Image credit: S.W. Angela Chen

JOHN TEMPLETON FOUNDATION

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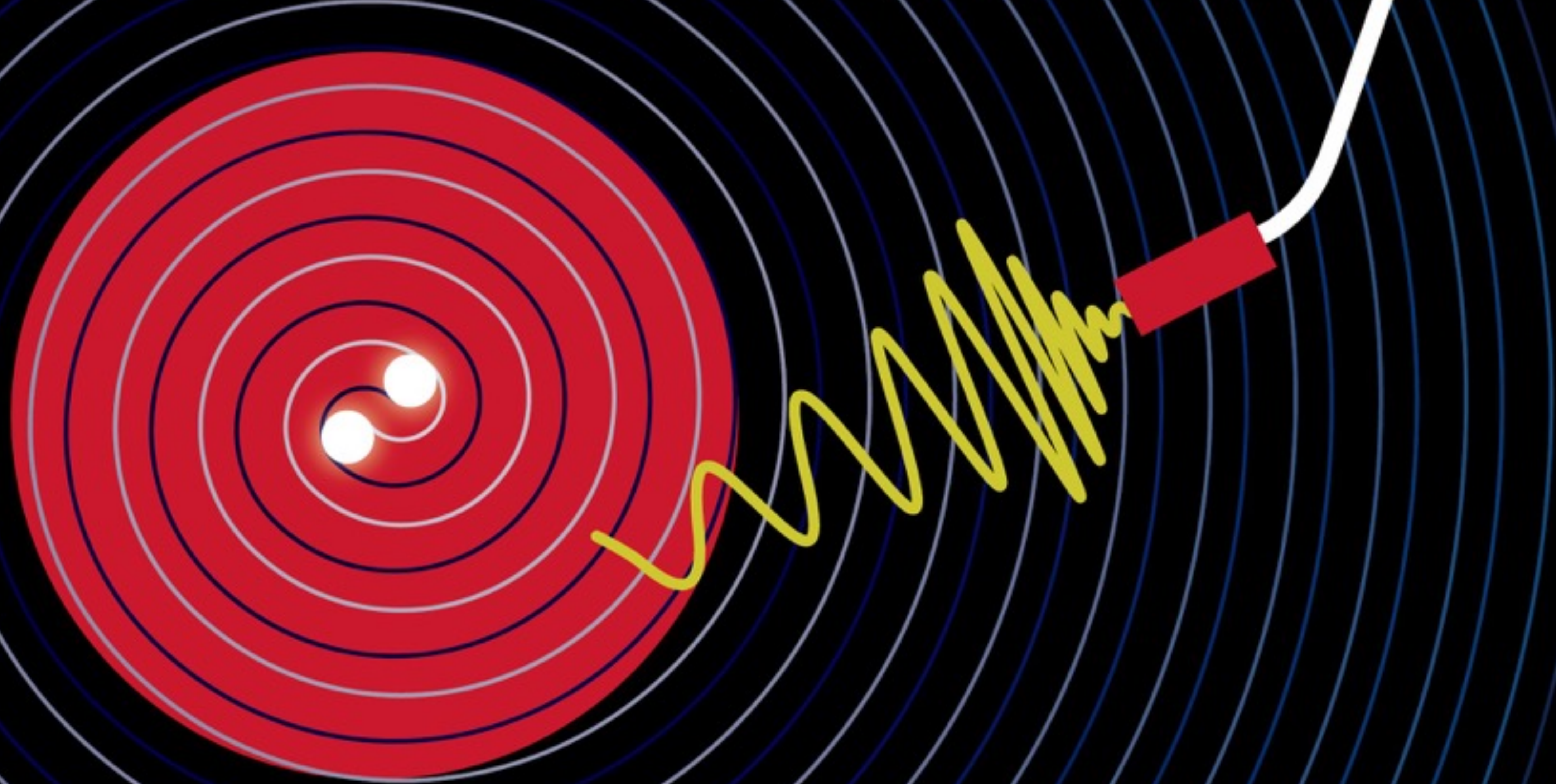
Listen to the Universe with gravitational-wave detections

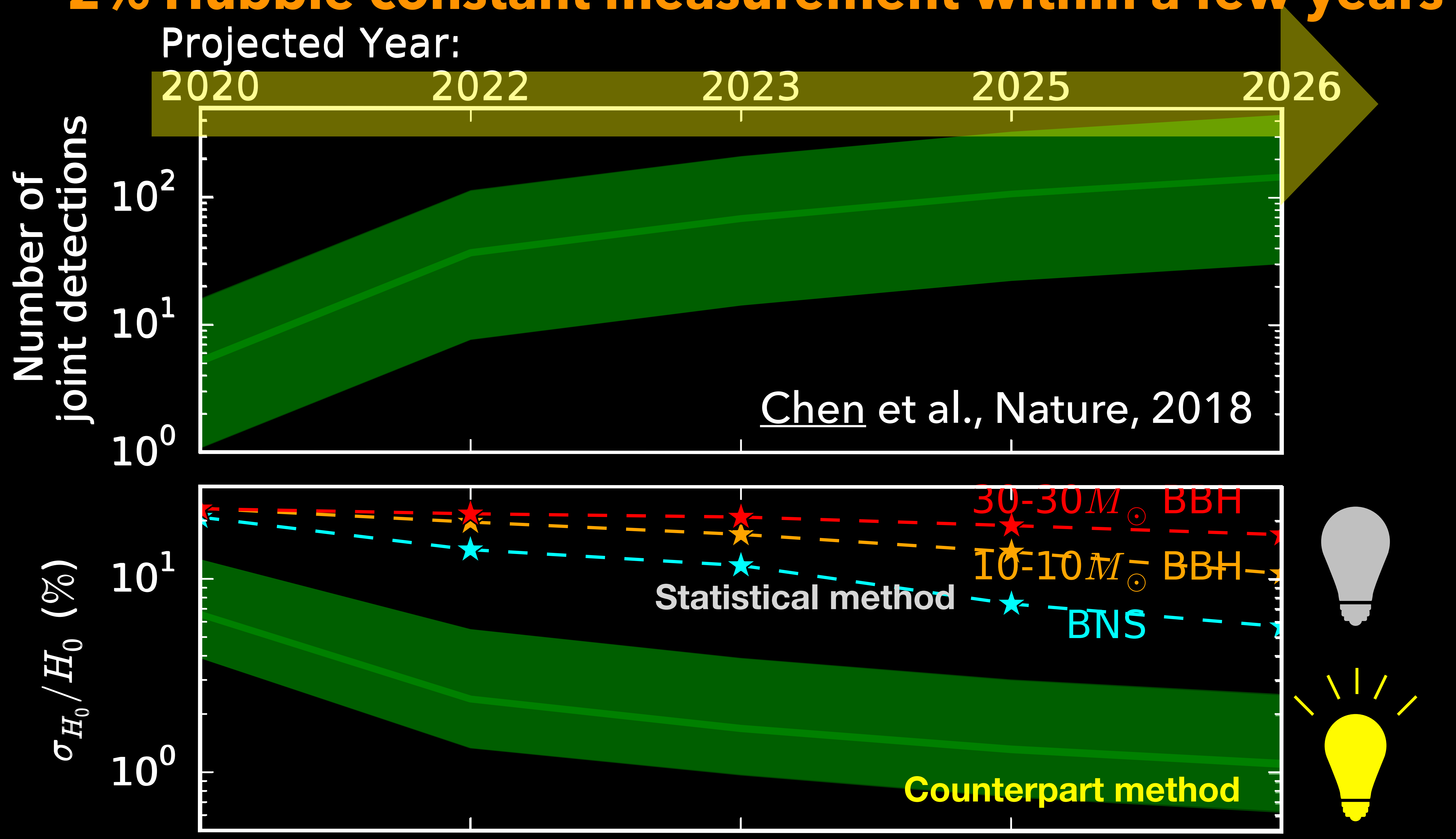


Hsin-Yu Chen

(Black Hole Initiative Fellow, Harvard University)

