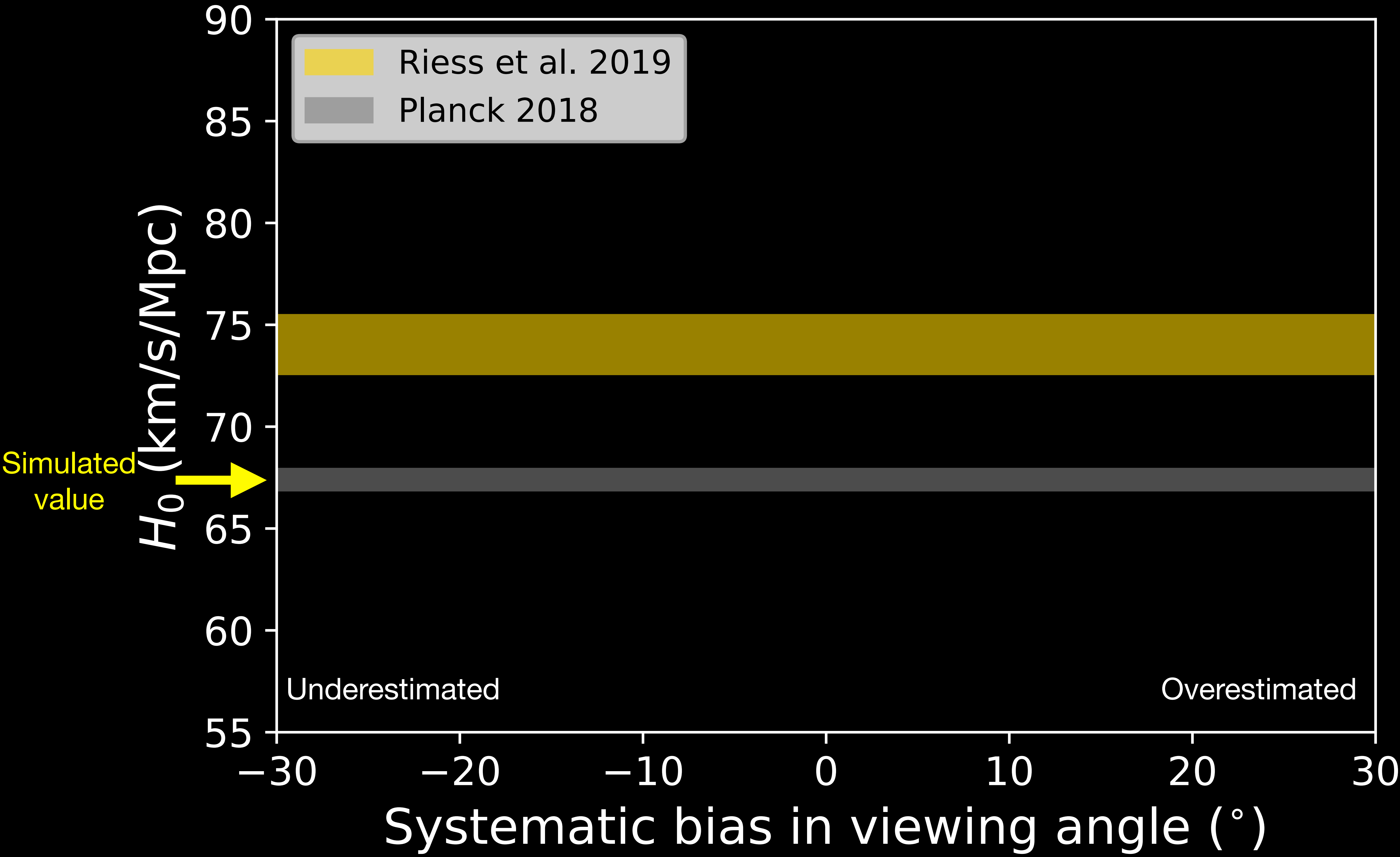
$$\sigma_{H_0} \propto \frac{1}{\sqrt{N}}$$



