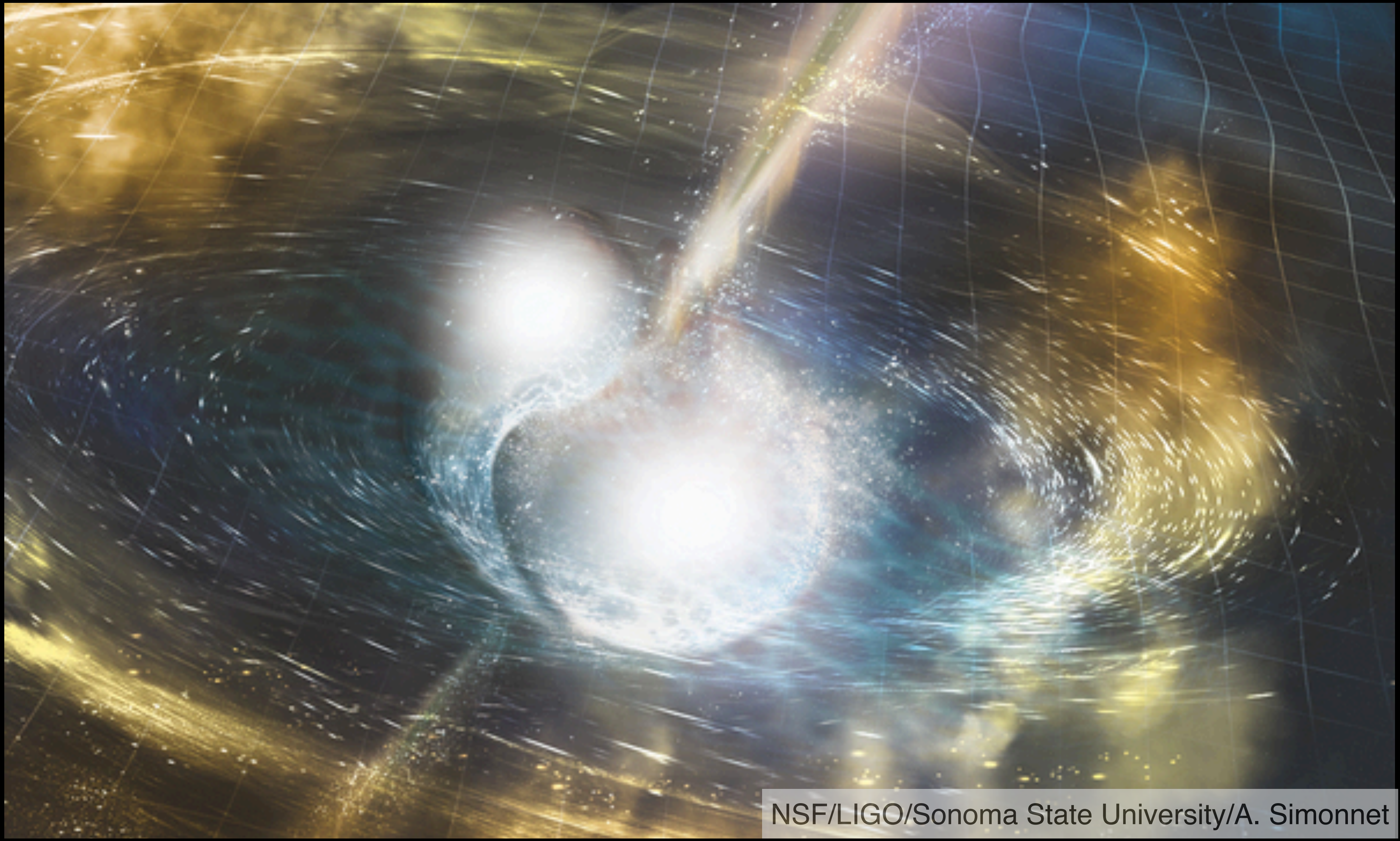
Observational Results from LIGO & Virgo


NSF/LIGO/Sonoma State University/A. Simonnet

Jonah Kanner

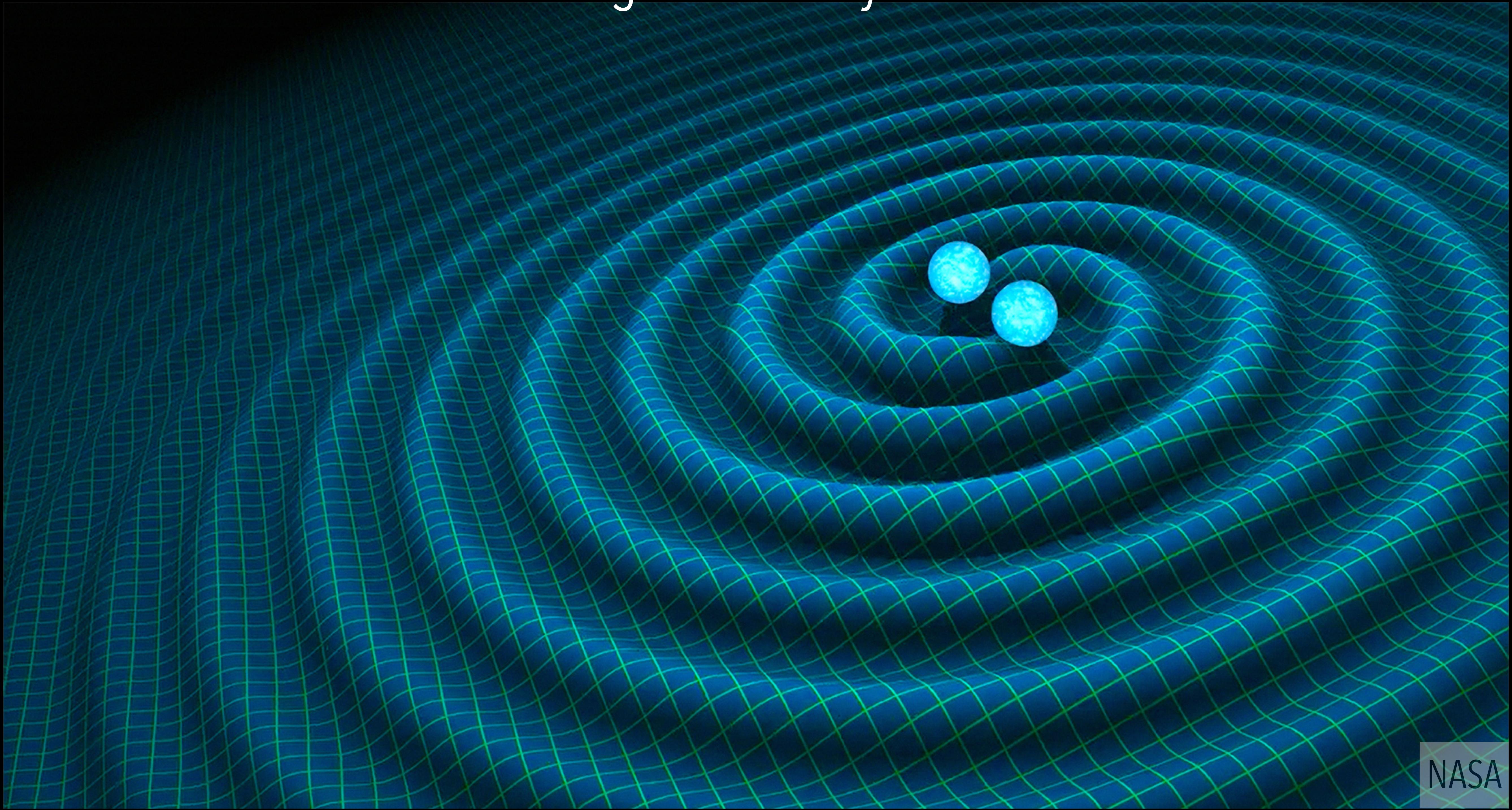
LIGO

Caltech

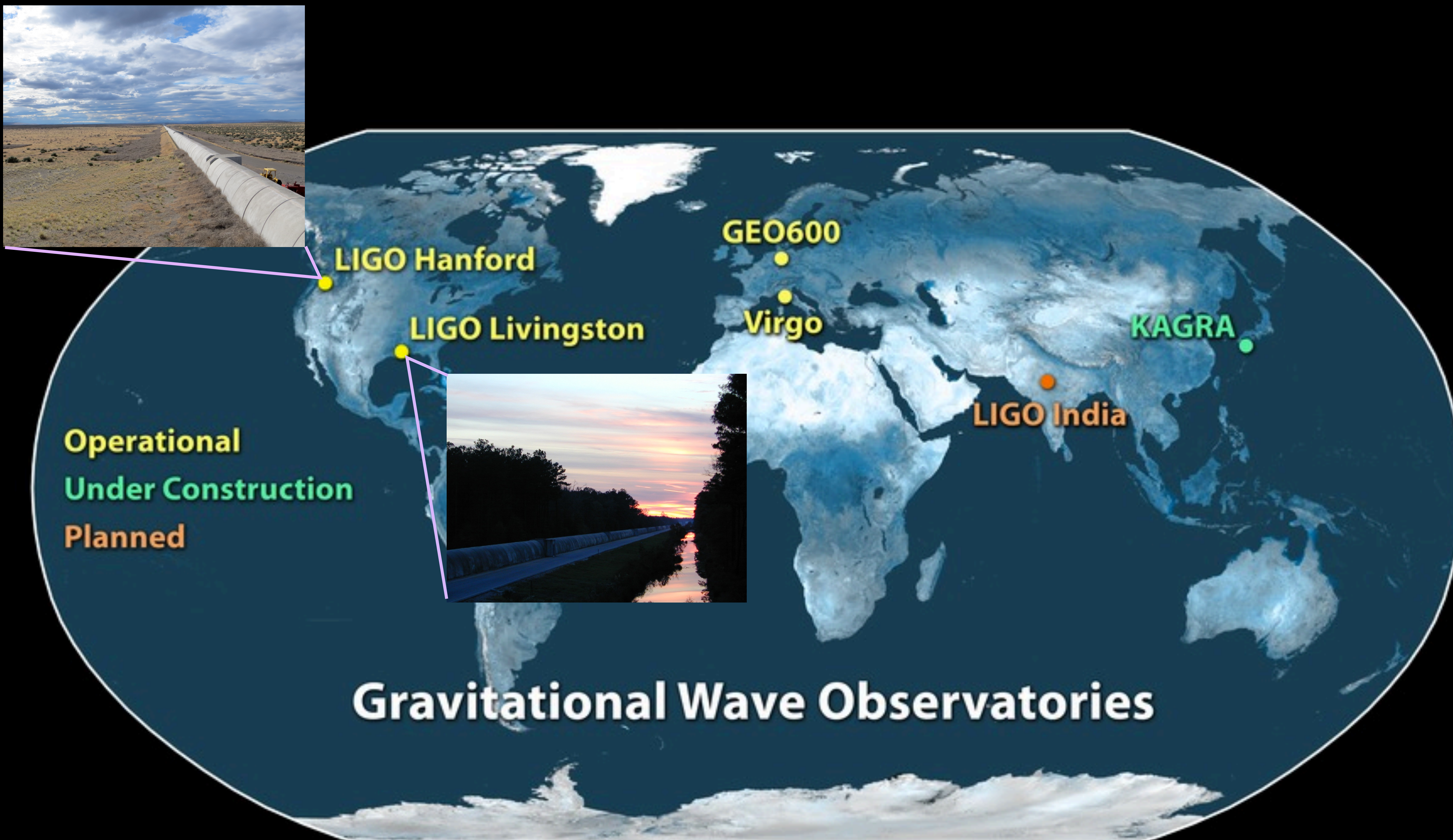
G2101350

Gravitational waves

Ripples in the fabric of spacetime
generated by the acceleration of matter



The global IGWN network



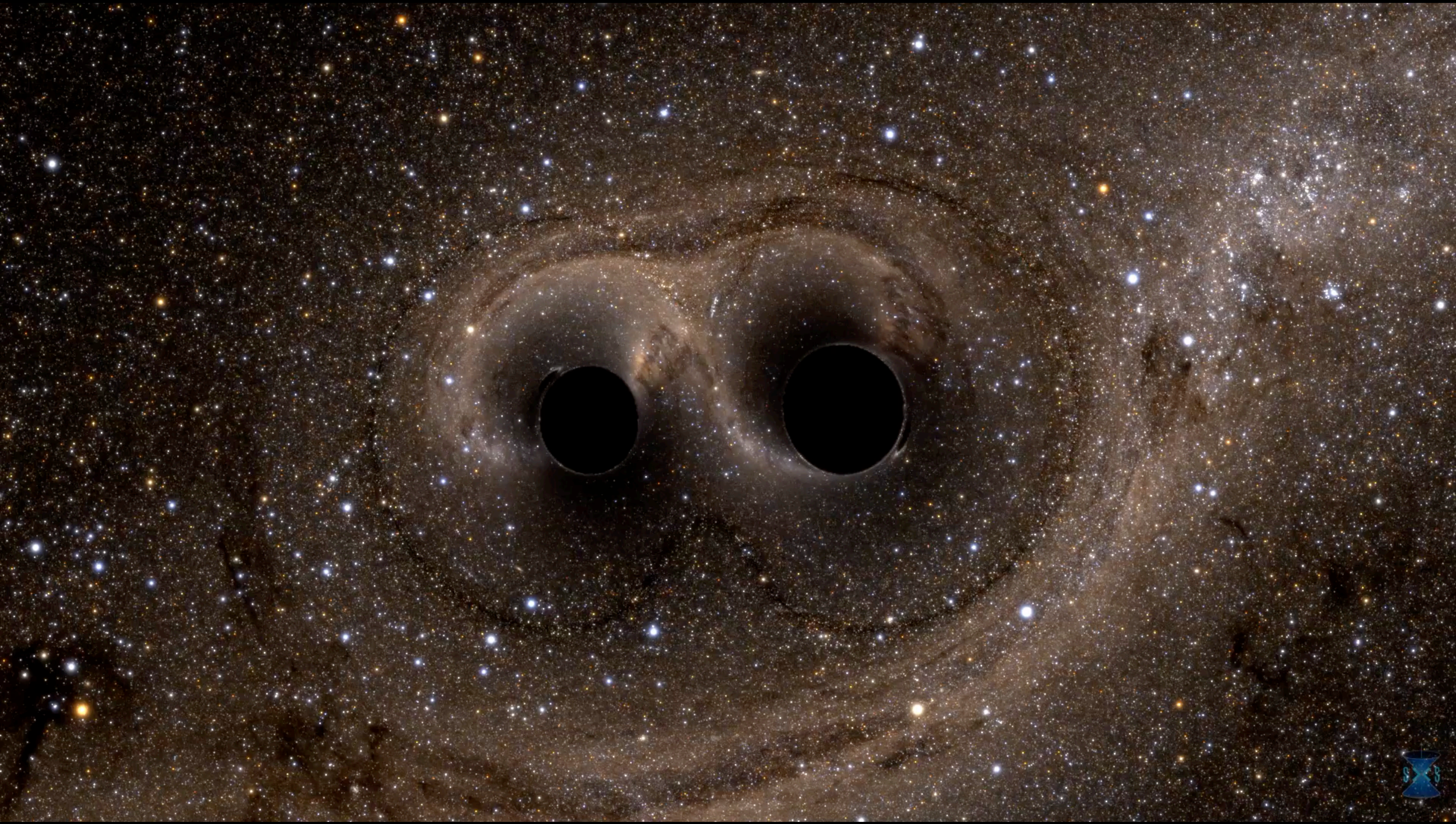
LIGO/Caltech

LIGO Livingston


Virgo

LIGO Hanford

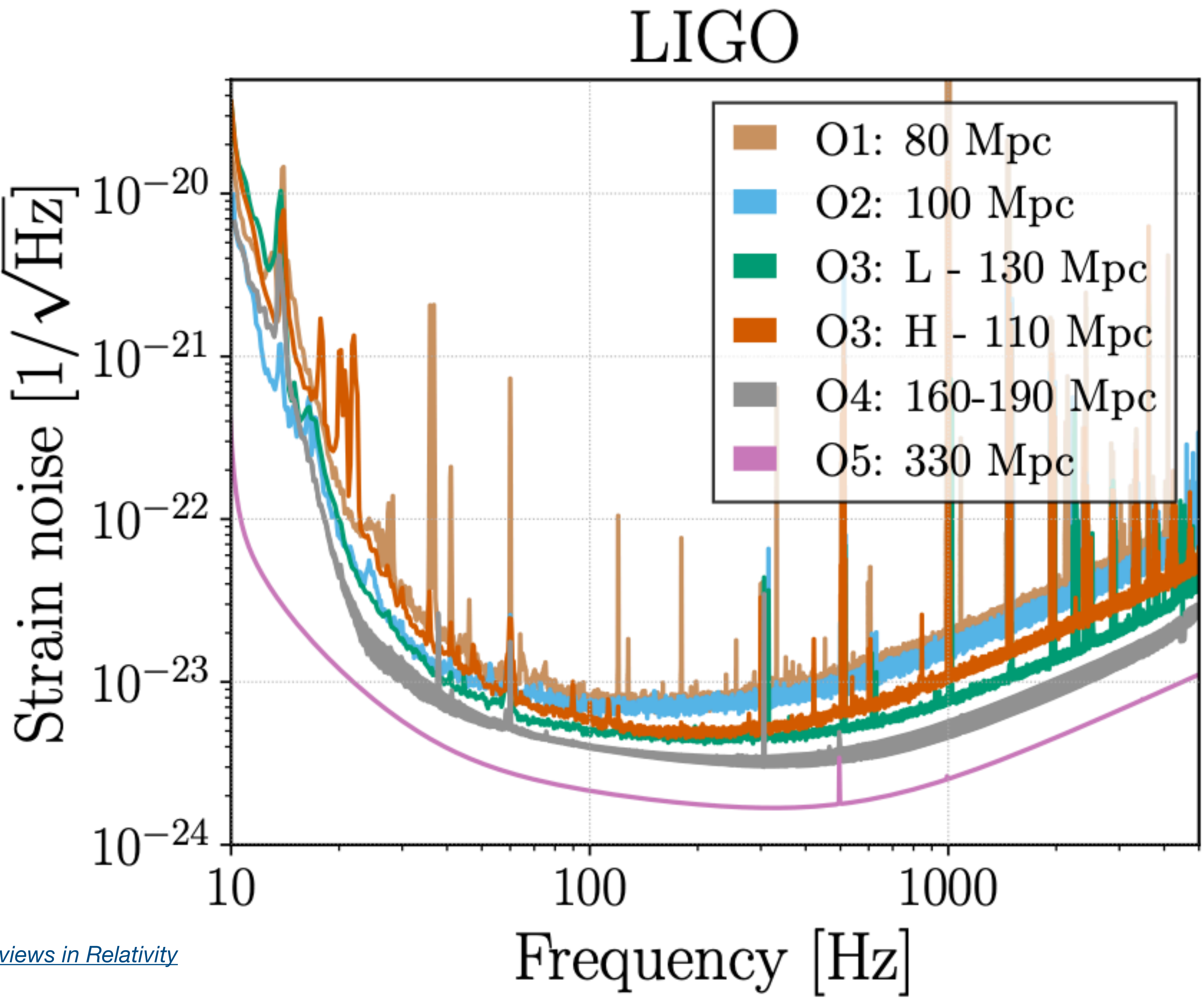
LIGO/Caltech



Merging Black Holes Animation created by SXS

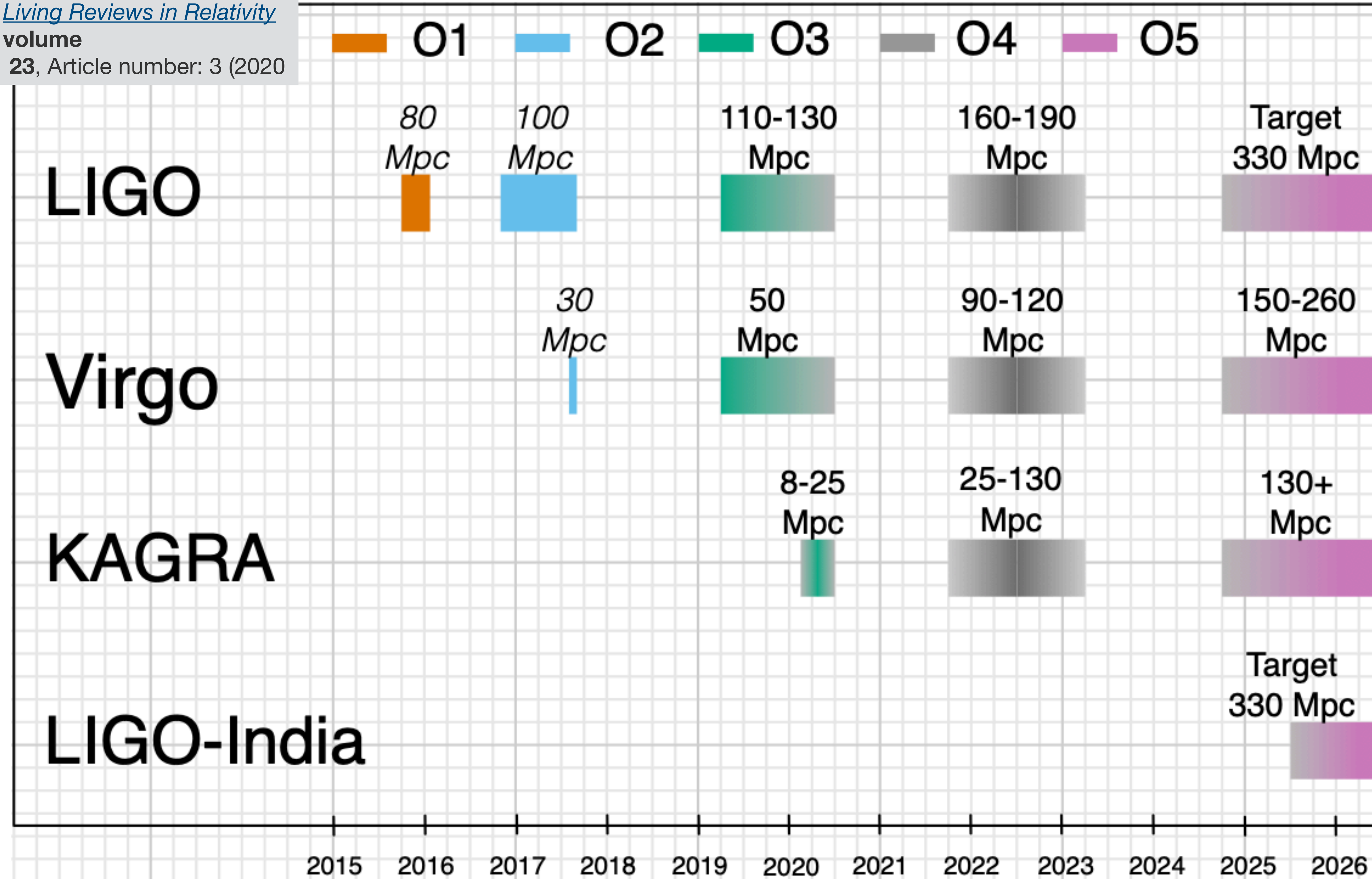
Merging Neutron Stars

Animation by NASA Goddard

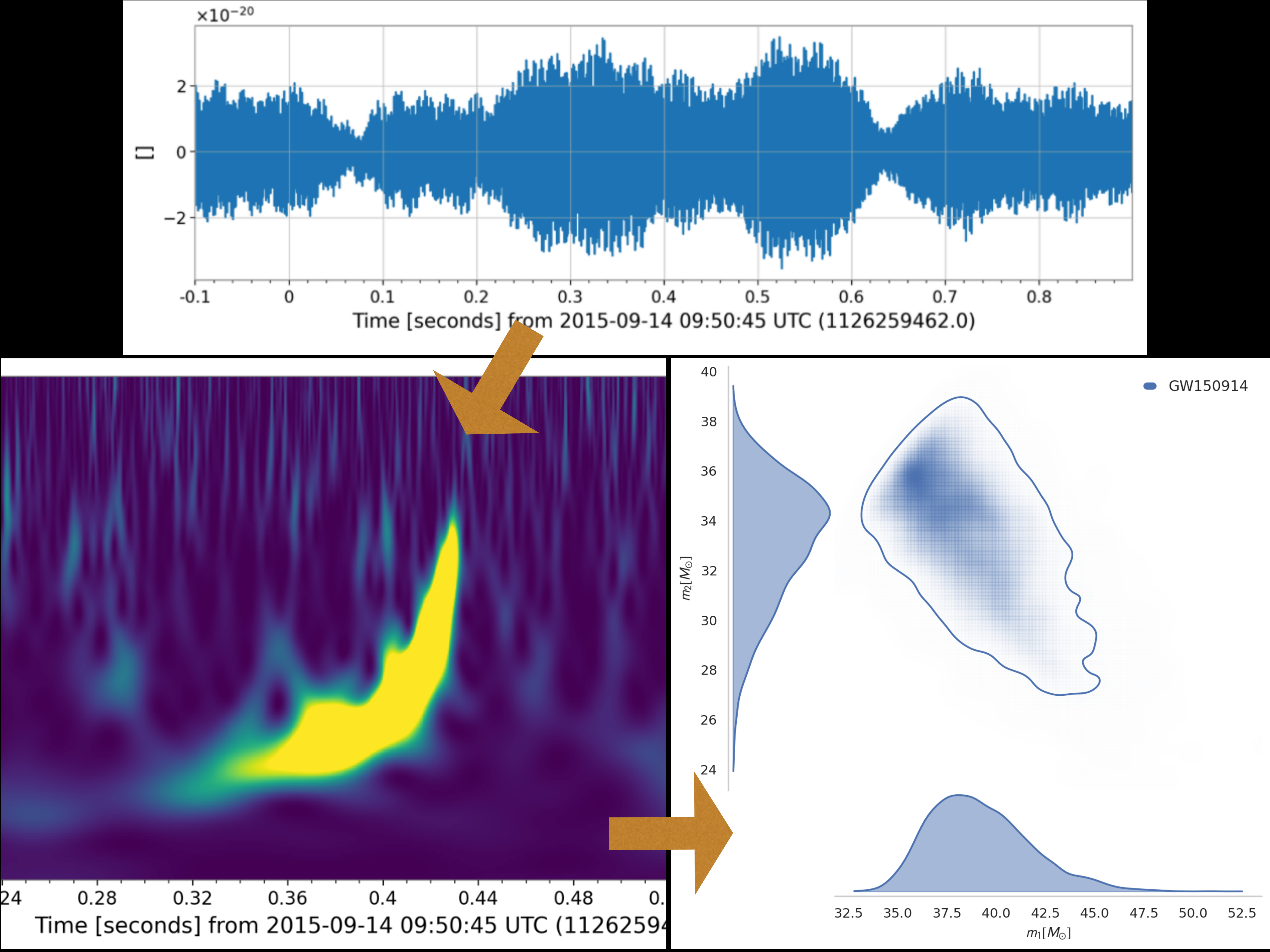


Living Reviews in Relativity **volume 23**, Article number: 3 (2020)

Living Reviews in Relativity volume 23, Article number: 3 (2020



$N \propto r^3$	O1	O2	O3	O4	O5
	N ~ 3	N ~ 8	N ~ 70	N ~ 200	N ~ 1000,


×10−20
2
0
−2
[]
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Time [seconds] from 2015-09-14 09:50:45 UTC (1126259462.0)
24
0.28
0.32
0.36
0.4
0.44
0.48
0.
Time [seconds] from 2015-09-14 09:50:45 UTC (1126259
GW150914
40
38
36
34
32
30
28
26
24
$m_2[M_\odot]$
32.5
35.0
37.5
40.0
42.5
45.0
47.5
50.0
52.5
$m_1[M_\odot]$

Gravitational Wave Transient Catalogs

GWTC - 1: O1 & O2

GWTC - 2: O3a

GWTC - 3: O3b

Soon!

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. X **9**, 031040 – Published 4 September 2019

R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. X **11**, 021053 – Published 9 June 2021

Catalogs and Data:
gw-openscience.org/eventapi

New Search | Help

Event List

GWTC

The GWTC (Gravitational Wave Transient Catalog) is a cumulative set of gravitational wave transients maintained by the LIGO/Virgo/KAGRA collaboration. The GWTC contains events from multiple data releases; for details, see documentation for individual releases: GWTC-1 and GWTC-2.

Note, this catalog is only updated periodically, and may not contain recently published events. For the most recent events, you can browse all available events.

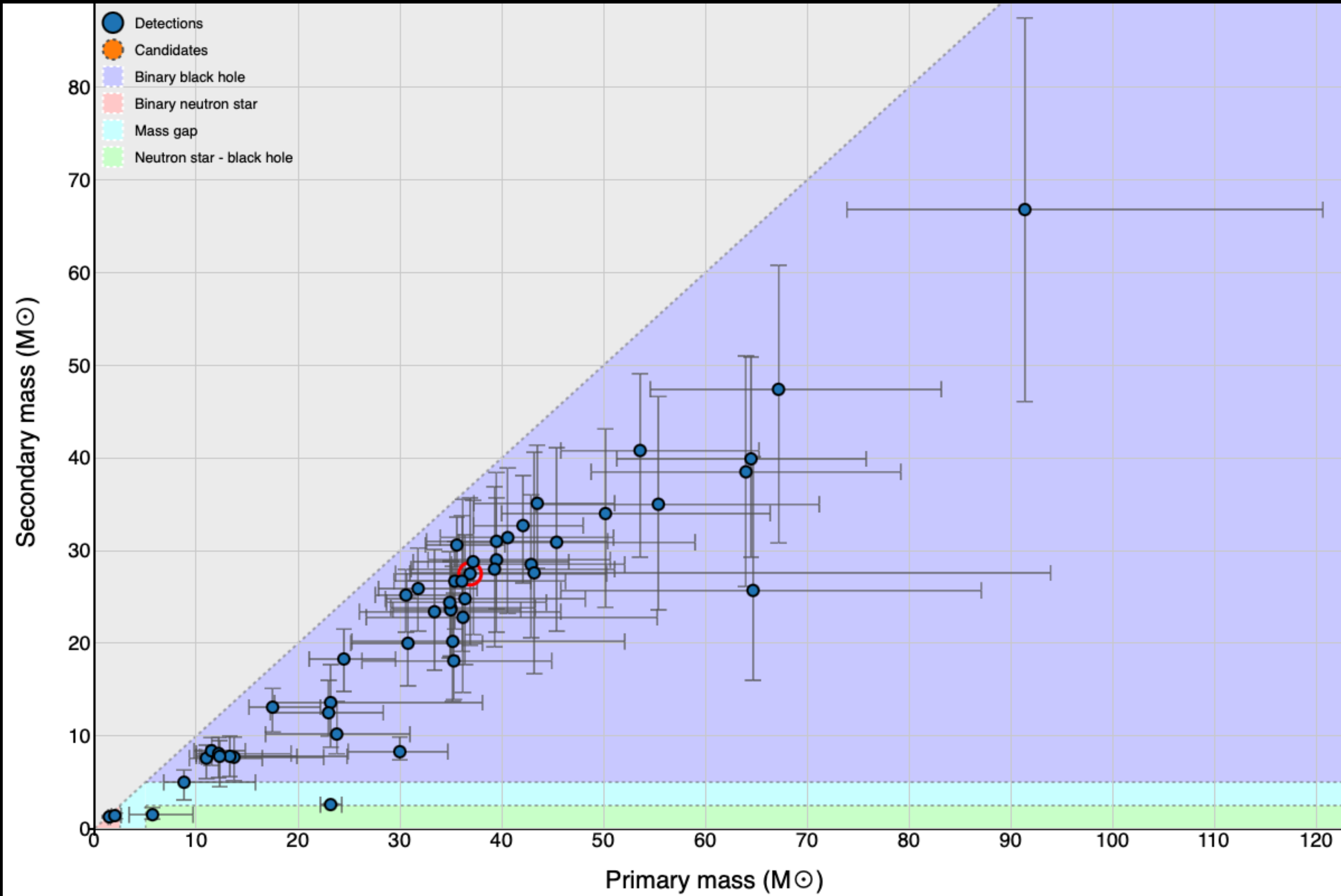