APCTP School on Gravitational-Wave Cosmology, Dec. 3 2019

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

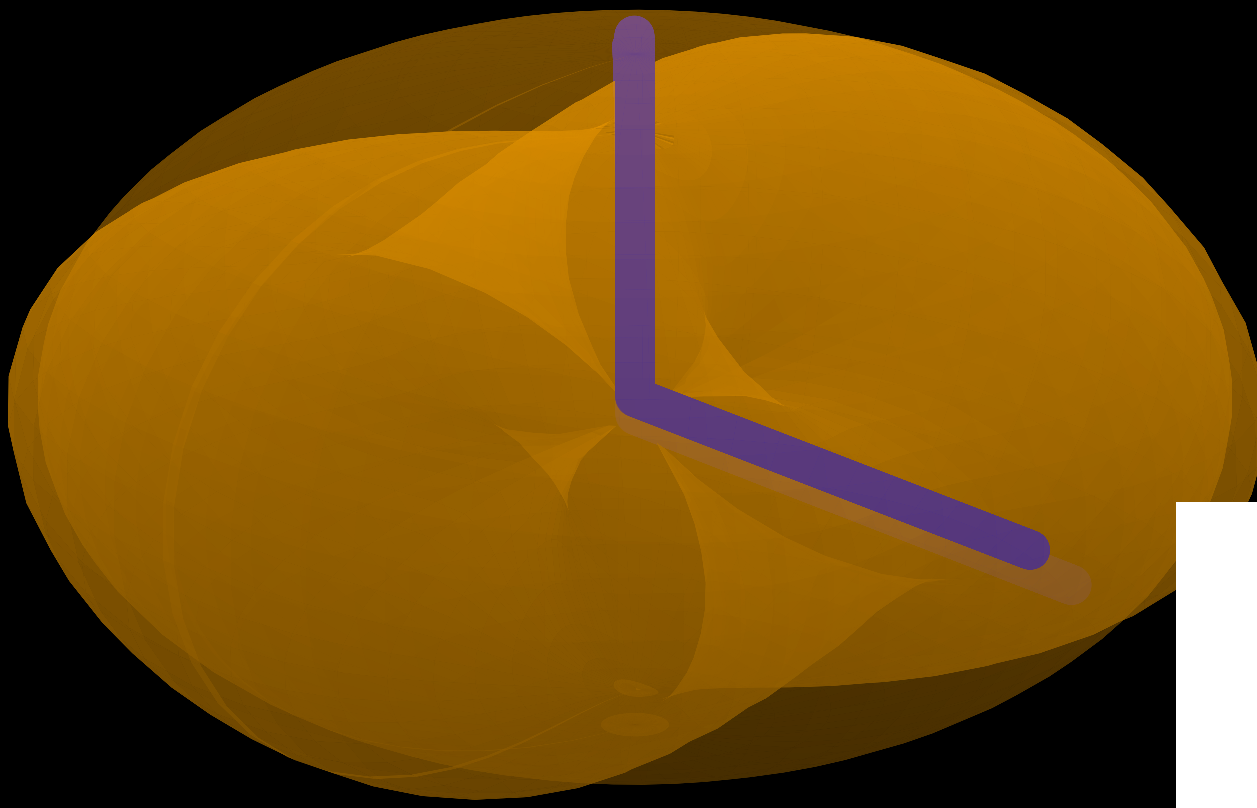
Gravitational-wave weather forecast

*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

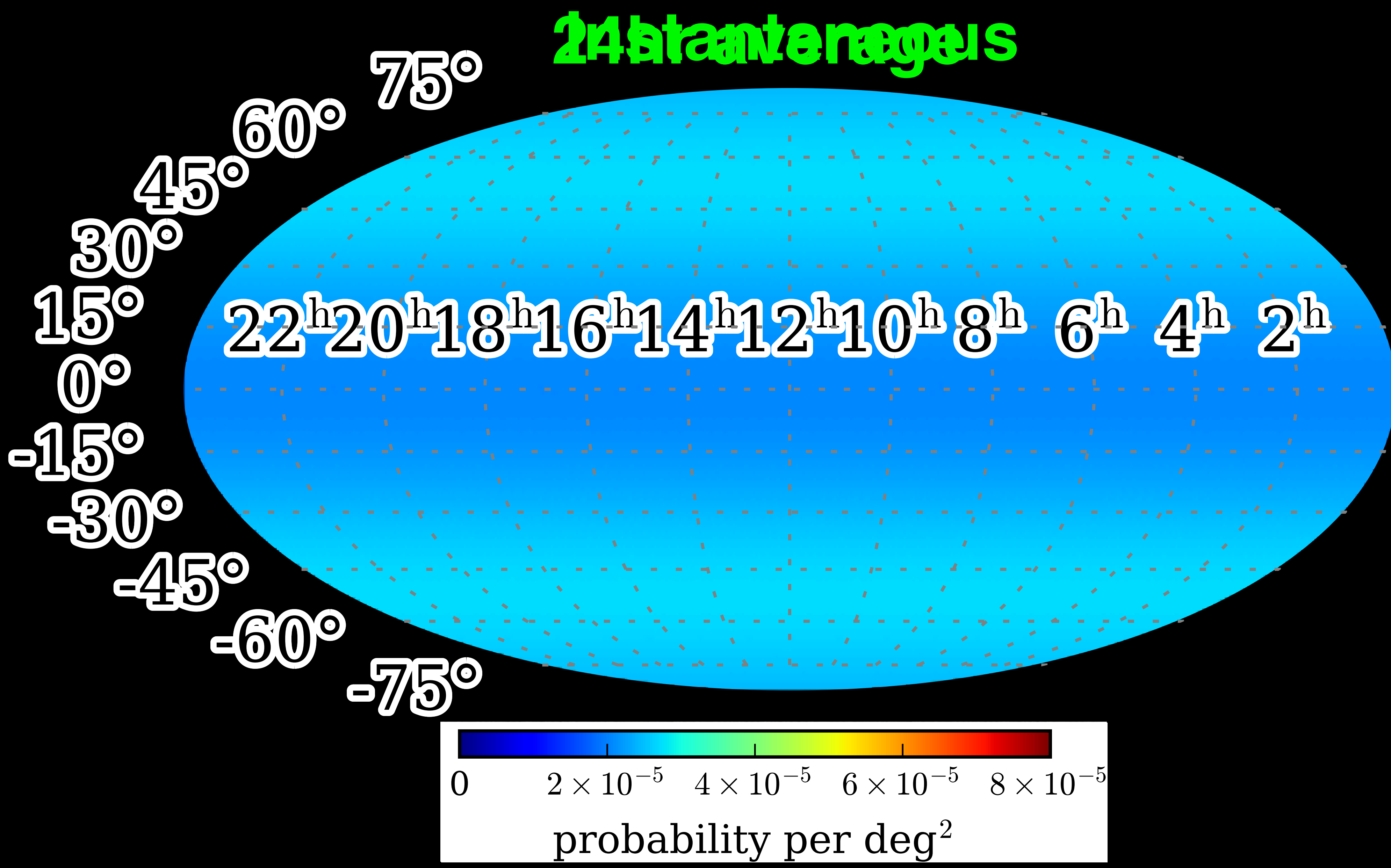
-Spatial selection effect: Antenna Patterns



Chen, Essick et al., ApJ, 2017

Gravitational-wave weather forecast

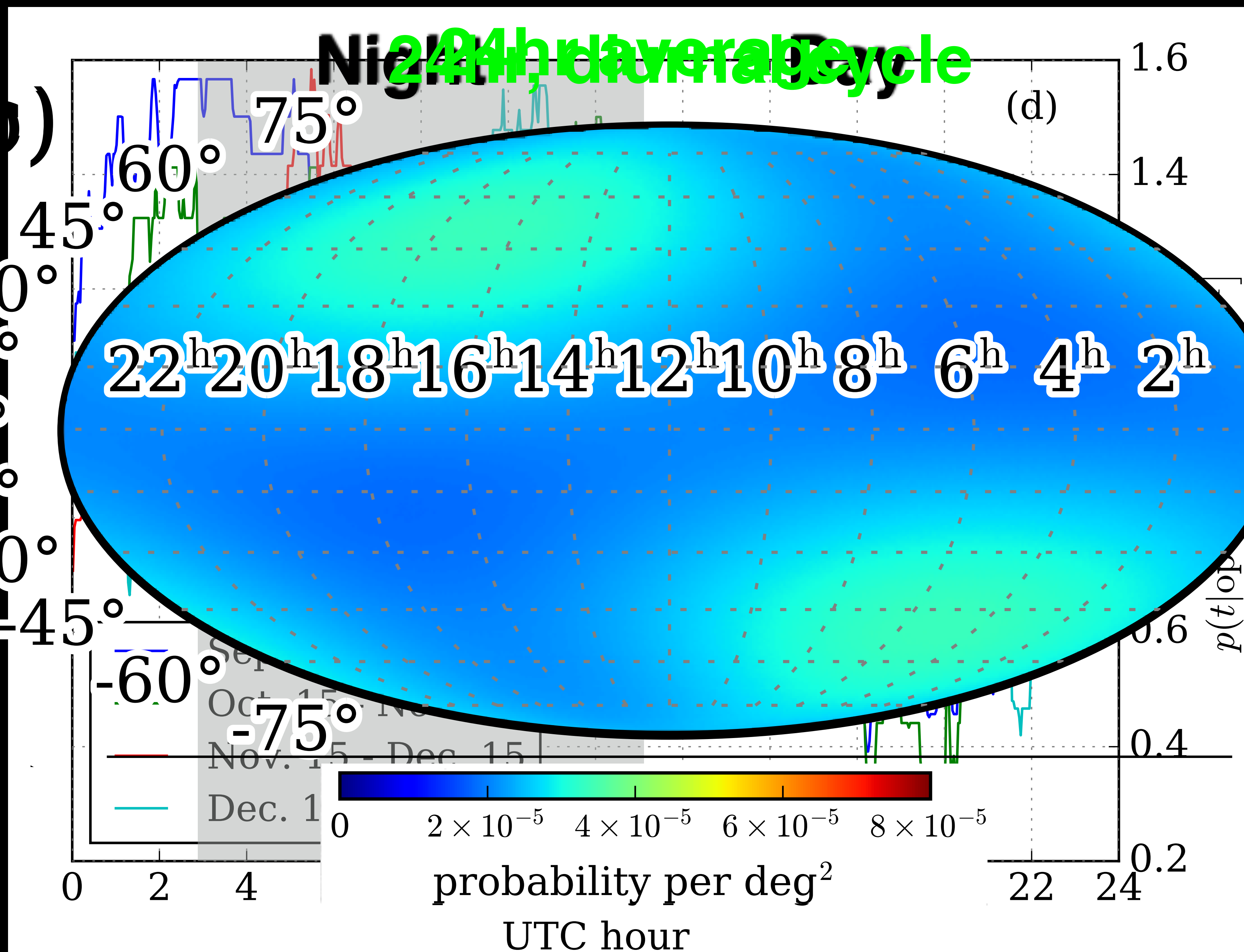
-Spatial selection effects: Antenna Patterns



