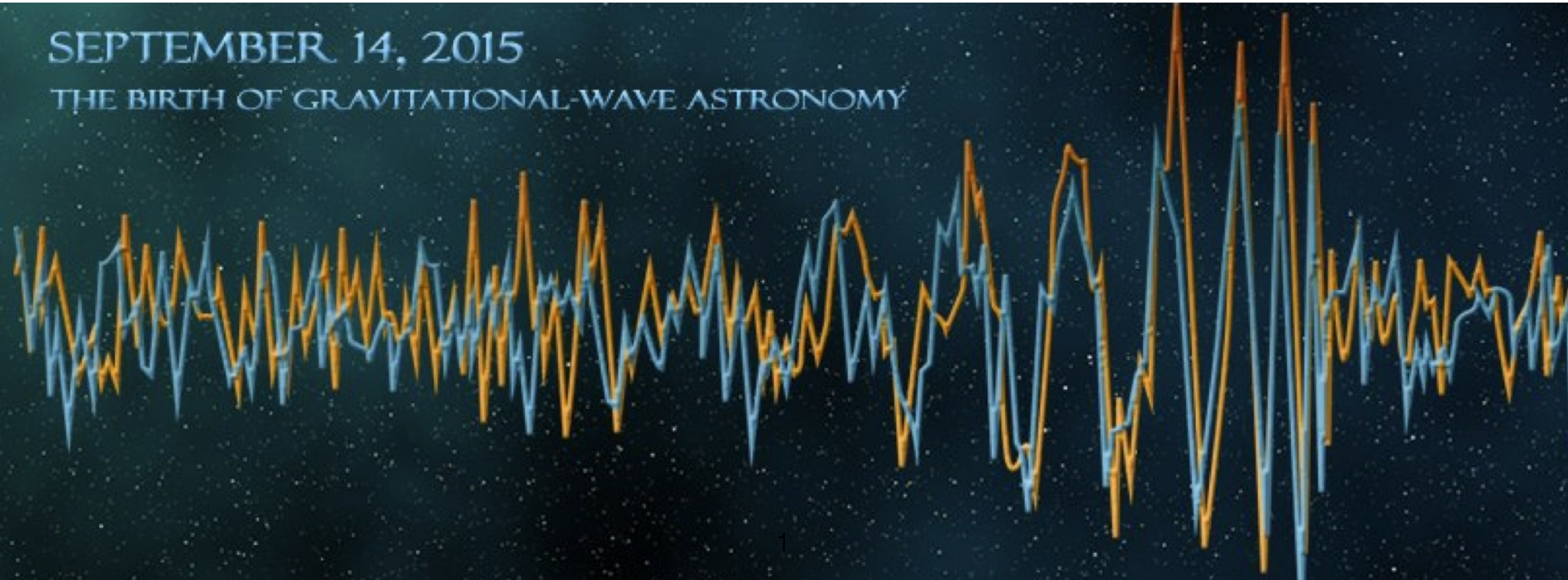
Perspectives on the Milestones and Challenges in Gravitational-wave Science: How Did We Get to Today?

Beverly K. Berger

LIGO-G1601284

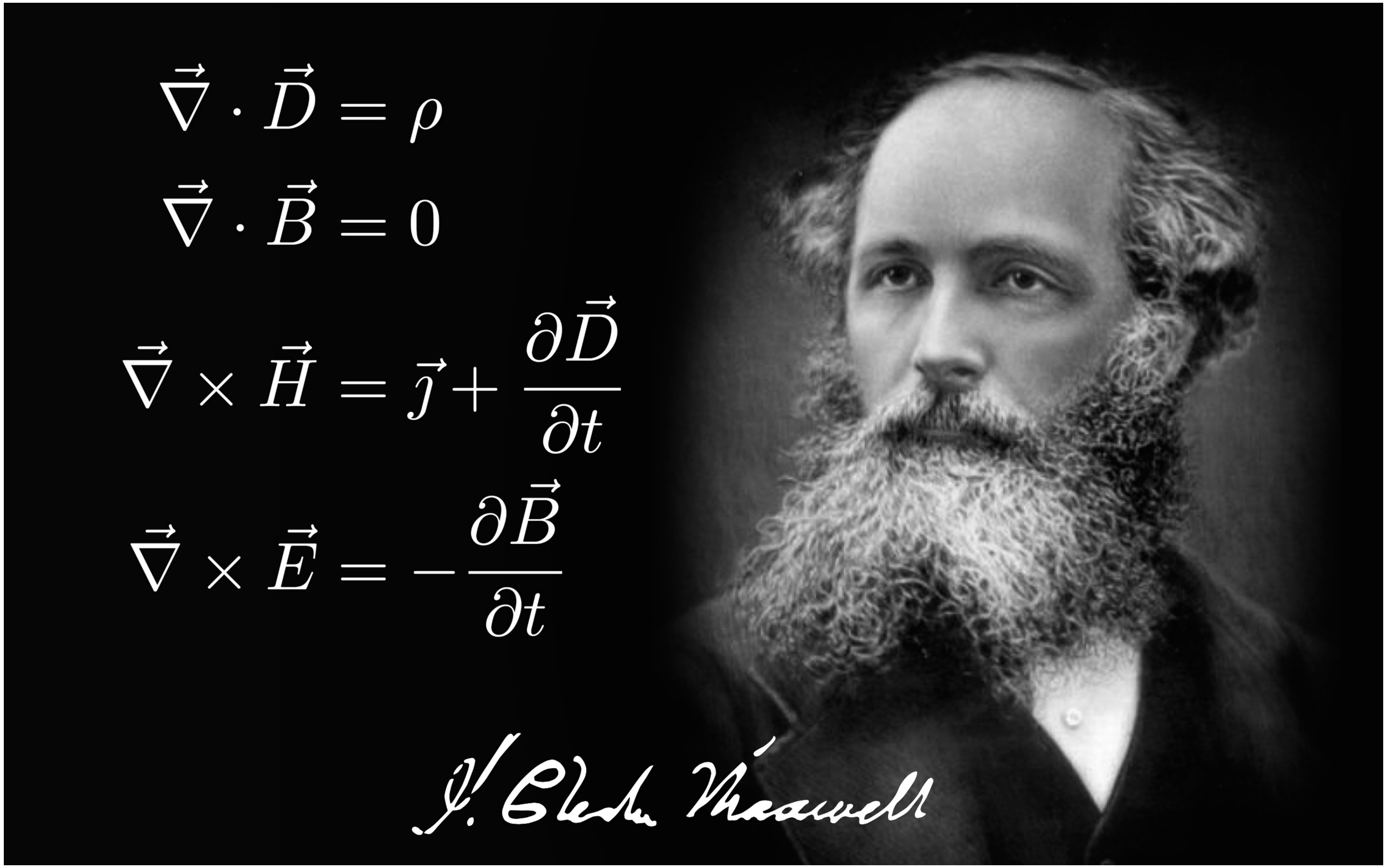


Main focus: Discoveries, inventions, and understanding on the path to gravitational-wave detection from the ground

- Why so long from field equations to detections?
- Why is it hard? EM vs GR
- 4 themes - key milestones:
  - Theory (aka mathematical relativity)
  - Simulation (aka numerical relativity)
  - Relativistic astrophysics
  - Experiment: instruments, data analysis
- Convergence: GW150914

General Relativity and Gravitation: a Centennial Perspective, ed. by A. Ashtekar et al, Cambridge U Press (2015), Intro. to Part 2

The E&M analog:

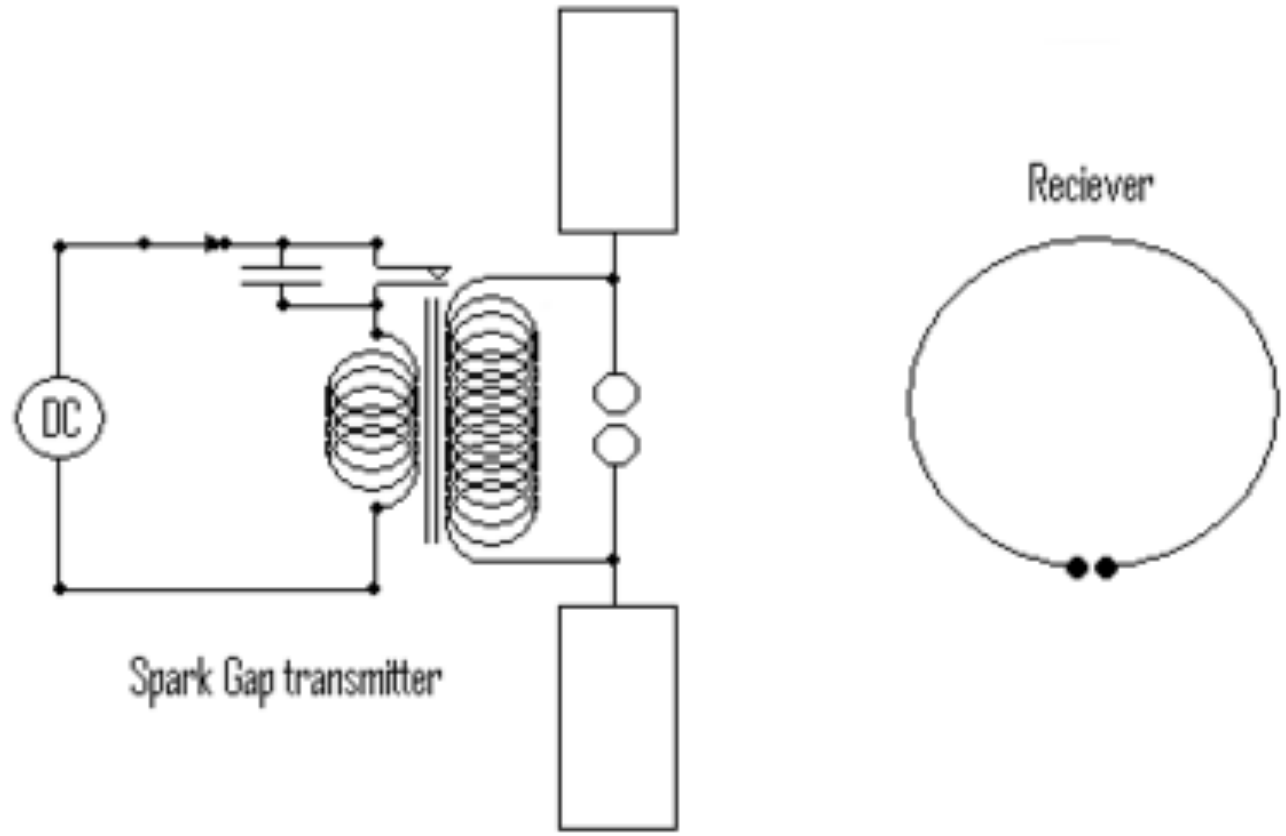


Field equations published in 1865

James Clerk Maxwell, "A Dynamical Theory of the Electromagnetic Field", *Philosophical Transactions of the Royal Society of London* **155**, 459–512 (1865).

The E&M analog:

Hertz experiment performed in 1887

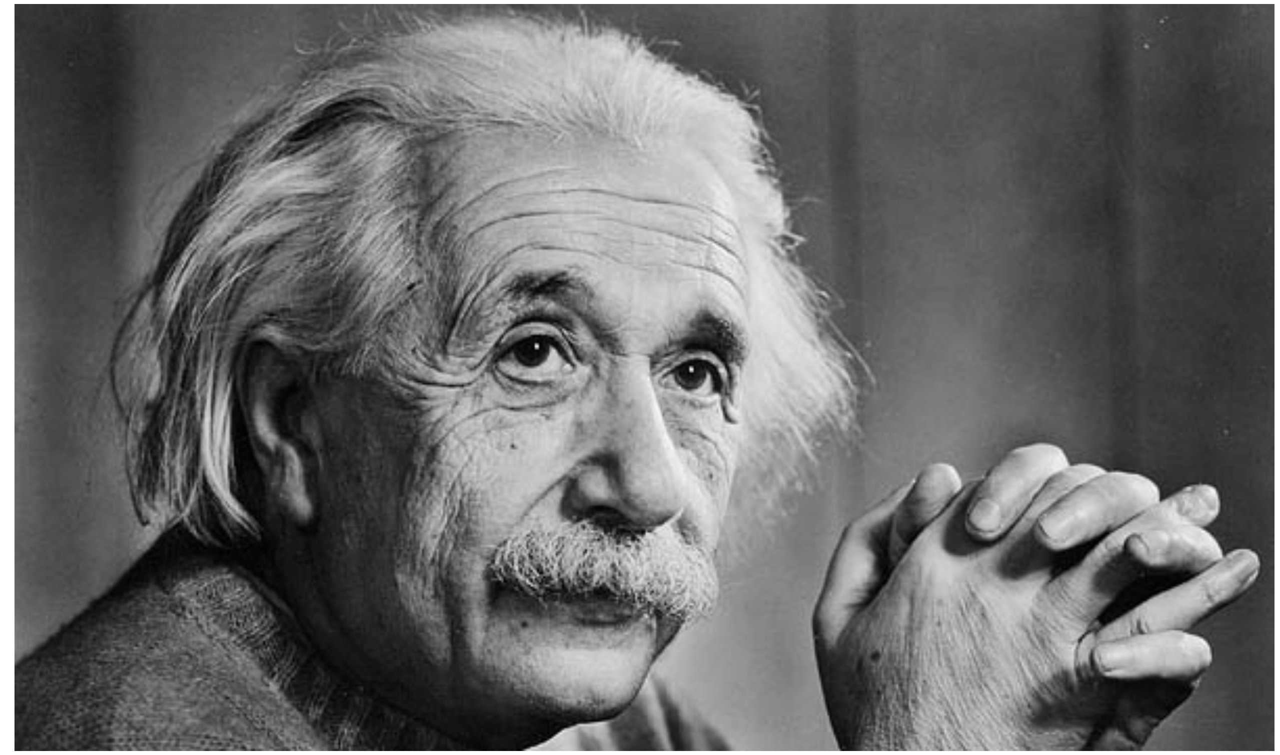


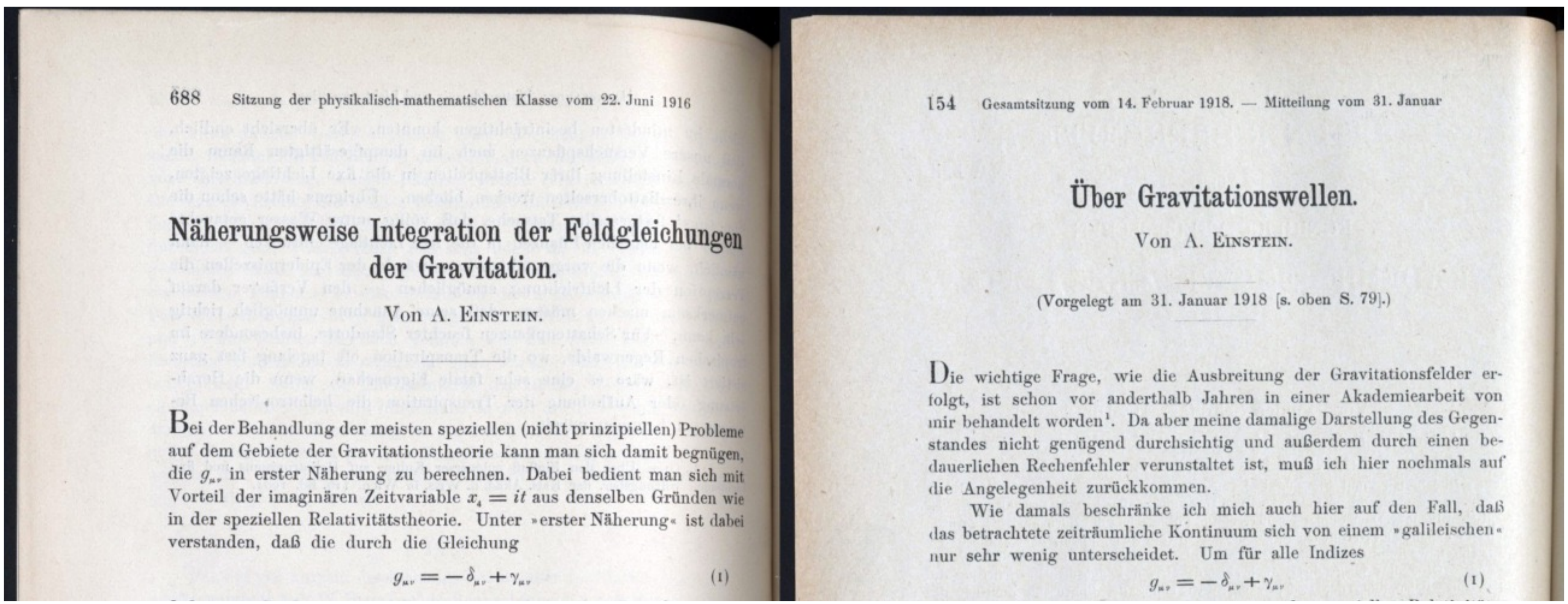
Control EM fields to generate waves and then detect them.

Heinrich Hertz (1893). *Electric Waves: Being Researches on the Propagation of Electric Action with Finite Velocity Through Space*. Dover Publications. ISBN 1-4297-4036-1. English translation

Field equations presented in 1915

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$





688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

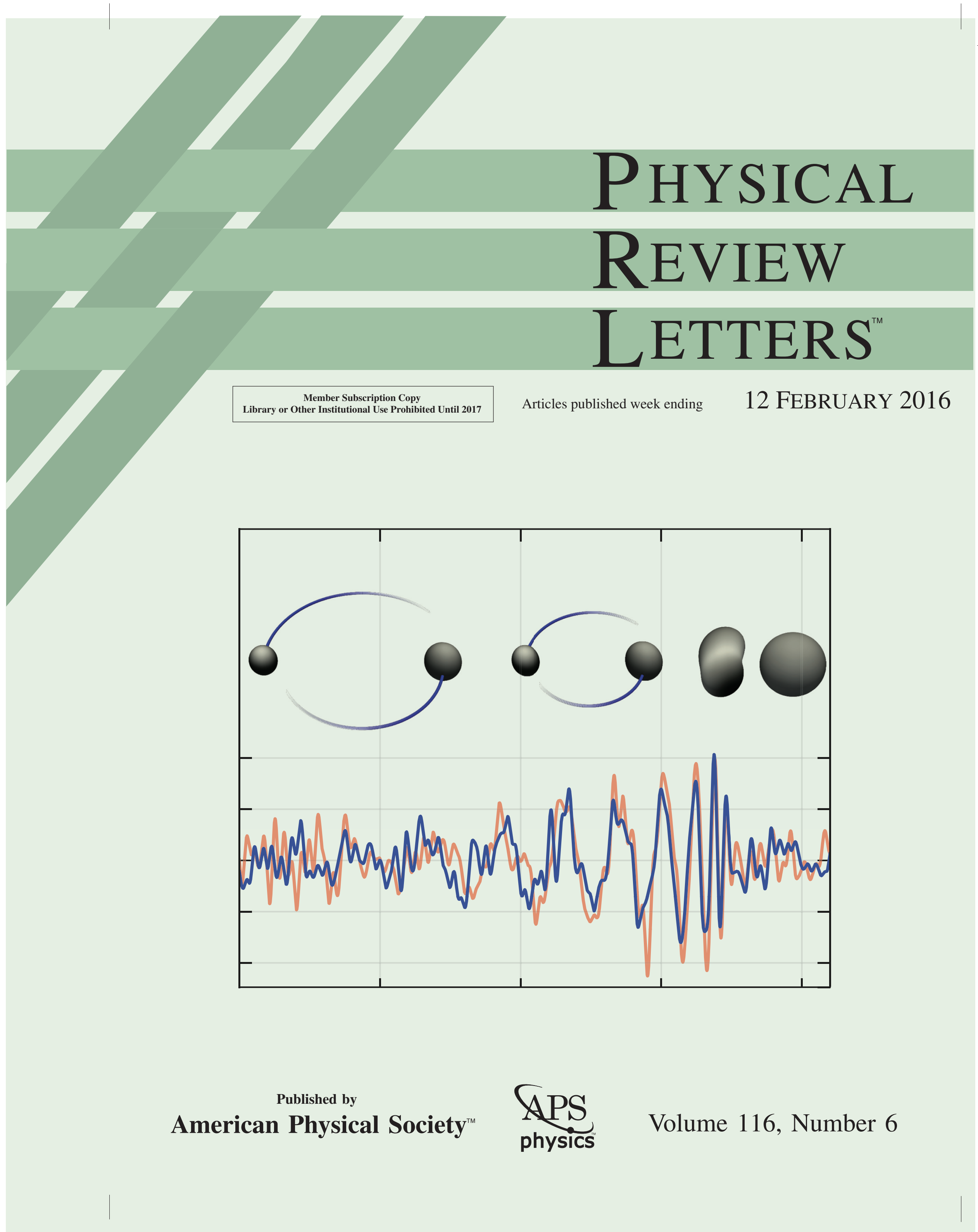
Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

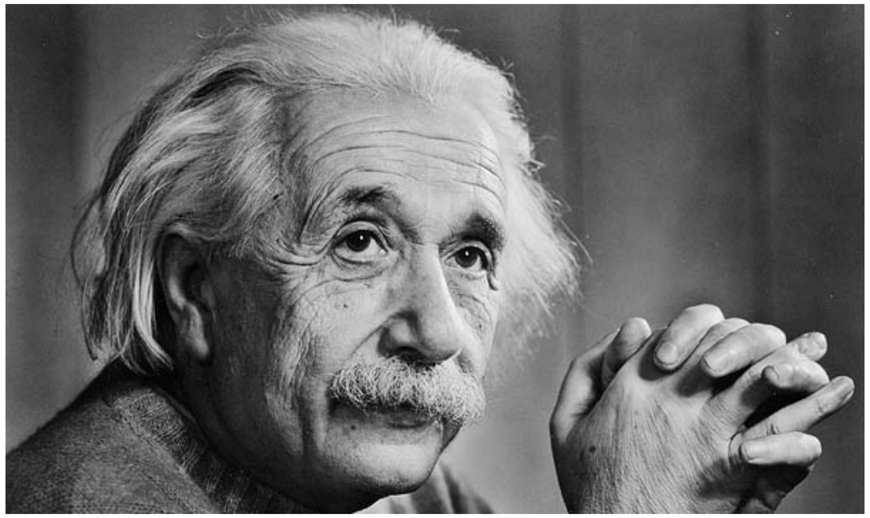


LIGO detection published in 2016 - detected in 2015

EM	GR
Equations, waves well understood	1st geometric theory, not well understood
Fixed background spacetime	GR provides the spacetime
Detectable laboratory sources	Lab sources **not** detectable
Strong signals easy to detect	Incredibly weak signals
Room sized experiment	Require kilometer-scale instruments
Cheap	Big science, big bucks
1 author	1000 authors
22 years	100 years

1915 – 1918

Linearized GR: gravitational waves



Einstein, A. 1916. Annalen der Physik, 49, 769–823; 1918. Sitzungsber. Preuss. Akad. Wiss., 154.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

spacetime metric   flat metric   perturbation

$$\Box_\eta \bar{h}_{\mu\nu} = 0$$ in vacuum

flat spacetime wave operator

$$\bar{h}_{\mu\nu} = A\epsilon_{\mu\nu} \exp(ik^\rho x_\rho)$$

Linearized GR: gravitational waves BUT

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$R_{\mu\nu} = \frac{1}{2}\left(h^{\alpha}_{\mu,\nu\alpha} + h^{\alpha}_{\nu,\mu\alpha} - h_{\mu\nu,}{}^{\alpha}{}_{\alpha} - h^{\alpha}_{\alpha}{}_{,\mu\nu}\right)$$

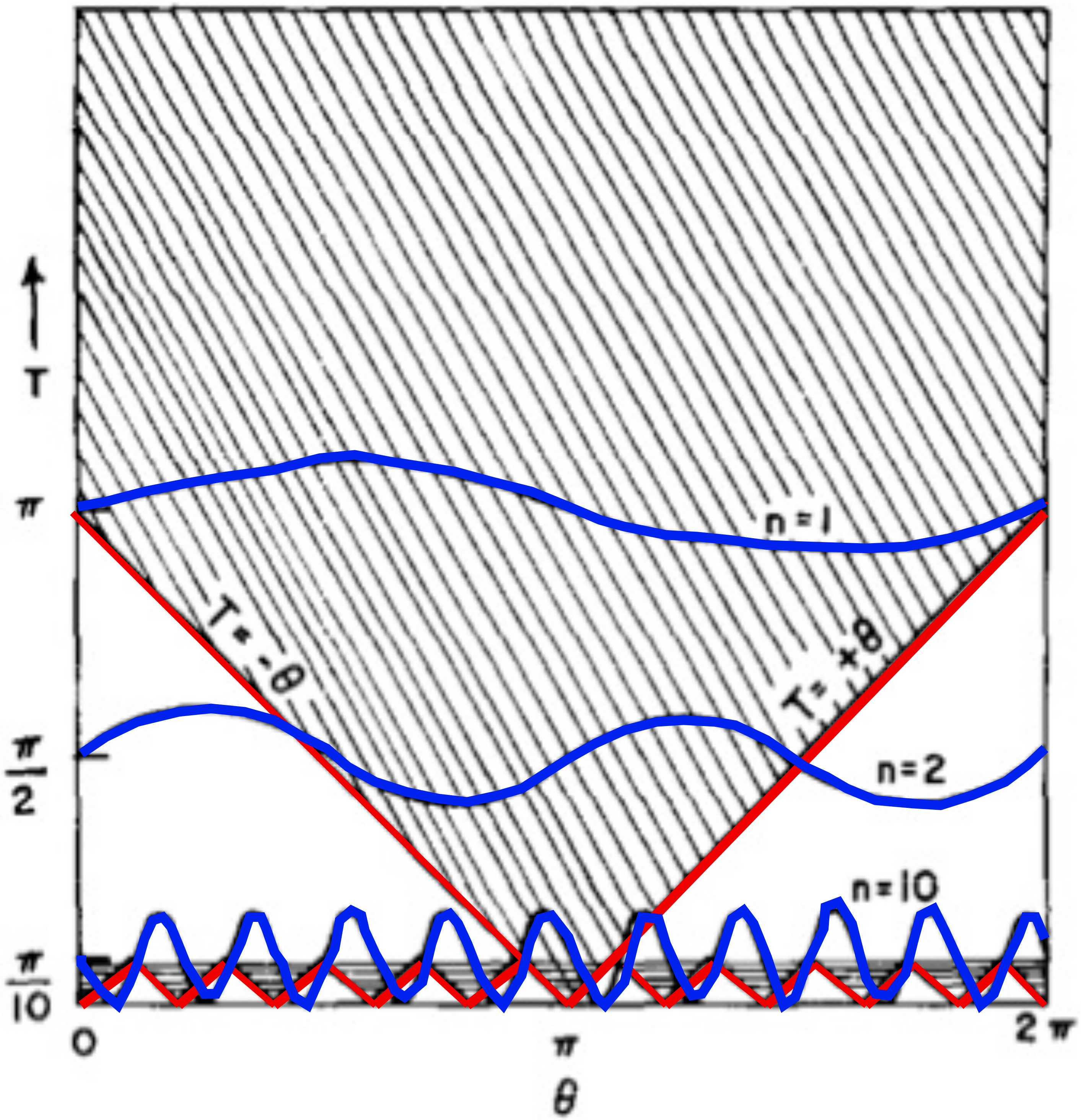
$$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h^{\alpha}_{\alpha}$$

Impose Lorentz gauge: $\bar{h}^{\mu\alpha}{}_{,\alpha} = 0$

$$\Box_{\eta}\, \bar{h}_{\mu\nu} = 0$$

Are gravitational waves physical?