- Toggle columns on/off with widget at right
- Click an event name for more information

GWTC

gw-openscience.org

SORT: GPS ↓

Name	Version	Release	GPS ↓	Mass 1 ($M_\odot$)	Mass 2 ($M_\odot$)	Network SNR	Distance (Mpc)	χ_{eff}	Total Mass ($M_\odot$)
GW190930_133541	v1	GWTC-2	1253885759.2	$12.3^{+12.4}_{-2.3}$	$7.8^{+1.7}_{-3.3}$	9.8	760^{+360}_{-320}	$0.14^{+0.31}_{-0.15}$	$20.3^{+8.9}_{-1.5}$
GW190929_012149	v1	GWTC-2	1253755327.5	$80.8^{+33.0}_{-33.2}$	$24.1^{+19.3}_{-10.6}$	9.9	2130^{+3650}_{-1050}	$0.01^{+0.34}_{-0.33}$	$104.3^{+34.9}_{-25.2}$
GW190924_021846	v1	GWTC-2	1253326744.8	$8.9^{+7.0}_{-2.0}$	$5.0^{+1.4}_{-1.9}$	13.2	570^{+220}_{-220}	$0.03^{+0.30}_{-0.09}$	$13.9^{+5.1}_{-1.0}$
GW190915_235702	v1	GWTC-2	1252627040.7	$35.3^{+9.5}_{-6.4}$	$24.4^{+5.6}_{-6.1}$	13.1	1620^{+710}_{-610}	$0.02^{+0.20}_{-0.25}$	$59.9^{+7.5}_{-6.4}$
GW190910_112807	v1	GWTC-2	1252150105.3	$43.9^{+7.6}_{-6.1}$	$35.6^{+6.3}_{-7.2}$	13.4	1460^{+1030}_{-580}	$0.02^{+0.18}_{-0.18}$	$79.6^{+9.3}_{-9.1}$
GW190909_114149	v1	GWTC-2	1252064527.7	$45.8^{+52.7}_{-13.3}$	$28.3^{+13.4}_{-12.7}$	8.5	3770^{+3270}_{-2220}	$-0.06^{+0.37}_{-0.36}$	$75.0^{+55.9}_{-17.6}$
GW190828_065509	v1	GWTC-2	1251010527.9	$24.1^{+7.0}_{-7.2}$	$10.2^{+3.6}_{-2.1}$	11.1	1600^{+620}_{-600}	$0.08^{+0.16}_{-0.16}$	$34.4^{+5.4}_{-4.4}$
GW190828_063405	v1	GWTC-2	1251009263.8	$32.1^{+5.8}_{-4.0}$	$26.2^{+4.6}_{-4.8}$	16.0	2130^{+660}_{-930}	$0.19^{+0.15}_{-0.16}$	$58.0^{+7.7}_{-4.8}$
GW190814	v2	GWTC-2	1249852257.0	$23.2^{+1.1}_{-1.0}$	$2.6^{+8.0e-02}_{-9.0e-02}$	22.2	240^{+40}_{-50}	$0.00^{+0.06}_{-0.06}$	$25.8^{+1.0}_{-0.9}$
GW190803_022701	v1	GWTC-2	1248834439.9	$37.3^{+10.6}_{-7.0}$	$27.3^{+7.8}_{-8.2}$	8.6	3270^{+1950}_{-1580}	$-0.03^{+0.24}_{-0.27}$	$64.5^{+12.6}_{-9.0}$
GW190731_140936	v1	GWTC-2	1248617394.6	$41.5^{+12.2}_{-9.0}$	$28.8^{+9.7}_{-9.5}$	8.5	3300^{+2390}_{-1720}	$0.06^{+0.24}_{-0.24}$	$70.1^{+15.8}_{-11.3}$
GW190728_064510	v1	GWTC-2	1248331528.5	$12.3^{+7.2}$	$8.1^{+1.7}$	13.6	870^{+260}	$0.12^{+0.20}$	$20.6^{+4.5}$



http://catalog.cardiffgravity.org

GWTC: 50 mergers & counting!

