Ondes gravitationnelles

L'aube d'une nouvelle science de l'univers

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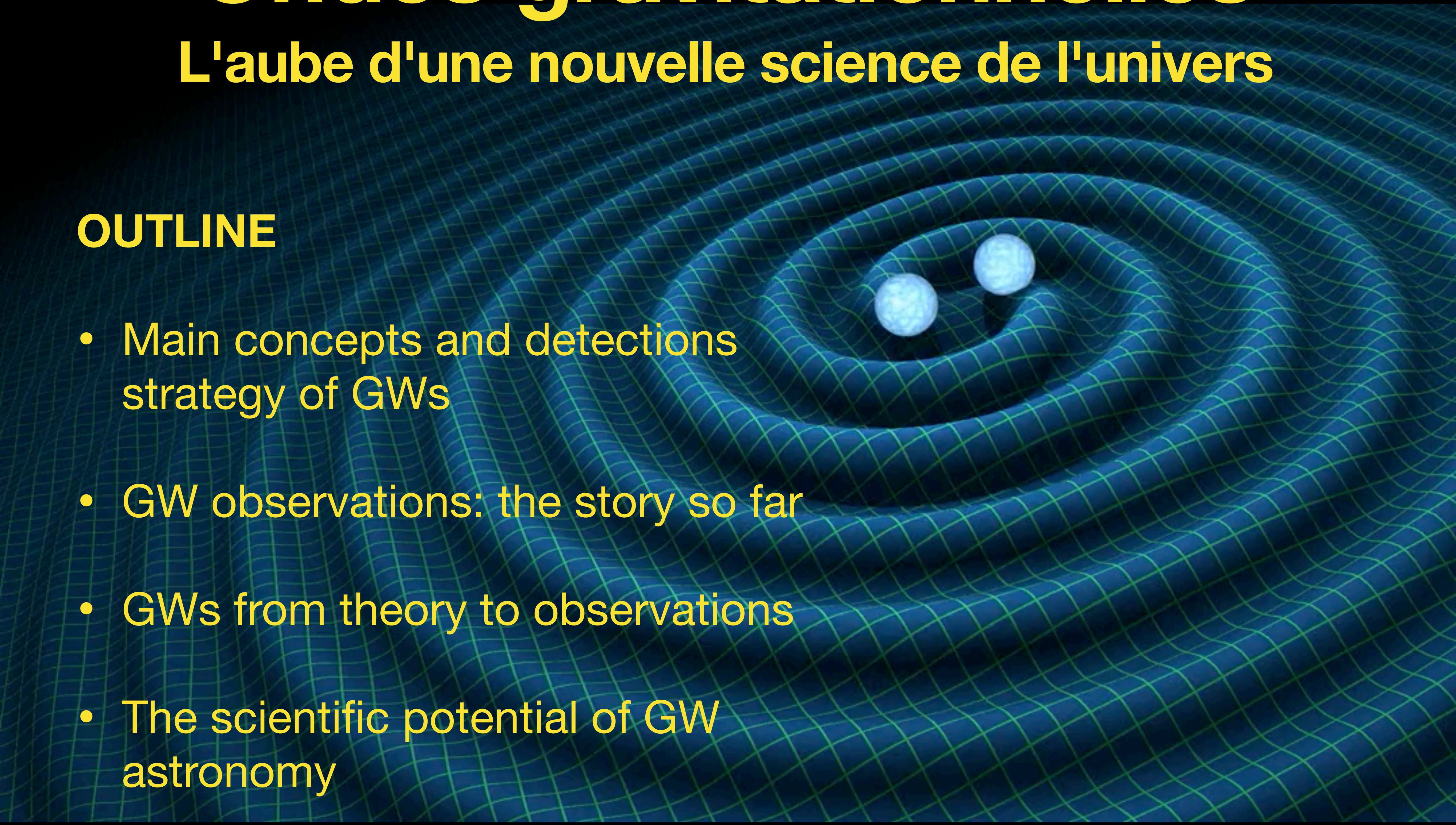
03/07/2023

Ondes gravitationnelles

L'aube d'une nouvelle science de l'univers



OUTLINE

- Main concepts and detections strategy of GWs
- GW observations: the story so far
- GWs from theory to observations
- The scientific potential of GW astronomy

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- **Main concepts and detections strategy of GWs**
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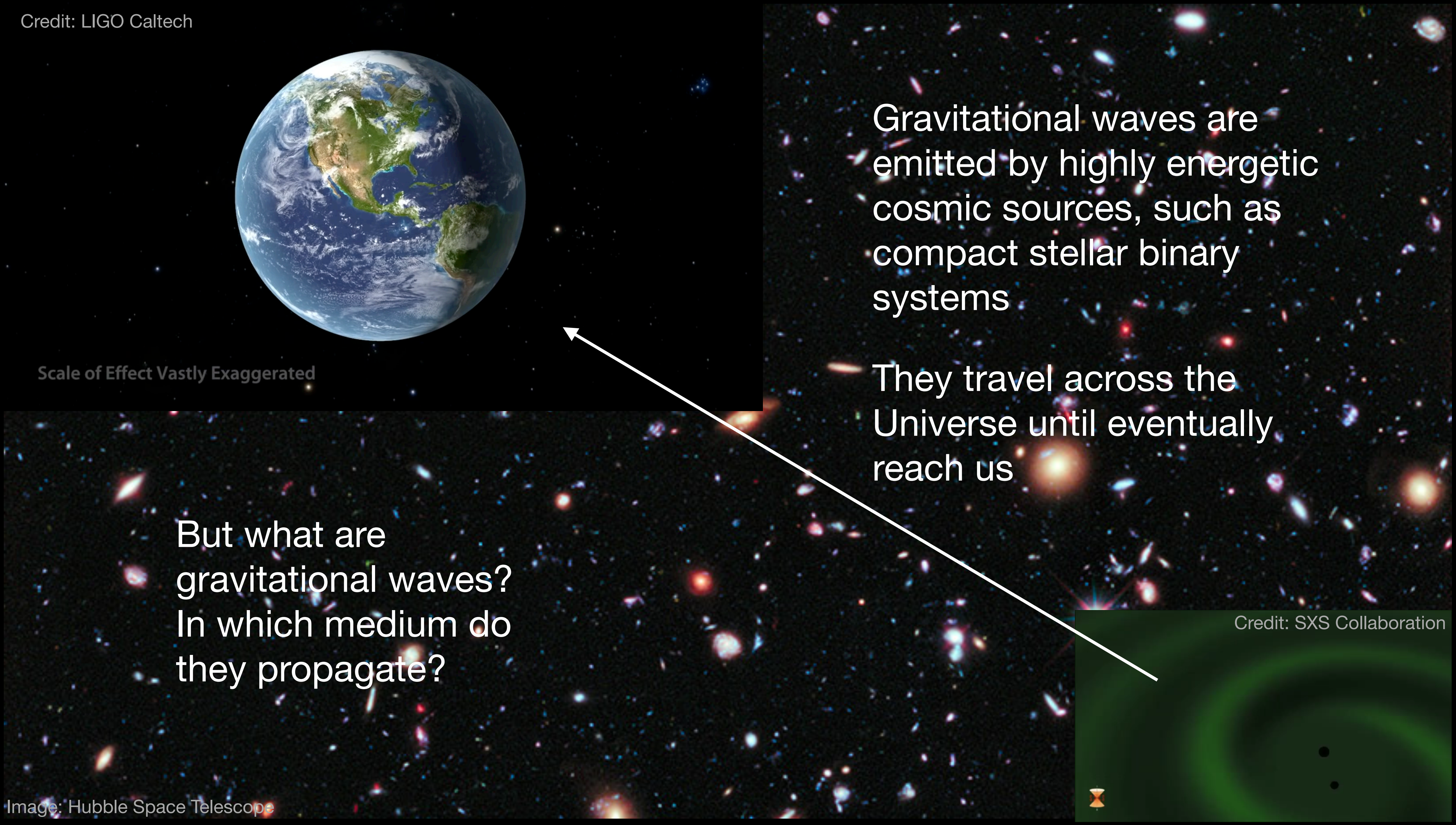
Gravitational waves from a merging binary system



Credit: LIGO Caltech

Credit: SXS Collaboration

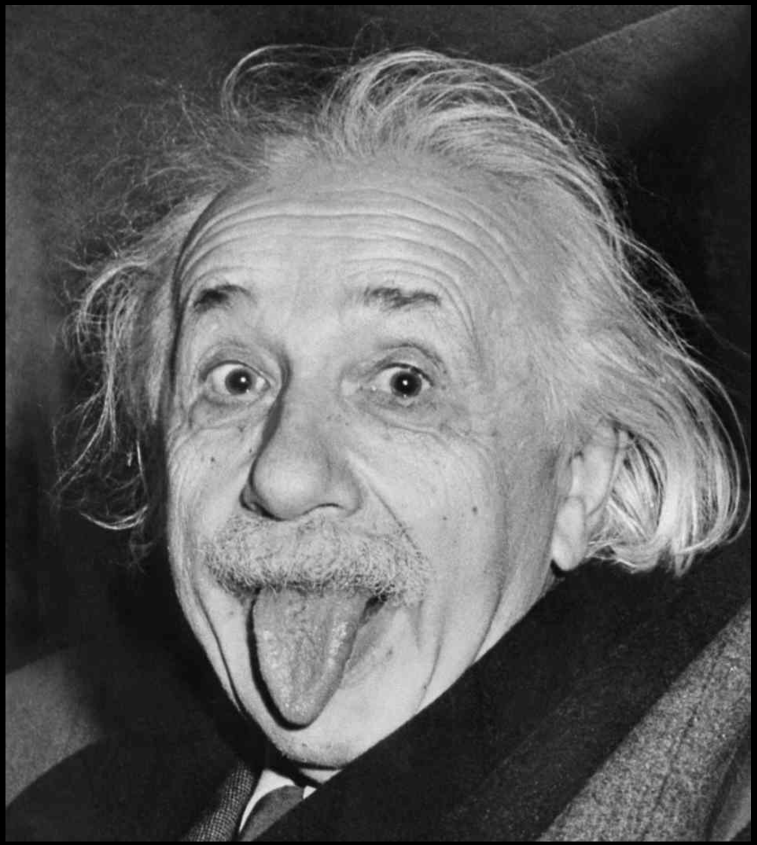
Image: Hubble Space Telescope

Gravitational waves are emitted by highly energetic cosmic sources, such as compact stellar binary systems

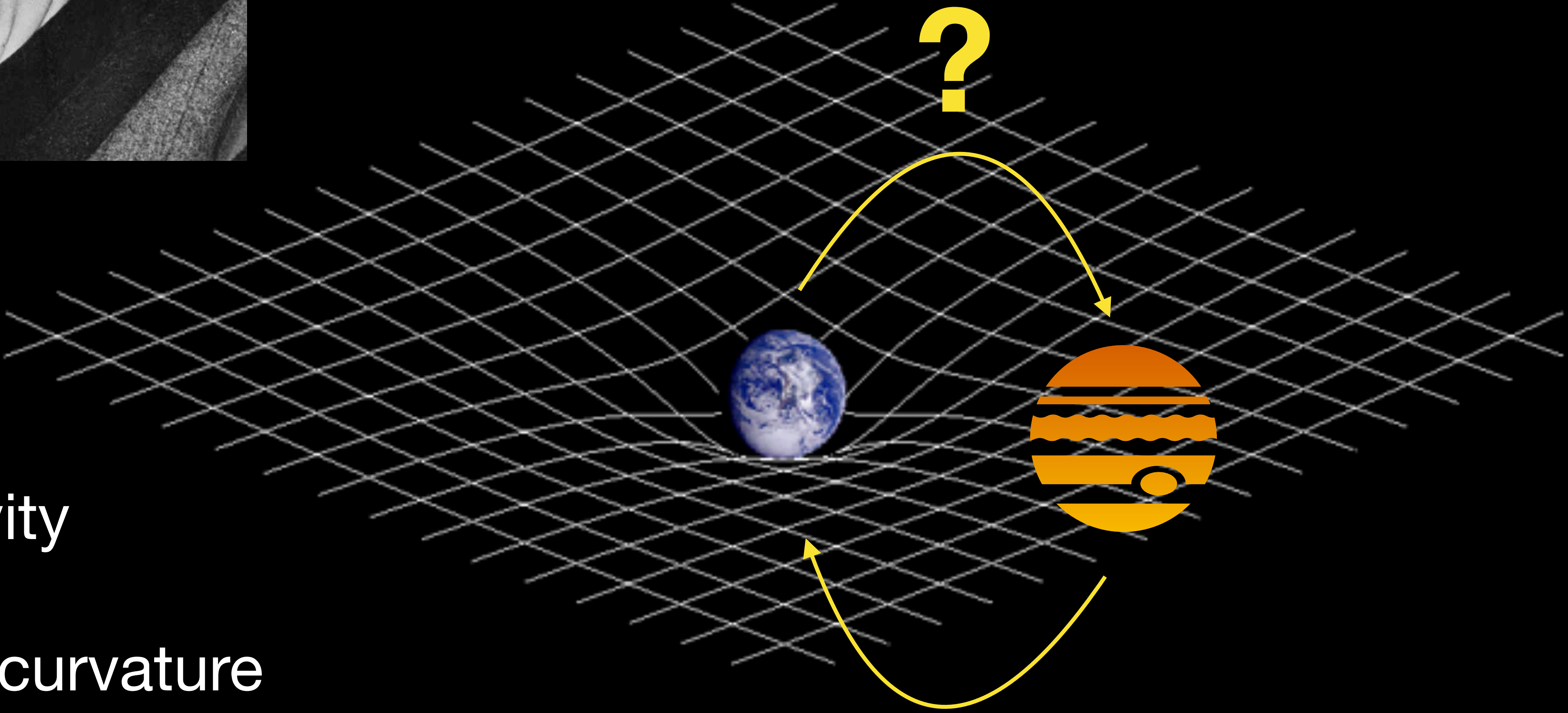
They travel across the Universe until eventually reach us

But what are gravitational waves? In which medium do they propagate?

Einstein's general relativity theory of gravity

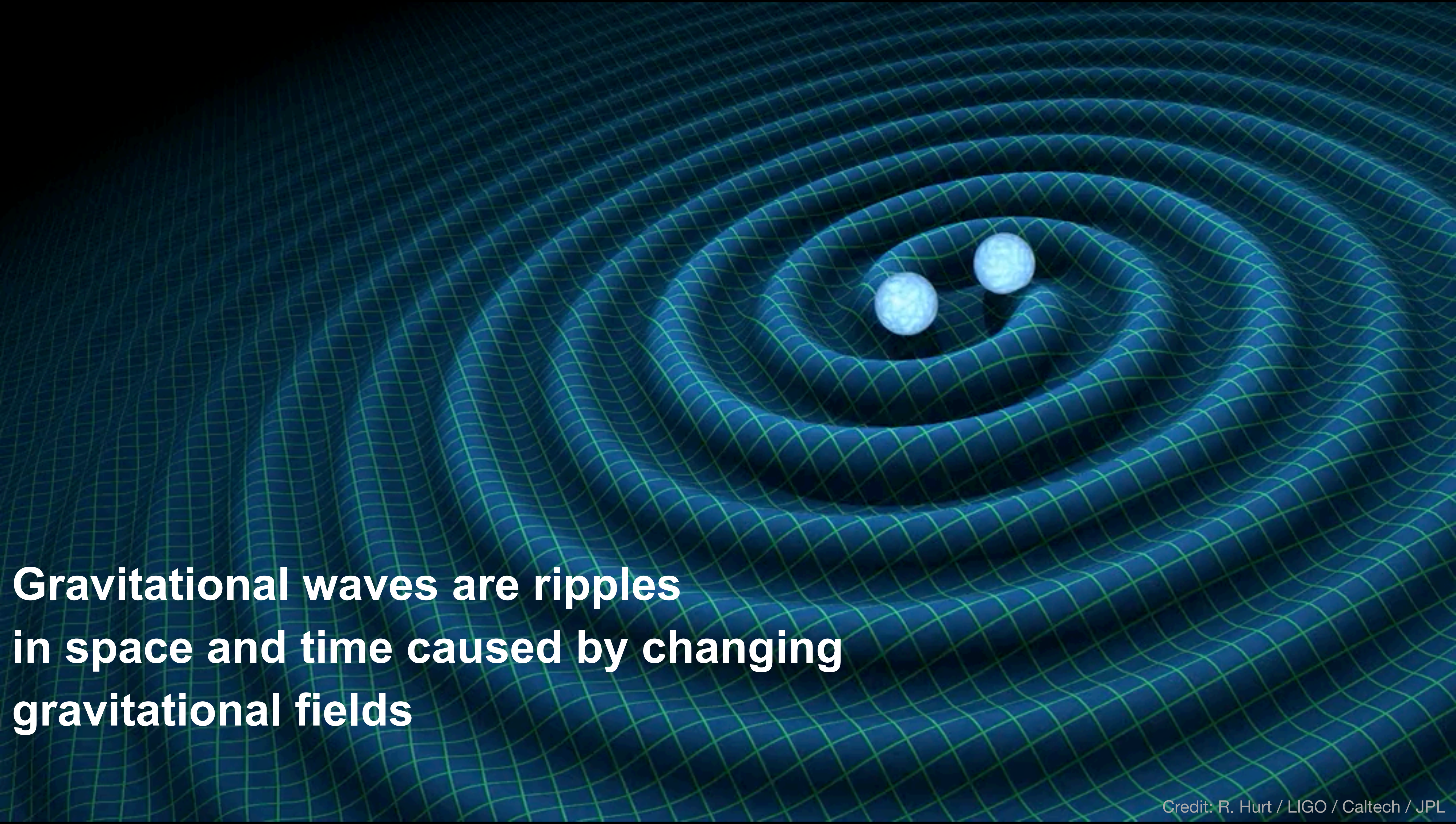


*"Spacetime tells matter how to move,
and matter tells spacetime how to curve"*



Gravity
=
Spacetime curvature

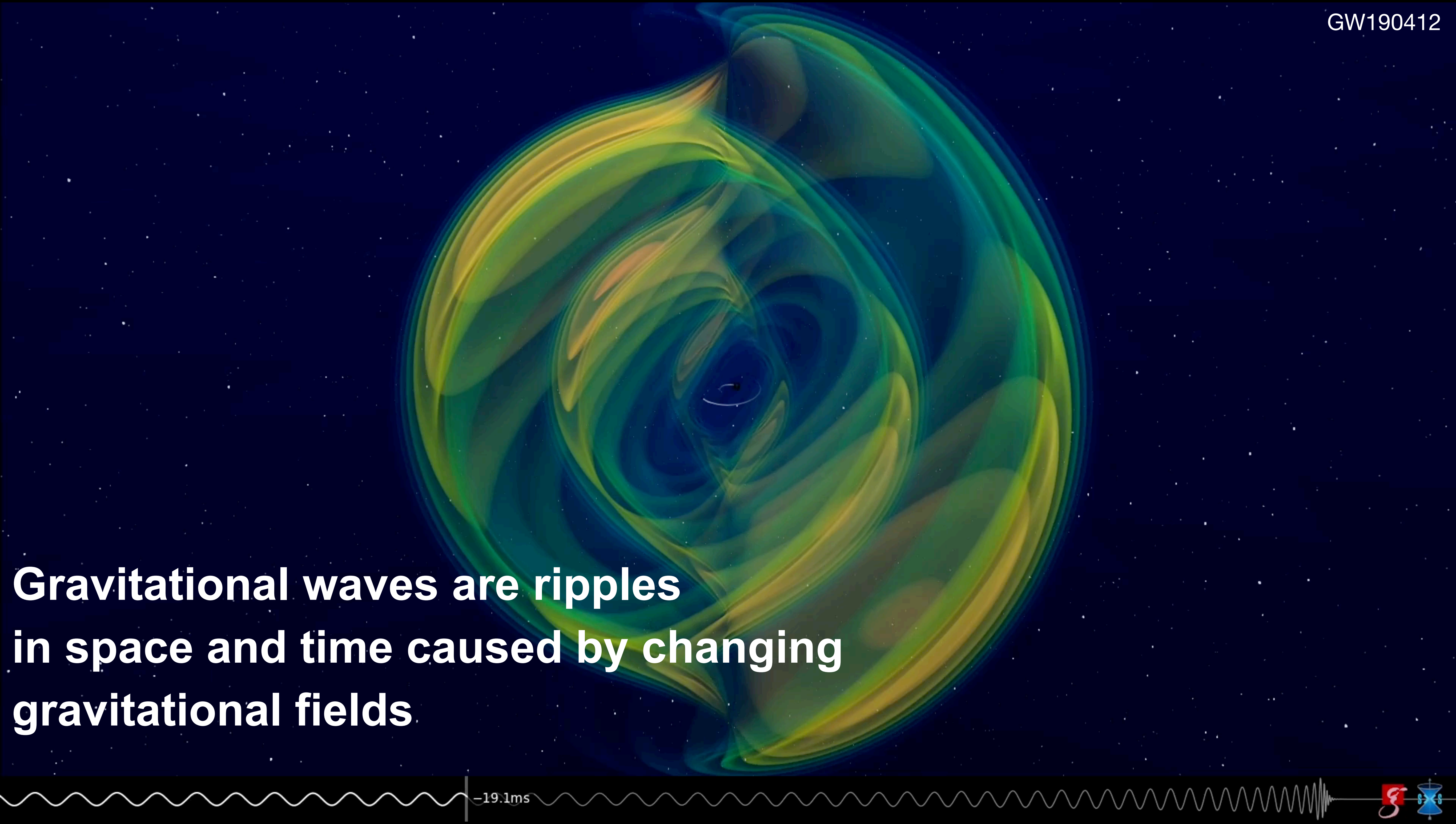
Gravitational waves = dynamical spacetime



Gravitational waves are ripples in space and time caused by changing gravitational fields

Credit: R. Hurt / LIGO / Caltech / JPL

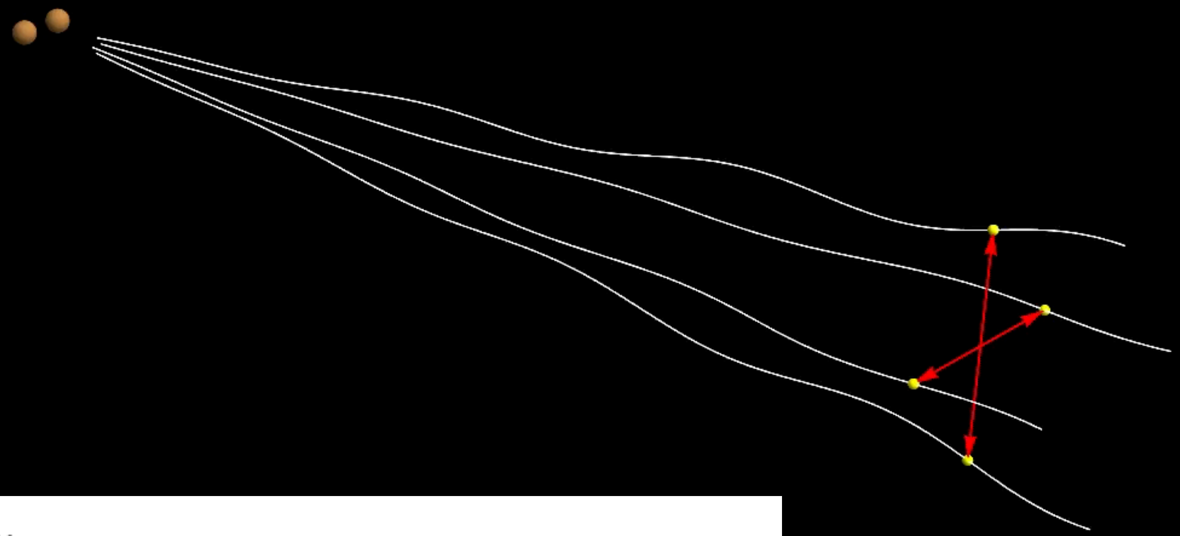
Gravitational waves = dynamical spacetime

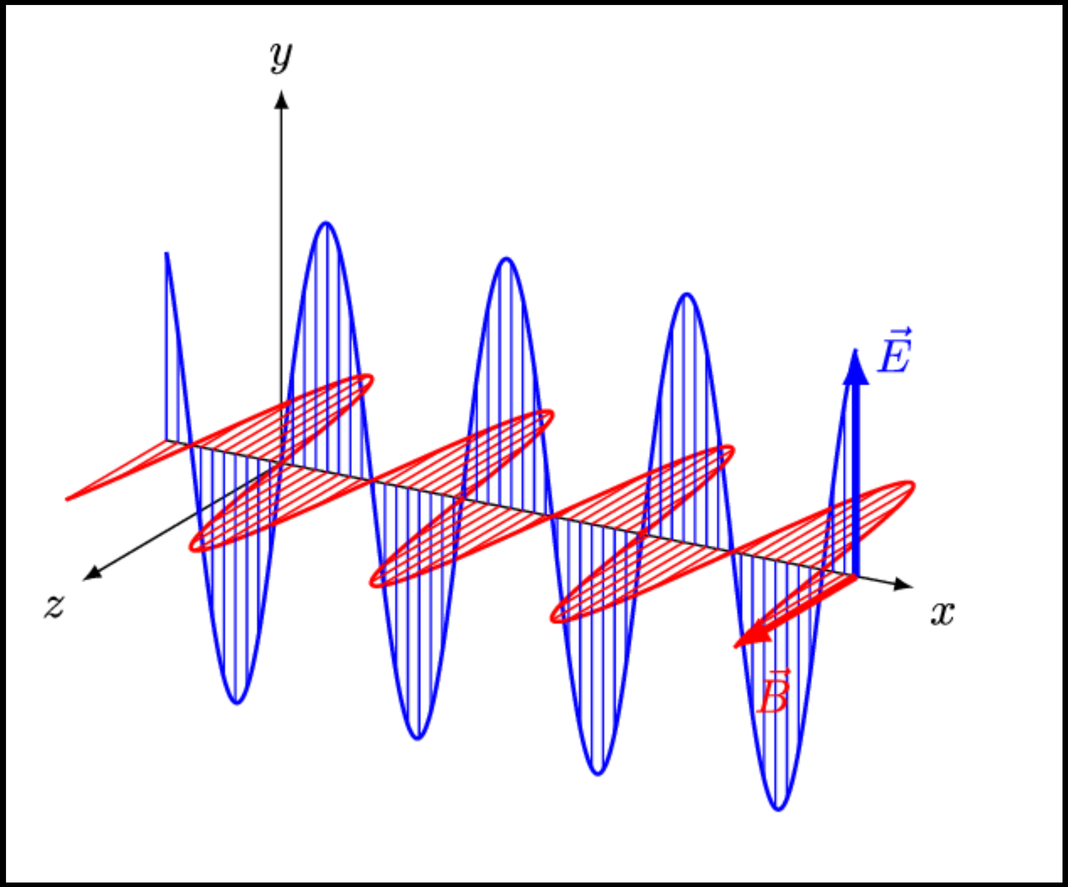


Gravitational waves are ripples in space and time caused by changing gravitational fields

How gravitational waves “move” matter

Gravitational Waves:
waves of space–time curvature
that accelerate free–falling particles

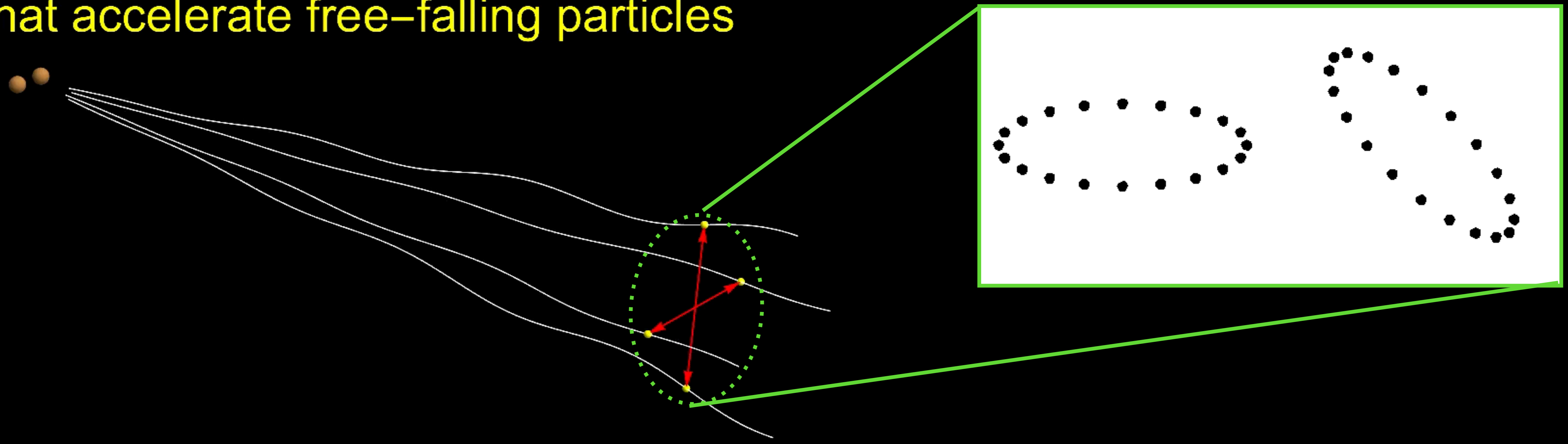




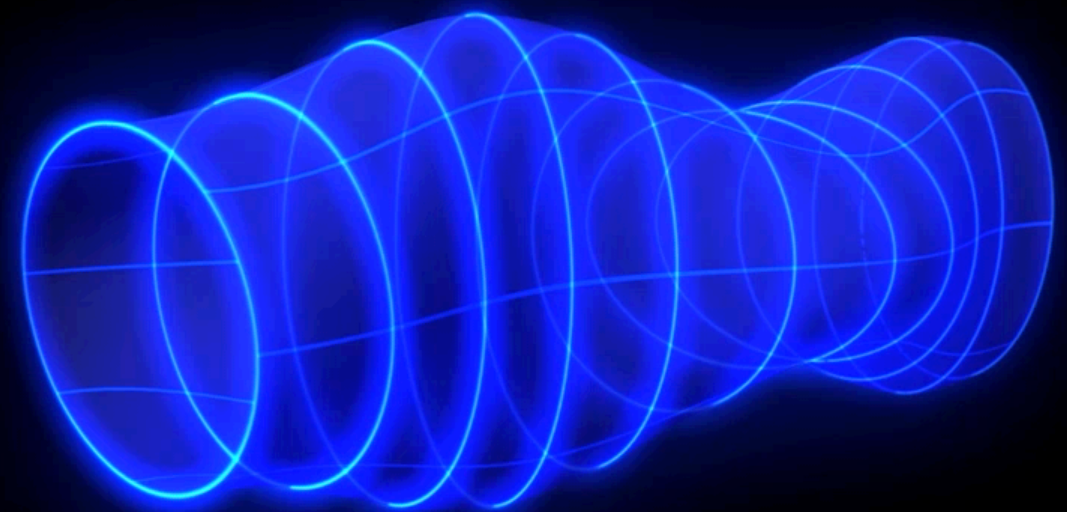
Electromagnetic waves:
waves of EM field that
accelerate charged
particles

How gravitational waves “move” matter

Gravitational Waves:
waves of space–time curvature
that accelerate free–falling particles

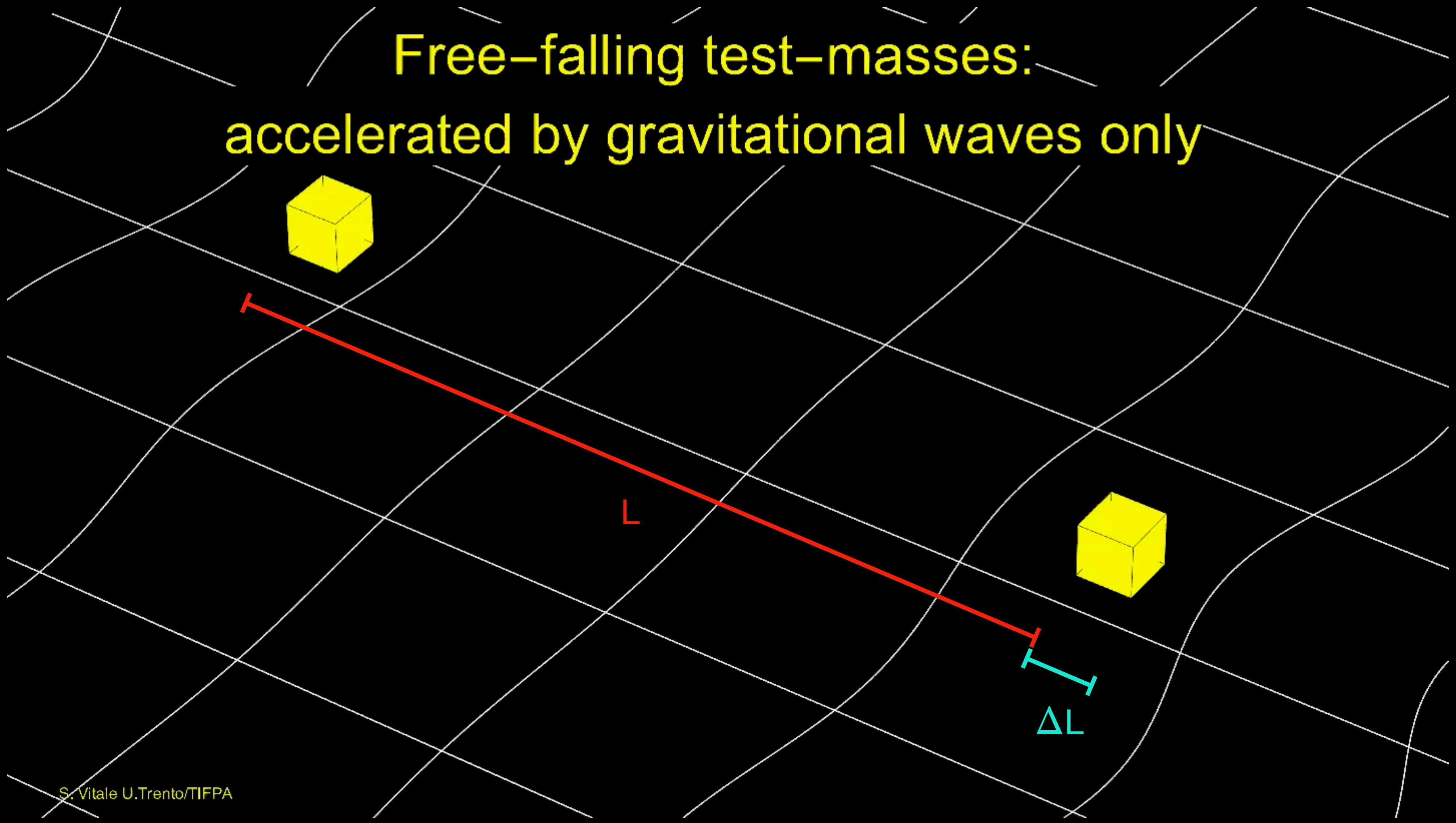


S. Vitale U.Trento/TIFPA



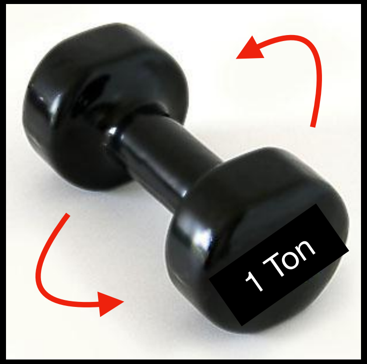
Credit: ESA

How gravitational waves “move” matter



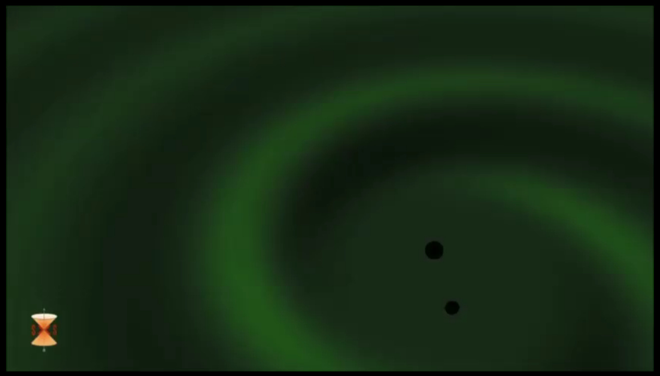
Free–falling test–masses:
accelerated by gravitational waves only

S. Vitale U.Trento/TIFPA



$$\Rightarrow \frac{\Delta L}{L} \sim 10^{-38}$$

@ laboratory distances

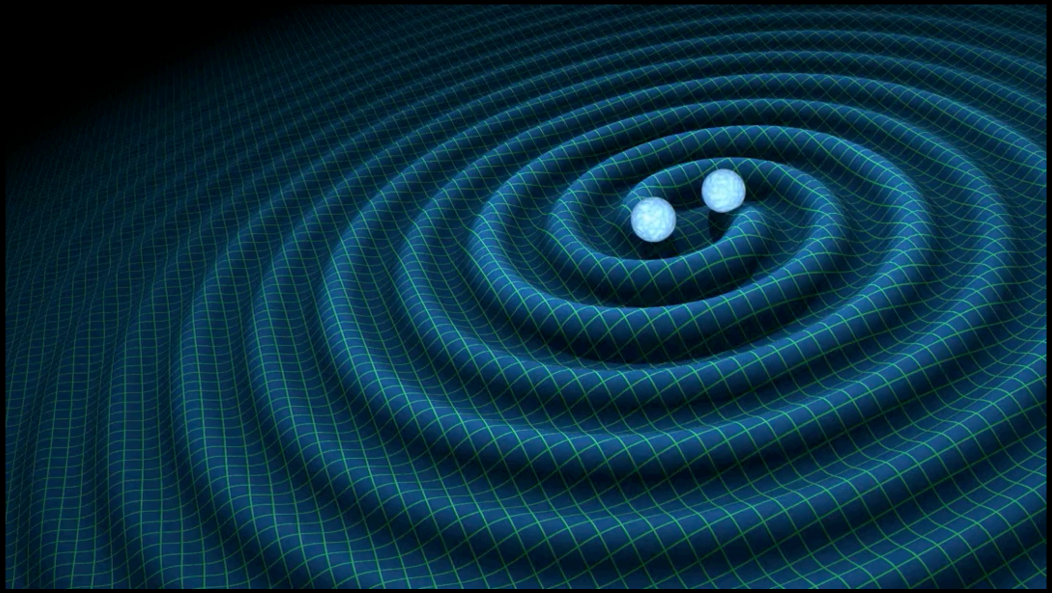


$$\Rightarrow \frac{\Delta L}{L} \sim 10^{-21}$$

@ cosmological distances

How to detect gravitational waves?

