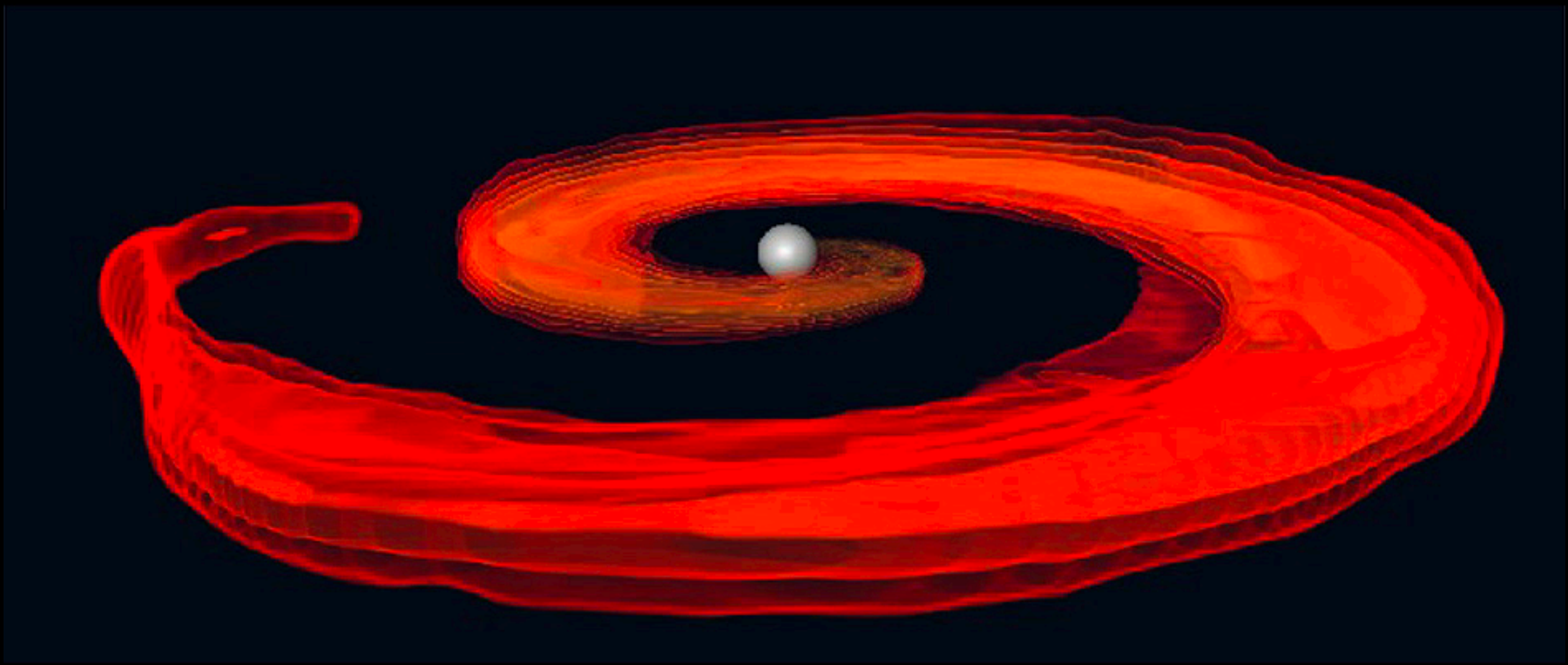
Image credit: A. Tonita, L. Rezzolla, F. Pannarale



Gravitational-wave Multi-messenger Astronomy Results

Hsin-Yu Chen (Black Hole Initiative Fellow, Harvard University)

October IPA 2018

Laser Interferometer Gravitational-wave Observatory

-Twin 4-km interferometers at Livingston and Hanford

-Most sensitive to O(10)-O(1000) Hz, correspond to stellar mass objects, e.g. stellar mass binary mergers, supernova.

-Currently finished the first (O1) and second (O2) observing runs and are undergoing upgrade. LIGO plan to resume observation at the beginning of next year.

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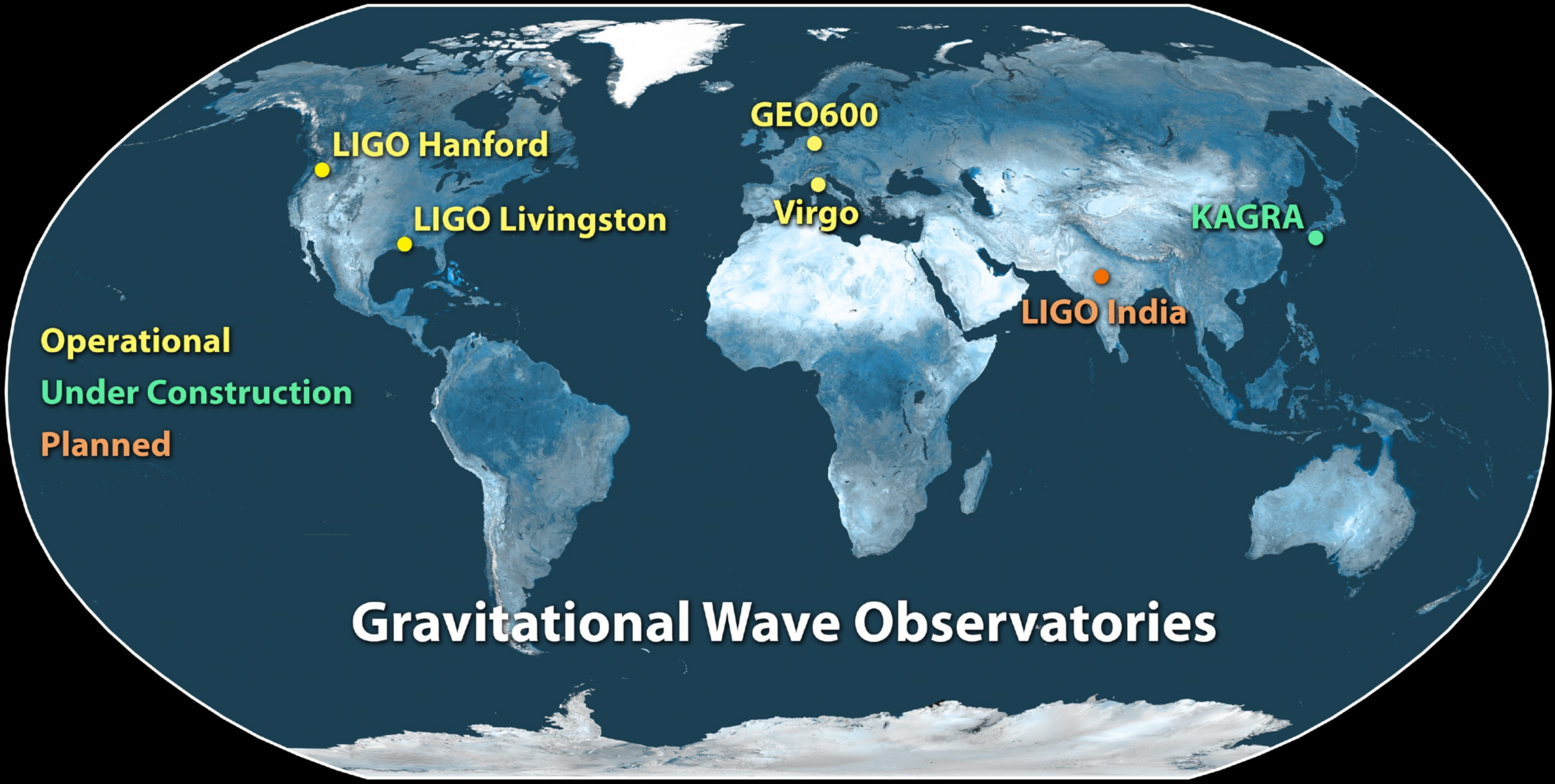
Gravitational-Wave Observatories Across the Globe



Possible gravitational-wave sources detectable by LIGO

-***Stellar mass compact binary mergers***

- *Binary black hole mergers*
- *Binary neutron star mergers*
- *Neutron star-black hole mergers*

-***Supernova***

-***Continuous waves****: compact binary, rotating star*

-***Stochastic background****: superposition of unresolved binaries*

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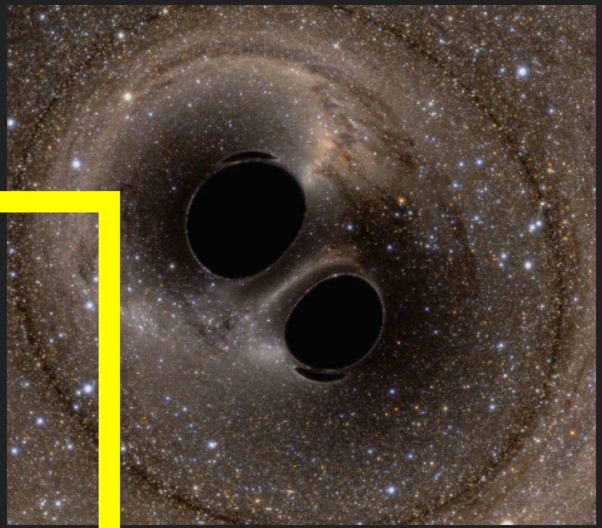

-***Stellar mass compact binary mergers***

- ✓ *Binary black hole mergers*
- ✓ *Binary neutron star mergers*
- *Neutron star-black hole mergers*

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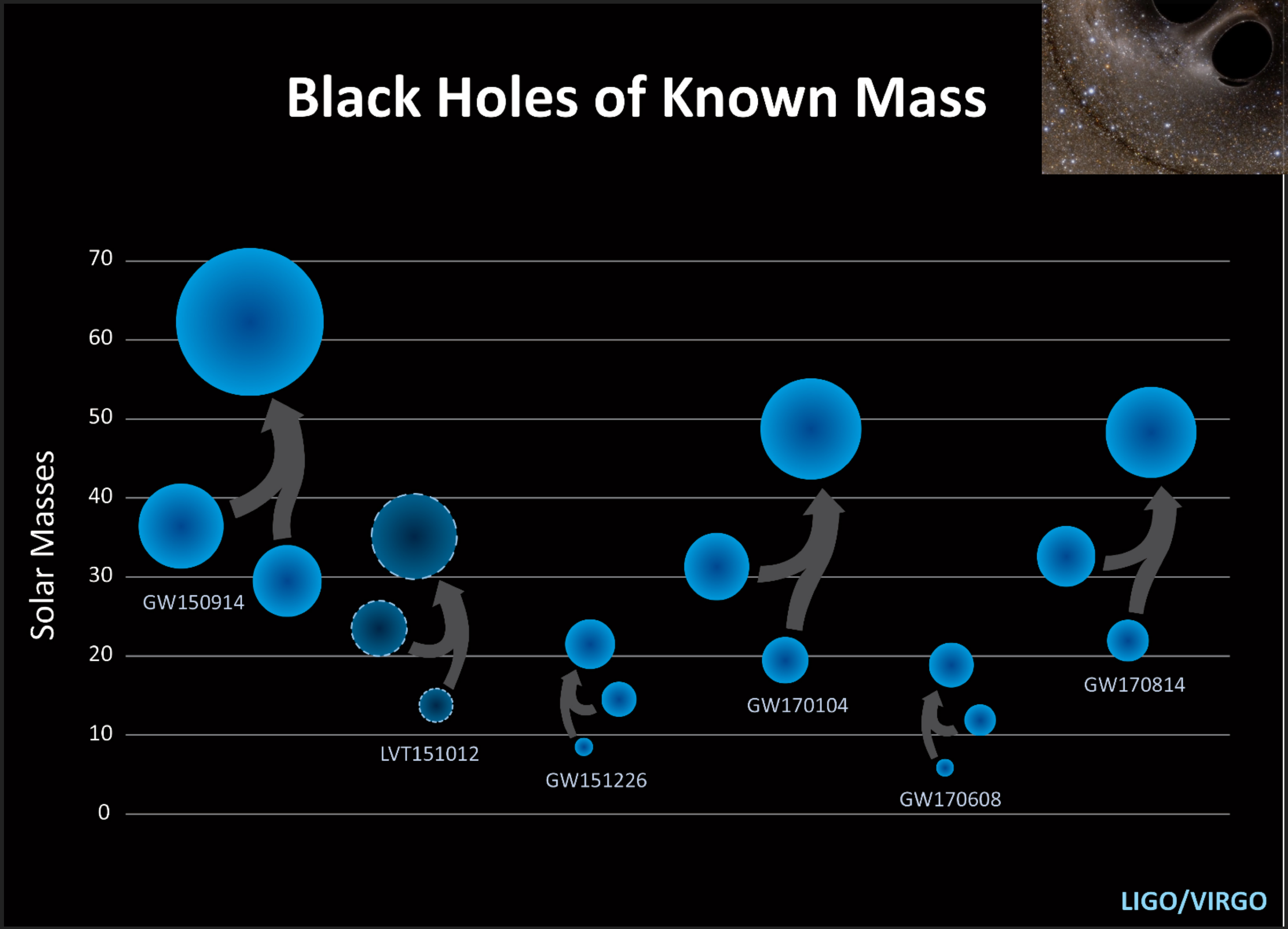
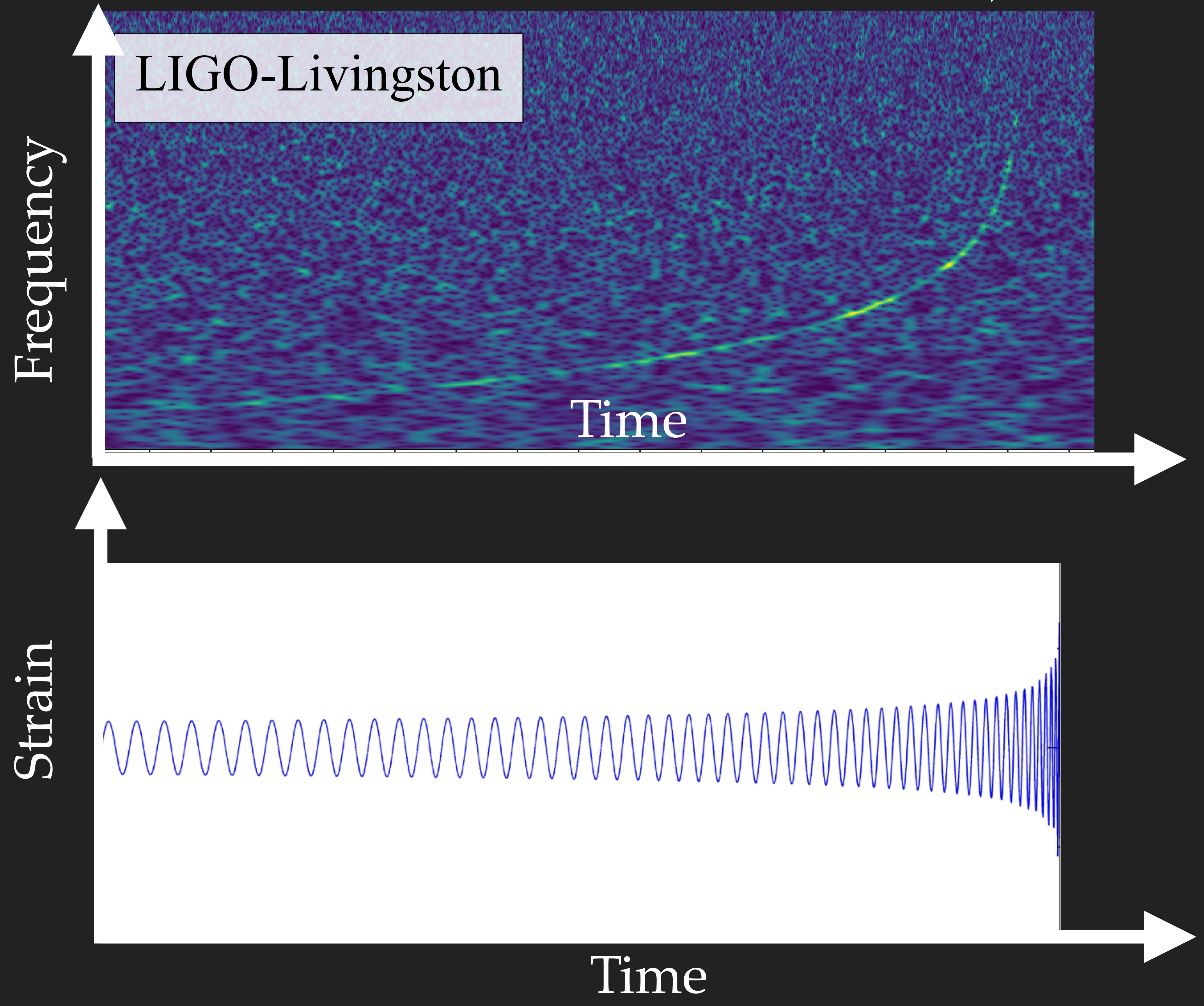
✓ *Binary black hole mergers*



No solid electromagnetic counterpart was found for any binary black hole merger.

