La phénoménologie des ondes gravitationnelles

Nicola Tamanini

LISA CONSORTIUM

L2IT

LIGO VIRGO KAGRA

Laboratoire des 2 Infinis - Toulouse
CNRS / IN2P3 / Univ. Paul Sabatier

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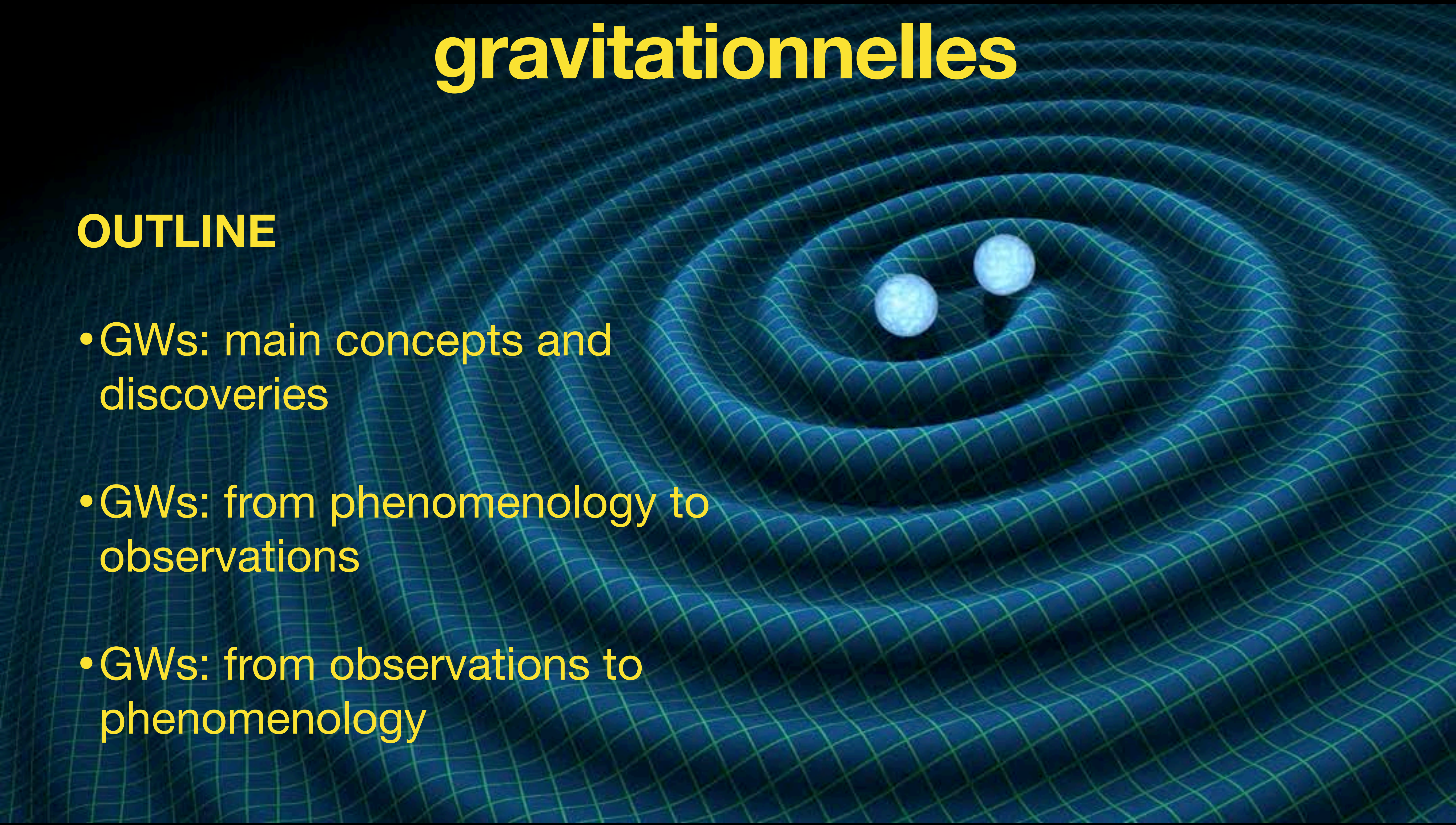
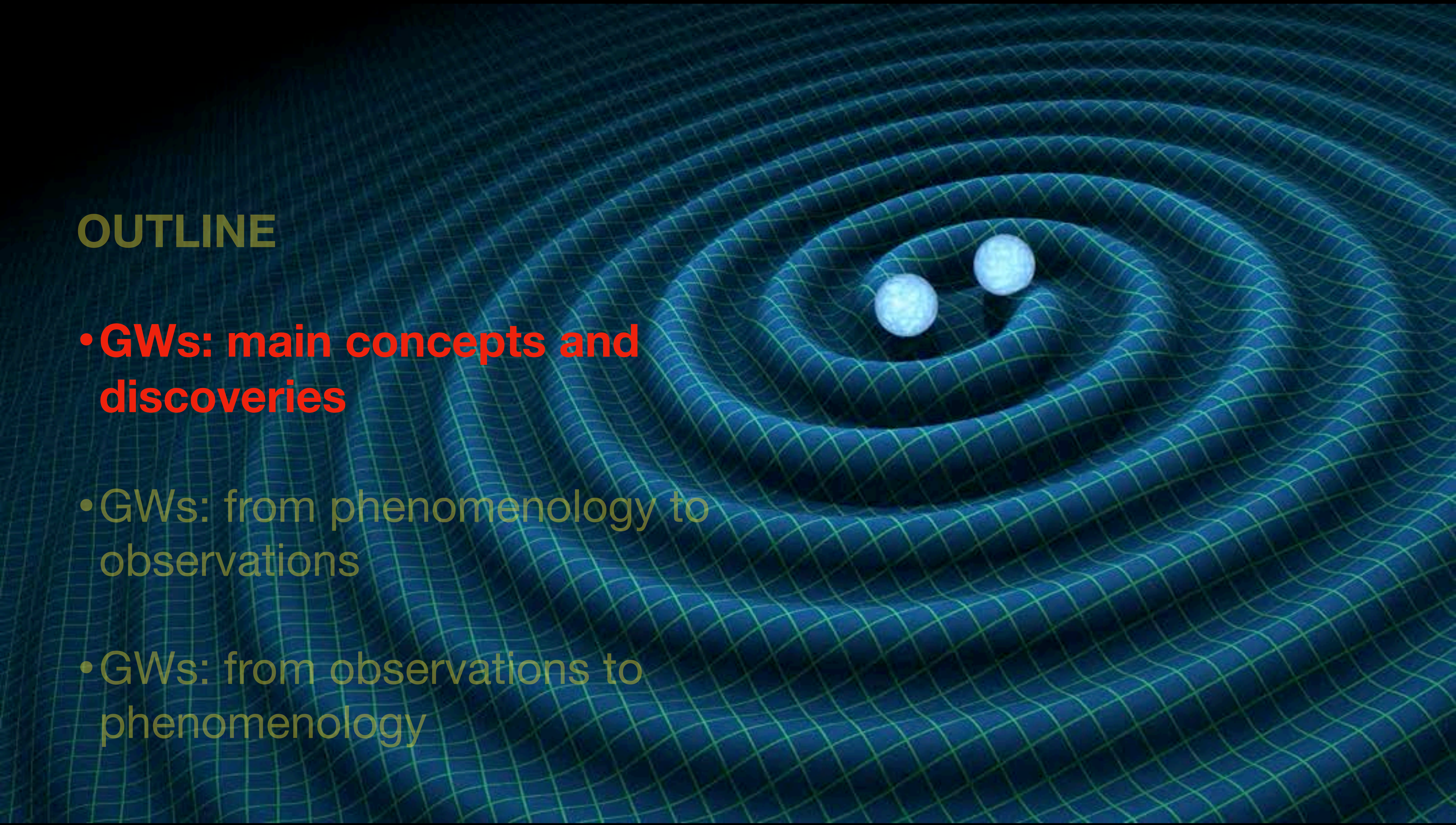
La phénoménologie des ondes gravitationnelles



OUTLINE

- GWs: main concepts and discoveries
- GWs: from phenomenology to observations
- GWs: from observations to phenomenology



OUTLINE

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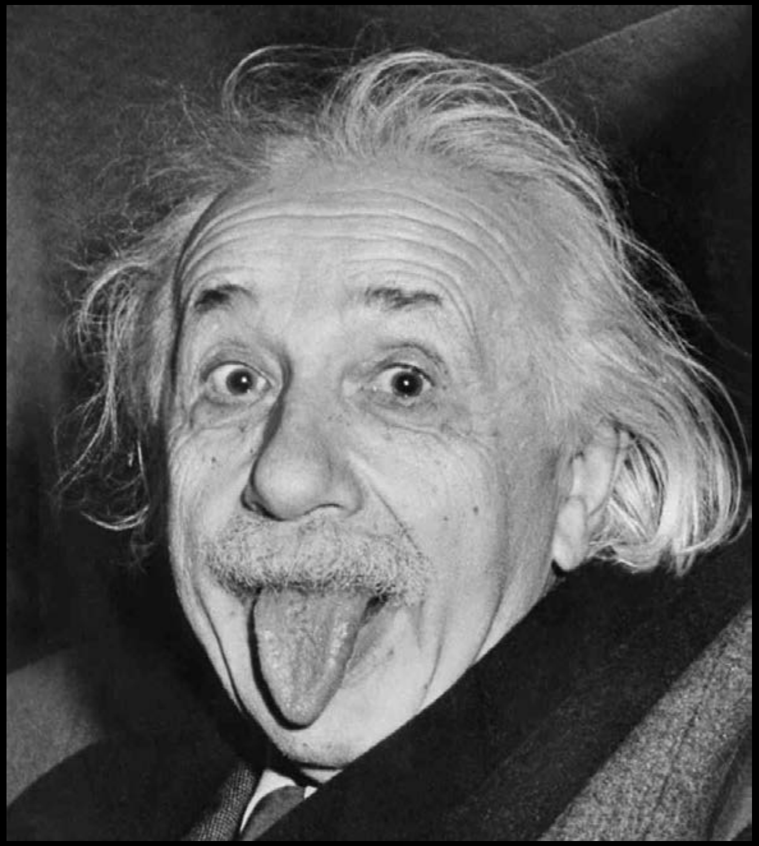
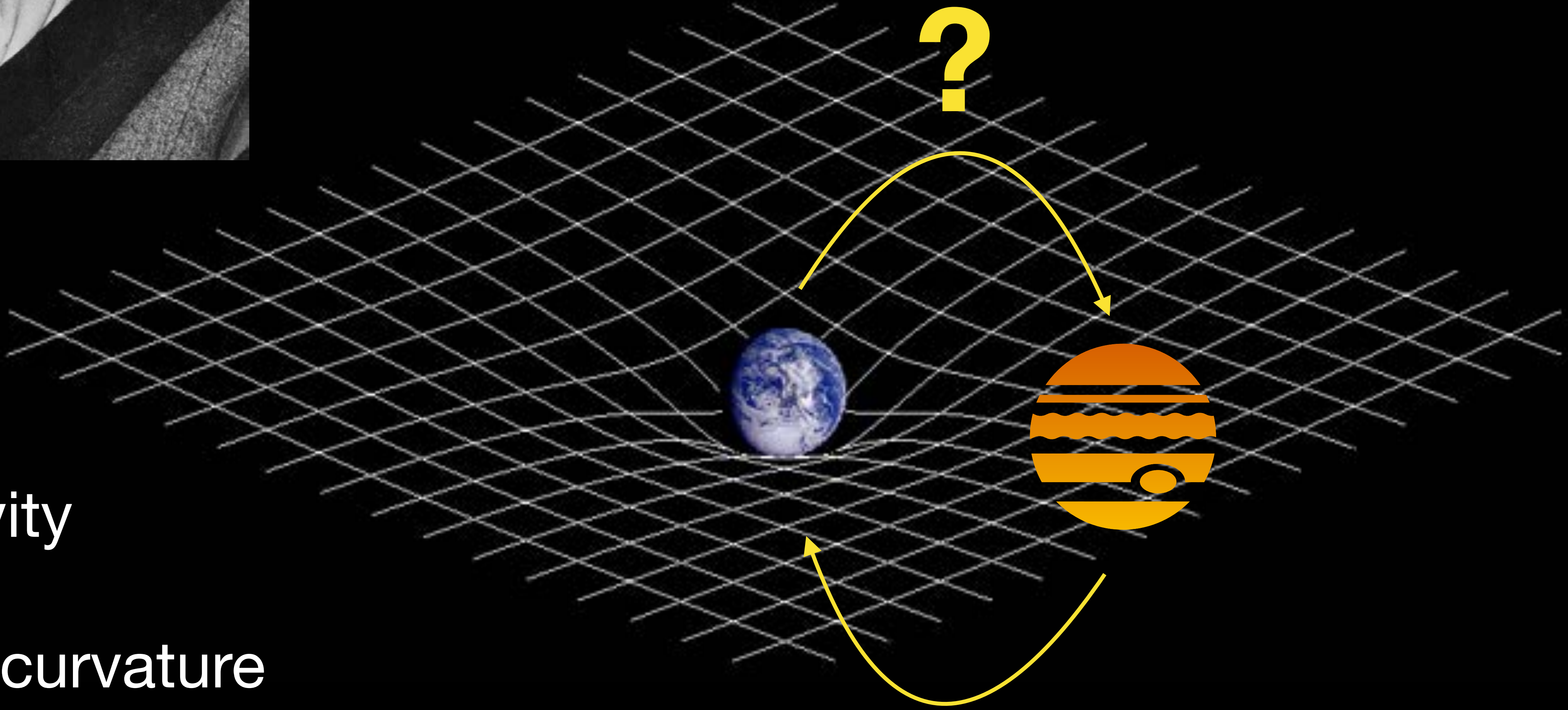
Einstein’s general relativity theory of gravity

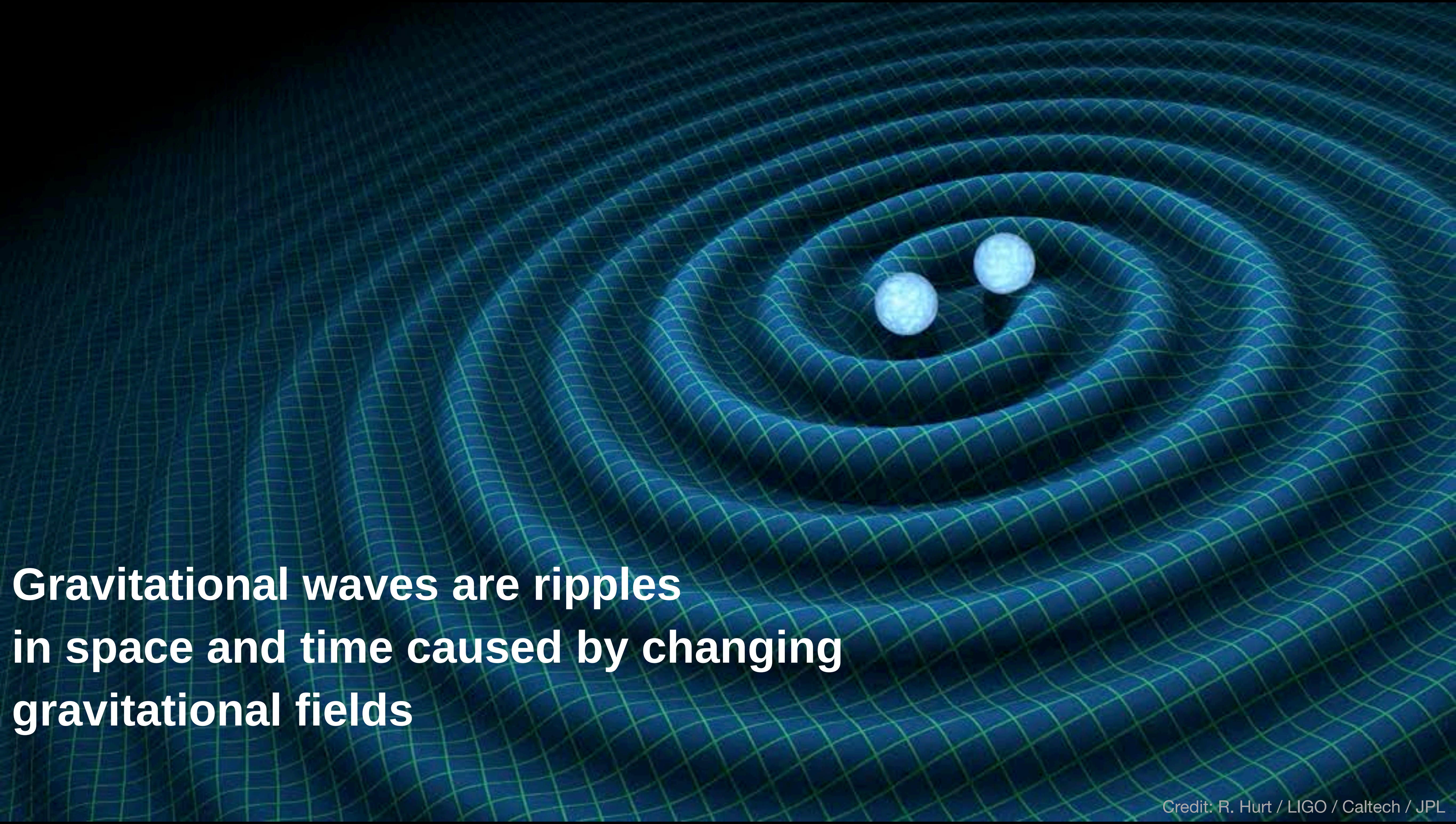


“Spacetime tells matter how to move, and matter tells spacetime how to curve”



Gravity
=
Spacetime curvature

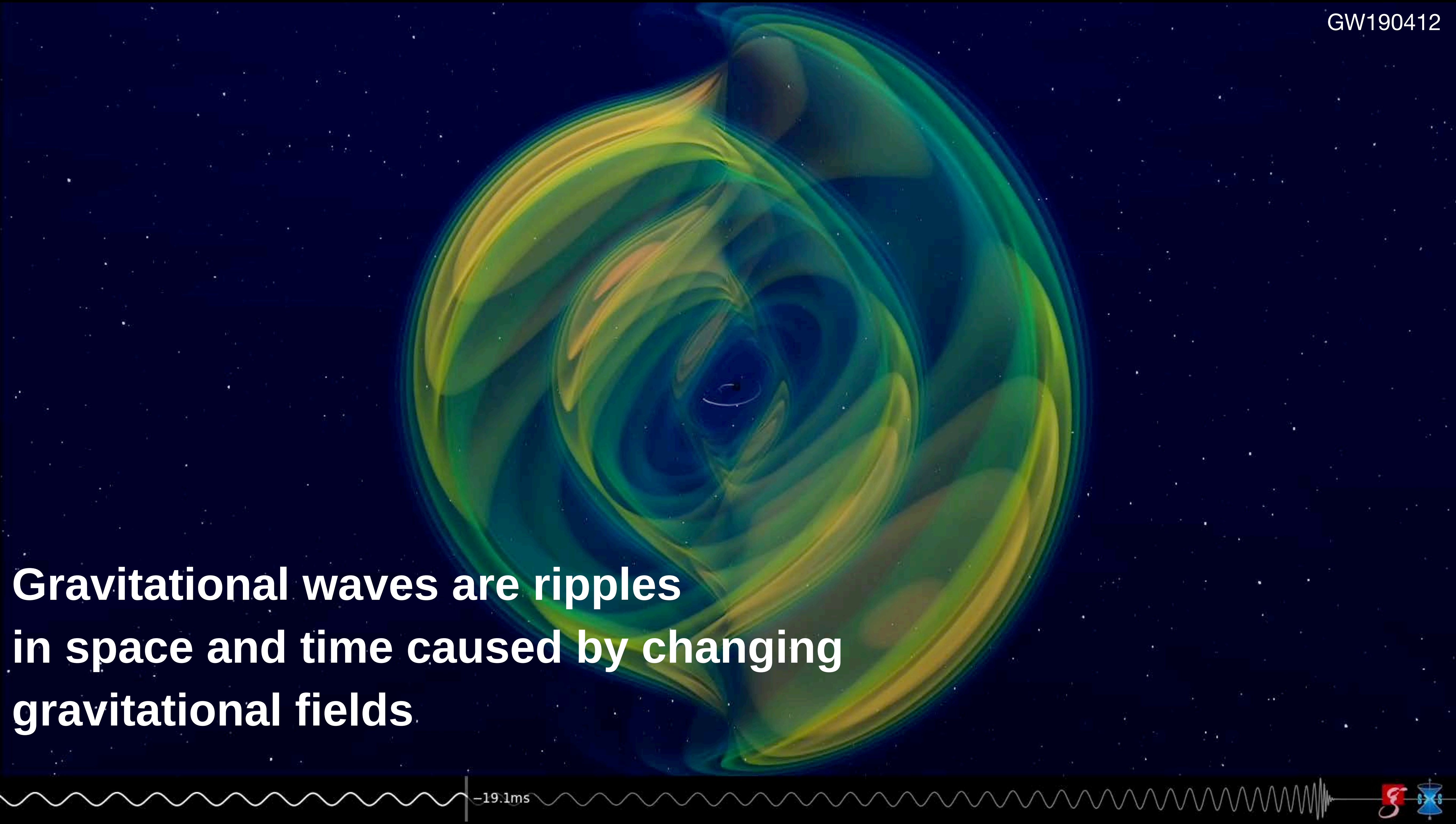
Gravitational waves = dynamical spacetime



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

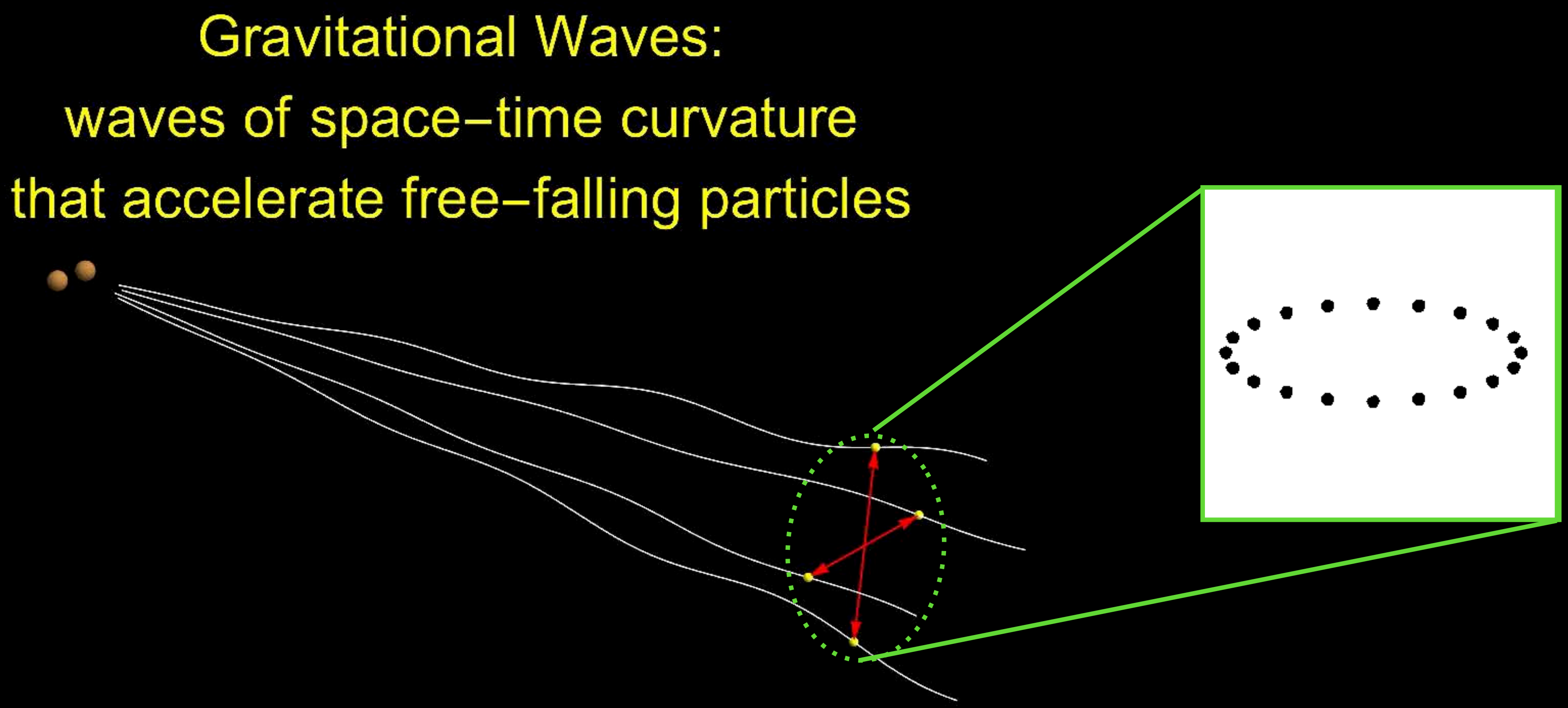
Credit: R. Hurt / LIGO / Caltech / JPL

Gravitational waves = dynamical spacetime



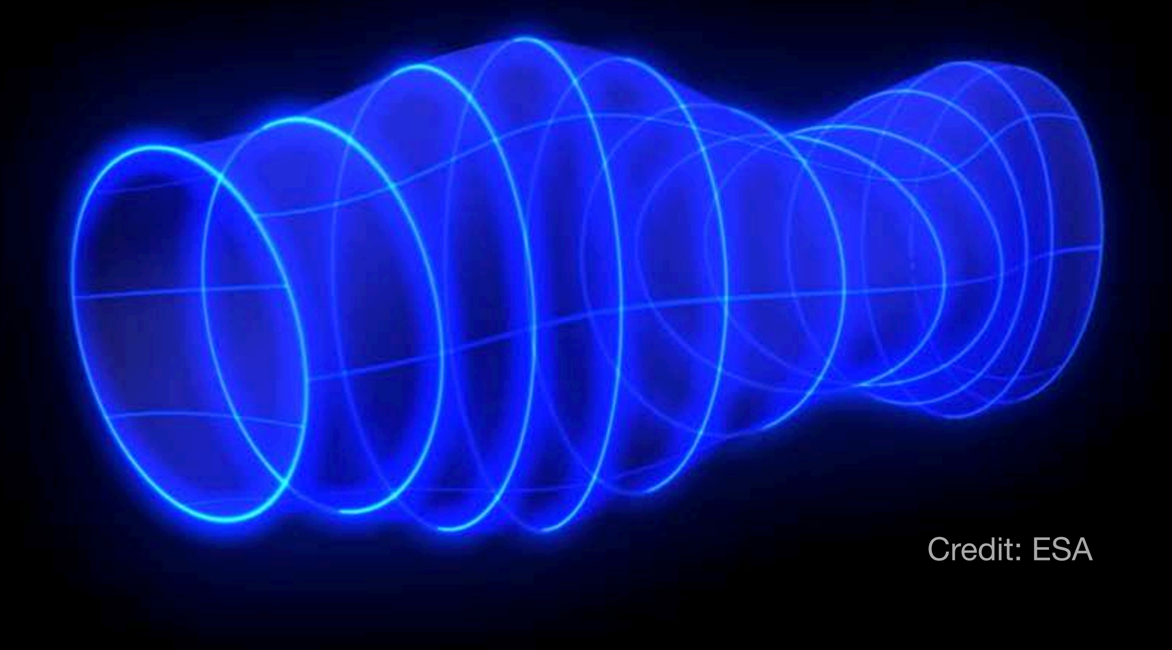
Gravitational waves are ripples in space and time caused by changing gravitational fields

