A Brief History of Gravitational Waves: From Denial to Multi-Messenger Astronomy

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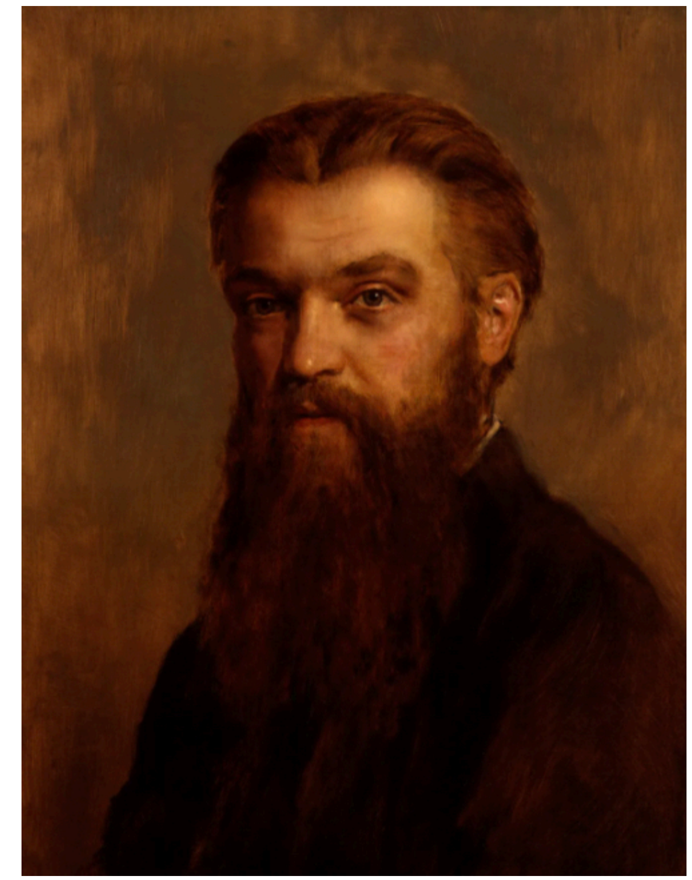
References

- Abraham Pais, **Subtle is the Lord**, Oxford, 2005.
- Harry Collins, **Gravity's shadow: The search for gravitational waves,** U of Chicago Press, 2004.
- Daniel Kennefick, **Traveling at the speed of thought: Einstein and the quest for gravitational waves,** Princeton UP, 2007.
- C.M. Chen, J.M. Nester & W. T. Ni, **A brief history of gravitational wave research,** arxiv # 1610.08803.
- J. L. Cervantes-Cota, S. Galindo-Uribarri and G. F. Smoot, **A Brief History of Gravitational Waves,** arxiv # 1609.09400.
- M. Díaz, G. González and J. Pullin, **The Sounds of the Cosmos, Gravitational Waves and the Birth of Multi-Messenger Astronomy**, MIT Press, 2023.

Prehistory

1876, William Kingdon Clifford: “I hold that…



(1) small portions of space are in fact of a nature analogous to little hills on a surface which is on average flat; namely that the ordinary laws of geometry are not valid for them.

(2) That the property of being curved or distorted is continually being passed on from one portion of space to another after the manner of a wave.

History: the first steps

- In 1779 Laplace wondered what would happen if gravity propagated at a finite speed.
- In 1900 Lorentz conjectured that gravitation “can be attributed to actions which can not propagate” faster than light. (Proc. K.Ak Amsterdam **8**, 603).
- In 1905 Poincaré coined the term “onde gravifique” (gravitational wave) discussing the extension of Lorentz invariance to gravitation (C. R. Ac. Sci. Paris **140**, 1504).

Einstein 1916: Weak field

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad \|h_{\mu\nu}\| \ll 1$$

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

$$\Box h'_{\mu\nu} = 0 \qquad \frac{\partial h'_{\mu\nu}}{\partial x'} = 0$$

Einstein 1918: Quadrupole formula

$$-\frac{dE}{dt} = \frac{G}{5c^5}\sum_{i,j} \dddot{Q}_{ij}\dddot{Q}_{ij}$$

$$Q_{ij} = \int \rho(x_i x_j - \tfrac{1}{2}\delta_{ij} r^2)\, d^3x \qquad h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{Q}_{\mu\nu}$$

- These calculations, although an approximation, provided a clear mathematical framework for the theory of gravitational radiation.
- But, being that no astrophysical sources were yet known, was it “real”?
- i.e. there was some skepticism regarding the detectability of gravitational radiation.
- There were not known solutions of Einstein’s eqs. representing astrophysical objects emitting gravitational waves.

1936: A letter to Max Born

Together with a young collaborator, I arrived at the interesting result that gravitational waves do no exist, though they had been assumed a certainty to the first approximation. This shows that the non-linear general relativistic field equations can tell us more or, rather, limit us more than we have believed up to now.

But in less than a year Einstein changed his view:

ON GRAVITATIONAL WAVES.

BY

A. EINSTEIN and N. ROSEN.

ABSTRACT.

The rigorous solution for cylindrical gravitational waves is given. For the convenience of the reader the theory of gravitational waves and their production, already known in principle, is given in the first part of this paper. After encountering relationships which cast doubt on the existence of *rigorous* solutions for undulatory gravitational fields, we investigate rigorously the case of cylindrical gravitational waves. It turns out that rigorous solutions exist and that the problem reduces to the usual cylindrical waves in euclidean space.

I. APPROXIMATE SOLUTION OF THE PROBLEM OF PLANE WAVES AND THE PRODUCTION OF GRAVITATIONAL WAVES.

It is well known that the approximate method of integration of the gravitational equations of the general relativity theory leads to the existence of gravitational waves. The method used is as follows: We start with the equations

$$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}R = -T_{\mu\nu}. \qquad (1)$$

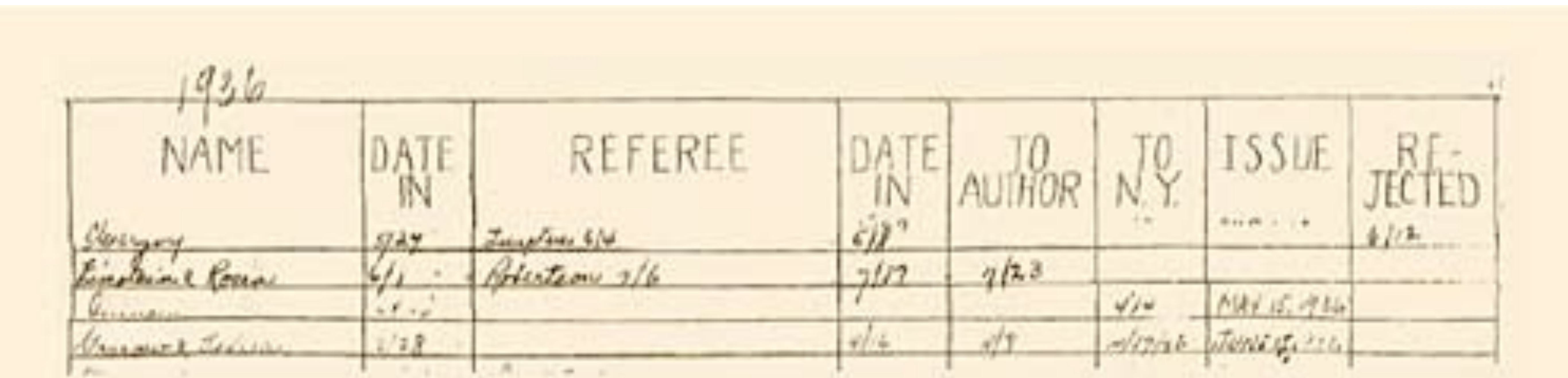
We consider that the $g_{\mu\nu}$ are replaced by the expressions

$$g_{\mu\nu} = \delta_{\mu\nu} + \gamma_{\mu\nu}, \qquad (2)$$

Journal of the Franklin Institute, January 1937, From Physics Today September 2005

