100 years of gravitational waves - history and discovery

Chris Messenger for the LIGO-Virgo Collaboration
University of Glasgow, UK

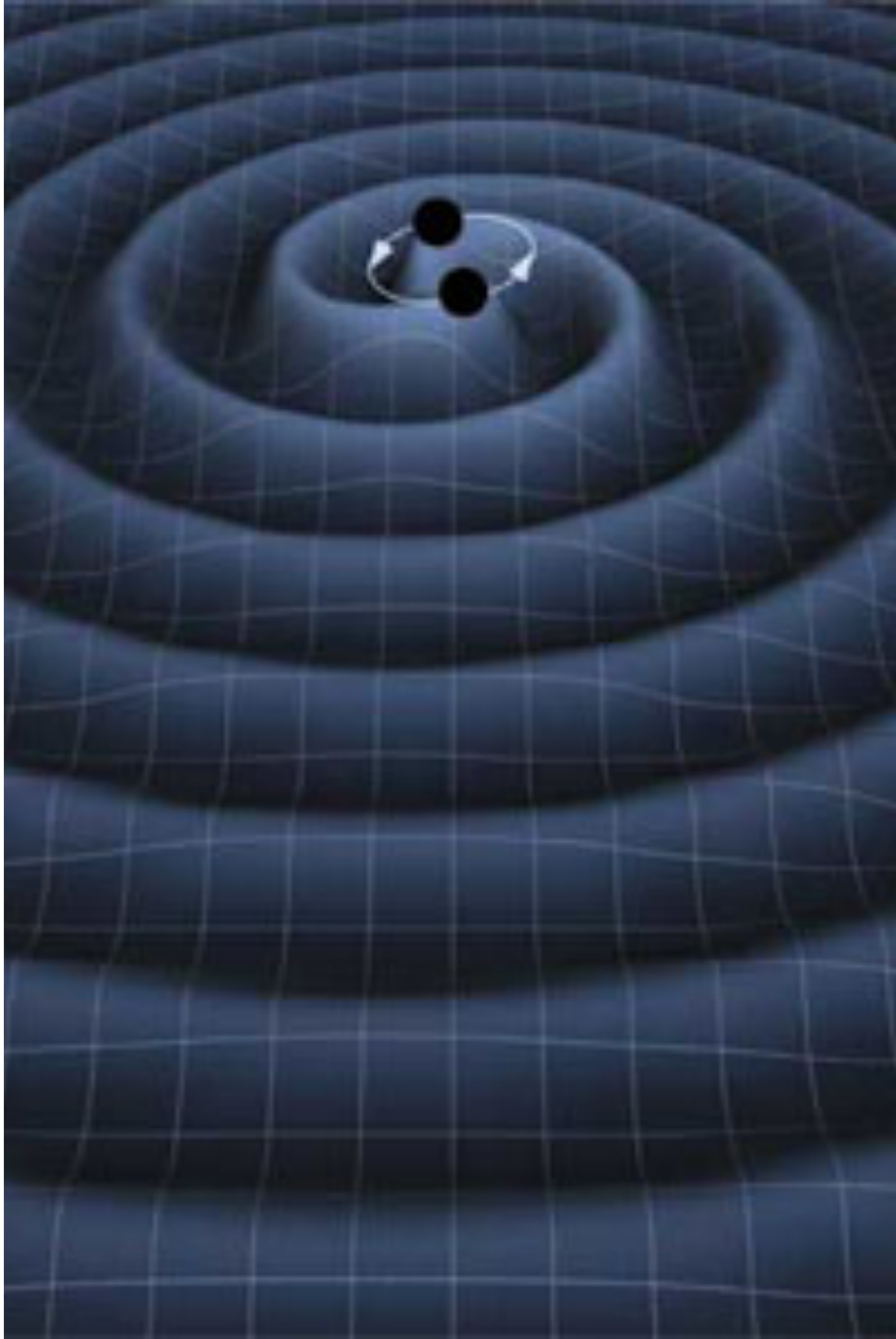
Spåtind 2018 - Nordic Conference on Particle Physics

LIGO-G1800001


2005-2007 & 2012-?
University of Glasgow
VIA VERITAS VITA
1997-2005
UNIVERSITY OF BIRMINGHAM
2007-2010
2010-2012
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD
North Sea
United Kingdom
Denmark
Germany
Belgium
Netherlands

Outline

- Einstein & GR
- Chapel Hill 1957
- Gravitational wave properties
- Bar detectors
- The binary pulsar
- Interferometers
- Gravitational wave sources
- Advanced detectors
- Detection
- Final remarks

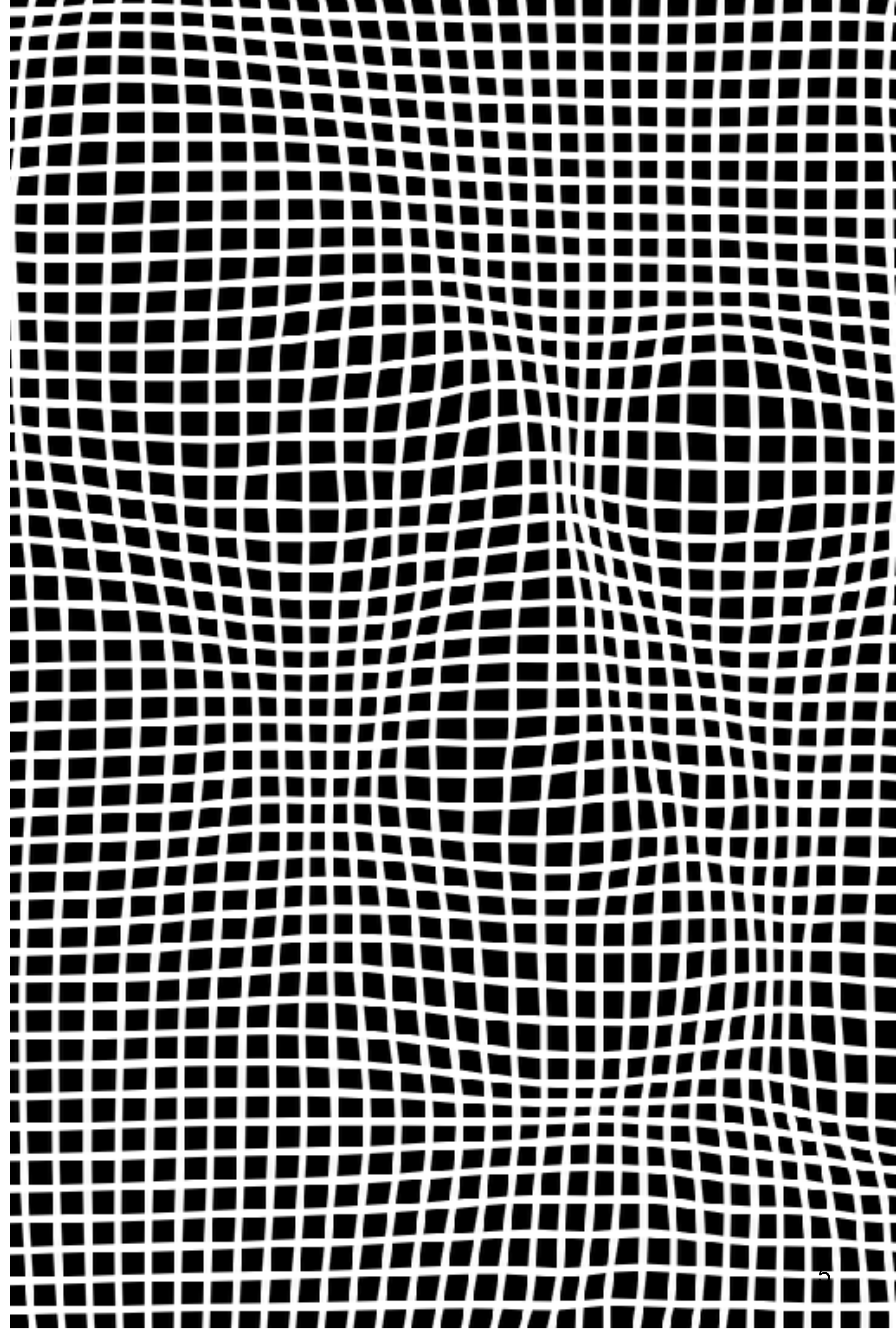


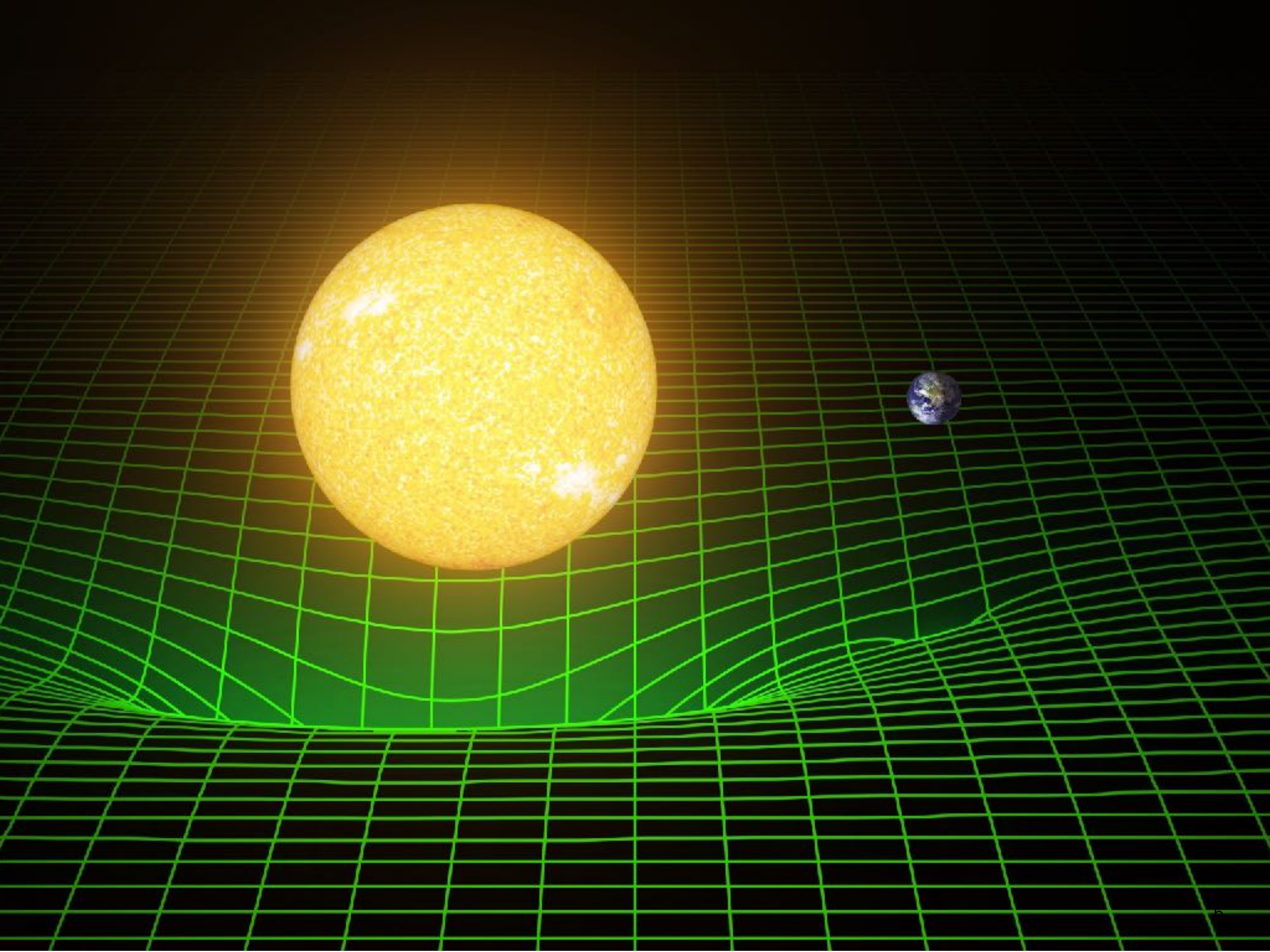
Disclaimer

There have been 1000's of scientists that have contributed to the 100 year effort to detect gravitational waves. I will only be able to mention a few of them.

Einstein & GR

The start of gravitational waves





Hieraus erhält man mit Hilfe von (8) und (1) für die $g_{\mu\nu}$ die Werte

$$\left.\begin{array}{cccc} -1-\frac{\varkappa}{4\pi}\frac{M}{r} & 0 & 0 & 0 \\ 0 & -1-\frac{\varkappa}{4\pi}\frac{M}{r} & 0 & 0 \\ 0 & 0 & -1-\frac{\varkappa}{4\pi}\frac{M}{r} & 0 \\ 0 & 0 & 0 & -1-\frac{\varkappa}{4\pi}\frac{M}{r} \end{array}\right\} \qquad (14)$$

Diese Werte, welche sich von den von mir früher angegebenen nur vermöge der Wahl des Bezugssystems unterscheiden, wurden mir durch Hrn. de Sitter brieflich mitgeteilt. Sie führten mich auf die im vorstehenden angegebene einfache Näherungslösung. Es ist aber wohl im Auge zu behalten, daß der hier benutzten Koordinatenwahl keine entsprechende im allgemeinen Falle zur Seite steht, indem die $\gamma_{\mu\nu}$ und $\gamma'_{\mu\nu}$ nicht beliebigen, sondern nur linearen, orthogonalen Substitutionen gegenüber Tensorcharakter besitzen.

§ 2. Ebene Gravitationswellen.

Aus den Gleichungen (6) und (9) folgt, daß sich Gravitationsfelder stets mit der Geschwindigkeit 1, d. h. mit Lichtgeschwindigkeit, fortpflanzen. Ebene, nach der positiven x-Achse fortschreitende Gravitationswellen sind daher durch den Ansatz zu finden

$$\gamma'_{\mu\nu} = \alpha_{\mu\nu} f(x_1 + i x_4) = \alpha_{\mu\nu} f(x - t). \qquad (15)$$

Dabei sind die $\alpha_{\mu\nu}$ Konstante; f ist eine Funktion des Arguments $x-t$. Ist der betrachtete Raum frei von Materie, d. h. verschwinden die $T_{\mu\nu}$, so sind die Gleichungen (6) durch diesen Ansatz erfüllt. Die Gleichungen (4) liefern zwischen den $\alpha_{\mu\nu}$ die Beziehungen

$$\left.\begin{array}{l} \alpha_{11} + i\alpha_{14} = 0 \\ \alpha_{12} + i\alpha_{24} = 0 \\ \alpha_{13} + i\alpha_{34} = 0 \\ \alpha_{14} + i\alpha_{44} = 0 \end{array}\right\}. \qquad (16)$$

Von den 10 Konstanten $\alpha_{\mu\nu}$ sind daher nur 6 frei wählbar. Wir können die allgemeinste Welle der betrachteten Art daher aus Wellen von folgenden 6 Typen superponieren

$$\left.\begin{array}{lll} \text{a)}\ \begin{array}{l}\alpha_{11} + i\alpha_{14} = 0 \\ \alpha_{14} + i\alpha_{44} = 0\end{array} & \begin{array}{l}\text{b)}\ \alpha_{12} + i\alpha_{24} = 0 \\ \text{c)}\ \alpha_{13} + i\alpha_{34} = 0\end{array} & \begin{array}{l}\text{d)}\ \alpha_{22} \neq 0 \\ \text{e)}\ \alpha_{23} \neq 0 \\ \text{f)}\ \alpha_{33} \neq 0\end{array} \end{array}\right\}. \qquad (17)$$

$$64\pi^2 R^2 \left[\left(\frac{\partial^3}{\partial t^3}\right) \quad \left(\frac{\partial^3}{\partial t^3}\right) \quad \left(\frac{\partial^3}{\partial t^3}\right)\right]$$

Hieraus ergibt sich weiter, daß die mittlere Energiestrahlung nach allen Richtungen gegeben ist durch

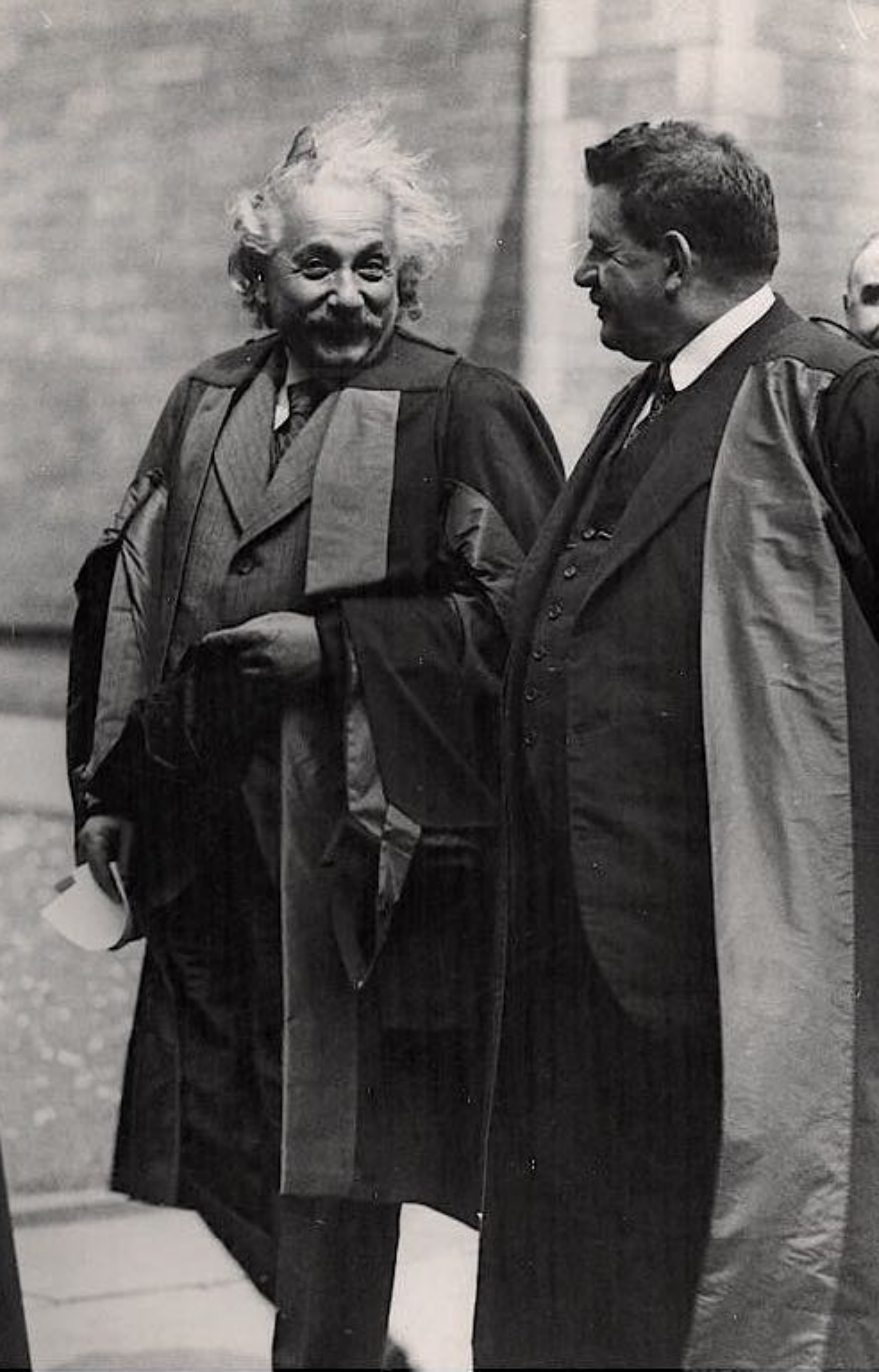
$$\frac{\varkappa}{64\pi^2 R^2} \cdot \frac{2}{3} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3}\right)^2,$$

wobei über alle 9 Kombinationen der Indizes 1—3 zu summieren ist. Denn dieser Ausdruck ist einerseits invariant gegenüber räumlichen Drehungen des Koordinatensystems, wie leicht aus dem (dreidimensionalen) Tensorcharakter von $J_{\alpha\beta}$ folgt; anderseits stimmt er im Falle radialer Symmetrie ($J_{11} = J_{22} = J_{33}$; $J_{23} = J_{31} = J_{12} = 0$) mit (20) überein. Man erhält aus ihm also die Ausstrahlung A des Systems pro Zeiteinheit durch Multiplikation mit $4\pi R^2$:

$$A = \frac{\varkappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3}\right)^2. \tag{21}$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

"… in any case one can think of A having a practically vanishing value."



Chapel Hill 1957

Is it a real thing?

The Role of Gravitation in Physics

Report from the 1957 Chapel Hill Conference

Cécile M. DeWitt and Dean Rickles (eds.)