Chen, Essick et al., ApJ, 2017

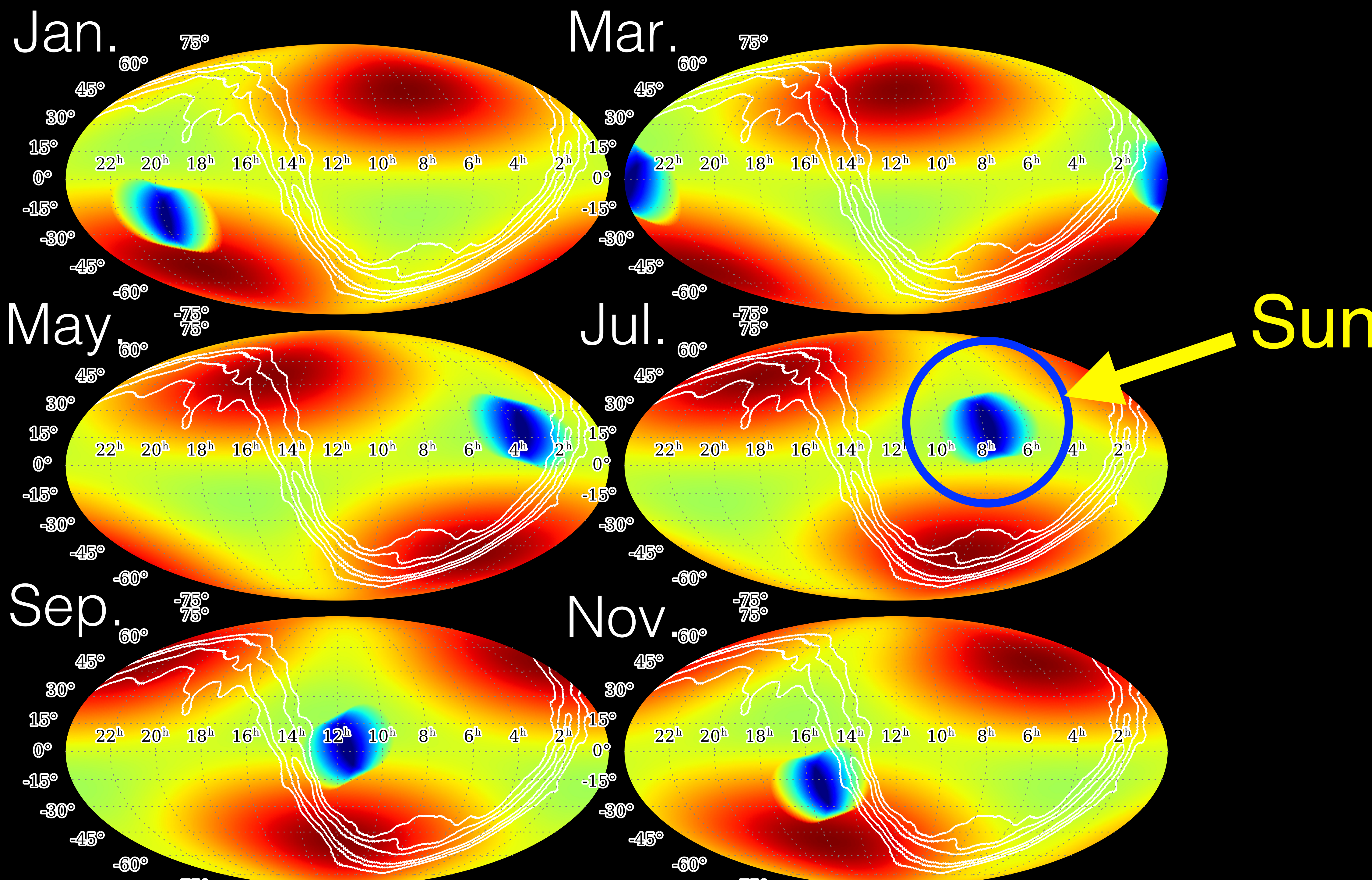
Gravitational-wave weather forecast

-Temporal selection effect: Diurnal cycle



Chen, Essick et al., ApJ, 2017

Gravitational-wave weather forecast



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

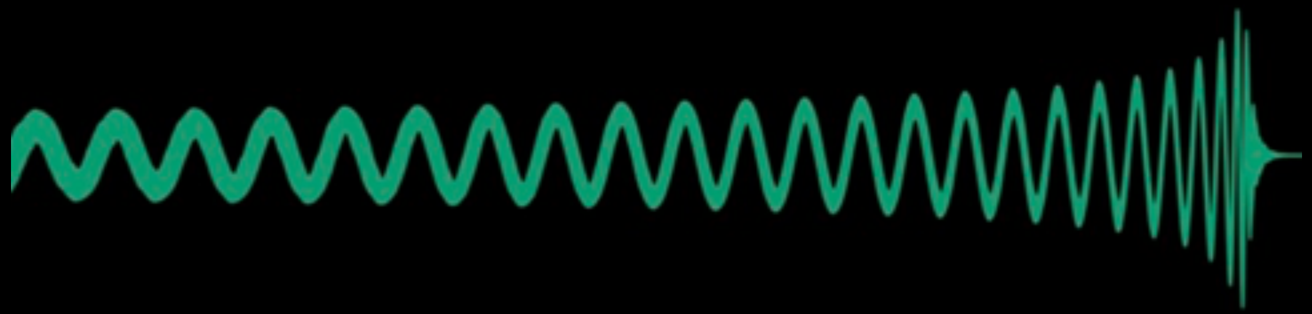
We still have only one binary neutron star with electromagnetic counterparts. Why?

Because we used up our luck in O1 and O2.

☹️

O3b is running!

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

Systematic uncertainties

- **Luminosity distance**:

  -Interferometer calibration uncertainty:

  3% in amplitude

  -Gravitational waveform:

  Currently negligible, but it could become a problem for future high signal-to-noise ratio events.

  -Binary viewing angle:

  Highly depends on the astrophysical models

Systematic uncertainties

- **Redshift**:

  -Host galaxy peculiar velocity:

  A few hundred km/s. Less significant for high redshift sources.

  -Host galaxy property:

  An assumption on the host galaxy property can help reducing the number of hosts, but it can also introduce bias.

  -Misidentification of electromagnetic counterpart

Gravitational-wave cosmology without standard sirens

-From the distribution of gravitational-wave detections.

GW170817 was an exceptional event

The probability distribution of gravitational-wave signal-to-noise ratio (SNR) has to follow a universal shape

-The u

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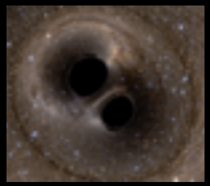
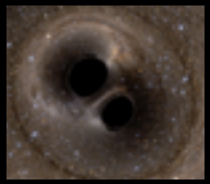
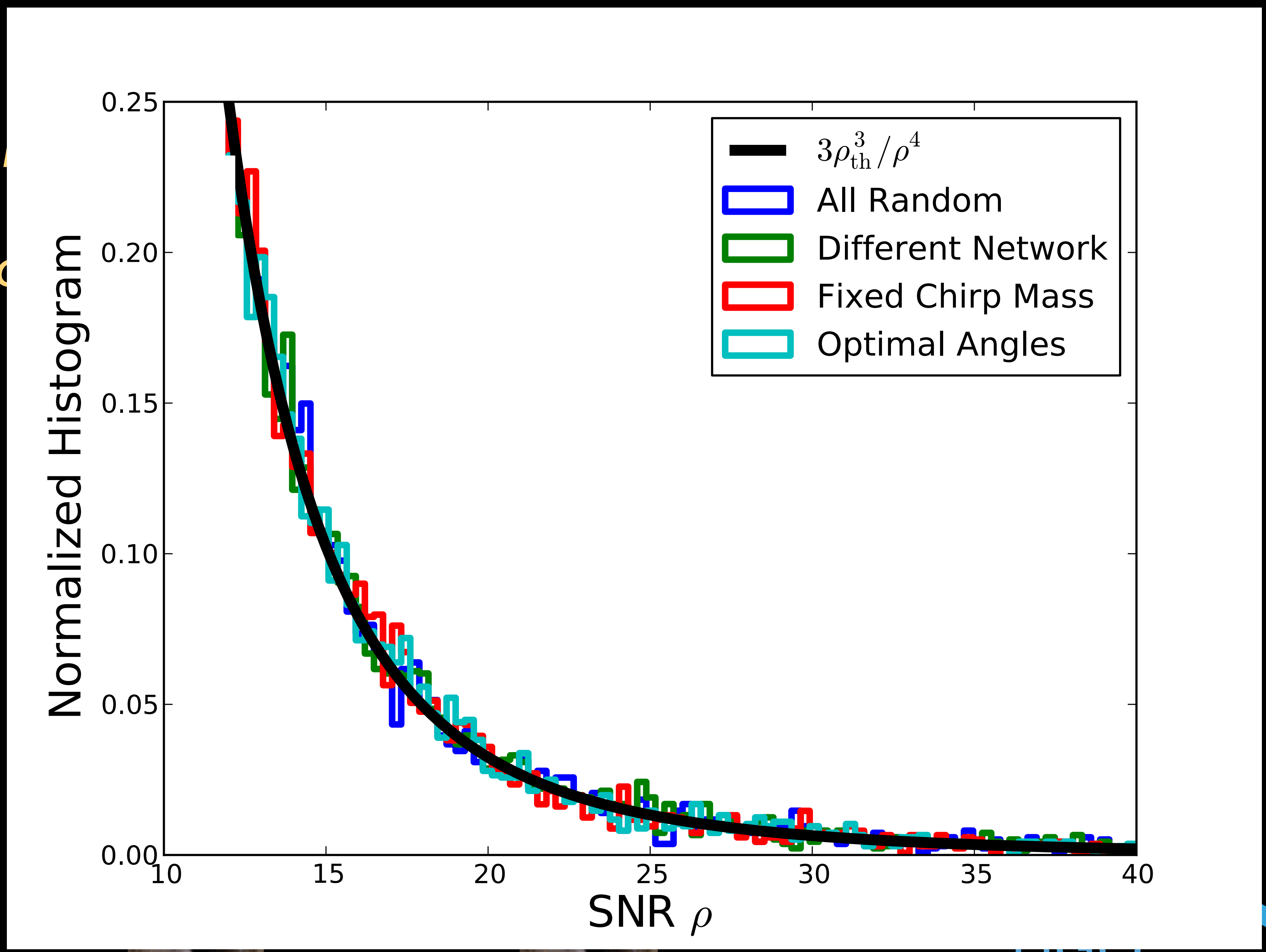






The probability distribution of gravitational-wave signal-to-noise ratio has to follow a universal shape

-If not? It possibly indicate

- *A violation of general relativity.*

Calabrese et al. 2016/Pardo et al. 2018

- *A defect in the detection process.*

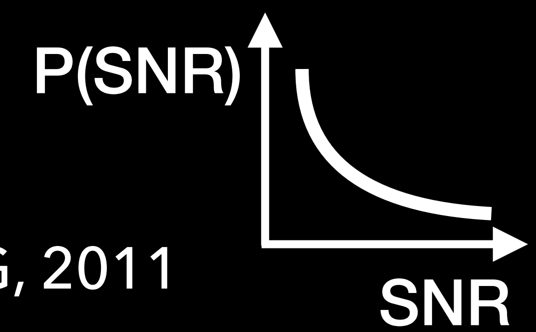
So far, no violation of the universal distribution has been found.

