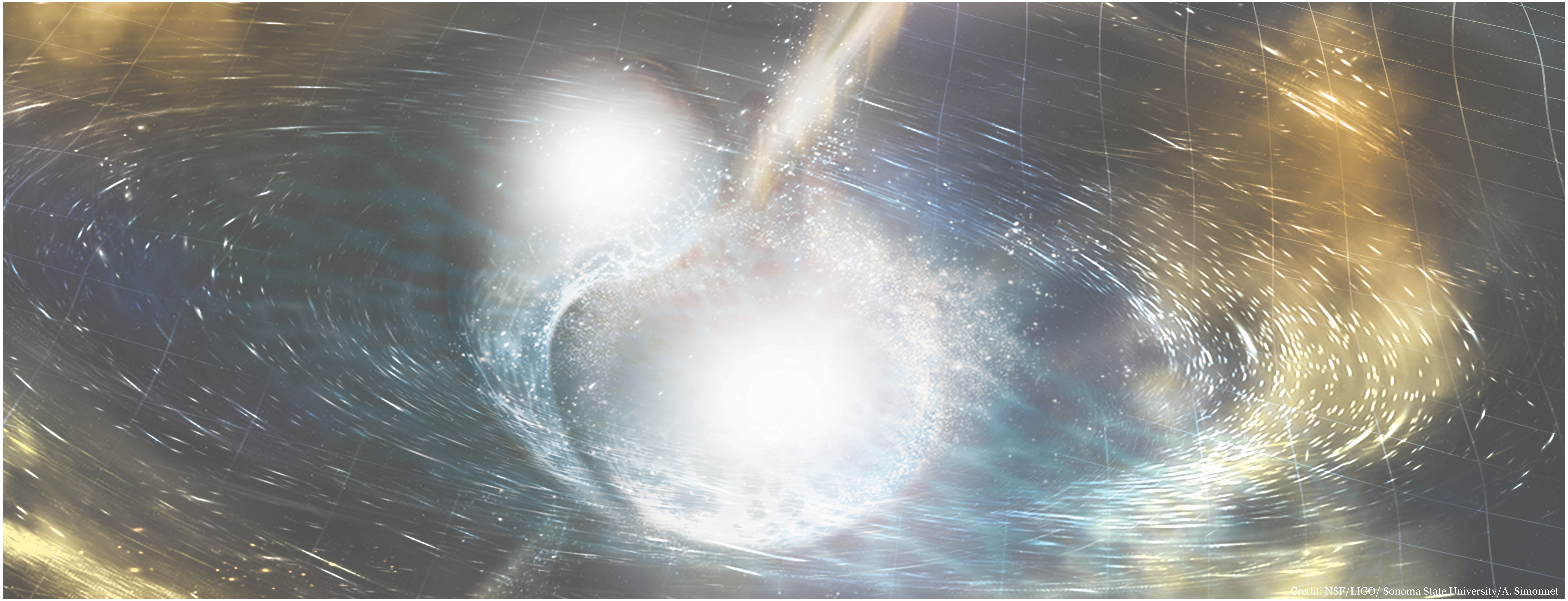
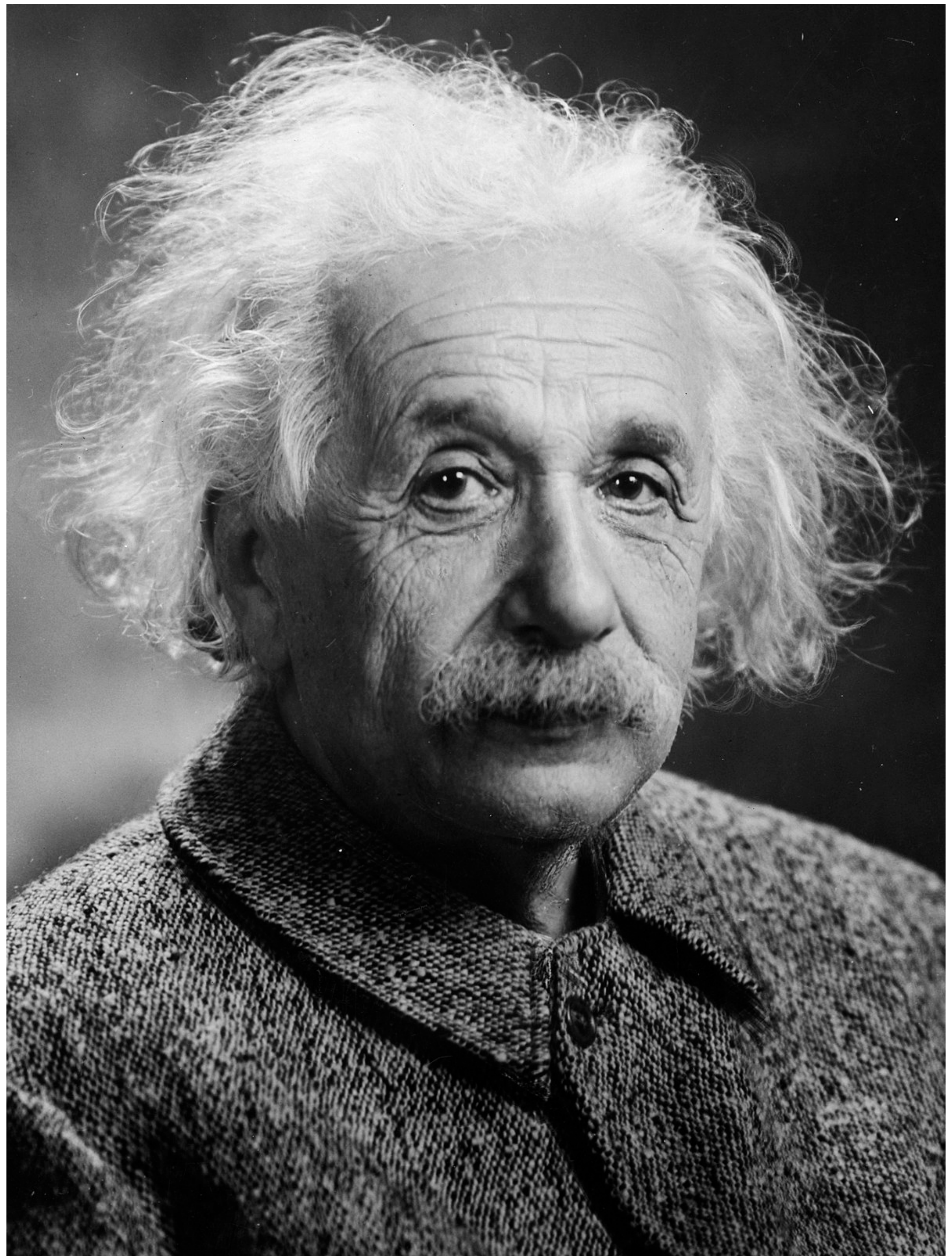
Gravity meets light

A multi-messenger revolution



Gravitational Waves



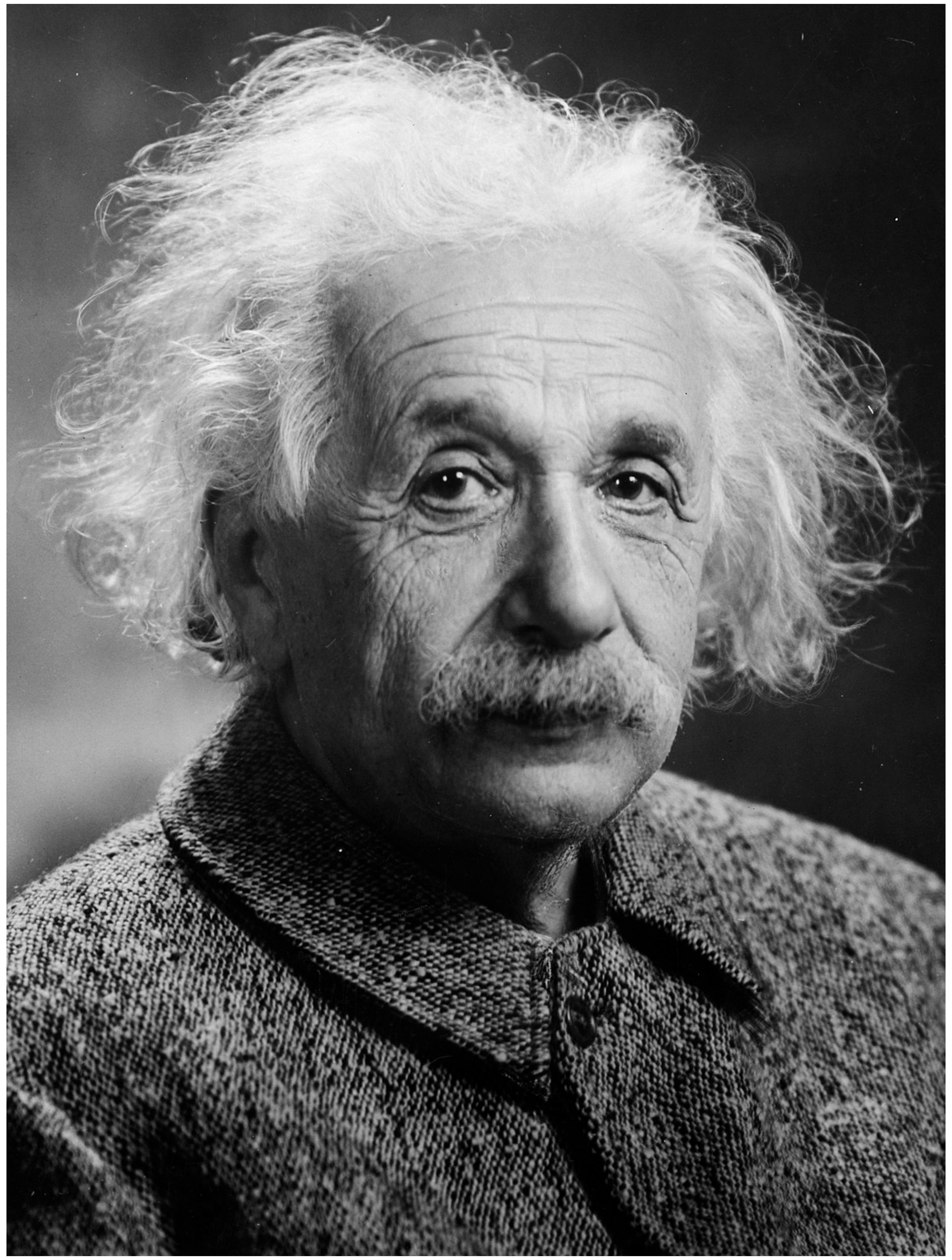
Einstein, Theory of General Relativity (1915)

Gravitational waves are ‘ripples’ in space-time caused by accelerating masses

Amplitude: h; Mass: M; Velocity: v; Distance: r

$$h \sim \frac{2G}{c^4}\frac{M v^2}{r}$$

Gravitational Waves



Einstein, Theory of General Relativity (1915)

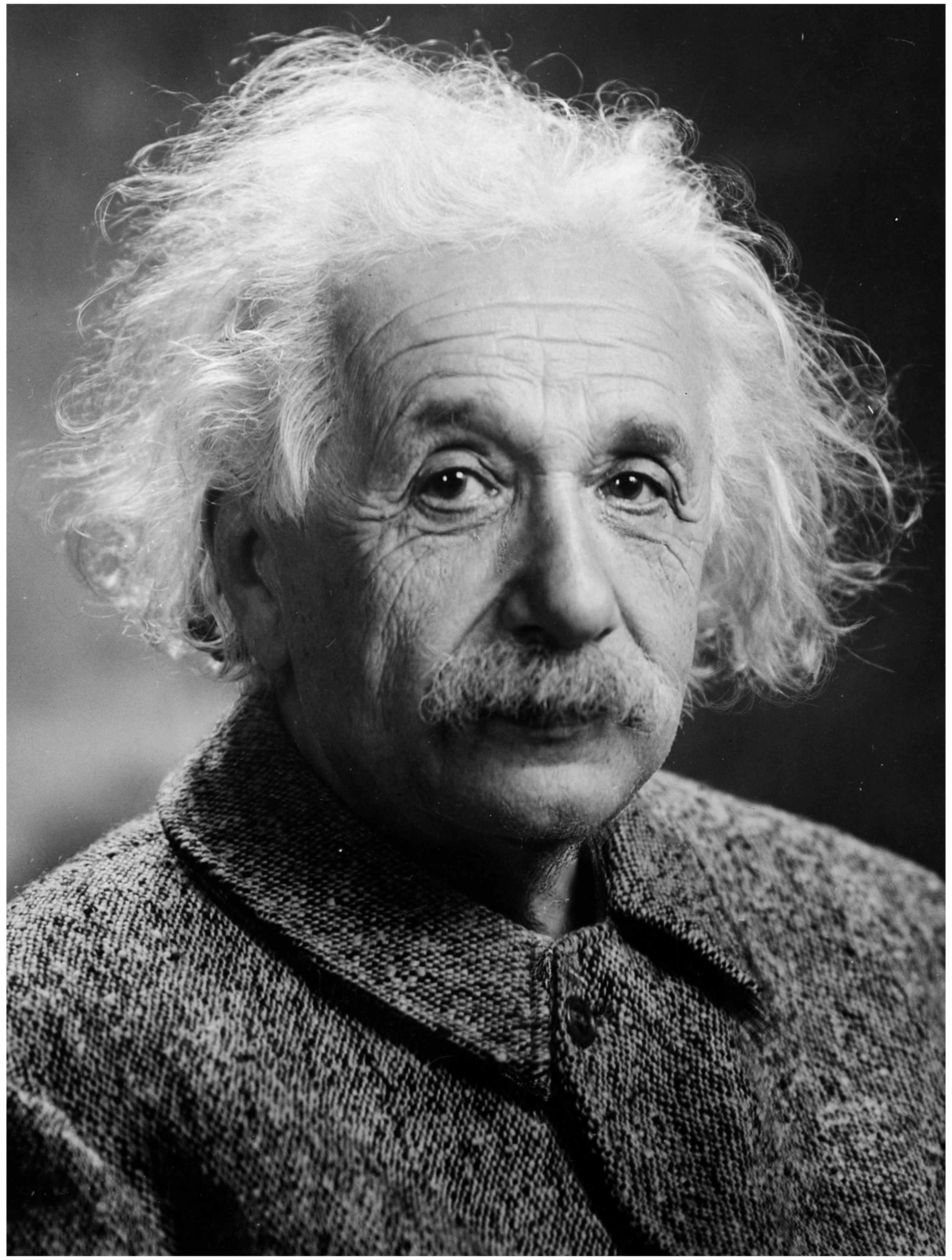
Gravitational waves are ‘ripples’ in space-time caused by accelerating masses

Amplitude — Mass — Velocity — Distance

$$h \sim \boxed{\frac{2G}{c^4}} \frac{M v^2}{r}$$

$\sim 10^{-44}\,\mathrm{s}^2\,\mathrm{m}^{-1}\,\mathrm{kg}^{-1}$

Gravitational Waves



Einstein, Theory of General Relativity (1915)

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Amplitude, Mass, Velocity, Distance

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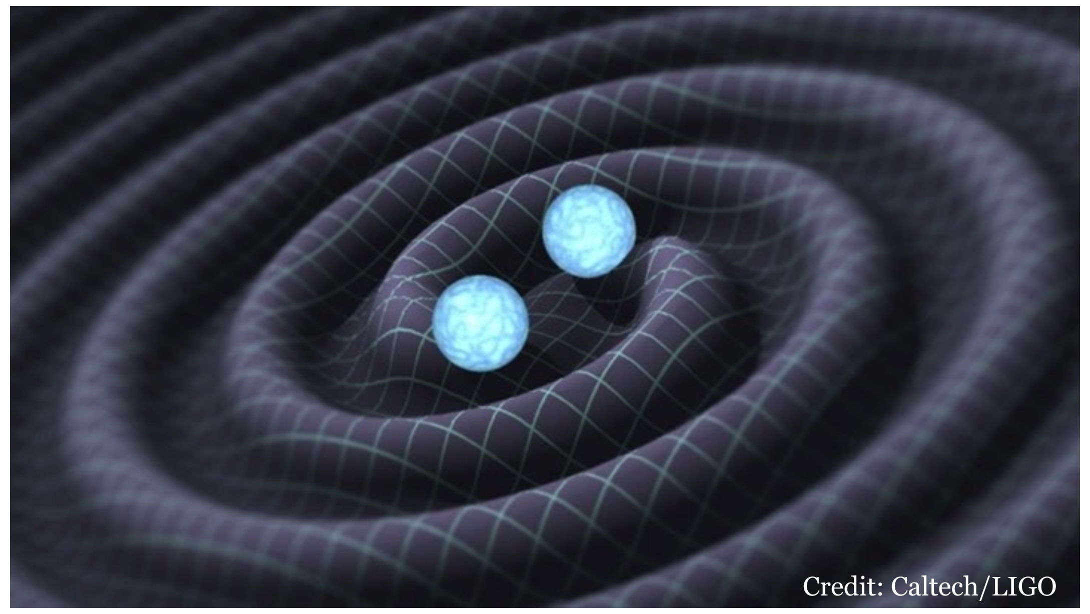
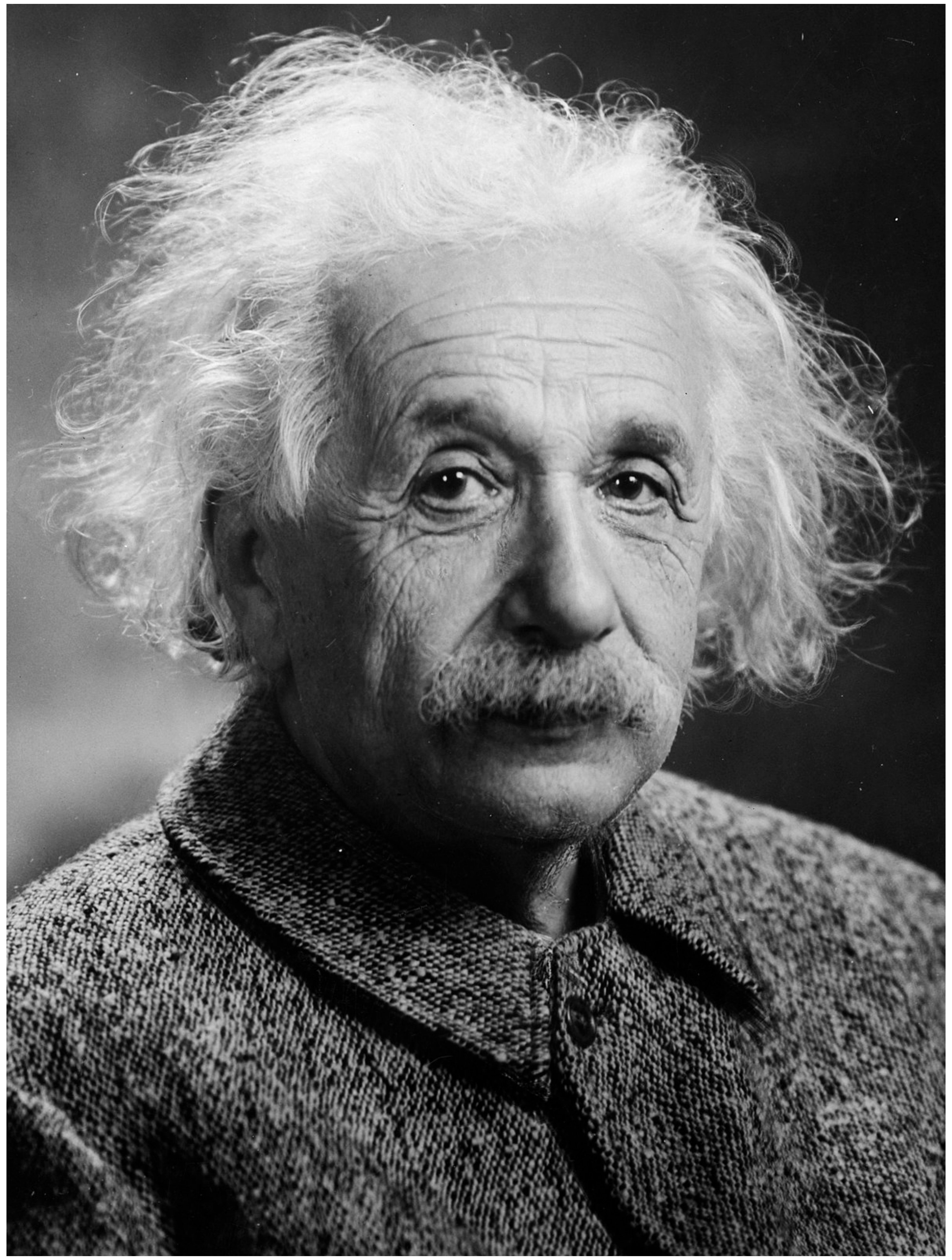


Gravitational Waves



Einstein, Theory of General Relativity (1915)