Catalogs using public data

There are groups searching public data for GW's
Some are finding new signals!

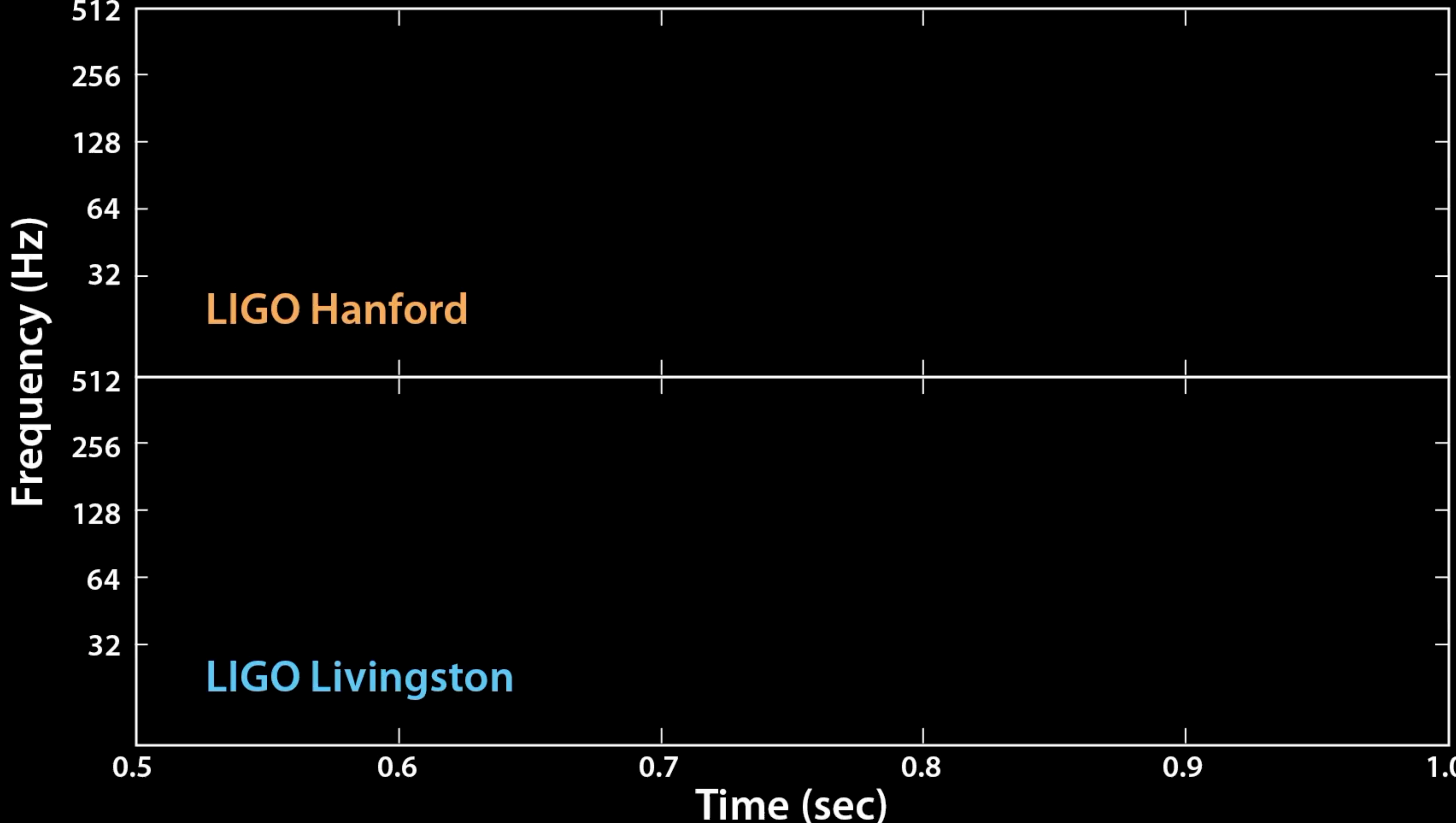
Third Open Gravitational-wave Catalog (3-OGC) reports 4 new binary black holes in O3a

Venumadhav et al (2020) report 6 discoveries in O2 data

Phys. Rev. D **101**, 083030 – Published 27 April 2020

Nitz et al, 2021 - arXiv:2105.09151

50	GW190910_112807	1252150105.32	LV	L	0.87	-	-	13.4	-
51	GW190915_235702	1252627040.70	HLV	HL	1.00	> 100	9.0	8.6	-
52	**GW190916_200658**	1252699636.90	HLV	HL	0.88	0.22	4.9	5.9	-
53	GW190924_021846	1253326744.84	HLV	HL	1.00	> 100	6.7	10.8	-
54	**GW190925_232845**	1253489343.12	HV	HV	1.00	> 100	8.2	-	5.4
55	**GW190926_050336**	1253509434.07	HLV	HL	0.88	0.27	5.4	5.6	-
56	GW190929_012149	1253755327.50	HLV	HL	0.98	3.08	5.8	7.4	-
57	GW190930_133541	1253885759.24	HL	HL	1.00	> 100	6.7	7.4	-



Caltech/MIT/LIGO Lab

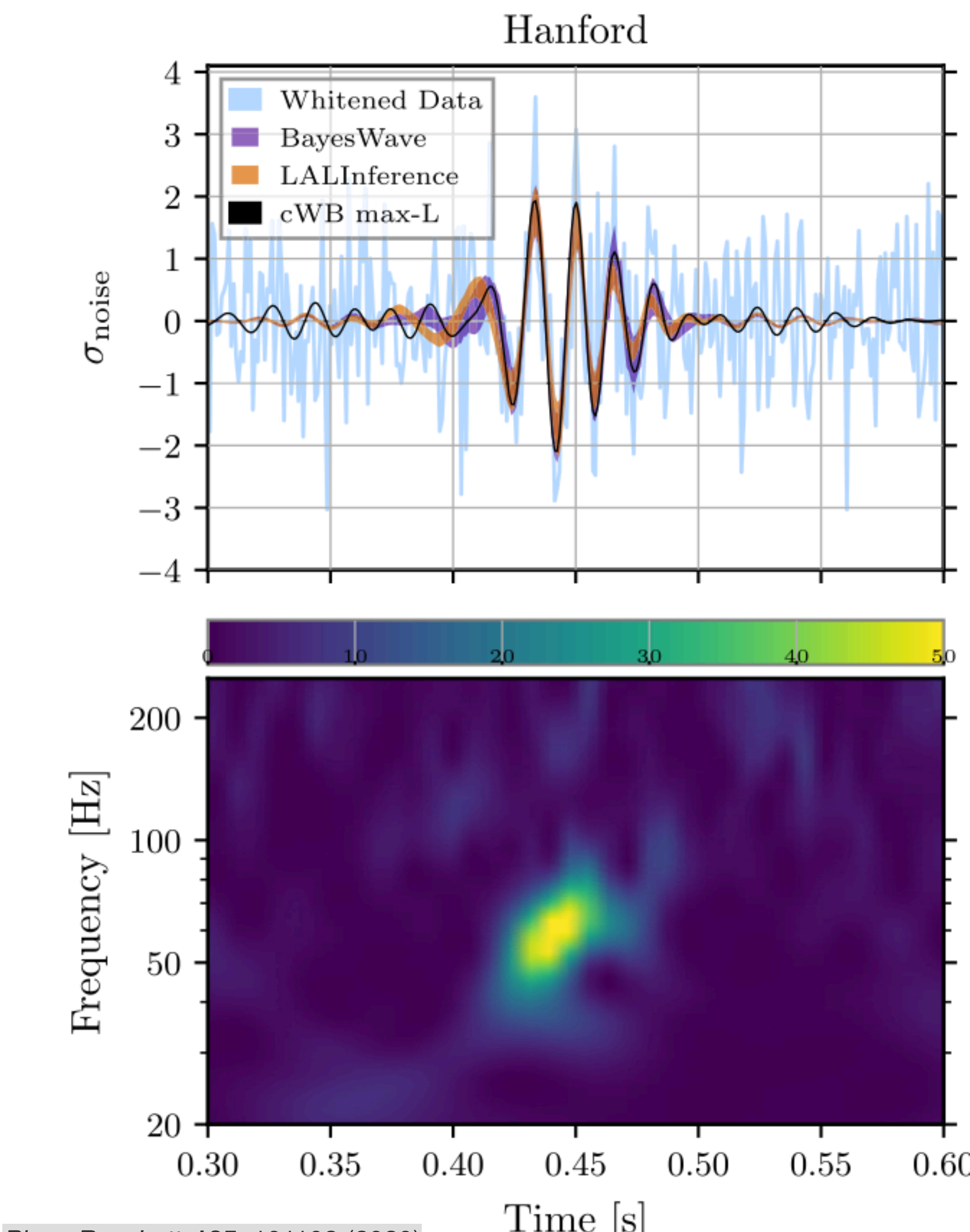
The first detection: GW150914

The biggest: GW190521

Mass 1 ($M_{\odot}$)	Mass 2 ($M_{\odot}$)
$95.3^{+28.7}_{-18.9}$	$69.0^{+22.7}_{-23.1}$

Component black holes are too large!

"Pair instability"should have shed mass from the star before collapse.



Phys. Rev. Lett. **125**, 101102 (2020)

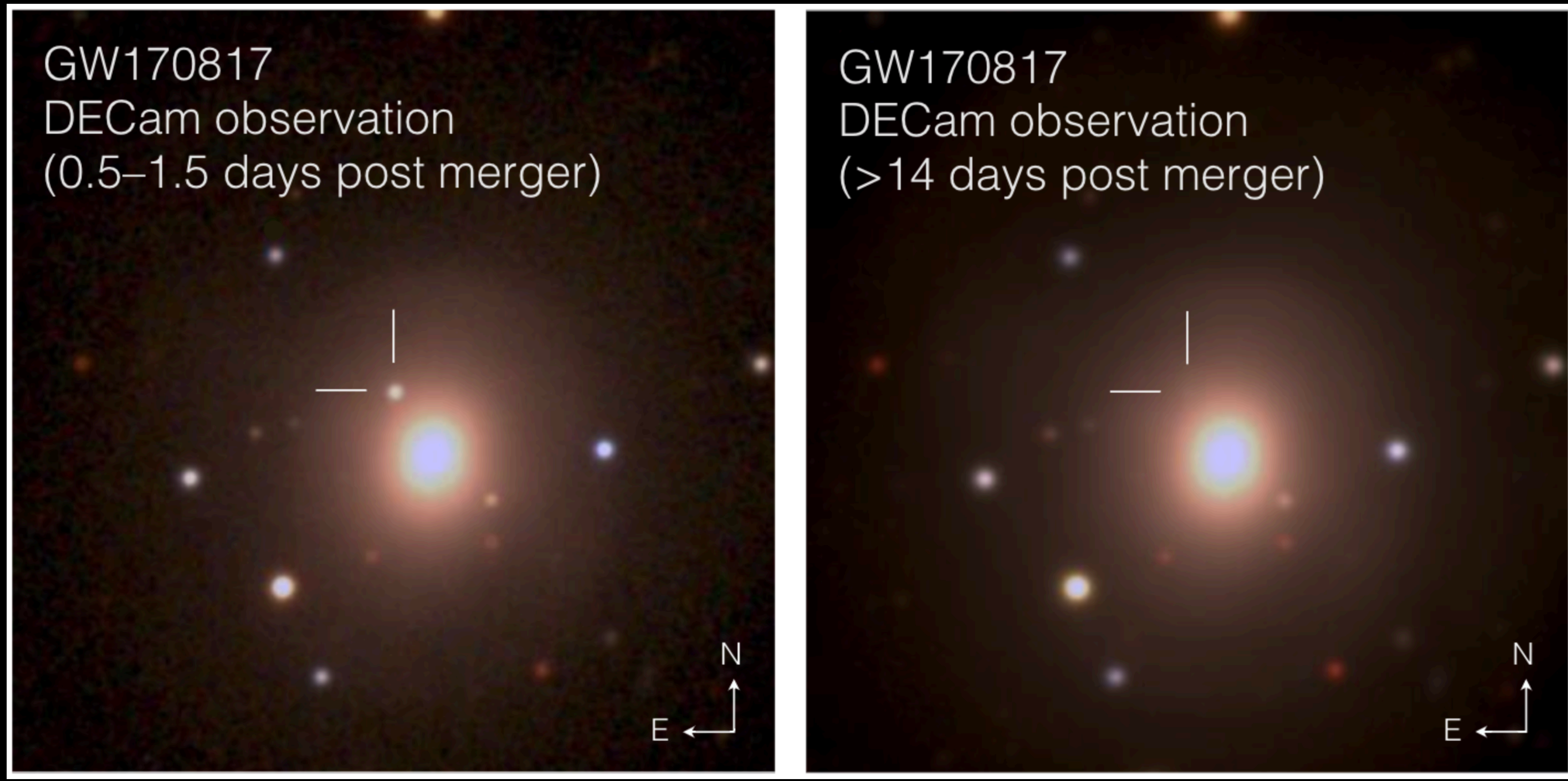
The Brightest: GW170817

First binary neutron star merger observed

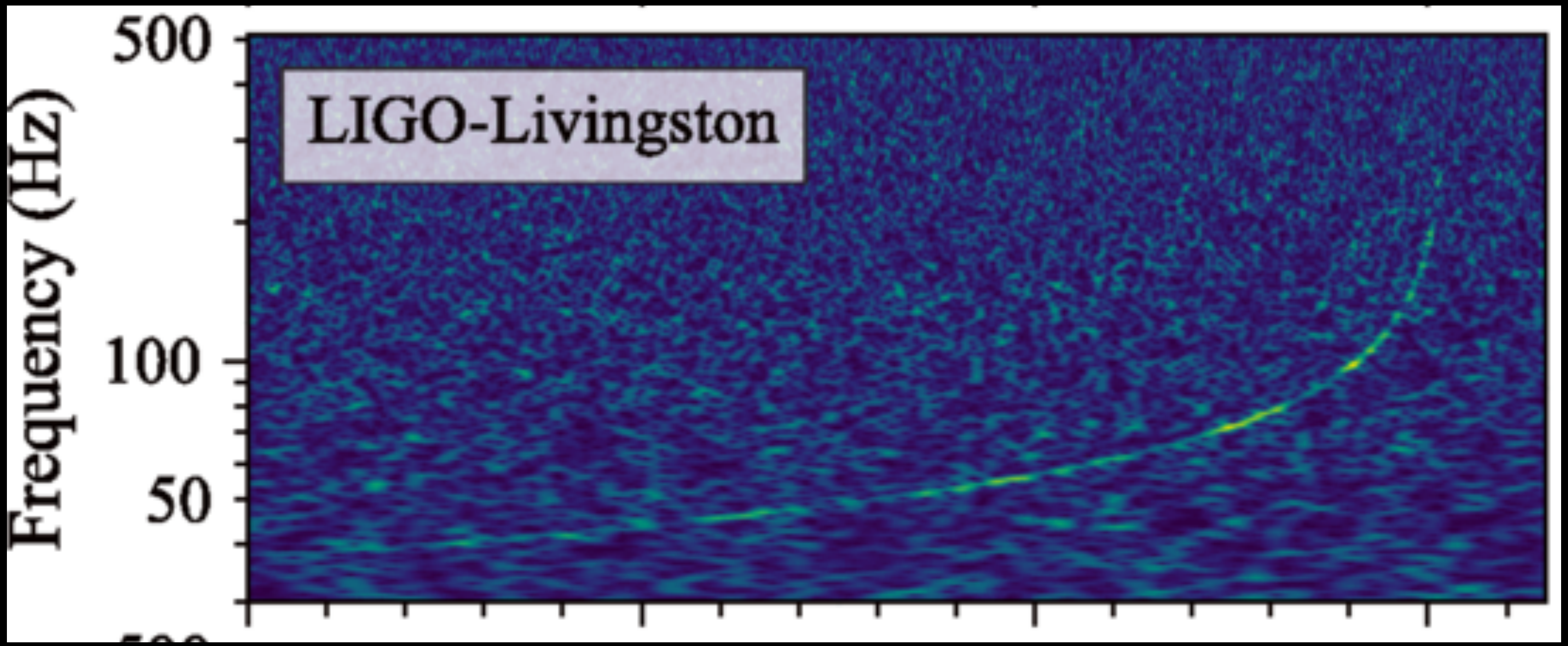
Highest SNR to date

Amazing counterpart !! [See Z. Marka's talk]