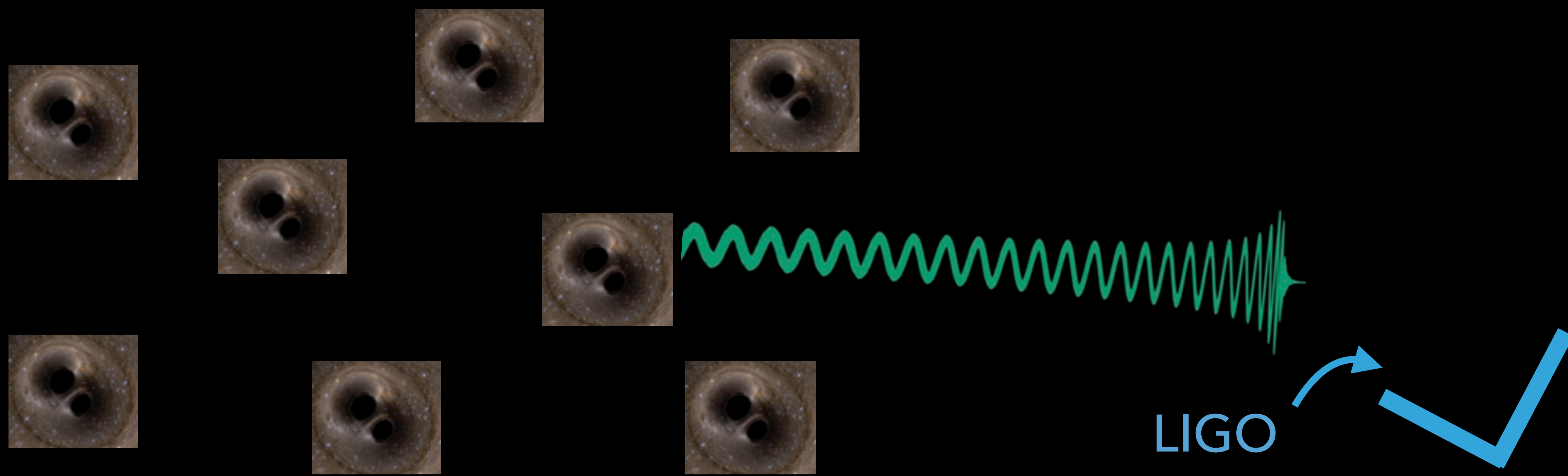
The probability distribution of gravitational-wave signal-to-noise ratio has to follow a <u>universal shape</u>

-The universal shape is

—A power-law: 2nd generation detectors

Schutz, CQG, 2011





The probability distribution of gravitational-wave signal-to-noise ratio has to follow a universal shape

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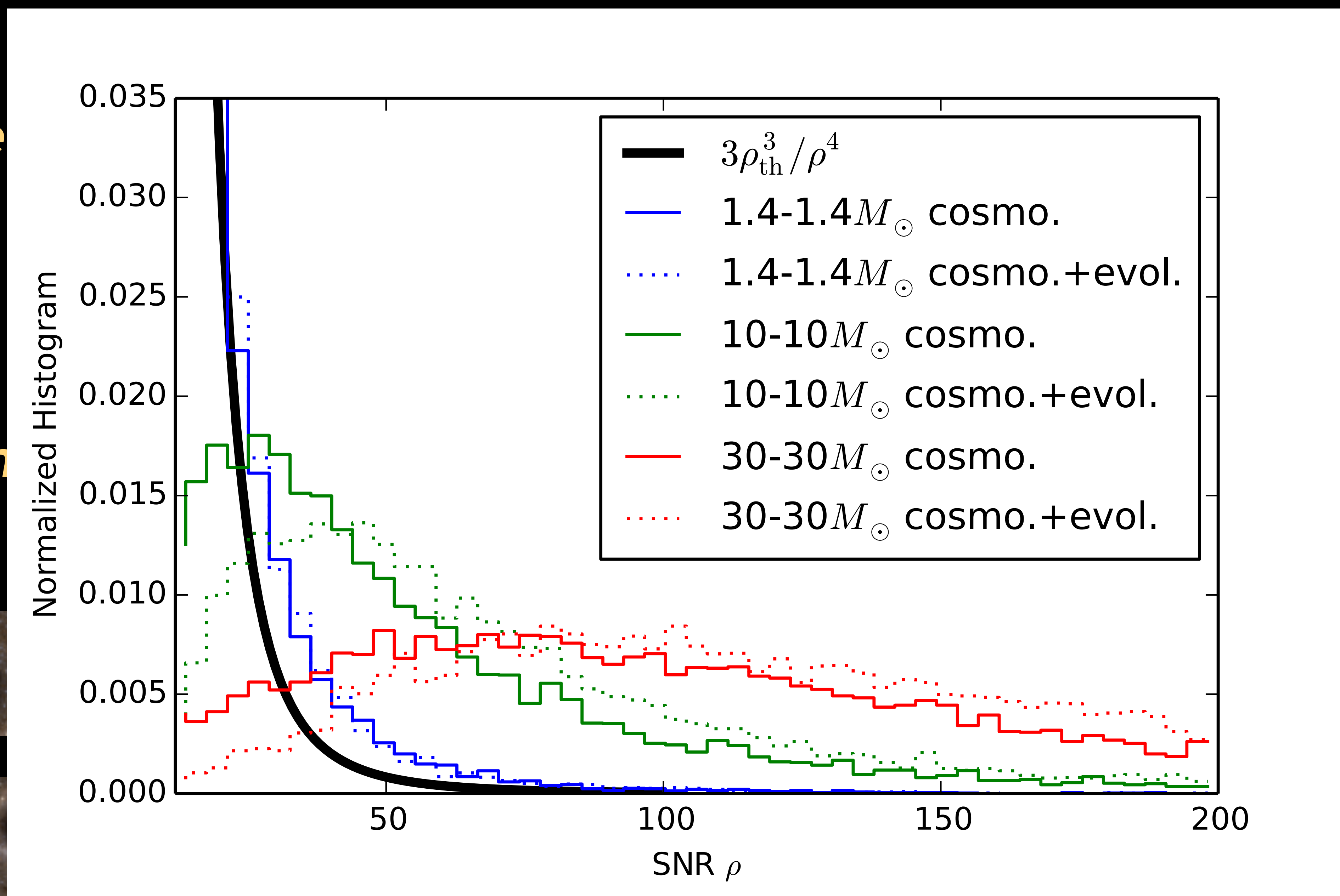
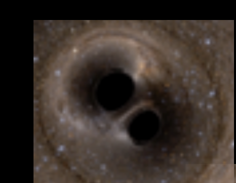
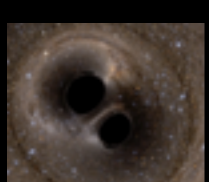
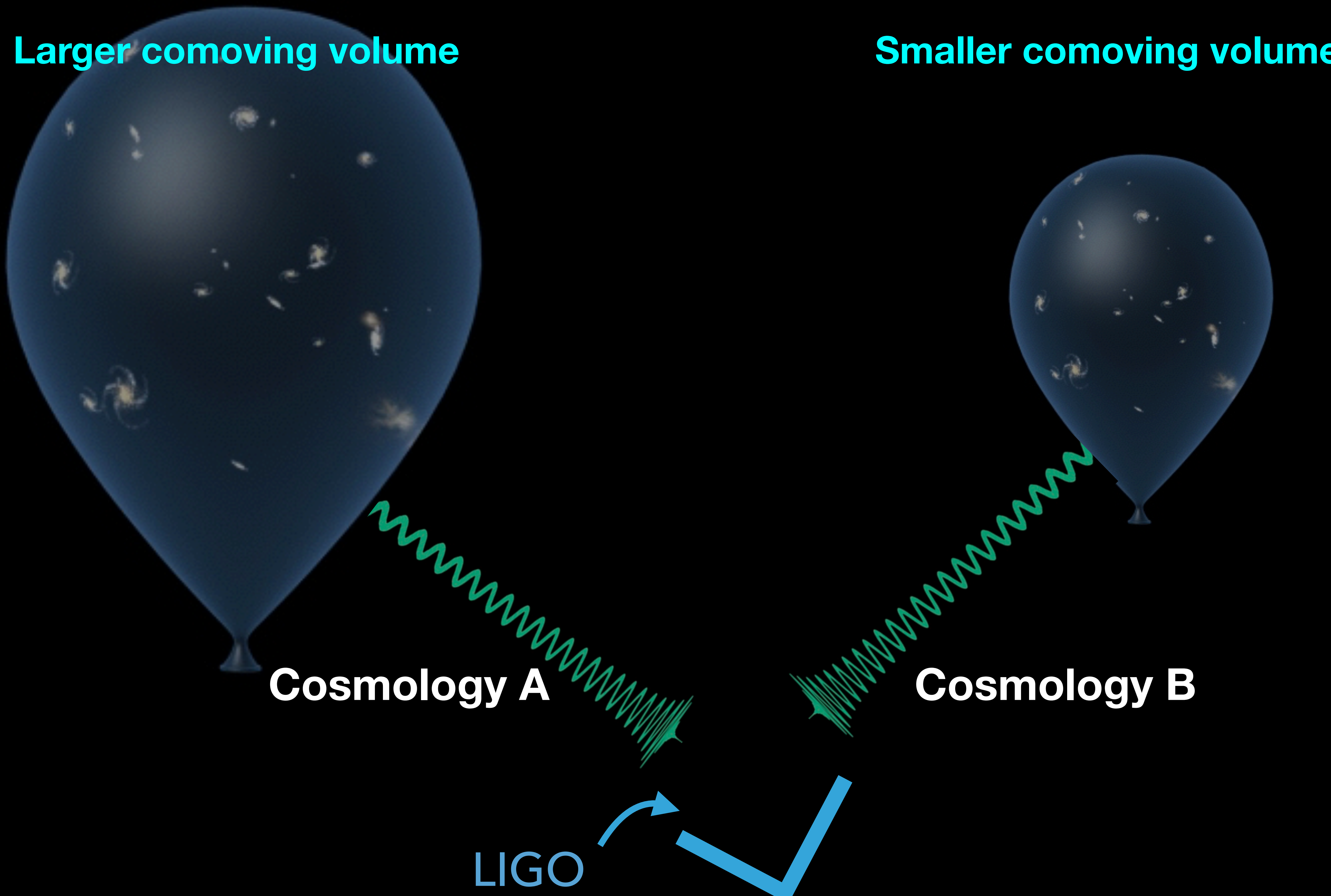