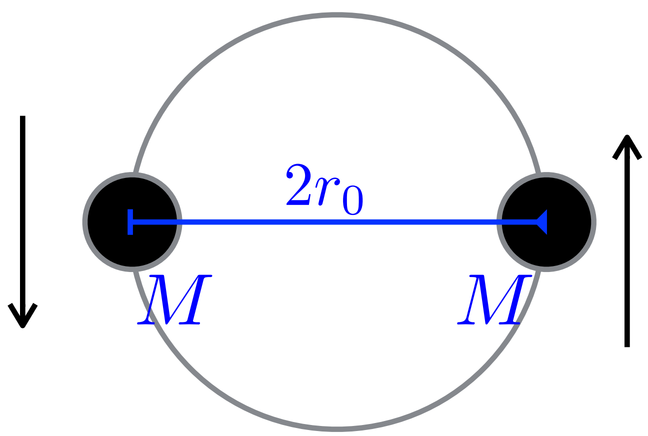
Another issue when the linear approximation is not appropriate? How does one separate waves from background?



B.K.B., Ph.D. thesis, 1972

Linearized GR: gravitational wave sources

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$



reduced moment of inertia at retarded time

$$\bar{h}_{\mu\nu} = \frac{2G}{rc^4} \left(\ddot{\mathcal{I}}_{\mu\nu} \right)_{\mathrm{ret}}$$

distance to detector

$$\mathcal{I}_{xx} = 2Mr_0^2 \left(\cos^2 2\pi f_{\mathrm{orb}} t - \frac{1}{3} \right)$$

Saulson, P. 1994. Fundamentals of interferometric gravitational wave detectors. Singapore: World Scientific

$$h_{xx} = \frac{32\pi^2 G}{rc^4} M r_0^2 f_{\mathrm{orb}}^2 \cos 2(2\pi f_{\mathrm{orb}})t$$

$$\Rightarrow \qquad |h| \approx \frac{r_S^2}{r_0 r}$$

$$f_{\mathrm{orb}} = \frac{GM}{16\pi^2 r_0^3} \qquad r_S = \frac{2GM}{c^2}$$

use Newtonian treatment of orbit

Plug in the numbers: very discouraging in 1918

$$|h| \approx \frac{r_S^2}{r_0 r}$$ For $1 M_\odot$, $r_S \approx 3\,\mathrm{km}$

$$r_0 \approx 1\,\mathrm{AU} \approx 1.5 \times 10^8\,\mathrm{km}$$

Binary stars $r \approx 100\,\mathrm{pc} \approx 3 \times 10^{15}\mathrm{km}$

$$|h| = \frac{\Delta L}{L} \approx 2 \times 10^{-23} \quad ; \quad f_{\mathrm{orb}} \approx 1/\mathrm{yr}$$

Binary neutron stars near merger

$$r_0 \approx 20\,\mathrm{km}$$

$$r \approx 15\,\mathrm{Mpc} \approx 4 \times 10^{20}\,\mathrm{km}$$

$$|h| \approx 10^{-21} \quad ; \quad f_{\mathrm{orb}} \approx 100\,\mathrm{Hz}$$

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Spherically symmetric, vacuum solution in GR:

$$ds^2 = -\left(1 - \frac{2GM}{c^2 r}\right) dt^2 + \frac{dr^2}{\left(1 - \frac{2GM}{c^2 r}\right)} + r^2 d\Omega^2$$

1916

Karl Schwarzschild

Reduces to Newtonian gravity for field outside mass *M* for large *r* and flat spacetime for *M = 0,*

BUT

something funny happens at $r = r_S = \dfrac{2GM}{c^2}$.

Physical implications unclear for a long time.

K. Schwarzschild (1916). Sitzungsber. Preuss. Akad. Wiss. 7: 189–196; 18: 424–434.

1918 - 1955

Not much happened

(relevant to this story).

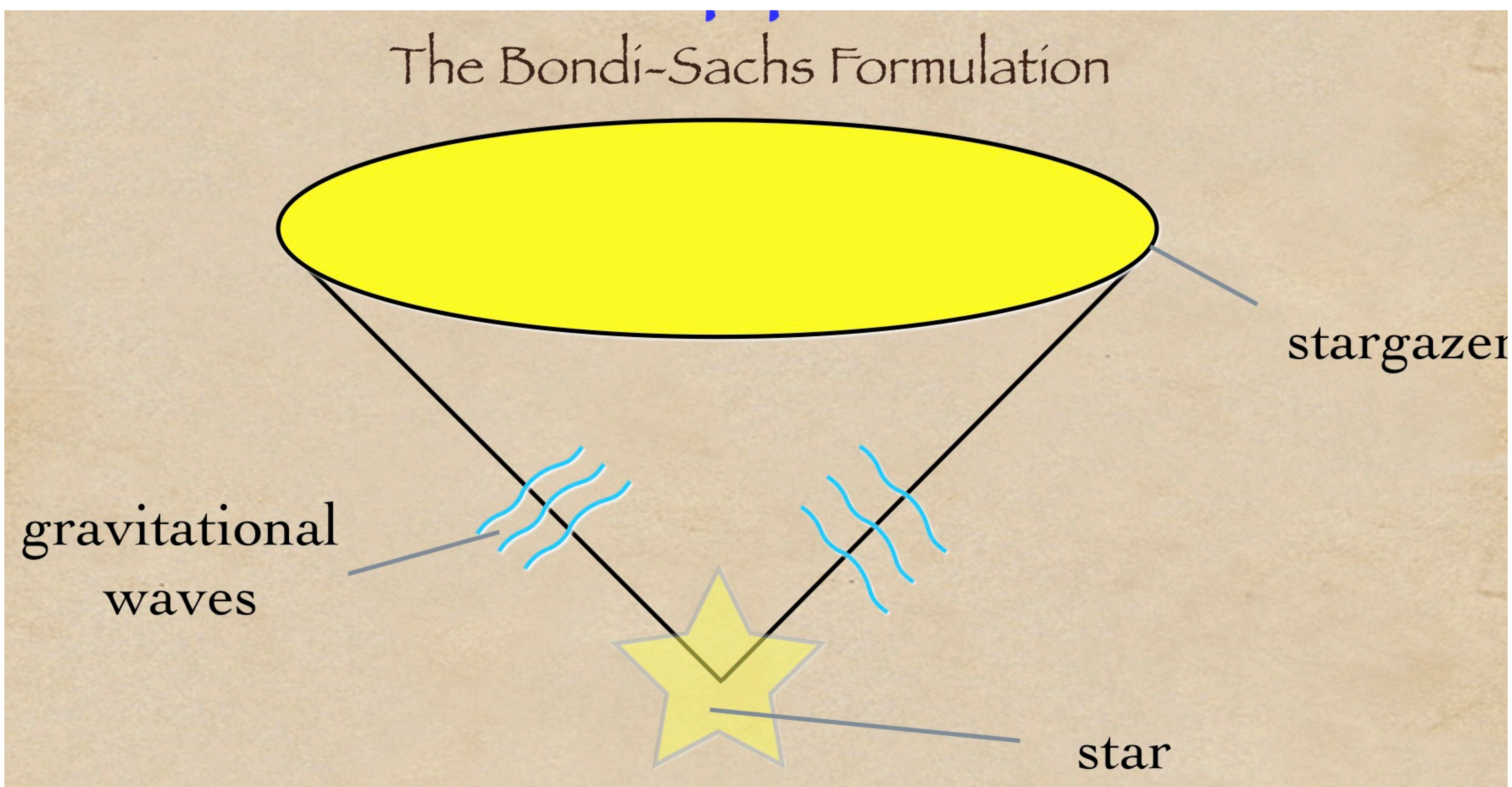
1955 - 1965

Theory

Are gravitational waves real? Do they carry energy?

1955+

Formalism was developed to identify outgoing radiation (Pirani, Bondi, Sachs, Goldberg, Newman, ...) using null coordinates (light-like trajectories) and the Weyl tensor.

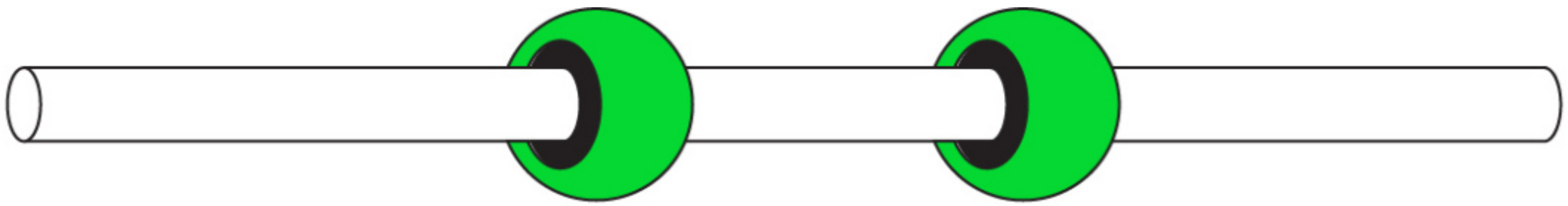


Are gravitational waves real? Do they carry energy?

Formalism was developed to identify outgoing radiation (Pirani, Bondi, Sachs, Goldberg, Newman, ...) using null coordinates (light-like trajectories) and the Weyl tensor.

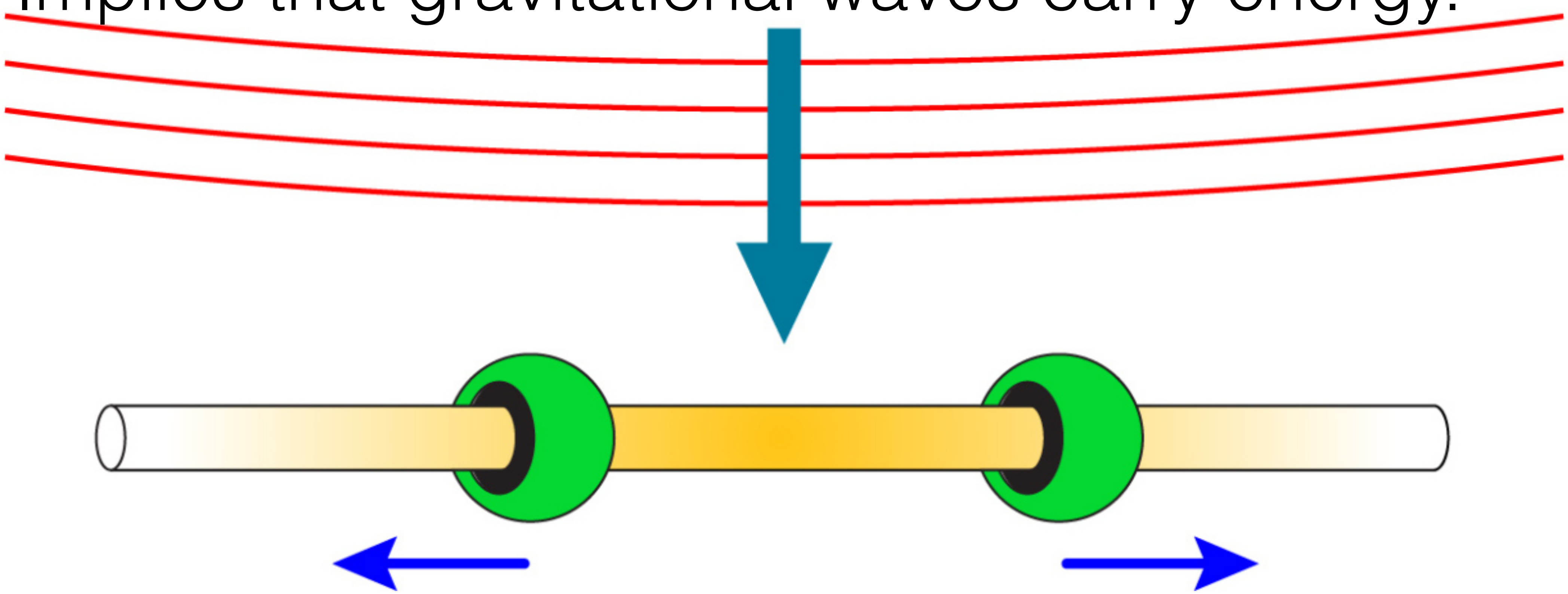
Pirani showed that gravitational waves would cause test masses to move.

Sticky bead argument in 1957 demonstrates (theoretically) physical effect of gravitational waves.



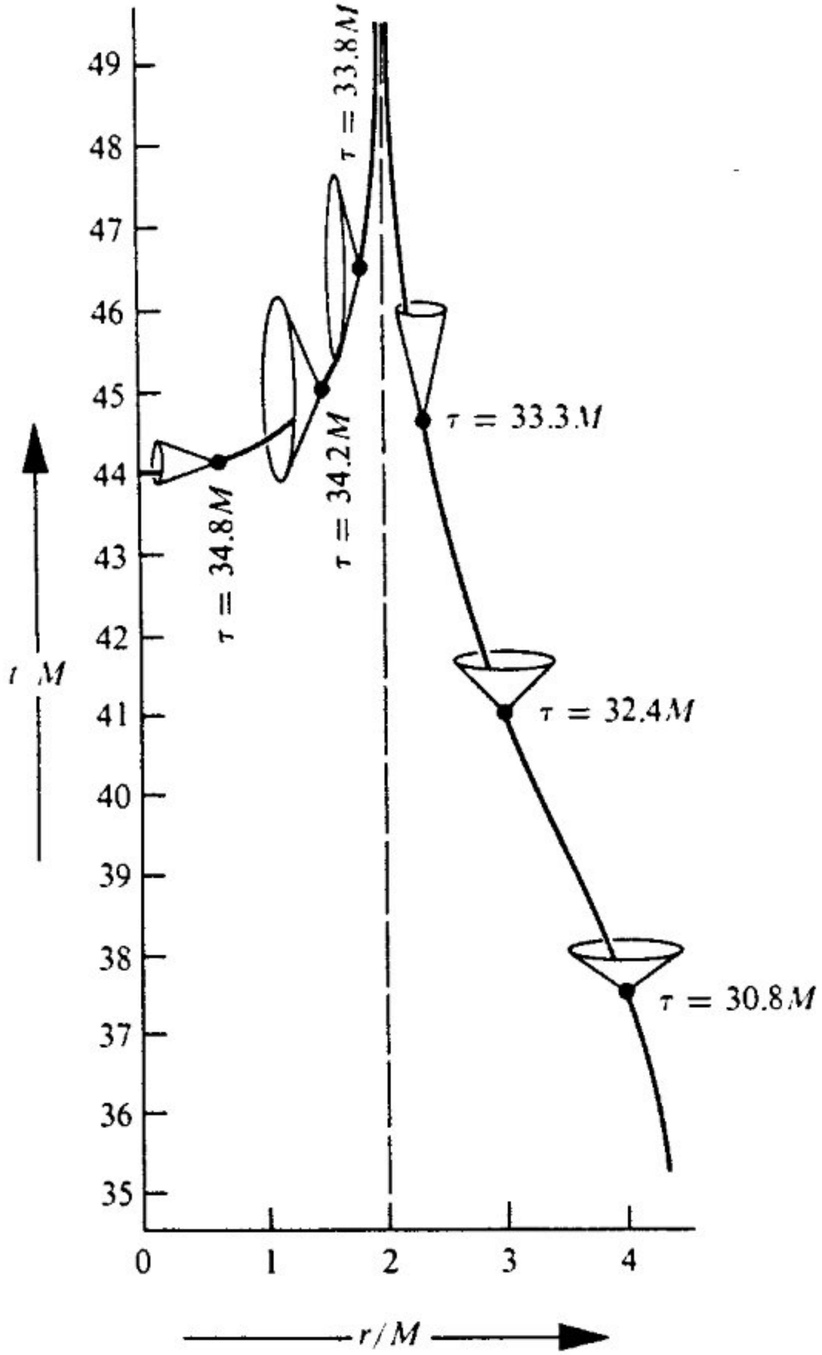
via Shane Larson's blog

Wave makes beads move but friction creates heat. Implies that gravitational waves carry energy.

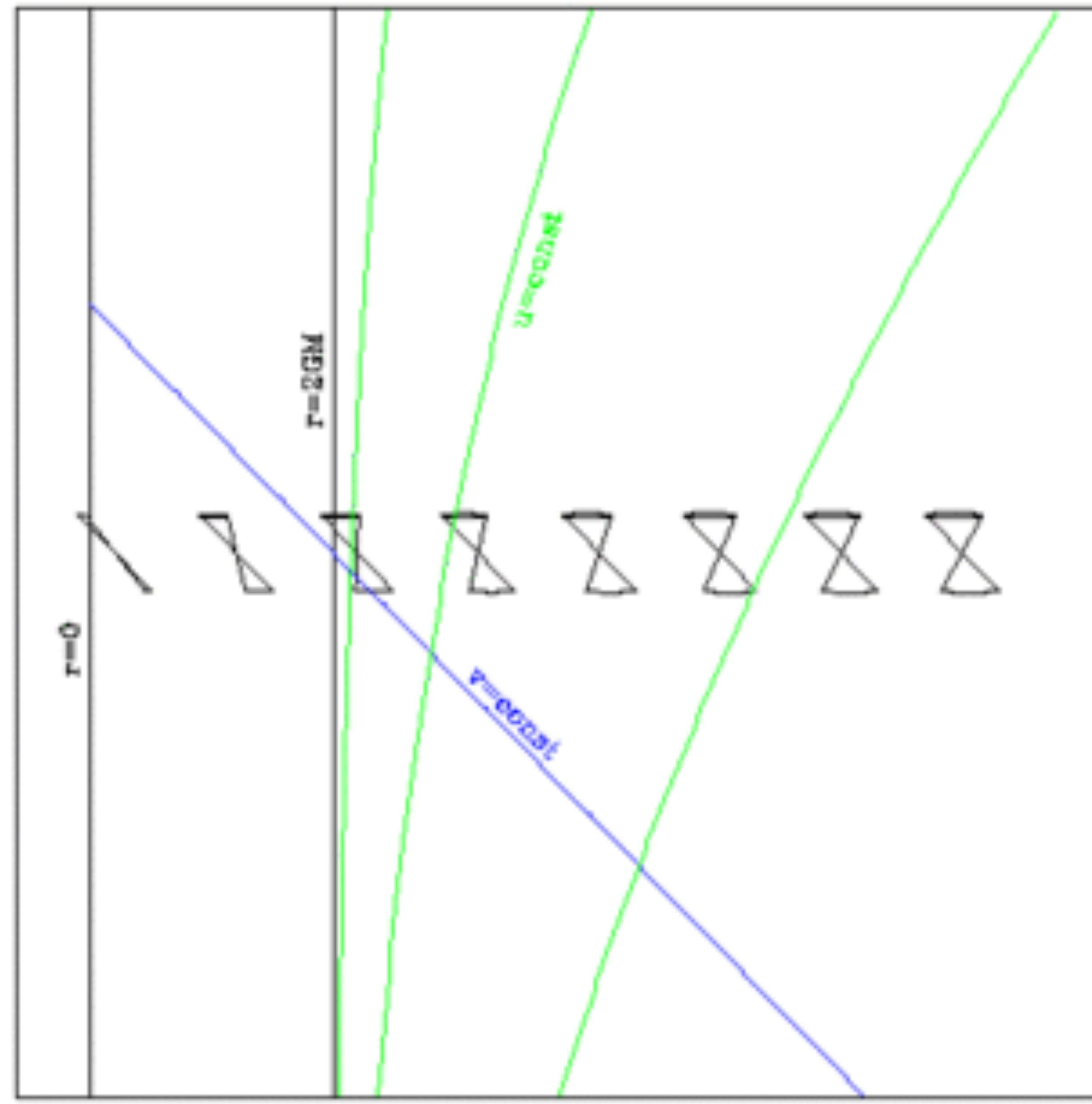


Bondi, Pirani, Robinson (1959). "Gravitational waves in General Relativity III: Exact plane waves". Proc. Roy. Soc., A 251: 519–533.

Schwarzschild solution (1916): behavior at r = 2 M not understood until about 1960, extended to rotating systems in 1963, BH candidates observed in X-rays in 1970s.



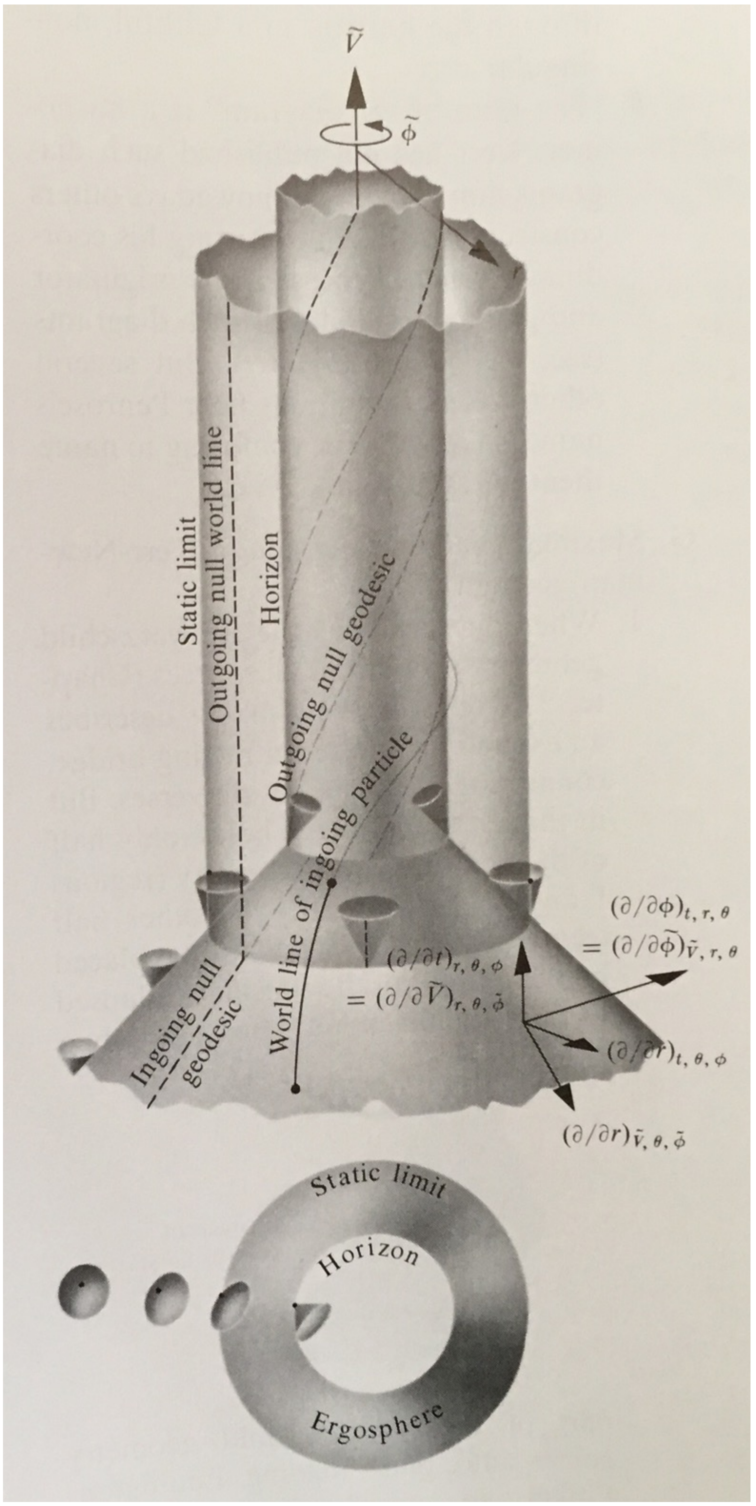
1958



Finkelstein, David (1958). "Past-Future Asymmetry of the Gravitational Field of a Point Particle". Phys. Rev 110: 965–967.

