Siste nytt om gravitasjonsbølger

Øyvind G. Grøn

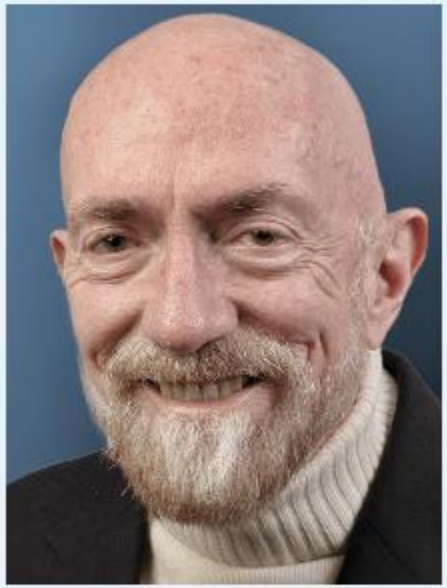
TAF

8. november 2016

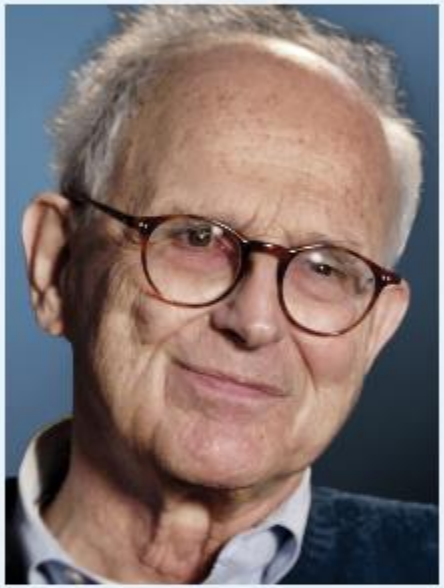
Det Norske Vitenskapsakademi annonserte 2. juni 2016

The Norwegian Academy of Science and Letters awards the 2016 Kavli Prize in Astrophysics to:

Ronald Drever
California Institute of Technology, USA



Kip Thorne
California Institute of Technology, USA

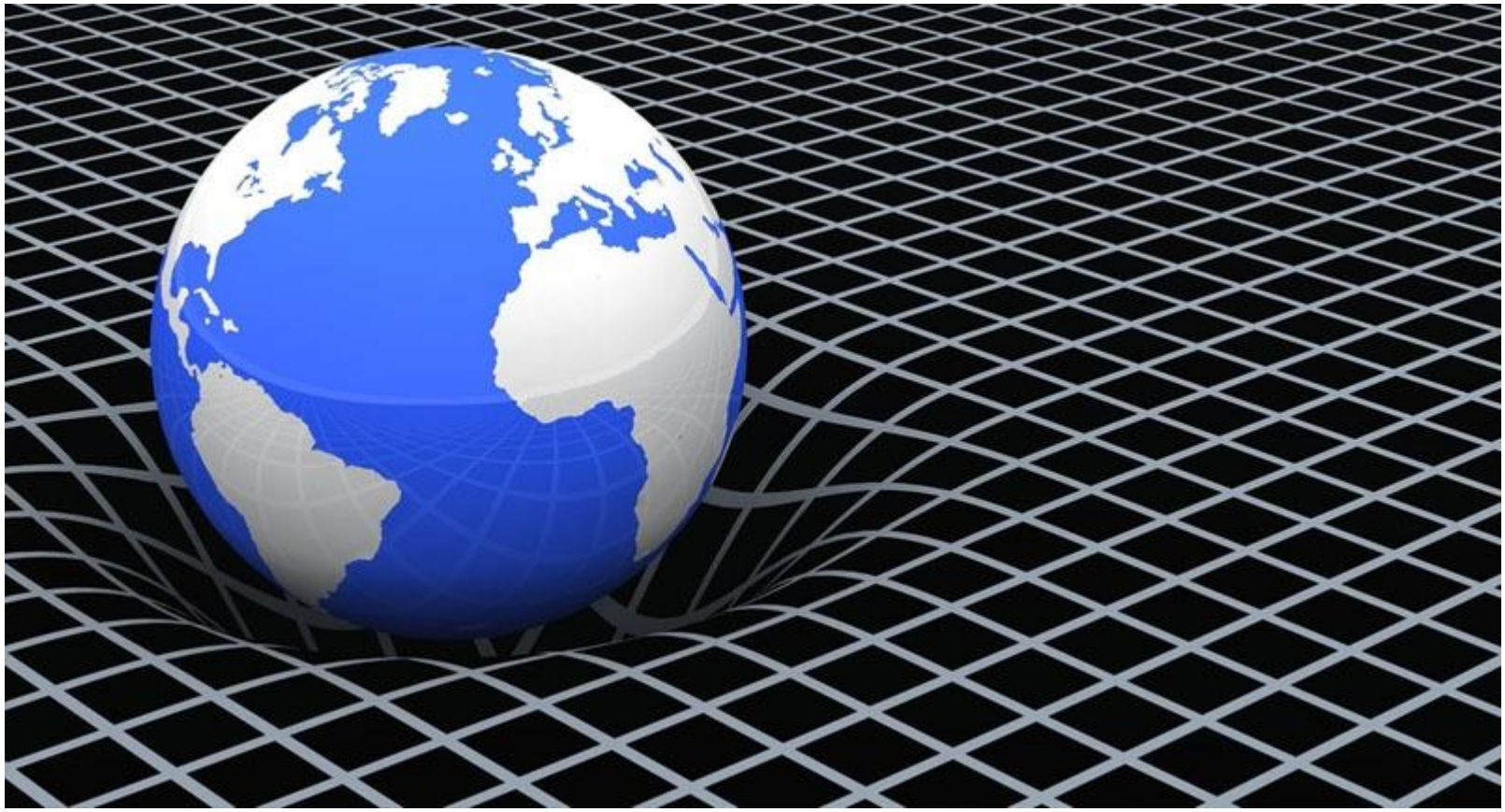


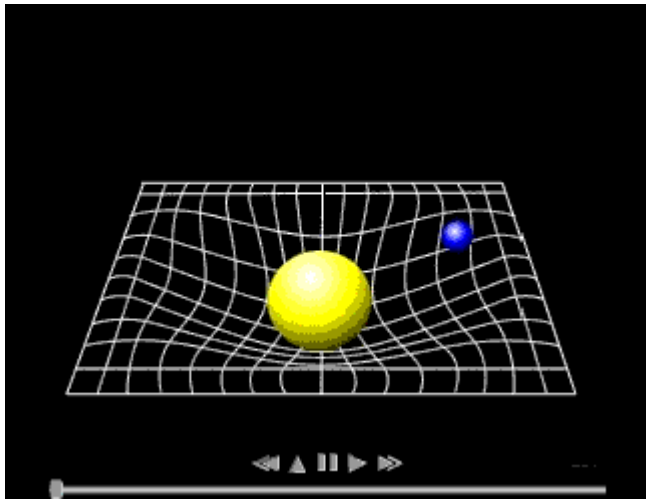
Rainer Weiss
Massachusetts Institute of Technology, USA

"for the direct detection of gravitational waves."

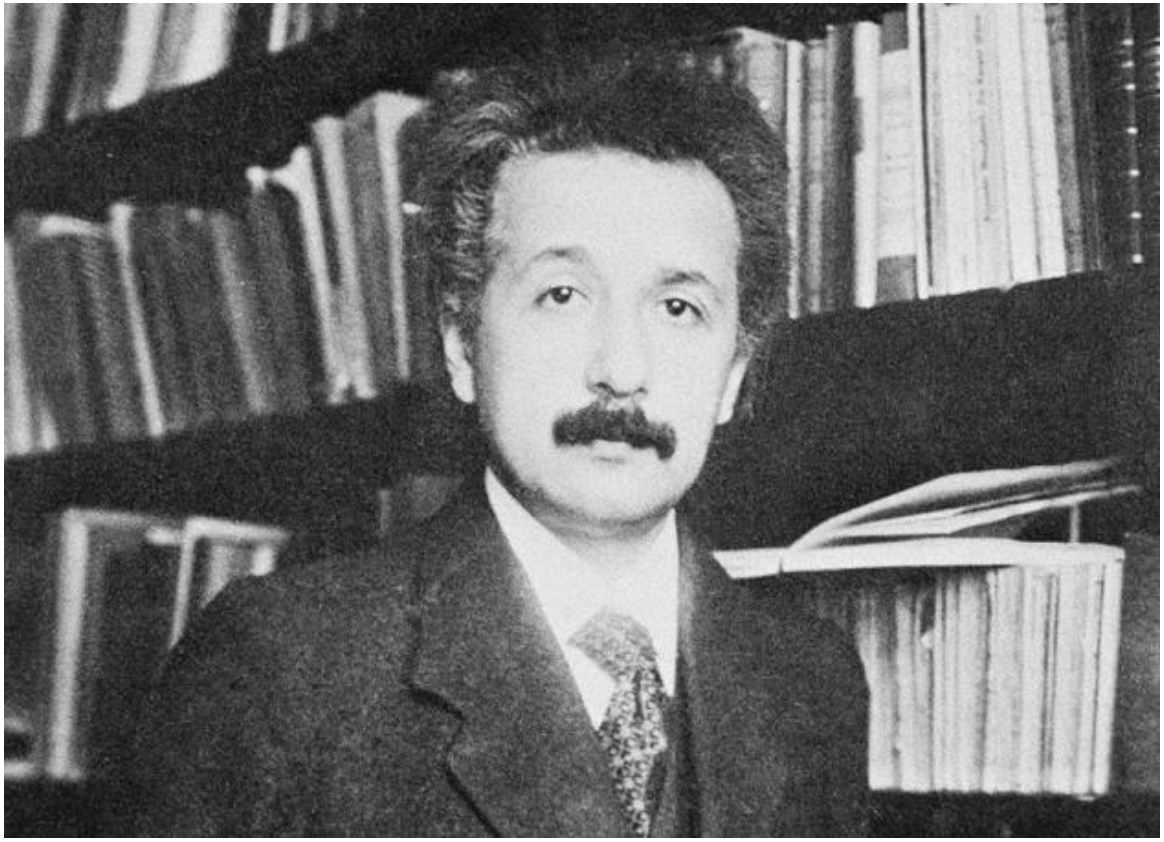
Mai 1916

Einsteins store artikkel i Annalen der Physik,
der han presenterte den generelle relativitetsteorien, kom på trykk .
Masse krummer rummet.





Det krumme rommet forteller frie partikler hvordan de skal bevege seg.



Juni 1916: Einstein forutsa eksistensen av gravitasjonsbølger
som en konsekvens av den generelle relativitetsteorien

Han mente at universet er fylt av gravitasjonsbølger,
men at de er for vanskelige å registrere
til at menneskene noensinne vil være i stand til
å «høre» denne kosmiske symfonien.

Einsteins teori kontra Newtons teori 2

Newton	Einstein
Tyngdeakselerasjon forårsakes av gravitasjonskraften til et legeme.	Tyngdeakselerasjon er noe en partikkel får når den er i et rom som ikke er i fritt fall.
Tidevannskrefter forårsakes av masser.	Gravitasjonsbølger forårsakes av legemer som forandrer fasong eller orientering.
Tidevannskrefter forårsaker formforandring	Gravitasjonsbølger forårsaker formforandring.

Elektromagnetiske bølger kontra gravitasjonsbølger

elektromagnetisme	gravitasjon
Sterk.	Svak.
Forårsakes av ladning med to fortegn.	Forårsakes av masse med ett fortegn.
Elektromagnetisk stråling sendes ut av akselererte ladninger.	Gravitasjonsbølger sendes ut av ikke symmetriske legemer som endrer form eller orientering.
Viser overflaten av legemer.	Viser legemets bevegelse.
Lette å registrere.	Vanskelige å registrere.
Lette å blokkere.	Trenger gjennom alt.
Universet er derfor mange steder ugjennomsiktig for elektromagnetisk stråling.	Åpner et vindu til universets begynnelse.

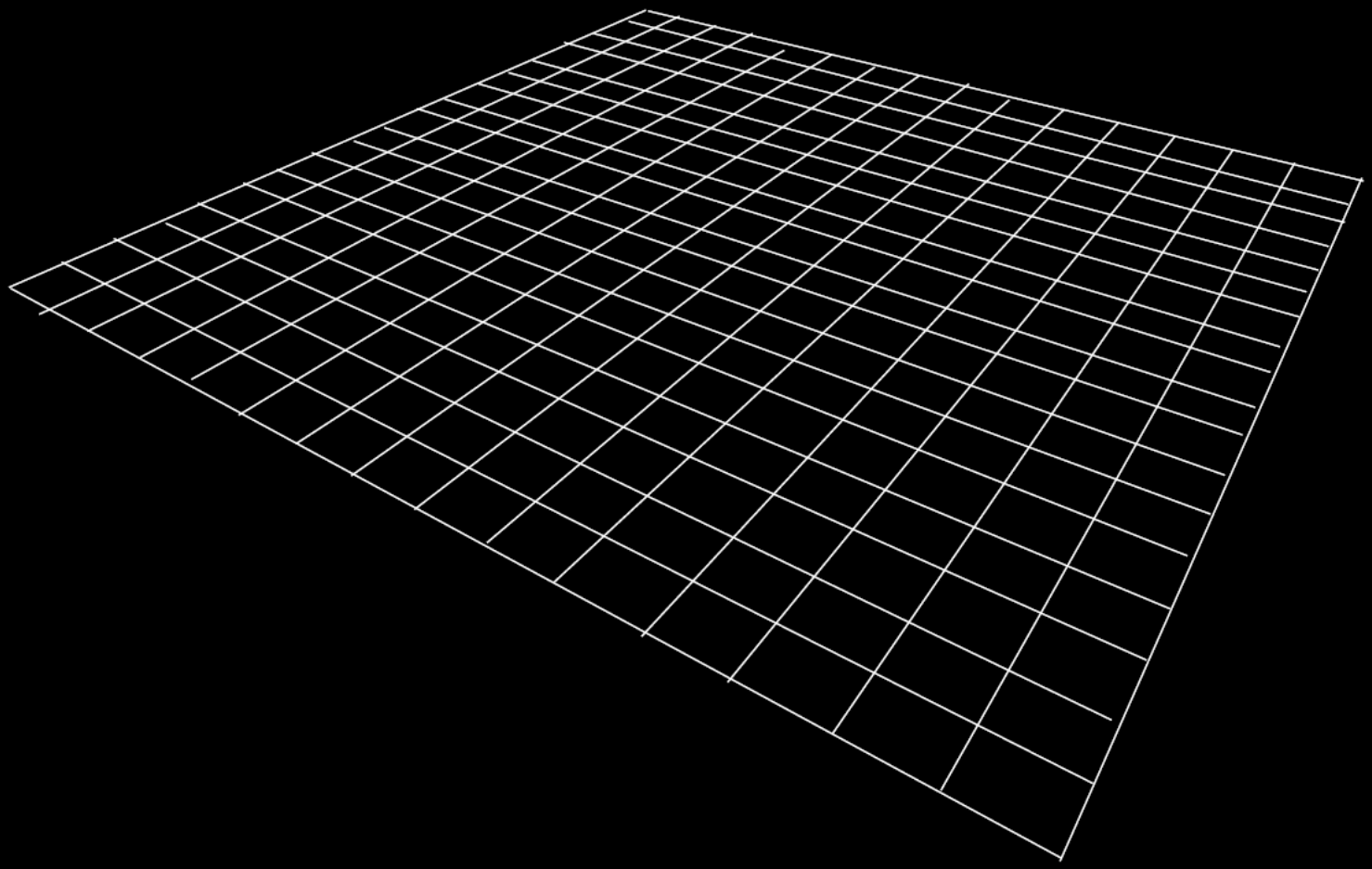
Hva er gravitasjonsbølger?

Gravitasjonsbølger er at krumning av romtiden forplanter seg i 3-rommet.

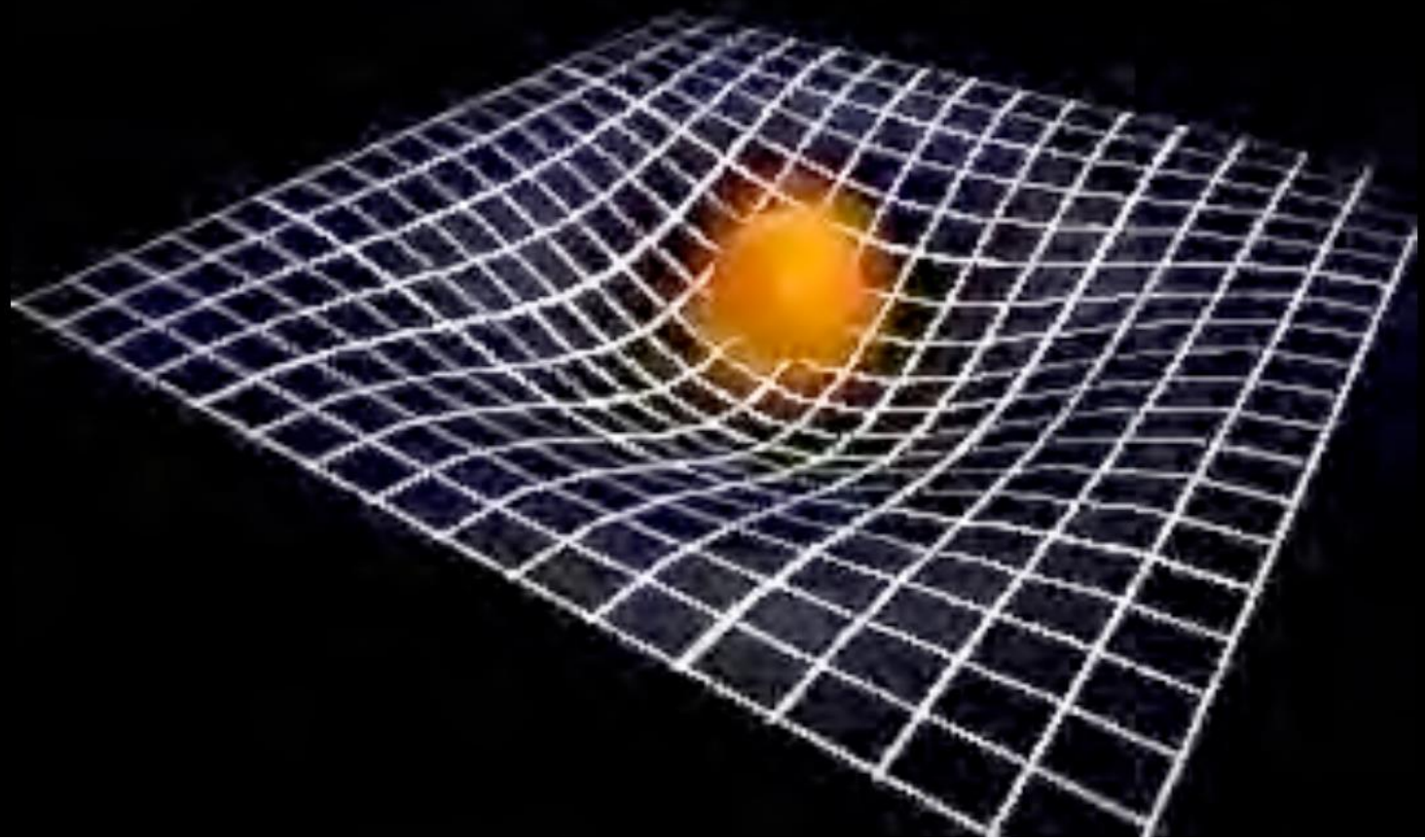
Gravitasjonsbølger forplanter seg med lyshastighet.

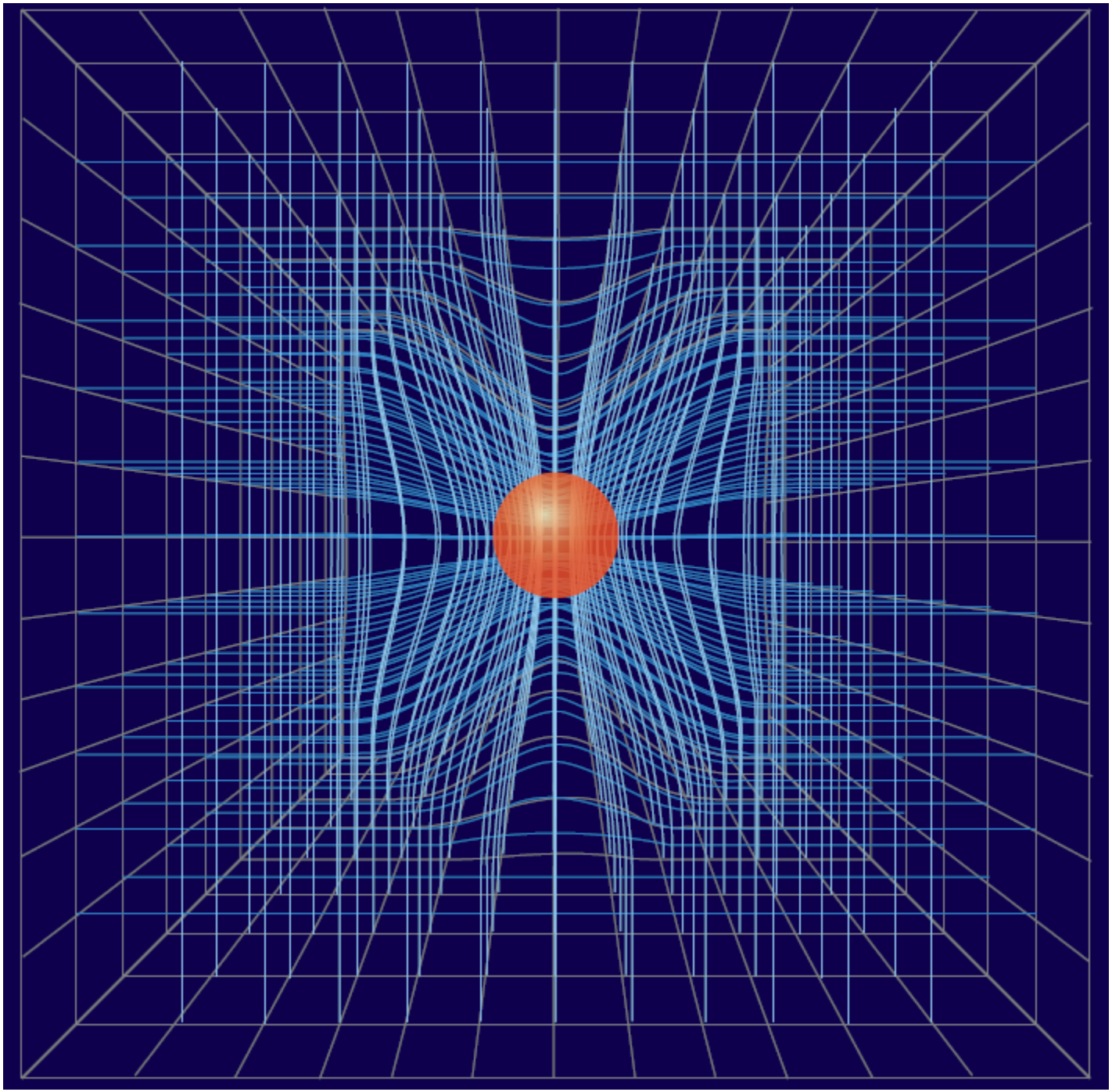
Gravitasjonsbølger endrer fasongen til en gravitasjonsbølgeantenne.