What happened:

Einstein had submitted, before publishing the article shown in the previous slide, another version to PR with a result consistent to what he said in his letter to Max Born



1936

NAME	DATE IN	REFEREE	DATE IN	TO AUTHOR	TO N.Y.	ISSUE	RE-JECTED
[illegible]	[illegible]	[illegible]	[illegible]				[illegible]
Einstein & Rosen	6/1	Robertson 7/6	7/17	7/23			
[illegible]	[illegible]				[illegible]	May 15, 1936	
[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	

The PR log book: Percy Robertson was the referee

From Physics Today September 2005

The first solution representing gravitational waves

was published in **1925** by Guido Beck.
In 1943 he emigrated to Argentina taking a position in what is today the FAMAF, UNC. In 1944 he founded the Argentine Physics Association, the first one in Latin America. In 1951 he moved to Brazil, in 1975 to Centro Brasileiro de Pesquisas Fisicas.

Zeitschrift für Physik 713

Zur Theorie binärer Gravitationsfelder.

Von **Guido Beck** in Wien.

(Eingegangen am 11. Juli 1925.)

Im folgenden sollen im Anschluß an die von Weyl[1]) und Levi-Civita[2]) entwickelte Theorie der axialsymmetrischen Gravitationsfelder einige spezielle Fälle diskutiert werden.

The Problem of Motion of a Wave Source

- Einstein, Infeld and Hofman (EIH) (1938): motion of particles completely determined by the field equations (not like EM!).
- The 2-body problem does not have an analytical solution.
- One treatment: slow moving Newtonian bodies and calculate GR corrections with the solution as a power series in v/c and GM/rc^2.
- This is the post-Newtonian expansion. Quadrupole radiation formula was in doubt.

Next Chapter in the saga: But do they exist?

- The Berne conference, GR0 (1955, the year of Einstein's death): was held as a jubilee in honor of the fiftieth anniversary of SR.
- A small group of specialized physicists, Lichnerowicz, Pauli, Infeld, Hoffman, Fock, astronomers, Lemaitre mathematicians, Levi-Civita, de Donder, Darmois.
- The themes: the structure of the Einstein field equations (the initial value problem) and the problem of motion.

Berne II

- Gravitational waves, received little attention in 1955.

- Nathan Rosen, in his talk, basically reviewed his work with Einstein of 1937 in which they had expressed doubts about the existence of gravitational waves in the full non-linear theory.

- According to them, the plane wave solutions of the linearized theory do not correspond to any exact solution of the full theory.

Feynman's views Chapel Hill (GR1): The role of gravitation in physics conference - 1957

- There exists, however, one serious difficulty...and that is the lack of experiments.
- …how to deal with problems where no experiments are available? There are two choices:
- mathematical rigor...or
- play games...
- The attempt at mathematically rigorous solutions without guiding experiments is exactly the reason the subject is difficult, but not the equations.

DeWitt and Rickles, 2017

Feynman's views
A thought experiment

The friction will heat up the particle on the right.

Feynman’s views I

“I am not getting anything out of the meeting. I am learning nothing. Because there are no experiments, this field is not an active one, so few of the best men are doing work in it. The result is that there are hosts of dopes here (126) and it is not good for my blood pressure. Remind me not to come to any more gravity conferences!”

GR Conference Warsaw 1962.

A recap

- 1936 Einstein-Rosen.
- 1938 EIH first post-Newtonian order.
- 1941 Landau and Lifshitz quadrupole formula applies to GW from binary stars.
- 1955 Rosen argues GW cannot carry energy.
- 1957 Bondi, Feynman present thought experiments to show that GW carry energy.
- 1962 Bondi and the News function: systems which emit GW loose mass.

A recap (cont)

- 1960 Infeld and Plebanski text-book
- 1965 Smith and Havas using fast motion calculations find energy gained by binary systems.
- 1970 Chandrasekhar and Esposito recover quadrupole formula for a binary star system (physically extended bodies).
- 1979 Rosen argues that binary stars do not lose energy.

After the war: the anti-gravity machine

- Gravity Foundation and Roger Babson.
- USAF main source of funding until 1970.
- A higher level than NSF.
- There was a relativity group at Wright-Patterson.
- J. Goldberg (1993).
- Mansfield Amendment (1969).

Jon Ronson's The Men who stare at goats

The low watermark 1930-60's

- The term was coined by Jean Eisenstaedt.
- Eventually DoD financing ended.
- Richard Isaacson goes to NSF.
- 1930's Karl Jansky finds a source of radio antennas noise in the Milky Way.

An important result during the low watermark

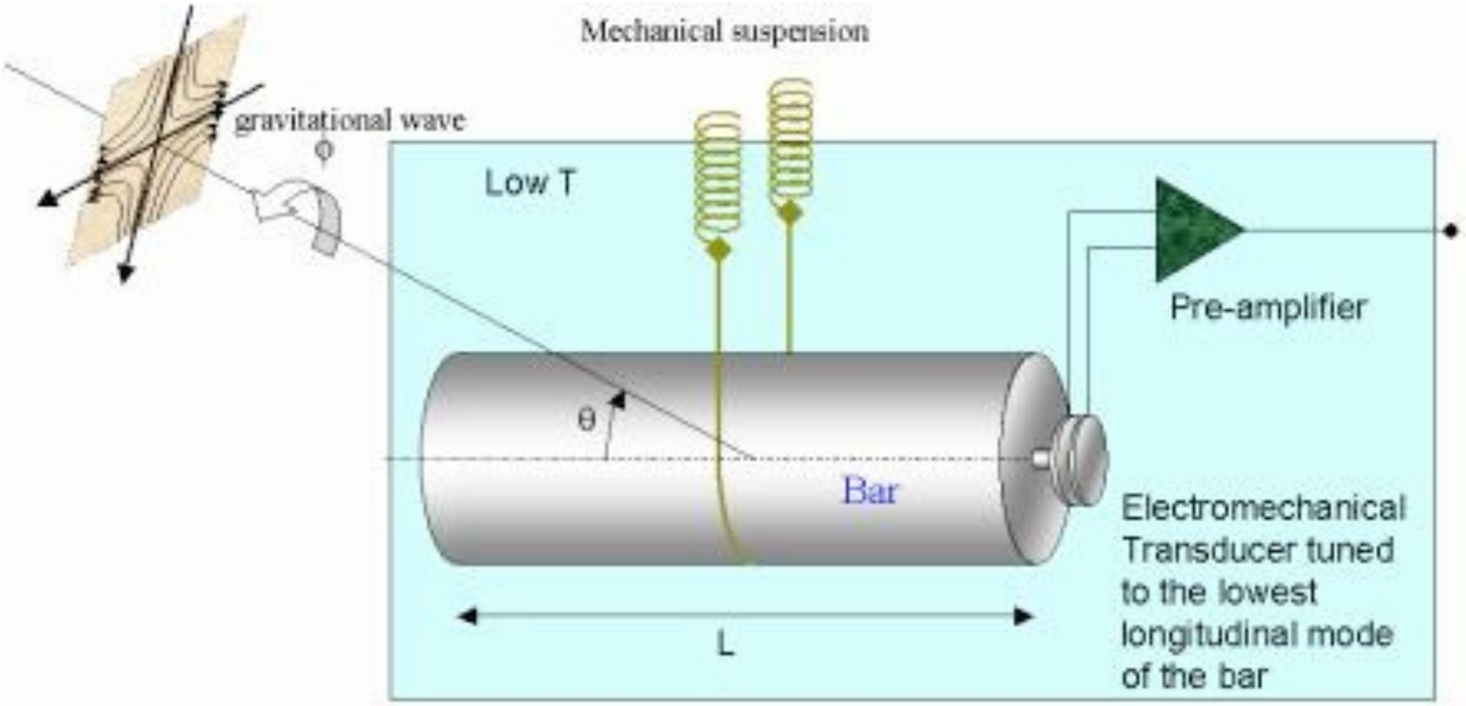
- Tolman–Oppenheimer–Volkoff (TOV) equation constrains the structure of a spherically symmetric body of isotropic material which is in static gravitational equilibrium, as modeled by general relativity.