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

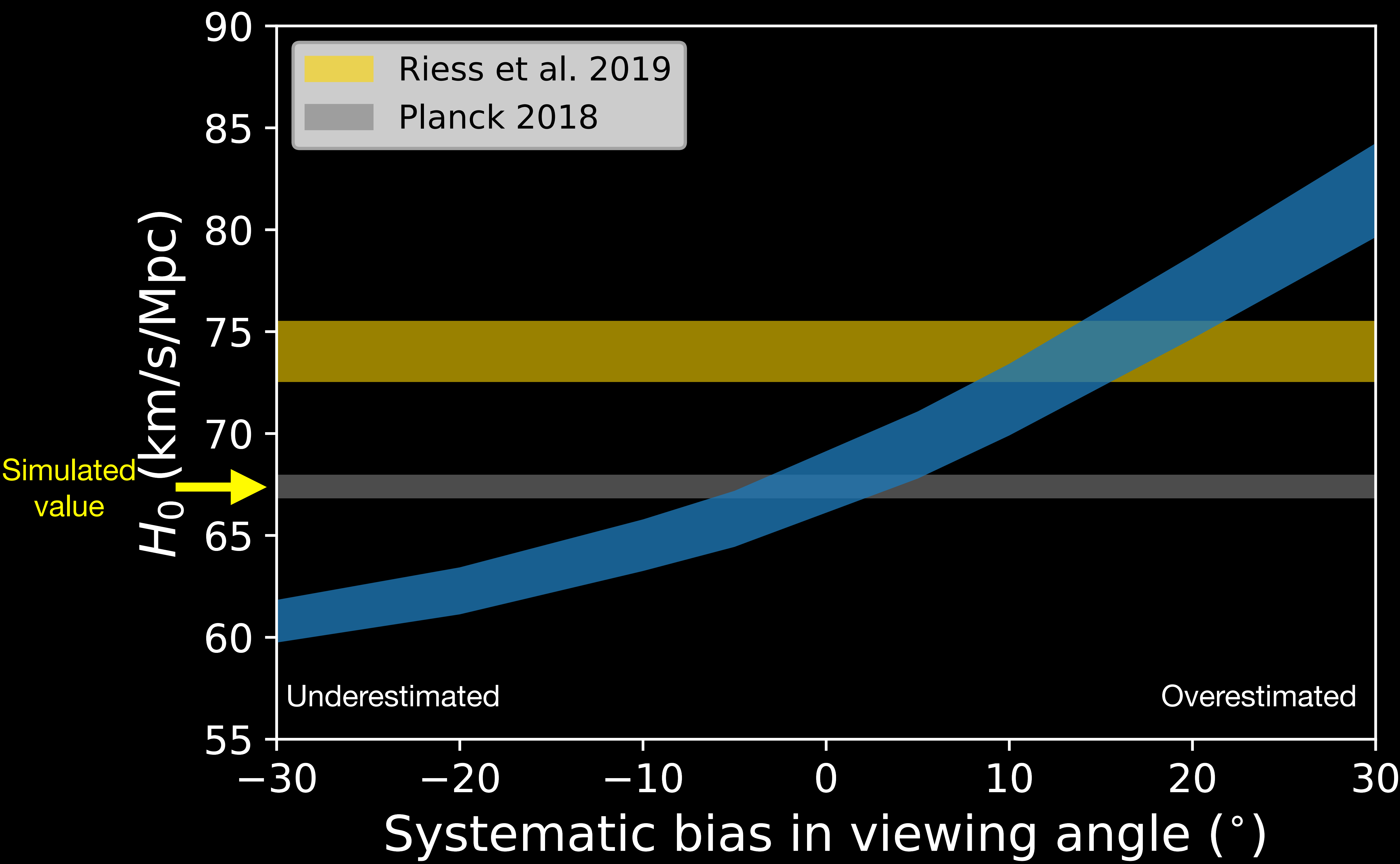
However, the estimation of viewing angle from electromagnetic observations has to be very accurate.