3G

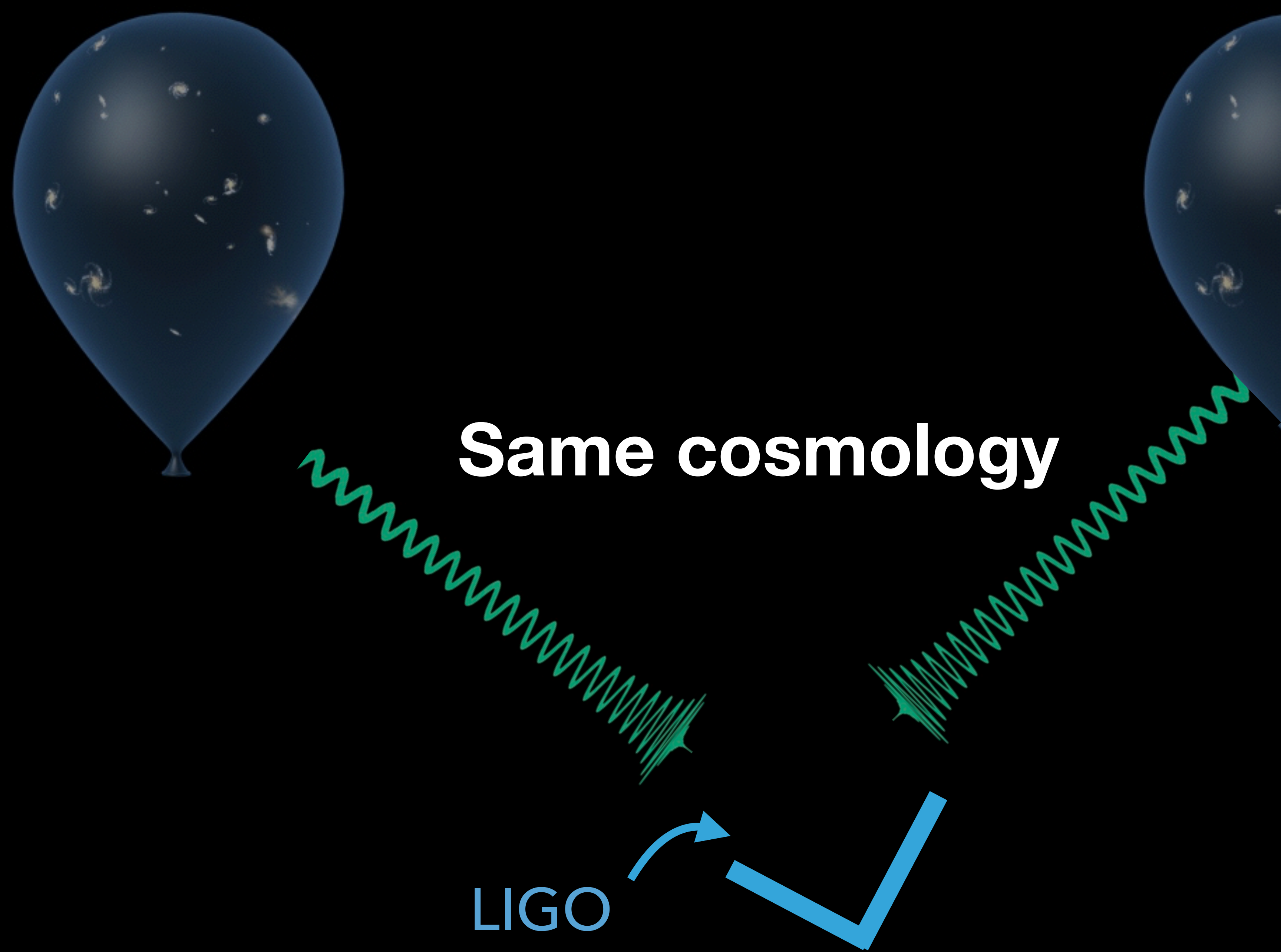
Measure H_0 without any redshift measurement



Chen & Holz, 2014

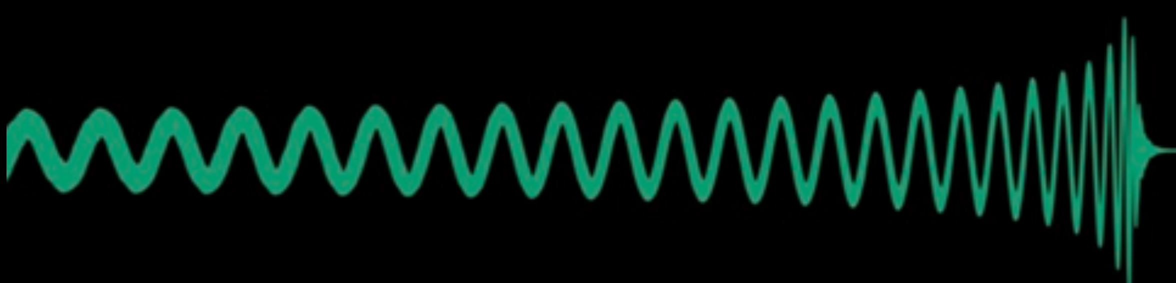
Measure H_0 without any redshift measurement

Same comoving volume | **Same comoving volume**
Higher astrophysical rate | **Lower astrophysical rate**

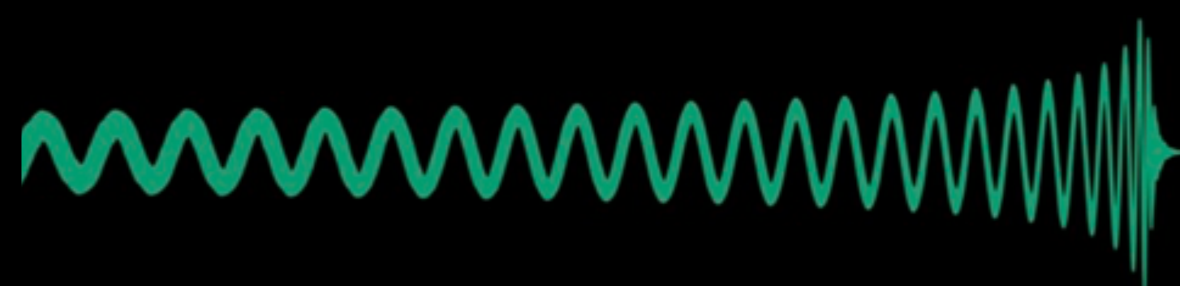


Chen & Holz, 2014

Determine the redshift of gravitational-wave source with the source frame mass



$(1+z_1)M_1$



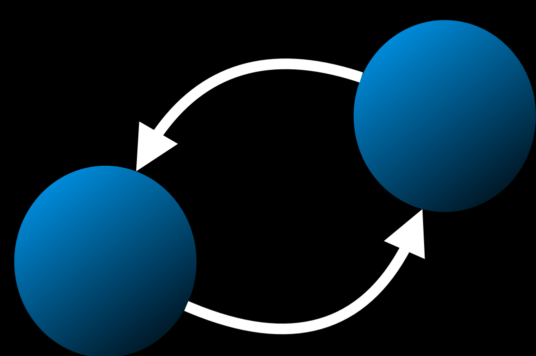
$(1+z_2)M_2$

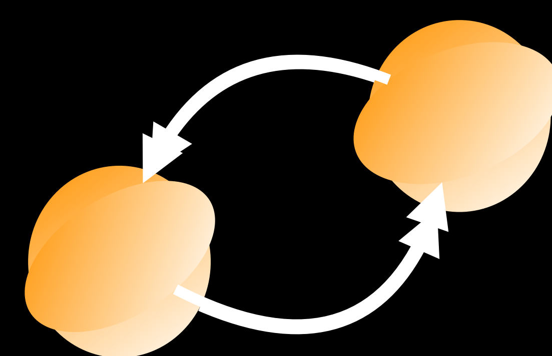
Identical signal

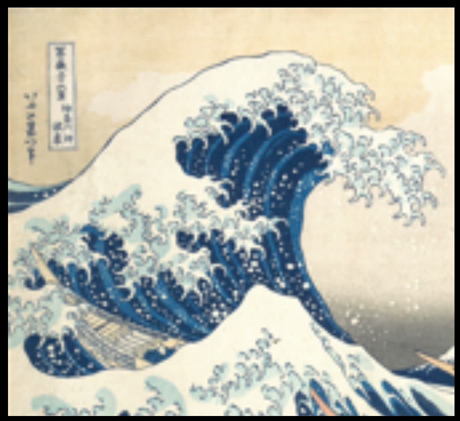
Gravitational-wave cosmology without standard sirens