Gravitational waves are 'ripples' in space-time caused by accelerating masses

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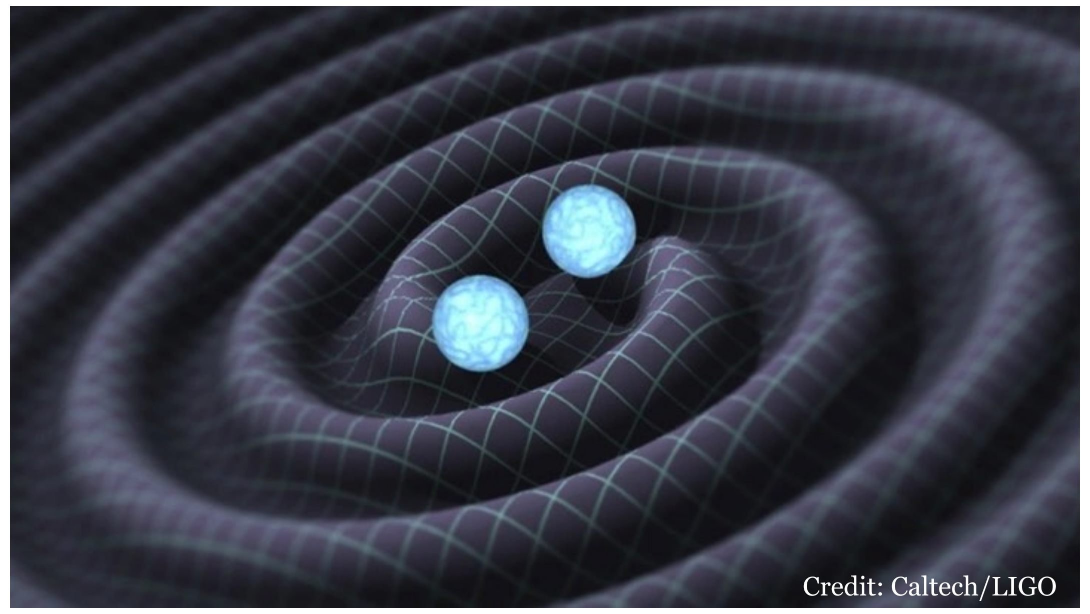
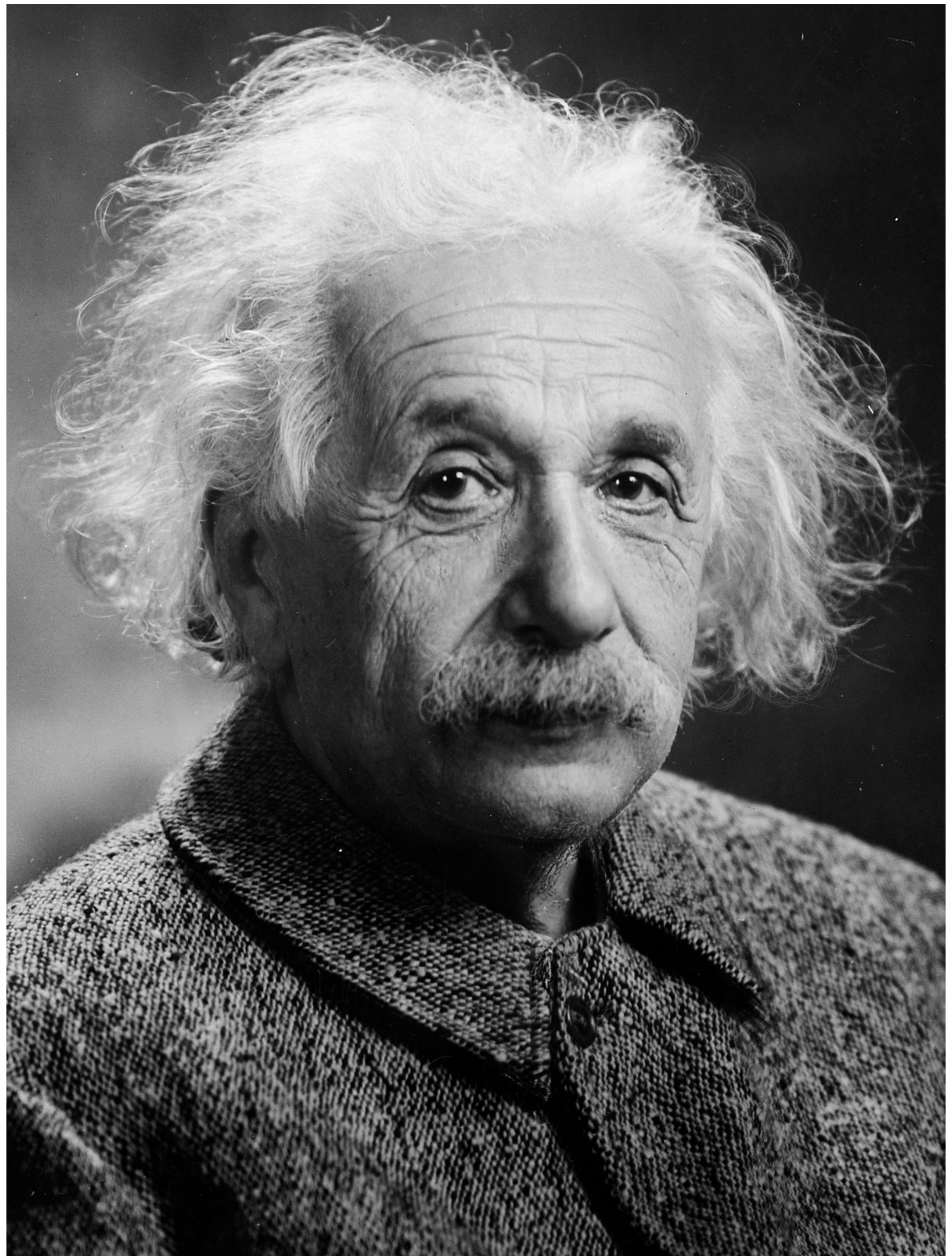


- Neutron Star + Neutron Star $\quad M = 2.8\,M_\odot\ ;\ v \sim c\ ;\ r = 10^8\,\mathrm{ly} \longrightarrow h \sim 4 \times 10^{-21}$
- Black hole + Black hole $\quad M = 50\,M_\odot\ ;\ v \sim c\ ;\ r = 5 \times 10^9\,\mathrm{ly} \longrightarrow h \sim 2 \times 10^{-21}$

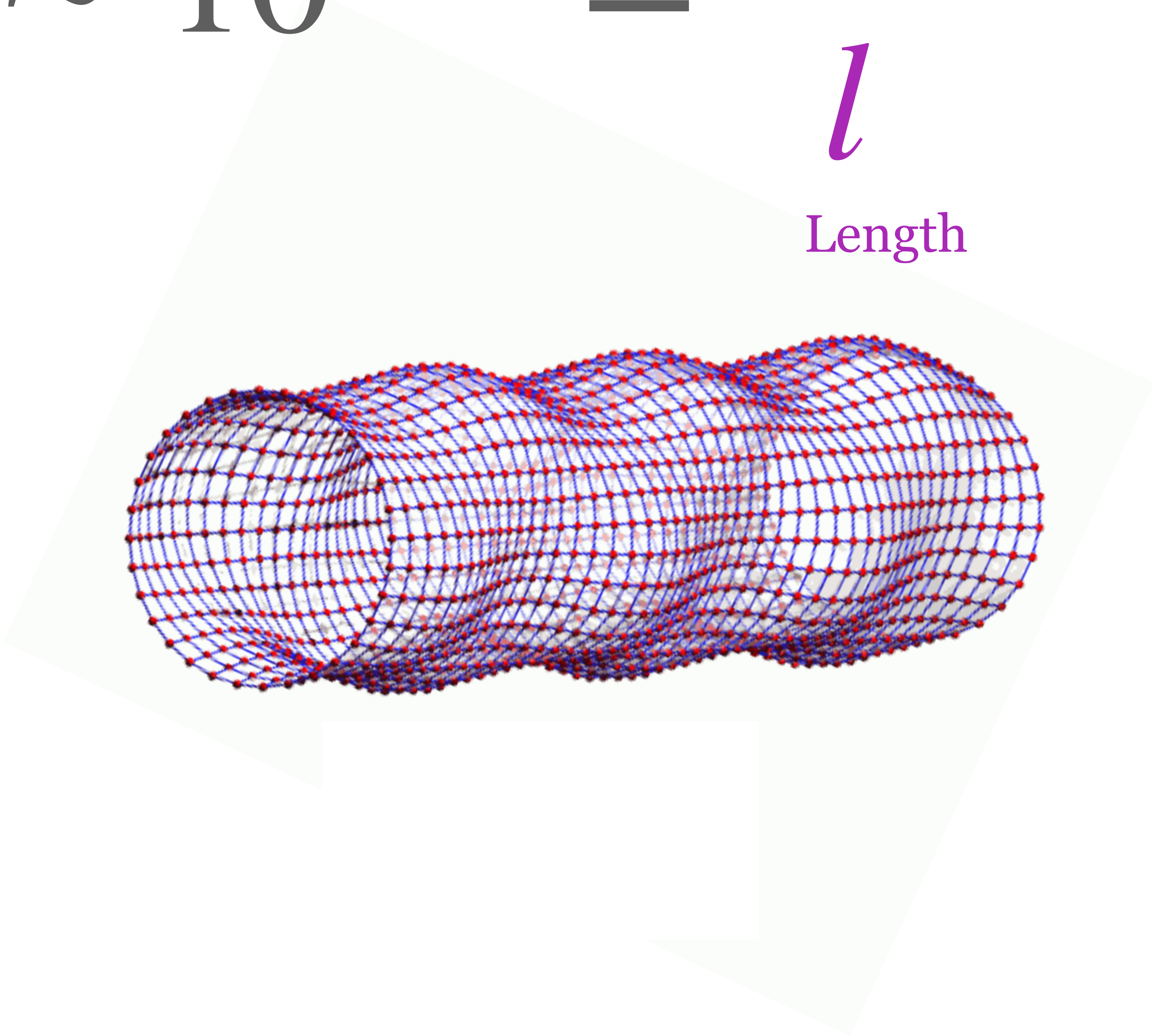
Gravitational Waves



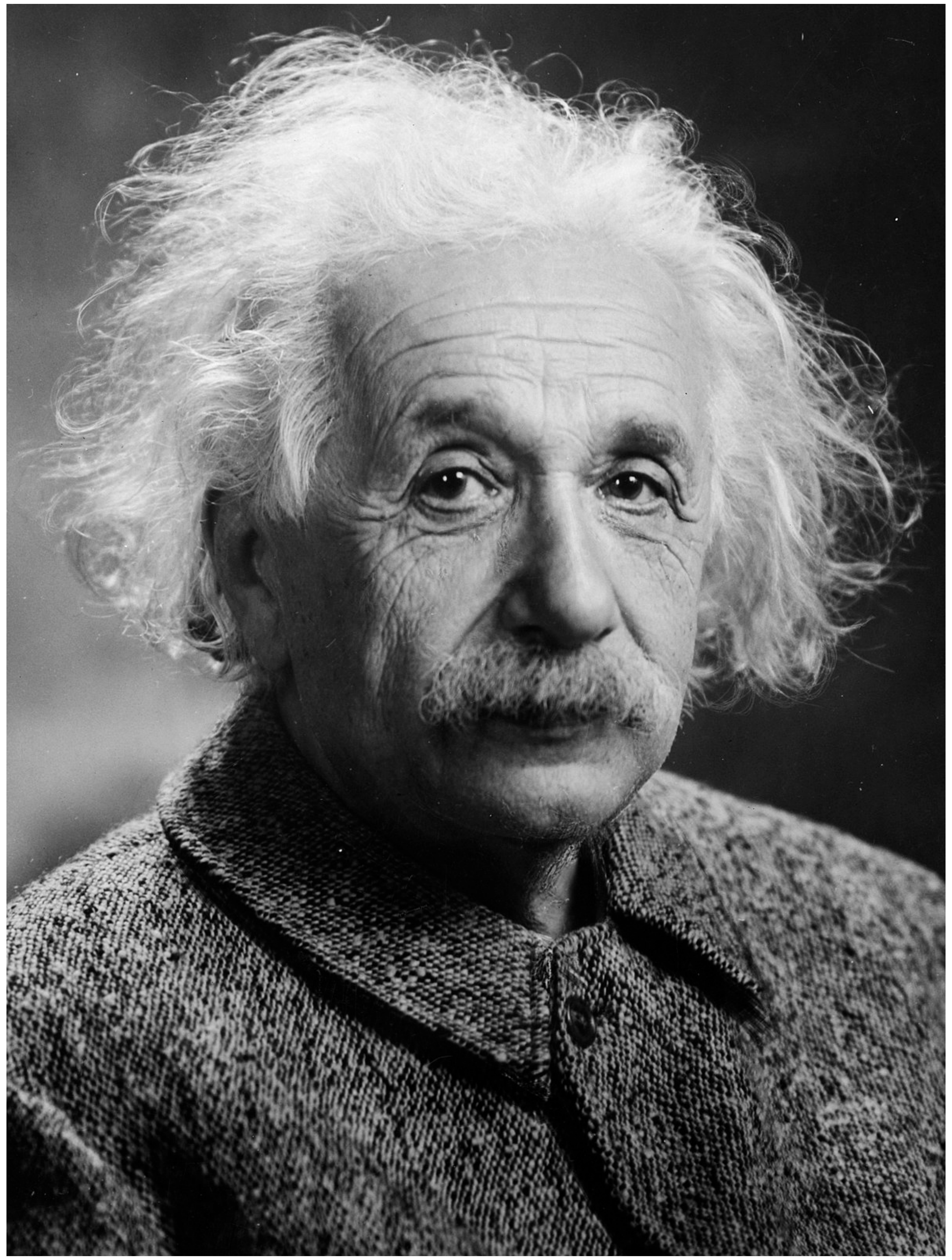
Einstein, Theory of General Relativity (1915)

Gravitational waves are 'ripples' in space-time caused by accelerating masses

$$\underset{\text{Amplitude}}{h} \sim \frac{2G}{c^4}\frac{\overset{\text{Mass}}{M}\,\overset{\text{Velocity}}{v}^2}{\underset{\text{Distance}}{r}} \sim 10^{-21} = \frac{\overset{\text{Change in length}}{\Delta l}}{\underset{\text{Length}}{l}}$$



Gravitational Waves



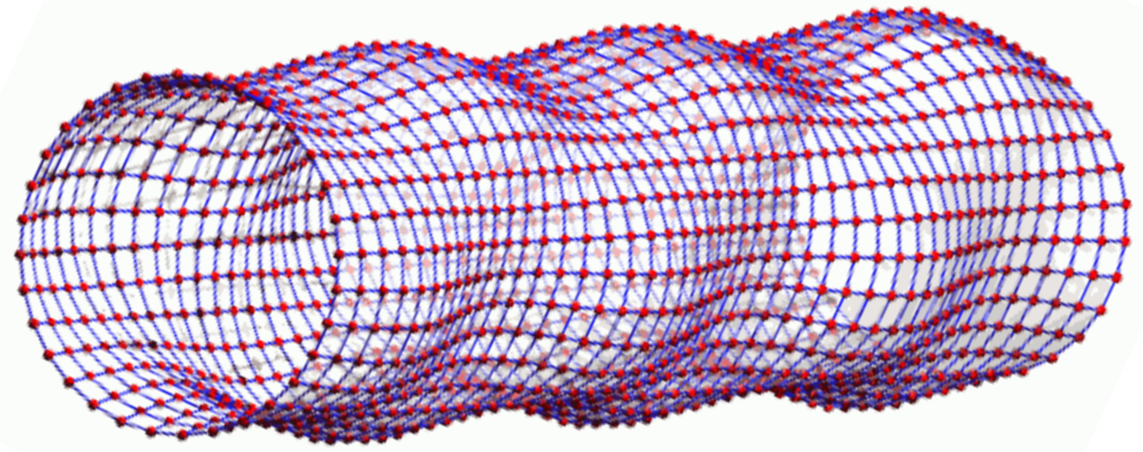
Einstein, Theory of General Relativity (1915)

Gravitational waves are ‘ripples’ in space-time caused by accelerating masses

Amplitude, Mass, Velocity, Change in length

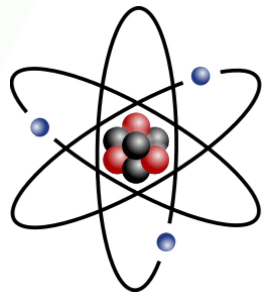
$$h \sim \frac{2G}{c^4}\frac{M\,v^2}{r} \sim 10^{-21} = \frac{\Delta l}{l}$$

Distance, Length

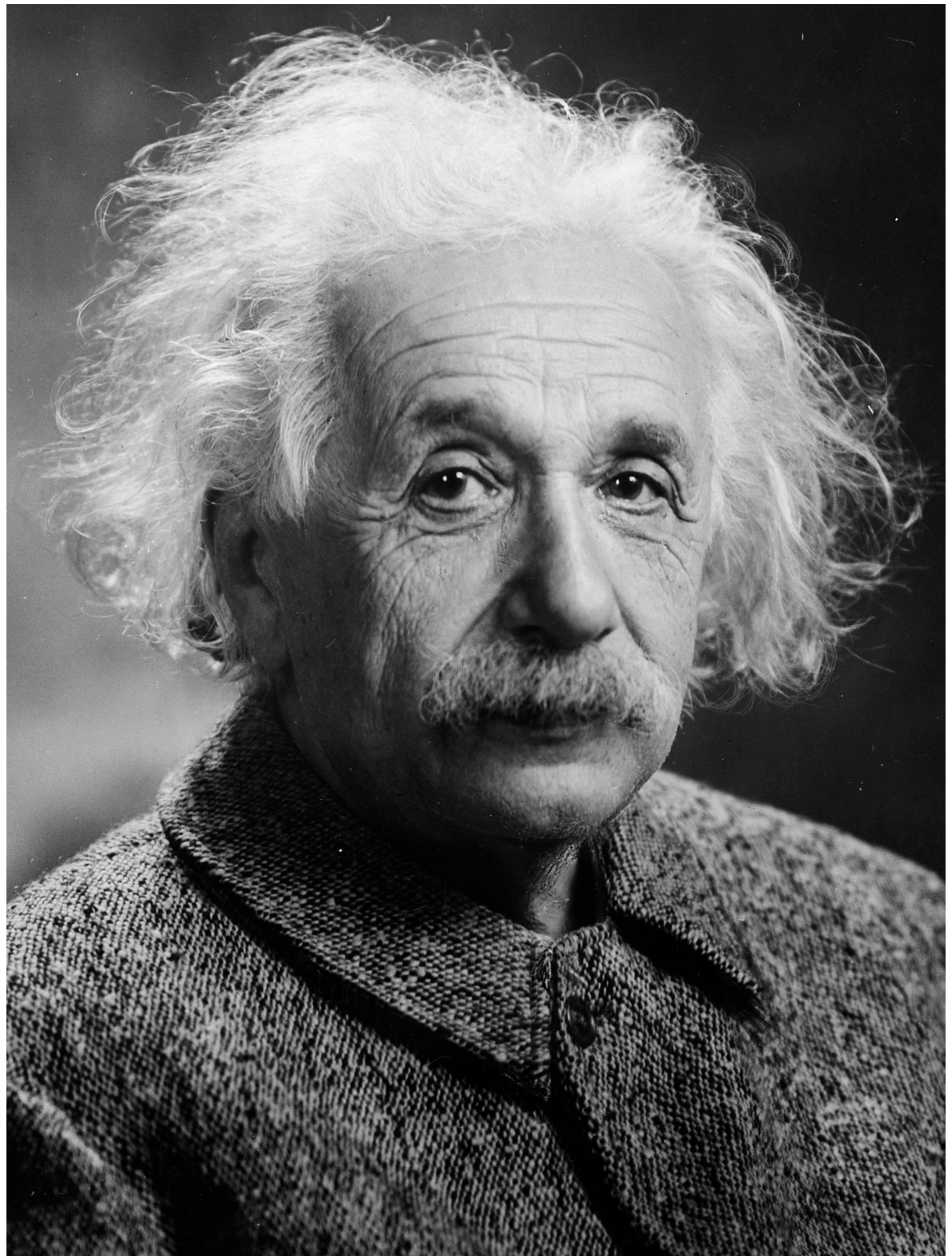


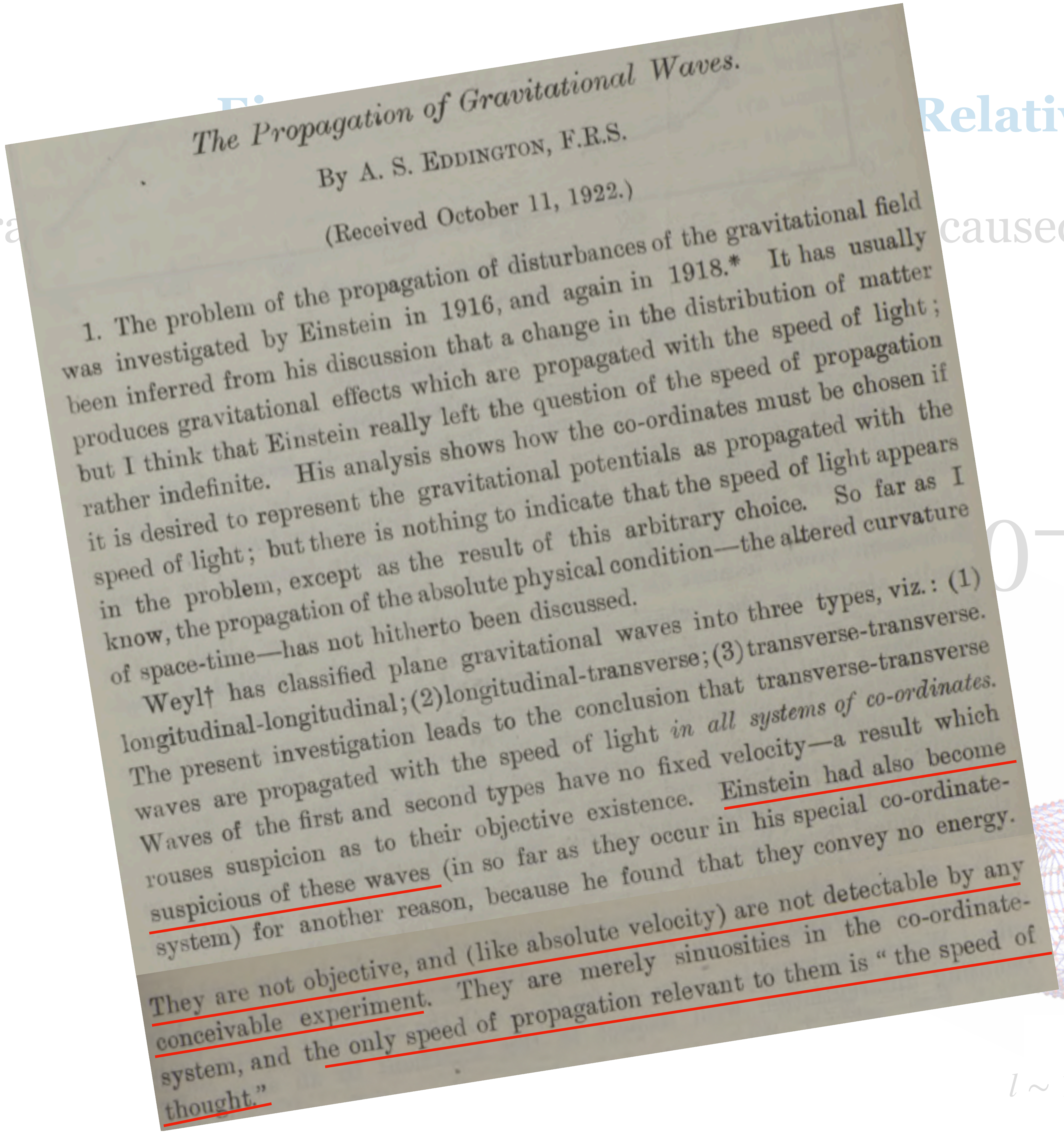
$l \sim 1\ \text{AU} \sim 150 \times 10^6\ \text{km}$

$\Delta l \sim 10^{-10}\ \text{m}$



Gravitational Waves





The Propagation of Gravitational Waves.

By A. S. Eddington, F.R.S.

(Received October 11, 1922.)

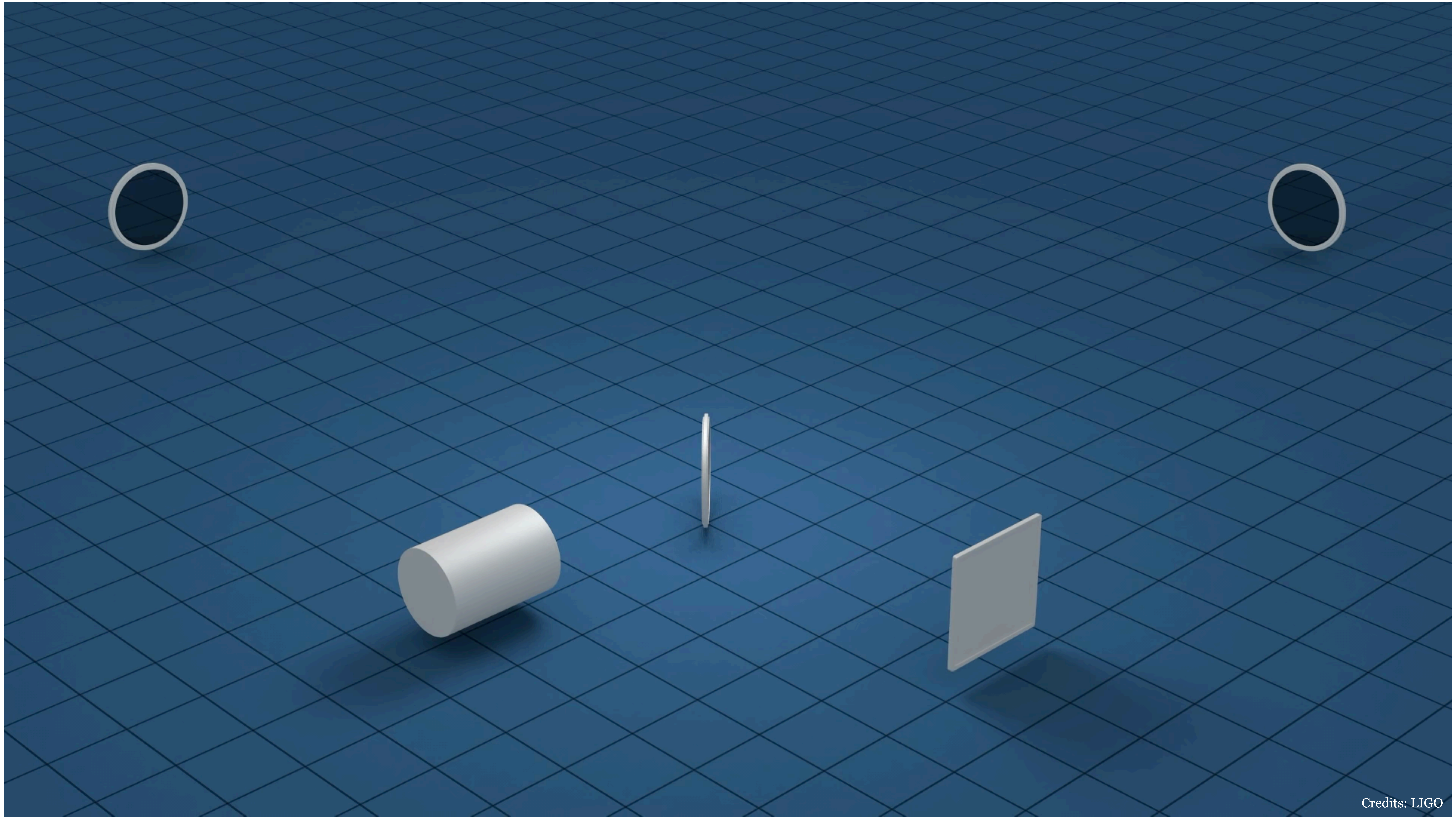
1. The problem of the propagation of disturbances of the gravitational field was investigated by Einstein in 1916, and again in 1918.* It has usually been inferred from his discussion that a change in the distribution of matter produces gravitational effects which are propagated with the speed of light; but I think that Einstein really left the question of the speed of propagation rather indefinite. His analysis shows how the co-ordinates must be chosen if it is desired to represent the gravitational potentials as propagated with the speed of light; but there is nothing to indicate that the speed of light appears in the problem, except as the result of this arbitrary choice. So far as I know, the propagation of the absolute physical condition—the altered curvature of space-time—has not hitherto been discussed.