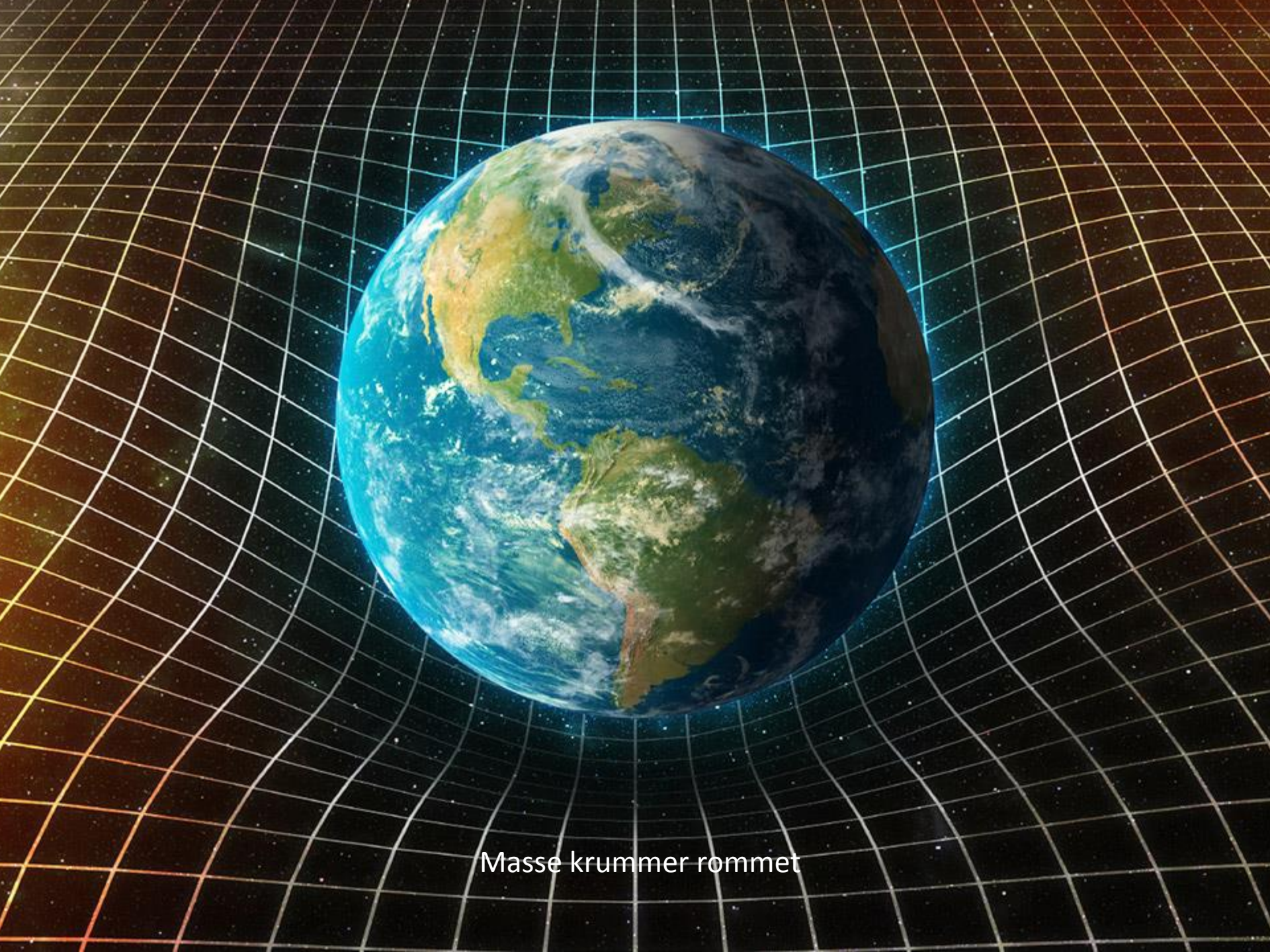
Mass-free “flat” Space-time

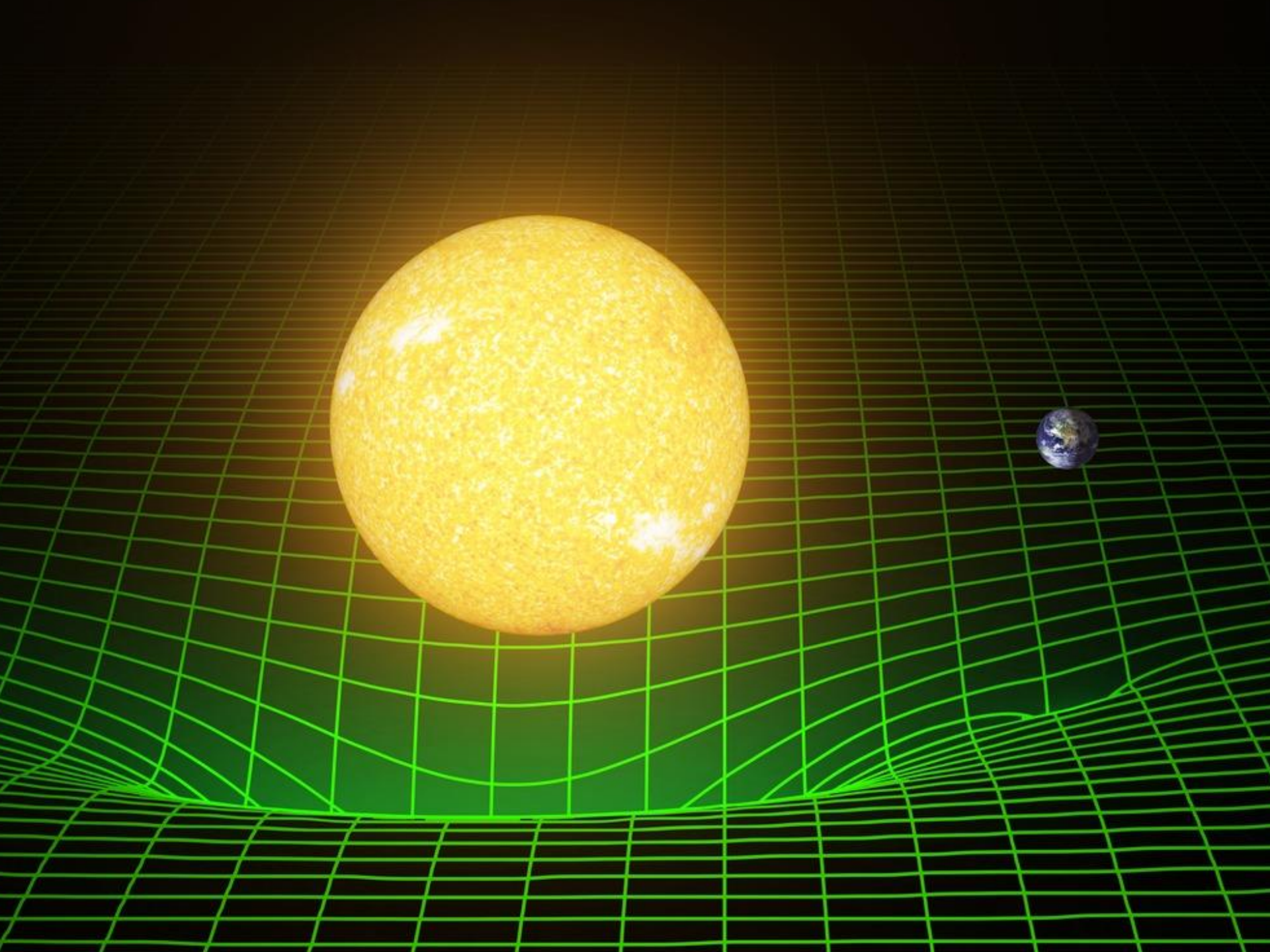


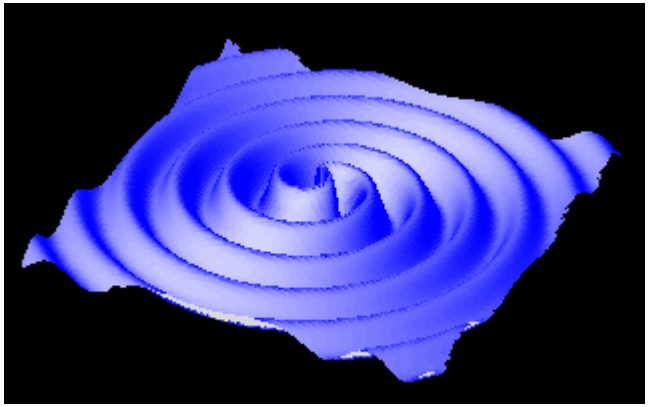
Mass “warps” Space-time

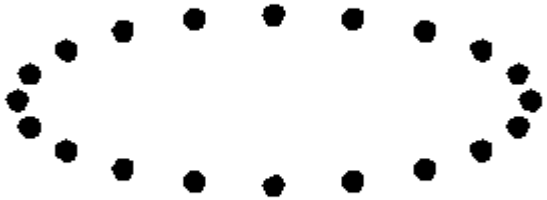


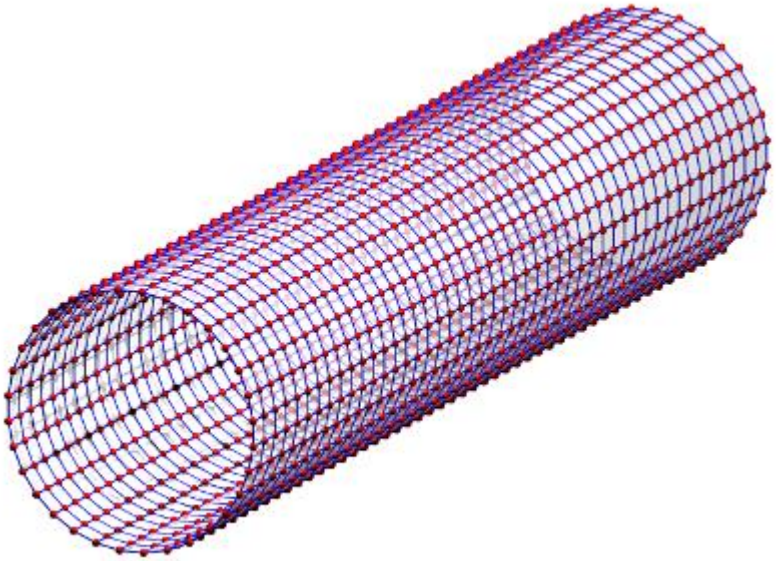



Masse krummer rommet

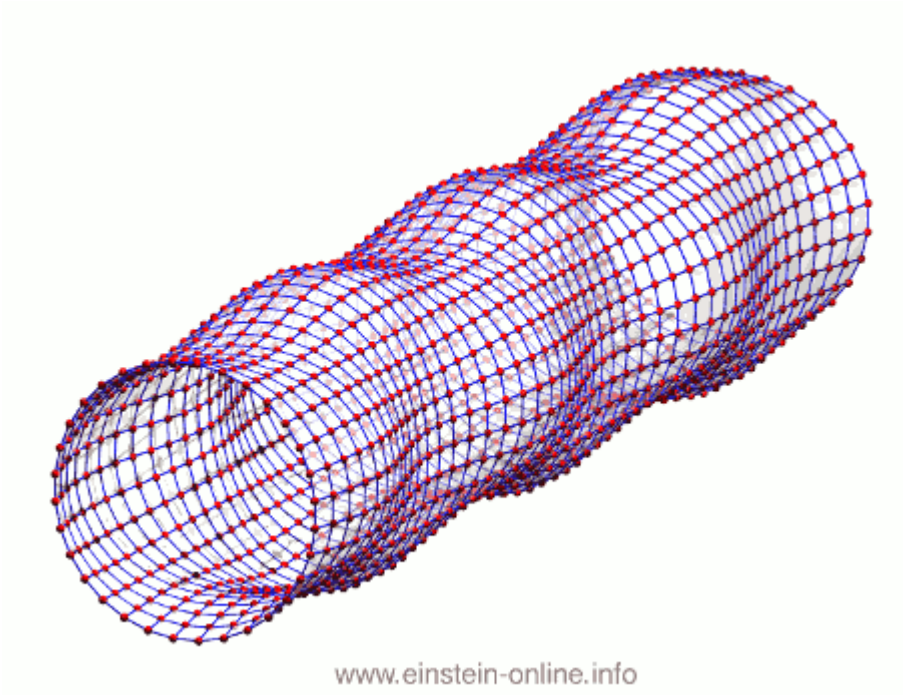






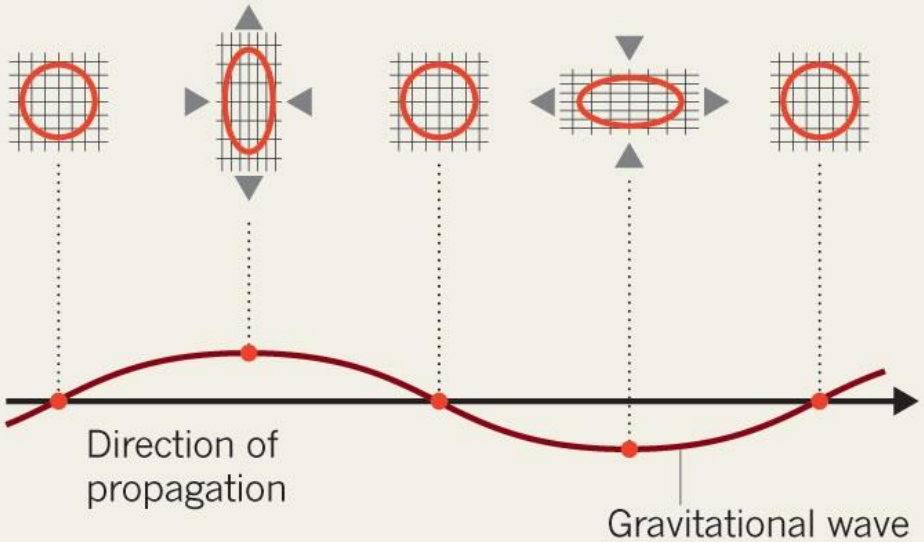


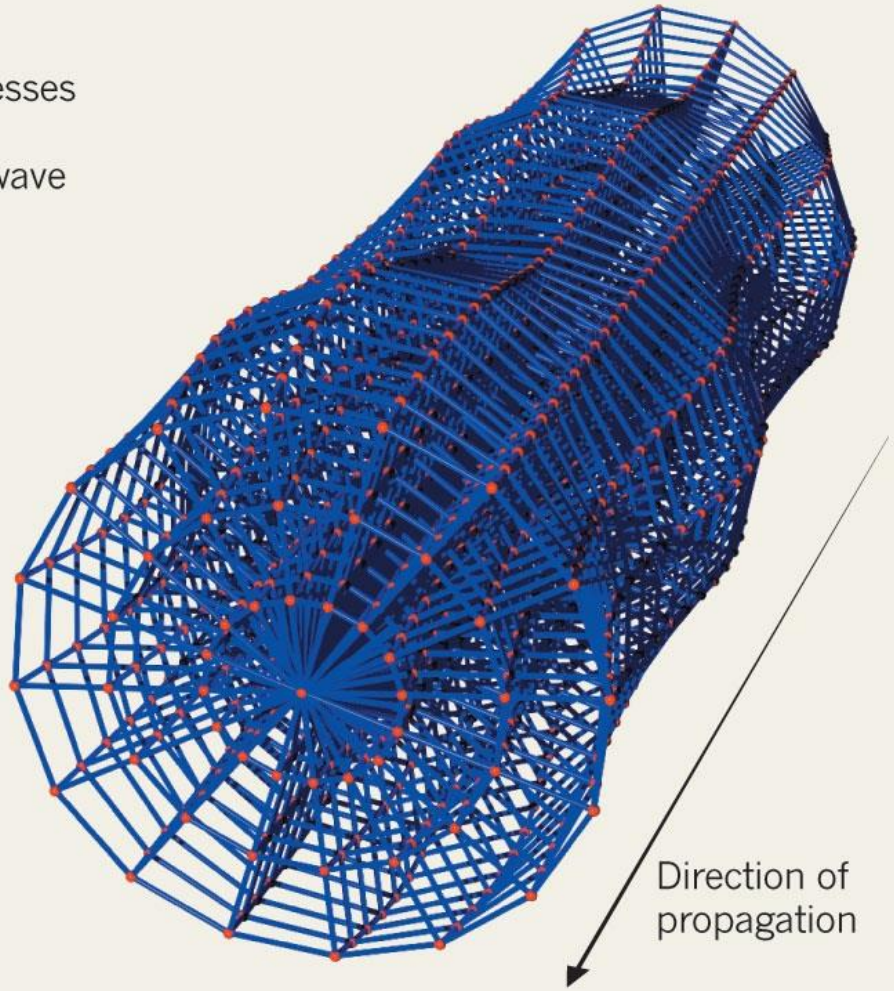
www.einstein-online.info

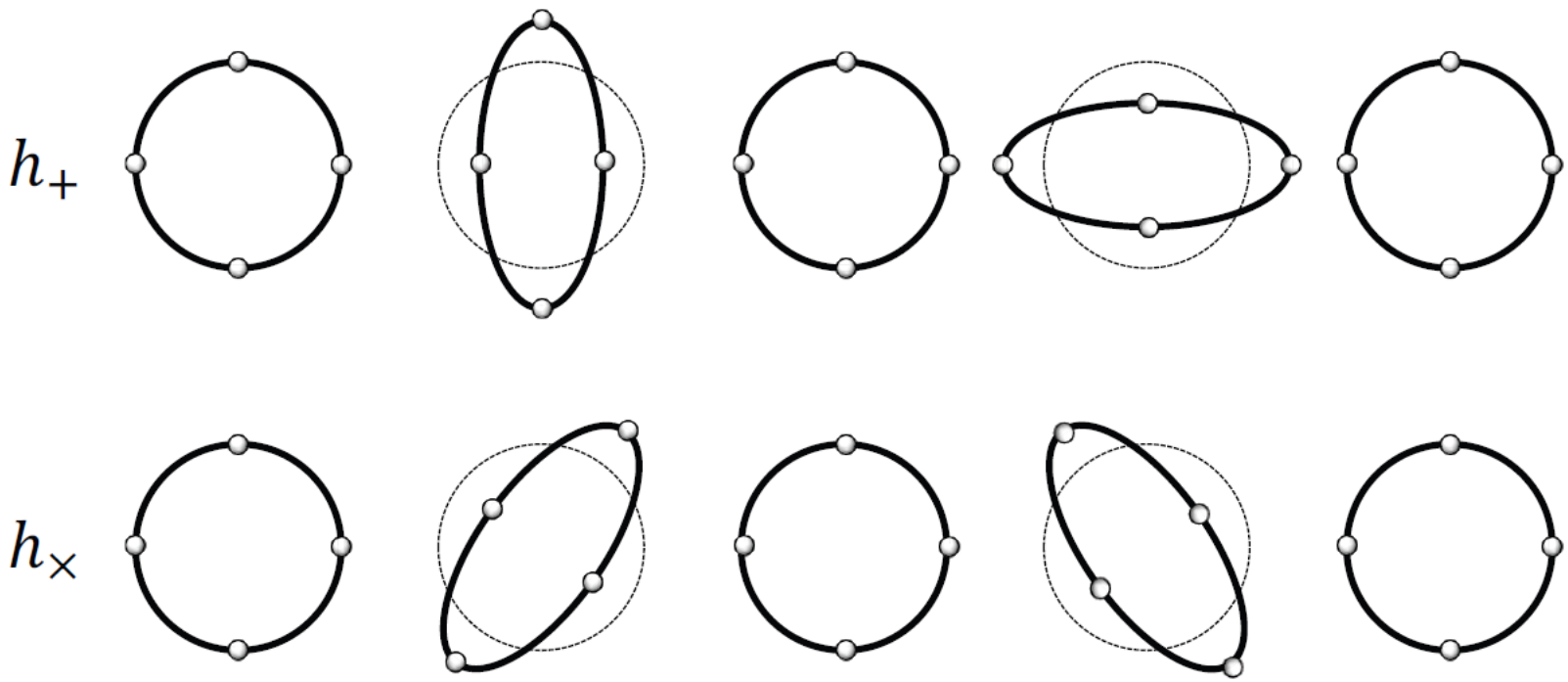

www.einstein-online.info

RIPPLE EFFECT

When a gravitational wave passes through space, it compresses it in one direction and stretches it in another, both at right angles to the wave's direction (red line). The effects of the wave moving along a blue tube are shown.

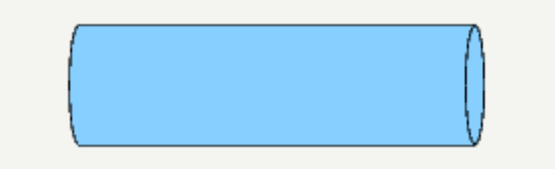


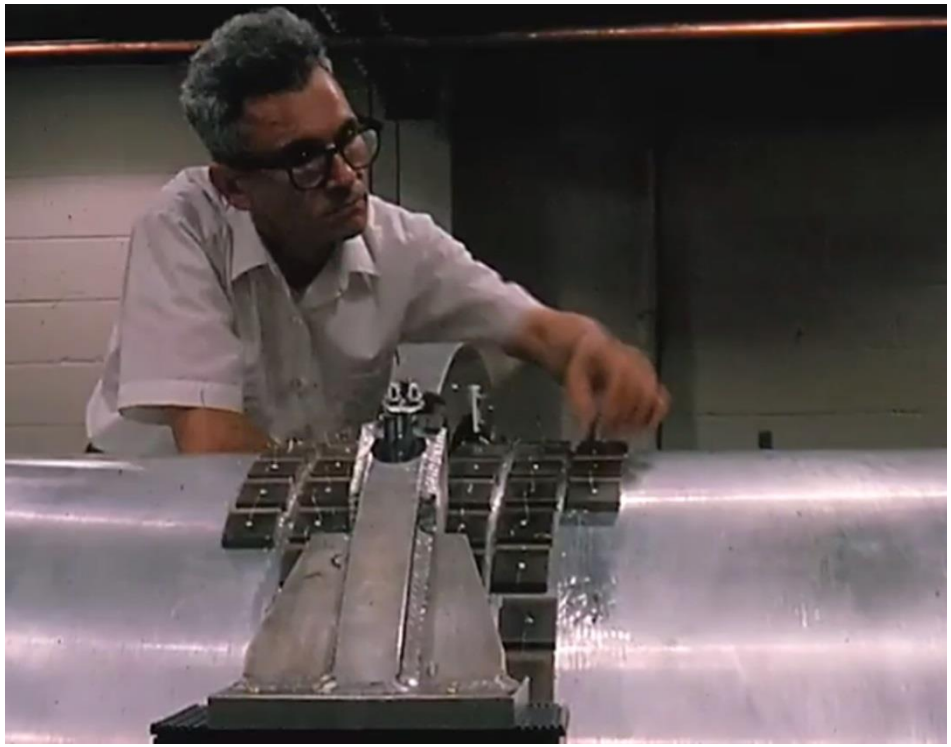




Gravitasjonsbølger opptrer med to typer polariseringer kalt pluss- og kryss-polarisering.

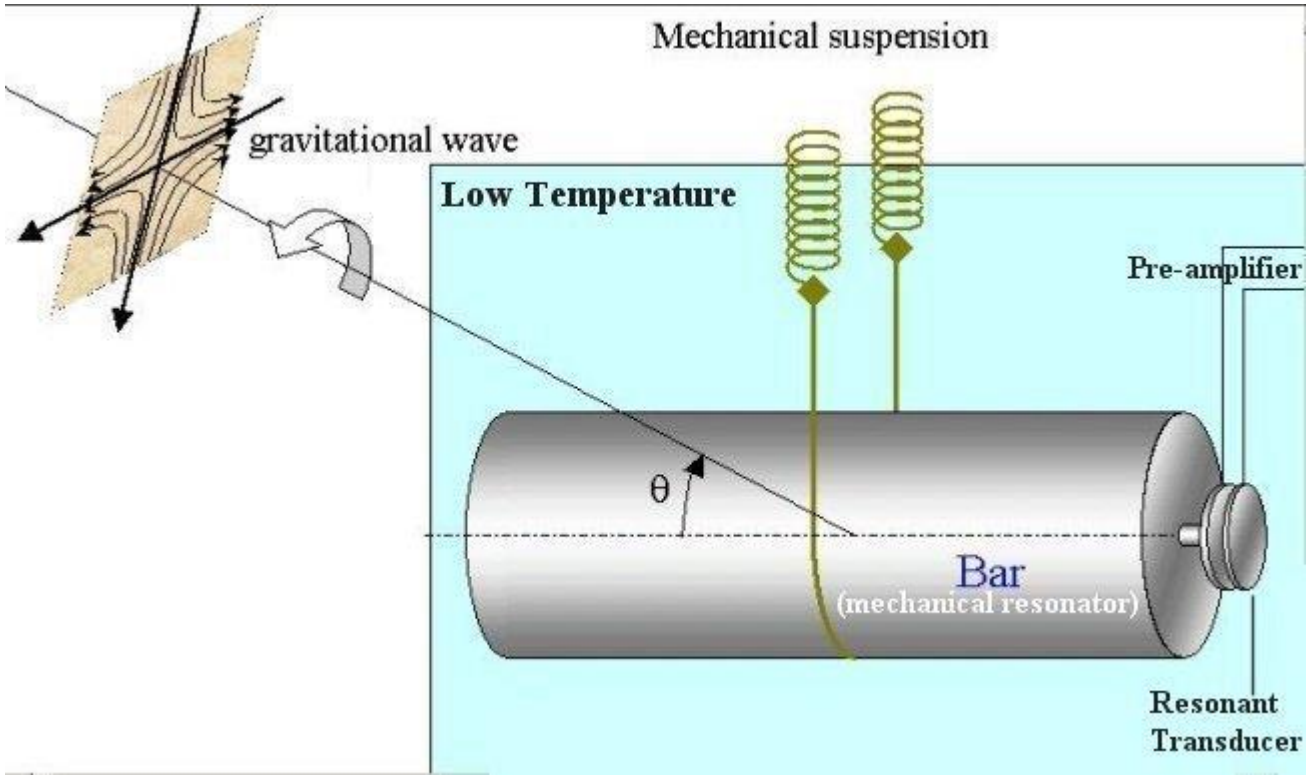
Den første gravitasjonsbølgedetektoren

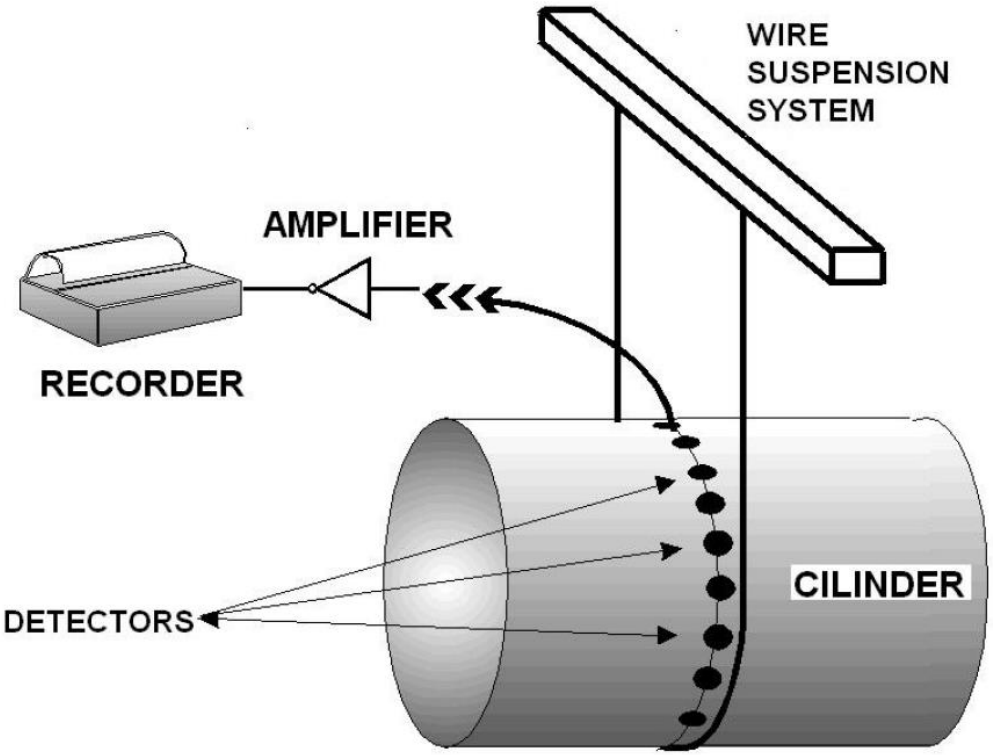




Joseph Weber omkring 1960

Weber prøvde i 1960-årene med flere sylindriske antenner å registrere gravitasjonsbølger fra Melkeveiens sentrum.


Mechanical suspension
gravitational wave
Low Temperature
Pre-amplifier
θ
Bar
(mechanical resonator)
Resonant
Transducer


WIRE
SUSPENSION
SYSTEM
AMPLIFIER
RECORDER
CILINDER
DETECTORS

EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION*

J. Weber
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 29 April 1969)

Coincidences have been observed on gravitational-radiation detectors over a base line of about 1000 km at Argonne National Laboratory and at the University of Maryland. The probability that all of these coincidences were accidental is incredibly small. Experiments imply that electromagnetic and seismic effects can be ruled out with a high level of confidence. These data are consistent with the conclusion that the detectors are being excited by gravitational radiation.

VIVA LE
GRAVITATION*

Andre prøvde å reprodusere Webers resultat uten å lykkes.

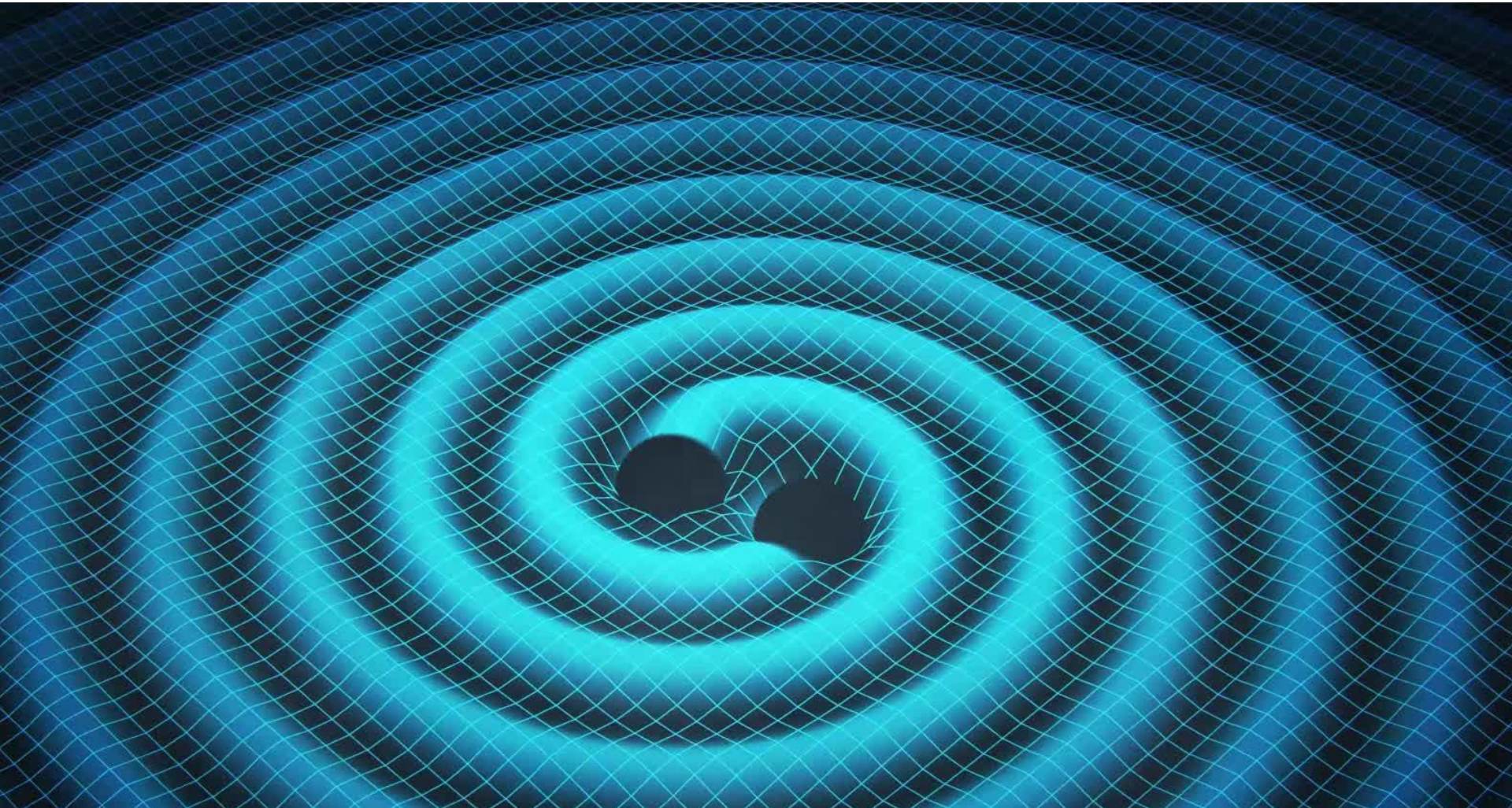
Senere ble det gjort beregninger som viste at det trengtes antenner med mye bedre følsomhet enn Webers sylindriske antenner for å registrere gravitasjonsbølger fra kilder ved Melkeveiens sentrum.

GLAZIER DESIGN 2016

GLAZIER DESIGN 2016

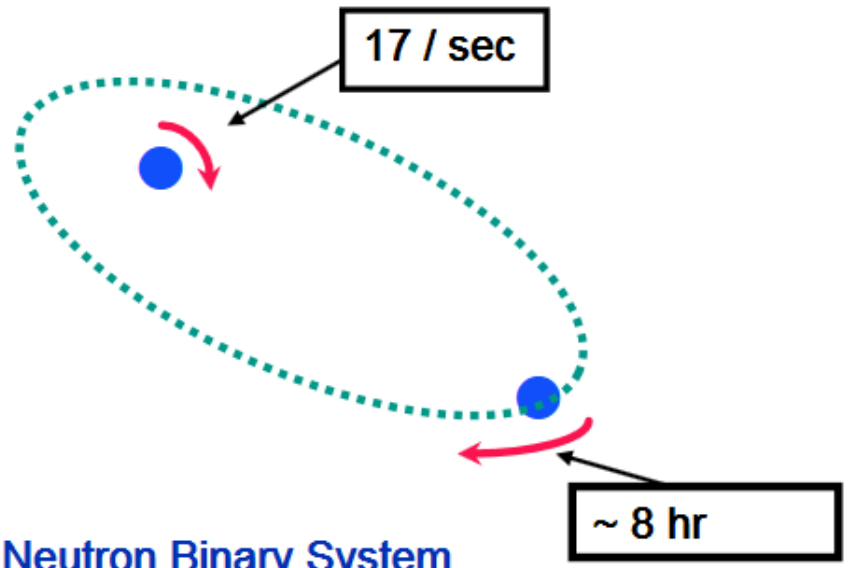
ISLE of MAN
95p
ALBERT EINSTEIN • STEPHEN HAWKING
GRAVITATIONAL WAVES
GLAZIER DESIGN 2016

Et system med to svarte hull i bane rundt hverandre,
sender ut gravitasjonsbølger
med frekvens lik det dobbelte av antall omløp per sekund.
Systemet mister energi, de svarte hullene kommer nærmere hverandre,
og frekvensen øker.



Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 – Timing of pulsars



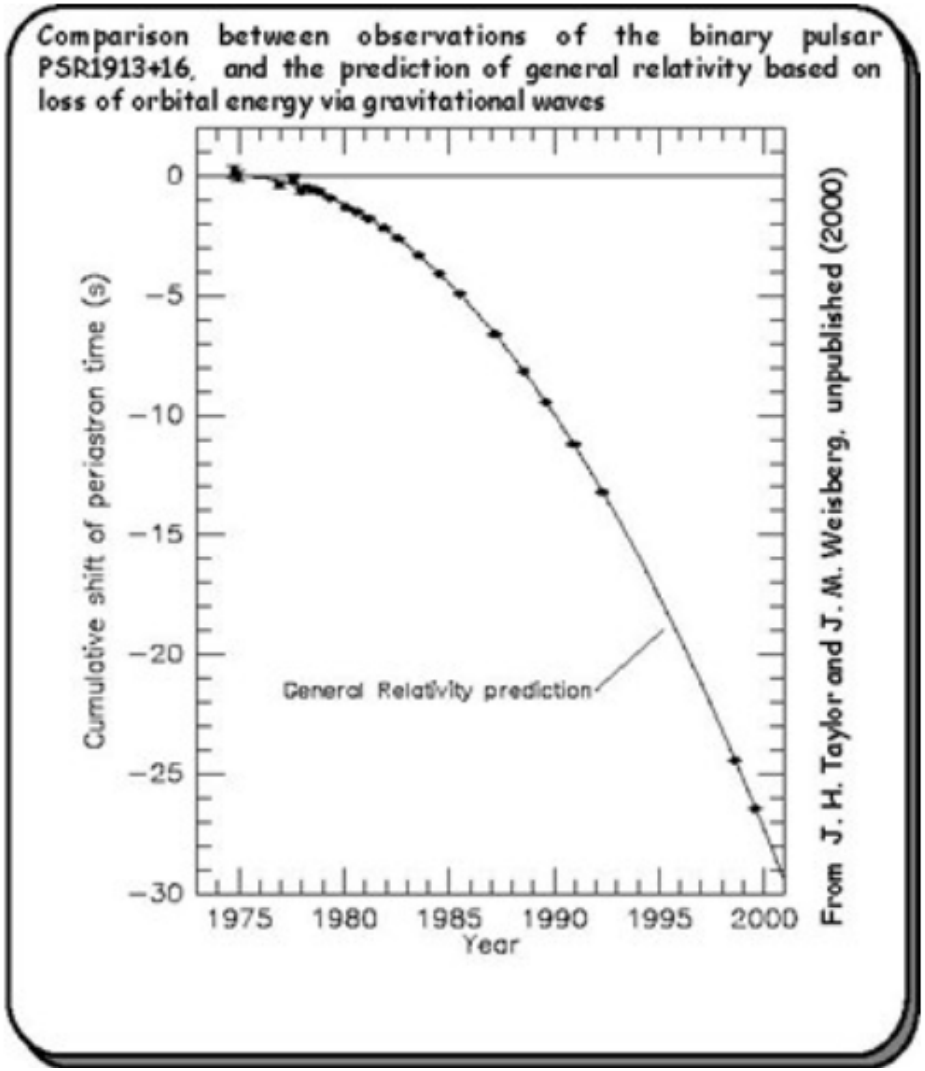
Neutron Binary System

- separated by 10^6 miles
- $m_1 = 1.4 m_\odot$; $m_2 = 1.36 m_\odot$; $\varepsilon = 0.617$

Prediction from general relativity

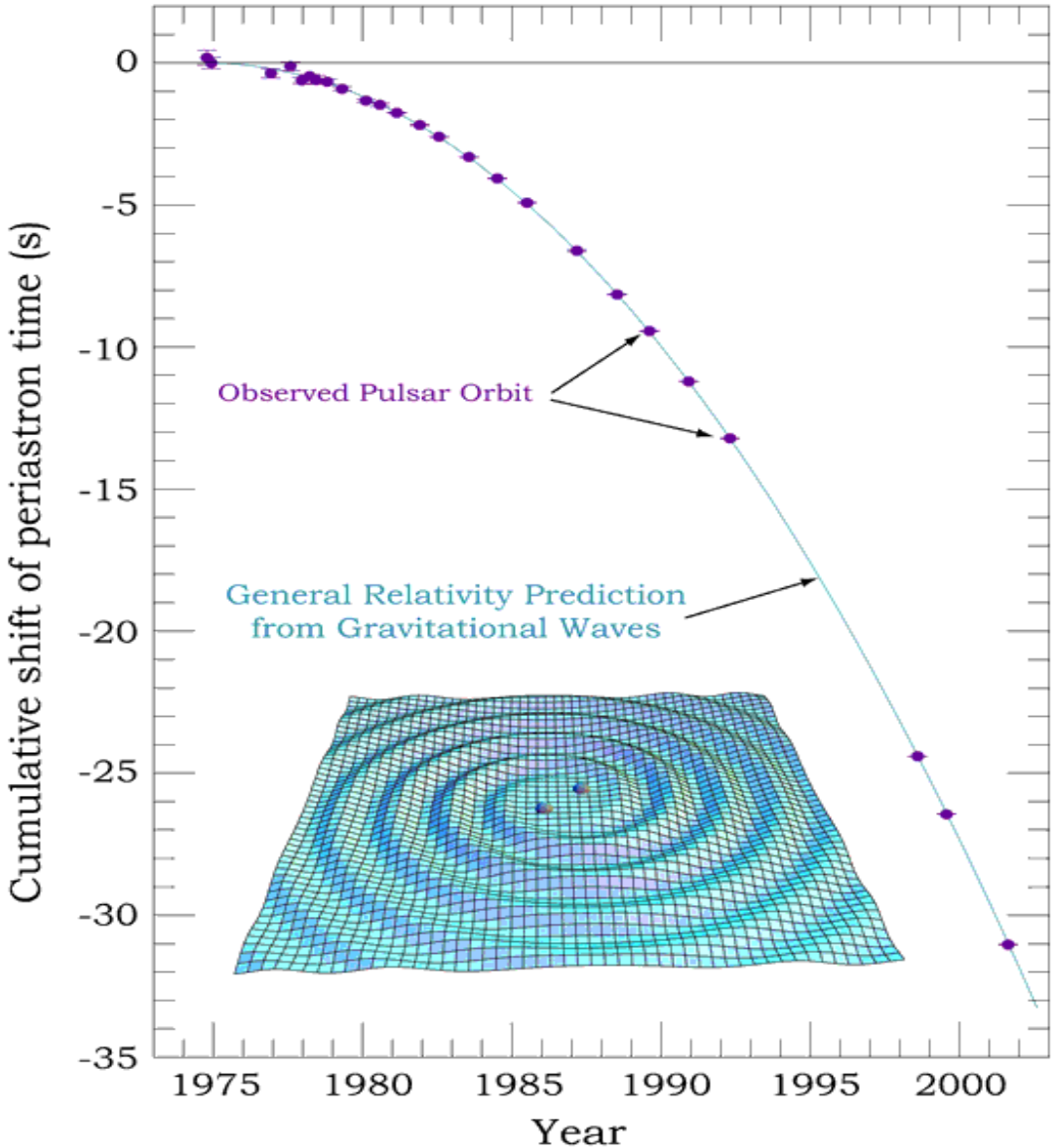
- spiral in by 3 mm/orbit
- rate of change orbital period

Emission of gravitational waves



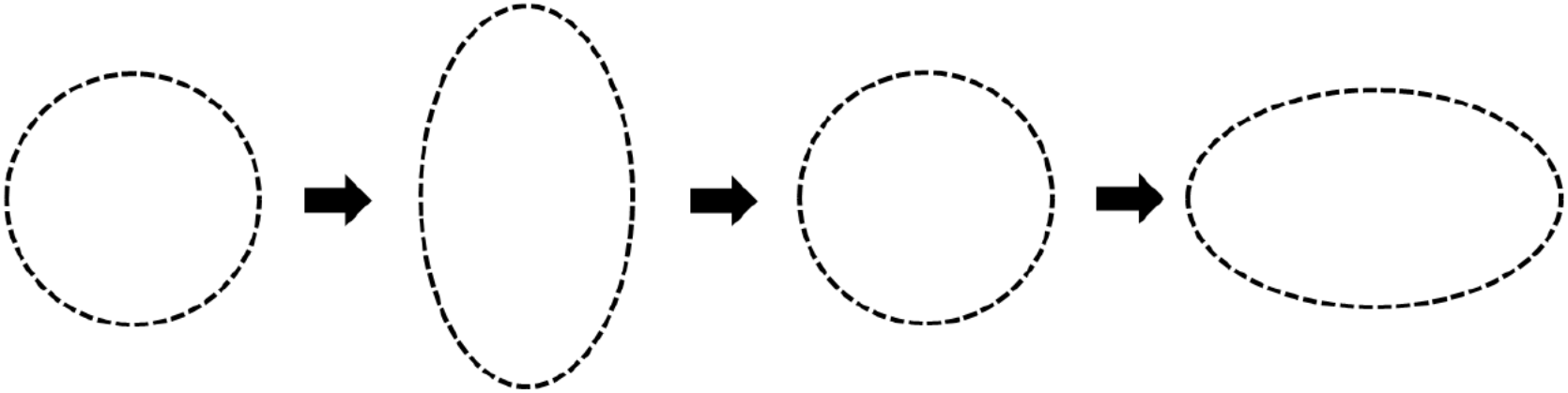
RELATIVISTIC BINARY PULSAR PSR B1913+16

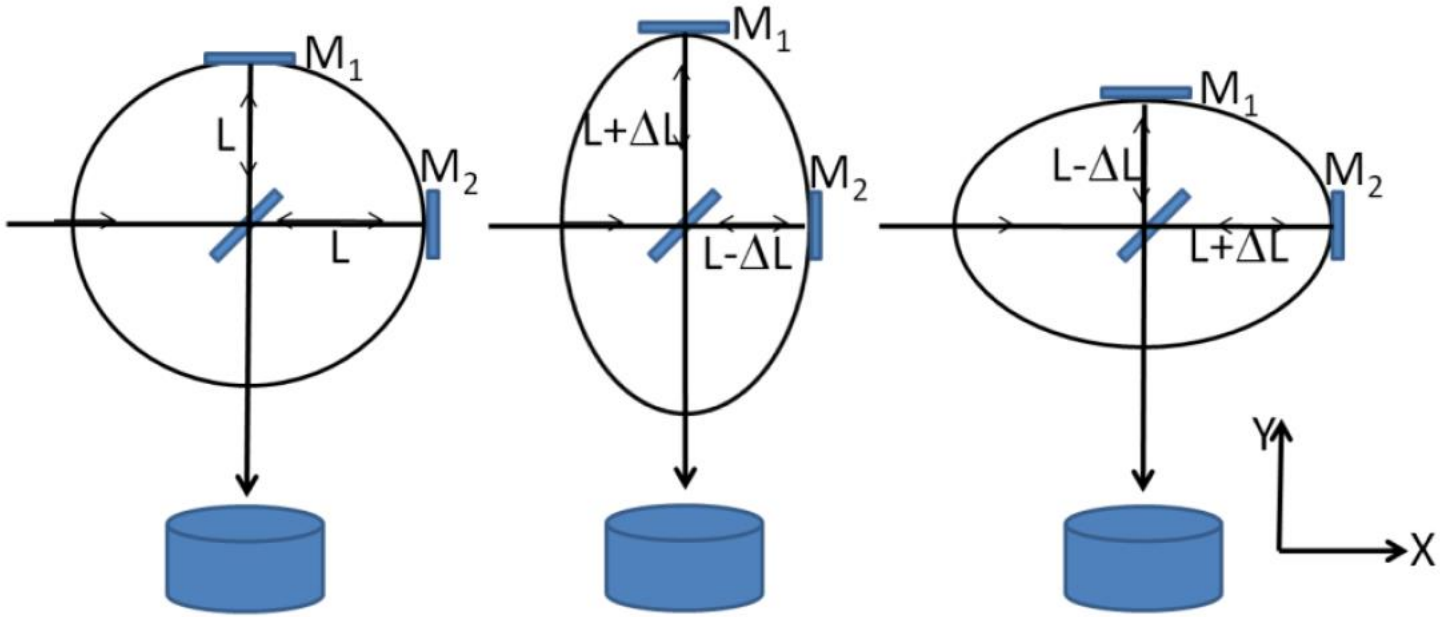
Russell A. Hulse

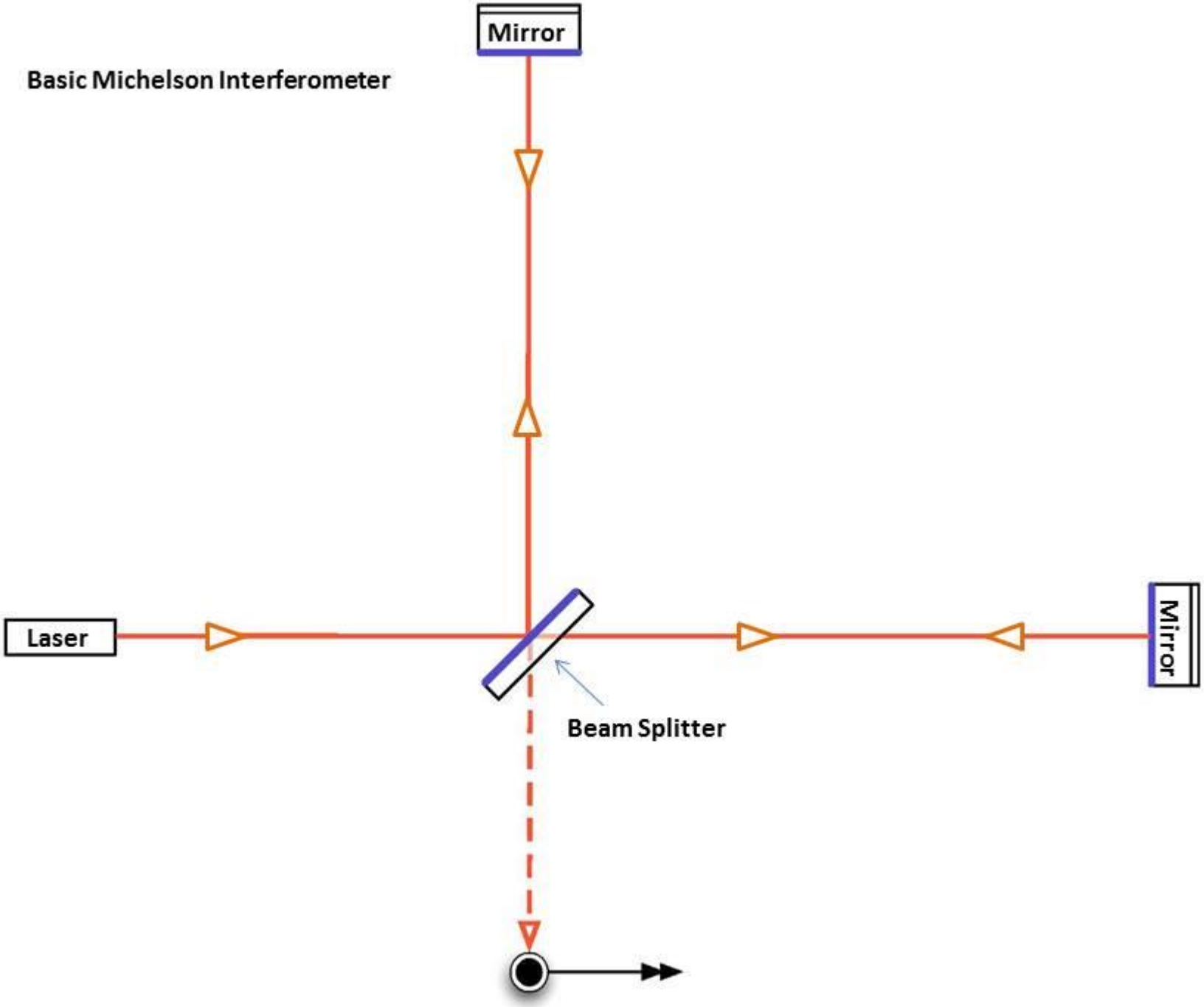


Joseph H. Taylor

Nobelpris til R. A. Hulse og J. H. Taylor i 1993
for denne indirekte deteksjonen av gravitasjonsbølger.




M1
L
M2
L
M1
L+ΔL
M2
L-ΔL
M1
L-ΔL
M2
L+ΔL
Y
X


Basic Michelson Interferometer
Mirror
Laser
Mirror
Beam Splitter

En kort LIGO historikk

1979: LIGO receives funding

US National Science Foundation funds construction of the Laser Interferometer Gravitational-Wave Observatory (LIGO).

1987: Another false alarm for gravitational waves

A false alarm on direct detection from Joseph Weber (again) with claimed signal from the supernova SN 1987A using his torsion bar.

1994: LIGO construction begins

It took a long time, but the construction of LIGO finally began in Hanford, Washington, and Livingston, Louisiana.

2002: LIGO starts first search

In August 2002, LIGO starts searching for evidence of gravitational waves.

2005: LIGO hunt ends

After five searches, the first phase of LIGO ends with no detection of gravitational waves. The sensors are then improved to give increased sensitivity, called Enhanced LIGO.

2009: Enhanced LIGO

Enhanced LIGO starts new hunt for gravitational waves.
It fails to detect and gravitational waves.
A major upgrade, called Advanced LIGO begins.

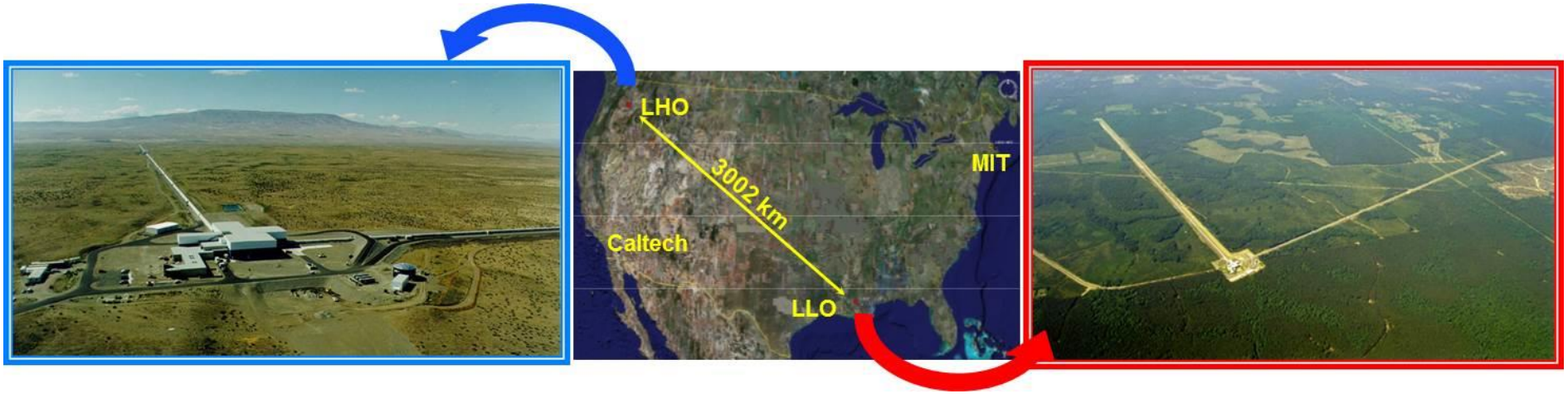
2014: Advanced LIGO upgrade completed

The new Advanced LIGO has finished installation and testing and is nearly ready to begin a new search.

2015: Advanced LIGO starts making measurements

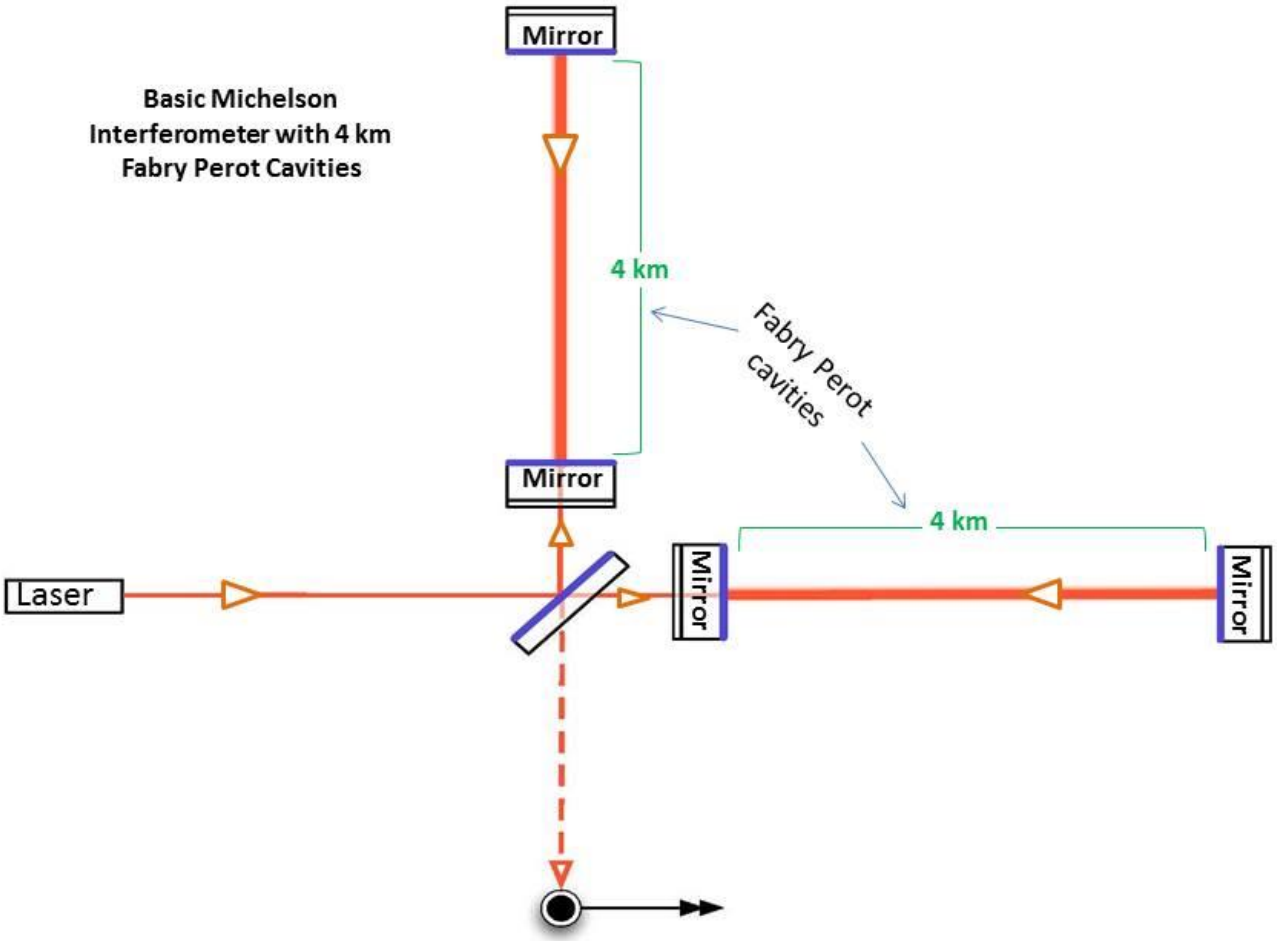
Advanced LIGO starts a new hunt for gravitational waves with four times the sensitivity of the original LIGO.

Hanford, Washington and Livingston, Louisiana



LIGO's interferometers are by far the largest ever built,
with 4 km long arms.
This is particularly important in the search for gravitational waves
because the longer the arms of an interferometer,
the farther the laser travels, and the more sensitive to length changes
the instrument becomes.
Attempting to measure a change in arm length
10000 times smaller than a proton
meant that LIGO had to be more sensitive than any scientific instrument
ever built, so the longer the better.
But there are obvious practical limitations to how long one can build an
interferometer. Even with arms 4 km long, if LIGO's interferometers
were basic Michelsons (with one reflection of light), they would *still* not
be long enough to detect gravitational waves...and yet they are.
How is this possible?

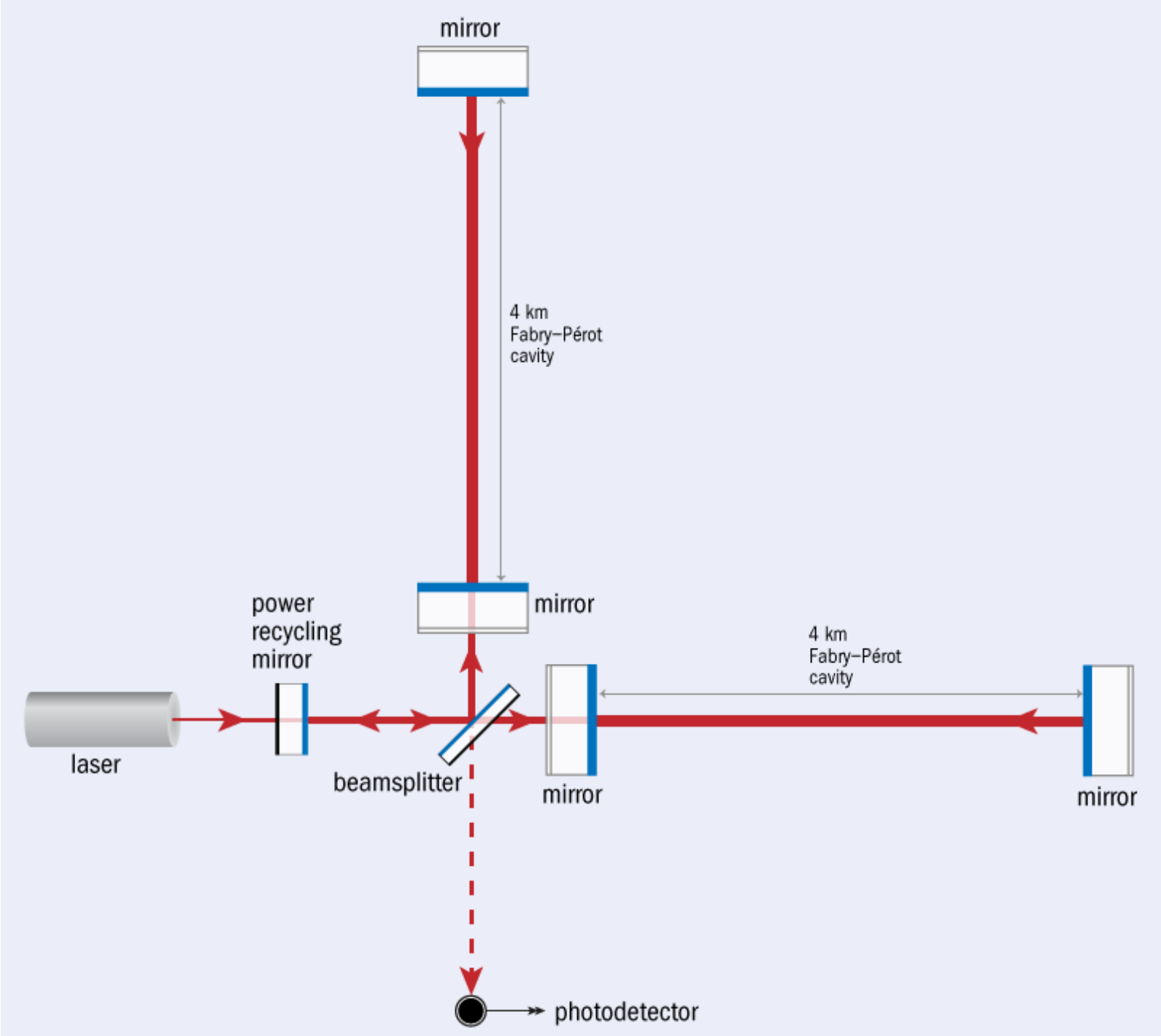
This obstacle was resolved by altering the design of the Michelson to include modifications called "Fabry Perot cavities."



The Fabry Perot 'cavity' actually *is* the full 4 km length of each arm between the beam splitter and the end of each arm.
Additional mirrors placed near the beam splitter are precisely aligned to reflect each laser beam back and forth along this 4 km length *about 280 times* before it finally merges with the beam from the other arm. These extra reflections serve two functions:

1. It stores the laser light within the interferometer for a longer period of time, which increases LIGO's sensitivity
2. It increases the distance traveled by each laser beam from 4 km to *1120 km*

With Fabry Perot cavities, LIGO's interferometer arms
are not just 4 km long, they are essentially 1120 km long,
This bit of 'mirror magic' greatly increases LIGO's sensitivity
and makes it capable of detecting changes in arm-length
thousands of times smaller than a proton,
while keeping the physical size of the interferometer manageable.


mirror
4 km
Fabry–Pérot
cavity
mirror
power
recycling
mirror
4 km
Fabry–Pérot
cavity
laser
beamsplitter
mirror
mirror
photodetector

How Small is 10^{-18} Meter?