Communicated by

Jürgen Renn, Alexander Blum and Peter Damerow

Edition Open Access
2011

Now the Newtonian equation corresponding to (14.2) is

$$\frac{\partial^2 \eta^a}{\partial \tau^2} + \frac{\partial^2 v}{\partial x^a \partial x^b} \eta^b = 0 \tag{14.3}$$

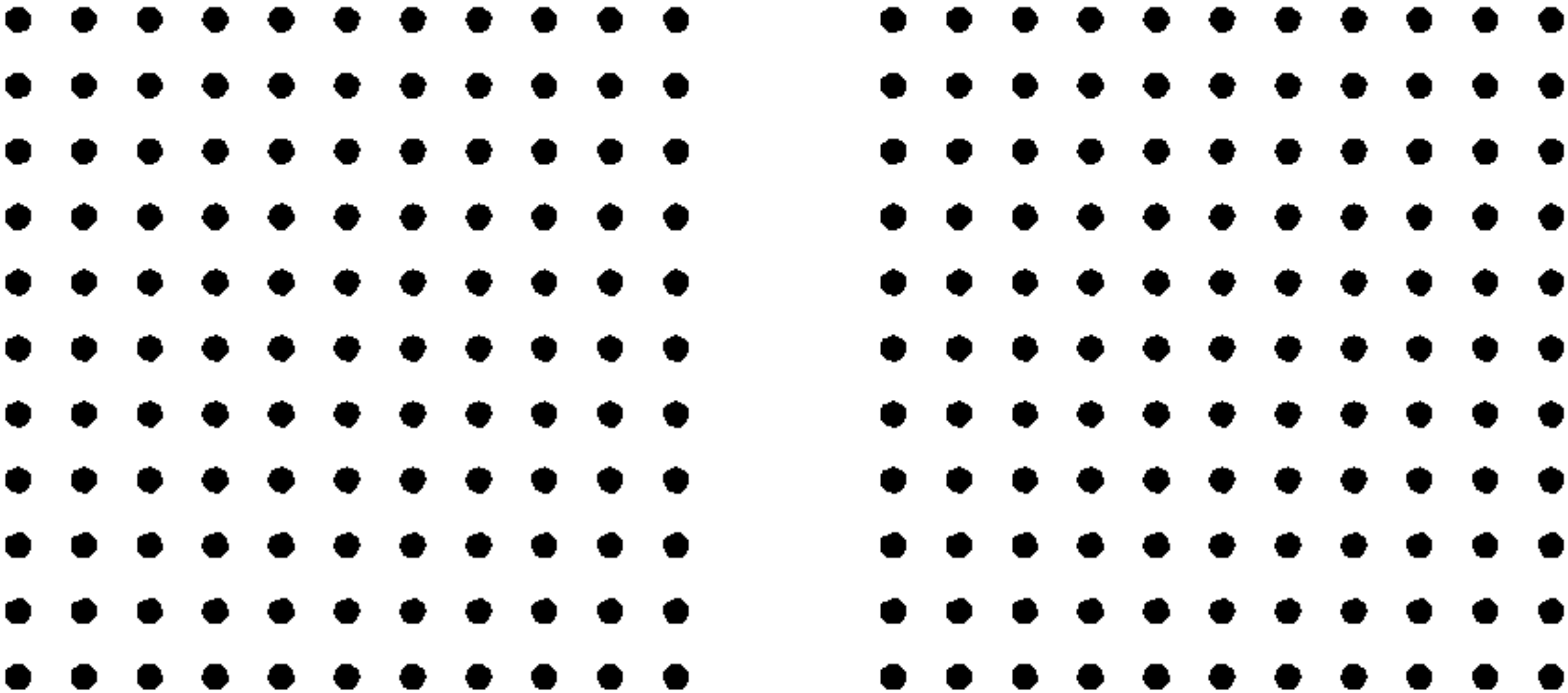
It is interesting that the empty-space field equations in the Newtonian and general relativity theories take the same form when one recognizes the correspondence $R^a_{0b0} \sim \frac{\partial^2 v}{\partial x^a \partial x^b}$ between equations (14.2) and (14.3), for the respective empty-space equations may be written $R^a_{0a0} = 0$ and $\frac{\partial^2 v}{\partial x^a \partial x^b} = 0$. (Details of this work are in the course of publication in *Acta Physica Polonica.*)

BONDI: Can one construct in this way an absorber for gravitational energy by inserting a $\frac{d\eta}{d\tau}$ term, to learn what part of the Riemann tensor would be the energy producing one, because it is that part that we want to isolate to study gravitational waves?

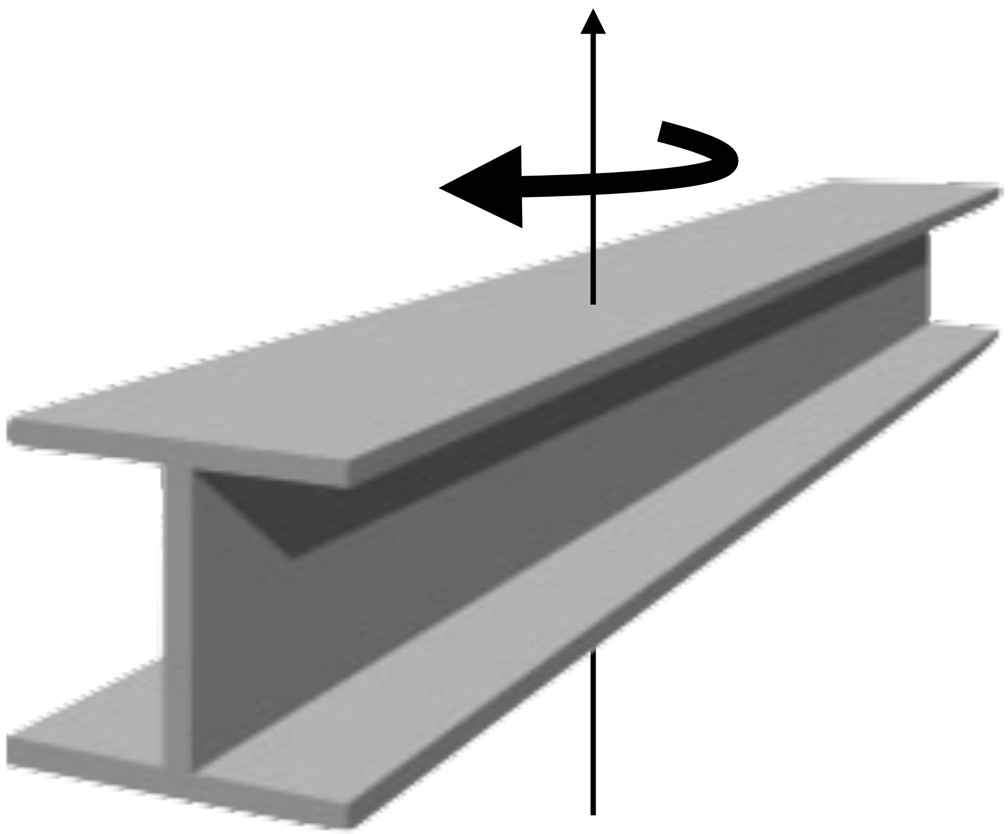
PIRANI: I have not put in an absorption term, but I have put in a "spring." You can invent a system with such a term quite easily.

GW properties

What do they do and how do you make them?

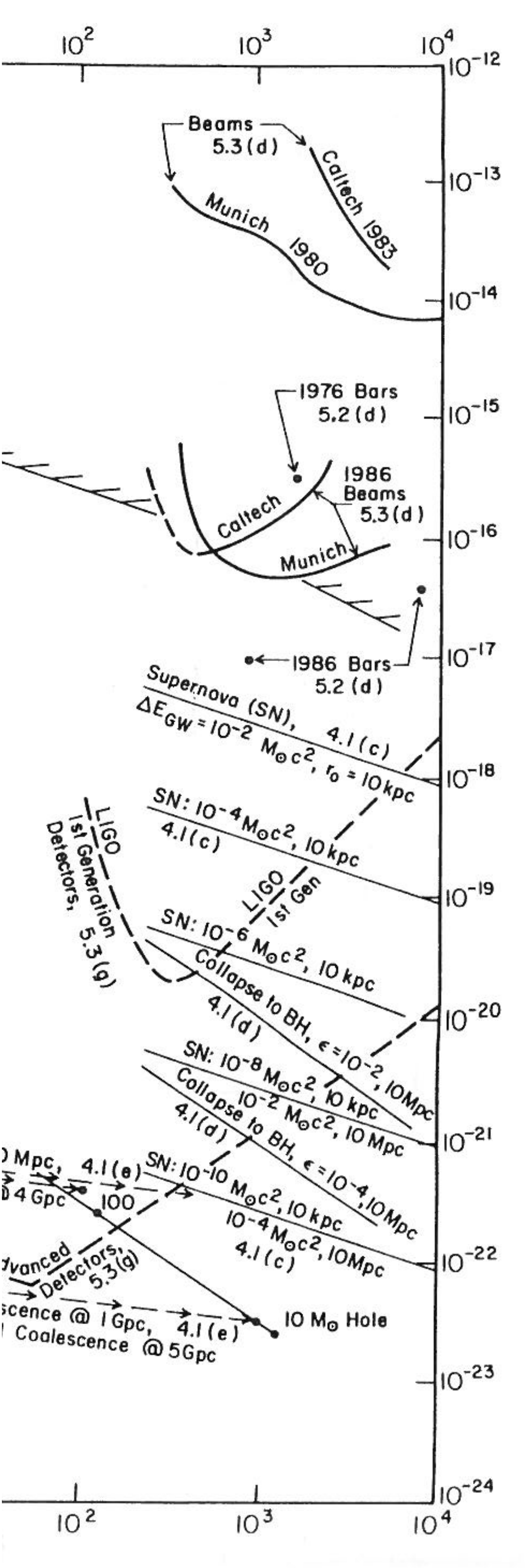


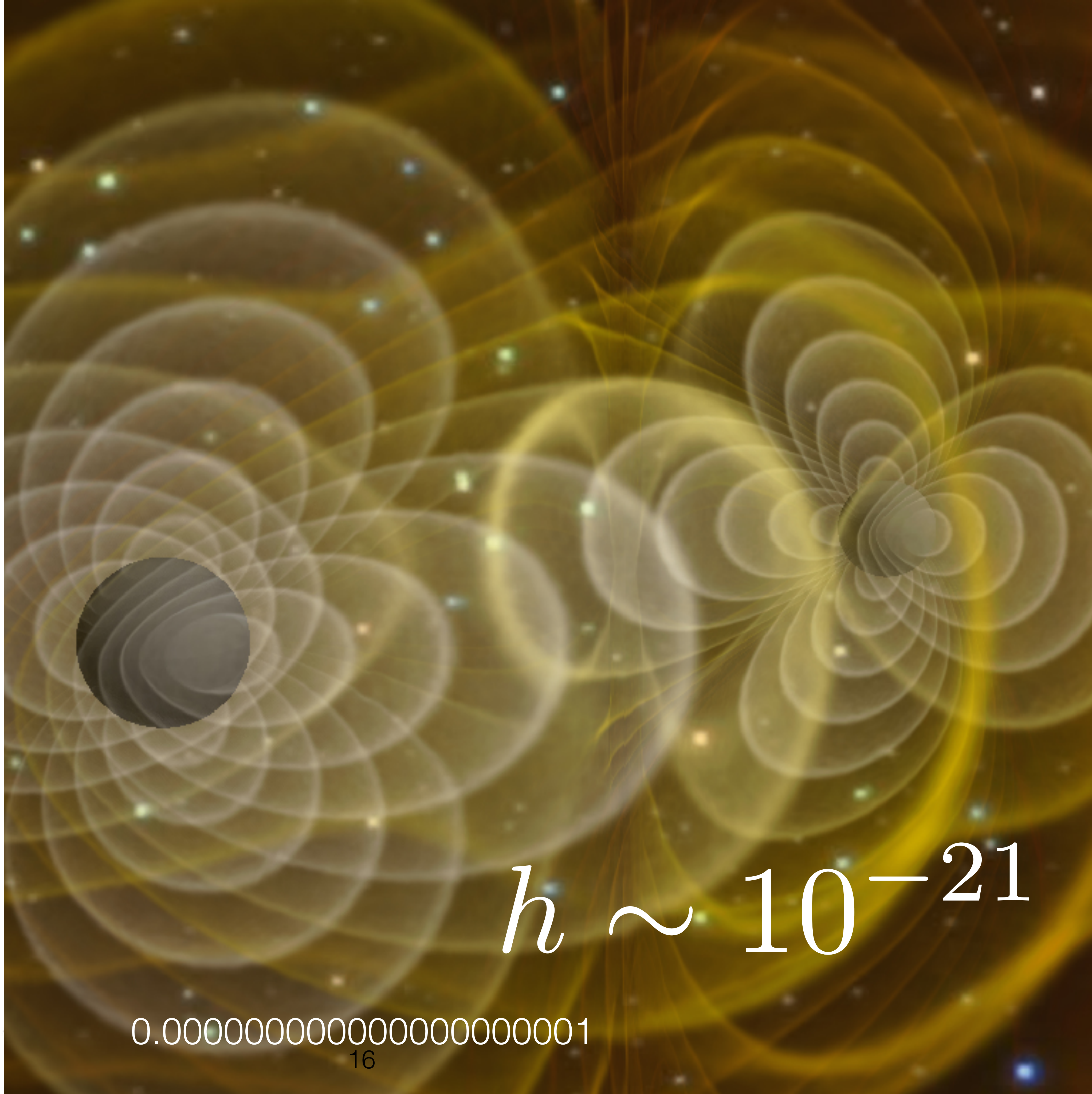
$$h \approx \frac{\varphi_{\mathrm{Newton}}}{c^2}\left(\frac{v}{c}\right)^2 = \frac{GM}{dc^2}\left(\frac{v}{c}\right)^2$$



$$h \sim 10^{-43}$$

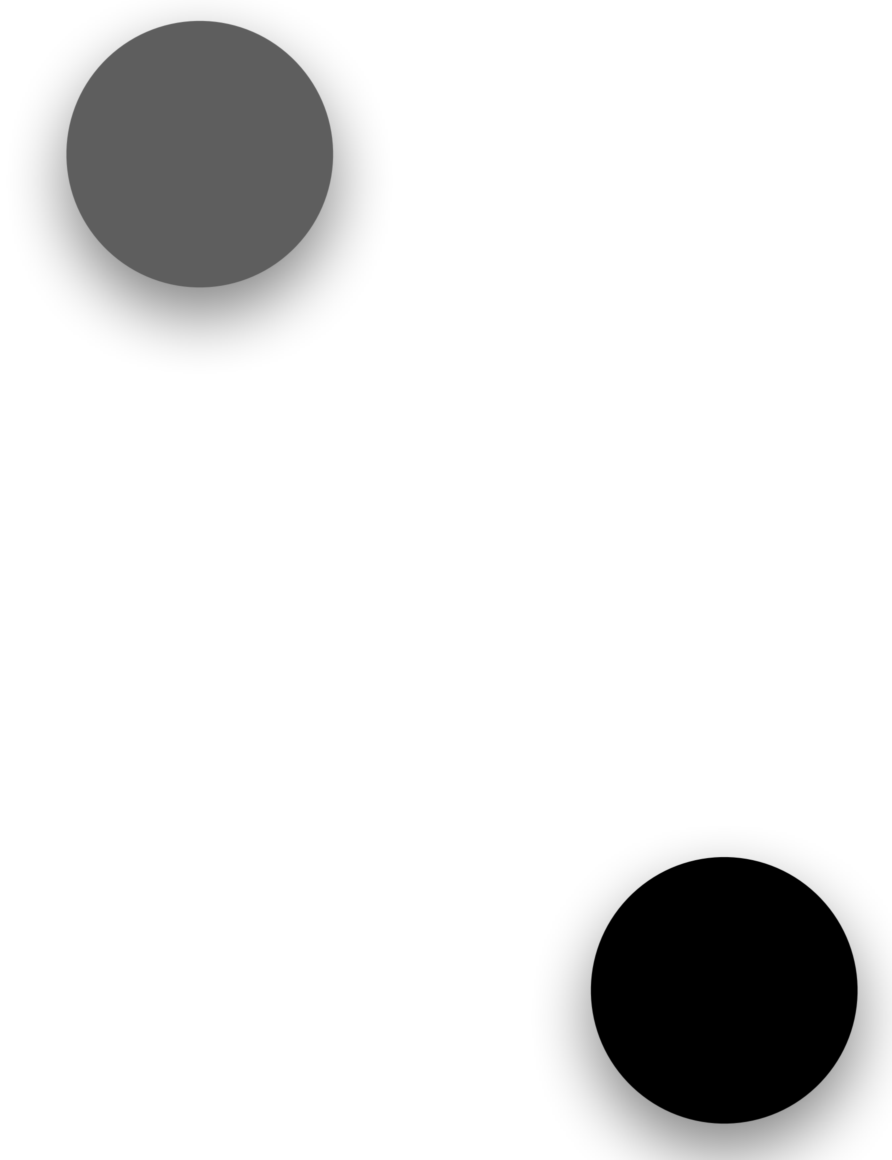
0.000000000000000000000000000000000000000001