1963

Kerr finds exterior (vacuum) solution for spinning mass

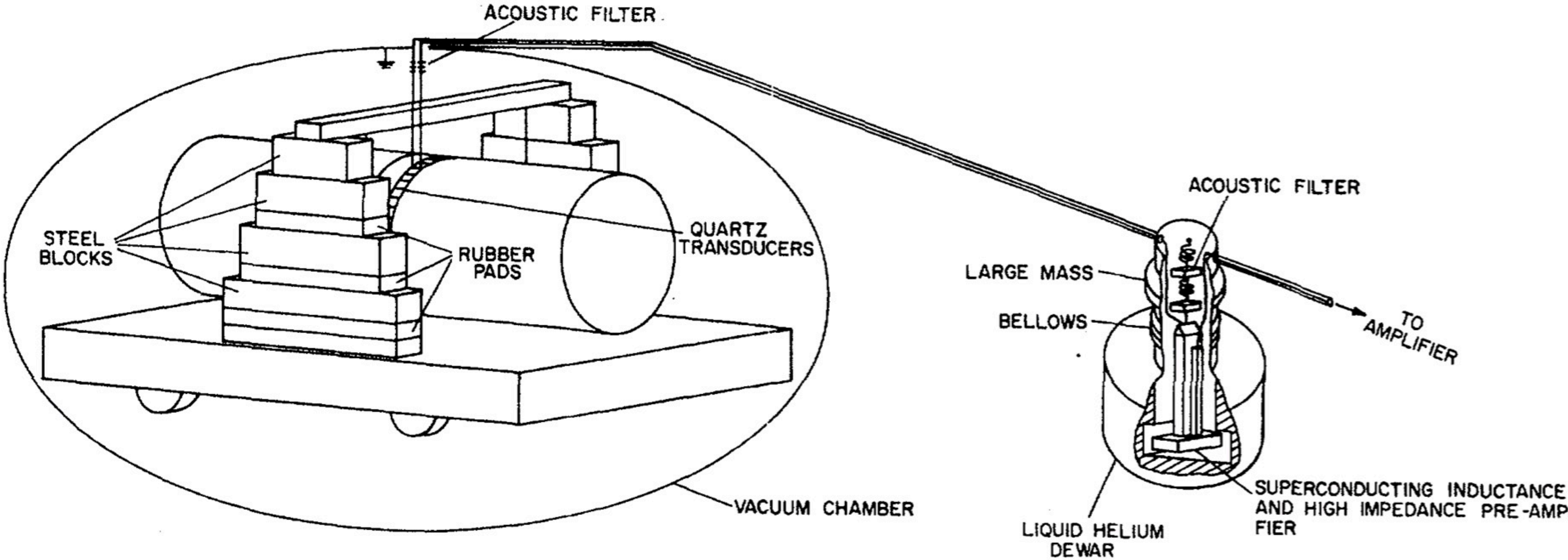


Gravitational Field of a Spinning Mass as an Example of Algebraically Special Metrics
Roy P. Kerr, Phys. Rev. Lett. 11, 237 – Published 1 September 1963

Gravitational wave detection

J. Weber, schematic of an early bar detector

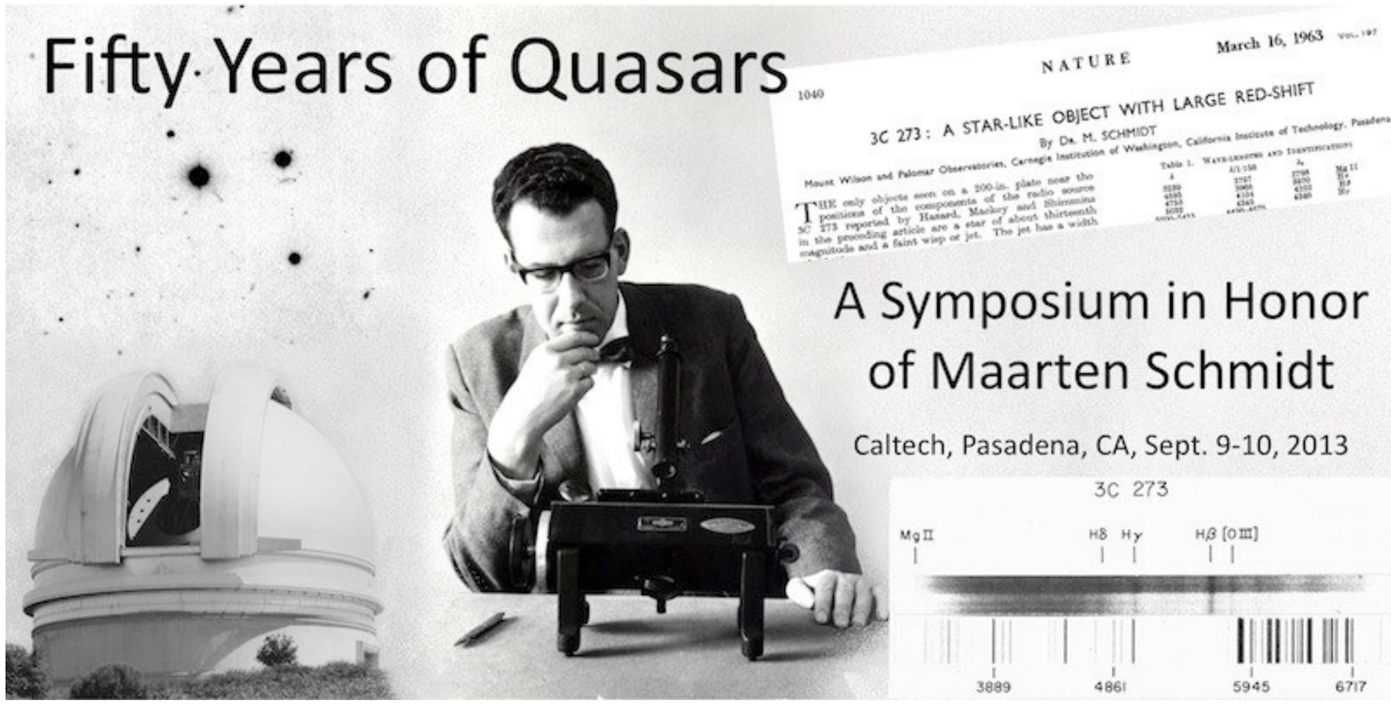
<1965



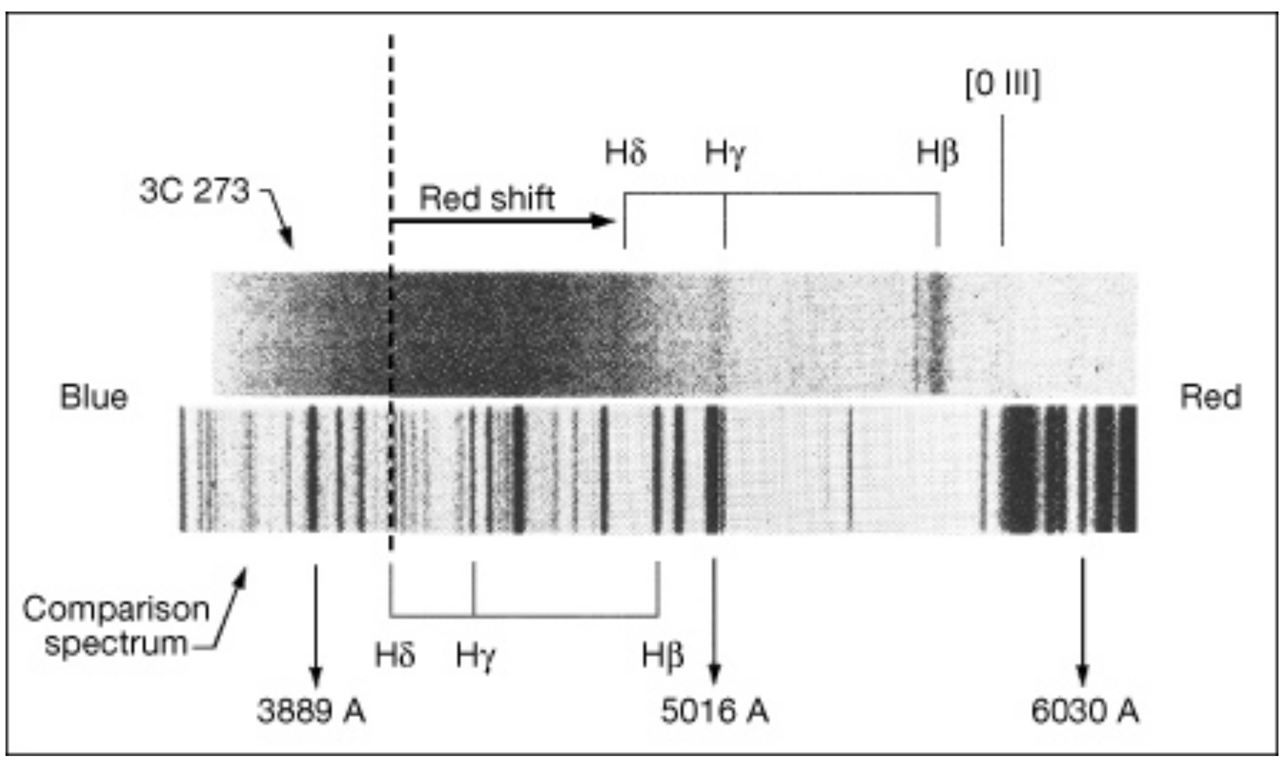
Weber, J.; and Wheeler, J.A. (1957). "Reality of the cylindrical gravitational waves of Einstein and Rosen". Rev. Mod. Phys. 29: 509–515.
Weber, J., Phys. Rev. Lett. **17**, 1228 (1966).

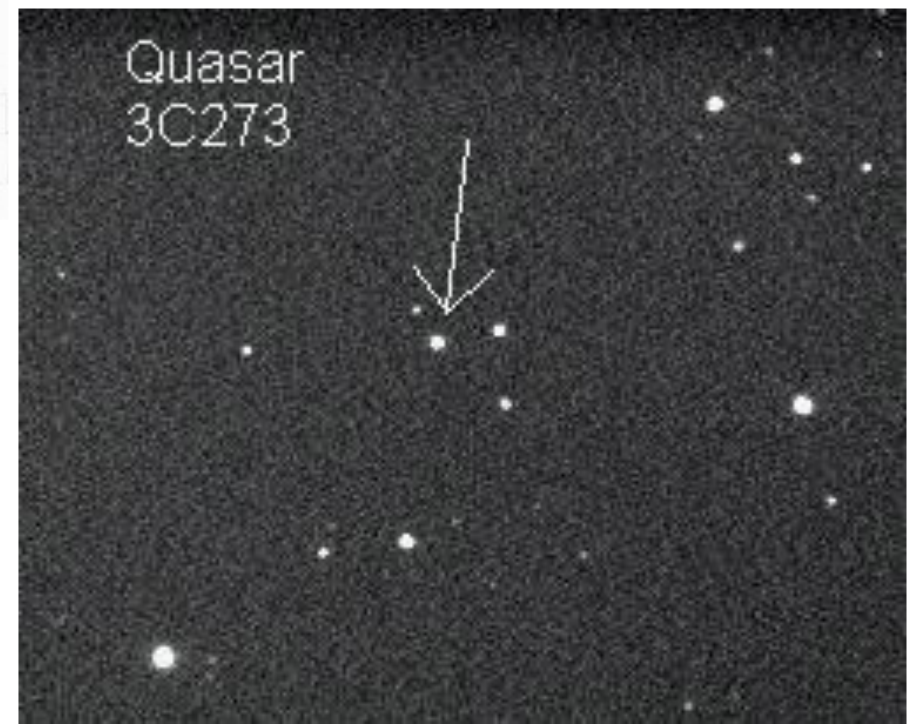
Astrophysics

1963



Quasars: stellar appearance, cosmological distance





M. Schmidt, *Nature* **197,** 1040 (1963)

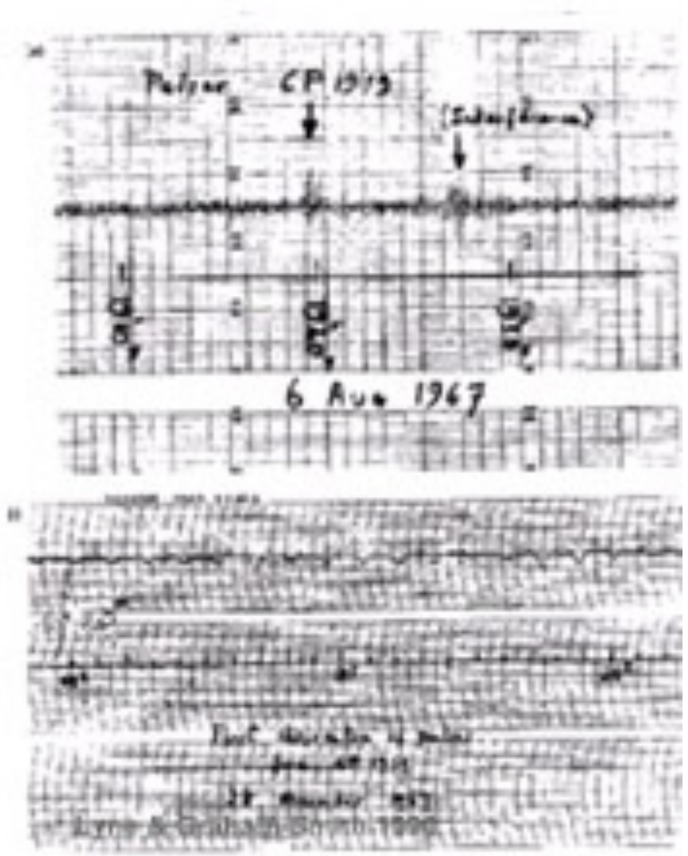
GR taken seriously as relevant to astrophysics. Black holes may exist ????

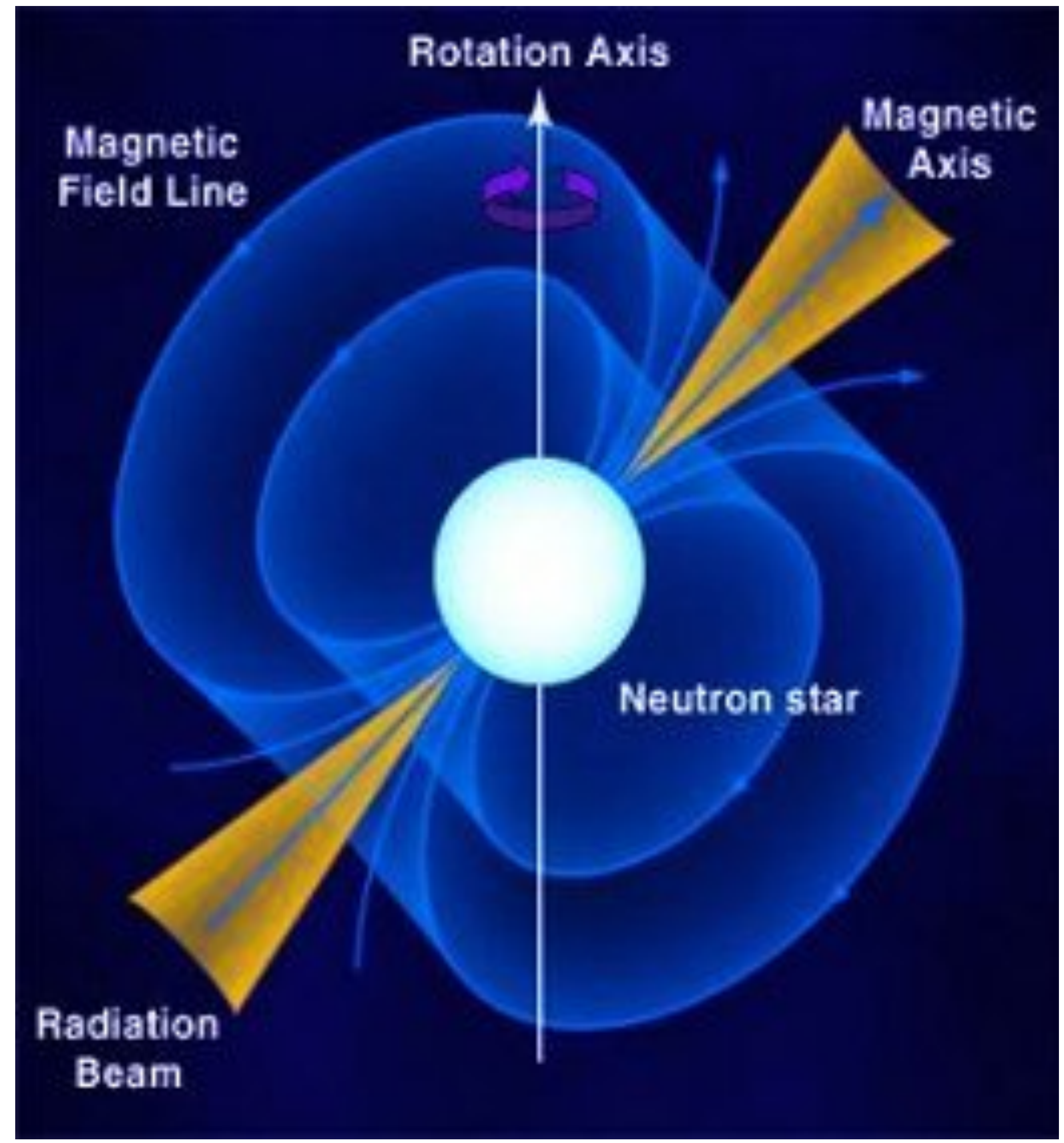
1965 - 1975

Astrophysics

Discovery of pulsars

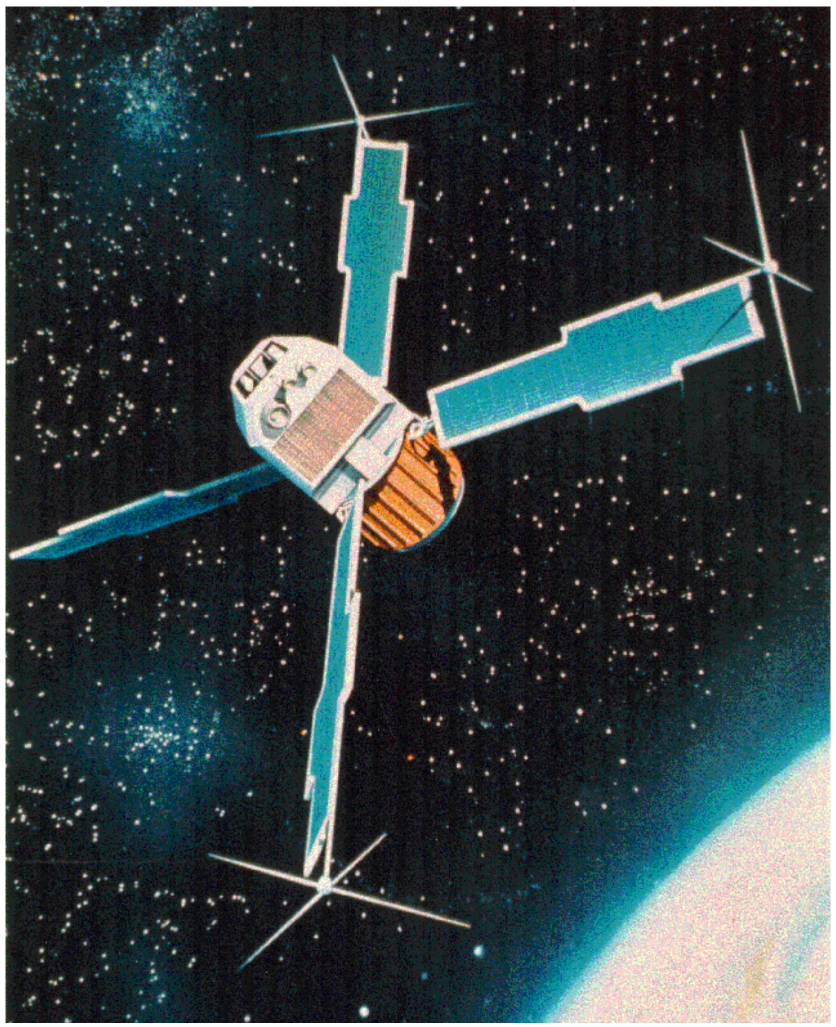
1967

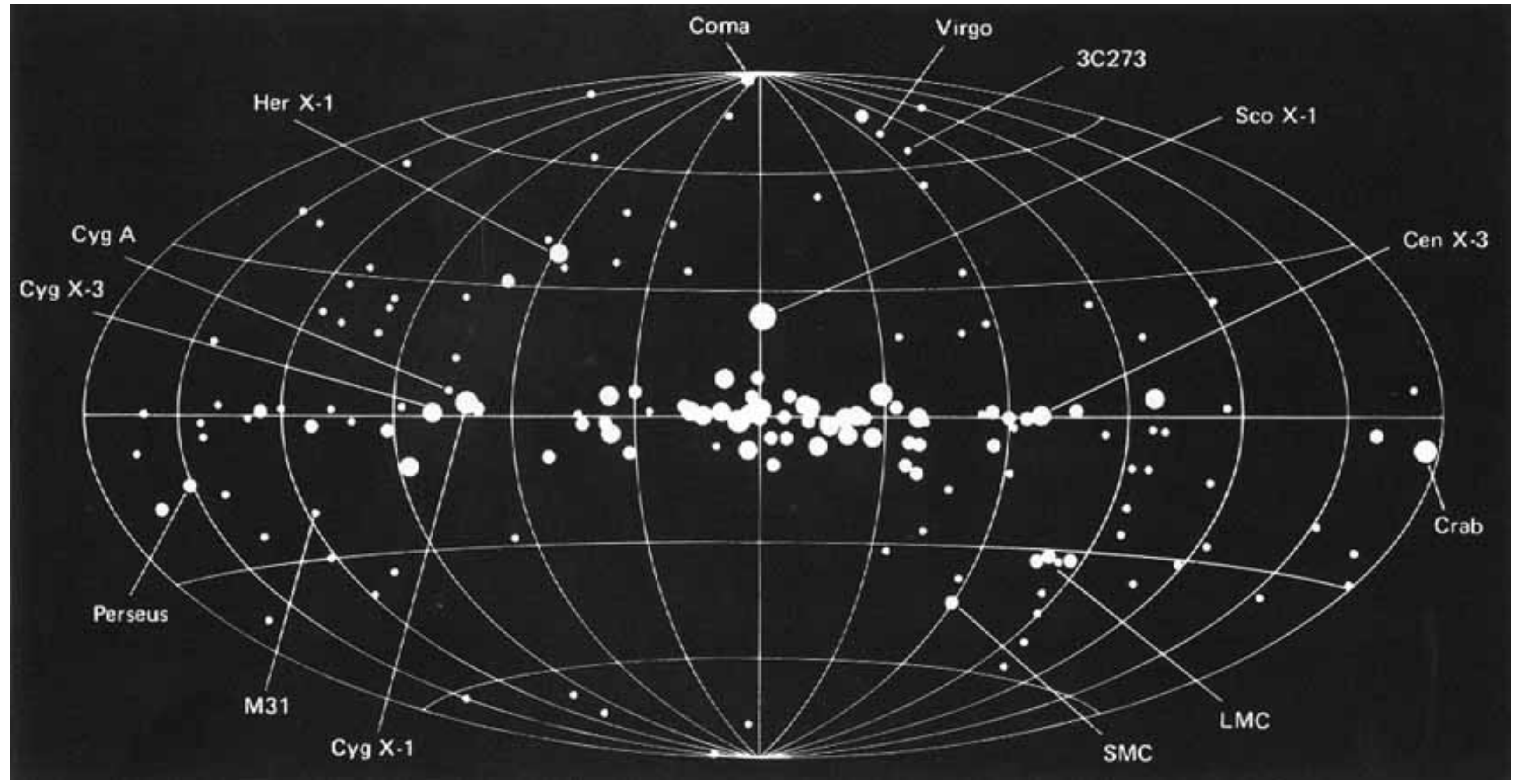


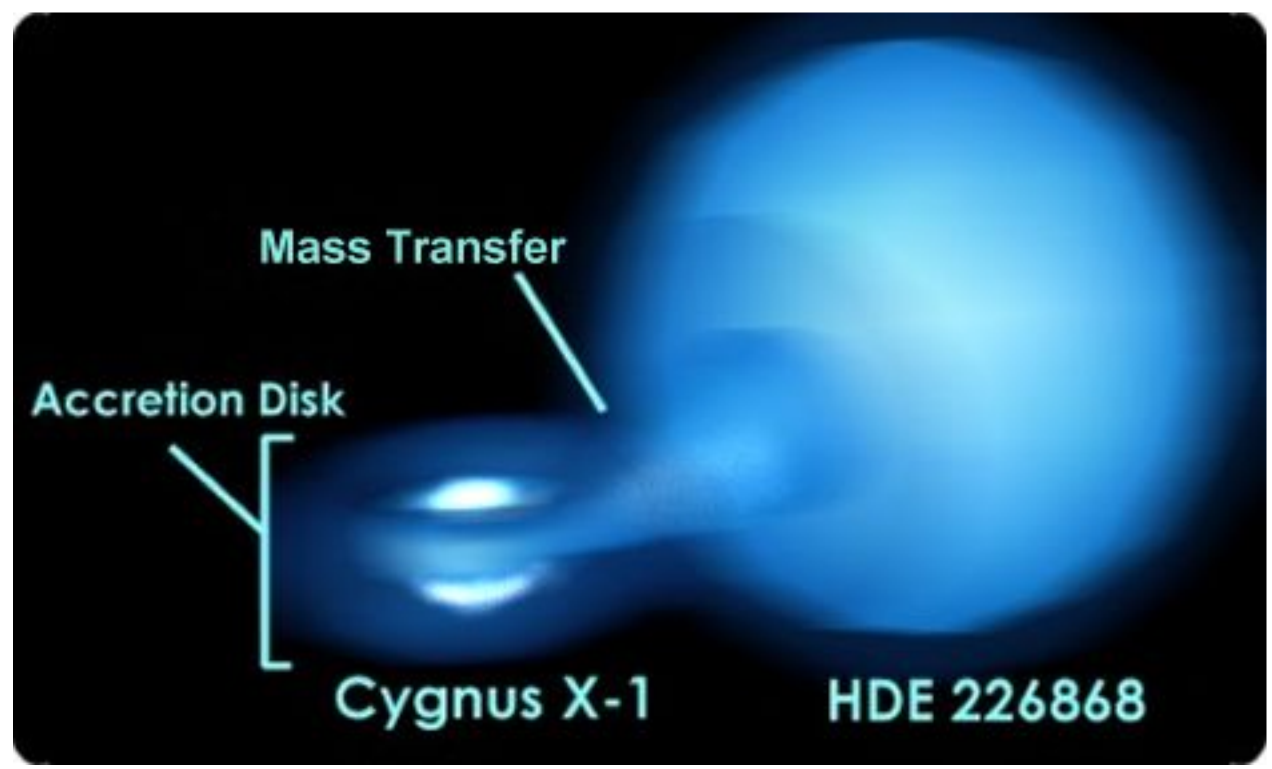


A Hewish, SJ **Bell**, JDH Pilkington, PF Scott, RA Collins - Nature **217**, 709, 1968

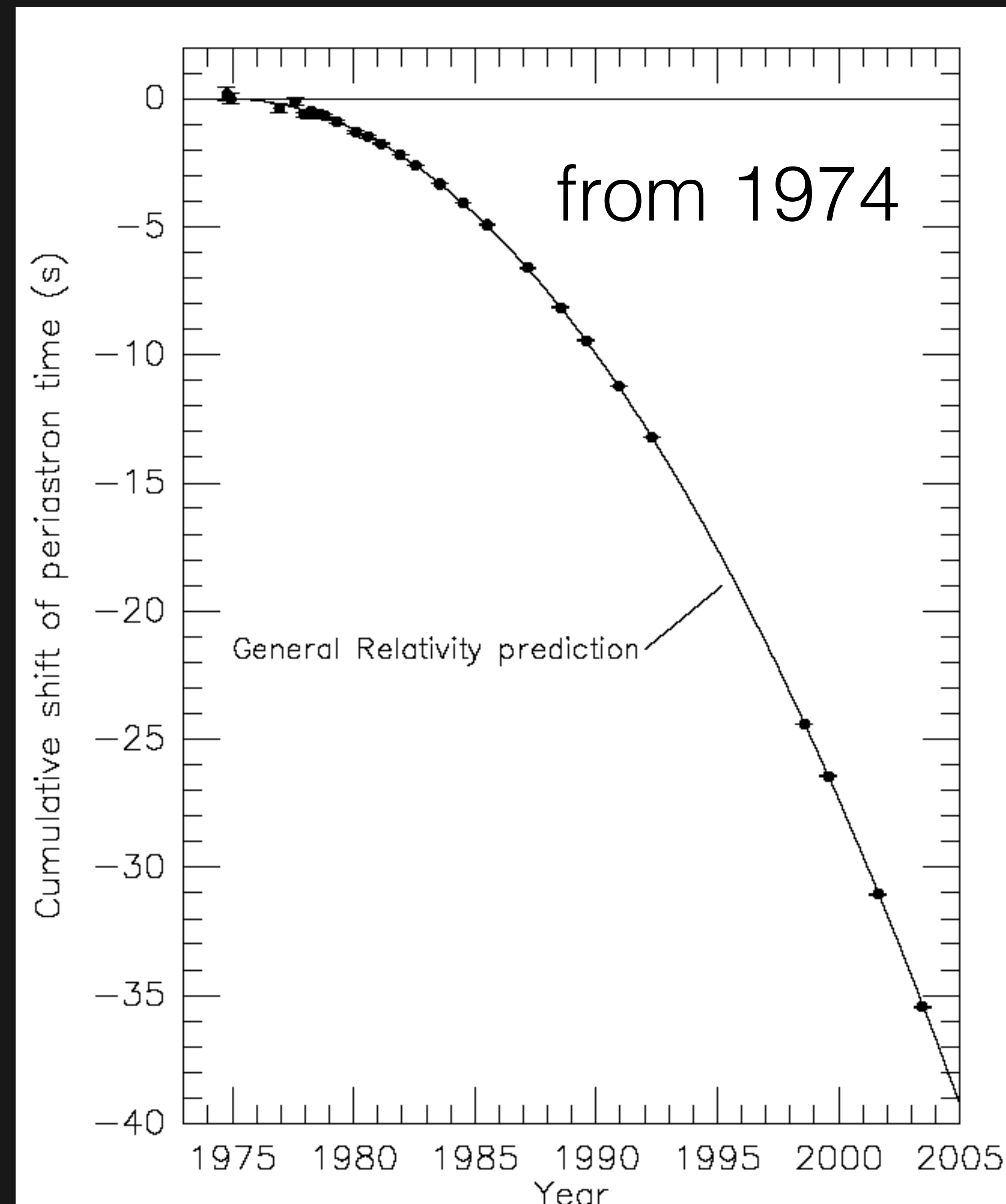
Uhuru, an X-ray satellite launched by NASA in 1970, discovered the first evidence for stellar mass black holes.