$$\frac{dp}{dr} = -\frac{(\rho + p)(m + 4\pi r^3 p)}{r(r - 2m)},$$

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho$$

- The Tolman–Oppenheimer–Volkoff limit (or TOV limit) is an upper bound to the mass of cold, nonrotating neutron stars, analogous to the Chandrasekhar limit for white dwarf stars.

Joe Weber



Resonant bar detectors: very narrow band and limited sensitivity

VOLUME 17, NUMBER 24 PHYSICAL REVIEW LETTERS 12 DECEMBER 1966

OBSERVATION OF THE THERMAL FLUCTUATIONS OF A GRAVITATIONAL-WAVE DETECTOR*

J. Weber†
Department of Physics and Astronomy, University of Maryland, College Park, Maryland
(Received 3 October 1966)

We report operation of apparatus to measure the Fourier transform of the Riemann curvature tensor at sensitivity limited by the thermal fluctuations. The gravitational interaction drives a mechanical system which in turn is coupled to the electromagnetic field. Strains as small as a few parts in 10^{16} are observable for a compressional mode of a large cylinder.

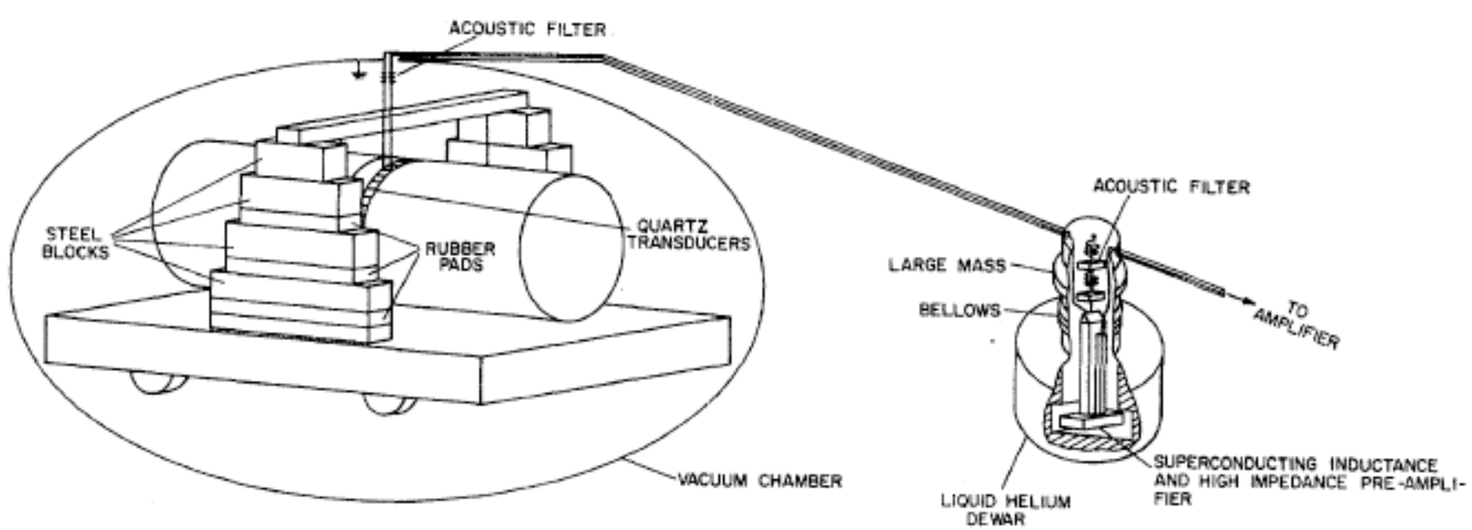


FIG. 1. Schematic diagram of apparatus to measure Fourier transform of the Riemann tensor.

FAPESP Advanced School, Sao Paulo, May 30, 2023

Bar detectors start the field of experimental GW detection

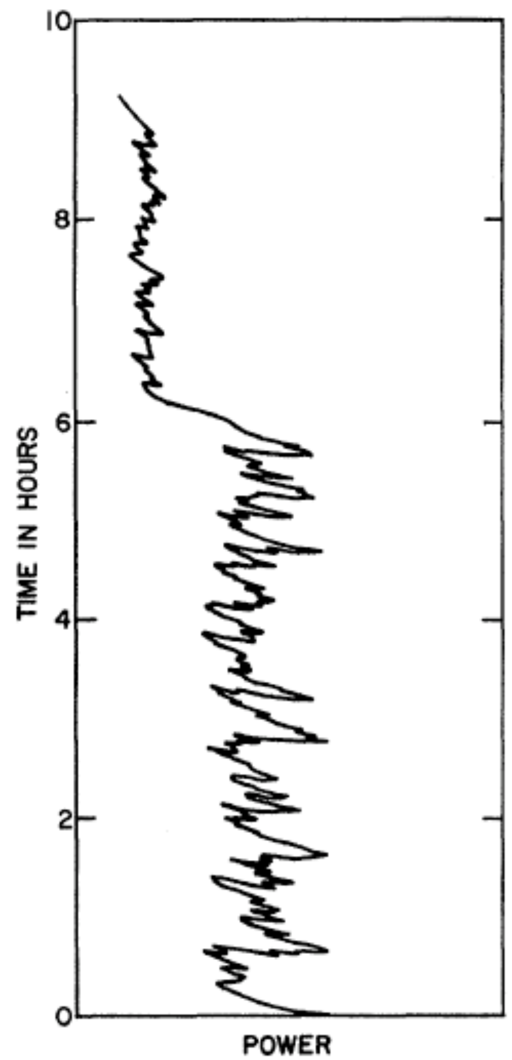


FIG. 2. Noise power output with cylinder tuned and detuned from preamplifier electronics.