Weyl† has classified plane gravitational waves into three types, viz.: (1) longitudinal-longitudinal; (2) longitudinal-transverse; (3) transverse-transverse. The present investigation leads to the conclusion that transverse-transverse waves are propagated with the speed of light *in all systems of co-ordinates*. Waves of the first and second types have no fixed velocity—a result which rouses suspicion as to their objective existence. Einstein had also become suspicious of these waves (in so far as they occur in his special co-ordinate-system) for another reason, because he found that they convey no energy. They are not objective, and (like absolute velocity) are not detectable by any conceivable experiment. They are merely sinusoities in the co-ordinate-system, and the only speed of propagation relevant to them is "the speed of thought."

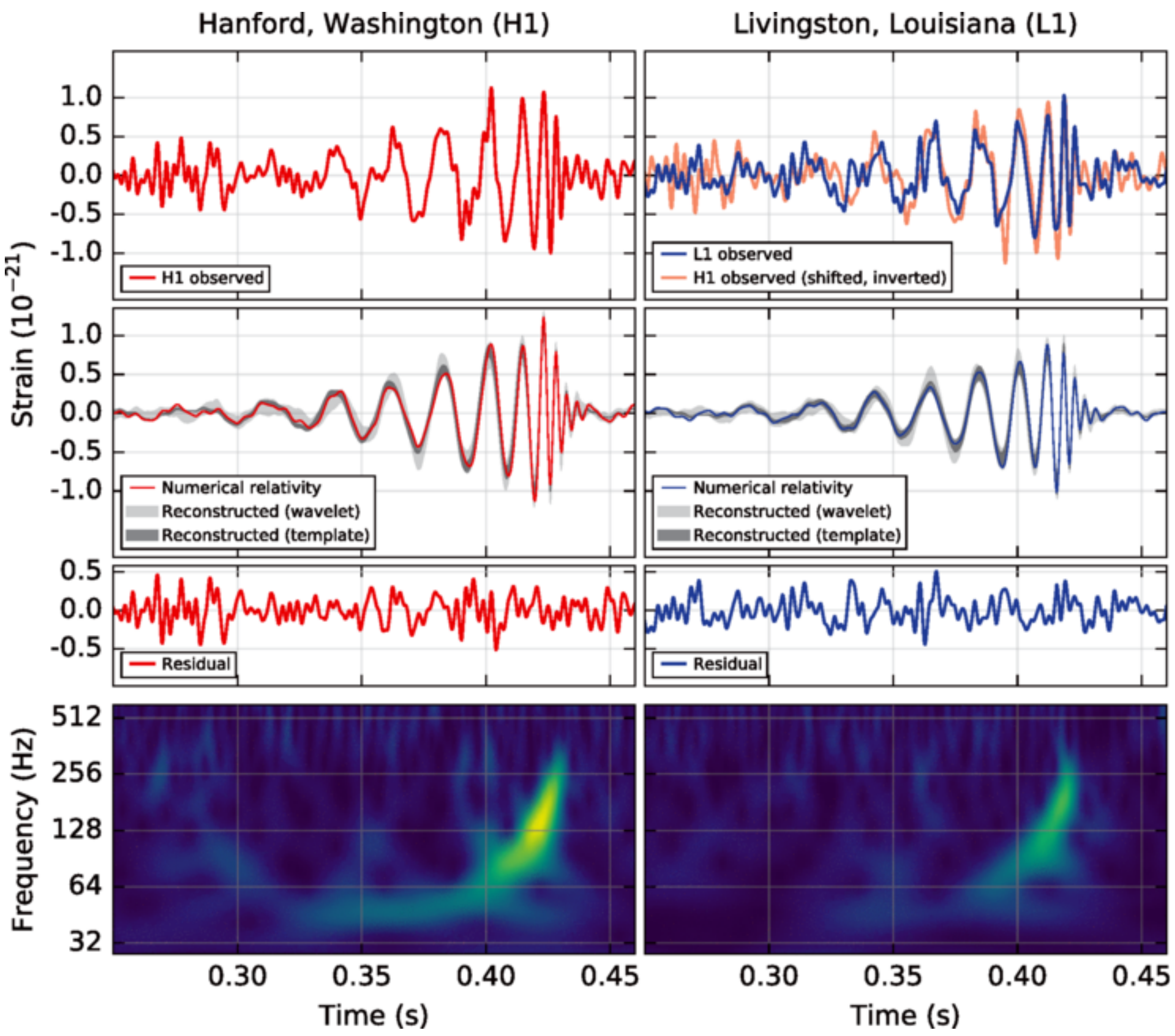
The most precise rulers ever constructed!

$l = 4\,\mathrm{km} \longrightarrow \Delta l \sim 4 \times 10^{-18}\,\mathrm{m}$ ~ 10 000 times smaller than the proton radius!!

The most precise rulers ever constructed!



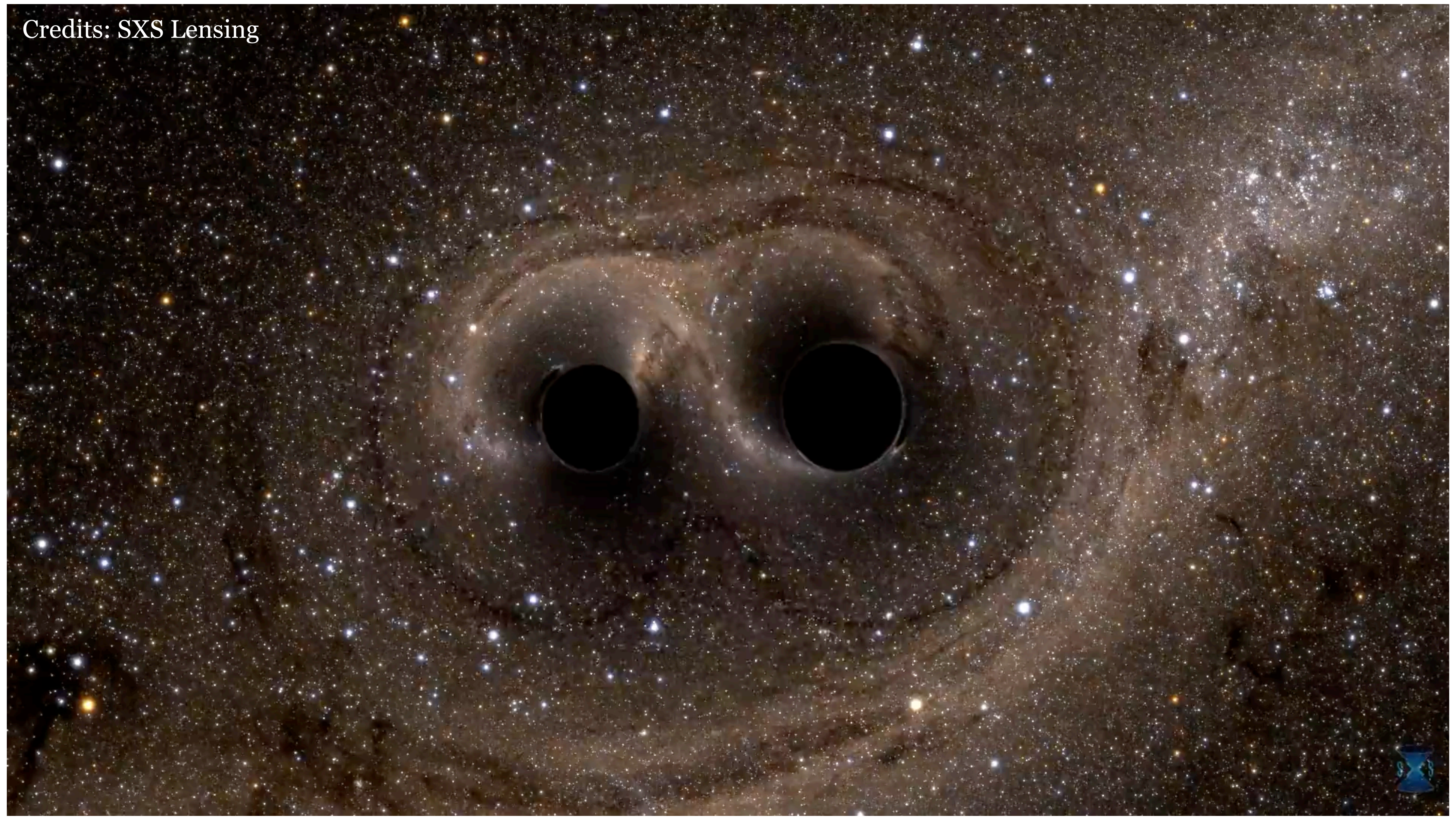
The first direct detection of gravitational waves



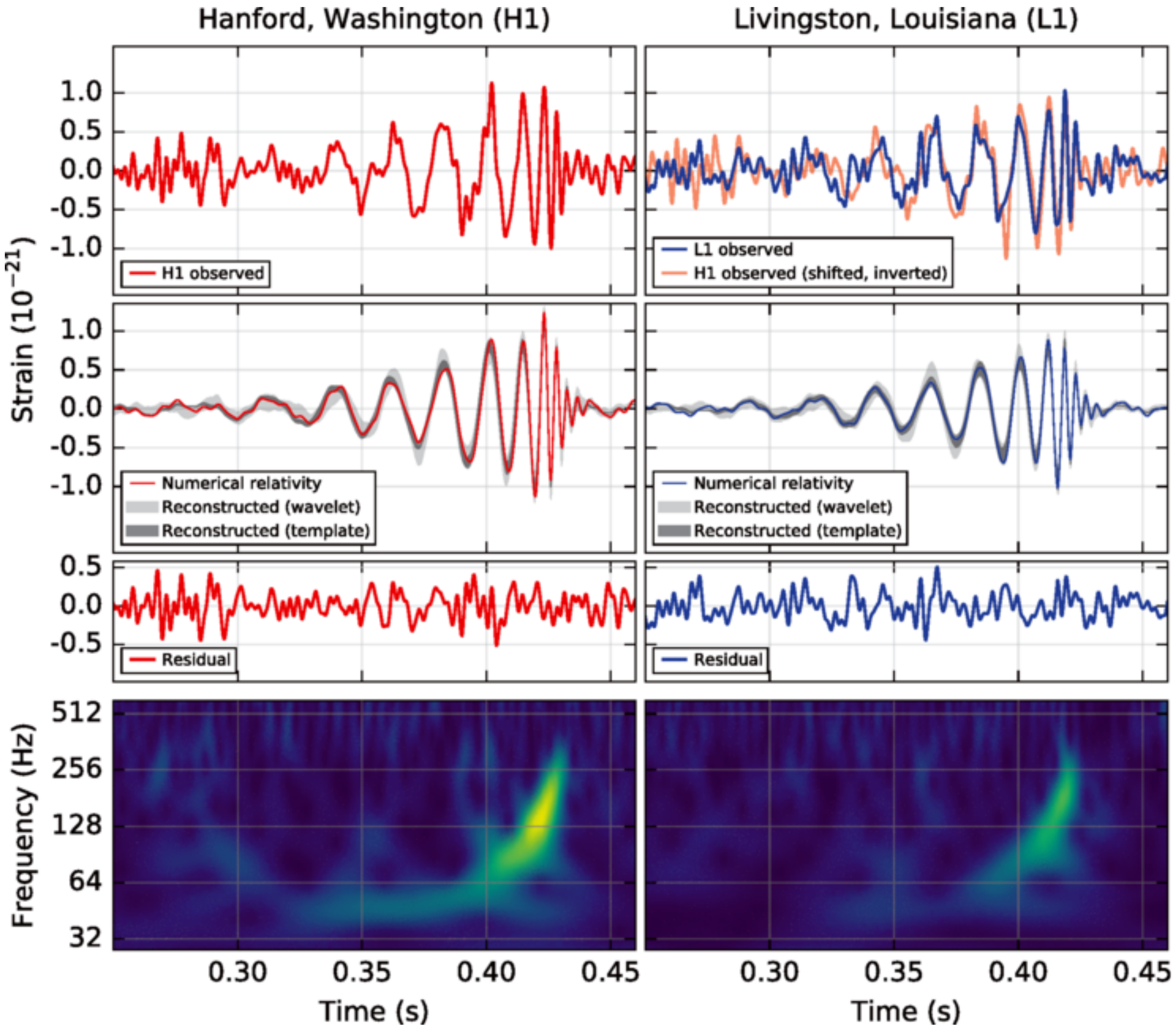
[Abbott+2016, PhRvL]

GW150914

Merger of two Black Holes of 29 and 36 $M_\odot$
at a distance of ~ 1.3 billion light years



The first direct detection of gravitational waves



[Abbott+2016, PhRvL]

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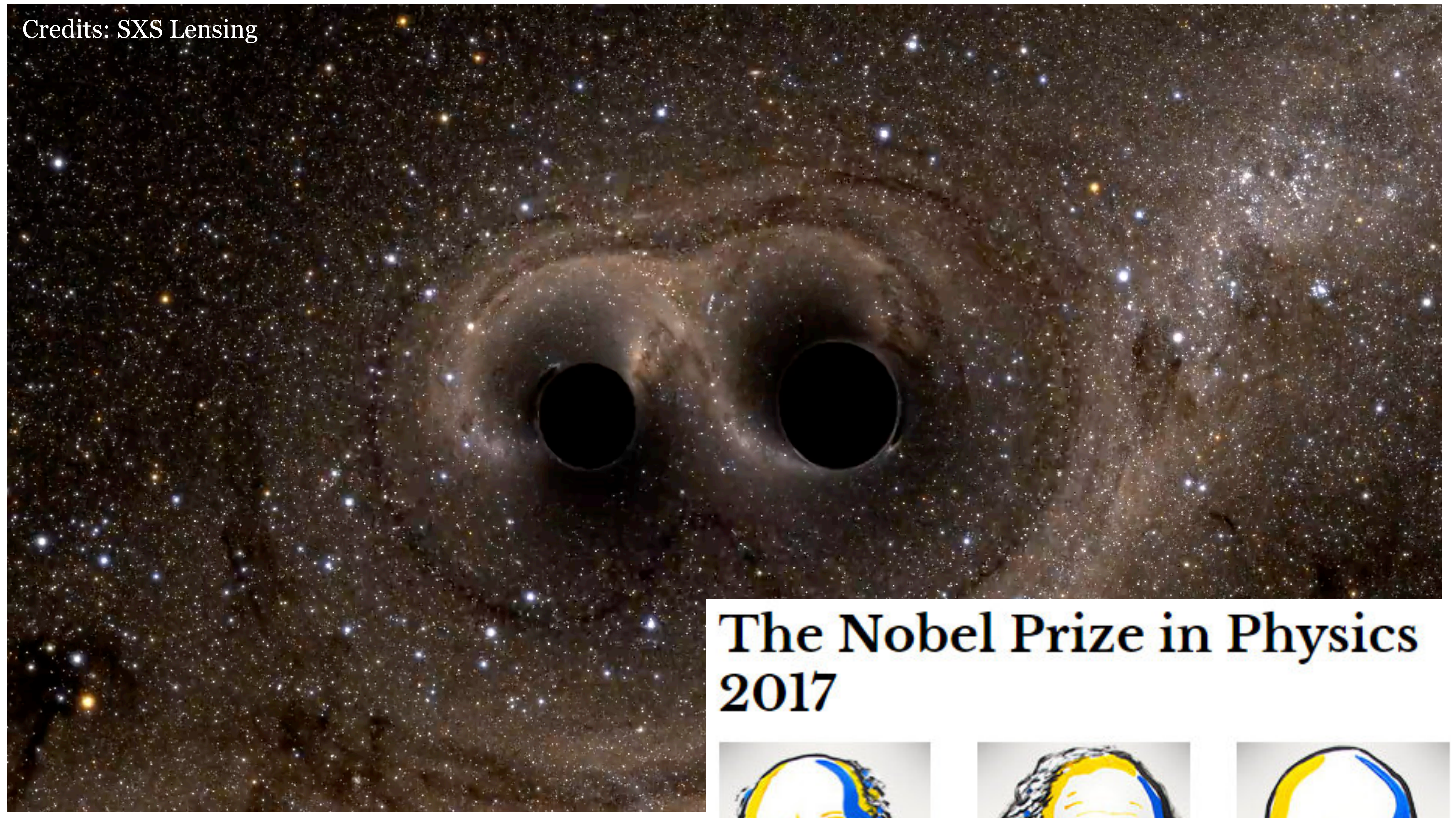
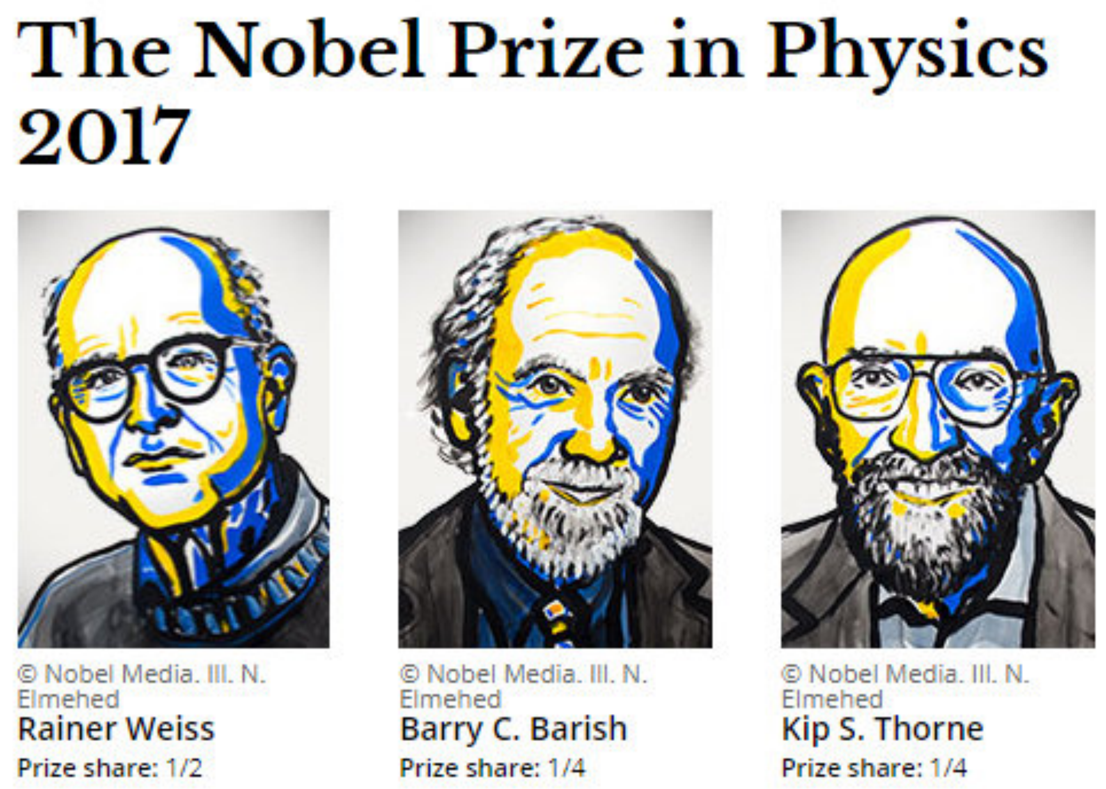
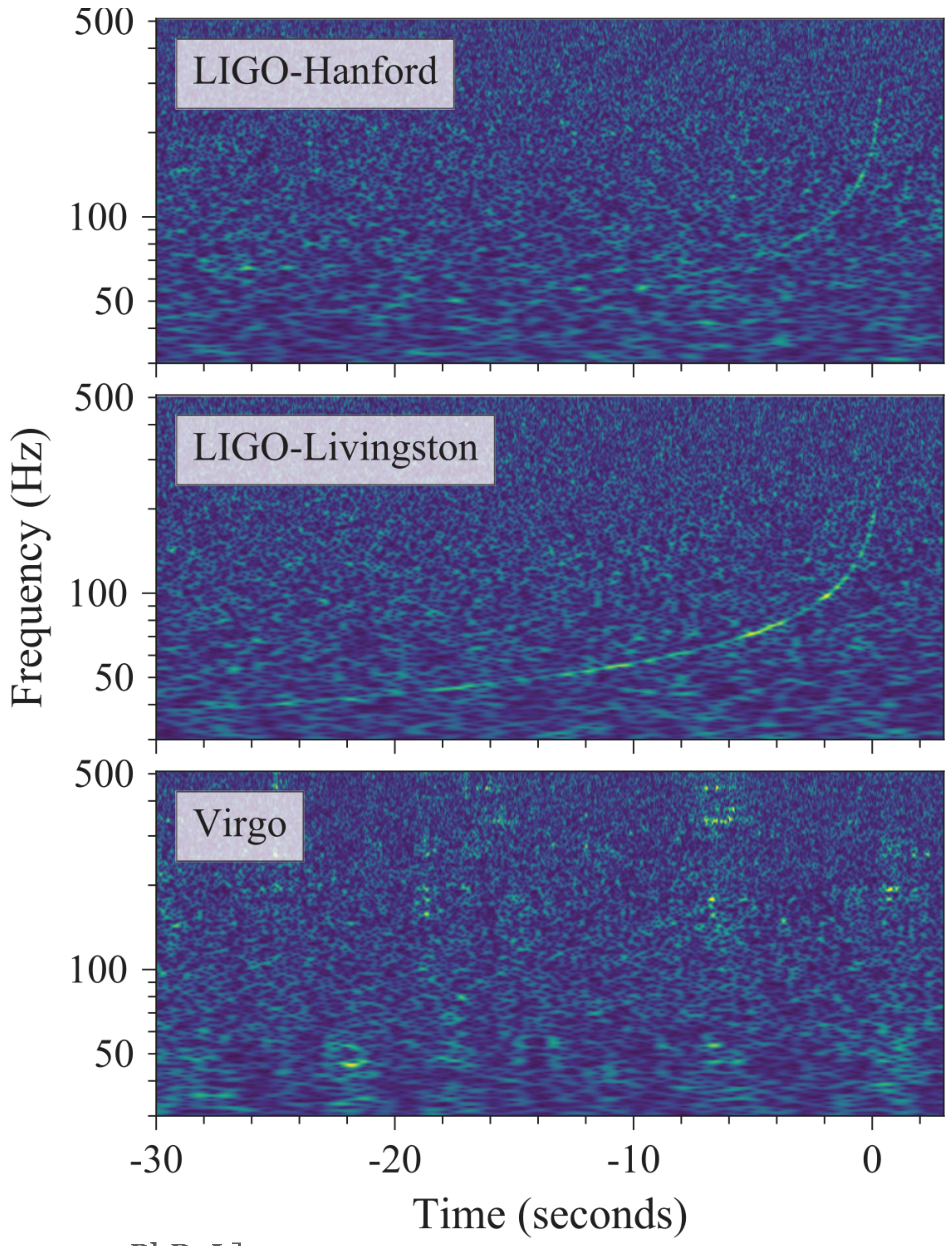