$$h \sim 10^{-21}$$

0.000000000000000000001



Bar detectors

Ringing like a bell

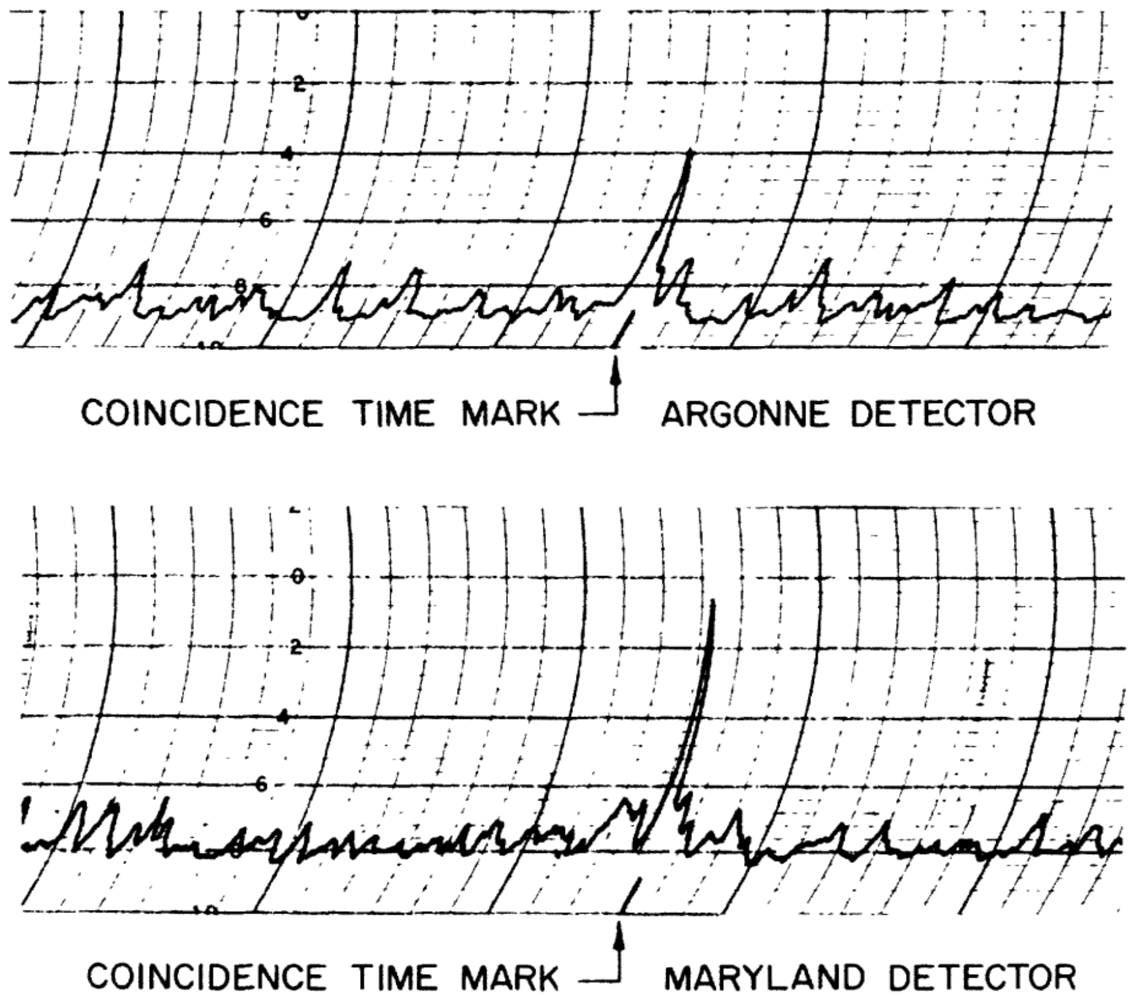
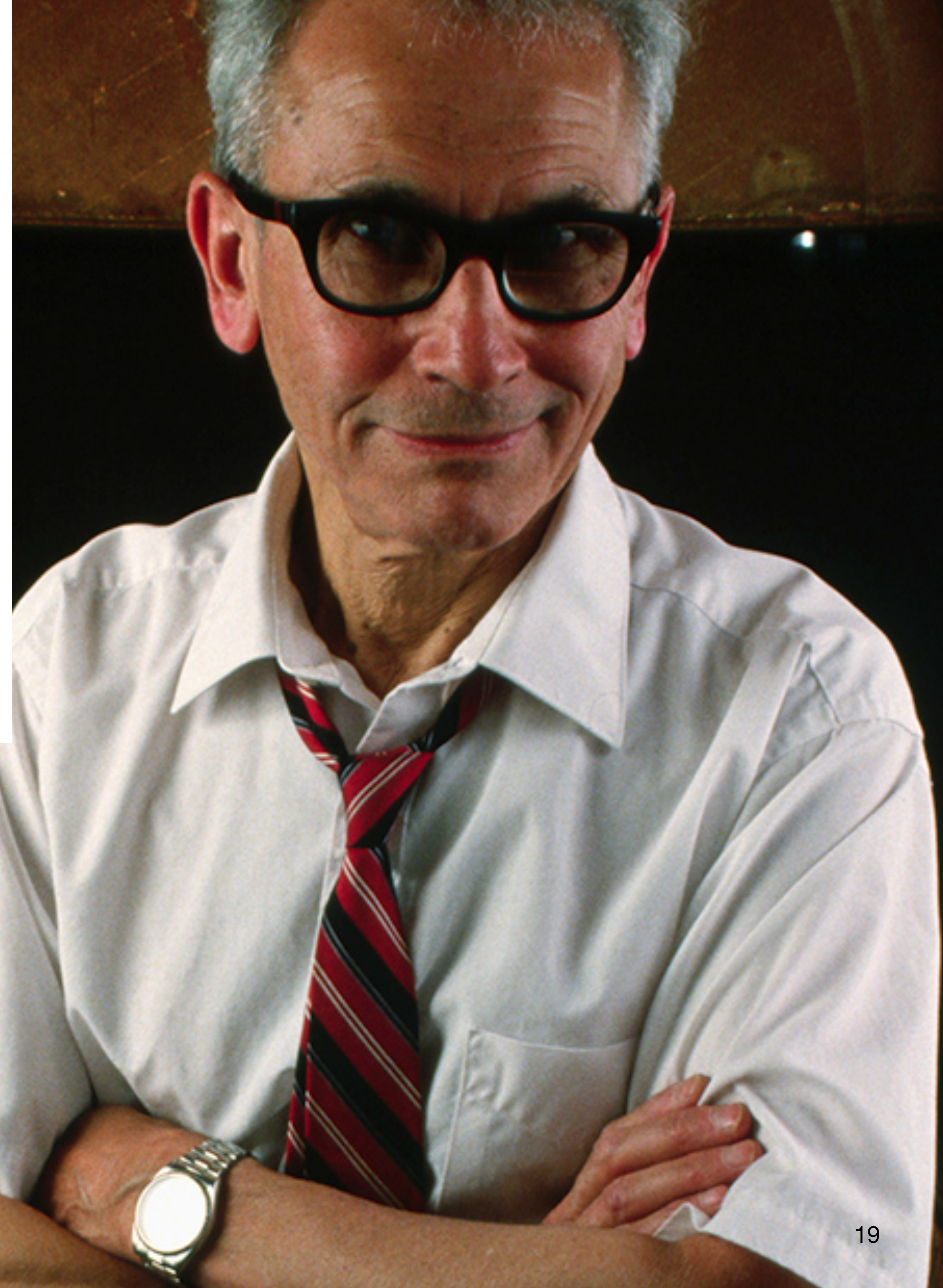
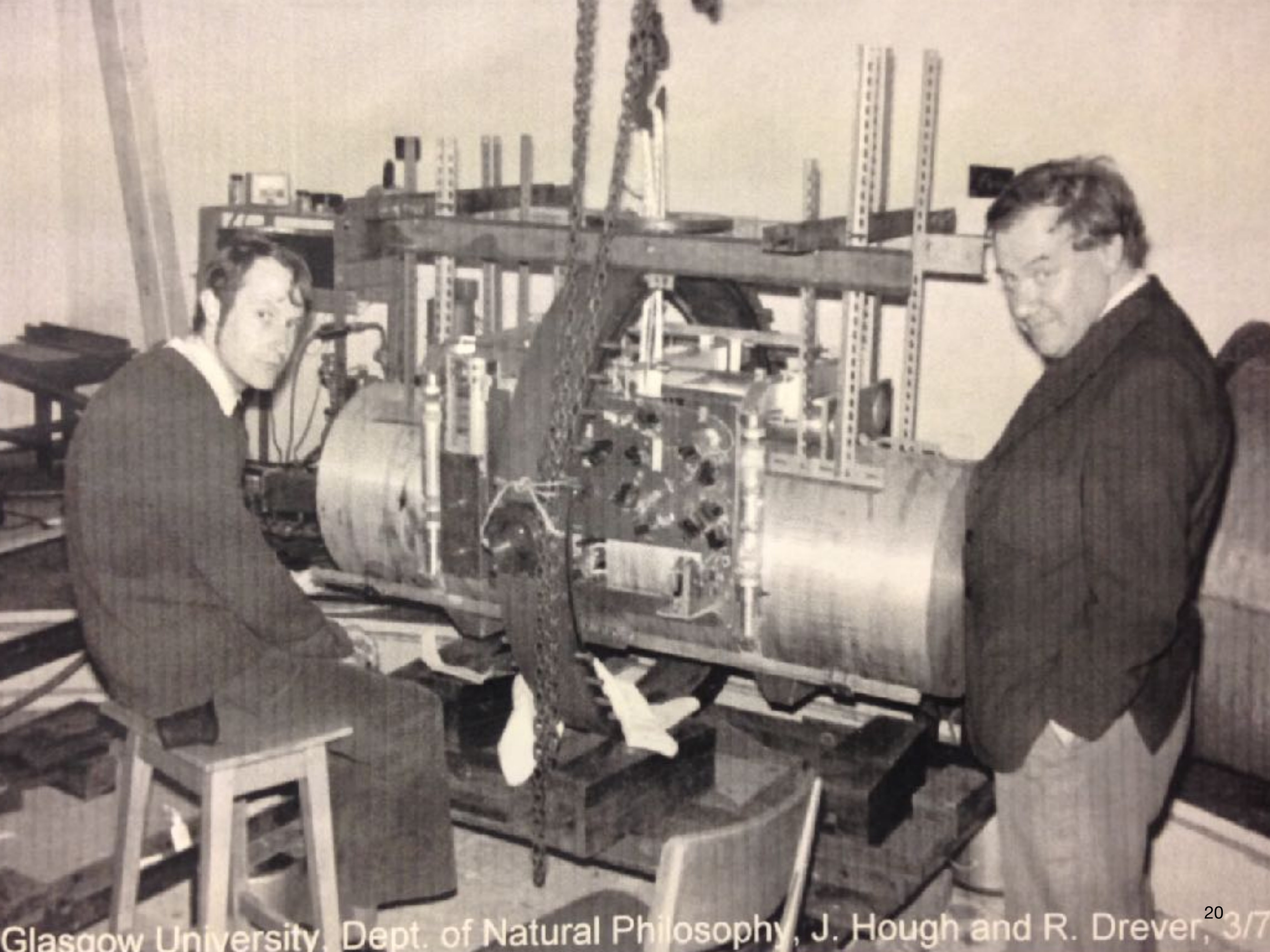
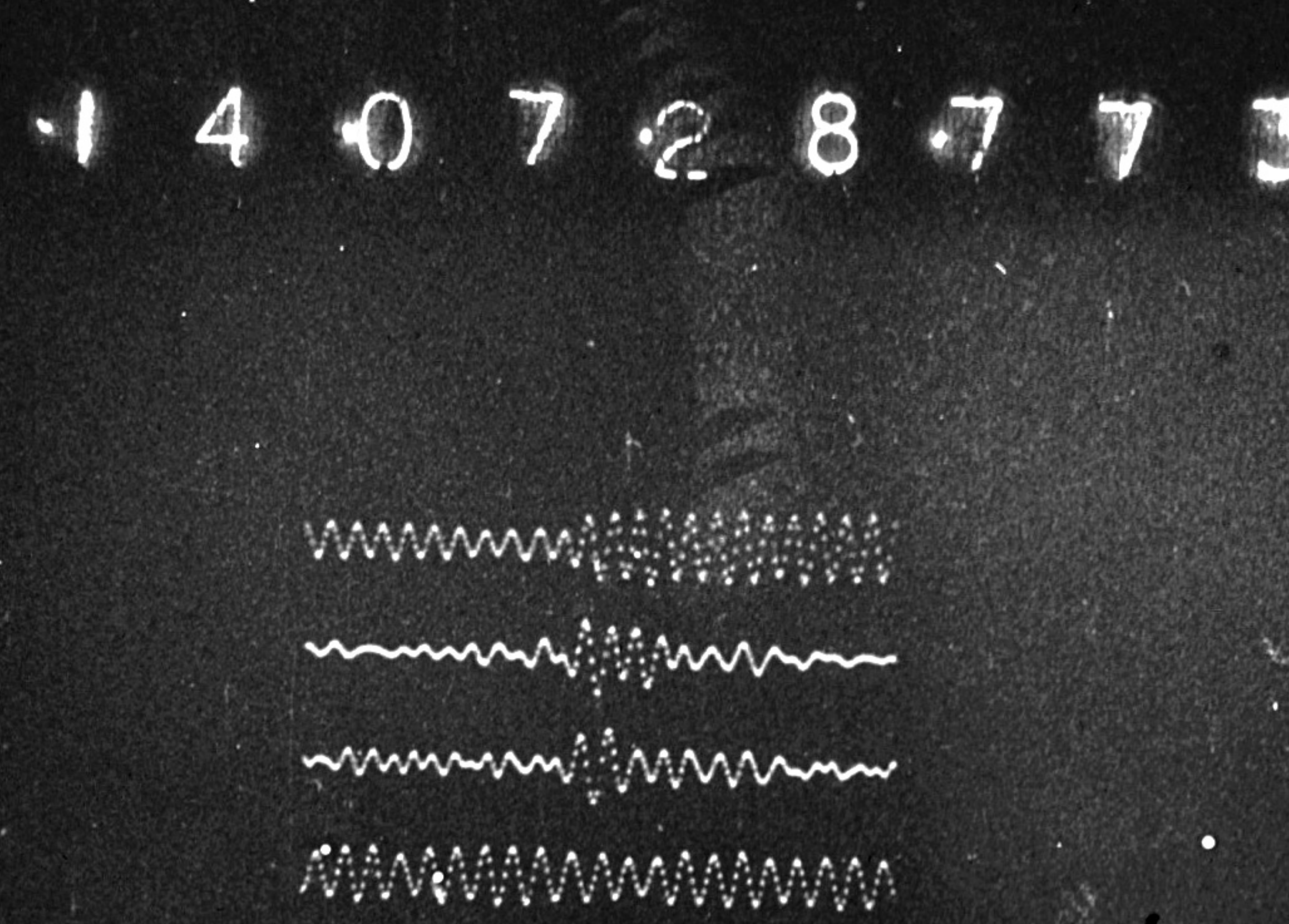


FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

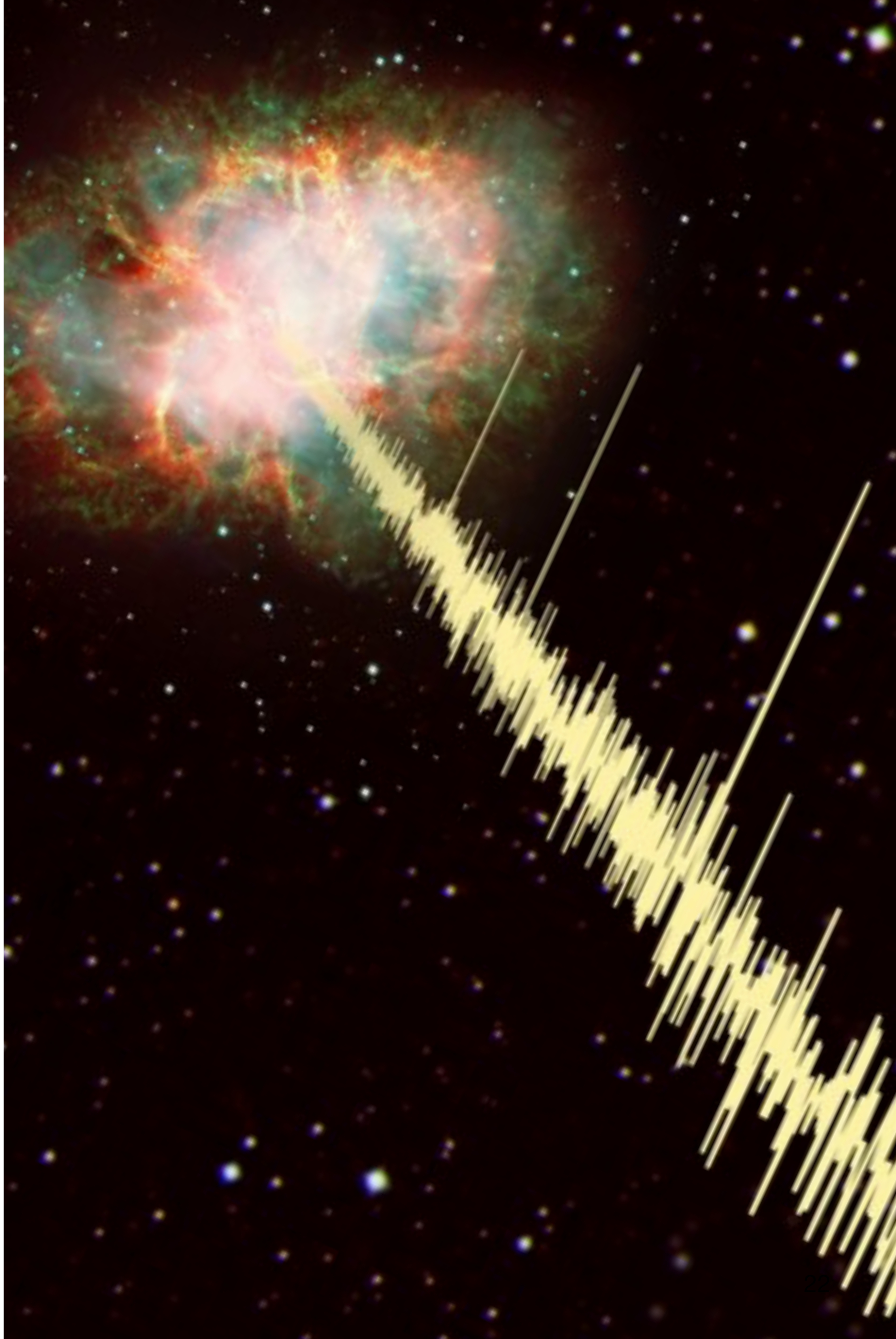


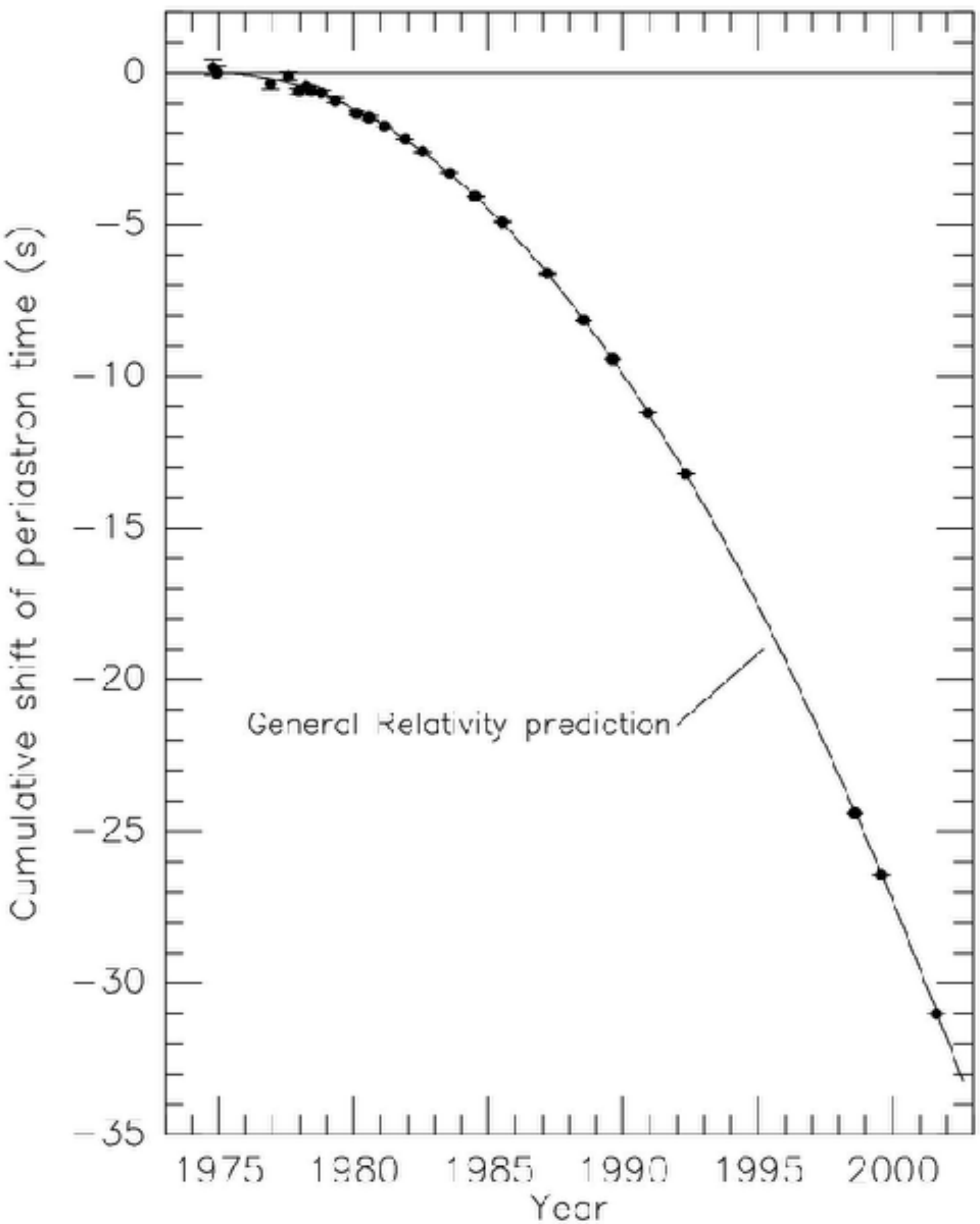

Glasgow University, Dept. of Natural Philosophy, J. Hough and R. Drever, 3/7


1 4 0 7 2 8 7 7

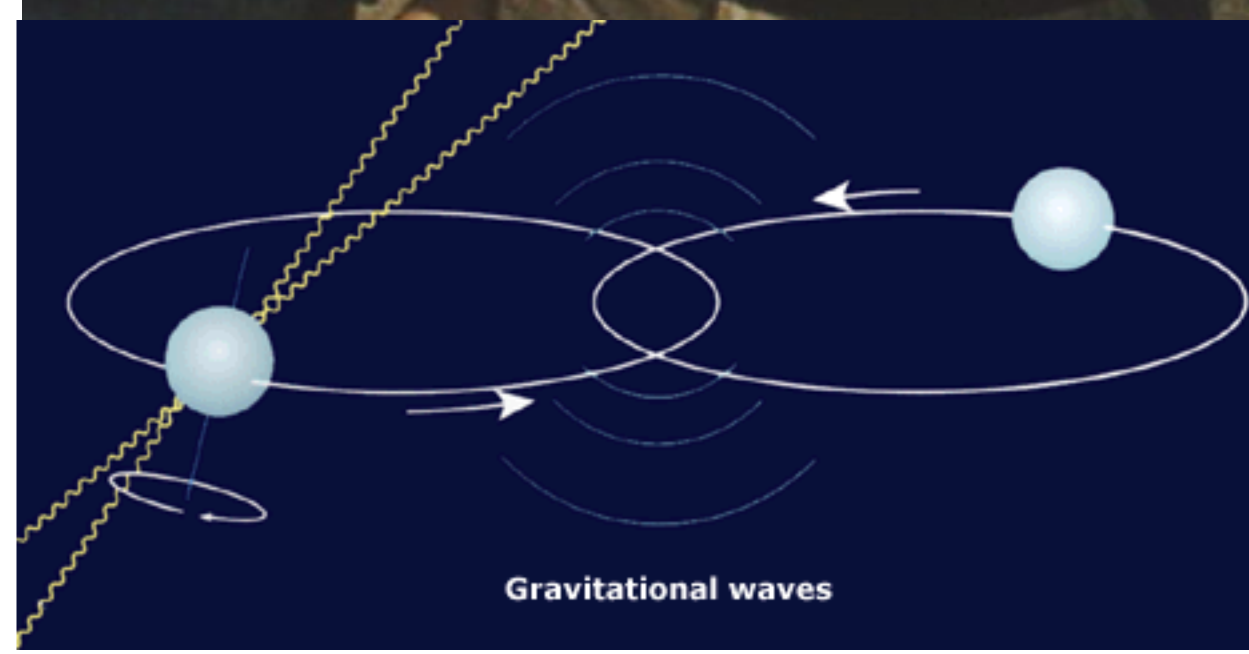
The binary pulsar

An indirect detection





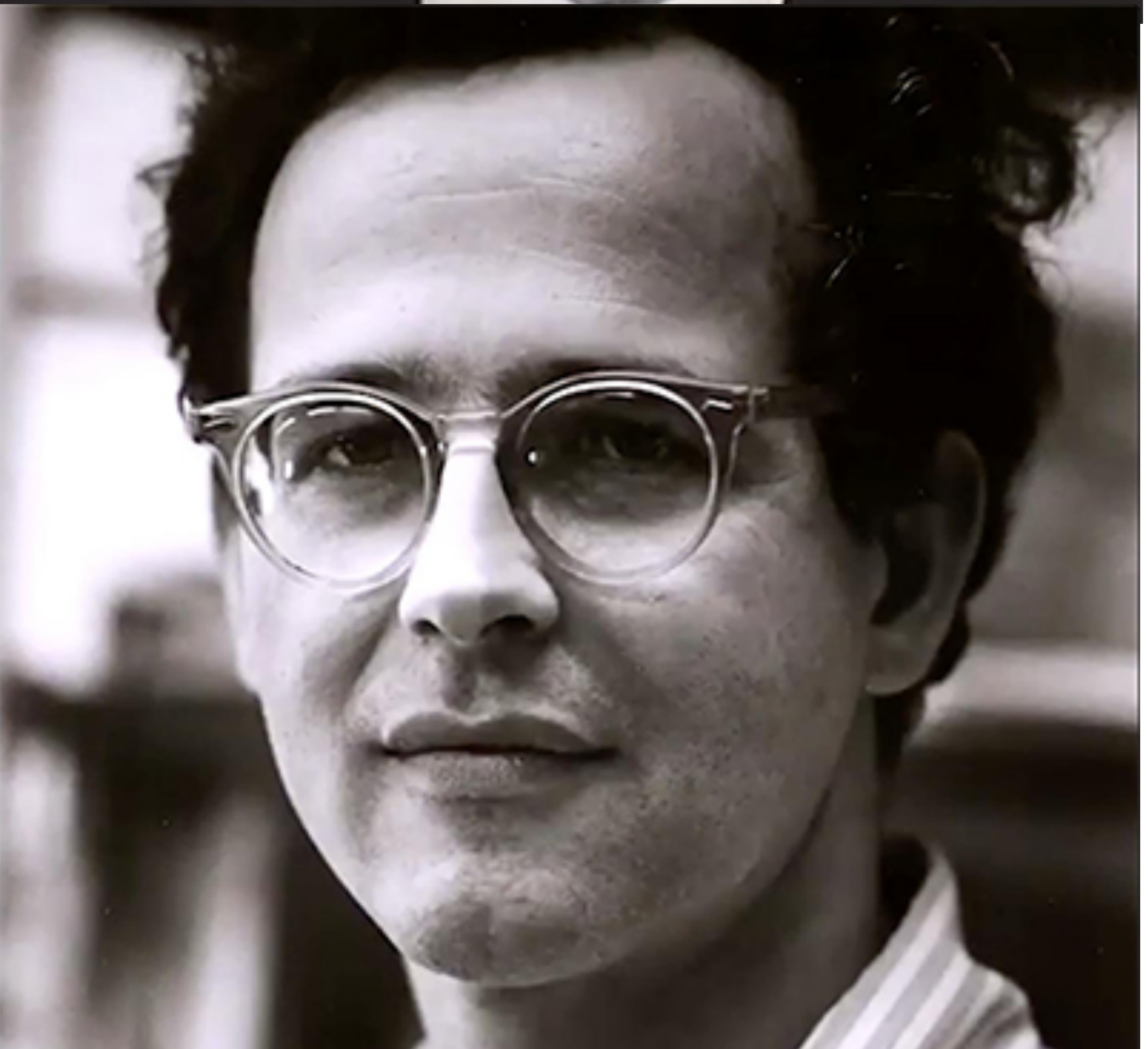
Cumulative shift of periastron time (s)
0
−5
−10
−15
−20
−25
−30
−35
1975
1980
1985
1990
1995
2000
Year
General Relativity prediction