If the EM inferred viewing angle is biased



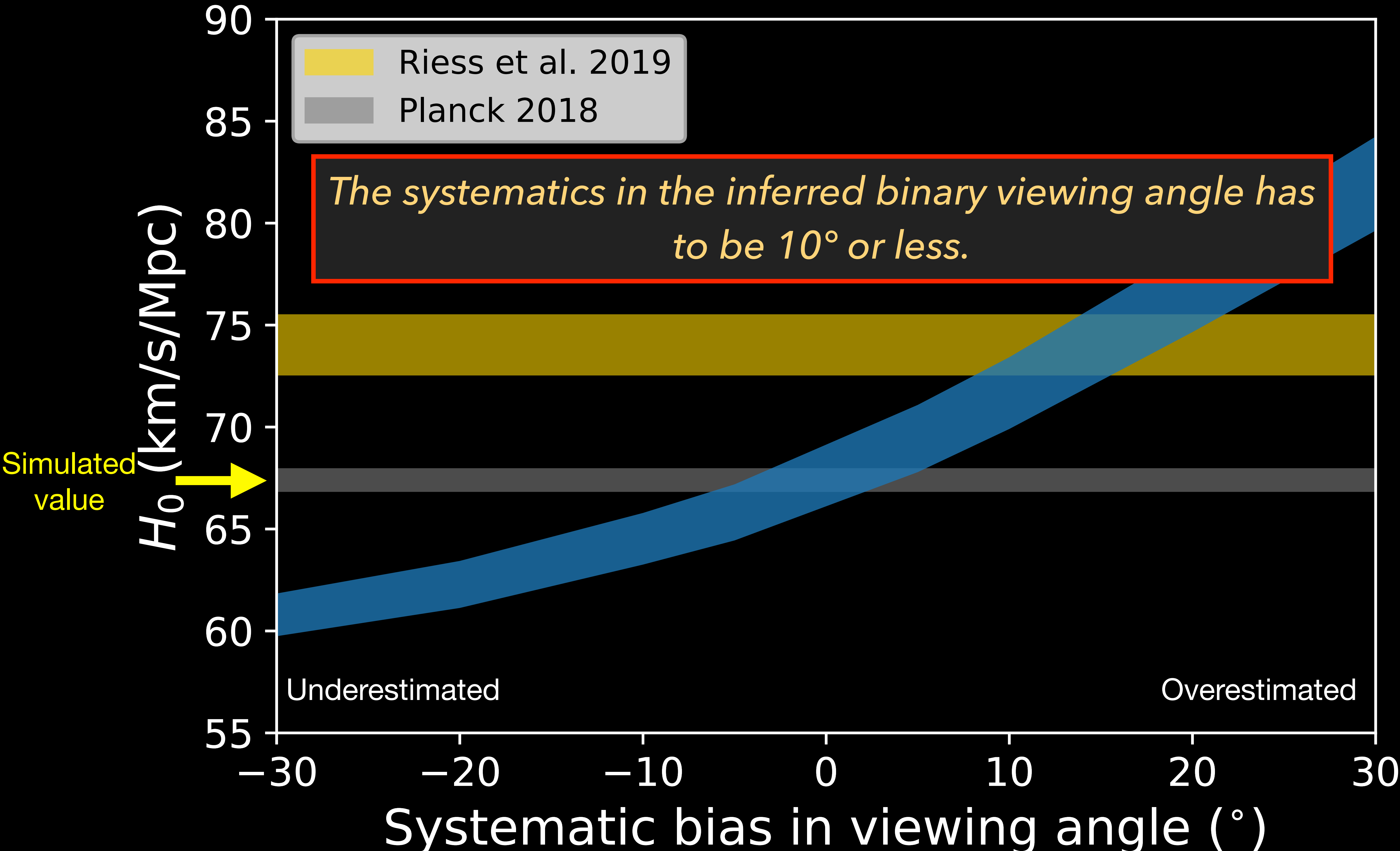
Chen, PRL, 2020

If the EM inferred viewing angle is biased



Chen, PRL, 2020

If the EM inferred viewing angle is biased



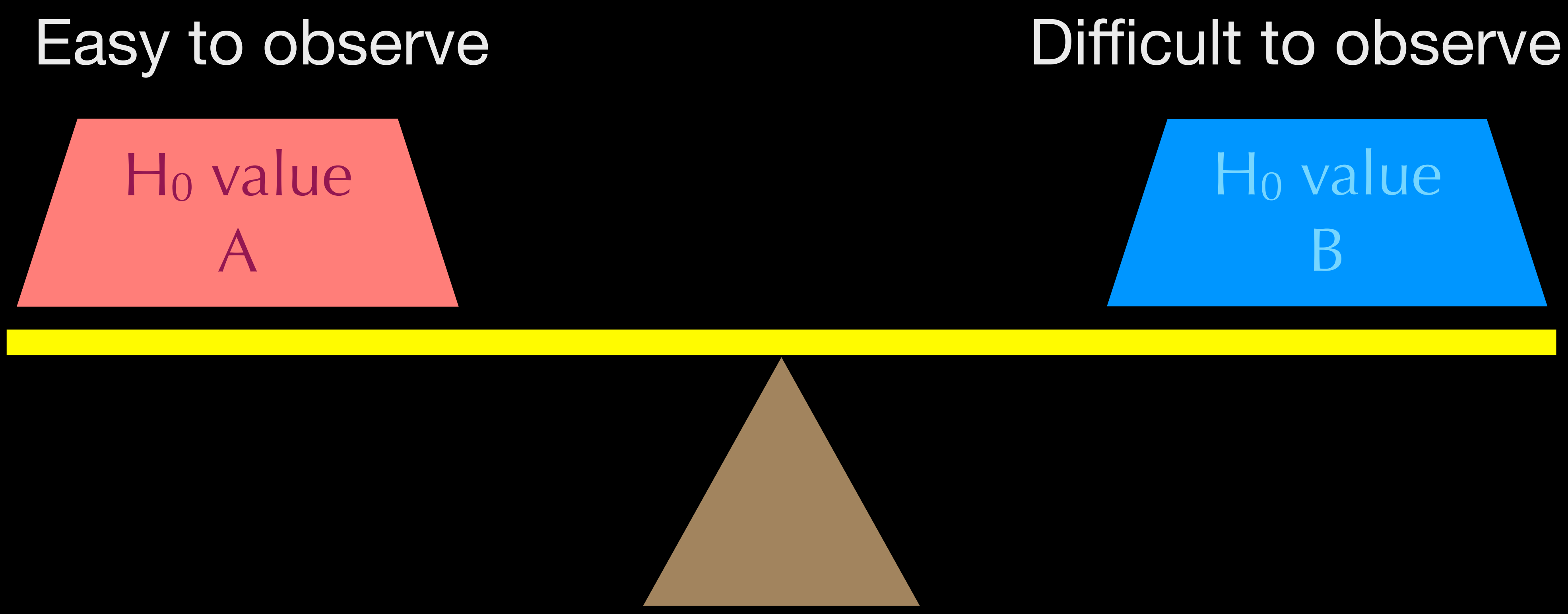
Chen, PRL, 2020

What if we don’t use the viewing angle information from EM observations?