Learn about EOS, Kilonova, origin of matter, cosmology …



Astrophys. J. Lett. **848**, L12 (2017)

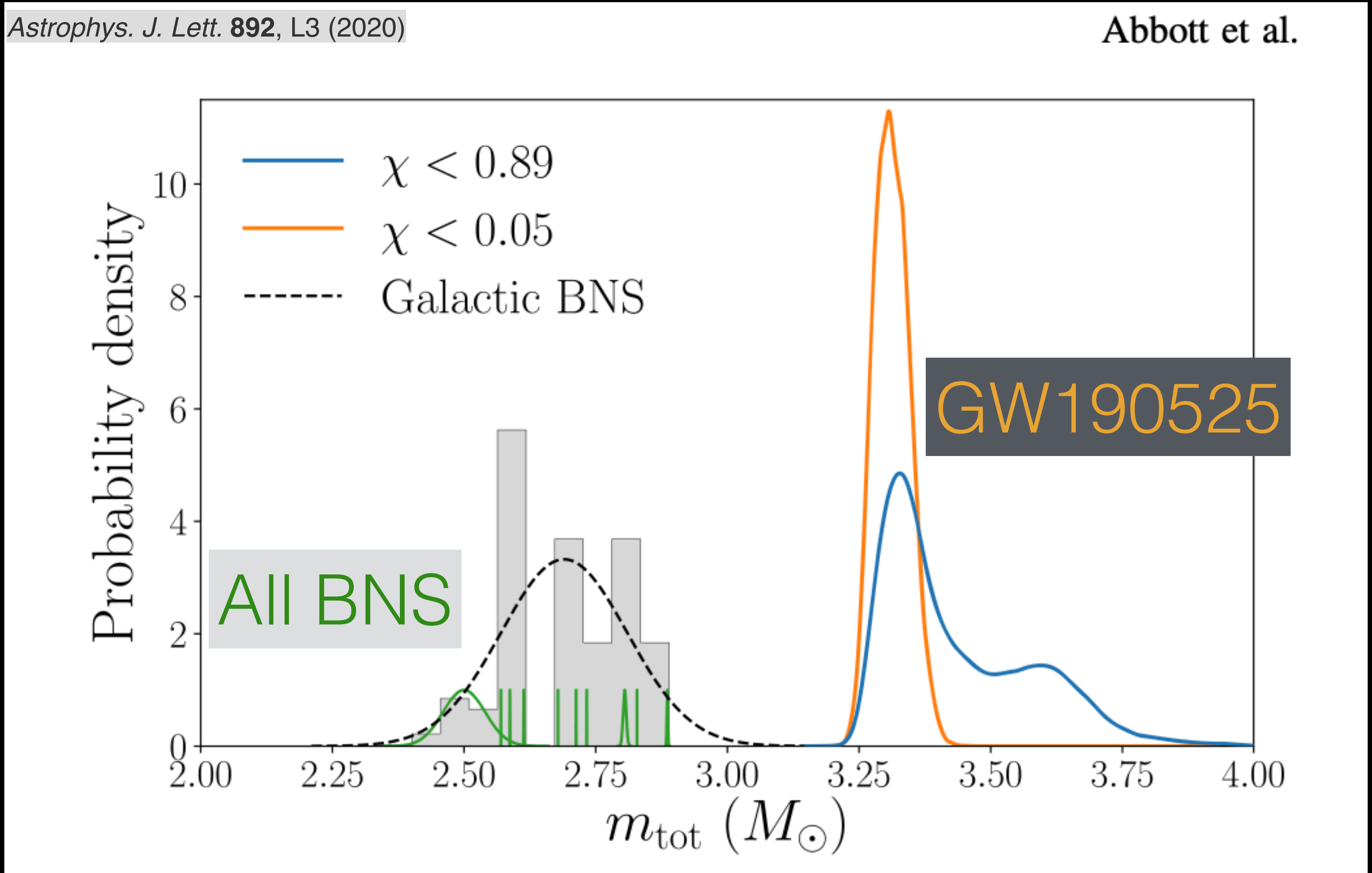


Phys. Rev. Lett. **119**, 161101 (2017)

An outlier: GW190425

Mass 1 ($M_\odot$)	Mass 2 ($M_\odot$)
$2.0^{+0.6}_{-0.3}$	$1.4^{+0.3}_{-0.3}$

- Largest binary neutron star
- Outlier from EM observed population
- Challenge to understand how it formed



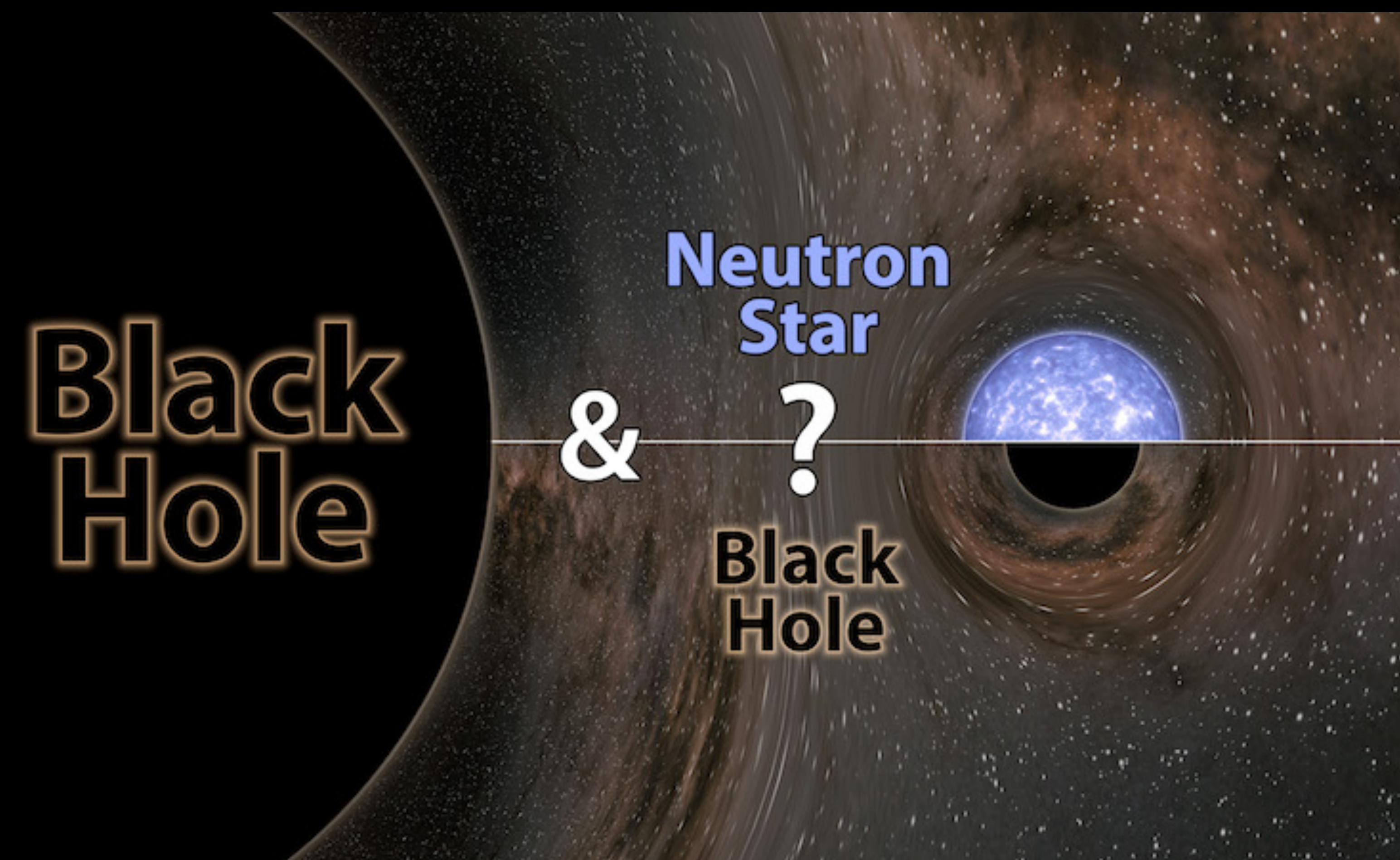
In the gap:
GW190814

Merger between a black hole and a …. ???

The 2nd object is in the “mass gap” between black holes and neutron stars

Mass 1 ($M_{\odot}$)	Mass 2 ($M_{\odot}$)
$23.2^{+1.1}_{-1.0}$	$2.6^{+8.0e-02}_{-9.0e-02}$

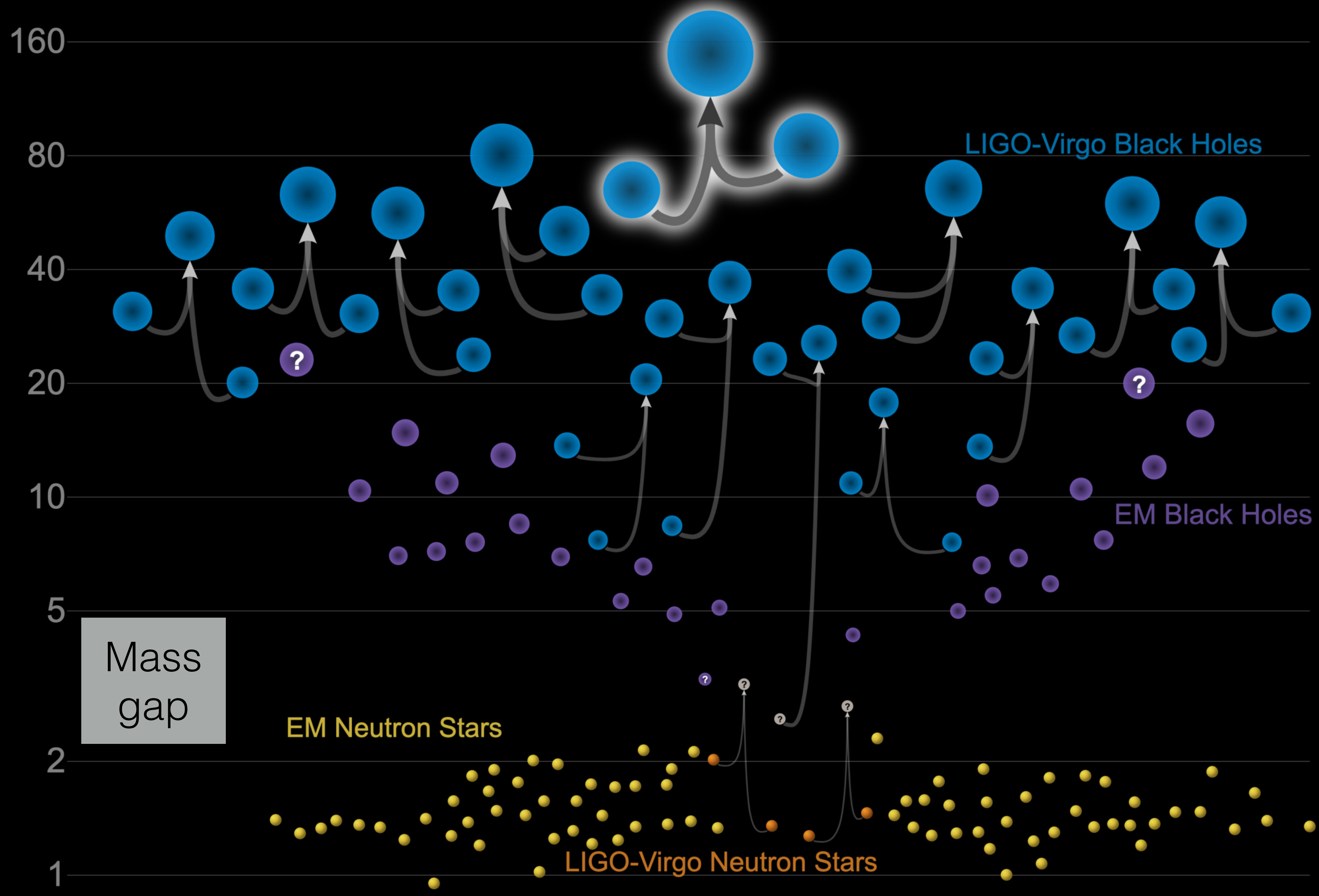
Creates a puzzle for stellar evolution models



Astrophys. J. Lett. **896**, L44 (2020)

Masses in the Stellar Graveyard

in Solar Masses

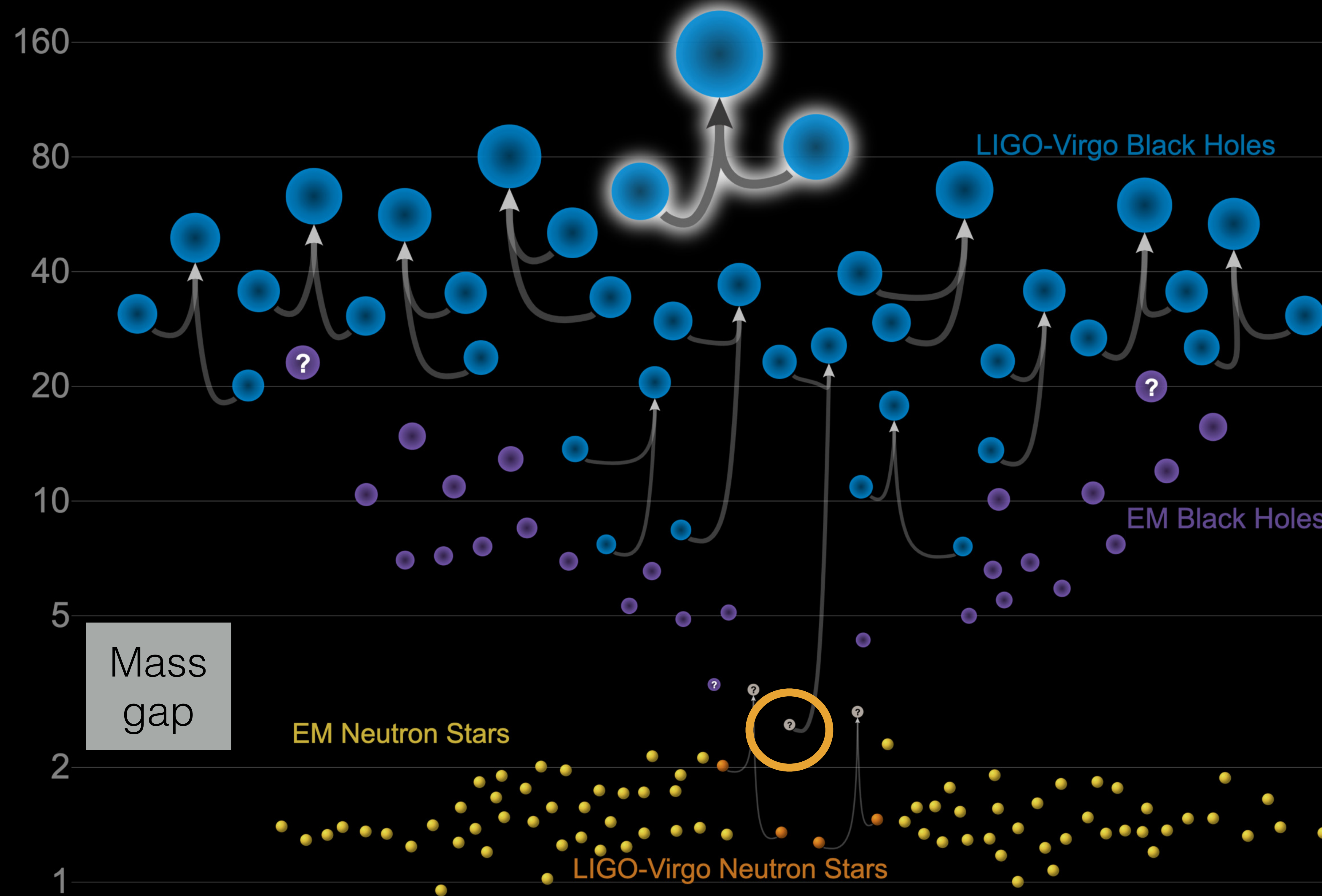


Updated 2020-09-02

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Masses in the Stellar Graveyard