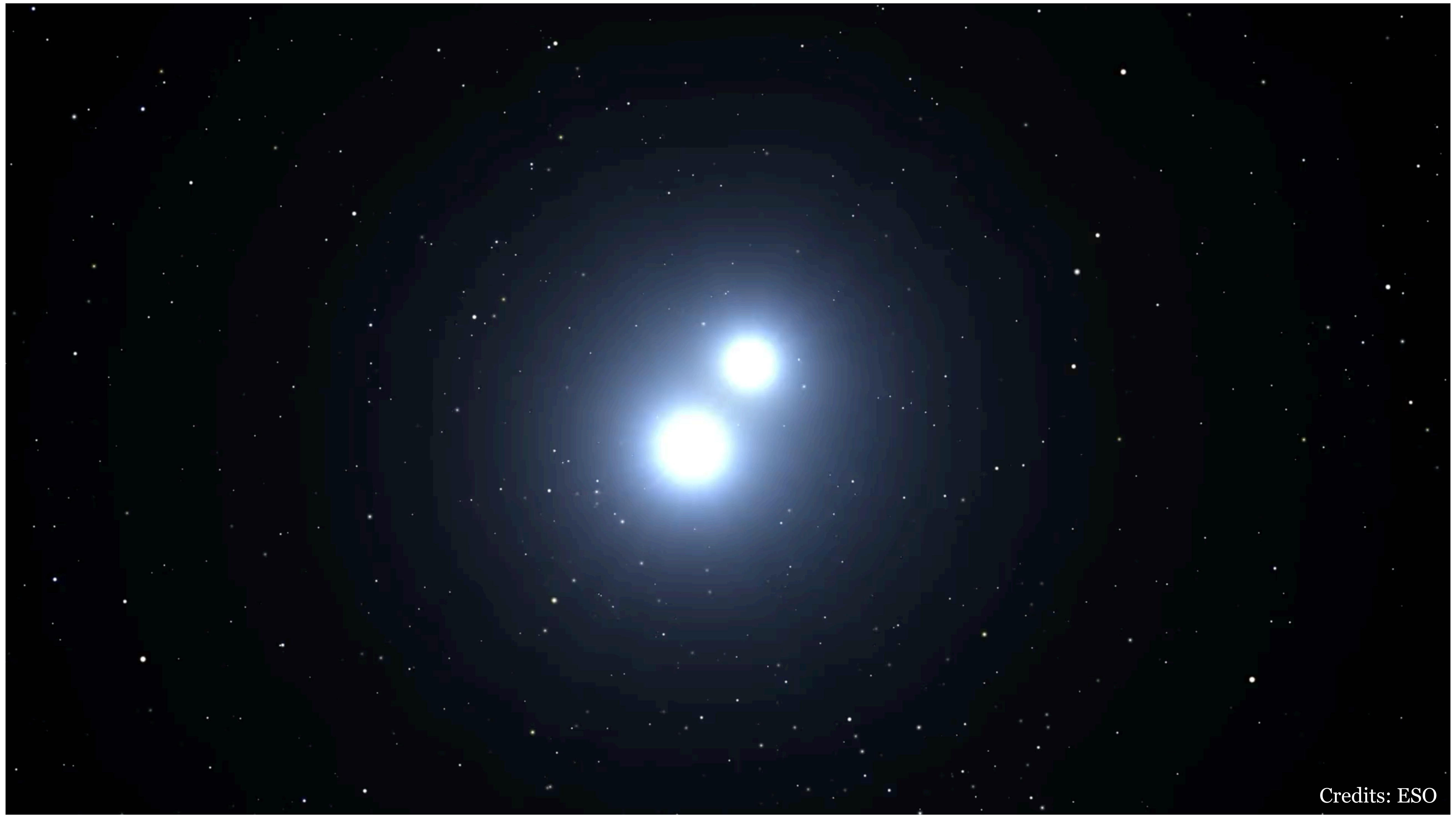
The first direct detection of GWs from two NSs



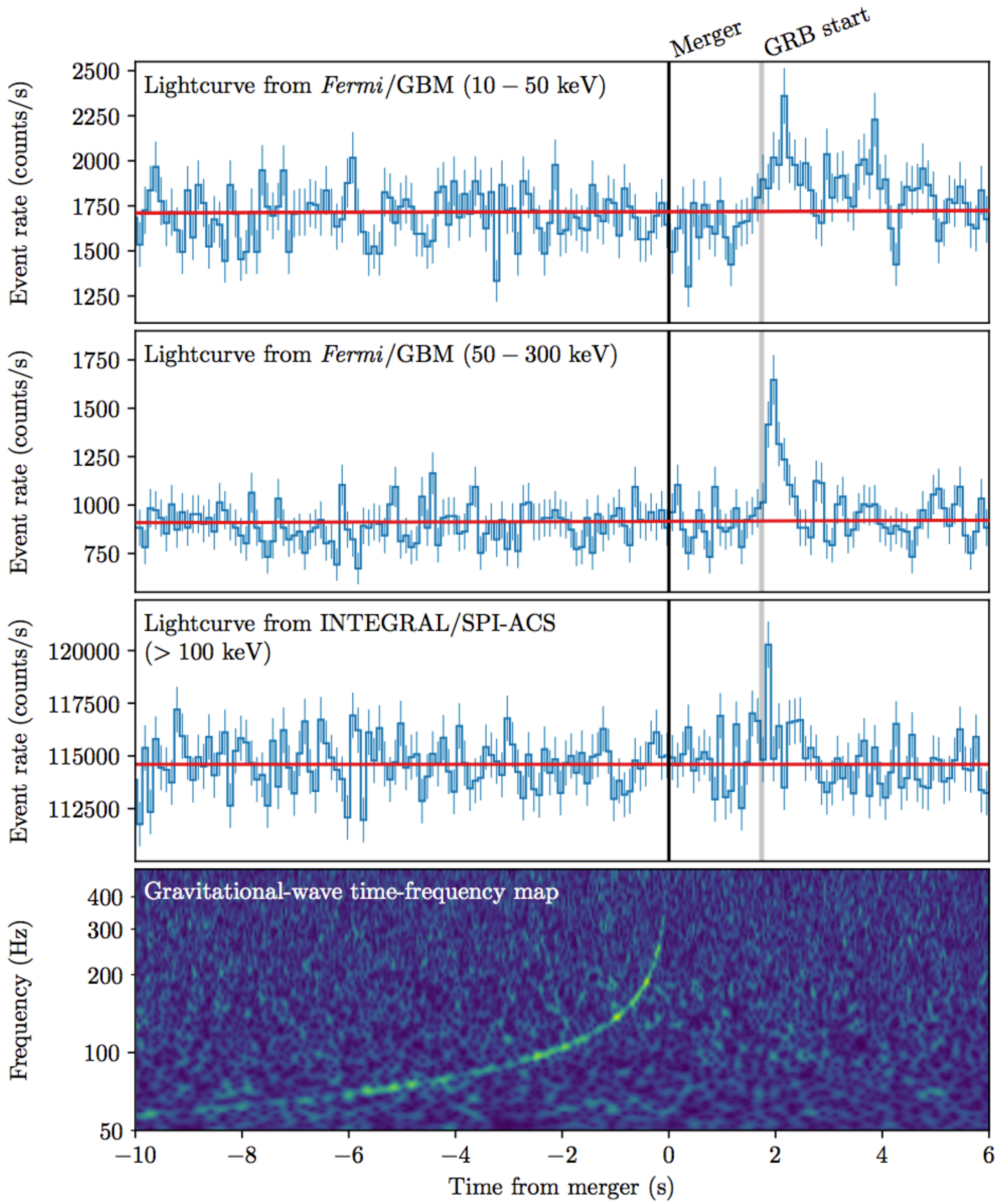
[Abbott+2017, PhRvL]

GW170817

Merger of two Neutron Stars at a distance of ~130 million light years

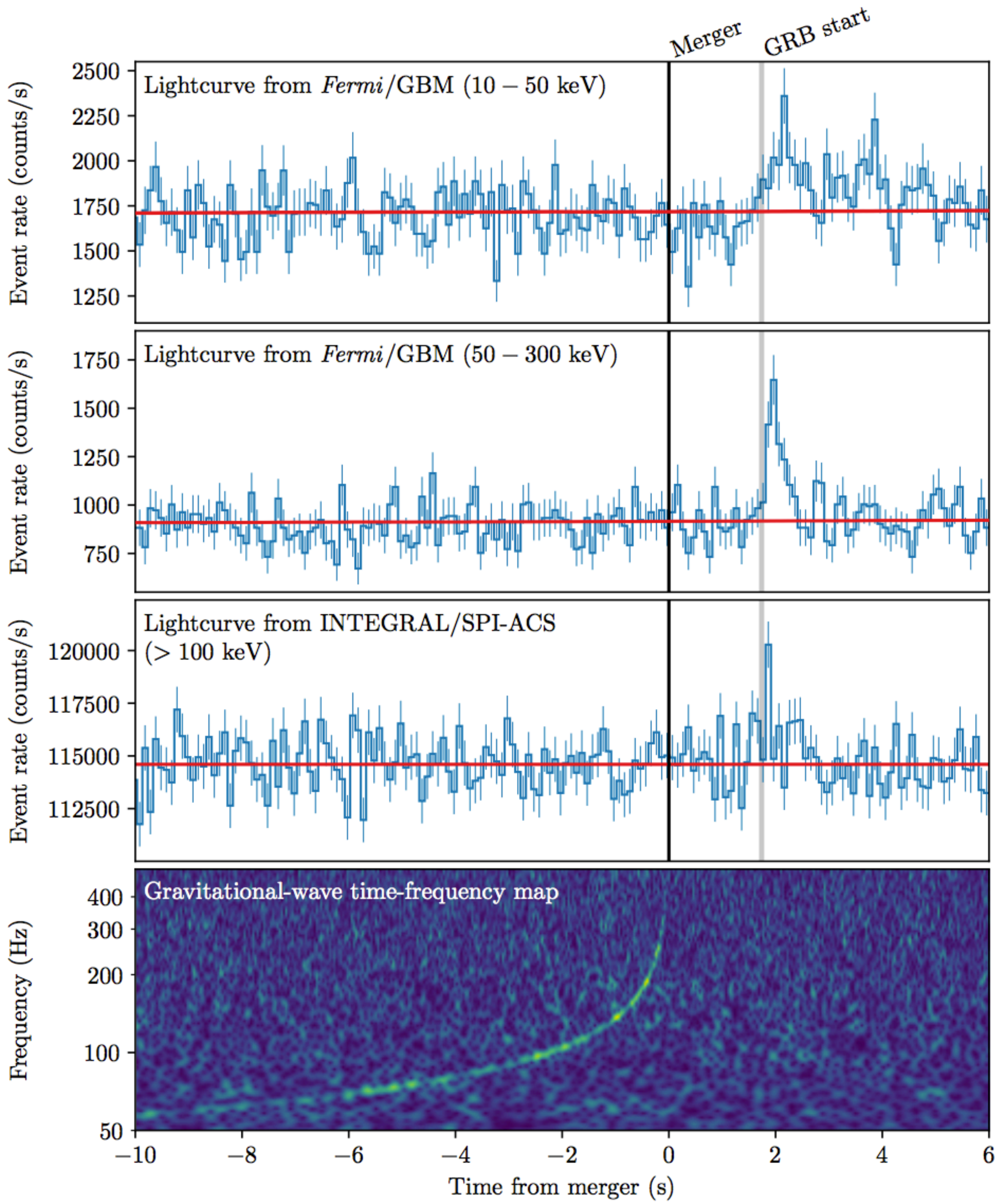


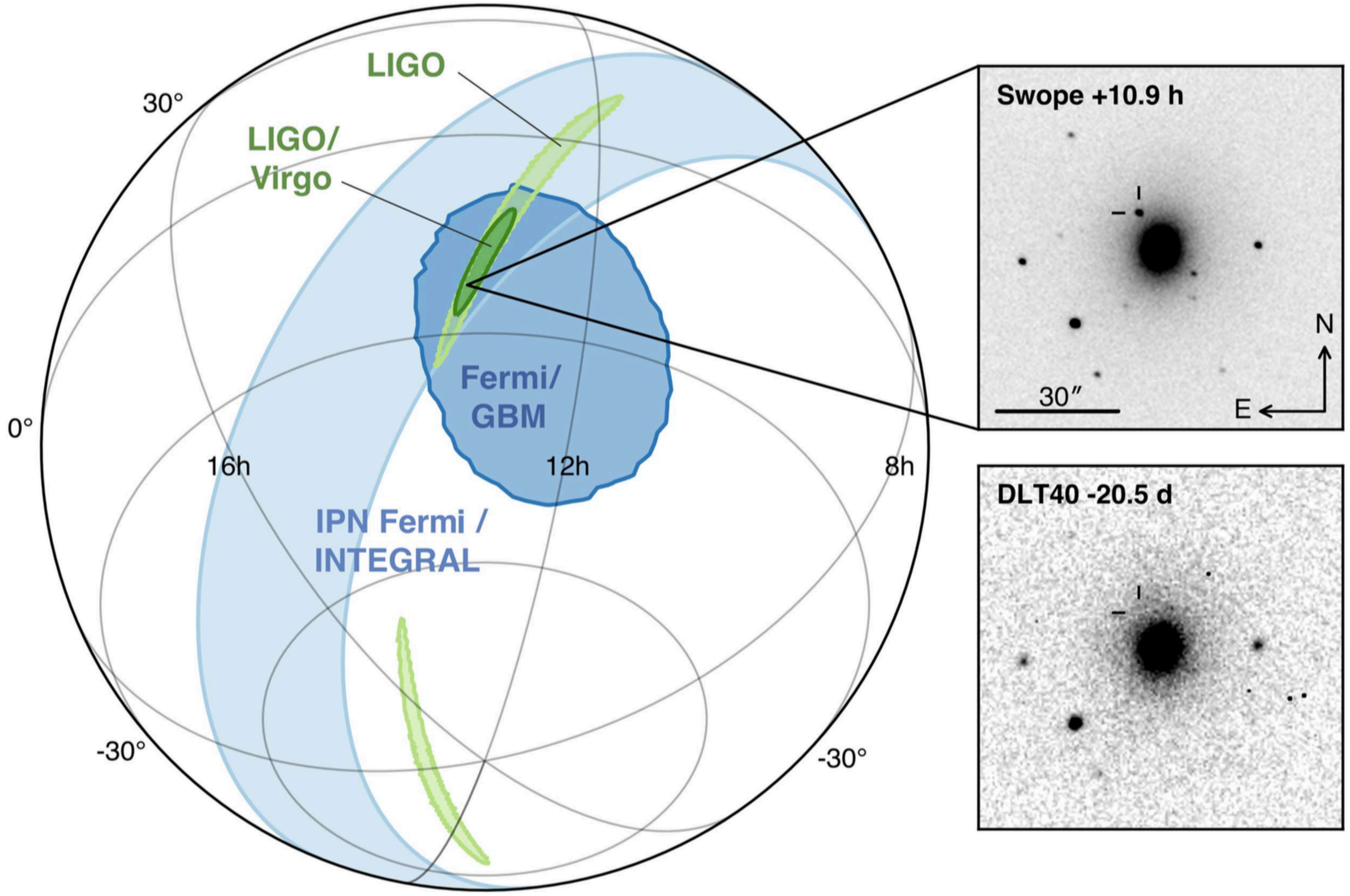
Gravity meets light



[Abbott+2017, PhRvL]

Gravity meets light

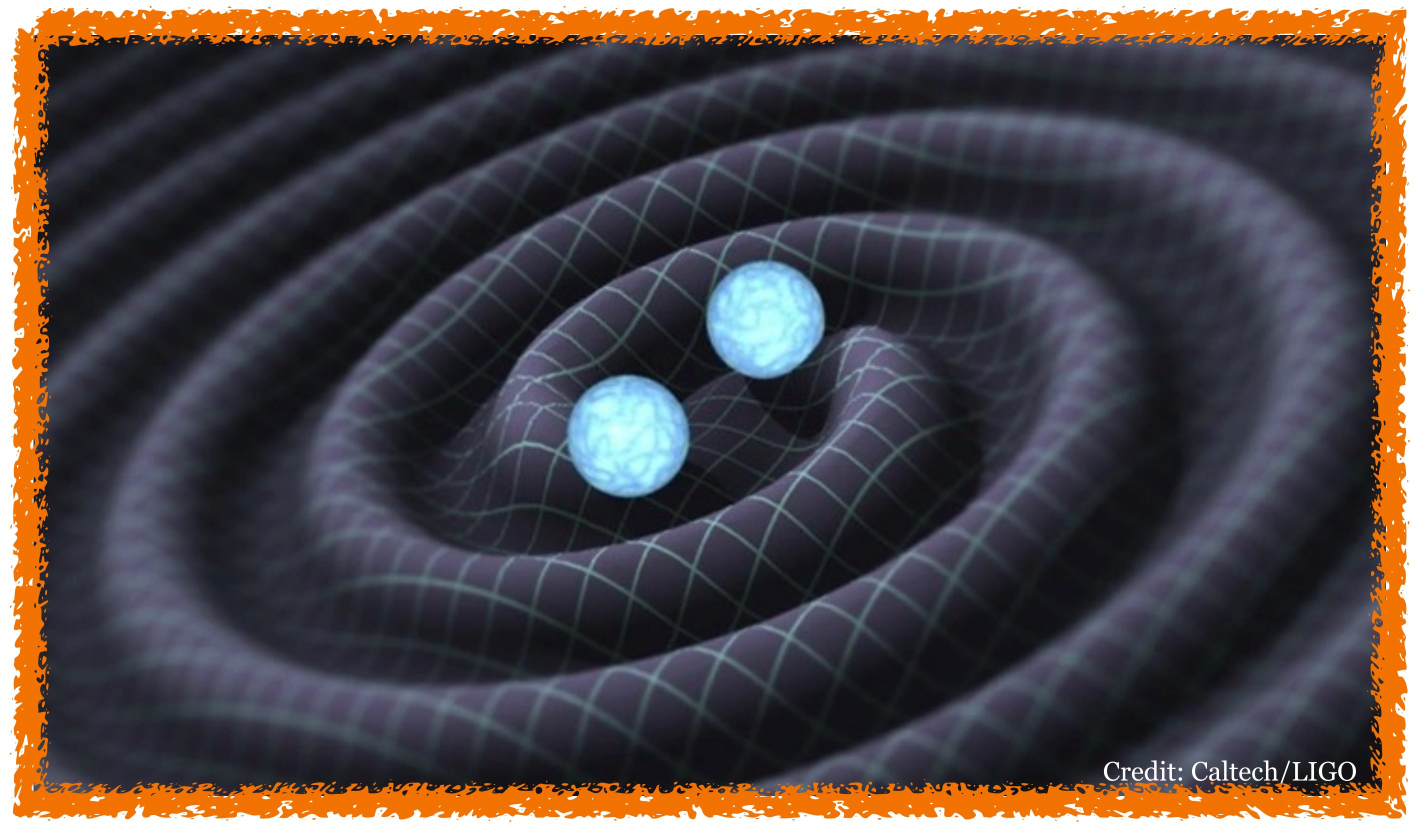




[Abbott+2017, PhRvL]

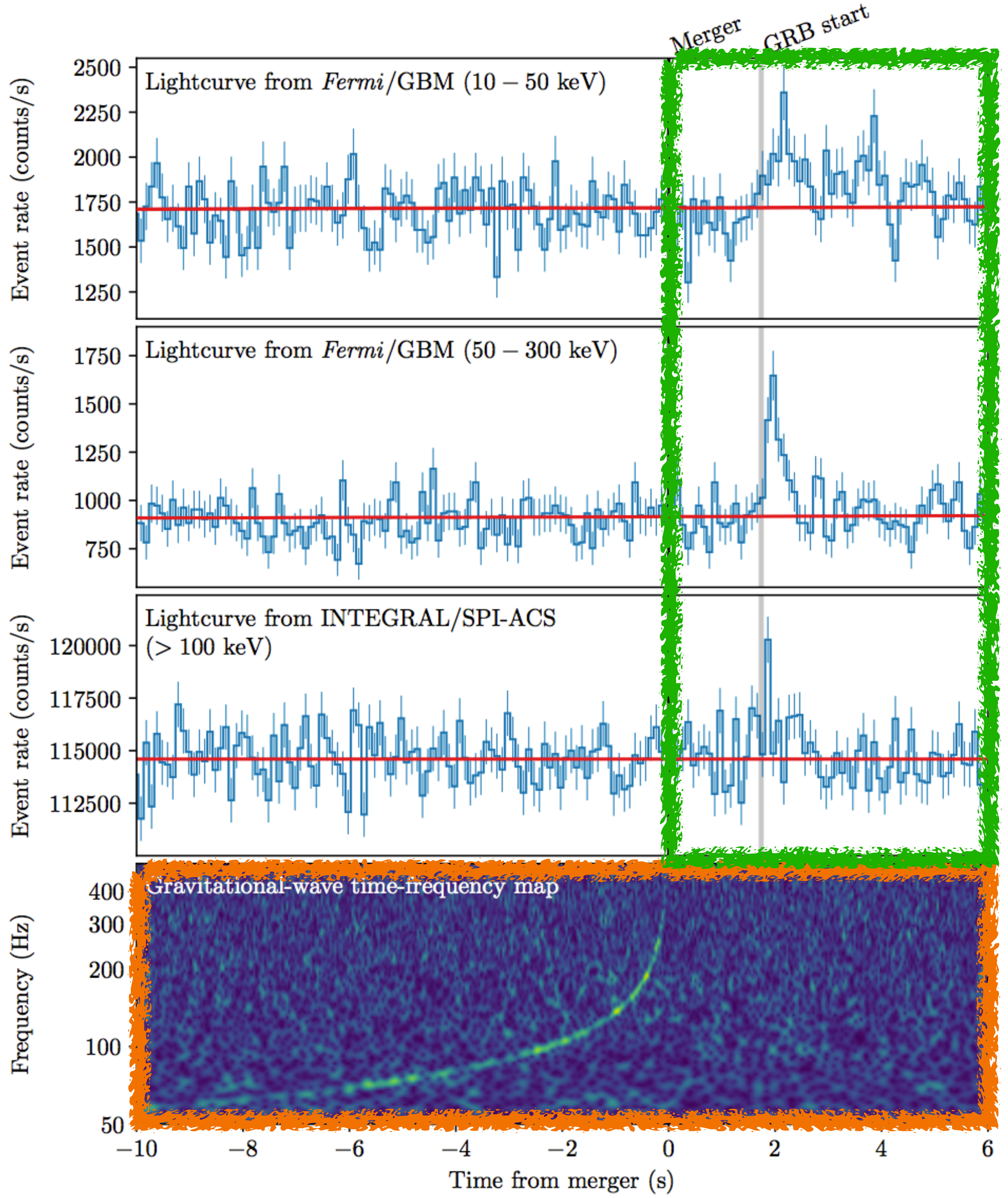
[Abbott+2017, ApJ]