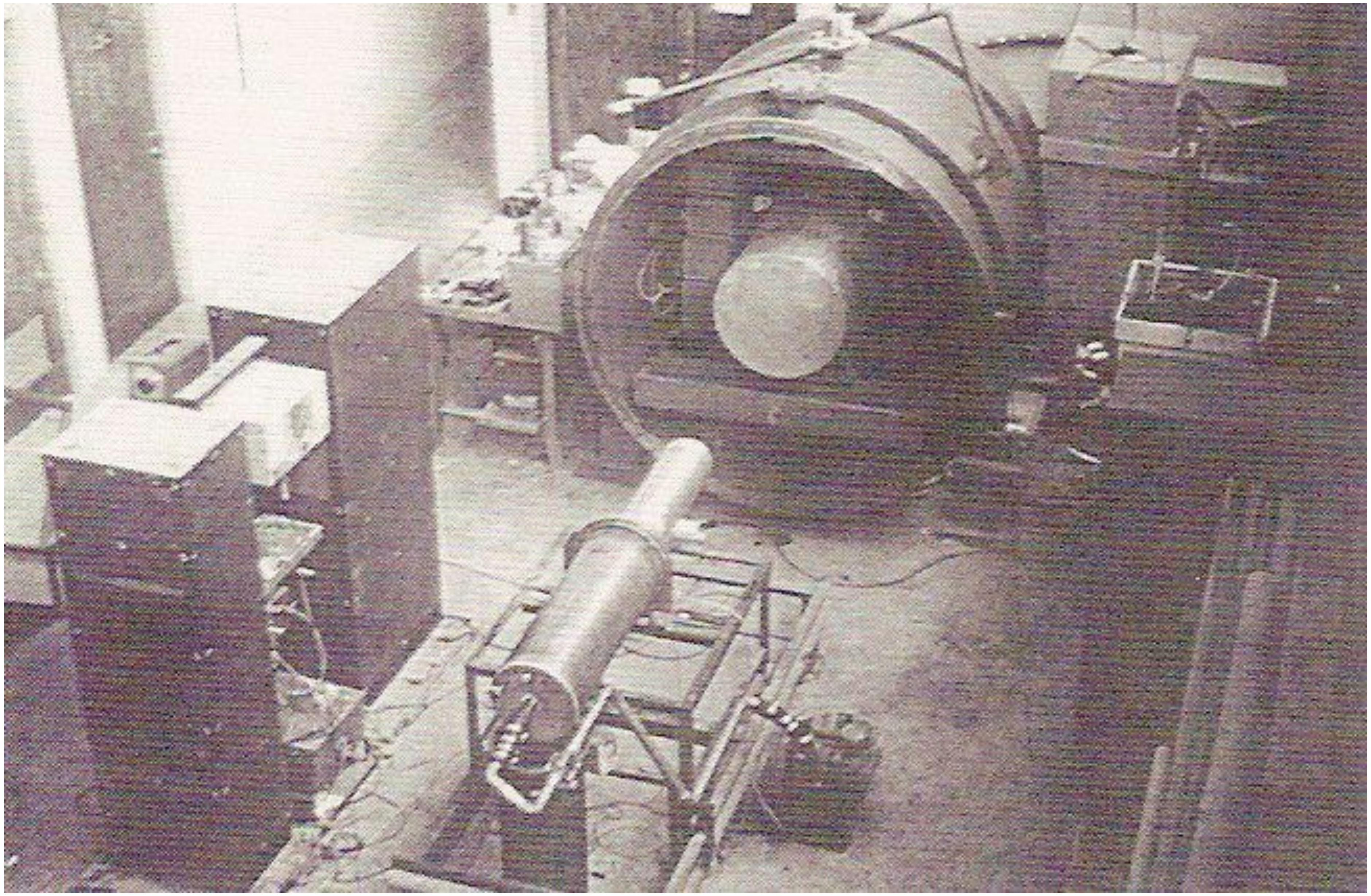
1. Sinsky: proved the sensitivity through calibration to detect changes in one bar induced by controlled changes in another one.

2. The detector was suspended in a vacuum chamber on acoustic filters with strongest sensitivity at 1660 Hz.

3. Quartz strain gauges converted mechanical strain to voltages.

4. The bar was sensitive to strains of 10^{-16}.

Sinsky's calibration



Absence of Gravity-Wave Signals in a Bar at 1695 Hz

James L. Levine and Richard L. Garwin
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 14 May 1973)

A 118-kg bar shows vector amplitude changes ("impulses") in successive 24-msec intervals which correspond to bar energies E distributed with a probability $N = N_0 \exp(-E/kT_e)$, with $T_e \sim 30$ K. Not more than one impulse larger than 537 K was observed in 9 days. Calibration impulses giving the bar 600 K of energy were detected with 60% efficiency above a 537-K threshold. In the following Letter, these results are contrasted with the gravity-wave detections of Weber.

Single Gravity-Wave Detector Results Contrasted with Previous Coincidence Detections

Richard L. Garwin and James L. Levine
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 14 May 1973)

Coincidence detectors of Weber have given a 10:1 ratio (R^*) of prompt to delayed coincidences. Simplified analysis indicates that such an R^* would require daily gravity-wave incidence rate and energy depositions that would have been seen in the single-bar detector of the preceding Letter (and were not), suggesting that Weber's 1969-1970 events were not produced by gravity waves or that such waves do not exist in similar numbers and intensity in 1973.

SN1987A

Supernova 1987A Gravitational Wave Antenna Observations, Cross Sections, Correlations with Six Elementary Particle Detectors, and Resolution of Past Controversies

Joseph Weber

Essays in Honor of Ted Newman (1991)

IL NUOVO CIMENTO C
Volume 13, Number 1, 19-33, DOI: 10.1007/BF02515772

SN 1987 A: Correlations between the Maryland and Rome gravitational wave detector data and the Mont Blanc and Kamiokande neutrino detector data

G. V. Pallottino

Abstract

Signals from SN 1987A in Amaldi-Weber antennas as the possible detection of scalar gravitational waves.
Baryshev, Yu. V.
AA(Astronomical Institute of St. Petersburg University)
Astrophysics, Volume 40, Issue 3, pp.244-251 (Ap Homepage)
07/1997
ARI; SPRINGER
Gravitational Radiation: Supernovae, Gravitational Radiation: Detection, Gravitational Radiation: Antennas
10.1007/BF03035737
1997Ap.....40..244B

The new Astrophysics

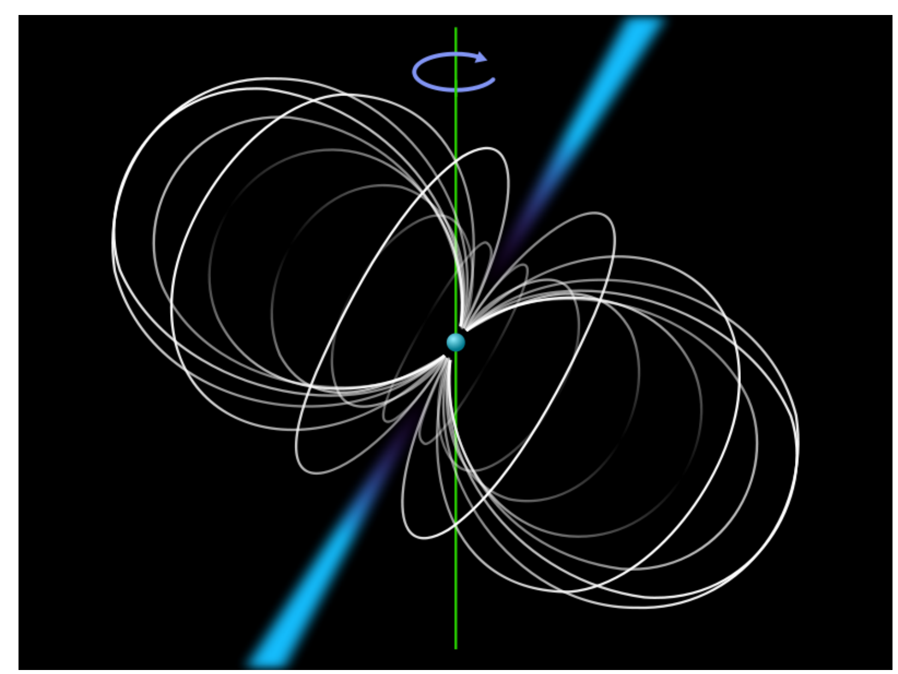
- 1950’2 a mysterious radio source can not be identified: Quasars.