in Solar Masses



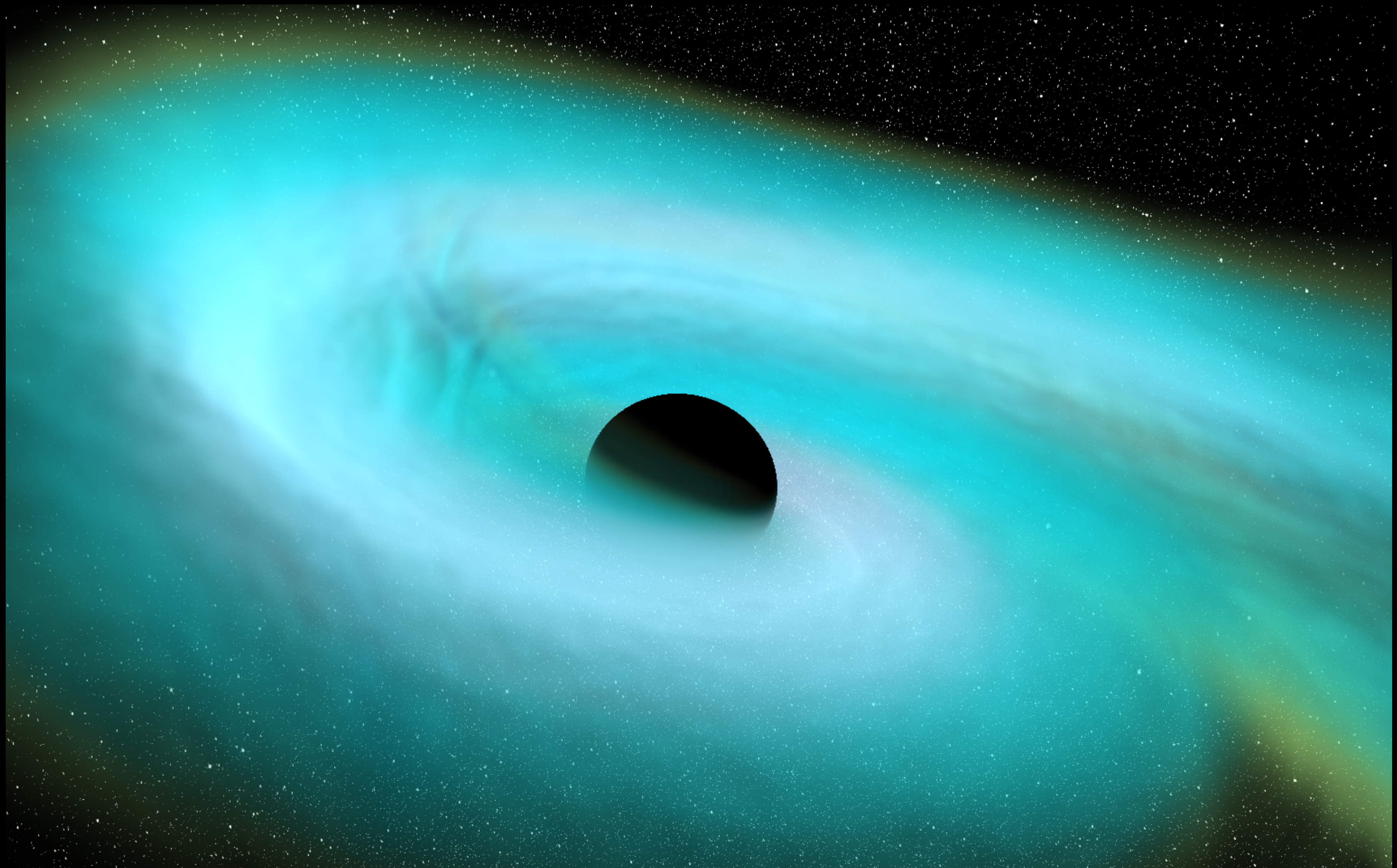
Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

The Odd Couples:
GW200105
GW200115

Most likely
Black Holes / Neutron Star mergers

Consistent with rate predictions for this type of merger

May tidally disrupt NS



Astrophys. J. Lett. **915**, L5 (2021)

VISUALIZATION: from a MAYA collaboration numerical relativity simulation of an NSBH binary merger. Focused on the merging objects showing the disruption of the NS. Under development by Deborah Ferguson (UT Ausitn), Bhavesh Khamesra (Georgia Tech), and Karan Jani (Vanderbilt).

What can we learn from these observations ?

Stellar Evolution & Population Studies

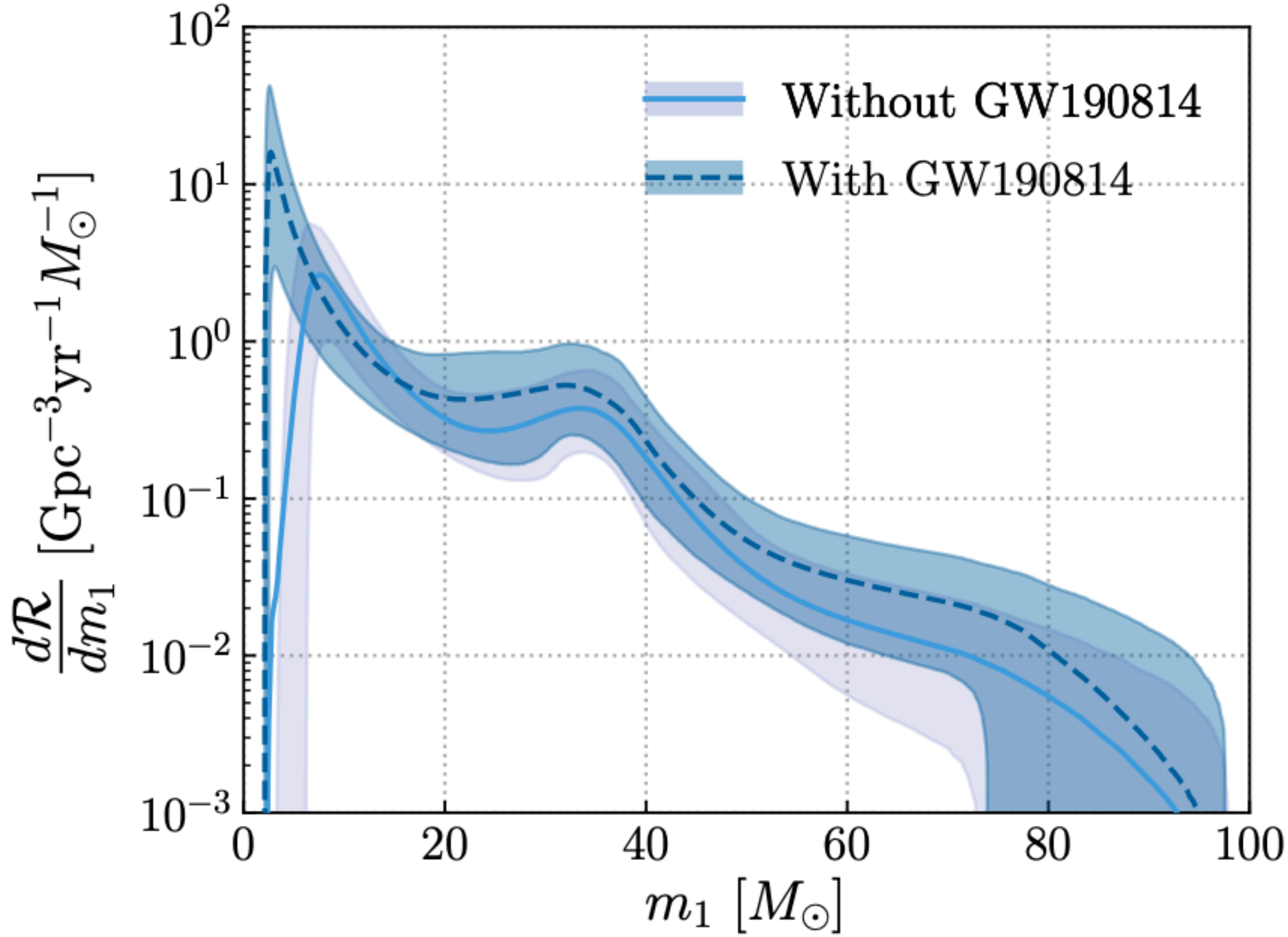
Compact object mergers are the end products of stellar evolution

By studying source populations, we learn how stars are born, grow, interact and die.

Where do black holes come from?
How many are there? How do their parent stars evolve?

There are 4 talks on this Tomorrow!

With LIGO & Virgo:
We're seeing populations we've never seen before
—> With measurements of masses and spins



(b) Power Law + Peak mass distribution fit.

Astrophys. J. Lett. **913**, L7 (2021)

Black hole mass distribution, based on GWTC-2

There is evidence for a “feature” at m = 40 (PI instability)

Less black holes above 40 solars masses (but not zero!)

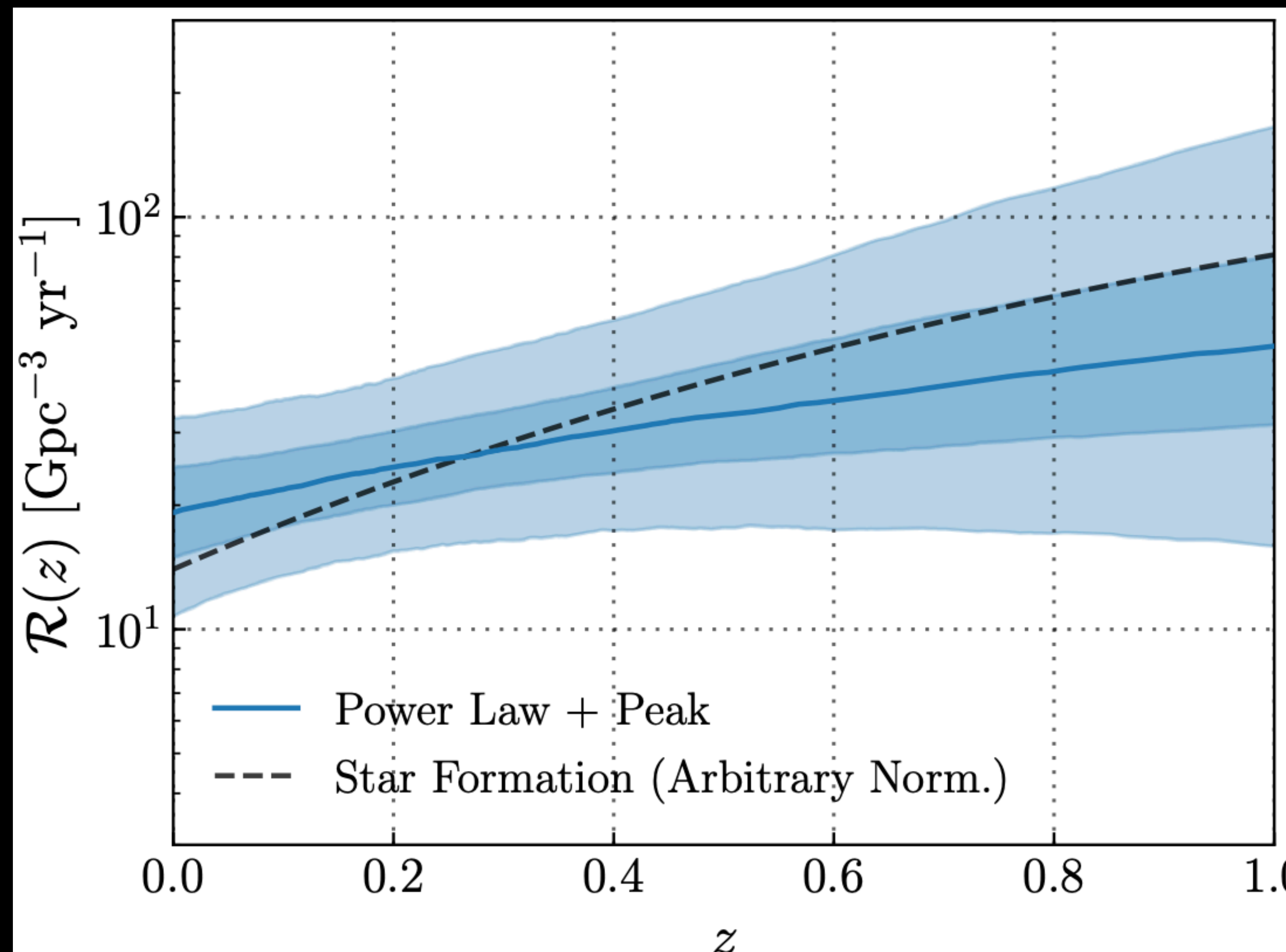
Low mass roll-off depends on how we count “gap” object

Looking back in time

Merger rate increases at higher redshift

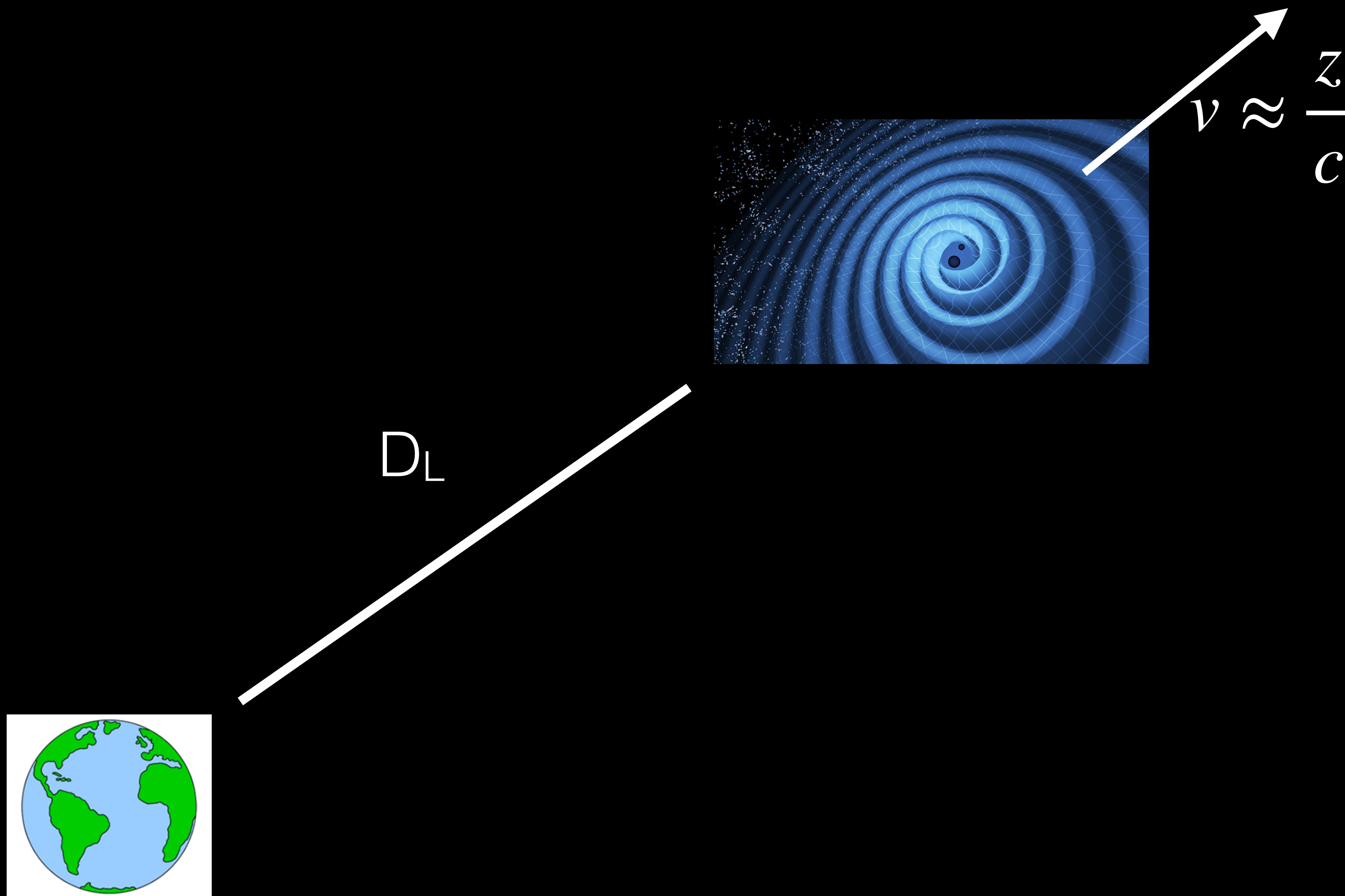
Not a shock, since star formation rate was higher in the past

Relationship will be an important clue for formation models

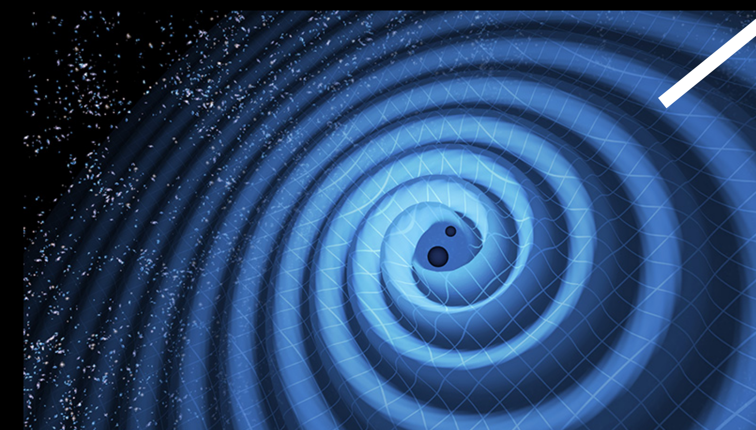


Astrophys. J. Lett. **913**, L7 (2021)

How fast is the universe expanding?