The origin of “short Gamma-ray Bursts”



GRAVITY

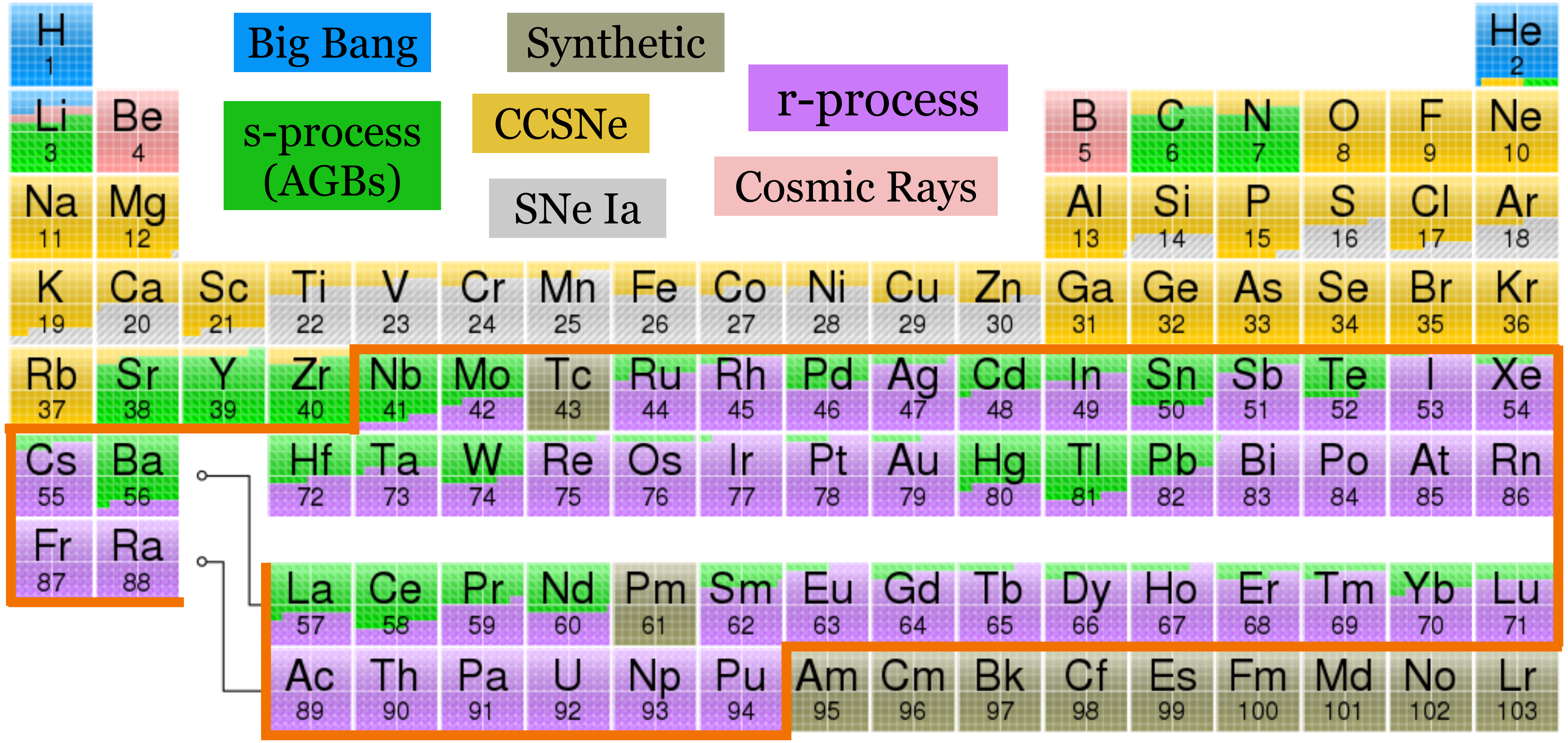
Binary Neutron Star Merger



LIGHT

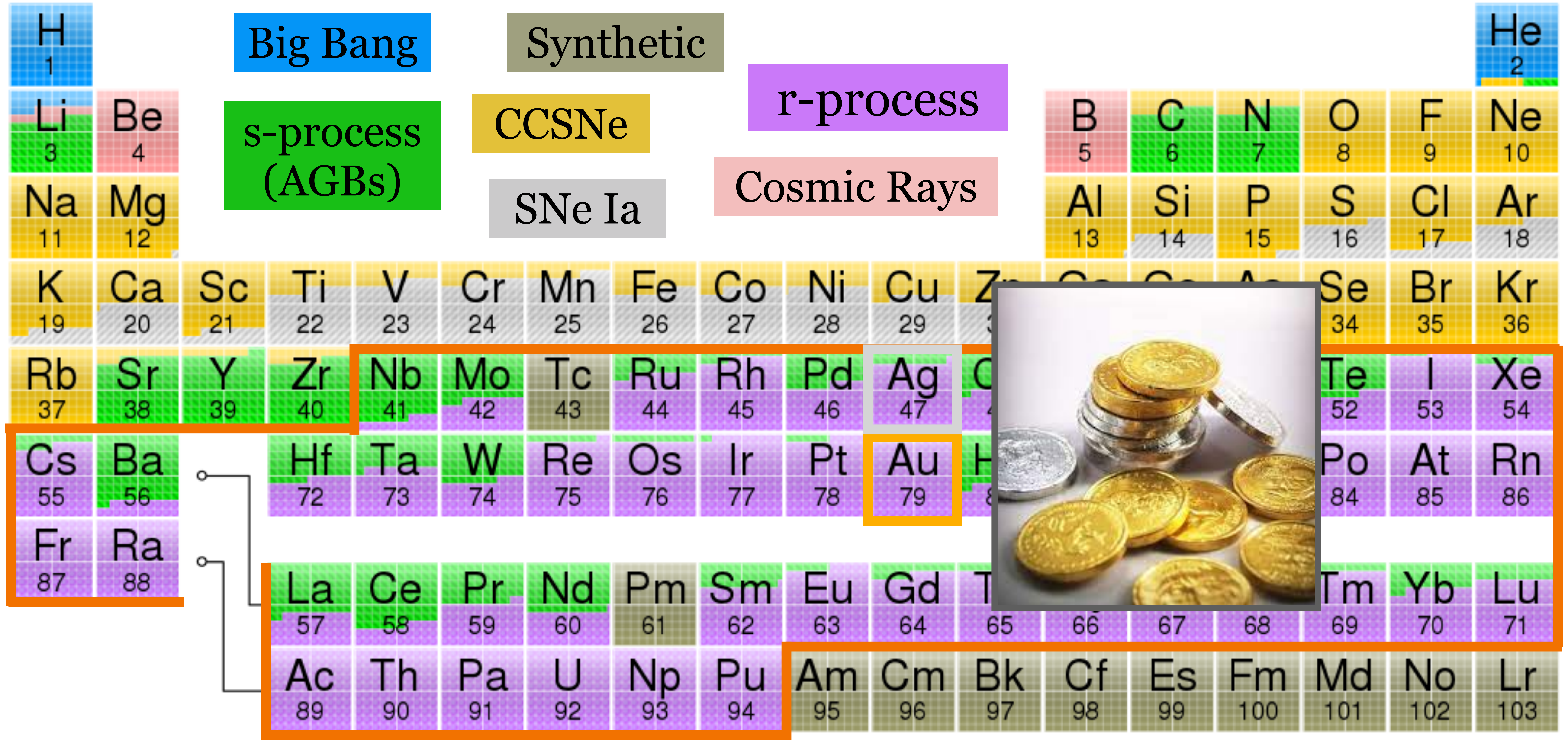
short Gamma-ray Burst

The origin of the heaviest elements in our Universe



r-process responsible for the creation of ~half of the nuclei heavier than Fe

The origin of the heaviest elements in our Universe



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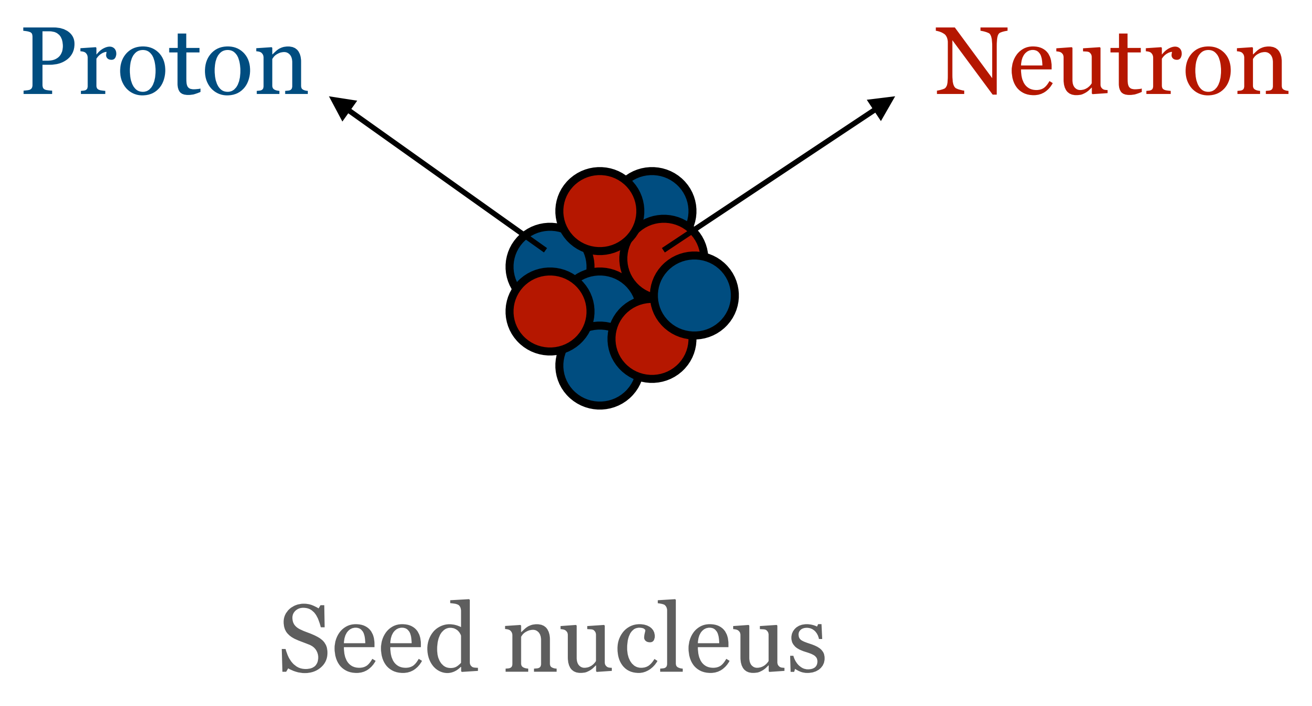
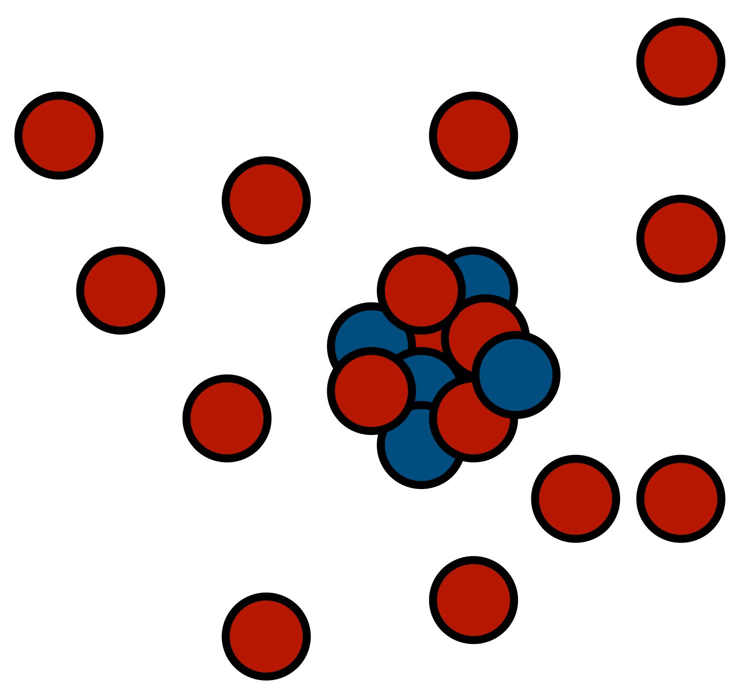


The origin of the heaviest elements in our Universe



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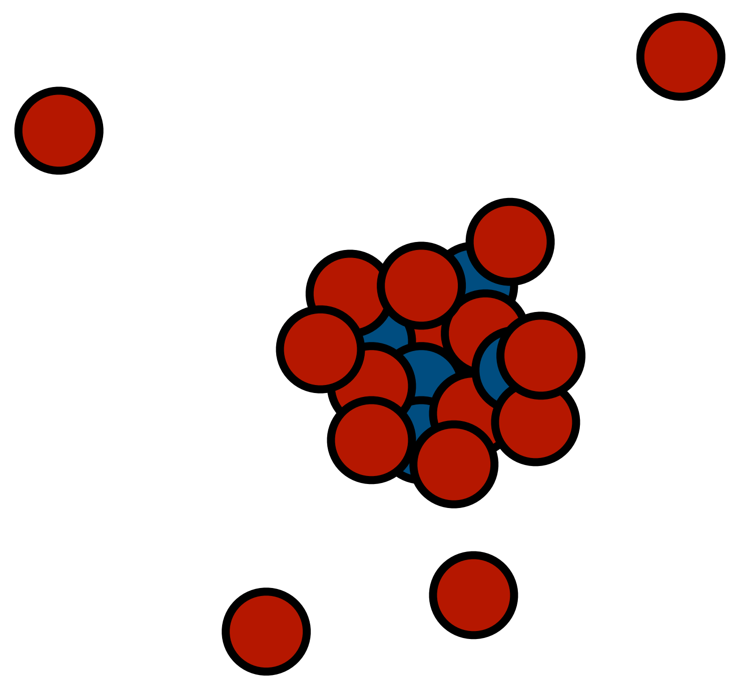
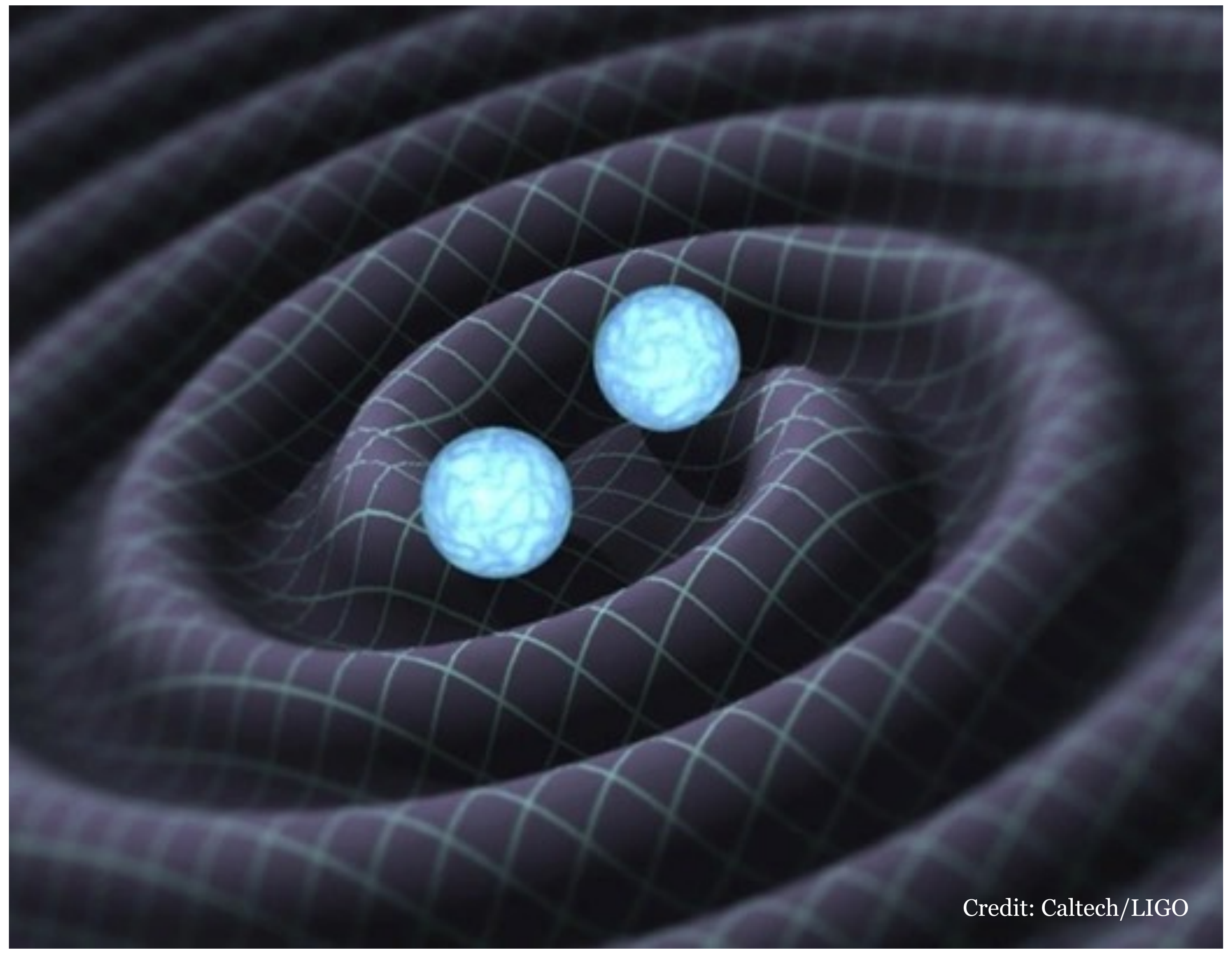
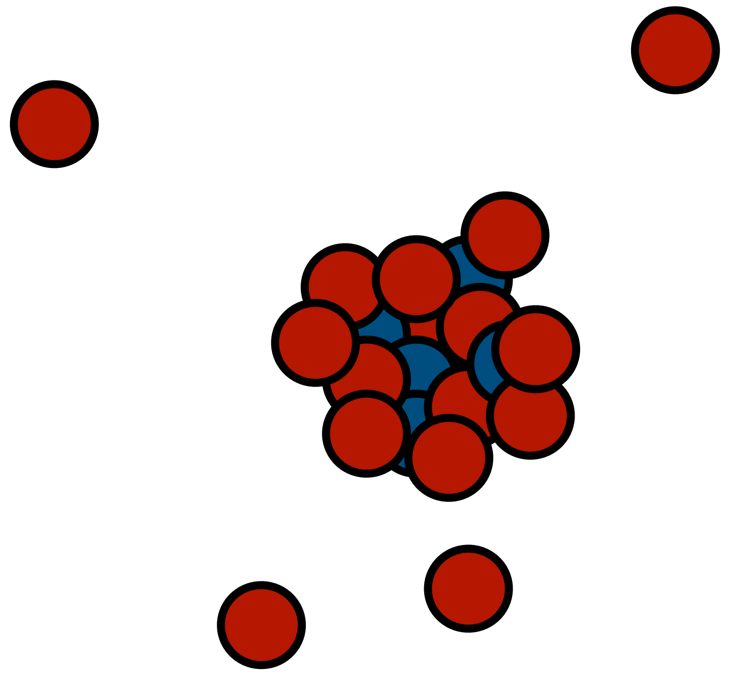