Gravitational waves

Interferometers

Using light as a ruler



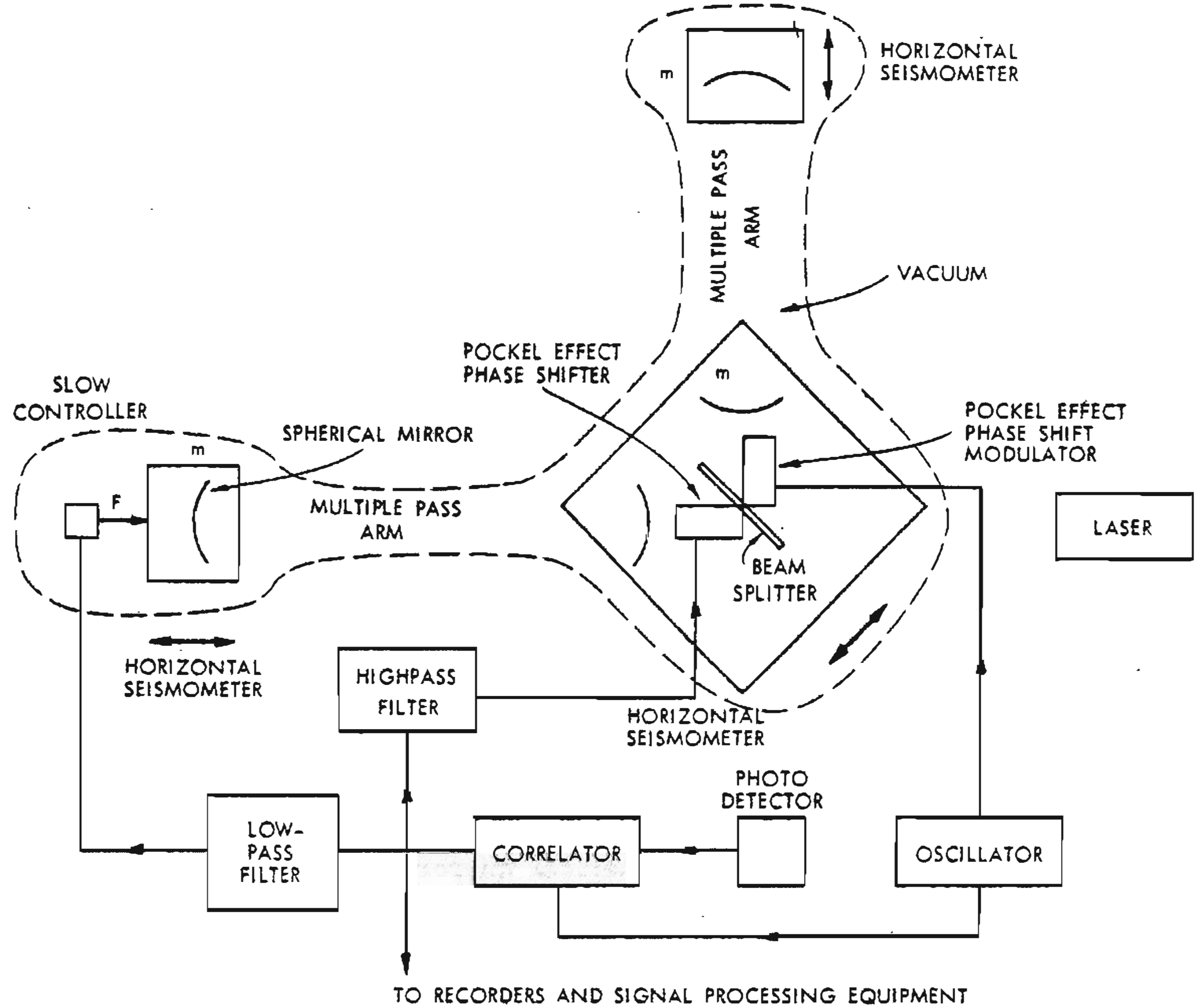
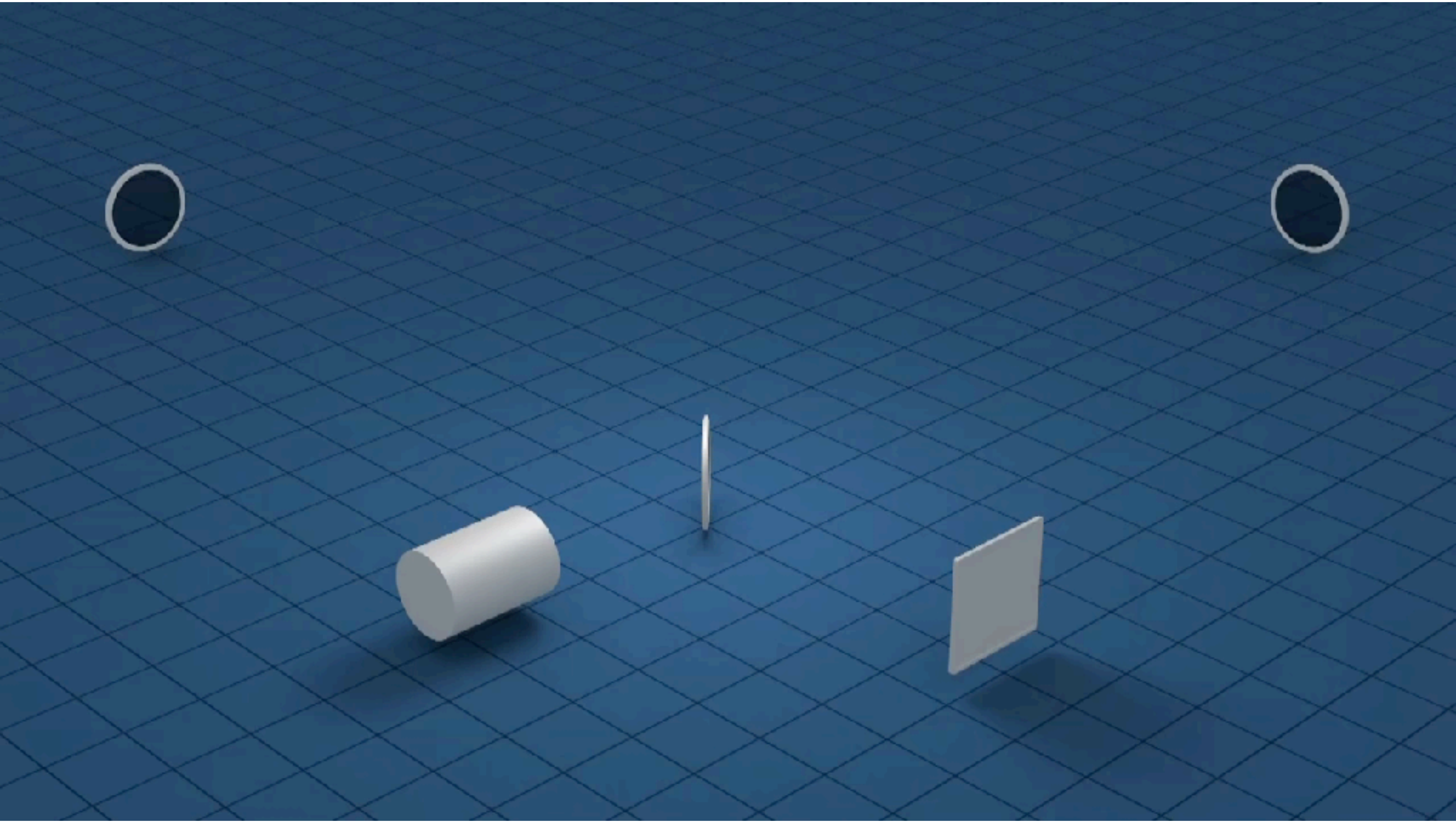
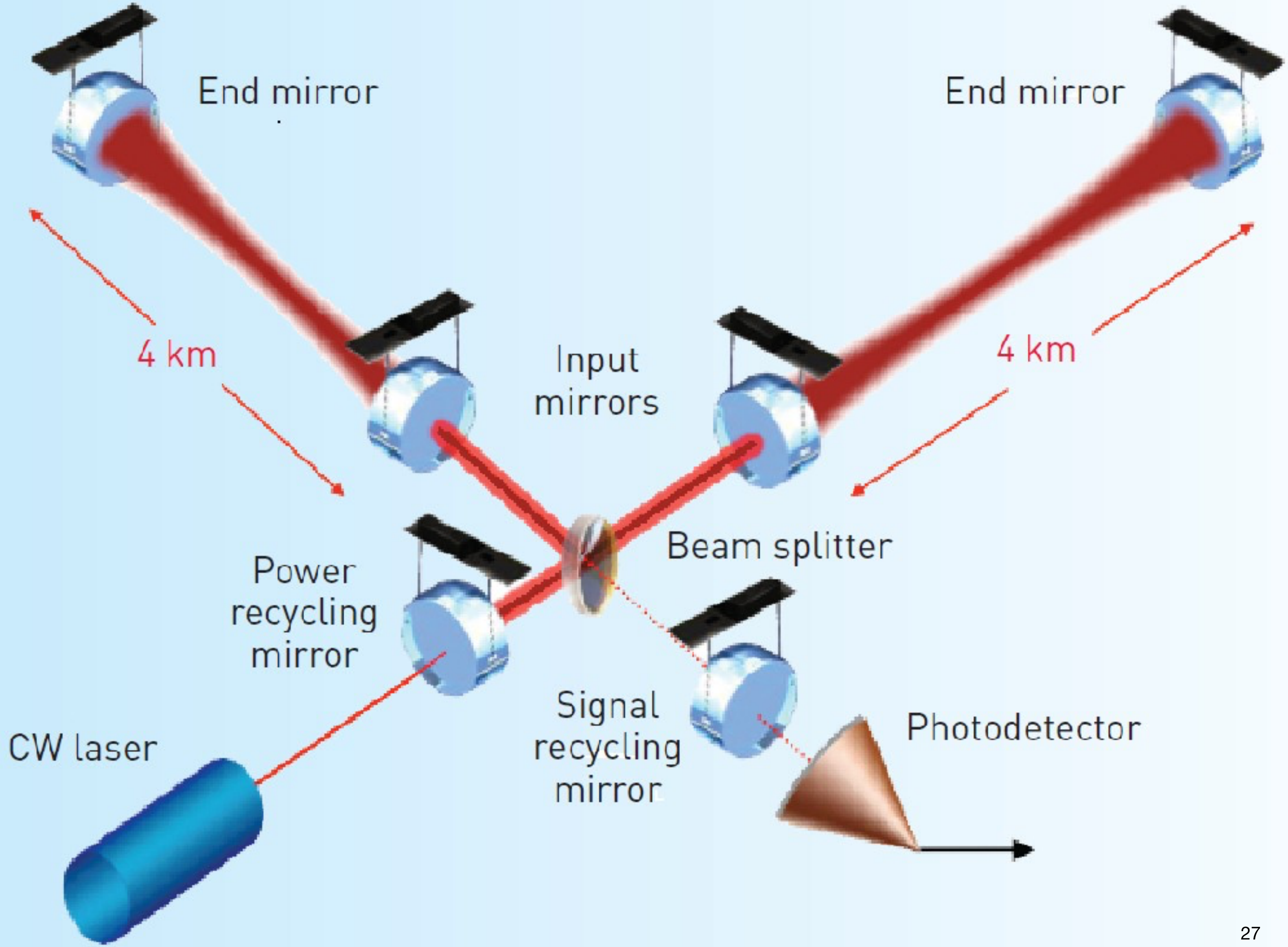
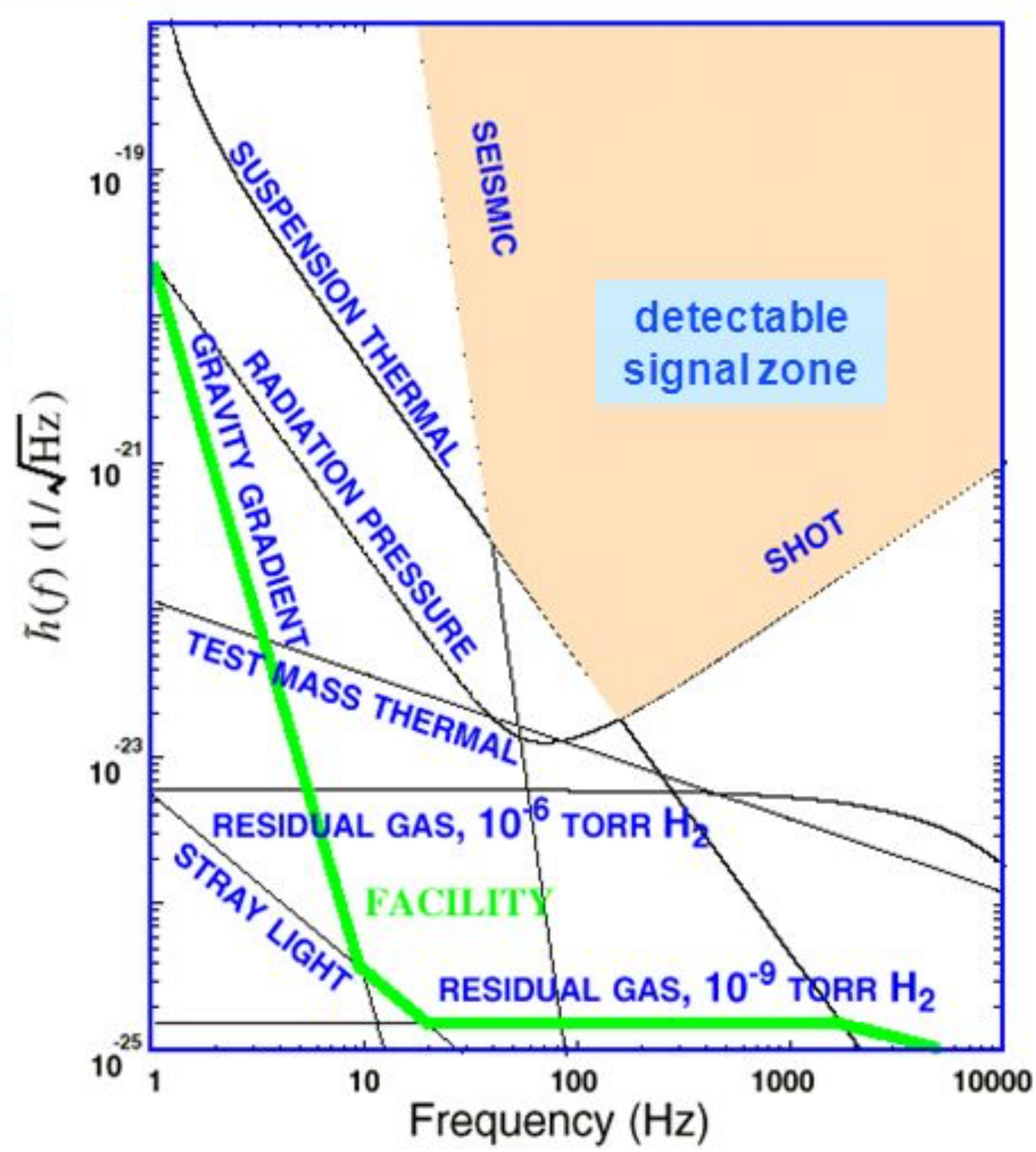


Fig. V-20. Proposed antenna.

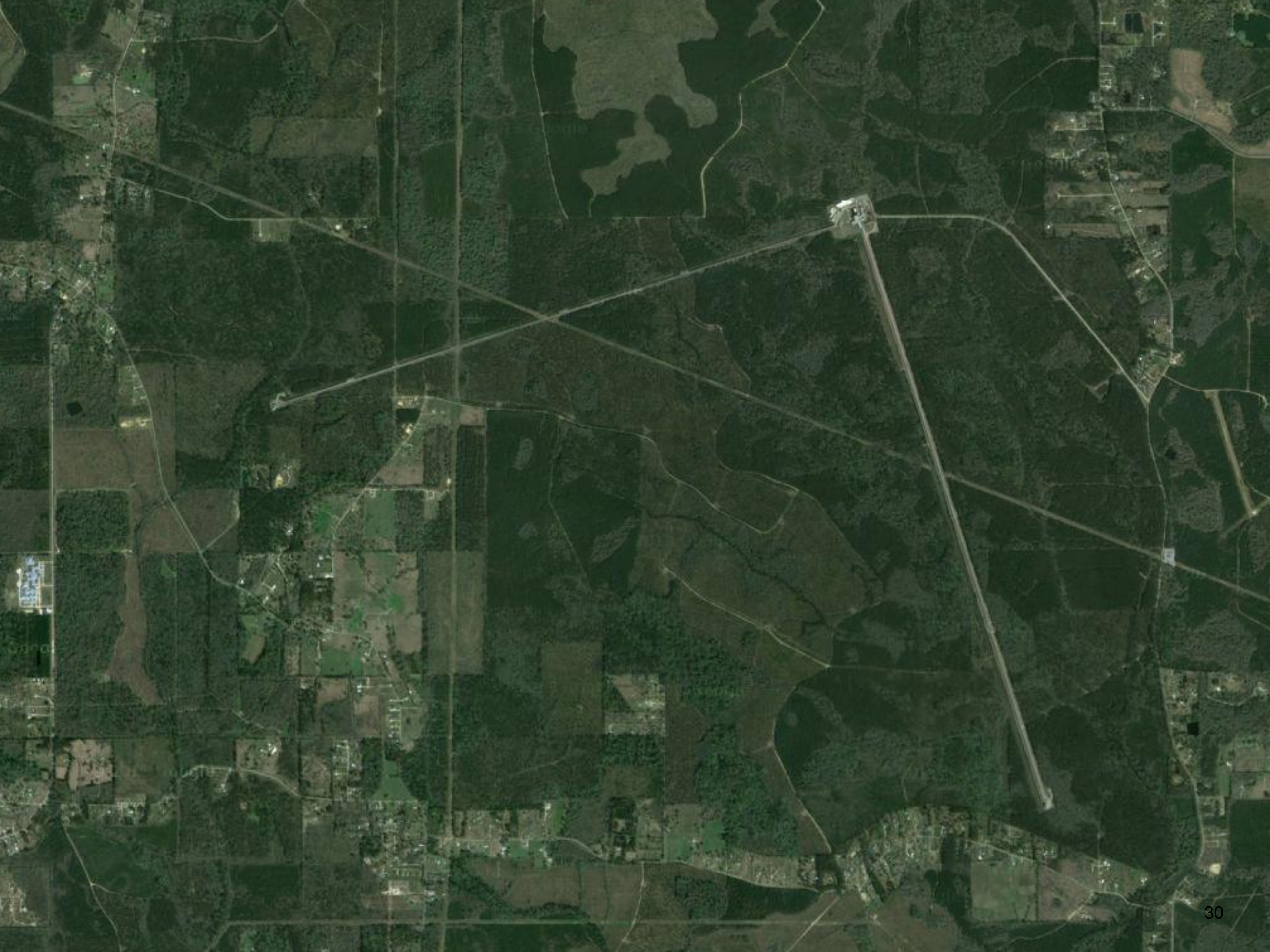


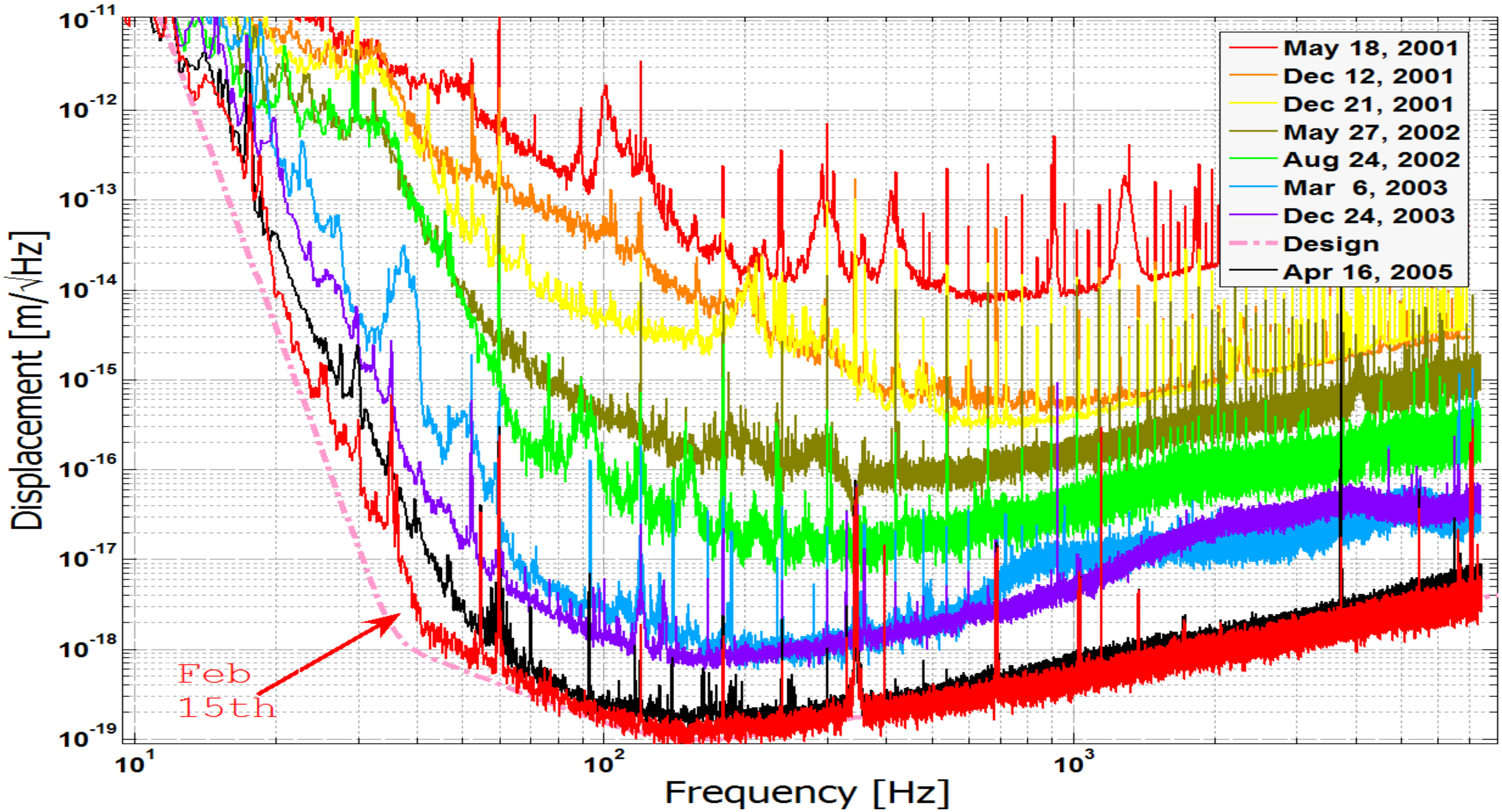

End mirror
End mirror
4 km
4 km
Input
mirrors
Beam splitter
Power
recycling
mirror
Signal
recycling
mirror
Photodetector
CW laser