How fast is the universe expanding?

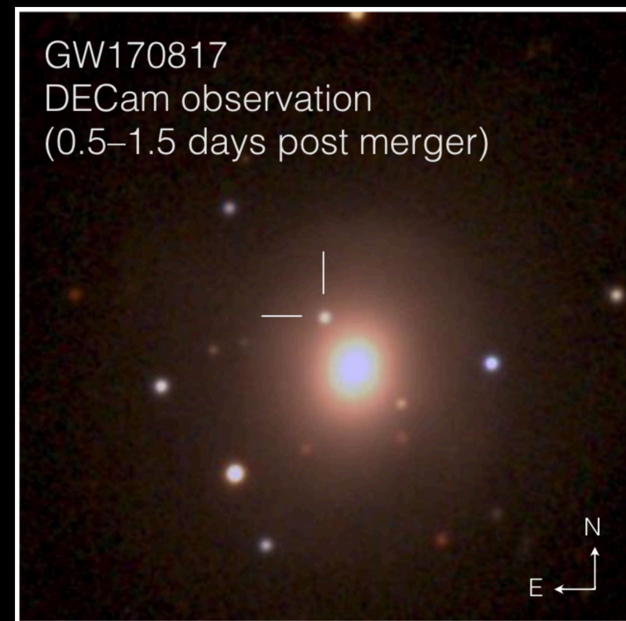


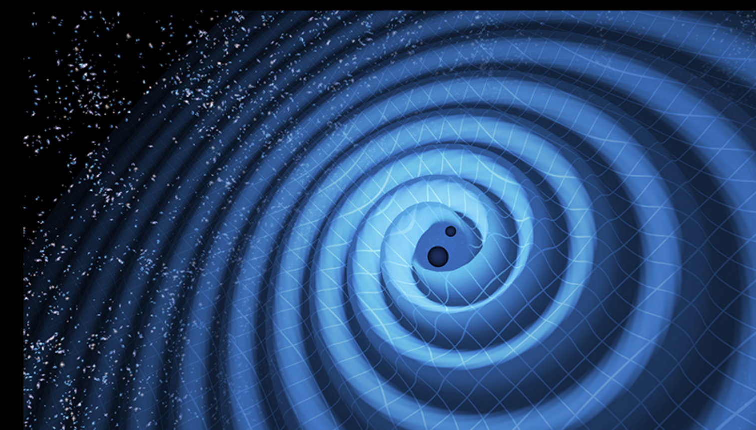
$$v \approx \frac{z}{c}$$

D_L

$$H_0 = \frac{v}{D_L}$$

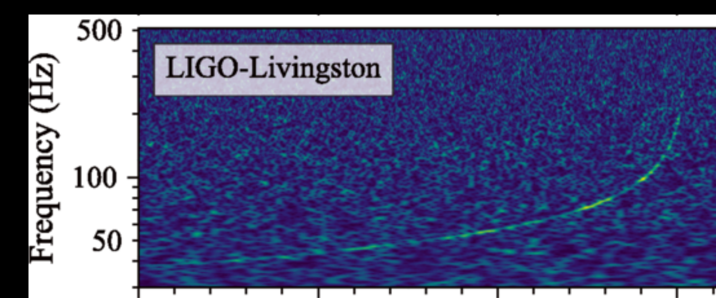
How fast is the universe expanding?





$$v \approx \frac{z}{c}$$

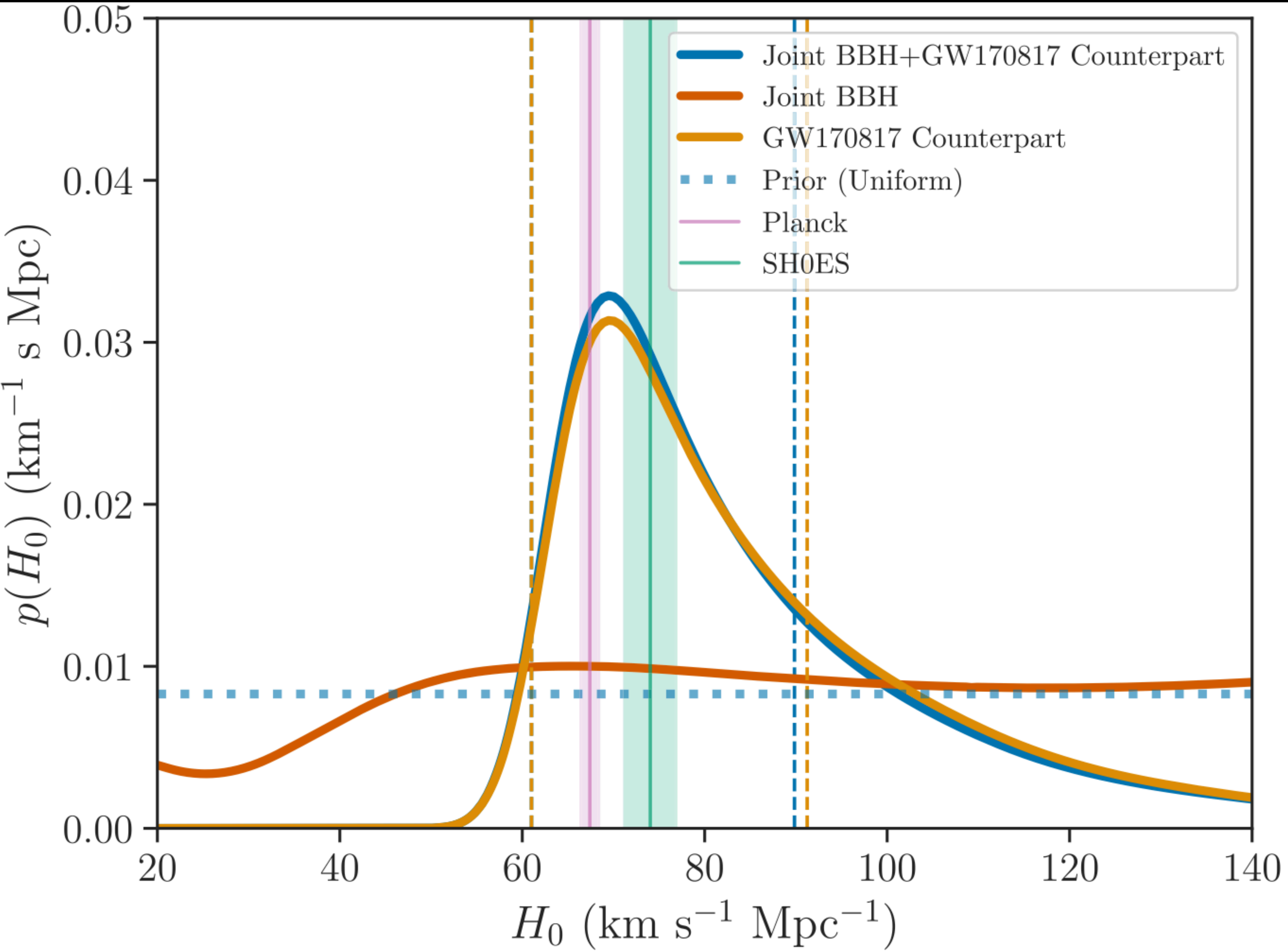
Measure z
of host galaxy



D_L

Measure D
using amplitude
of GW

$$H_0 = \frac{v}{D_L}$$



The Astrophysical Journal, 909:218 (18pp), 2021 March 10

Testing General Relativity

Merging black holes have:

- fast motion (v ~ c)
- strong gravitational fields

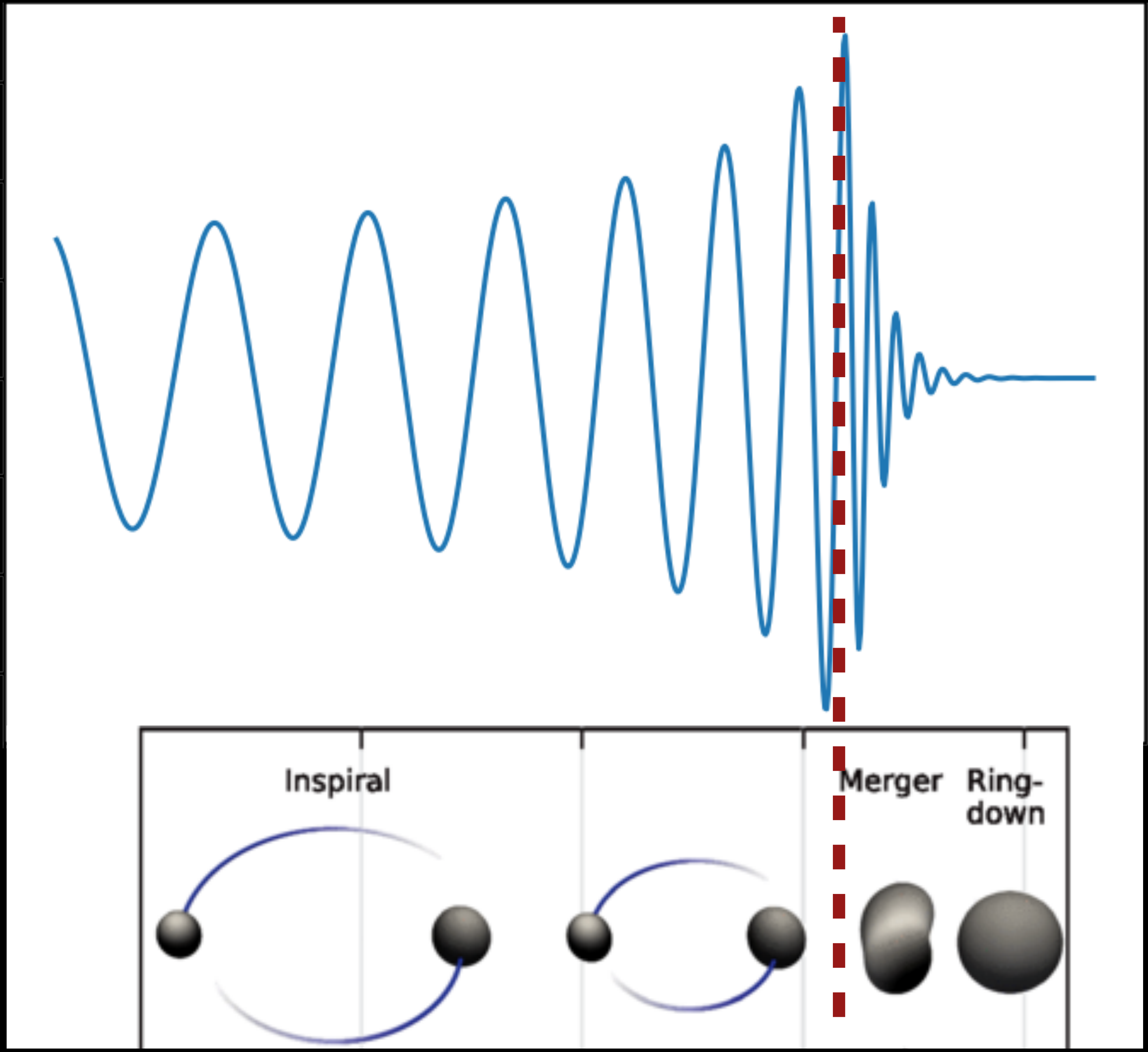
Merging black holes are a special laboratory, where we can test the “strong field” predictions of GR

Many methods! Measure mass of graviton, constrain non-GR parameters, search for echoes, search for additional polarizations …

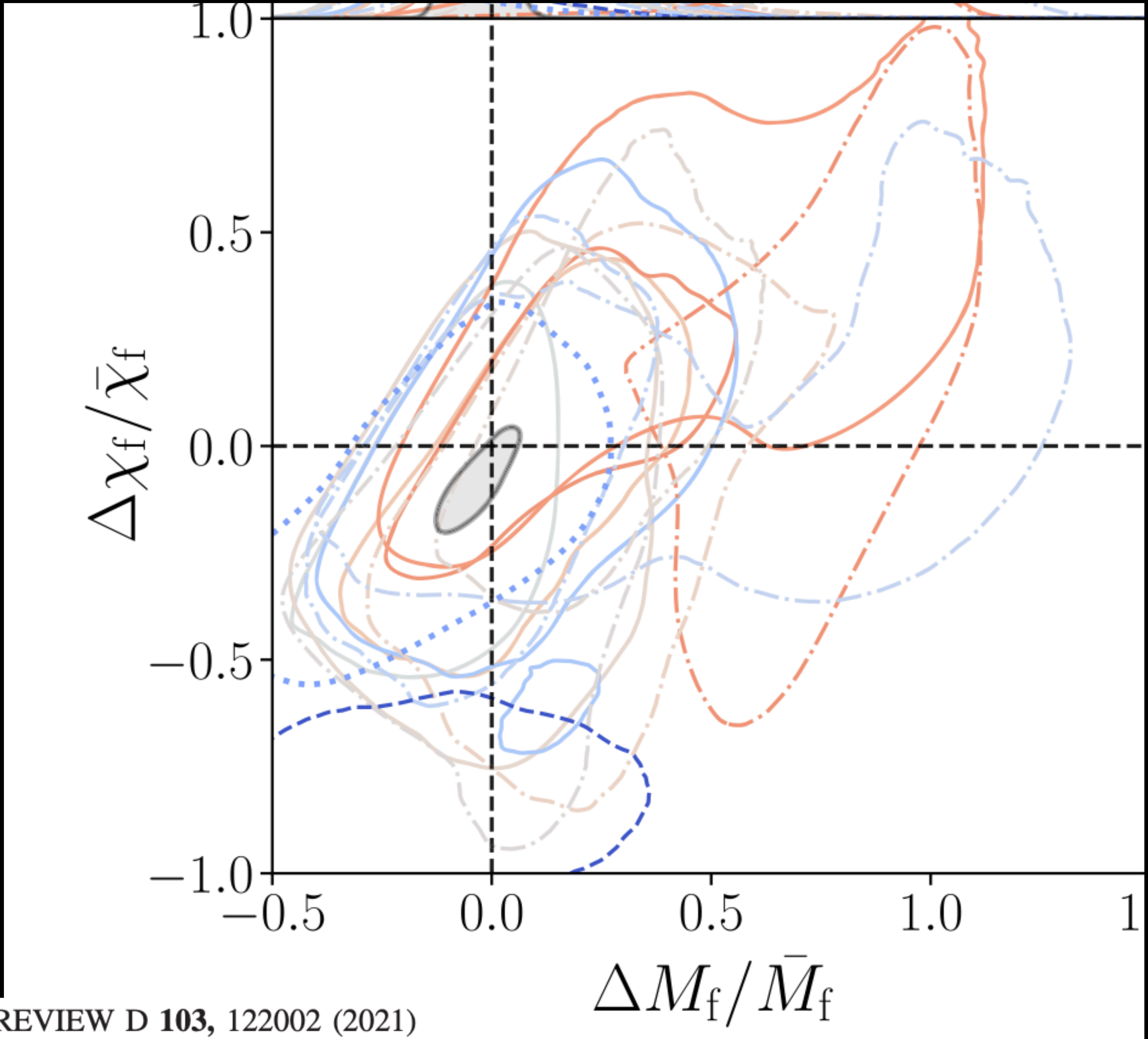
So far, GR has passed every test (!)