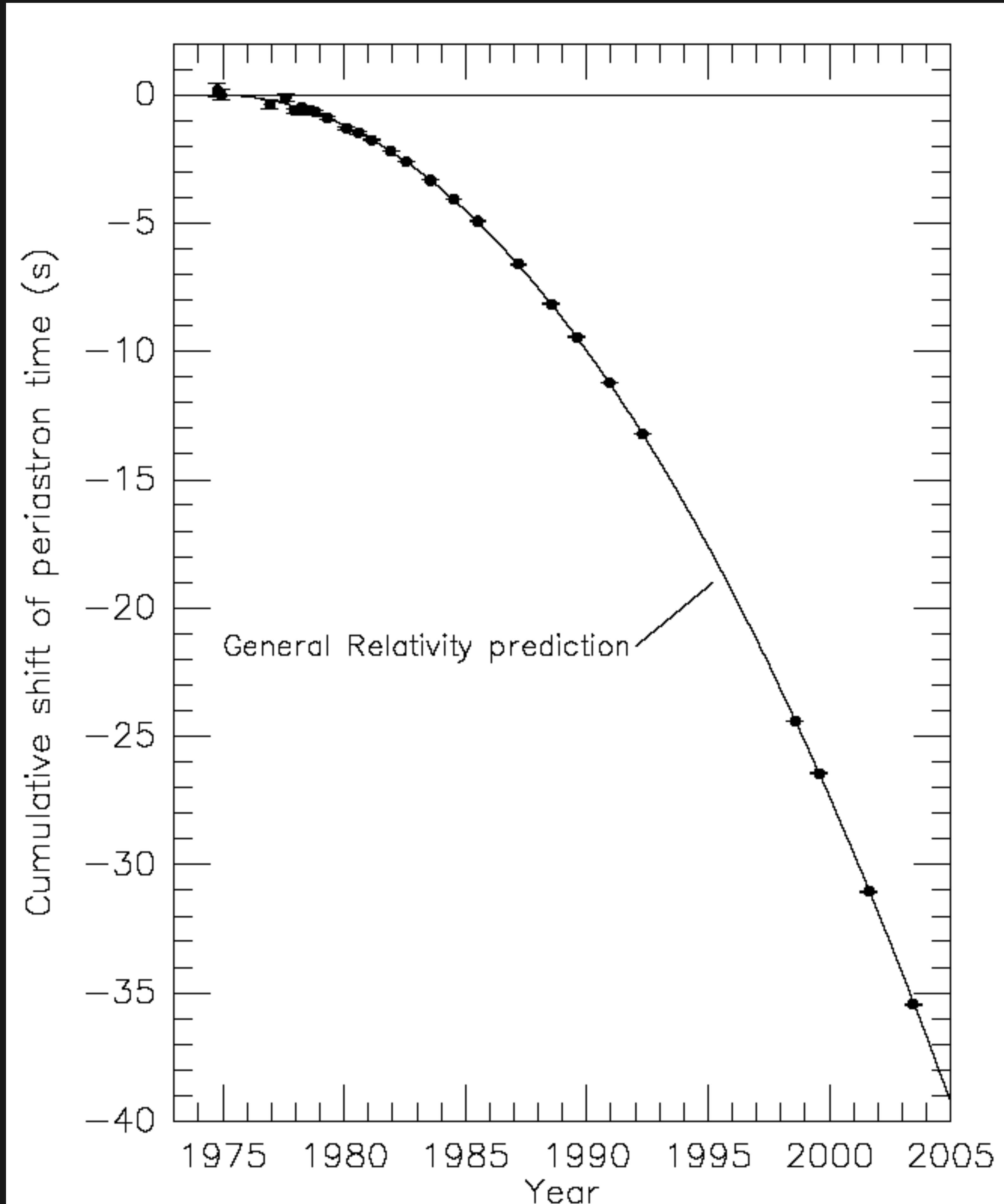






Indirect detection of gravitational waves from PSR 1913+16 leads to nobel prize for Hulse and Taylor in 1993.

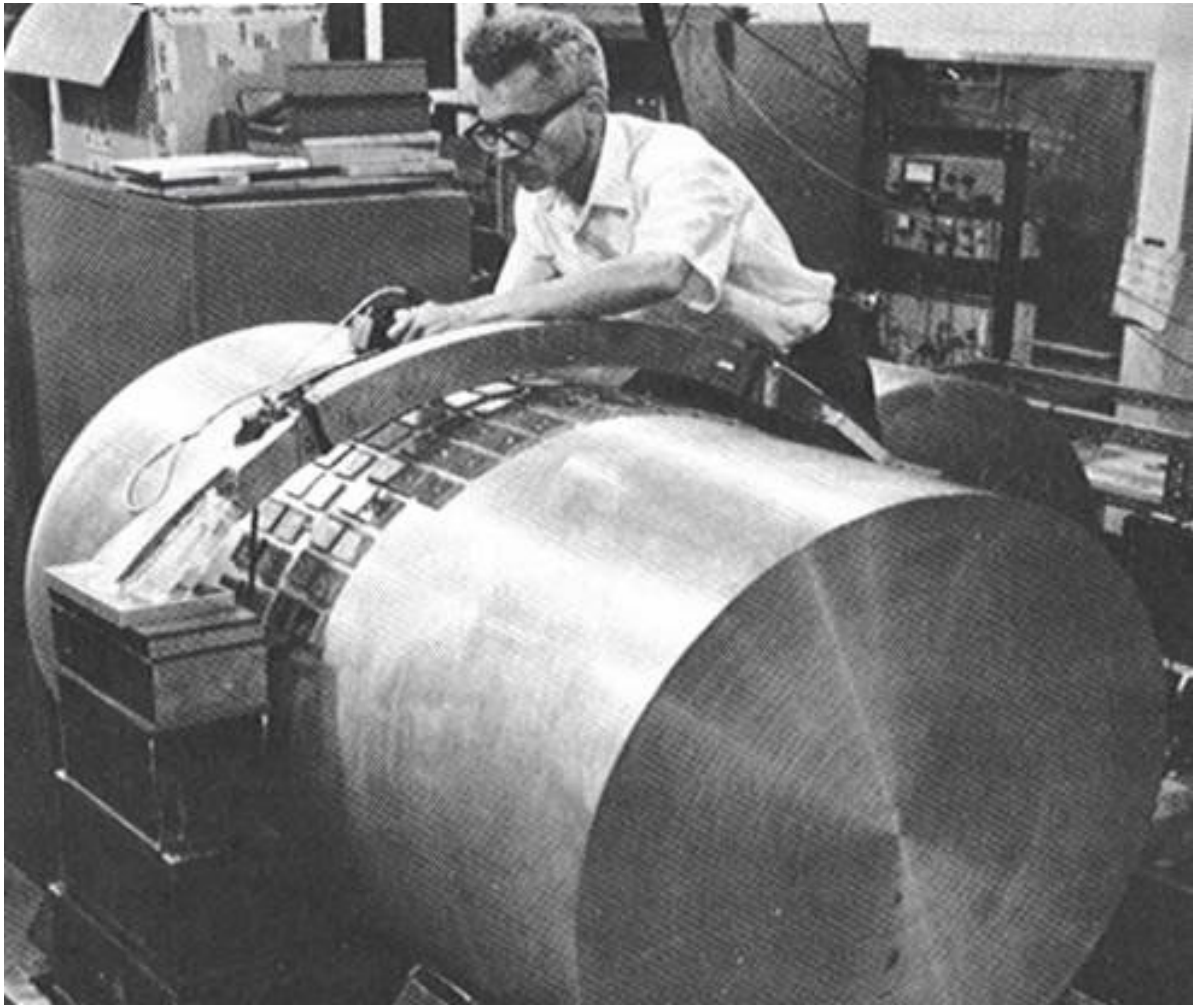




0
−5
−10
−15
−20
−25
−30
−35
−40
Cumulative shift of periastron time (s)
General Relativity prediction
1975
1980
1985
1990
1995
2000
2005
Year

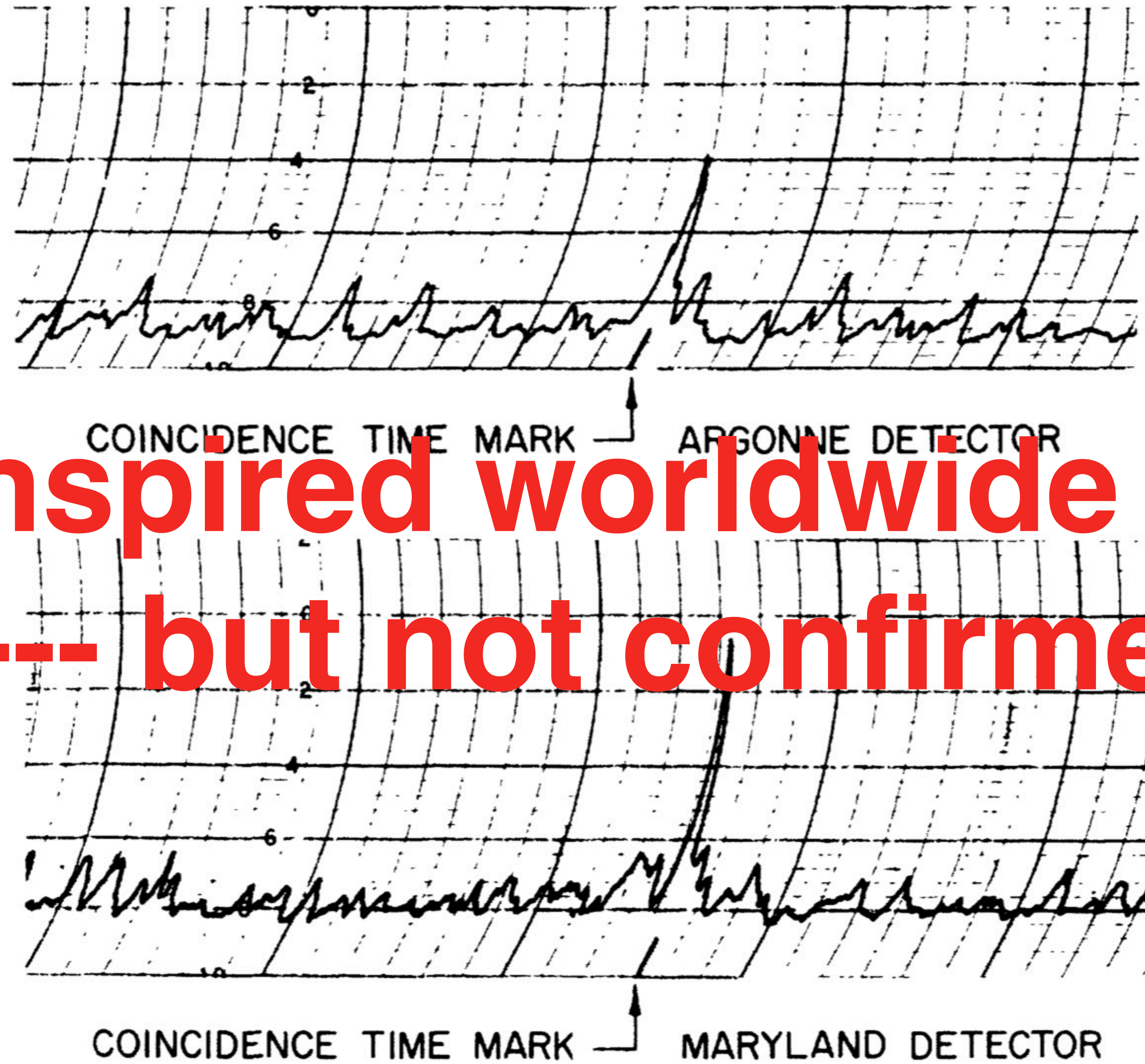
Gravitational wave detection

J. Weber with an early bar detector



Weber, J.; and Wheeler, J.A. (1957). "Reality of the cylindrical gravitational waves of Einstein and Rosen". Rev. Mod. Phys. 29 (3): 509–515.

J. Weber detection claim in 1969



Inspired worldwide effort

---- but not confirmed

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

J. Weber, Phys. Rev. Lett. 22, 1320 (1969) - Published 16 June 1969

Computer Simulation

Colliding black hole simulations: U Texas late 1960s

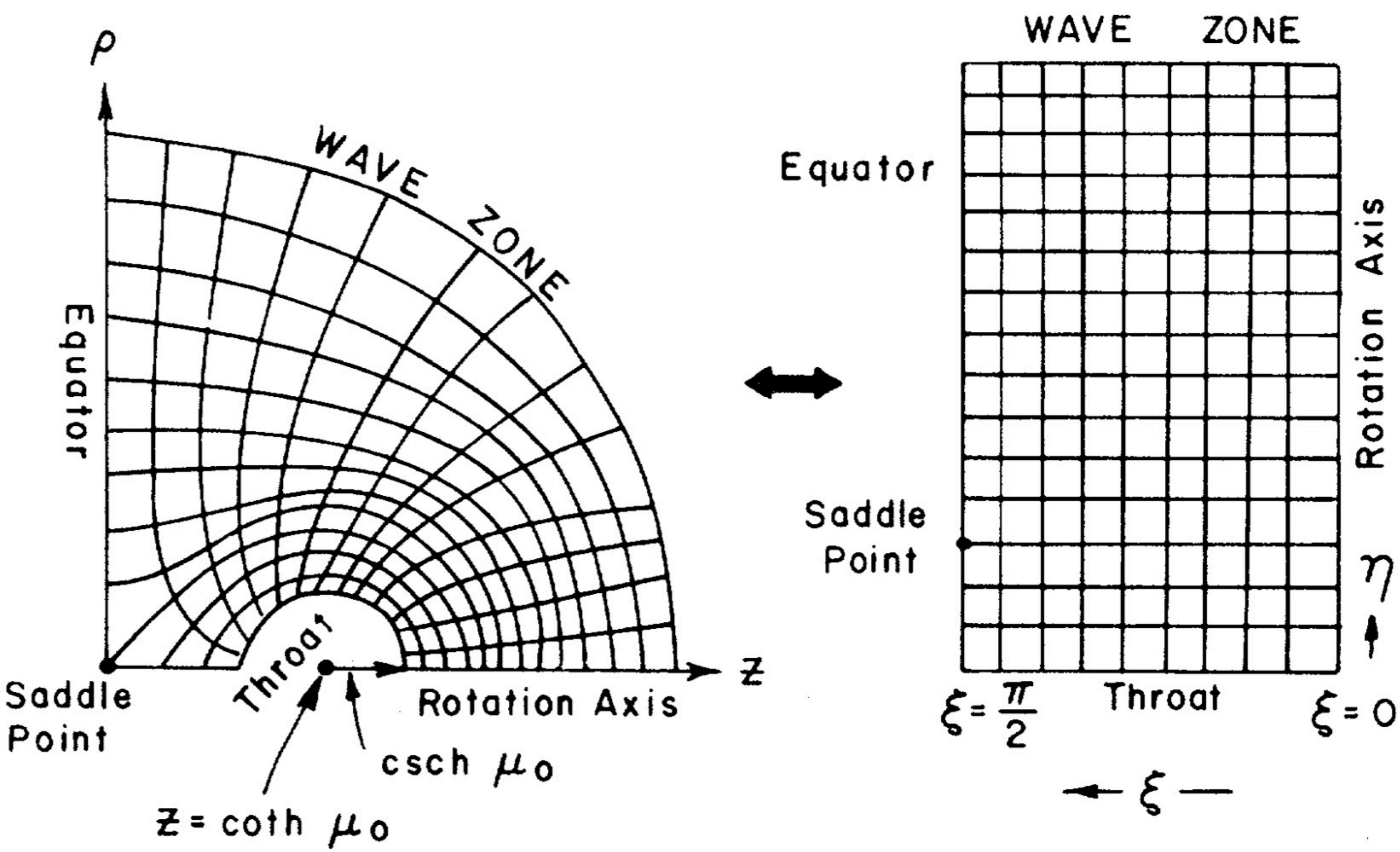


FIG 3. Schematic representation of the coordinate grid for two black holes.

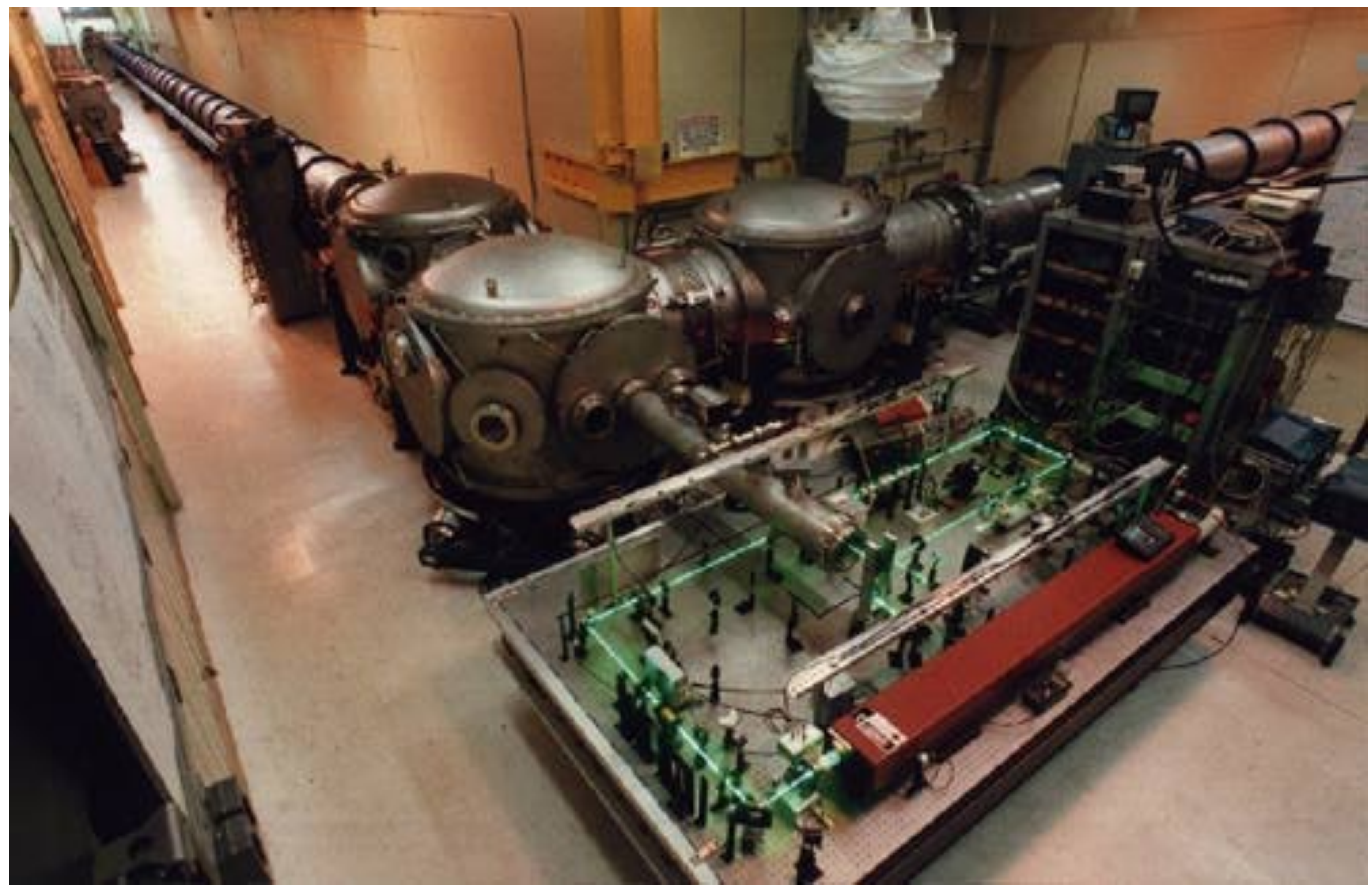
1975 - 1990

Gravitational wave detection

R. Weiss

Interferometric detectors were developed by R. Weiss and R. Drever (in the US). They are scalable and yield waveforms, h(t), rather than energy deposition.

R. Drever



40-meter prototype at Caltech

Unsung hero:

R. Isaacson (Gravitation at NSF)

Rich Isaacson was the Gravity program officer at NSF for 29 years, from 1973.

He convinced his division director and the NSF director to buy into the LIGO project.

He also ensured that early obstacles were overcome.

By the time I arrived at NSF, LIGO was operating smoothly.