One meter, about 40 inches

÷10,000

Human hair, about 100 microns

÷100

Wavelength of light, about 1 micron

÷10,000

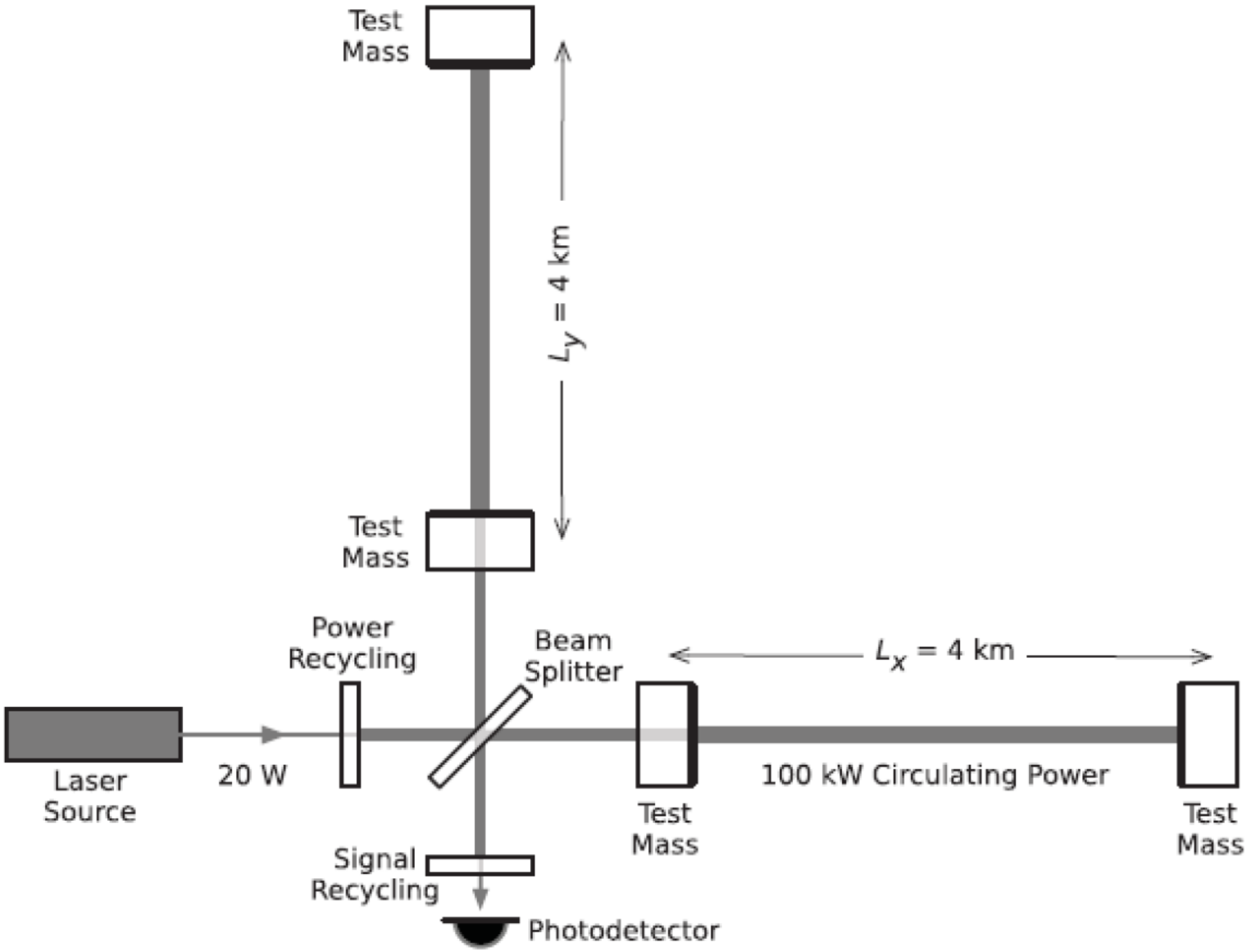
Atomic diameter, 10^{-10} meter

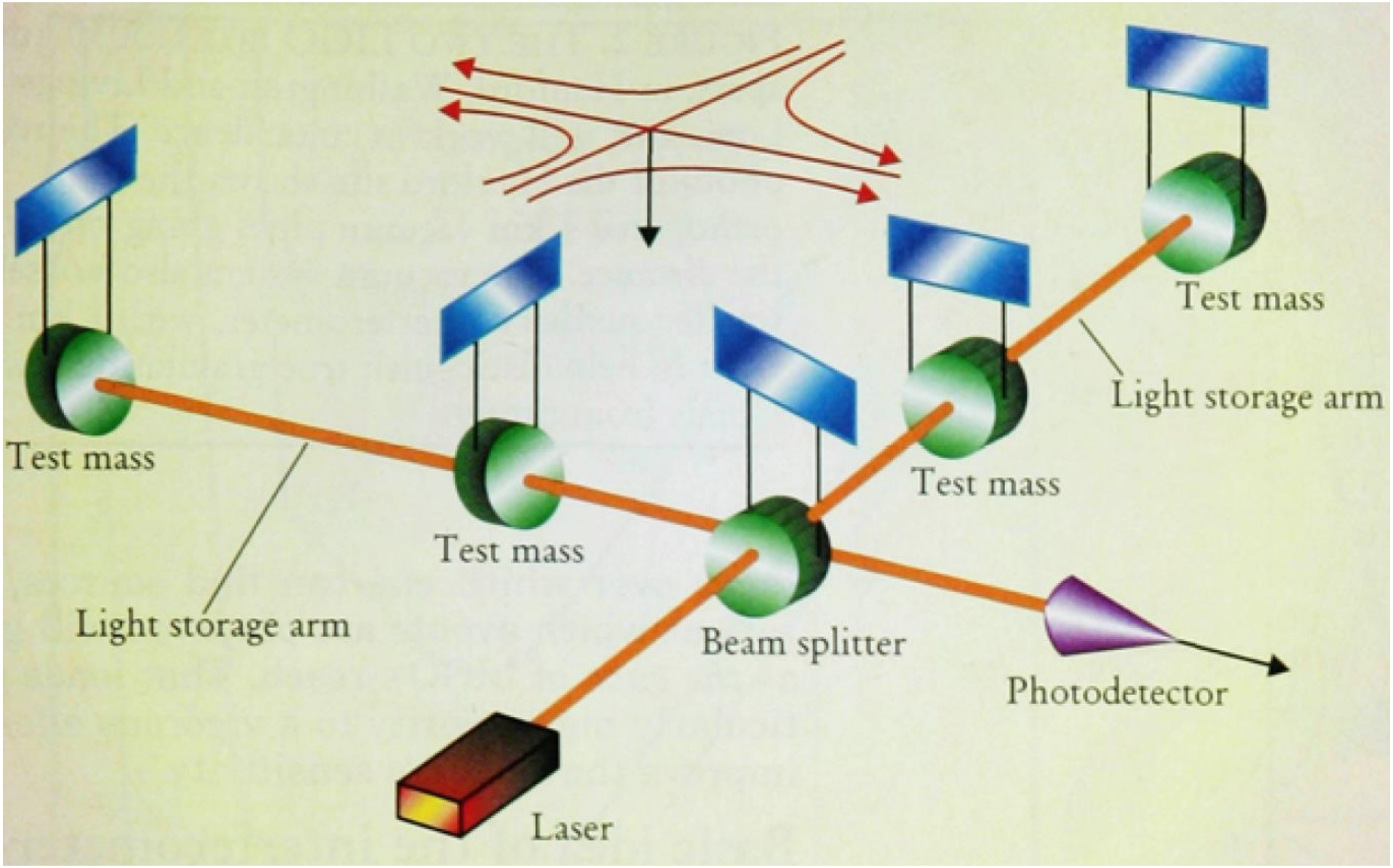
÷100,000

Nuclear diameter, 10^{-15} meter

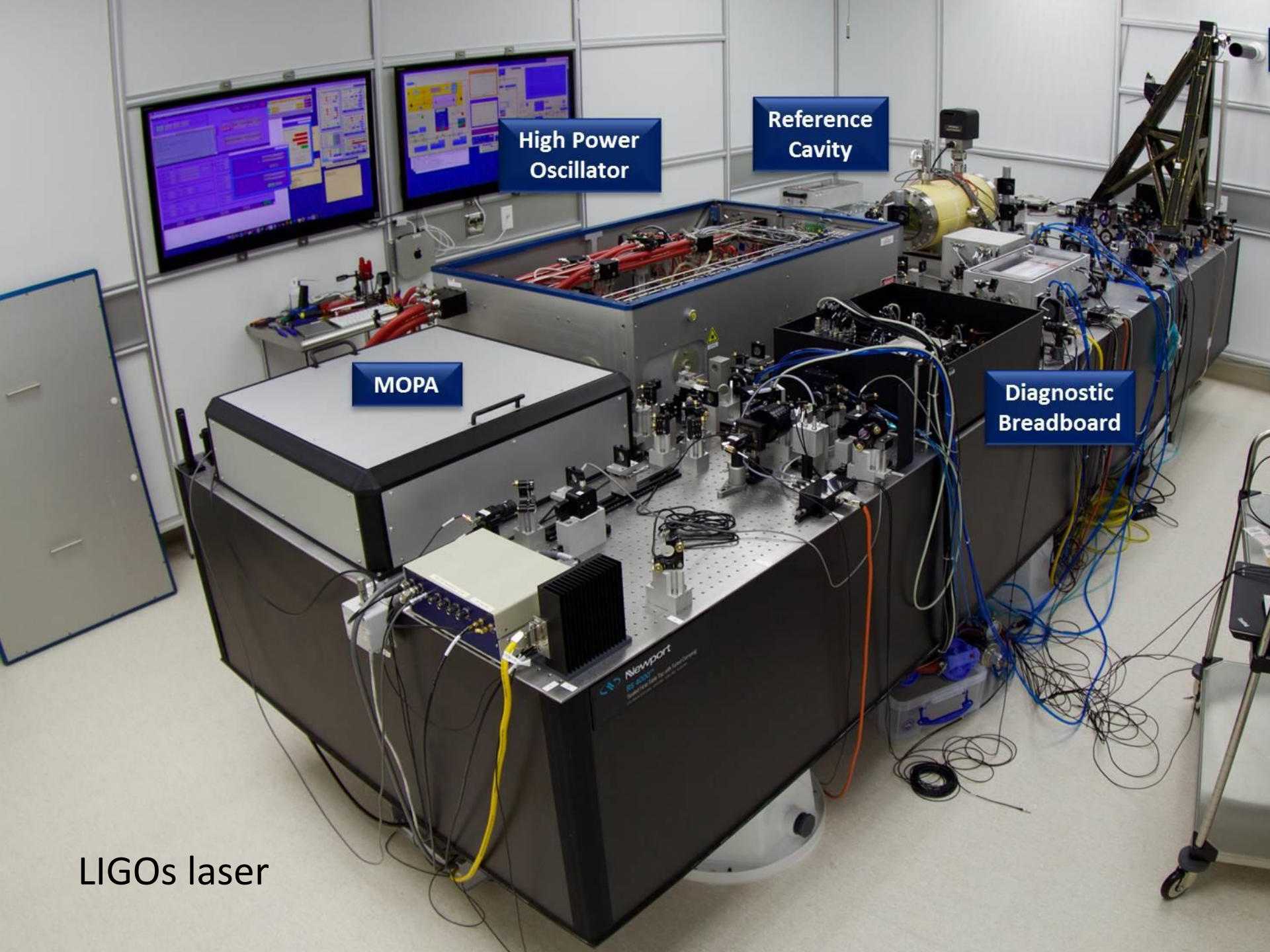
÷1,000

LIGO sensitivity, 10^{-18} meter


Test
Mass
L_y = 4 km
Test
Mass
Power
Recycling
Beam
Splitter
L_x = 4 km
Laser
Source
20 W
100 kW Circulating Power
Test
Mass
Test
Mass
Signal
Recycling
Photodetector

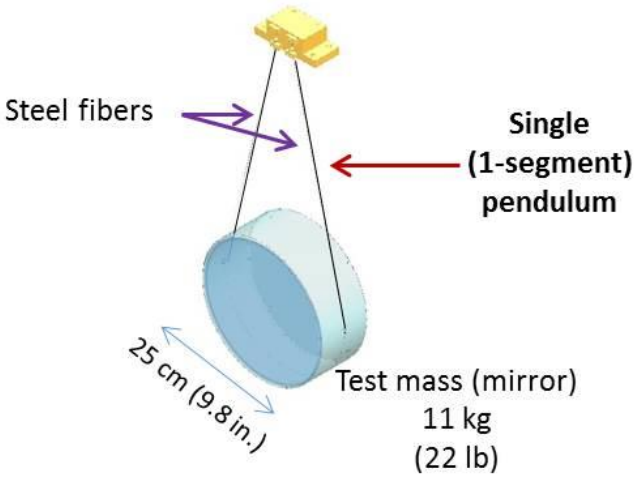


Prinsippskisse for LIGO: Øverst en gravitasjonsbølge som beveger seg nedover.
Den presser sammen armen i den opprinnelige laserstrålens retning,
og strekker armen på tvers. Fotodetektoren mottar bare lys hvis en gravitasjonsbølge passerer.

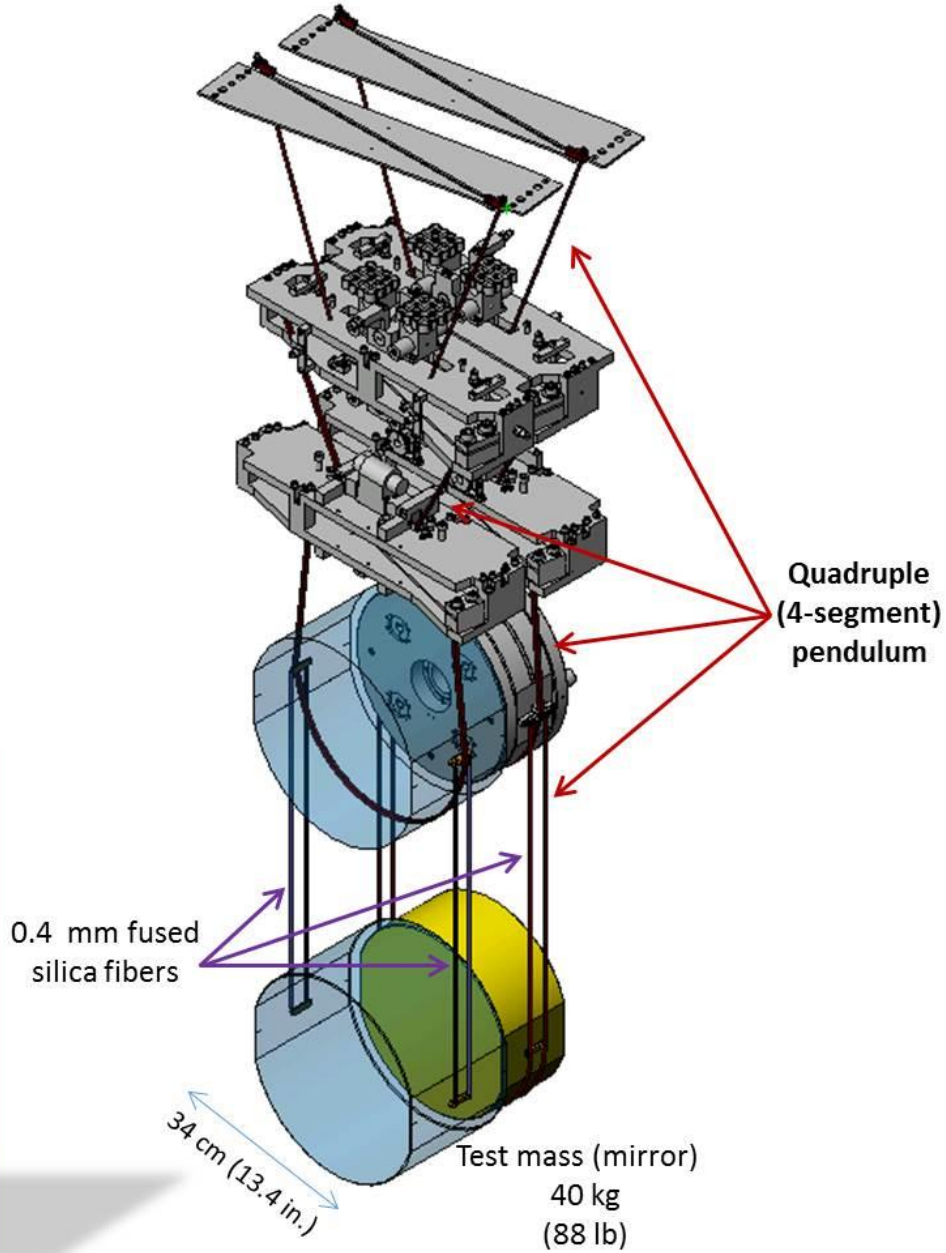

High Power Oscillator
Reference Cavity
MOPA
Diagnostic Breadboard
Newport

LIGOs laser

To av speilene omtalt som “testmasser” på forrige figur.
Hvert av dem veier 40 kg og er hengt opp slik at de kan bevege seg fritt i armens retning.



Initial LIGO Suspension



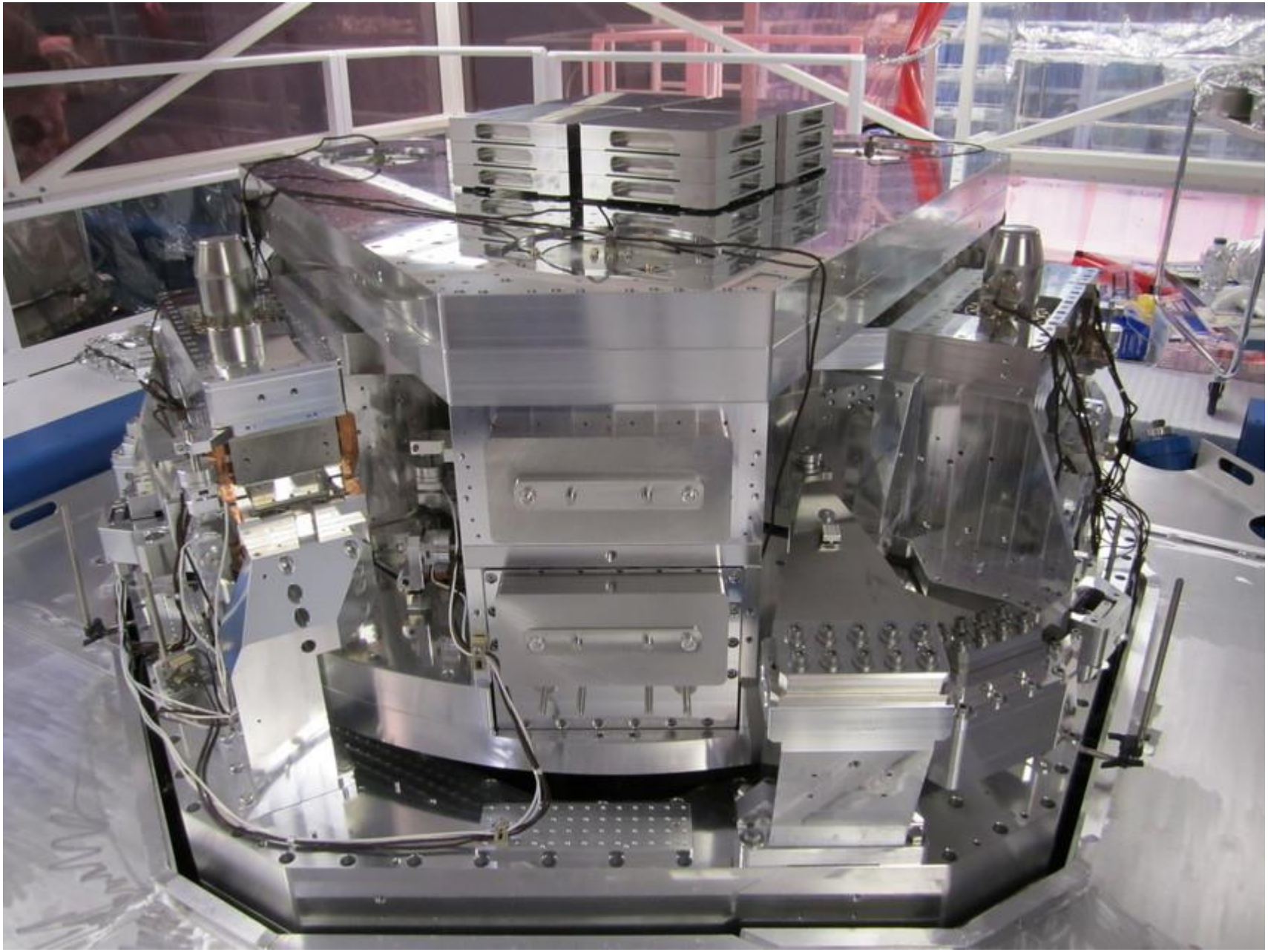
Advanced LIGO Suspension

iLIGO vs aLIGO suspension systems

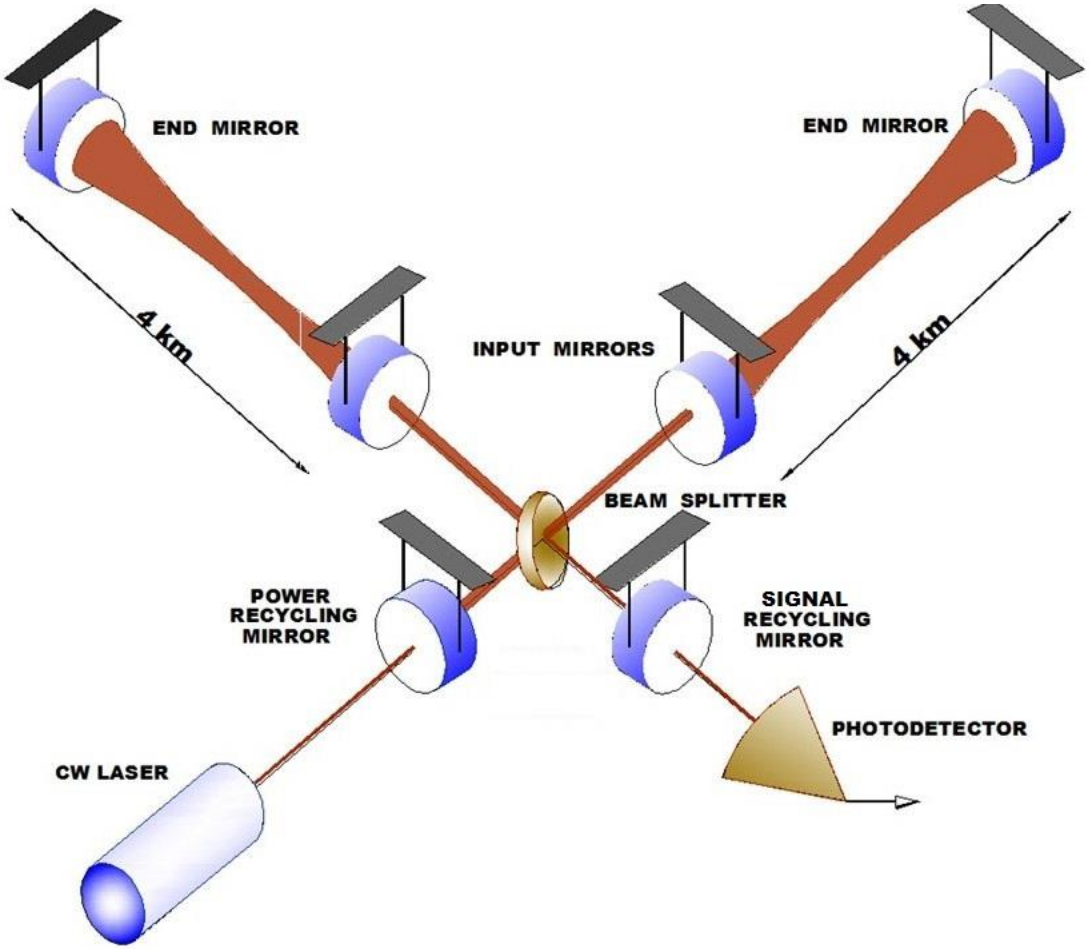
These engineering drawings illustrate the striking differences between Initial- and Advanced LIGO's suspensions. The suspensions are shown to scale.

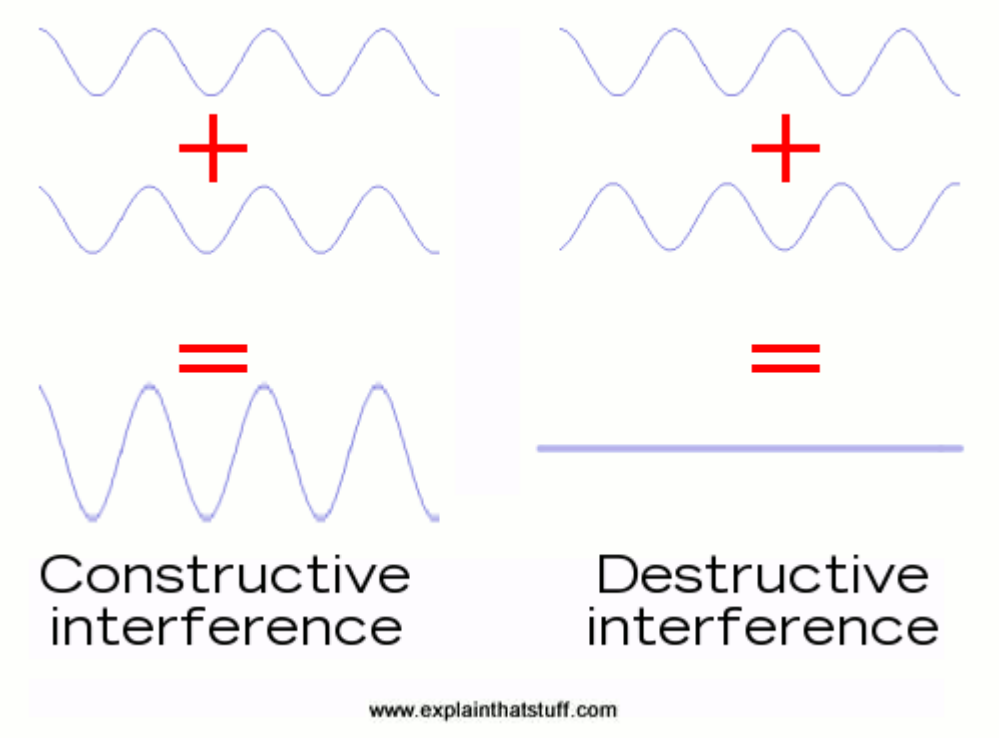
Initial LIGO's suspension was a single pendulum design with an 11 kg (22 lb) 'test mass' (mirror) hung by steel fibers.

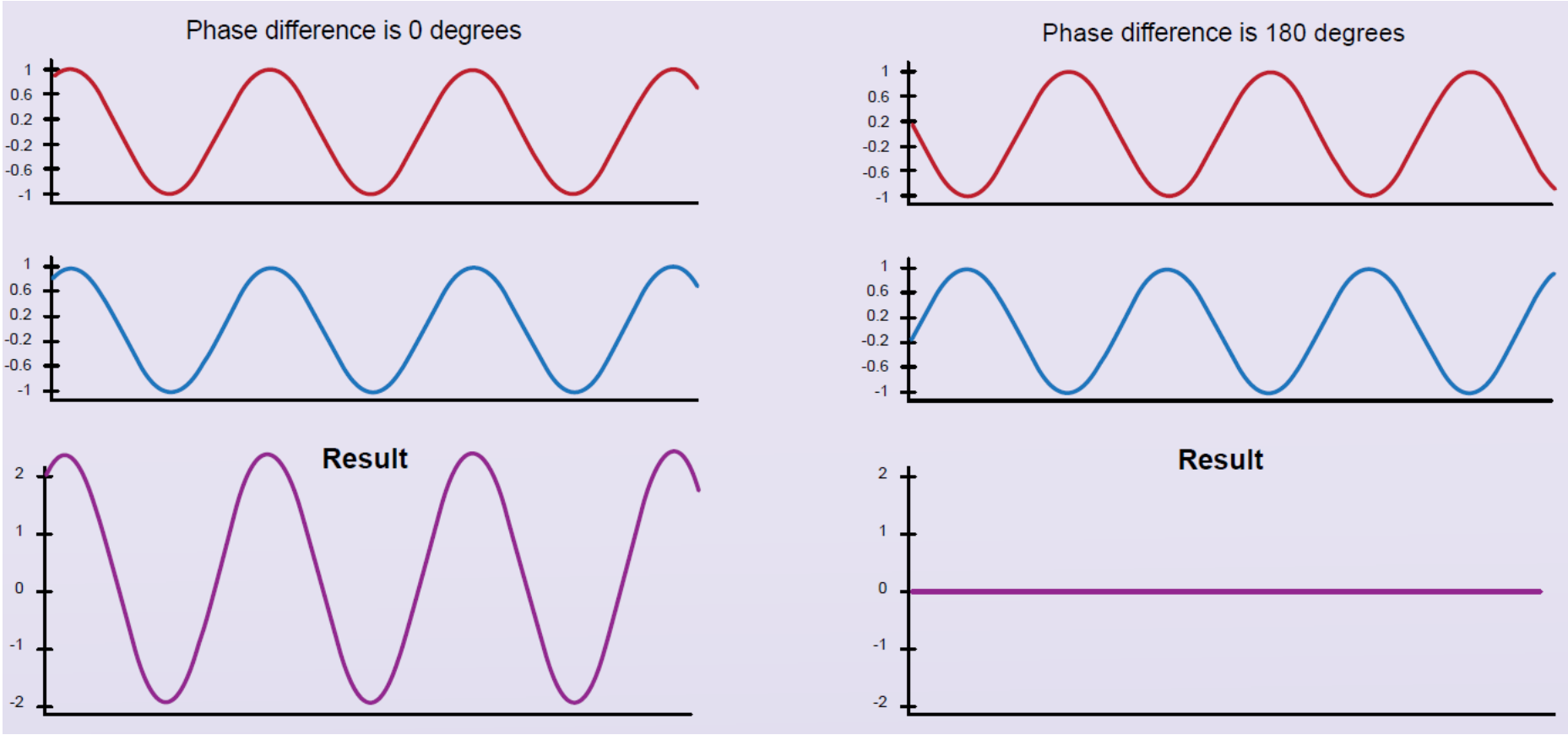
Advanced LIGO's suspension system is a **much** heftier quadruple ("quad") pendulum with a 40 kg (88 lb) 'test mass' (mirror) hung by fused silica fibers.