- The 60’: quick development of astrophysics.

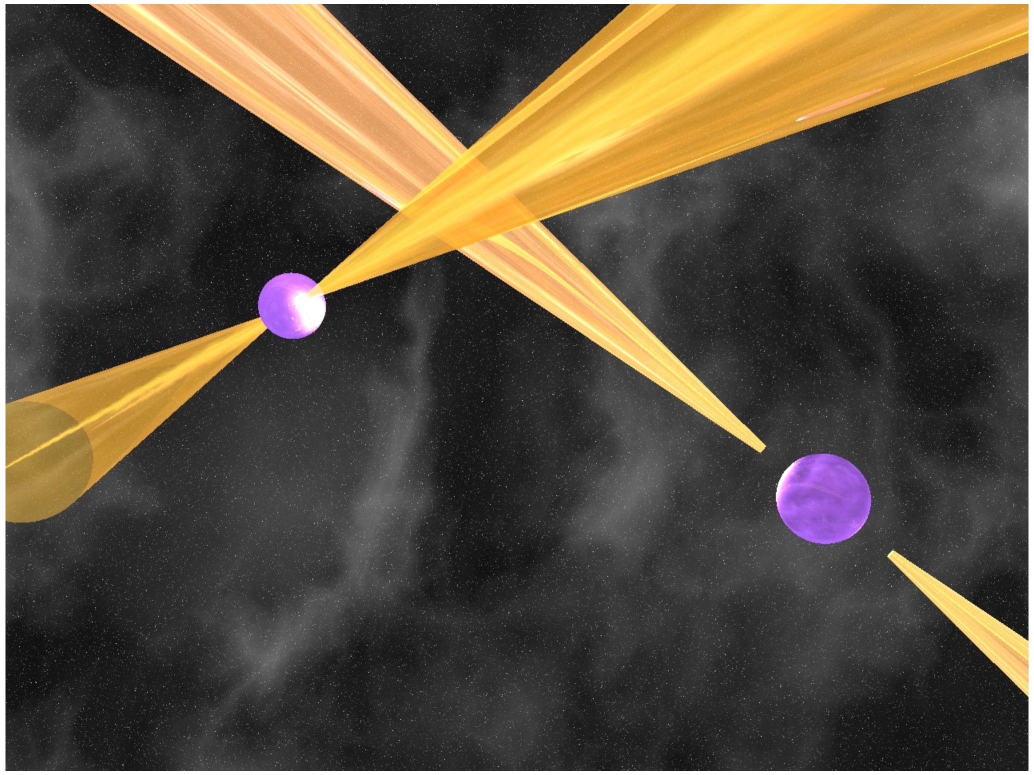
- Jocelyn Bell and Antony Hewish discovered a pulsating radio source (P=1.33s): LGM-1.

- 1963 Marteen Schmidt discovered the first quasar: 3C 273.

- Kerr metric: the birth of Relativistic Astrophysics.



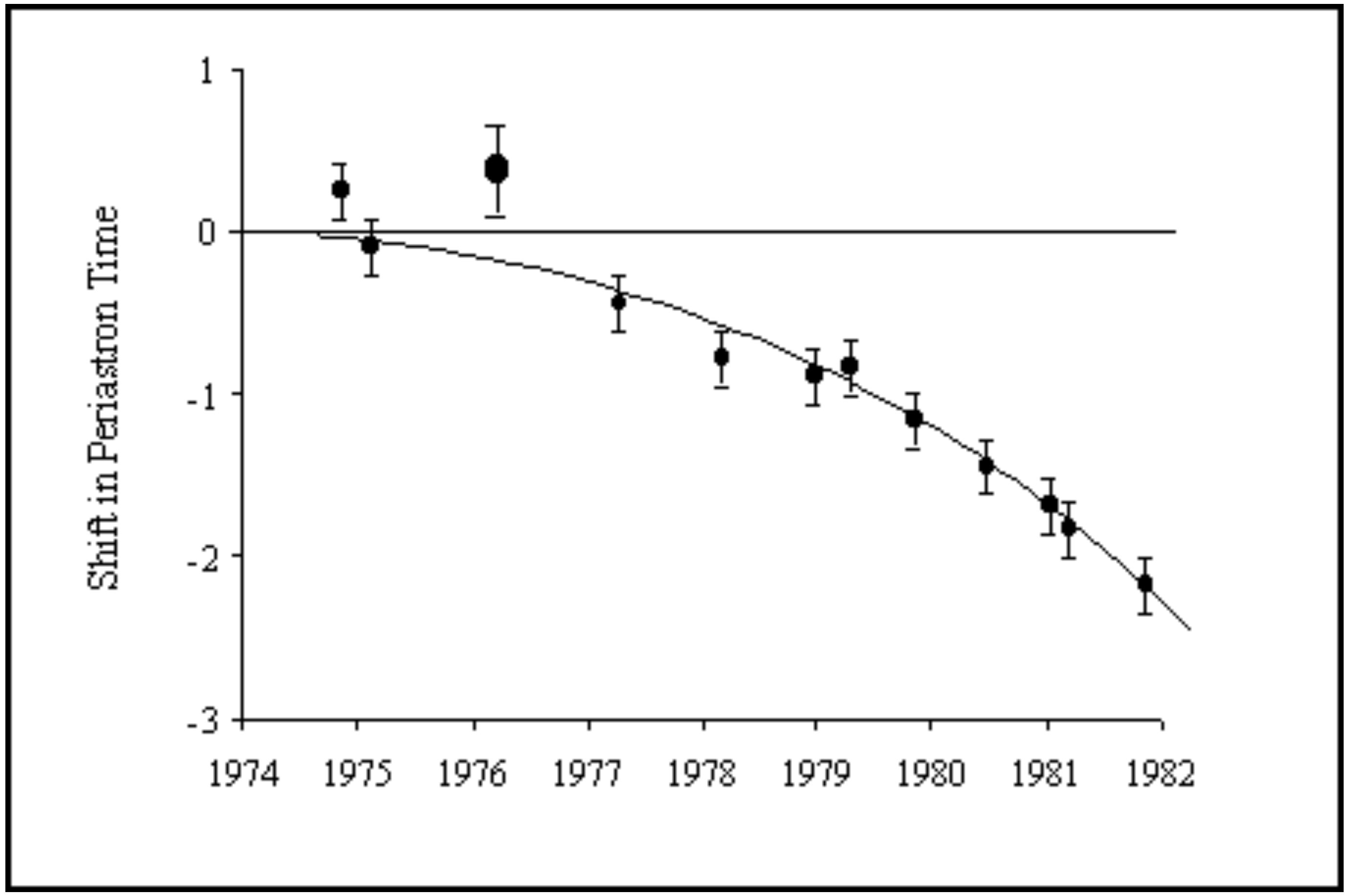
The binary pulsar



The first binary pulsar, PSR B1913+16 or the "Hulse-Taylor binary pulsar" was discovered in 1974 at Arecibo by Joseph Taylor, Jr. and Russell Hulse, for which they won the 1993 Nobel Prize in Physics.