How gravitational waves “move” matter



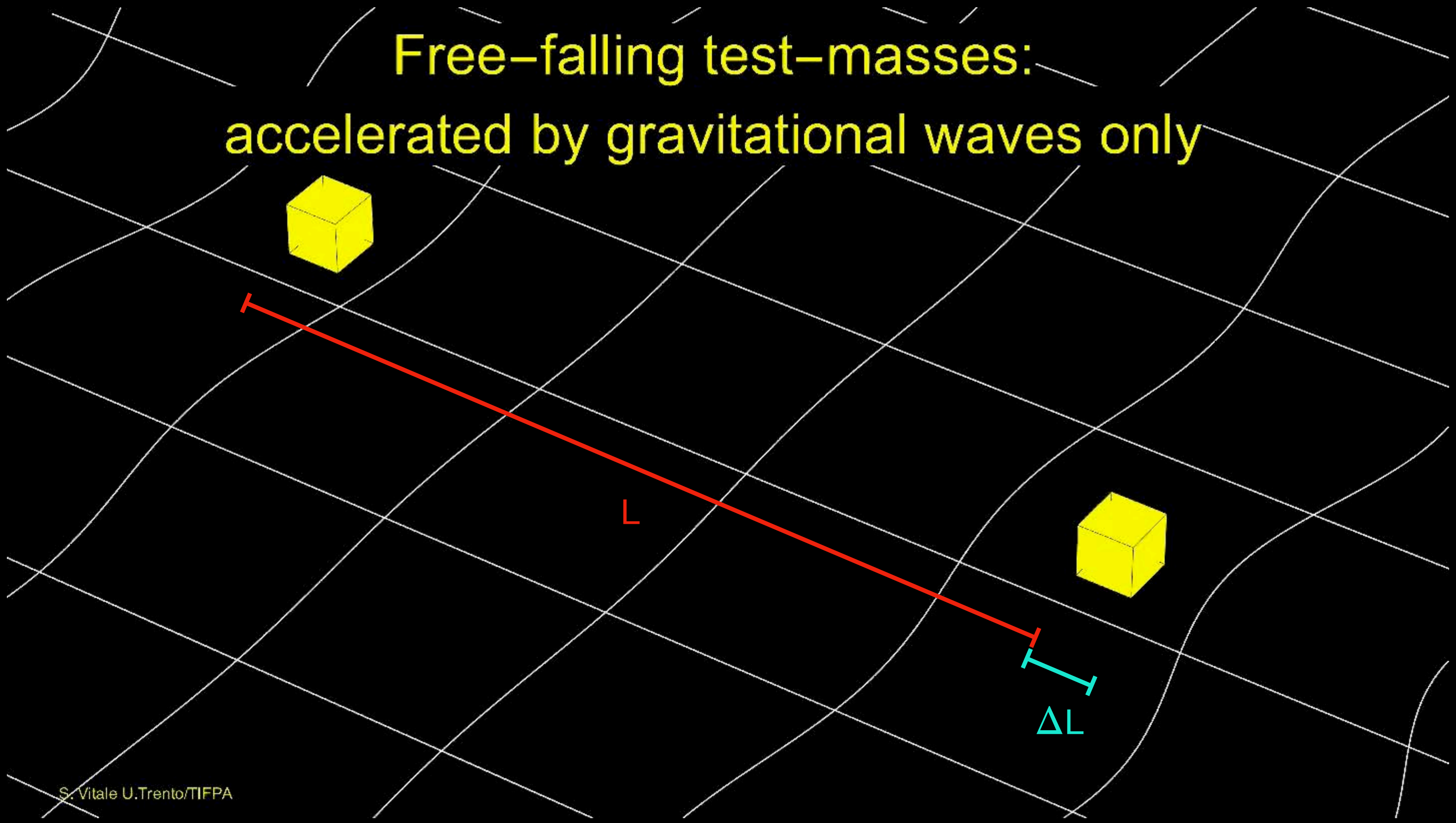
Gravitational Waves:
waves of space–time curvature
that accelerate free–falling particles

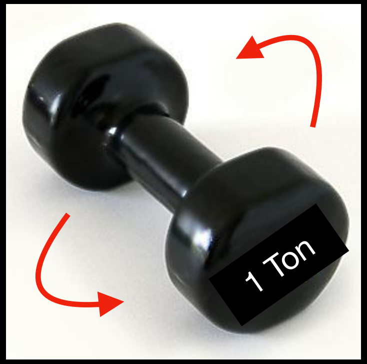
S. Vitale U.Trento/TIFPA



Credit: ESA

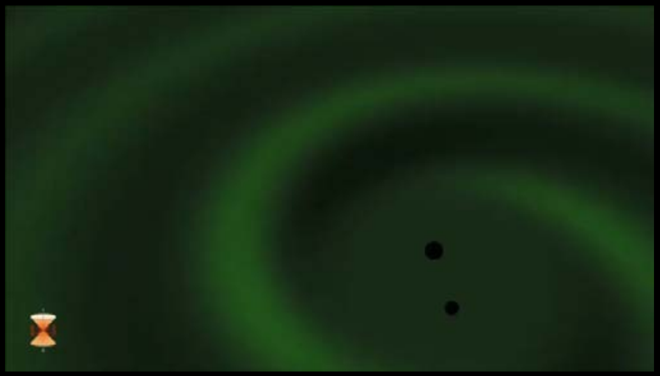
How gravitational waves “move” matter





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

@ laboratory distances

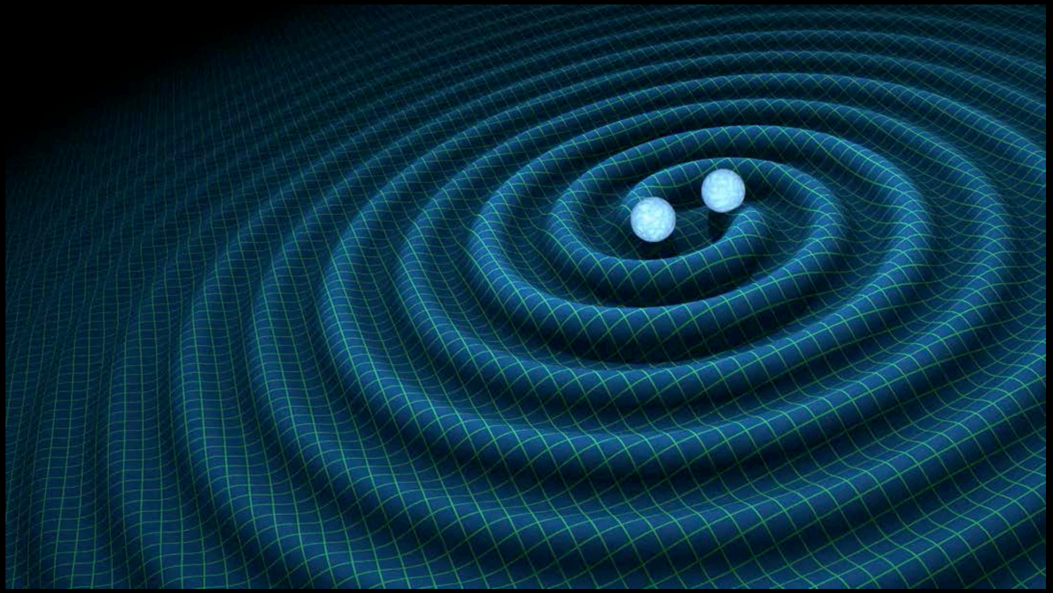


$$\Rightarrow \frac{\Delta L}{L} \sim 10^{-21}$$

@ cosmological distances

How to detect gravitational waves?

INDIRECT DETECTION



Indirectly from the effects they leave on a source

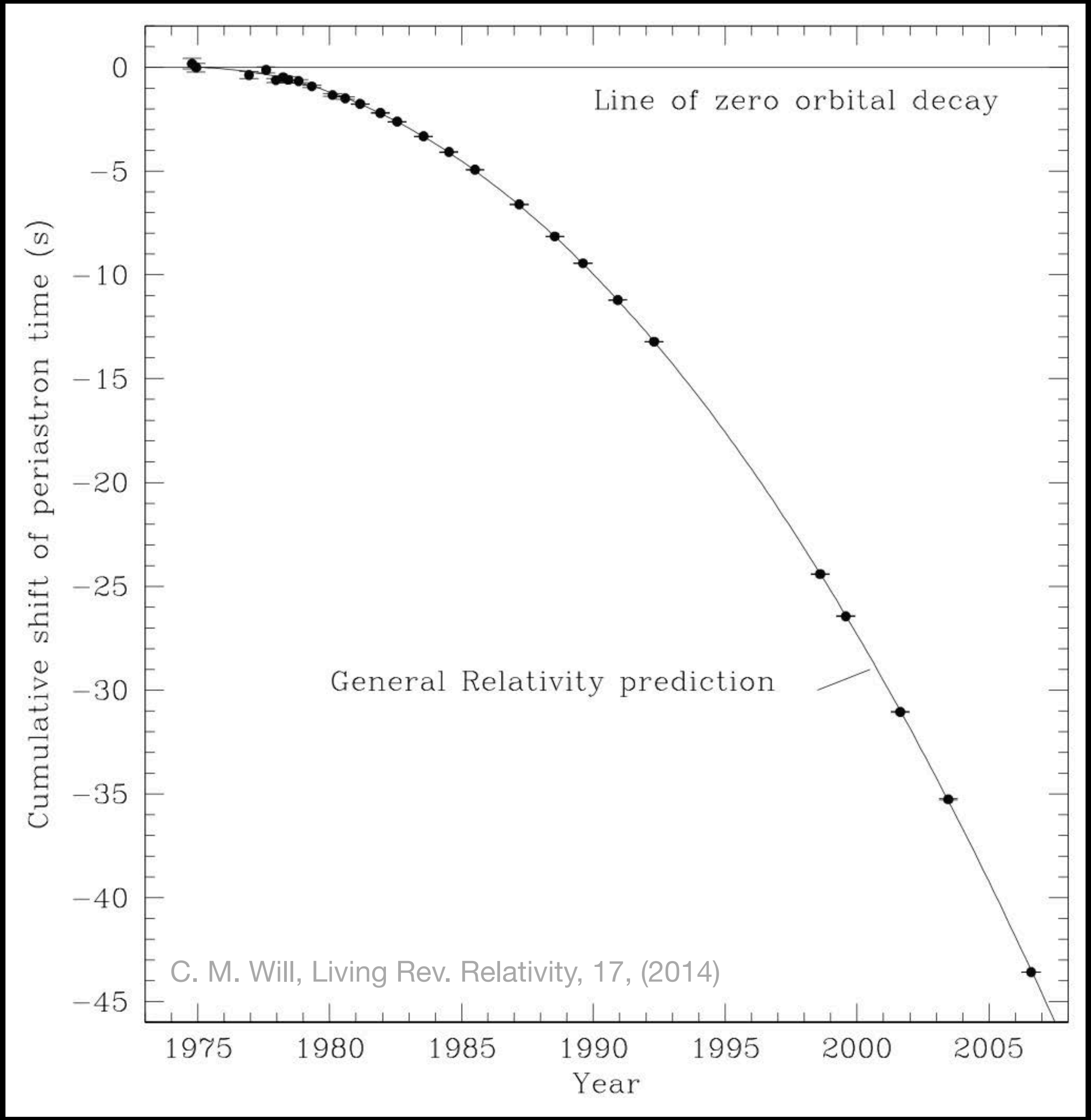
GWs take away energy and (angular) momentum

⇓

Orbits shrinks / period decreases

How to detect gravitational waves?

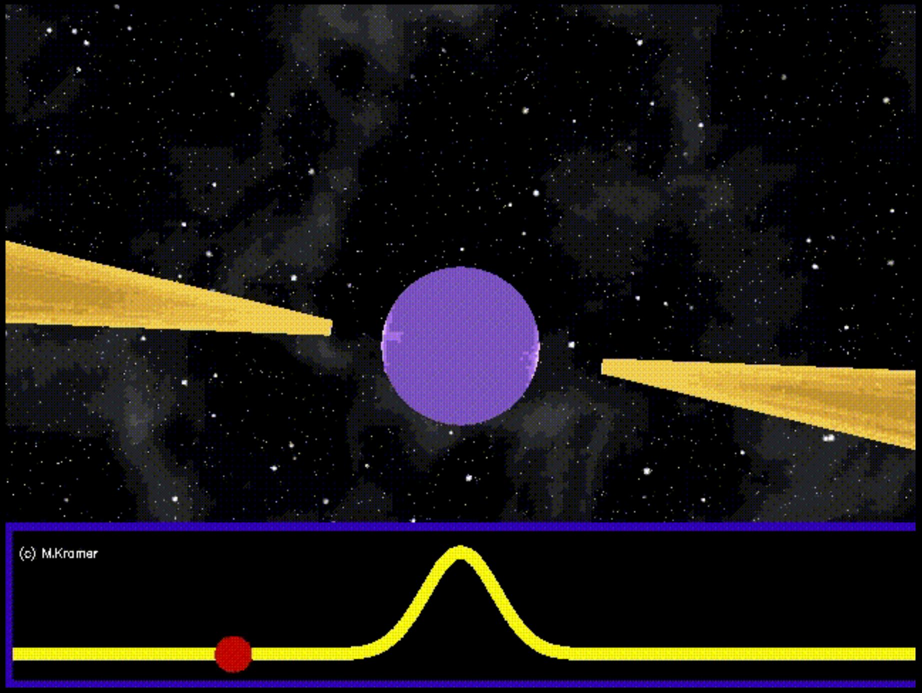
INDIRECT DETECTION

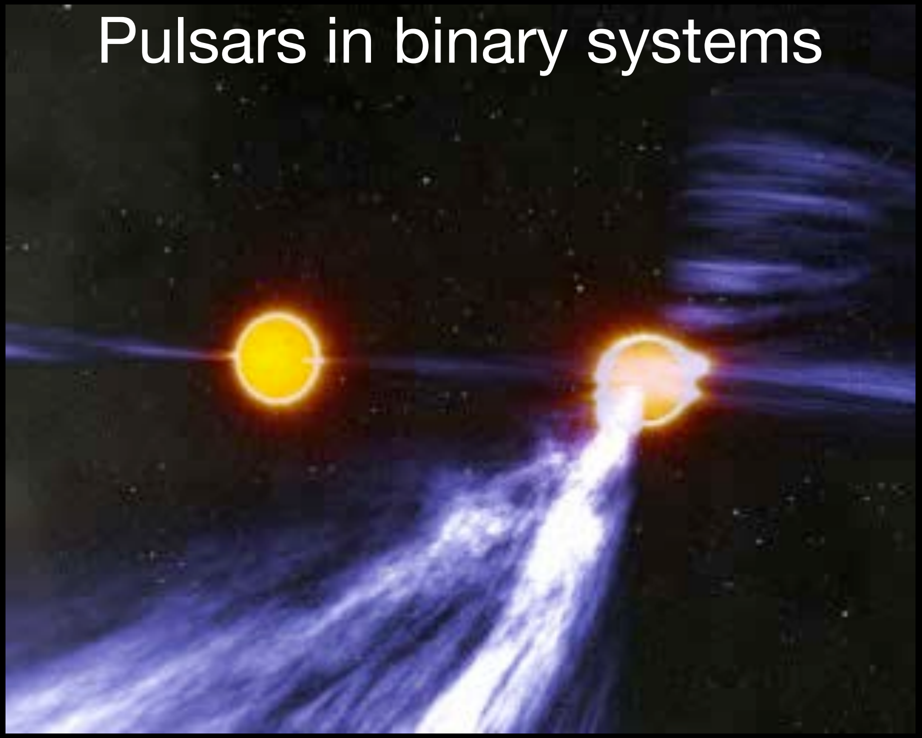


C. M. Will, Living Rev. Relativity, 17, (2014)

Hulse–Taylor pulsar
Nobel Prize 1993

Credit: Michael Kramer



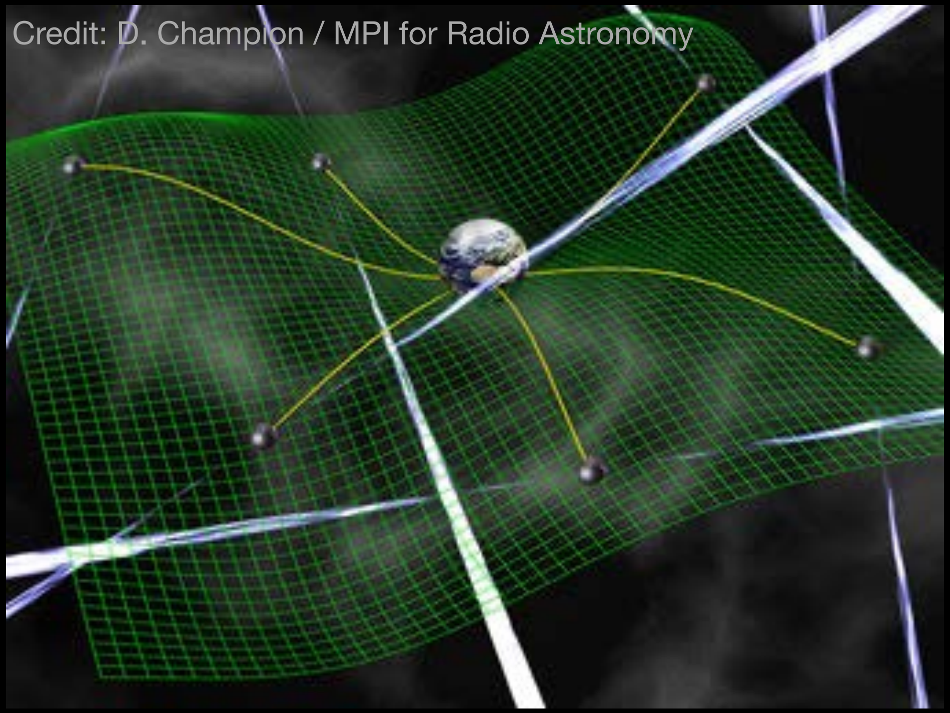


Pulsars in binary systems

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

⇓

Change in the arrival time of EM pulses

How to detect gravitational waves?

PTA DETECTION 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*

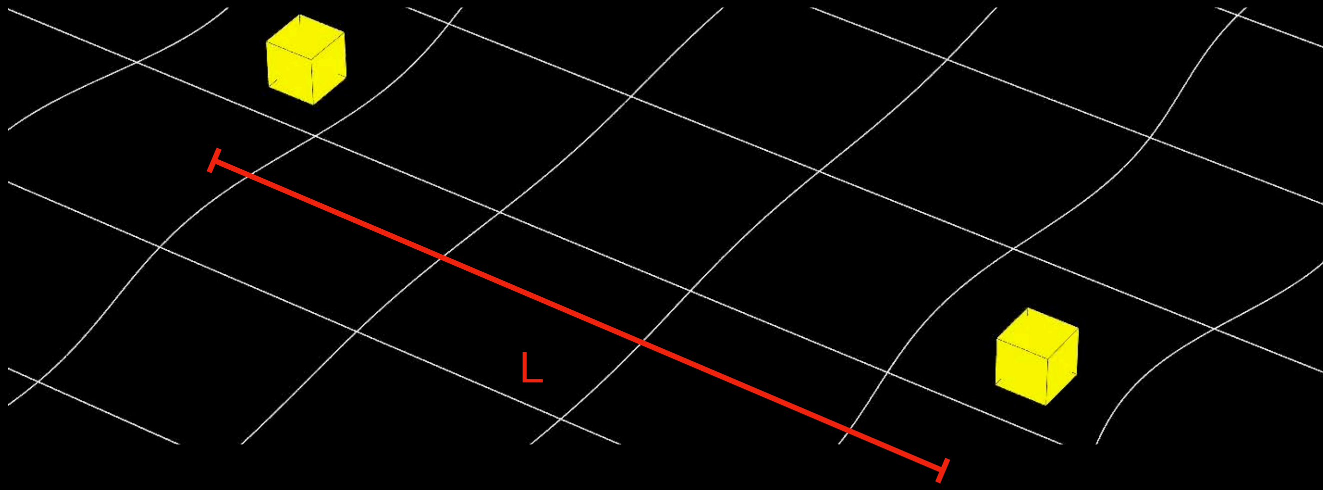
Public Briefing

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)

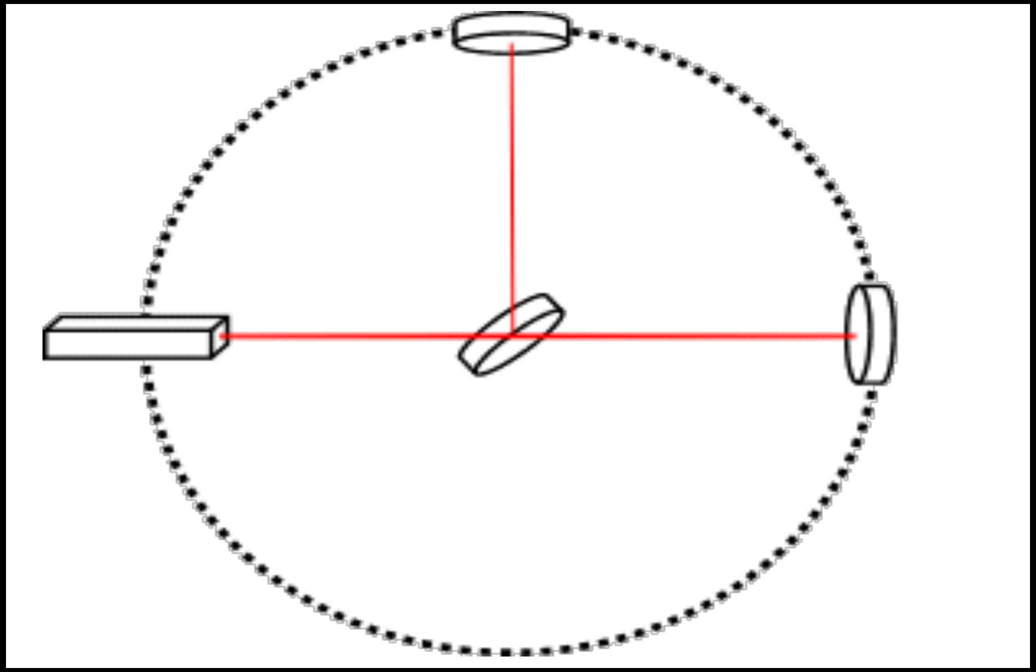
⇓

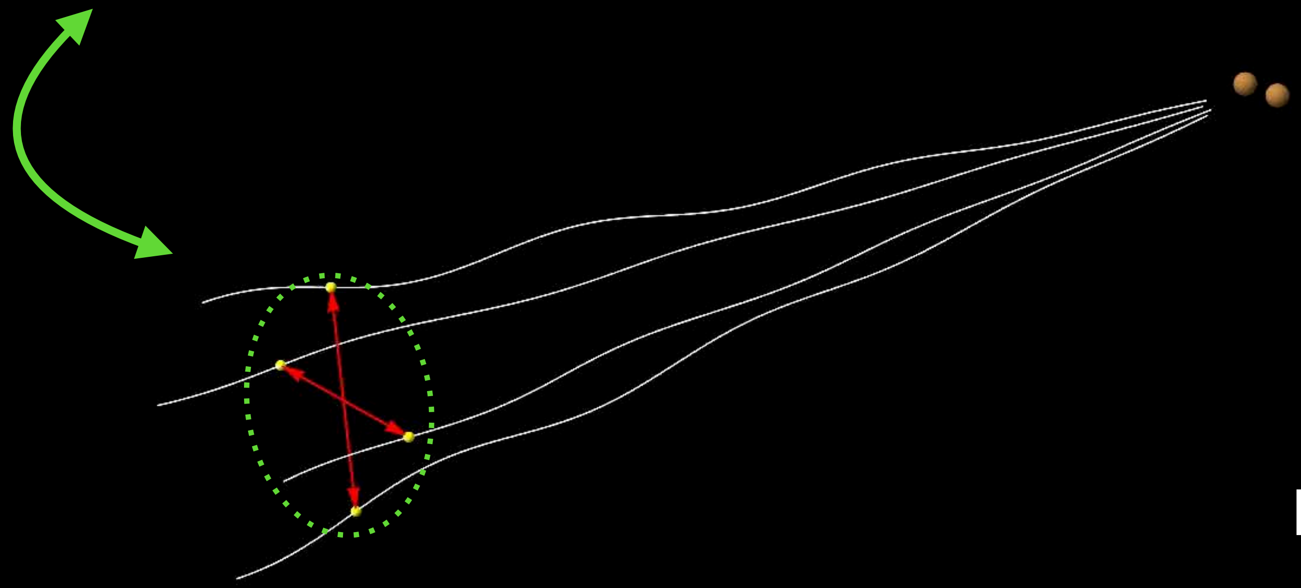
Distance between to free-falling masses change

How to detect gravitational waves?

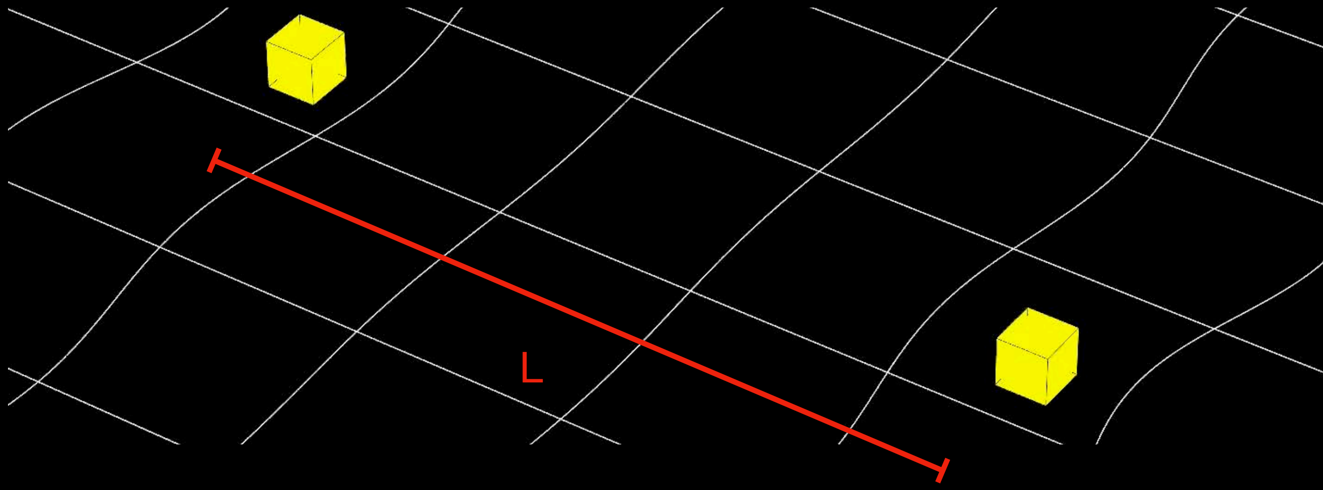
LASER INTERFEROMETRY

(See next talks on Virgo, ET, LISA)





DIRECT DETECTION



Directly from the effects they imprint on test masses

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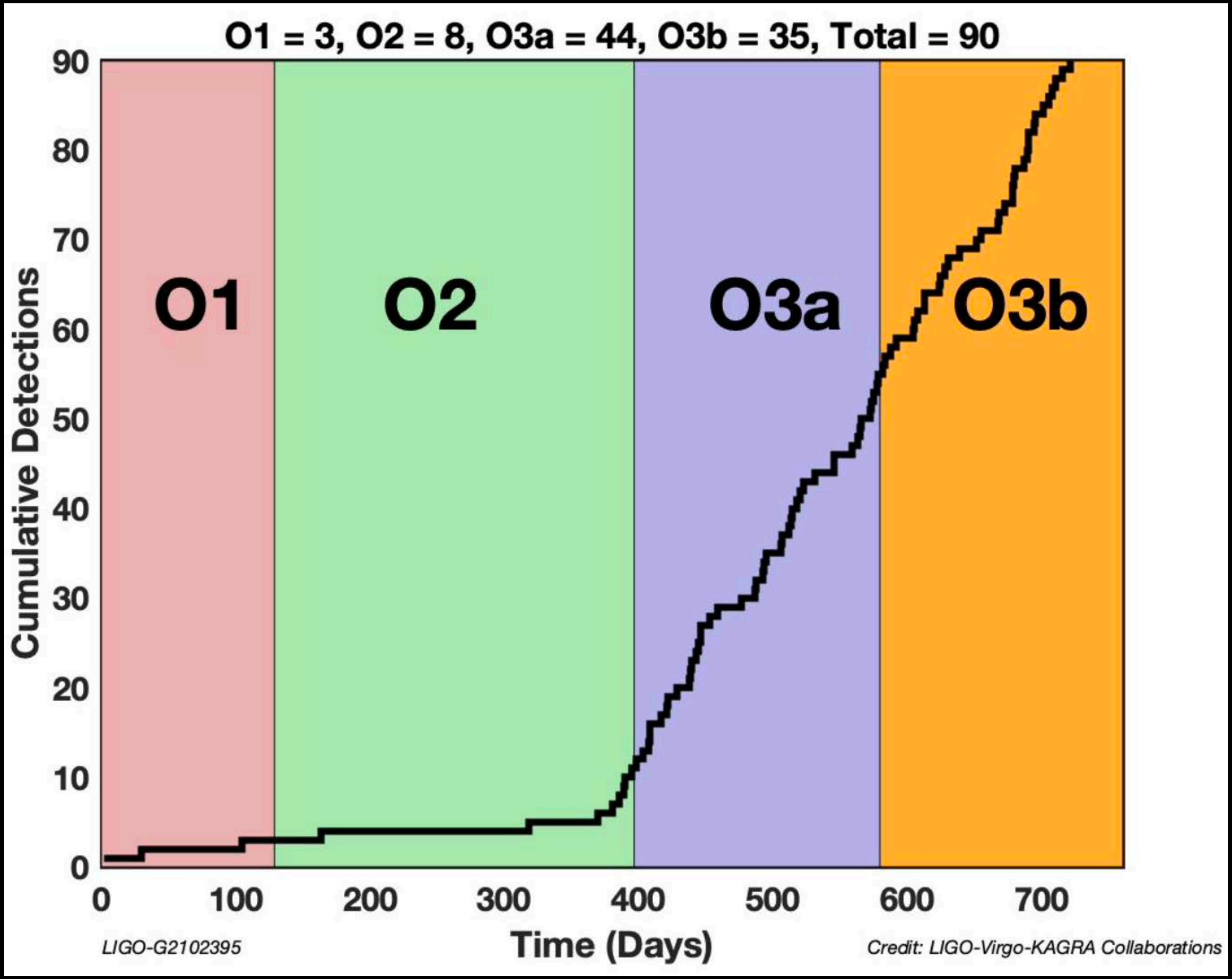
⇓