PHYSICAL REVIEW D **103,** 122002 (2021)

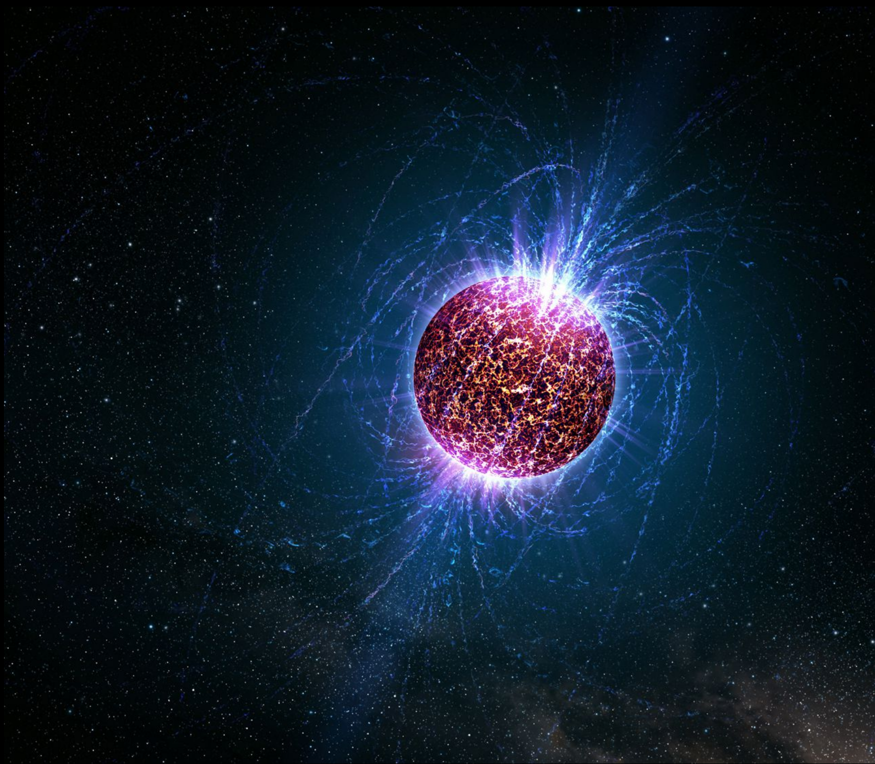
Inspiral / Ringdown Tests "no hair" theorem



Inspiral / Ringdown Tests "no hair" theorem



PHYSICAL REVIEW D **103**, 122002 (2021)

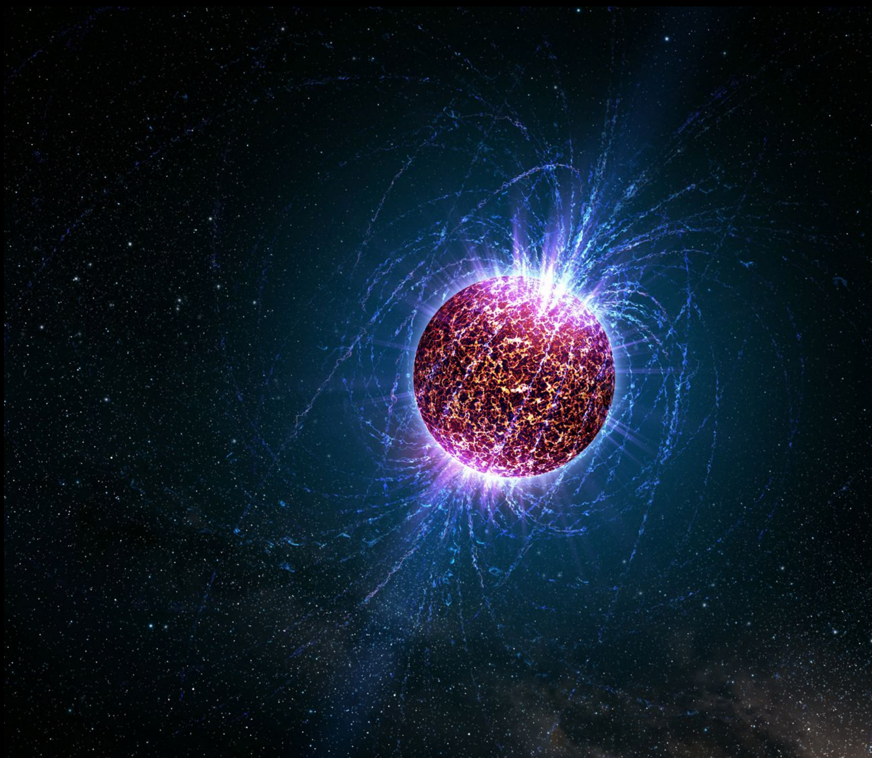


Neutron Star Equation of State

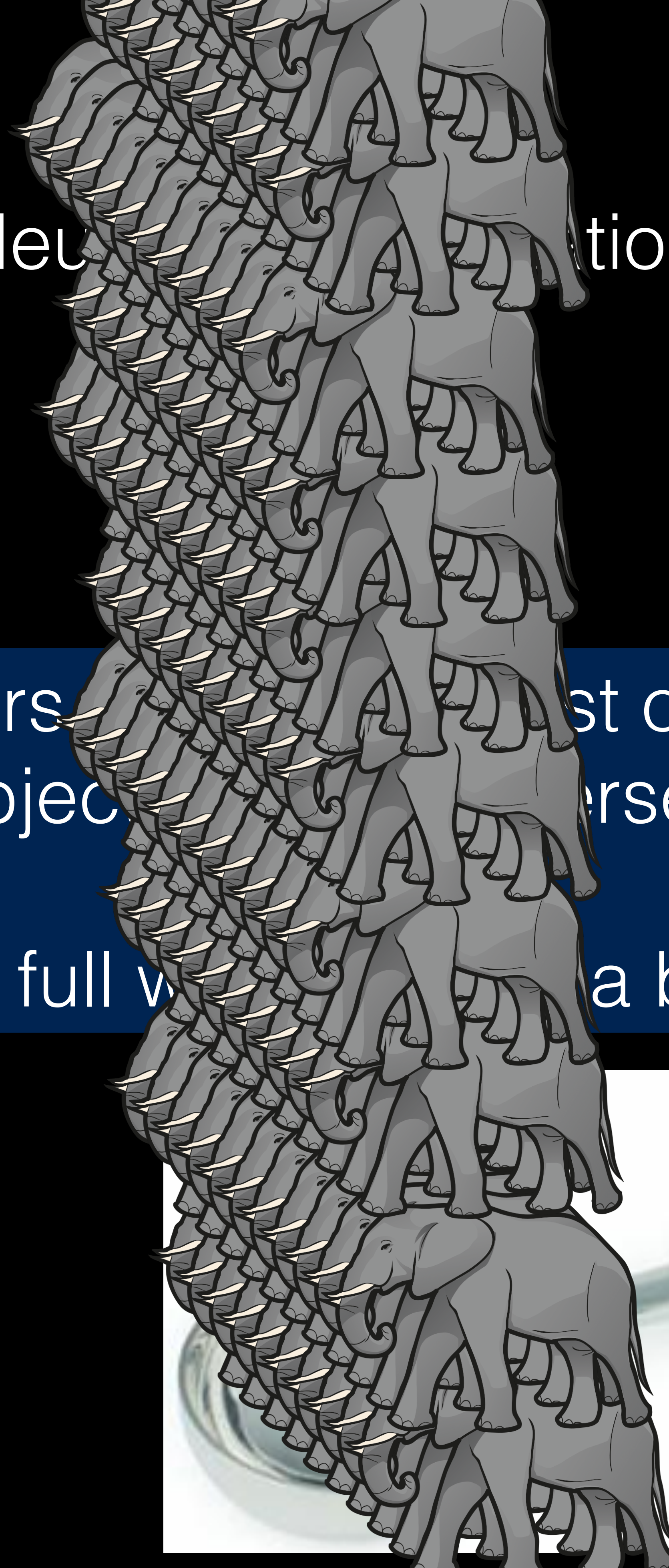
Neutron stars are the densest observable objects in the universe

[a teaspoon full would weigh a billion tons]

What's inside?

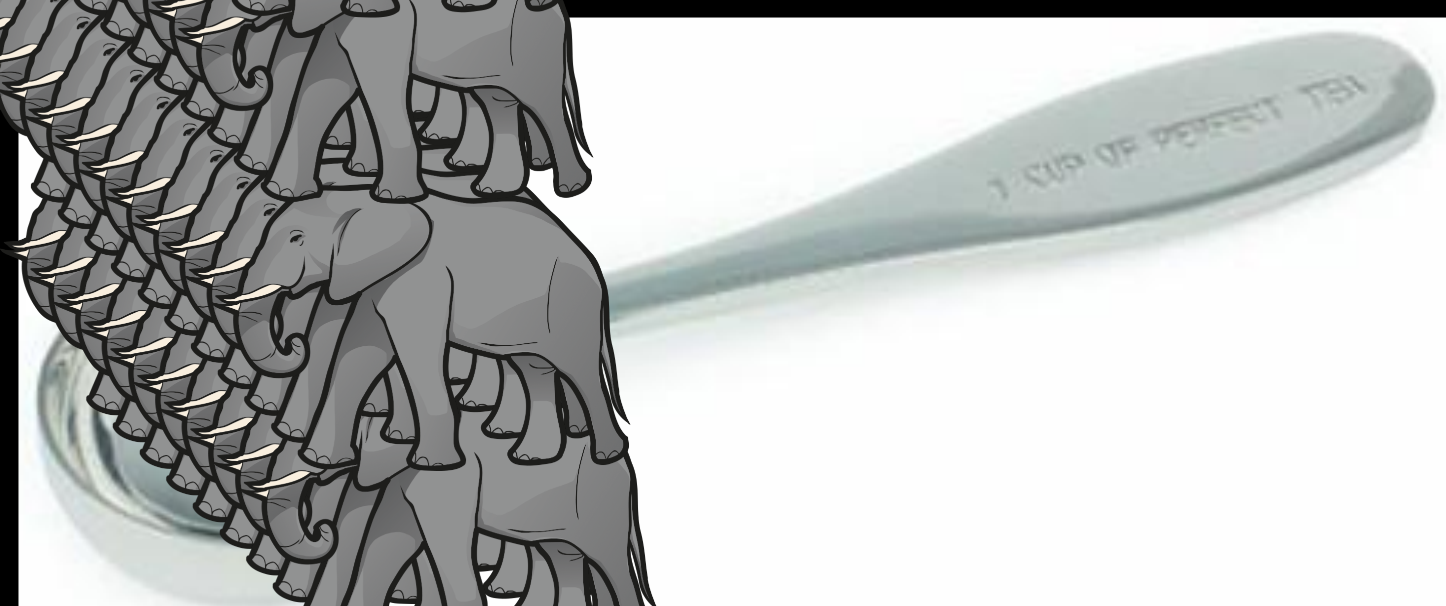


Neu tion of State



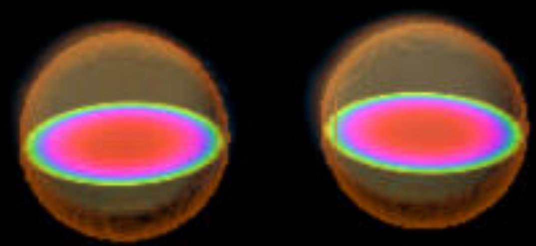
Neutron stars st observable
objec erse

[a teaspoon full w a billion tons]

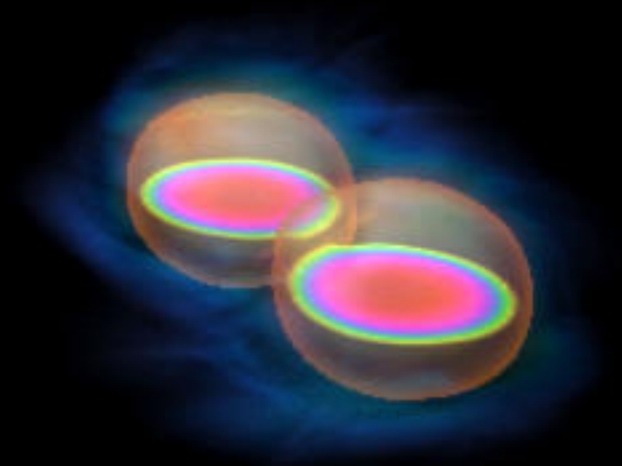


What's inside?

Neutron Star Equation of State



As neutron stars merge, tidal forces stretch them and throw off matter

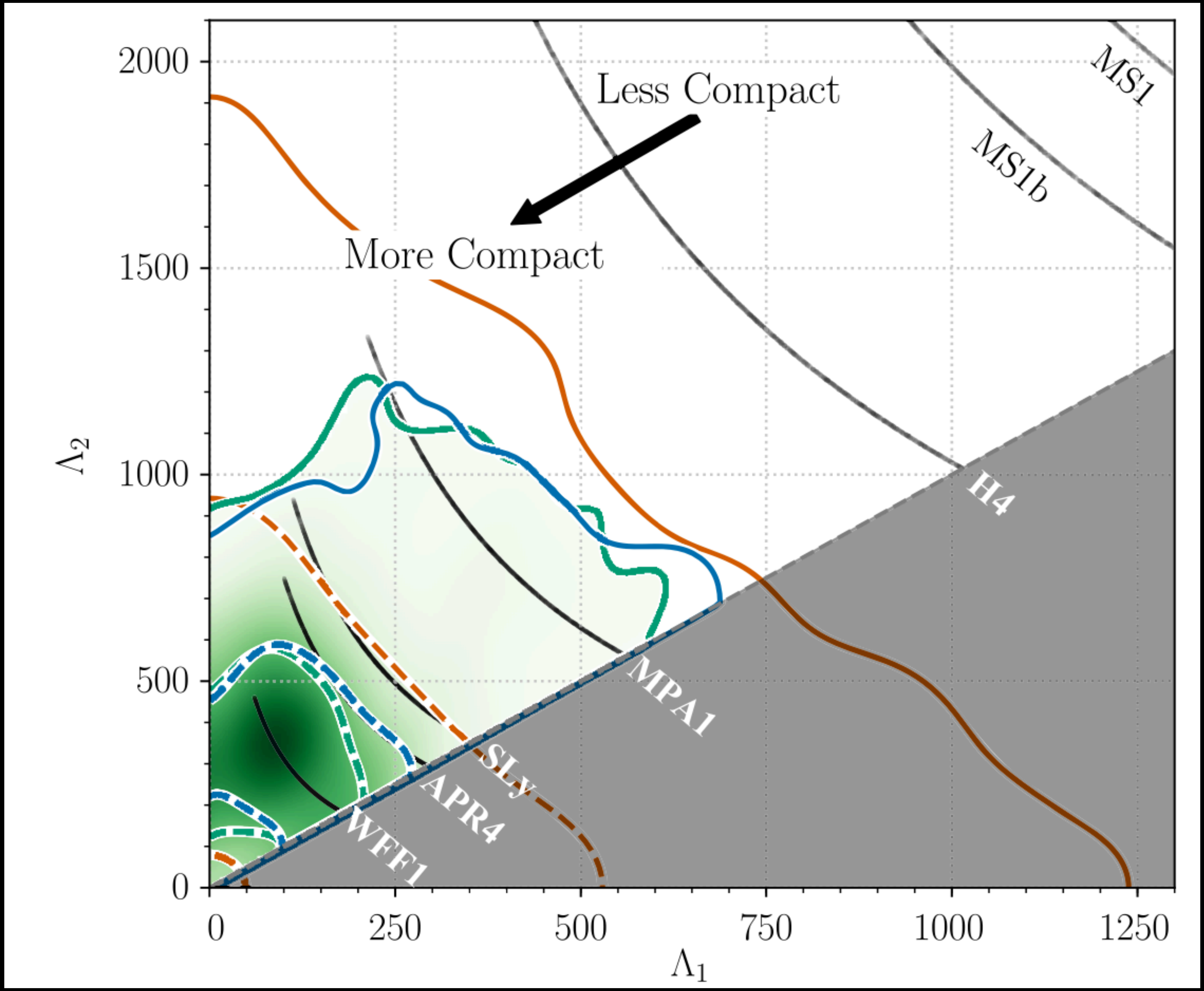


The amount of stretching leaves an imprint on the gravitational waves

We can use this signal to measure the “deformability” of the neutron star, and so measure its density and “equation of state”

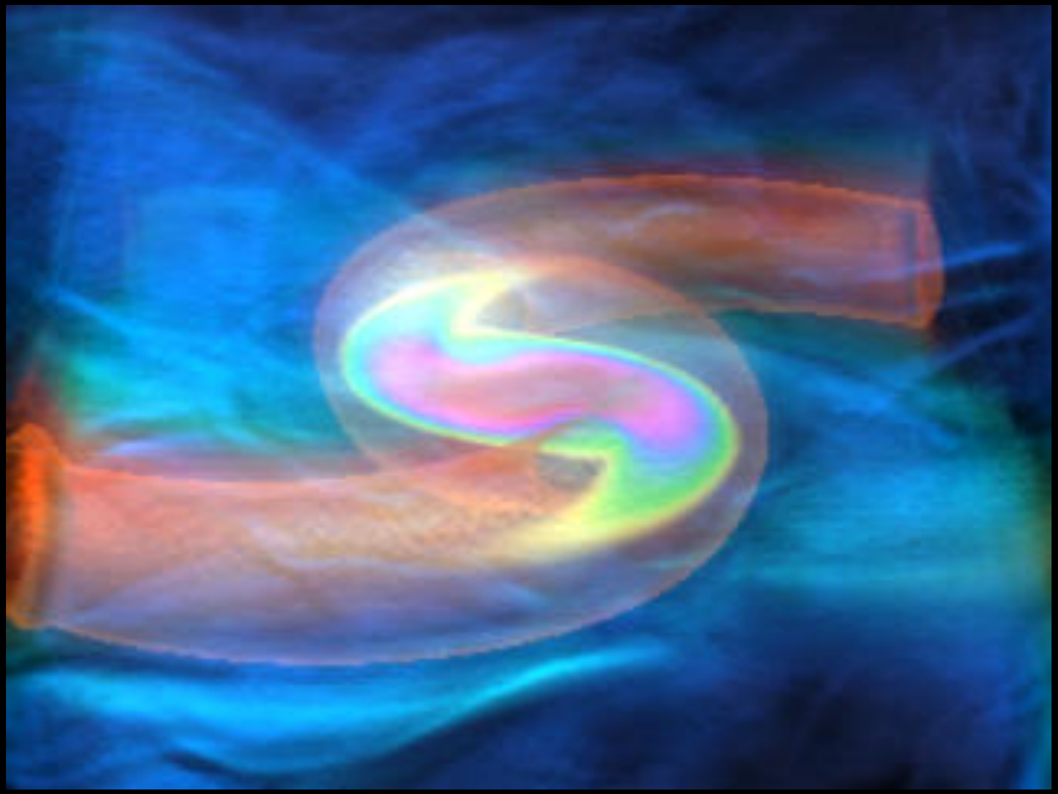
Studying extreme pressure & energy tells us about fundamental physics

Measuring the Neutron Star Equation of State



PHYSICAL REVIEW LETTERS **121,** 161101 (2018)