INDIRECT DETECTION



Indirectly from the effects they leave on a source

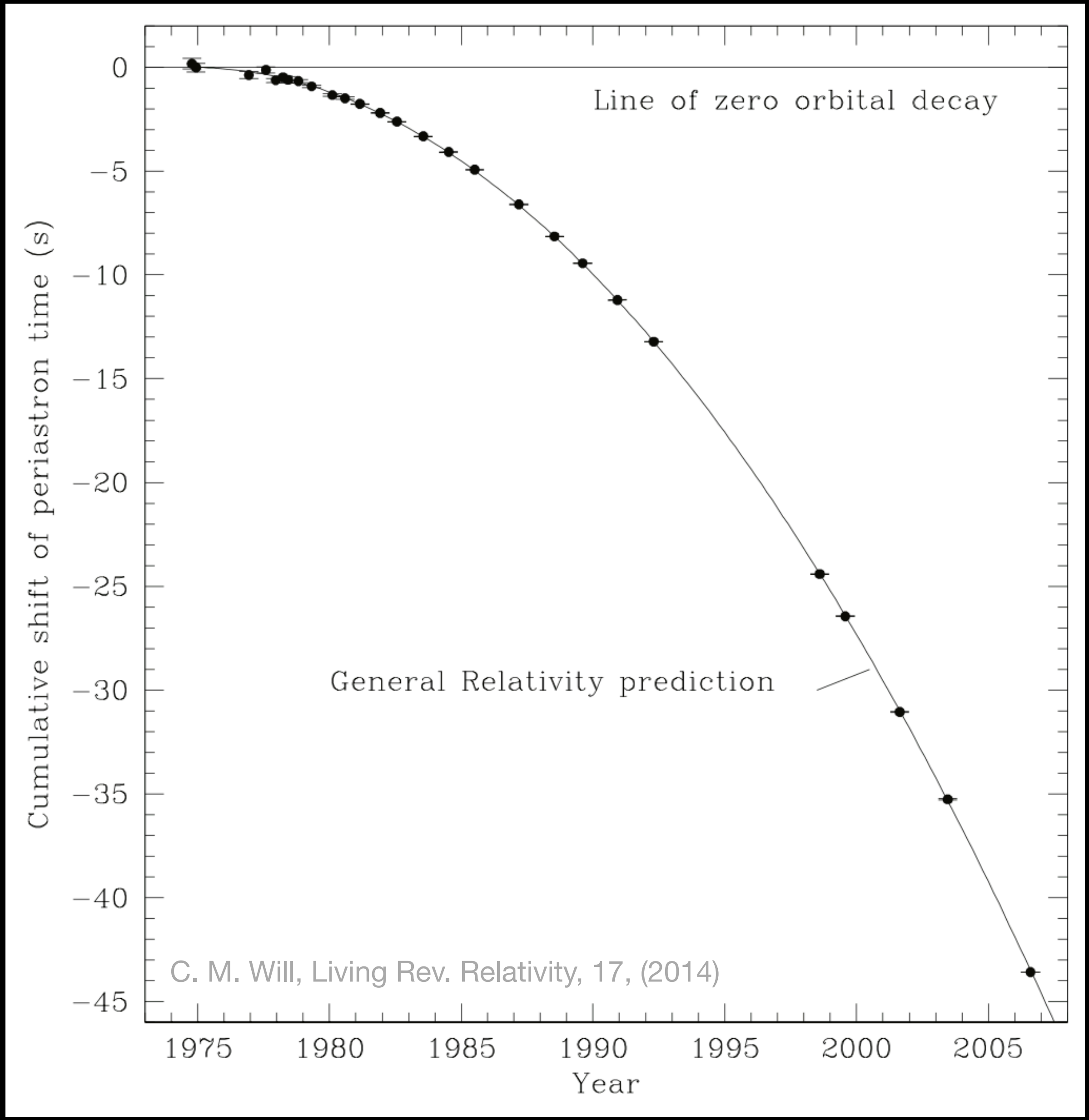
GWs take away energy and (angular) momentum

$\Downarrow$

Orbits shrinks / period decreases

How to detect gravitational waves?

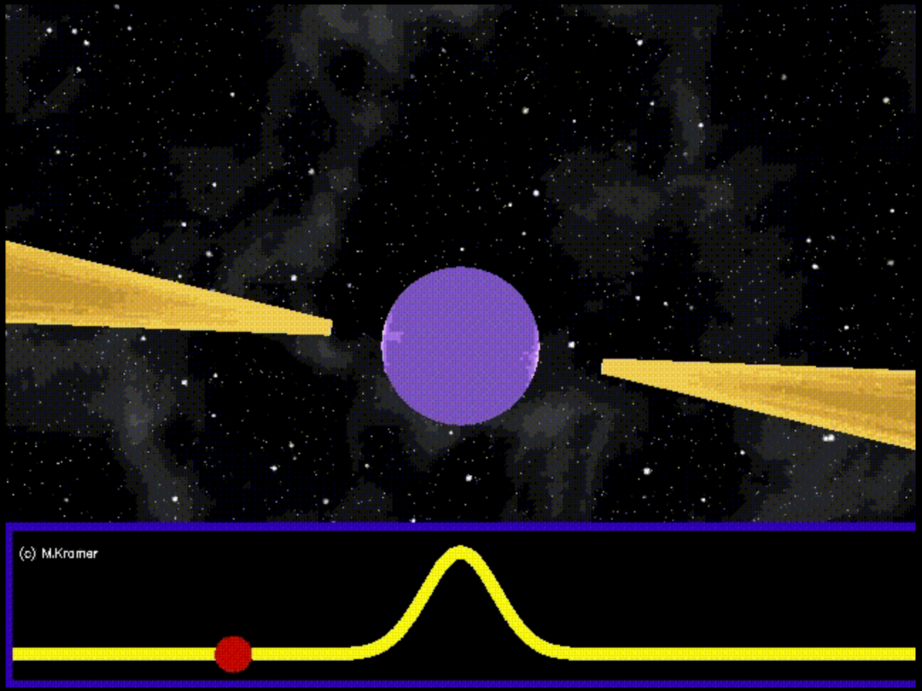
INDIRECT DETECTION

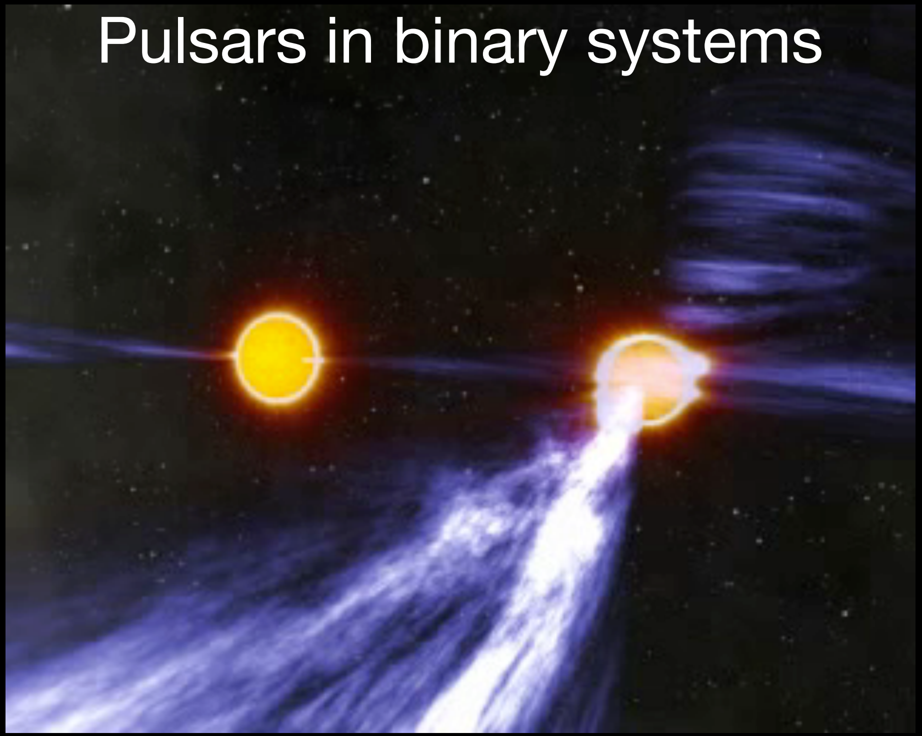


C. M. Will, Living Rev. Relativity, 17, (2014)

Hulse–Taylor pulsar
Nobel Prize 1993

Credit: Michael Kramer



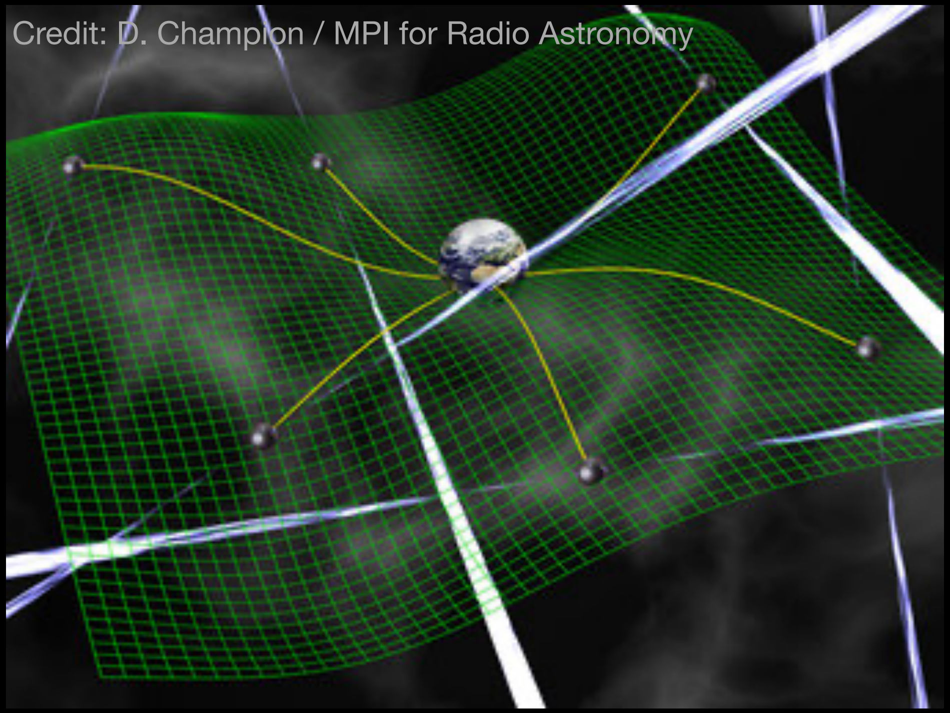


Pulsars in binary systems

Credit: John Rowe animations

How to detect gravitational waves?

PTA DETECTION



Credit: D. Champion / MPI for Radio Astronomy

Indirectly from the effects they leave on an array of EM sources

GWs stretch the spacetime in between us and the pulsars

$\Downarrow$

Change in the arrival time of EM pulses

How to detect gravitational waves?

PTA DETECTION

HIER!!!
29/06/2023

Press Releases

EPTA announces evidence for nanohertz gravitational waves

EPTA joins international teams in reporting evidence for low frequency gravitational waves

NANOGrav's 15-Year Data Release

PUB: 28 JUN 2023

Artist's interpretation of an array of pulsars being affected by gravitational ripples produced by a supermassive black hole binary in a distant galaxy. *Credit: Aurore Simonnet for the NANOGrav Collaboration*

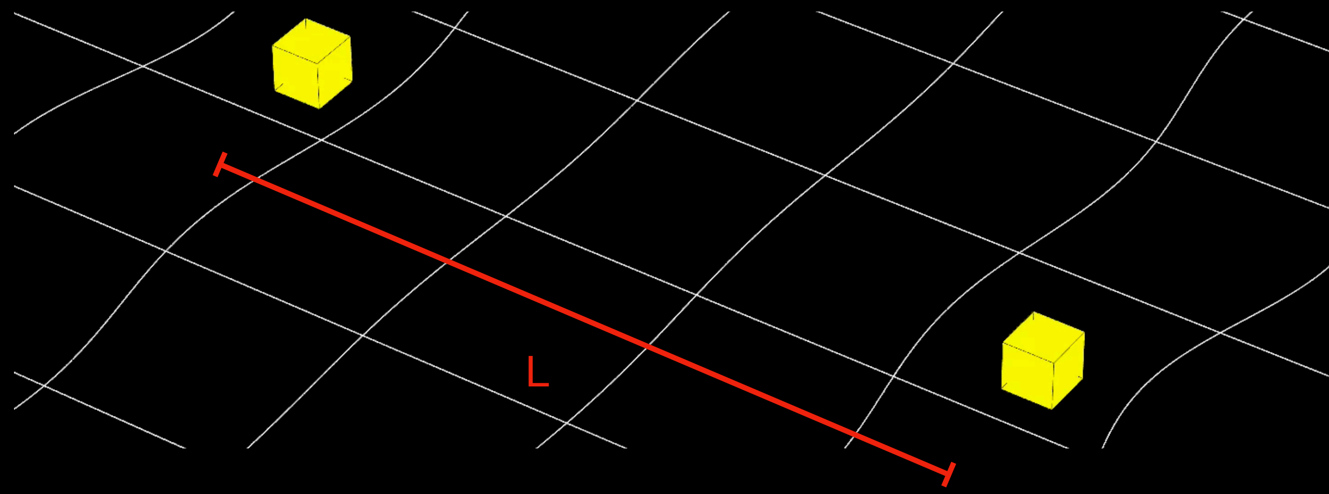
Public Briefing

We invite all interested members of the public to join our public announcement event on **Thursday, June 29, 2023 at 1:00 PM Eastern US Time.** The announcement will report results of the analysis of NANOGrav's 15-year data set, and interpretations of those results.

The announcement will be broadcast live on YouTube ↗ from the National Science Foundation (NSF), and will report on NANOGrav's ongoing search for low-frequency gravitational waves.

How to detect gravitational waves?

DIRECT DETECTION



Directly from the effects they imprint on test masses

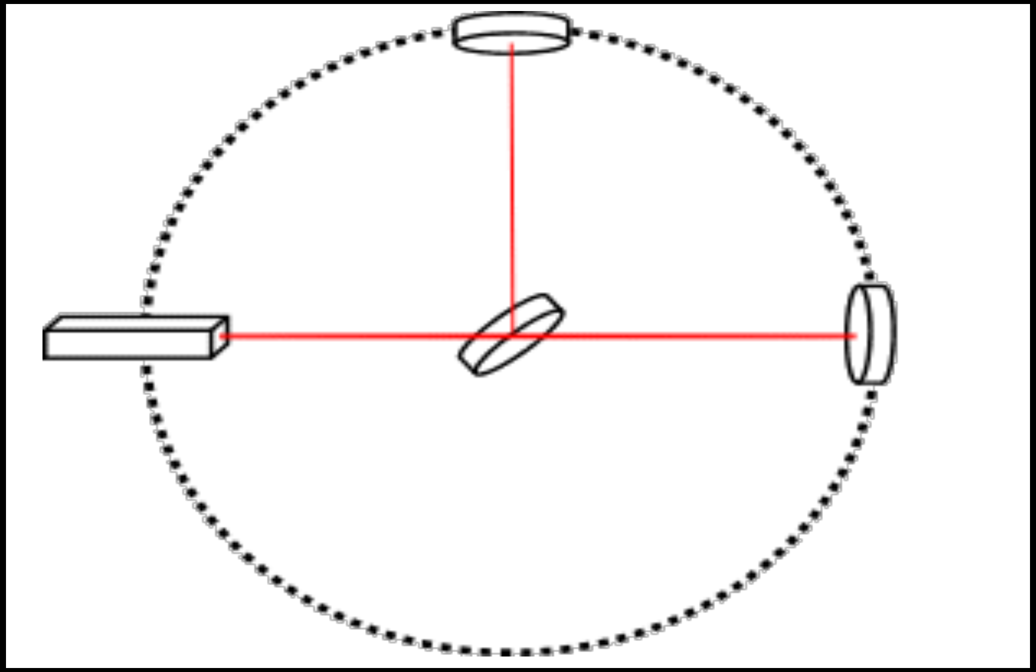
GWs transfer energy (and momentum)

⇓

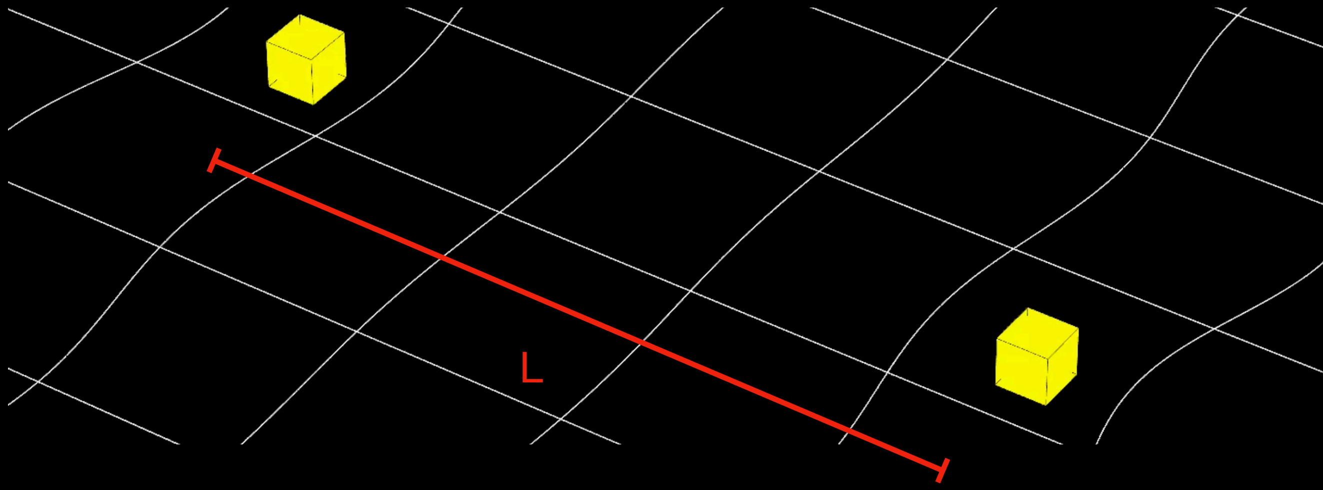
Distance between to free-falling masses change

How to detect gravitational waves?

LASER INTERFEROMETRY



DIRECT DETECTION



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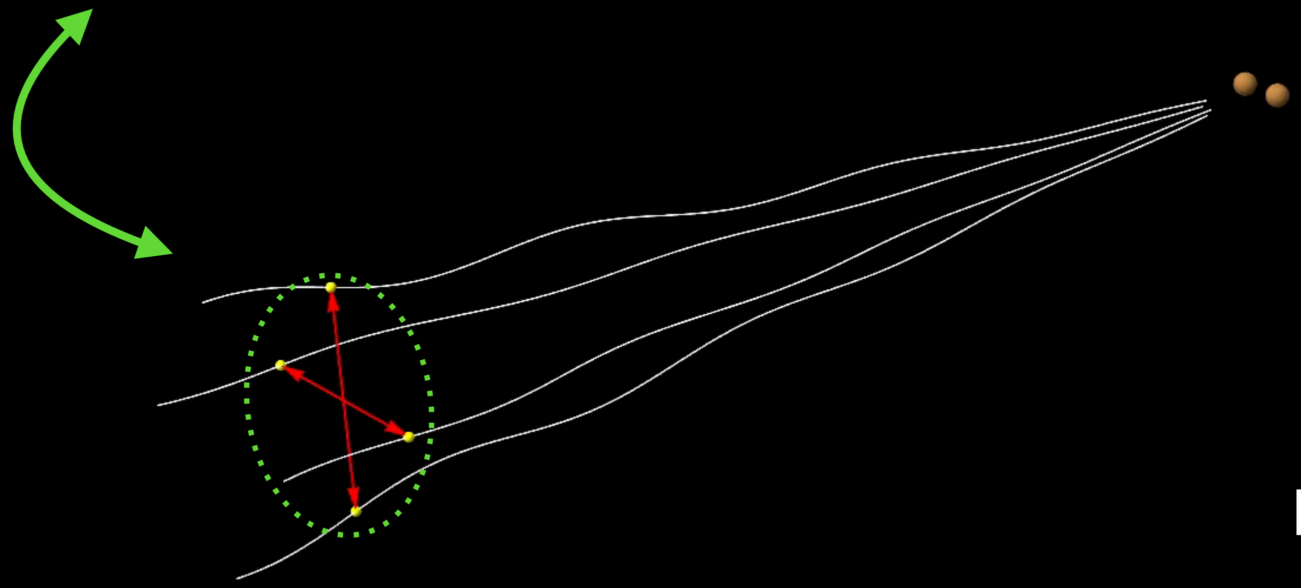
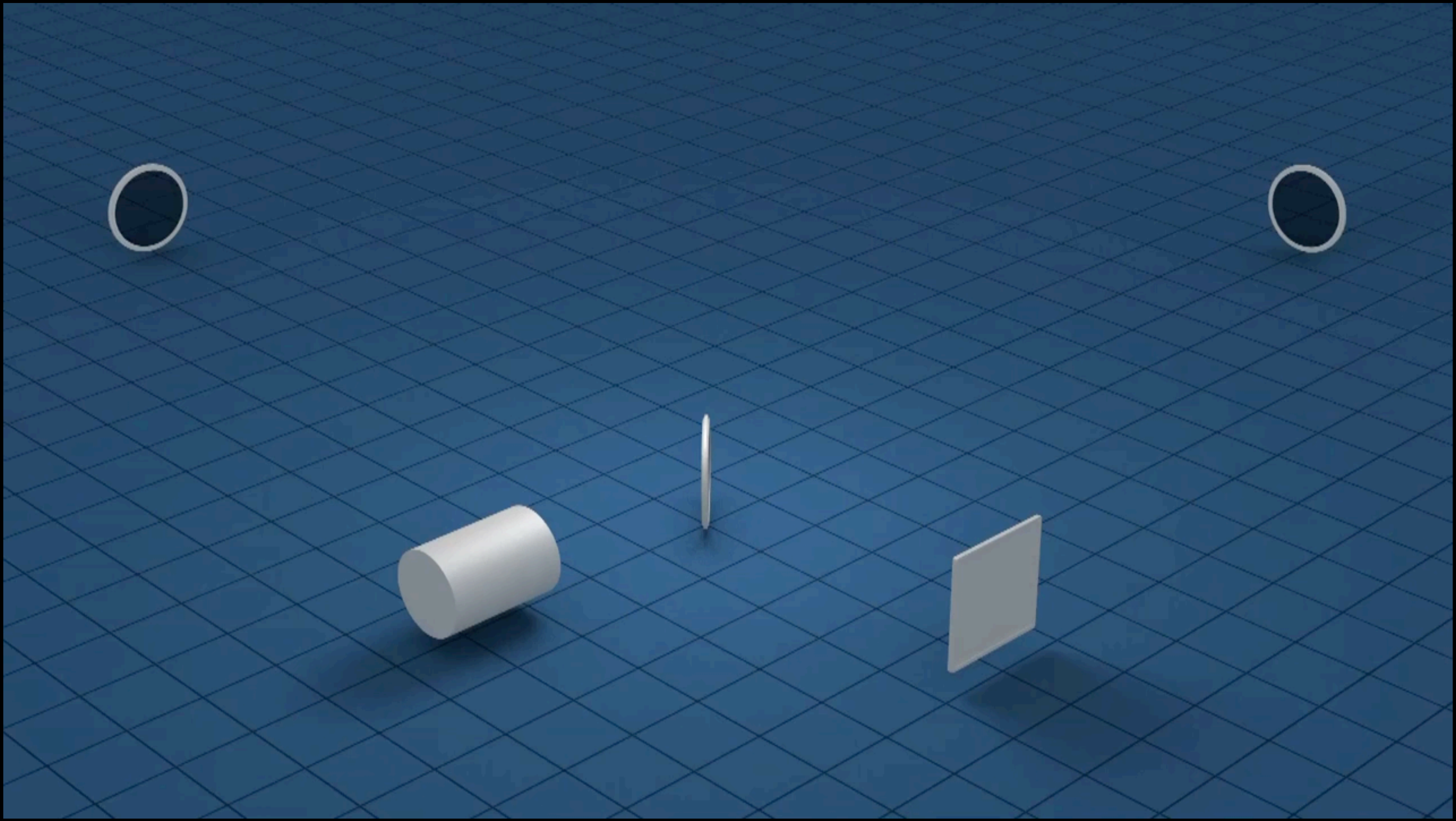


How to detect gravitational waves?

Laser interferometry

DIRECT DETECTION



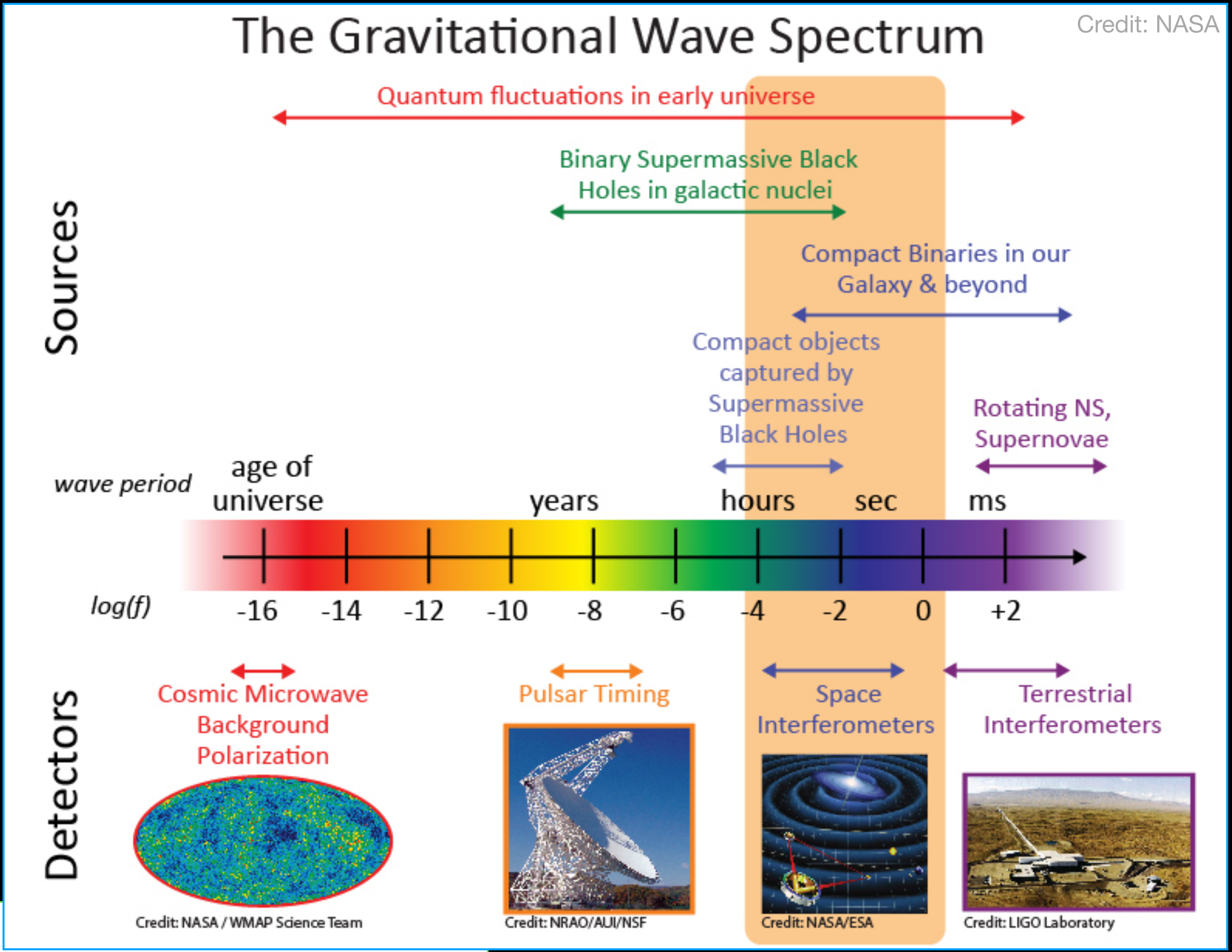
Credit: T. Pyle, Caltech/MIT/LIGO Lab

The gravitational wave spectrum

Different GW instruments observe at different frequencies / wavelengths

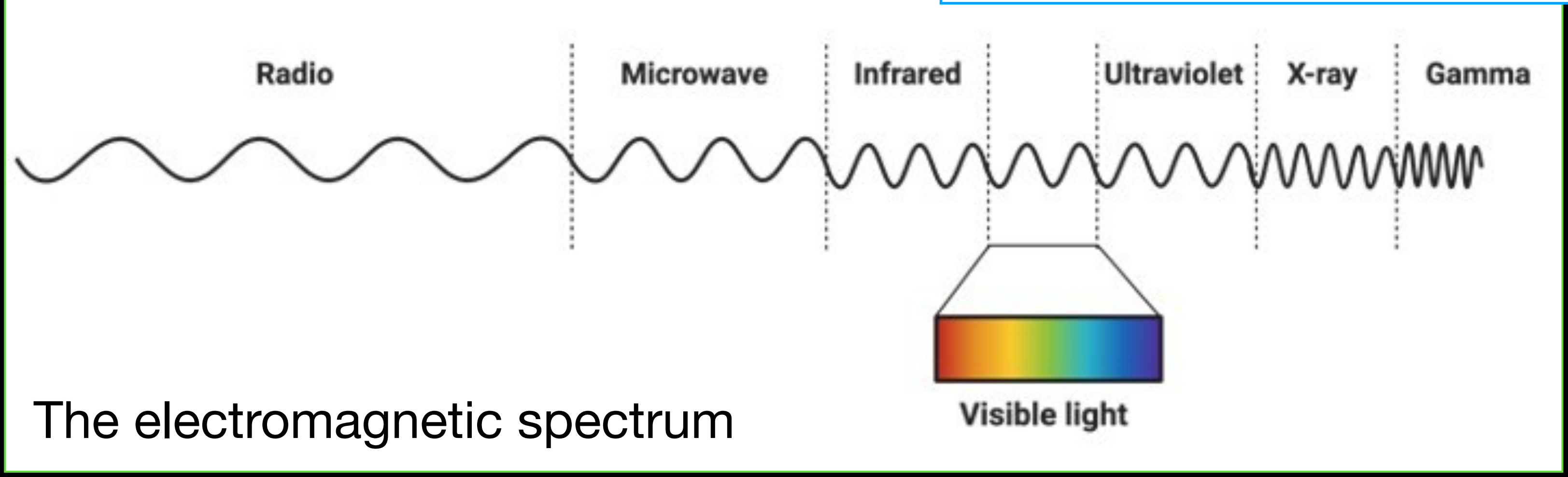
⇓

Different target sources



Credit: NASA

The gravitational wave spectrum



The electromagnetic spectrum

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The current network of interferometers