Distance between to free-falling masses change

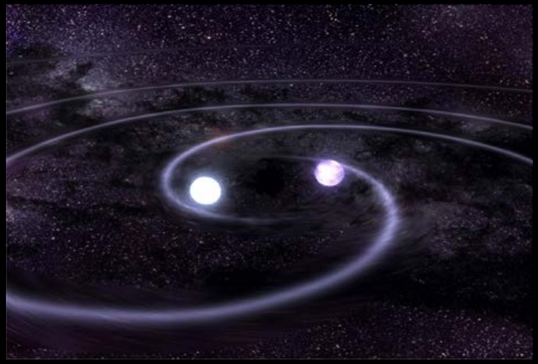
The current network of interferometers

All LVK detections so far



Astrophysical sources of gravitational waves

SOURCES ALREADY DETECTED BY THE LVK DETECTORS:

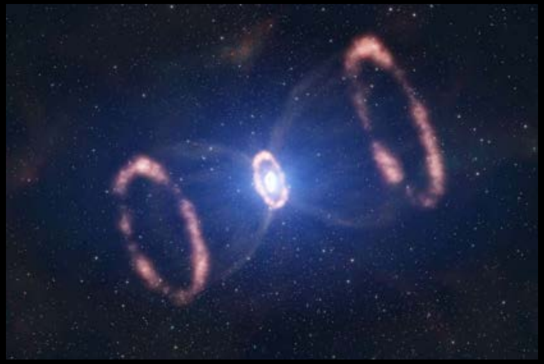


Binary neutron stars

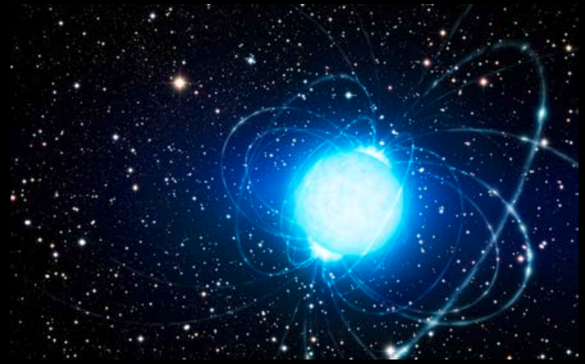
Binary black holes

Neutron star - black hole binaries

OTHER TARGETS FOR THE LVK DETECTORS:



Supernovae



Single (asymmetric) neutron stars

Stochastic GW background

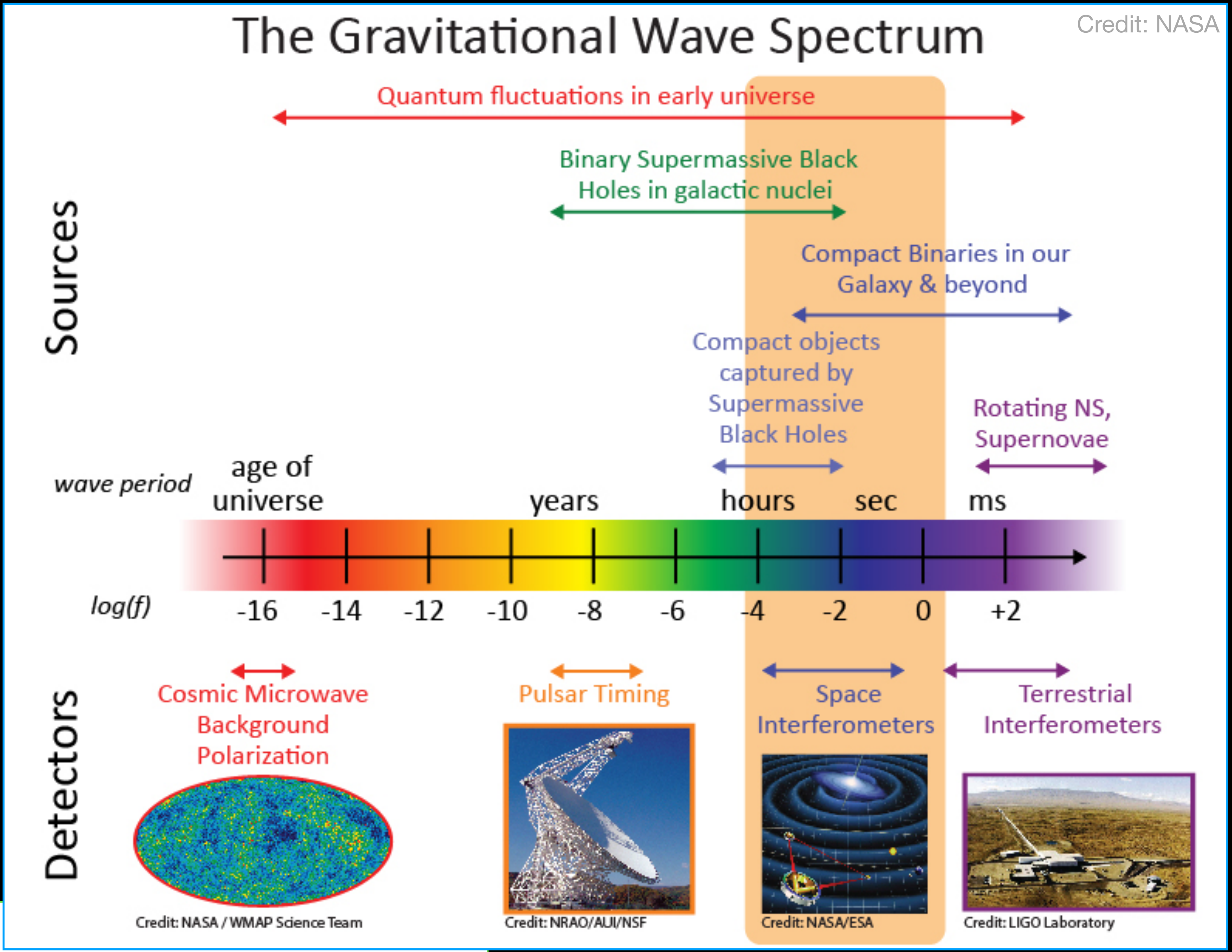
CAN WE DETECT OTHER SOURCES?

The gravitational wave spectrum

Different GW instruments observe at different frequencies / wavelengths

⇓

Different target sources



Credit: NASA

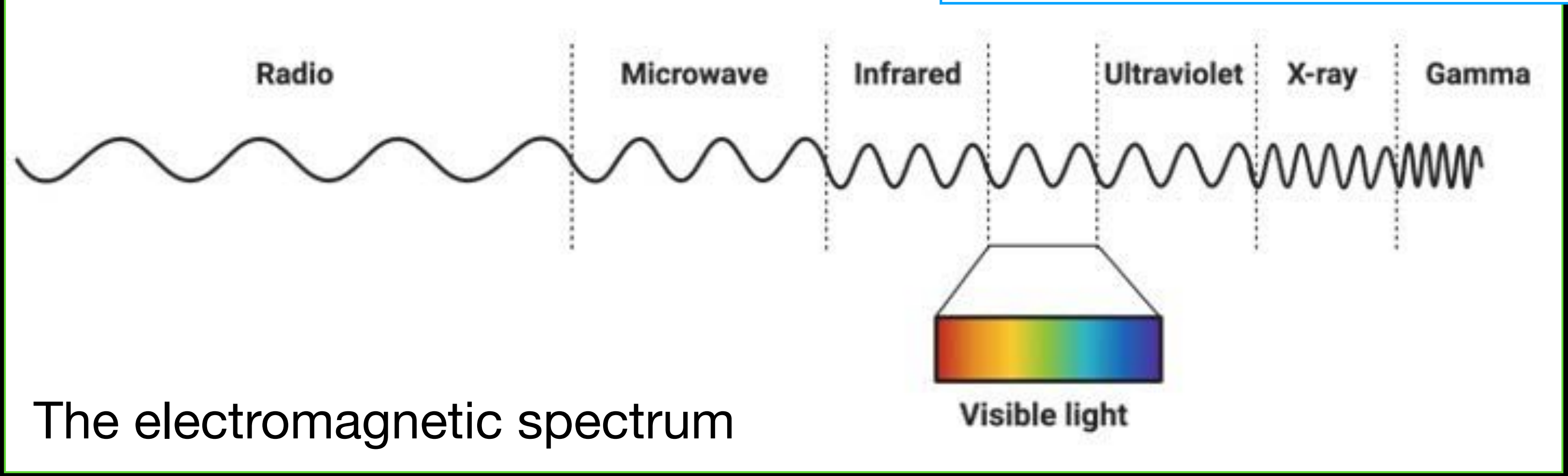
Credit: NASA / WMAP Science Team

Credit: NRAO/AUI/NSF

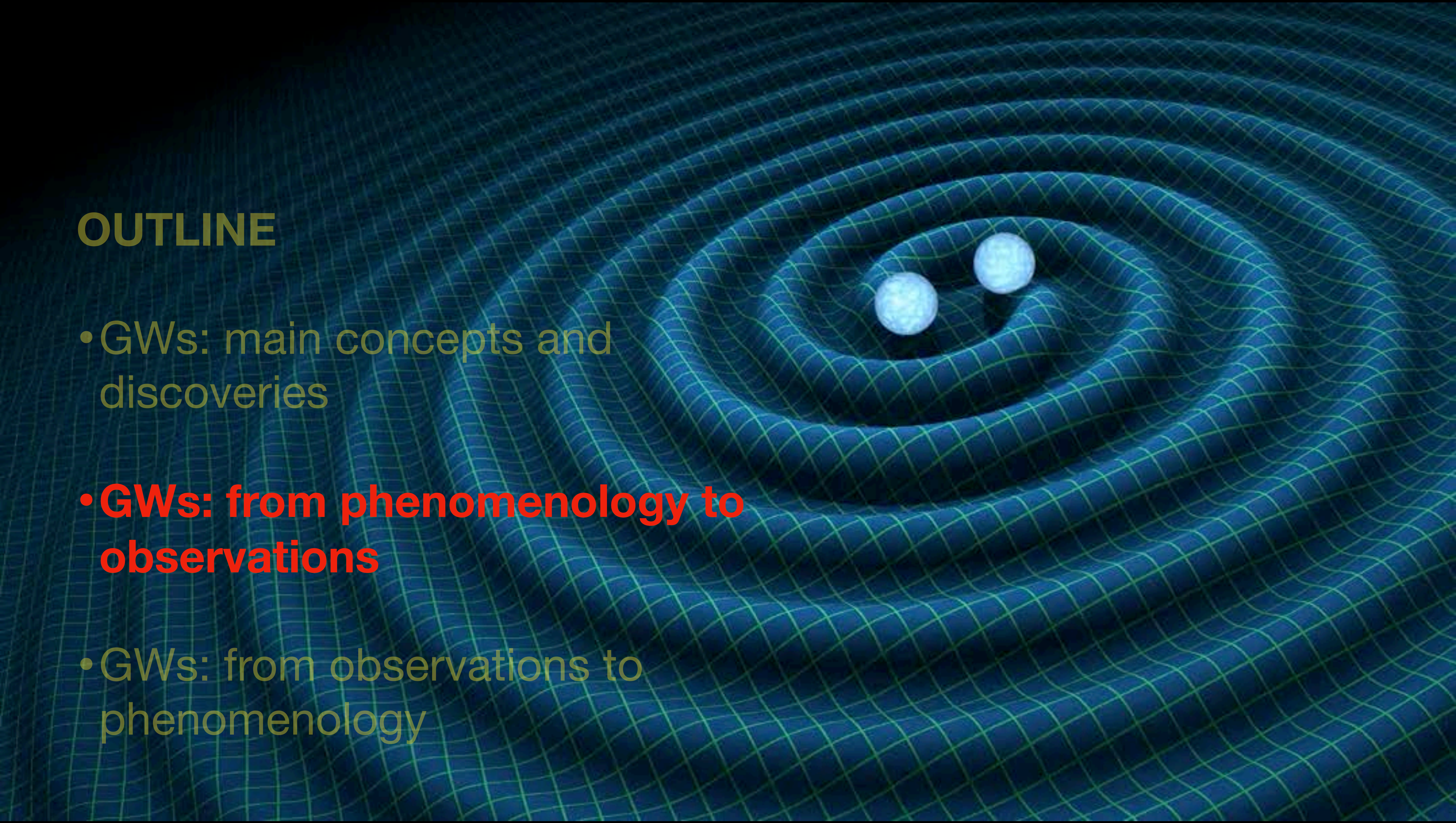
Credit: NASA/ESA

Credit: LIGO Laboratory

The gravitational wave spectrum



The electromagnetic spectrum



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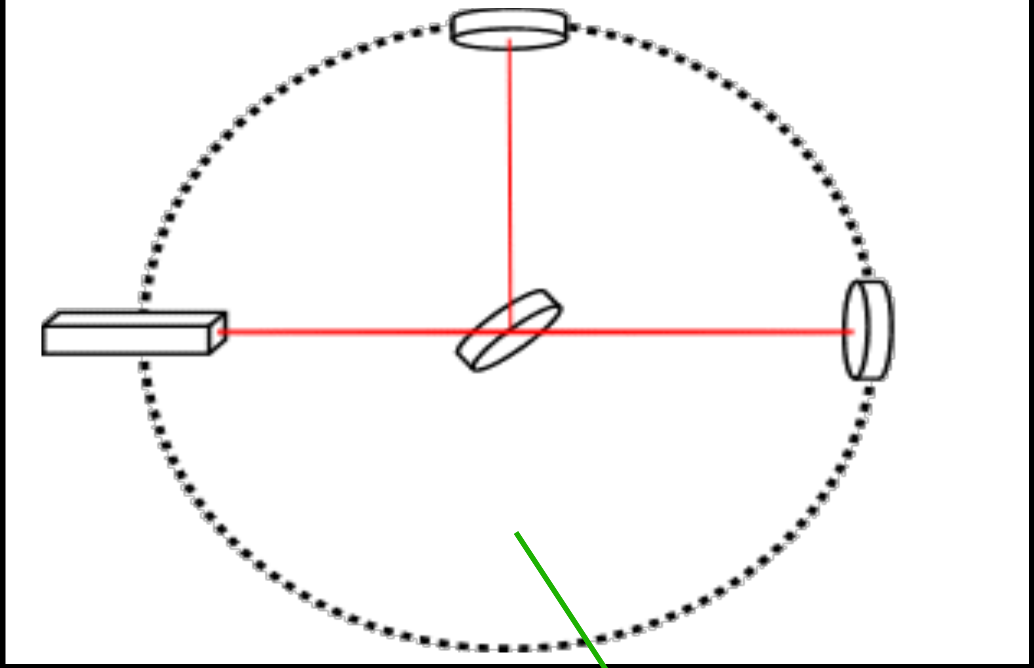
How do we detect and characterise the signal?



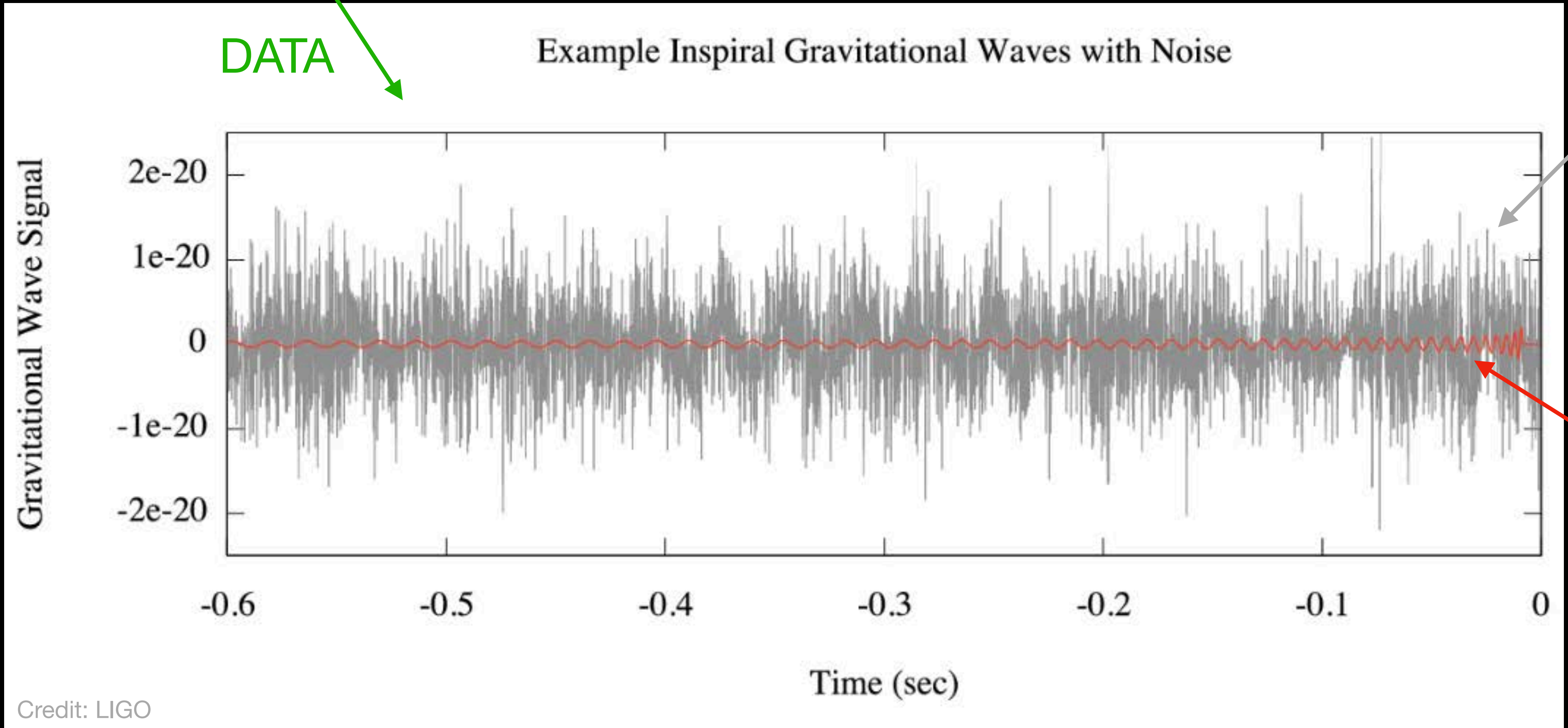
How to extract the signal from the noise?

MATCHED FILTERING

Model the signal theoretically

Find and characterise the signal in the data efficiently

DATA



Noise

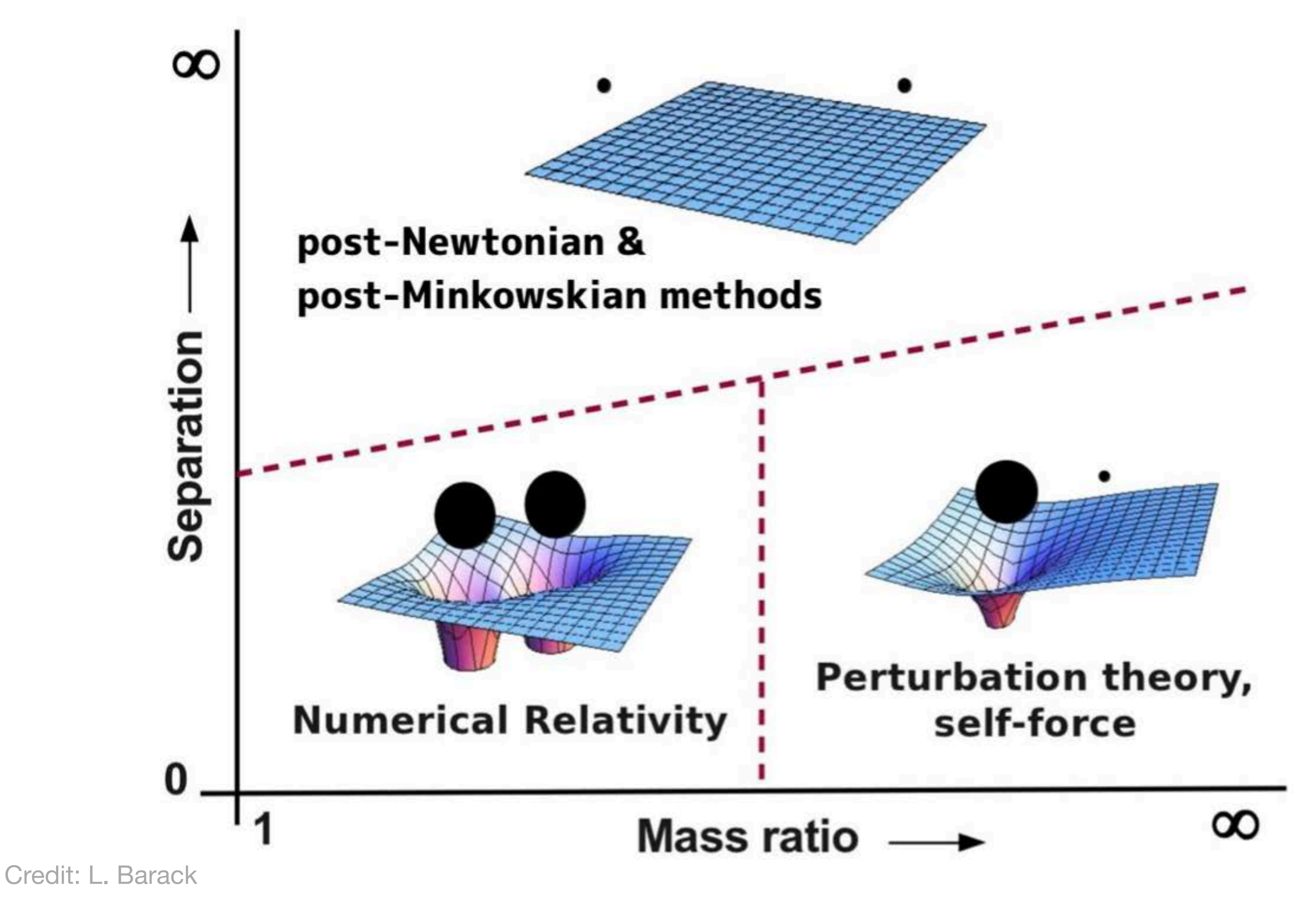
Signal

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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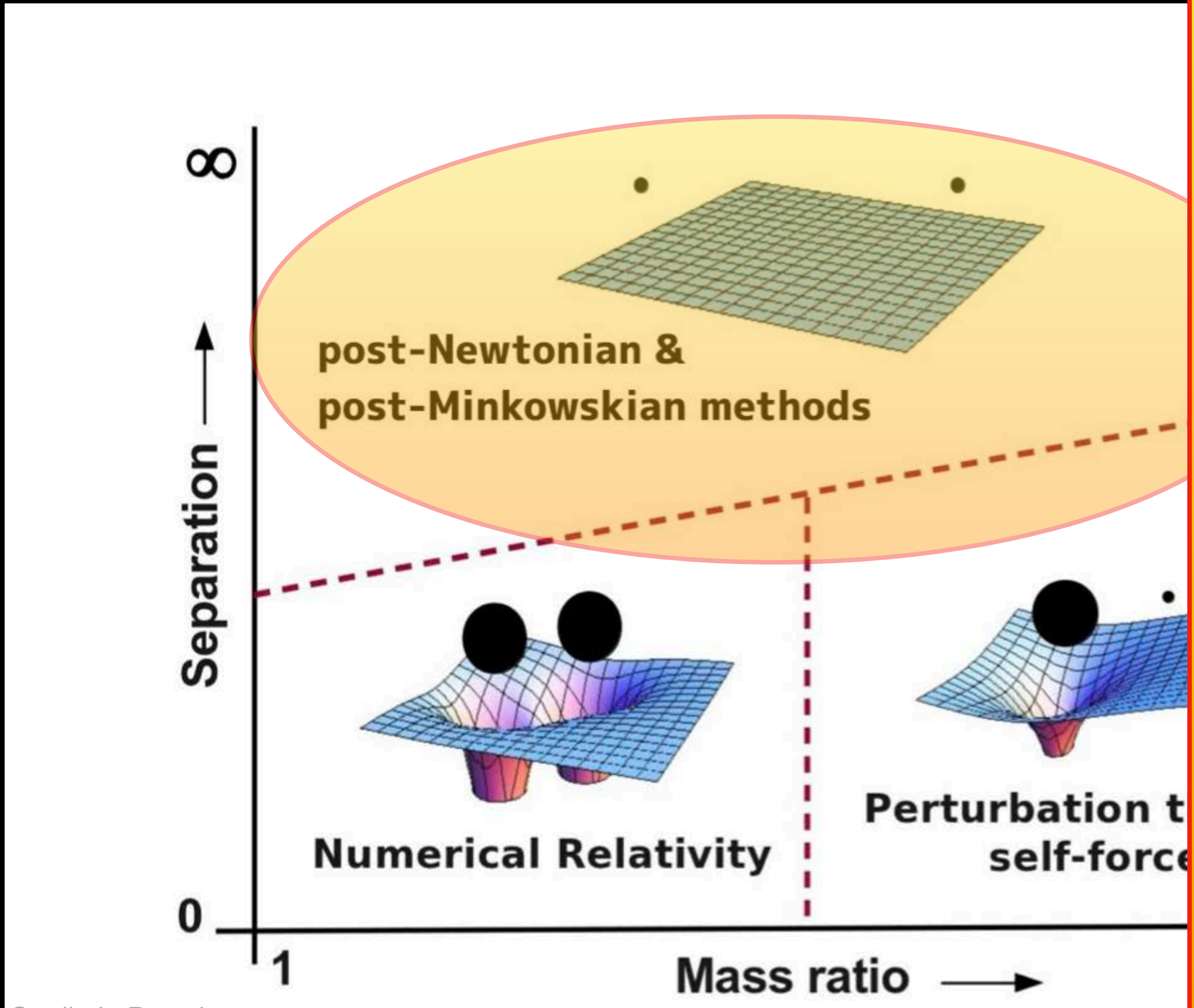
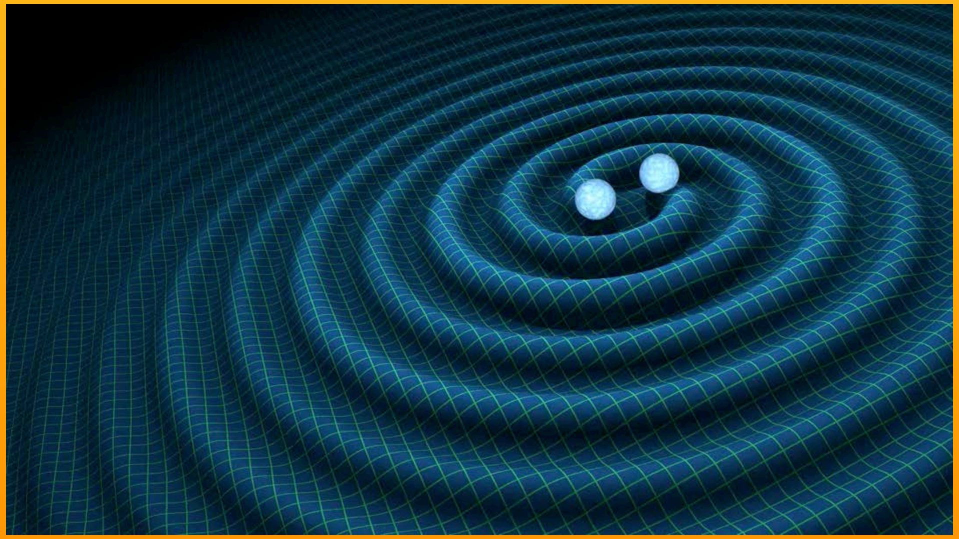