Neutron capture
via r-process

The origin of the heaviest elements in our Universe



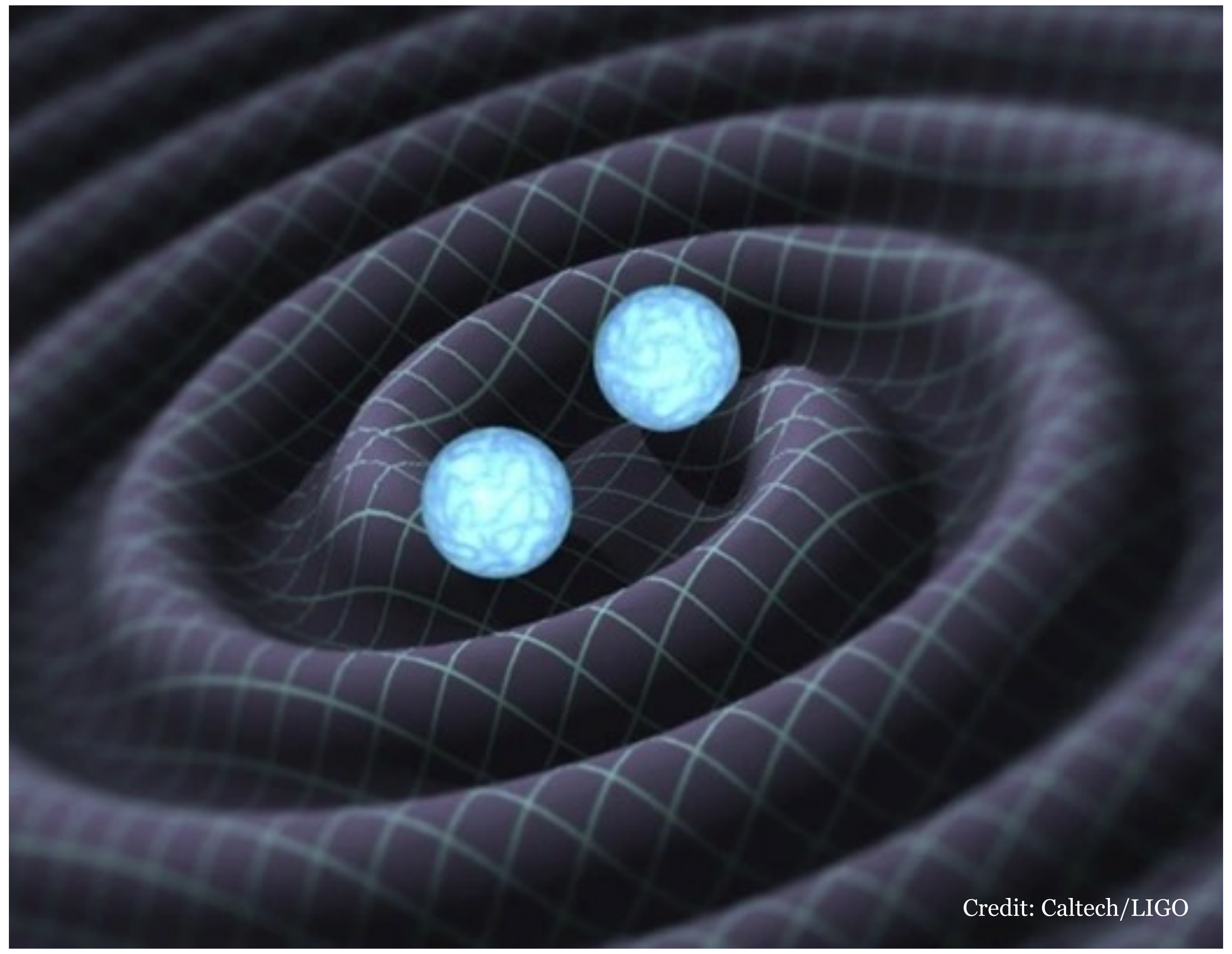
Binary Neutron Star Merger



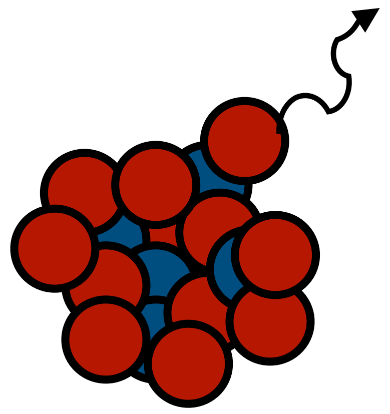
Neutron capture
via r-process

"Core-collapse" supernova explosion of massive stars

The origin of the heaviest elements in our Universe

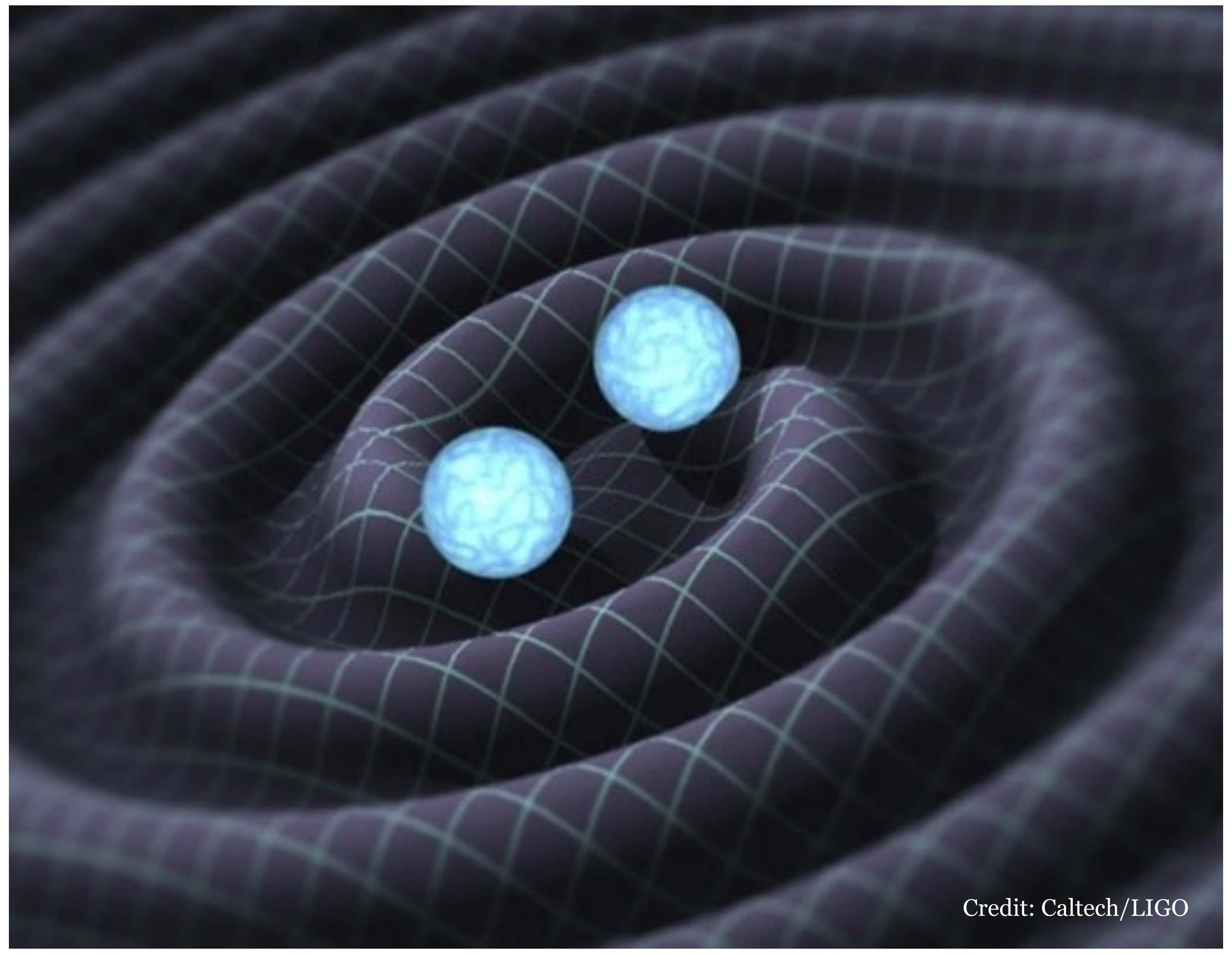


Binary Neutron Star Merger



Unstable nuclei -> radioactive decay

The origin of the heaviest elements in our Universe



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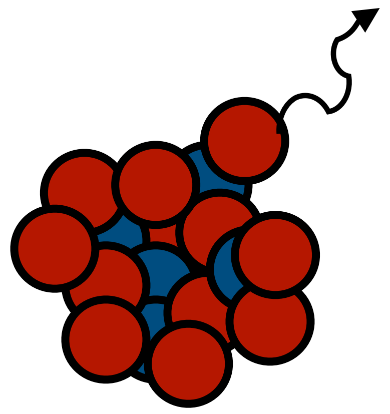
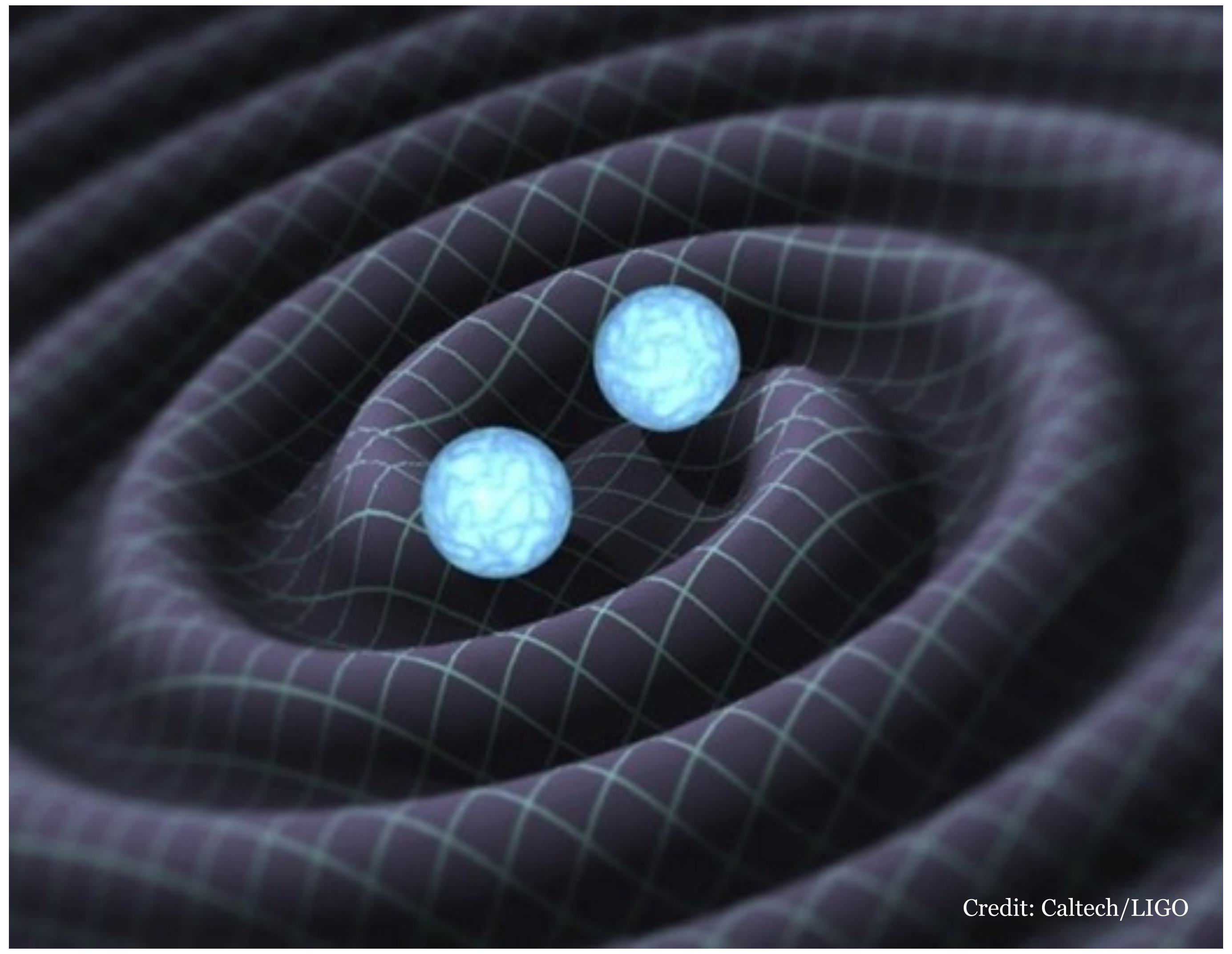
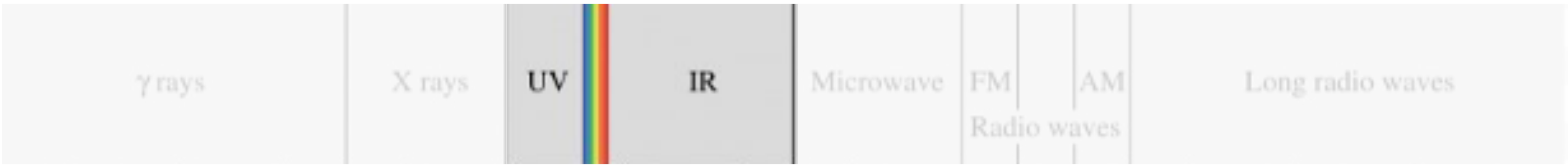


Decay products thermalise within the dense ejected material (T ~ 10 000 K)

The origin of the heaviest elements in our Universe

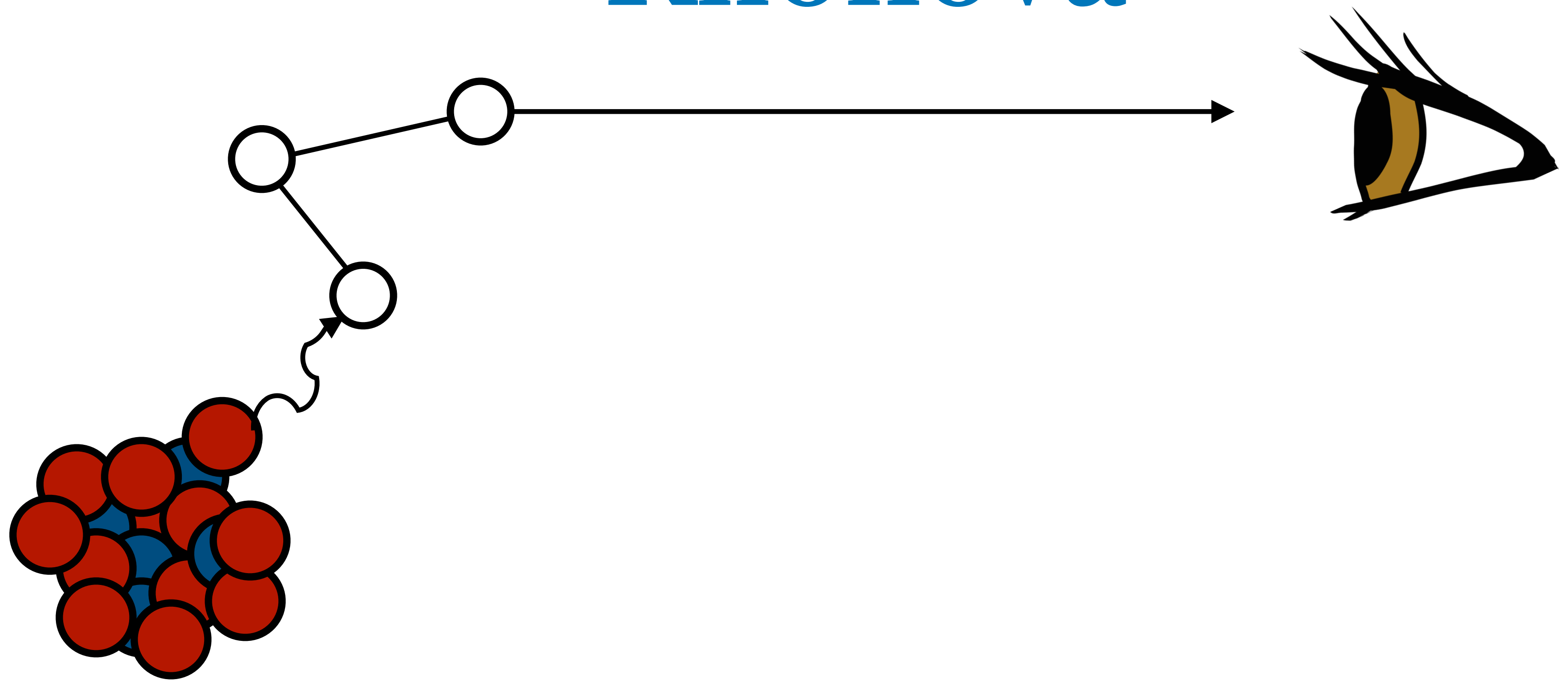


Binary Neutron Star Merger



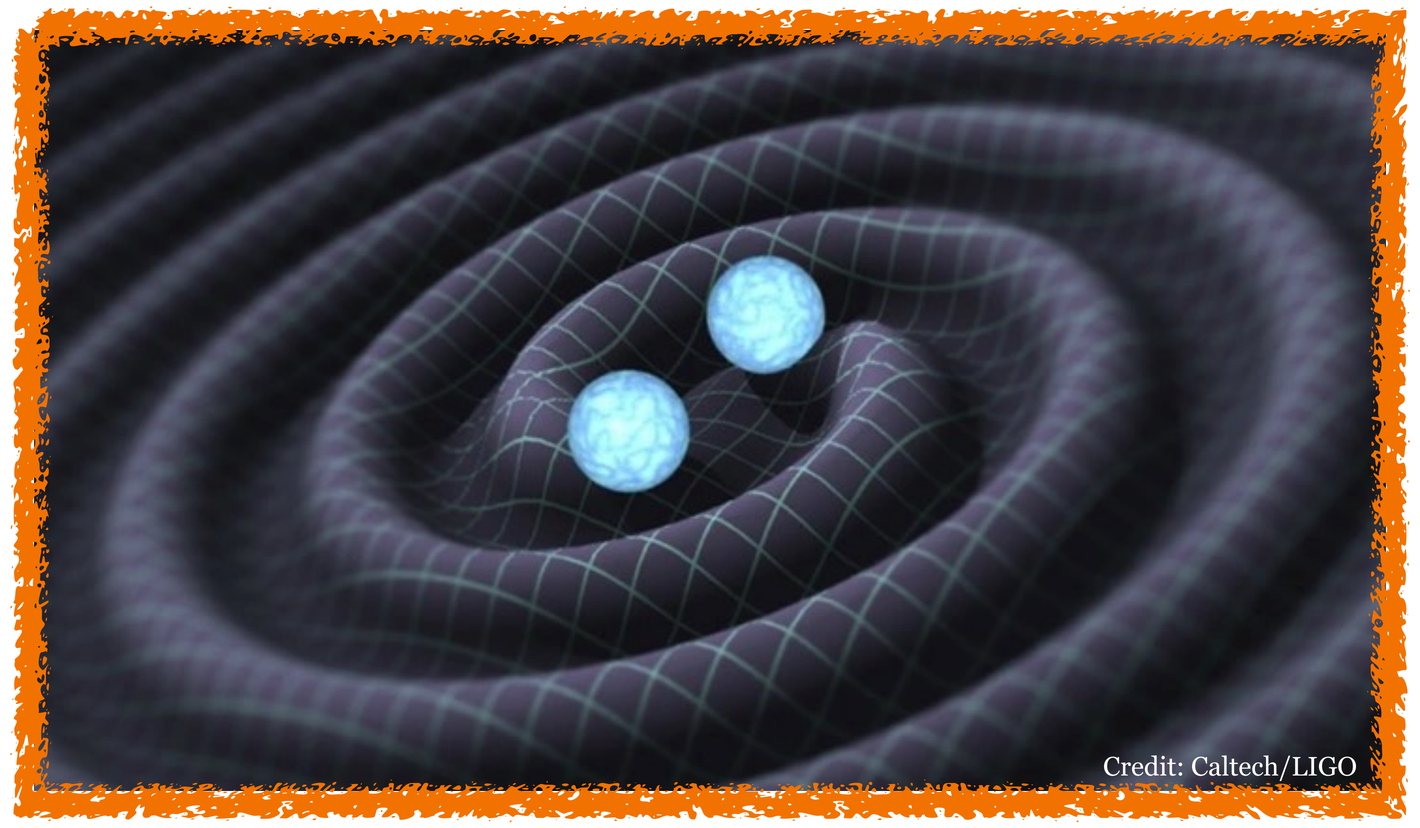
—> Increasing wavelength

Kilonova



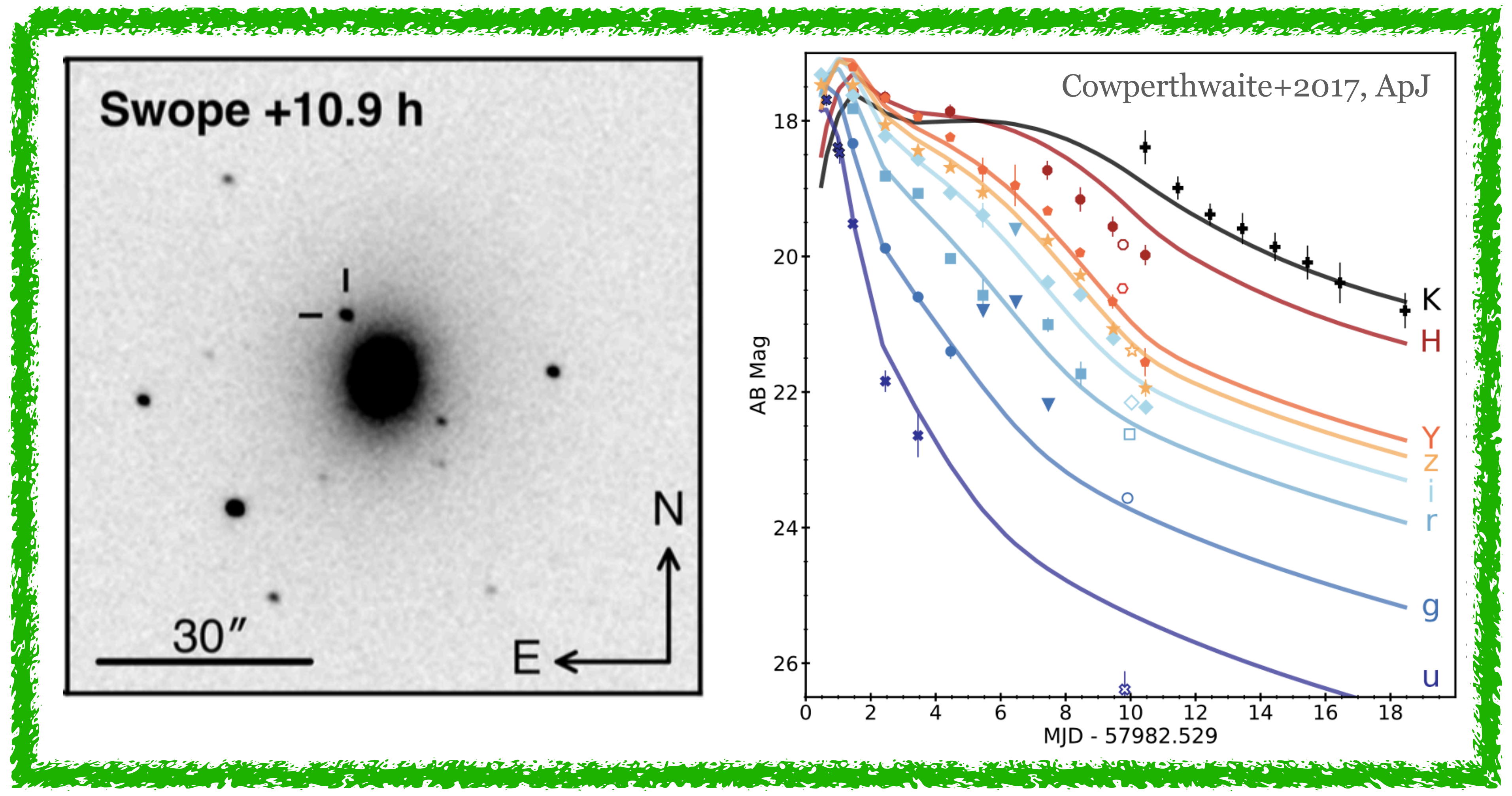
Thermal emission at ultraviolet-optical-infrared wavelengths

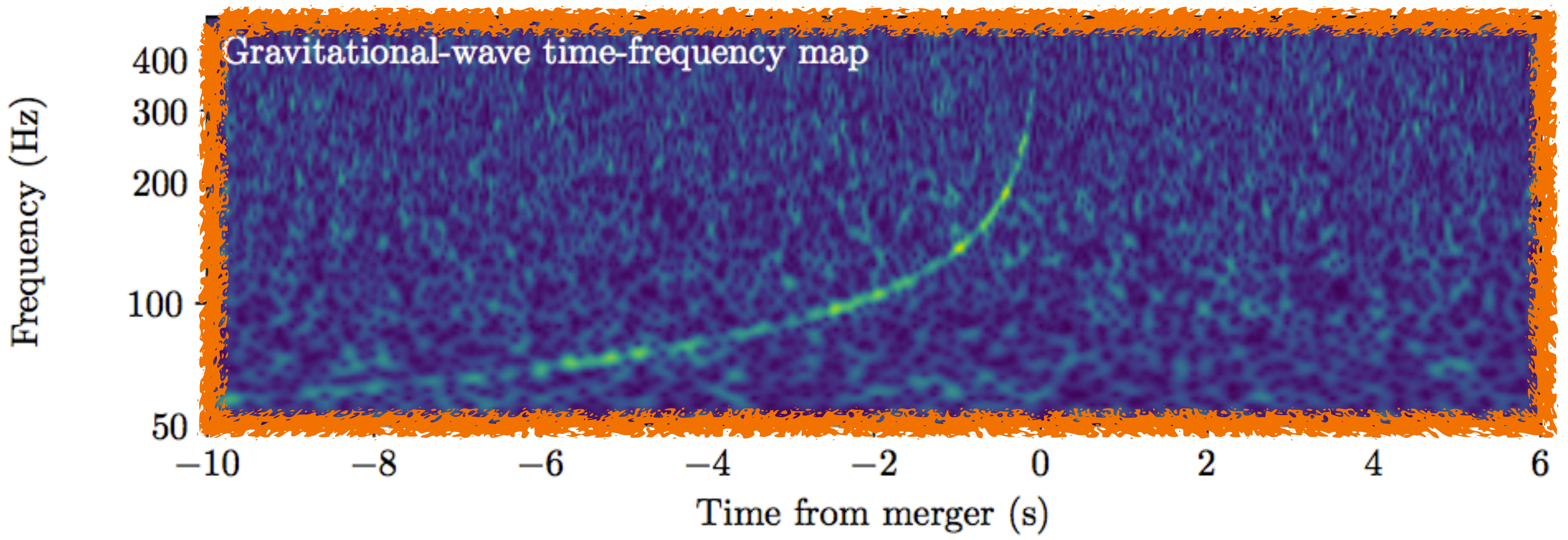
The origin of the heaviest elements in our Universe