Current 2nd generation GW detector network

LIGO Hanford

GEO 600

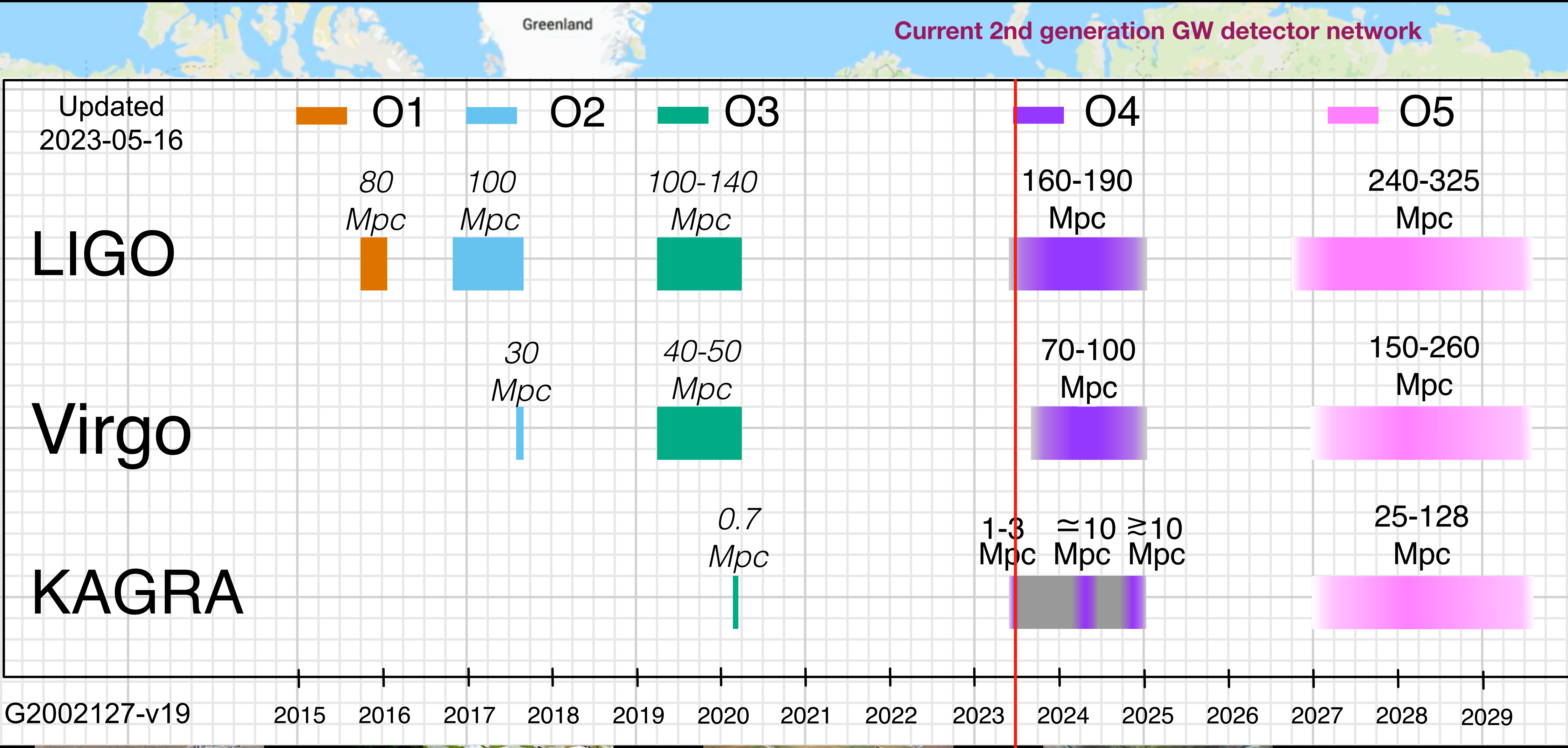
KAGRA

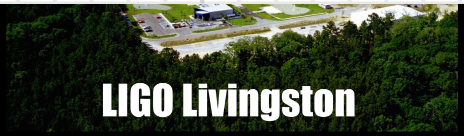
Virgo

LIGO Livingston

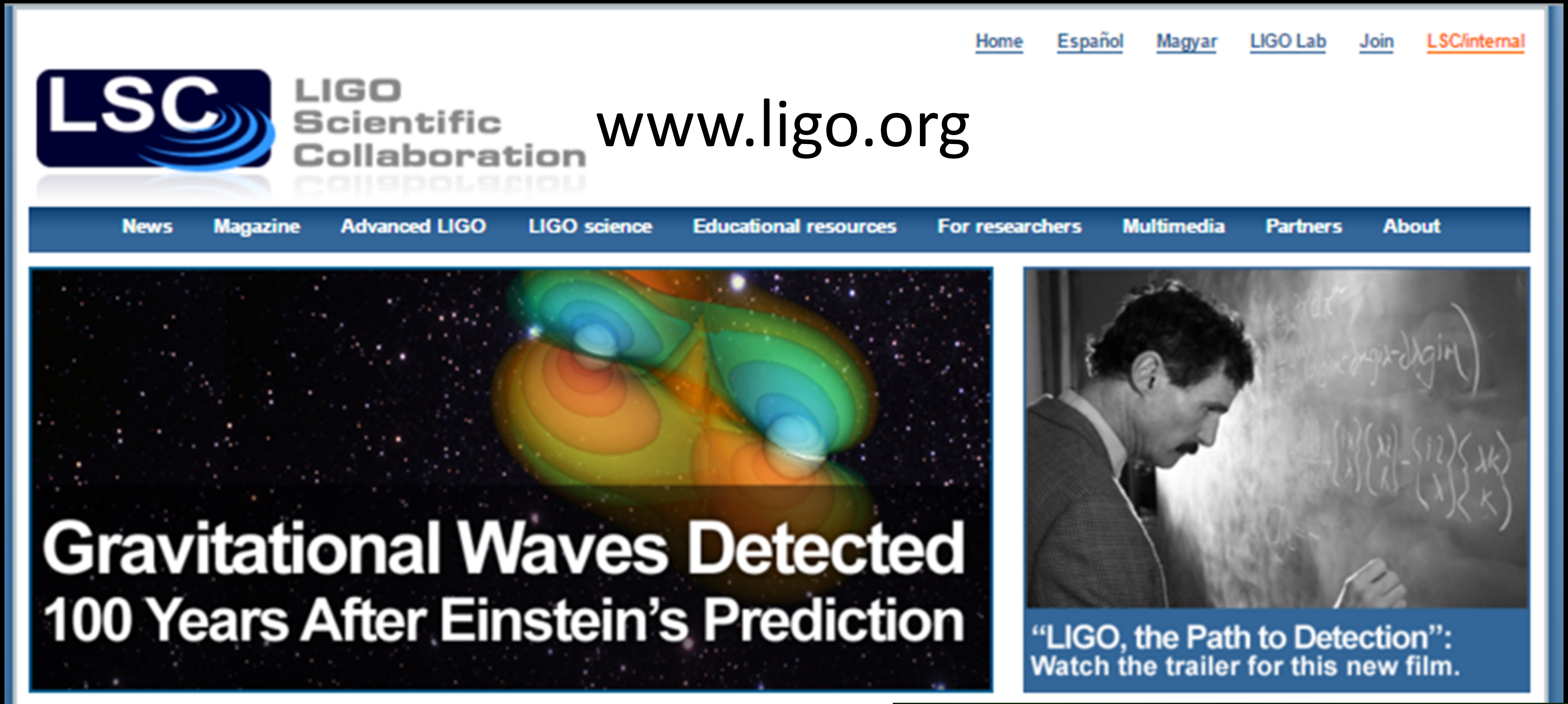
LIGO India

The current network of interferometers





GW150914: the first gravitational wave detection



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LSC LIGO Scientific Collaboration

www.ligo.org

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Gravitational Waves Detected 100 Years After Einstein's Prediction

"LIGO, the Path to Detection": Watch the trailer for this new film.

NEWS

Feb 24, 2016 LIGO members to testify on the discovery at US Congress

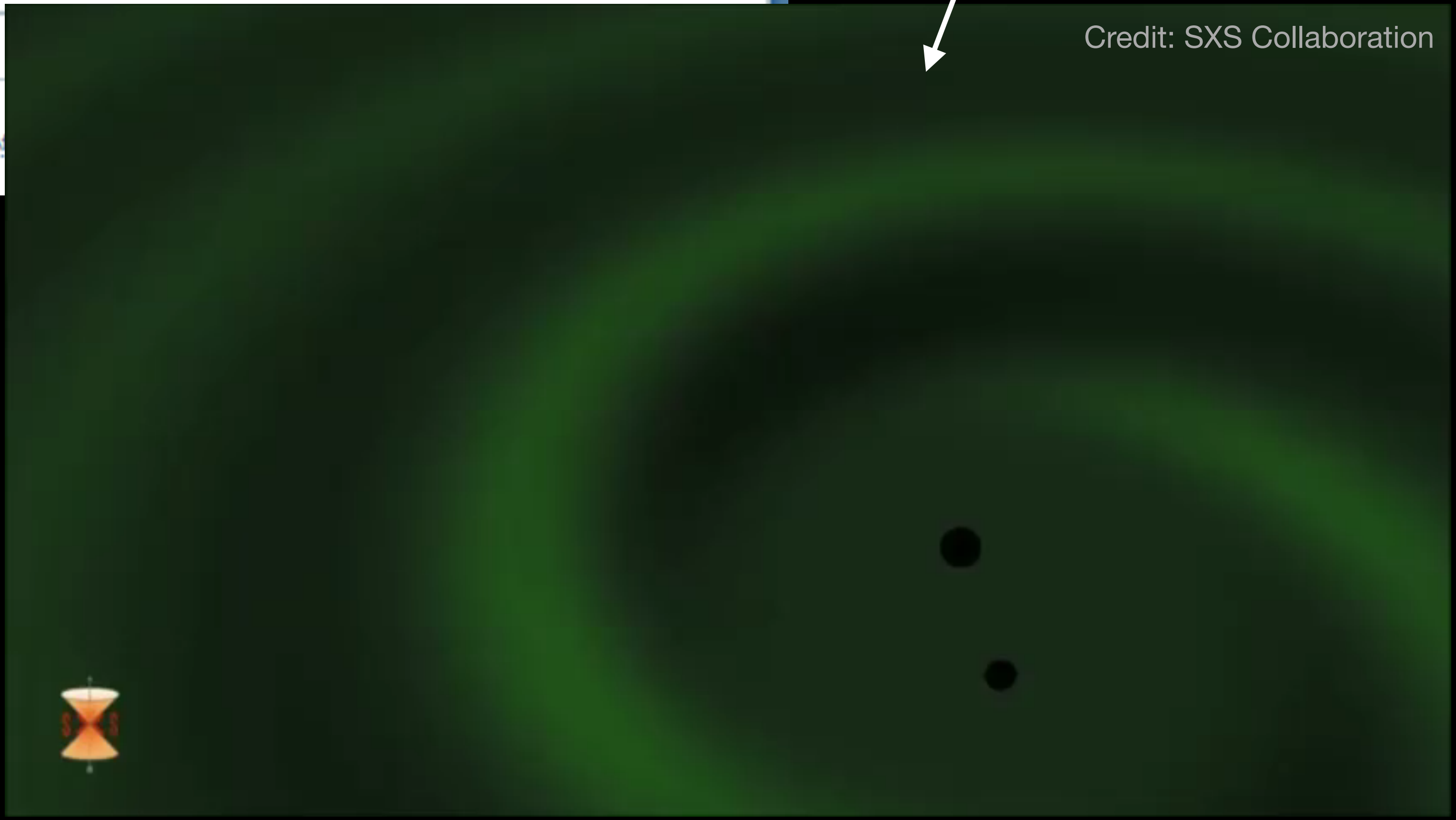
Feb 17, 2016 LIGO-India approved

PRESS RELEASE

Feb 11, 2016 Gravitational Waves Detected 100 Years A

Einstein's Prediction

Binary black holes



Credit: SXS Collaboration

2015: first detection of gravitational waves

GW150914: the first gravitational wave detection

LIGO Scientific Collaboration

www.ligo.org

Gravitational Waves Detected 100 Years After Einstein's Prediction

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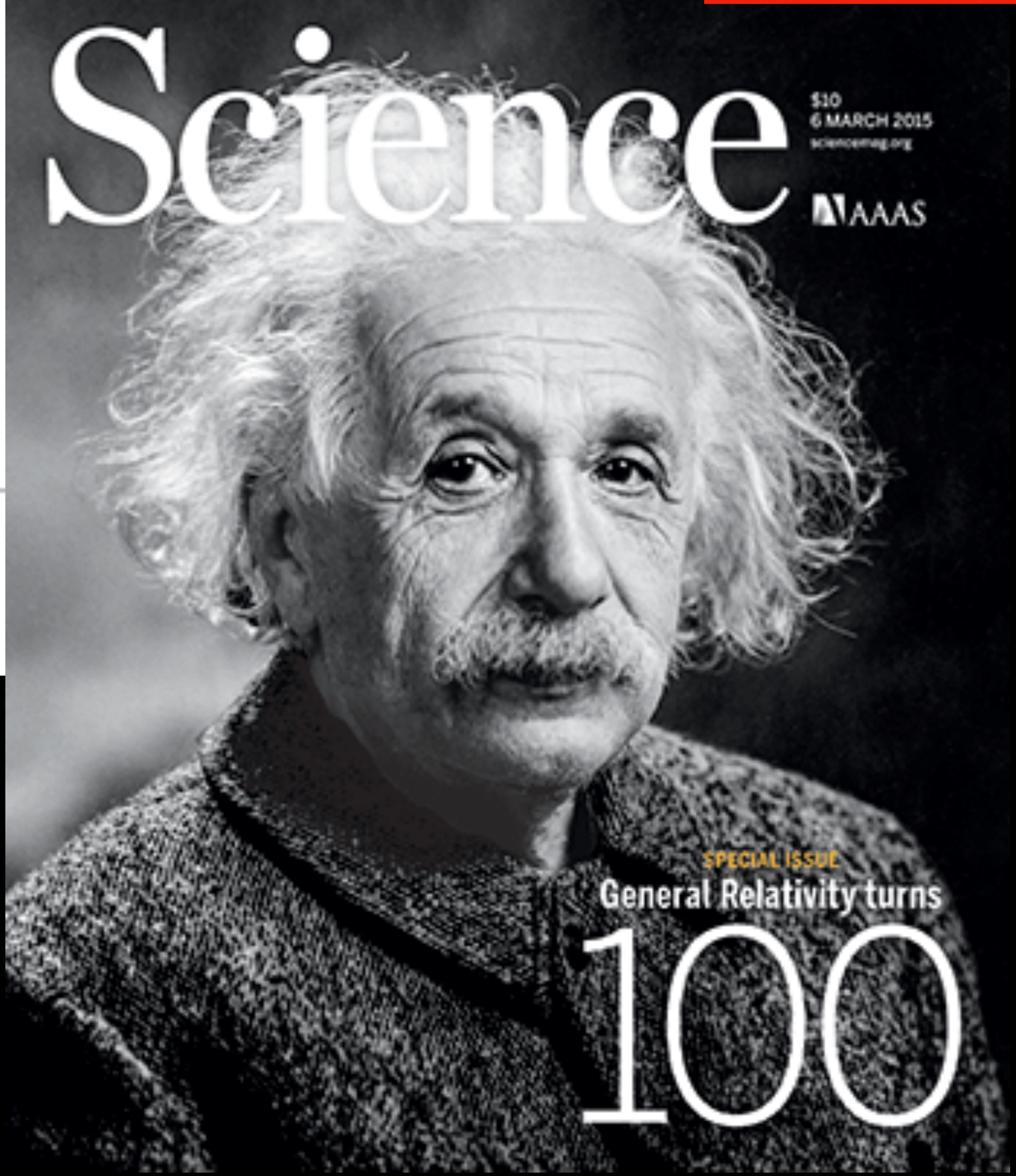

Origin of *Homo* pushed back 400,000 years p. 1056

Countering antibiotic resistance pp. 1062 & 1064

Science

$10 6 MARCH 2015 sciencemag.org

AAAS

SPECIAL ISSUE

General Relativity turns 100

Binary black holes

2015: first detection of gravitational waves

1915: Einstein proposes the theory of general relativity

GW150914: the first gravitational wave detection

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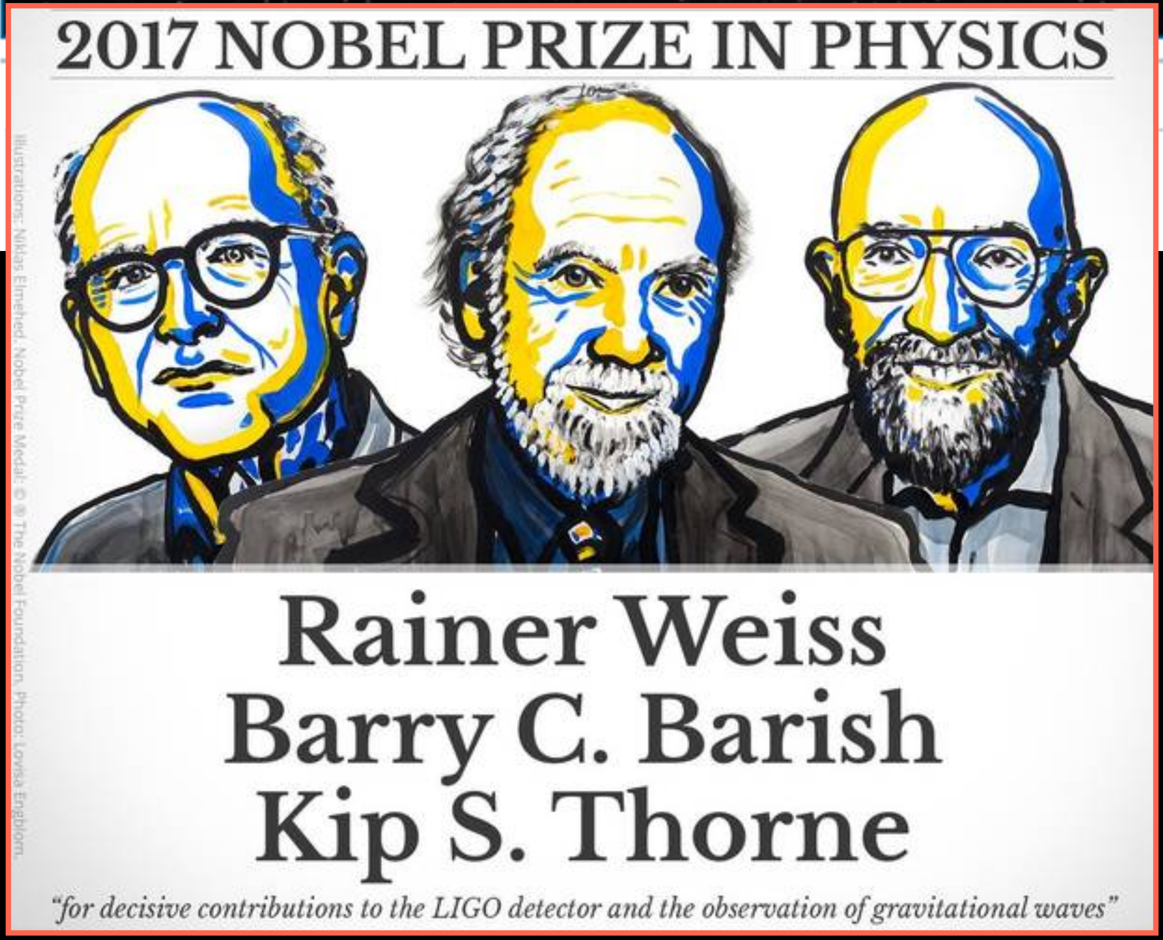
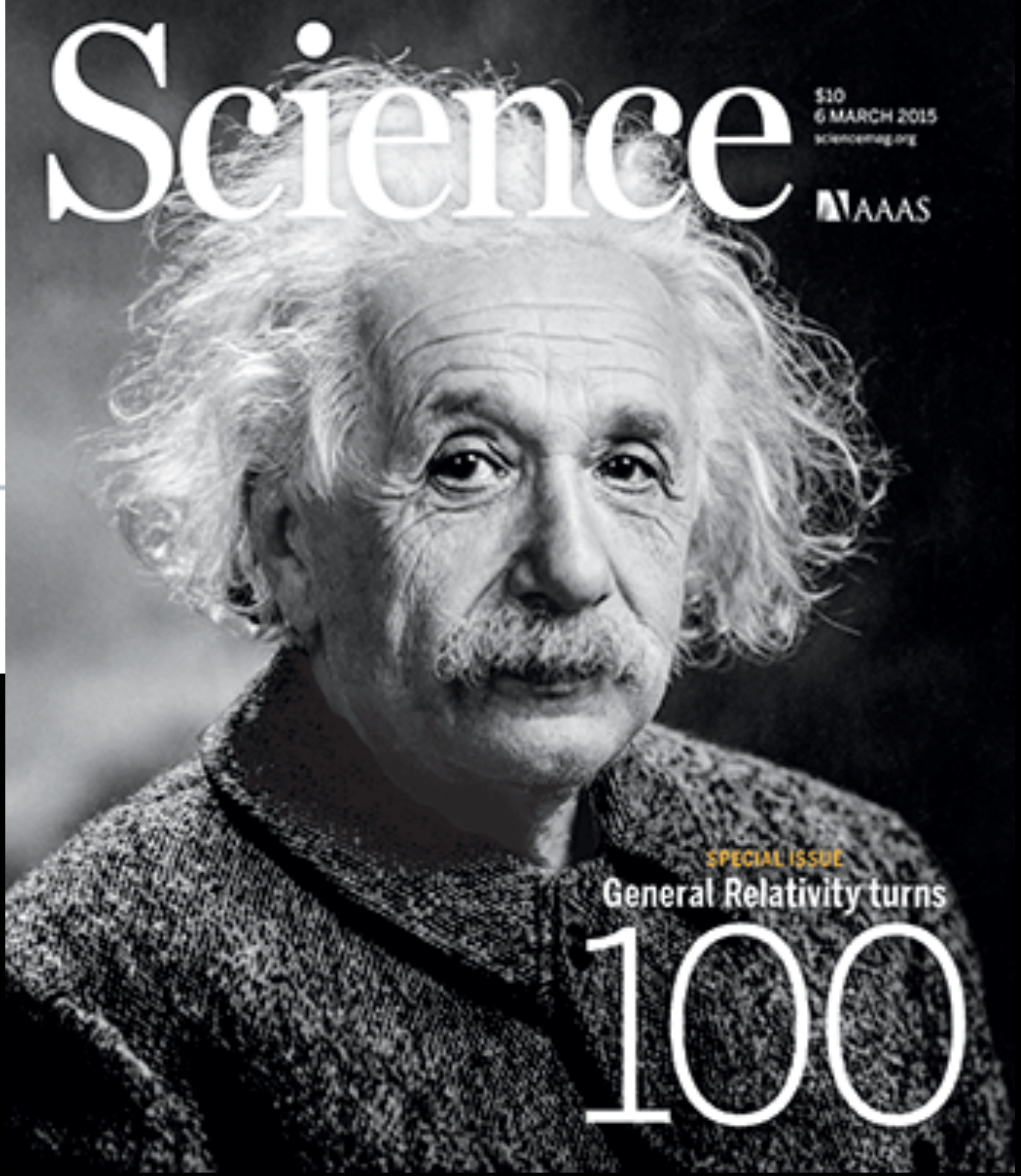
Gravitational Waves Detected
100 Years After Einstein's Prediction



2017 NOBEL PRIZE IN PHYSICS

Rainer Weiss
Barry C. Barish
Kip S. Thorne

"for decisive contributions to the LIGO detector and the observation of gravitational waves"



Origin of *Homo* pushed back 400,000 years p. 1056 | Countering antibiotic resistance pp. 1052 & 1064

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sciencemag.org

AAAS

SPECIAL ISSUE
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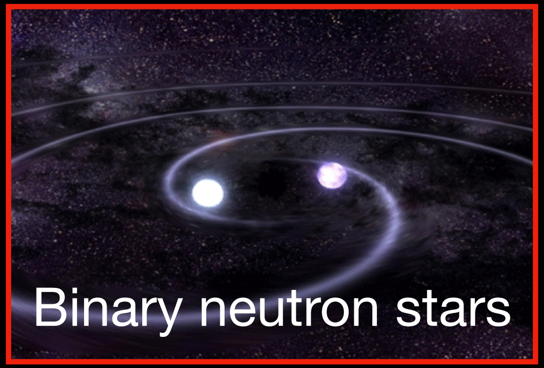
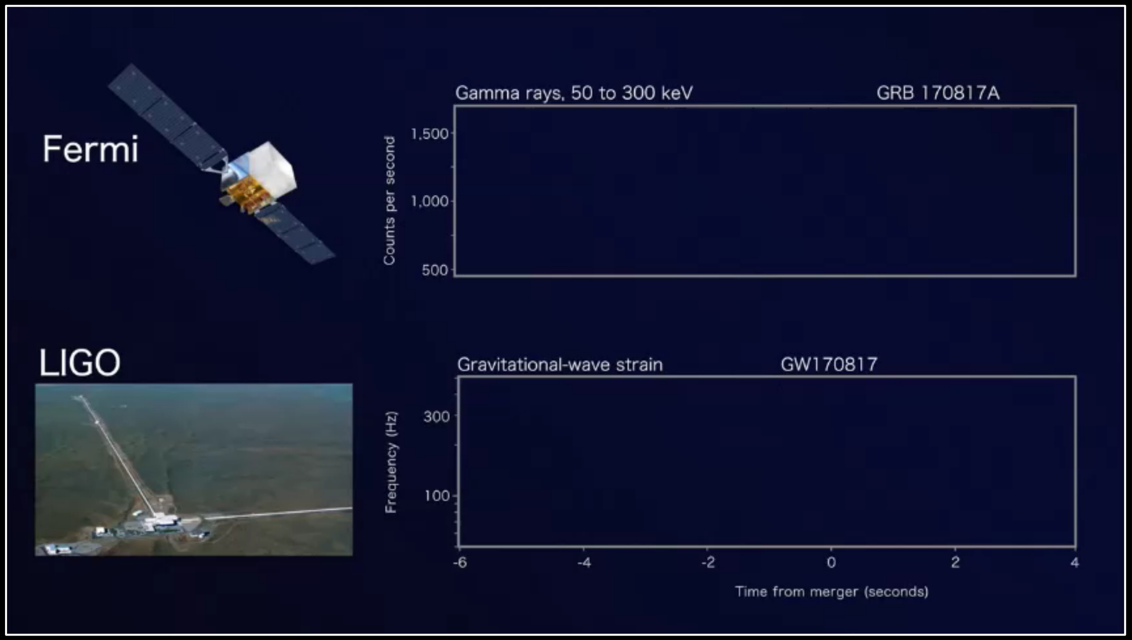
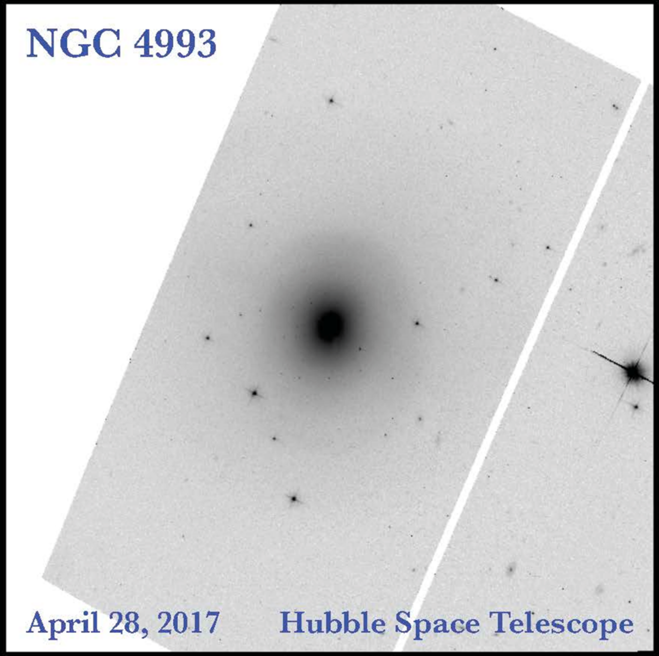
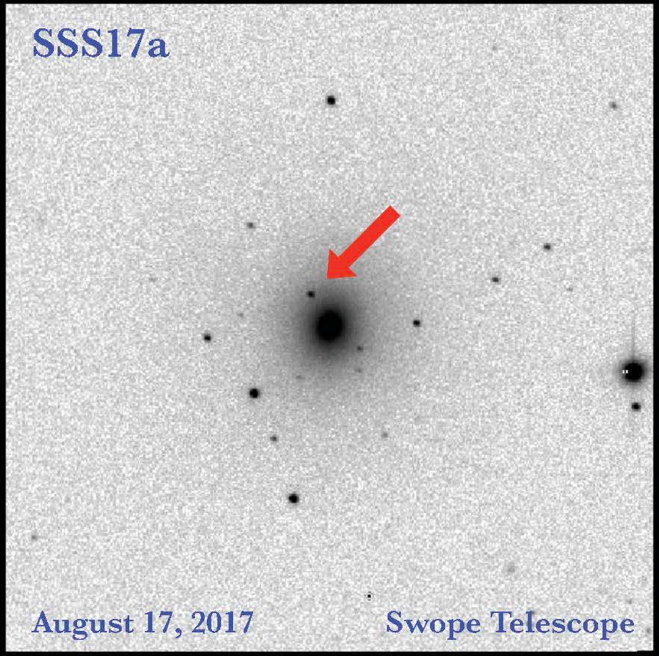
GW170817: the first multi-messenger detection





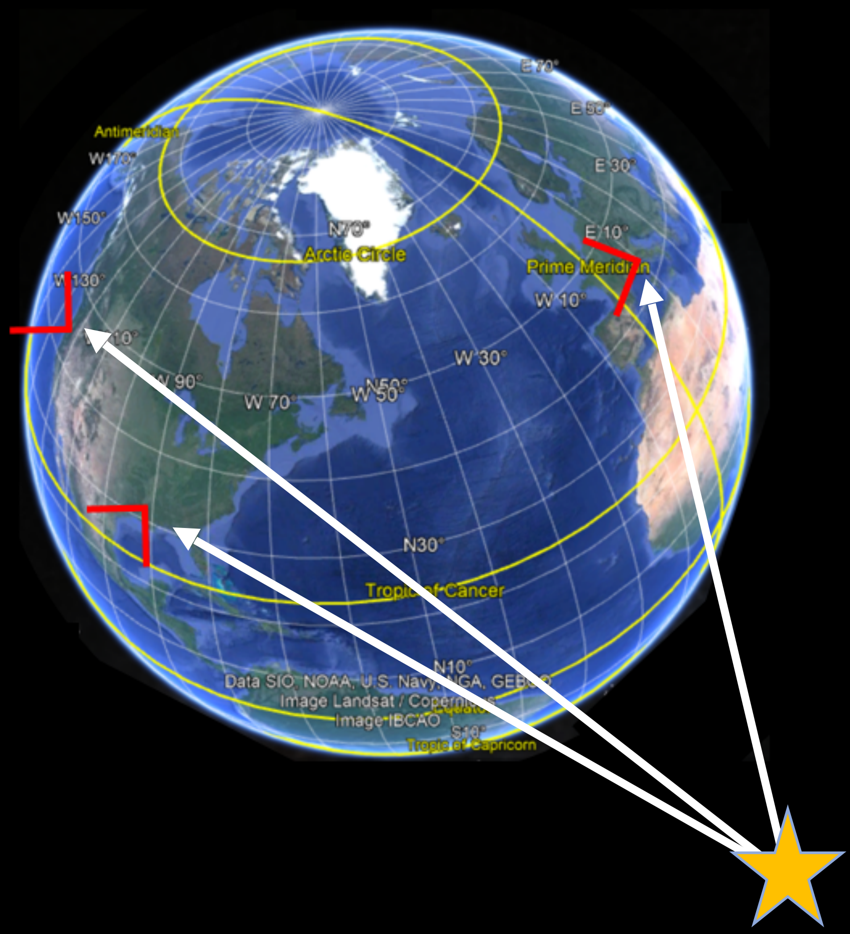


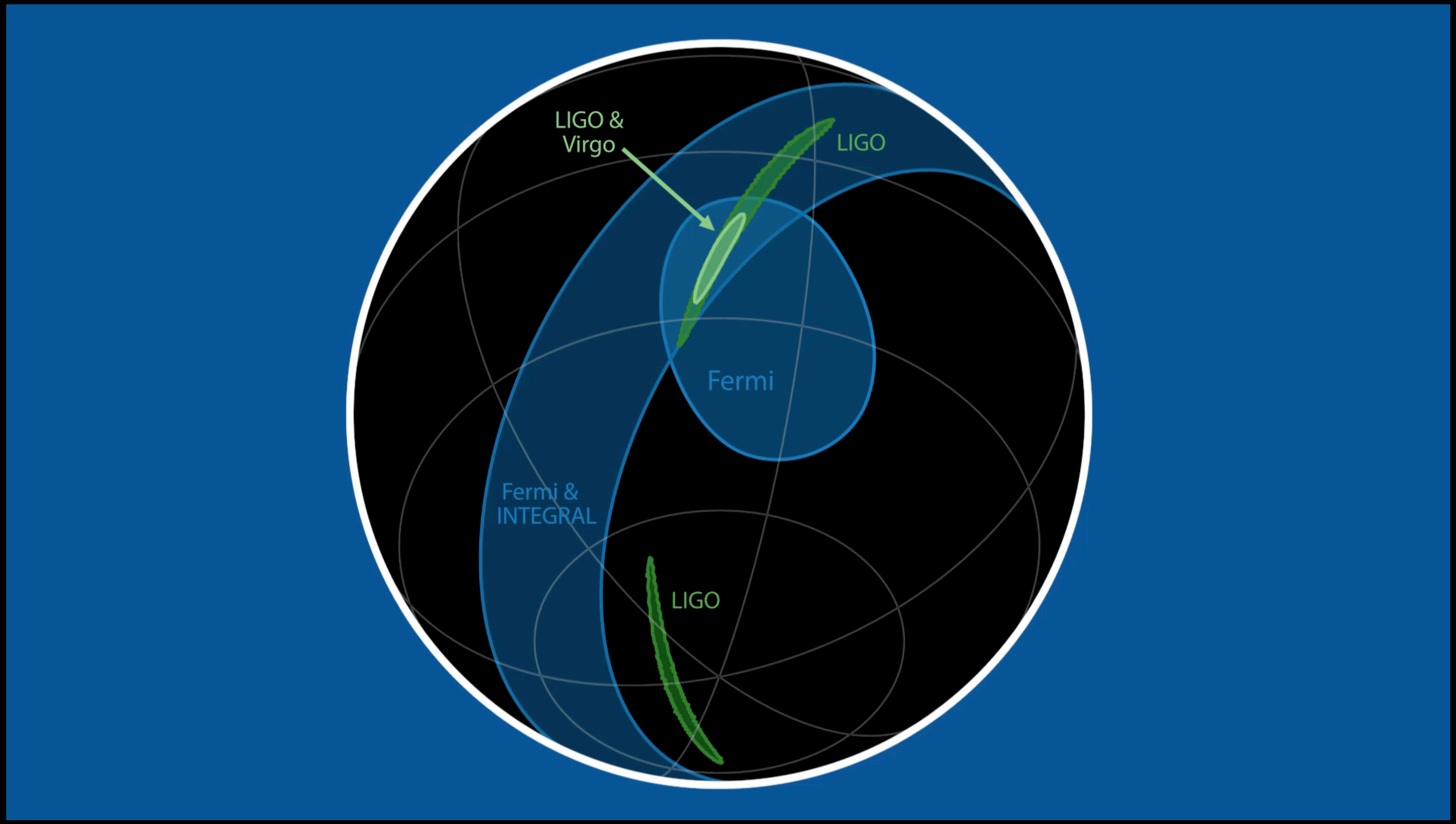


GW170817: the first multi-messenger detection

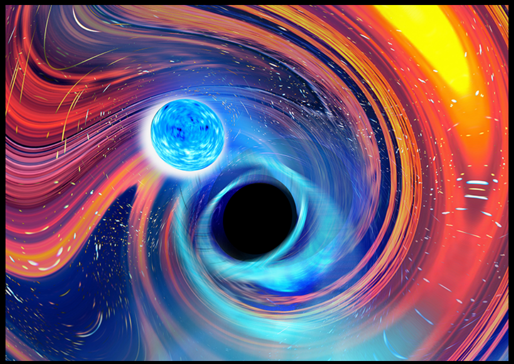
Multiple detectors allow for a better sky-localisation thanks to triangulation