Credit: L. Barack

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



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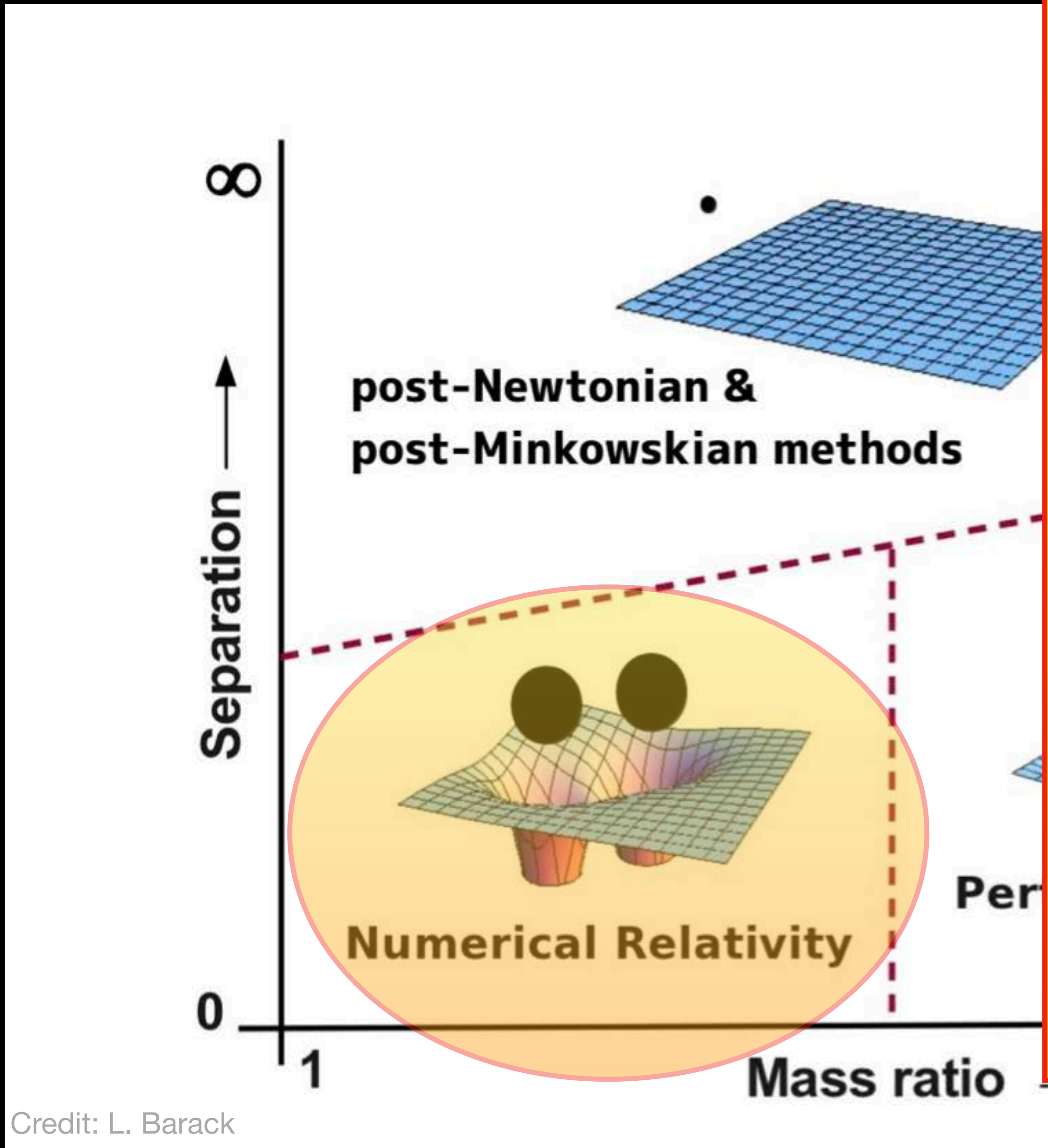
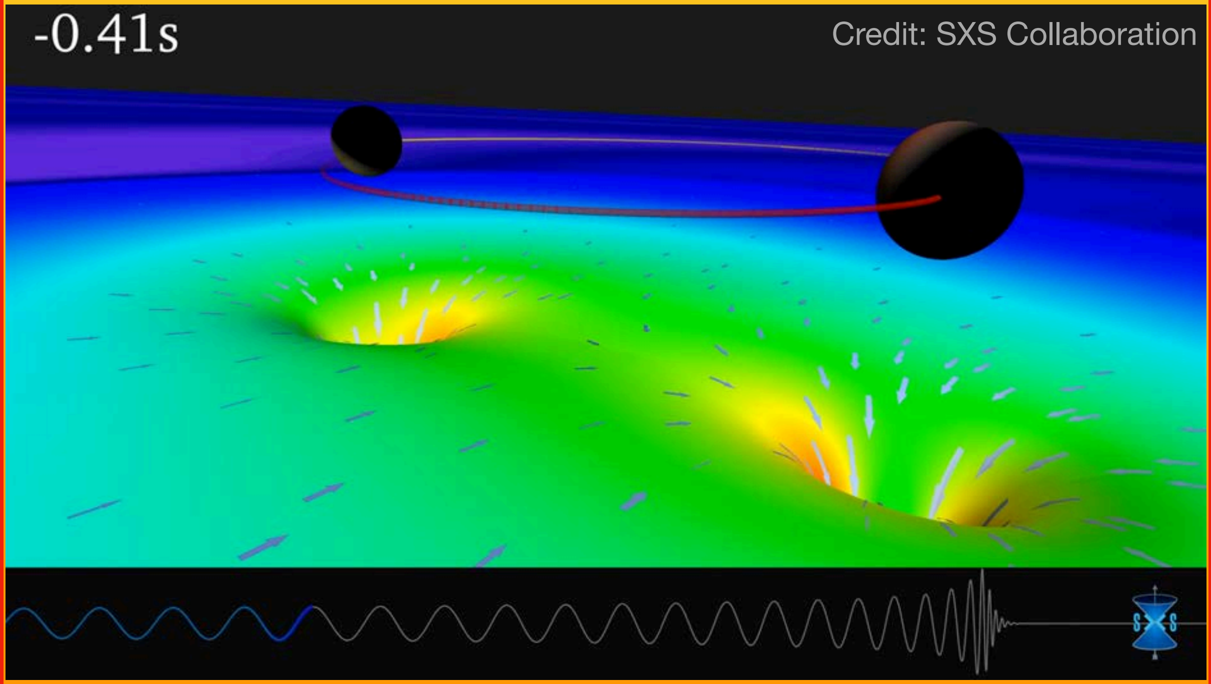


Credit: L. Barack

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

in g

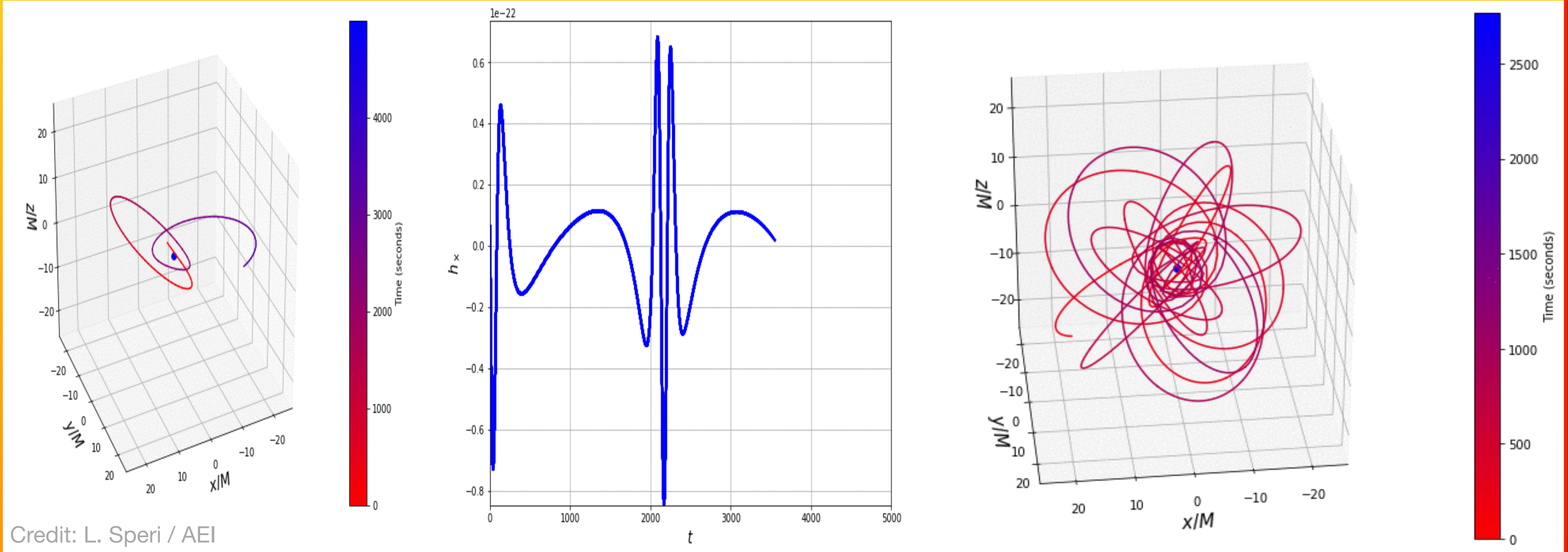
Diff

reg

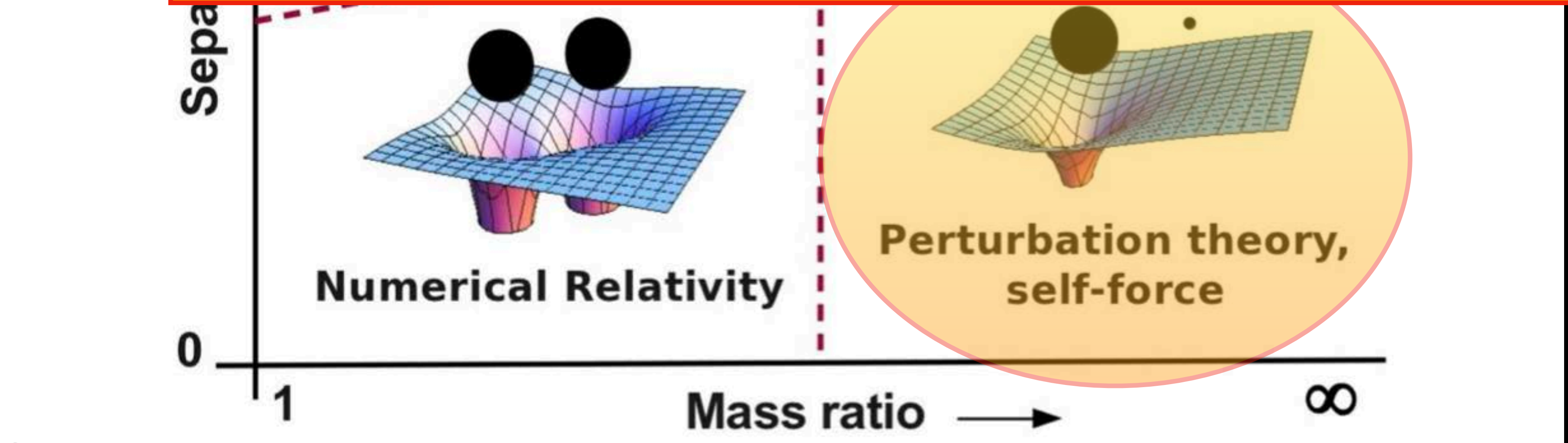
No expansion over flat spacetime possible

Need complex analytical techniques

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

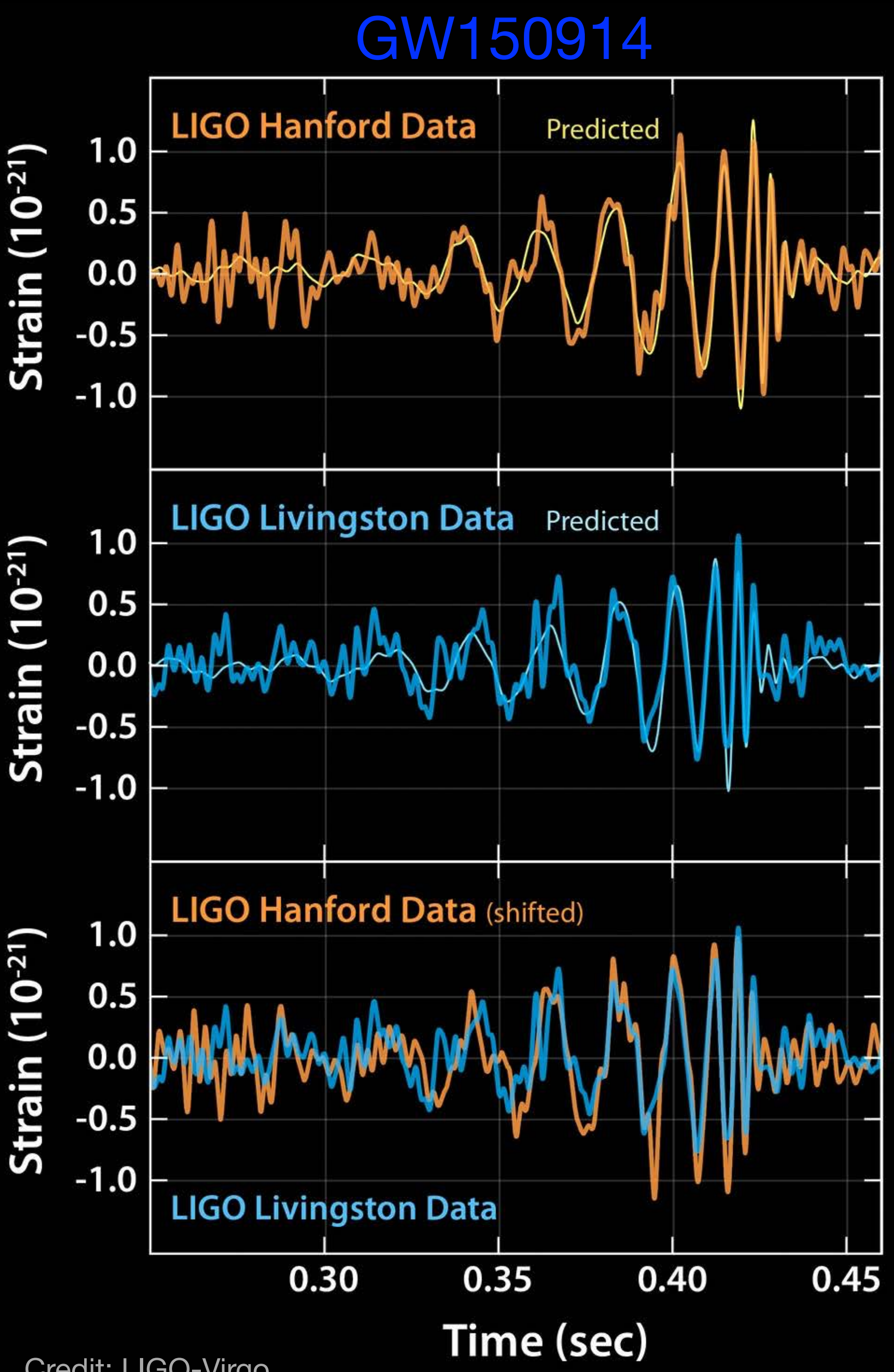


Credit: L. Speri / AEI

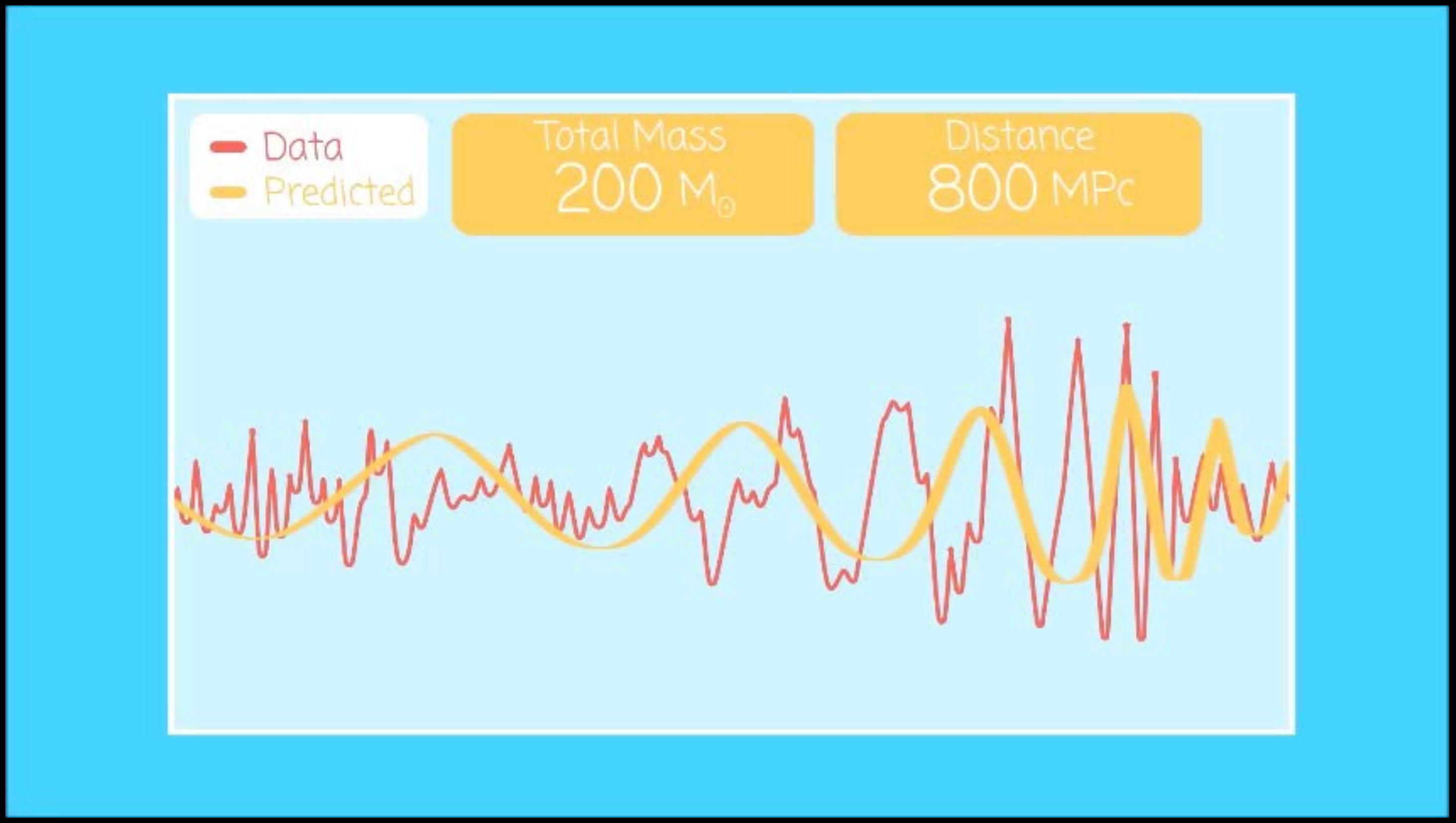


Credit: L. Barack

Finding and characterising the signal


GW150914

Credit: LIGO-Virgo

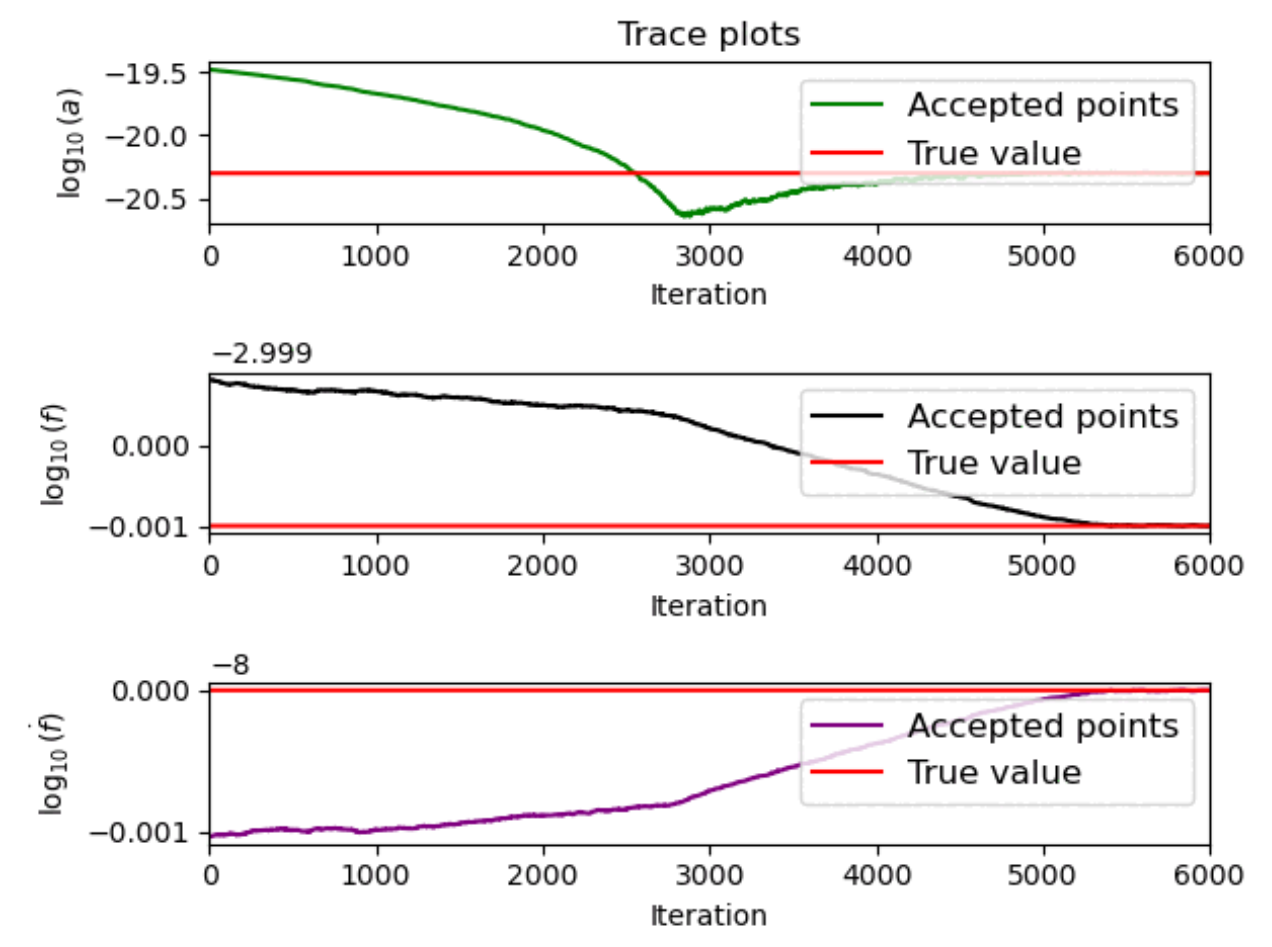


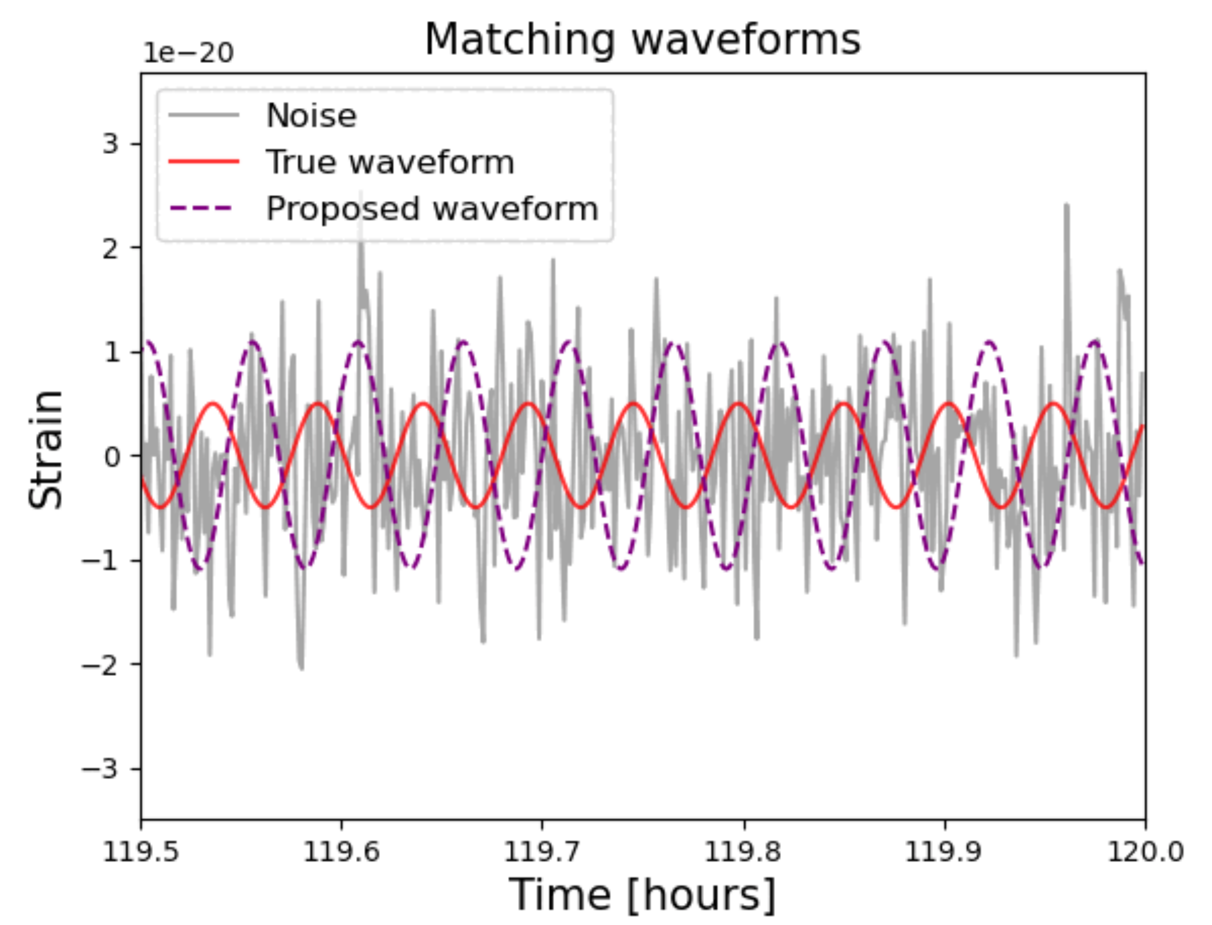
We must find the signal that better reproduce the observed data

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

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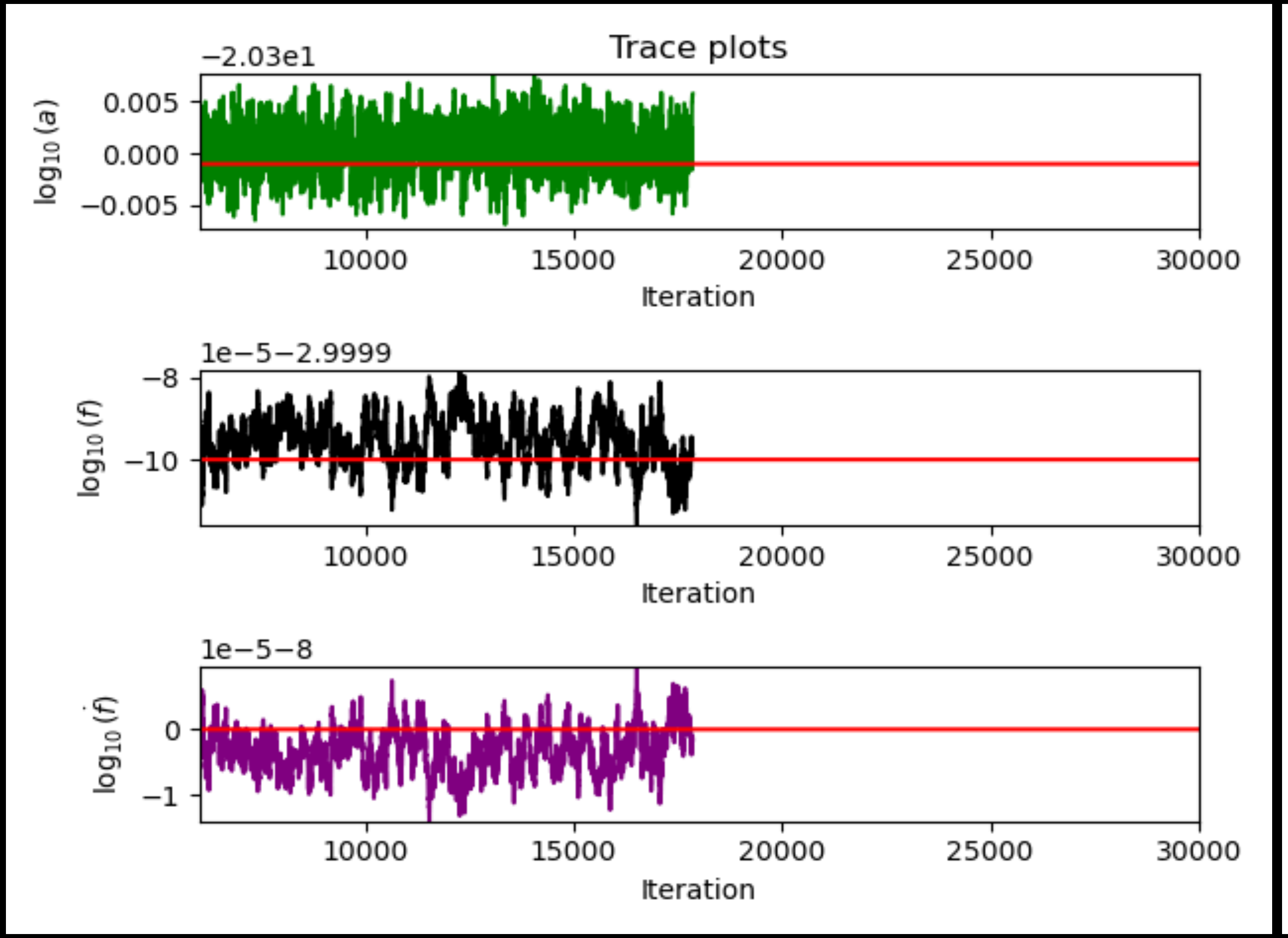