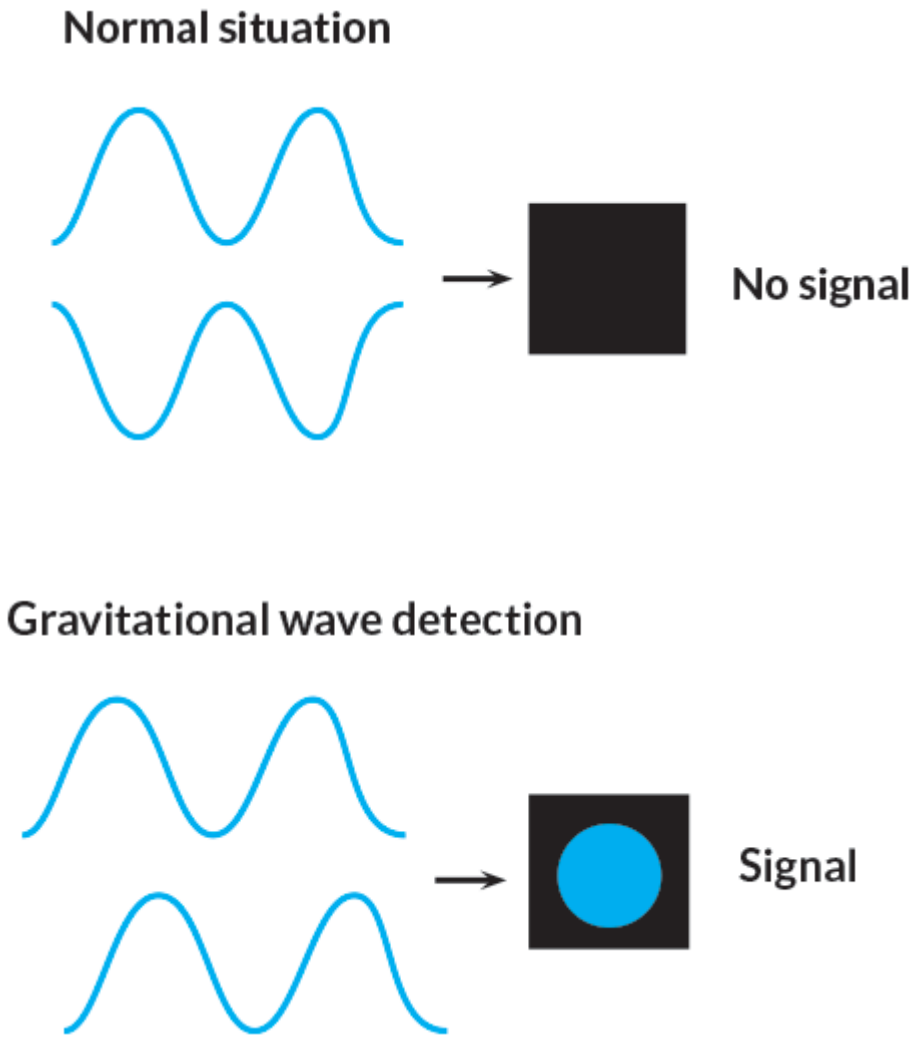


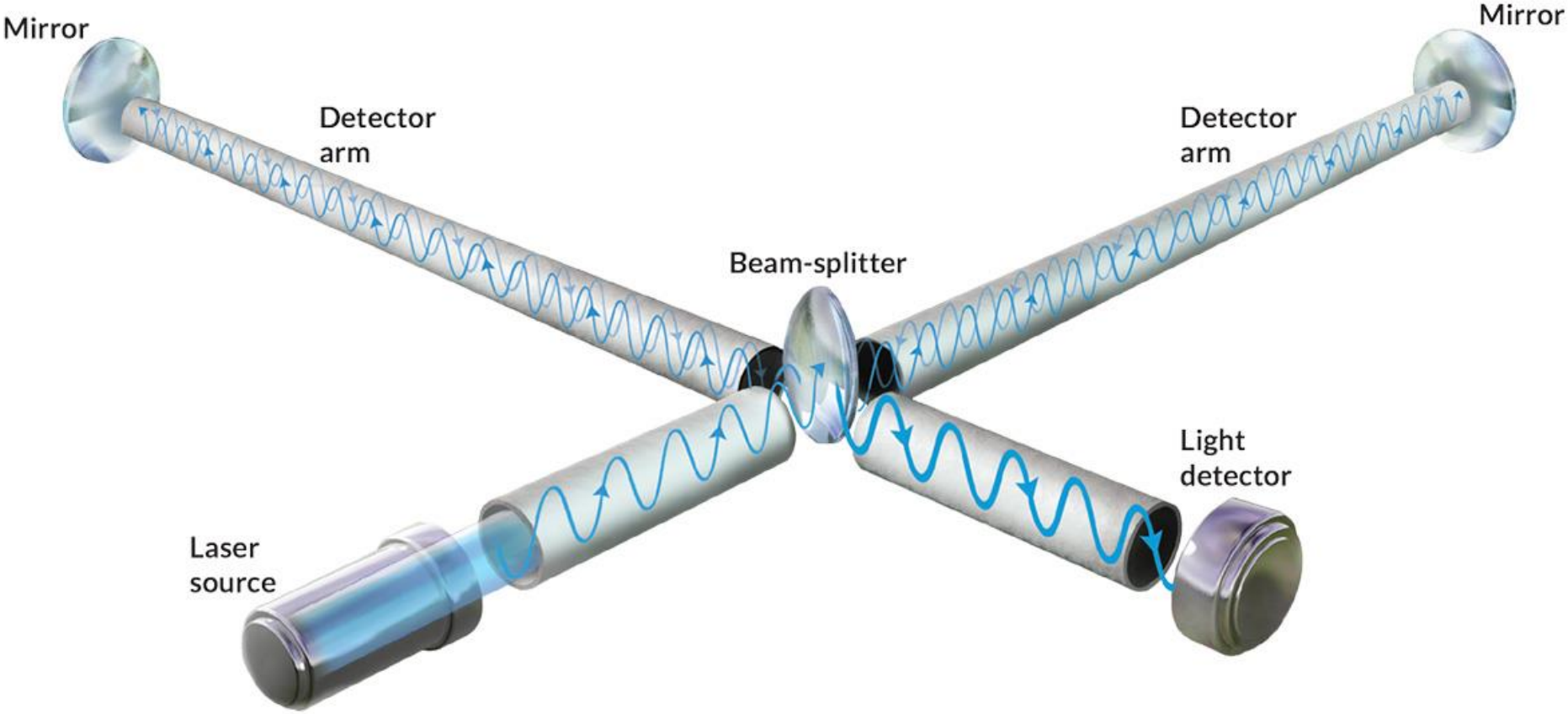
LIGOs seismiske isolasjonsplattform. Speilene henger i vakuumkamre under slike plattformer som er konstruert for at seismiske vibrasjoner ikke skal påvirke speilenes posisjon.


END MIRROR
END MIRROR
4 km
4 km
INPUT MIRRORS
BEAM SPLITTER
POWER
RECYCLING
MIRROR
SIGNAL
RECYCLING
MIRROR
PHOTODETECTOR
CW LASER


Constructive interference
Destructive interference
www.explainthatstuff.com

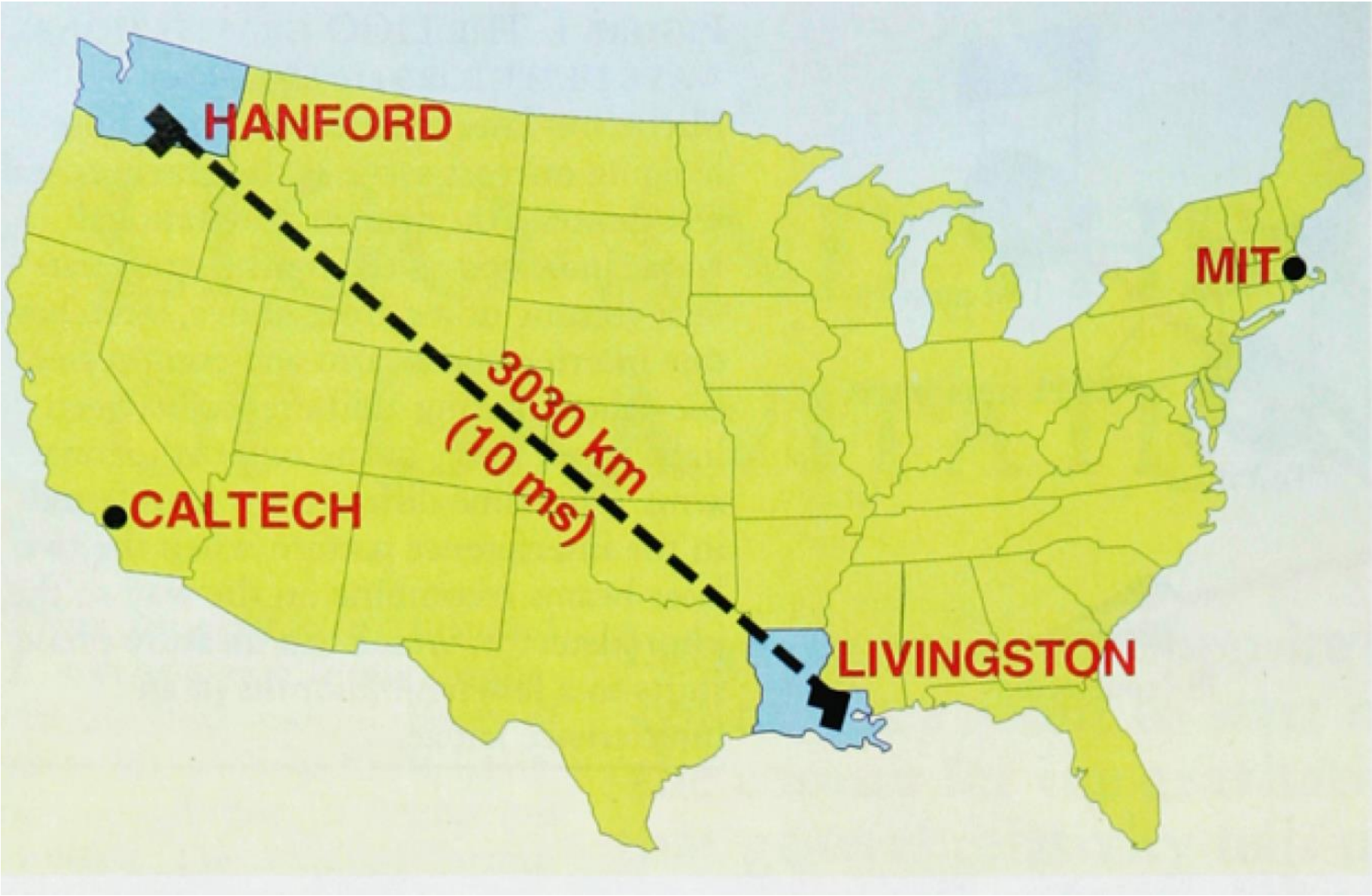

Phase difference is 0 degrees
1
0.6
0.2
-0.2
-0.6
-1
1
0.6
0.2
-0.2
-0.6
-1
Result
2
1
0
-1
-2
Phase difference is 180 degrees
1
0.6
0.2
-0.2
-0.6
-1
1
0.6
0.2
-0.2
-0.6
-1
Result
2
1
0
-1
-2

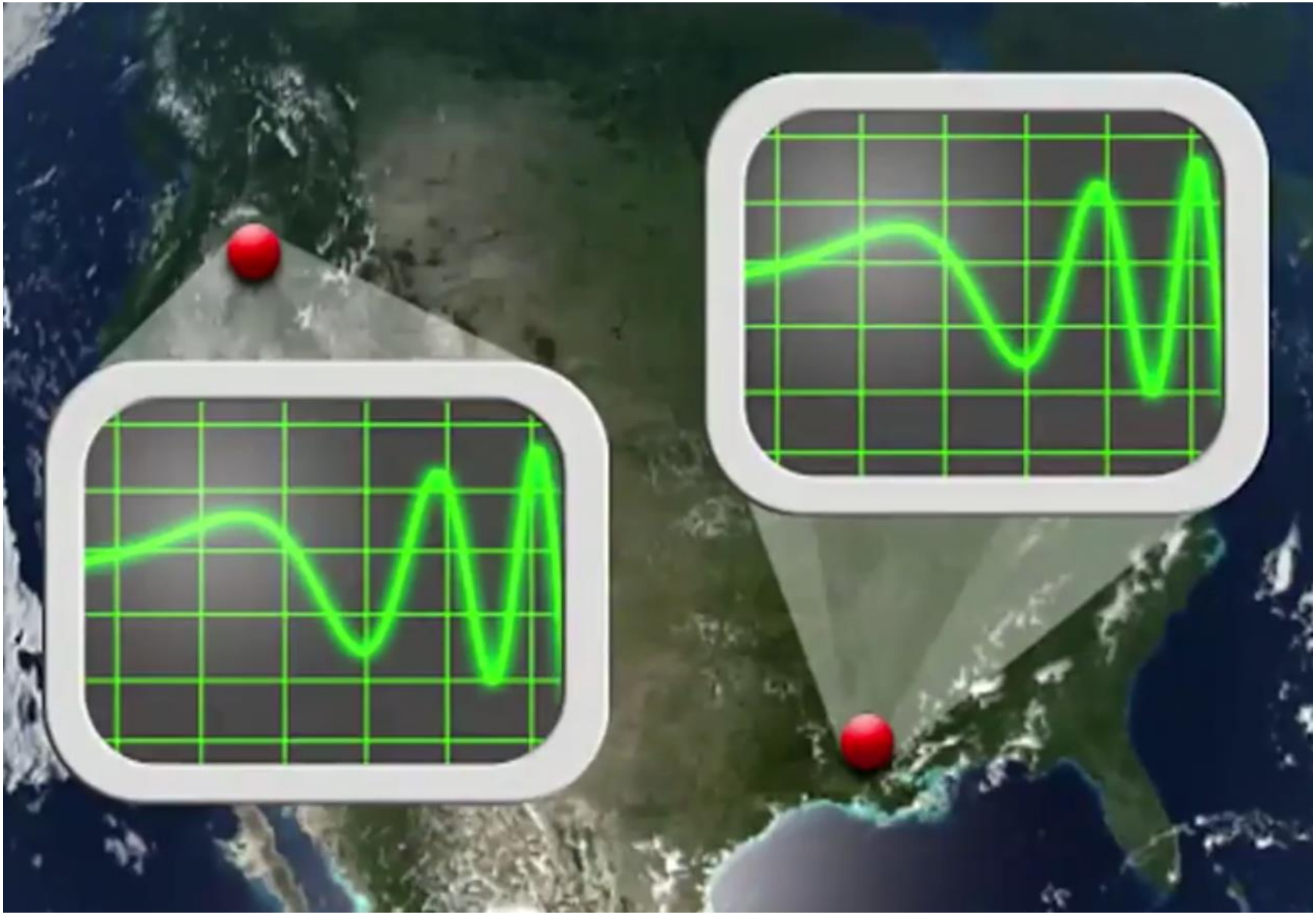

Normal situation
No signal
Gravitational wave detection
Signal


Mirror
Mirror
Detector arm
Detector arm
Beam-splitter
Light detector
Laser source

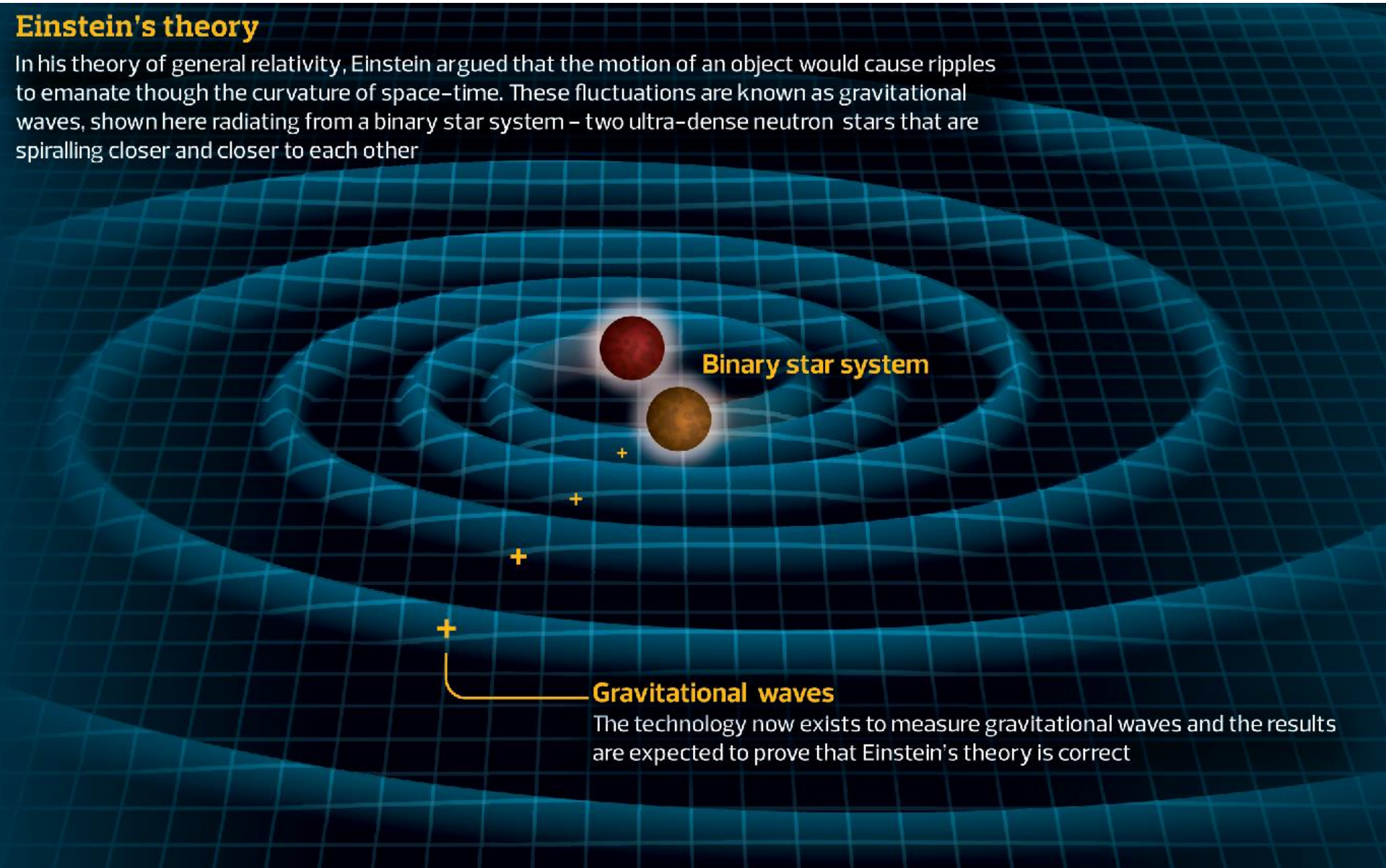
LIGO er omtalt som et teknologisk vidunder
Her er noen av de tekniske dataene

- Lyset reflekteres slik at den totale veilengden fra sender til detektor blir 1120 km.
- Seismisk isolering: Speilene er hengt opp i 4-trinns pendler som absorberer bevegelser. I tillegg er det et feedback system som hindrer uønskede forflytninger.
- Et ekstremt vakuum i et volum på 15000 m^3 er nødvendig for å hindre lydbølger og temperaturvariasjoner i målekammeret.
- Speilene veier 40 kg, er polert med nanometers jevn overflate og absorberer bare ett av 3,3 millioner fotoner som treffer dem.
- Laserstrålene må avbøyes i de 4 km lange armene på grunn av jordkrumningen, som utgjør en høydeforskjell på over en meter.


HANFORD
MIT
3030 km
(10 ms)
CALTECH
LIVINGSTON

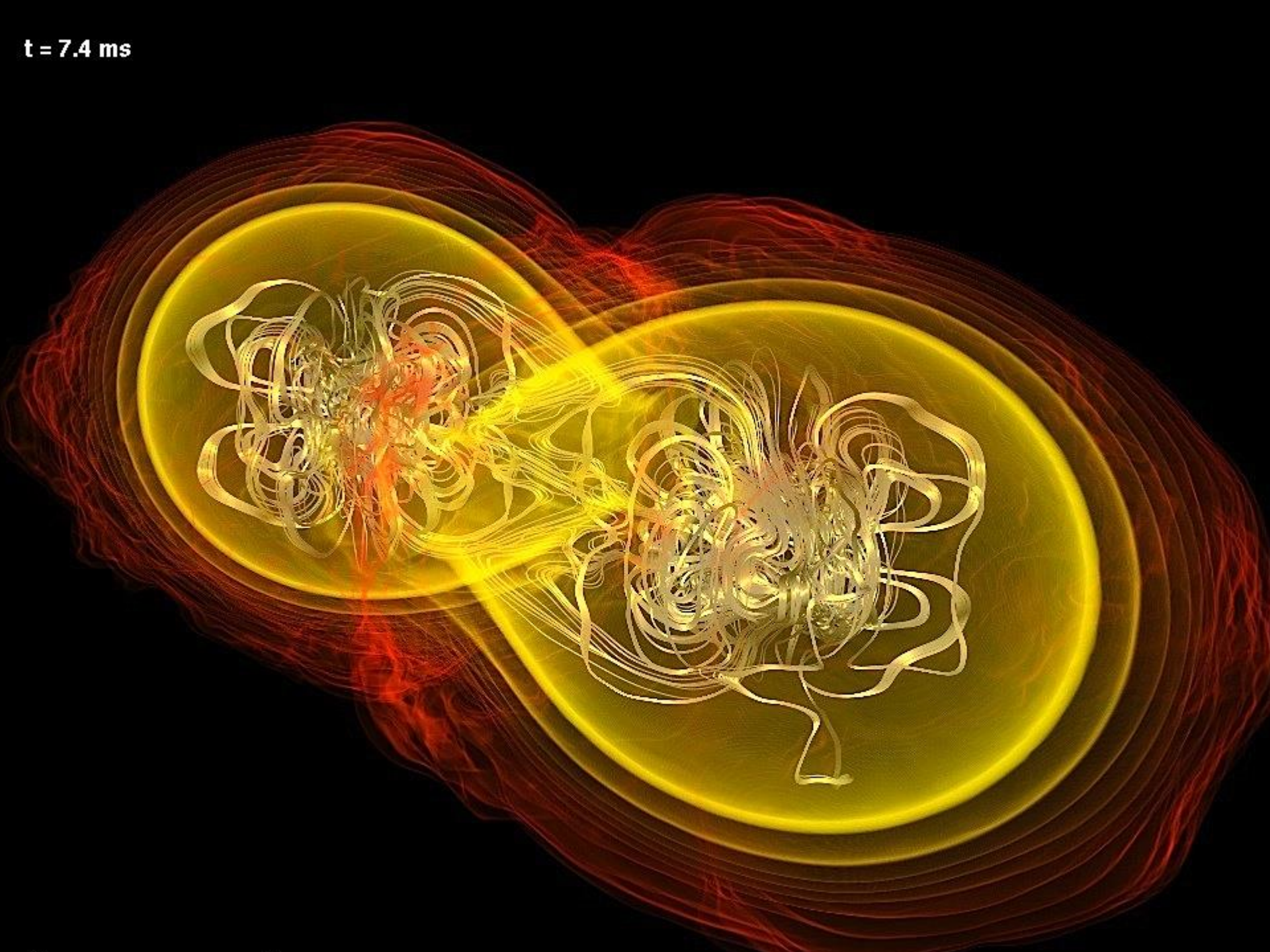


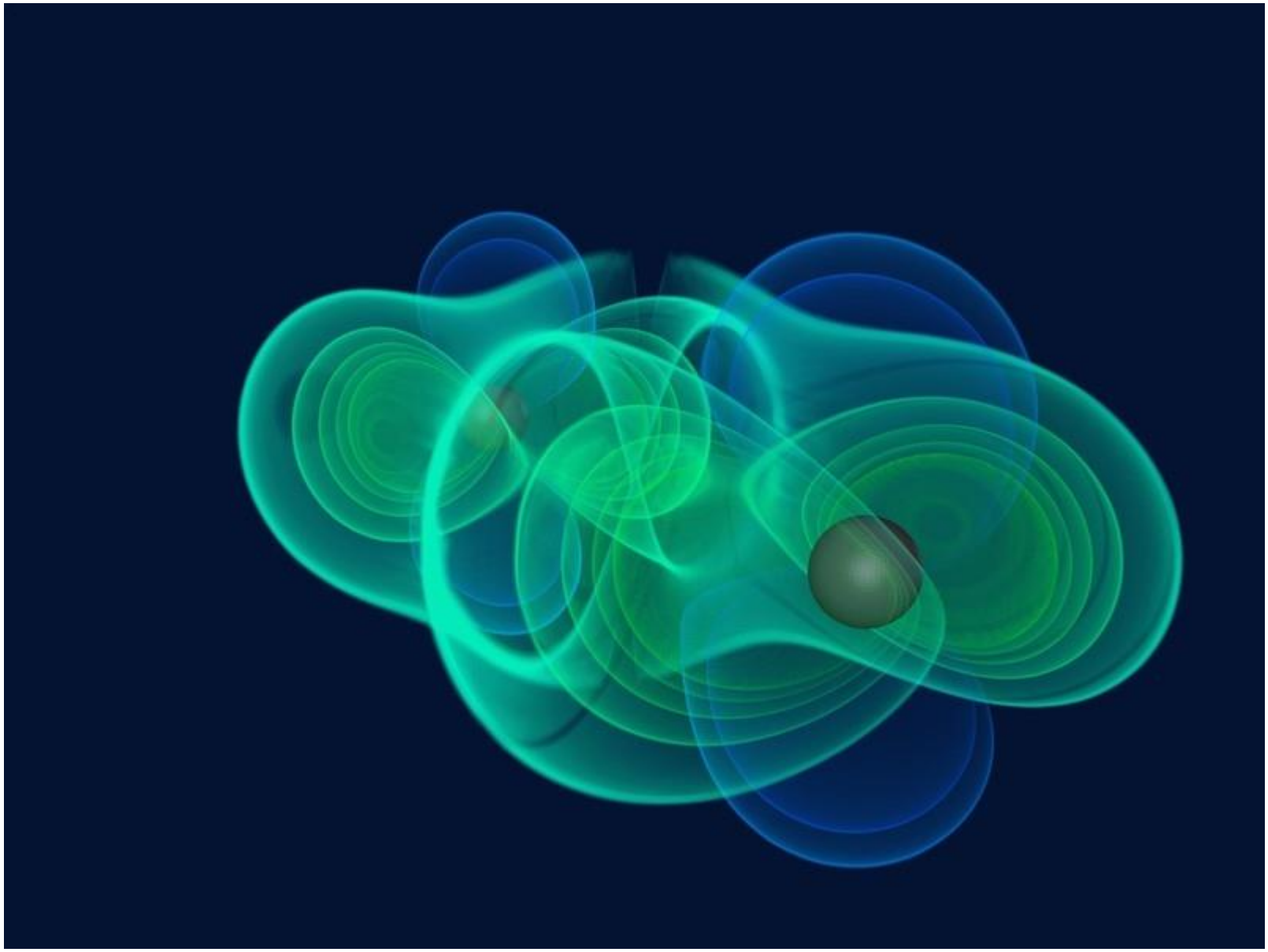
Gravitasjonsbølger er et relativistisk fenomen forutsagt av Einsteins relativitetsteori. Newtons gravitasjonsteori forutsier ikke eksistensen av gravitasjonsbølger. Dobbeltstjernesystemer der to stjerner roterer rundt systemets massesenter, sender ut gravitasjonsbølger.