Helping telescopes to find the associated electromagnetic signal

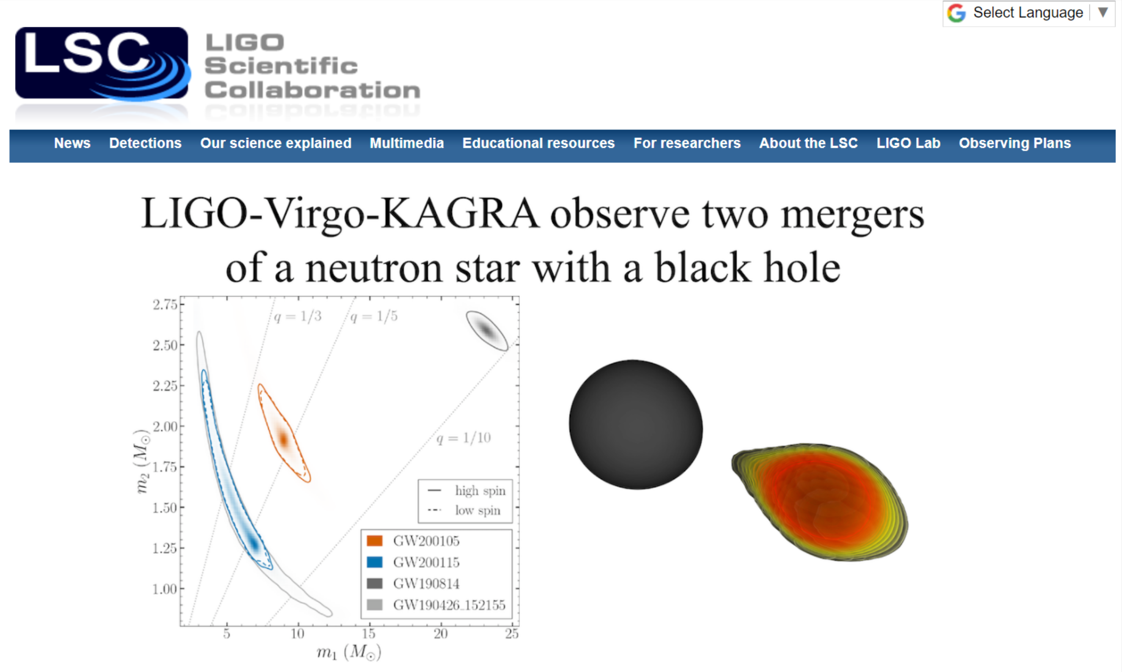




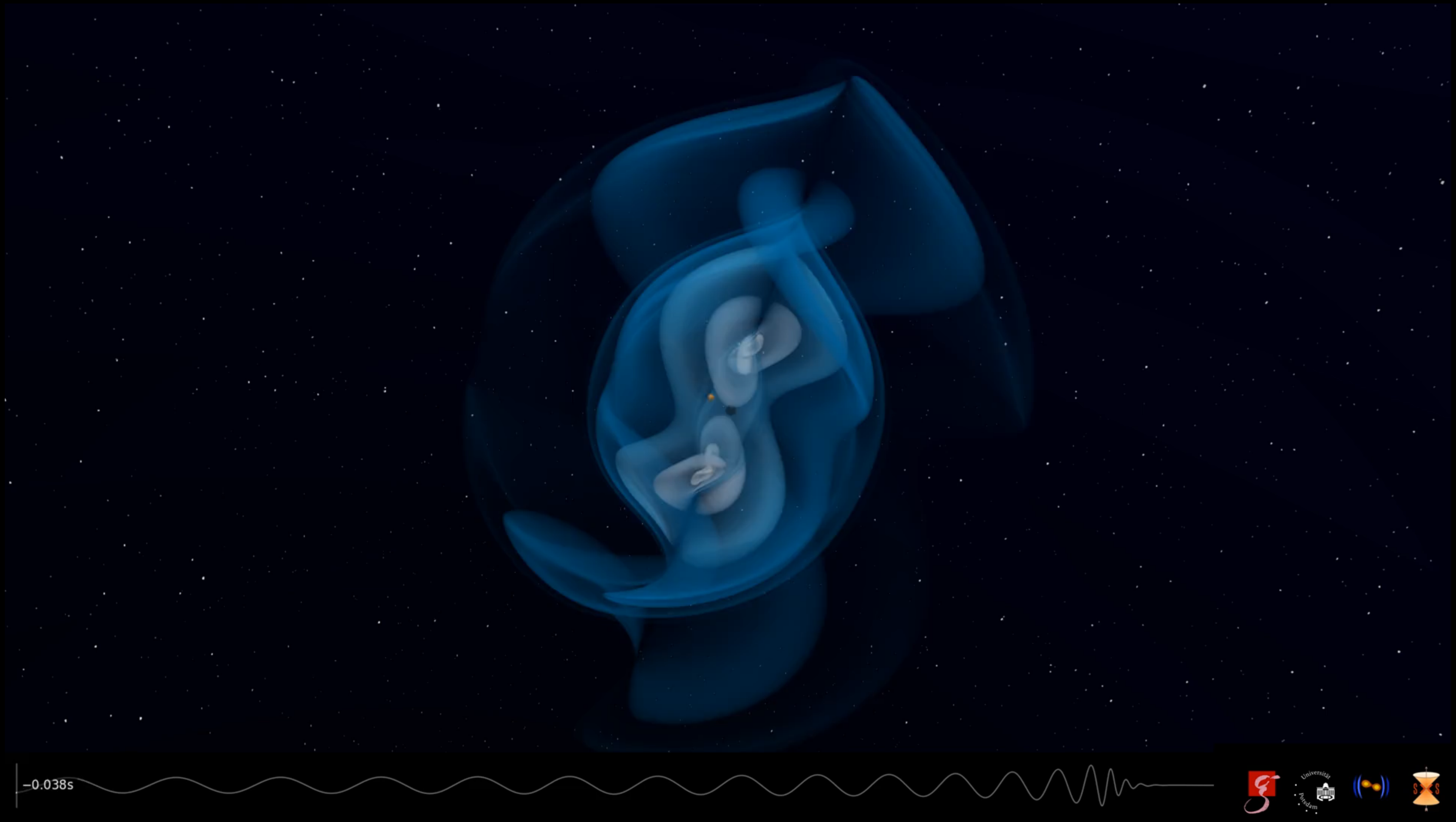
GW200115: a neutron star - black hole merger



Neutron star - black hole binaries



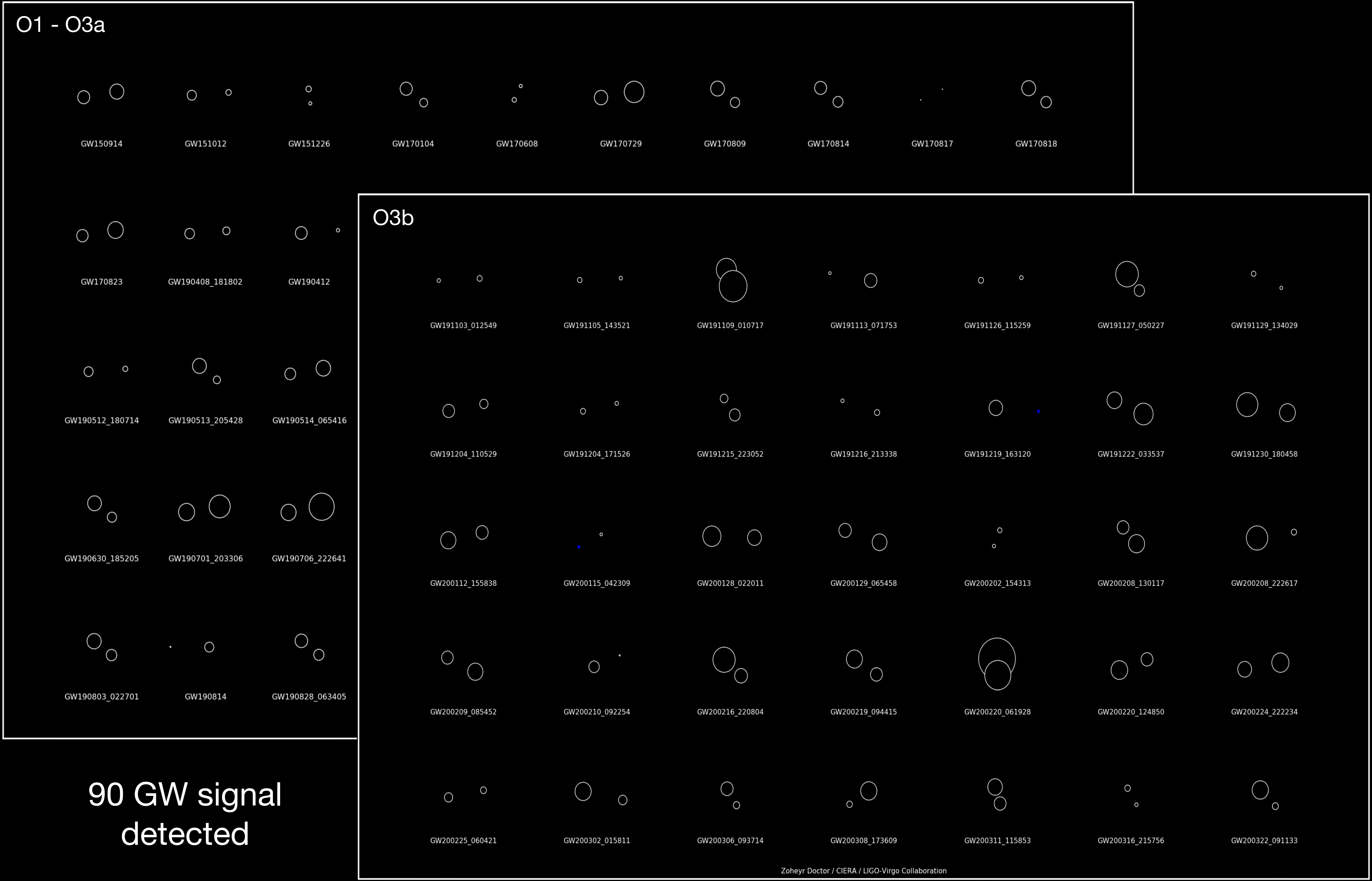
LIGO-Virgo-KAGRA observe two mergers of a neutron star with a black hole



~3 neutron star - black hole binaries detected so far

No electromagnetic counterpart

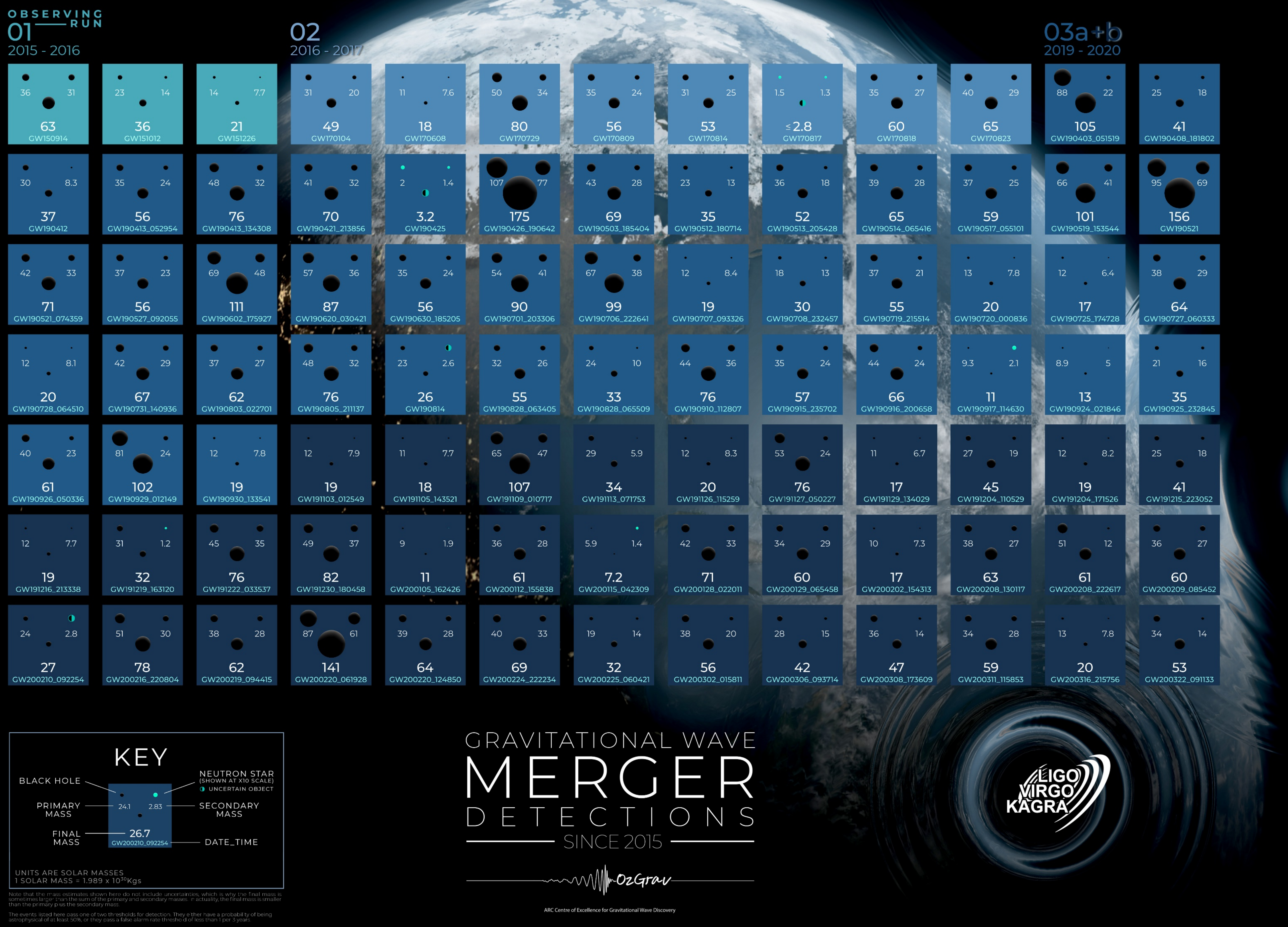
All LIGO-Virgo detections so far



90 GW signal detected

Credit: Z. Doctor / LVK

All LIGO-Virgo detections so far



OBSERVING RUN 01 2015 - 2016			02 2016 - 2017								03a+b 2019 - 2020	
36 31 63 GW150914	23 14 36 GW151012	14 7.7 21 GW151226	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729	35 24 56 GW170809	31 25 53 GW170814	1.5 1.3 ≤ 2.8 GW170817	35 27 60 GW170818	40 29 65 GW170823	88 22 105 GW190403_051519	25 18 41 GW190408_181802
30 8.3 37 GW190412	35 24 56 GW190413_052954	48 32 76 GW190413_134308	41 32 70 GW190421_213856	2 1.4 3.2 GW190425	107 77 175 GW190426_190642	43 28 69 GW190503_185404	23 13 35 GW190512_180714	36 18 52 GW190513_205428	39 28 65 GW190514_065416	37 25 59 GW190517_055101	66 41 101 GW190519_153544	95 69 156 GW190521
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 48 111 GW190602_175927	57 36 87 GW190620_030421	35 24 56 GW190630_185205	54 41 90 GW190701_203306	67 38 99 GW190706_222641	12 8.4 19 GW190707_093326	18 13 30 GW190708_232457	37 21 55 GW190719_215514	13 7.8 20 GW190720_000836	12 6.4 17 GW190725_174728	38 29 64 GW190727_060333
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 27 62 GW190803_022701	48 32 76 GW190805_211137	23 2.6 26 GW190814	32 26 55 GW190828_063405	24 10 33 GW190828_065509	44 36 76 GW190910_112807	35 24 57 GW190915_235702	44 24 66 GW190916_200658	9.3 2.1 11 GW190917_114630	8.9 5 13 GW190924_021846	21 16 35 GW190925_232845
40 23 61 GW190926_050336	81 24 102 GW190929_012149	12 7.8 19 GW190930_133541	12 7.9 19 GW191103_012549	11 7.7 18 GW191105_143521	65 47 107 GW191109_010717	29 5.9 34 GW191113_071753	12 8.3 20 GW191126_115259	53 24 76 GW191127_050227	11 6.7 17 GW191129_134029	27 19 45 GW191204_110529	12 8.2 19 GW191204_171526	25 18 41 GW191215_223052
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155838	5.9 1.4 7.2 GW200115_042309	42 33 71 GW200128_022011	34 29 60 GW200129_065458	10 7.3 17 GW200202_154313	38 27 63 GW200208_130117	51 12 61 GW200208_222617	36 27 60 GW200209_085452
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234	19 14 32 GW200225_060421	38 20 56 GW200302_015811	28 15 42 GW200306_093714	36 14 47 GW200308_173609	34 28 59 GW200311_115853	13 7.8 20 GW200316_215756	34 14 53 GW200322_091133

KEY

BLACK HOLE

NEUTRON STAR
(SHOWN AT X10 SCALE)
◐ UNCERTAIN OBJECT

PRIMARY MASS — 24.1

SECONDARY MASS — 2.83

FINAL MASS — 26.7

DATE_TIME — GW200210_092254

UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}Kgs

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

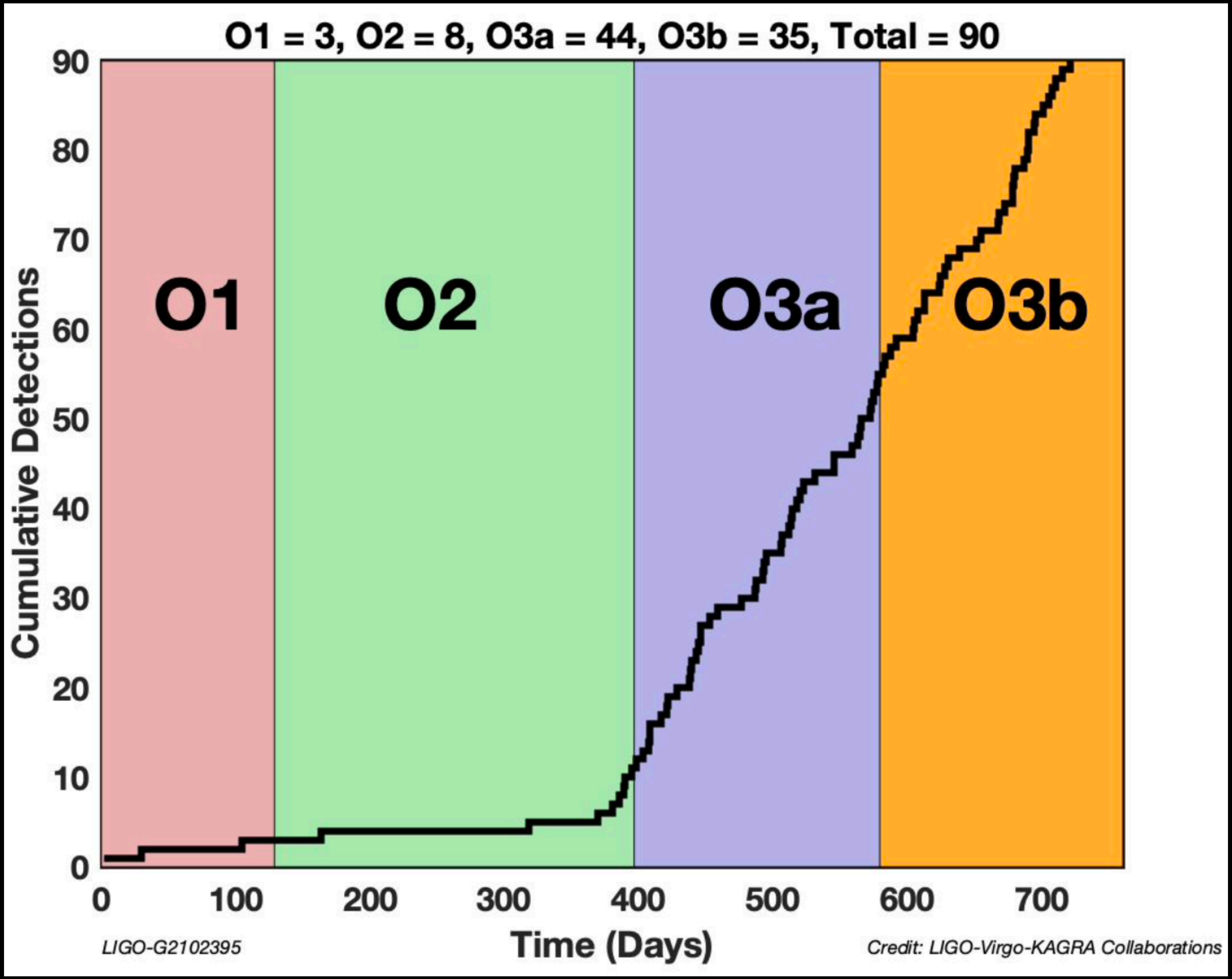
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

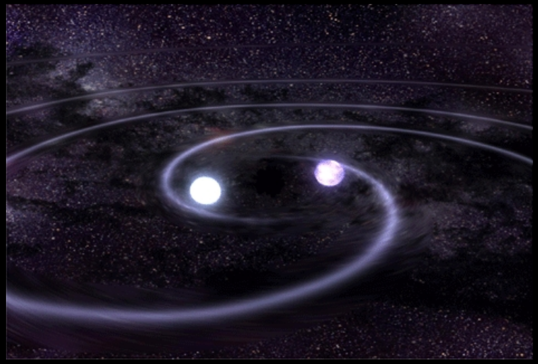
LIGO
VIRGO
KAGRA

All LIGO-Virgo detections so far

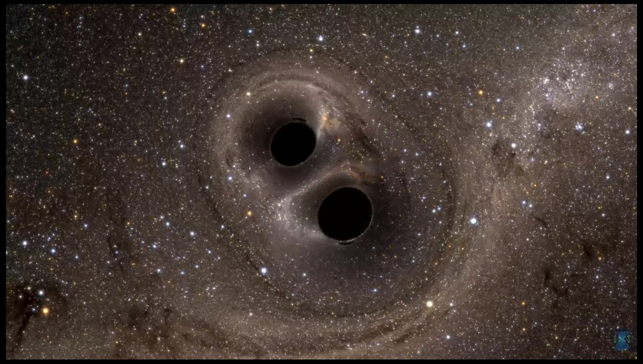


Astrophysical sources of gravitational waves

SOURCES ALREADY DETECTED BY THE LVK DETECTORS:



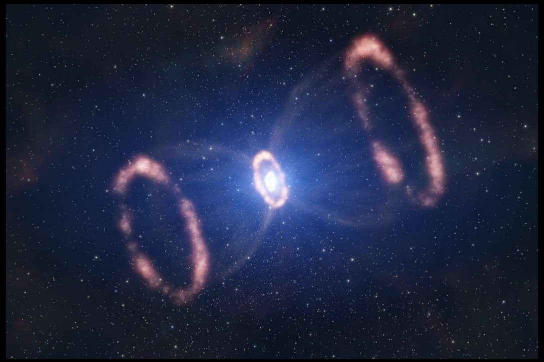
Binary neutron stars



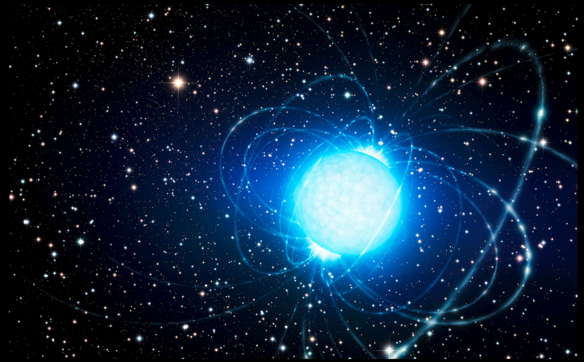
Binary black holes

Neutron star - black hole binaries

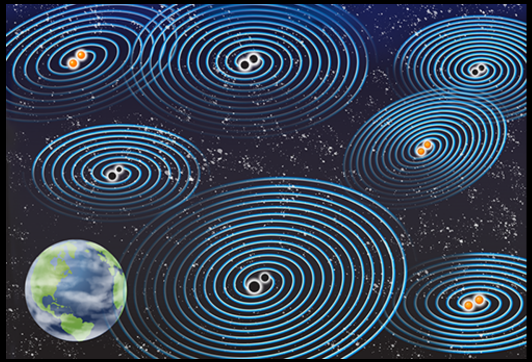
OTHER TARGETS FOR THE LVK DETECTORS:



Supernovae



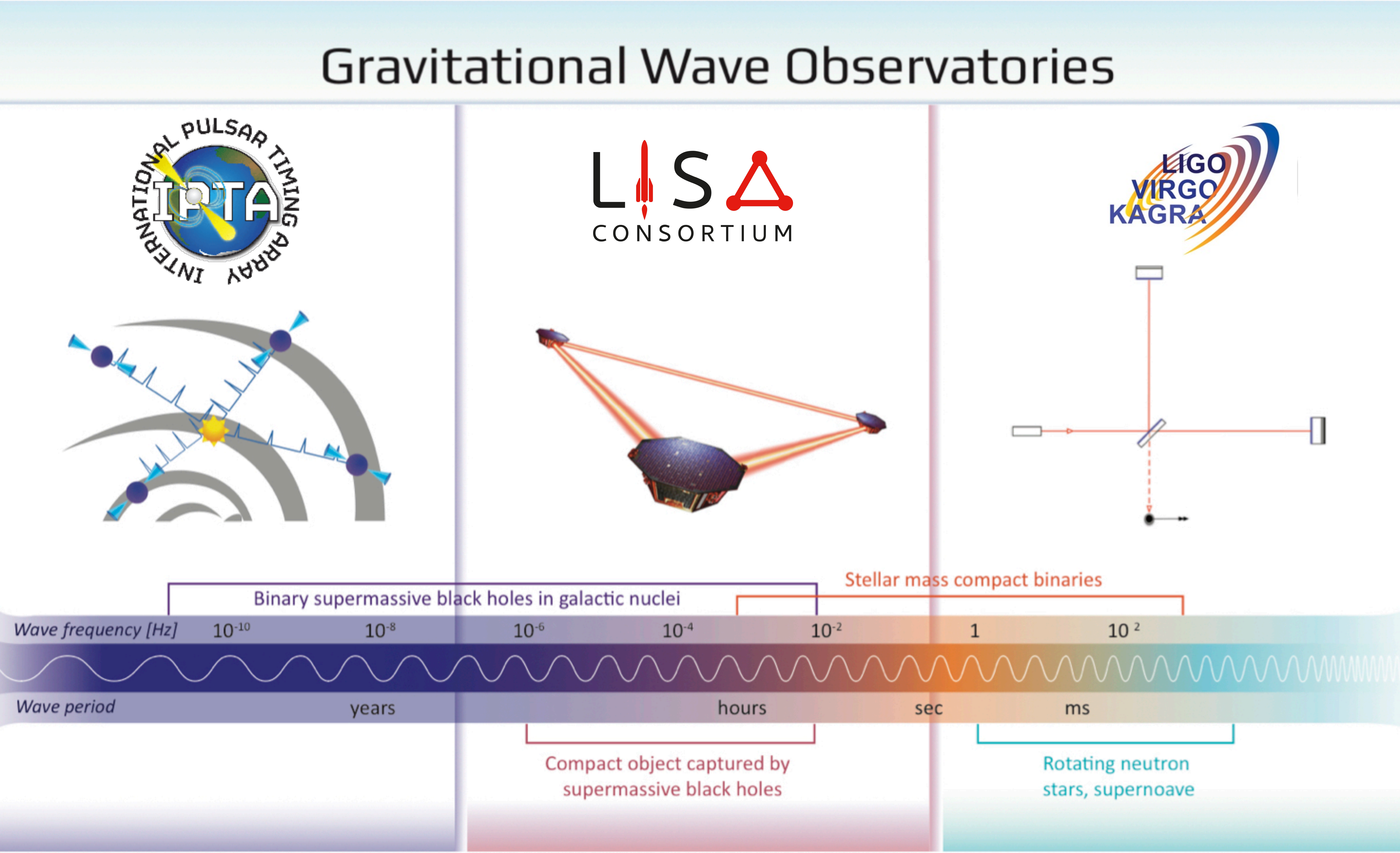
Single (asymmetric) neutron stars



Stochastic GW background

CAN WE DETECT OTHER SOURCES?

GW sources across the spectrum

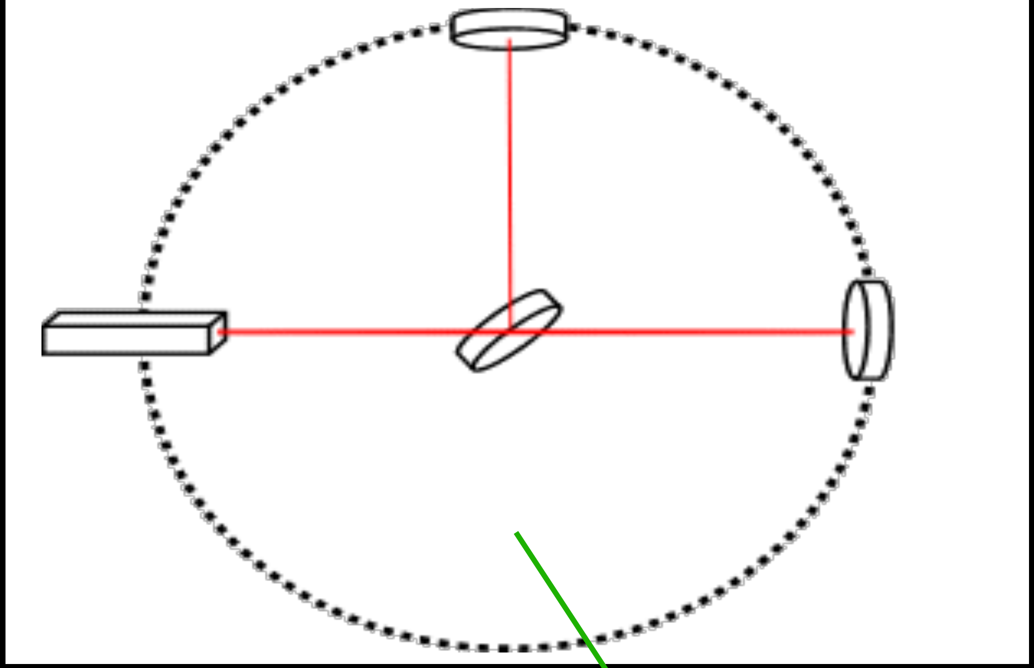


Credit: NASA

OUTLINE

- Main concepts and detections strategy of GWs
- GW observations: the story so far
- **GWs from theory to observations**
- The scientific potential of GW astronomy

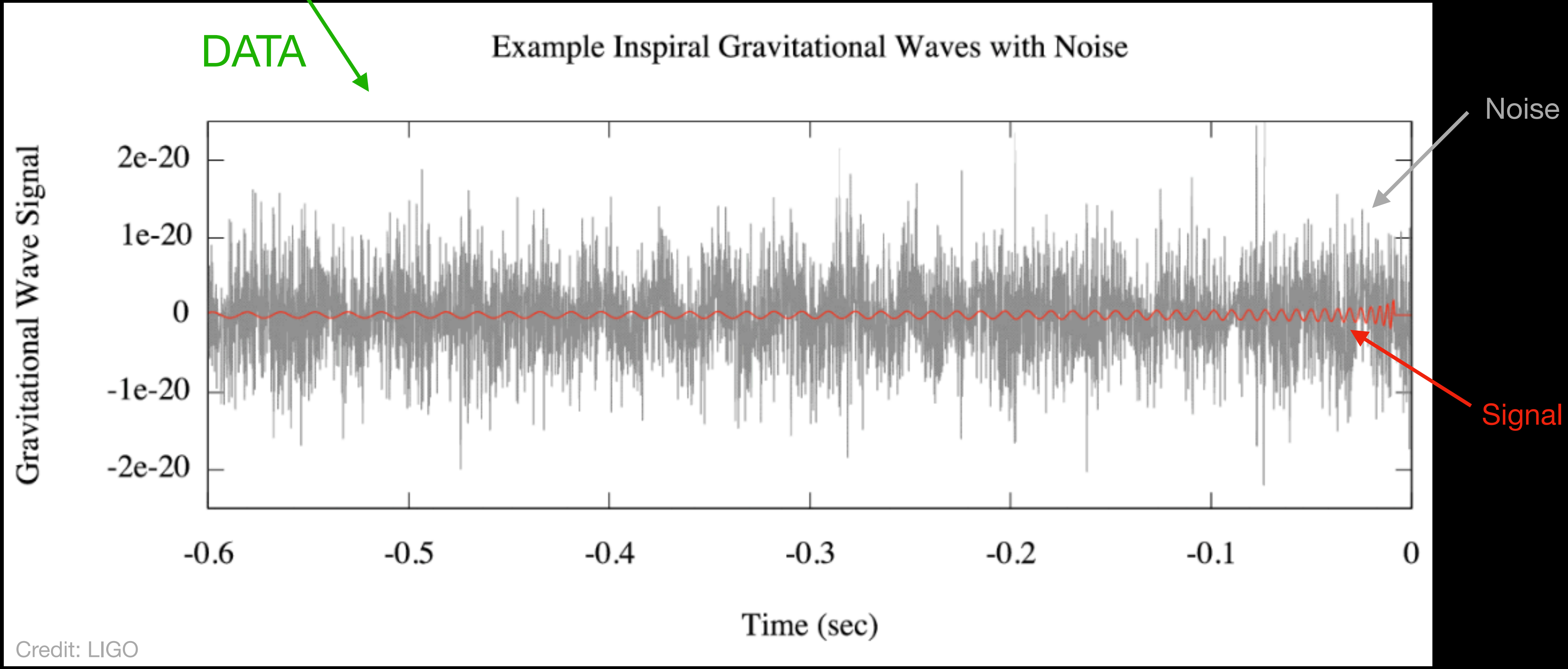
How do we detect and characterise the signal?



How to extract the signal from the noise?

MATCHED FILTERING

- Model the signal theoretically
- Find and characterise the signal in the data efficiently

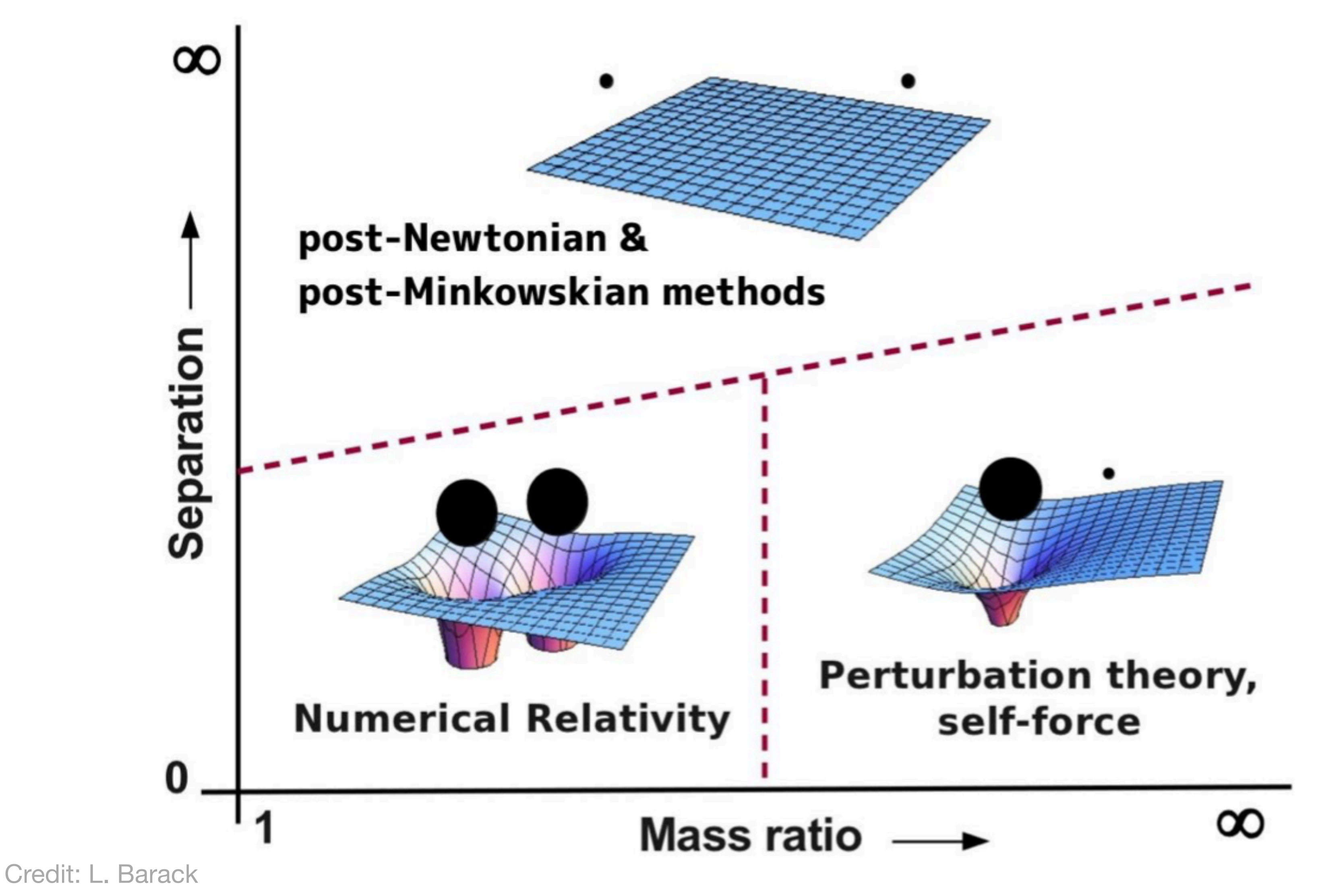


Credit: LIGO

Modelling the GW signal from compact binaries

No general analytical solution to the 2-body problem has (yet) been found in general relativity!