-From the tidal effects of neutron star binaries

Tidal deformation of neutron stars



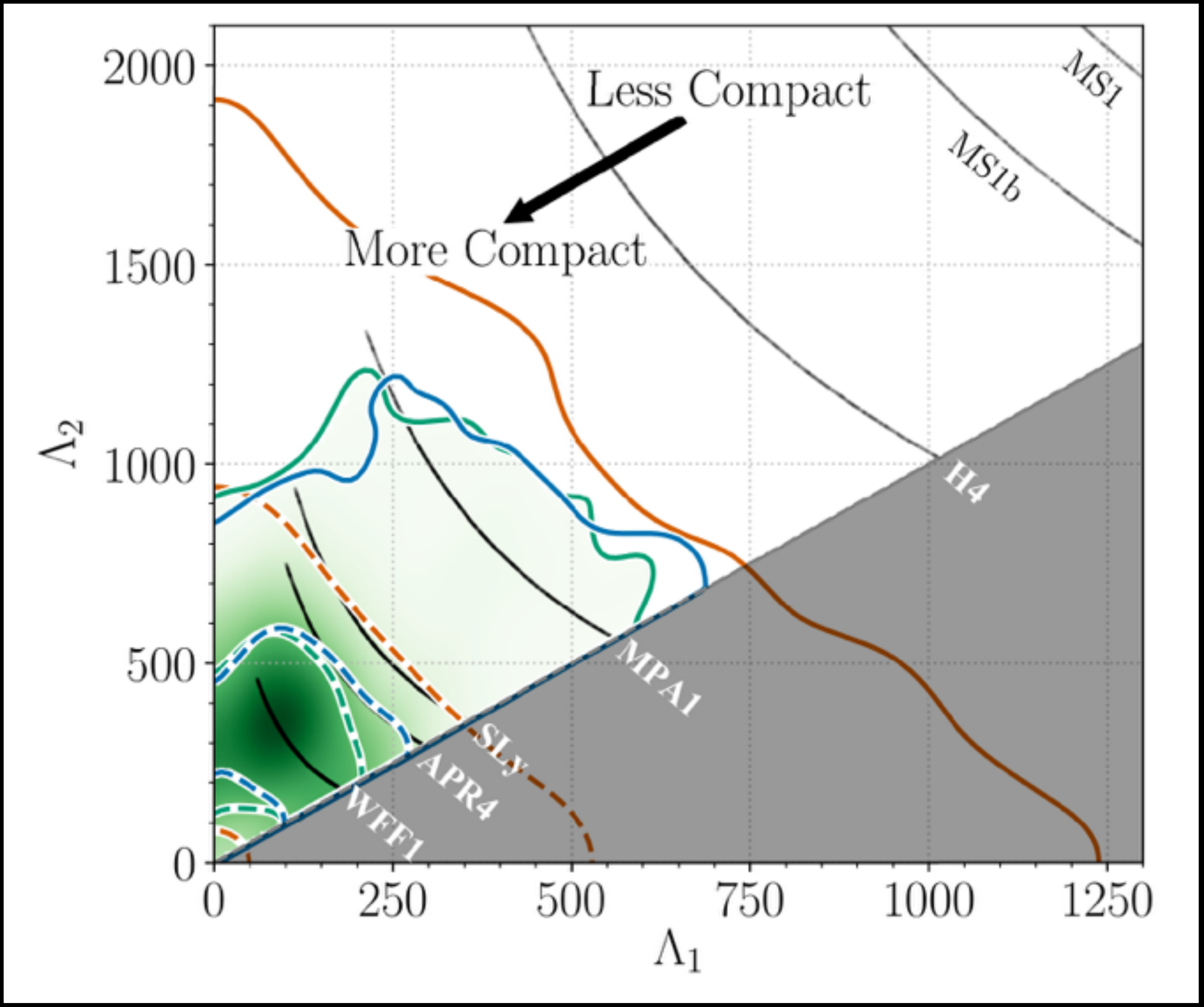




-Neutron star equation-of-state.

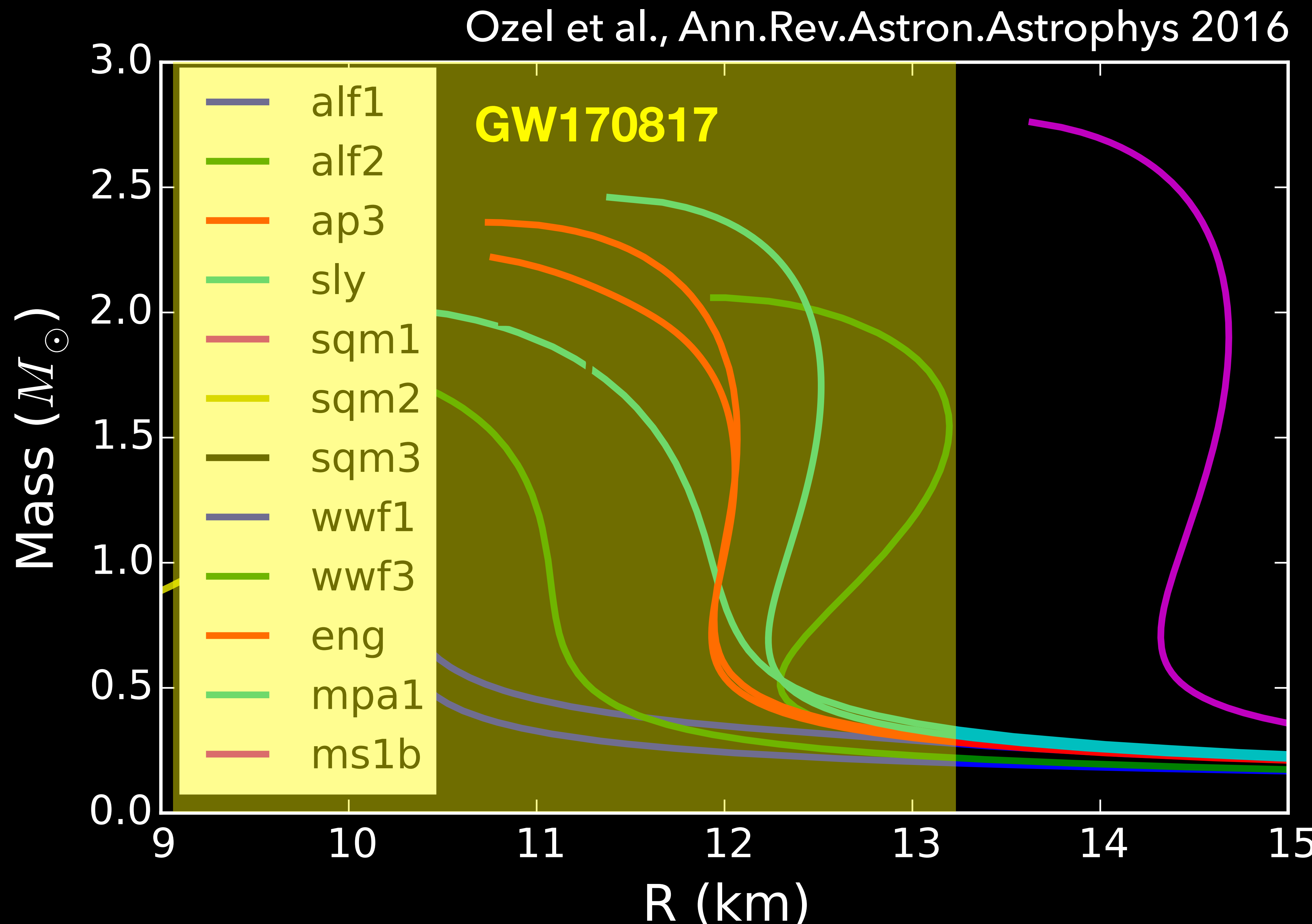
GW170817 Equation-of-state
(Abbott et al., PRX 2019)