These sources exist!

The Hulse and Taylor pulsar PSR 1913+16



The periastron advances 4.2 degrees p/day.

Weisberg *et al*. 1981

Reported in 1976 at the Texas Astrophysics Relativity Symposium

Two neutron stars in orbit

Each has mass 1.4 $M_\odot$ and the orbital period is 7.5 Hrs

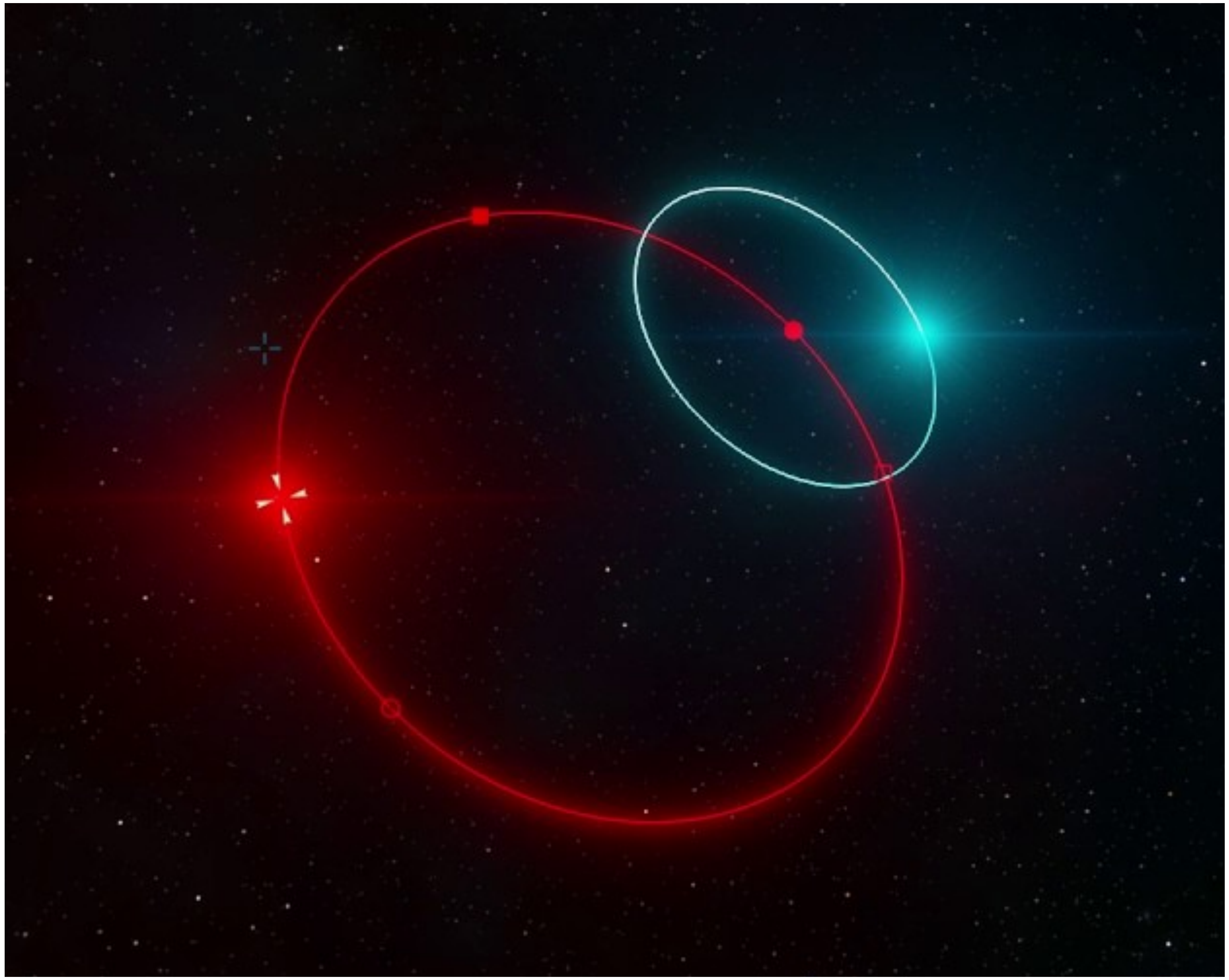
The stars are orbiting at a thousandth of the speed of light

Emission of the gravitational radiation causes the two stars to spiral towards each other getting closer and decreasing then the orbital period

The decrease, about 10 micro seconds per year, is *exactly* the one predicted by Einstein's theory (1 part in 10^{14}).

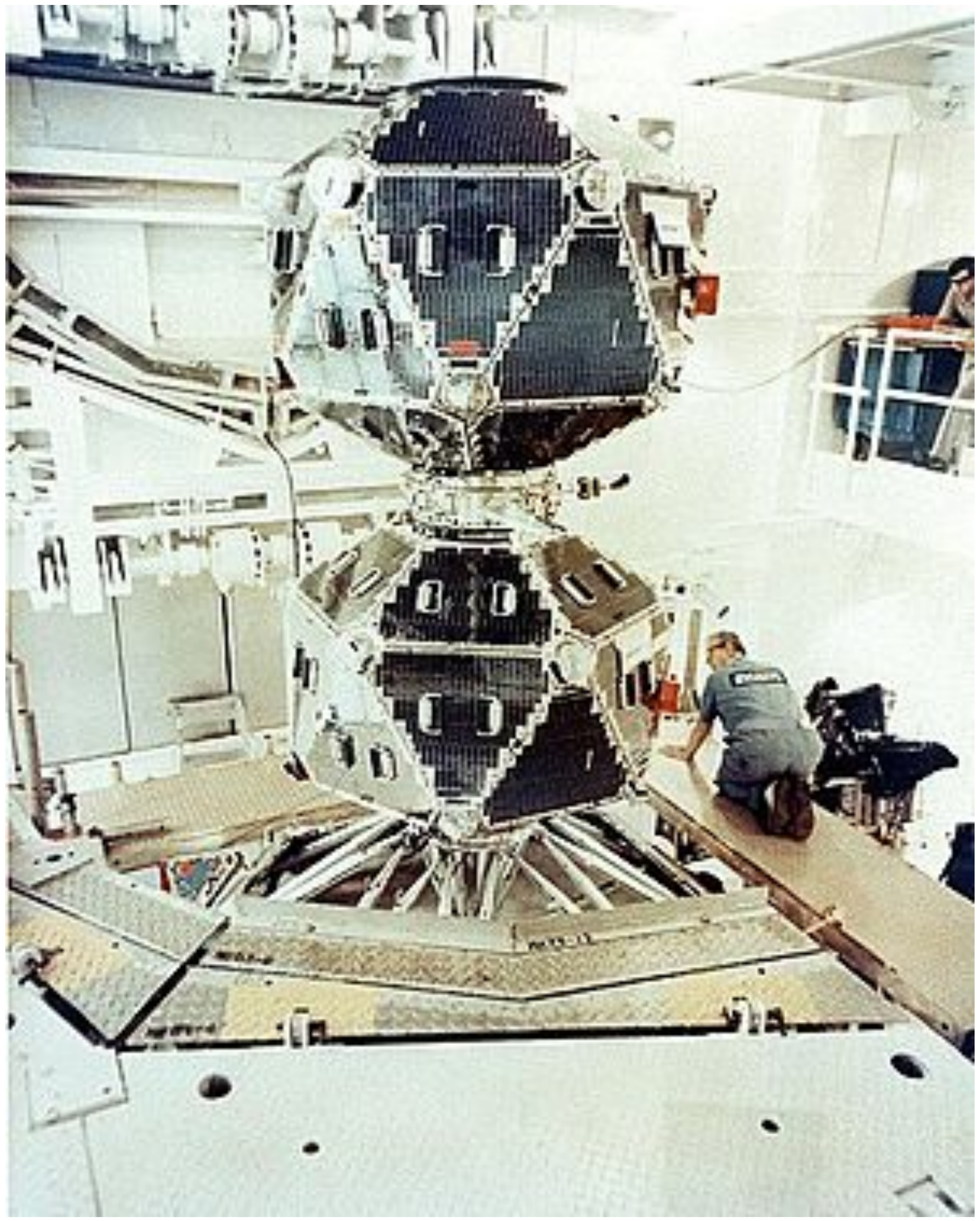
Eventually the binary system will coalesce emitting a burst of GW.
Just in a 300 million years!