Different approximated or numerical techniques must be used in different regimes:



Credit: L. Barack

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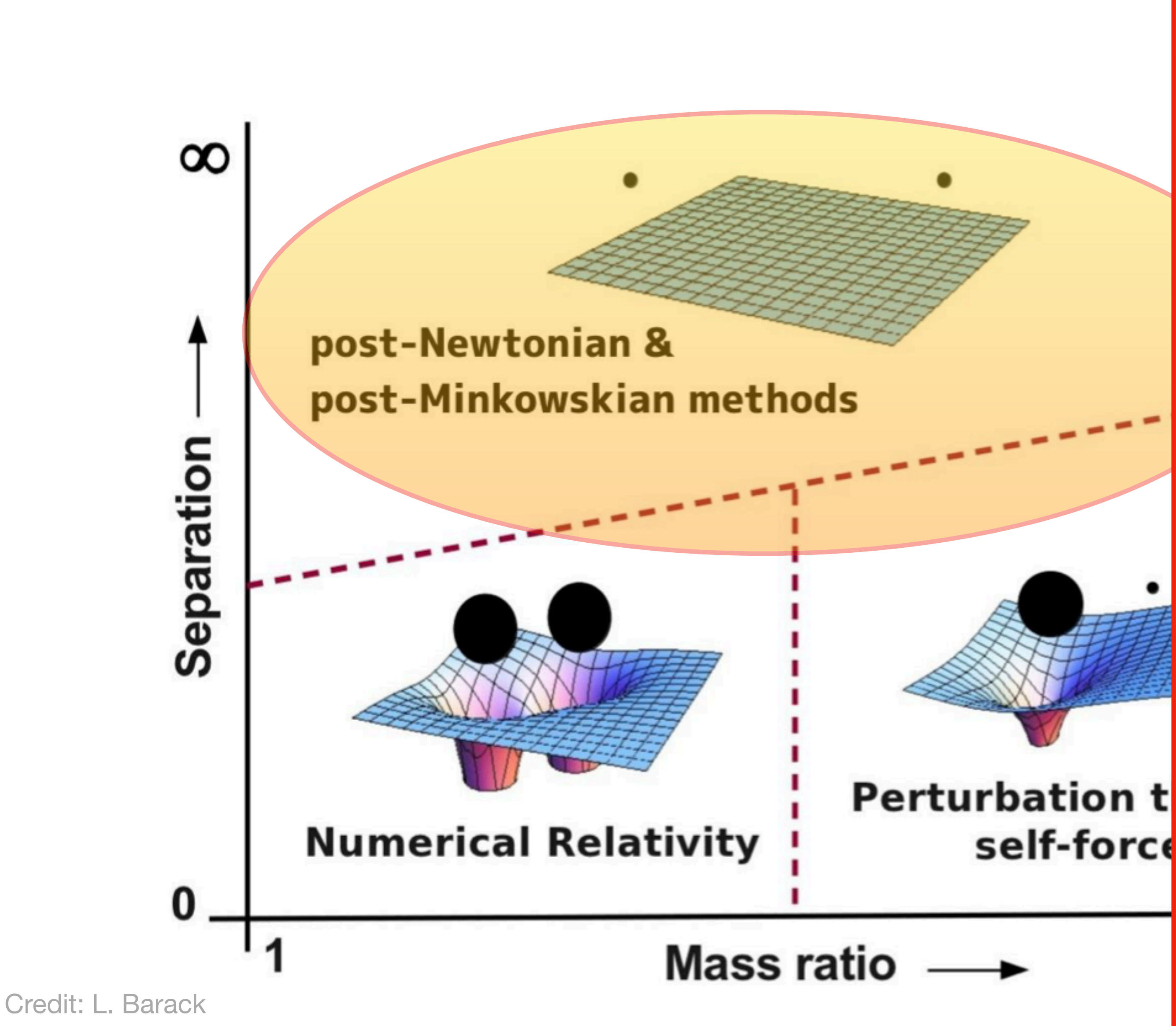
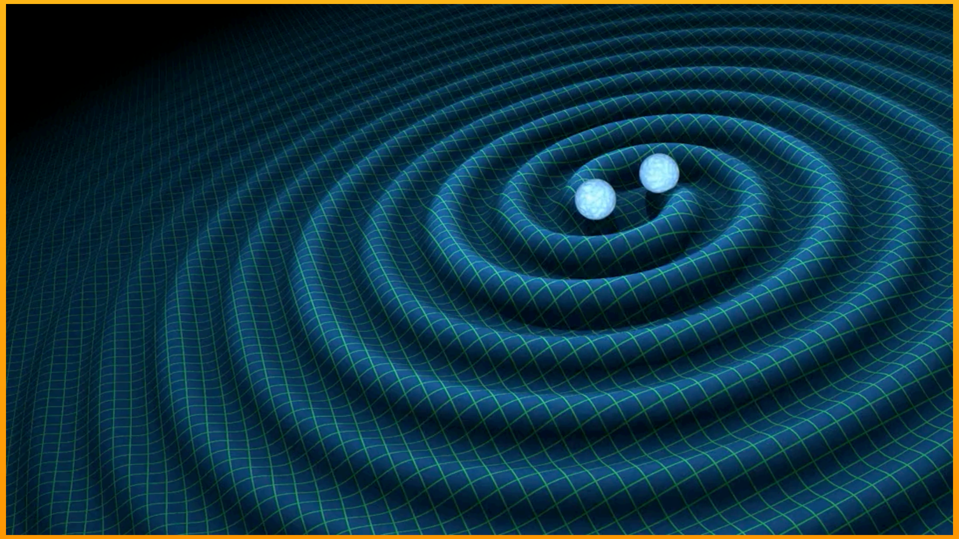


Credit: L. Barack

Analytical methods based on expansion in small velocities / weak gravitational field over a flat spacetime

Very efficient in the *inspiral*, large separation phase, of a binary

Can be expanded to include information from other regimes using the *Effective One Body* approach



Modelling the GW signal from compact binaries

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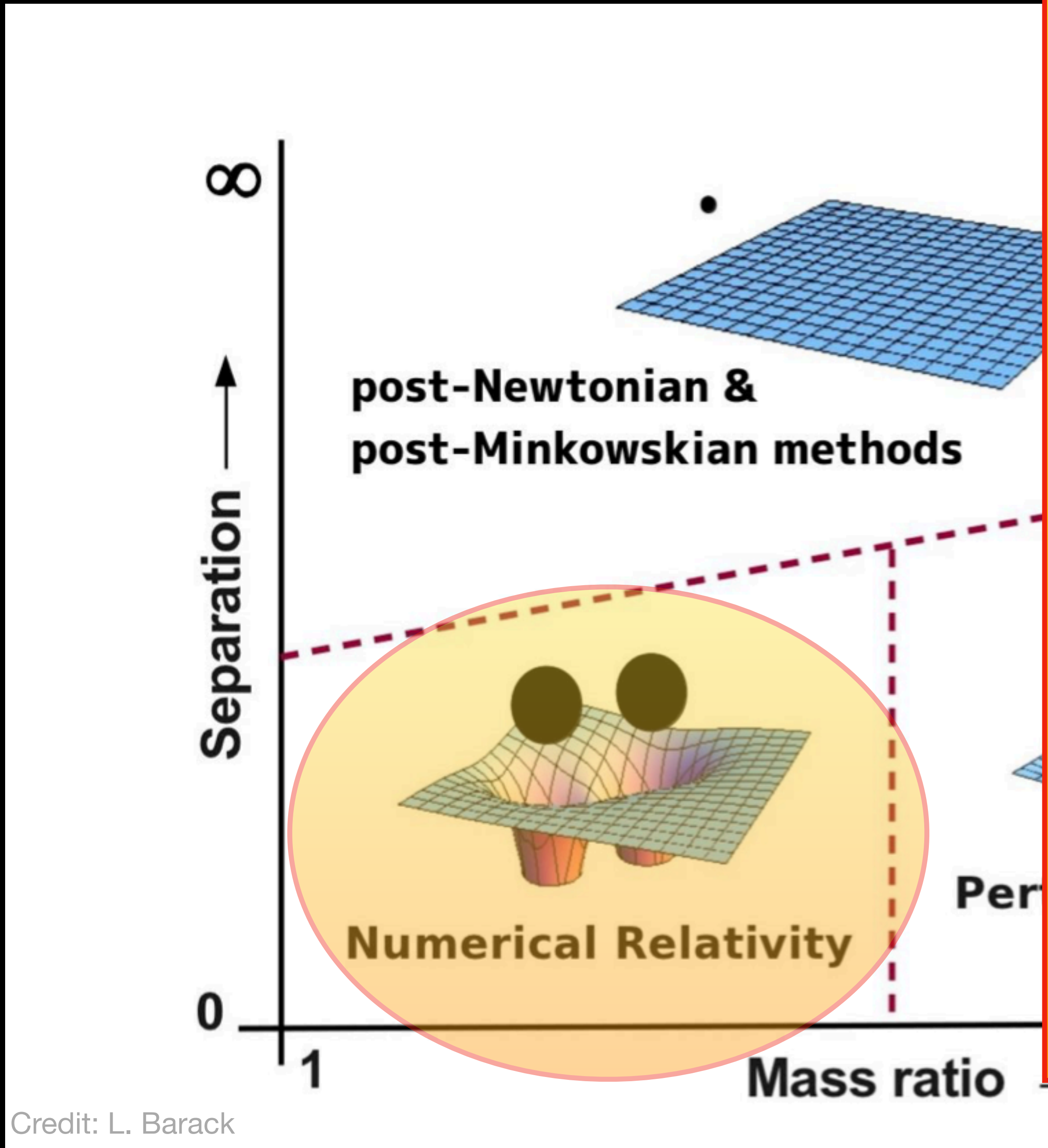
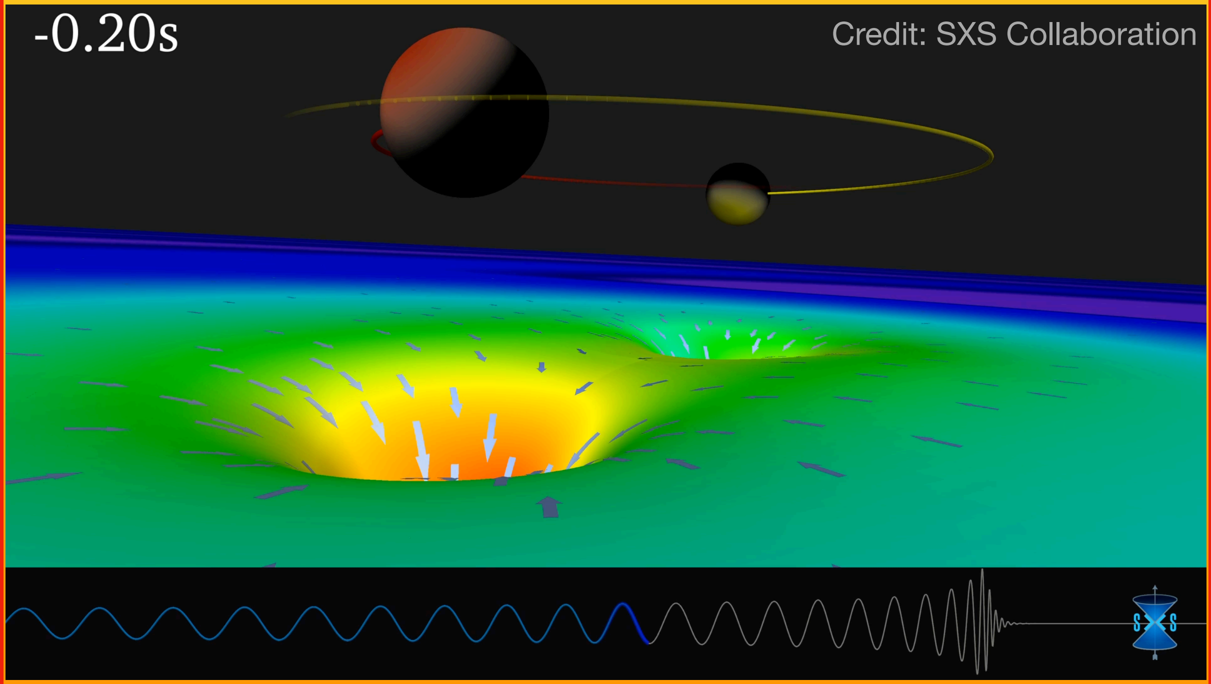


Credit: L. Barack

No analytical approach available

Fully numerical methods needed: solving the Einstein equation on a computer

Need high performance computing



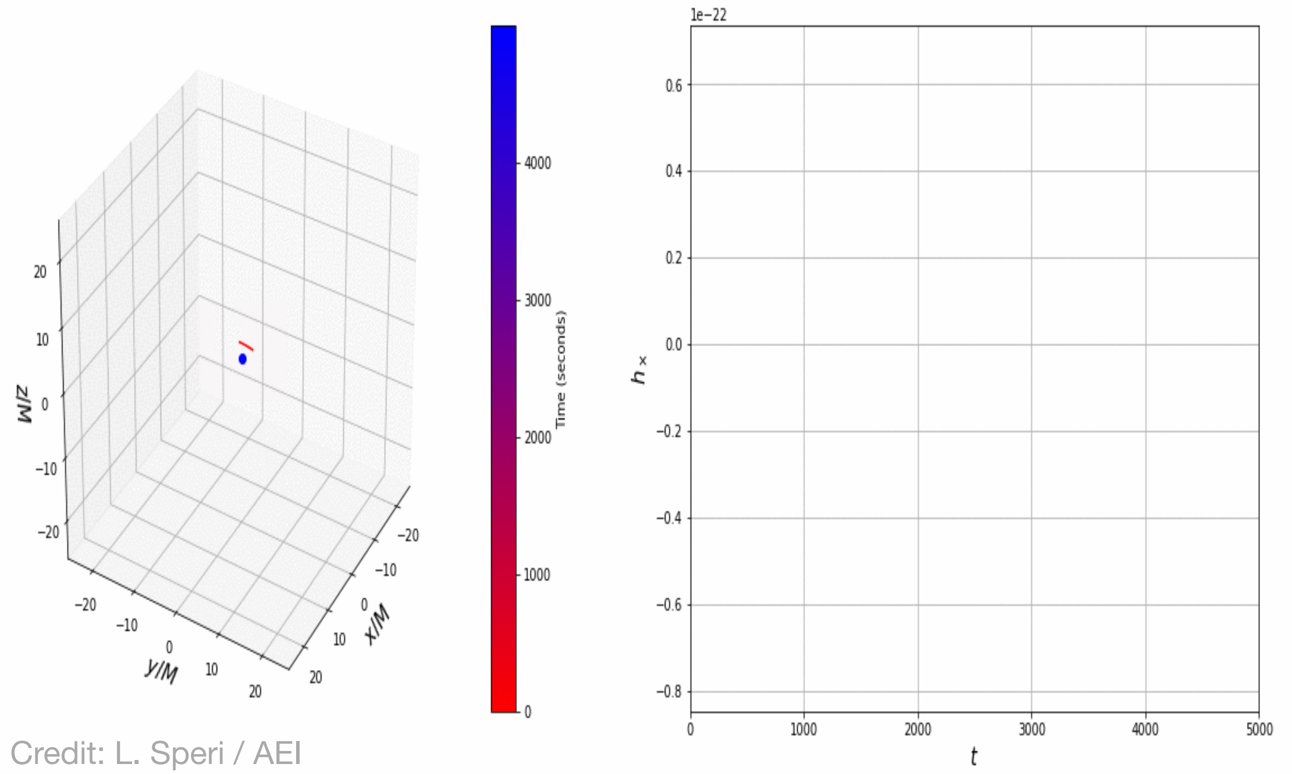
Credit: SXS Collaboration

Modelling the GW signal from compact binaries

No expansion over flat spacetime possible

Need complex analytical techniques

Still an “unsolved” problem (very relevant for future detectors, in particular LISA)



Credit: L. Speri / AEI

Credit: O. Burke / L2IT

No

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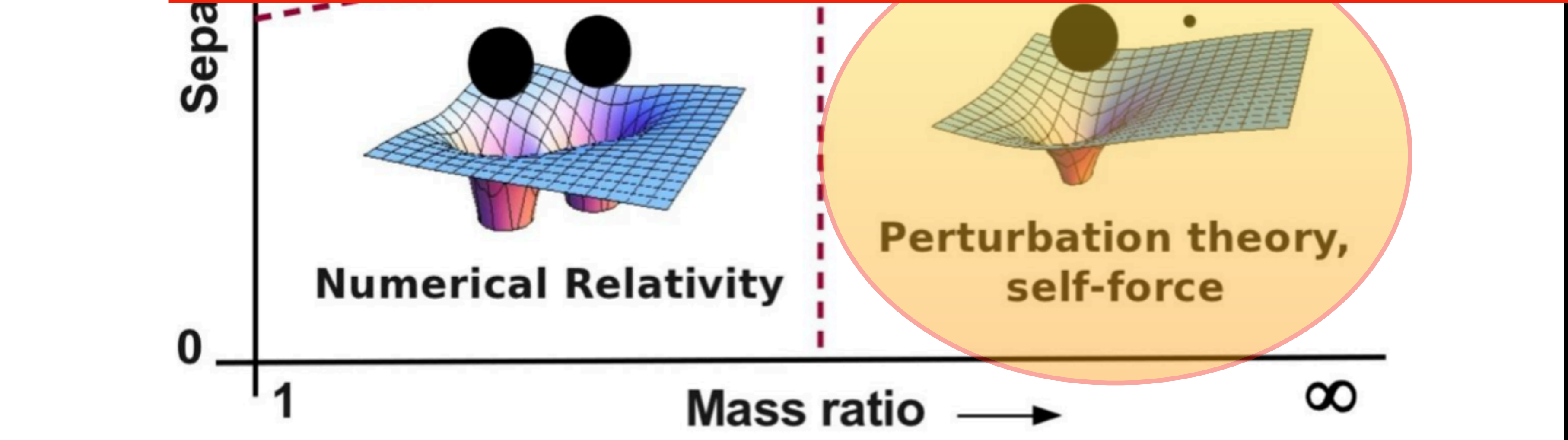
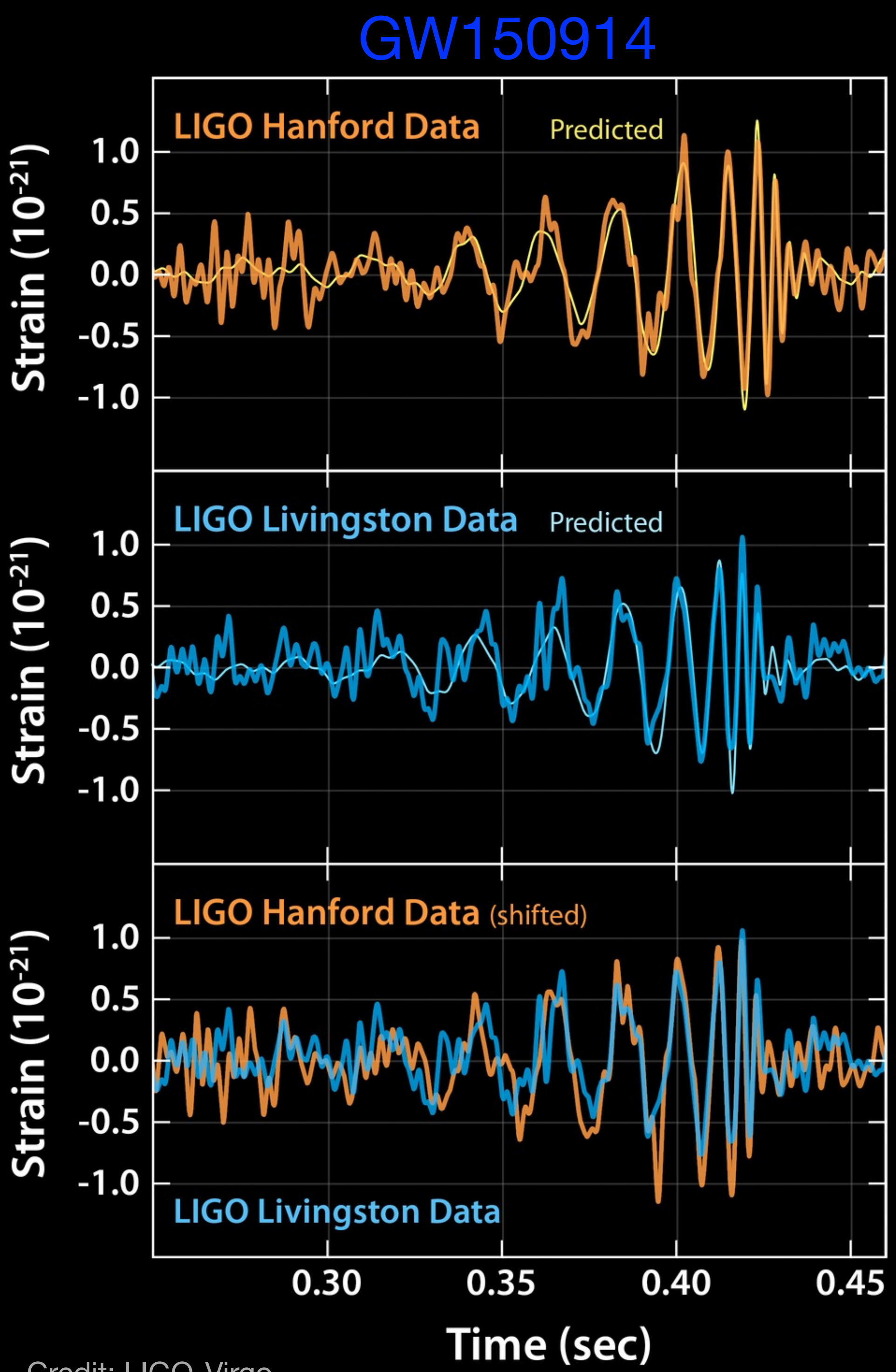
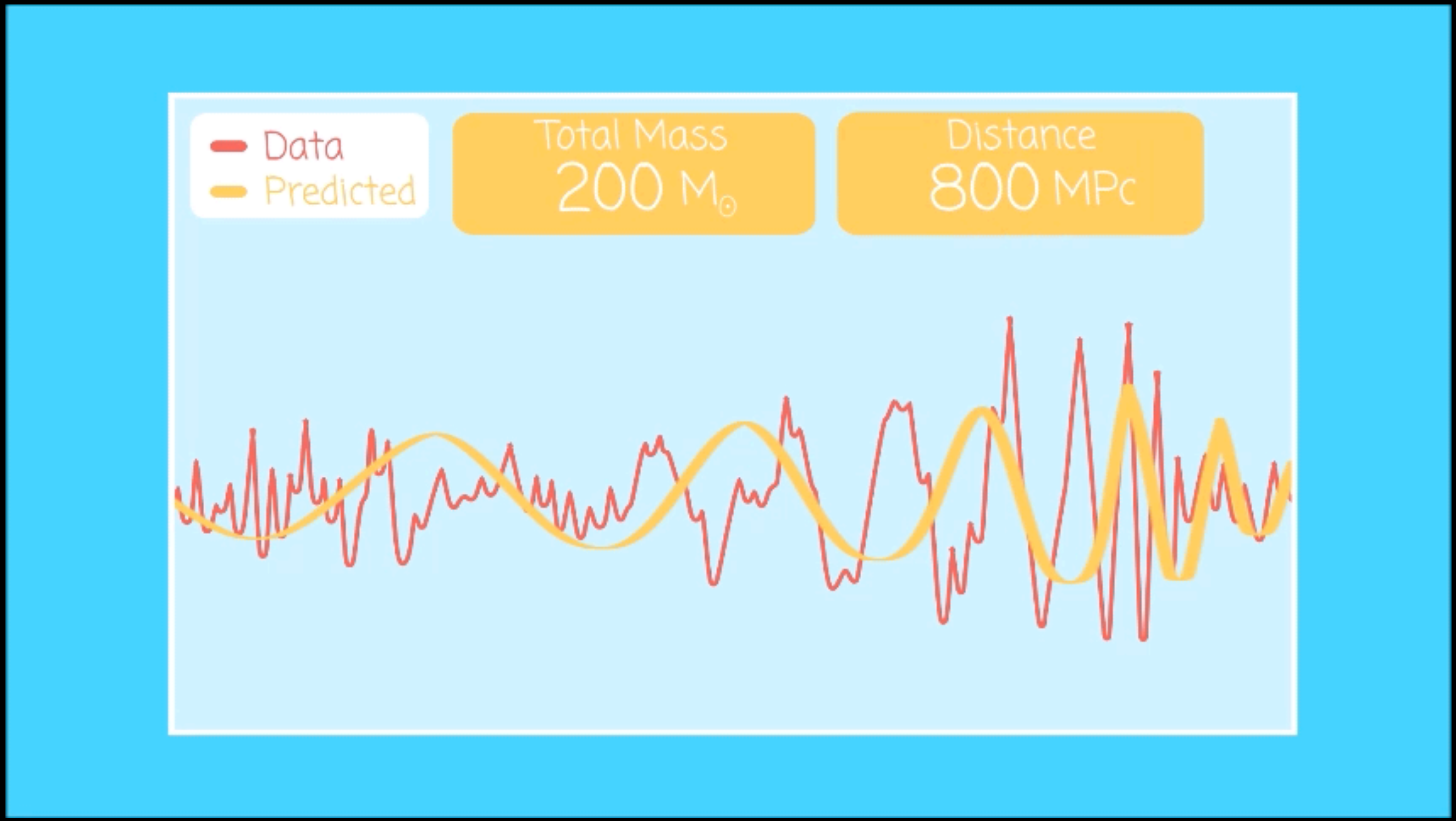


Credit: L. Barack

Finding and characterising the signal



Credit: LIGO-Virgo

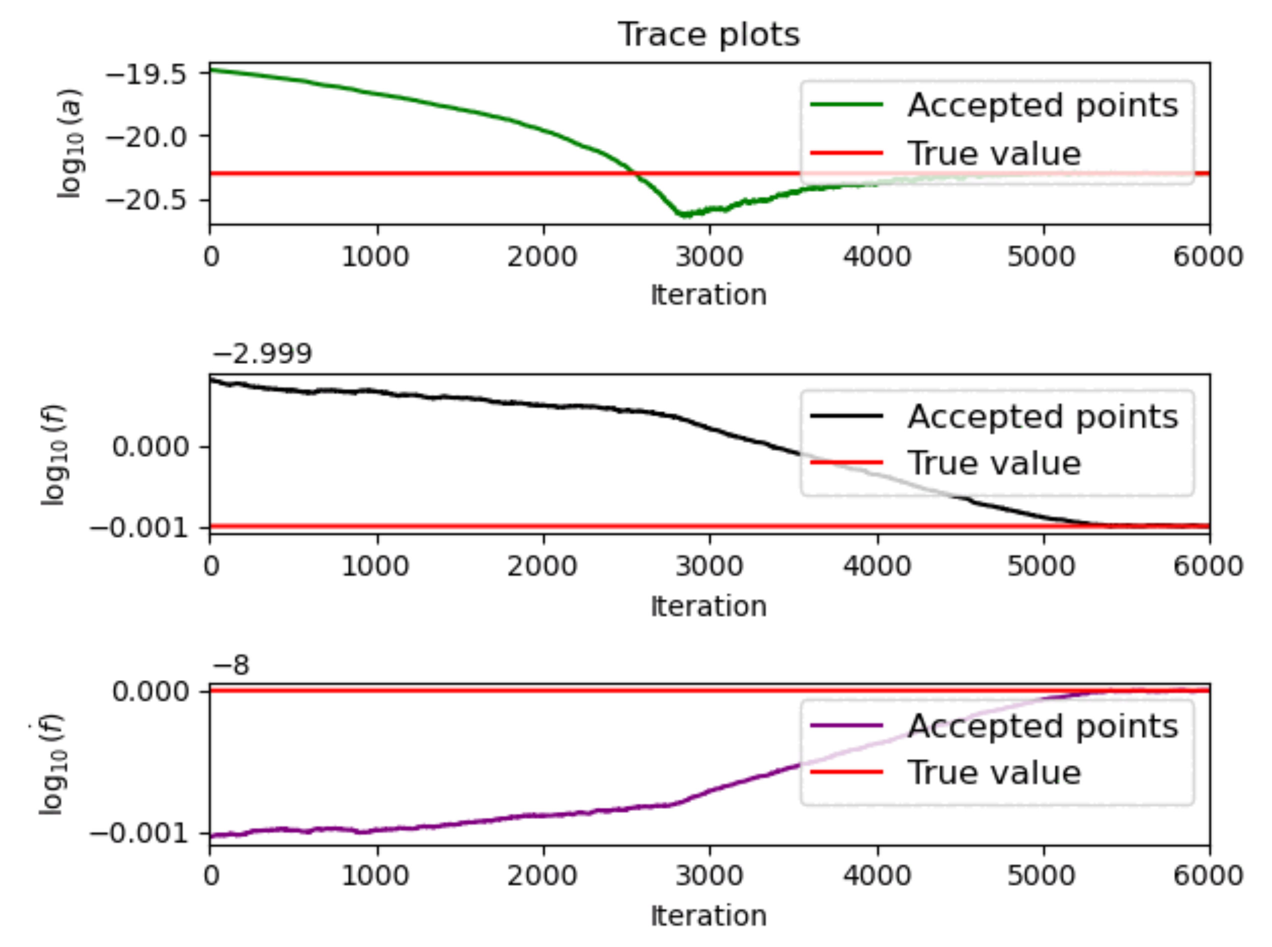


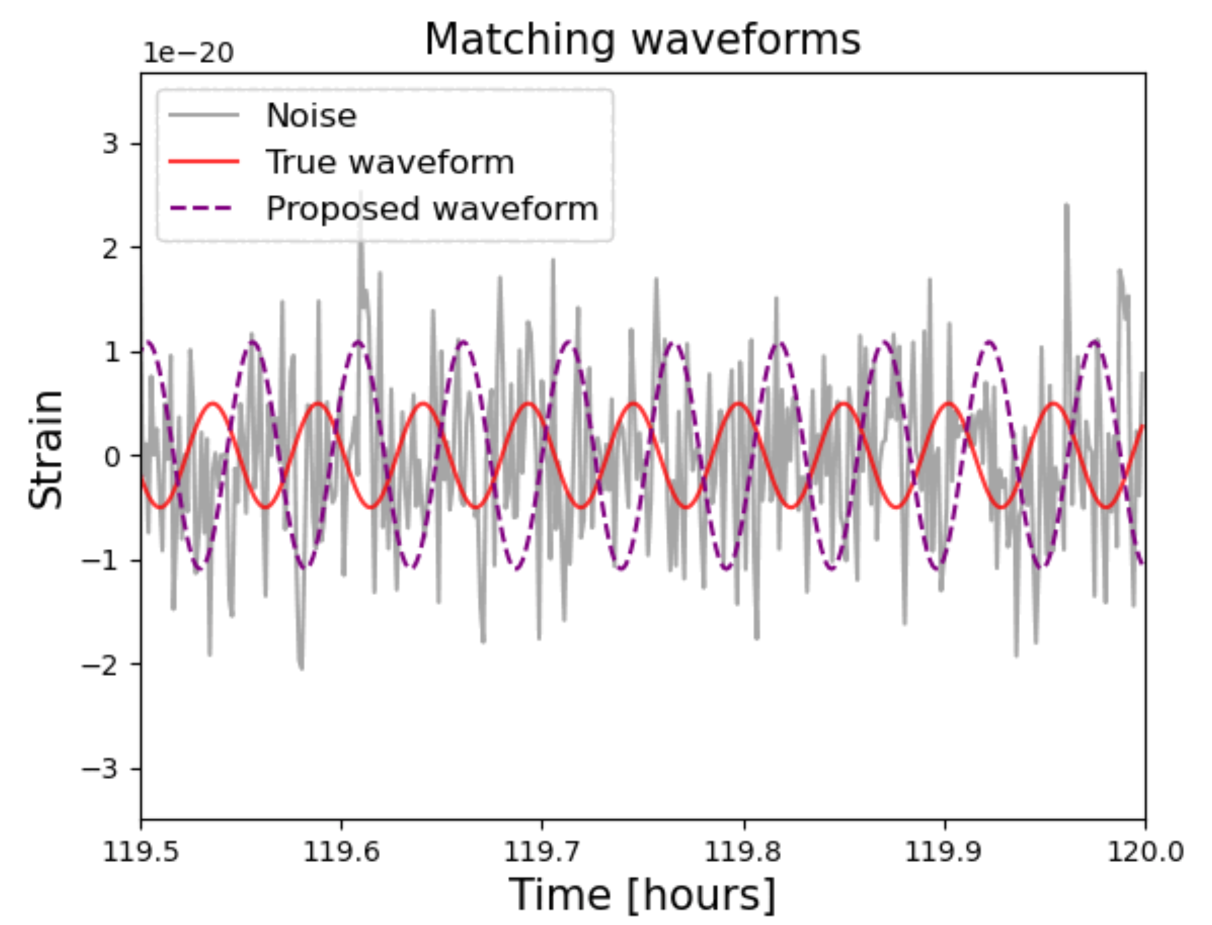
We must find the signal that better reproduce the observed data

Signal parameters are varied until the best match is found

Finding and characterising the signal

Efficient sampling methods (MCMC, Nested Sampling, …) must be applied in order to find the best value of the single parameters and their statistical uncertainties