SEISMIC
SUSPENSION THERMAL
detectable signal zone
RADIATION PRESSURE
GRAVITY GRADIENT
SHOT
TEST MASS THERMAL
RESIDUAL GAS, 10^{-6} TORR H_2
STRAY LIGHT
FACILITY
RESIDUAL GAS, 10^{-9} TORR H_2
$\tilde{h}(f)$ $(1/\sqrt{\mathrm{Hz}})$
10^{-19}
10^{-21}
10^{-23}
10^{-25}
1
10
100
1000
10000
Frequency (Hz)

Initial LIGO Timeline

- 1983 - Funded for design studies
- 1991 - NSF grants funding for initial LIGO (MIT and Caltech project)
- 1994 - Construction begins
- 1997 - The LSC is formed (10s to >1000 scientists)
- 1999 - LIGO is built
- 2001 - The first Science run (S1)
- 2007 - Design sensitivity achieved (S5)
- 2010 - Enhanced LIGO (S6)





Displacement [m/√Hz]
Frequency [Hz]
May 18, 2001
Dec 12, 2001
Dec 21, 2001
May 27, 2002
Aug 24, 2002
Mar 6, 2003
Dec 24, 2003
Design
Apr 16, 2005
Feb 15th


GEO600
Virgo
LIGO Livingston
LIGO Hanford
LIGO-India
LIGO-INDIA
PROPOSAL FOR AN INTERFEROMETRIC GRAVITATIONAL-WAVE OBSERVATORY
IndIGO
Indian Initiative in Gravitational-wave Observations
KAGRA
Data SIO, NOAA, U.S. Navy, NGA,
Image Landsat
Image IBCAO
Image U.S. Geological Survey

LIGO Scientific Collaboration

LIGO

LSC

University of Maryland 1856

Michigan

University of Strathclyde

ACIGA

Loyola University New Orleans

Leland Stanford Junior University 1891

Montana State University

PAH

University of Washington

ANU
The Australian National University

Montclair State University

Syracuse University
Suos cultores scientia coronat
Founded AD 1870

Tsinghua University
清華大學

Trinity University

San José State University

University of Wisconsin
UW Milwaukee

부산대학교
Pusan National University

The University of Western Australia

1754

University of Glasgow

NASA
Goddard Space Flight Center

Per ardua alta

Università degli Studi del Sannio

LSU

UTB TSC

R·I·T

The University of Melbourne

KiSTi
www.kisti.re.kr

Andrews University

Massachusetts Institute of Technology 1861

Southeastern Louisiana University

Moscow State University

California Institute of Technology 1891

Northwestern University

Hanyang University
한양
1939

University of Cambridge

The University of Adelaide
Australia

P A N

The University of Texas at Austin

GEO 600

Embry-Riddle Aeronautical University

University of Massachusetts Amherst 1863

Lund University

ISI

University of New Hampshire

PennState
1855

Coll. Carleton
Northfield, Minn. A.D. 1866

Cardiff University

California State University Fullerton

Washington State University

국가수리과학연구소
National Institute for Mathematical Sciences

The University of Mississippi
1848

Charles Sturt University

UIB
Universitat de les Illes Balears

UF University of Florida

PI
Perimeter Institute

CITA-ICAT

Seoul National University

University of Rochester

NAOJ

University of Southampton

Hobart and William Smith Colleges

William Smith College 1908

University of Minnesota

Universität Hannover

Southern University and Agricultural & Mechanical College

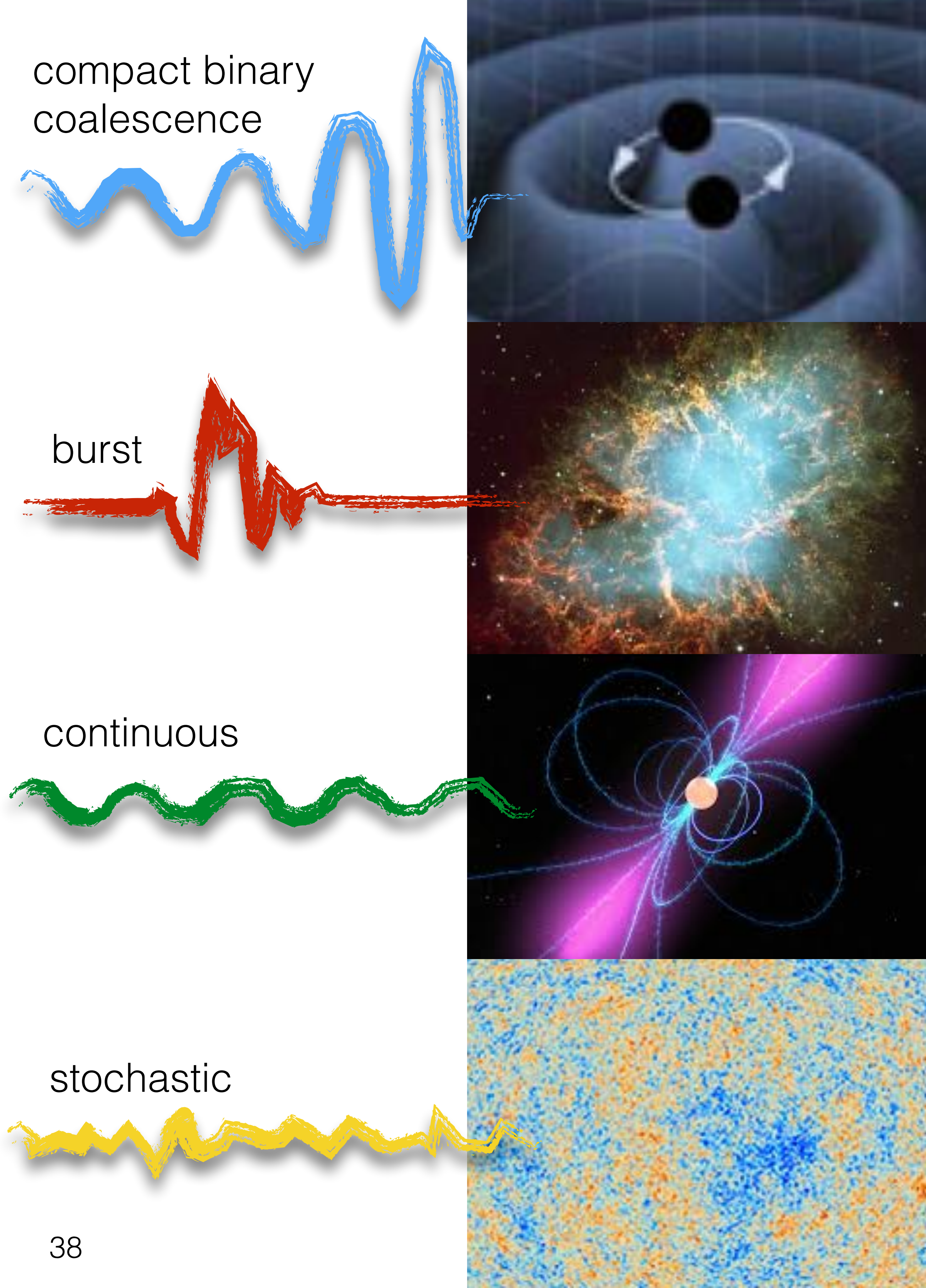
Science & Technology Facilities Council
Rutherford Appleton Laboratory

A global collaboration

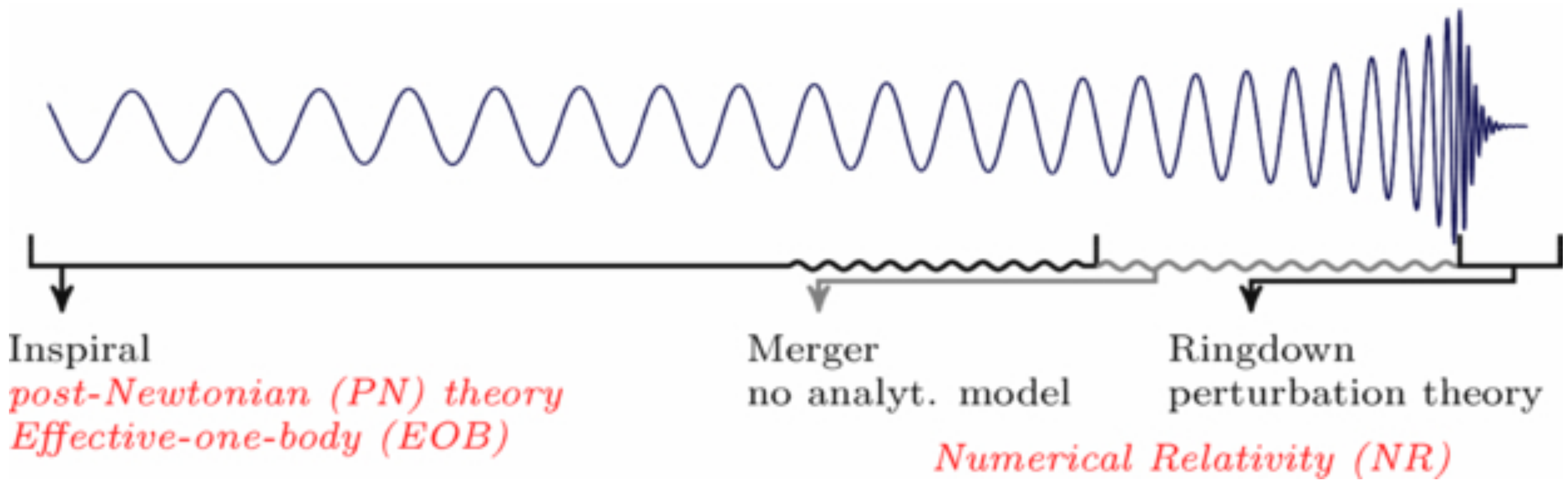
- We have over 1000 members spread across 5 continents and over 100 institutions.