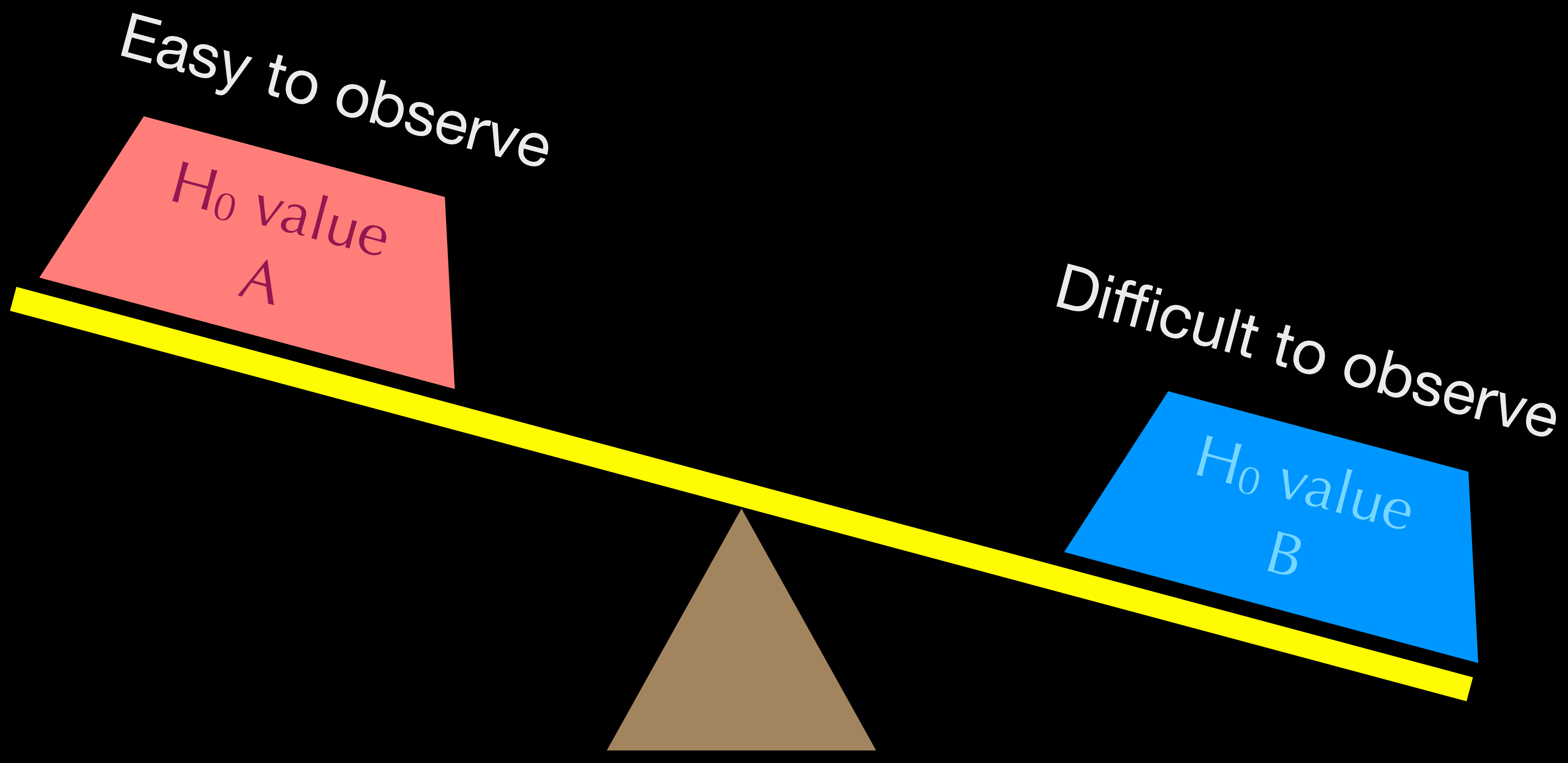
What if we don’t use the viewing angle information from EM observations?

-The binaries available for standard siren measurement can still suffer from the undetermined selection over binary viewing angle.