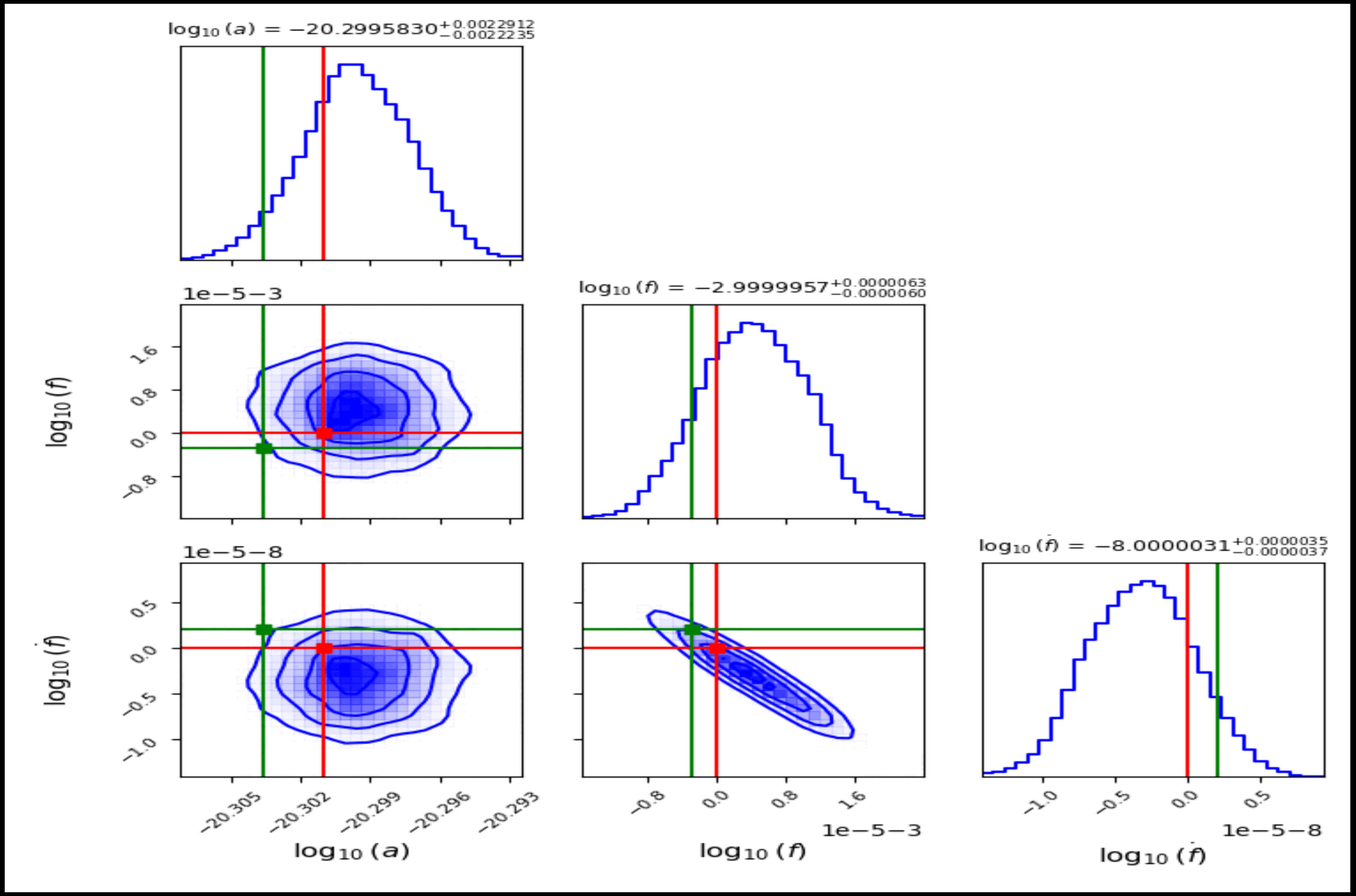

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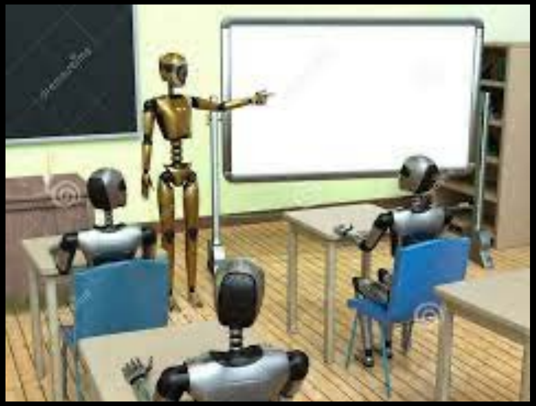
Finding and characterising the signal

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

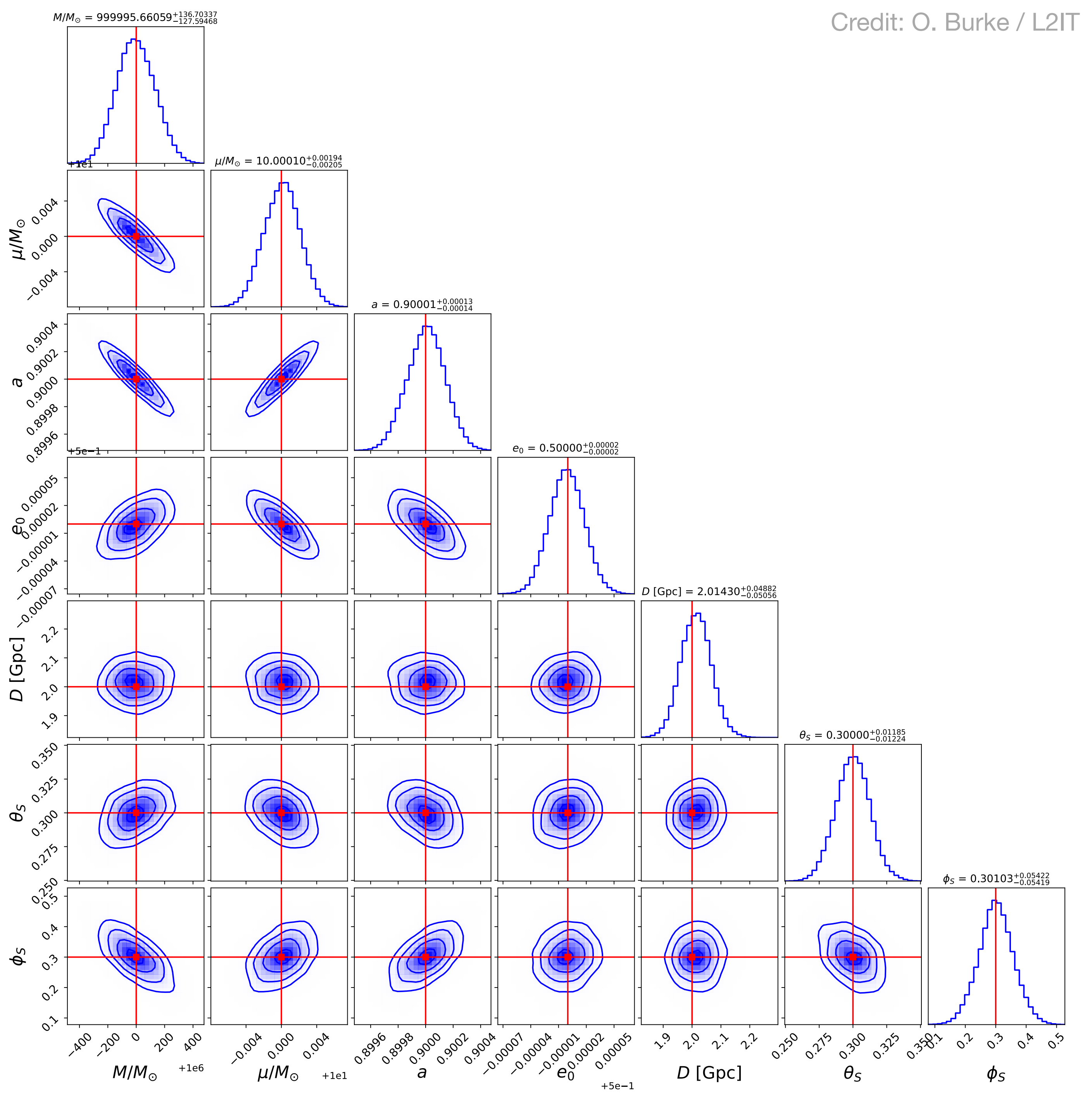
Algorithms must be:
- Fast to find results as soon as possible (esp. for EM alert)
- Accurate to retrieve parameters close to true values

Much improvement over the last decades thanks to technological progress

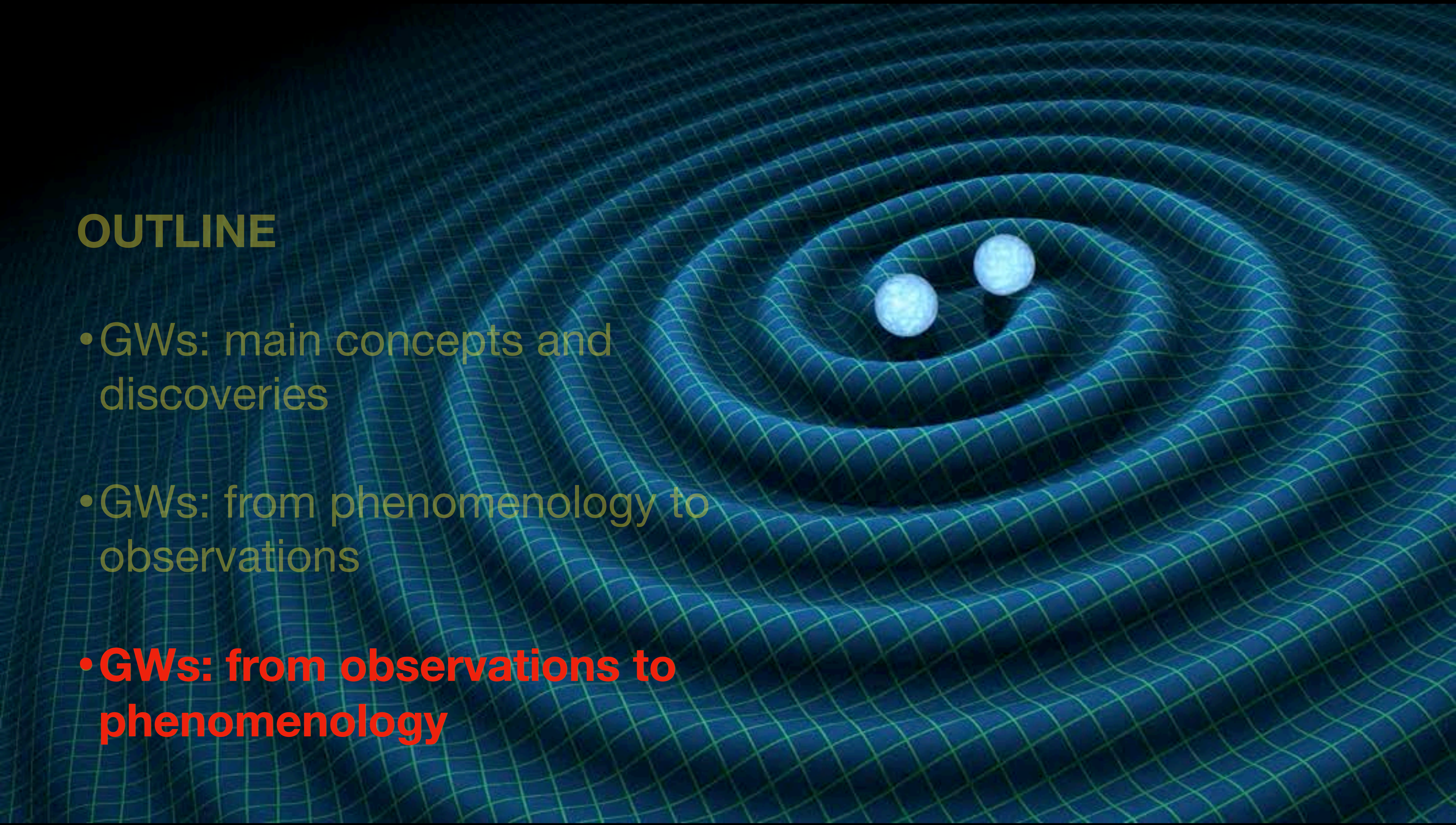
Ample space for AI application in the near future (esp. Machine Learning)



Credit: Dreamstime



Credit: O. Burke / L2IT



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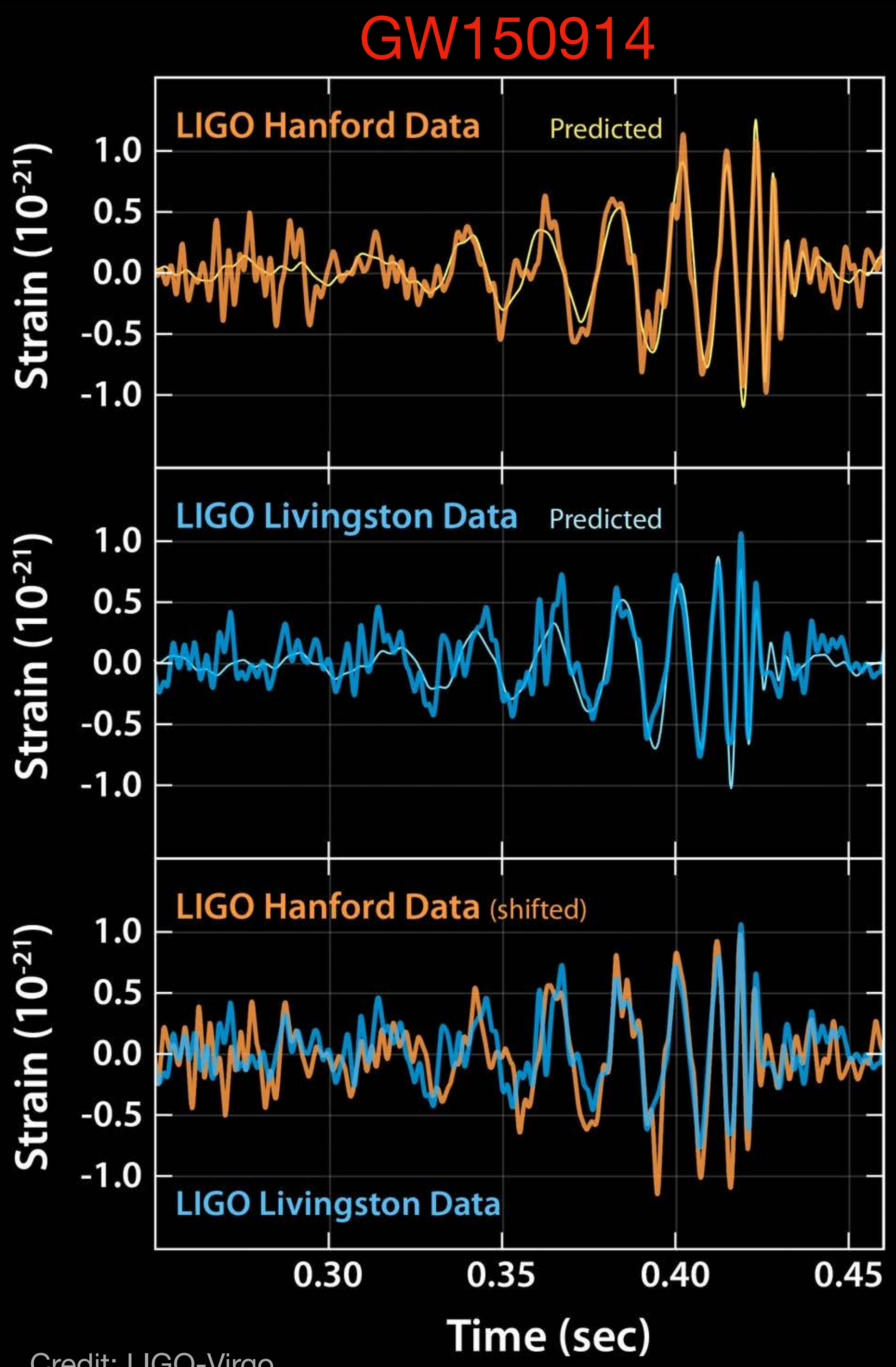
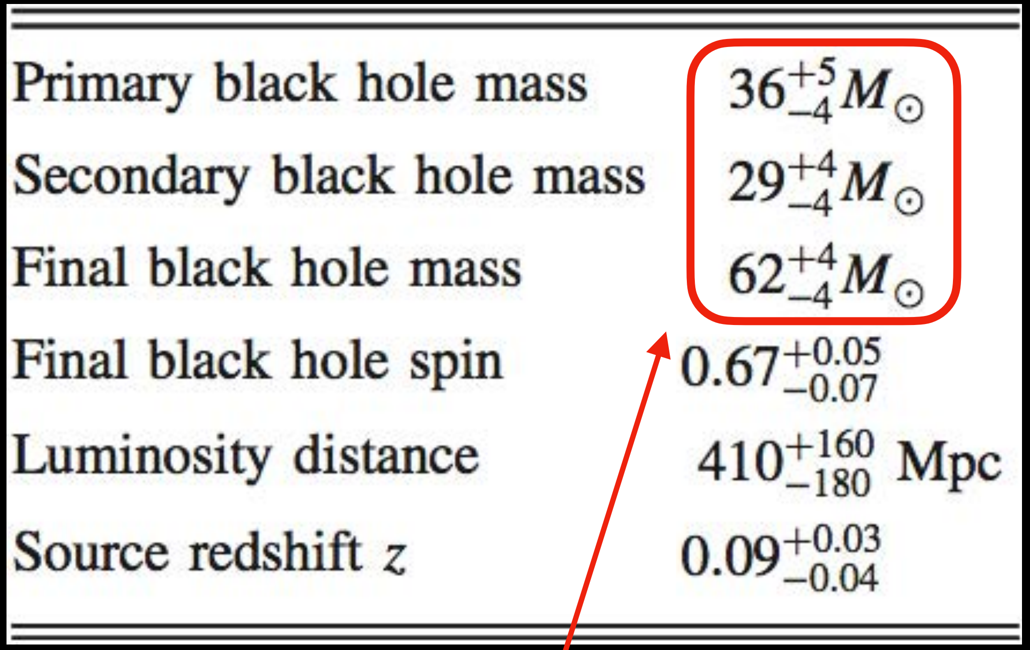
GW observational science: black holes



Credit: LIGO-Virgo

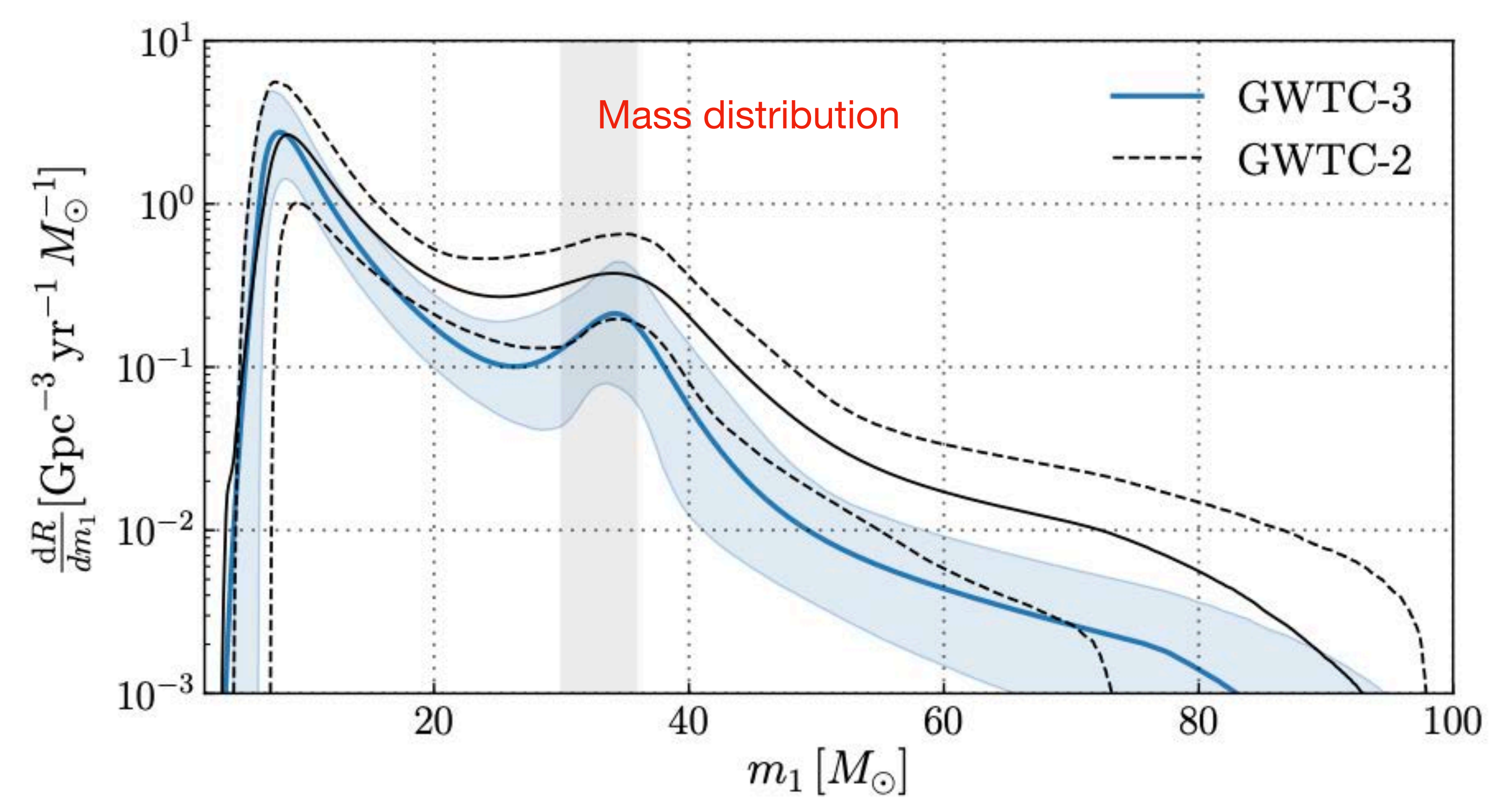
The first GW detection allowed us to discover stellar-mass black holes



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	$0.09^{+0.03}_{-0.04}$

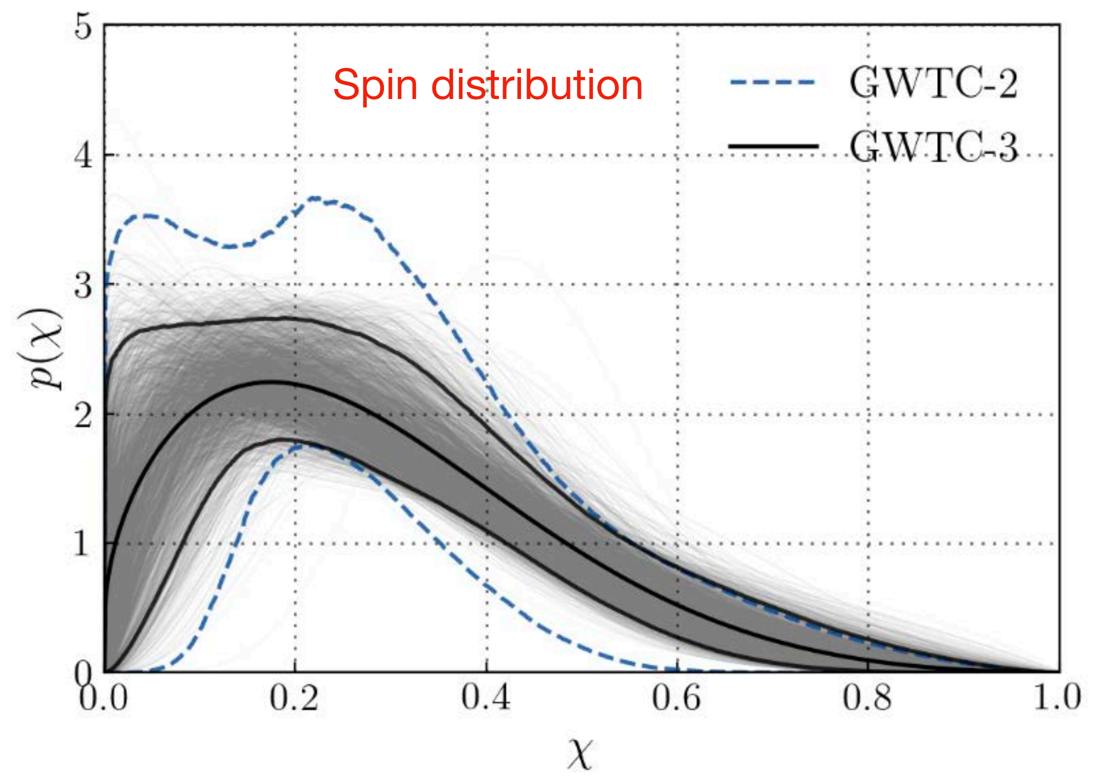
Black holes with masses $\gtrsim 10 M_\odot$ were discovered

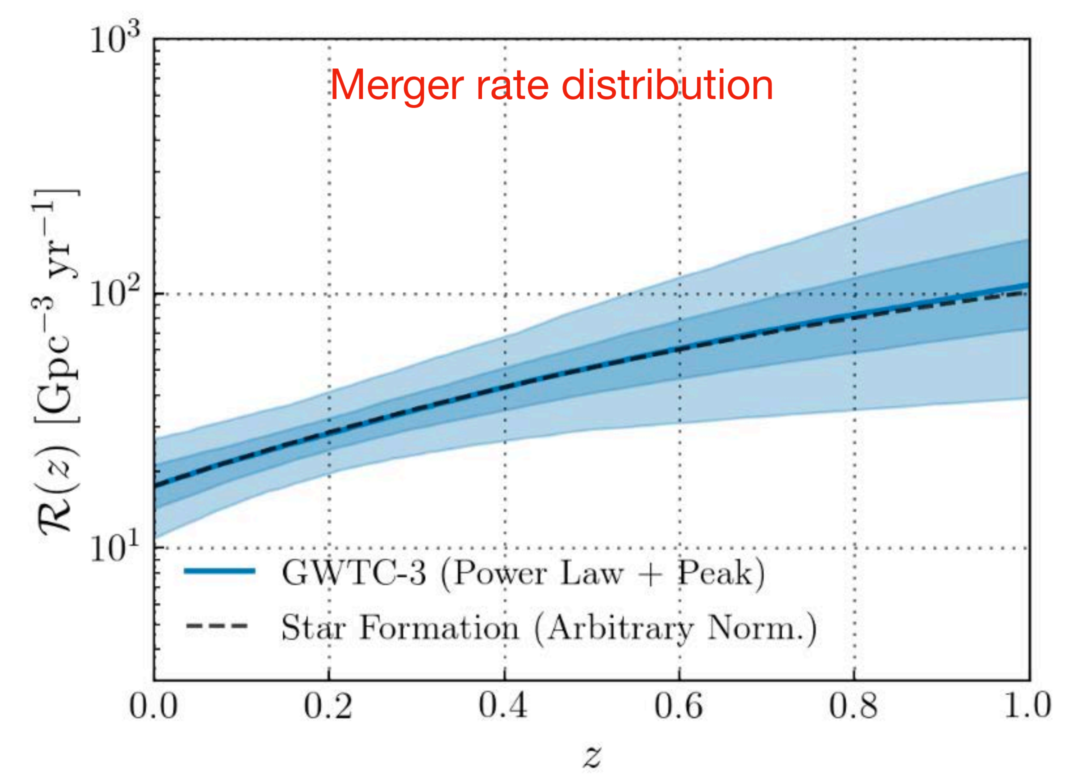
GW observational science: black holes



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

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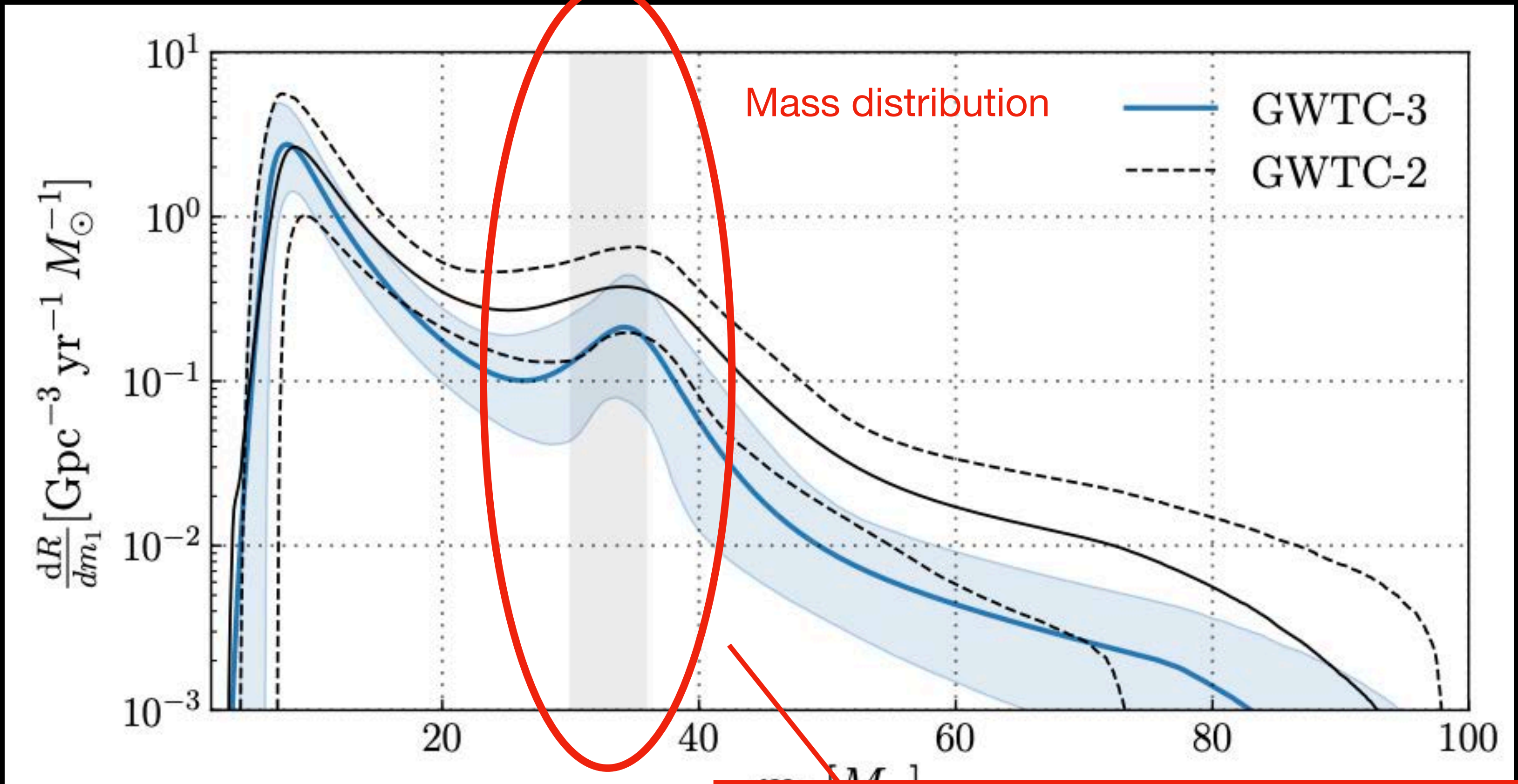