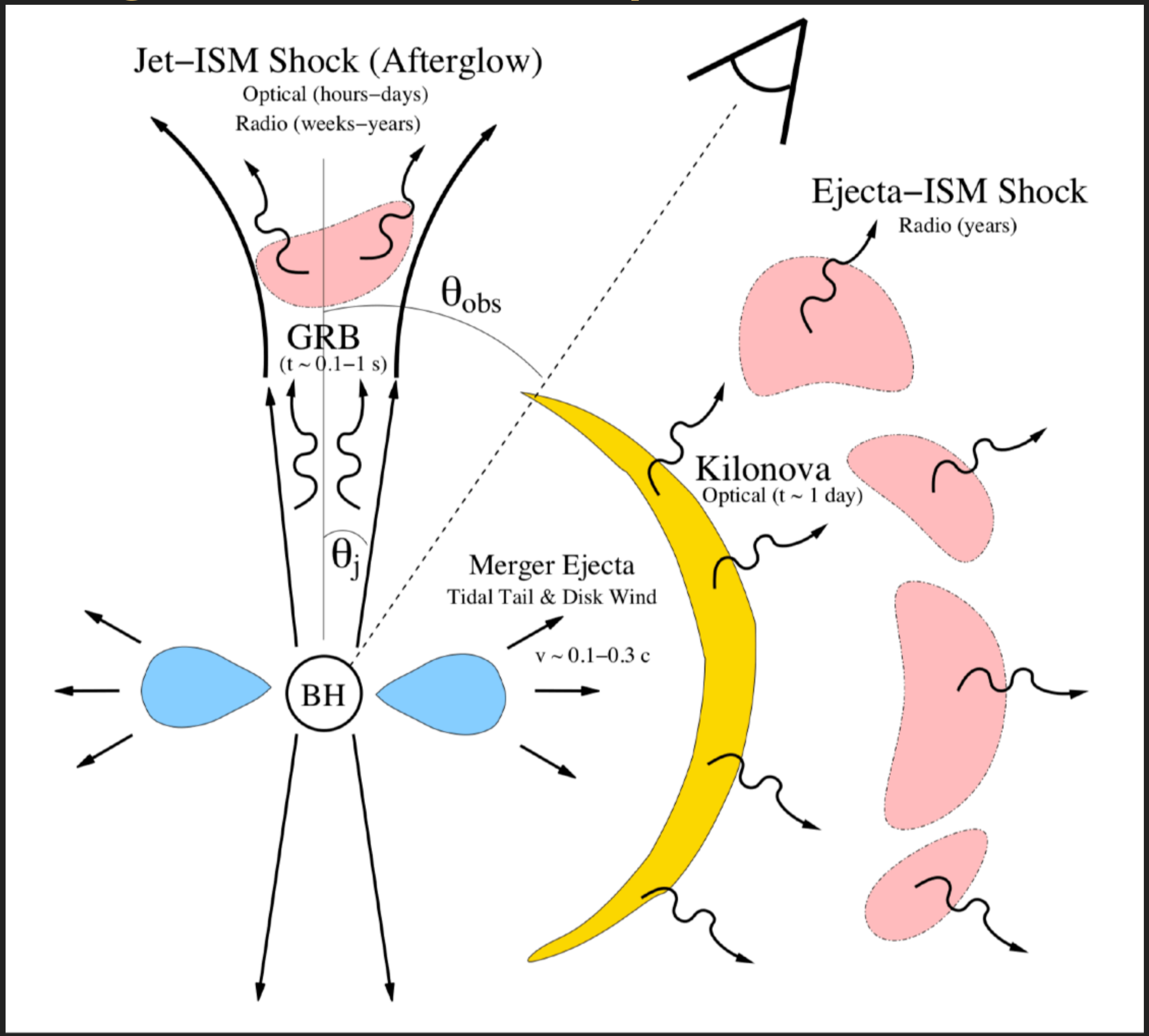
✓ *Binary neutron star mergers*

Abbott et al., 2017



✓ *Binary neutron star mergers*

✓ *Electromagnetic counterparts*



Metzger & Berger, 2012

Binary neutron star merger GW170817 were accompanied by a **short gamma-ray burst** and a **kilonova**.

✓ *Binary neutron star mergers*

- *Neutrino counterparts*

-Short time scale (O(100) seconds) prompt emissions associate with the short gamma-ray burst.

-Long time scale (days to weeks) emissions associate with long-lived hyper massive neutron star.

No neutrino counterparts has been found so far.

Gravitational-wave Multi-messenger Astronomy

Gravitational Wave	Electromagnetic Wave
mass	spectrum
spin	light curve
sky location	sky location
luminosity distance	redshift
inclination	host galaxy

Gravitational-wave Multi-messenger Astronomy

Gravitational Wave

- mass
- spin
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Electromagnetic Wave

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Image credit: NASA's Goddard Space Flight Center

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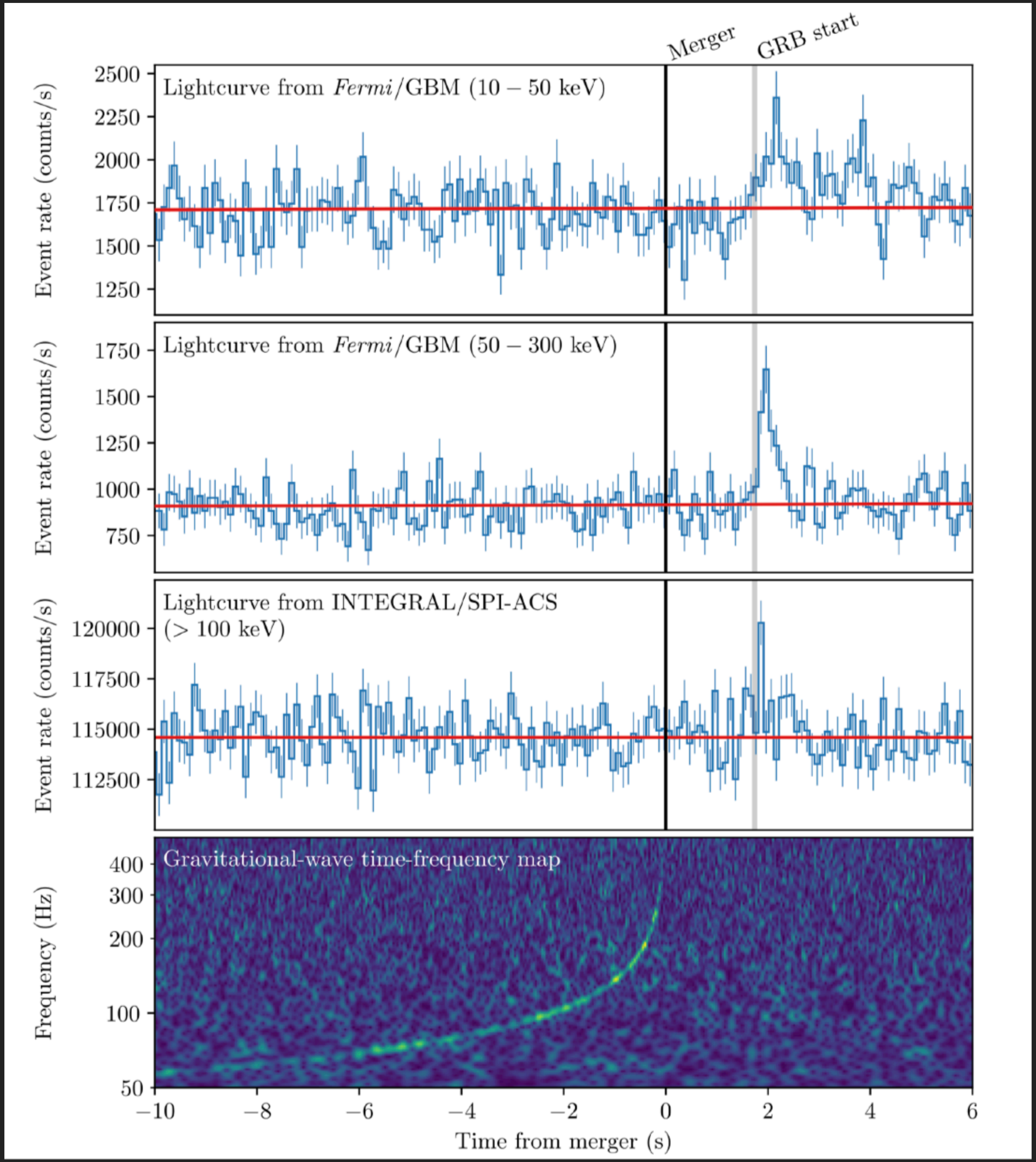
LVC collaboration, Fermi collaboration, INTEGRAL collaboration (2017)

Time coincidence

Fermi GBM

INTEGRAL

LIGO



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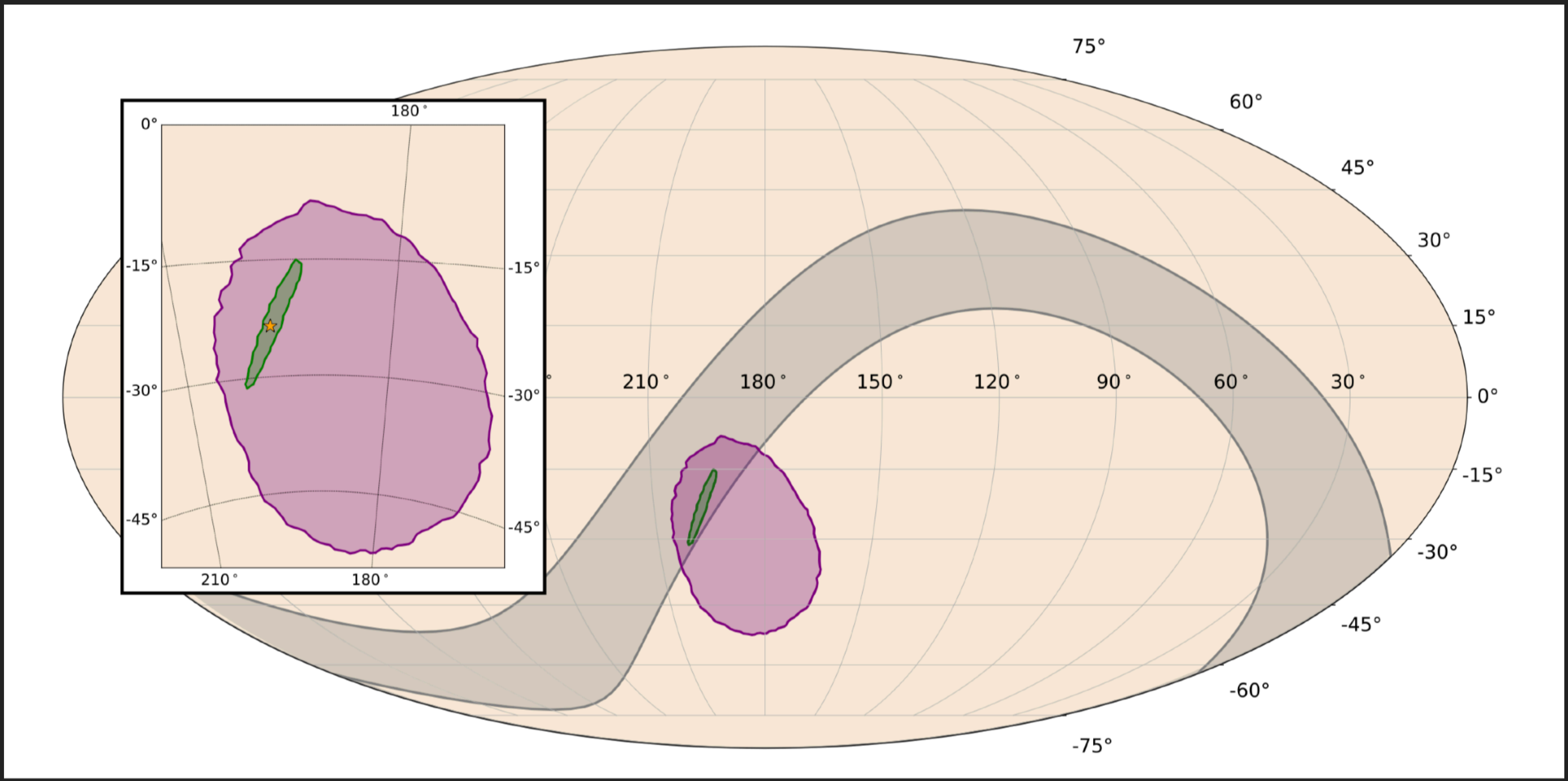
Spatial Agreement