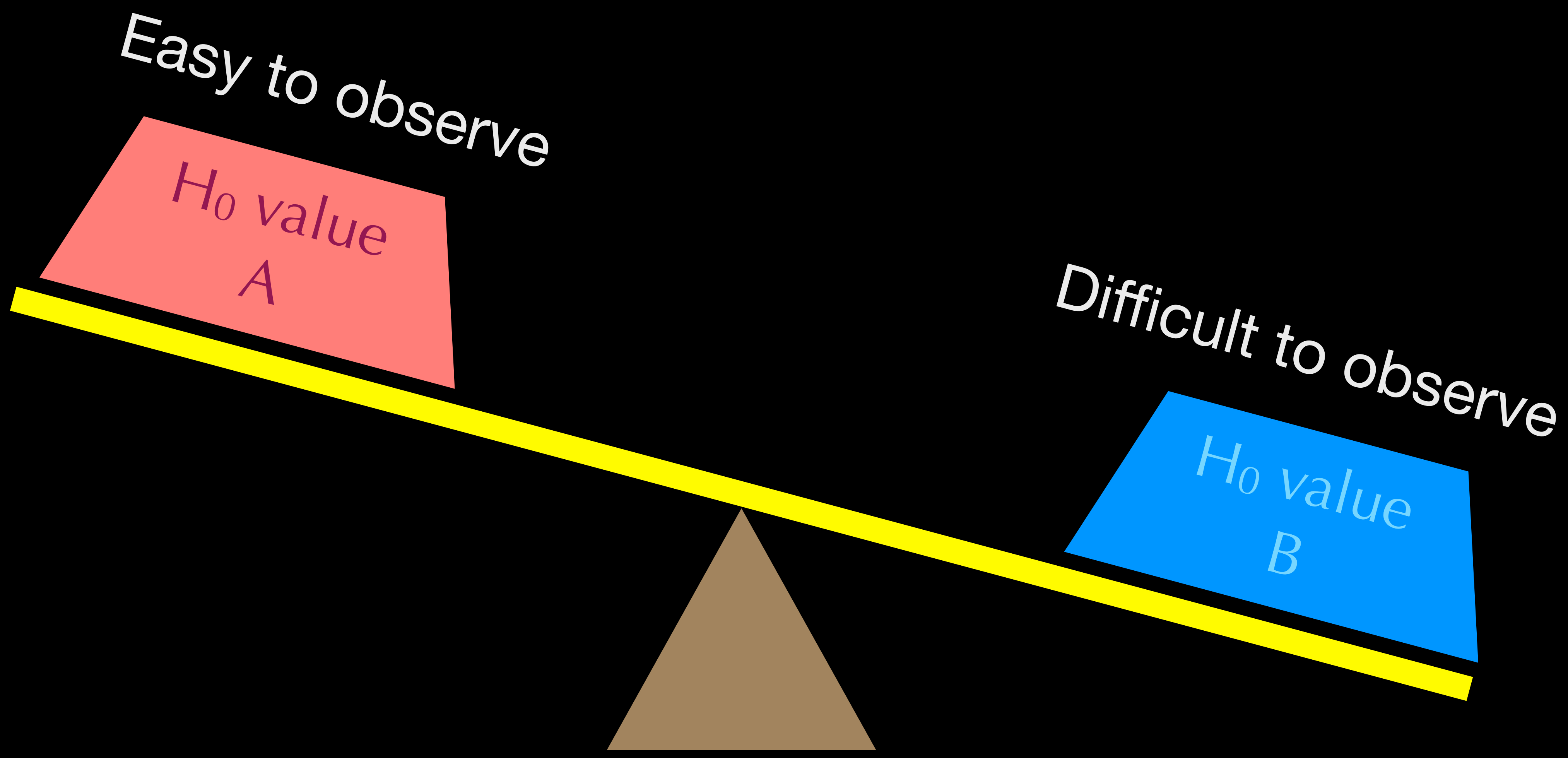
Selection effect from binary viewing angle