R.A. Isaacson, http://ligo.org/magazine/LIGO-magazine-issue-6.pdf#page=14, http://ligo.org/magazine/LIGO-magazine-issue-8.pdf#page=34

Proposal to the National Science Foundation

1989

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY

Rochus E. Vogt
Principal Investigator and Project Director
California Institute of Technology

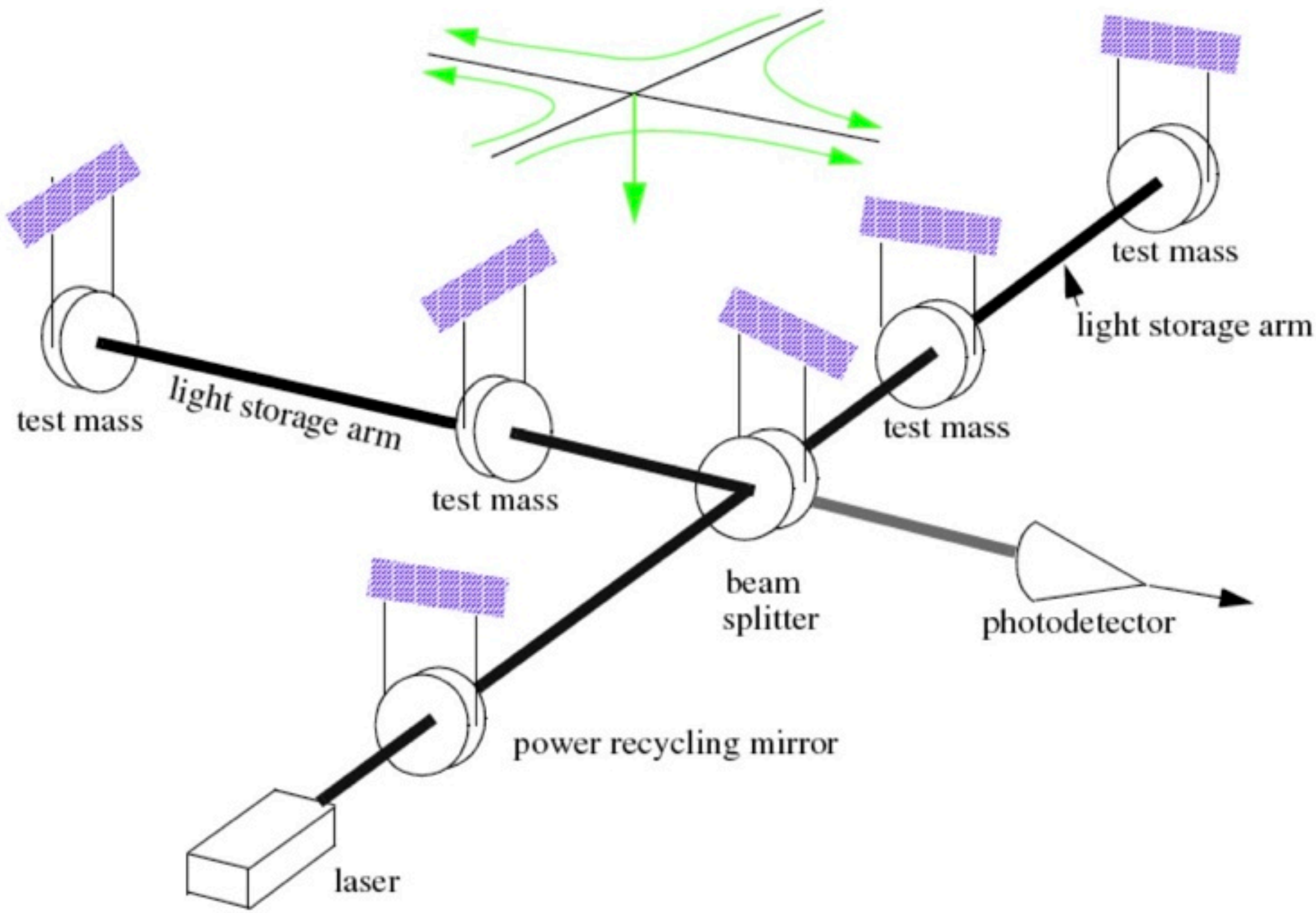
Ronald W. P. Drever
Co-Investigator
California Institute of Technology

Kip S. Thorne
Co-Investigator
California Institute of Technology

Frederick J. Raab
Co-Investigator
California Institute of Technology

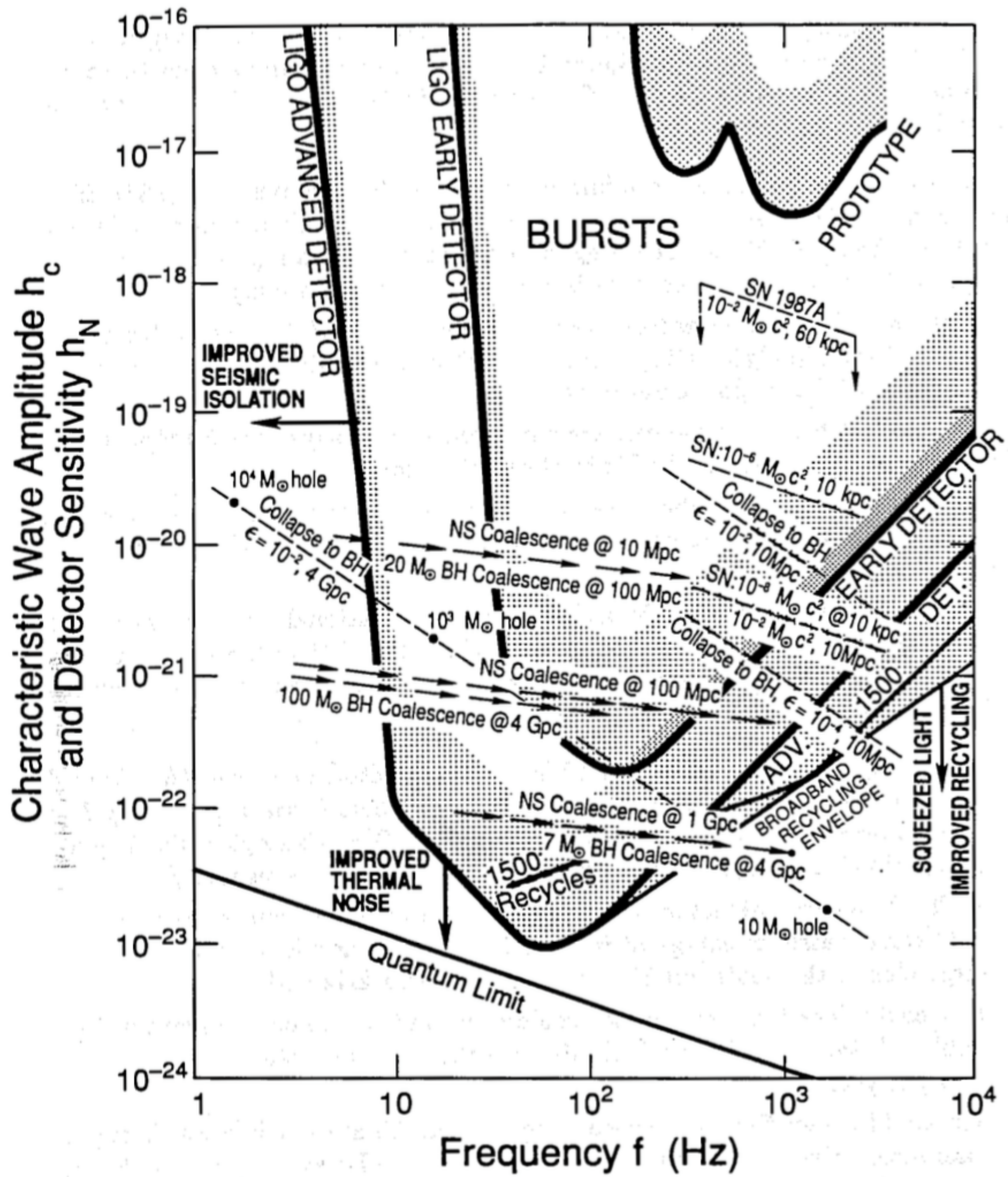
Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

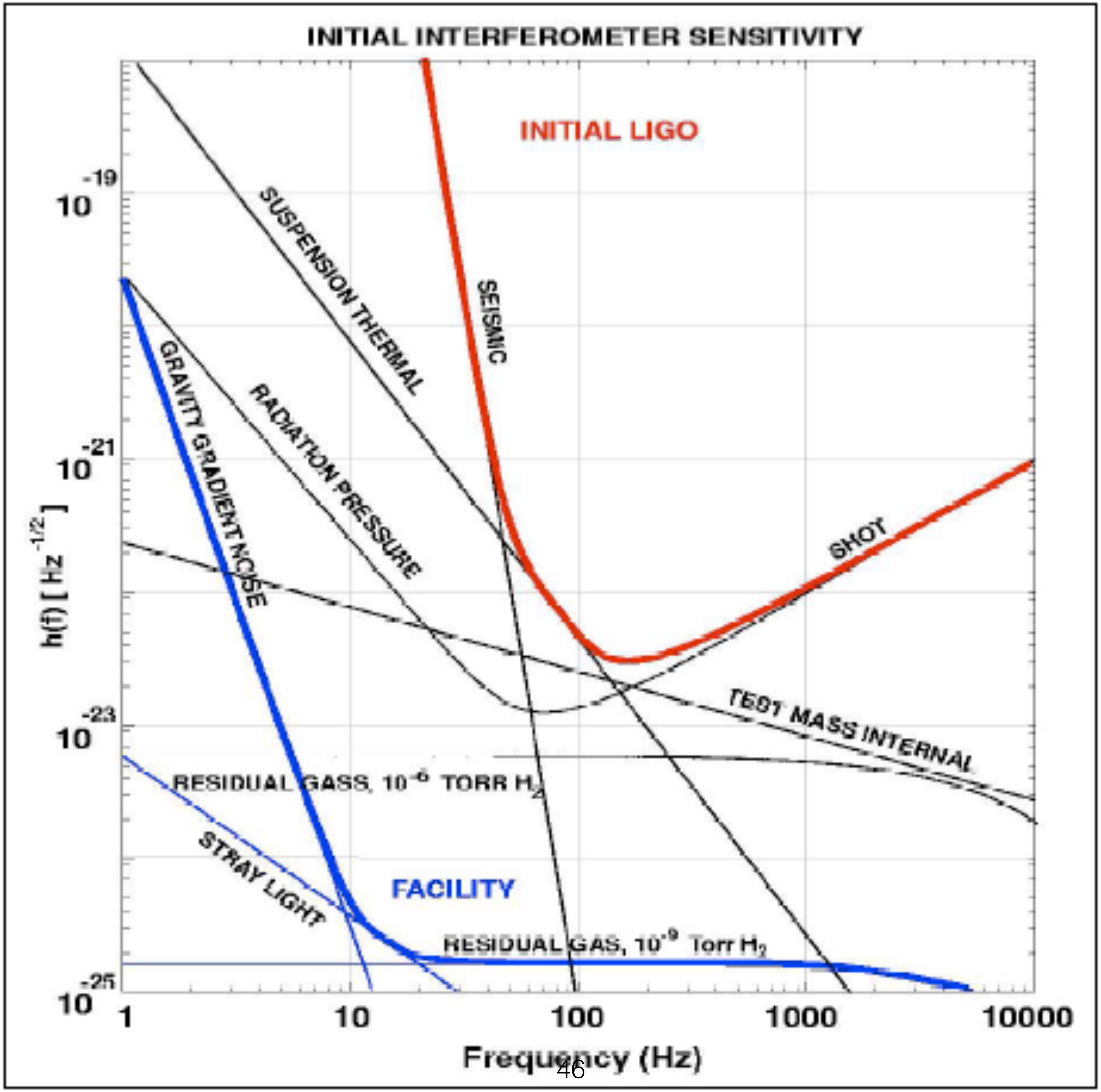
LIGO realizes this design with test mass mirrors 4 km apart.



GWs from a double neutron star coalescence at a distance of 15 million light years will change LIGO's length by about 10^{-18} meters.

The plan in the proposal for LIGO and Advanced LIGO



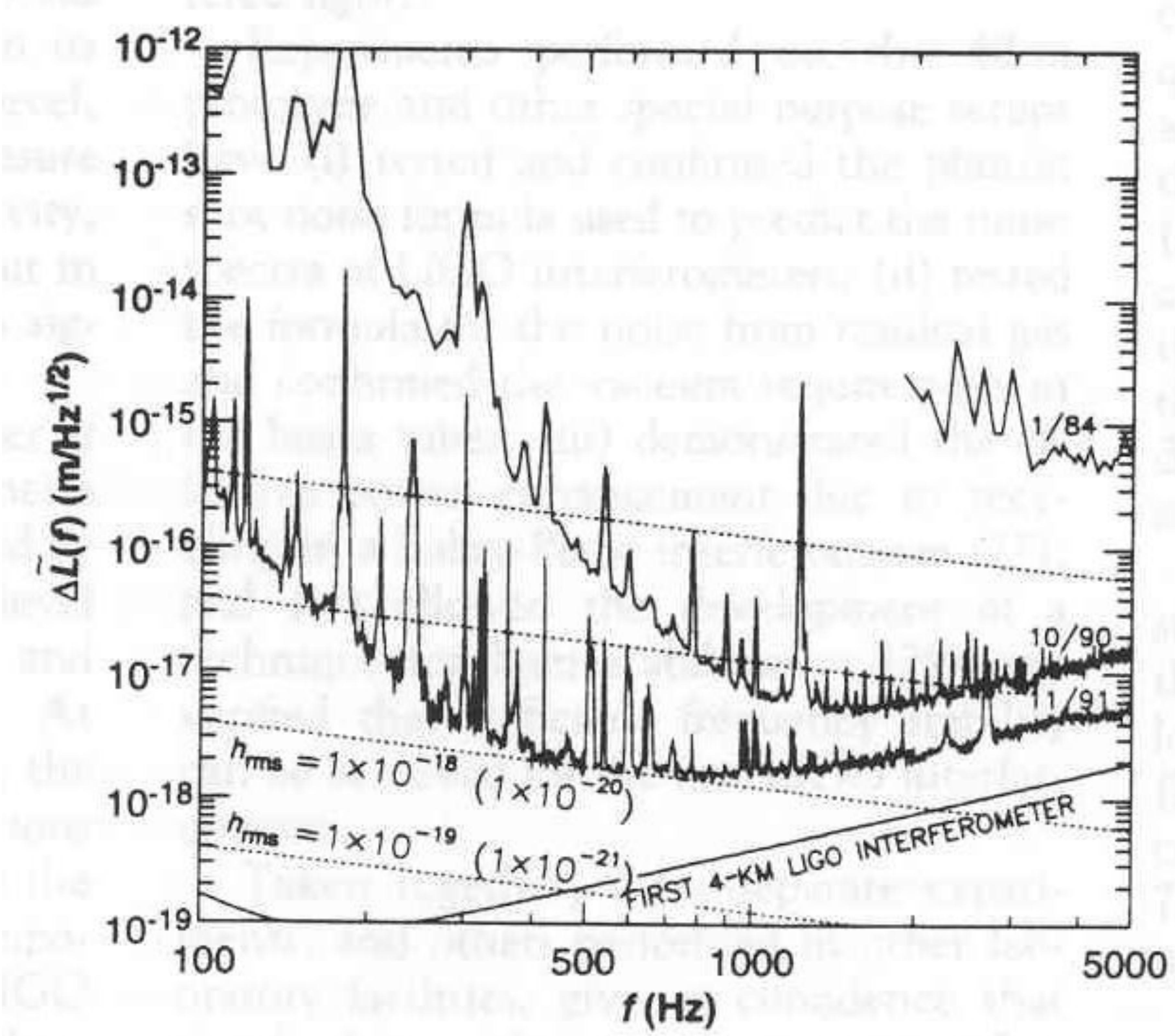

INITIAL INTERFEROMETER SENSITIVITY
INITIAL LIGO
SUSPENSION THERMAL
SEISMIC
GRAVITY GRADIENT NOISE
RADIATION PRESSURE
SHOT
TEST MASS INTERNAL
RESIDUAL GASS, 10^-6 TORR H2
STRAY LIGHT
FACILITY
RESIDUAL GAS, 10^-9 Torr H2
h(f) [Hz^-1/2]
10^-19
10^-21
10^-23
10^-25
1
10
100
1000
10000
Frequency (Hz)

1990 - 2000

Gravitational wave detection

Progression of sensitivity of Caltech 40-meter convinced me that LIGO would work.

1991

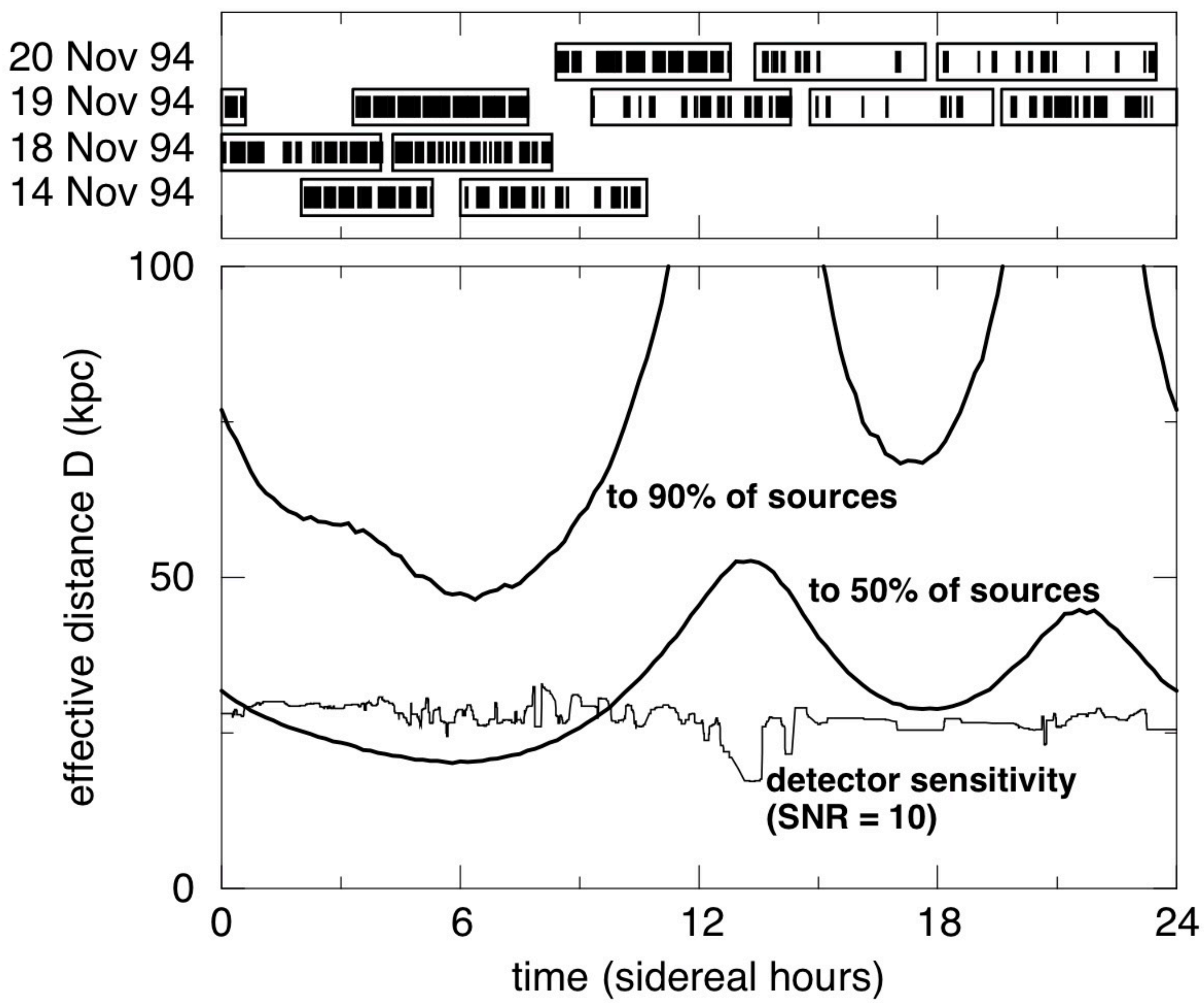


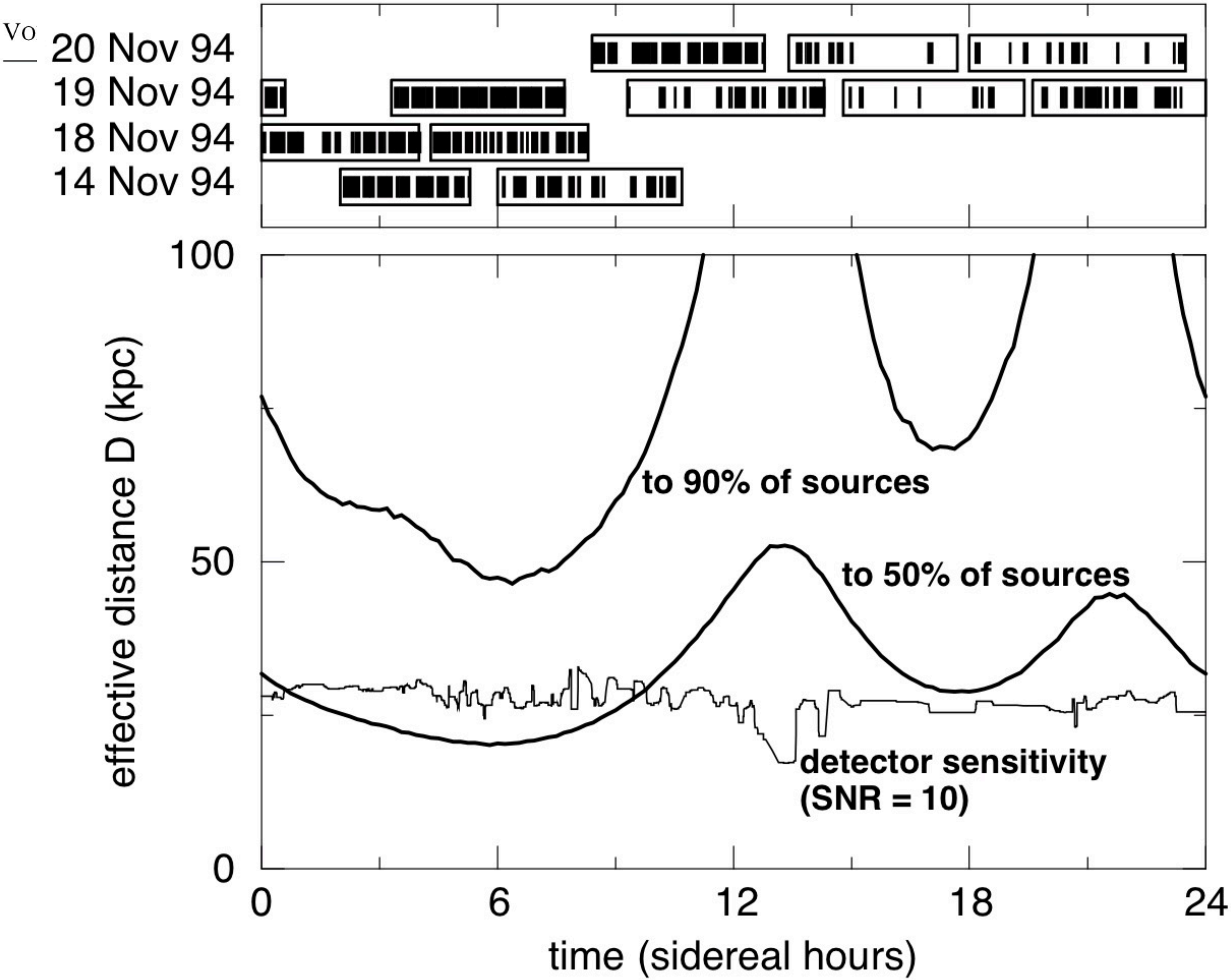
A. Abramovici et al, *Science*, **256**, 325-333 (1992)

VOLUME 83, NUMBER 8 PHYSICAL REVIEW LETTERS 23 AUGUST 1999

Observational Limit on Gravitational Waves from Binary Neutron Stars in the Galaxy

B. Allen,[1] J. K. Blackburn,[2] P. R. Brady,[3] J. D. E Creighton,[1,4] T. Creighton,[4] S. Droz,[5] A. D. Gillespie,[2] S. A. Hughes,[4] S. Kawamura,[2] T. T. Lyons,[2] J. E. Mason,[2] B. J. Owen,[4] F. J. Raab,[2] M. W. Regehr,[2] B. S. Sathyaprakash,[6] R. L. Savage, Jr.,[2] S. Whitcomb,[2] and A. G. Wiseman[1]



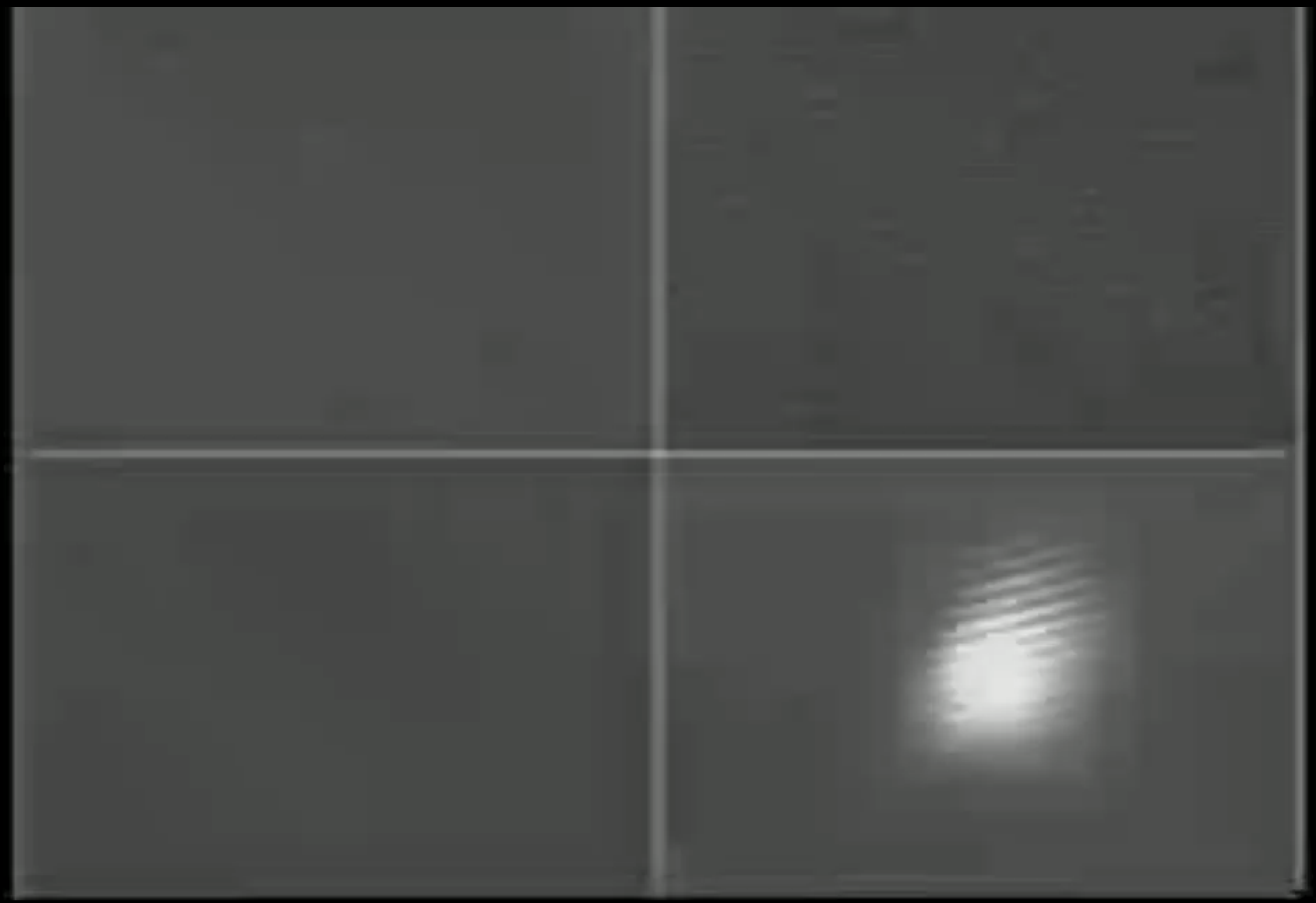


20 Nov 94
19 Nov 94
18 Nov 94
14 Nov 94
100
50
0
effective distance D (kpc)
to 90% of sources
to 50% of sources
detector sensitivity
(SNR = 10)
0
6
12
18
24
time (sidereal hours)