Credit: O. Burke / L2IT

Finding and characterising the signal

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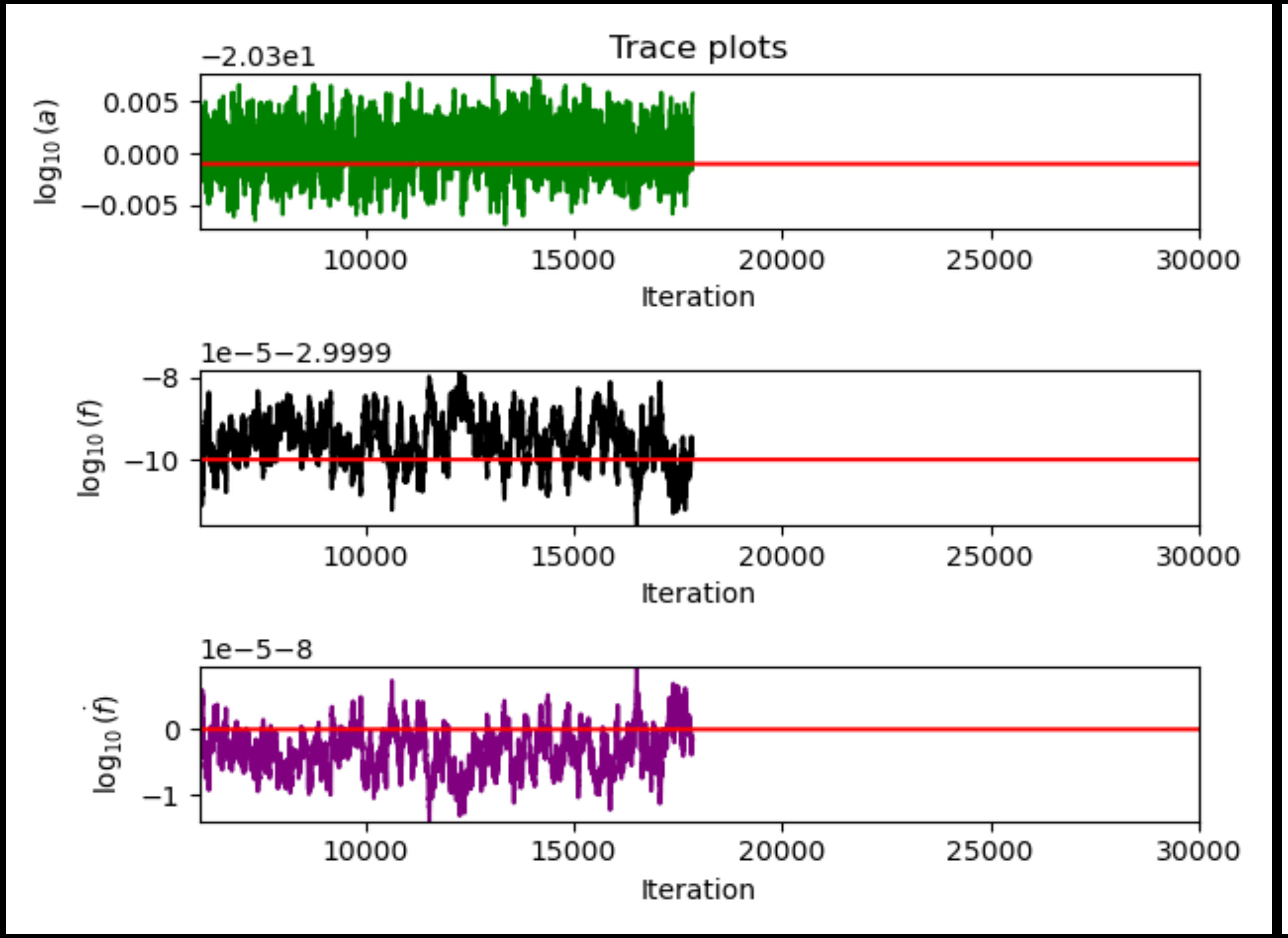
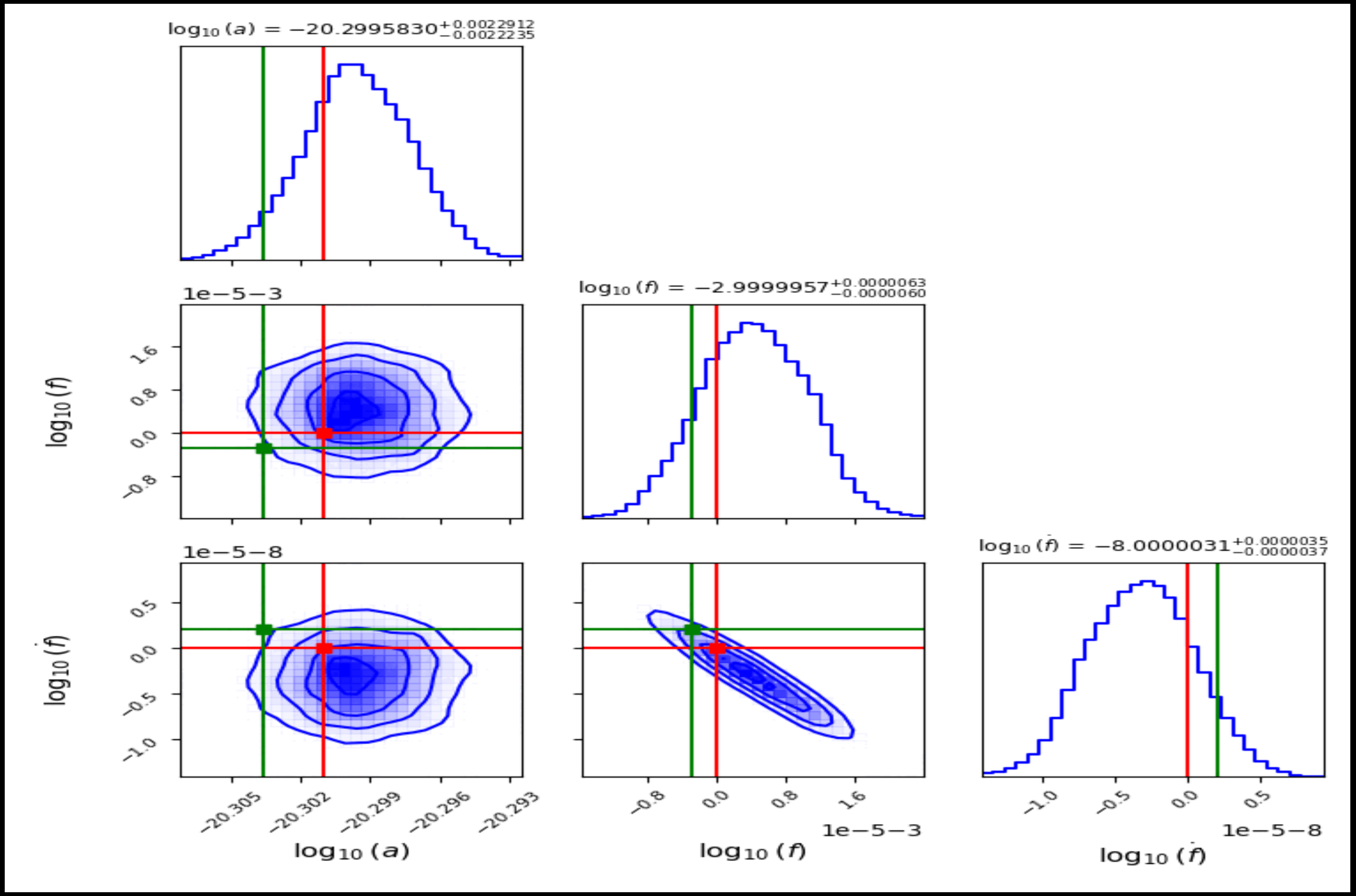




Credit: O. Burke / L2IT

Finding and characterising the signal

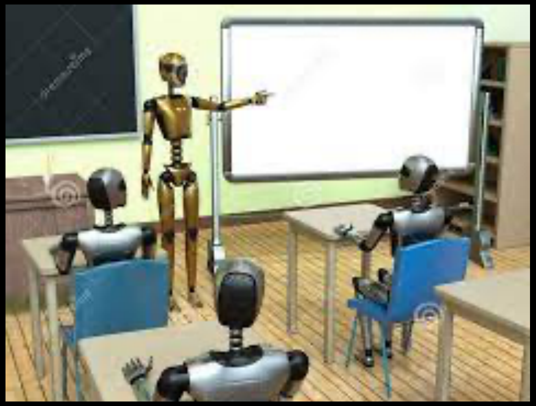
Efficient sampling methods (MCMC, Nested Sampling, …) must be applied in order to find the best value of the single parameters and their statistical uncertainties

Algorithms must be:

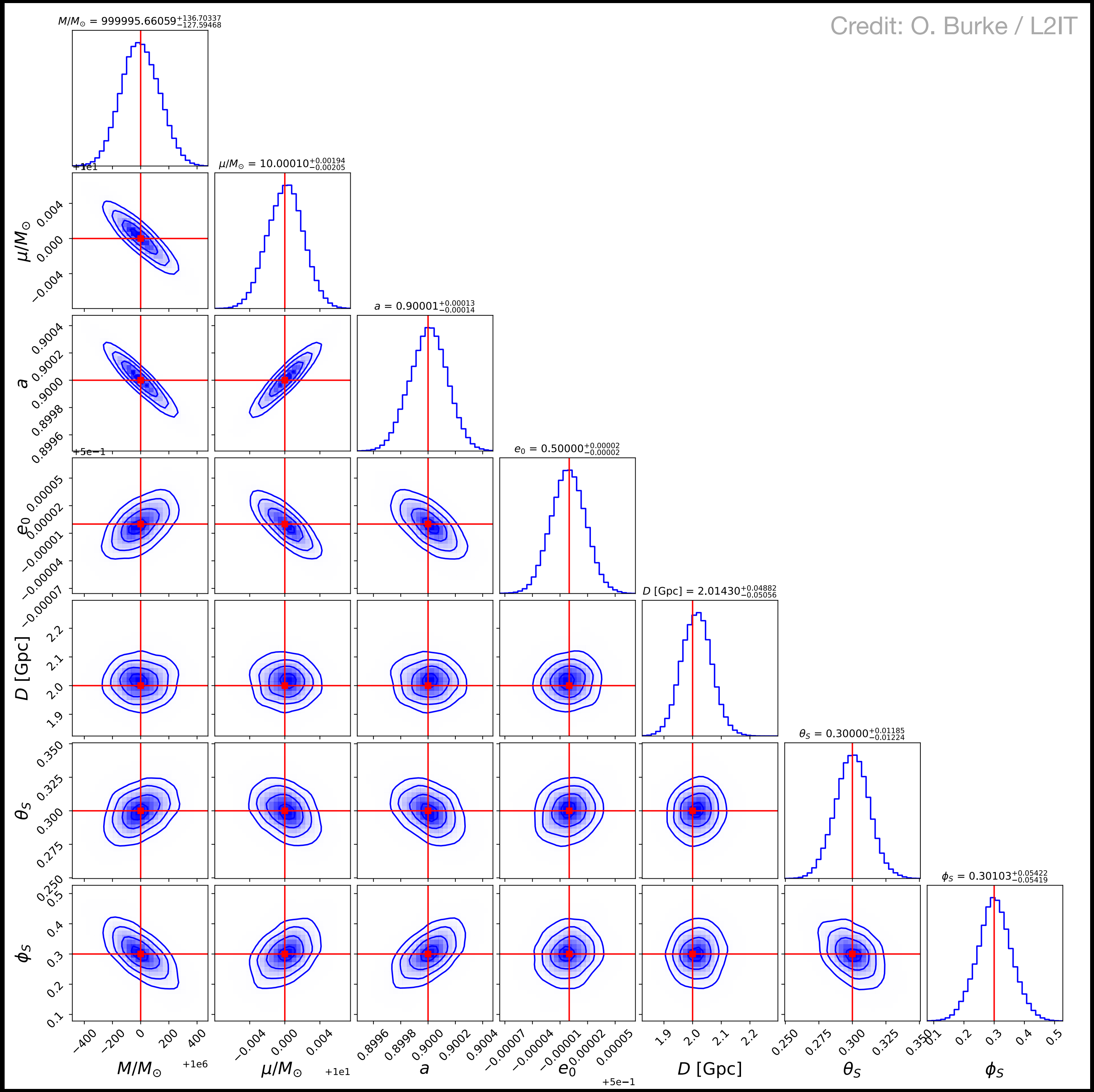
- Fast to find results as soon as possible (esp. for EM alert)
- Accurate to retrieve parameters close to true values

Much improvement over the last decades thanks to technological progress

Ample space for AI application in the near future (esp. Machine Learning)



Credit: Dreamstime

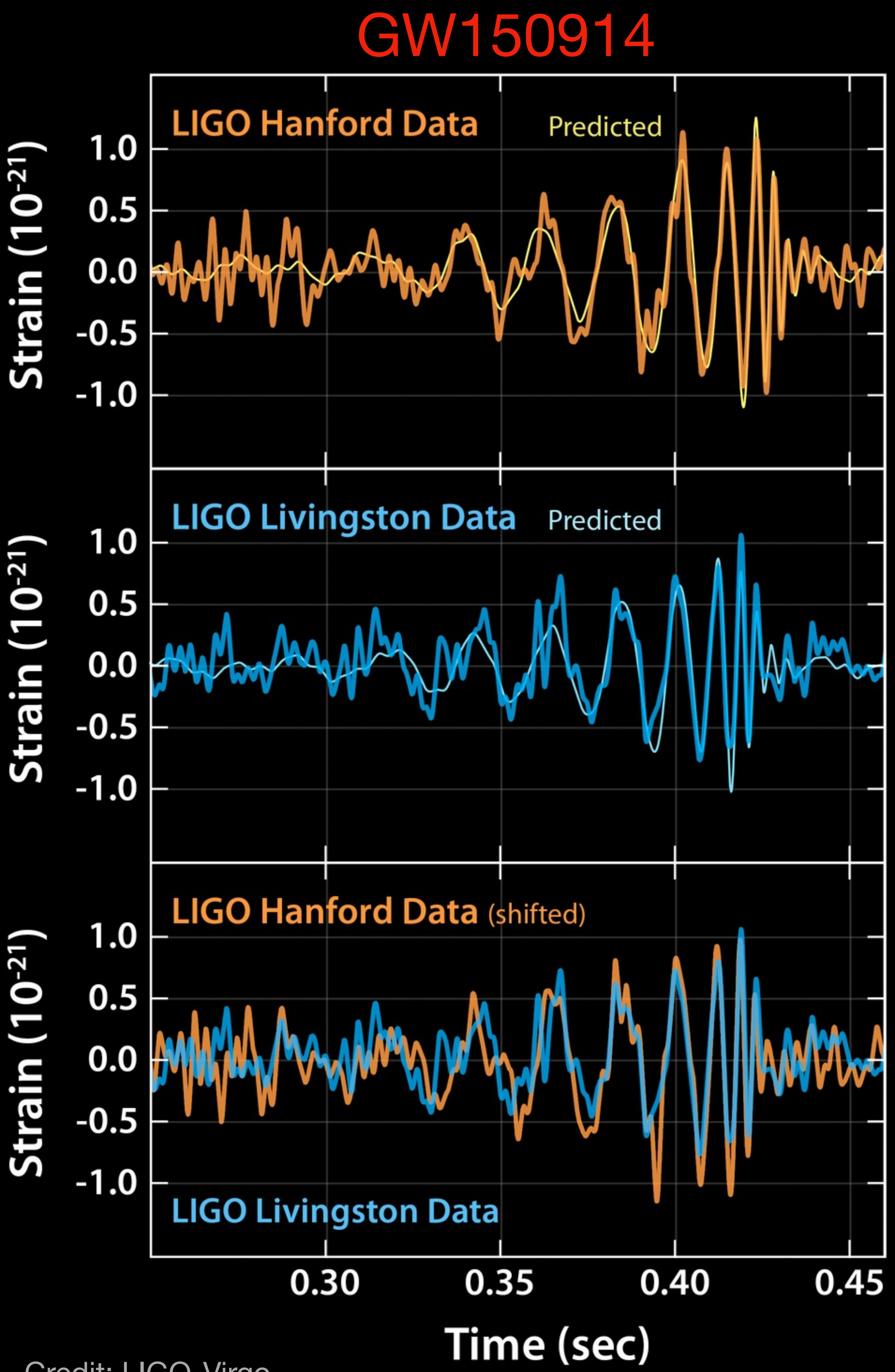


Credit: O. Burke / L2IT

OUTLINE

- Main concepts and detections strategy of GWs
- GW observations: the story so far
- GWs from theory to observations
- **The scientific potential of GW astronomy**

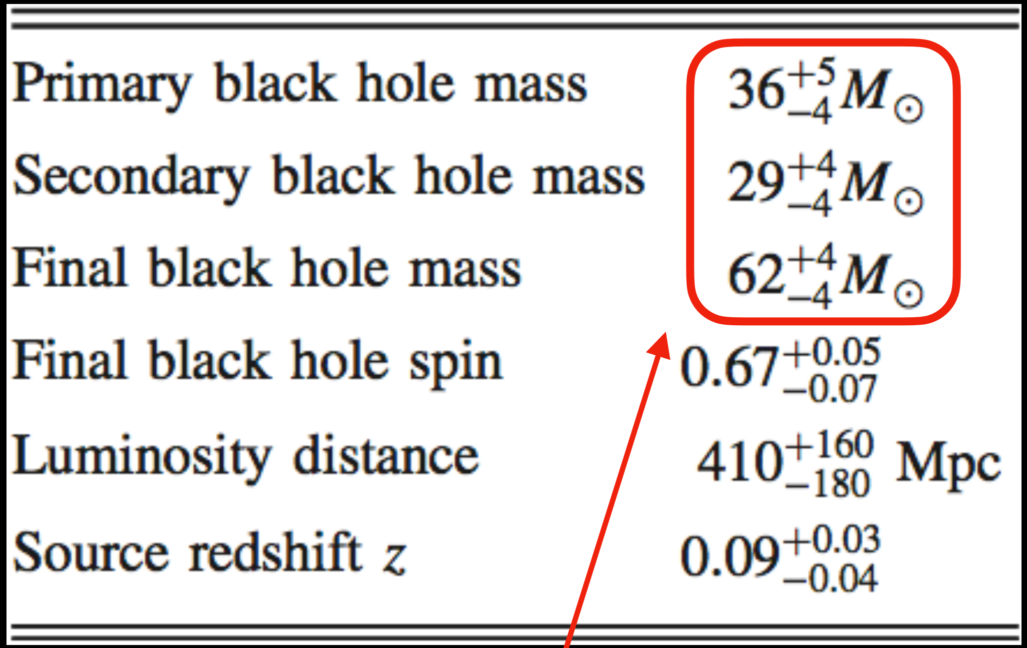
GW observational science: black holes



GW150914

Credit: LIGO-Virgo

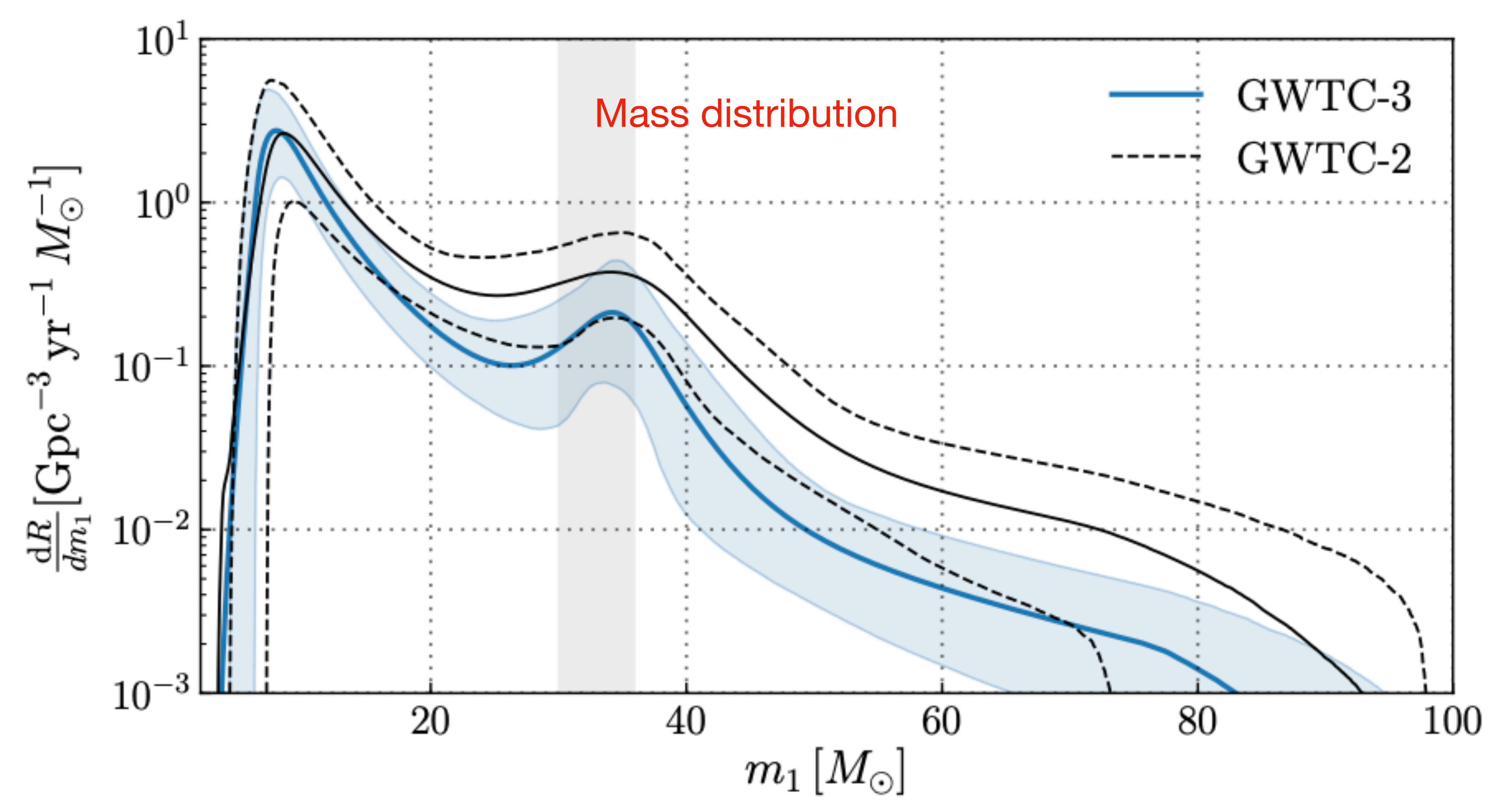
The first GW detection allowed us to discover stellar-mass black holes



Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

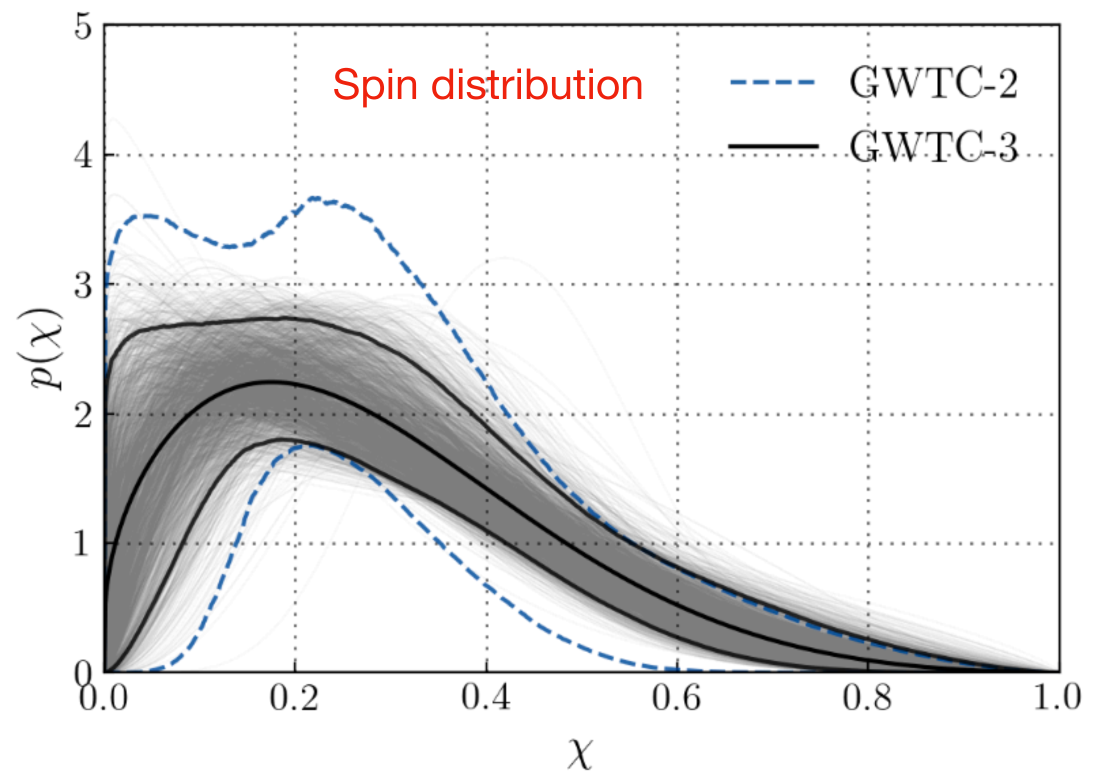
Black holes with masses $\gtrsim 10 M_\odot$ were discovered

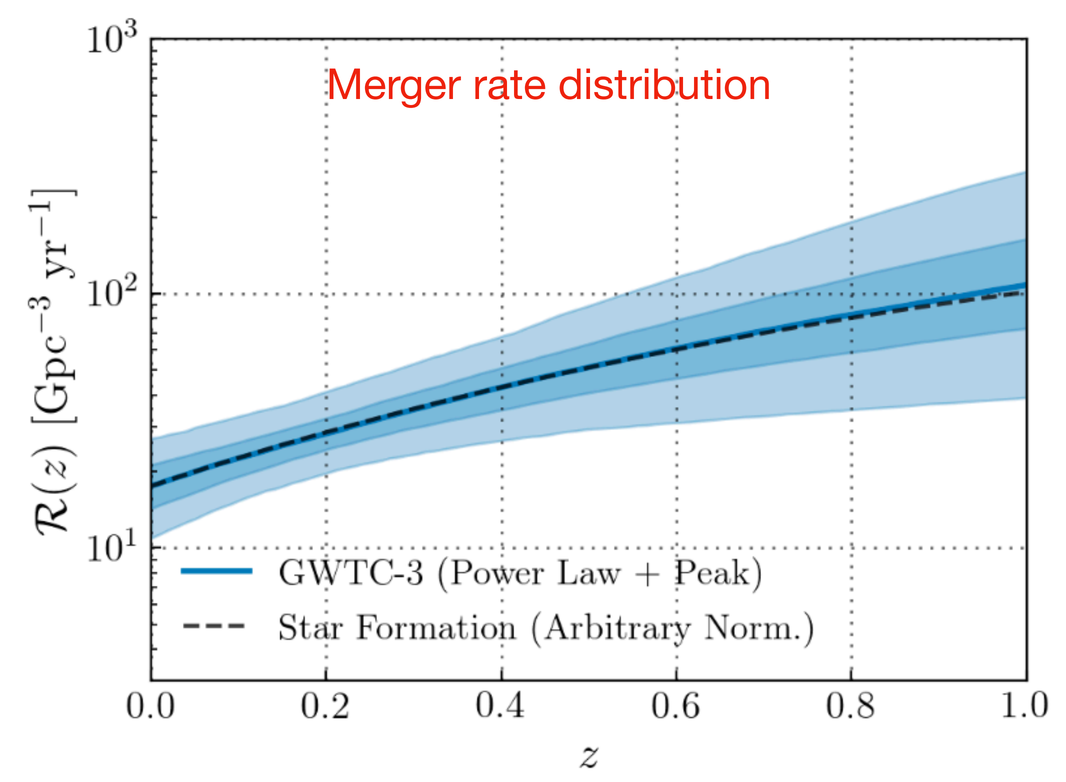
GW observational science: black holes



The first GW detection allowed us to discover stellar-mass black holes

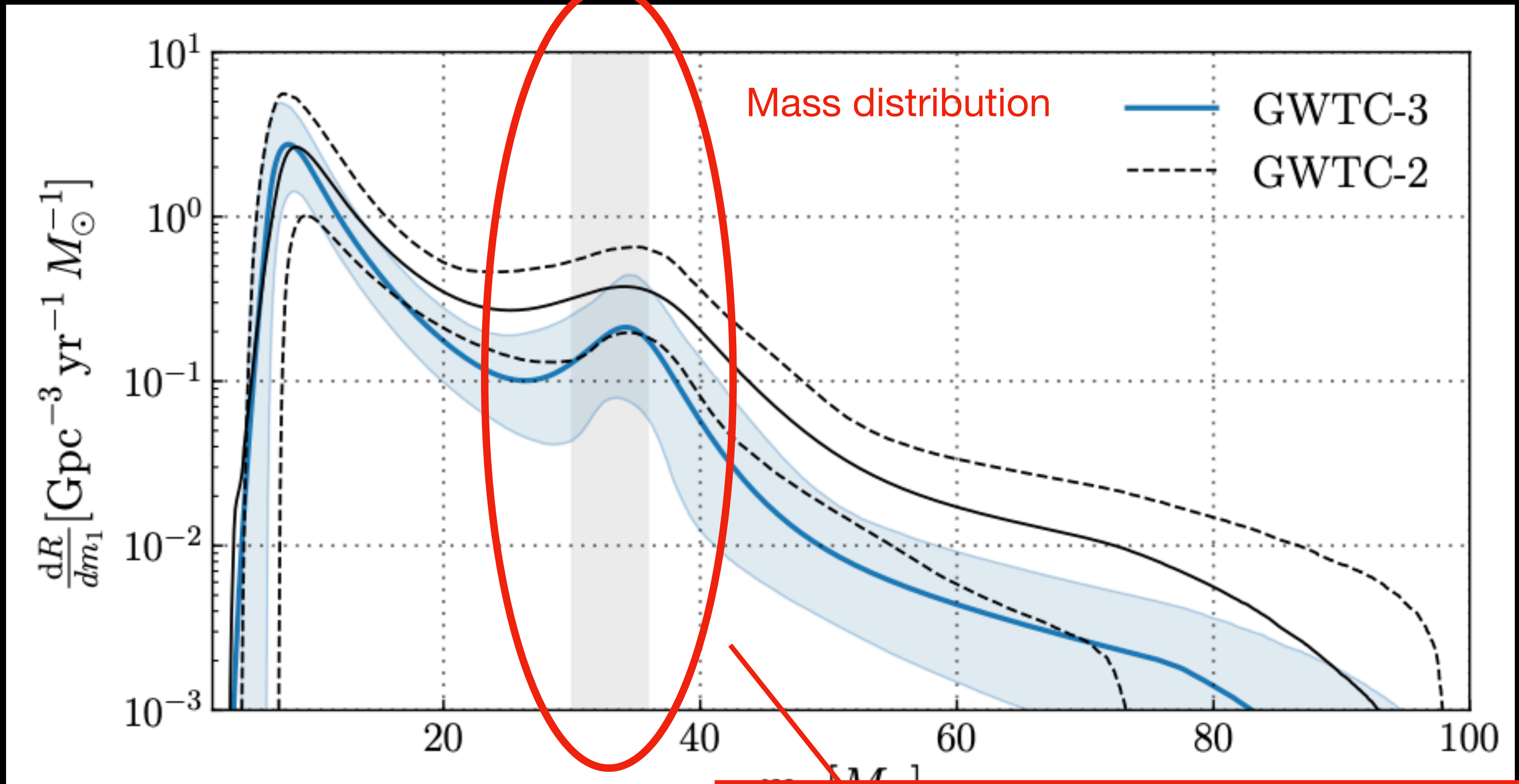
With many detections we can now start constraining the population properties and investigate their formation and evolution mechanisms





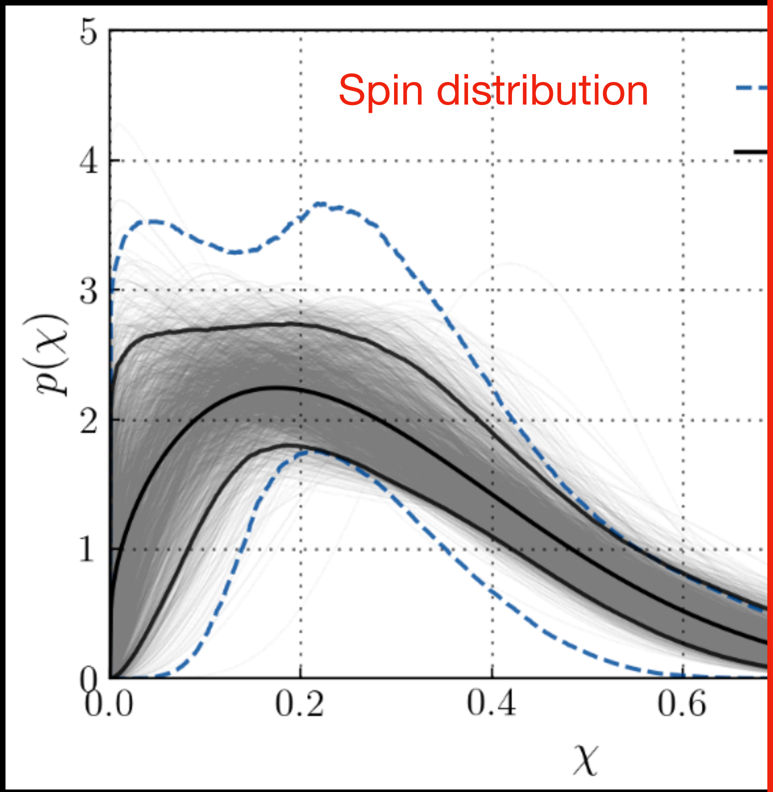
Credit: LIGO-Virgo-KAGRA

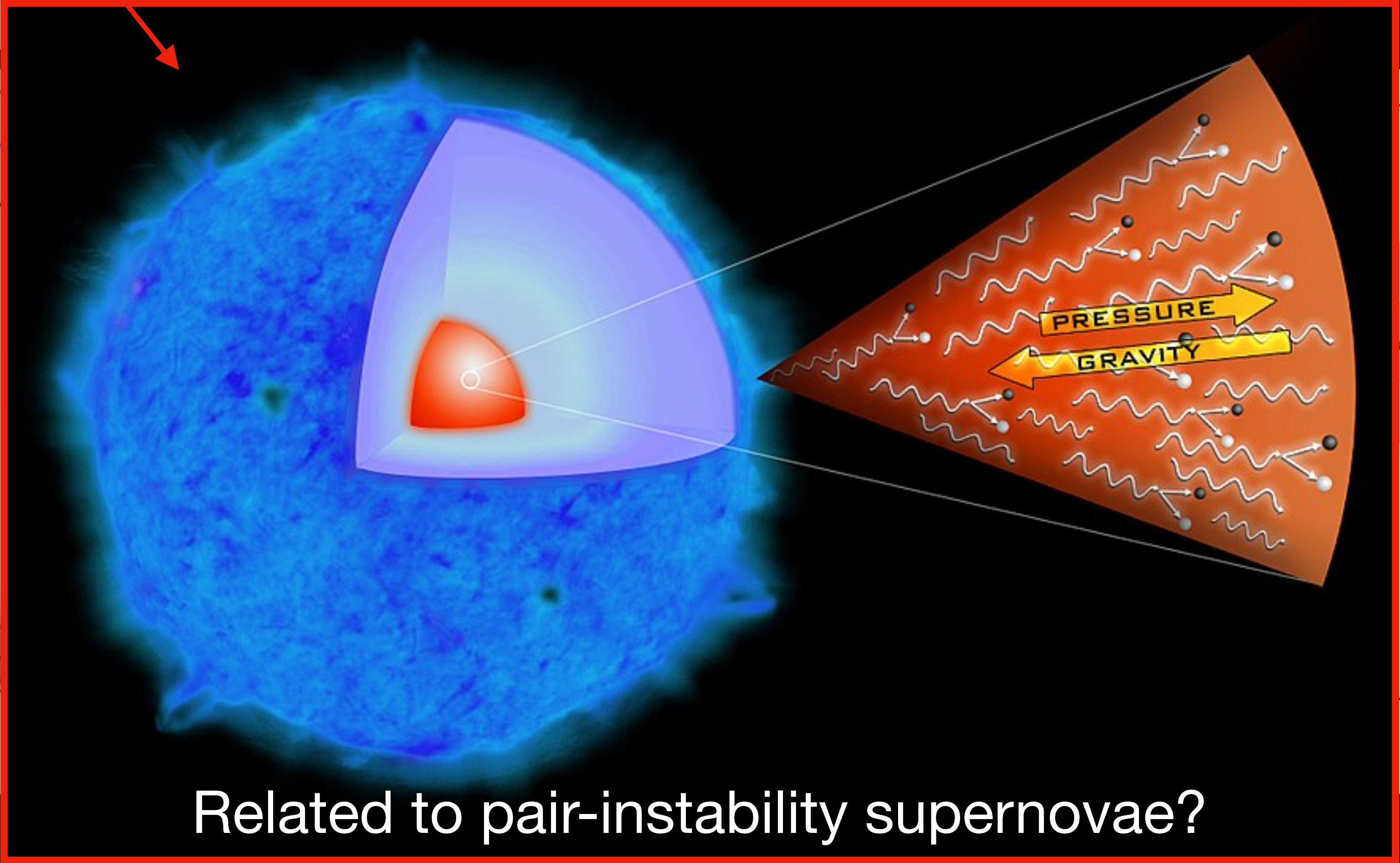
GW observational science: black holes


Mass distribution

The first GW detection allowed us to discover stellar-mass black holes

With many detections we can now start constraining the population properties and investigate their formation and evolution mechanisms


Spin distribution



Related to pair-instability supernovae?