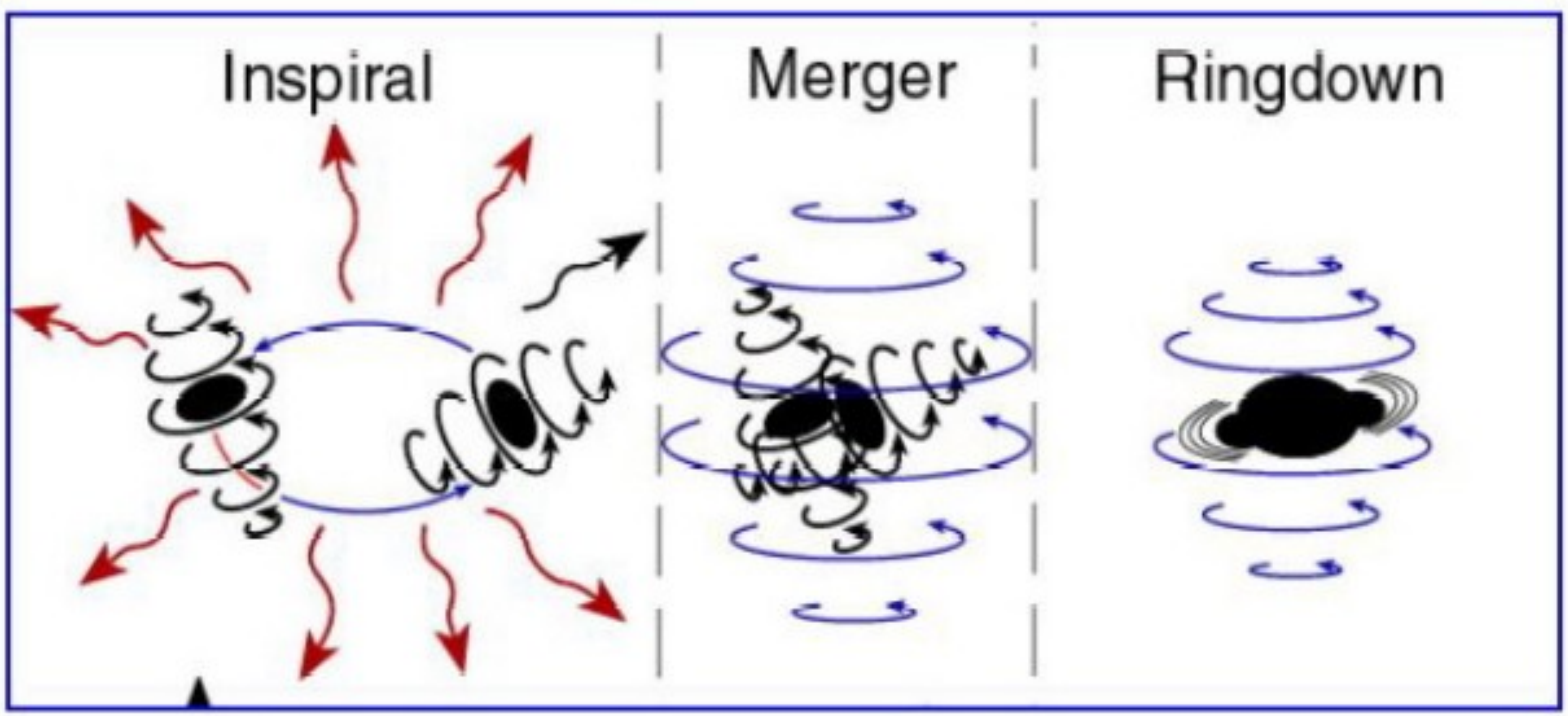
Gravitational wave sources

Pretty violent events

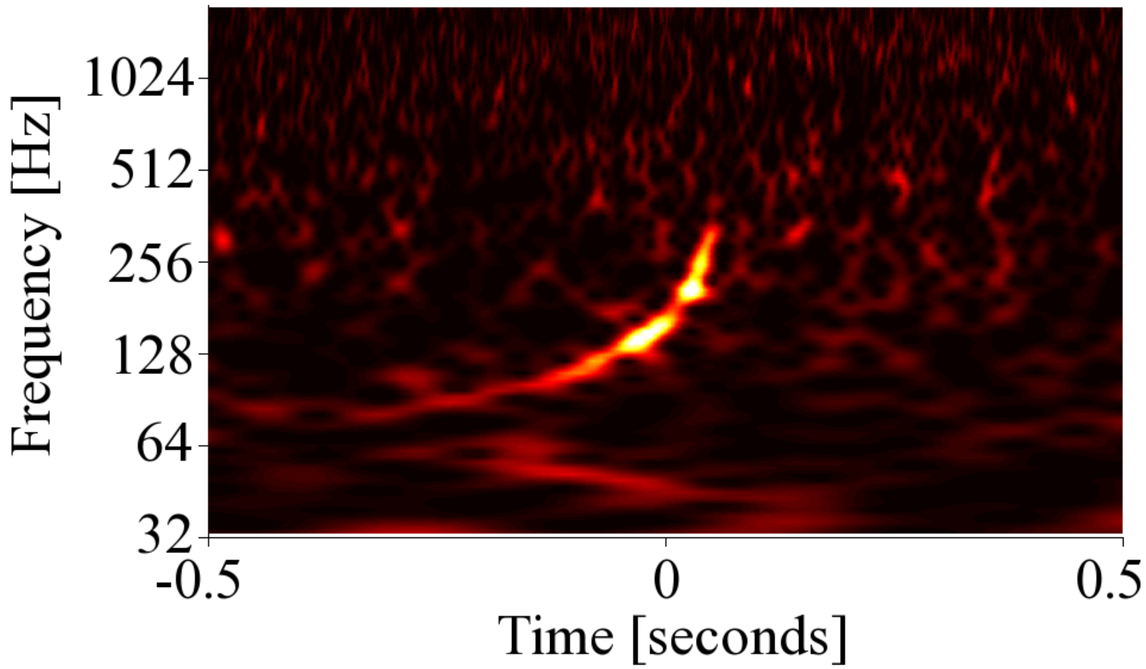

compact binary
coalescence
burst
continuous
stochastic

Compact binary coalescence

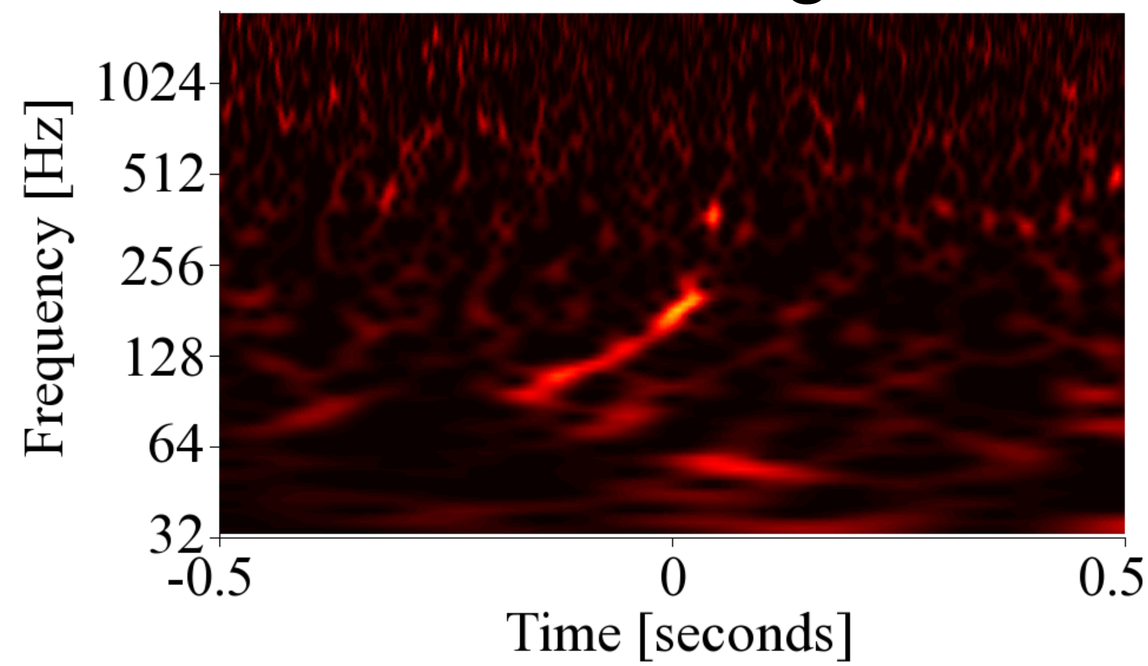




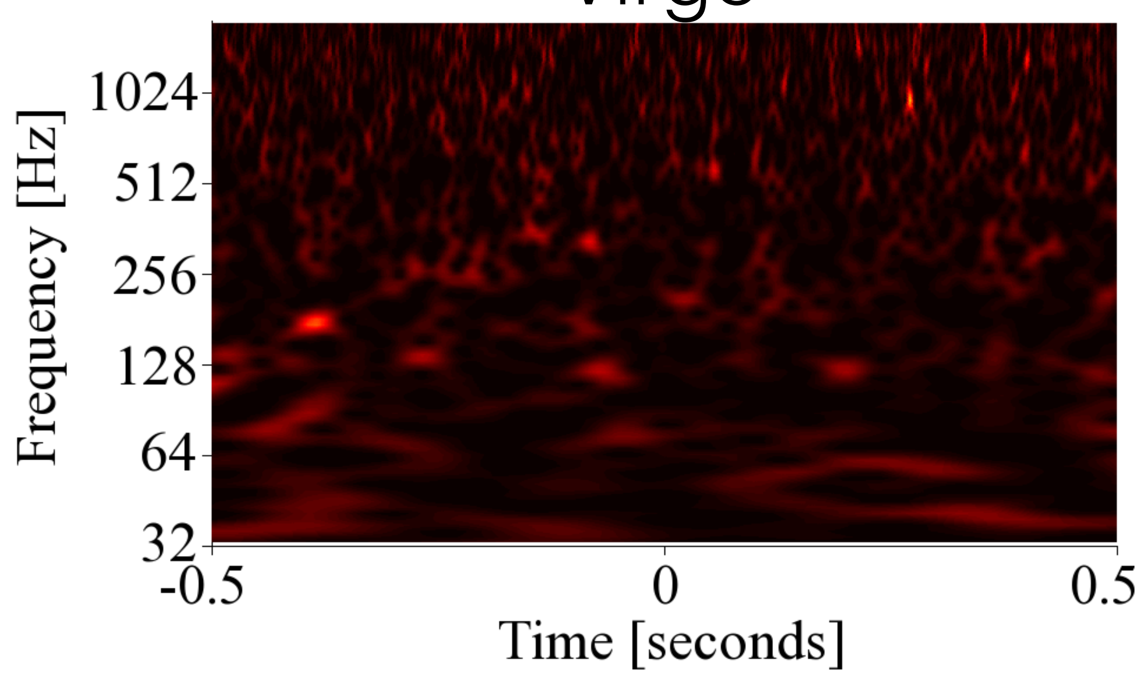
LIGO Hanford



LIGO Livingston

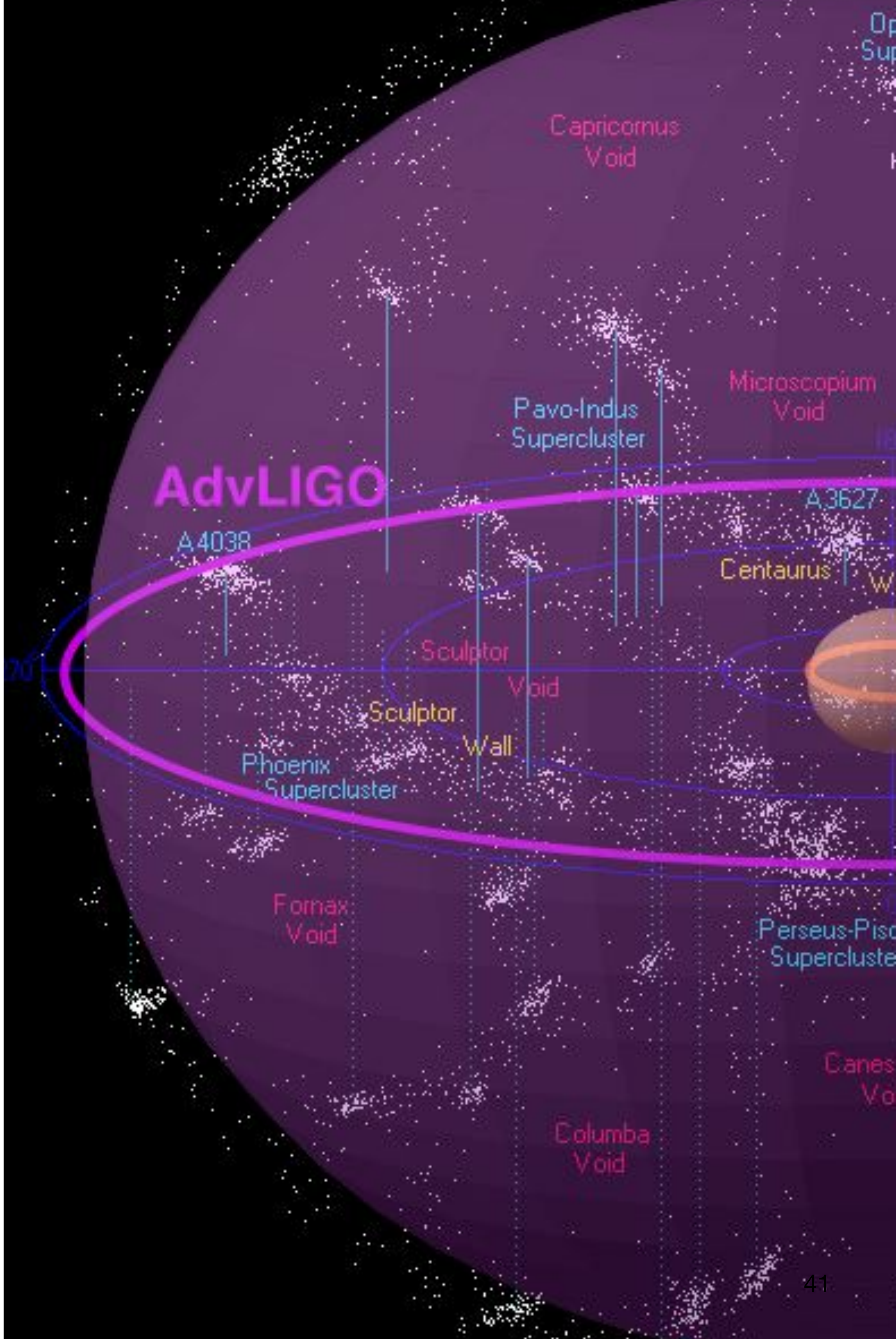


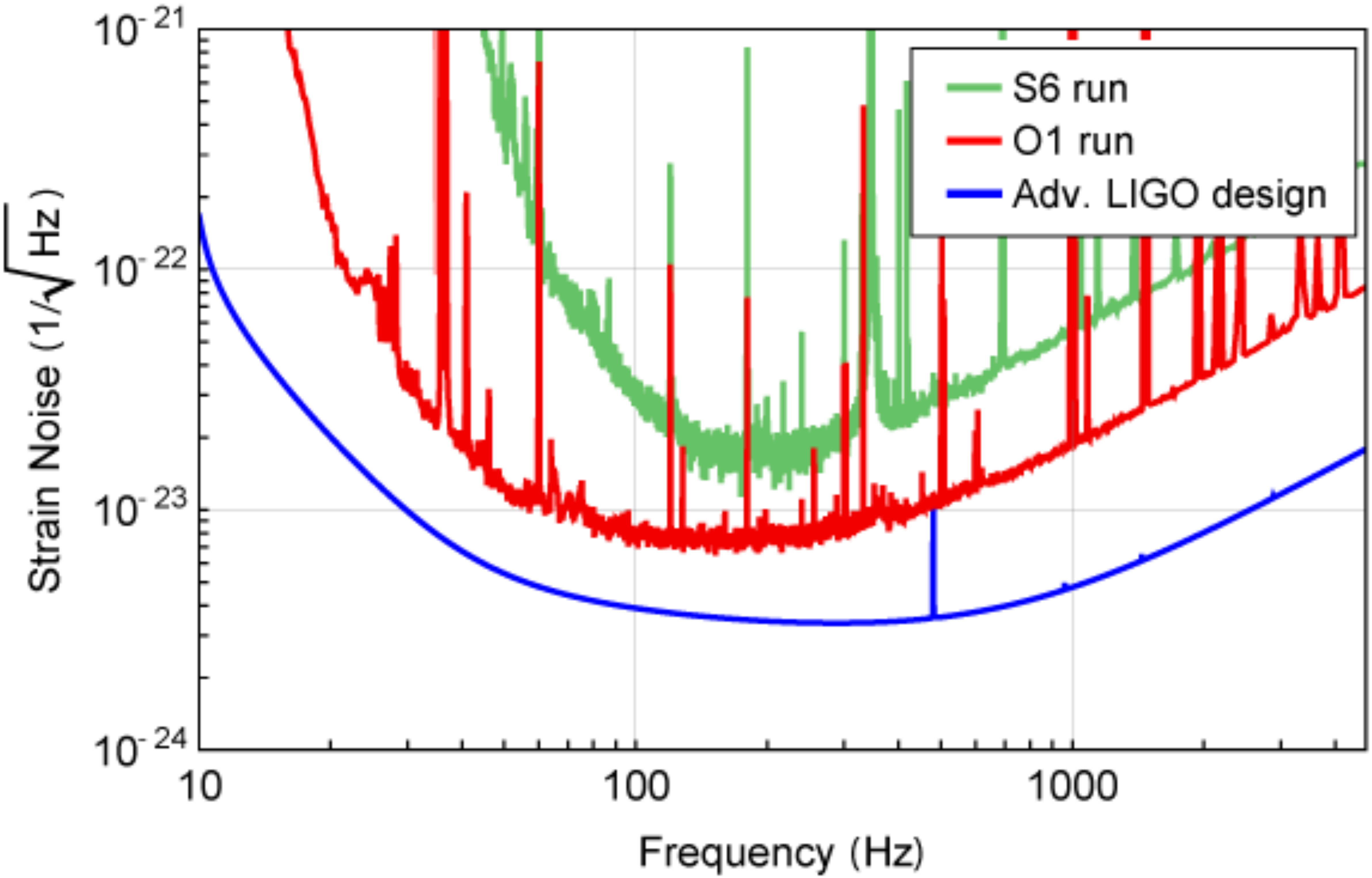
Virgo



Advanced Detectors

A 10 fold improvement

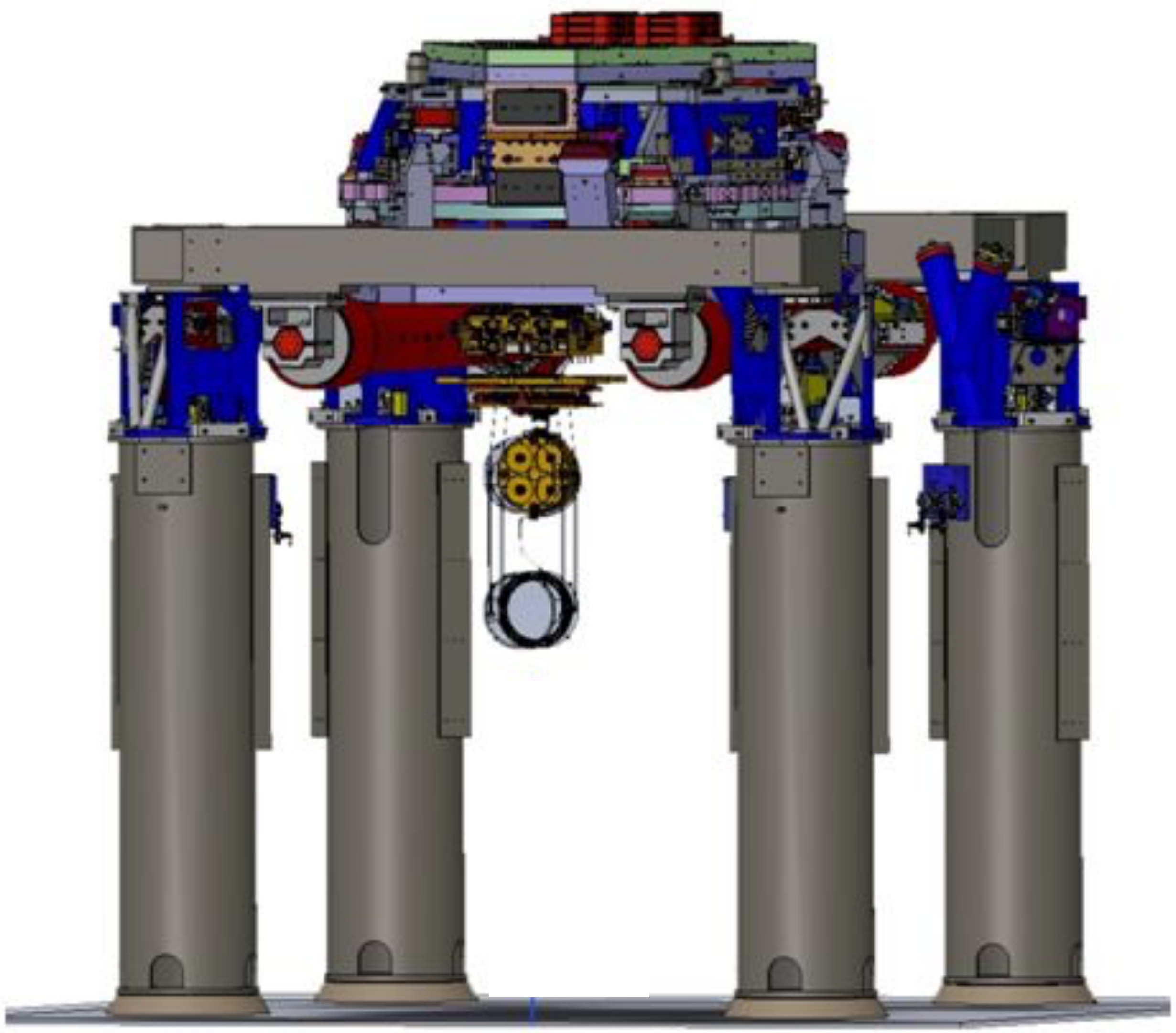


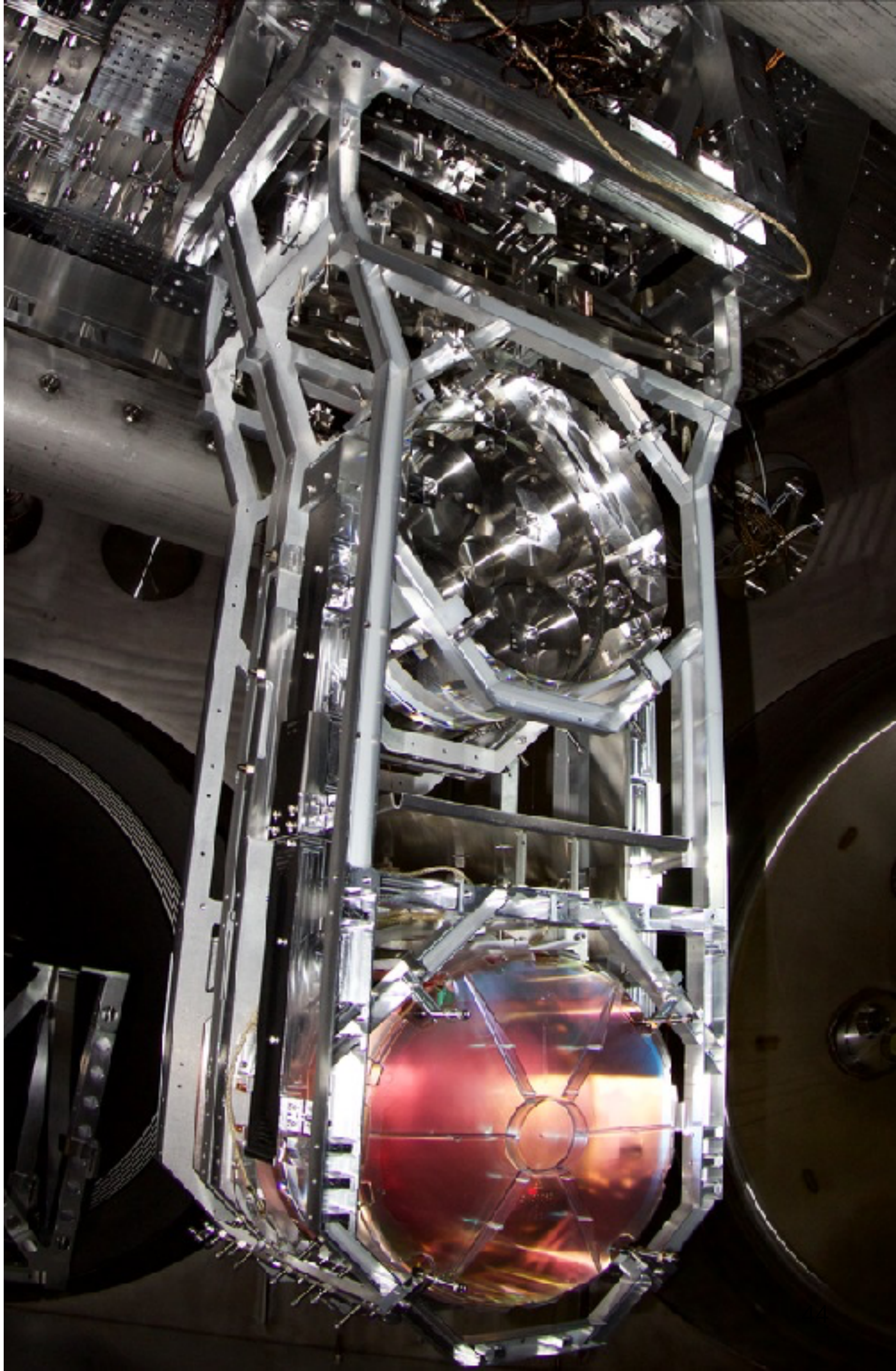


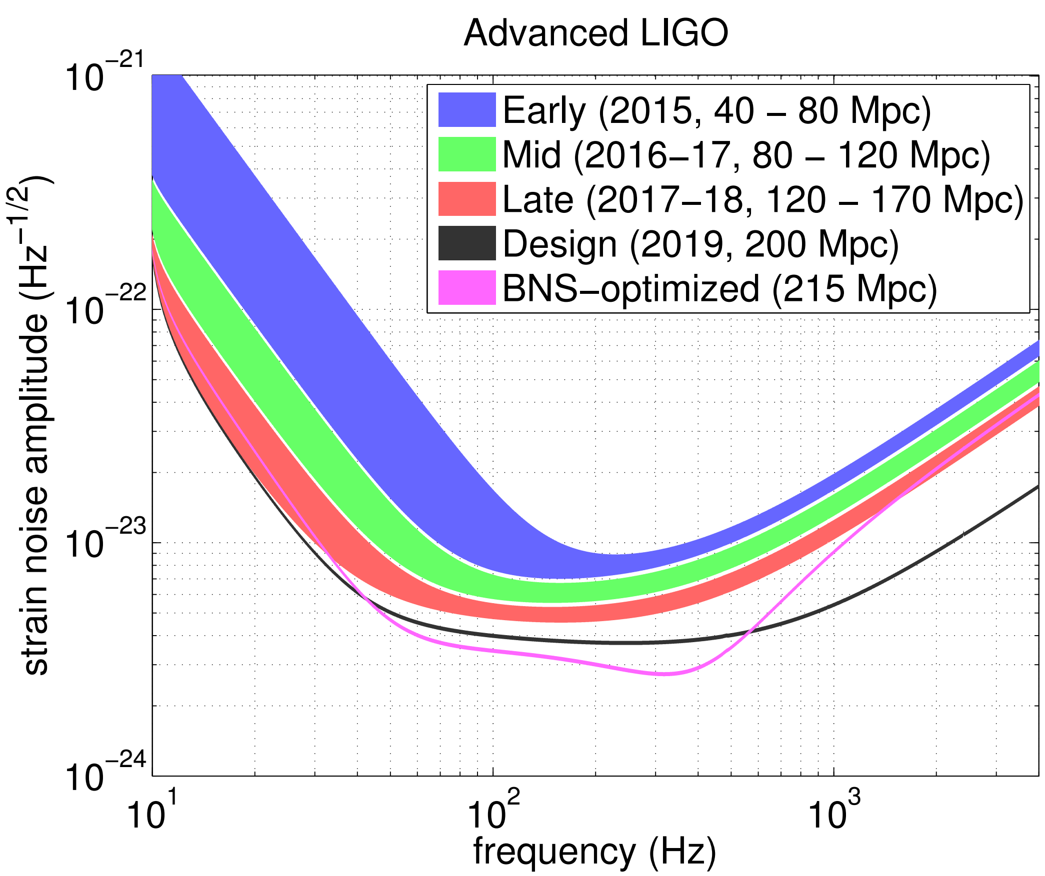
Strain Noise (1/√Hz)
Frequency (Hz)
S6 run
O1 run
Adv. LIGO design
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10
100
1000

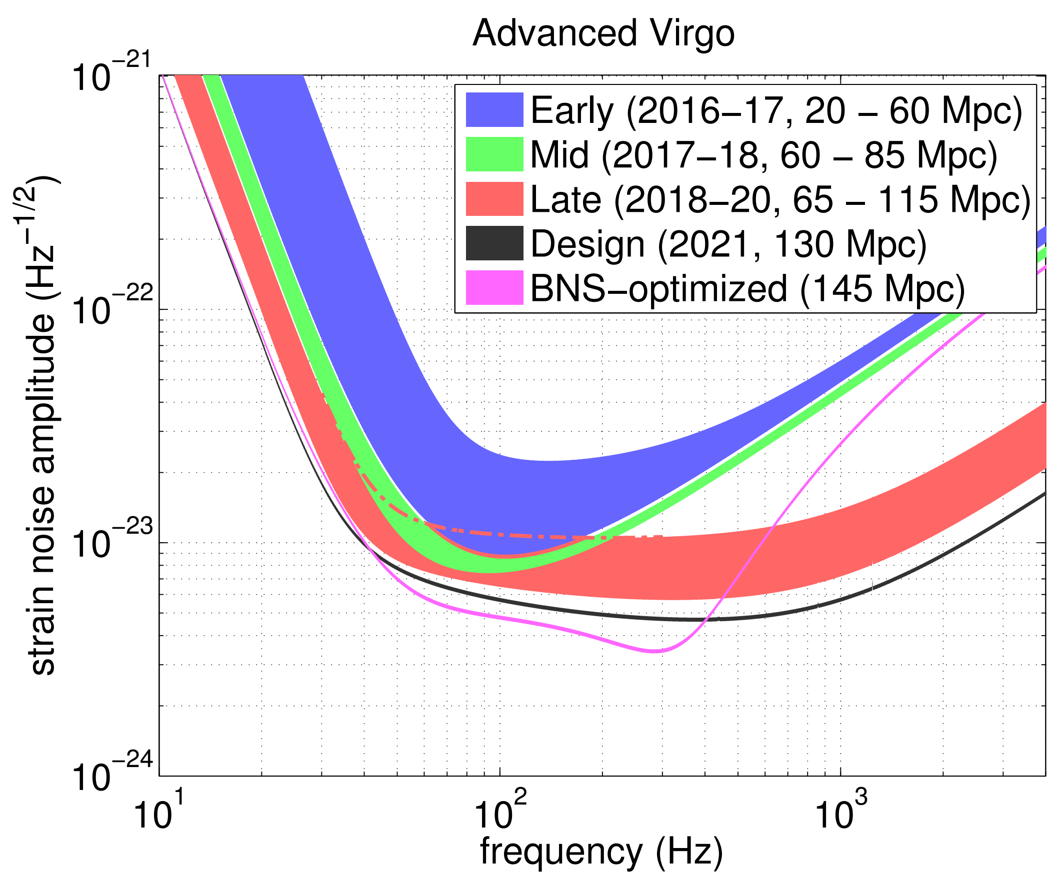
Advanced LIGO Timeline

- 2010 - Decomissioning of initial LIGO
- Sep 2015 - Jan 2016 - The first observing run (O1)
- Nov 2016 - Aug 2017 - The second observing run (O2)
- late 2018 - planned O3
- 2019+ - Achieve design sensitivity