Hanford, WA
3002 km
(L/c = 10 ms)
MIT
Caltech
Livingston, LA


Washington

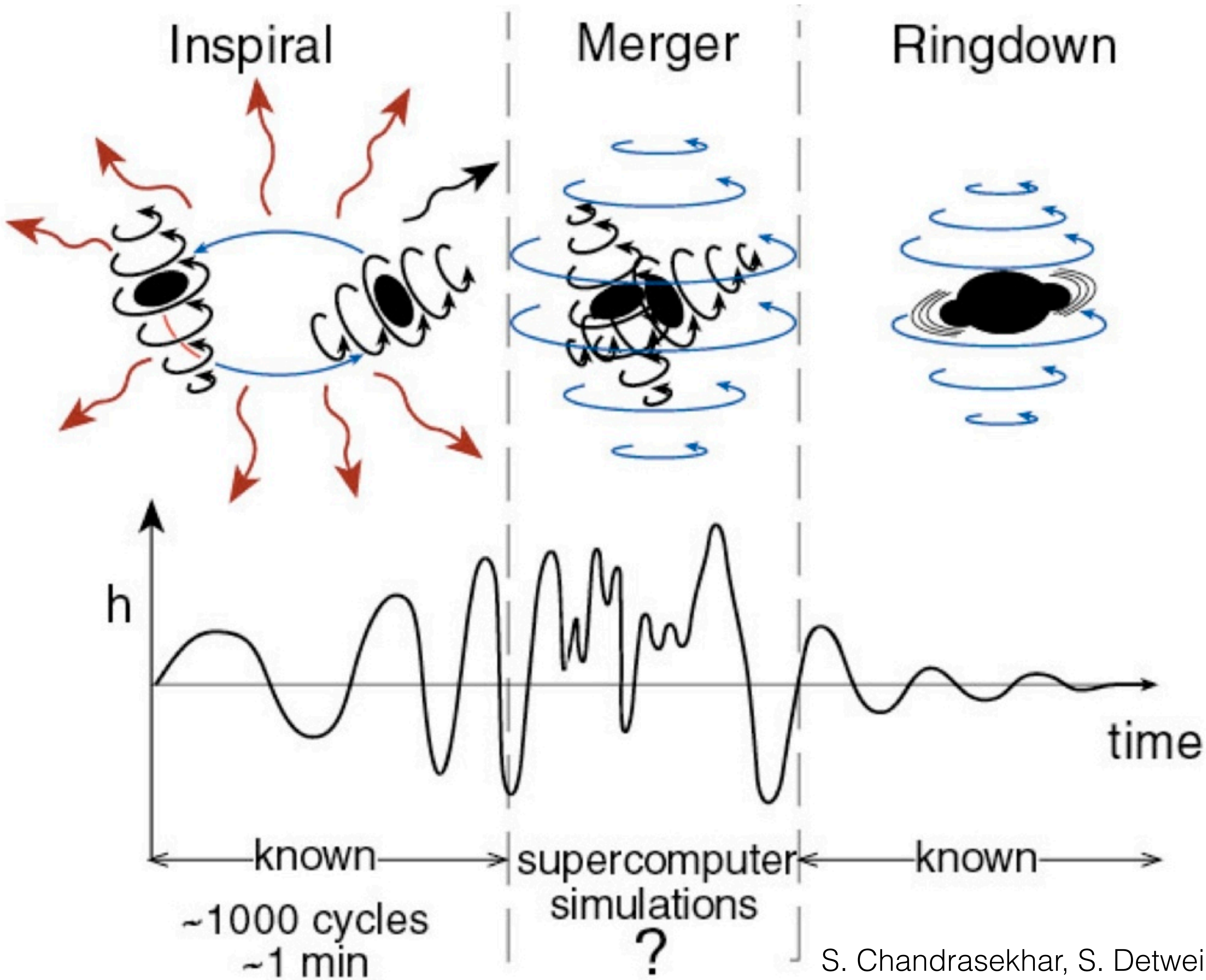
First lock, LIGO Hanford 2 km, 20 Oct 2000



http://www.ligo.caltech.edu/LIGO_web/firstlock/

Computer simulations

The role of simulations (K. Thorne)



L. Blanchet, Living Rev. Relativity

S. Chandrasekhar, S. Detweiler, Proc. Royal Soc. A 10, 1098 (1975)

1993

VOLUME 71, NUMBER 18 PHYSICAL REVIEW LETTERS 1 NOVEMBER 1993

Collision of Two Black Holes

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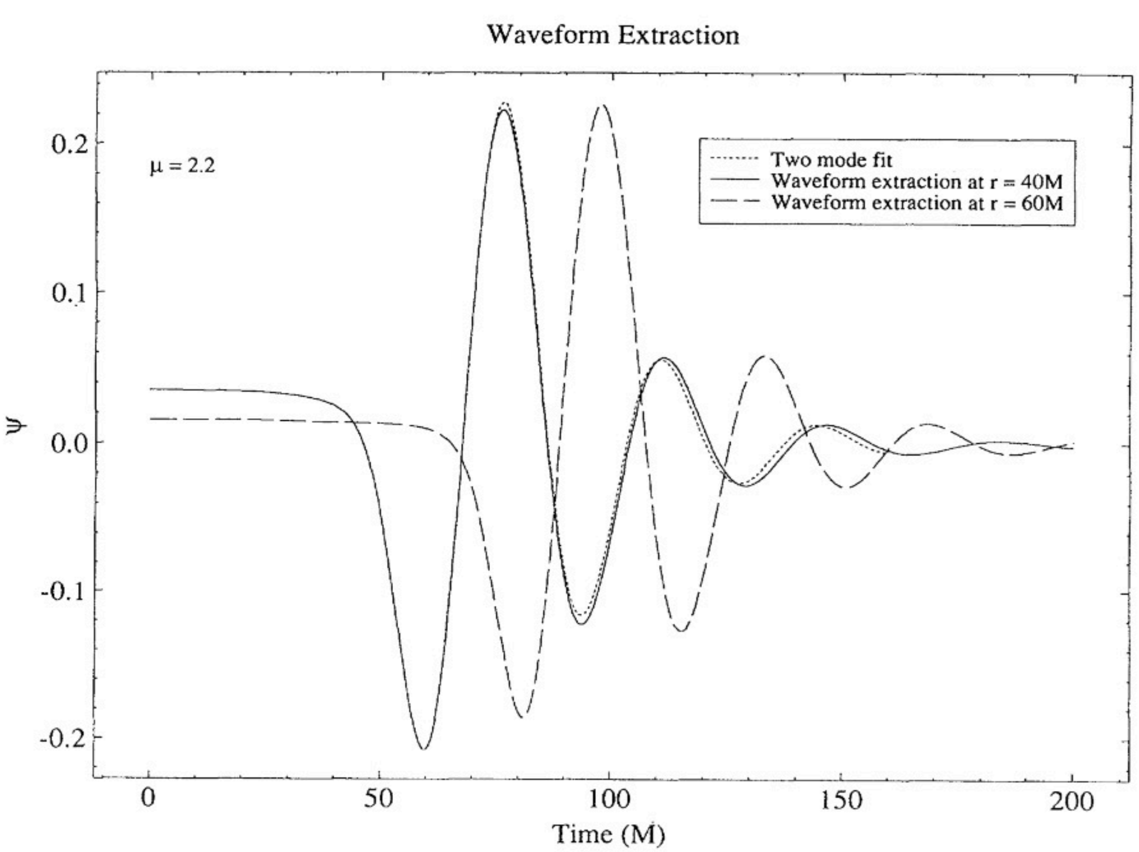
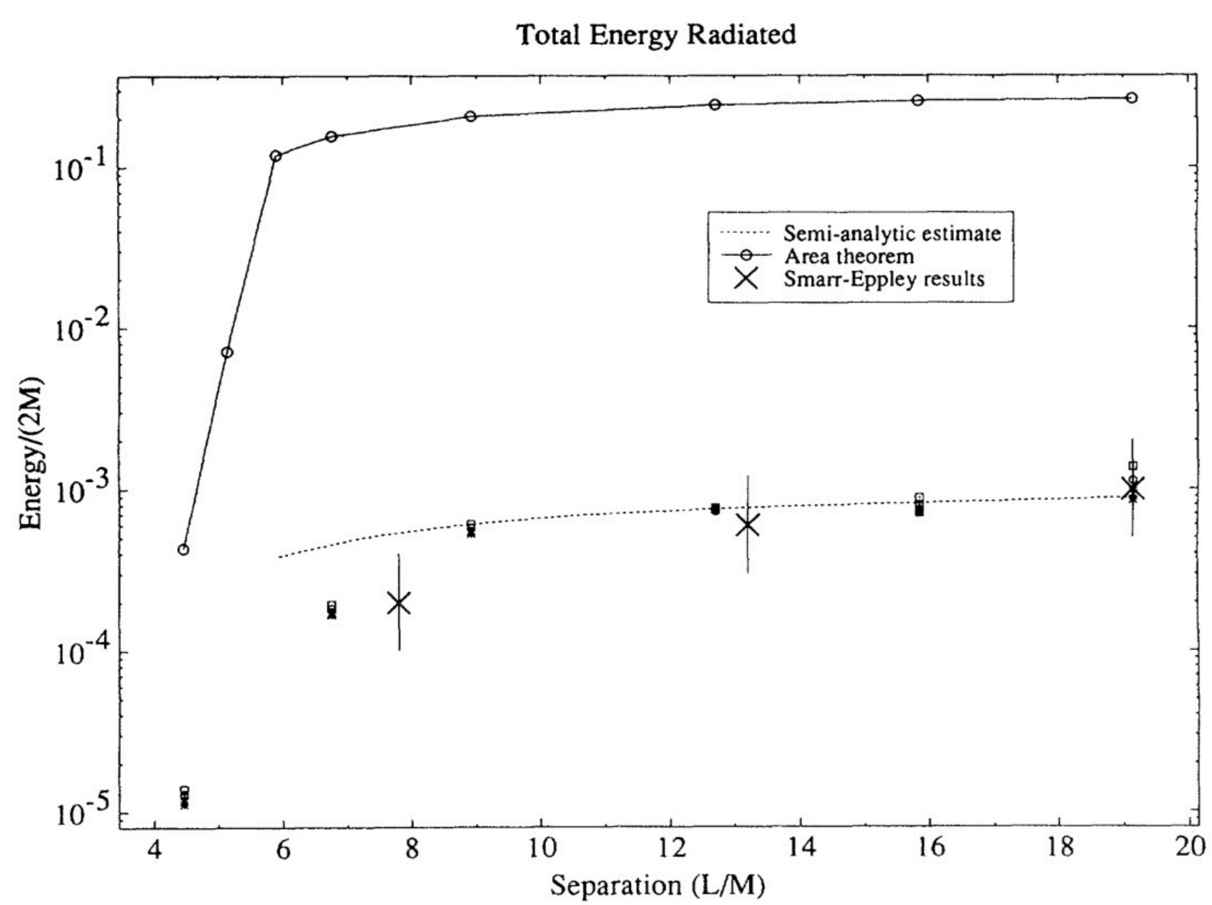
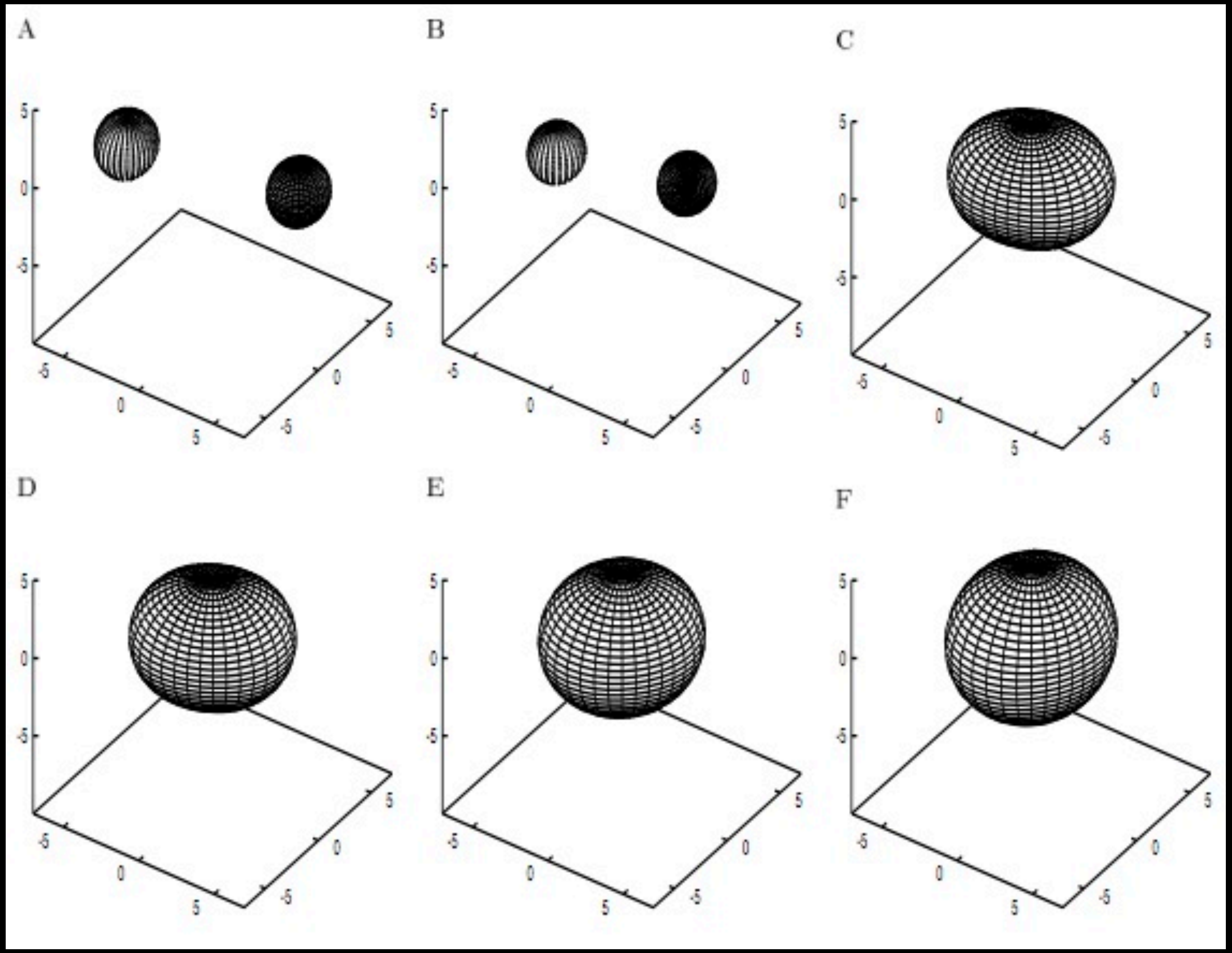
[1]*National Center for Supercomputing Applications, Beckman Institute, 405 N. Mathews Avenue, Urbana, Illinois 61801*
[2]*Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada T2N 1N4*
[3]*McDonnell Center for the Space Sciences, Department of Physics, Washington University, St. Louis, Missouri 63130*
(Received 13 August 1993)

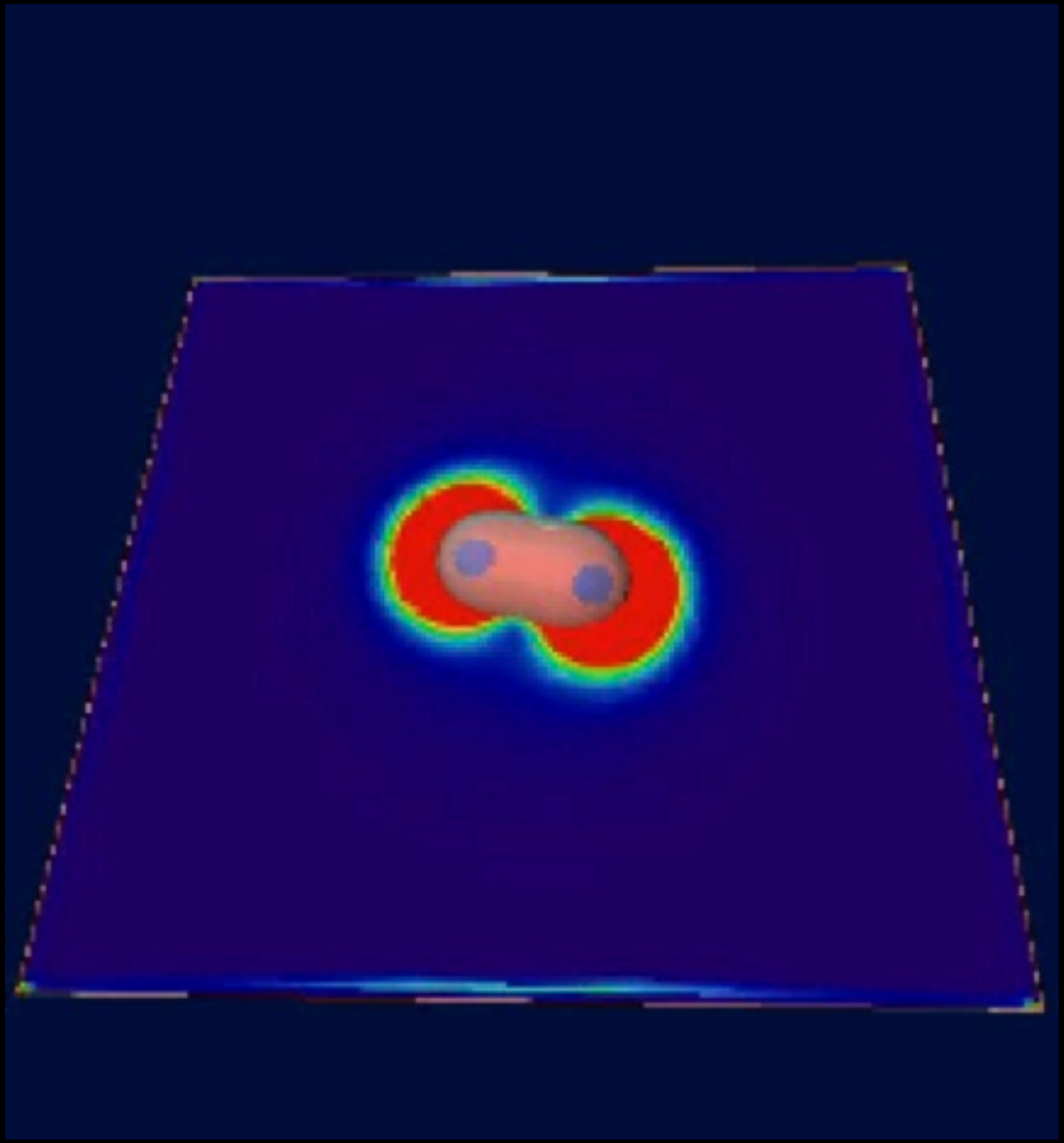
We study the head-on collision of two equal-mass, nonrotating black holes. We consider various cases, from holes surrounded by a common horizon to holes separated by about $20M$, where M is the mass of each hole. The wave forms and energy output are computed, showing that normal modes of the final black hole are clearly excited. We also estimate analytically the total gravitational radiation emitted, considering tidal heating of horizons and other effects. The analytic calculations, perturbation theory, and strong-field, nonlinear numerical calculations agree very well with each other.





Binary black hole simulations (circa 2000):





S. Brandt et al, Phys.Rev.Lett.85:5496-5499,2000

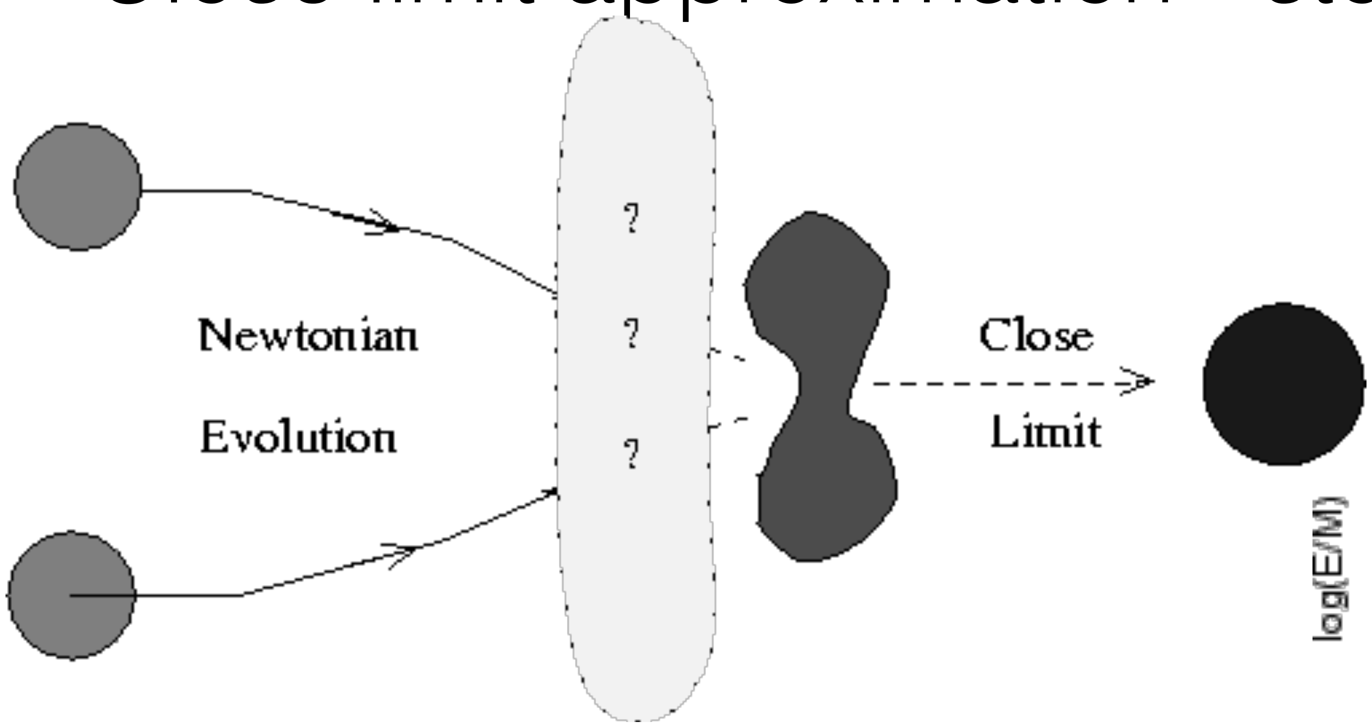
Grazing incidence + excision

Steve Brandt, Randall Correll, Roberto Gómez, Mijan Huq, Pablo Laguna, Luis Lehner, Pedro Marronetti, Richard A. Matzner, David Neilsen, Jorge Pullin, Erik Schnetter, Deirdre Shoemaker, and Jeffrey Winicour

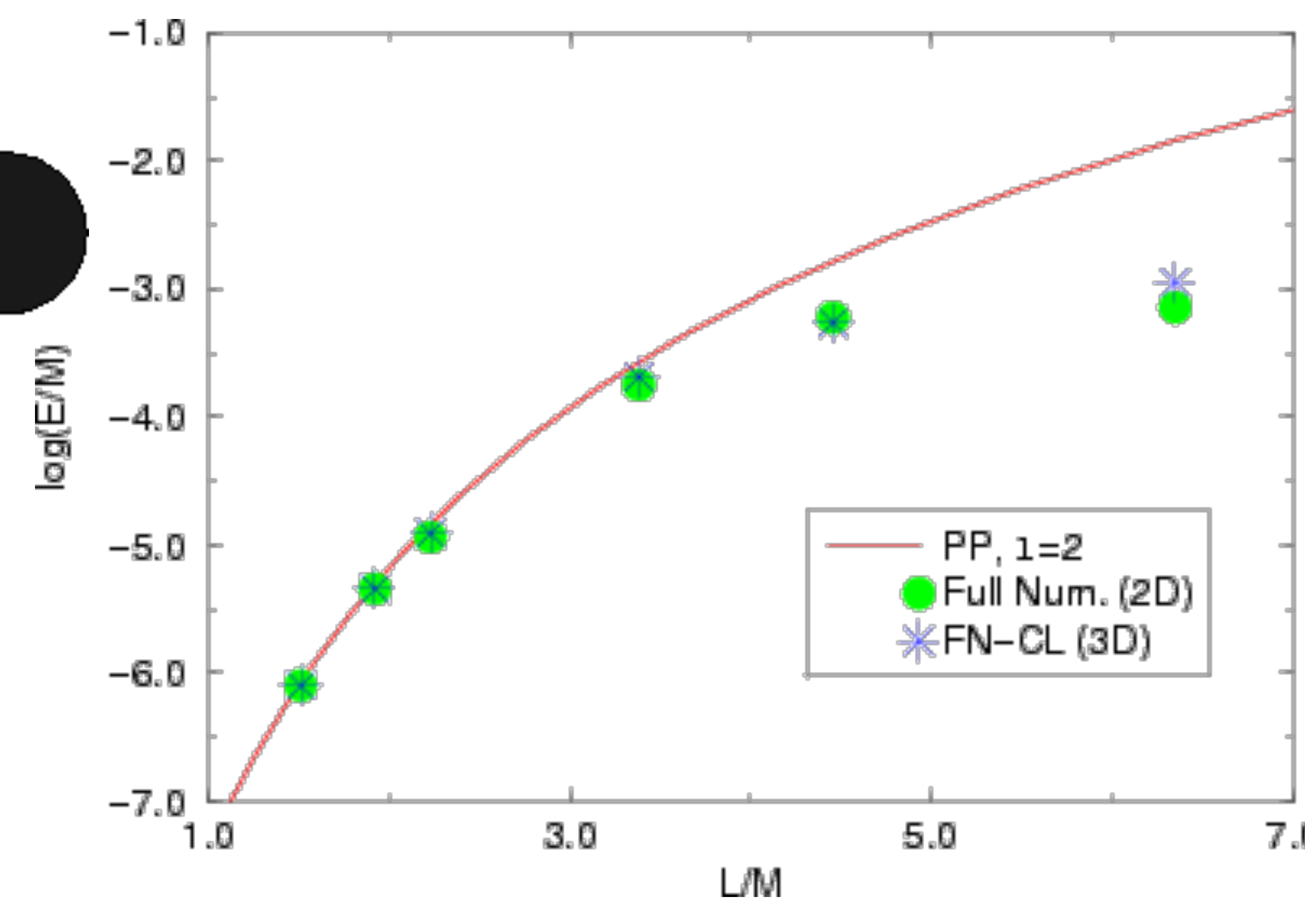
Why so hard?

Input spacetime grid is not physical; no unique way to write evolution equations - some ill-posed; issues of initial conditions - constraints; ......