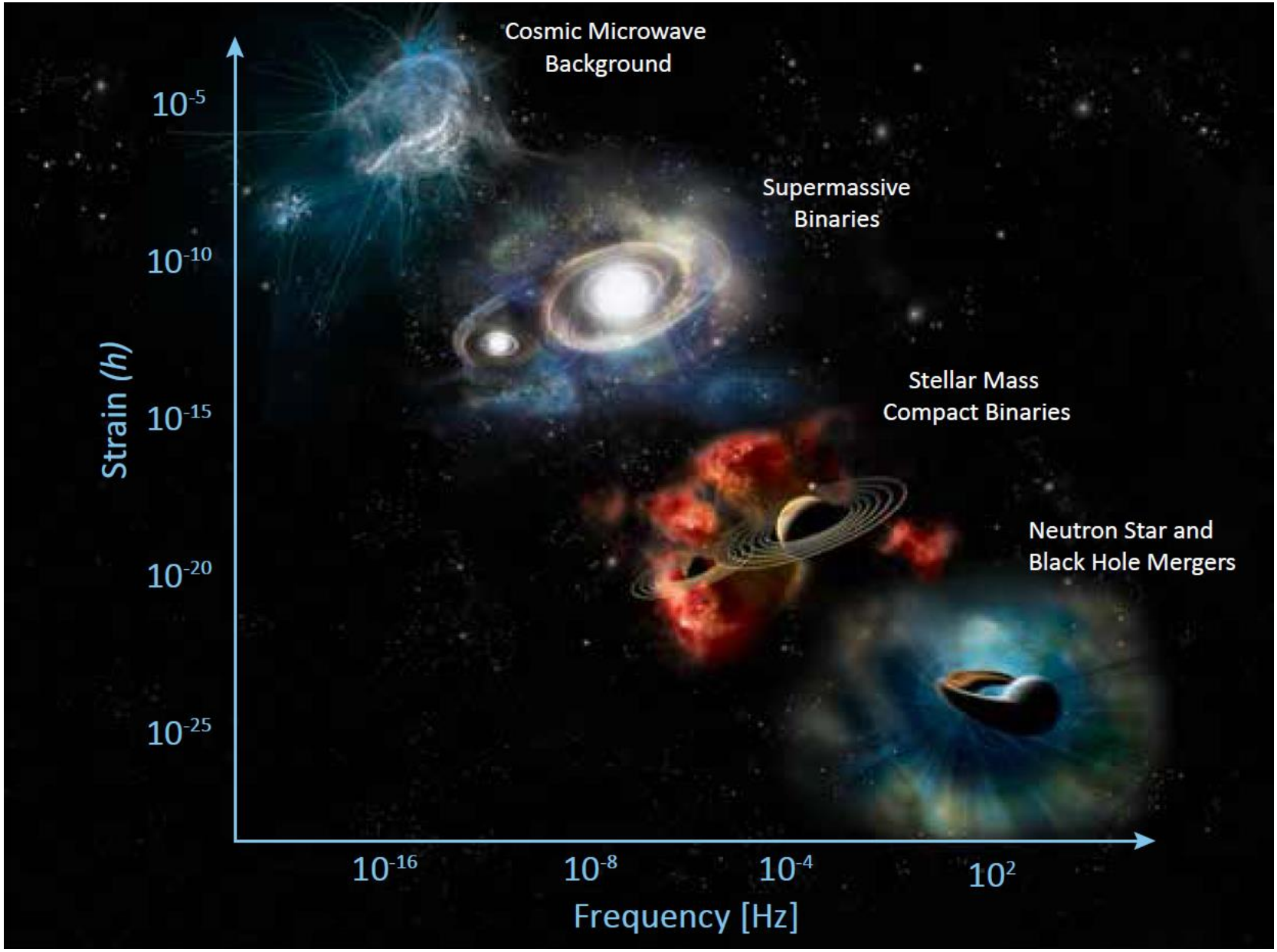
Illustrasjon av utbrudd på en nøytronstjerene som lager gravitasjonsbølger

Kolliderende nøytronstjerner lager gravitasjonsbølger


t = 7.4 ms

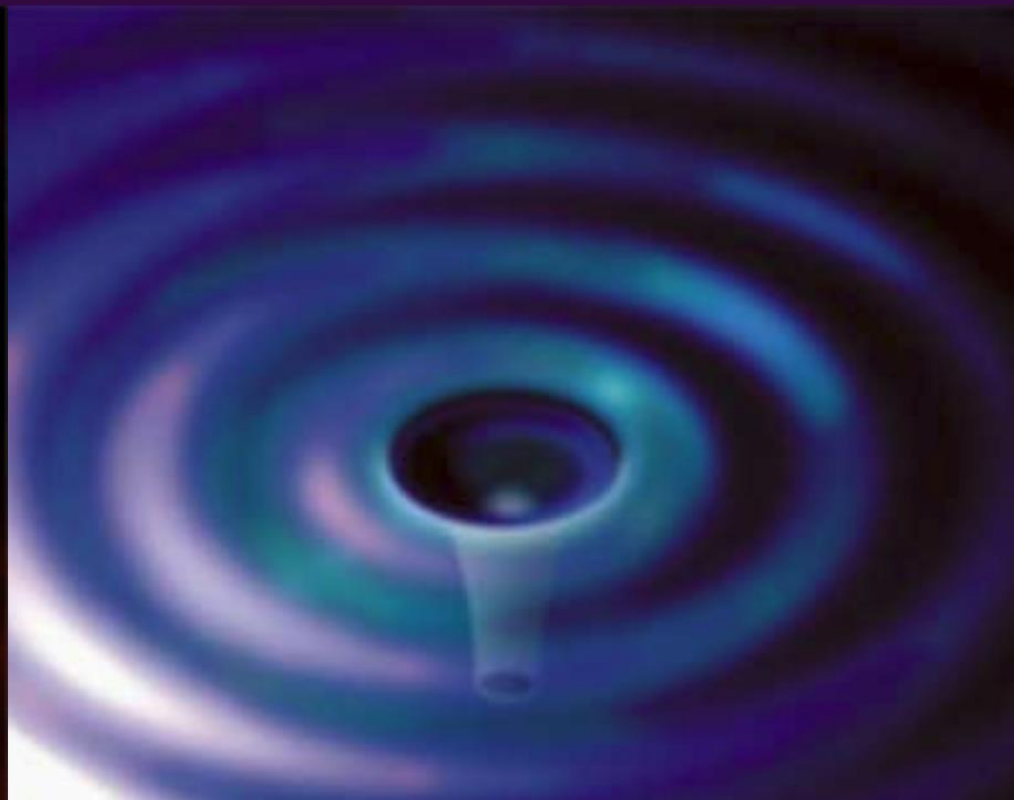


Cosmic collision: Gravitational waves are generated when black holes encircle each other and even collide – simulated here on a computer.
MPI for Gravitational Physics / Institute for Theoretical Physics, Frankfurt / Zuse Institute Berlin

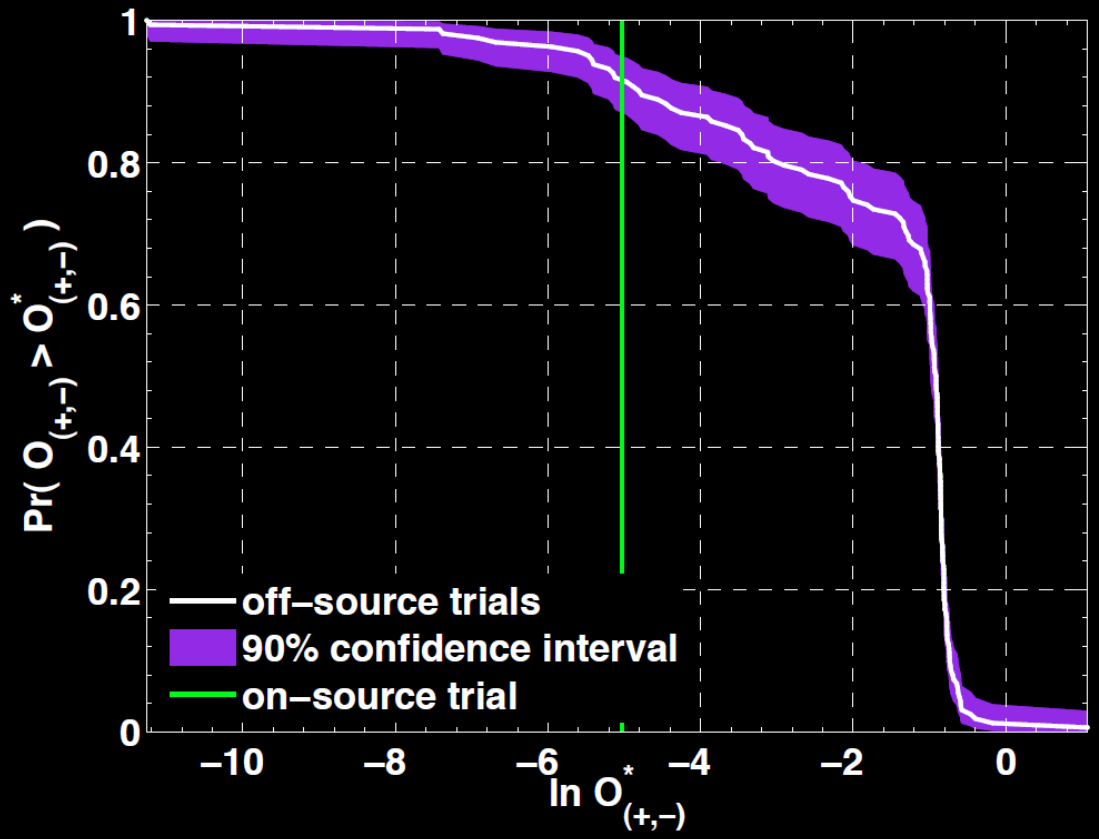

Cosmic Microwave Background
Supermassive Binaries
Stellar Mass Compact Binaries
Neutron Star and Black Hole Mergers
Strain (h)
10-5
10-10
10-15
10-20
10-25
10-16
10-8
10-4
102
Frequency [Hz]

A search for gravitational waves associated with the August 2006 timing glitch of the Vela pulsar

http://arxiv.org/abs/1011.1357



August 2006 Vela Glitch: Results



- Use **161** off-source segments of 120 s to estimate background distribution of detection statistic (odds ratio)
- Estimate probability of obtaining an odds ratio greater than or equal to the value found in the on-source segment
- **Probability of obtaining on-source data for no GW present = 0.92**

Conclusion: no evidence for ring-down gravitational wave signal associated with Vela August 2006 Glitch

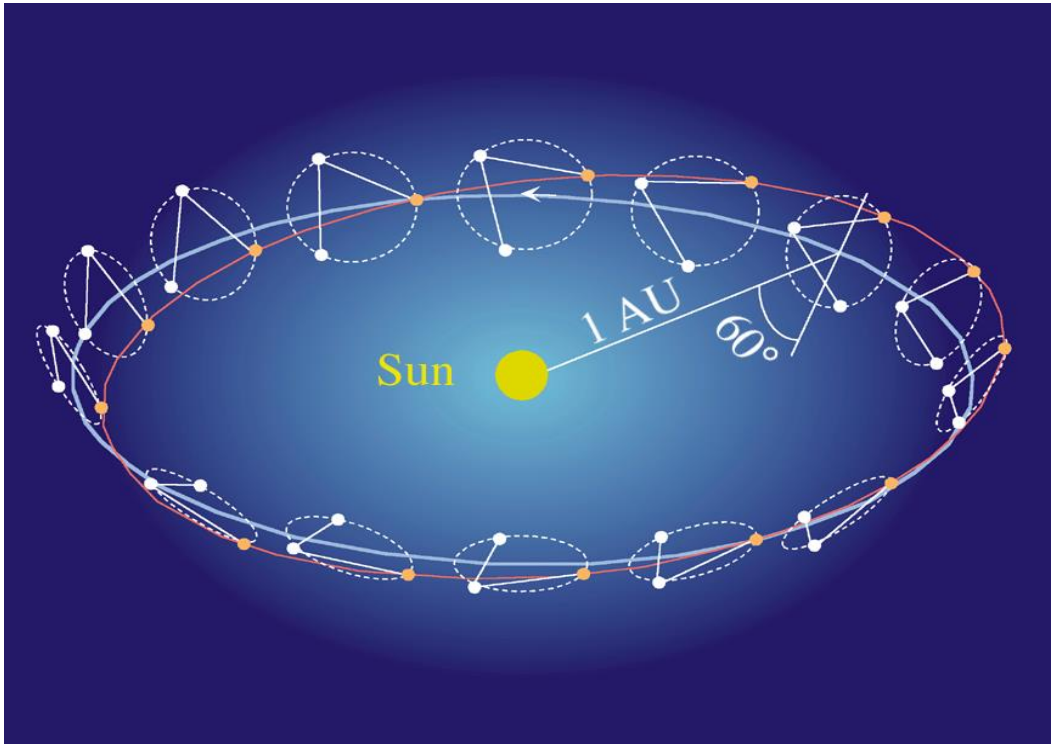
LISA

Laser Interferometer
Space Antenna

LISA: A NASA/ESA Mission to Observe the Universe with Gravitational Waves

http://lisa.nasa.gov

LISA - Laser interferometer romantenne



Beskrivelse av antennen

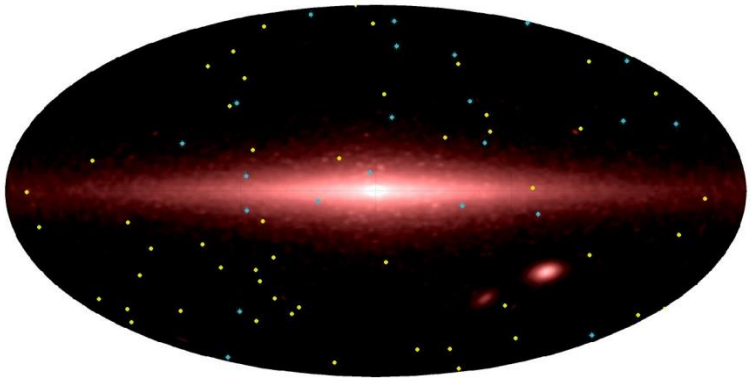
- *3 sonder i bane rundt sola med fem millioner km avstand fra hverandre.*
- *Gravitasjonsbølger detekteres ved å måle endringer i avstand mellom referanselegemer i hver sonde ved å bruke laser interferometri.*

Observasjonsmål

- *Kollisjoner mellom svarte hull.*
- *Ultrakompakte binære systemer (nøytronstjerner og svarte hull) i Melkeveien.*
- *Gravitasjonsbølger fra det tidlige univers.*

"LISA is an extraordinarily original and technically bold mission concept. The first direct detection of low-frequency gravitational waves will be a momentous discovery, of the kind that wins Nobel Prizes. The mission will open up an entirely new way of observing the universe, with immense potential to enlarge our understanding of both physics and astronomy in unforeseen ways."

- National Research Council (2007) -



LISA highly ranked in all major reviews:

2000 Decadal Review, 2003 Quarks to Cosmos,
2005 Mid-Course Decadal Update, 2007 Beyond Einstein Review,

2010 Astro2010 Decadal Review

LISA: 202x (?)

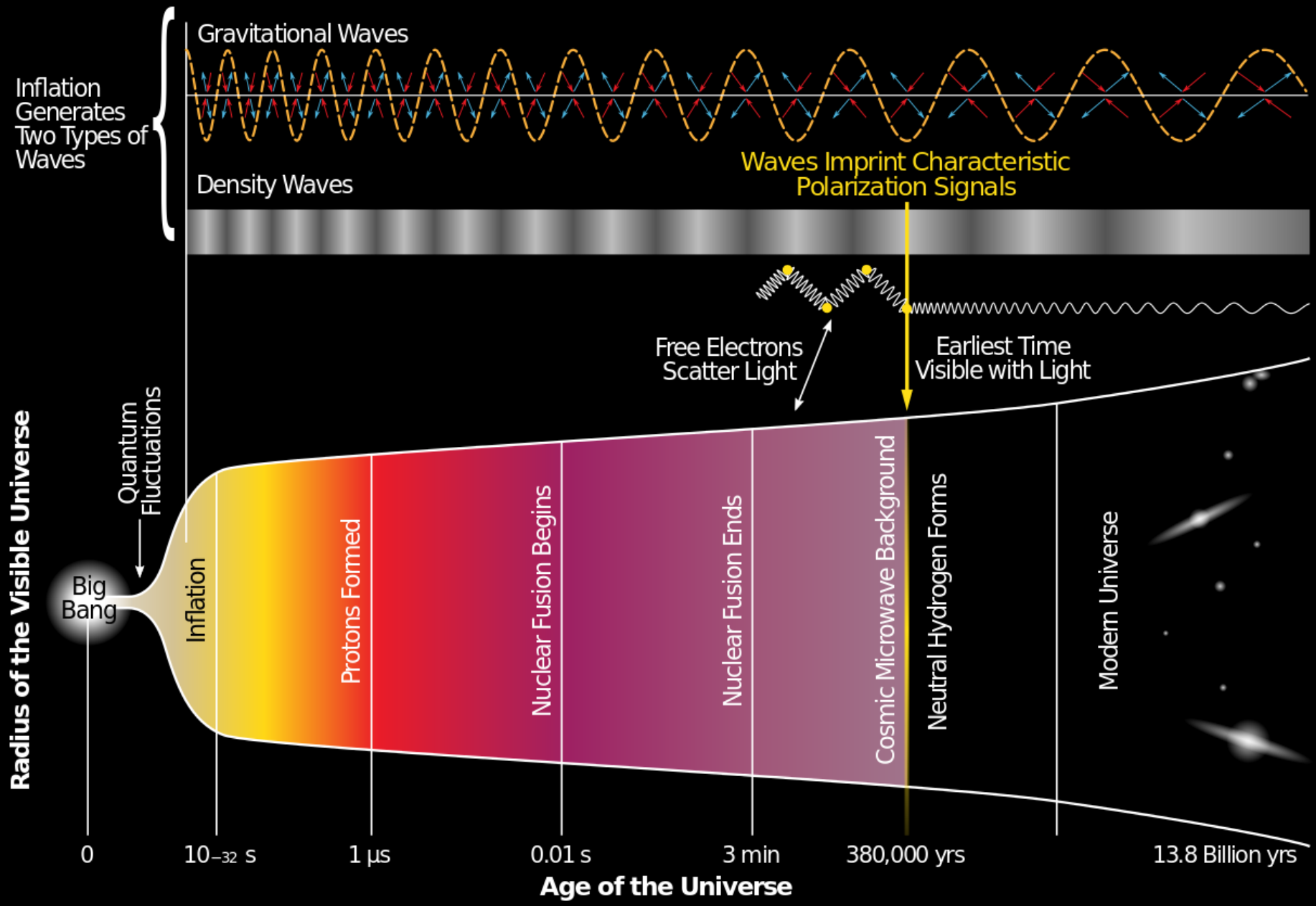
http://www.lisa-science.org/resources/mission

The LISA project was previously a joint effort between the United States space agency NASA and the European Space Agency ESA.

However, on April 8, 2011, NASA announced that it would be unable to continue its LISA partnership with the European Space Agency, due to funding limitations.

ESA has therefore revised the mission's concept to fit into a European-only cost envelope with a tentative launch date in 2034.

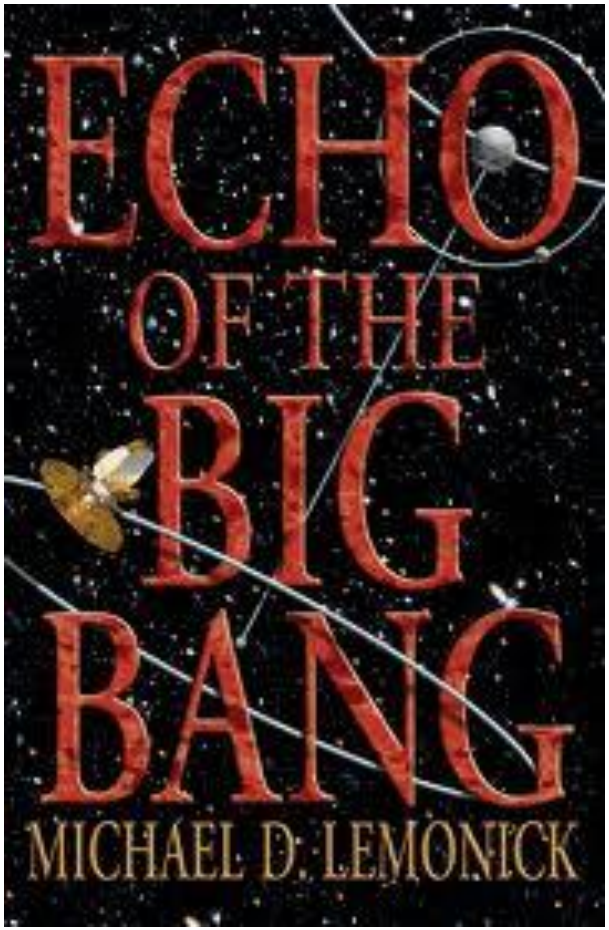
History of the Universe



Gravitational Waves

Listening to the Universe

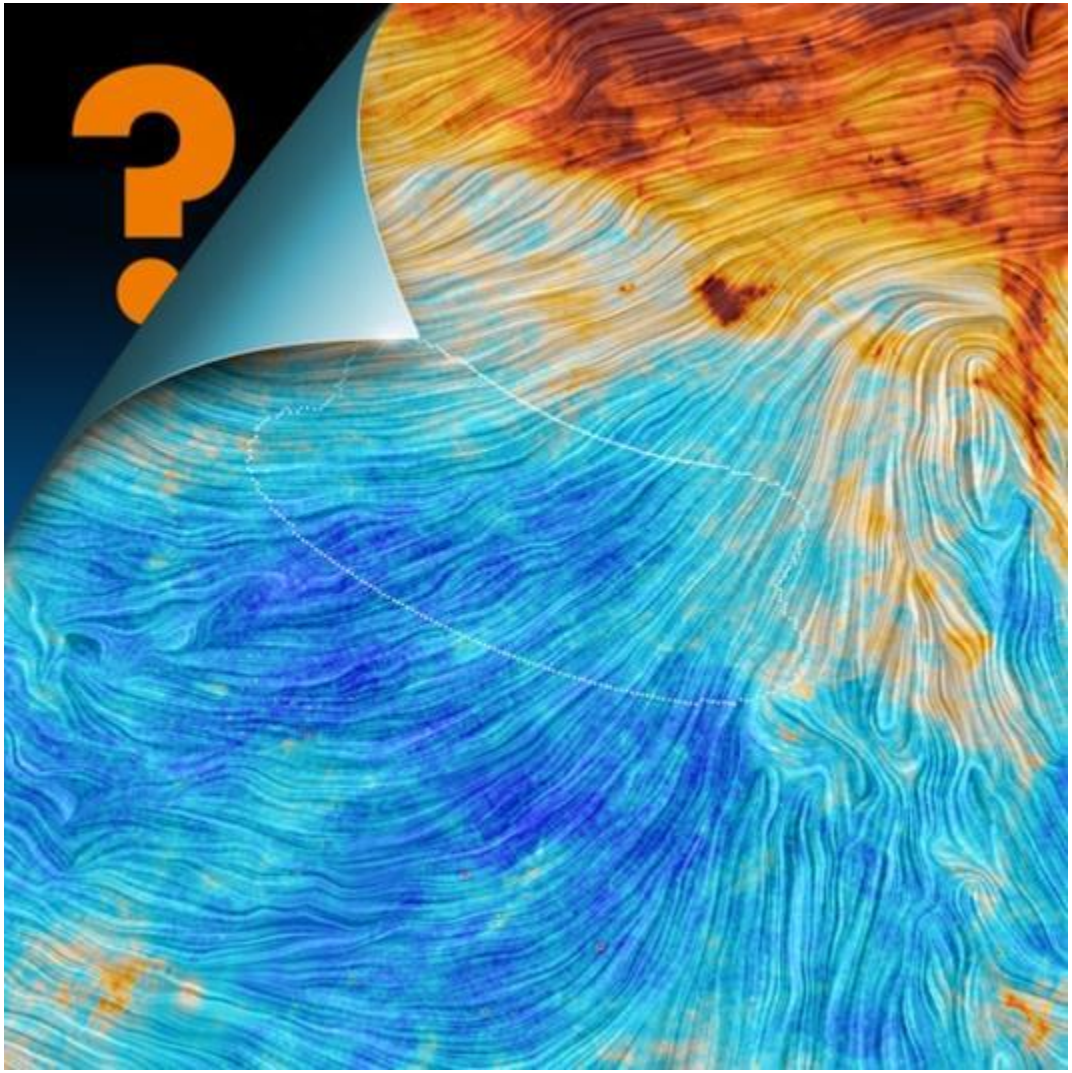
Teviet Creighton
LIGO Laboratory
California Institute of Technology



BICEP2 på Sydpolen

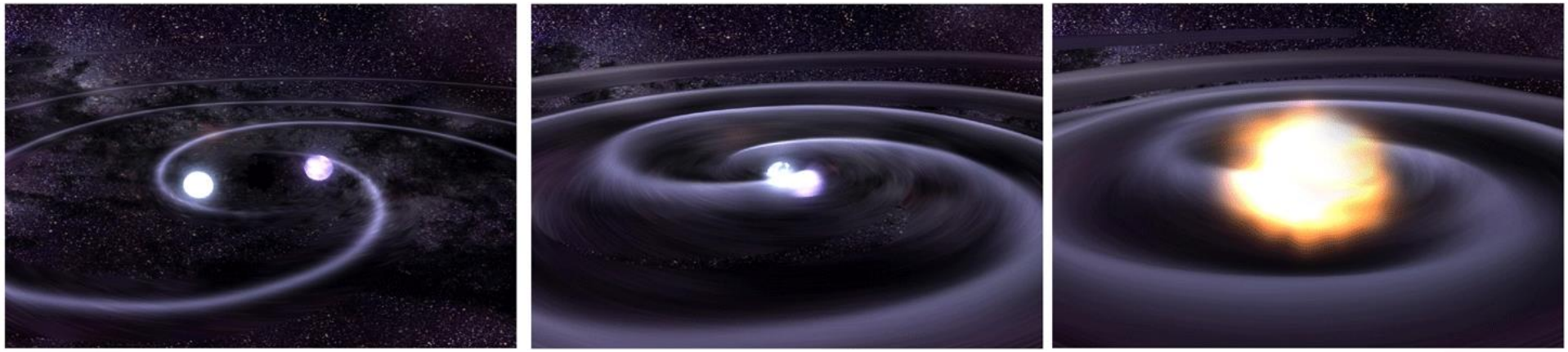
Den 17. mars 2014 sammenkalte BICEP 2-teamet til pressekonferanse om en mulig oppdagelse av spor etter gravitasjonsbølger produsert i den tidlige inflasjonsfasen av Universets historie i polarisasjonsmønsteret CMB.

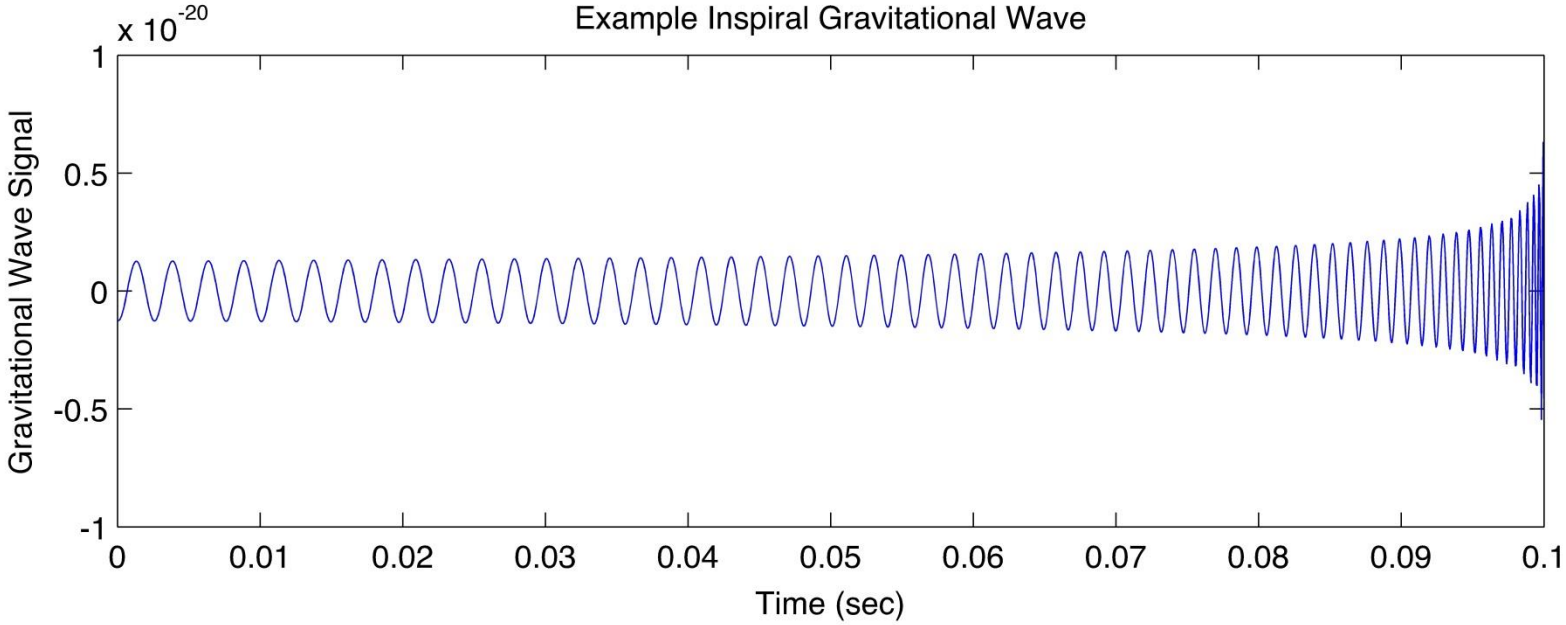
'Listen! There they are again – echoes of the Big Bang. The beginning of creation!'



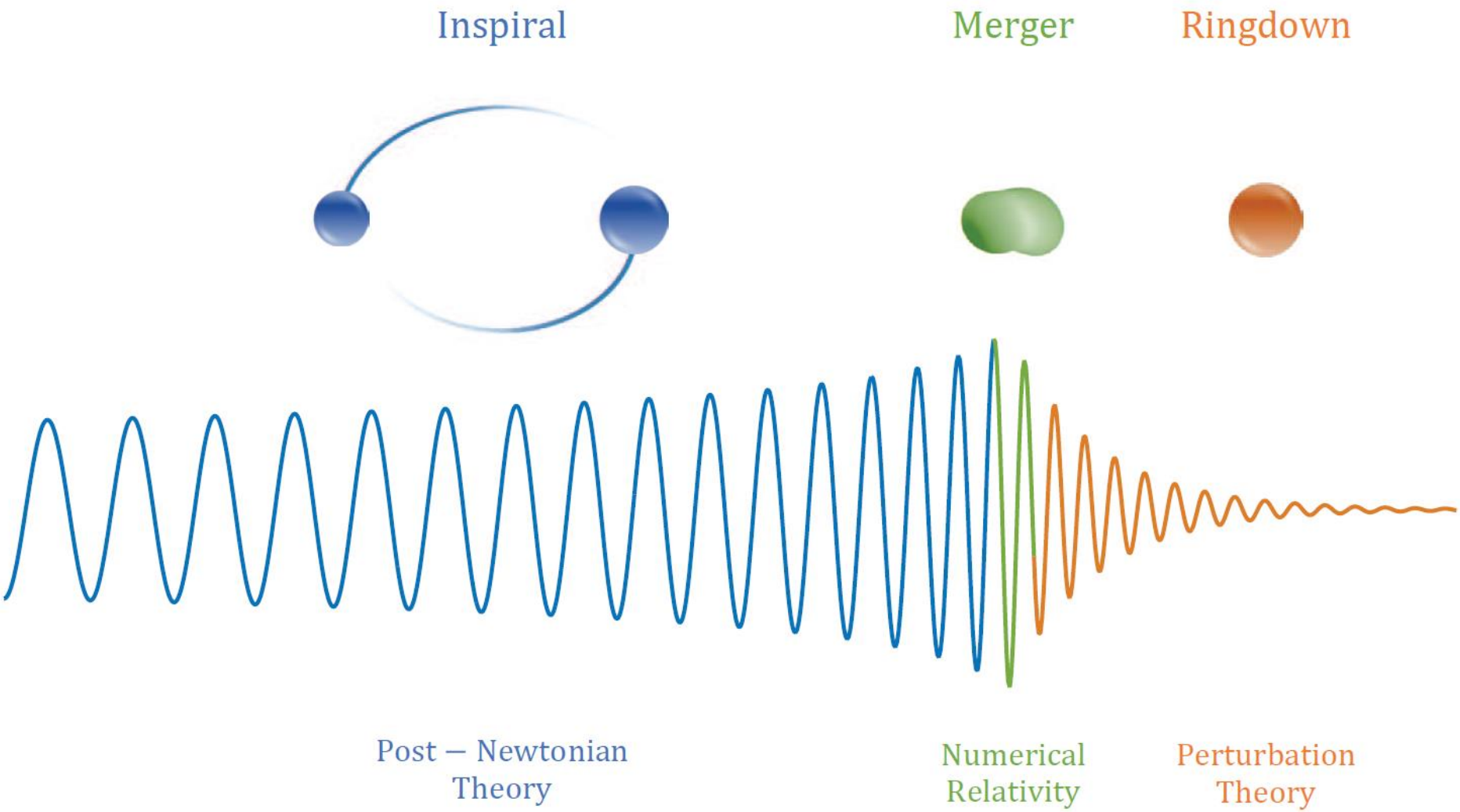
Plancks-teamets målinger av polariserende støv i Melkeveien og det galaktiske magnetfeltet i en del av Melkeveien. Spørsmålstegnet illustrerer at man ikke vet hva som skjuler seg i bakgrunnen.