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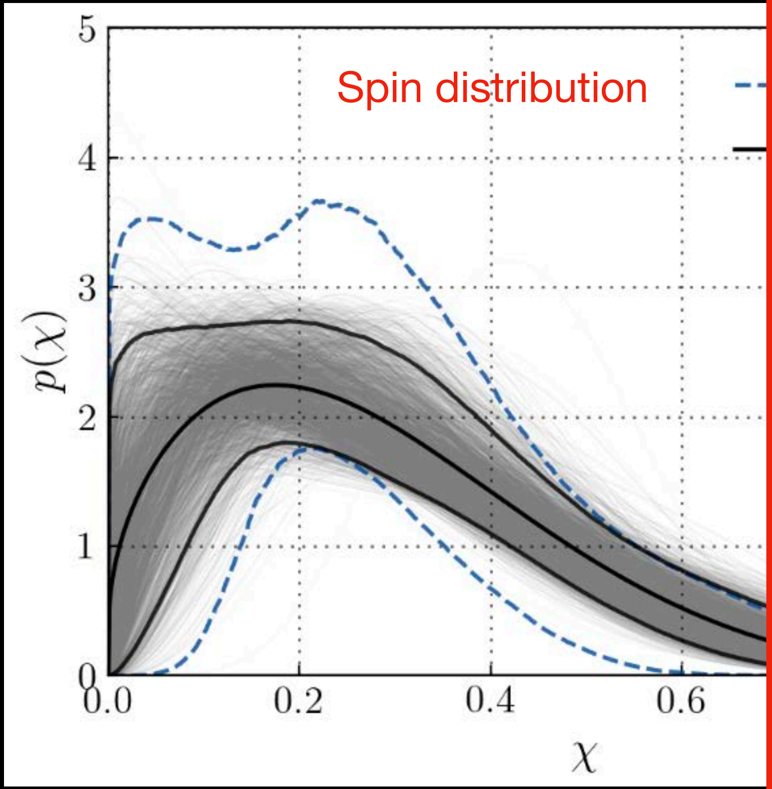

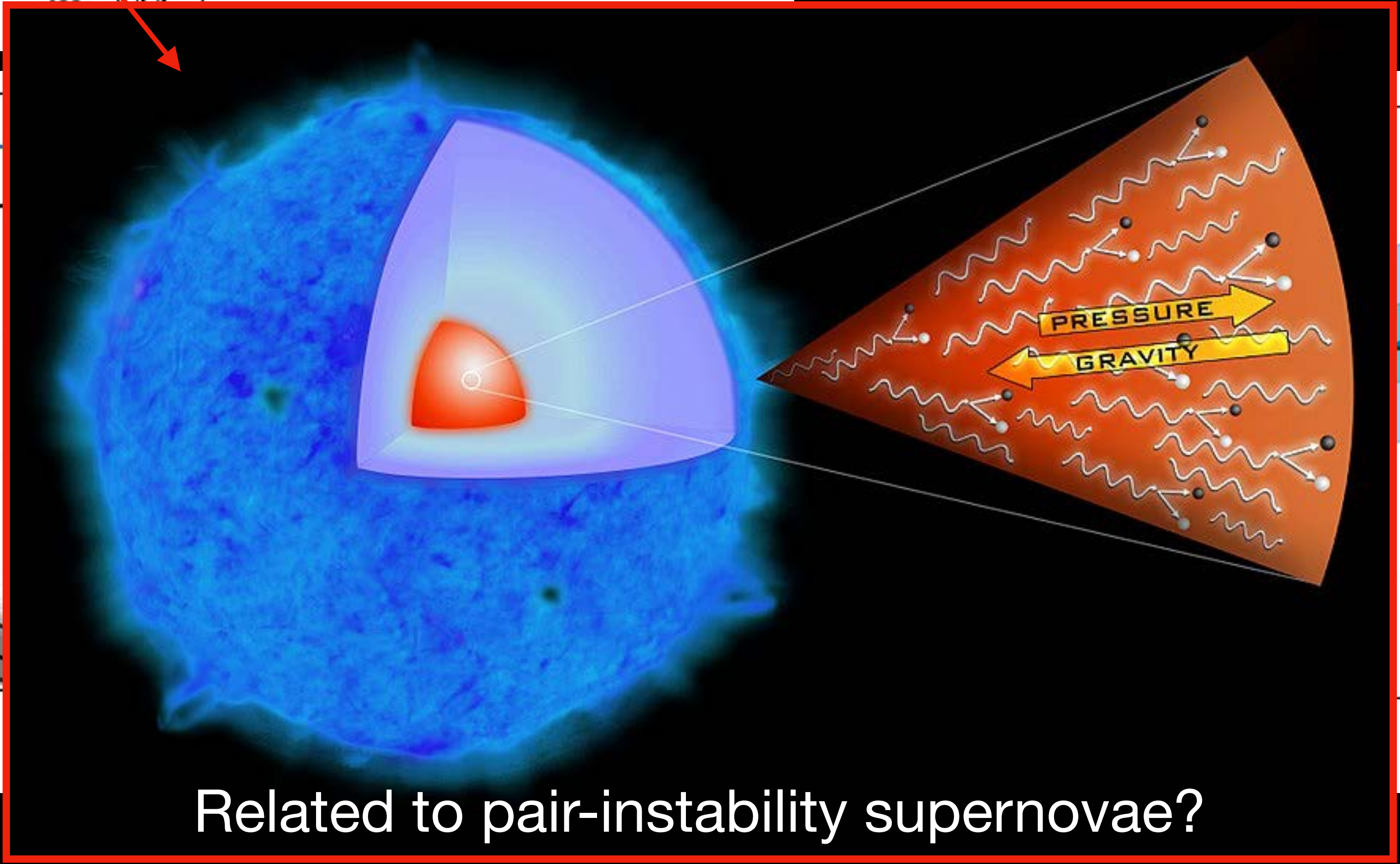

Related to pair-instability supernovae?

Credit: LIGO-Virgo-KAGRA

GW observational science: black holes

The first GW detection
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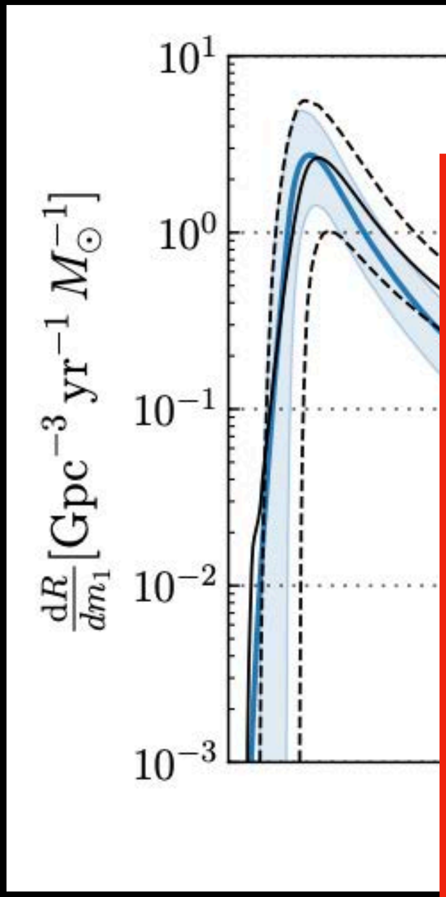
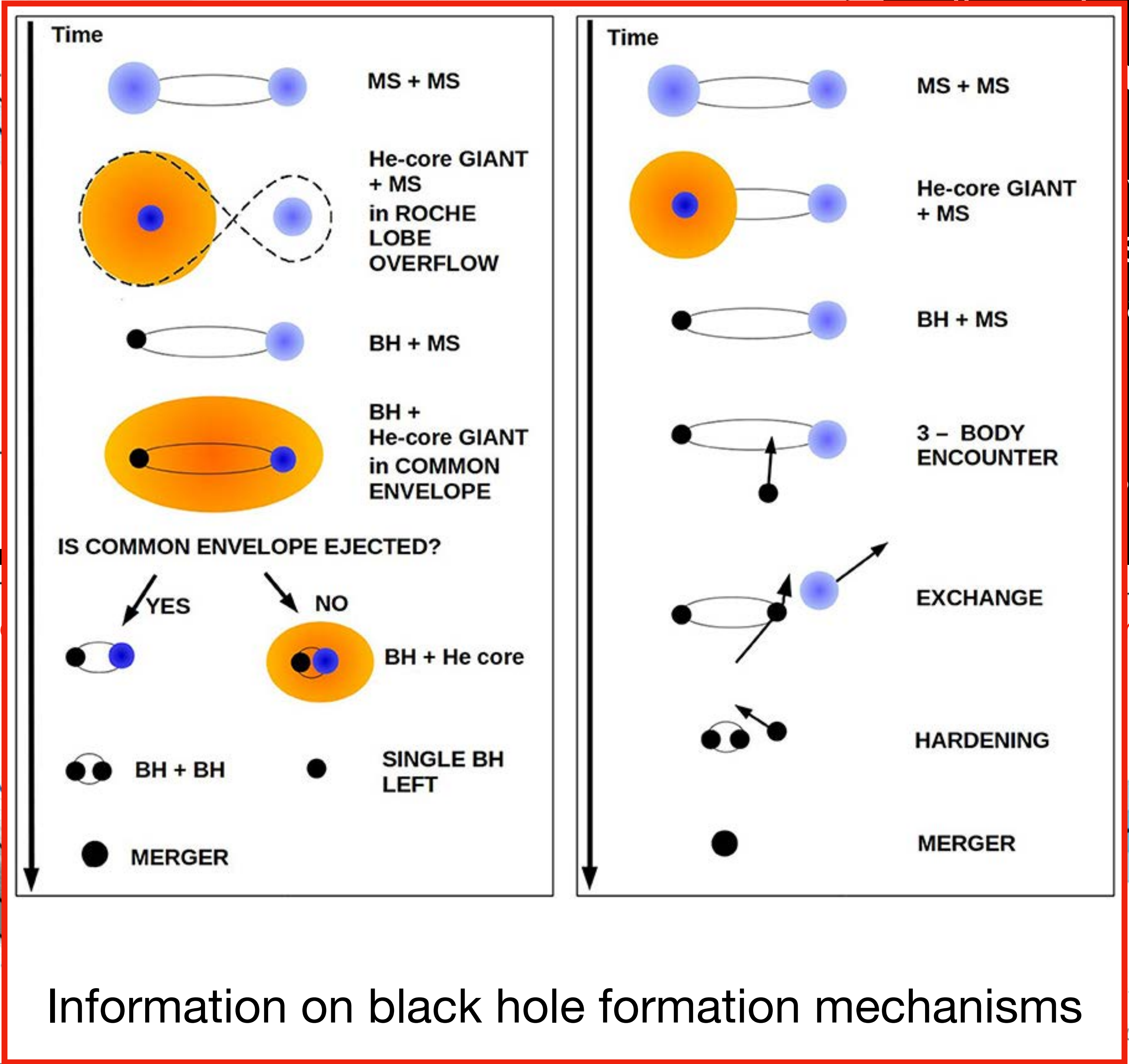
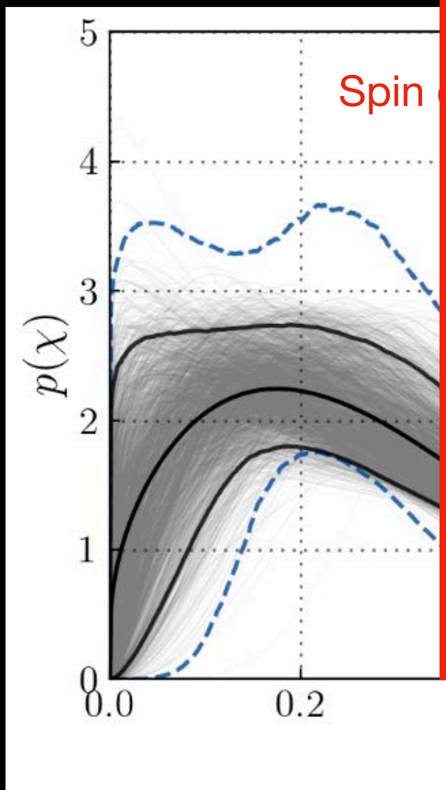
Mass distribution



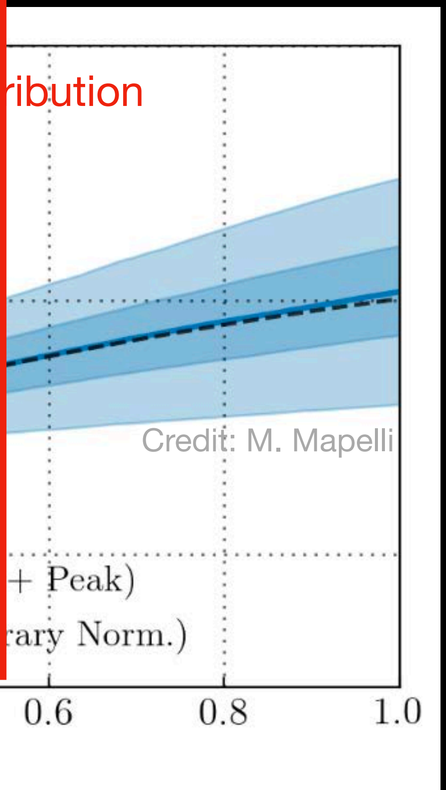


Information on black hole formation mechanisms

Spin



ribution



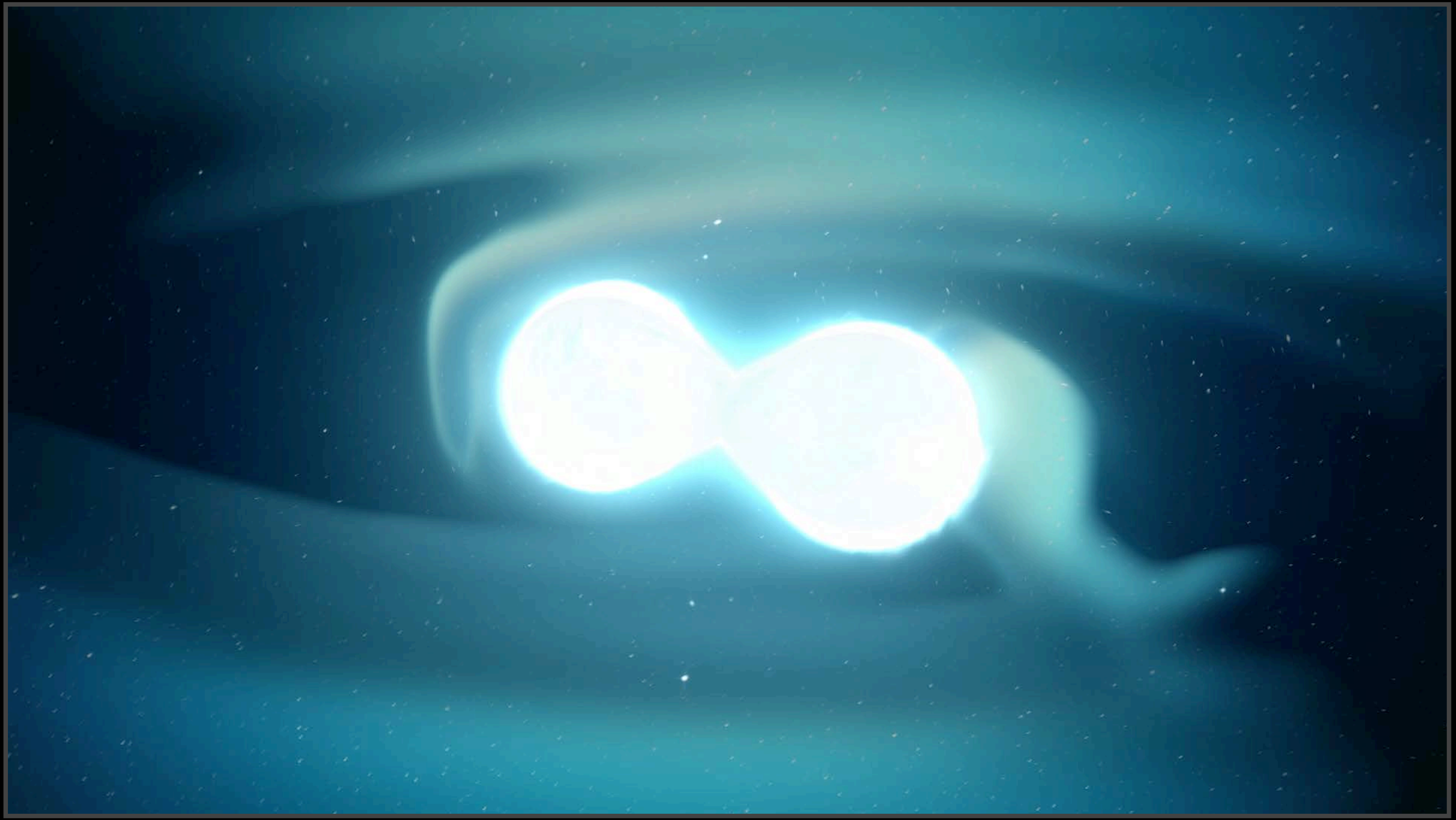
Credit: M. Mapelli

Credit: LIGO-Virgo-KAGRA

GW observational science: neutron stars

GW170817

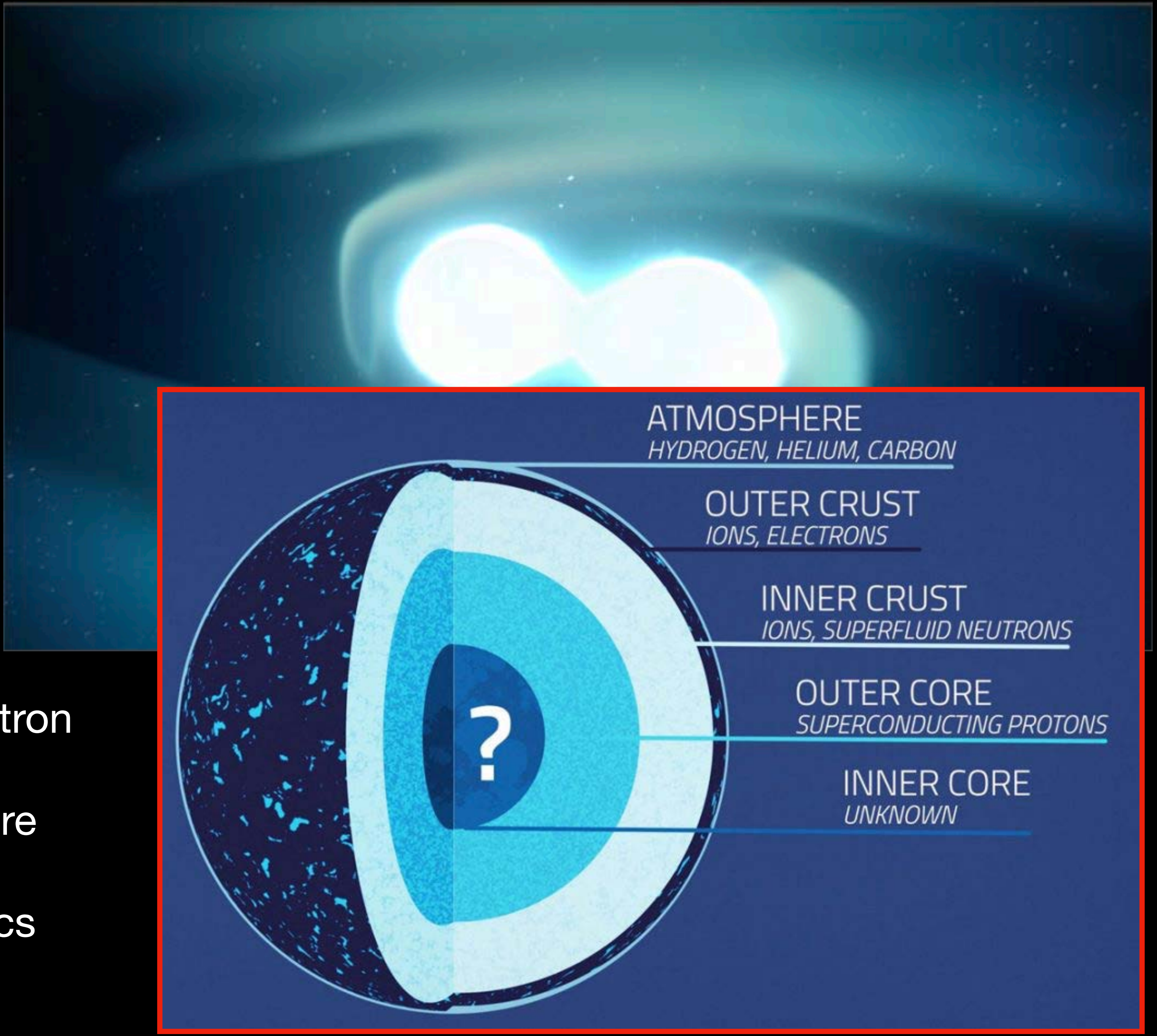
Credit: NASA



GW observational science: neutron stars

GW170817

Credit: NASA

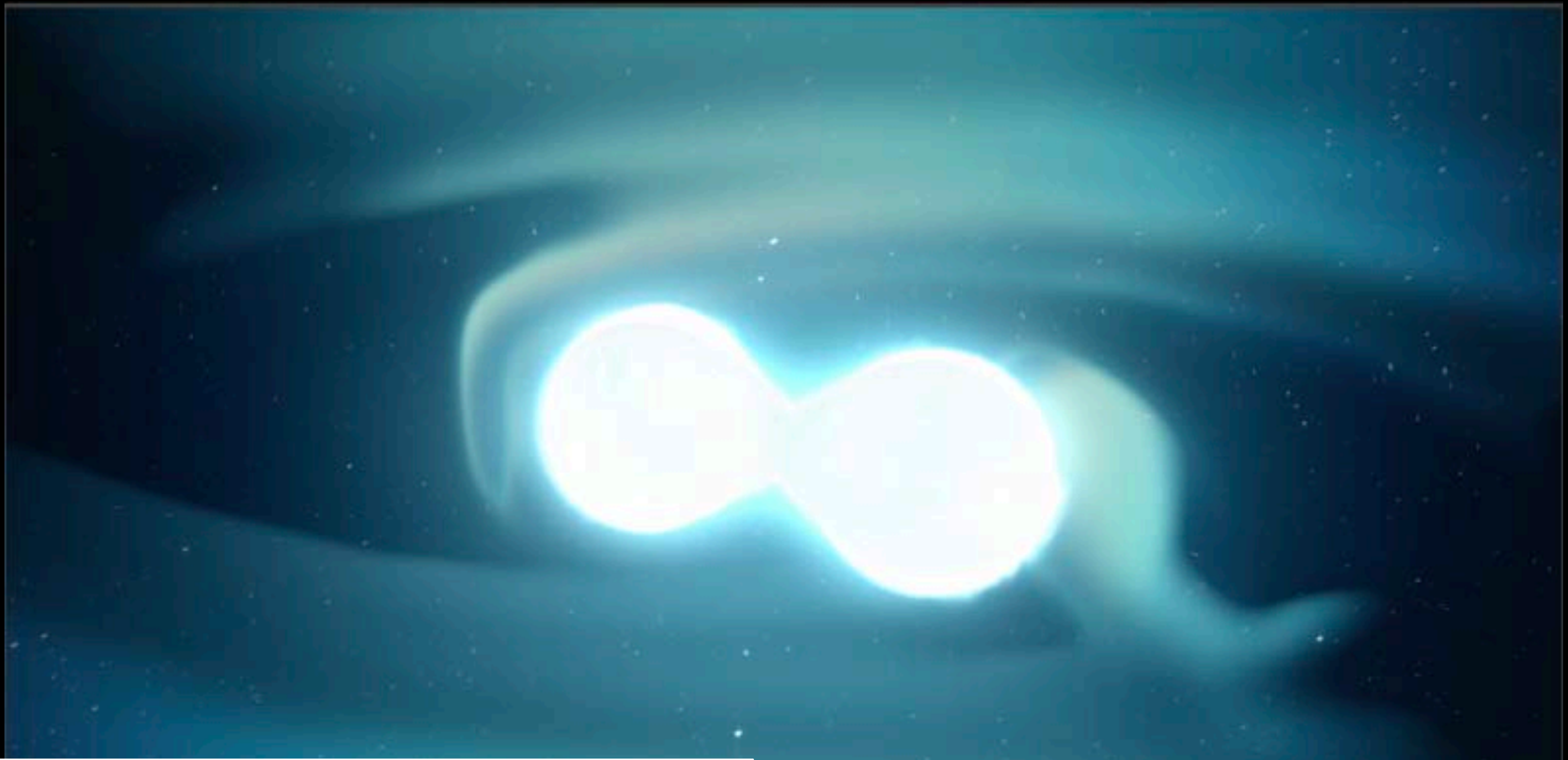


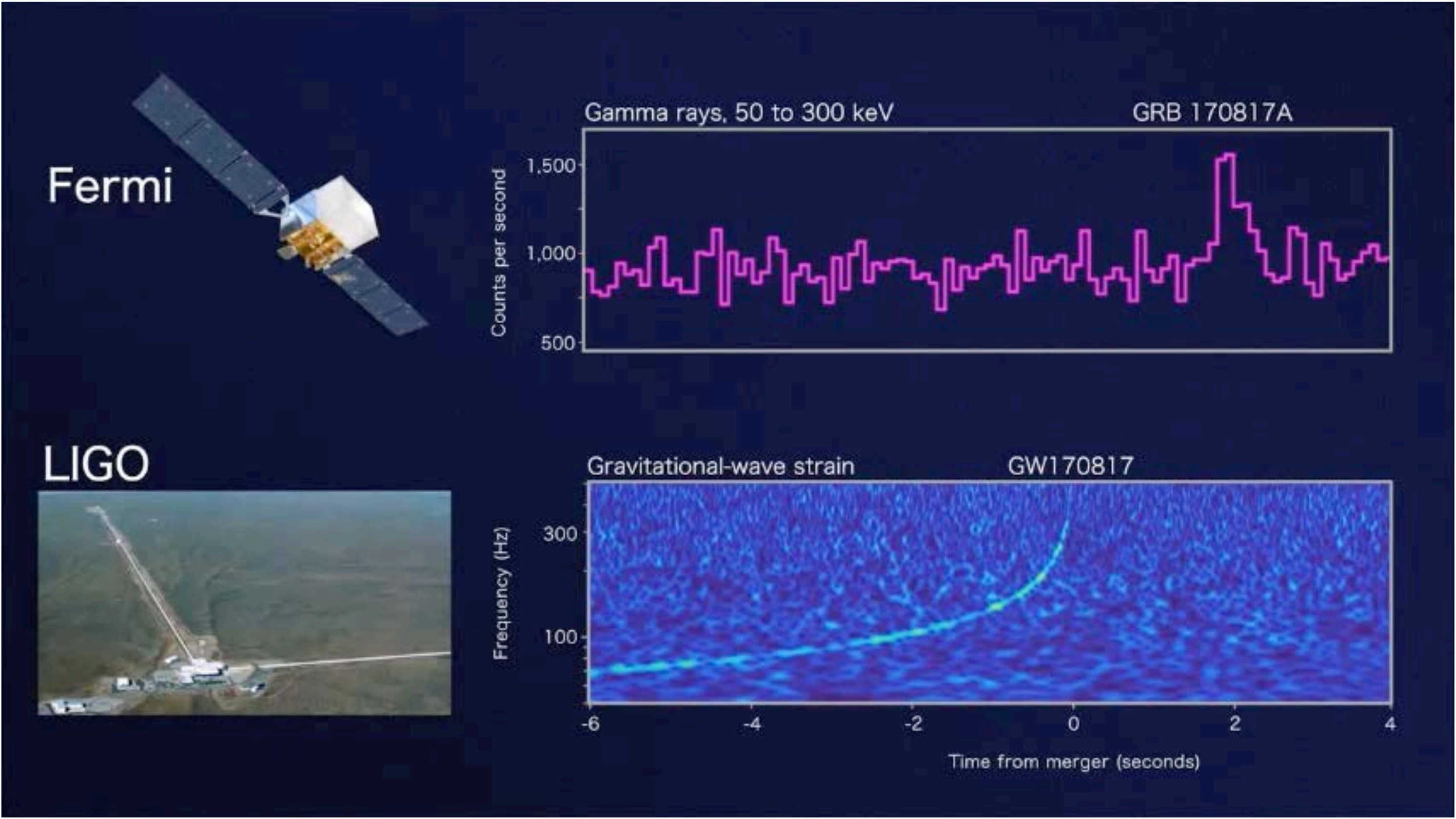
GW data from binary neutron star mergers allow us to probe the internal structure of neutron stars and its associated nuclear physics