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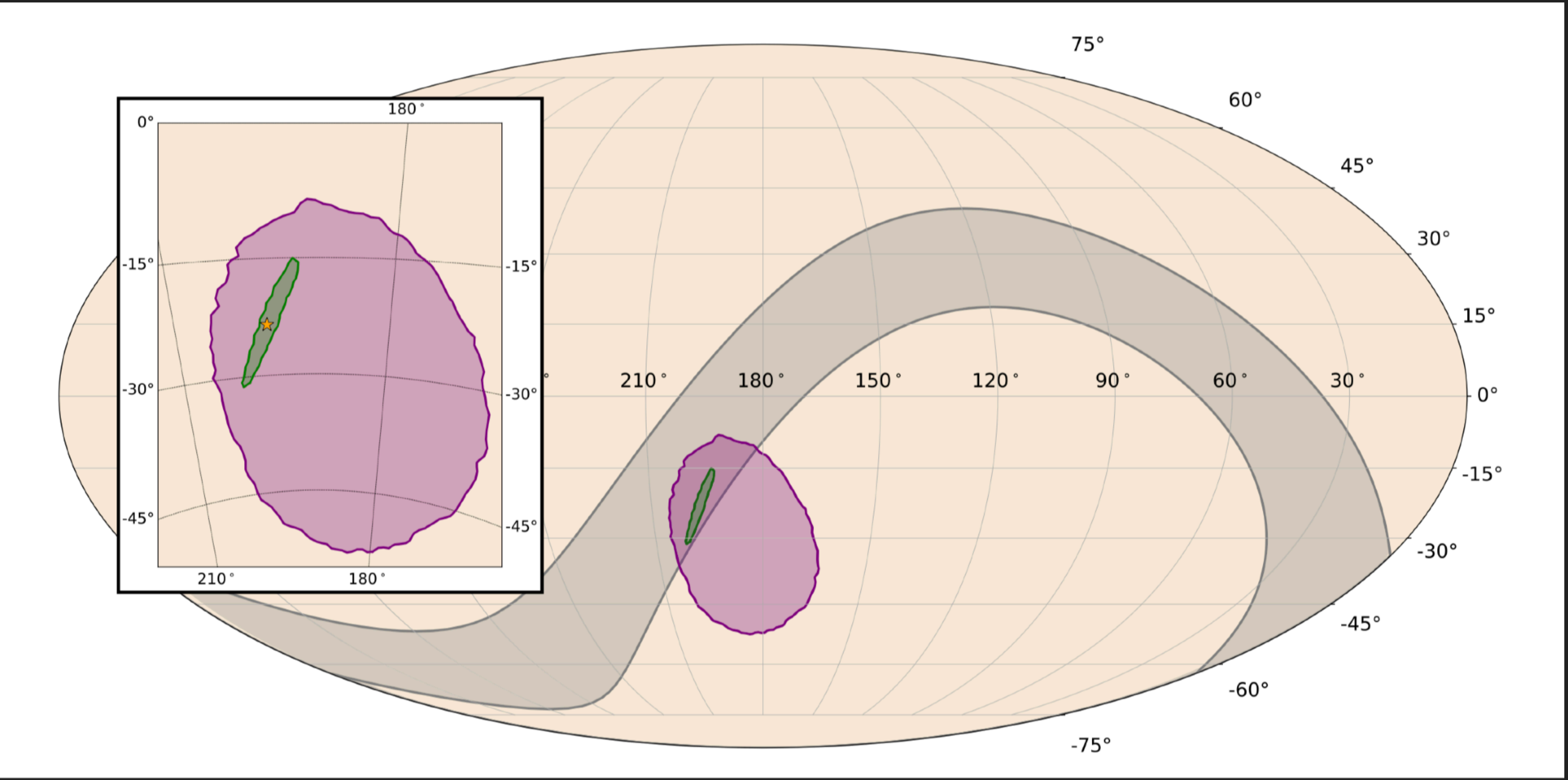
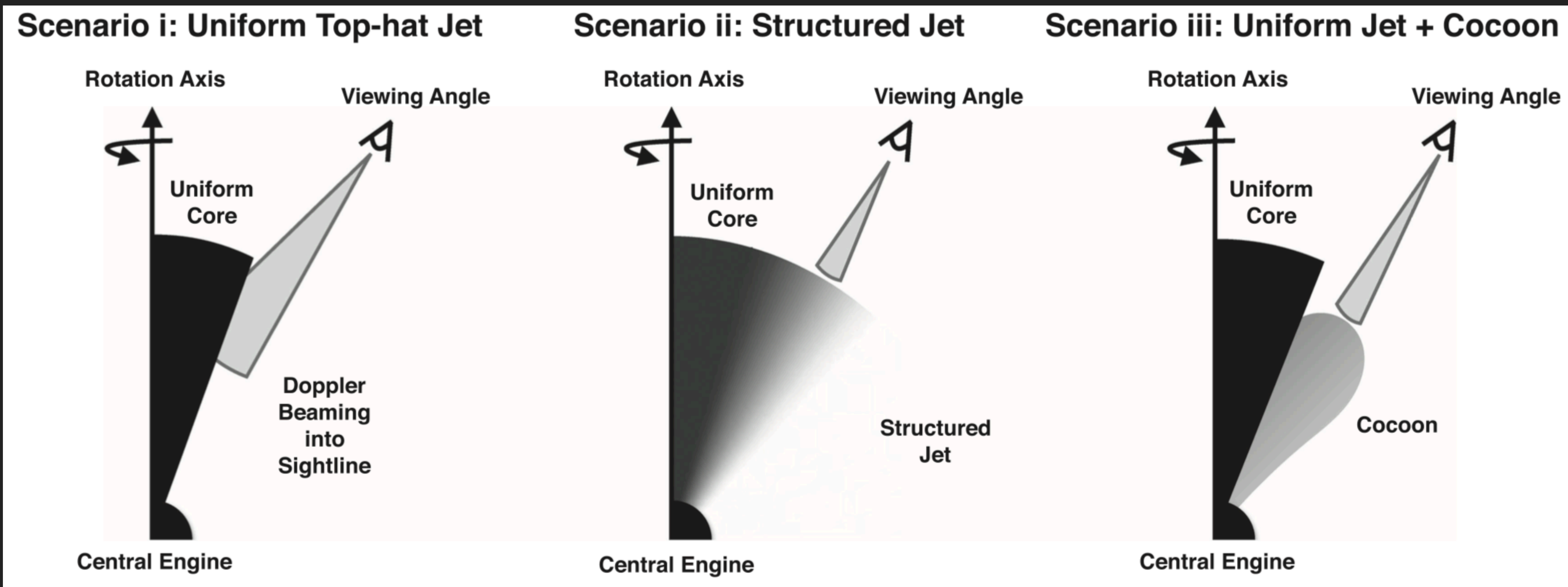


The connection between short gamma-ray bursts and binary neutron star mergers is confirmed.

What we learned from GRB170817A?



LVC collaboration, Fermi collaboration, INTEGRAL collaboration (2017)

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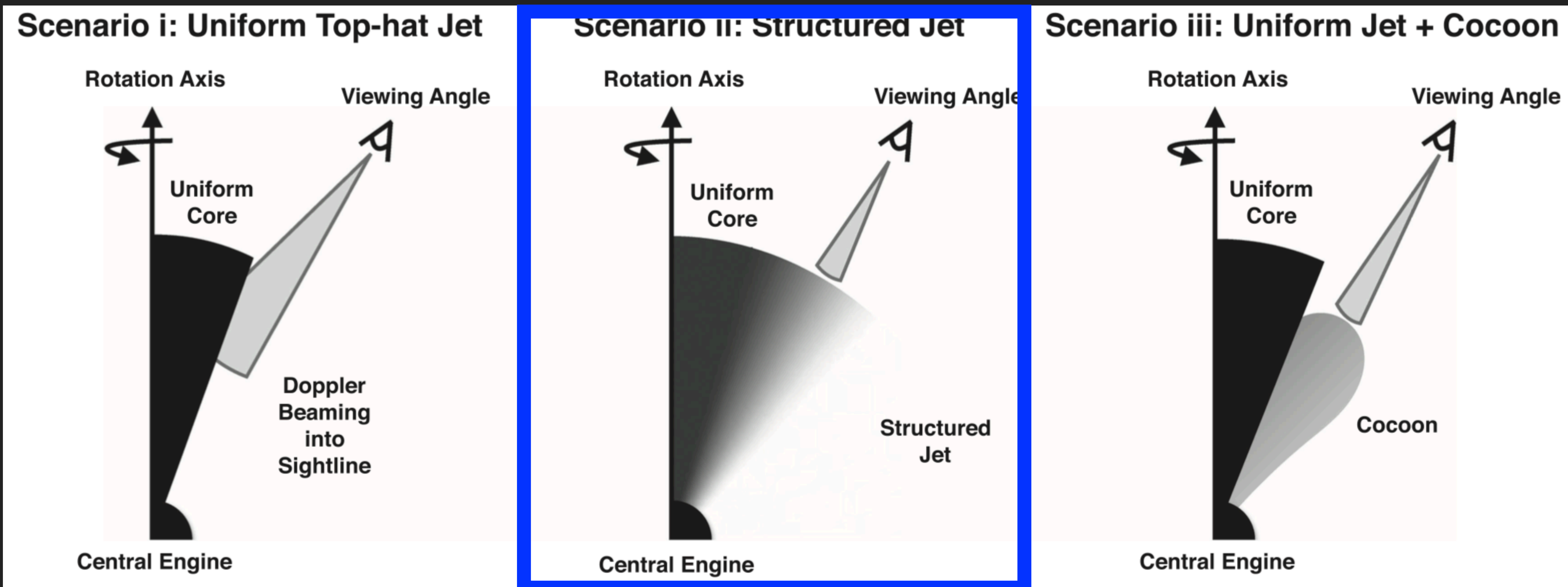

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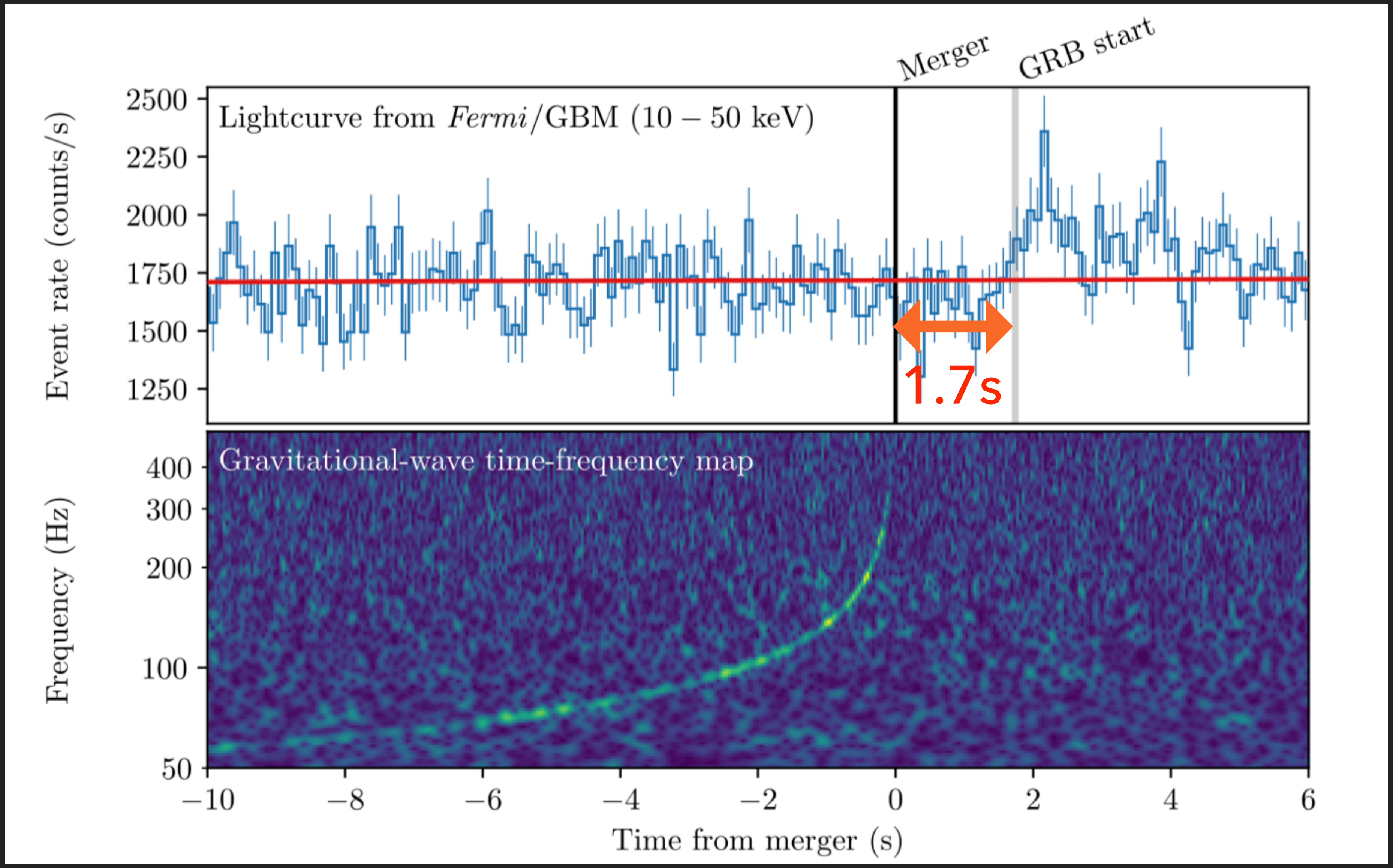

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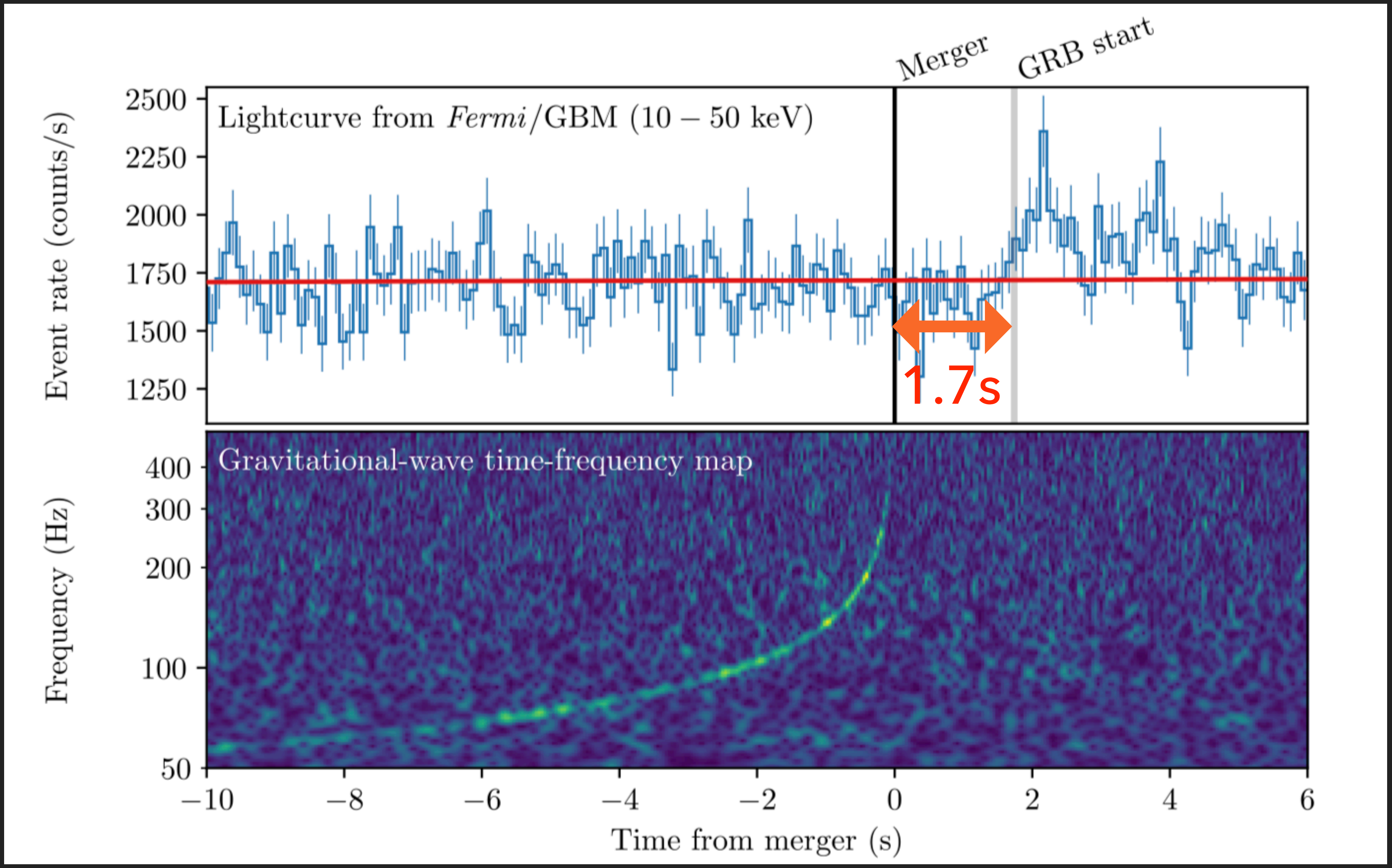