Credit: LIGO-Virgo-KAGRA

GW observational science: black holes

The first GW detection
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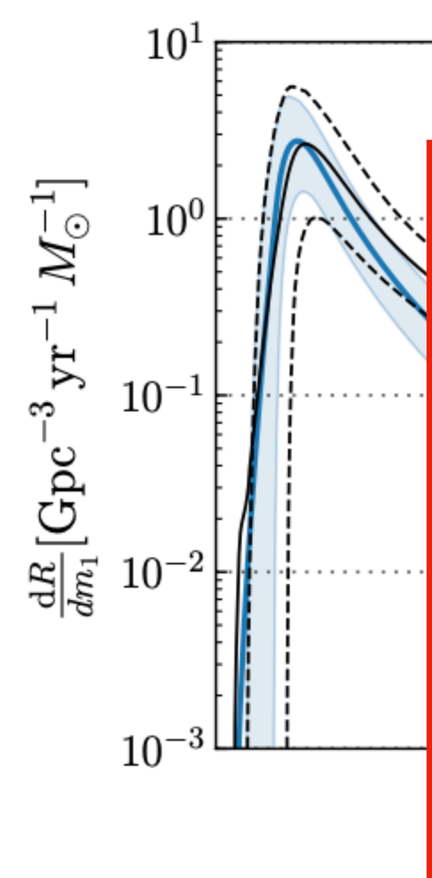
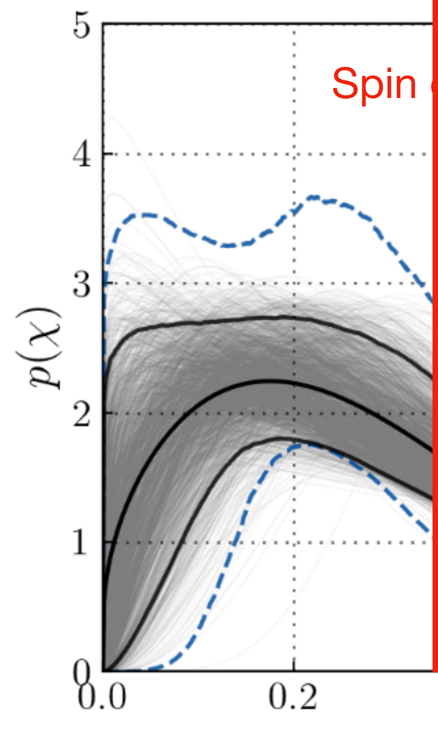
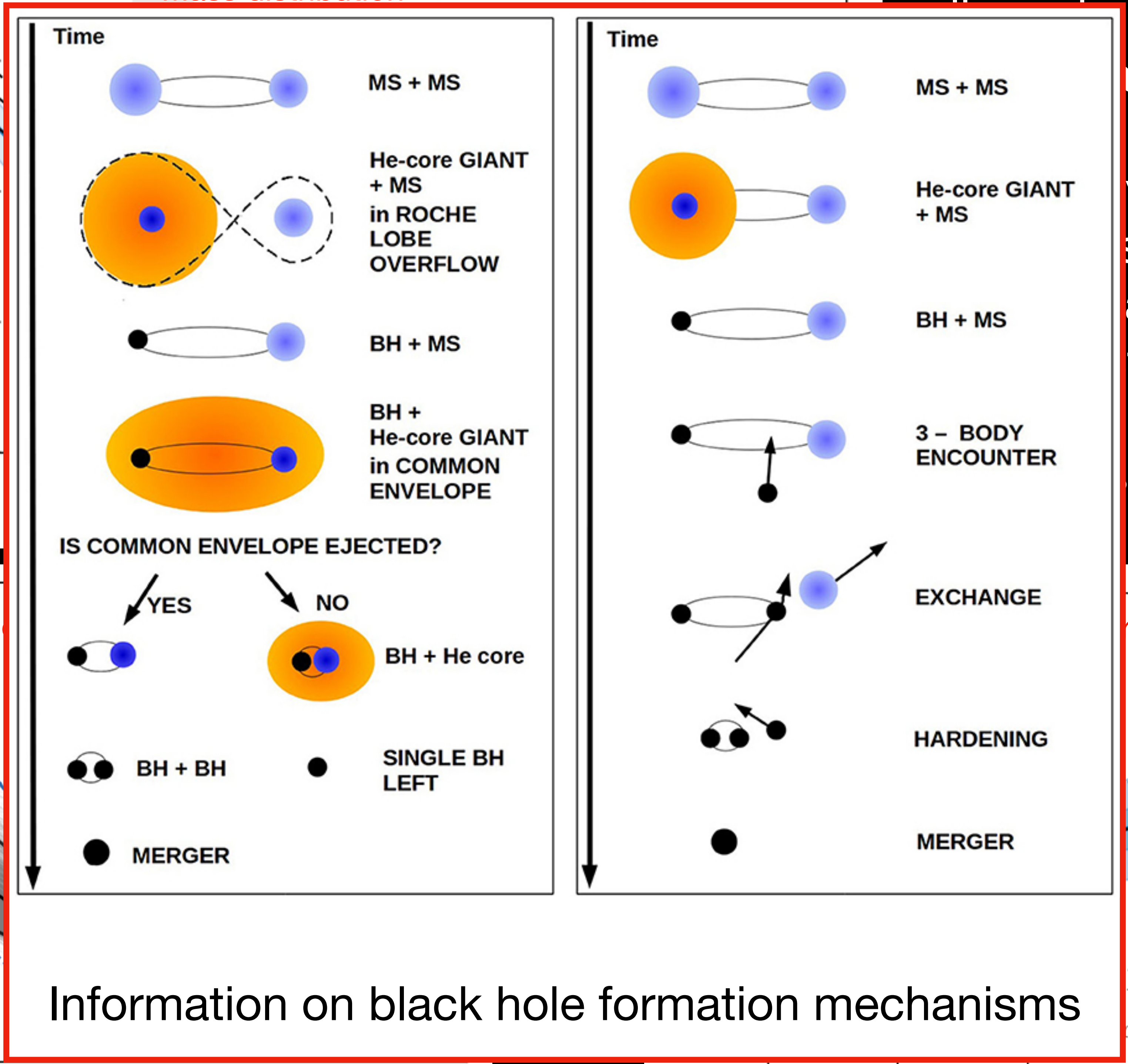
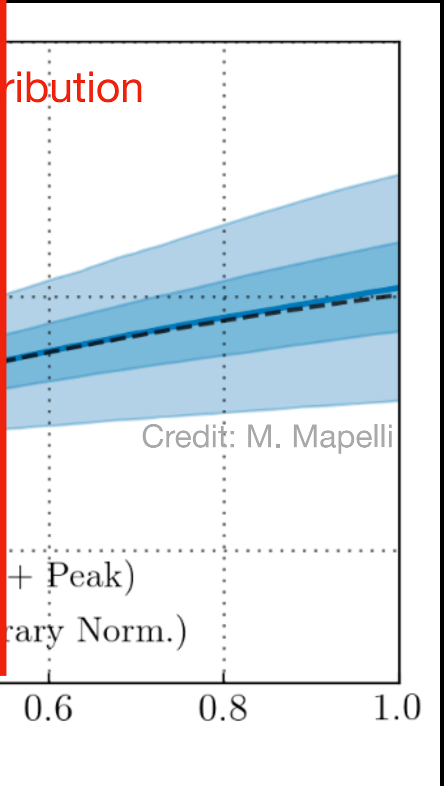






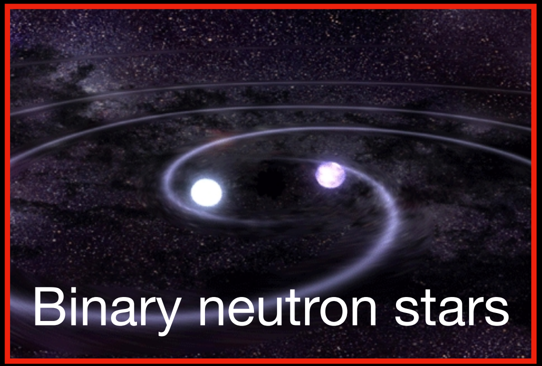
Information on black hole formation mechanisms

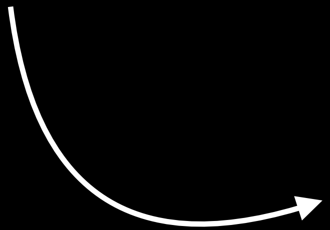


Credit: M. Mapelli

Credit: LIGO-Virgo-KAGRA

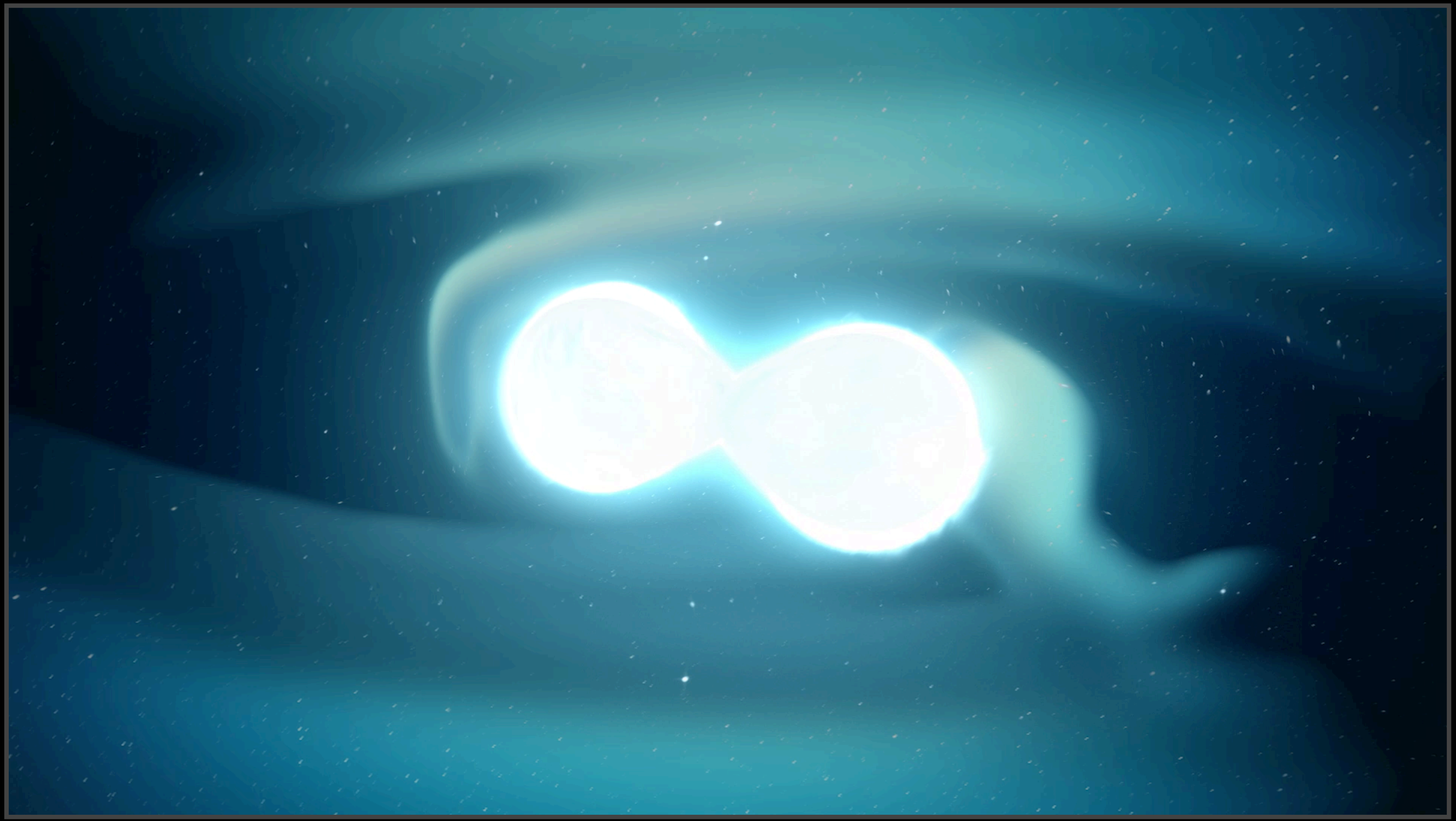
GW observational science: neutron stars



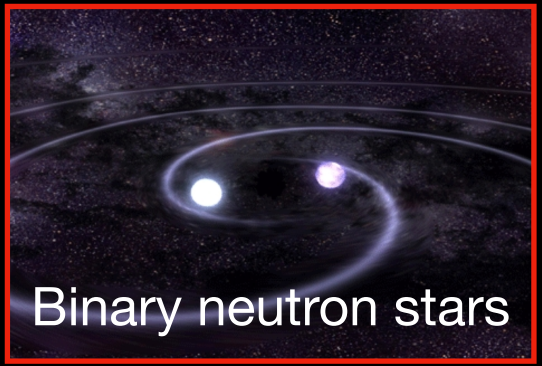


GW170817

Credit: NASA

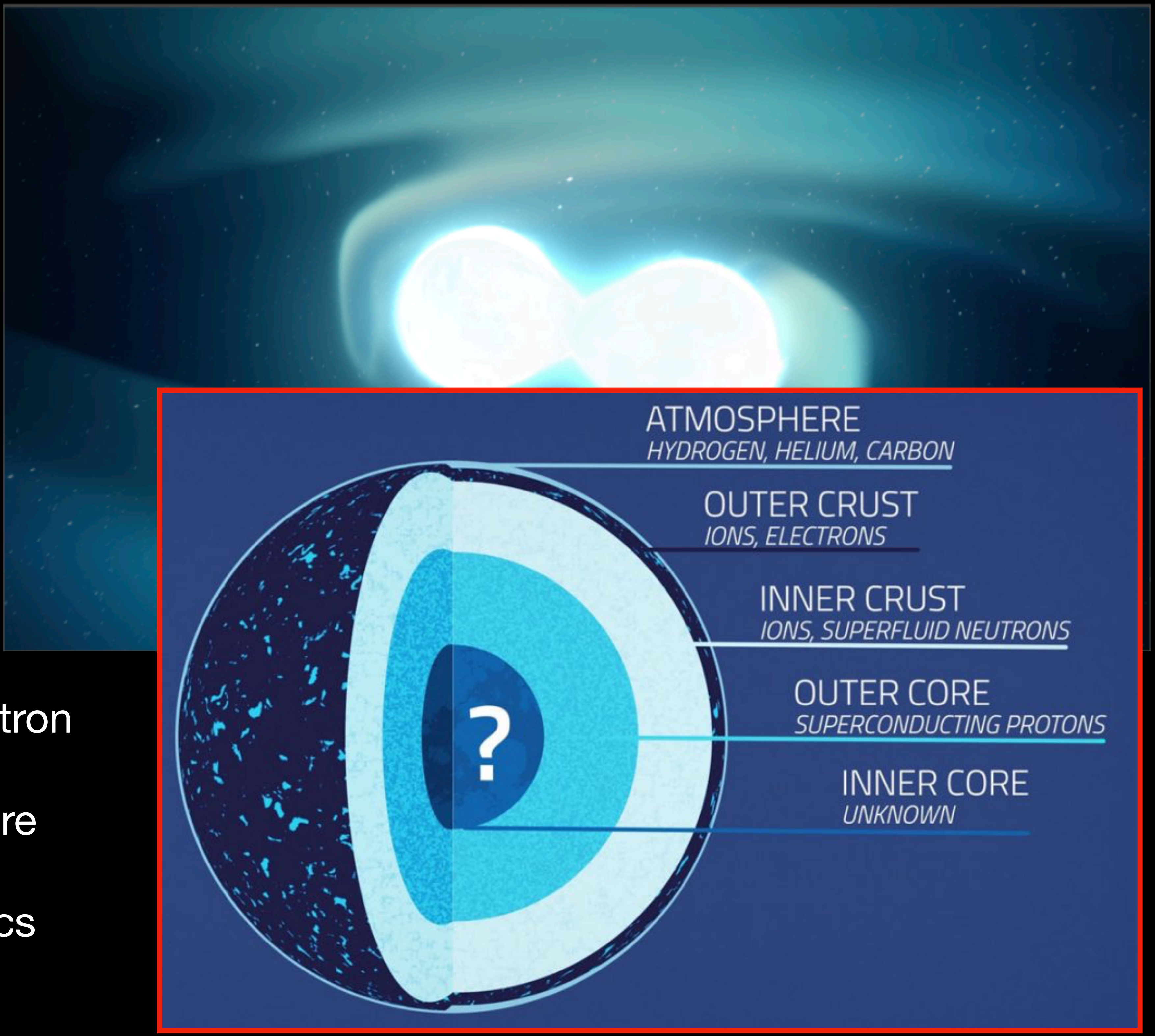


GW observational science: neutron stars



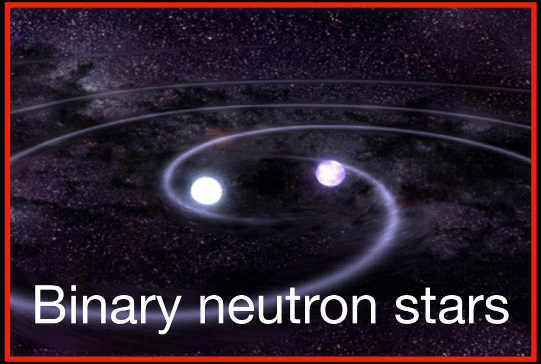
GW170817

Credit: NASA

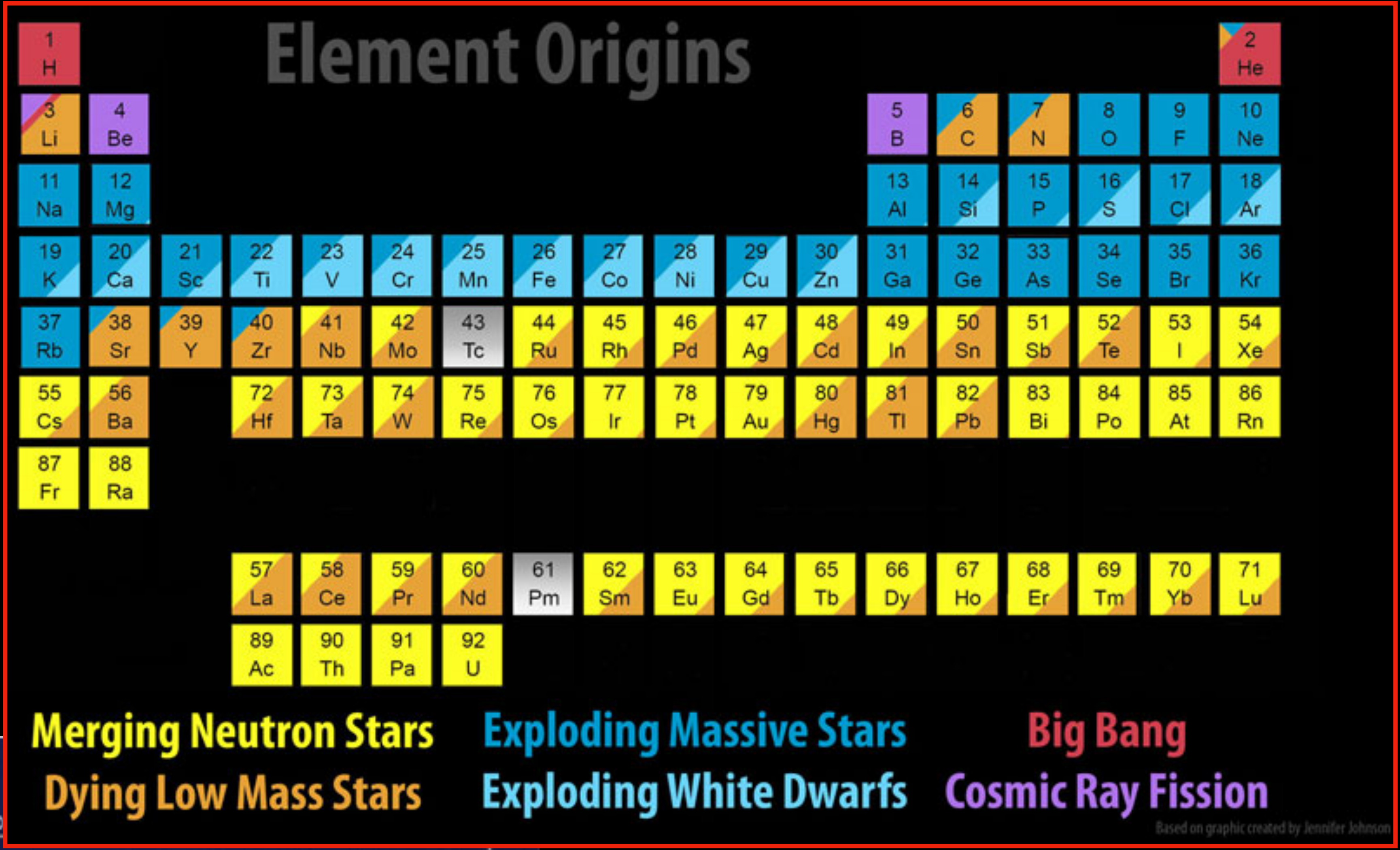


GW data from binary neutron star mergers allow us to probe the internal structure of neutron stars and its associated nuclear physics

GW observational science: neutron stars



Credit: J. Johnson / SDSS



Element Origins

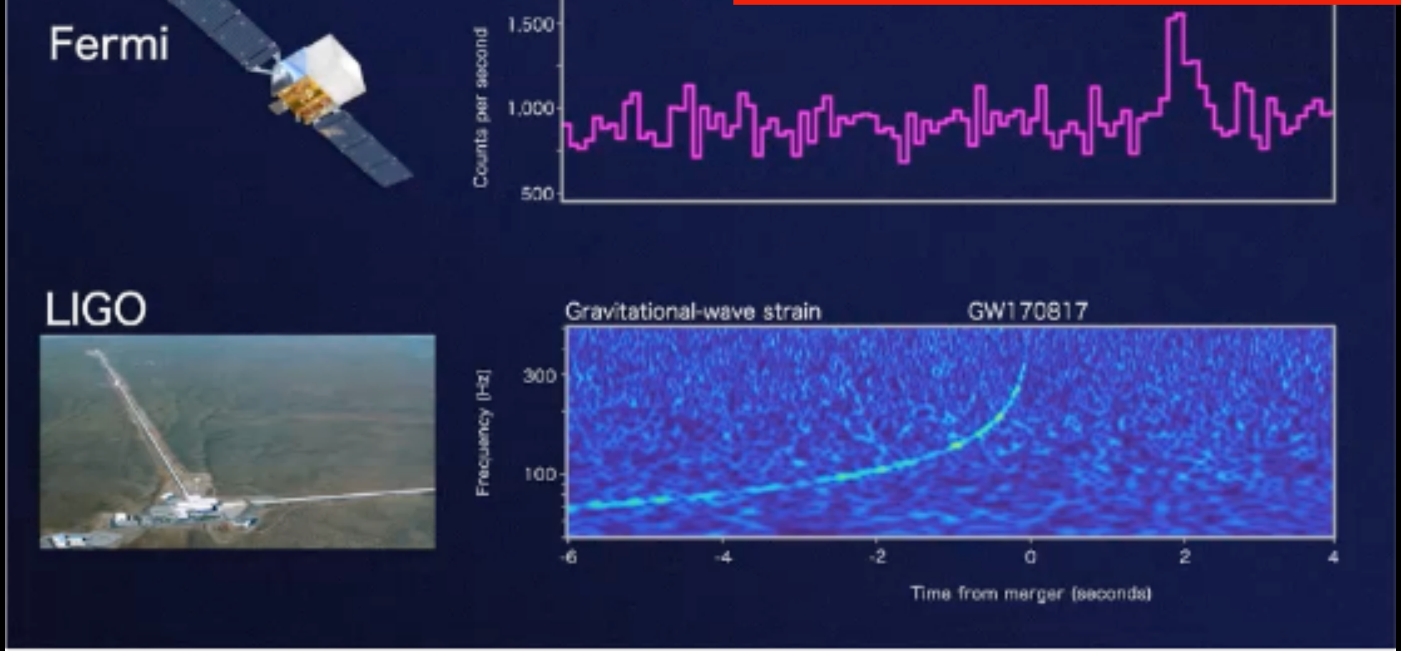
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

Merging Neutron Stars — Exploding Massive Stars — Big Bang

Dying Low Mass Stars — Exploding White Dwarfs — Cosmic Ray Fission

Based on graphic created by Jennifer Johnson

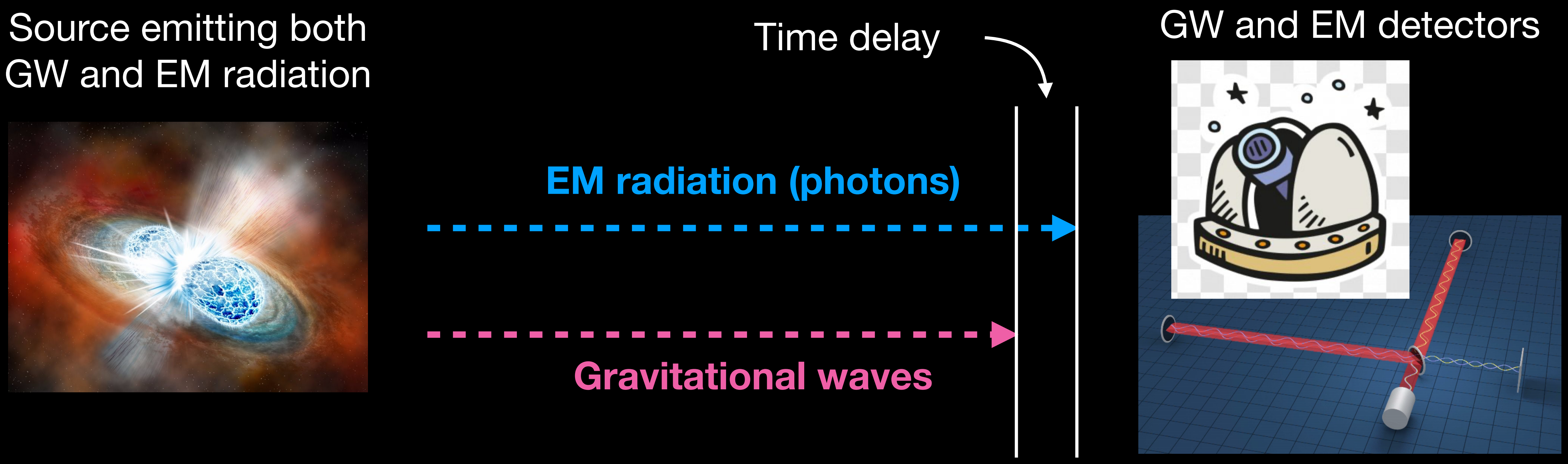
GW170817



Credit: LIGO-Virgo

The EM follow-up campaign of GW170817 allowed us to confirm that heavy elements are created in binary neutron star mergers

GW observational science: fundamental physics



Source emitting both
GW and EM radiation

Time delay

GW and EM detectors

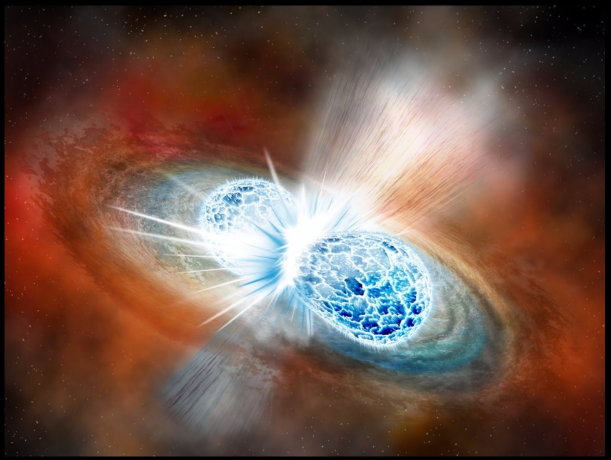
EM radiation (photons)

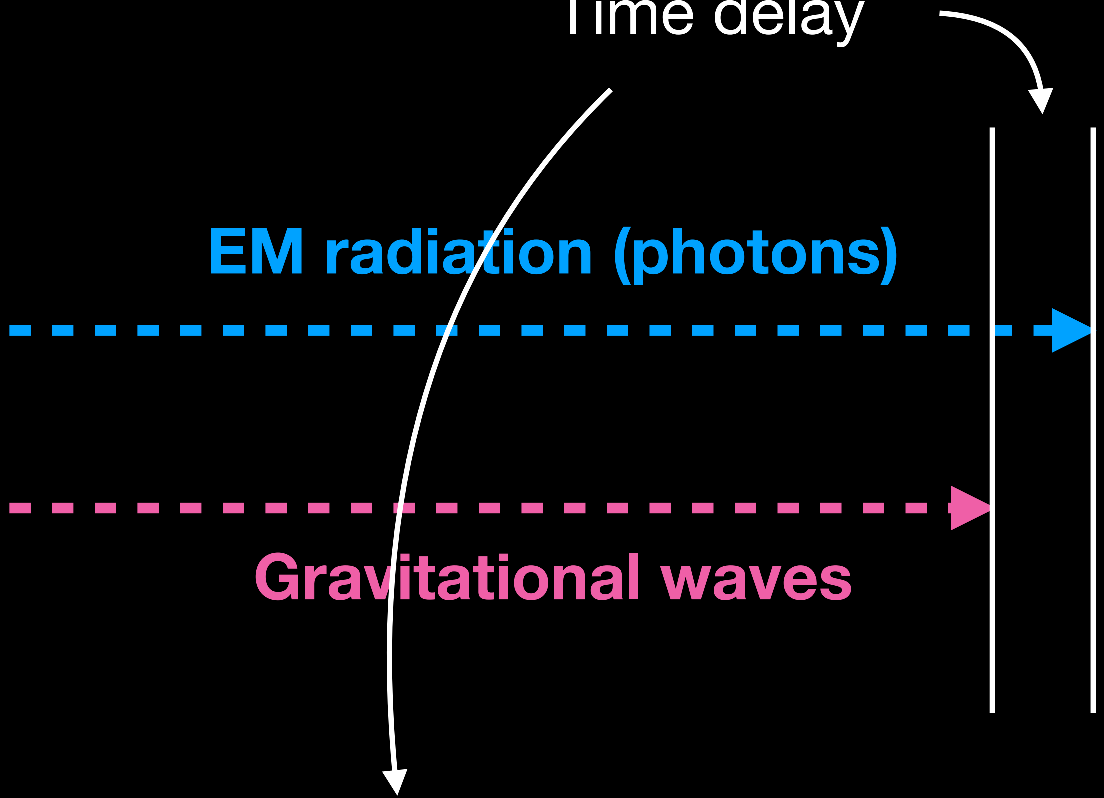
Gravitational waves

Multi-messenger event can be used to test the speed of propagation of GWs

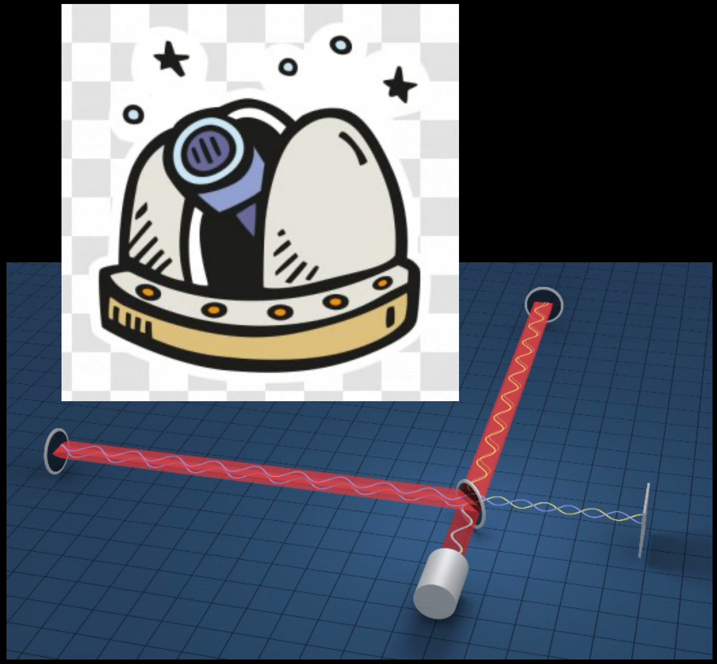
GW observational science: fundamental physics