GRAVITY

Binary Neutron Star Merger

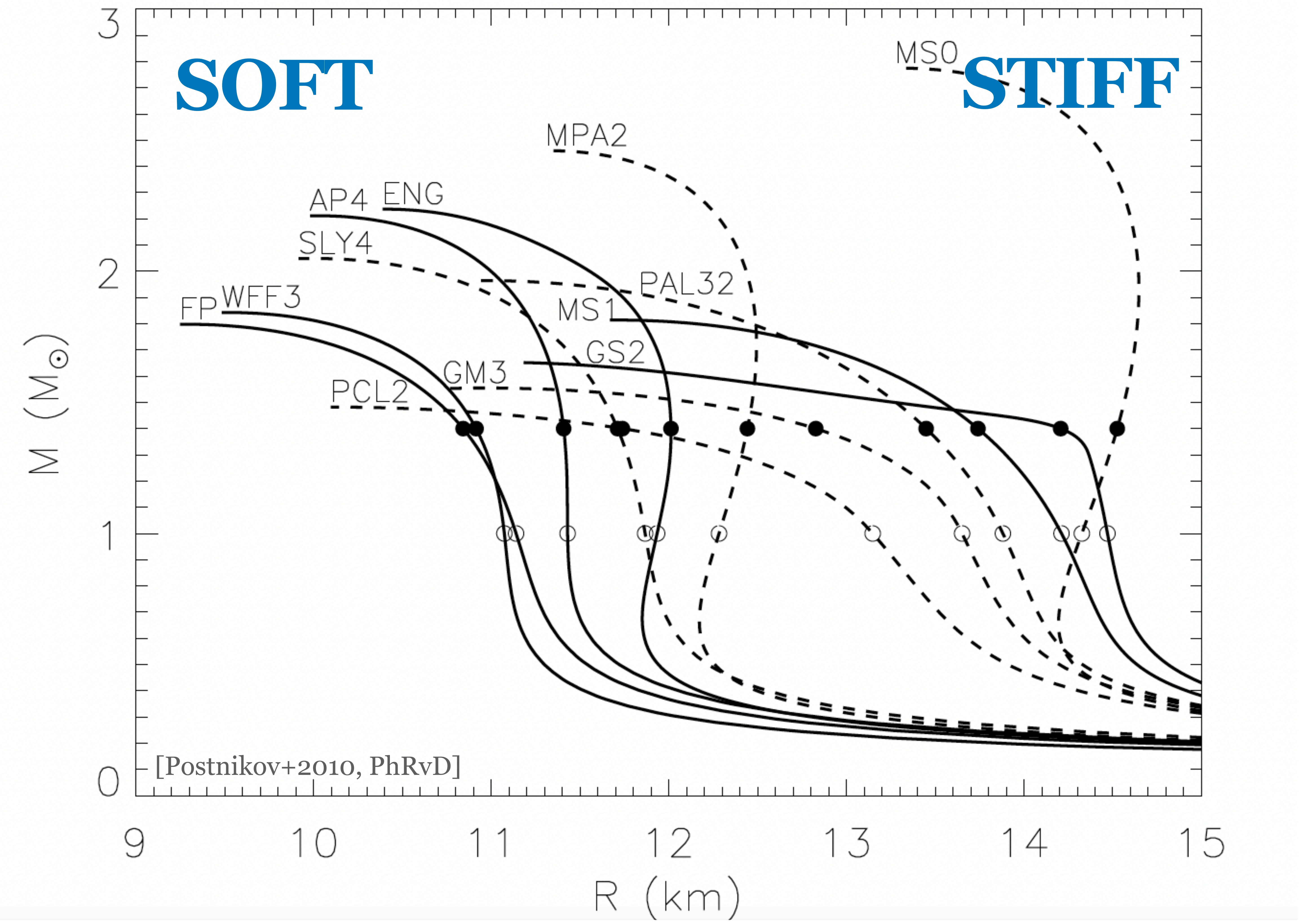




LIGHT

Kilonova
from radioactive decay of
r-process elements
freshly synthesised

Constraints on the Equation of State of nuclear matter



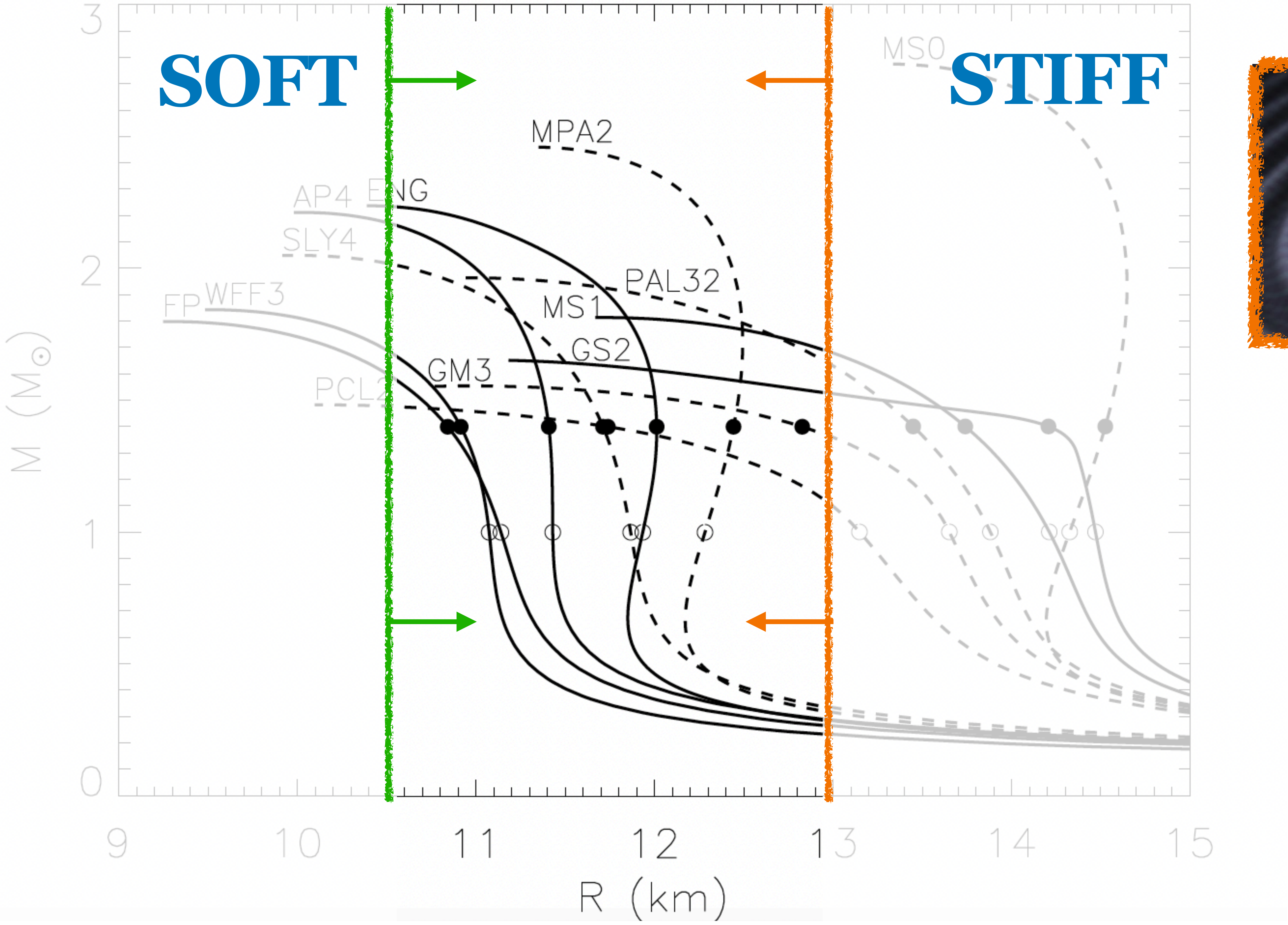
Constraints on the Equation of State of nuclear matter

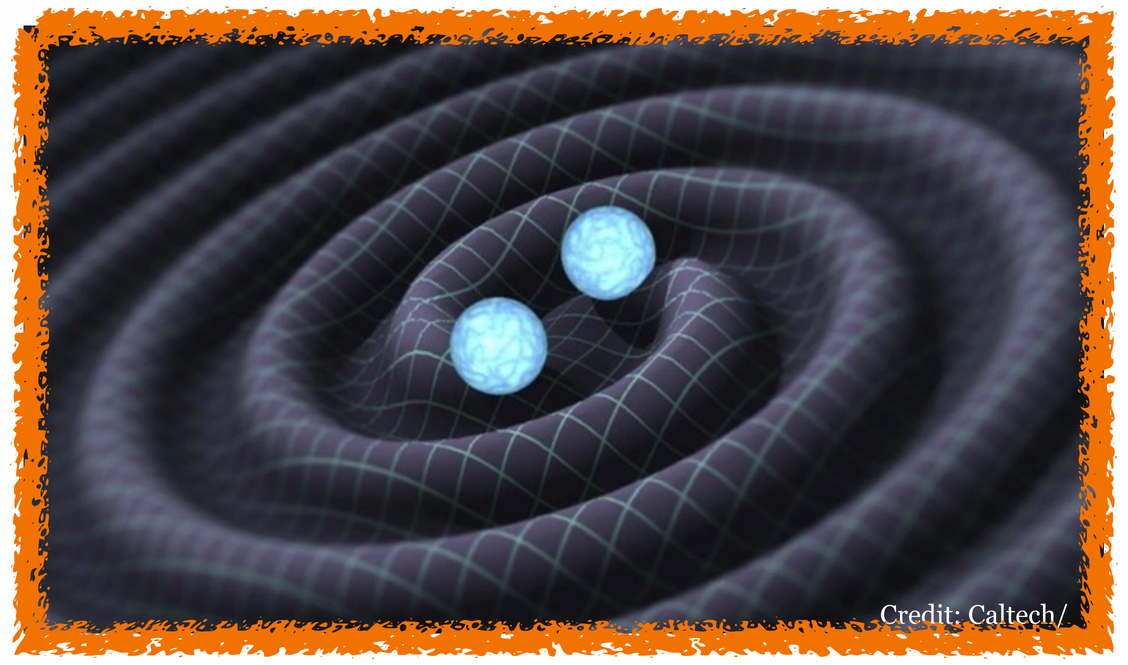
LIGHT

Some matter
was ejected

↓

no direct collapse
to a black hole





GRAVITY

No tidal effects

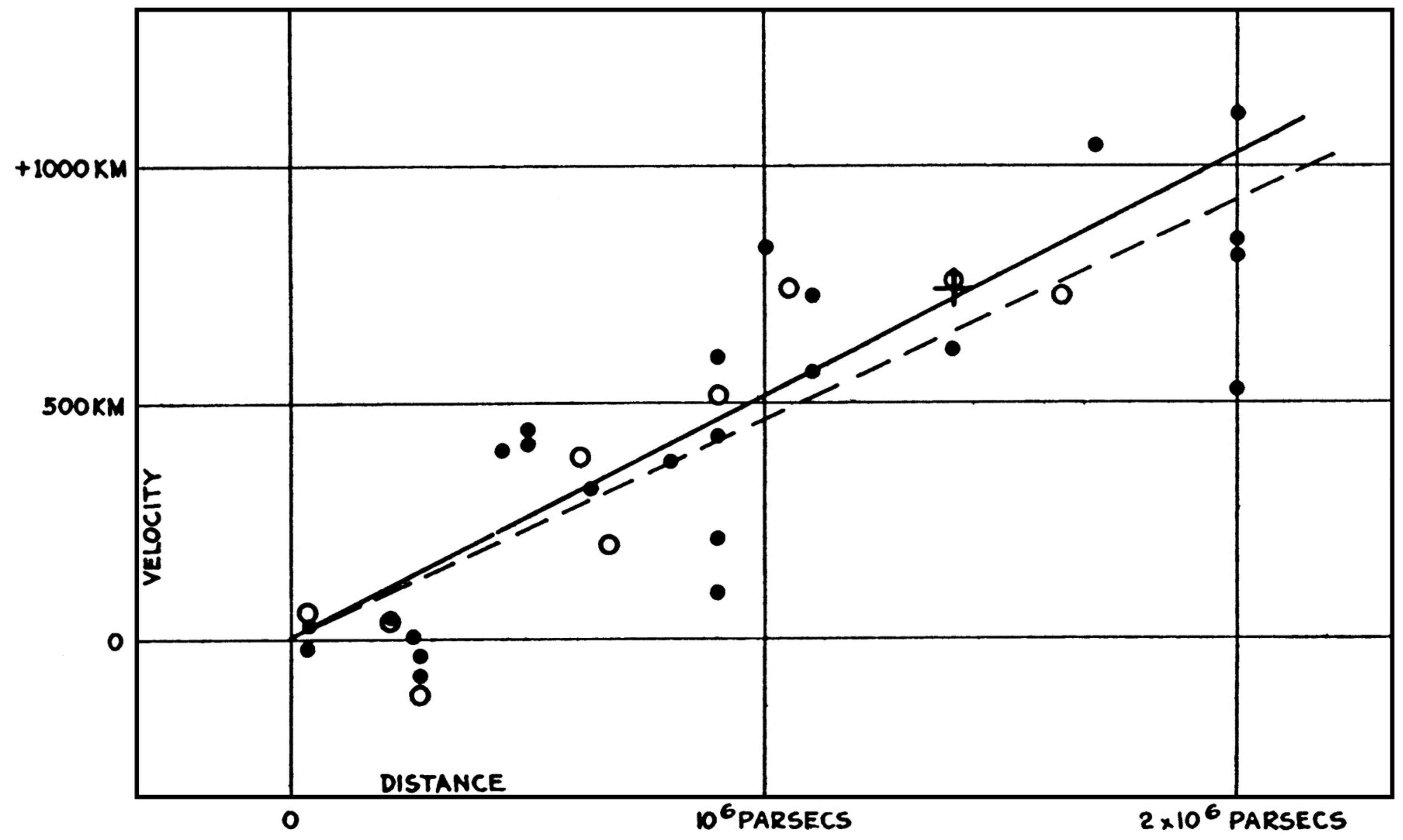
The Hubble constant H_0

The local expansion rate of the Universe

$$H_0 = \frac{\text{Velocity}}{\text{Distance}}$$

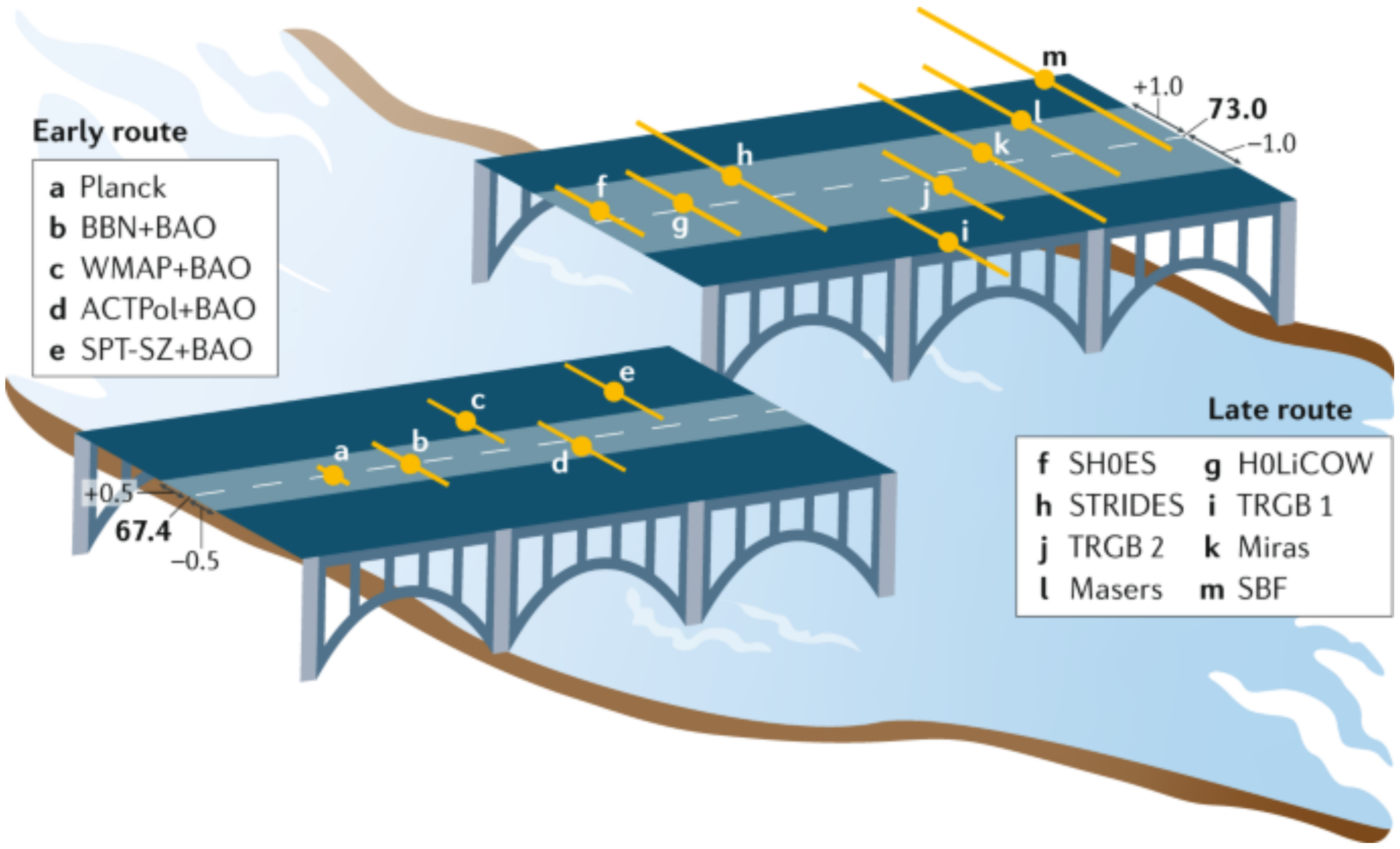
[Hubble 1929, PNAS]

Velocity



Distance

The Hubble tension



[Riess 2019, NatRP]

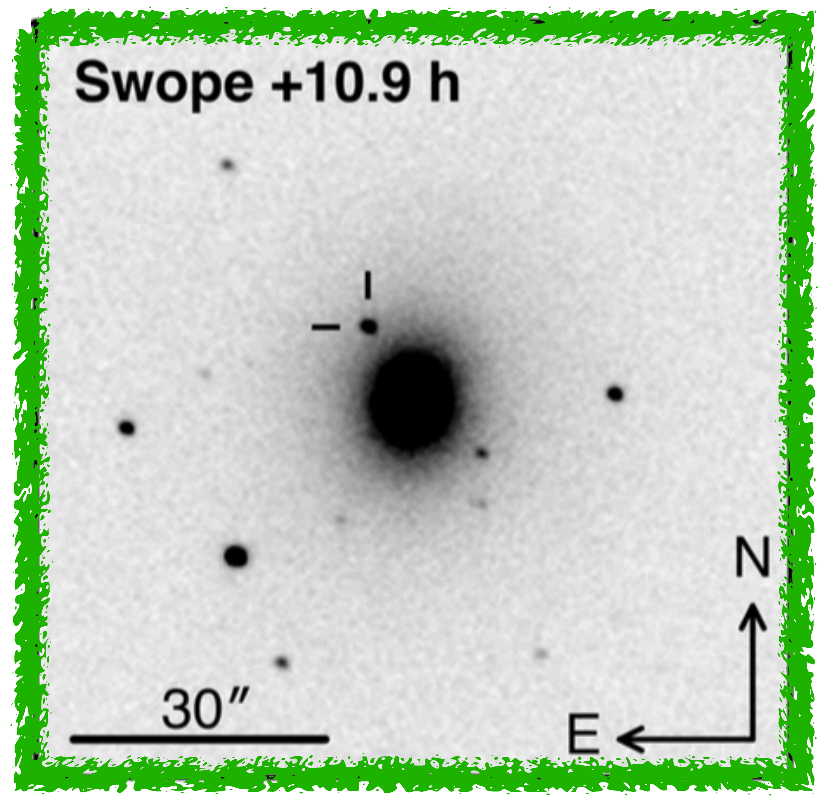
The Hubble constant H₀

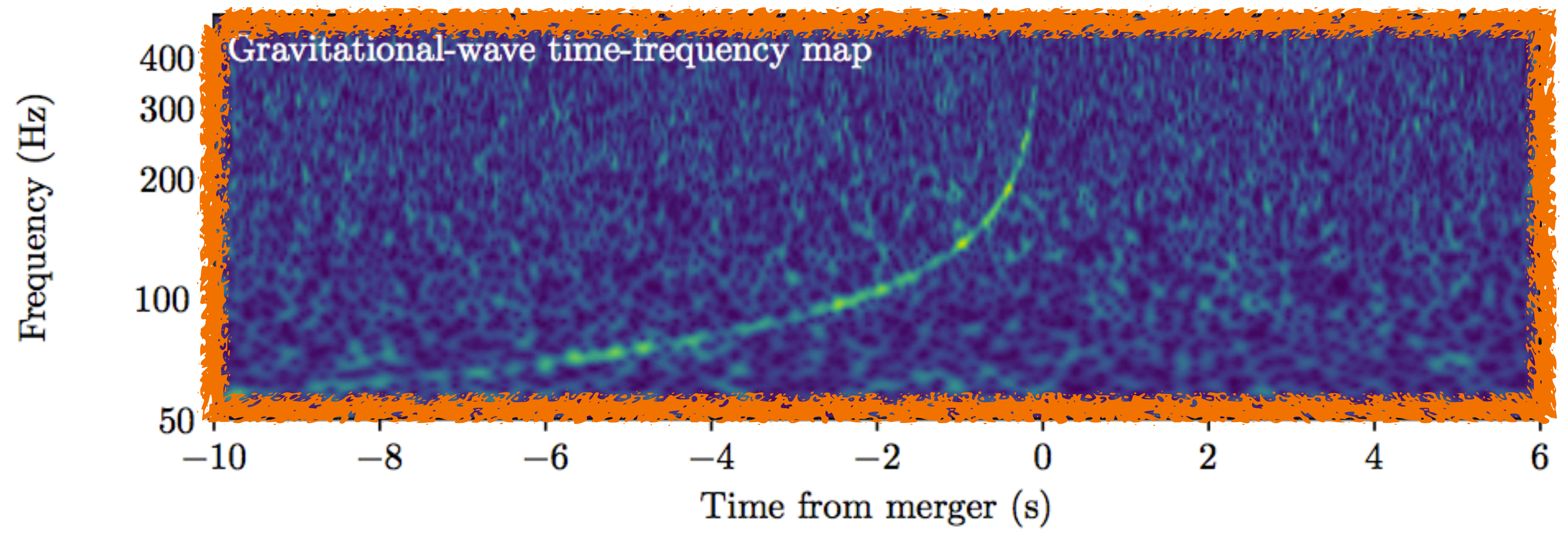
Gravitational Waves as Standard Sirens

[Schutz 1986, Nature; Holz & Hughes 2005, ApJ]

LIGHT

$$H_0 = \frac{\text{Velocity}}{\text{Distance}} = \frac{[\text{speed of light}] \cdot \boxed{\text{Redshift}}}{\boxed{\text{Distance}}}$$





GRAVITY

The Hubble constant H_0

Gravitational Waves as Standard Sirens

[Schutz 1986, Nature; Holz & Hughes 2005, ApJ]