GW observational science: neutron stars

GW170817

Credit: NASA



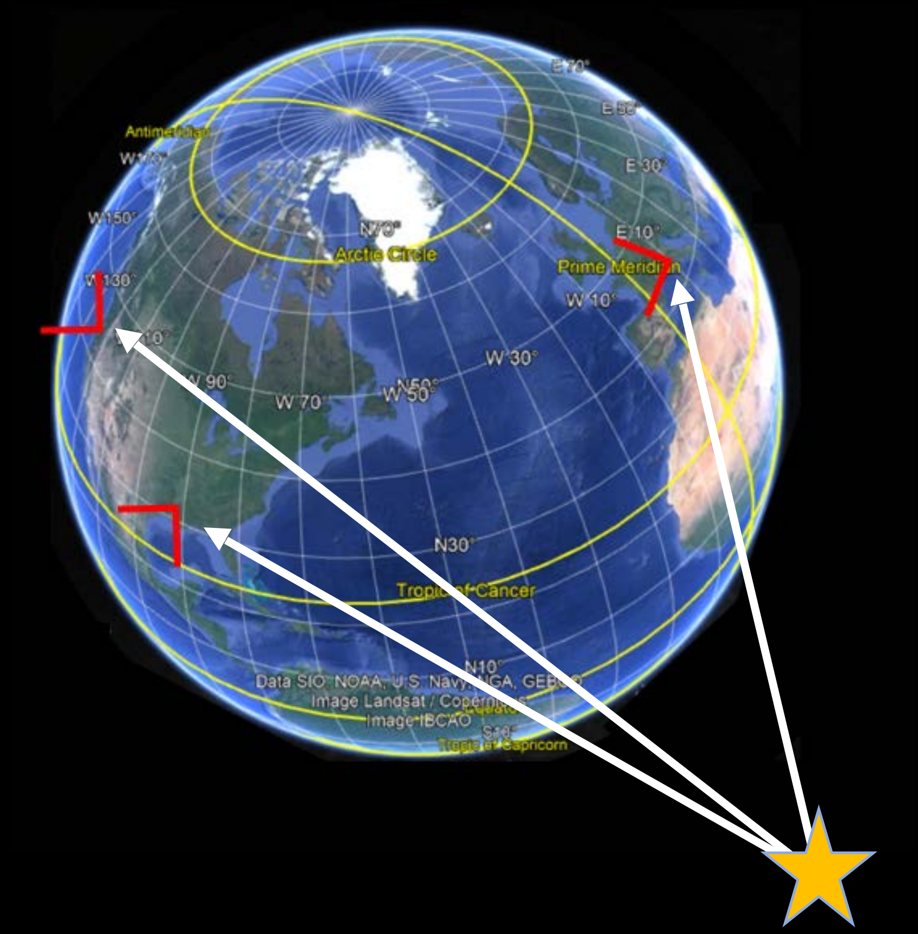


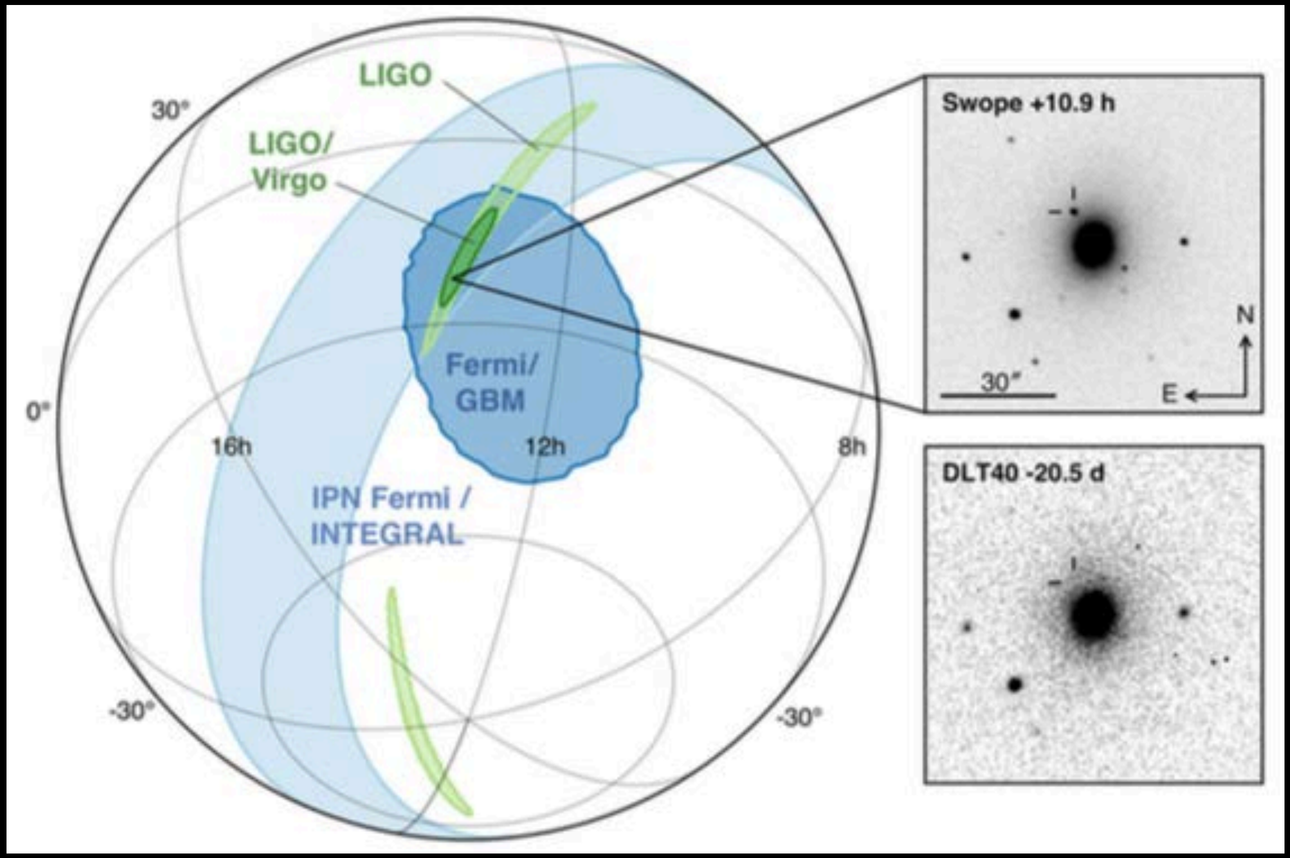
Credit: LIGO-Virgo

Binary neutron stars are also possible multi-messenger events

GW observational science: neutron stars

Multiple detectors allow for a better sky-localisation thanks to triangulation helping telescopes to find the associated electromagnetic signal

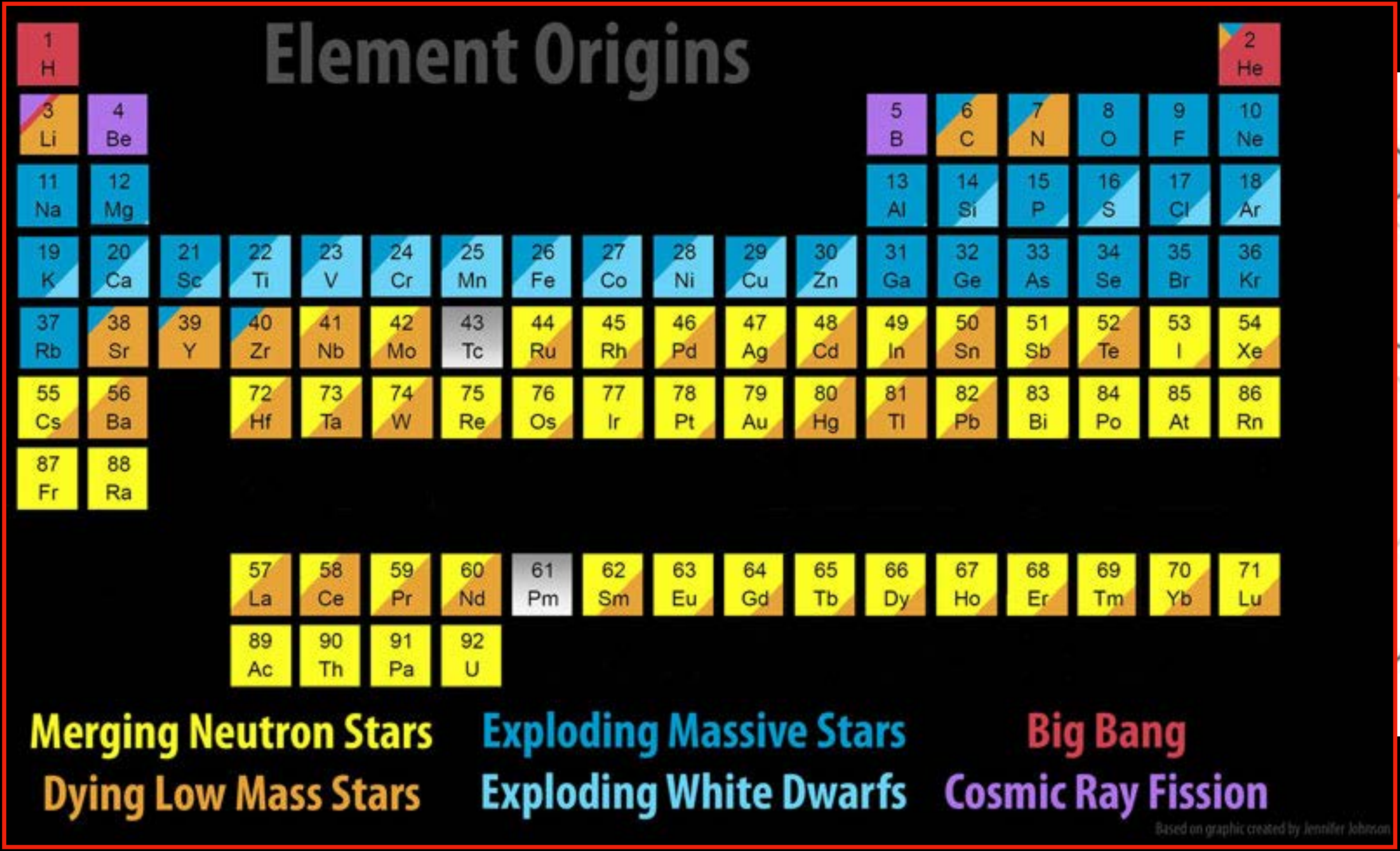




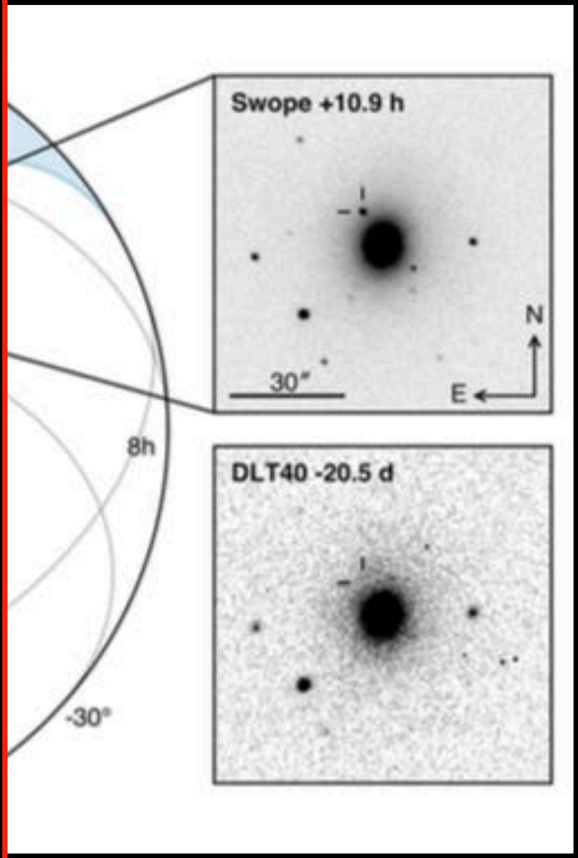
Credit: LIGO-Virgo

GW observational science: neutron stars

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



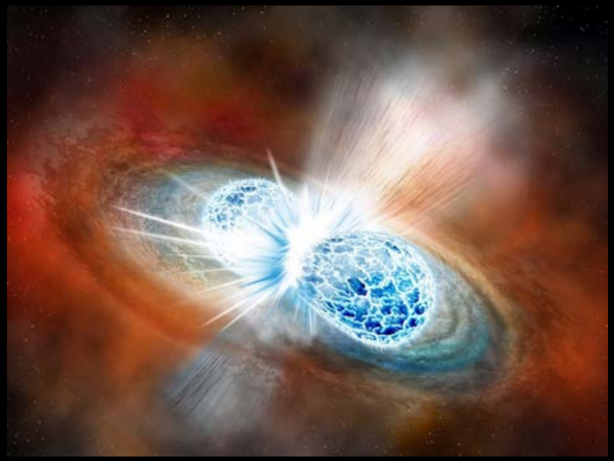
Credit: J. Johnson / SDSS



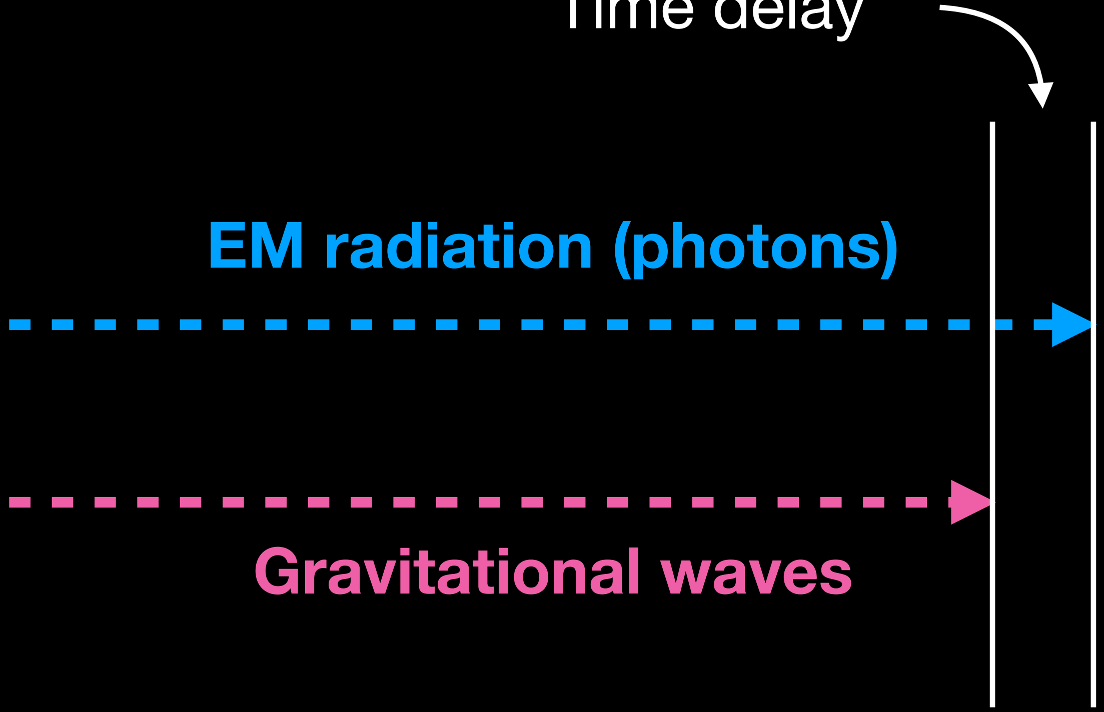
Credit: LIGO-Virgo

GW observational science: fundamental physics

Source emitting both GW and EM radiation



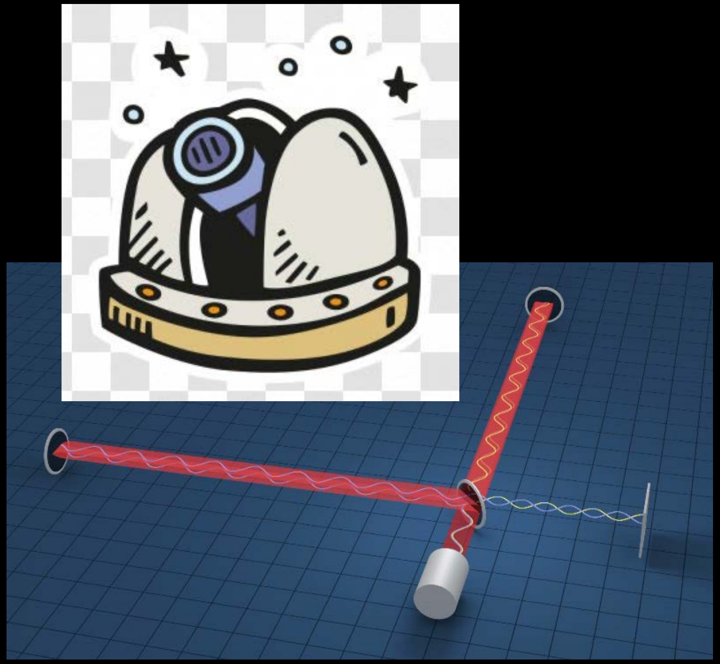
Time delay



EM radiation (photons)

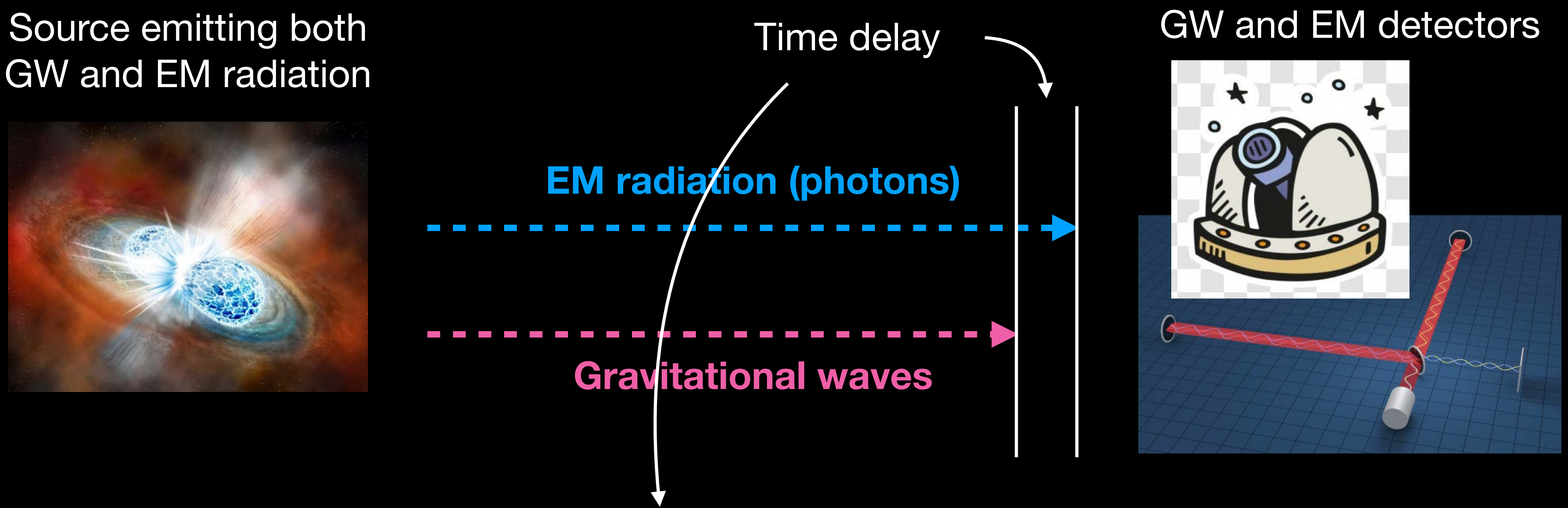
Gravitational waves

GW and EM detectors



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

GW observational science: fundamental physics



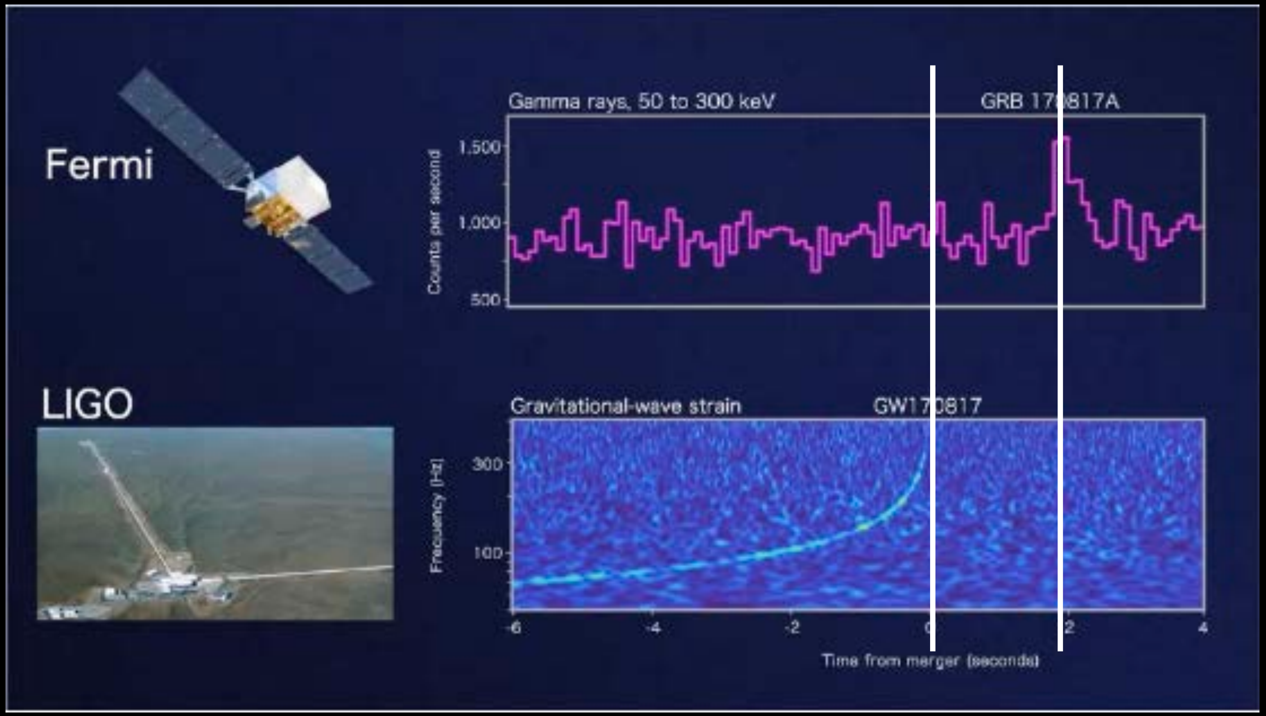
Source emitting both GW and EM radiation

Time delay

GW and EM detectors

EM radiation (photons)

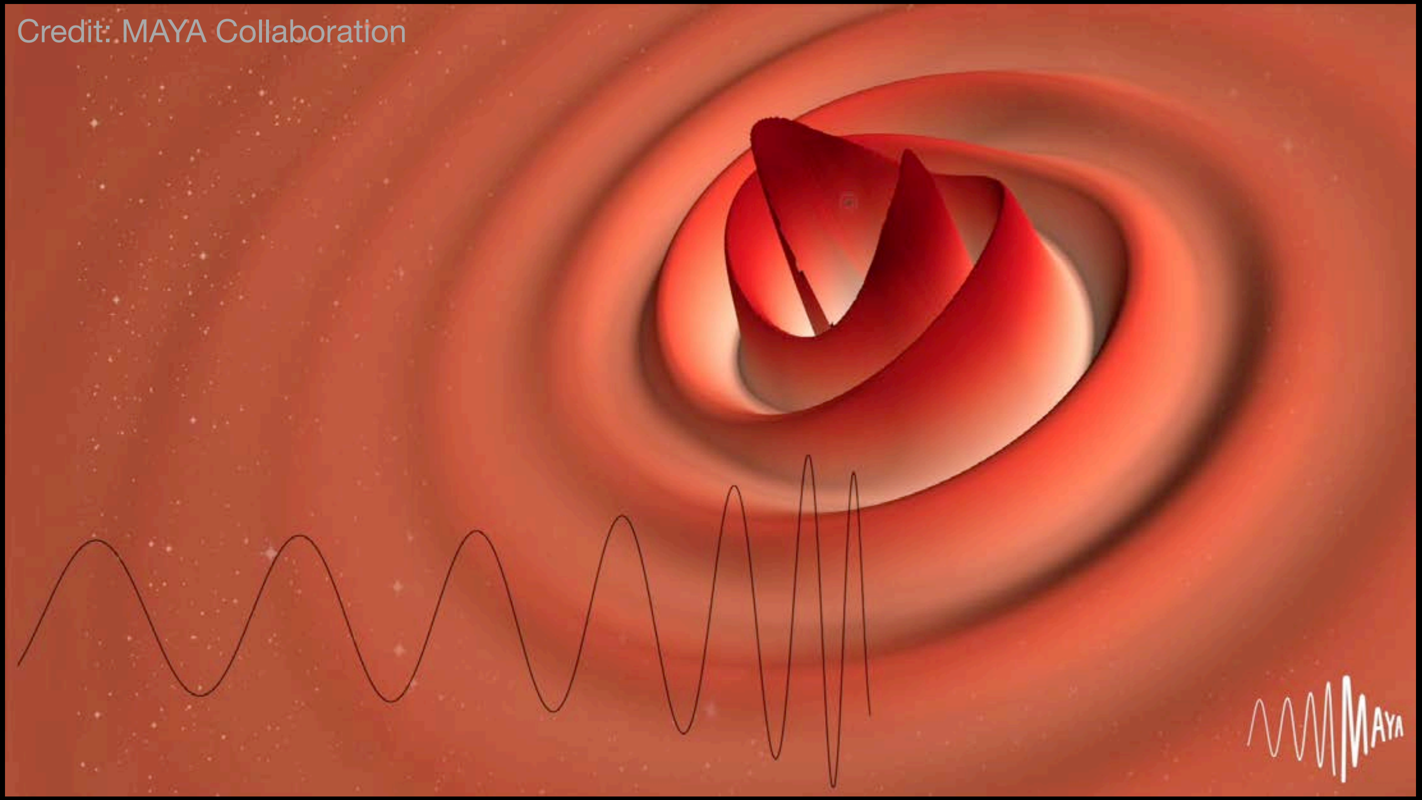
Gravitational waves



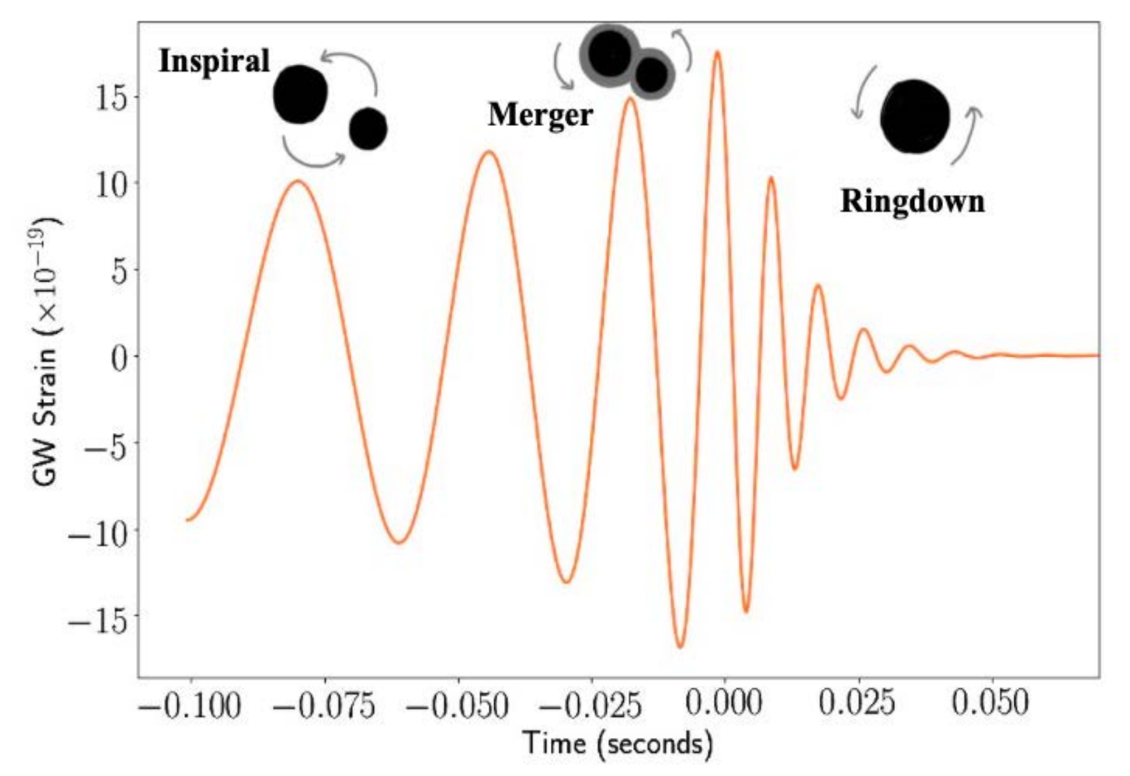
Multi-messenger event can be used to test the speed of propagation of GWs