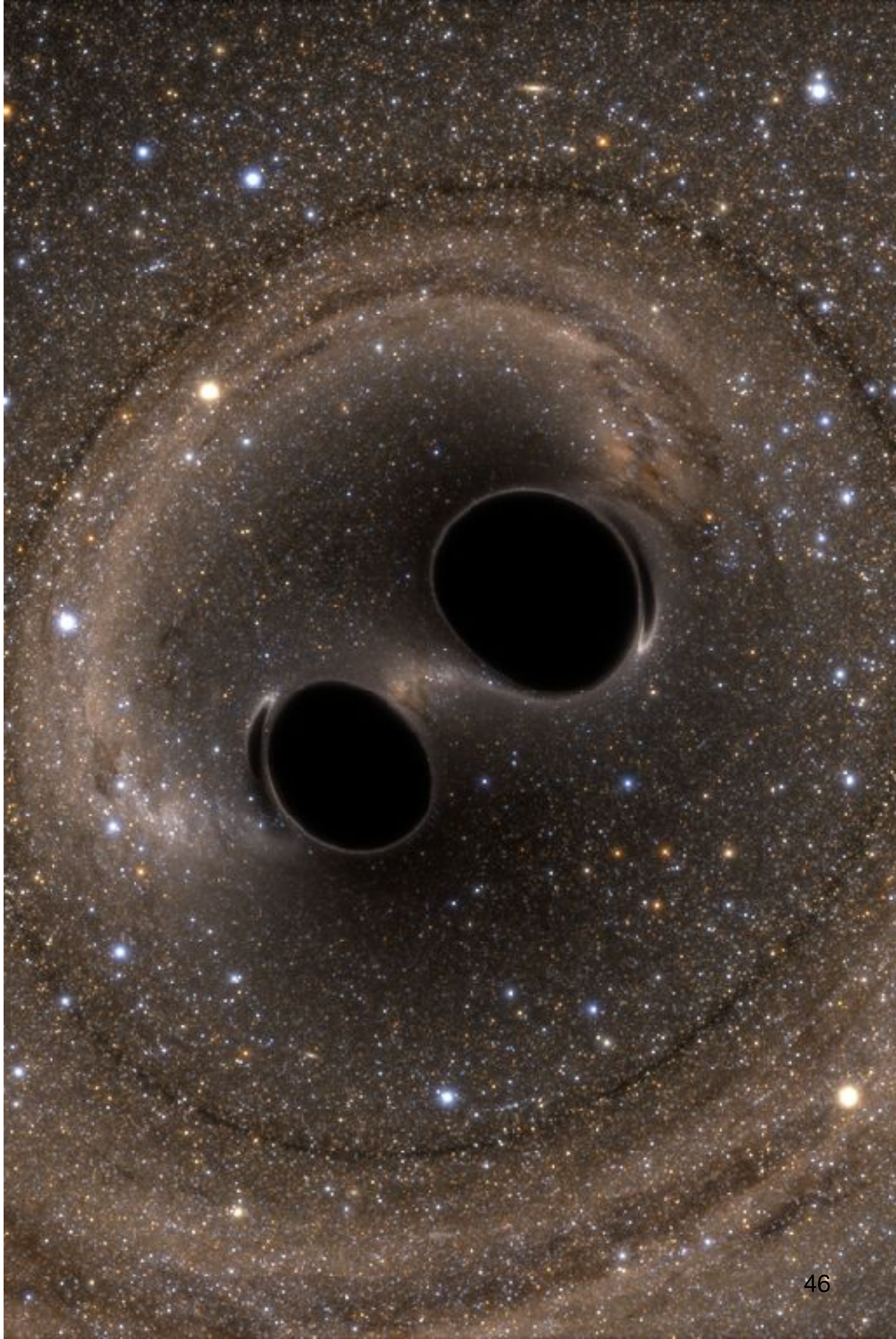


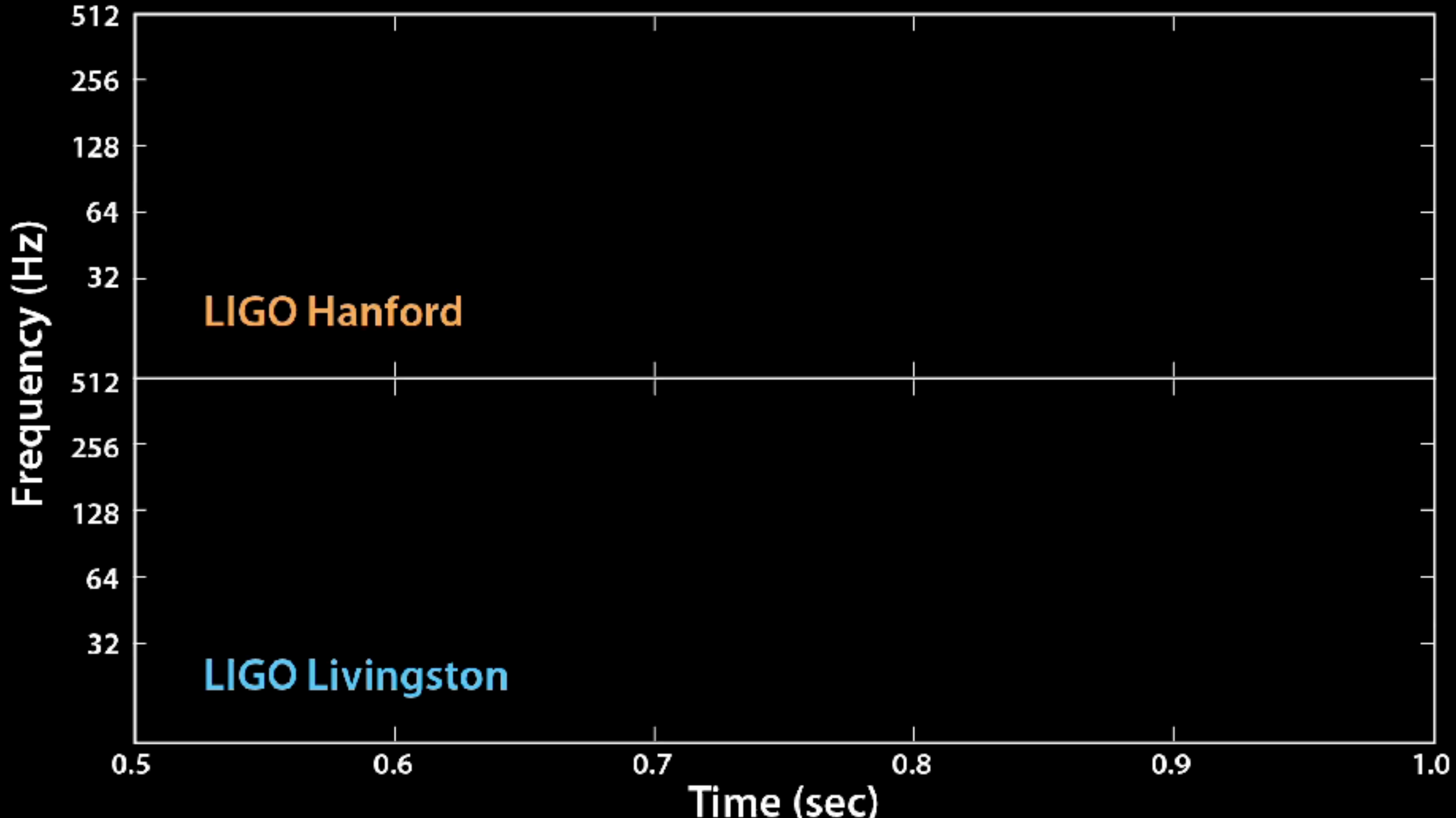


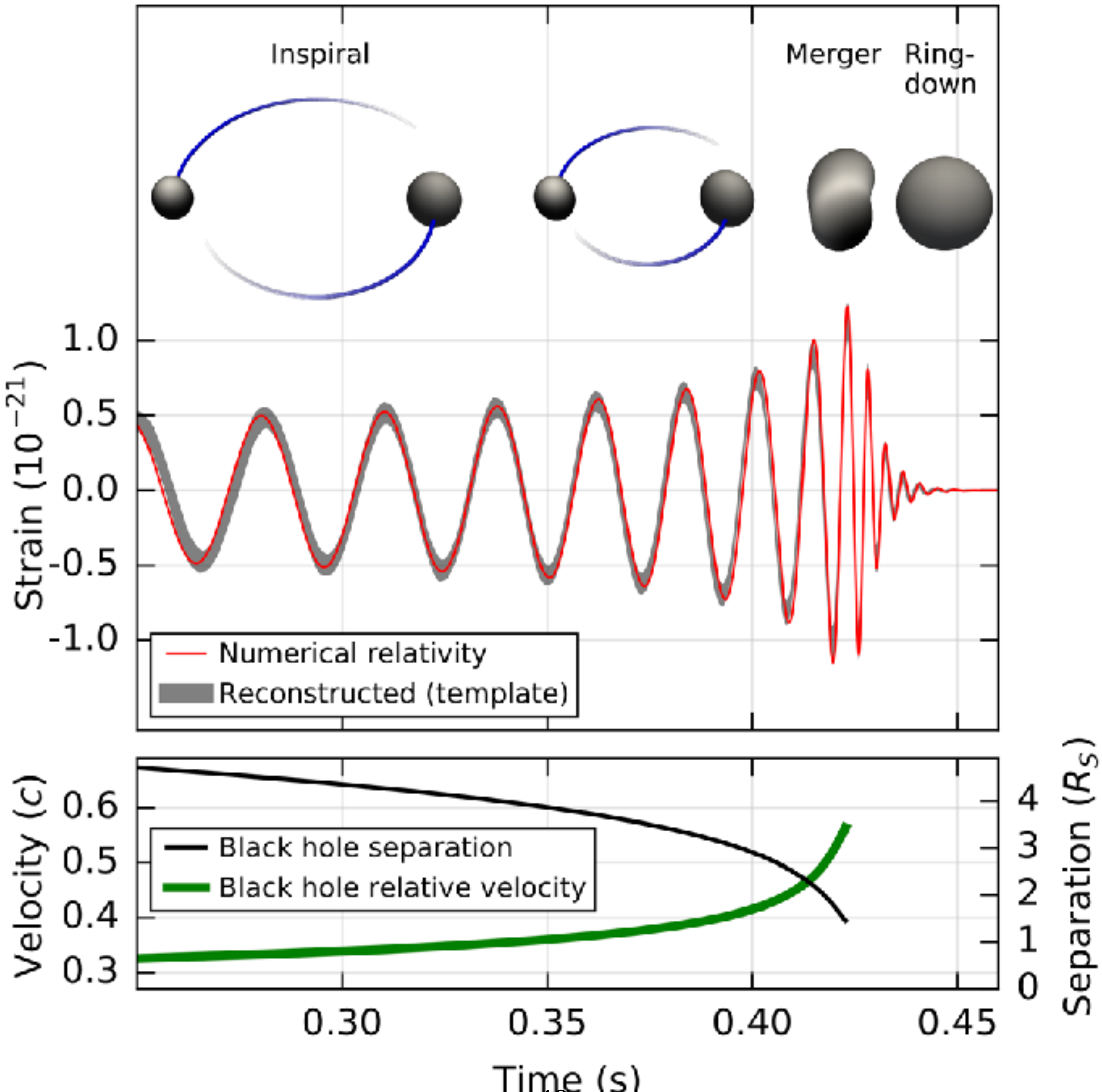
Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Detection

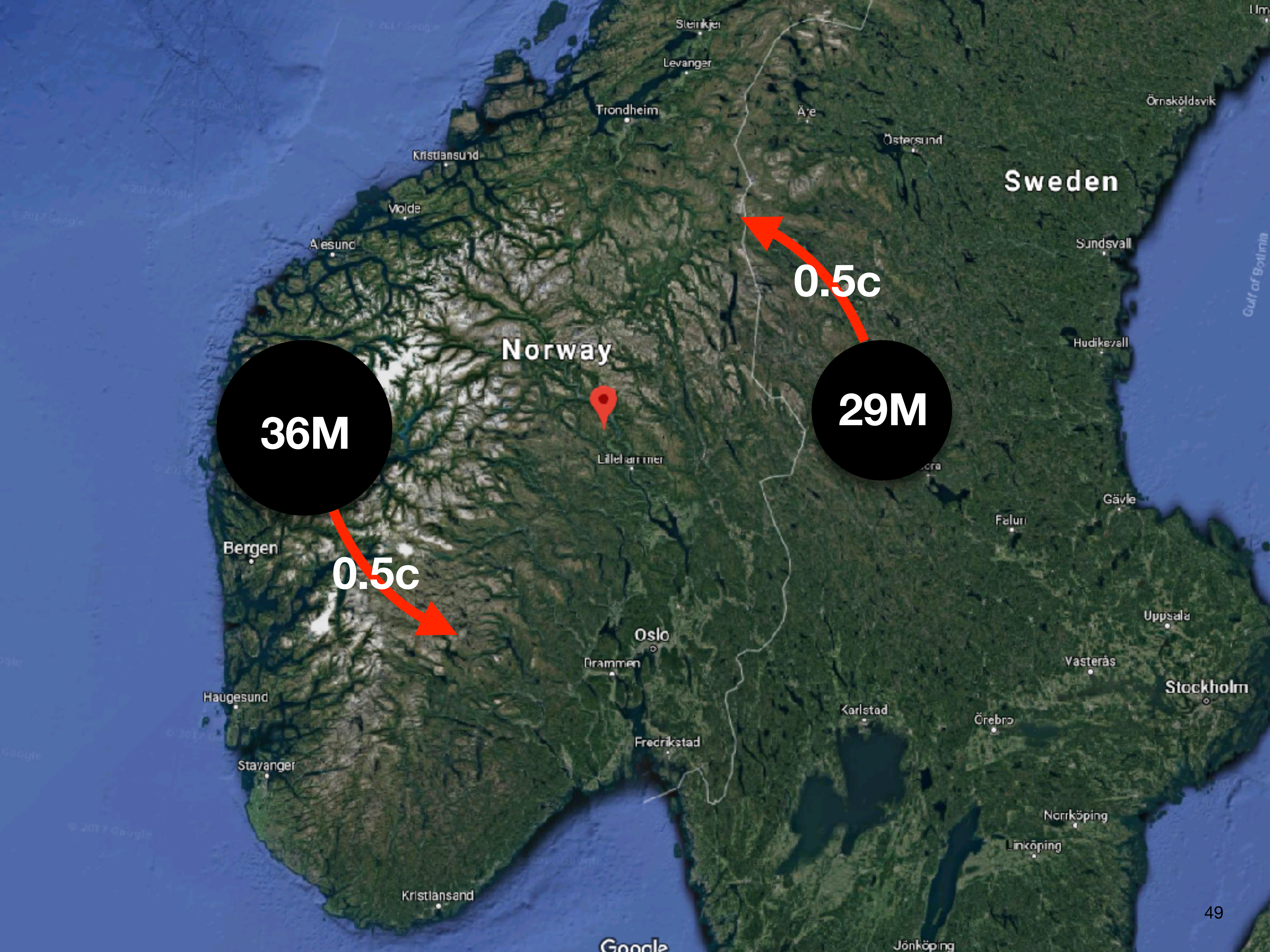
A binary black hole merger, and more




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
Time (sec)

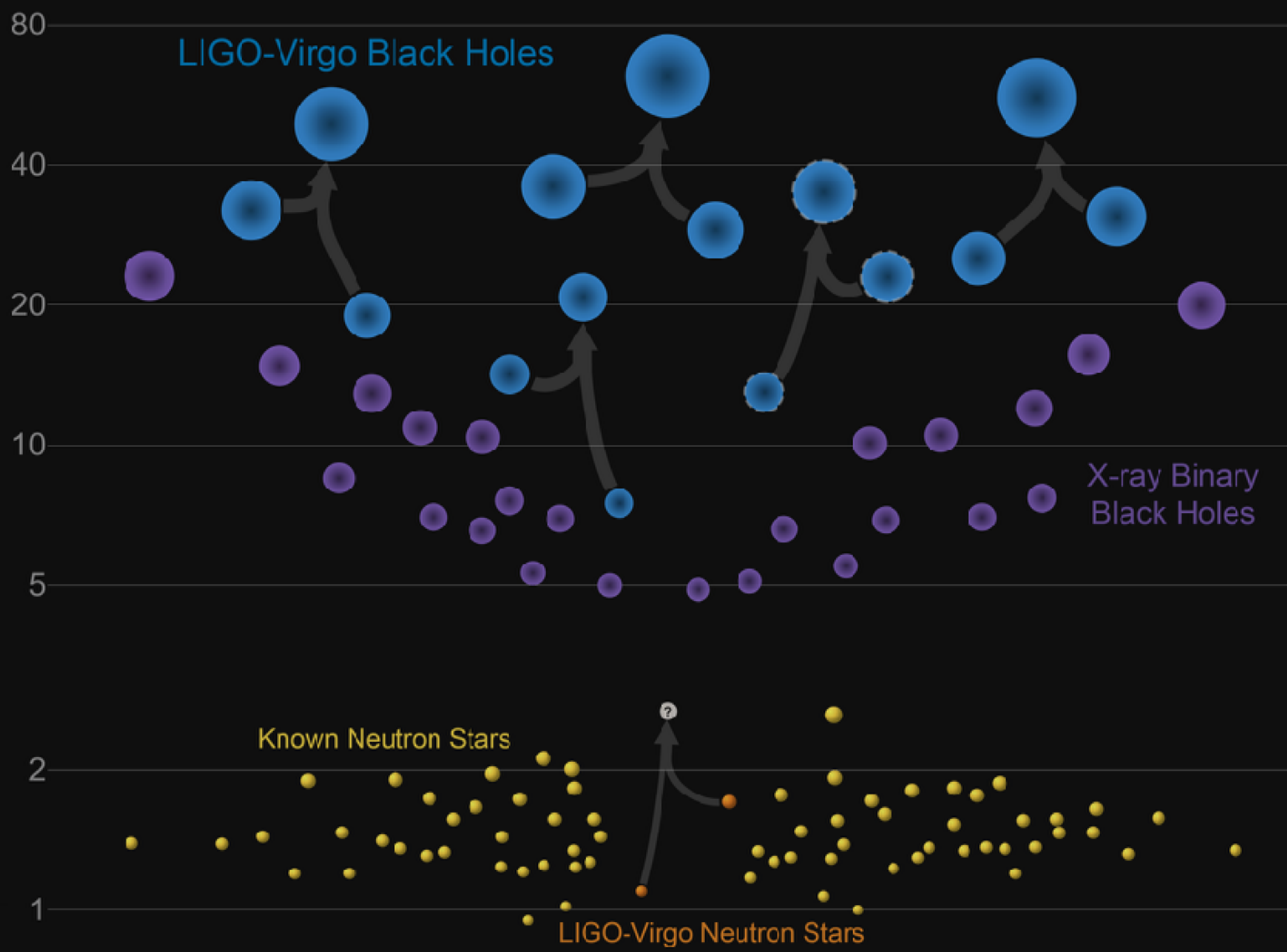


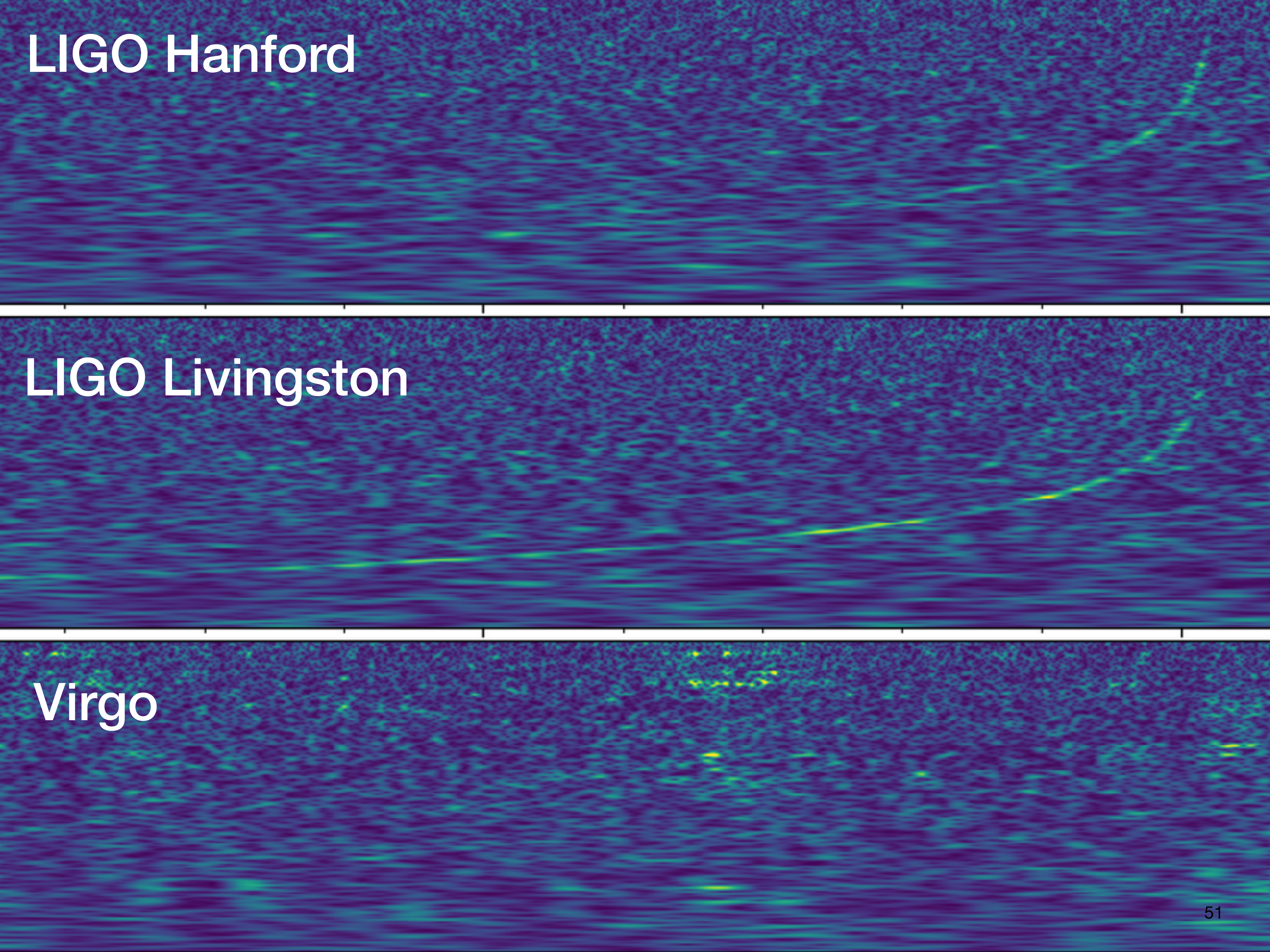
LIGO-Virgo Collaboration, PRL **116**, 061102 (2016)