LIGHT

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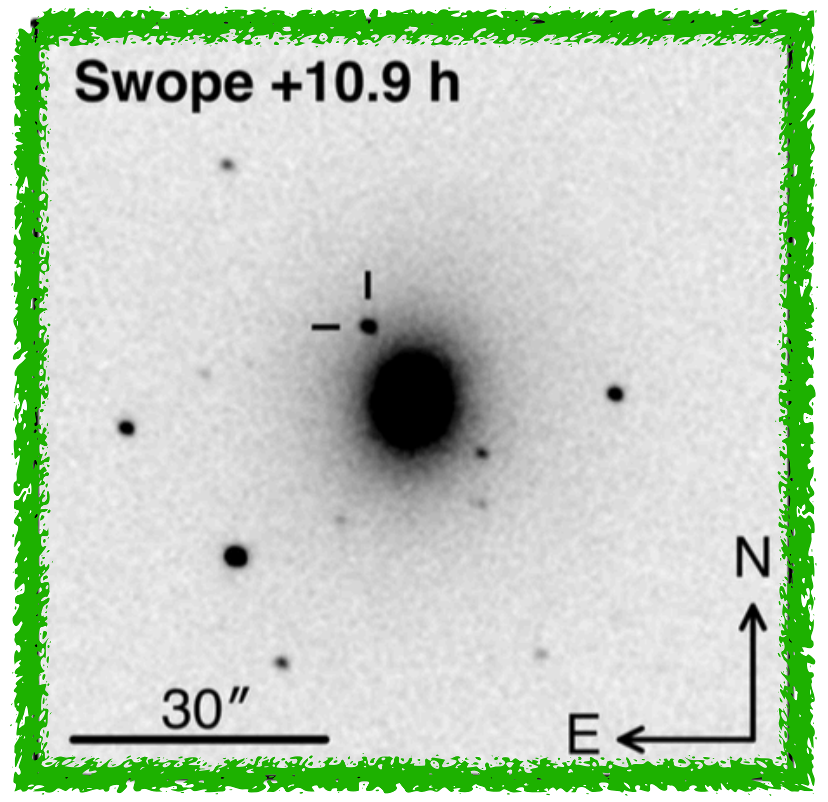
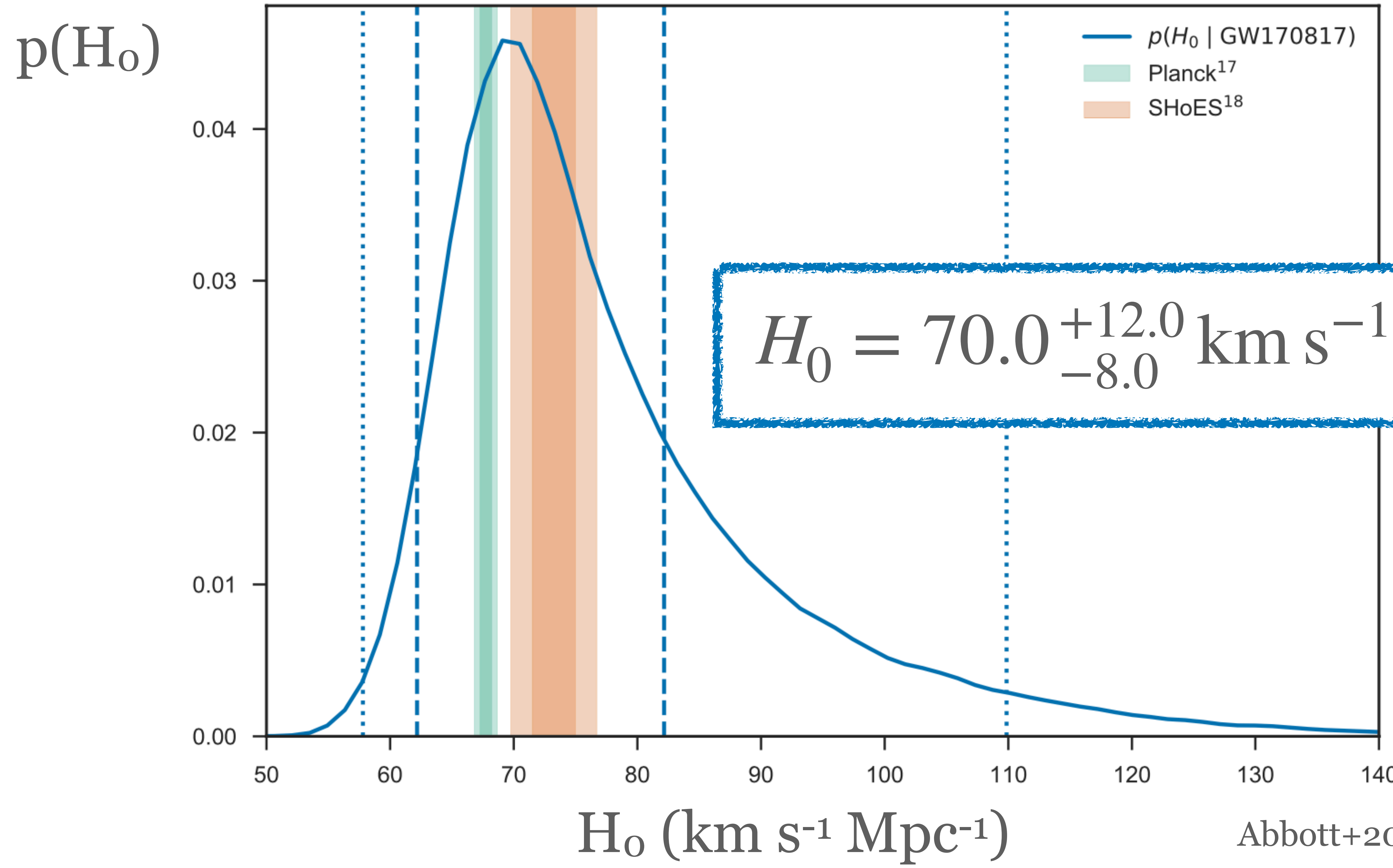
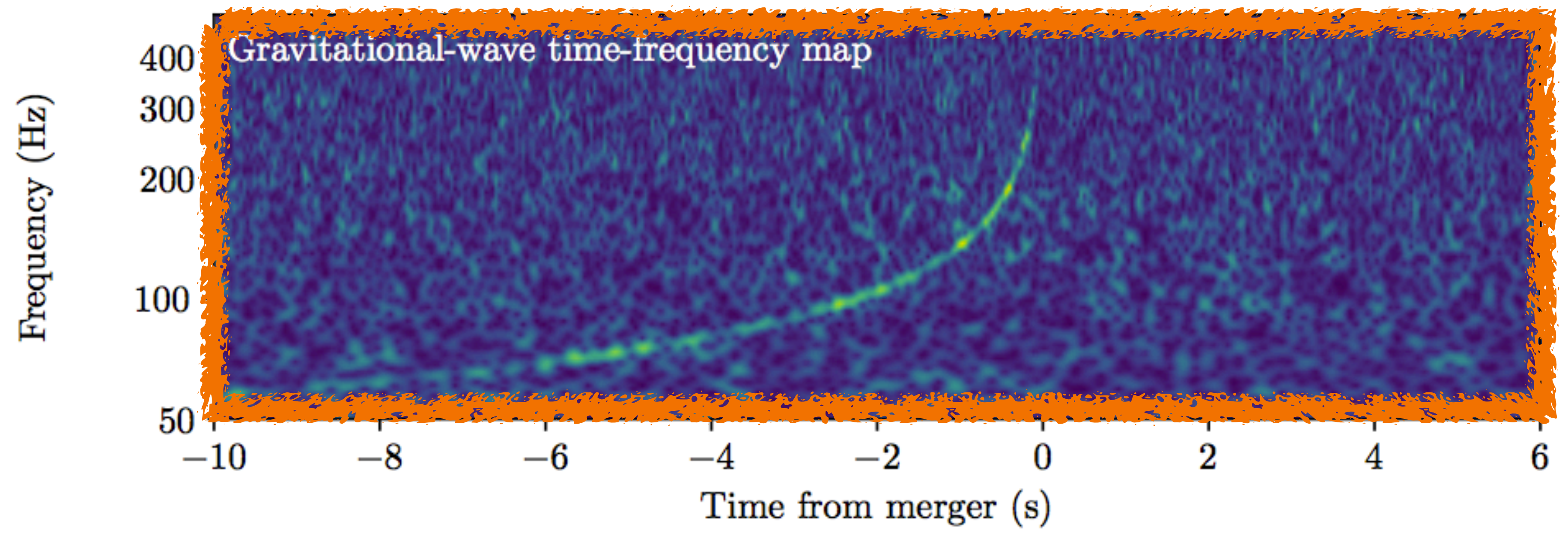




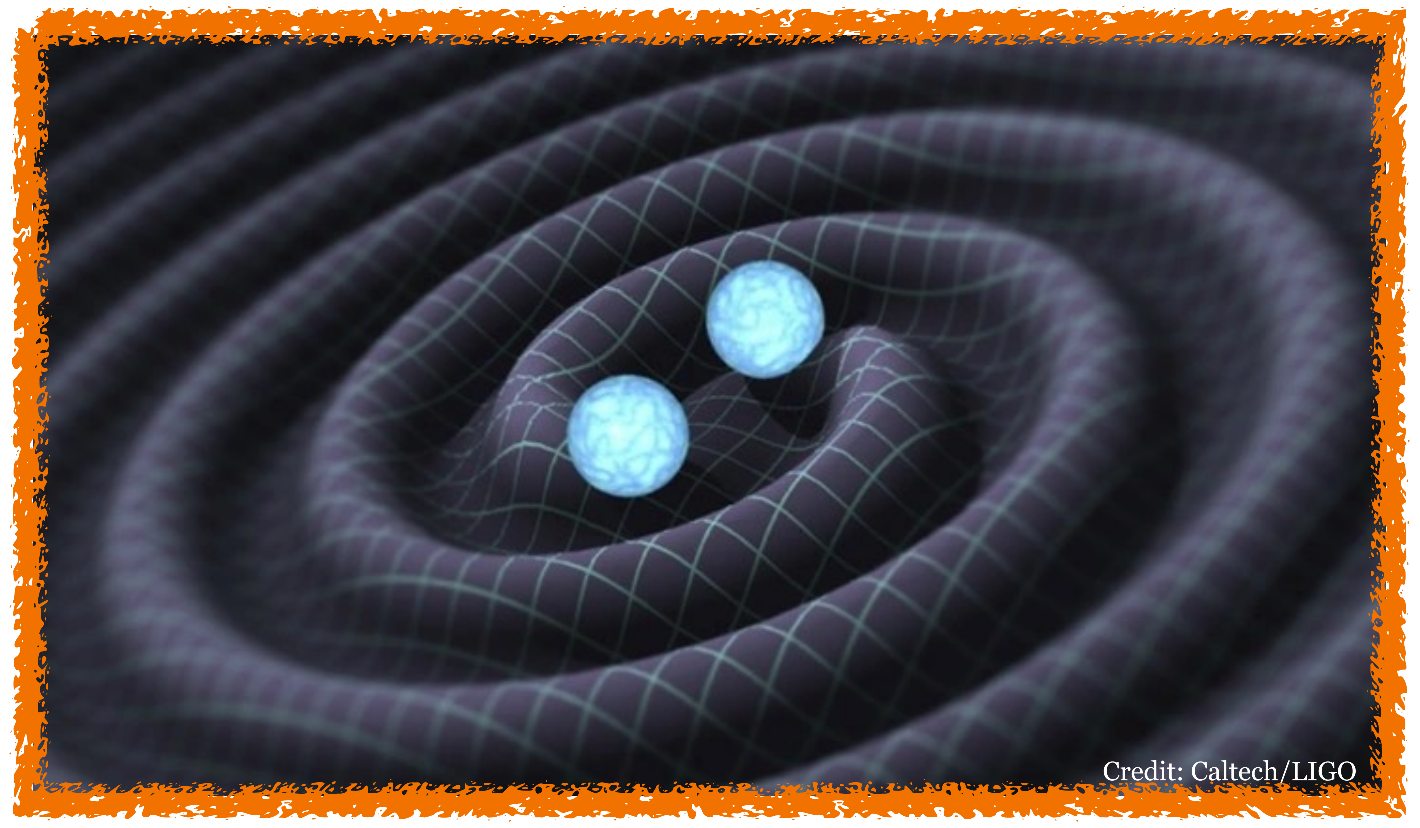
$$\boxed{H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}$$



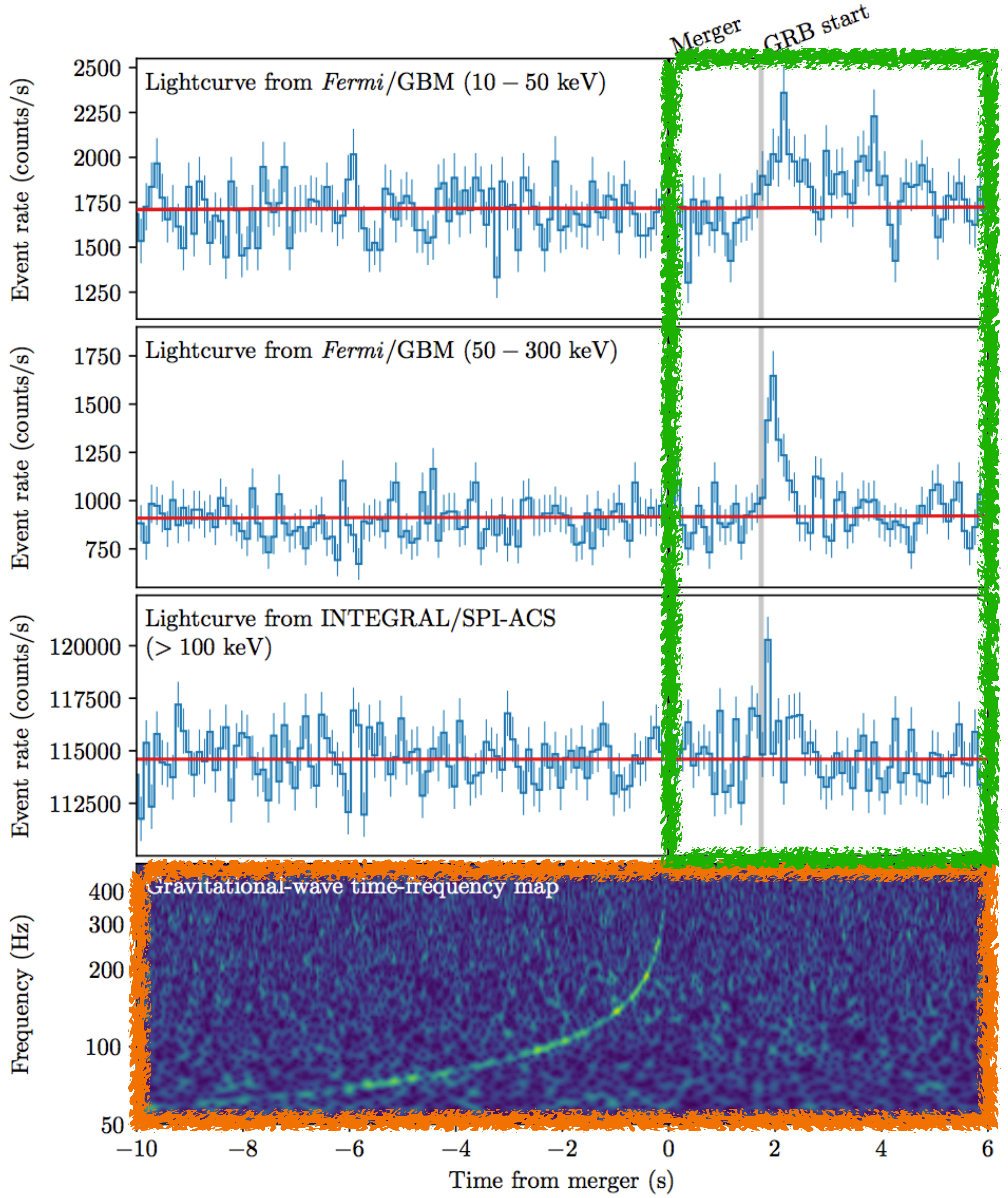
Abbott+2017, Nature

GRAVITY

Ruling out some Dark Energy models



GRAVITY



LIGHT

1.7 s delay in a journey of ~130 million light years

Ruling out some Dark Energy models

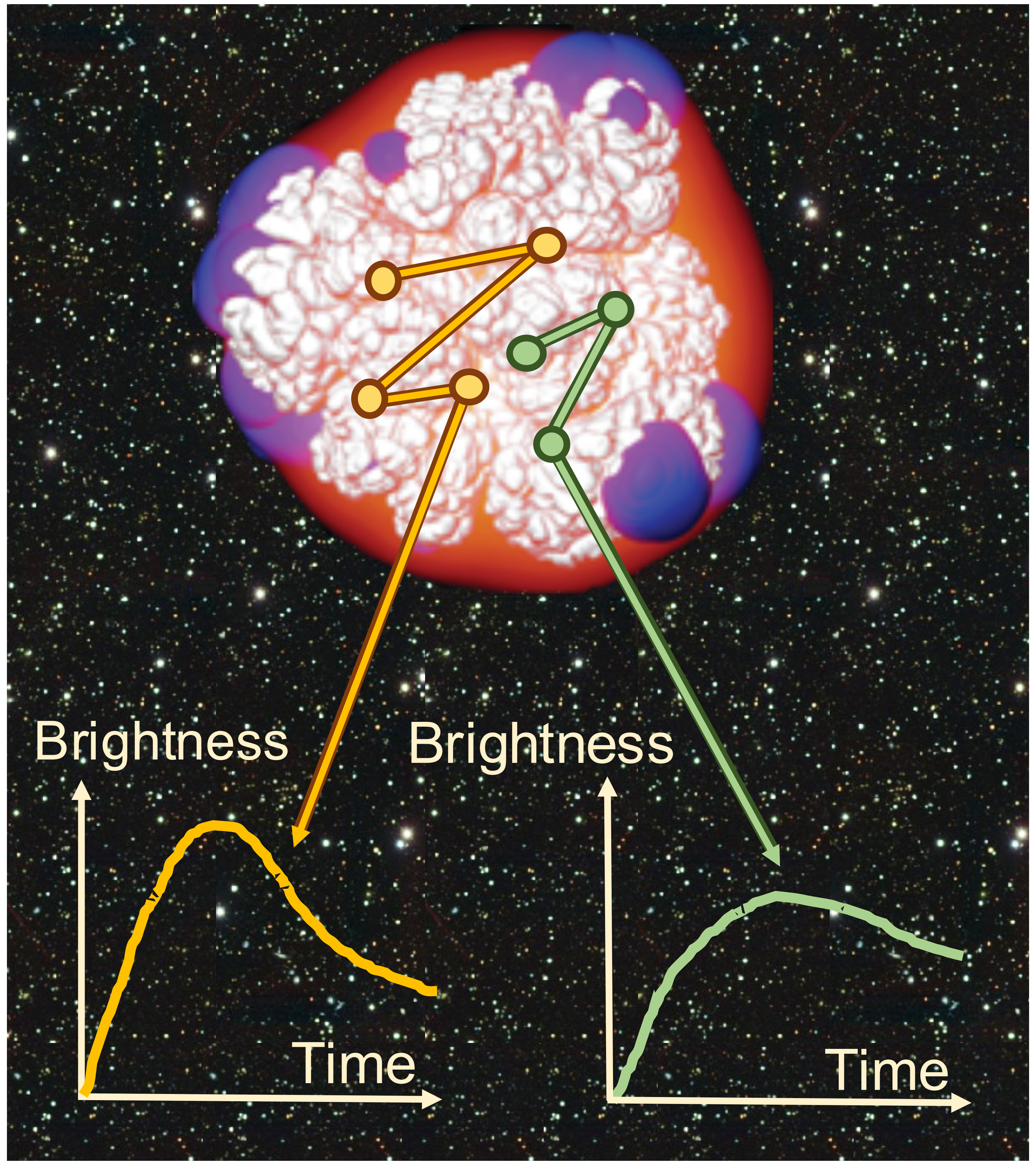
	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/$f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu}\phi^\mu\phi^\nu$ [51], $f(\phi)\cdot$Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

$$\left| \frac{c_g}{c} - 1 \right| < 5 \times 10^{-16}$$

Ezquiaga & Zumalacárregui 2017, PRL

A few words about my research in Stockholm

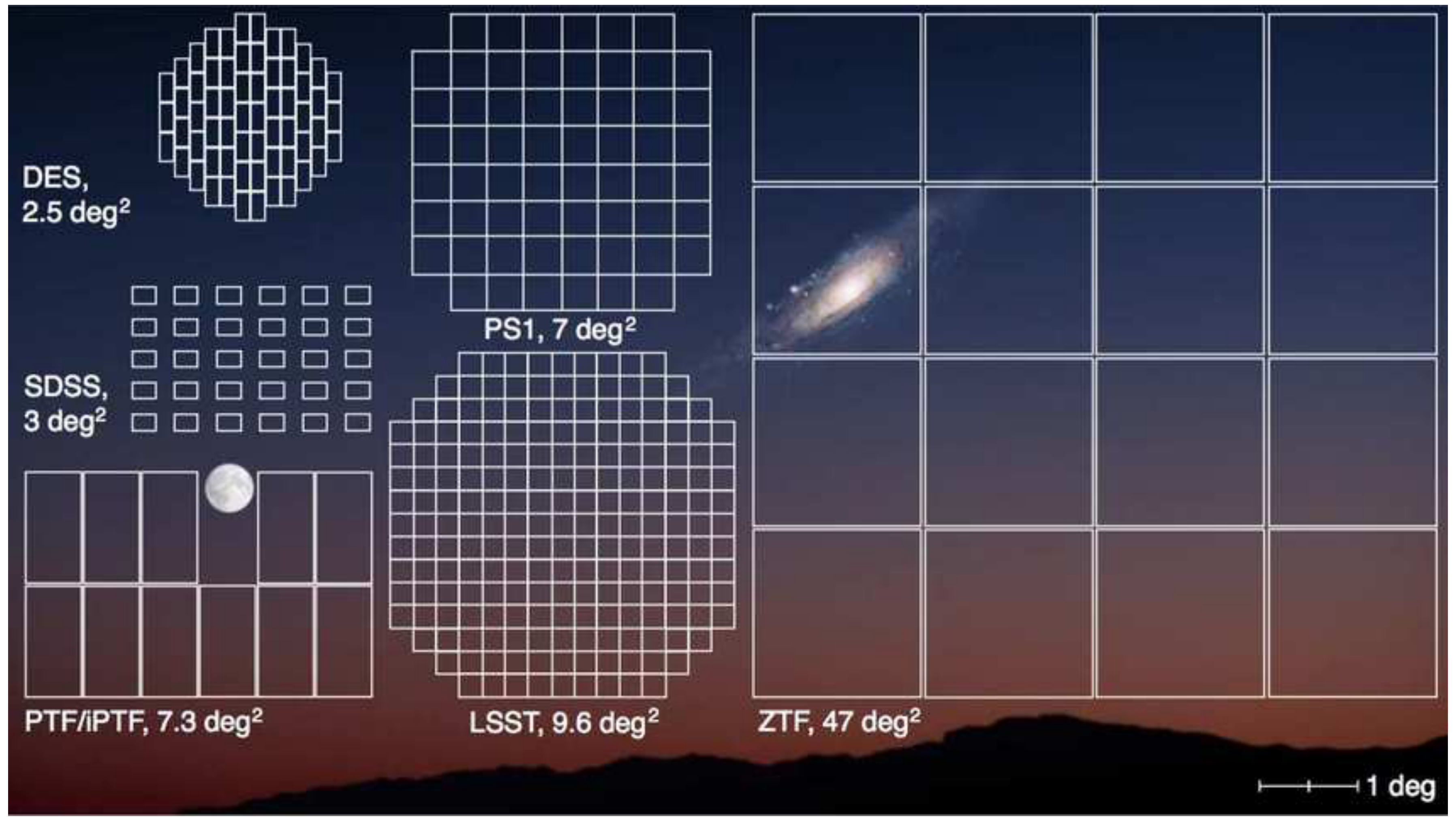
Modelling kilonovae



Radiative transfer code POSSIS [MB 2019, MNRAS]

Hunting for kilonovae with the Zwicky Transient Facility

Palomar Observatory
1872 m above sea level in California



Large camera ideal for catching
rare and rapidly-fading events like kilonovae

Stockholm University
Oskar Klein centre
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