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



Credit: MAYA Collaboration

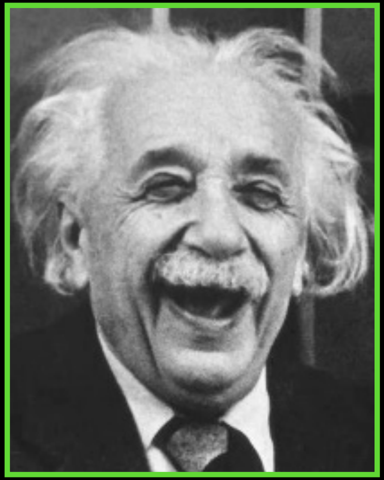


Credit: LIGO-Virgo

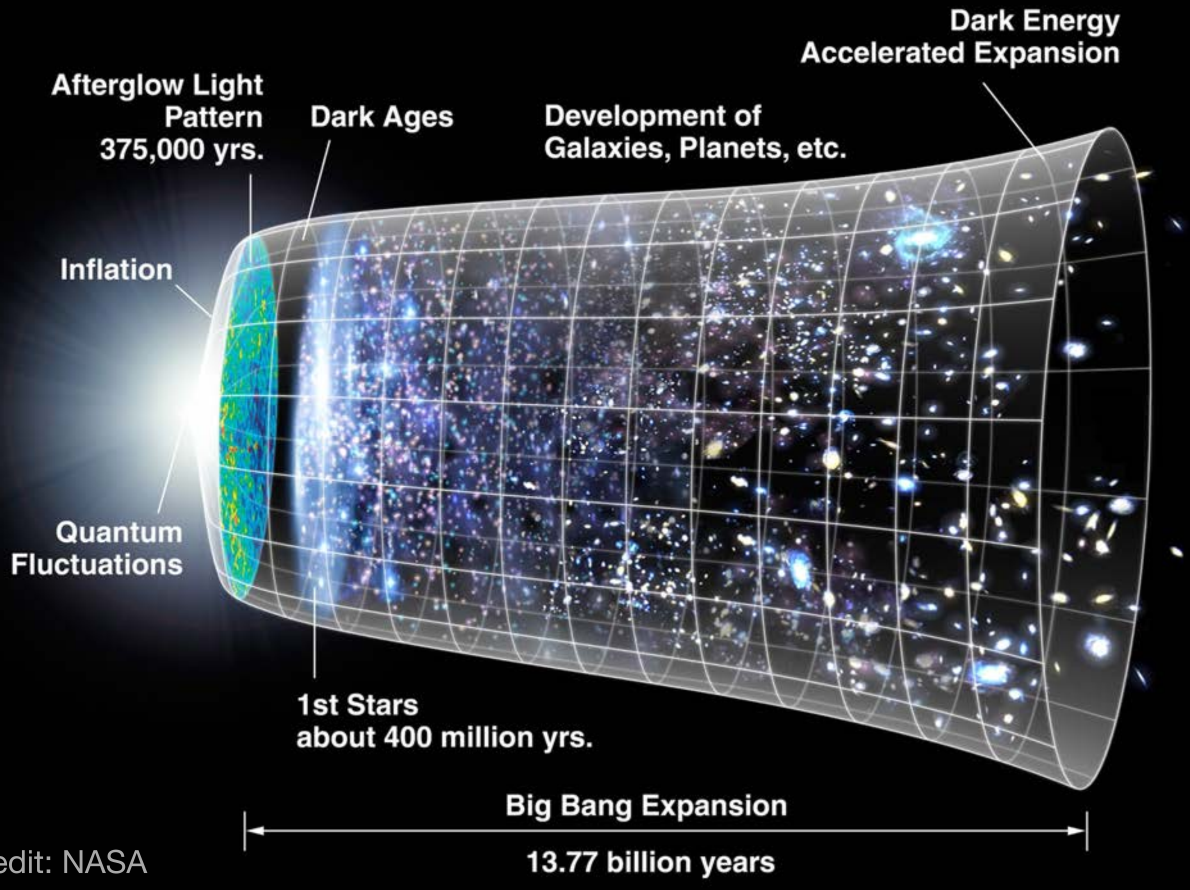
GWs data can be used to test general relativity in the strong field regime

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

All observations in agreement with general relativity so far

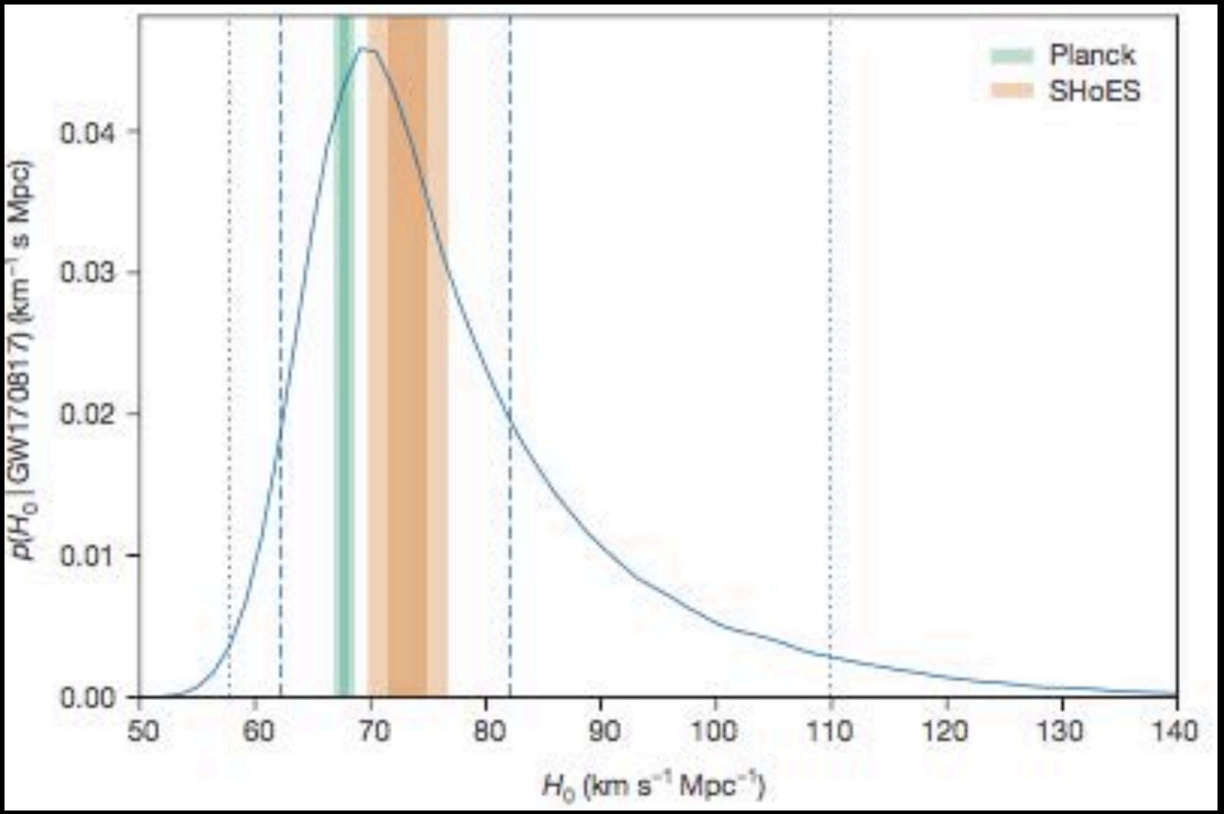


GW observational science: cosmology

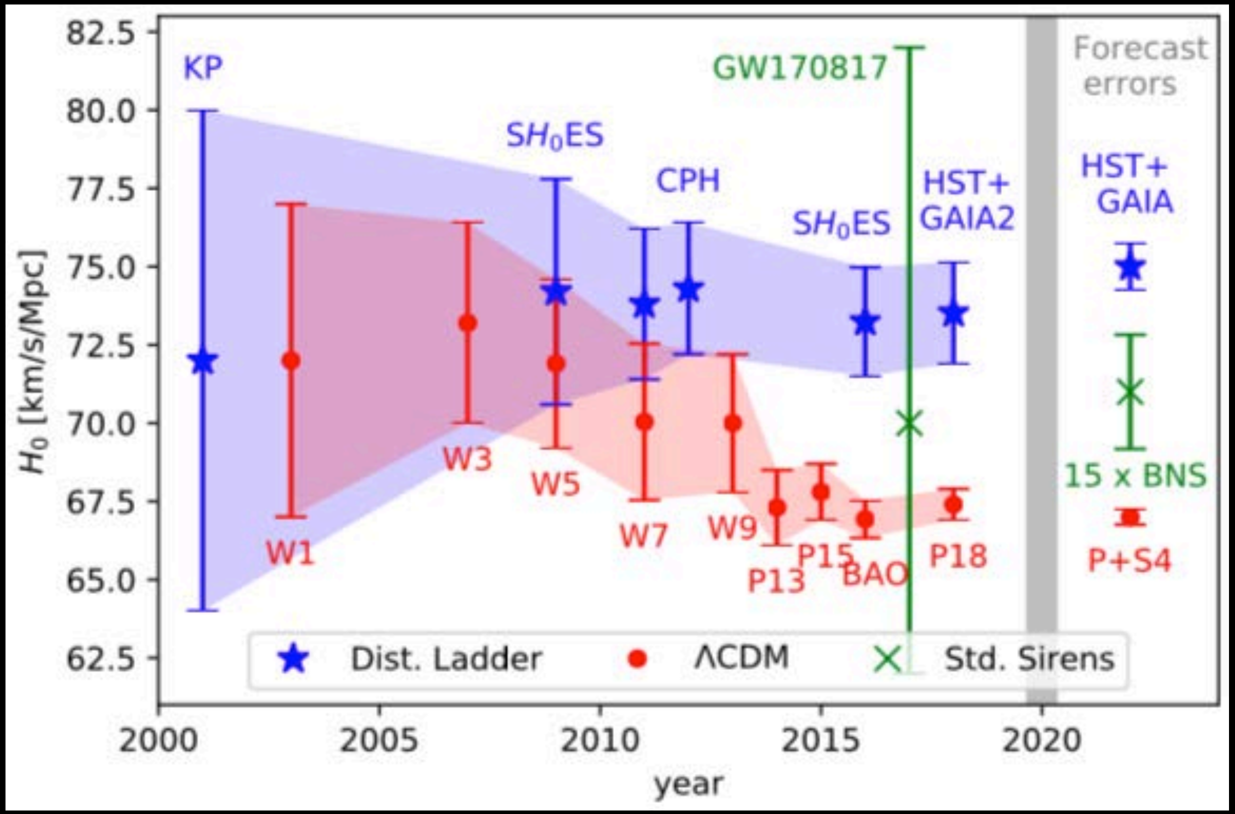


Credit: NASA

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

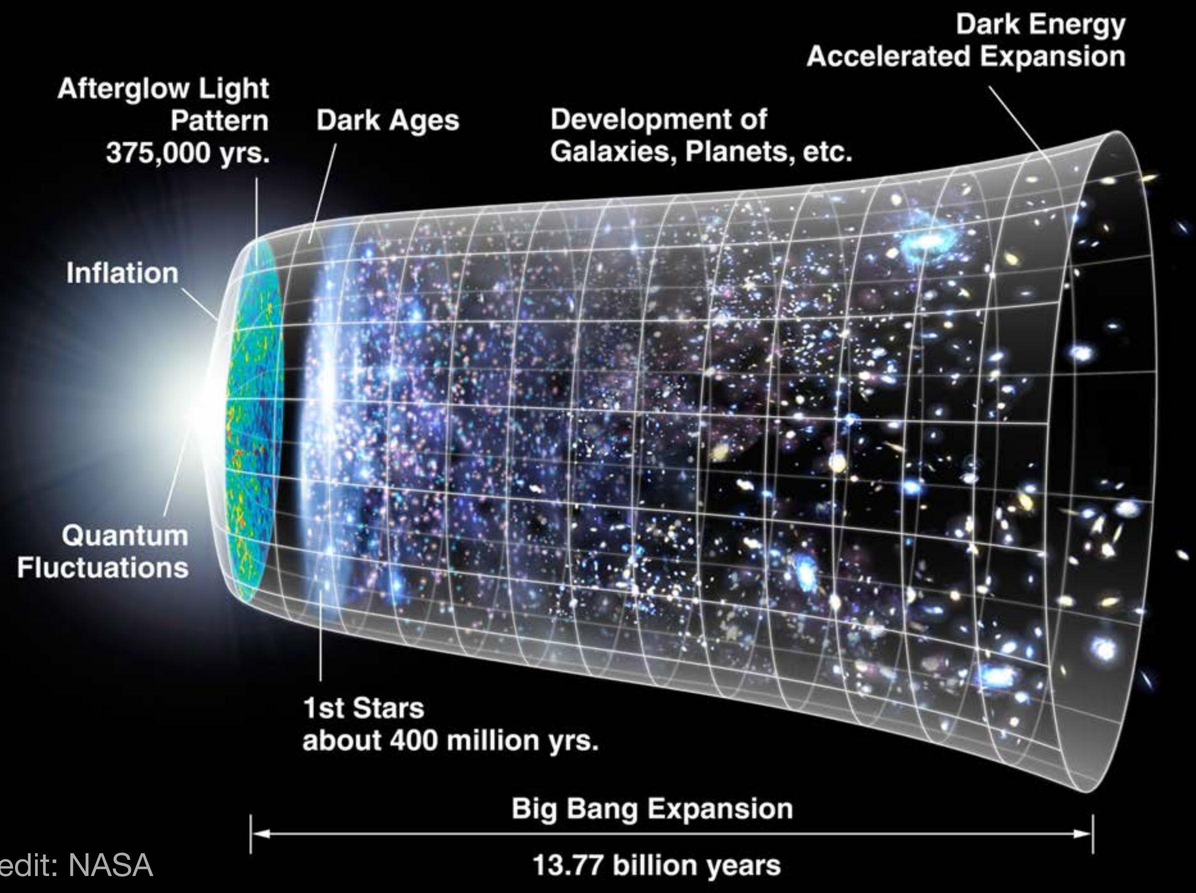


Credit: LIGO-Virgo



Credit: J. M. Ezquiaga & M. Zumalacarregui

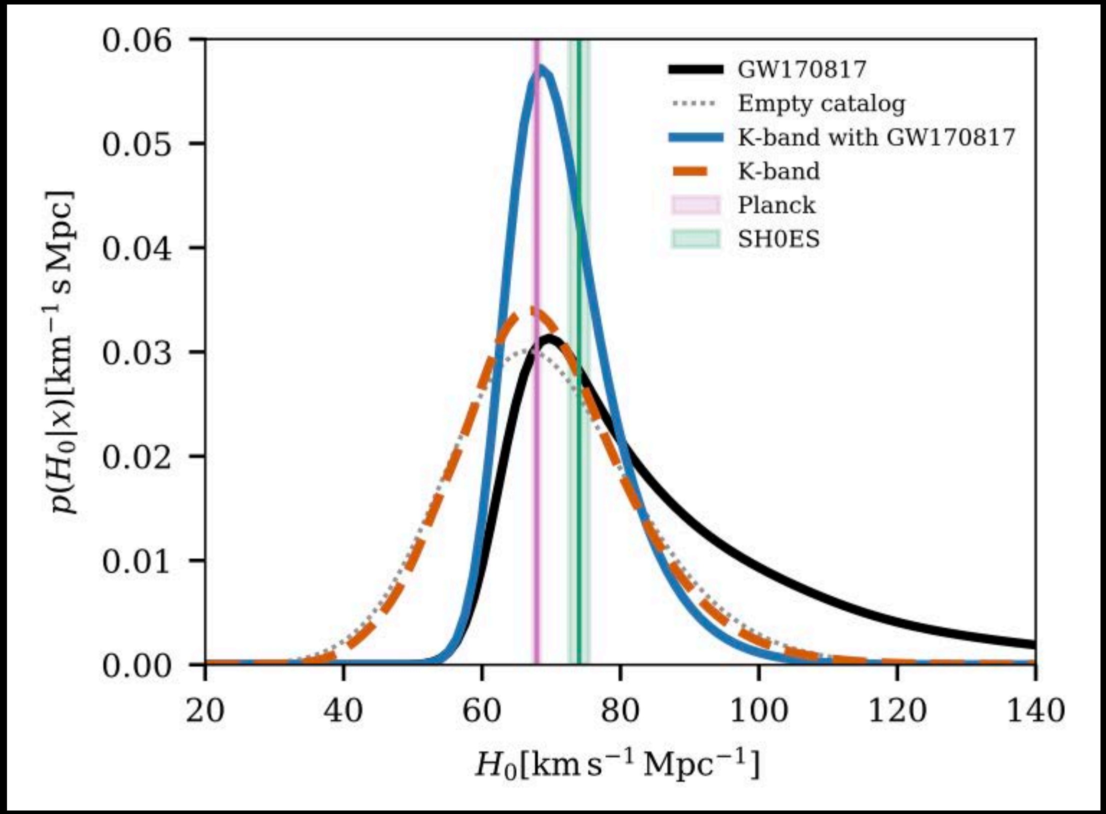
GW observational science: cosmology



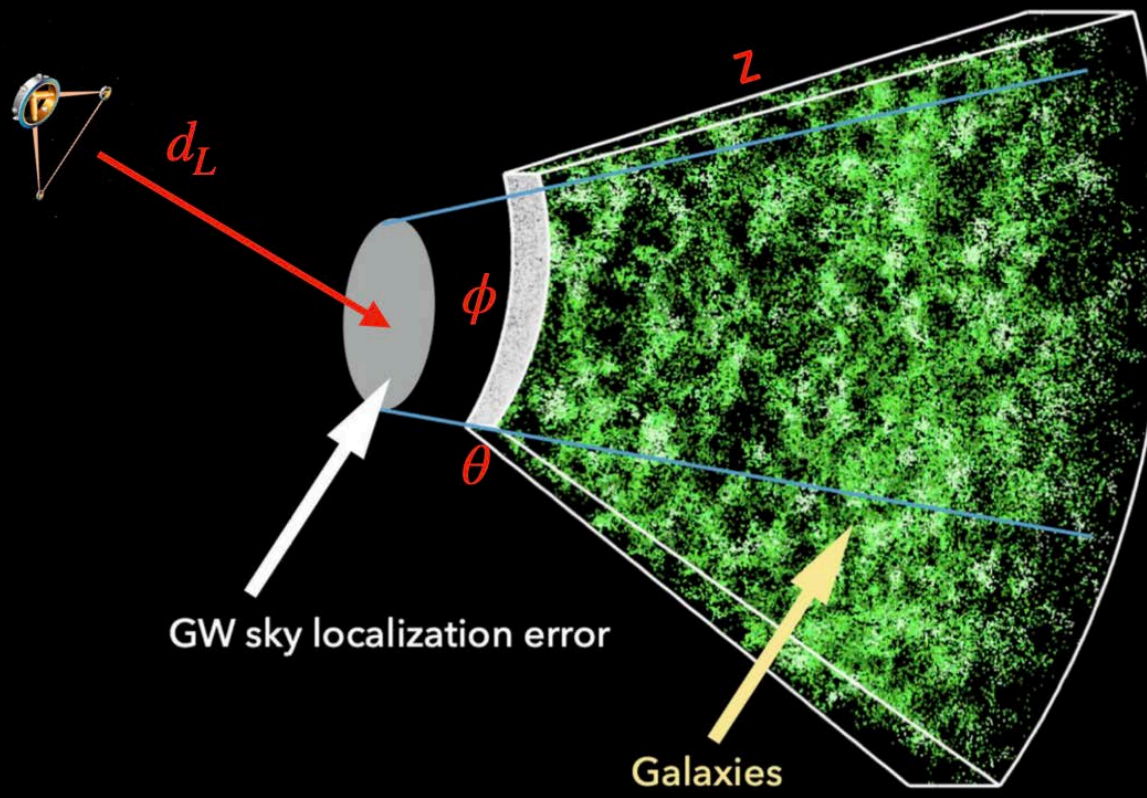
Credit: NASA

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

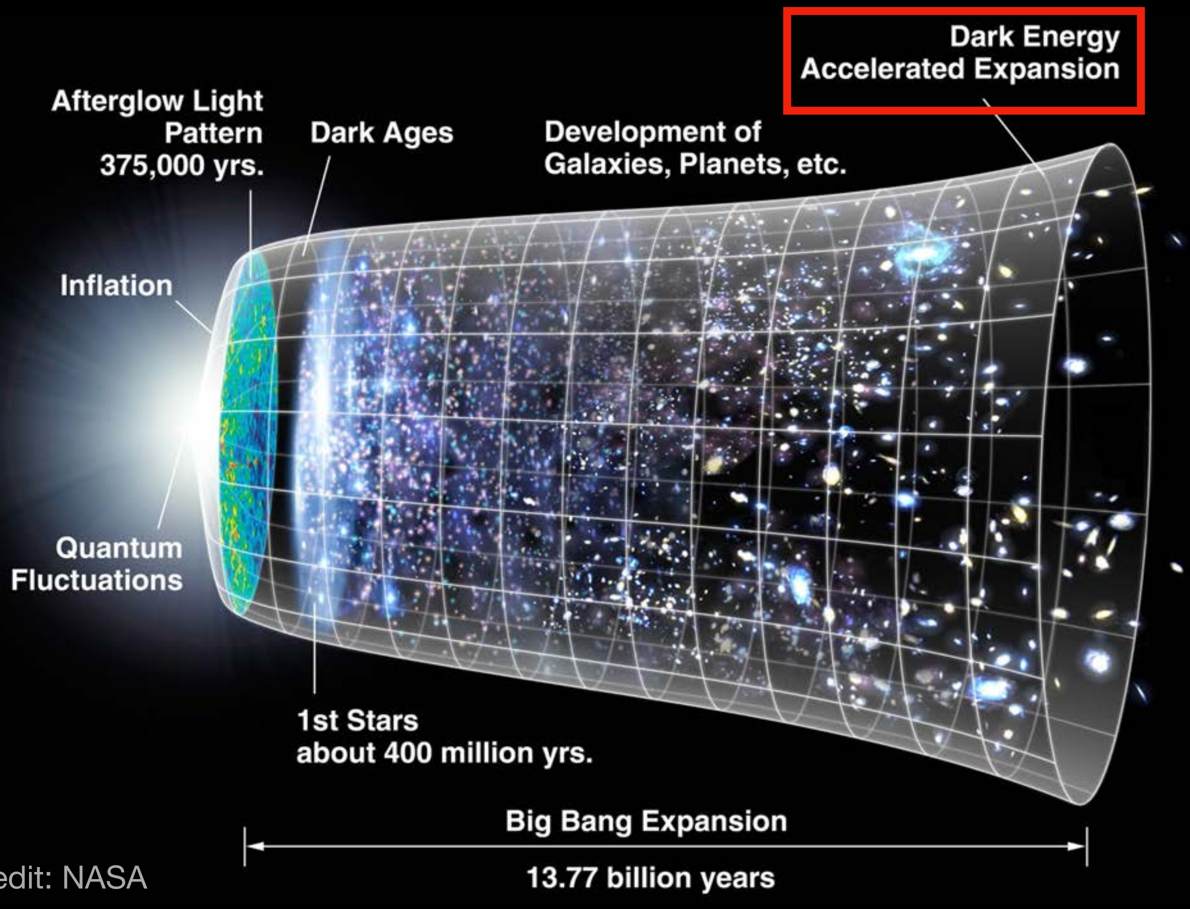


Credit: LIGO-Virgo

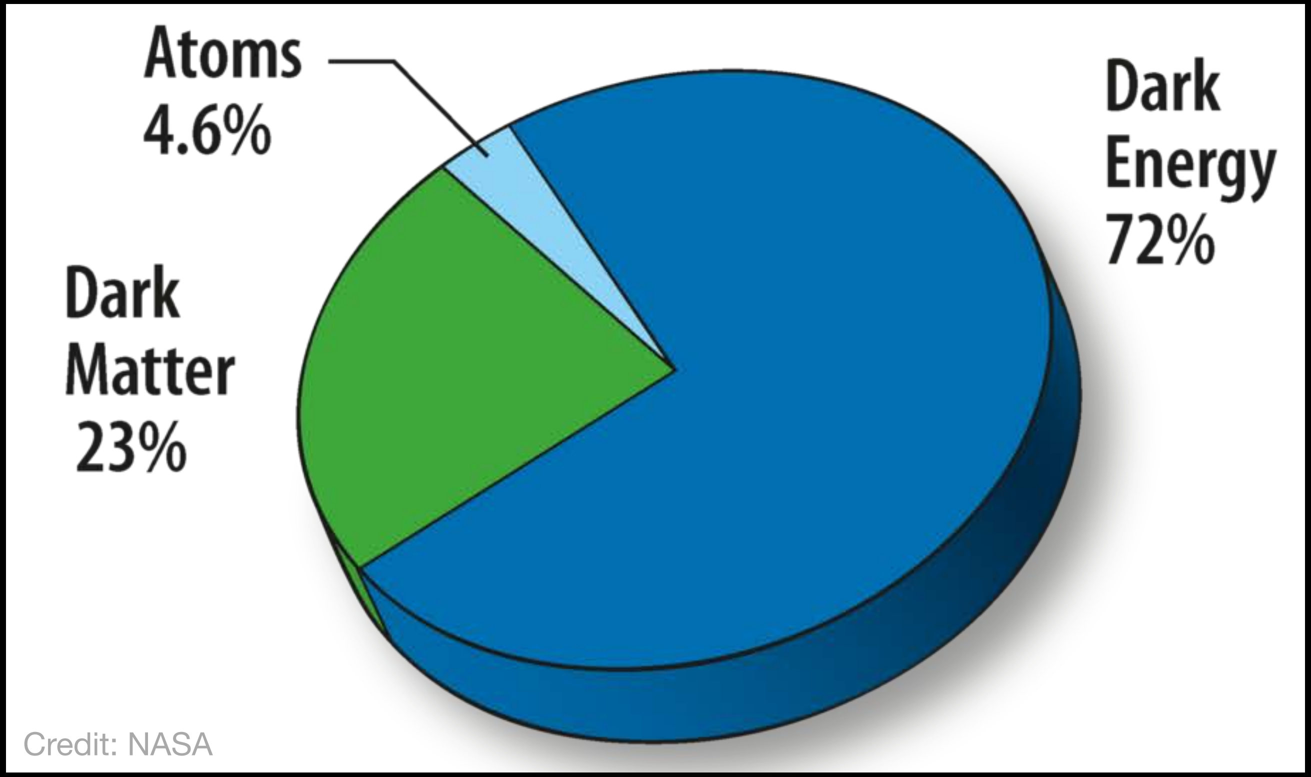


Credit: J. Tinker / SDSS

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*

Conclusion and future prospects

- GWs already provided new important scientific discoveries and will deliver new fundamental insights in the future
- In order to fully exploit future observations a coordinated development is required between:
    - Theory: ever more precise GW waveforms will be needed
    - Numerical methods: faster and accurate data analysis approaches are necessary (fertile ground for AI)
    - Science interpretation: new GW data will widen our understanding of the Universe and will have repercussions on several scientific fields
    - Instrument: R&D is necessary to harvest the huge technological and scientific potential of future detectors (see next talks on Virgo_nEXT, ET, LISA!)

THANK YOU !