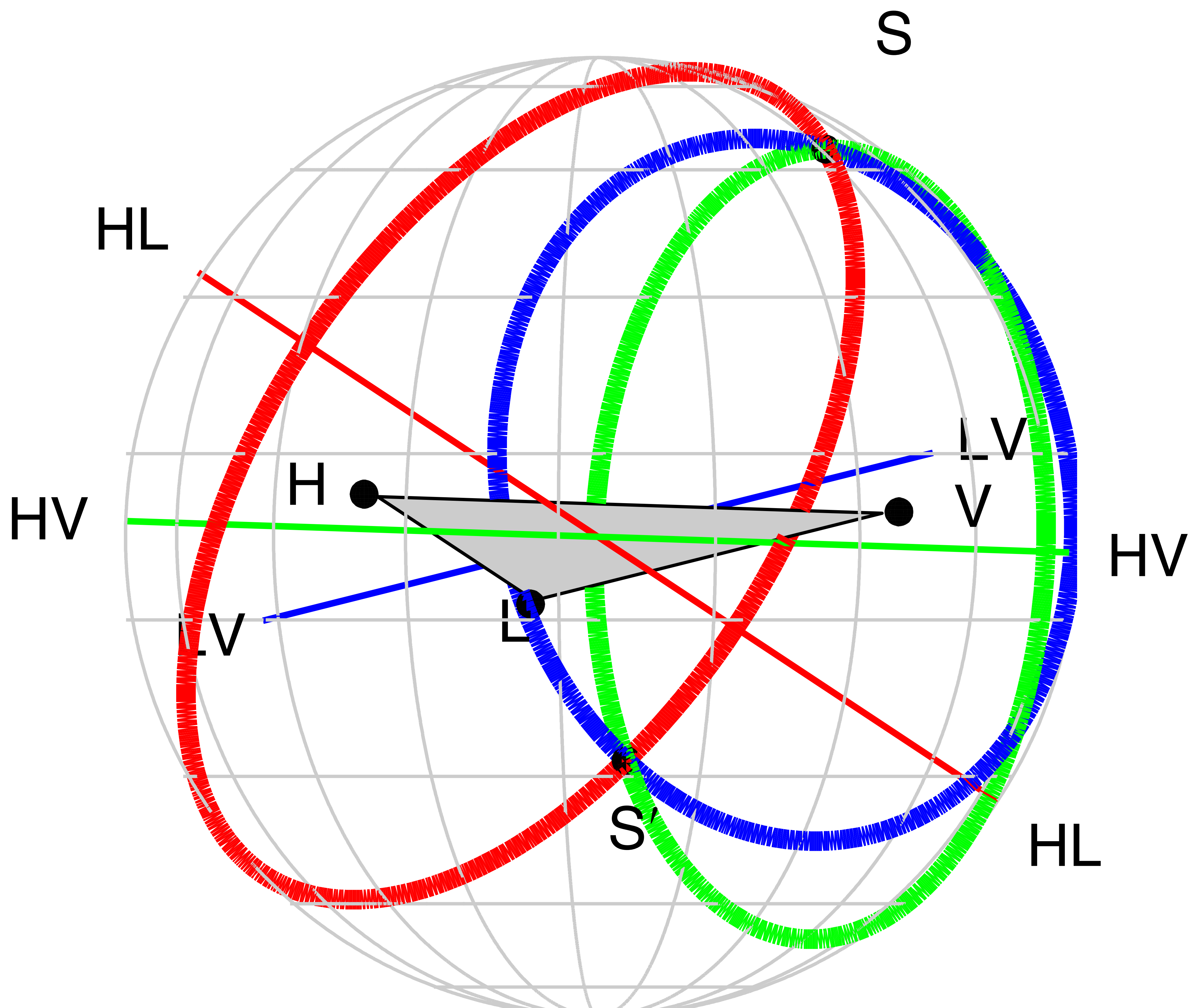

36M
0.5c
29M
0.5c
Norway
Sweden
Steinkjer
Levanger
Trondheim
Åre
Östersund
Örnsköldsvik
Kristiansund
Molde
Ålesund
Sundsvall
Hudiksvall
Lillehammer
Gävle
Falun
Bergen
Oslo
Drammen
Uppsala
Västerås
Stockholm
Haugesund
Karlstad
Örebro
Fredrikstad
Stavanger
Norrköping
Linköping
Kristiansand
Jönköping
Google

Masses in the Stellar Graveyard

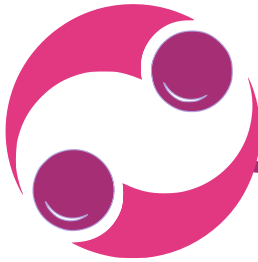
in Solar Masses




LIGO Hanford
LIGO Livingston
Virgo



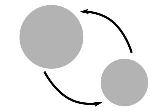
LIGO-Virgo Collaboration, arXiv:1304.0670 (2013)



12:41:04 UTC

A gravitational wave from a binary neutron star merger is detected.

17 August 2017

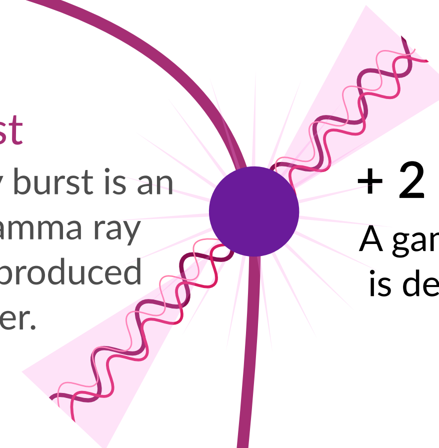


Type

Neutron star merger

gravitational wave signal

Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.

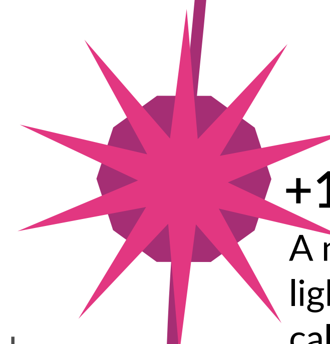


gamma ray burst

A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

+ 2 seconds

A gamma ray burst is detected.



+10 hours 52 minutes

A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

kilonova

Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

+11 hours 36 minutes

Infrared emission observed.

+15 hours

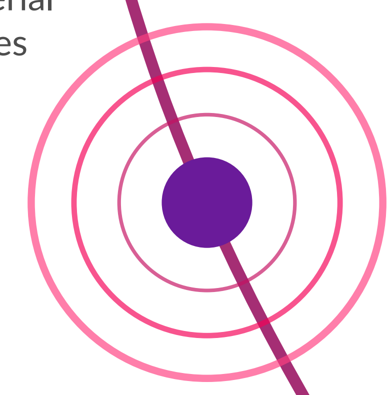
Bright ultraviolet emission detected.

+9 days

X-ray emission detected.

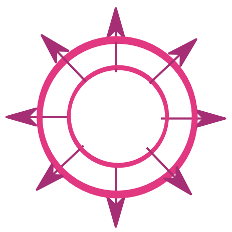
radio remnant

As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

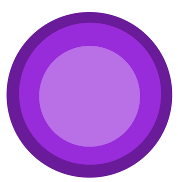


+16 days

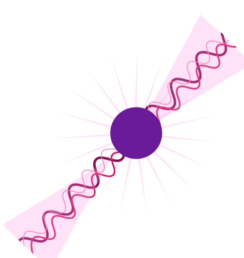
Radio emission detected.



GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time.

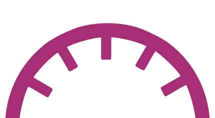


Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.

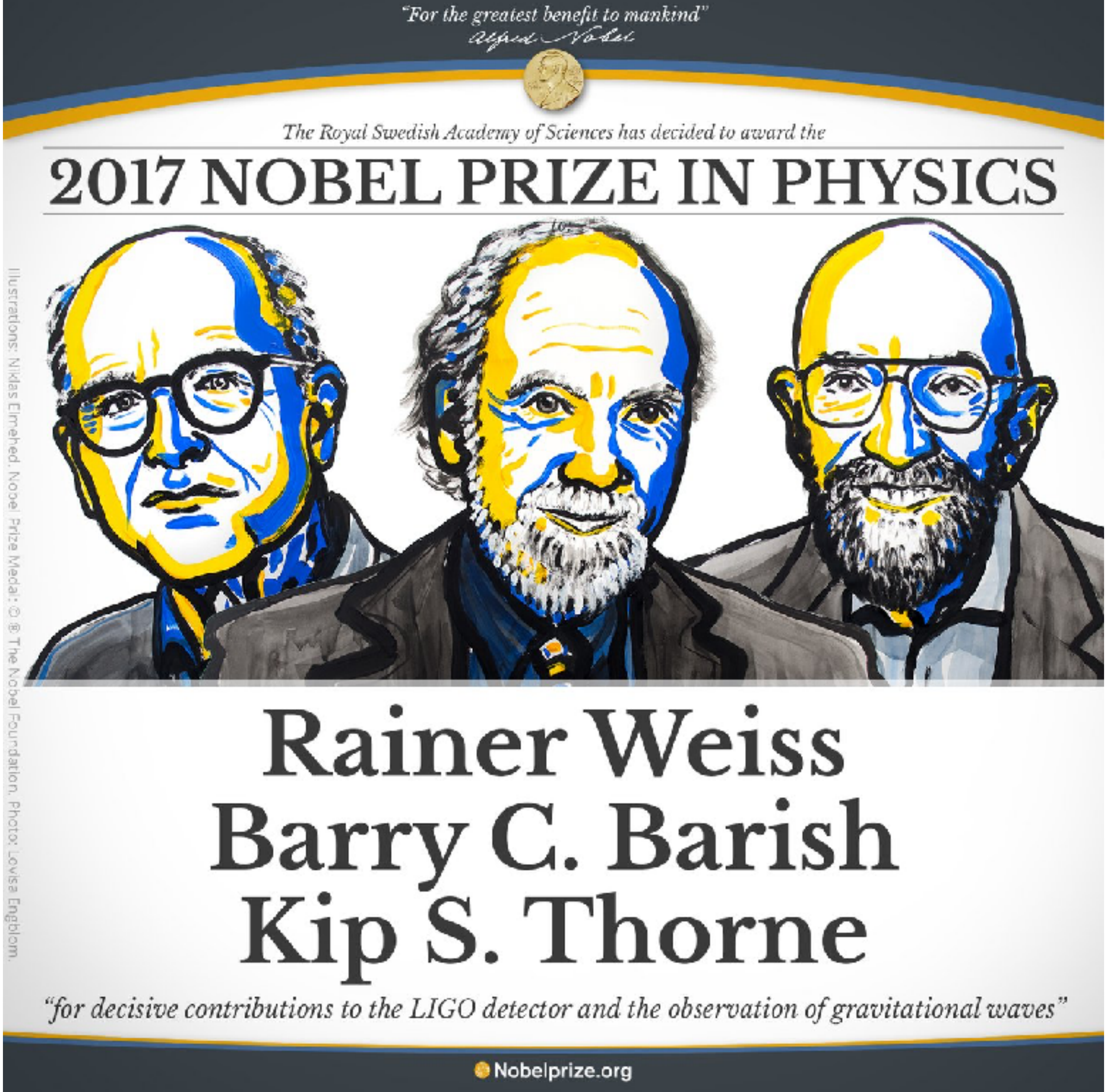


This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.

The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production of most of the heavy elements, like gold, in the universe.

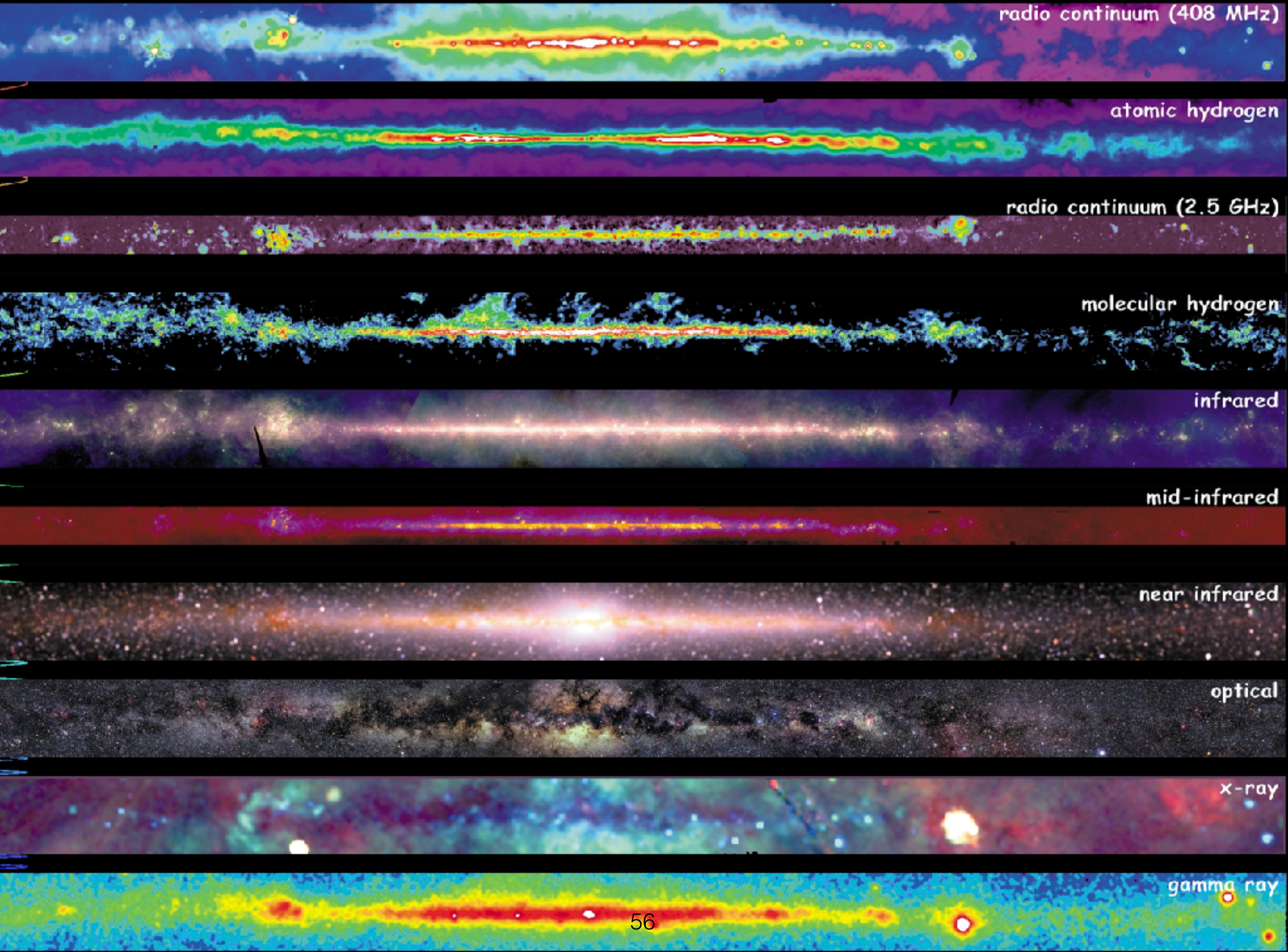


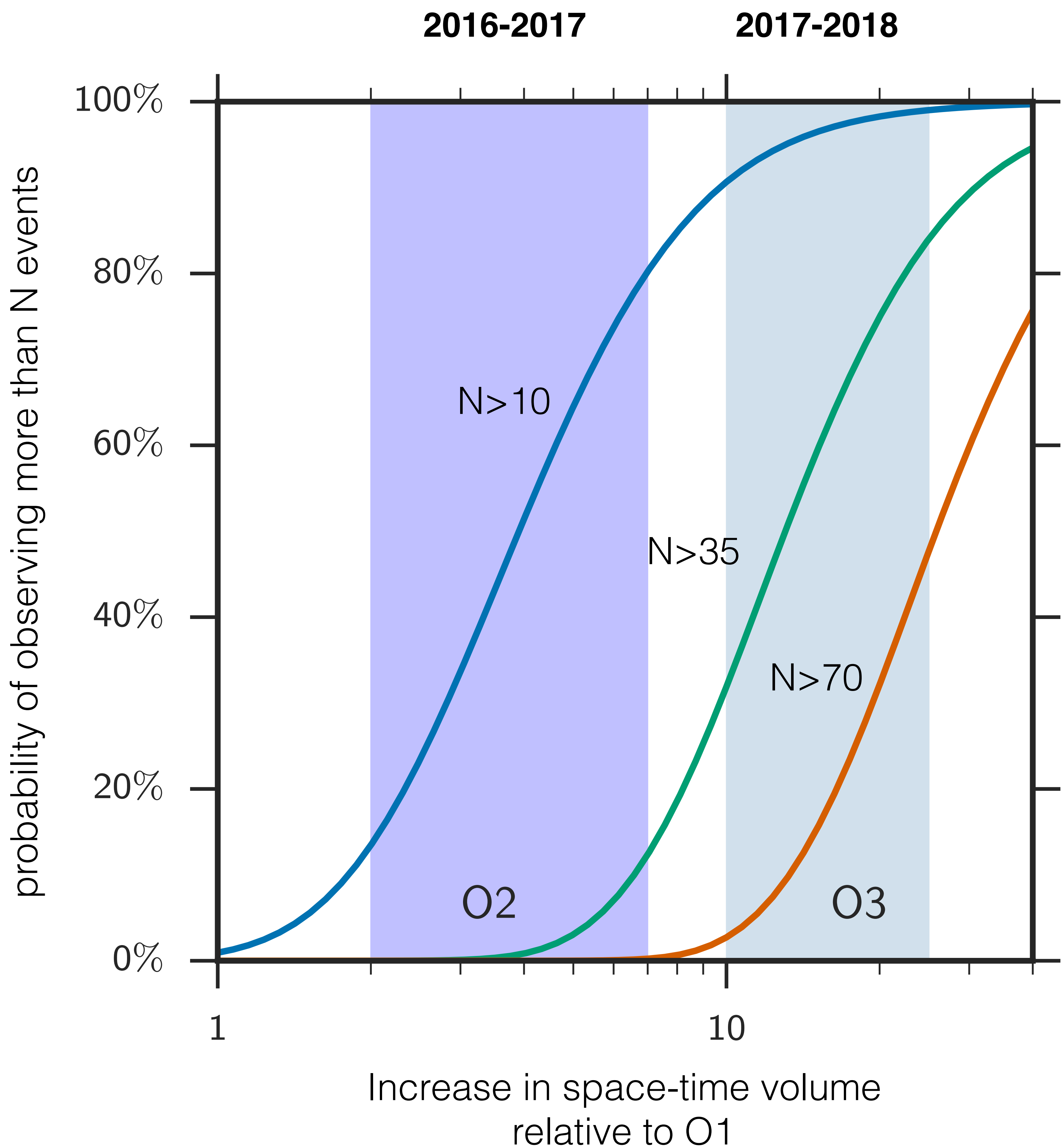
Observing both electromagnetic and gravitational waves from the


"For the greatest benefit to mankind"
Alfred Nobel
The Royal Swedish Academy of Sciences has decided to award the
2017 NOBEL PRIZE IN PHYSICS
to
Rainer Weiss
Barry C. Barish
Kip S. Thorne
"for decisive contributions to the LIGO detector and the observation of gravitational waves"
Nobelprize.org
Illustrations: Niklas Elmehed. Nobel Prize Medal: ® © The Nobel Foundation. Photo: Lovisa Engblom.

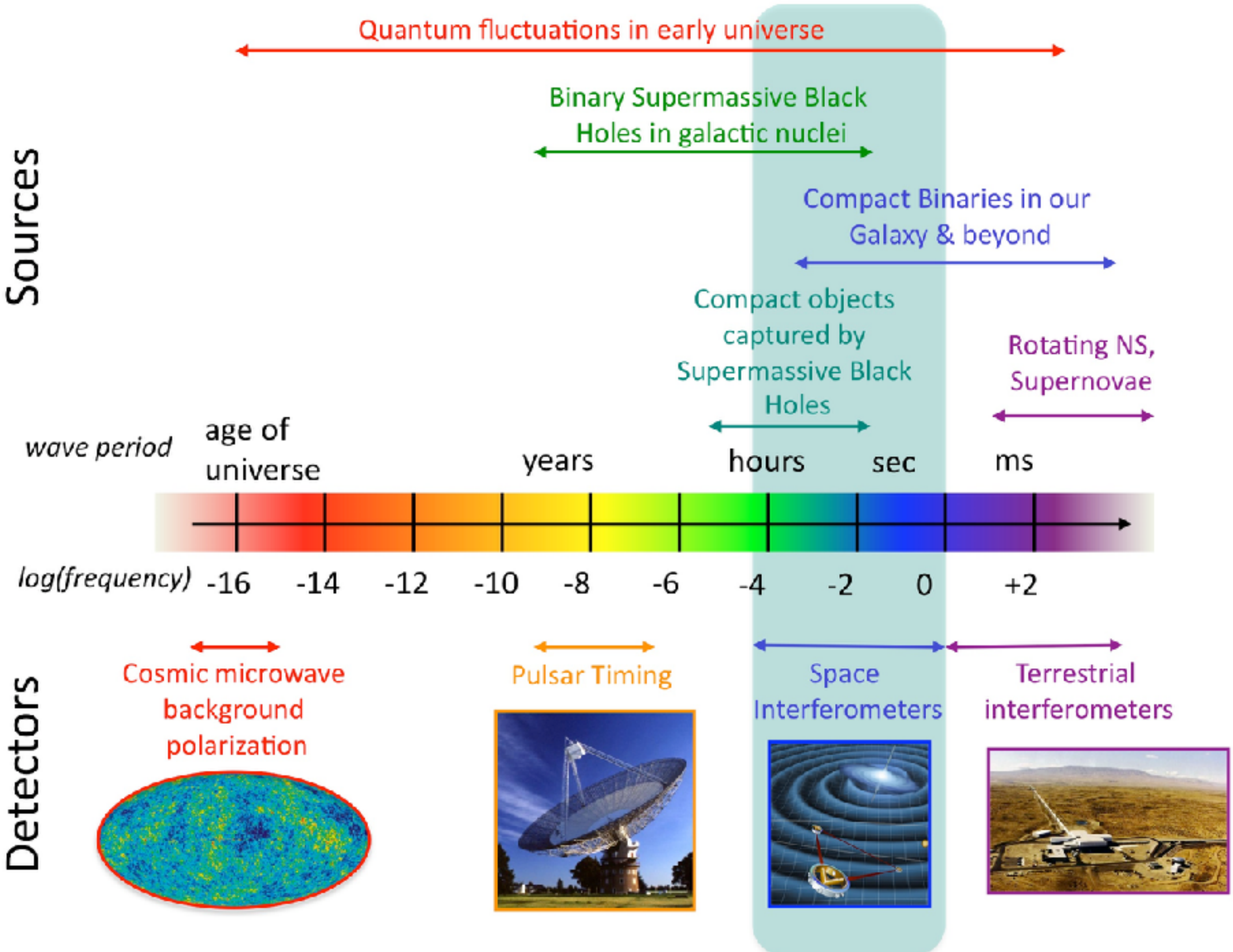
Final remarks

The promise of gravitational wave astronomy


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray



LIGO-Virgo Collaboration, arXiv:1606.04856 (2016)


Quantum fluctuations in early universe
Binary Supermassive Black Holes in galactic nuclei
Compact Binaries in our Galaxy & beyond
Compact objects captured by Supermassive Black Holes
Rotating NS, Supernovae
Sources
wave period
age of universe
years
hours
sec
ms
log(frequency)
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
Detectors
Cosmic microwave background polarization
Pulsar Timing
Space Interferometers
Terrestrial interferometers

Thanks for your attention

More details on the detections on Friday morning