The Holy Grail



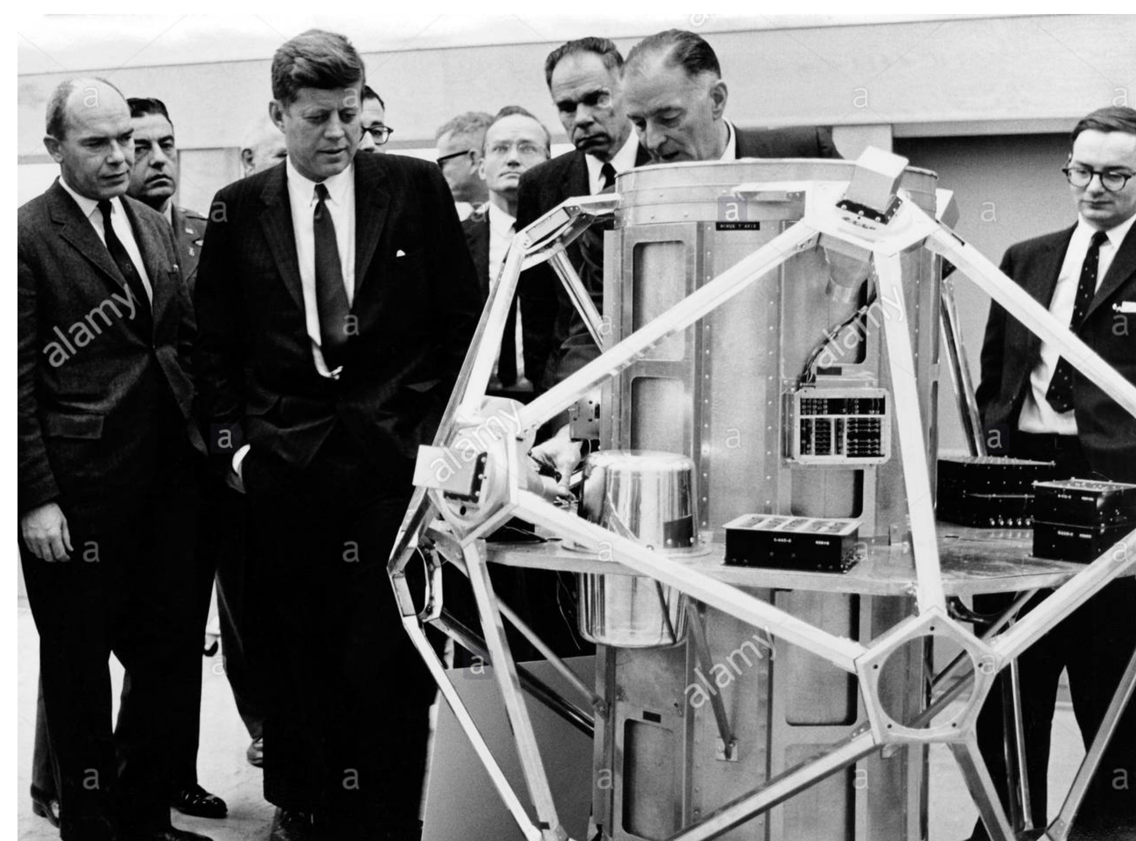
- Mercury’s perihelion precession 43 arcsec/100 year.
- PSR B1913+16: 4 degrees per year !

The Vela Satellites



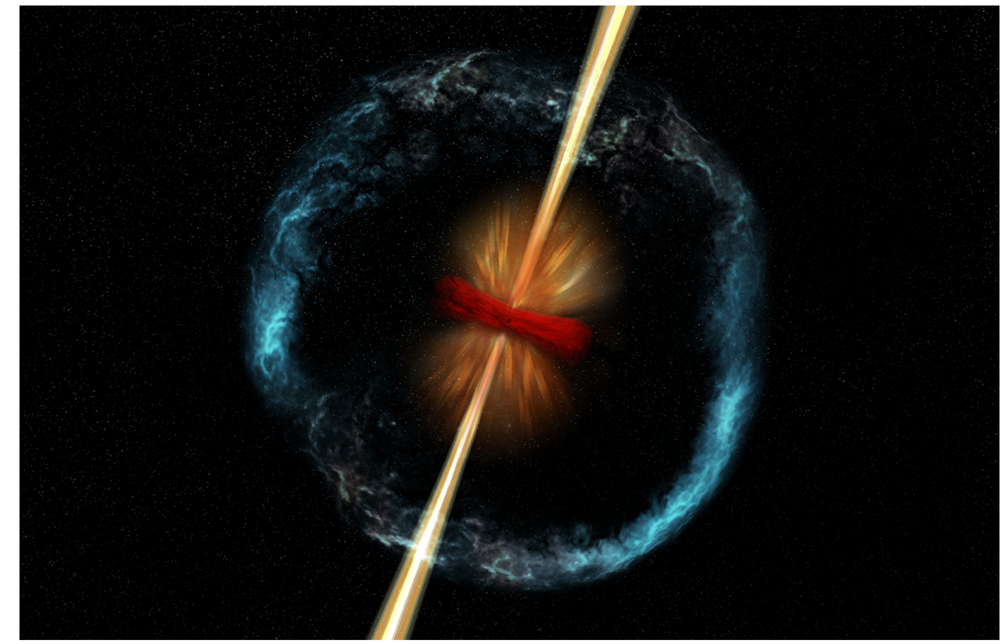
USA project to monitor compliance with the international nuclear testing banning treaty by the Soviet Union.