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Image credit: NASA's Goddard Space Flight Center and CI Lab

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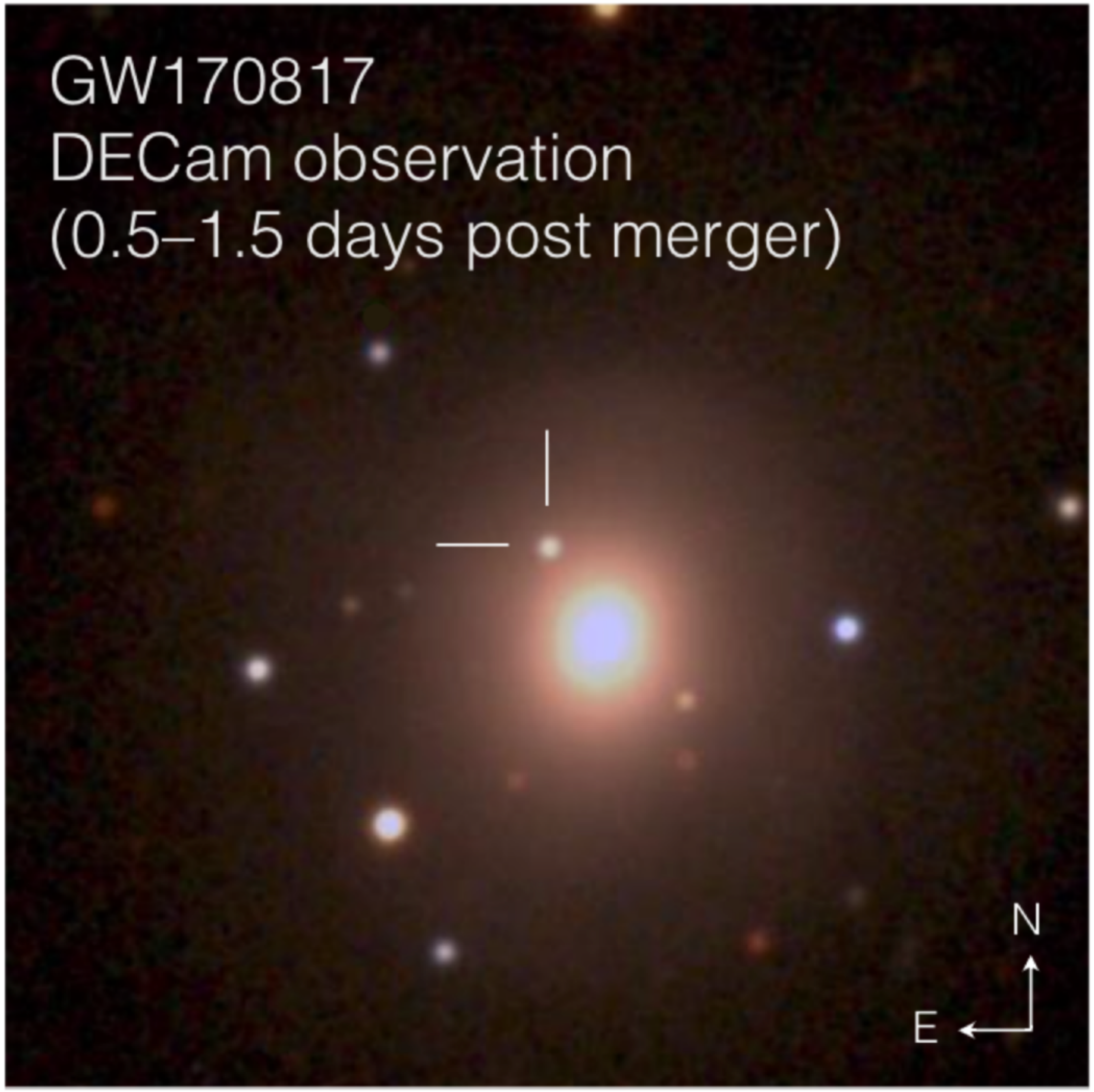
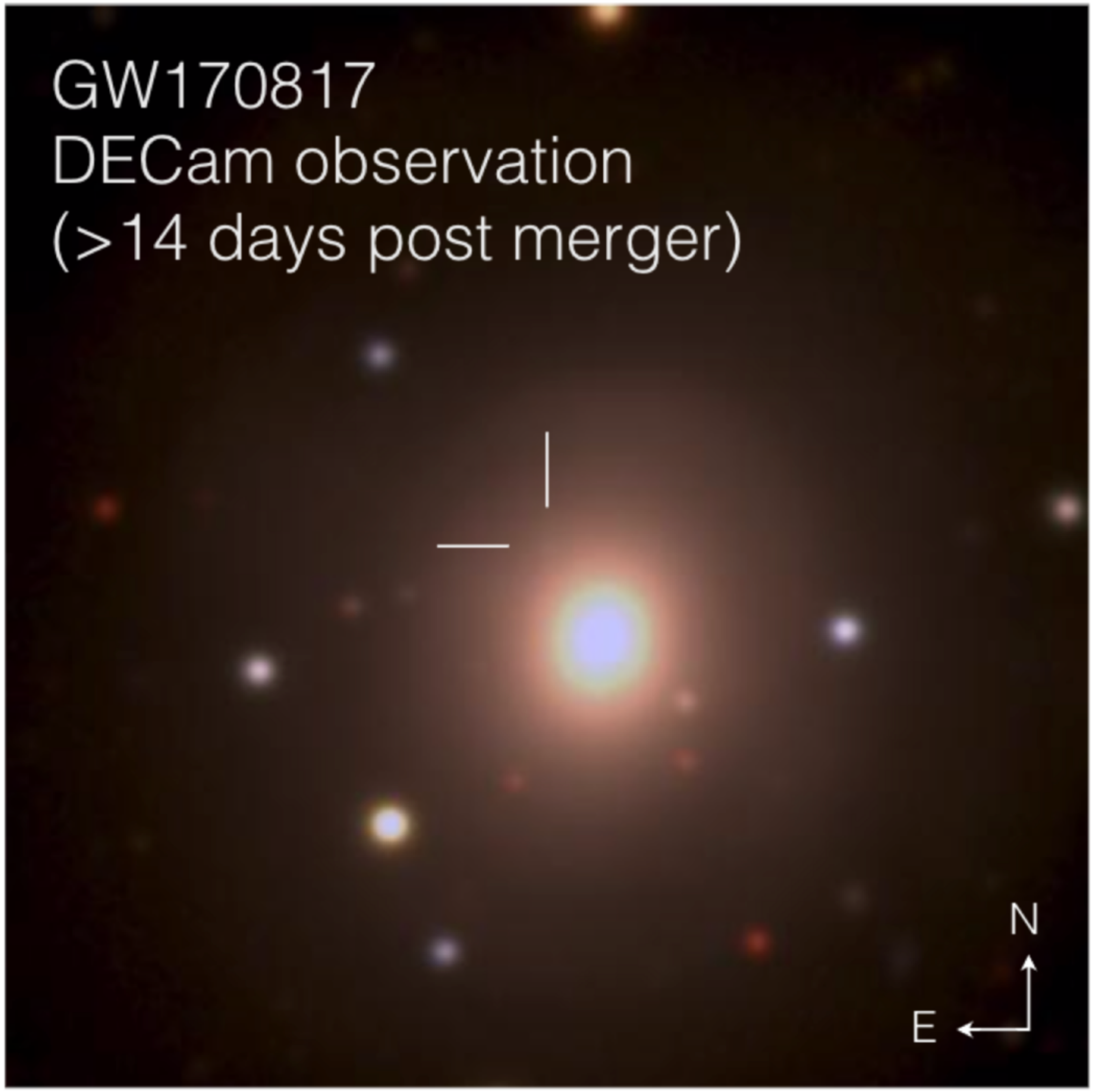
DECam kilonova discovery





Soares-Santos, ~, Chen et al., ApJL, 2017

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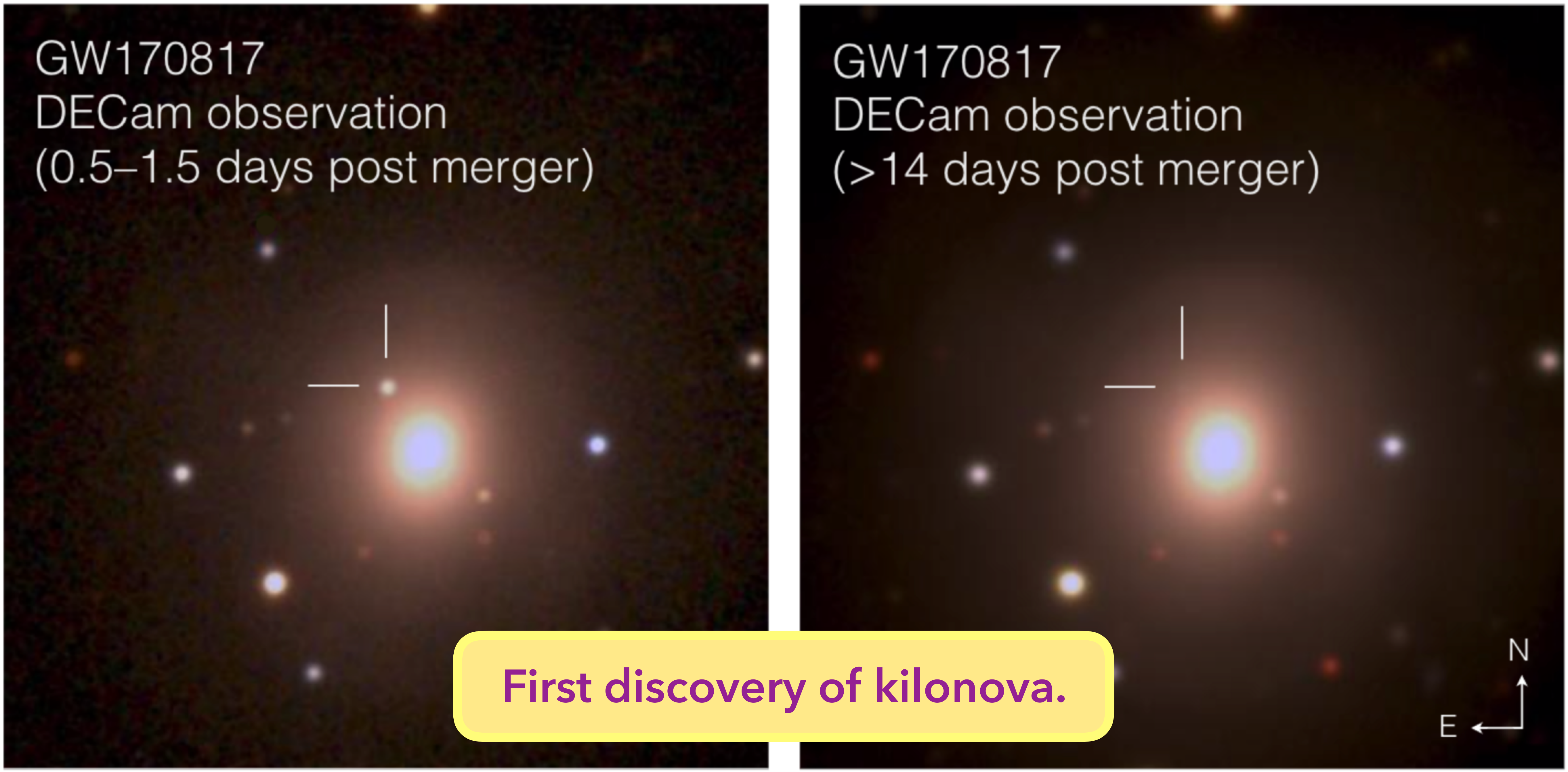

First discovery of kilonova.