Selection effect from binary viewing angle

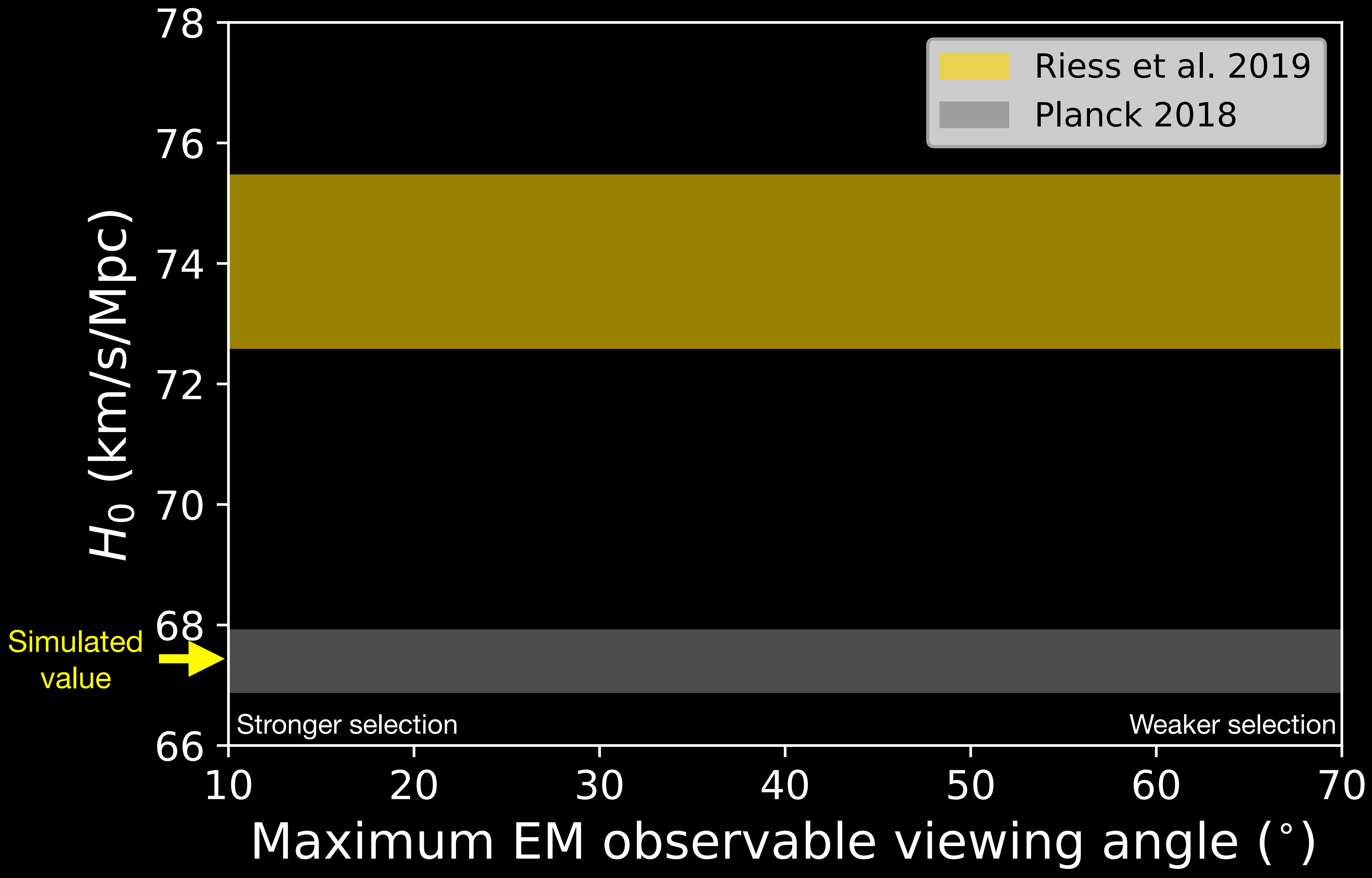


Selection effect from binary viewing angle



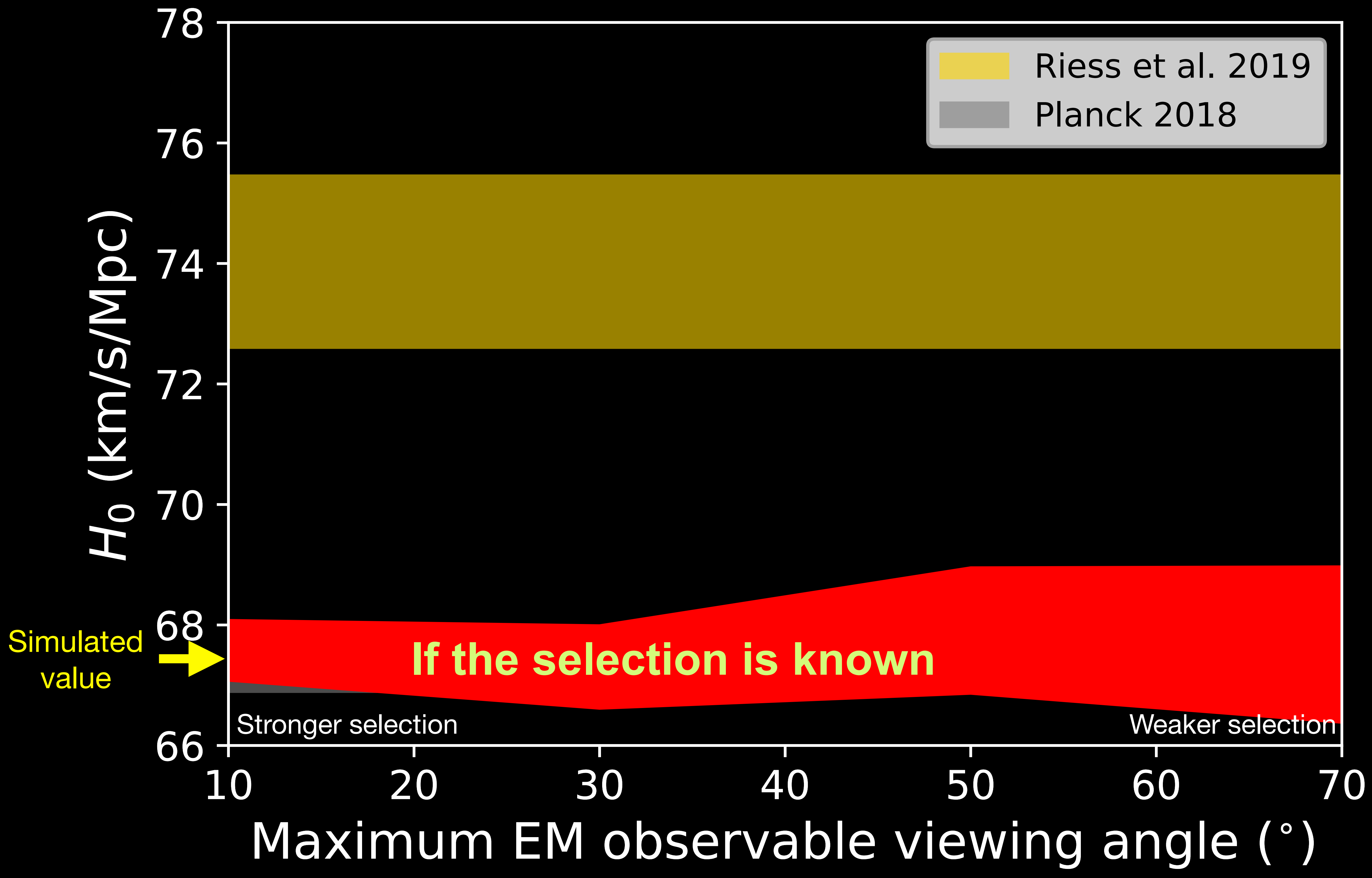
We don't know how to reweigh if the selection effect is unclear.