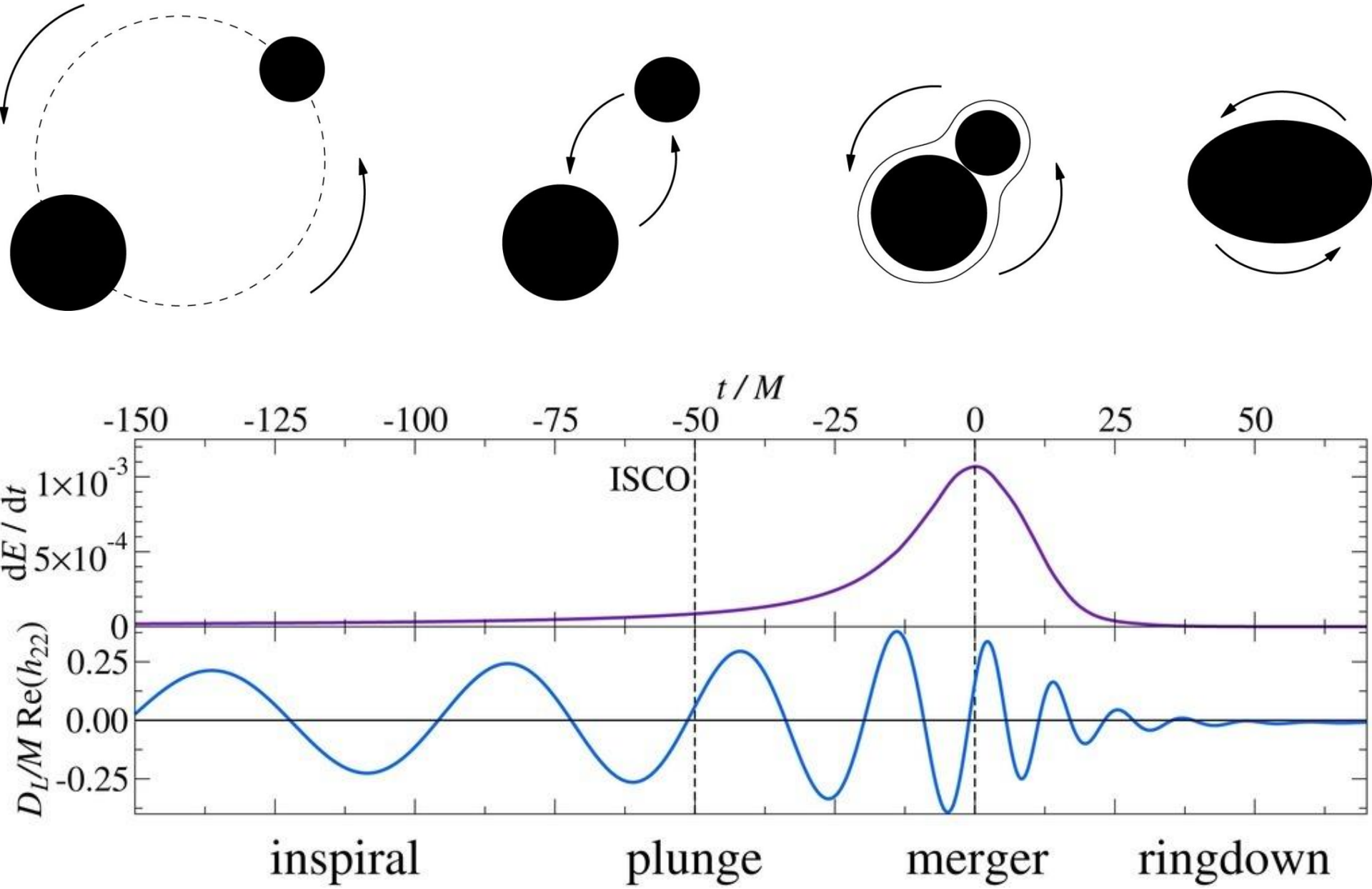
I en ny felles rapport offentliggjort 2. februar 2015 har forskere fra BICEP2 og Planck teamene annonsert at det observerte polarisasjonsmønsteret kan skyldes polarisering av stråling fra støv i Melkeveien.



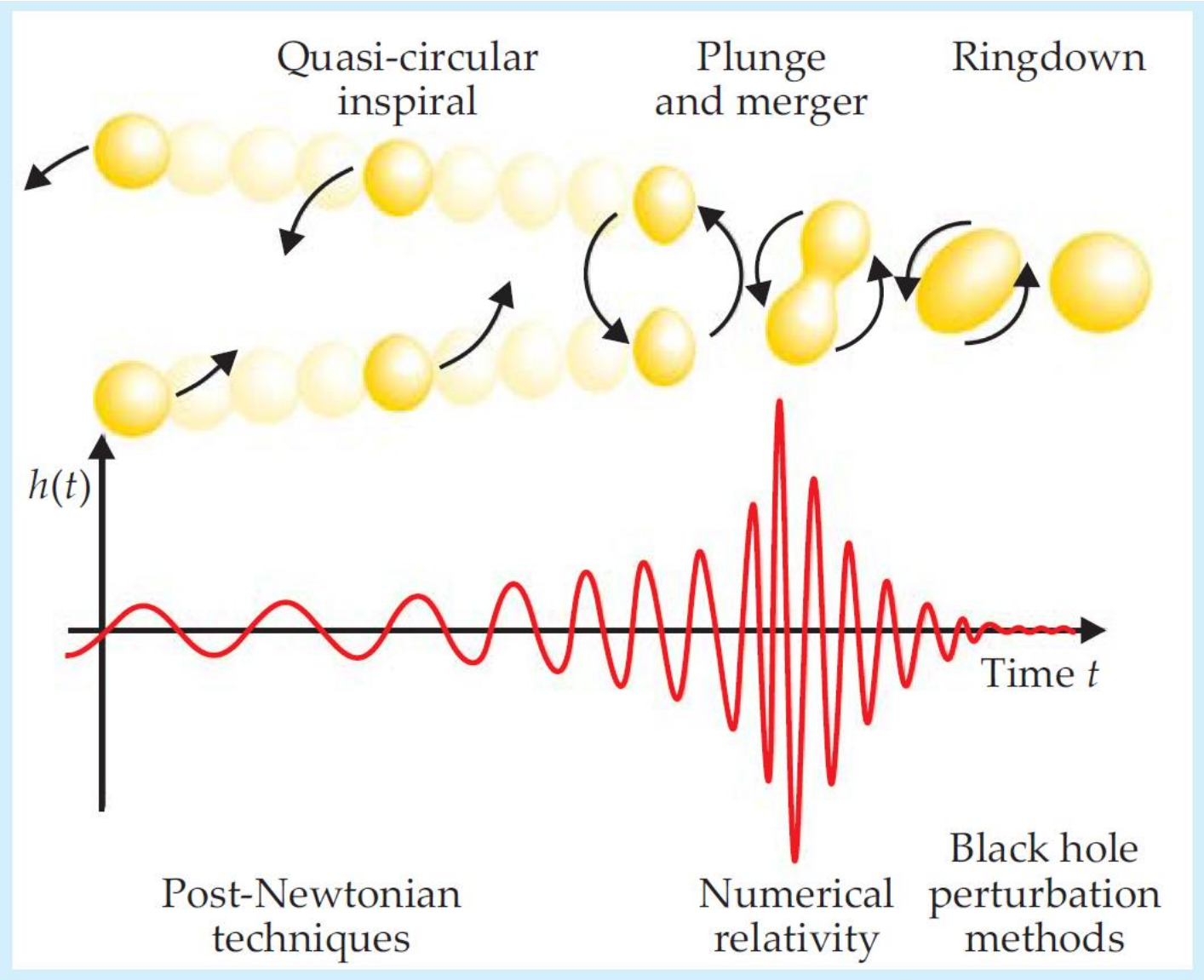


Illustrasjon av to stjerner i bane rundt hverandre.
De sender ut gravitasjonsbølger og taper dermed energi.
Det gjør at de vil bevege seg i spiralbane mot hverandre.
Da vil gravitasjonsbølgene bli kraftigere som illustrert nederst.

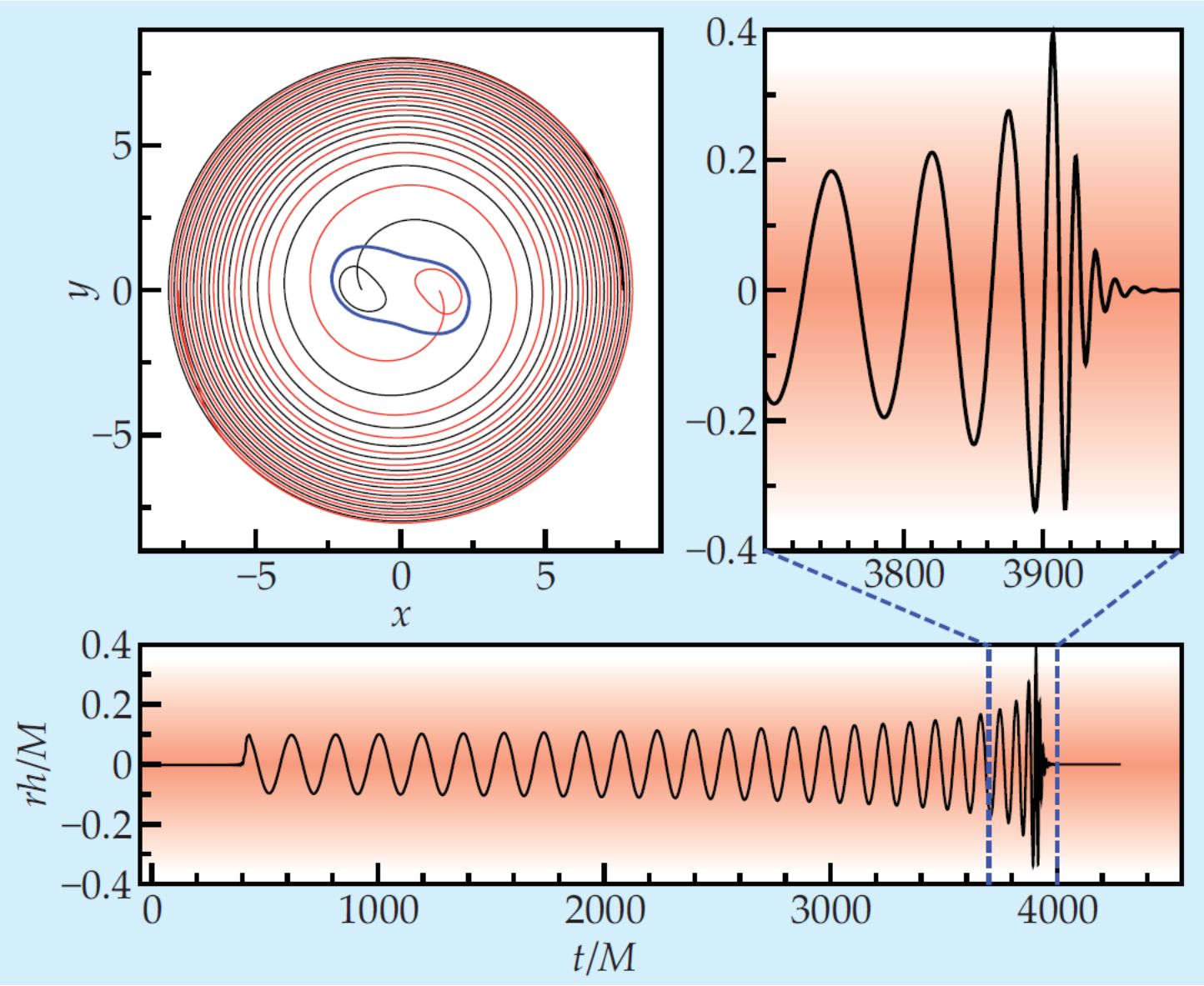

Inspiral
Merger
Ringdown
Post – Newtonian Theory
Numerical Relativity
Perturbation Theory


t / M
-150
-125
-100
-75
-50
-25
0
25
50
ISCO
dE / dt
1×10^-3
5×10^-4
0
D_L/M Re(h_22)
0.25
0.00
-0.25
inspiral
plunge
merger
ringdown

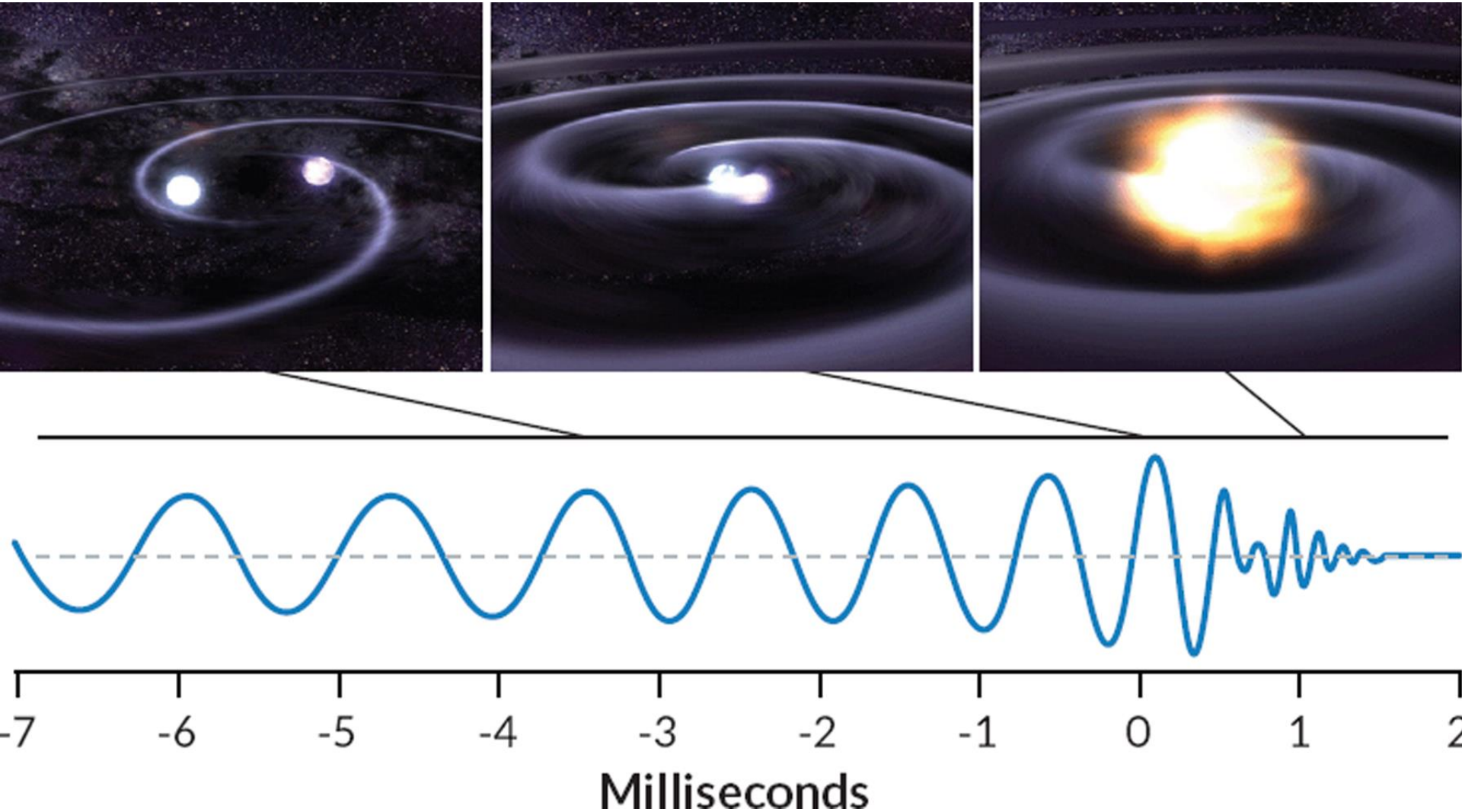
Fra en artikkel: ***Binary black hole mergers*** i Physics Today oktober 2011



Amplituden til de utsendte gravitasjonsbølgene som funksjon av tiden. Nederst fortelles hvilke beregningsmetoder som er brukt.



Øverst til venstre vises banene til to svarte hull som ender med å kollidere. Nederst og til høyre vises svingningene til gravitasjonsbølger som sendes ut.


-7
-6
-5
-4
-3
-2
-1
0
1
2
Milliseconds

10. februar 2016
Man har foreløpig
ingen direkte deteksjon
av gravitasjonsbølger

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

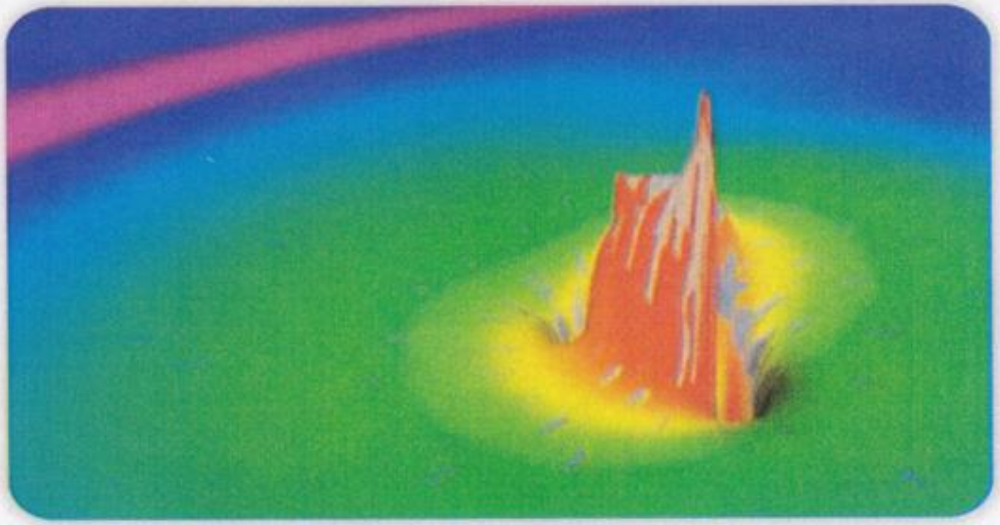
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.



PASADENA, CA 91105
FEB 11 2016

LIGO

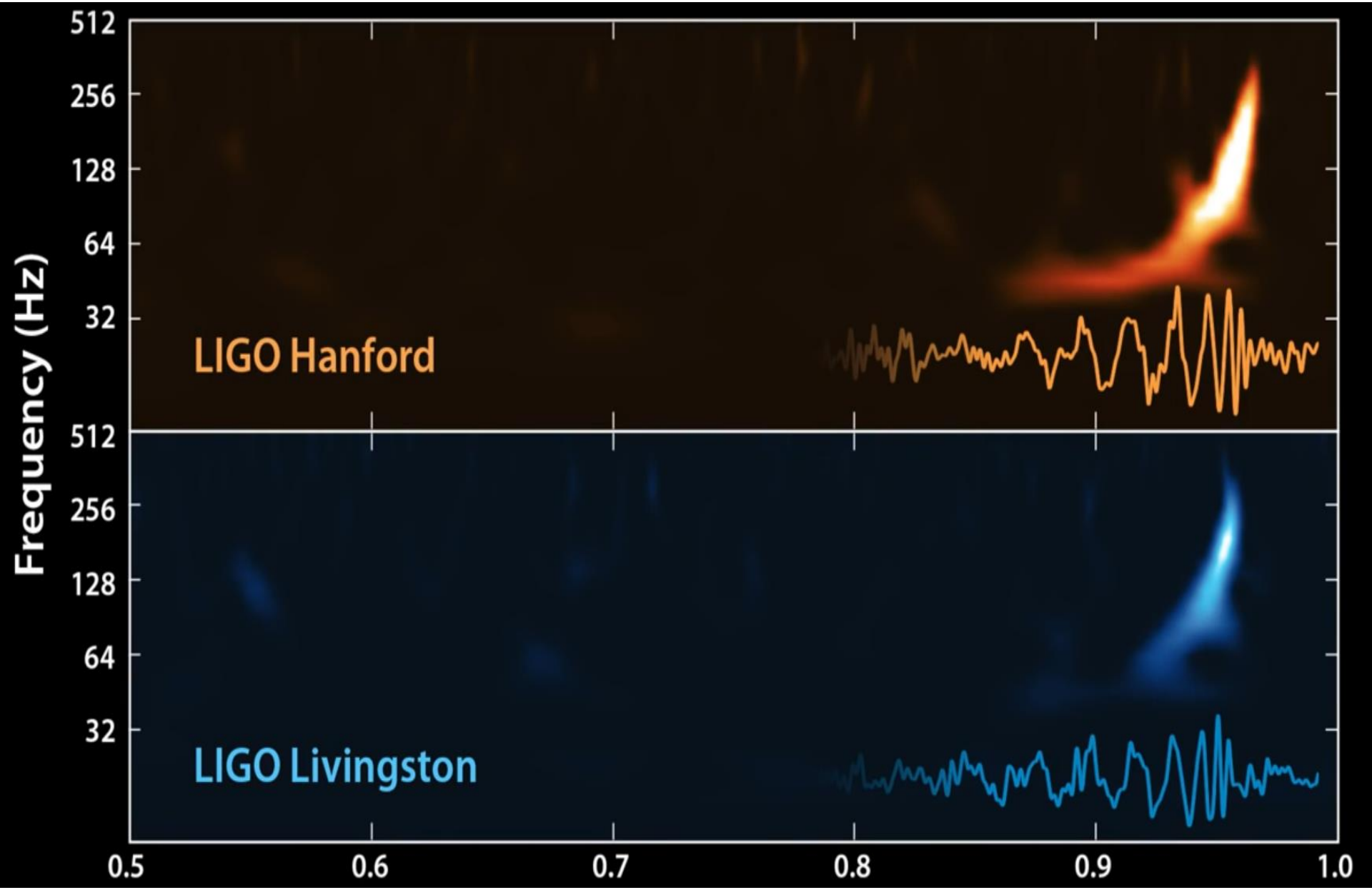
Announces Discovery of
Gravitational Waves

A founding father

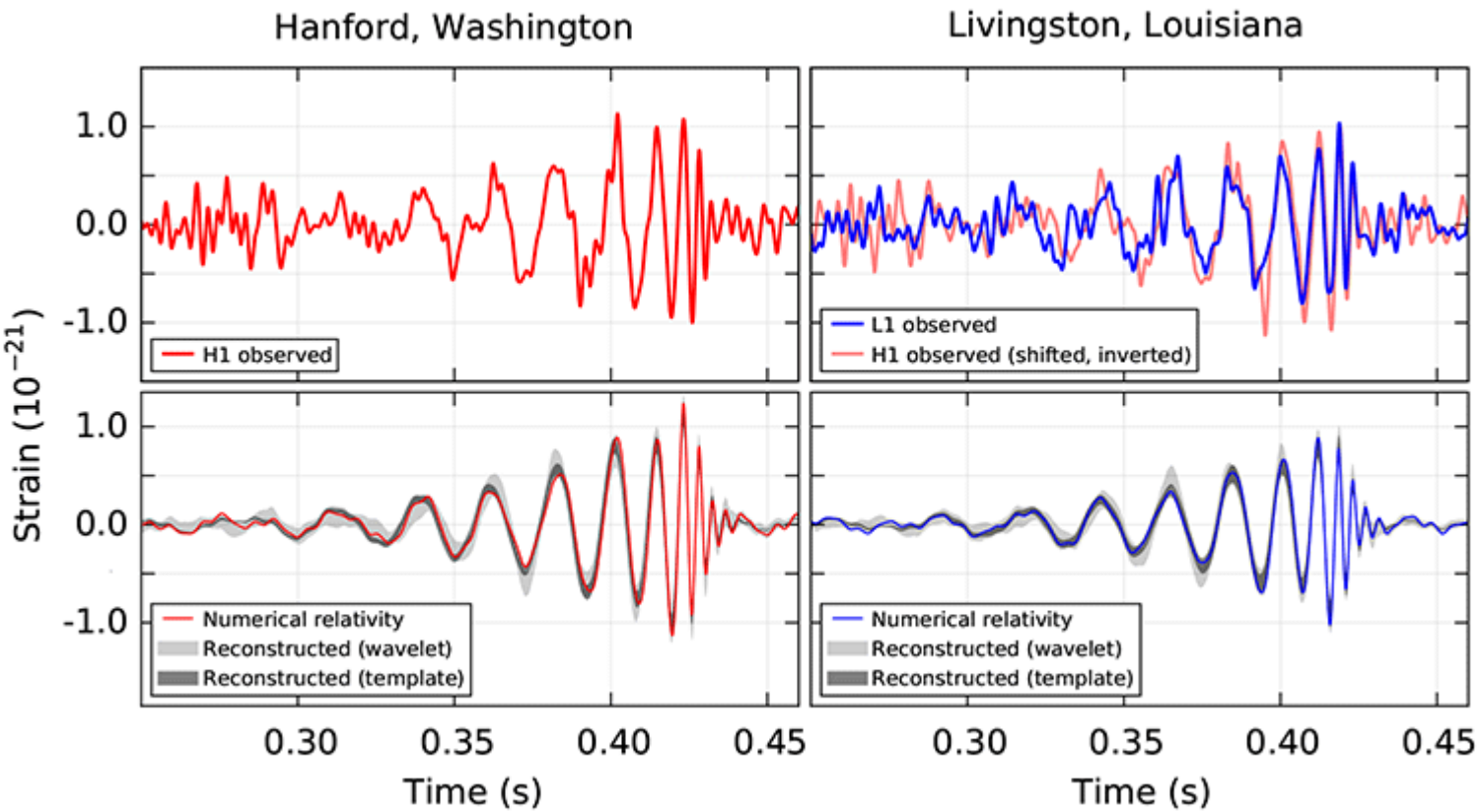
Physicist Kip Thorne helped to found LIGO, along with his California Institute of Technology colleague Ronald Drever and physicist Rainer Weiss of the Massachusetts Institute of Technology.

Ronald W. P. Drever er en skotsk eksperimentalfysiker.
Han ble rekruttert av Kip Thorne til å være med å designe en gravitasjonsbølgedetektor.
Kip Thorne, Rainer Weiss og Ronald Drever betraktes som drivkreftene bak opprettelsen av LIGO-observatoriet.

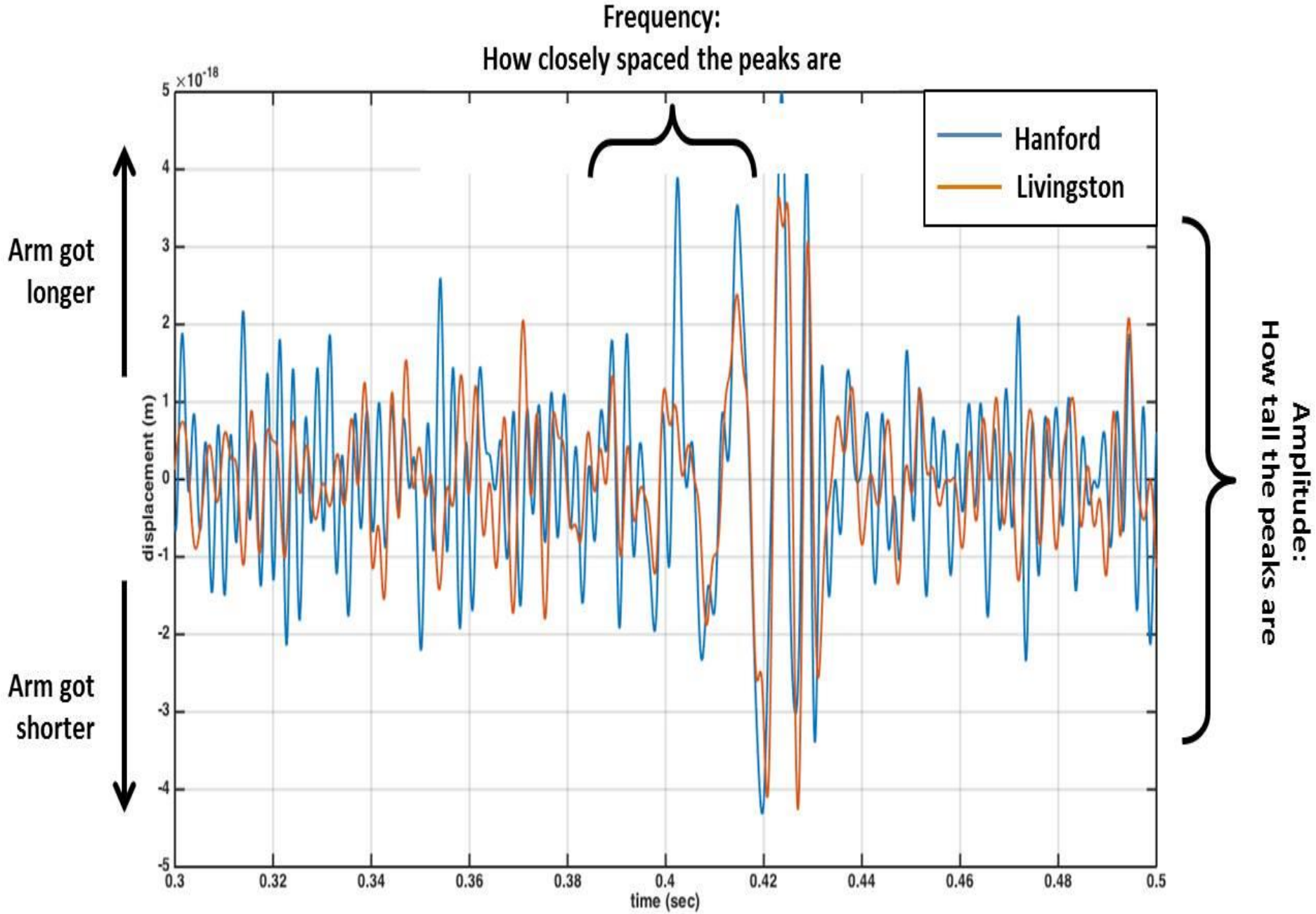
Her bruker Rainer Weiss et elastisk nett for å illustrere hvordan gravitasjonsbølger strekker og presser sammen rommet i to retninger vinkelrett på hverandre.