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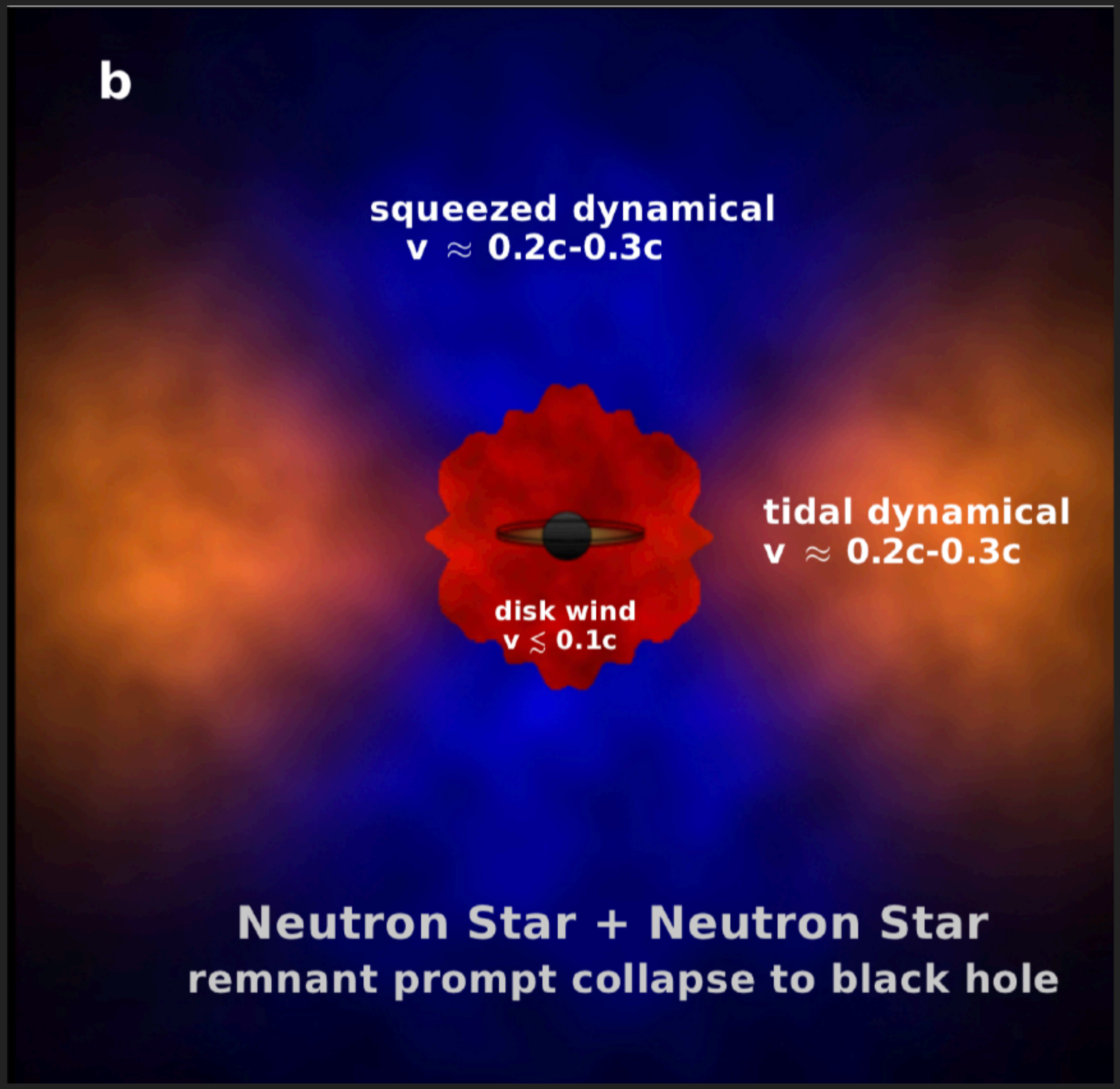
Combining the mass of ejecta and the merger rate of binary neutron stars–



Kasen et al. Nature (2017)

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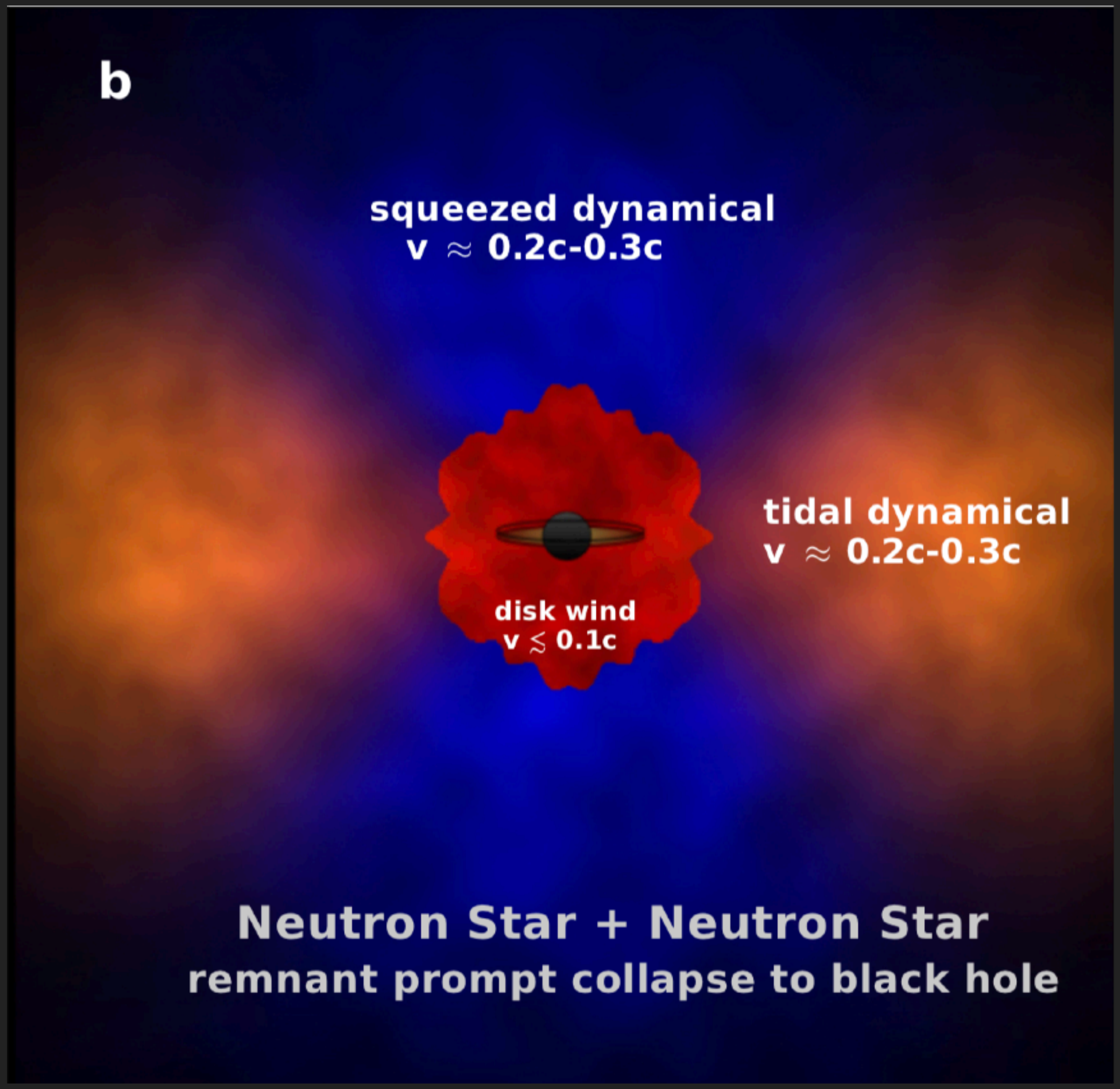

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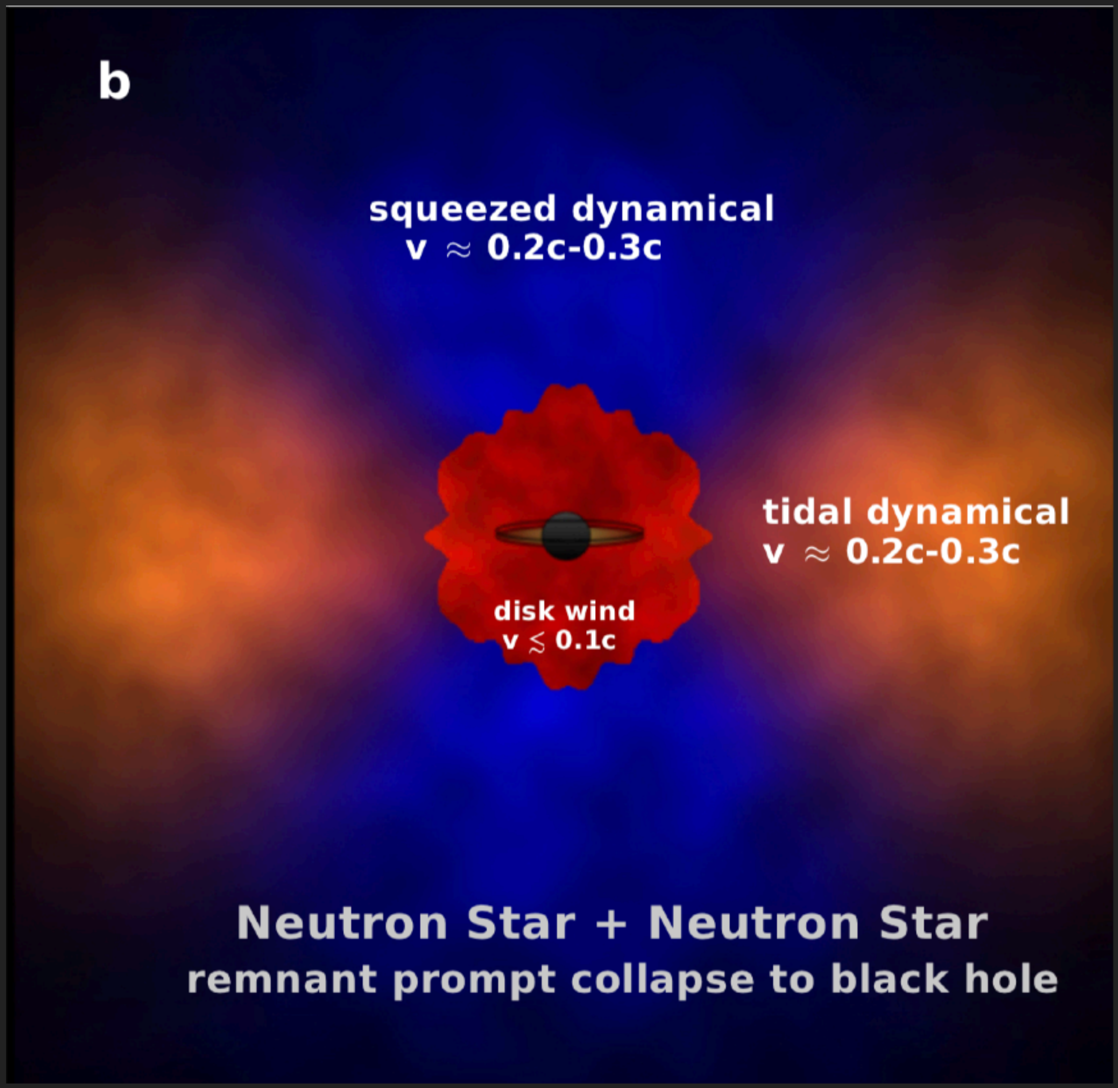
From observations:

-Early time featureless optical emission.

-Late time broad spectral bump in infrared.



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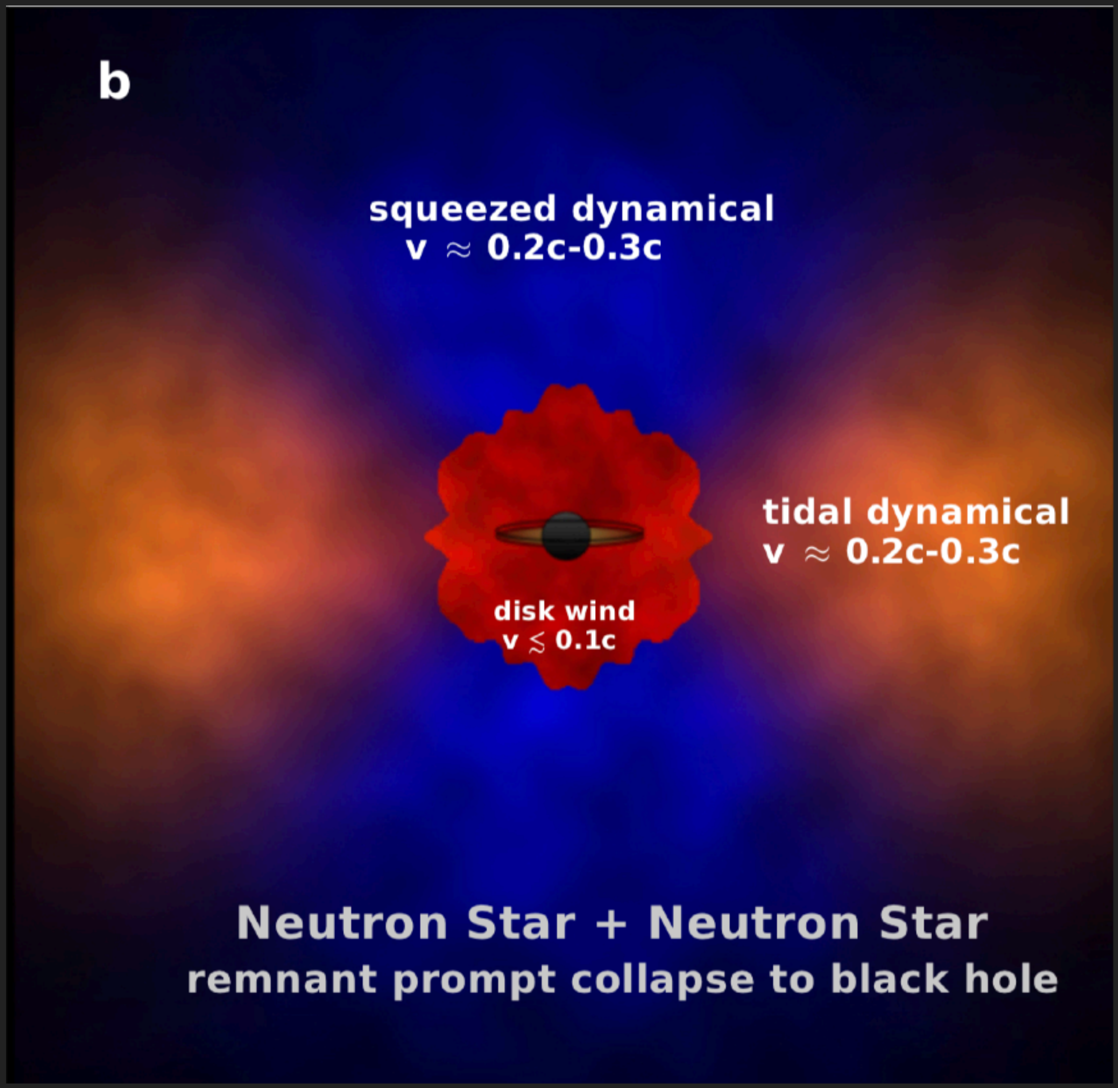

Kasen et al. Nature (2017)

Image credit: IceCube Collaboration

ICECUBE

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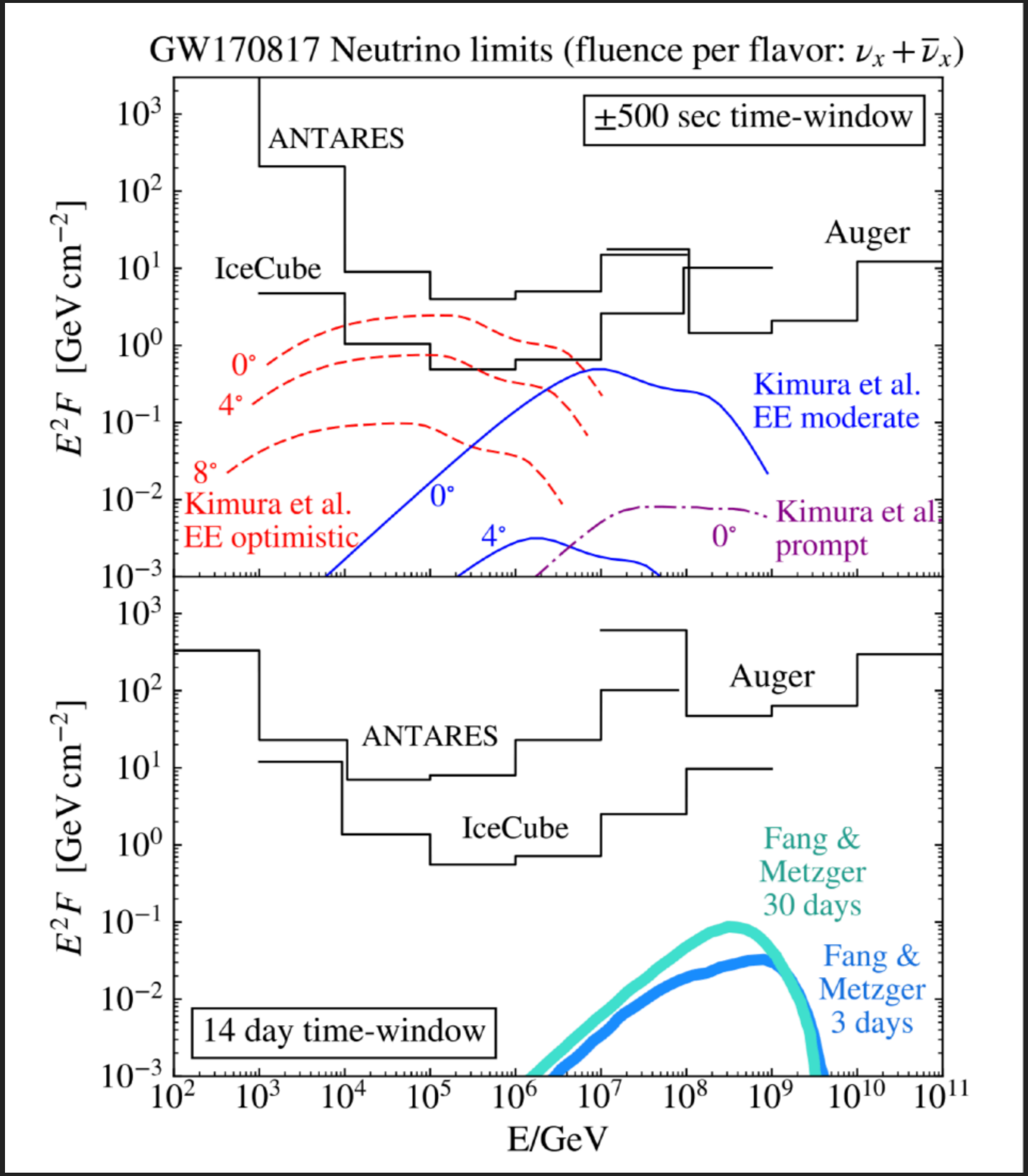
What we learned from the non-detection of neutrinos?