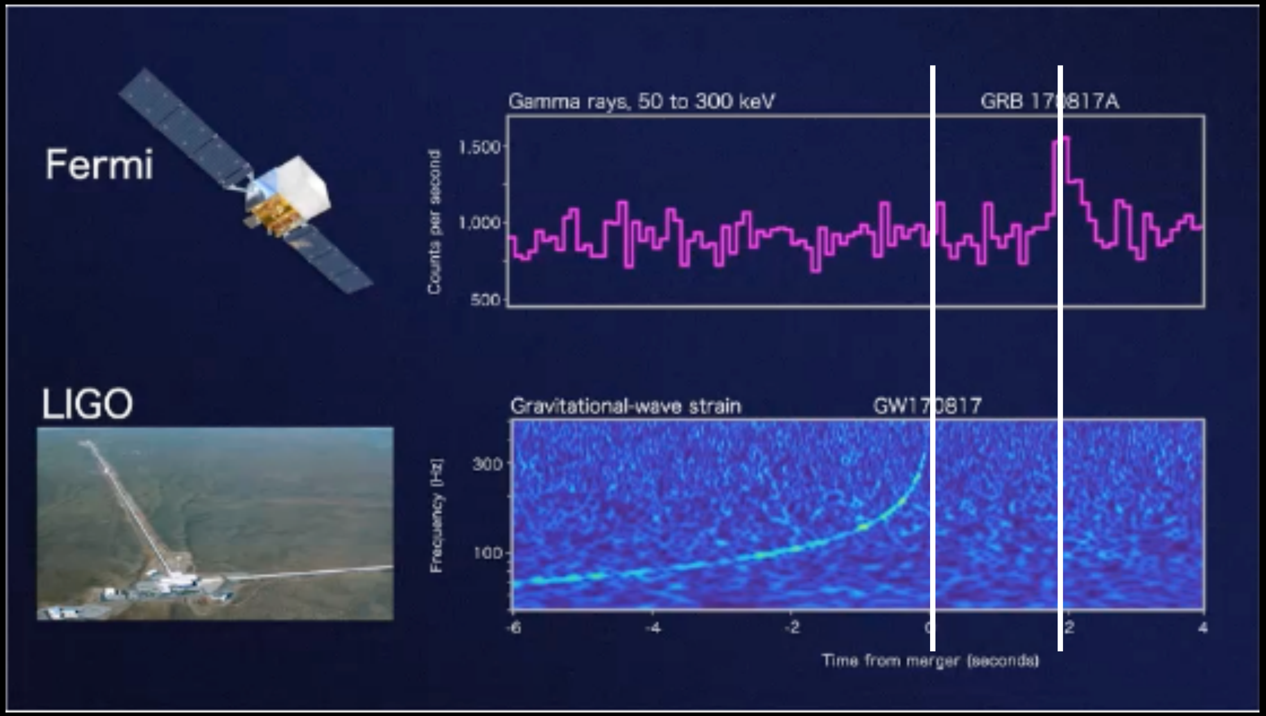
Source emitting both GW and EM radiation





GW and EM detectors

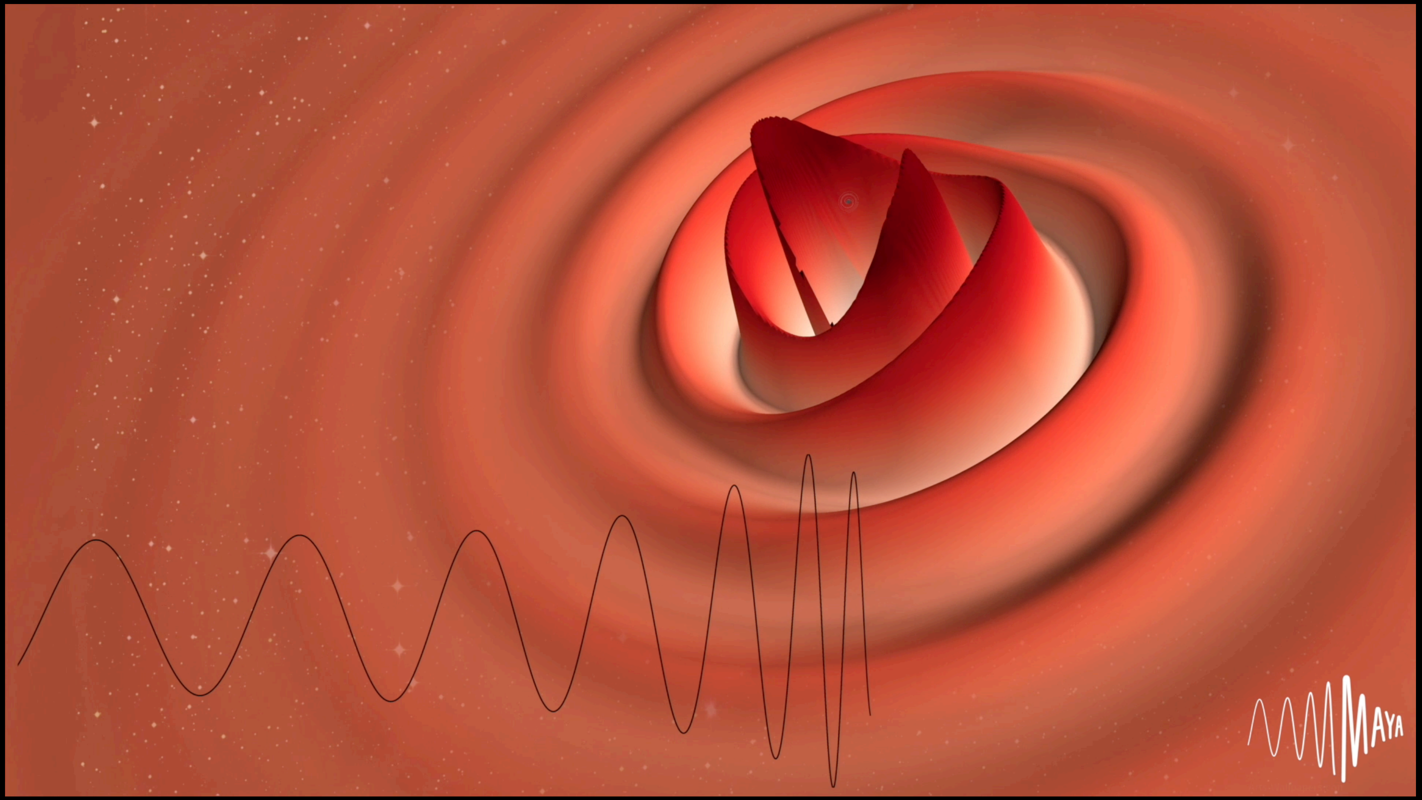




Multi-messenger event can be used to test the speed of propagation of GWs

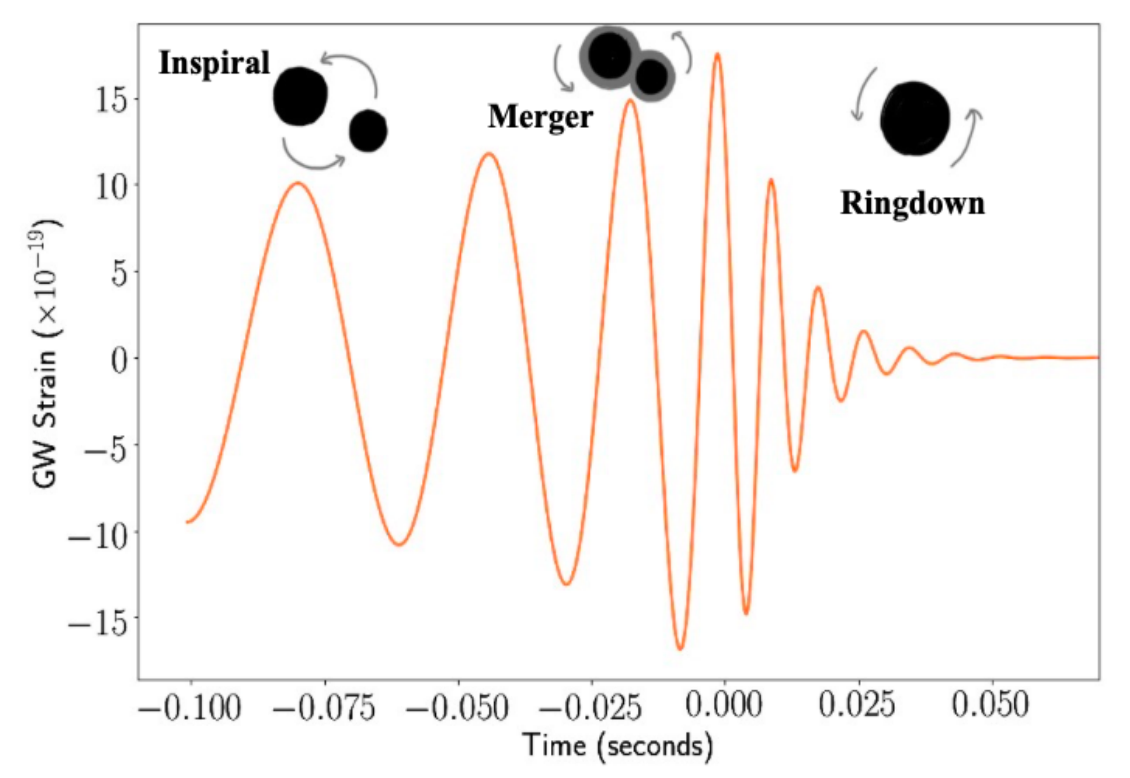
GW170817 constrained the speed of GWs to be equal to the speed of light with a relative precision of 10^{-15}

GW observational science: fundamental physics



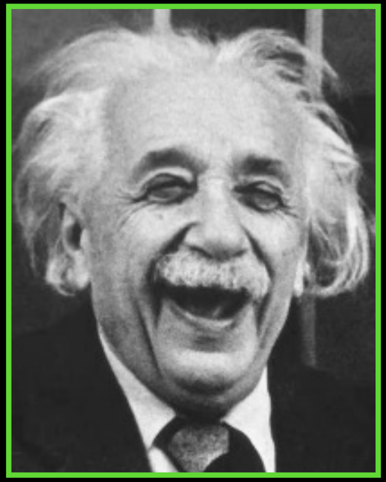
GWs data can be used to test general relativity in the strong field regime

Tests can be performed with all phases of the GW waveform using different methods

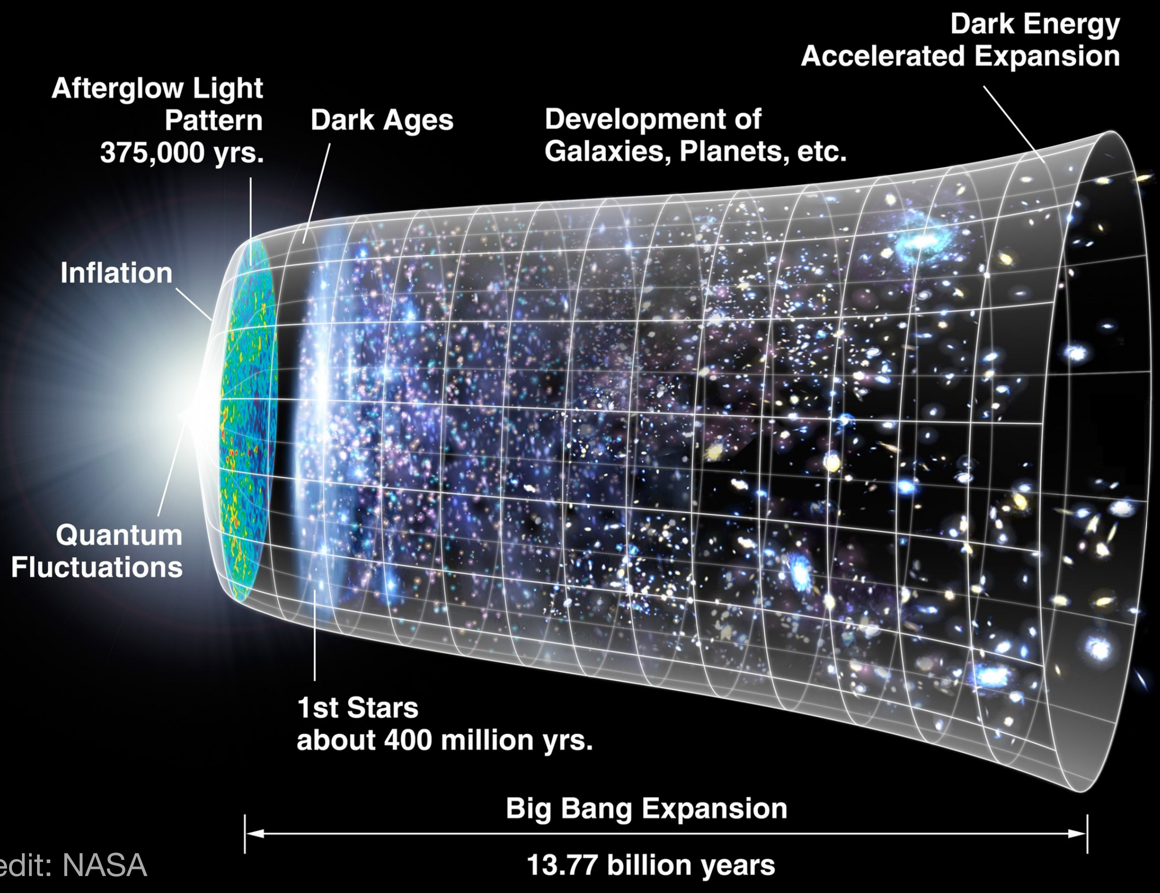


Credit: LIGO-Virgo

All observations in agreement with general relativity so far

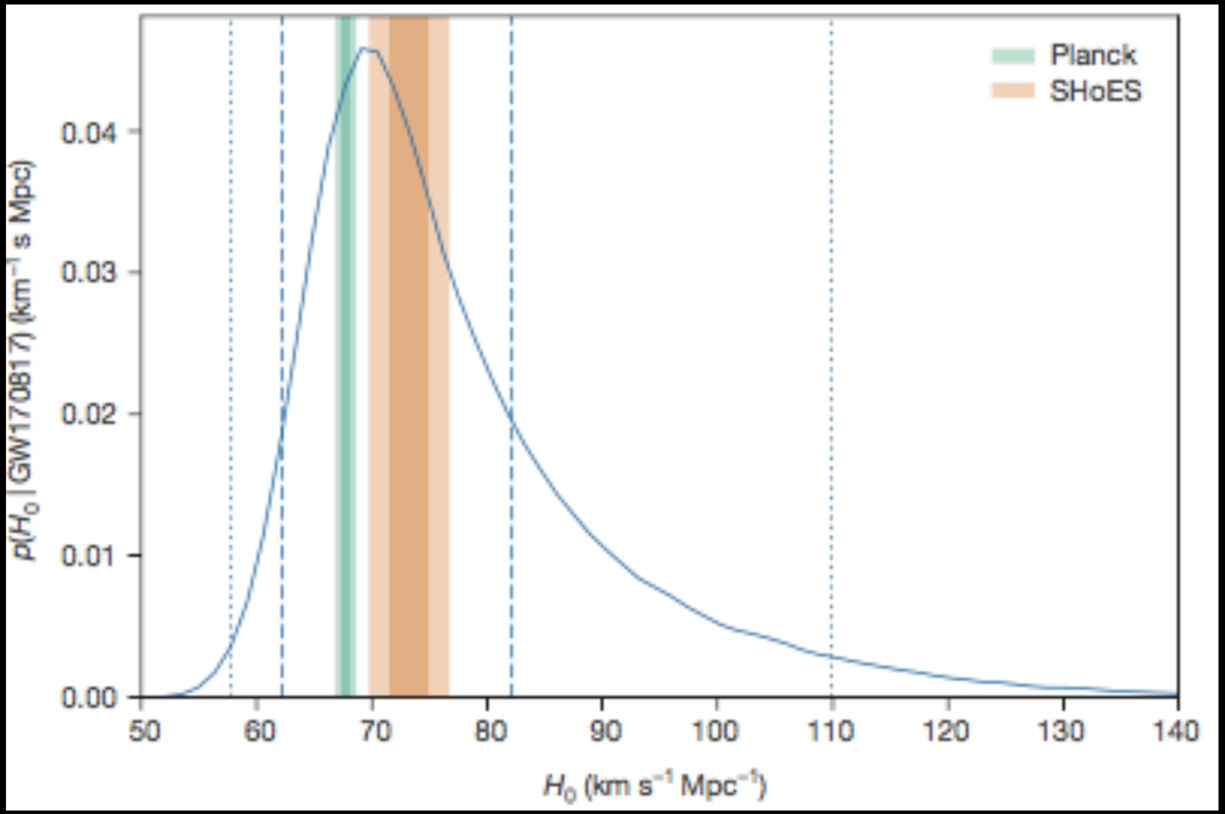


GW observational science: cosmology

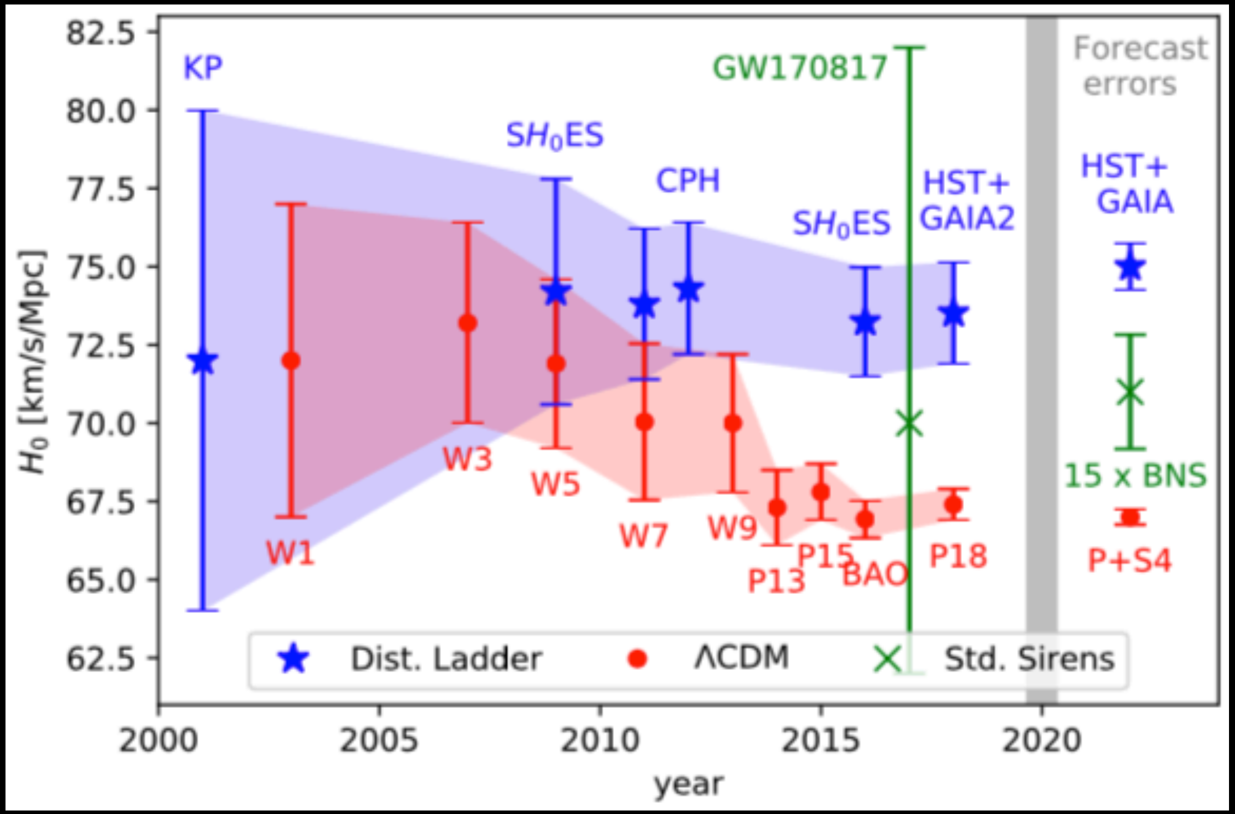


Credit: NASA

An EM counterpart to a GW events provides a direct way to probe the expansion of the Universe and possibly solve the *Hubble tension*

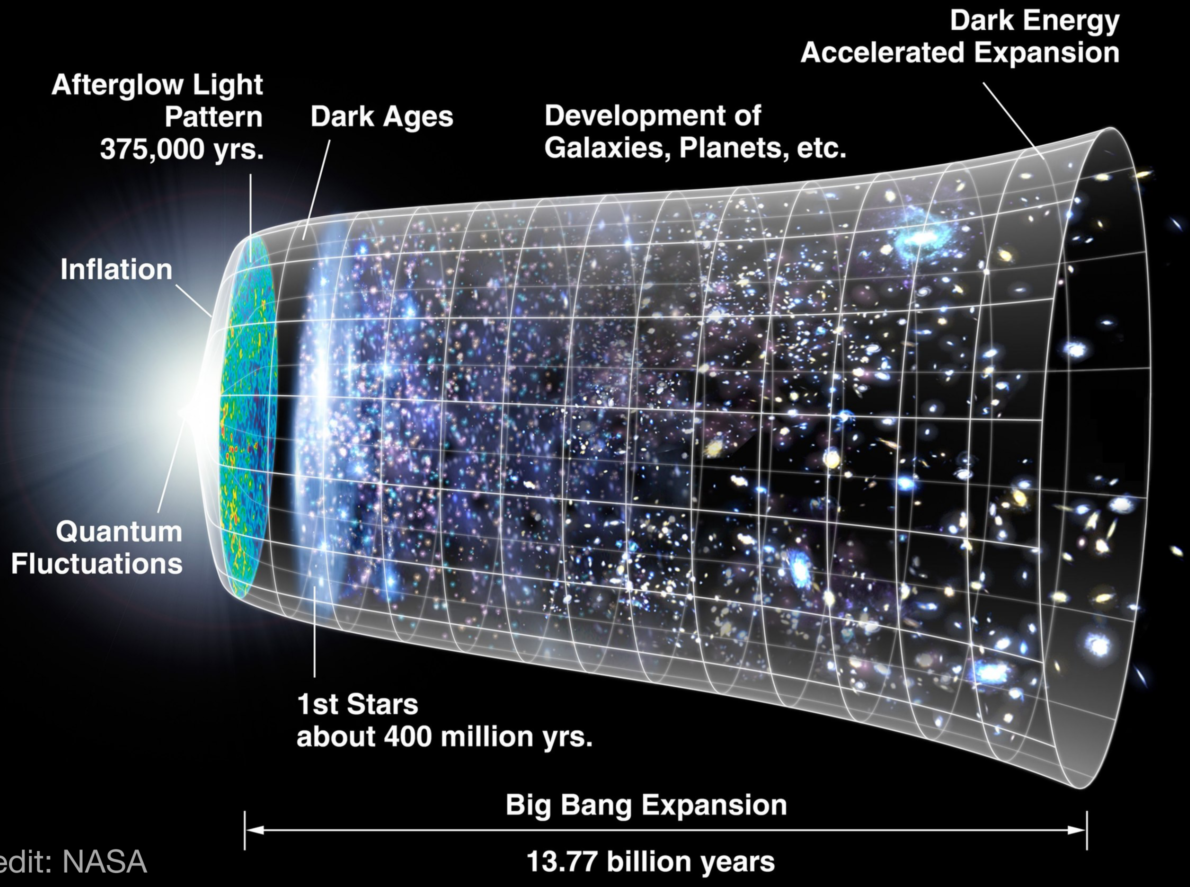


Credit: LIGO-Virgo



Credit: J. M. Ezquiaga & M. Zumalacarregui

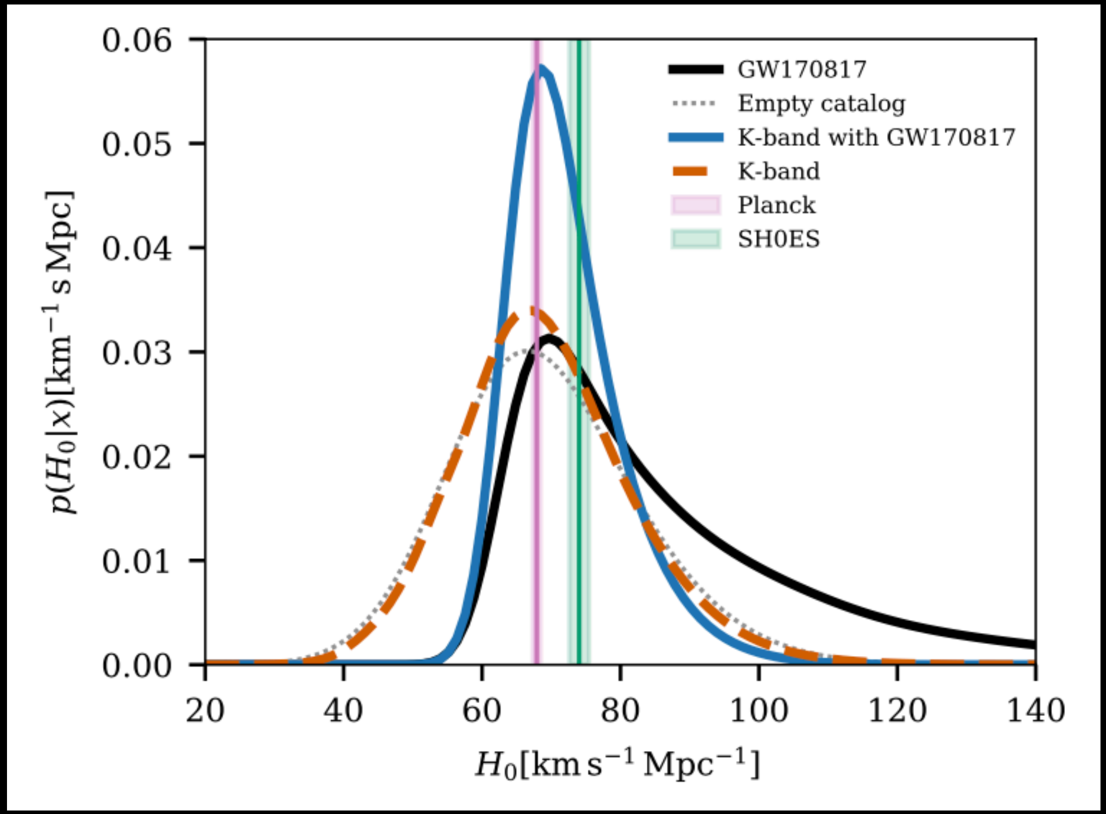
GW observational science: cosmology



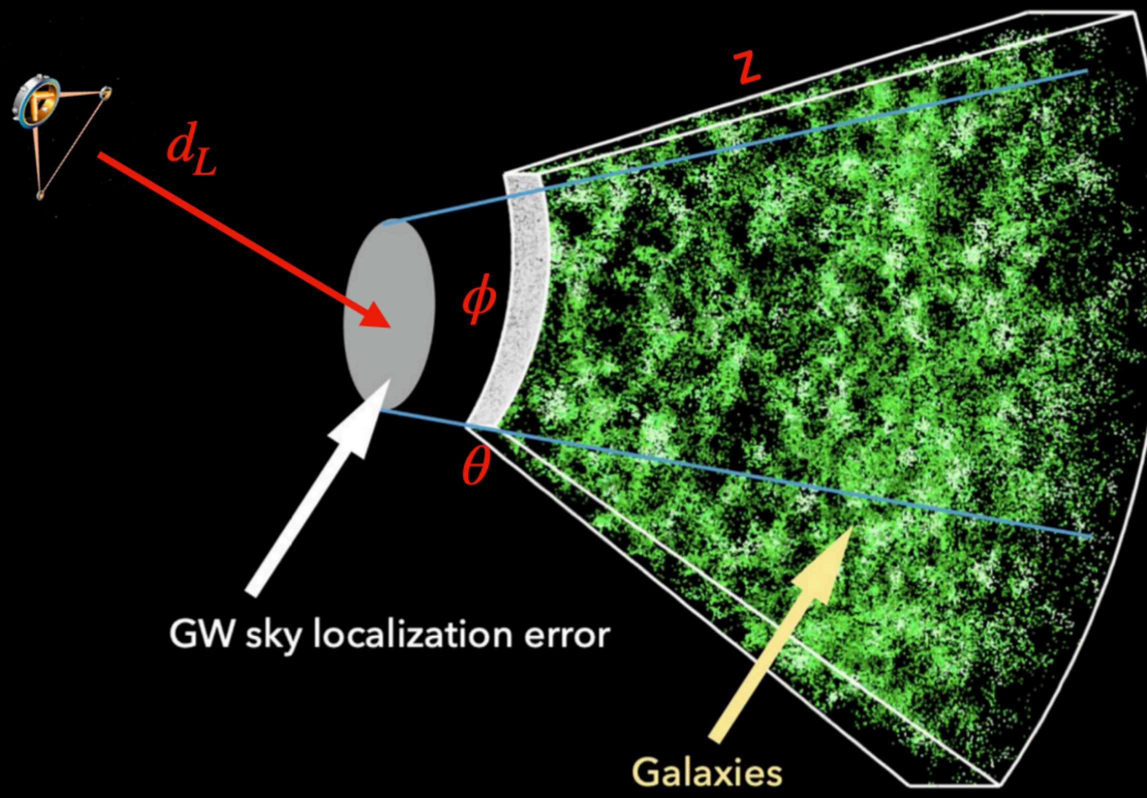
Credit: NASA

An EM counterpart to a GW events provides a direct way to probe the expansion of the Universe and possibly solve the *Hubble tension*

Without an EM counterpart cosmological information can still be extracted from GW data with the help of galaxy catalogues

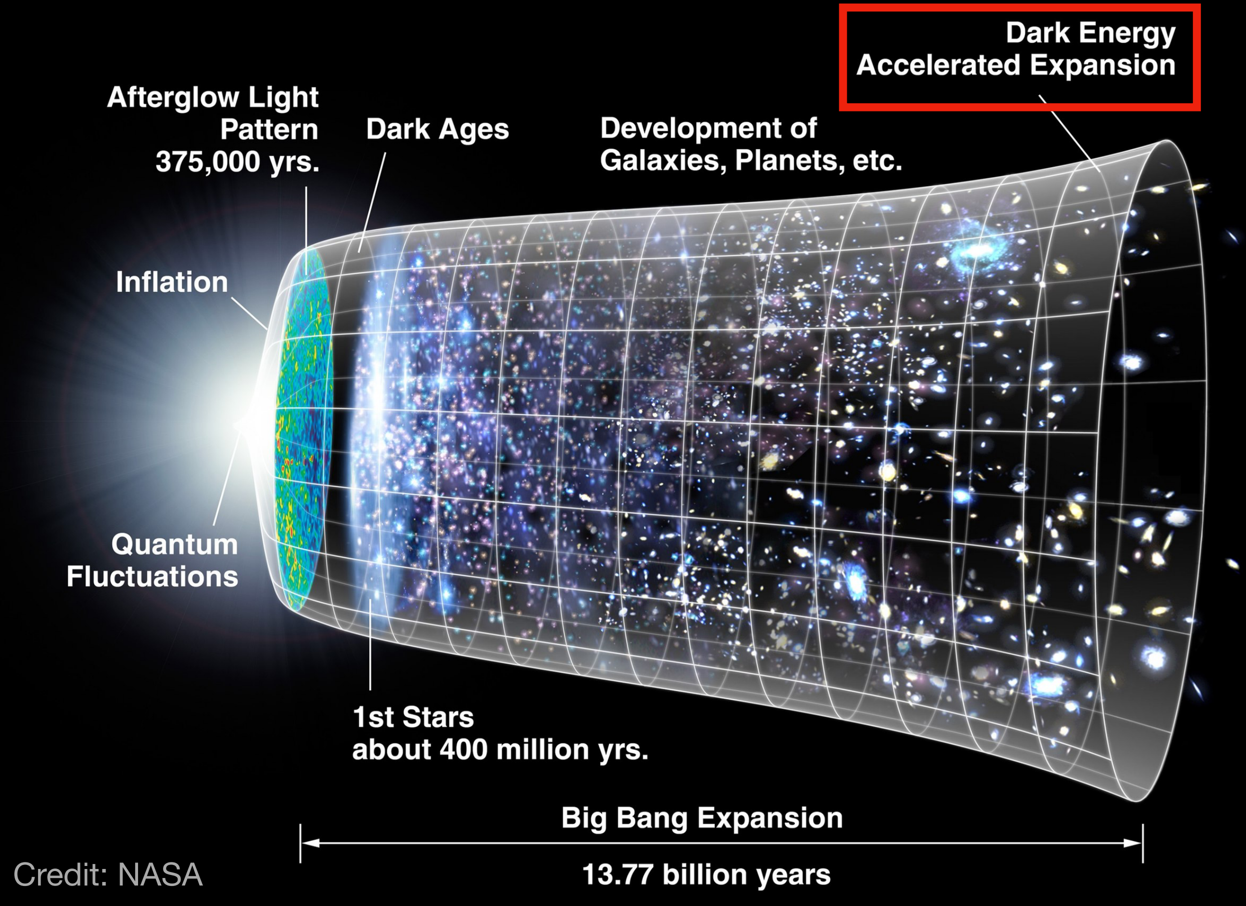


Credit: LIGO-Virgo

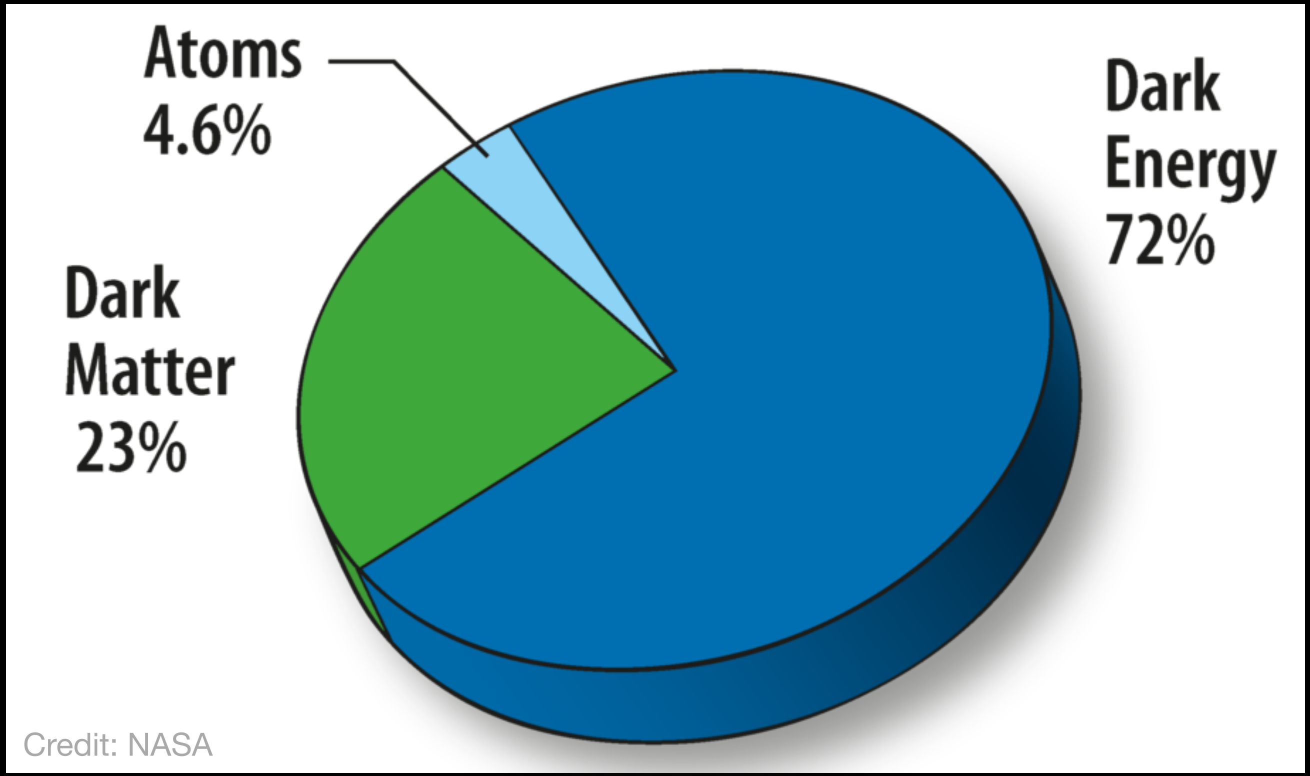


Credit: J. Tinker / SDSS

GW observational science: cosmology



Credit: NASA



Credit: NASA

An EM counterpart to a GW events provides a direct way to probe the expansion of the Universe and possibly solve the *Hubble tension*

Without an EM counterpart cosmological information can still be extracted from GW data with the help of galaxy catalogues

Future GW observations will provide information on the nature of *dark energy*

THANK YOU !