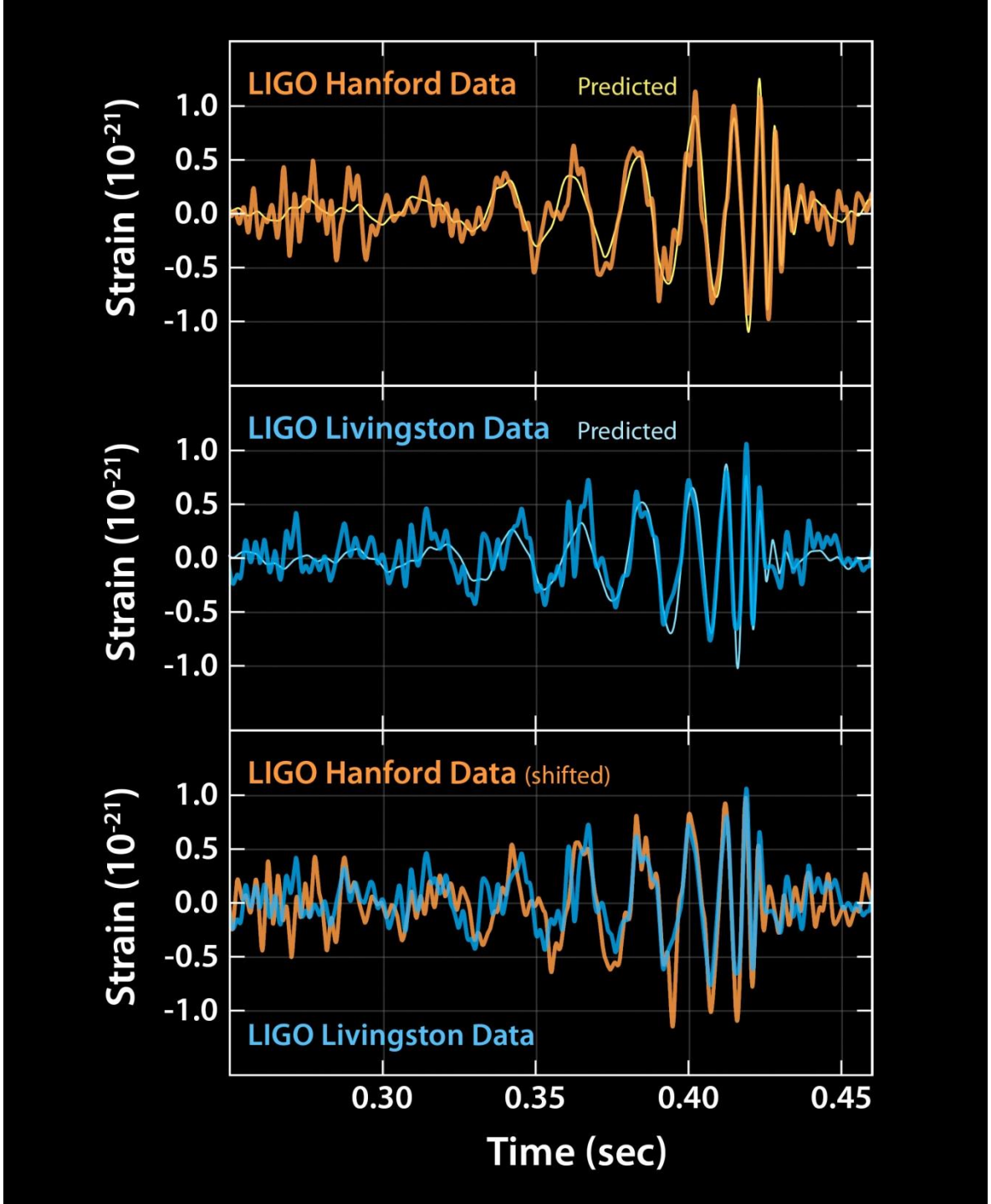

Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0

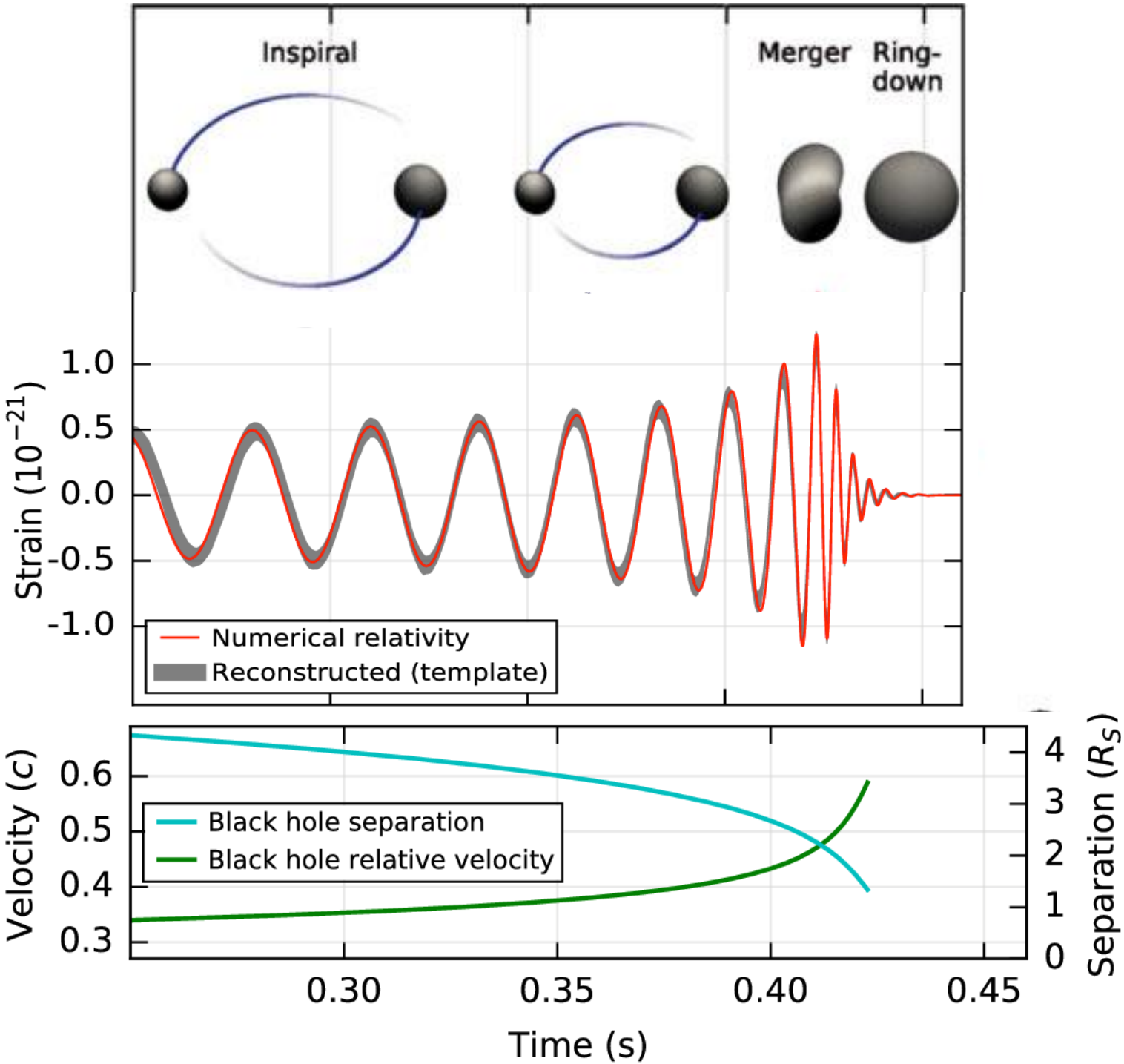
Den **11. februar 2016** ble det annonsert at man for første gang hadde en direkte registrering av gravitasjonsbølger. LIGO hadde registrert gravitasjonsbølger fra to kolliderende svarte hull.

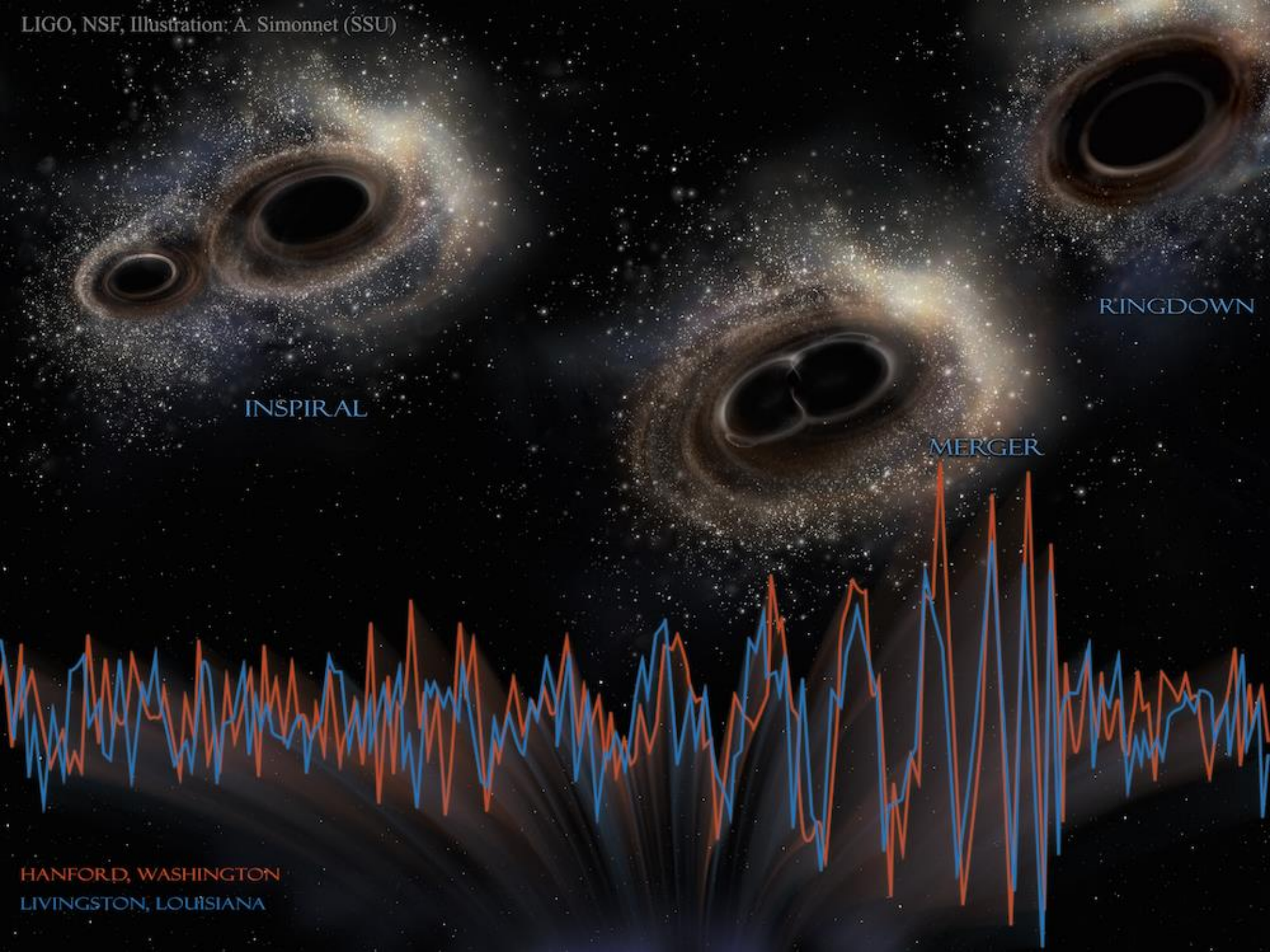


On **September 14, 2015**, similar signals were observed in both of LIGO's interferometers. The top panels show the measured signal in the Hanford (top left) and Livingston (top right) detectors. The bottom panels show the expected signal produced by the merger of two black holes, based on numerical simulations.


Frequency:
How closely spaced the peaks are
Arm got longer
Arm got shorter
Amplitude:
How tall the peaks are
Hanford
Livingston
displacement (m)
time (sec)
×10^-18
5
4
3
2
1
0
-1
-2
-3
-4
-5
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
0.5


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)


LIGO, NSF, Illustration: A. Simonnet (SSU)
INSPIRAL
MERGER
RINGDOWN
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

LIGO har latt oss høre den første tonen i den kosmiske symfonien som Einstein trodde at ingen noensinne ville få høre.

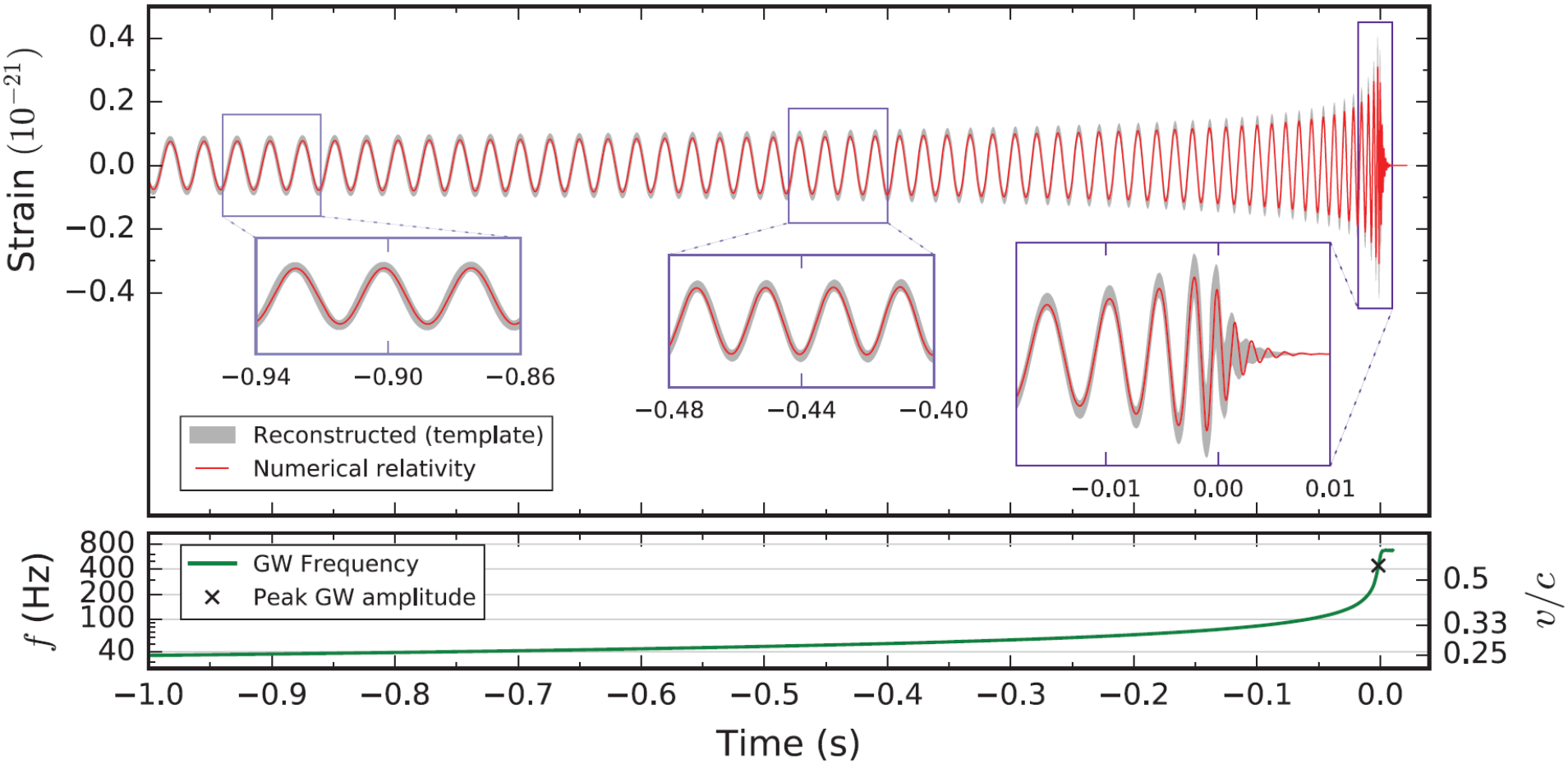
Hadde Einstein vært her i dag, ville han kanskje sagt:

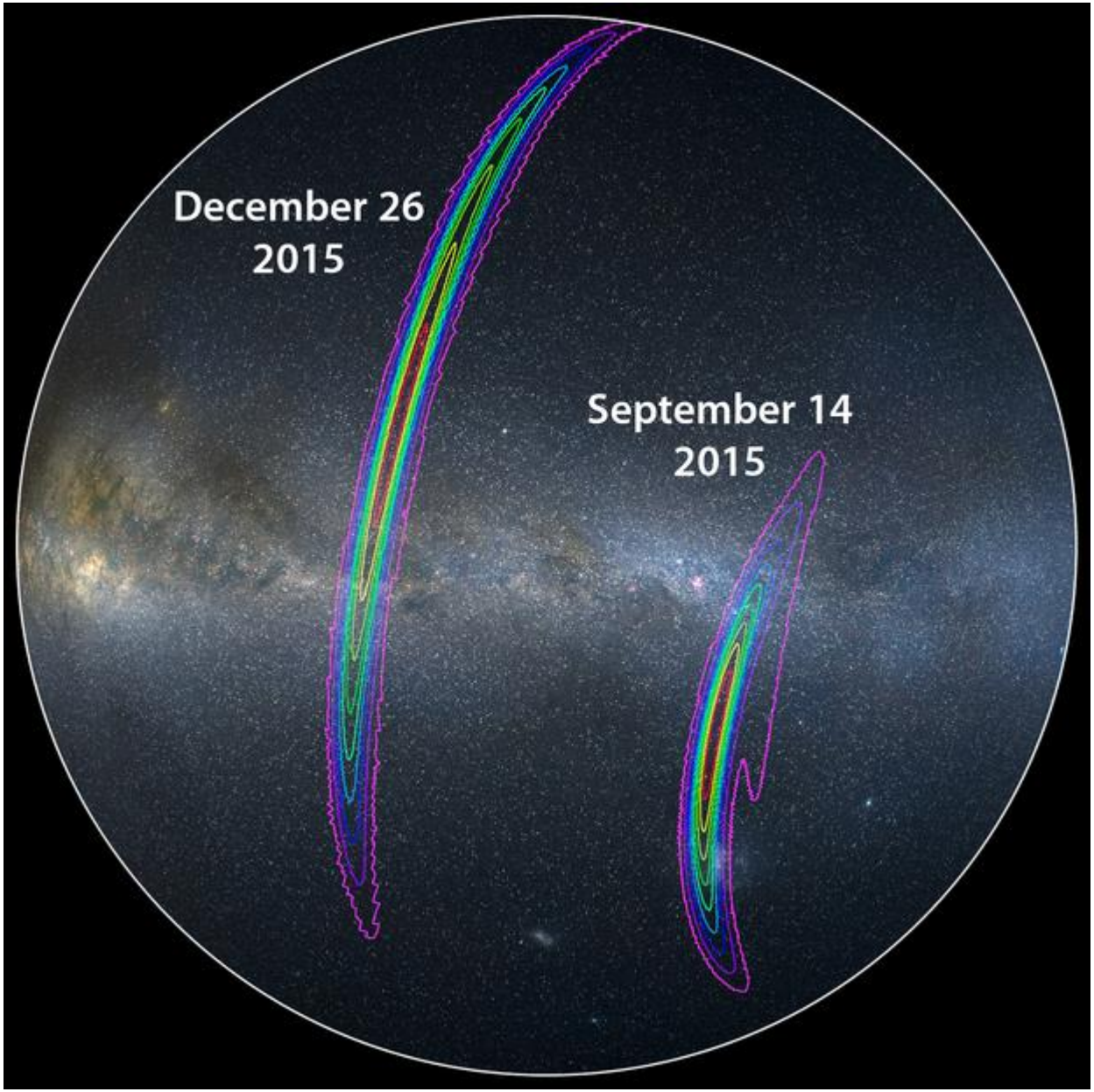
All ære til forskere og ingeniører som har hatt
innsikten, troen og dyktigheten som gjorde det mulig å
overgå selv det jeg var i stand til å forestille meg.
Det er en stor glede for meg at de har gitt oss denne spektakulære
bekreftelsen av min teori – en bekreftelse
som åpner et nytt vindu for å studere vår forunderlige univers.

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

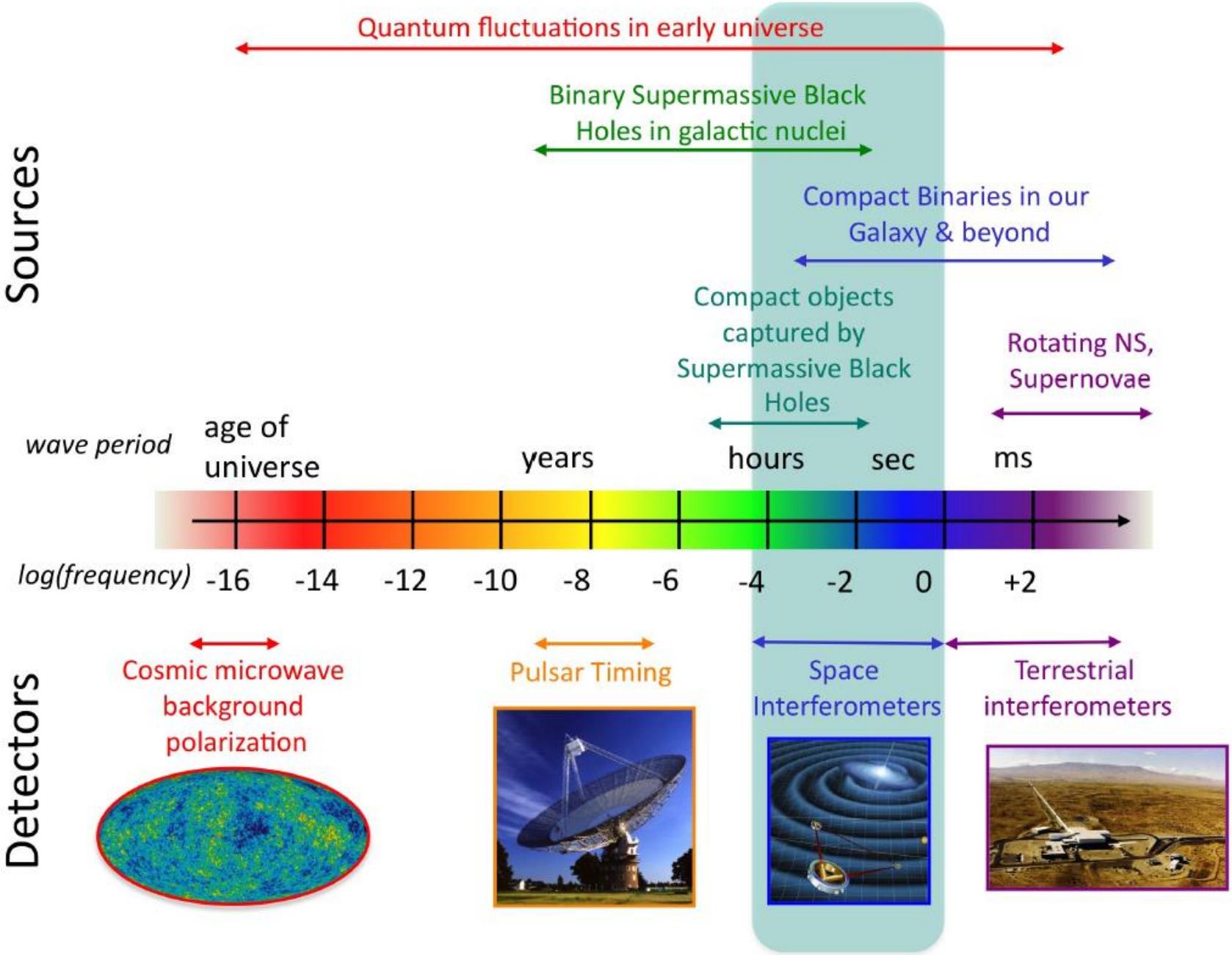
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 31 May 2016; published 15 June 2016)

We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than 5σ. The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of $3.4^{+0.7}_{-0.9} \times 10^{-22}$. The inferred source-frame initial black hole masses are $14.2^{+8.3}_{-3.7} M_\odot$ and $7.5^{+2.3}_{-2.3} M_\odot$, and the final black hole mass is $20.8^{+6.1}_{-1.7} M_\odot$. We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of 440^{+180}_{-190} Mpc corresponding to a redshift of $0.09^{+0.03}_{-0.04}$. All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.

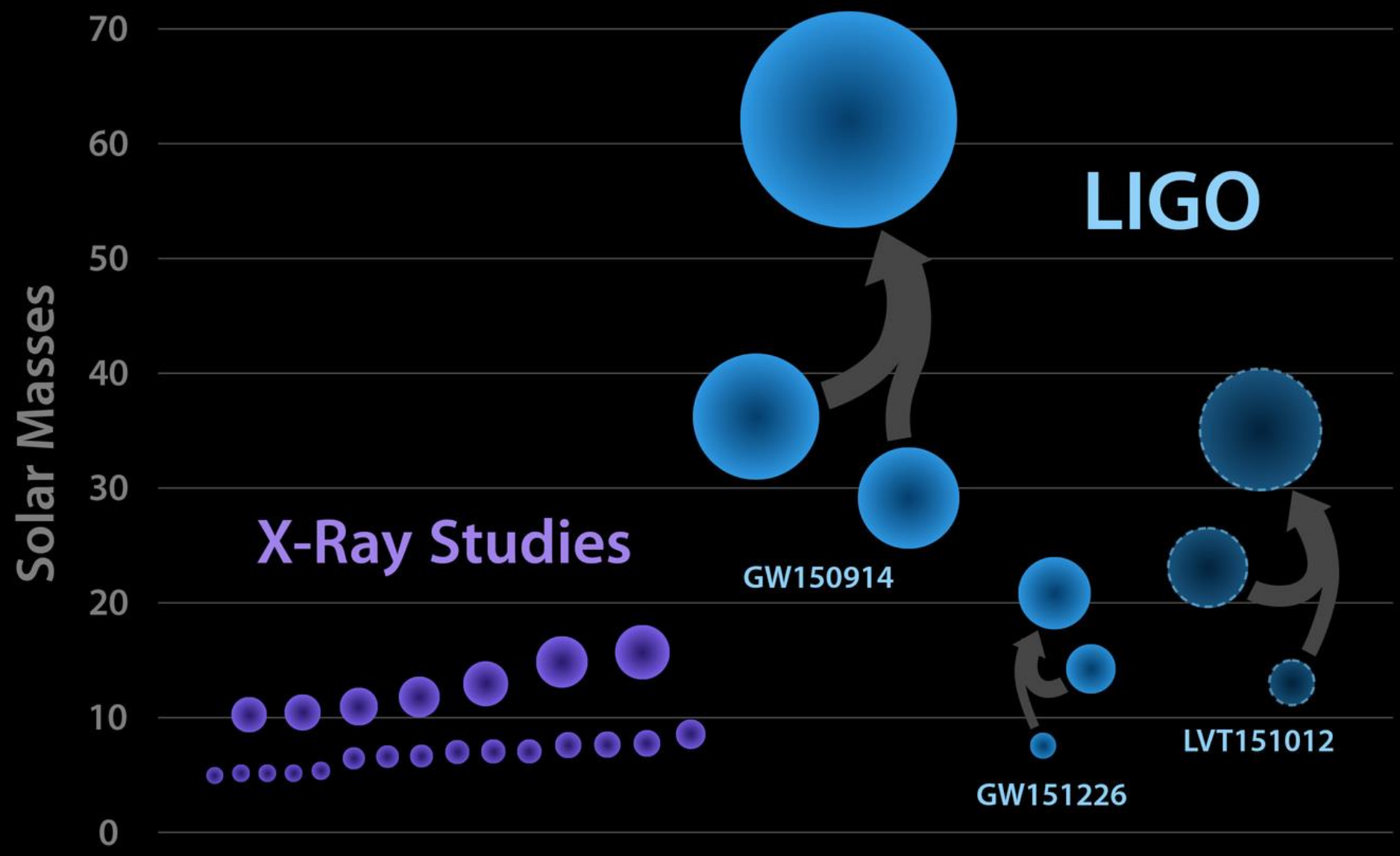

Strain (10^{-21})
0.4
0.2
0.0
−0.2
−0.4
−0.94
−0.90
−0.86
−0.48
−0.44
−0.40
−0.01
0.00
0.01
Reconstructed (template)
Numerical relativity
f (Hz)
800
400
200
100
40
GW Frequency
Peak GW amplitude
0.5
0.33
0.25
v/c
−1.0
−0.9
−0.8
−0.7
−0.6
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
Time (s)


December 26
2015
September 14
2015

The Gravitational Wave Spectrum



Black Holes of Known Mass



PRL 116, 201301 (2016) PHYSICAL REVIEW LETTERS week ending 20 MAY 2016

Did LIGO Detect Dark Matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess
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(Received 4 March 2016; published 19 May 2016)

PRL 117, 061101 (2016) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2016

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

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(Received 3 April 2016; published 2 August 2016)

ScienceNews

LIGO's black holes may be dark matter

Analysis of gravitational wave detection suggests primordial origin of merging masses

By

Emily Conover

7:00am, August 7, 2016

Constraint on the abundance of primordial black holes in dark matter from Planck data

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(Dated: August 9, 2016)

We use Planck data released in 2015 to constrain the abundance of primordial black holes (PBHs) in dark matter in two different reionization models (one is the instantaneous reionization and the other is the asymmetric reionization), and significantly improve the upper limits on the abundance of PBHs from WMAP 3-year data by around two orders of magnitude. Furthermore, these new limits imply that the event rates of mergers of PBH binaries ($\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$) are less than 0.002 for $M_{\mathrm{pbh}} = 30M_{\odot}$, 5 for $M_{\mathrm{pbh}} = 10M_{\odot}$ and 2000 for $M_{\mathrm{pbh}} = 2M_{\odot}$ at 95% confidence level (C.L.), and thus GW150914 seems very unlikely produced by the merger of a PBH binary.