No neutrino counterparts were found by IceCube, ANTARES, and Pierre Auger within the [-500,500] second and the 14-days time window

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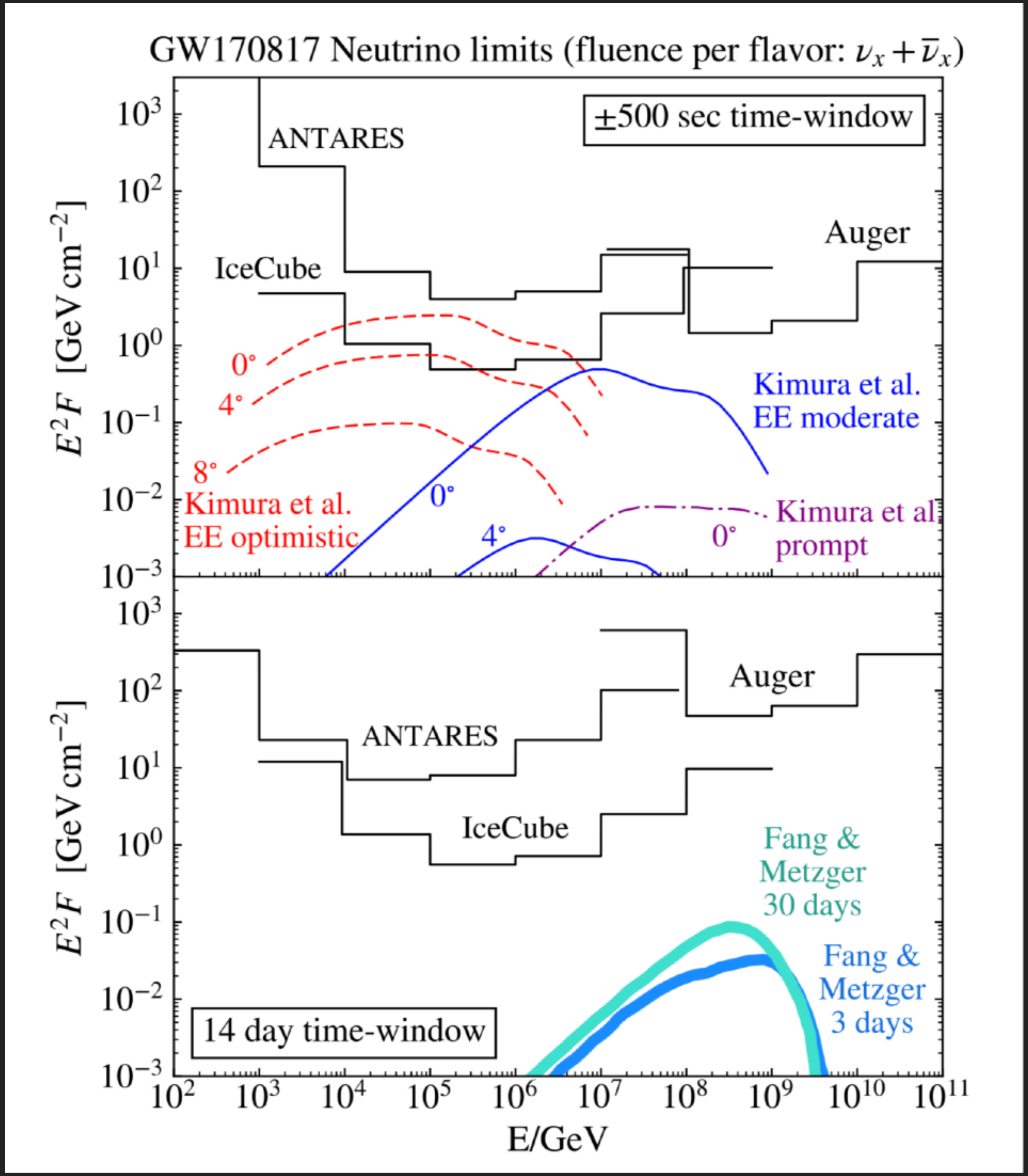

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Image credit: TAKE 27 LTD/SPL

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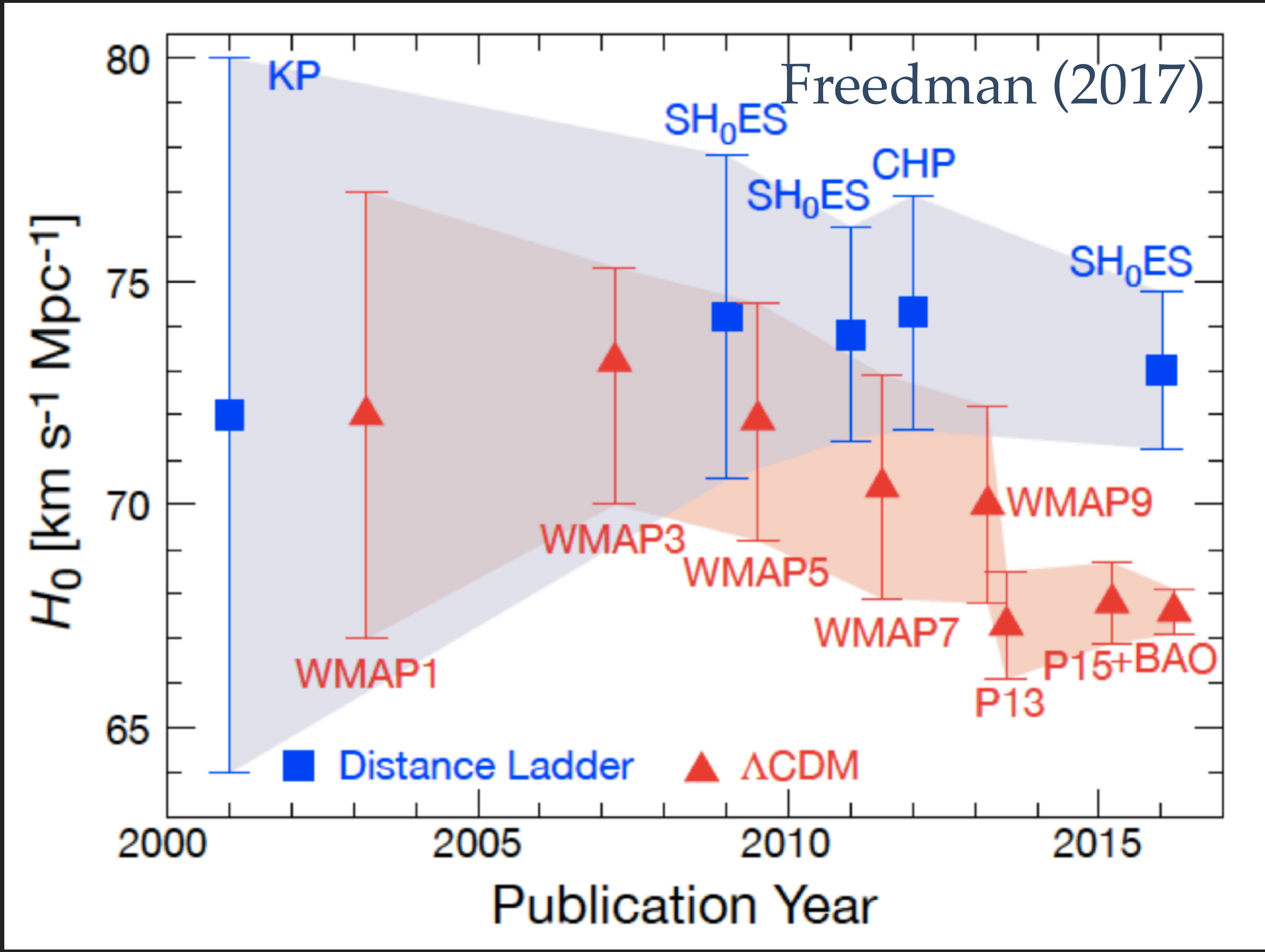
Tension in Hubble constant measurement

The H_0 measurement from local distance ladder and cosmic microwave background are inconsistent.



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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 used 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 stars. Today, various CMB calculations of the Hubble constant differ from stellar and supernovae versions by more than 5 percent, equivalent to about three standard deviations. To a smaller degree, the Hubble constant differs between different CMB observations, too.

The New York Times

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

A small discrepancy in the value of a long-sought number has fostered a debate about just how well we know the cosmos.

Dennis Overbye

OUT THERE FEB. 20, 2017

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

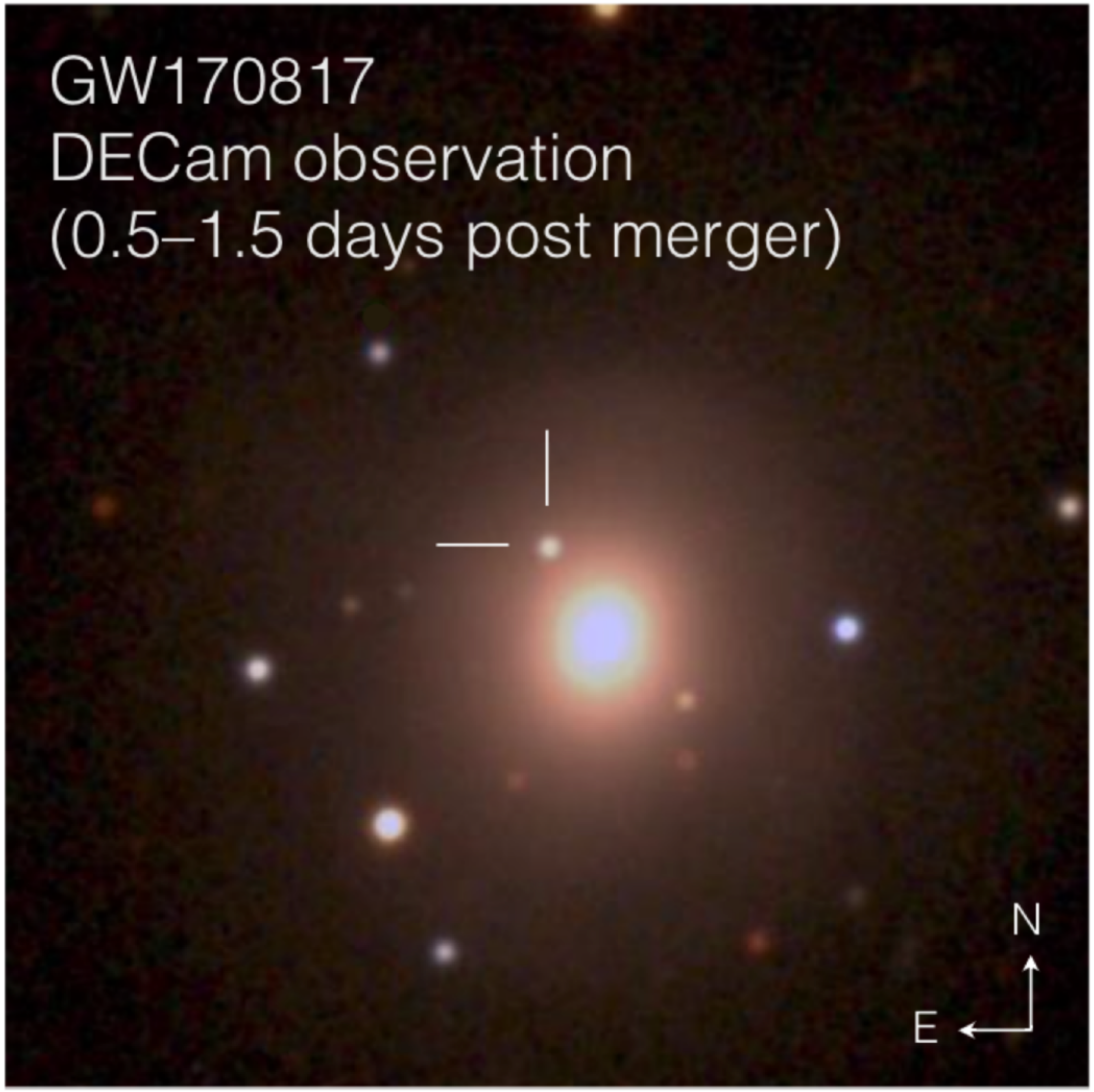
$$H(z) = H_0\sqrt{\Omega_{\rm M}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w_0+w_a)}e^{-3w_a z/(1+z)}}$$