If the EM emissions are only observable up to a maximum viewing angle



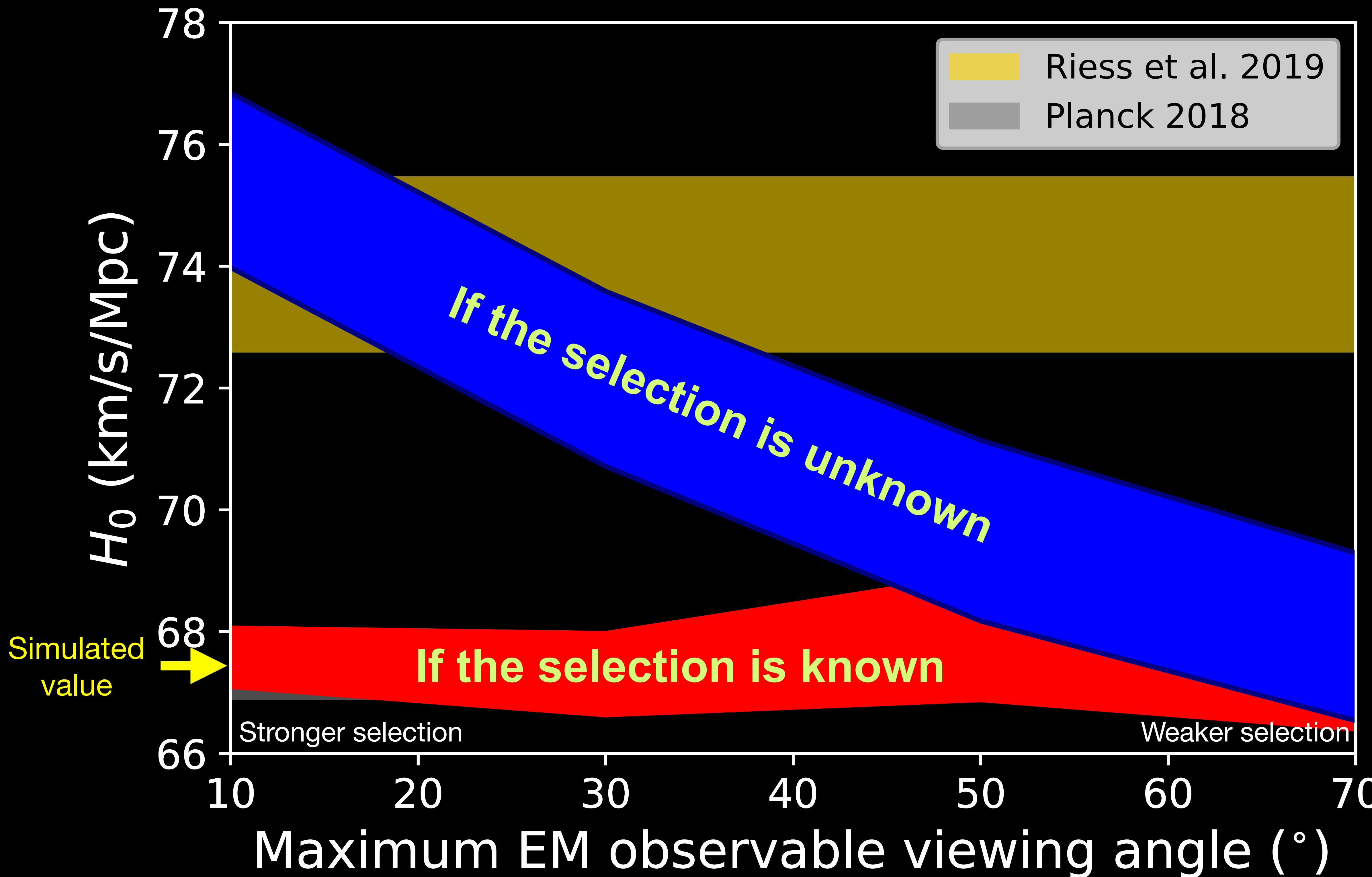
Chen, PRL, 2020

If the EM emissions are only observable up to a maximum viewing angle



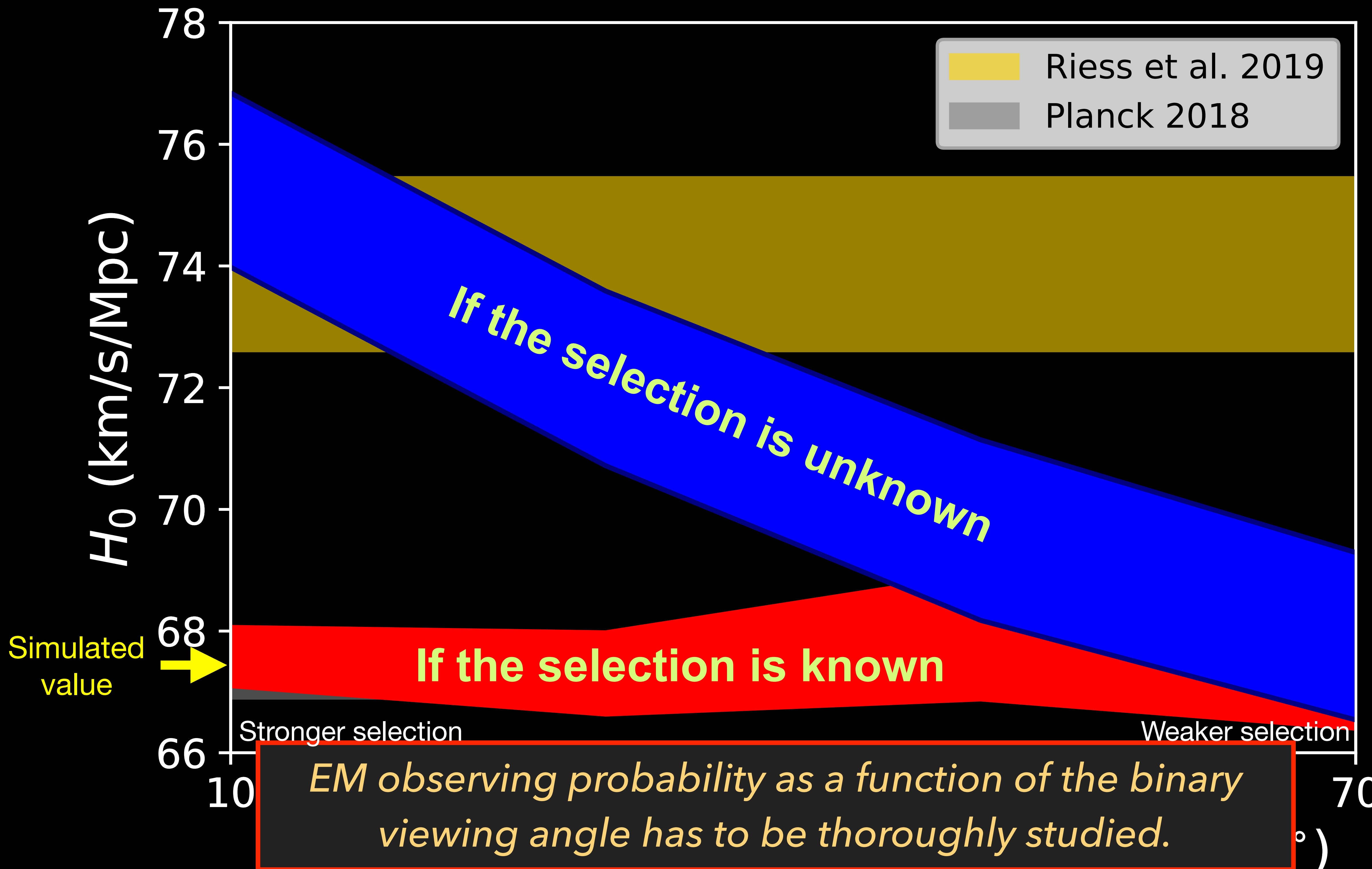
Chen, PRL, 2020

If the EM emissions are only observable up to a maximum viewing angle



Chen, PRL, 2020

If the EM emissions are only observable up to a maximum viewing angle



EM observing probability as a function of the binary viewing angle has to be thoroughly studied.

Chen, PRL, 2020

Comparing to other systematic uncertainties of standard sirens

Host galaxy peculiar velocities

Howlett & Davis (2019), Mukherjee et al. (2019), Nicolaou et al.(2019)

Gravitational waveform systematics

Abbott et al., PRX, 2019

Instrumental calibration uncertainty

- <2% for LIGO-Virgo third observing run.

Sun et al. (2020)

- Expected to be smaller in the future.

Karki et al. (2016)

Comparing to other systematic uncertainties of standard sirens

Host galaxy peculiar velocities

Howlett & Davis (2019), Mukherjee et al. (2019), Nicolaou et al.(2019)

Gravitational waveform systematics

Abbott et al., PRX, 2019

Instrumental calibration uncertainty

- <2% for LIGO-Virgo third observing run.

Sun et al. (2020)

- Expected to be smaller in the future.

Karki et al. (2016)

Viewing angle selection effect can dominate the systematics of standard sirens.

Summary

Summary

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

Summary

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

-There are many different possibilities to reduce the statistical uncertainty of standard siren measurements.

Summary

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

-There are many different possibilities to reduce the statistical uncertainty of standard siren measurements.

-However, we have to first figure out how to reduce the systematics!

Thank you!