Close limit approximation - stopgap until real solution



Price R H and Pullin J 1994 *Phys. Rev. Lett.* **72** 3297



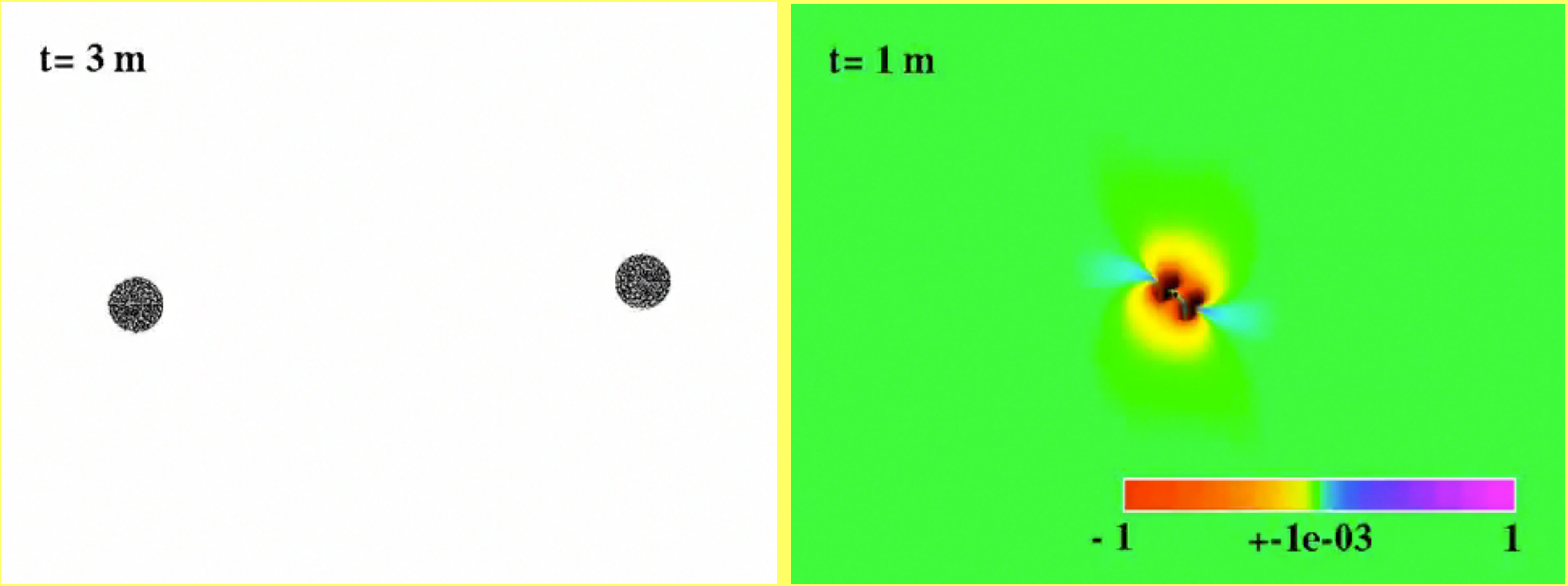
J. Baker et al, Class. Quantum Grav. **17** No 20 (21 October 2000) L149-L156

2000 - today

Computer simulations

Computer simulation of orbiting black holes:

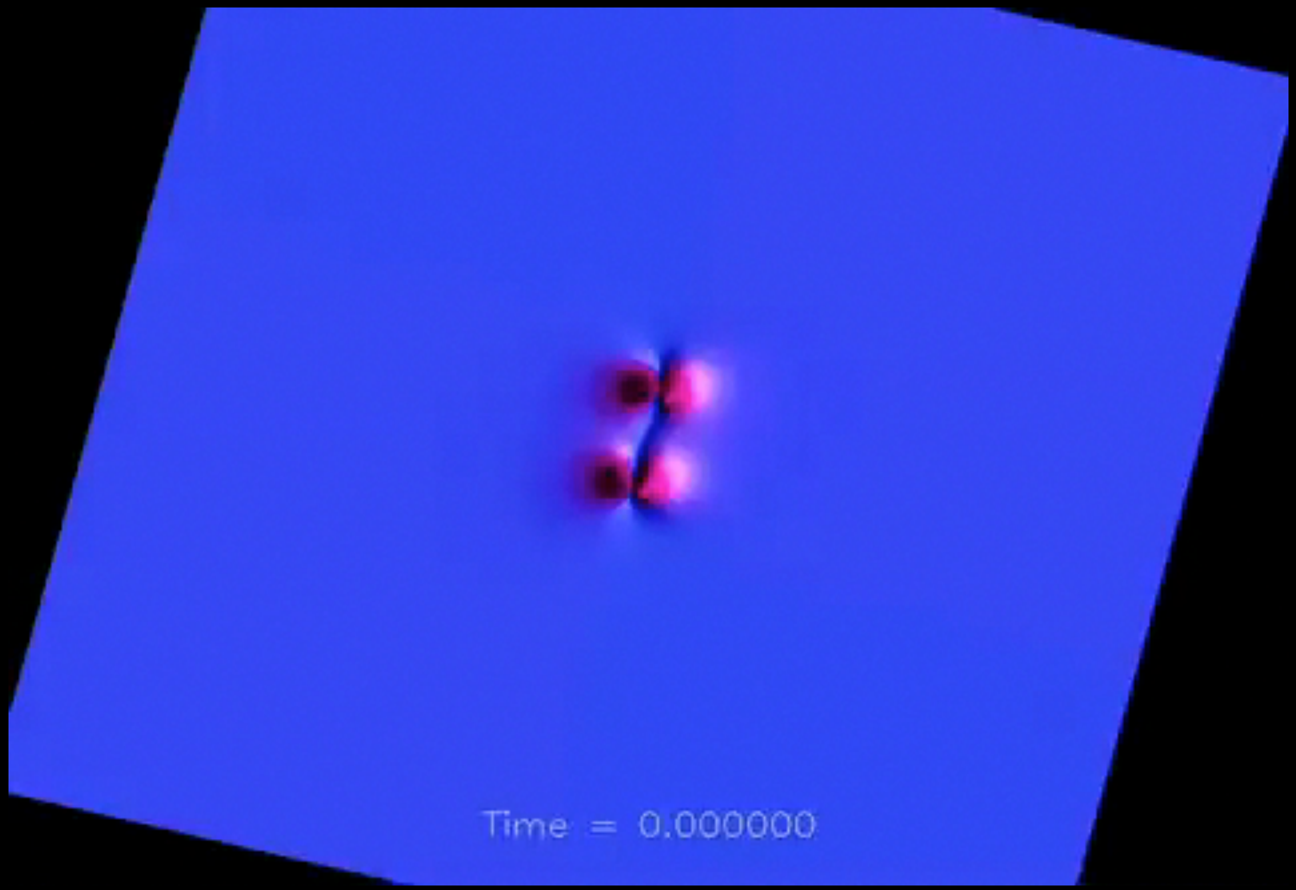
2005



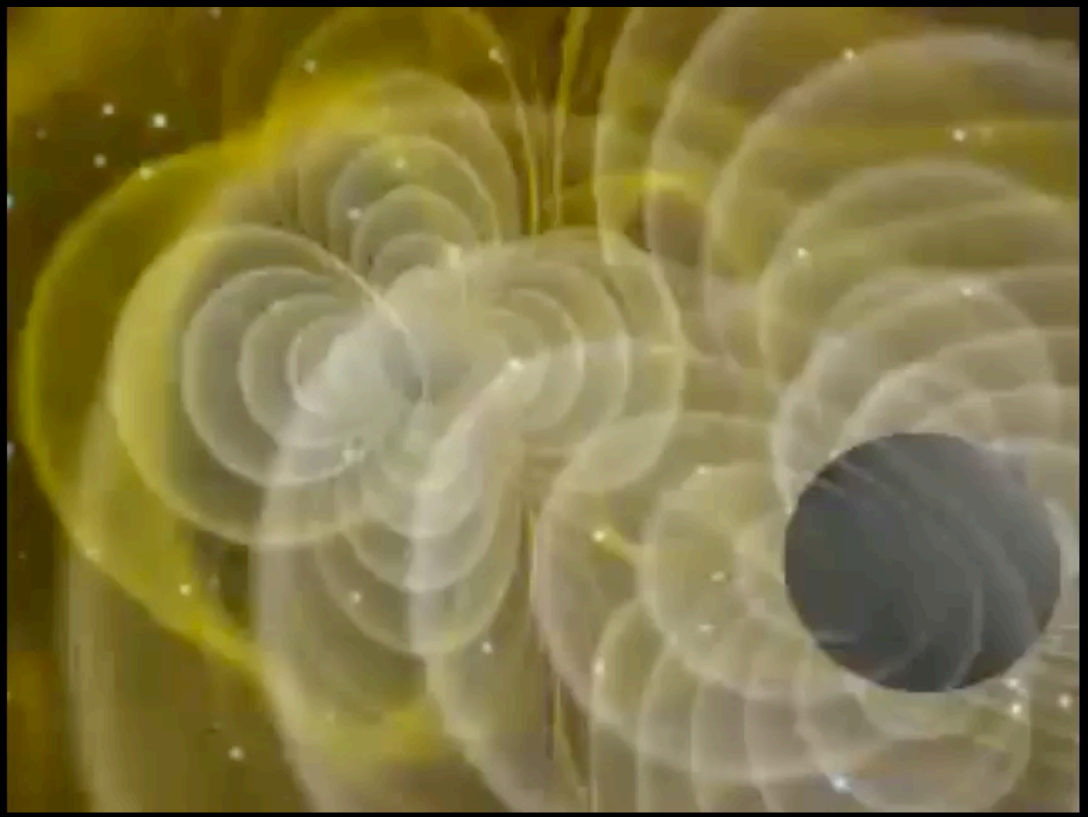
Pretorius used non-standard methods to demonstrate that black hole binaries could be simulated.

F. Pretorius

Binary black hole simulations: standard methods were quickly modified



UTB/RIT



NASA/GSFC

F. Pretorius, Phys.Rev.Lett.95:121101,2005

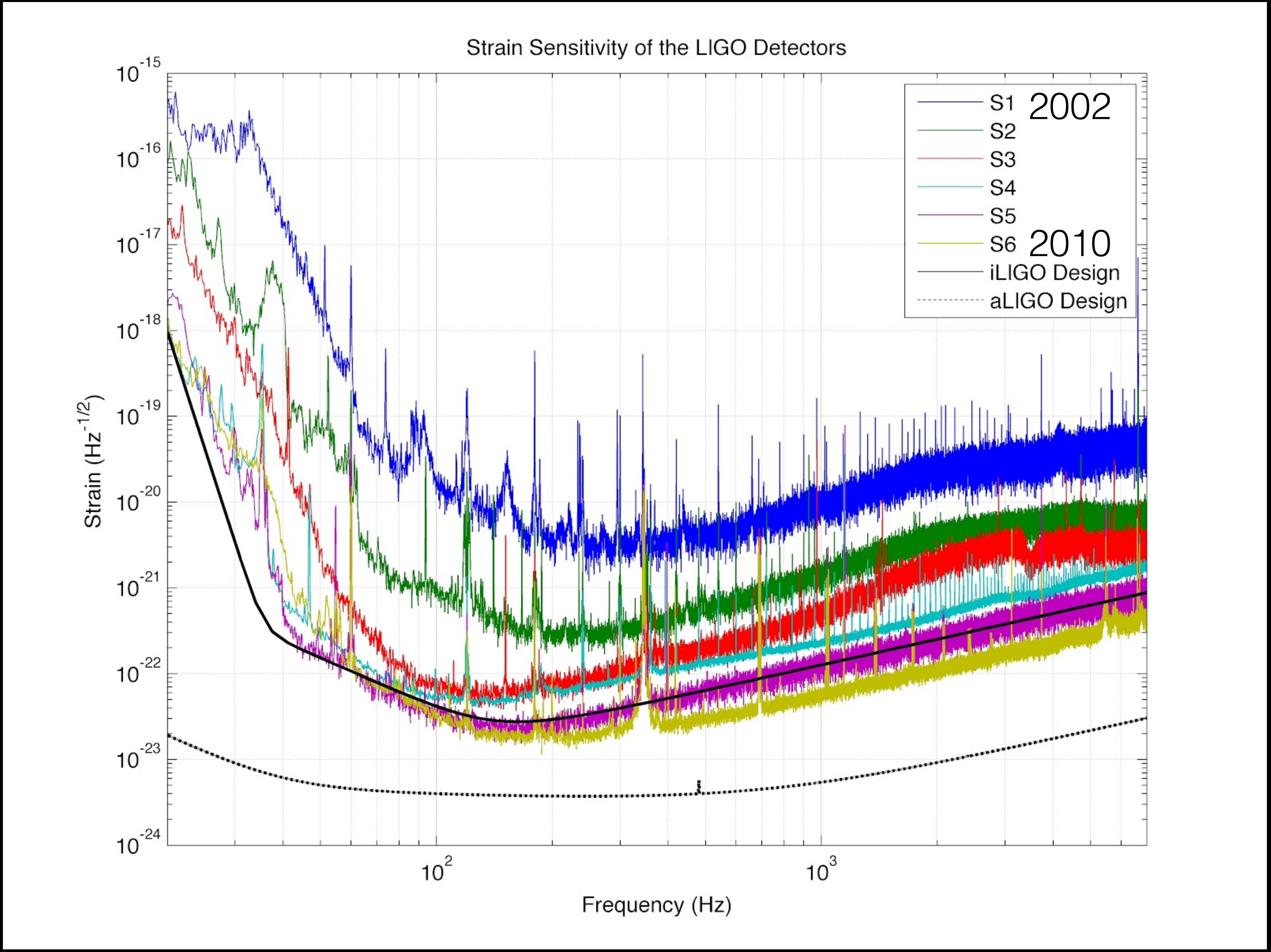
M. Campanelli, C. O. Lousto, P. Marronetti, Y. Zlochower, Phys.Rev.Lett. 96:111101,2006

J. G. Baker, J. Centrella, D.-I. Choi, M. Koppitz, J. van Meter, Phys.Rev.Lett. 96:111102,2006

Gravitational wave detection

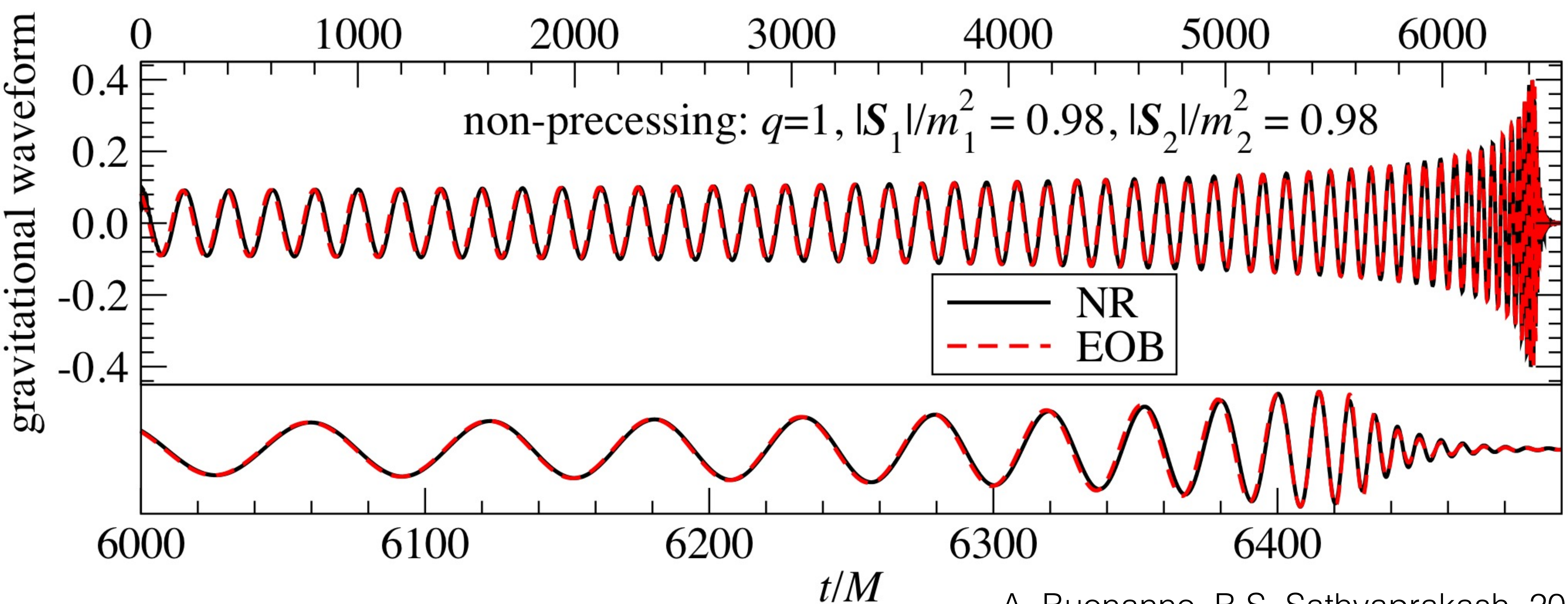
Initial LIGO

How sensitive was Initial LIGO?



Approximations for data analysis:

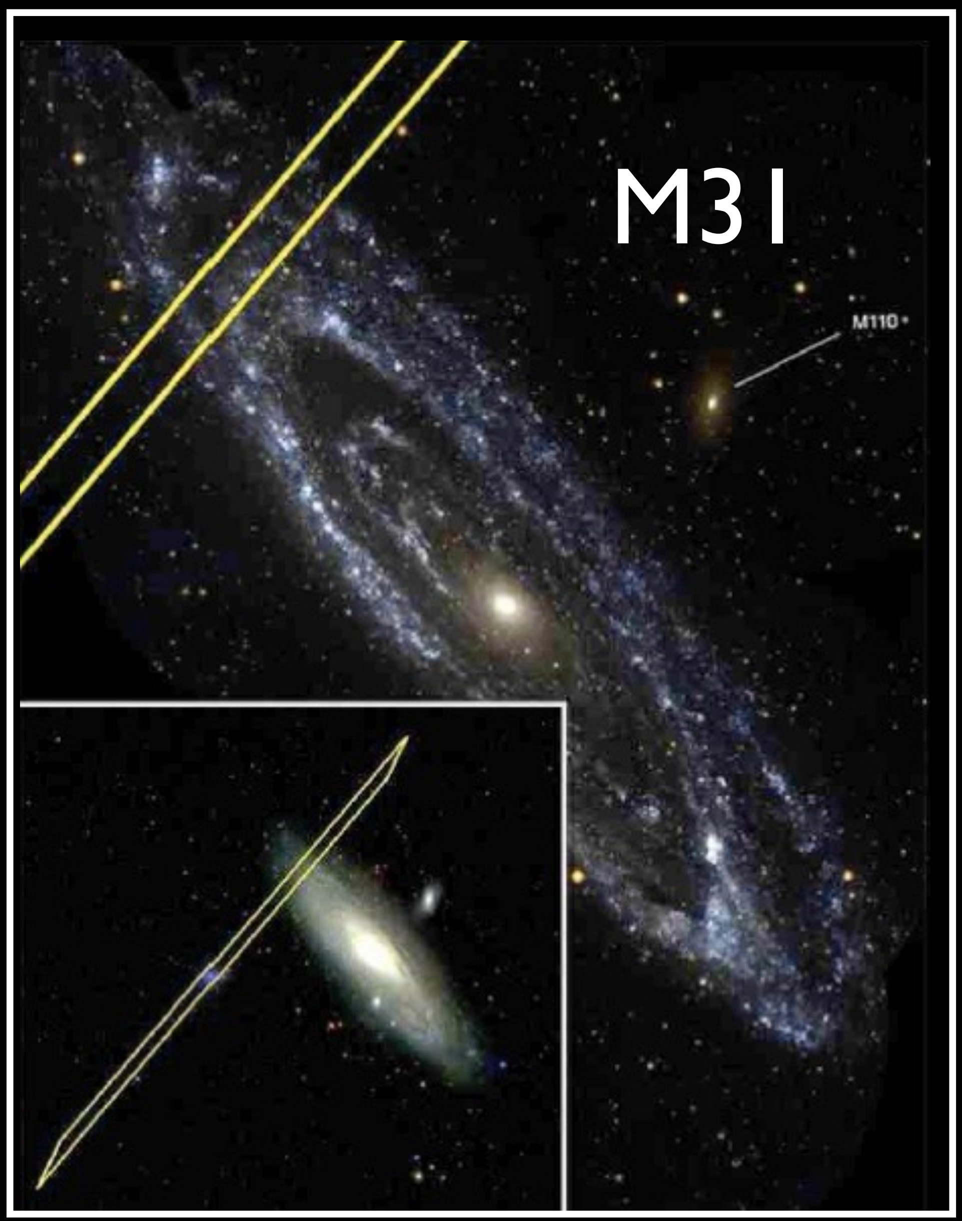
Hundreds of thousands of templates are constructed with approximate waveforms (EOB). These are calibrated with simulations (NR).



A. Buonanno, B.S. Sathyaprakash, 2015

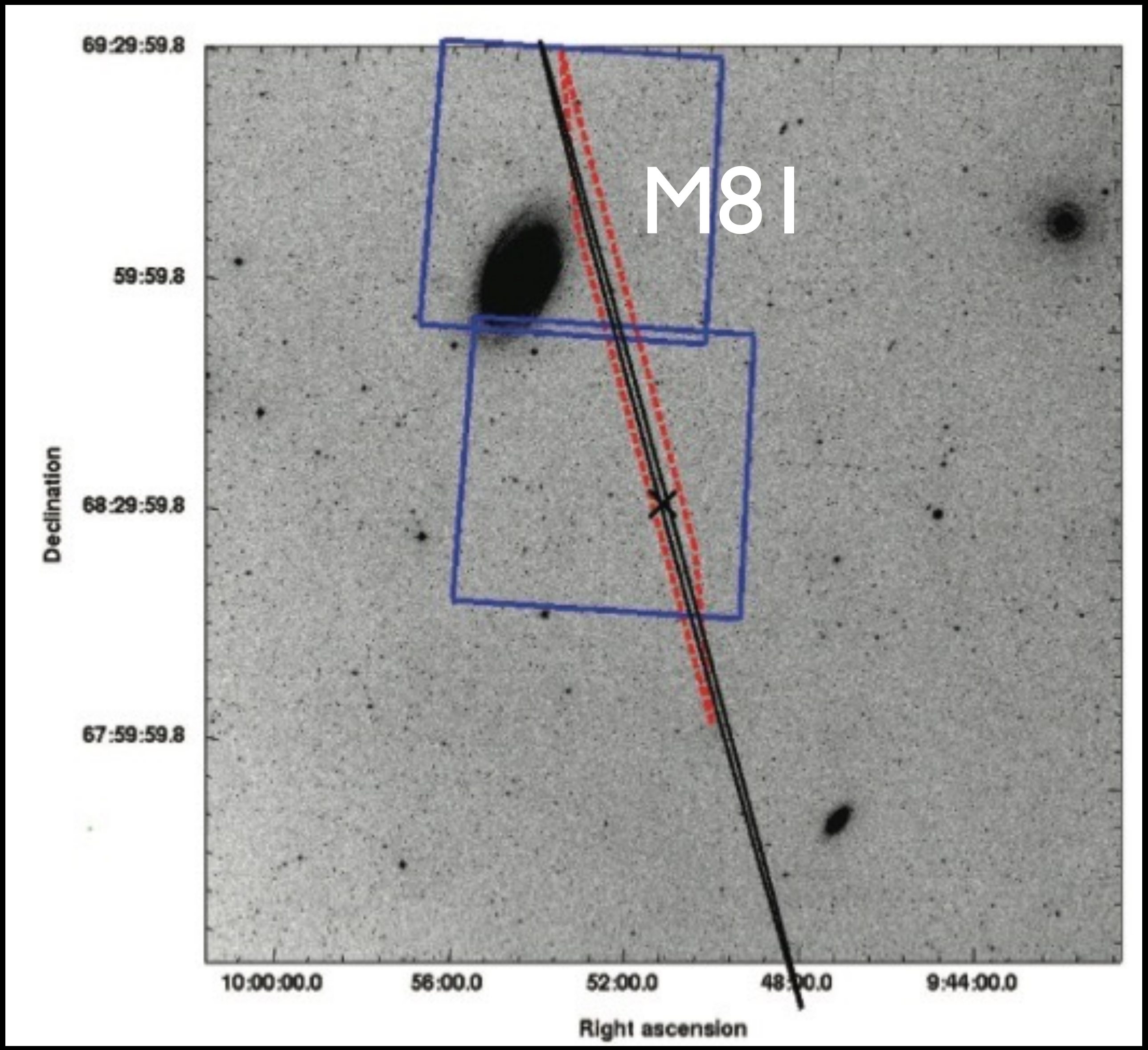
A. Buonanno and T. Damour, Phys. Rev. D 59, 084006 (1999)

LIGO Science: The dog that didn't bark in the night: no GW signal from nearby short GRBs rules out compact binary coalescence as origin.