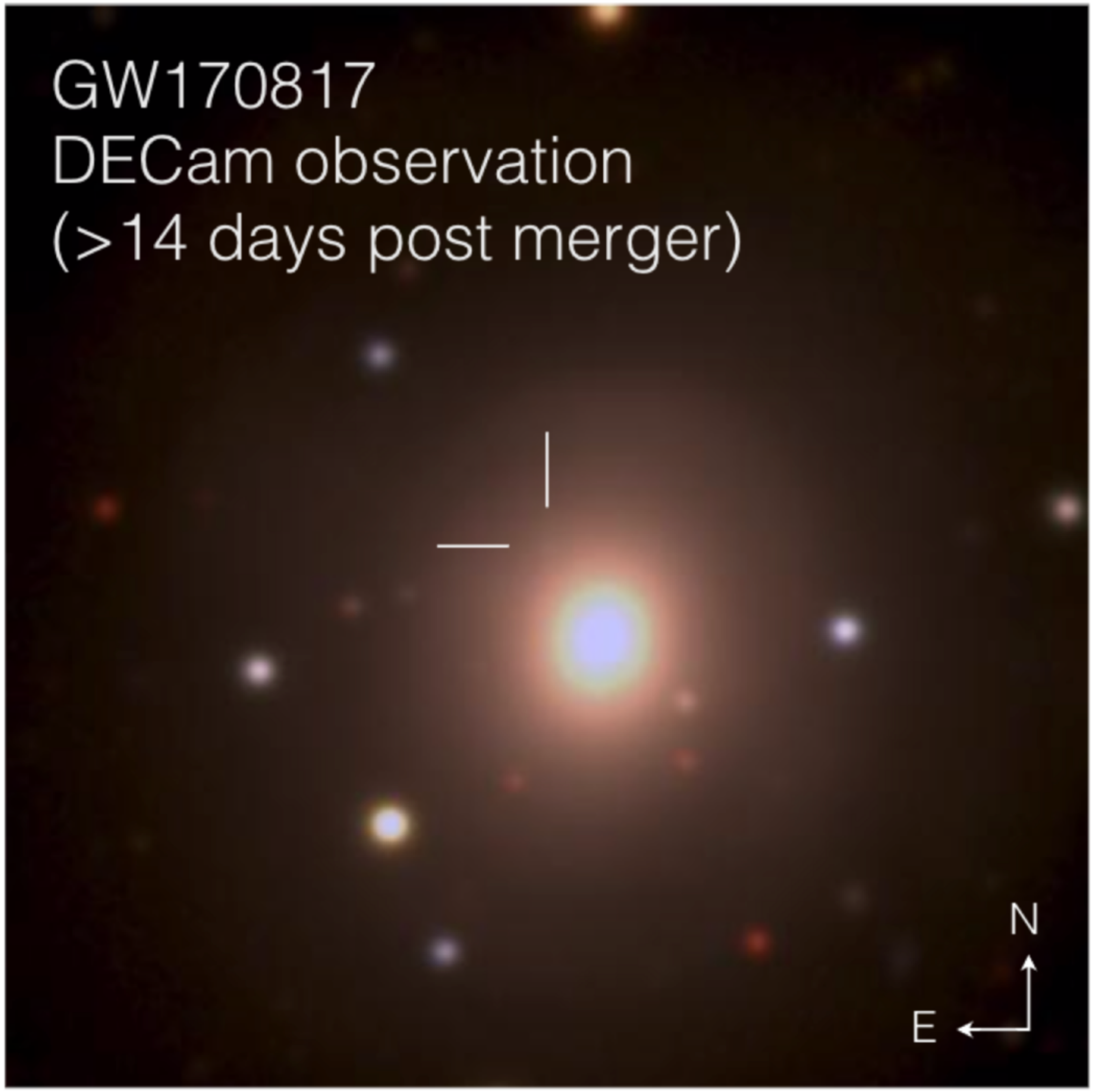
Standard siren (Schutz 1986, Holz & Hughes 2005):

-D_L Luminosity distance:
Amplitude of the gravitational-wave signal

-z (~v/c) Redshift:
Electromagnetic-wave counterpart
and/or the host of the system

First Hubble constant measurement from binary neutron star merger (GW170817)





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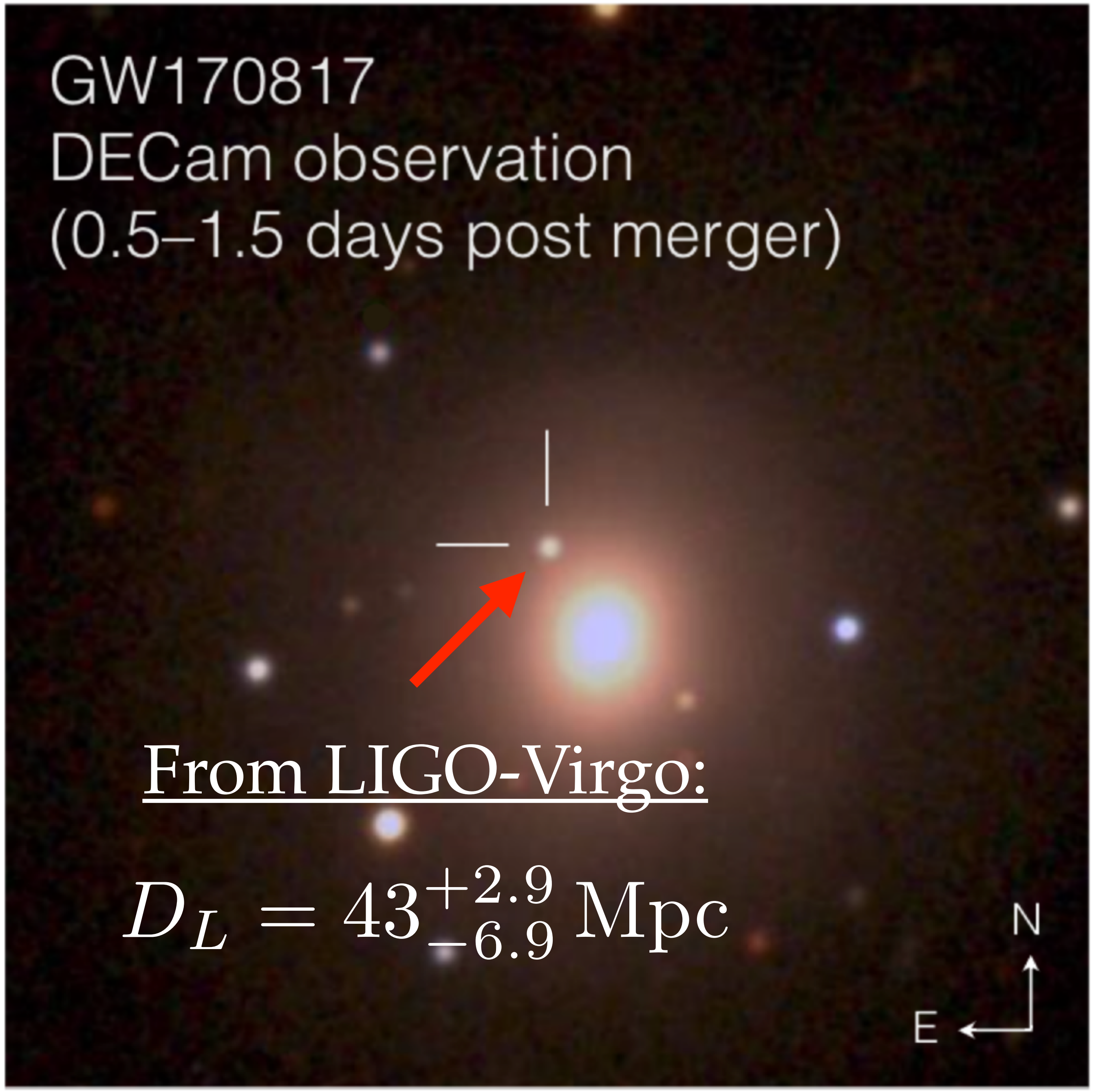

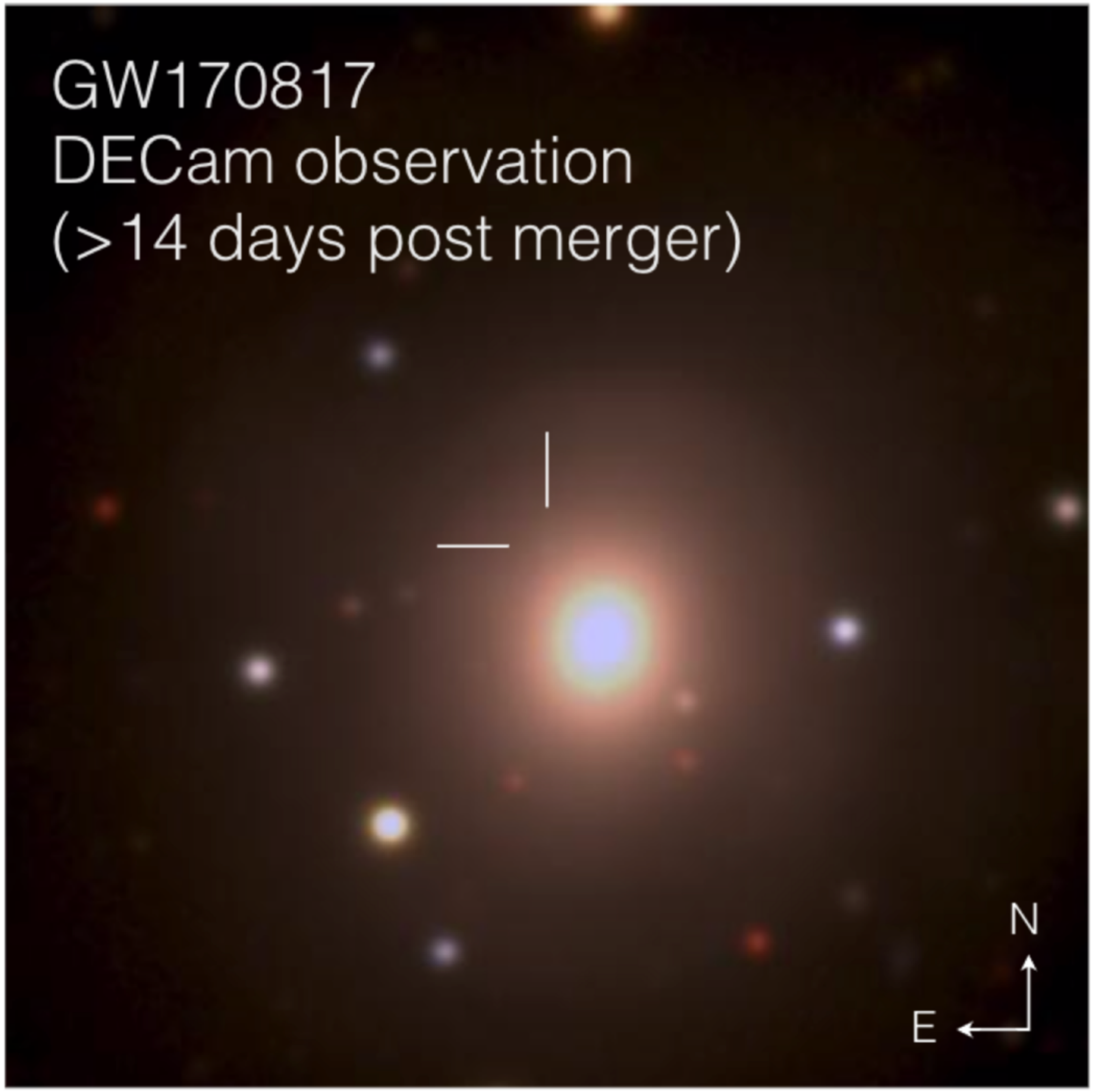

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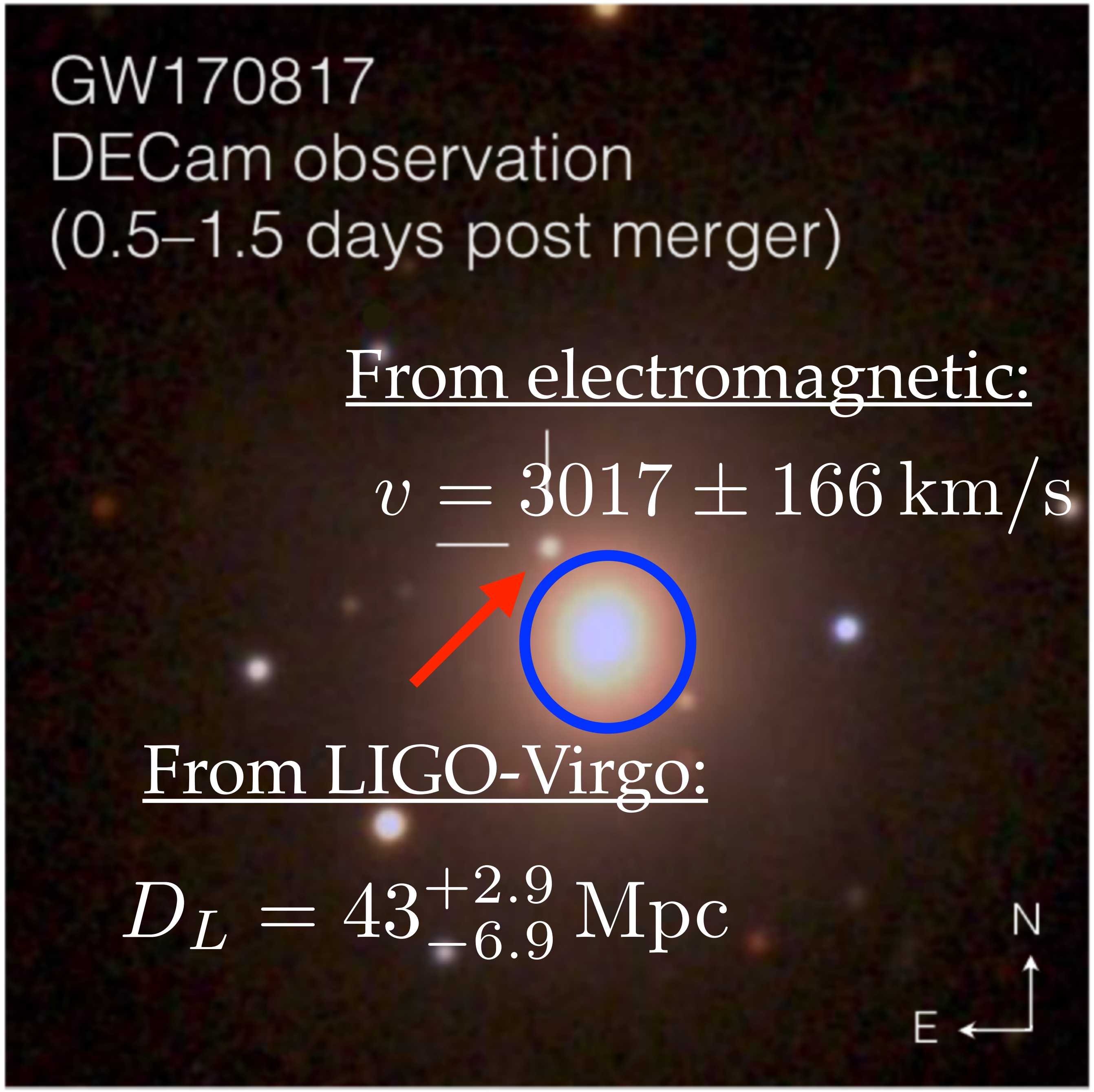