Tidal deformability of GW170817



Abbott et al., PRX 2019

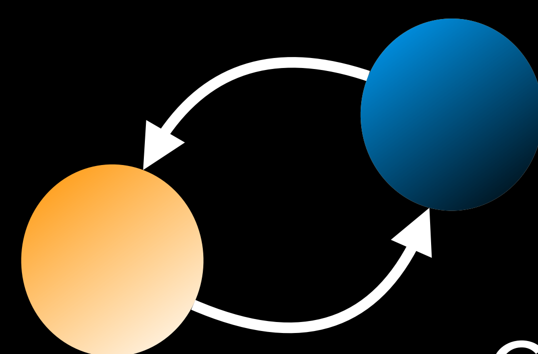
Neutron star mass-radius relation



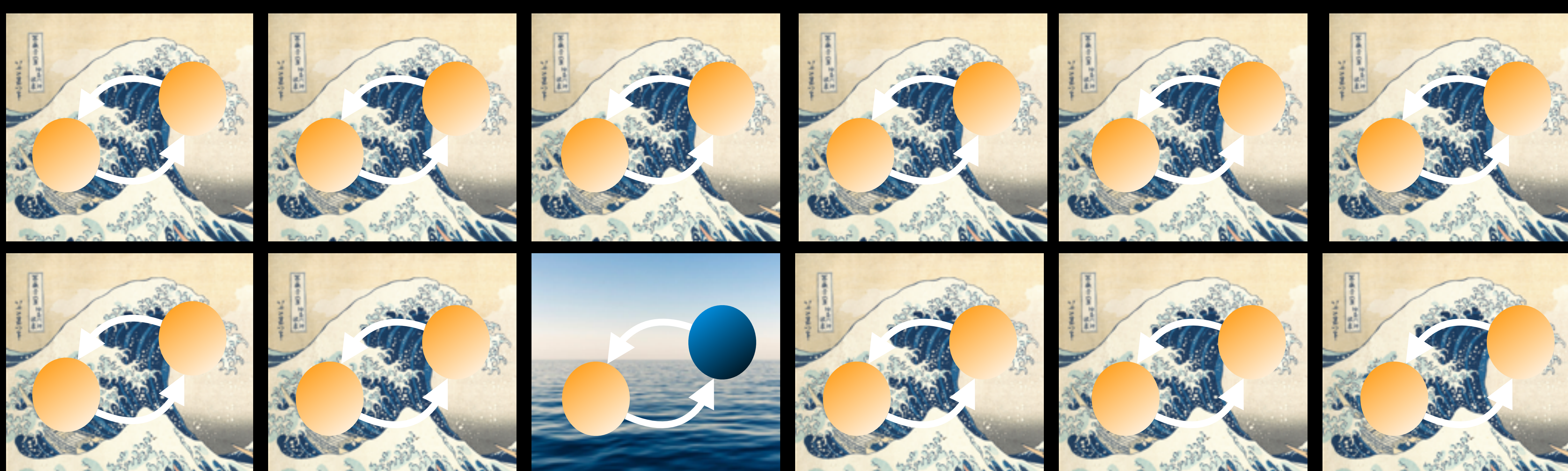
Abbott et al., PRX 2019

Were they really binary neutron stars?
Could they be…

A) Neutron star-black hole mergers



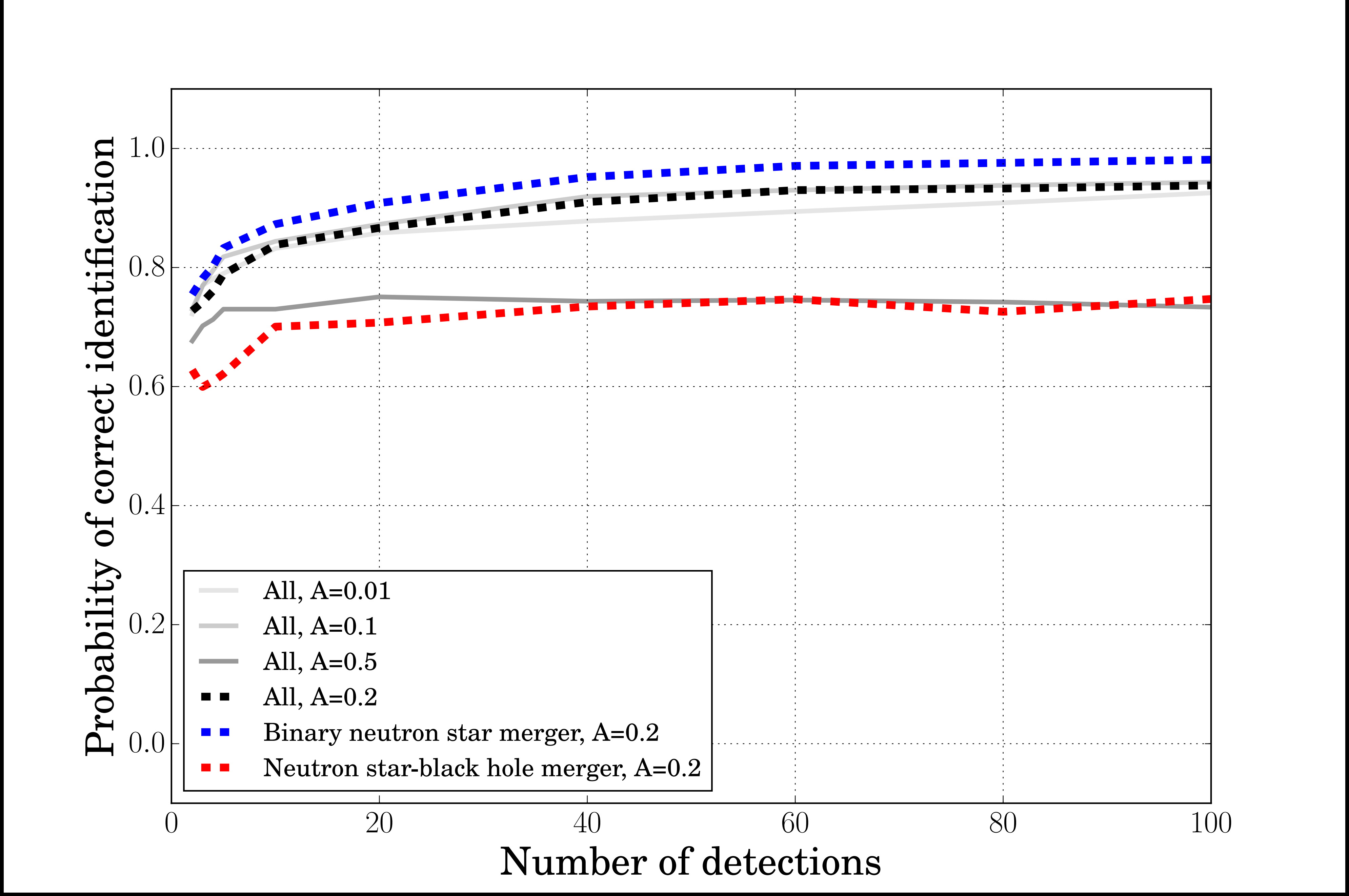
Chen & Chatziioannou, 2019



Were they really binary neutron stars? Could they be…

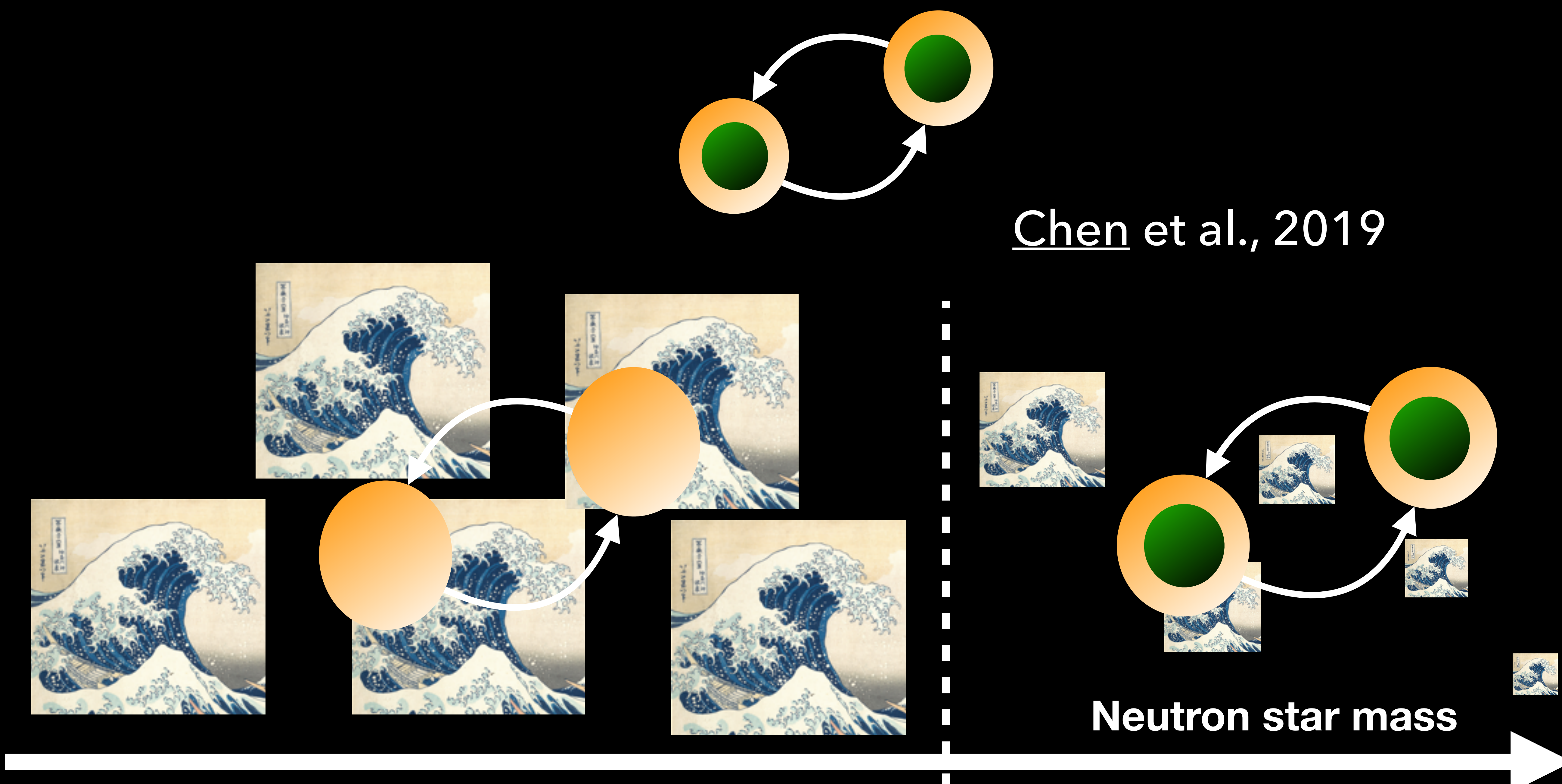
Chen & Chatziioannou, 2019

A) Neutron star-black hole mergers



Were they really binary neutron stars?
Could they be…

B) Hybrid star mergers (Quark matter core)