LSC+Hurley, Astrophys. J. **681** (2008) 1419

GRB 070201

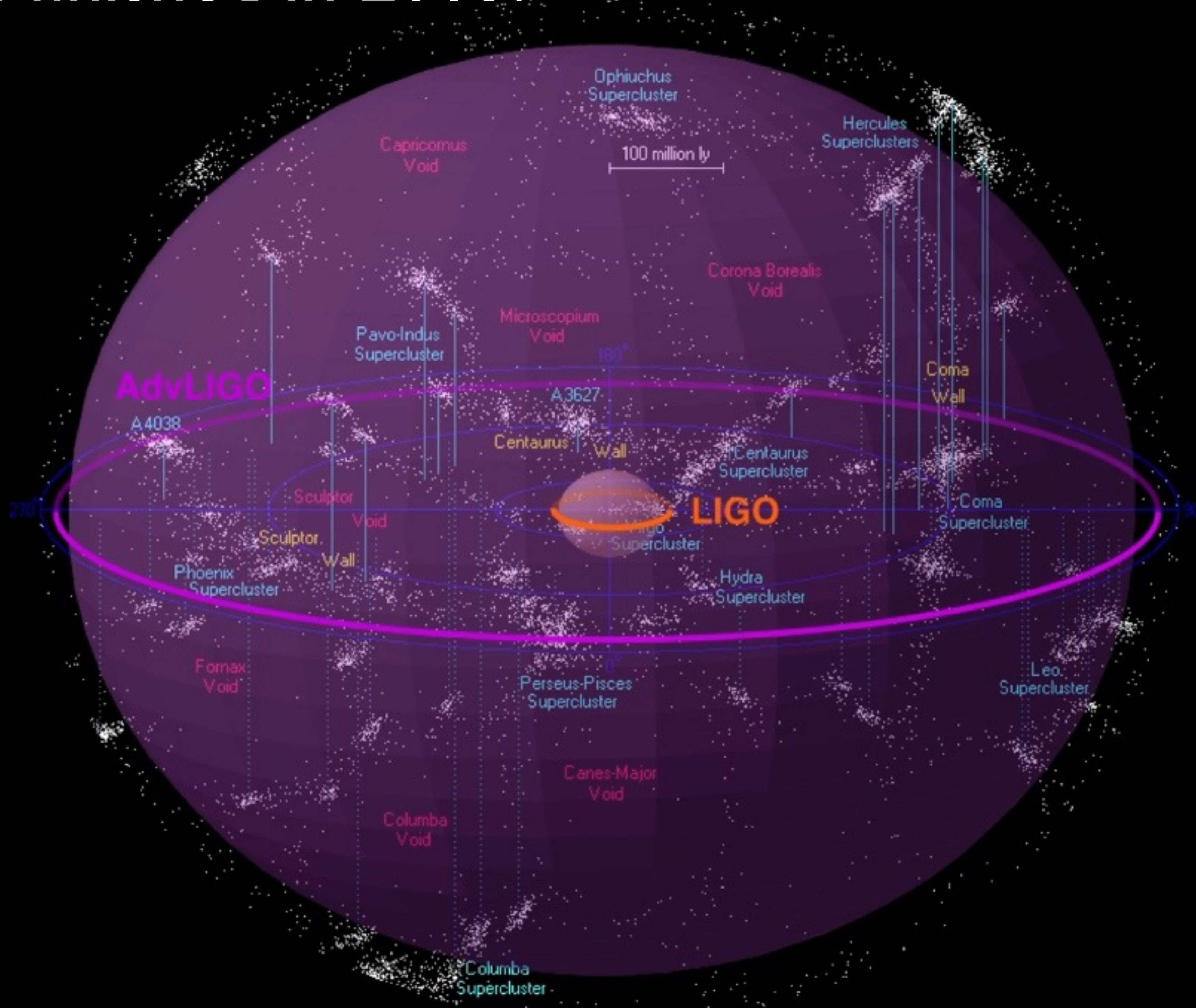


LSC + others, Astrophys. J. **755** (2012) 2

GRB 051103

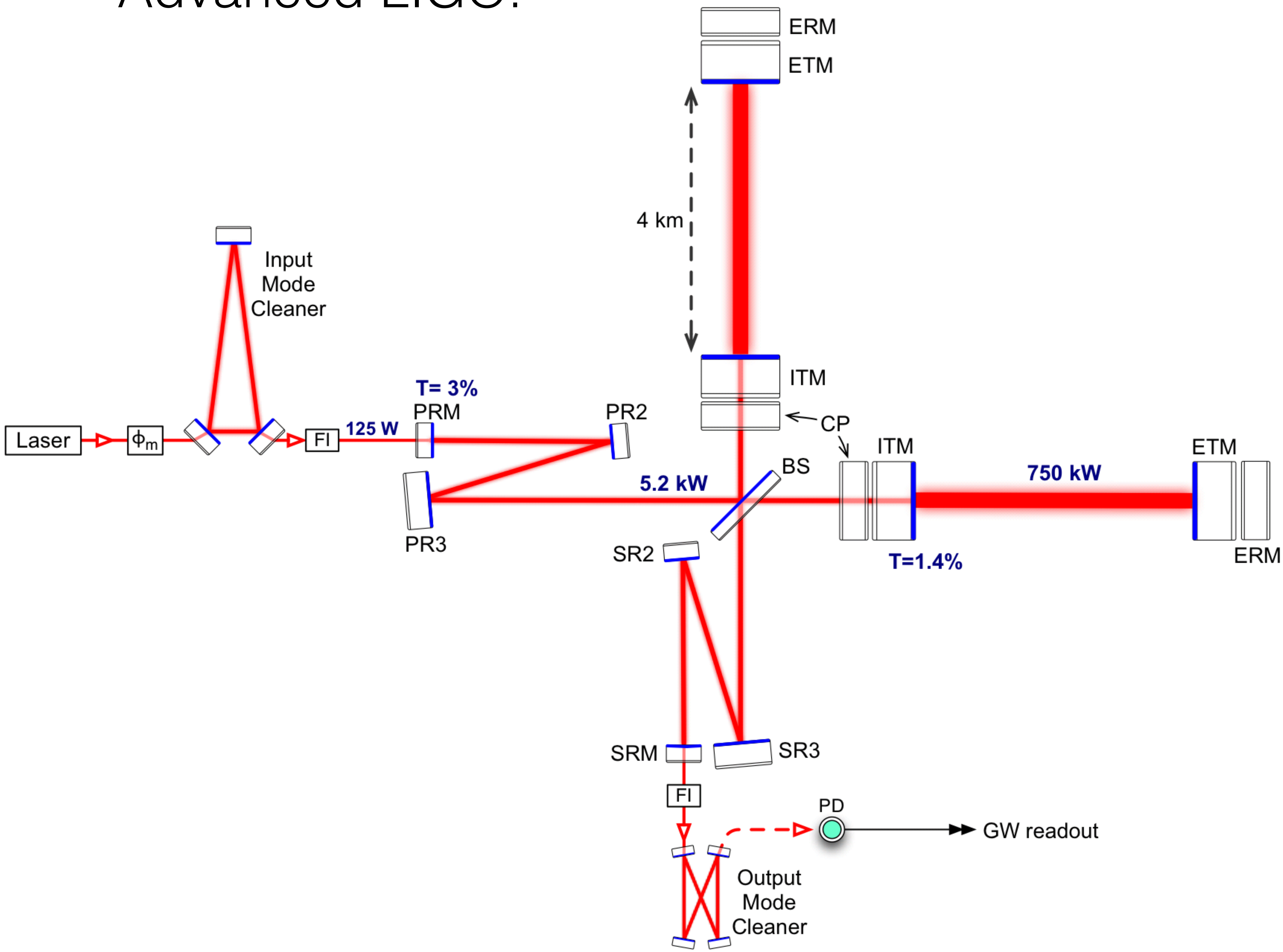
Advanced LIGO

The upgrade from LIGO to Advanced LIGO started in 2008 and finished in 2015:



Sampling 1000 X the universe for rare events should increase the event rate by 1000 X.

Advanced LIGO:



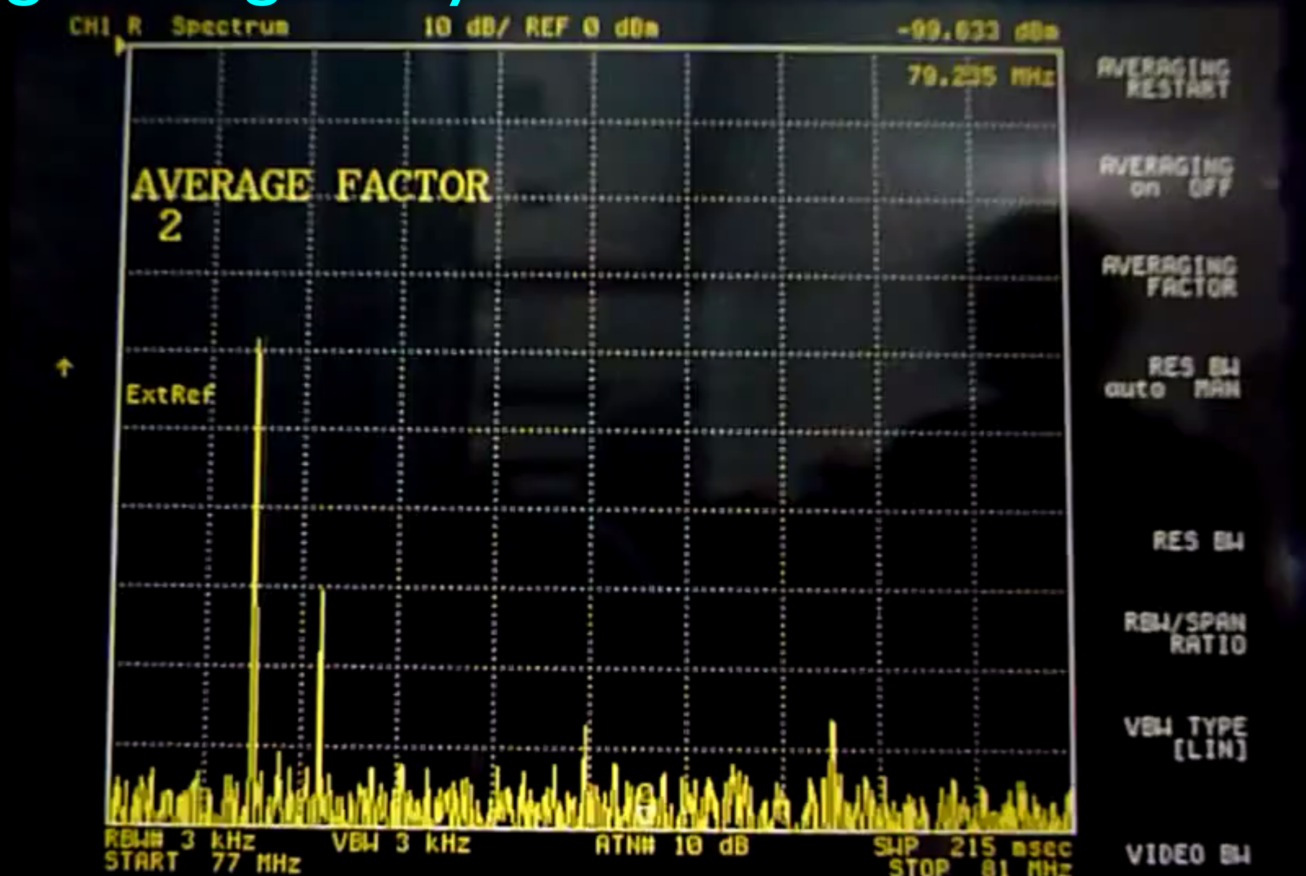
LSC, Class. Quantum Grav. 32 (2015) 074001

Advanced LIGO

https://www.advancedligo.mit.edu/

January 2013: First lock of Input Mode Cleaner at Hanford

June 2013: First lock of IR laser using green light in y-arm at Hanford

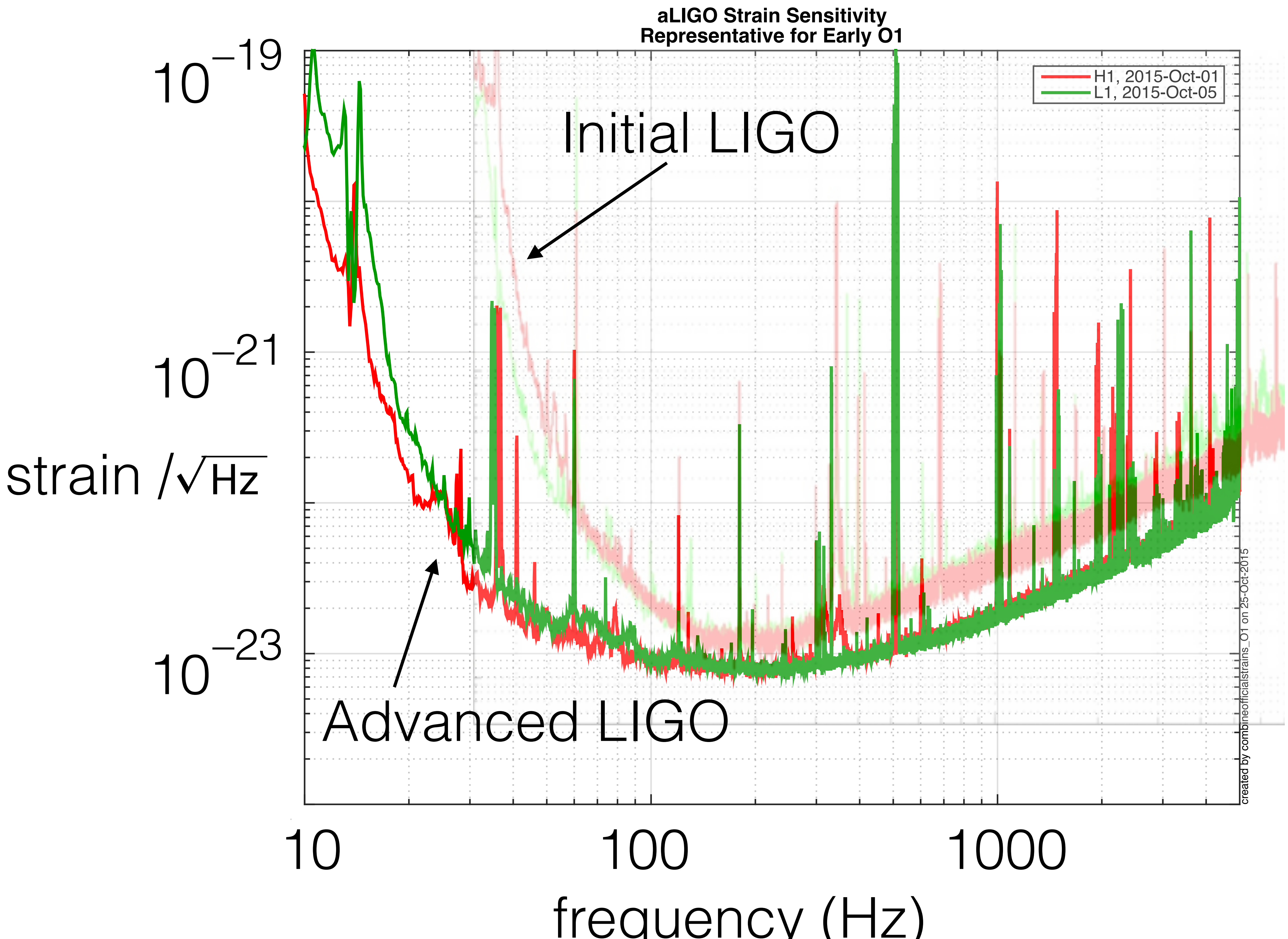


October 2013: Inspecting installed optic at Livingston

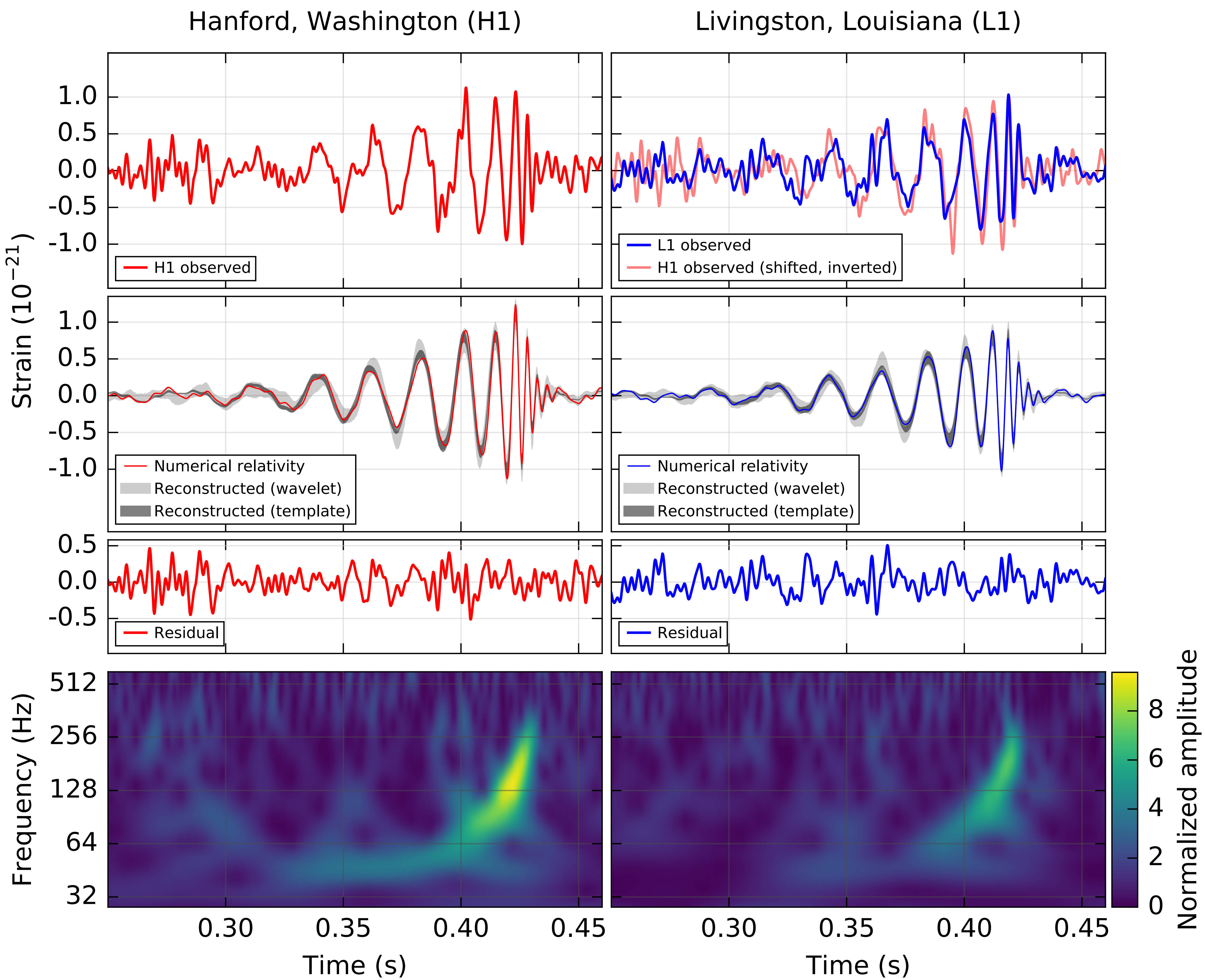
October 2013: Aligning installed optics at Livingston

14 September 2015

Advanced LIGO Sensitivity — early October 2015

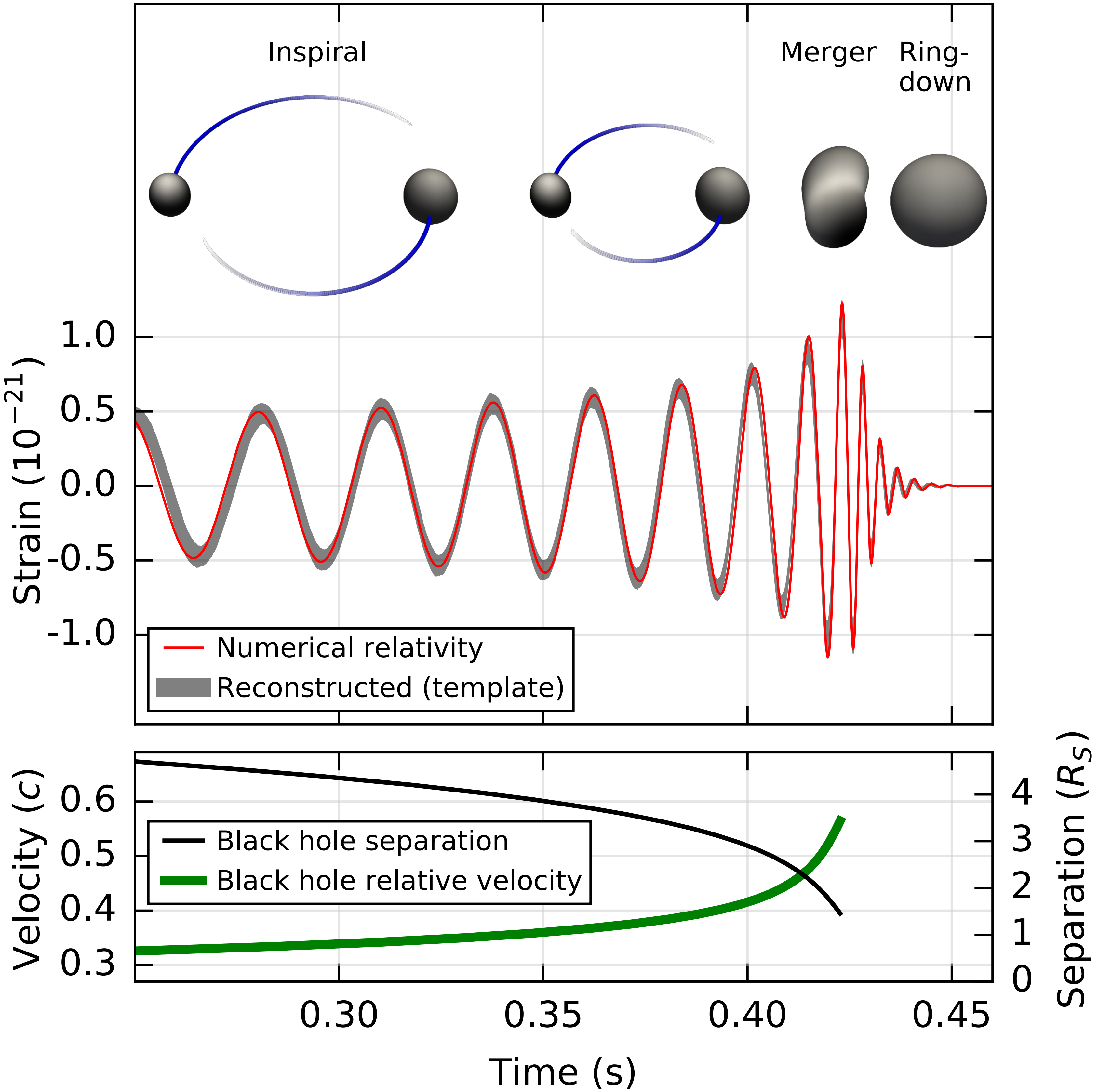


The data:

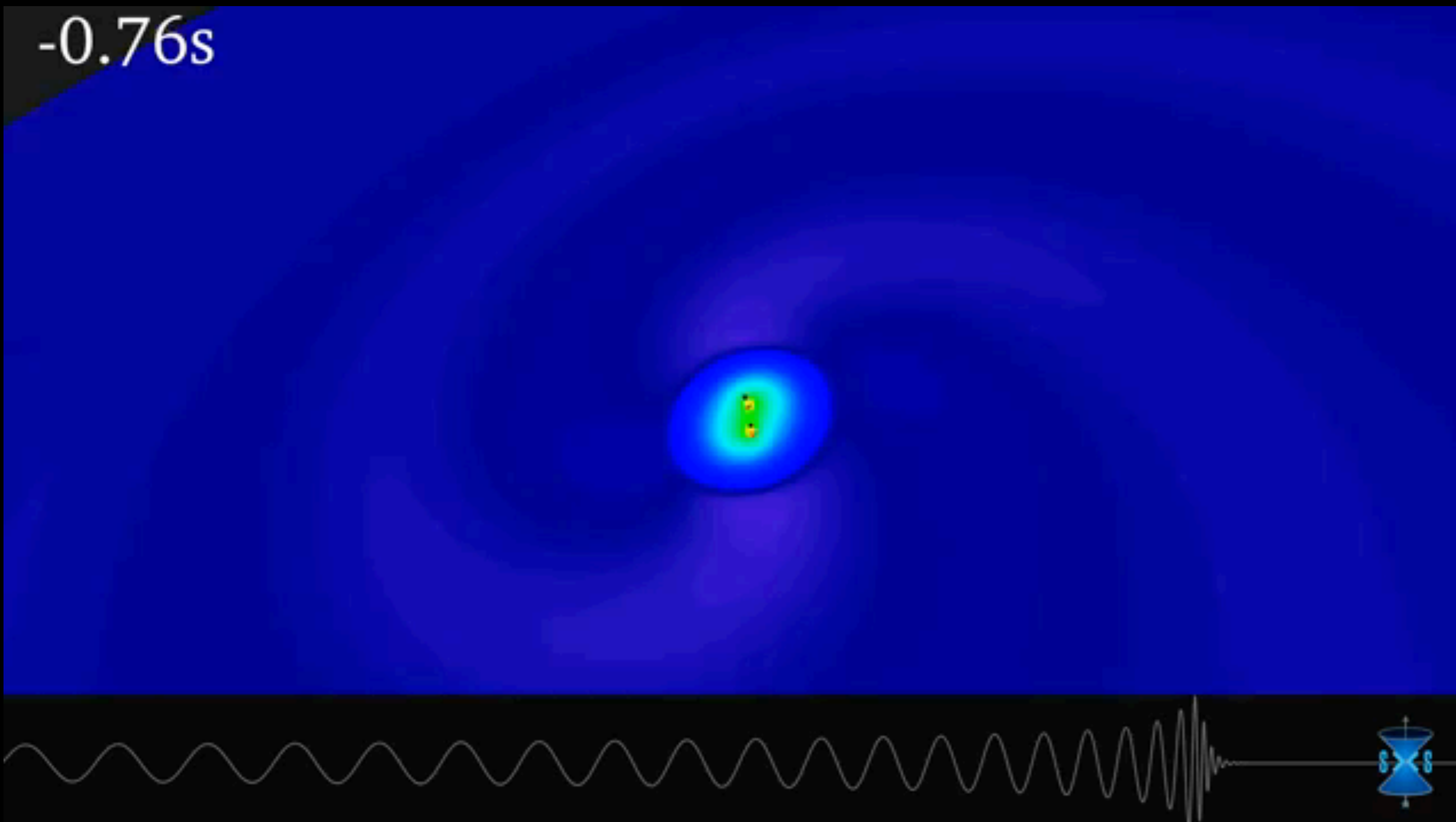


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
8
6
4
2
0

The interpretation:



A simulation (by SXS group) of GW150914. Many other groups also performed simulations.



LIGO

LSC

LIGO Scientific Collaboration

Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Whitman College
American University
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
University of the West of Scotland UWS
Texas Tech University
清華大學 Tsinghua University
R·I·T
Max Planck Institute for Gravitational Physics Albert Einstein Institute
University of Strathclyde
Michigan
CITA ICAT
Università degli Studi del Sannio
NASA Goddard Space Flight Center
ICTP SAIFR
The University of Western Australia
University of Cambridge
The University of Chicago
Montana State University
The University of Mississippi
The University of Adelaide Australia
Southern University Agricultural & Mechanical College
Columbia University in the City of New York
Caltech
University of Minnesota
University of Birmingham
The University of Melbourne
UIB Universitat de les Illes Balears
University of Washington
UTRGV
University of Wisconsin Milwaukee
Cardiff University Prifysgol Caerdydd
Northwestern
Monash University
UF University of Florida
Georgia Institute of Technology
Korean Gravitational-Wave Group
LSU Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
PennState
Science & Technology Facilities Council Rutherford Appleton Laboratory

Theory

Gravitational waves as solutions of linearized GR:

$$\bar{h}_{\mu\nu} = A\epsilon_{\mu\nu}\exp(ik^\rho x_\rho)$$

Schematic of gravitational waves in a non-flat background:

$$g \sim \gamma + h$$

$$\lambda << c\,\frac{\gamma}{\dot{\gamma}}$$

$$R_{\mu\nu}(\gamma) - \tfrac{1}{2}\gamma_{\mu\nu}R(\gamma) \sim T^{\text{eff}}_{\mu\nu}[(hh)_{\text{avg}}]$$

$$\Box_\gamma h = 0$$

Obtain the background by averaging over the waves.

R. A. Isaacon

Are gravitational waves real? Do they carry energy?

Formalism was developed to identify outgoing radiation (Pirani, Bondi, Sachs, Goldberg, Newman, ...) using null coordinates (light-like trajectories) and the Weyl tensor.