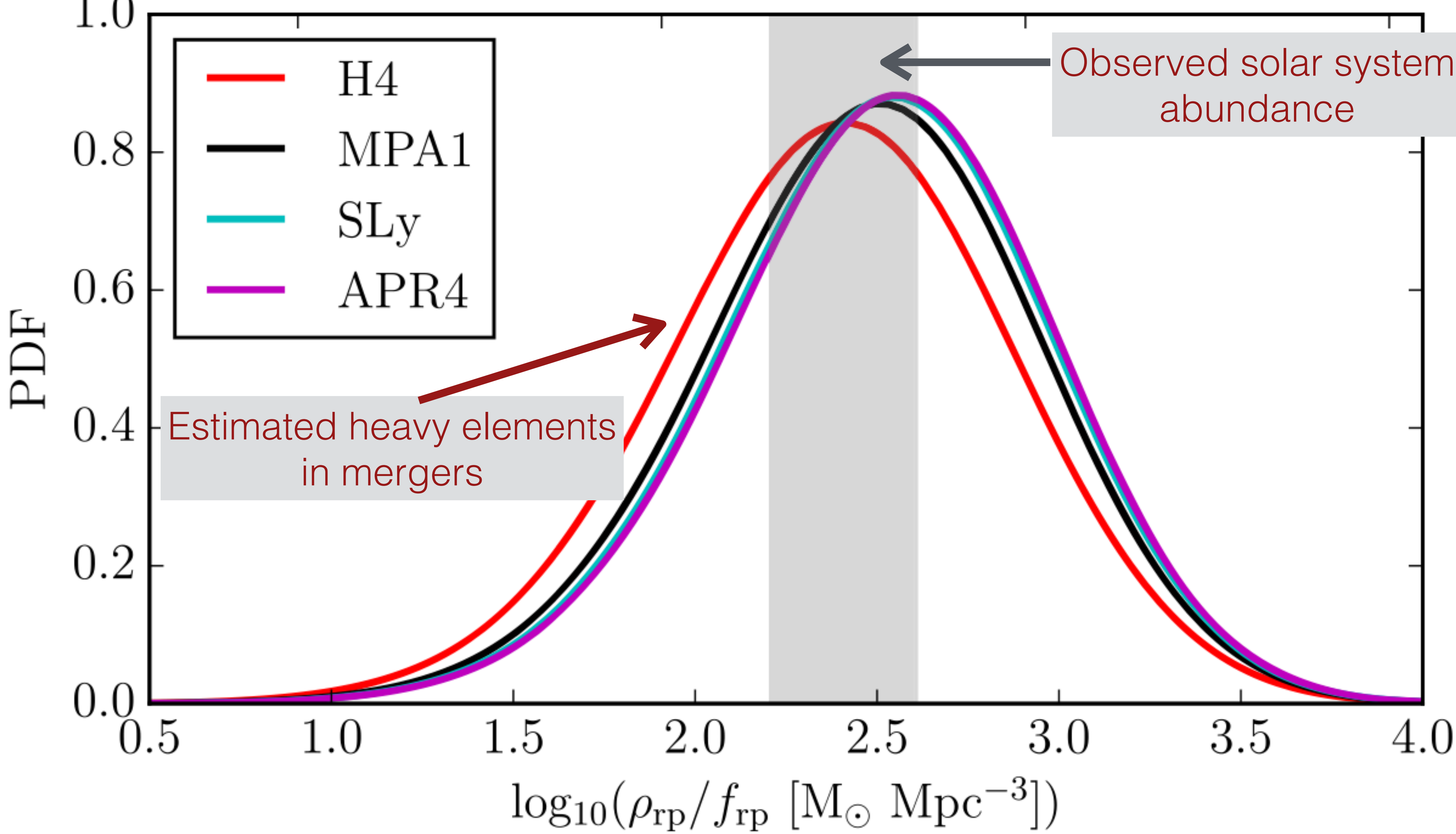
Kilonova physics & creation of heavy elements



The “stuff” that gets flung out of a NS merger is unstable

Atoms capture extra neutrons, which decay into protons, building heavier elements like gold and platinum

Can estimate the fraction of heavy elements formed in these mergers



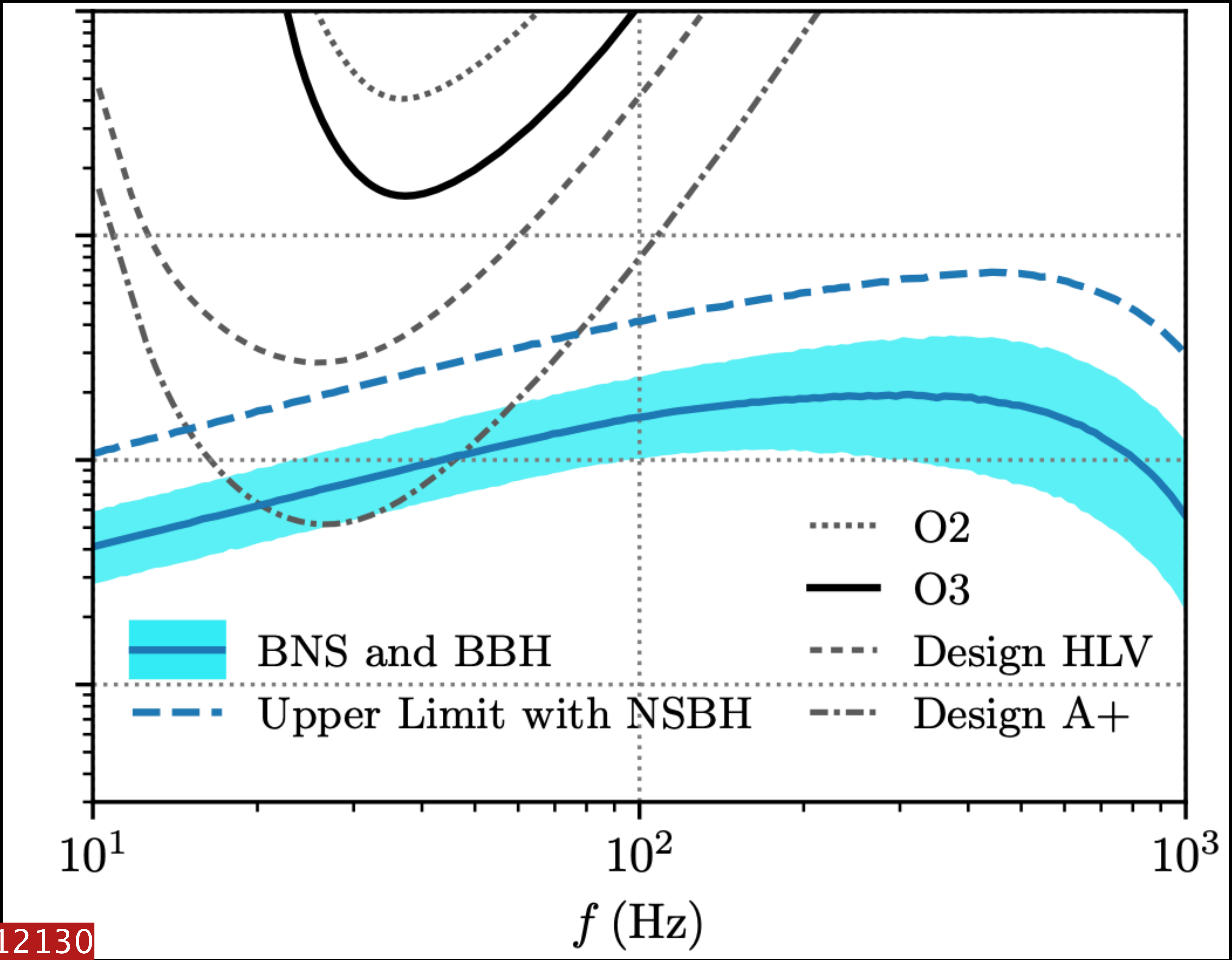
The Astrophysical Journal Letters, 850:L39 (13pp), 2017 December 1

Use GW signal to estimate amount of matter “flung out”
—> Estimate the amount of heavy elements created

There's a lot of science with mergers

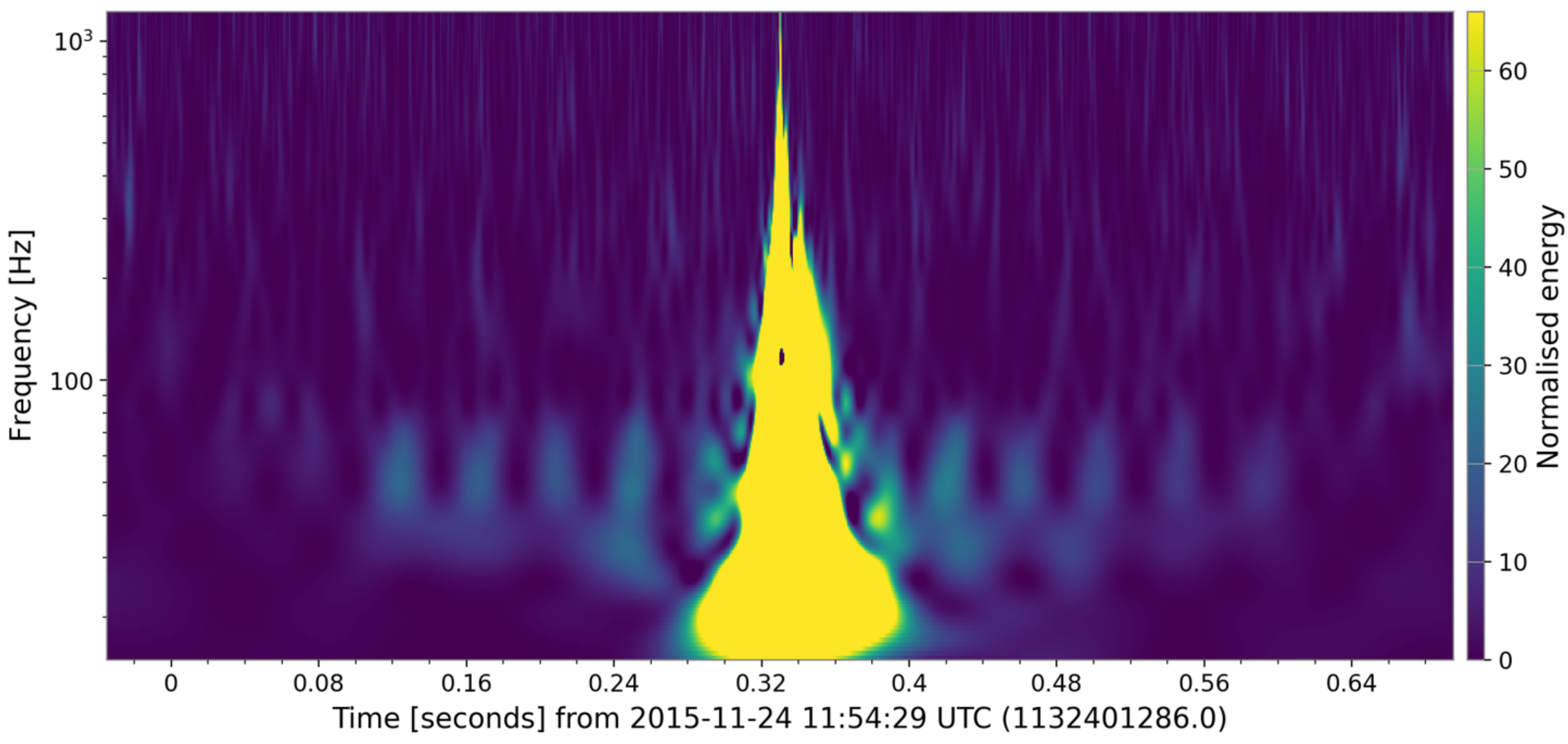
And there's so much more …

Stochastic Searches look for a “background” of GW’s. LIGO could be sensitive to this in O5 !!



arXiv:2101.12130

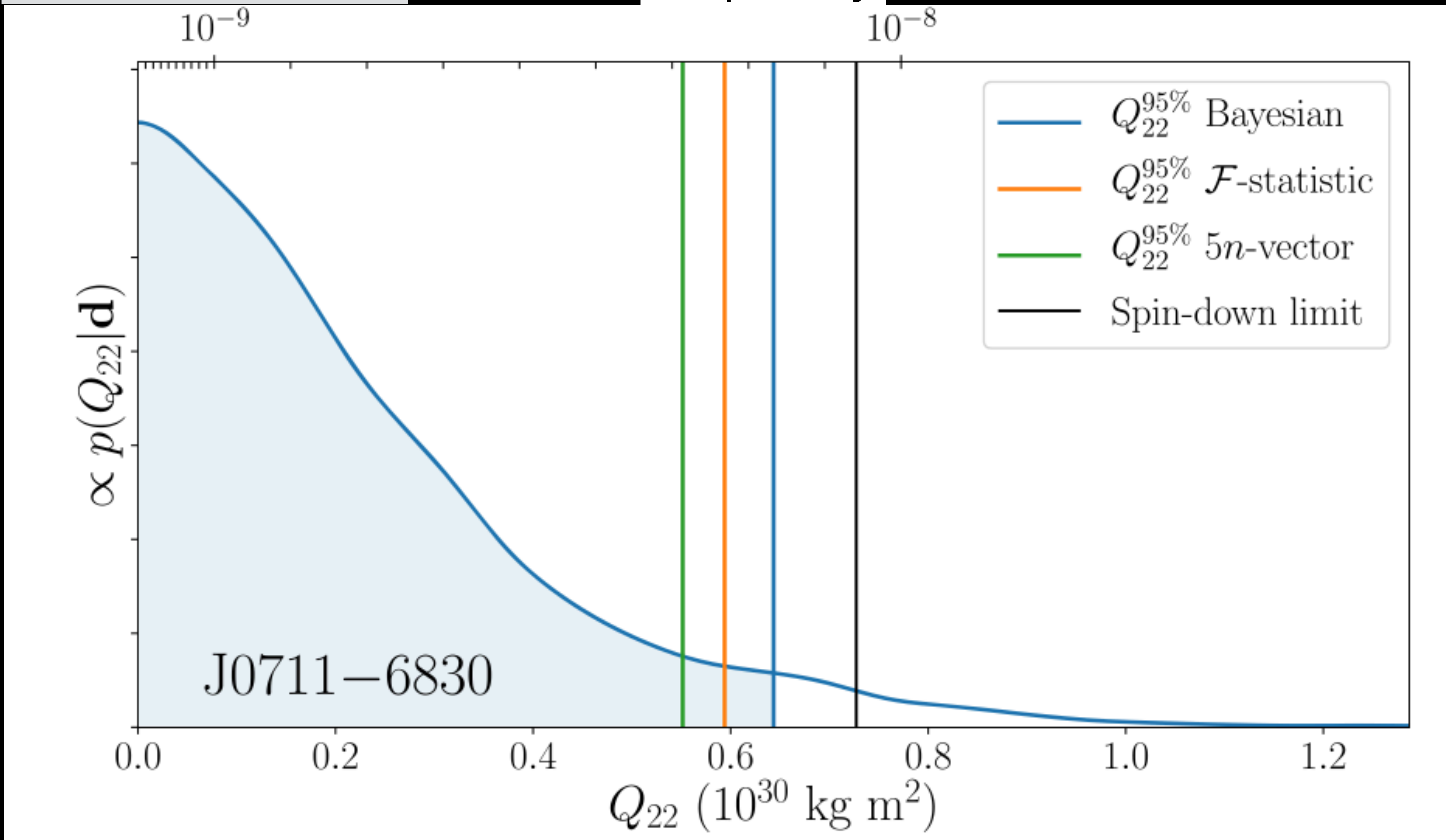
Burst searches look for transients of any kind. Large black hole mergers, supernovae, cosmic string kinks, neutron star pops, …



Continuous Wave searches look for signals from pulsars.
GW's made by non-spherical features
—> measure shape of neutron star to 1 in 10^8 (!)

Abbott *et al* 2020 *ApJL* **902** L21

Ellipticity



Summary

The IGWN network is quickly growing and improving
—> LIGO + Virgo + KAGRA + LIGO India

There are over 50 detections, and growing
—> Likely to be around ~100 after publishing O3b catalogs
—> A merger a day in O5

Wide range of science with LIGO / Virgo detections
—> Stellar evolution and dynamics
—> Hubble constant and cosmology
—> Heavy element production
—> Equation of state and particle physics
—> Tests of General Relativity
—> And more to come

Thank you

Getting Started with LIGO data

The Learning Path
https://www.gw-openscience.org/path/

Introductory signal processing tutorials
https://github.com/jkanner/gw-intro

Open Data Workshop Online course:
https://gw-odw.thinkific.com

Open Data Workshop tutorials
https://github.com/gw-odw/odw-2021

All of this and more:
gw-openscience.org

LIGO/Virgo/KAGRA Hands on program

3:15 - 3:45: Introduction to signal processing
Apps [Headphones recommended]
https://share.streamlit.io/jkanner/streamlit-audio/main/app.py
Python tutorials:
https://github.com/jkanner/gw-intro

3:45 - 4:30: Working with LIGO data
Online course
https://gw-odw.thinkific.com
https://mybinder.org/v2/gh/gw-odw/odw-2021/master
Try tutorials 1.2, 1.3, 1.4, and 2.2

4:30 - 5:00: Data challenge!
https://github.com/gw-odw/odw-2021/tree/master/Challenge
Try Challenges 1, 2, and 3

Thank you