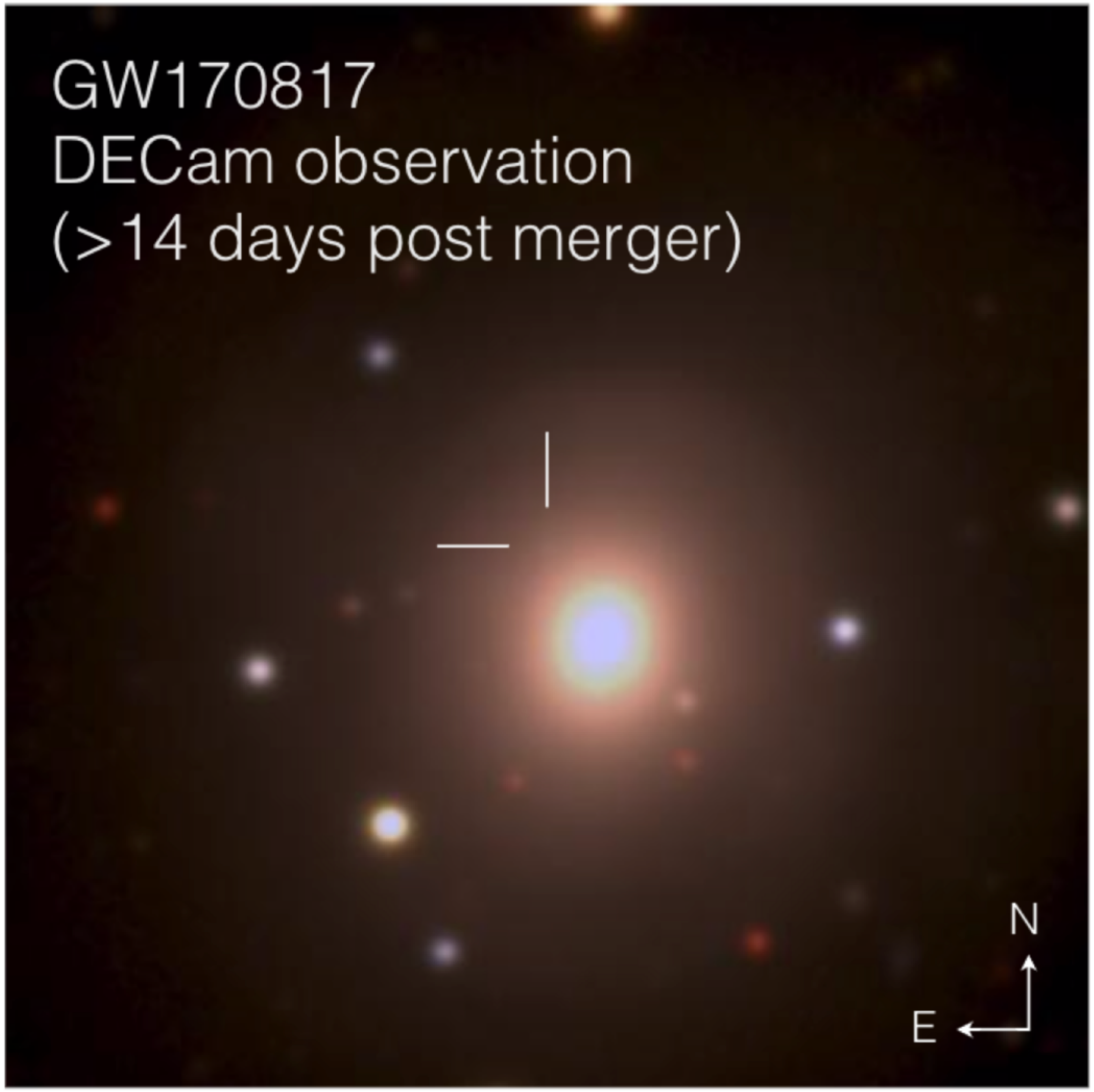

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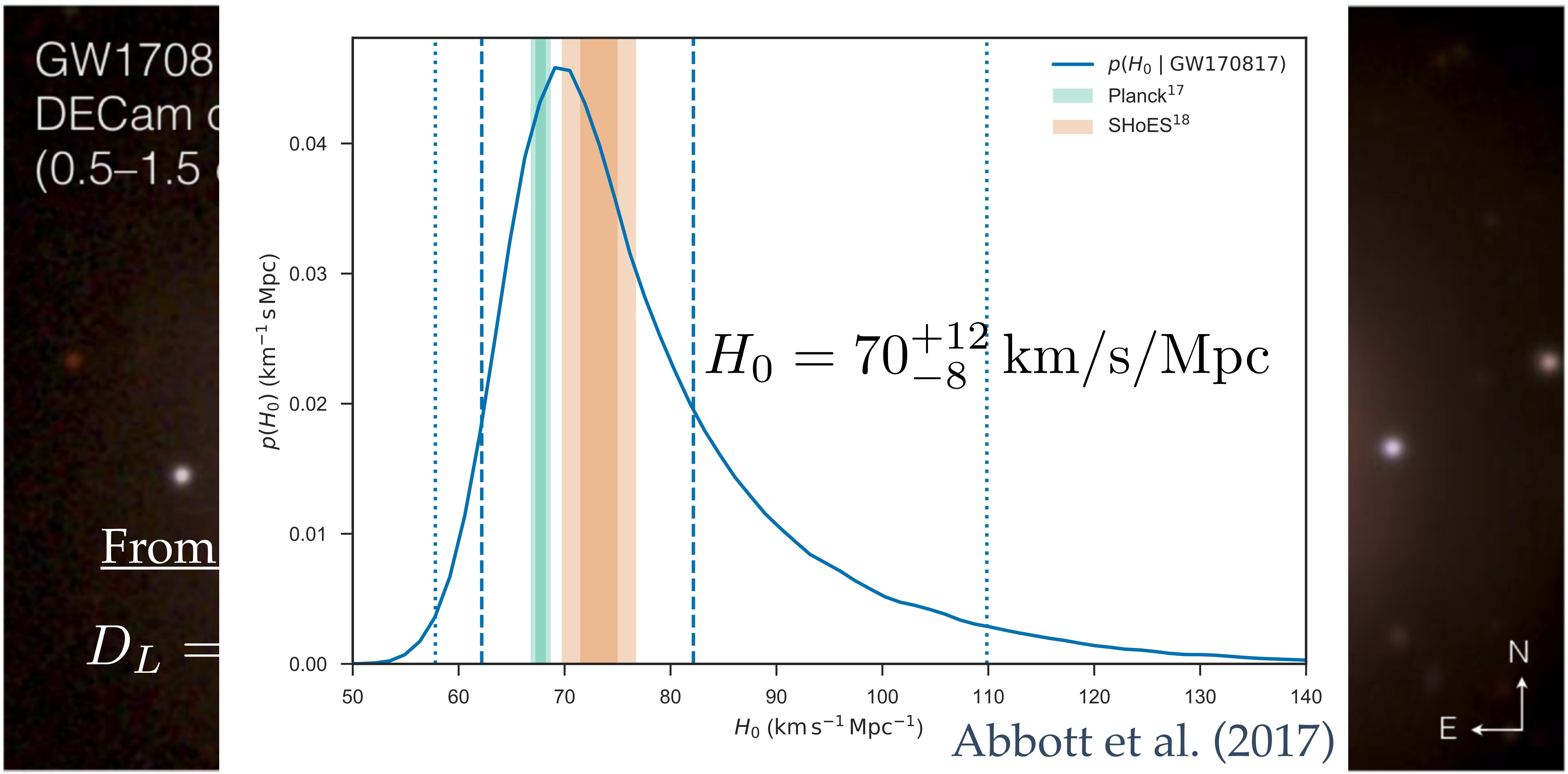

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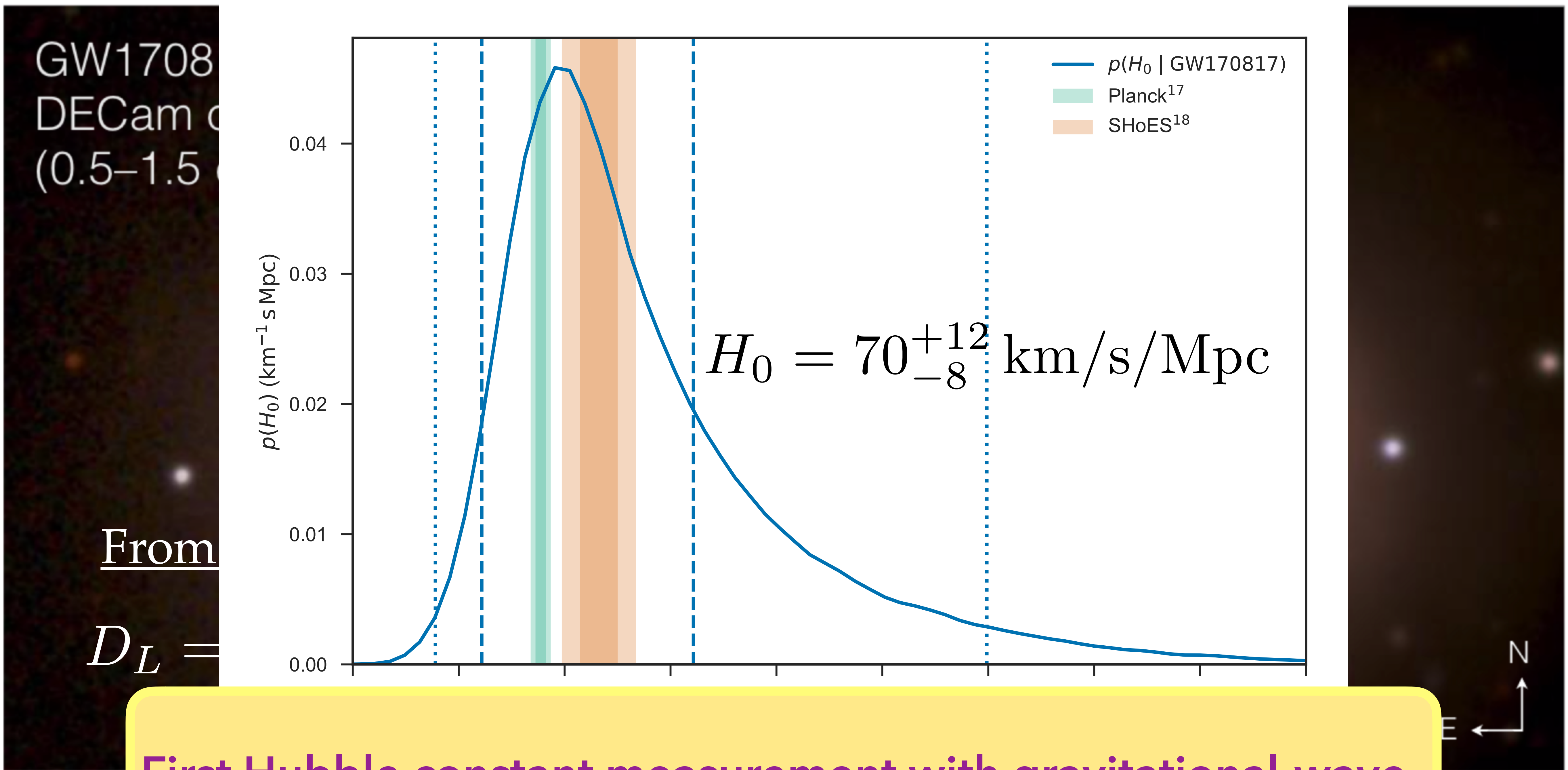
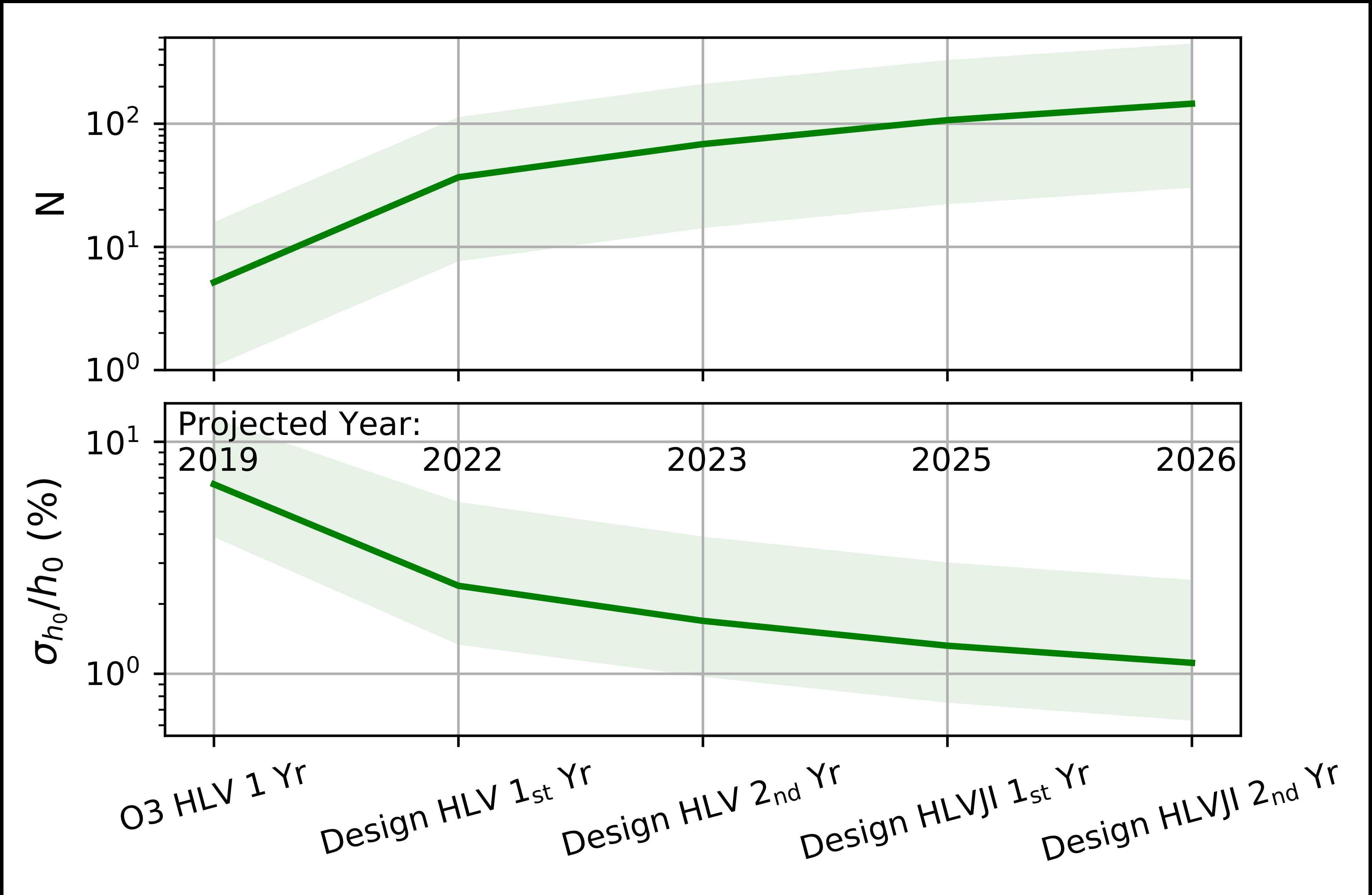


First Hubble constant measurement with gravitational-wave.

2% Hubble constant measurement within 5 years



Chen et al. Nature in press

Image credit: TAKE 27 LTD/SPL

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Test of general relativity

-Vector and scalar polarizations in gravitational-wave.

Using the sky location of the EM counterpart to constrain the corresponding antenna patterns of the vector and scalar polarizations.

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Summary

The era of gravitational-wave astronomy and cosmology has begun. More collaborations between multi-messenger communities will be important to obtain the best scientific outcome.