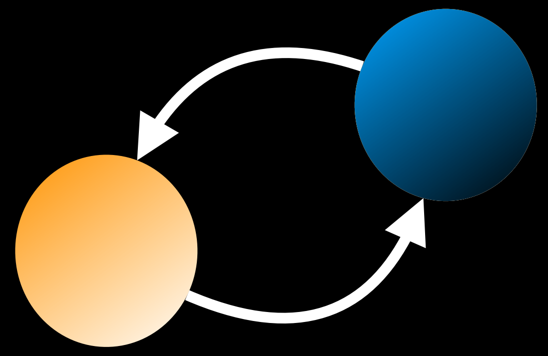


Chen et al., 2019

Were they really binary neutron stars?
Could they be…

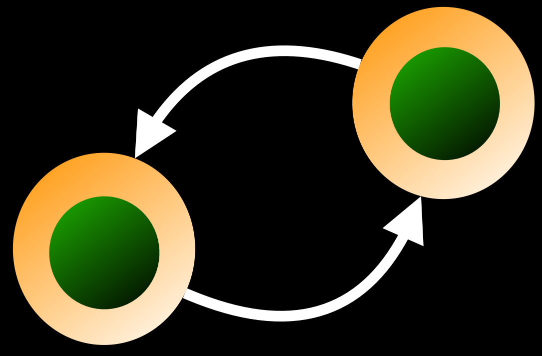
A) Neutron star-black hole mergers

Chen & Chatziioannou, 2019



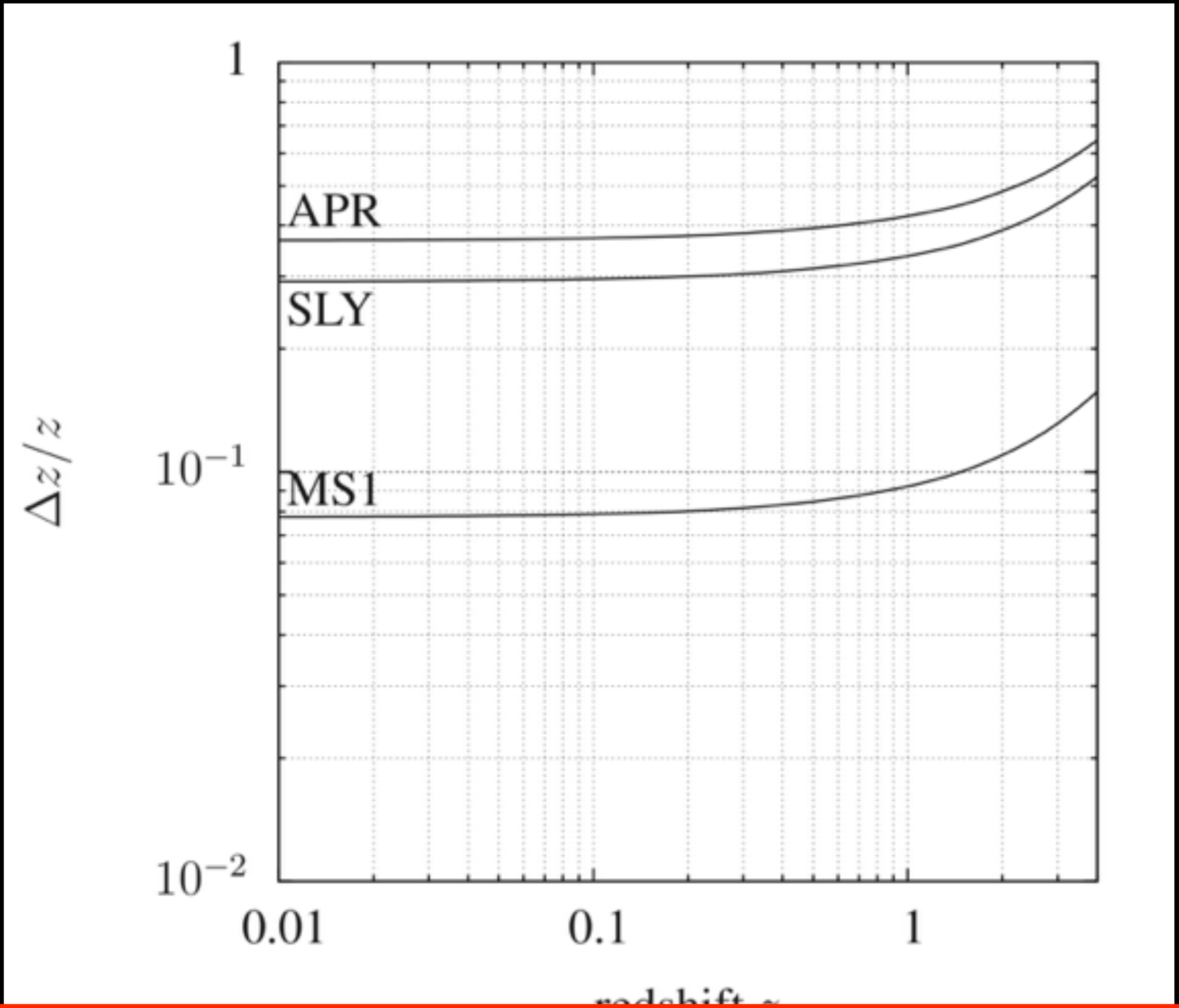
B) Hybrid star mergers
(Quark matter core)

Chen et al., 2019



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

Constrain neutron star mass from the observation of tidal effects



The sensitivities of the 3rd generation detectors will allow for better than 40% determination of redshift without electromagnetic observations.

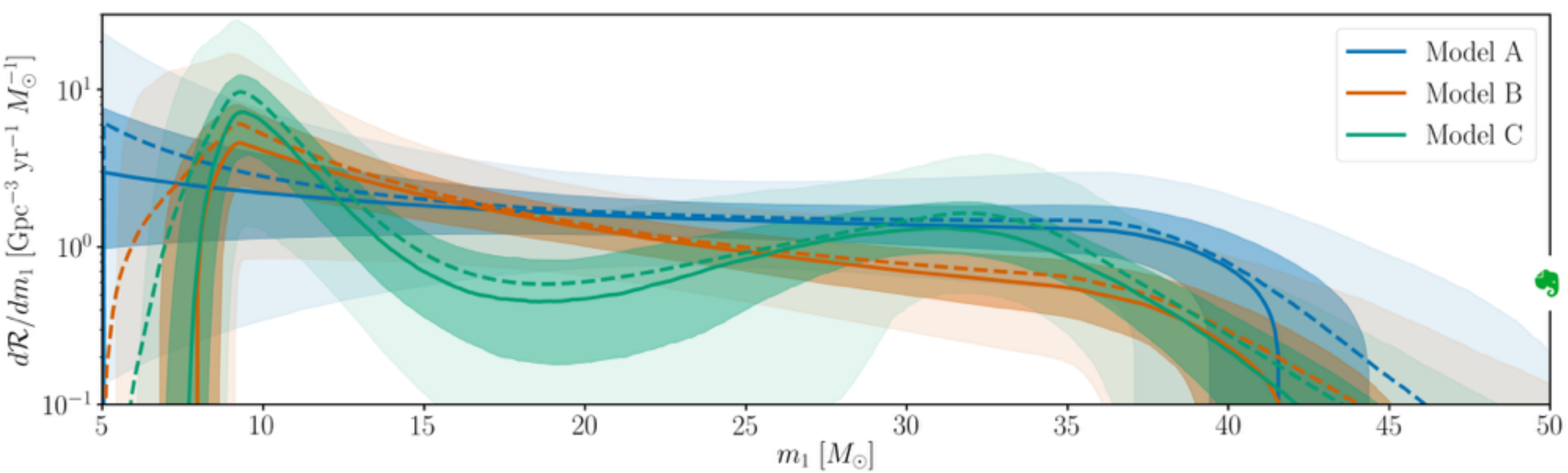
Messenger & Read, 2011

Gravitational-wave cosmology without standard sirens

-From the mass distribution of binaries.

Taylor et al., 2012

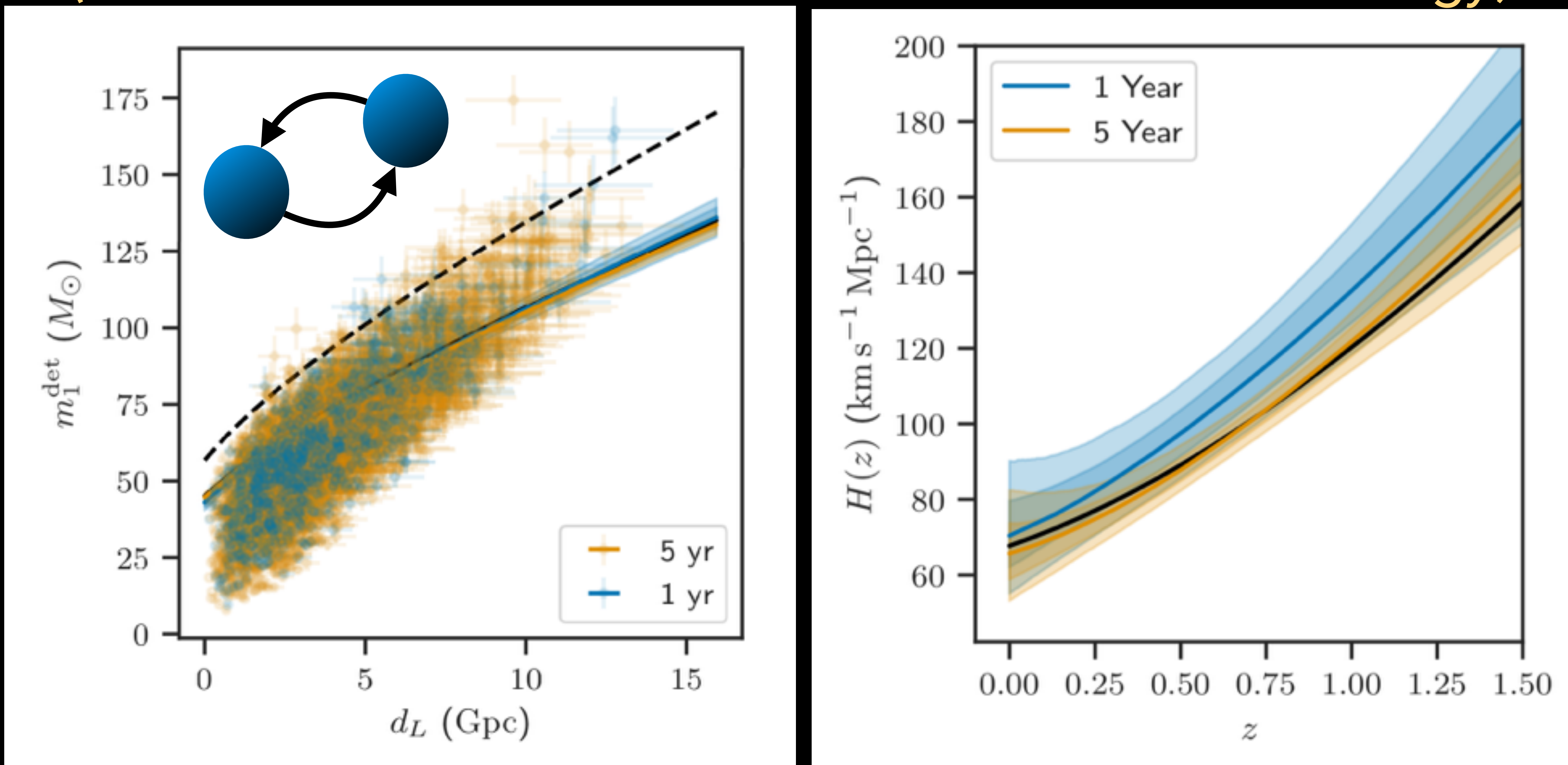
Stellar pair instability that destroys black hole above ~65 $M_\odot$



Abbott et al., 2019

Jointly fit the black hole mass distribution and the cosmological parameters

(Mass and redshift distribution+ PISN cutoff + cosmology)



After one year of LIGO observation H(z) can be constrained to 6% at z=0.8.

Farr et al., 2019

Caution

- 70 $M_\odot$ black hole has been found recently.

  Liu et al., arXiv: 1911.11989

- There are several different proposals on how to make black holes in the upper mass gap.

- It is unclear whether the upper mass gap will stay or not $\Longrightarrow$ gravitational-wave observations can help.

Summary

-There are other possibilities to estimate cosmological parameters with gravitational-wave observations.

-Different methods allow for cross-check of systematics.