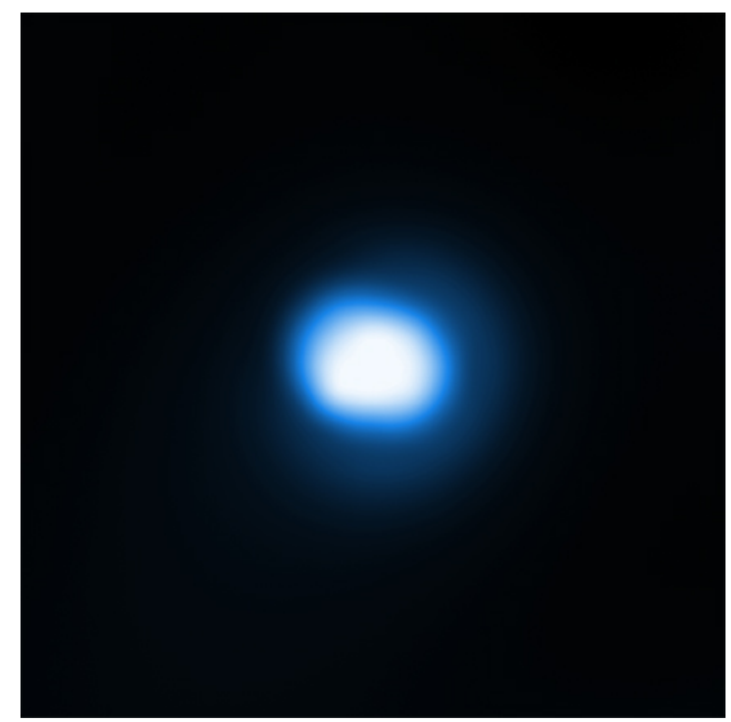
Image credit: wikipedia



GRBs

- GRBs can be classified:
- Longer than 2 seconds: now clearly associated with core collapse of massive stars (supernovae)
- Less than 2 seconds ?
- Possible: neutron star collision.

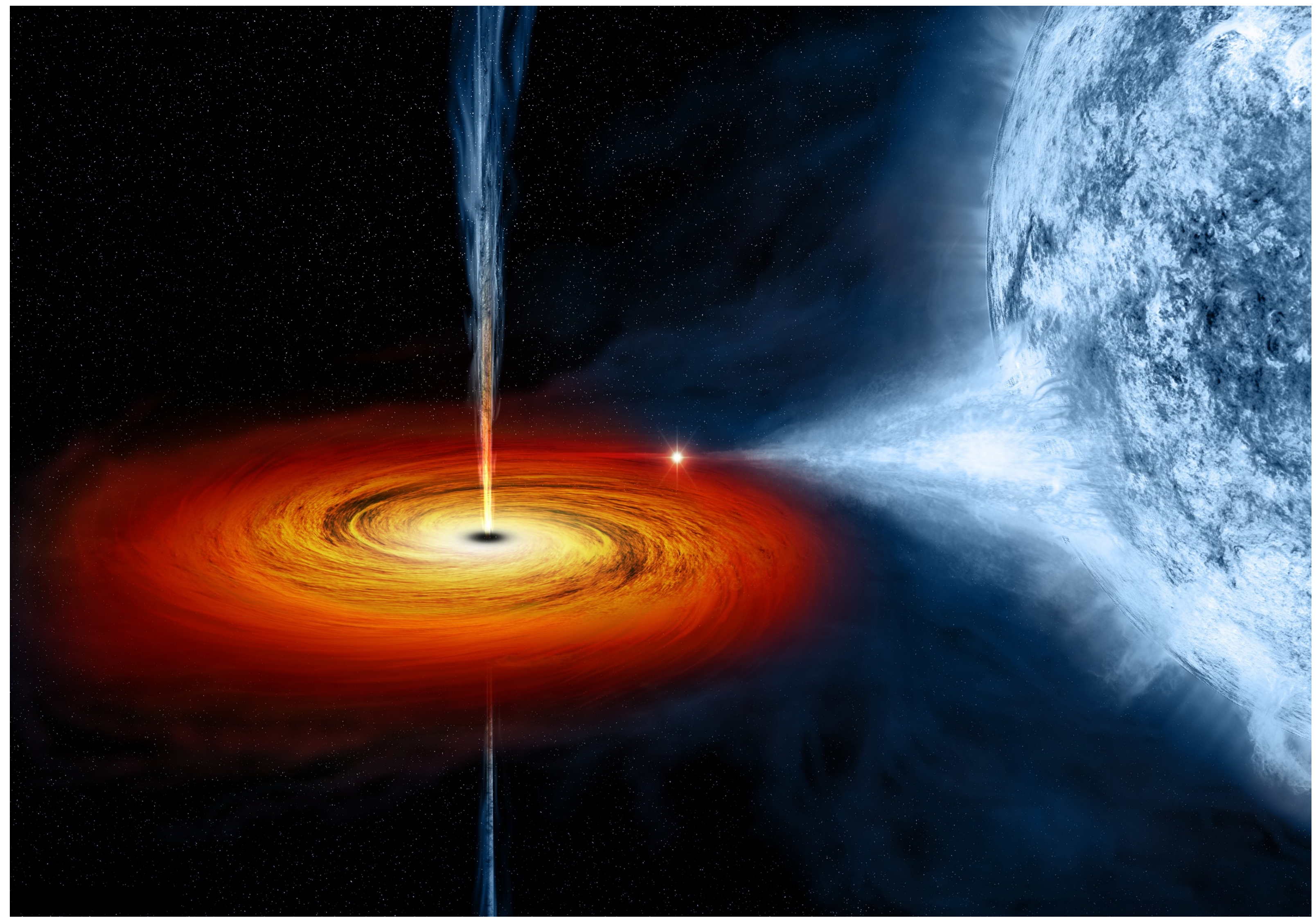




GRB 140903A credit Chandra, NASA

1971: Black Holes

- Cygnus X-1
- An X ray binary.
- BH are real!



Interferometers

SOVIET PHYSICS JETP VOLUME 16, NUMBER 2 FEBRUARY, 1963

ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES

M. E. GERTSENSHTEĬN and V. I. PUSTOVOĬT

Submitted to JETP editor March 3, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 605-607 (August, 1962)

It is shown that the sensitivity of the electromechanical experiments for detecting gravitational waves by means of piezocrystals is ten orders of magnitude worse than that estimated by Weber.[1] In the low frequency range it should be possible to detect gravitational waves by the shift of the bands in an optical interferometer. The sensitivity of this method is investigated.

Experts Clash Over Project To Detect Gravity Wave

By MALCOLM W. BROWNE
Published: April 30, 1991

A PROPOSAL to stake $211 million in public money on the chance that gravity waves could be exploited to fathom black holes and other cosmic enigmas has deeply divided scientists and will force Congress to make a difficult decision in the next few weeks.

But many, if not most, American astronomers believe the observatories could be financed only at the expense of hundreds of smaller research projects, many of which would be more likely to produce important results.

When he was asked to testify last month before a panel of the House Committee on Science, Space and Technology, Dr. J. Anthony Tyson, an astrophysicist at A.T.&T. Bell Laboratories who is chairman of the Astronomy Advisory Committee of the National Science Foundation, prepared by polling astronomers as to their views about the project.

"I perused a list of about 2,000 astronomers and picked 70 who seemed to me likely to have thought about LIGO," Dr. Tyson said in an interview. "I got 60 replies, and they ran 4 to 1 against LIGO. Most of the astrophysical community seems to feel it would be very difficult to get any important information from a gravity-wave signal, even if one should be detected." A Difficult Decision

The challenge

Imagine this distance: around the world 100,000 million times (the total is 3, 840 billions of kilometers, or a million times the distance from Earth to Neptune). Take two small objects separated by this distance. A strong gravitational wave will modify it less than the thickness of a human hair. There is less than a few tenths of a second to measure this. And we don't know if this event will happen next month, next year or in thirty years.

(testimony from Anthony Tyson to the subcommittee of Science from the Committee of Science, Space and Technology in the House of Representatives when the construction of LIGO was under consideration, March 13 1991).

FROM THE ARCHIVES

Don't hold your breath for massive gravity wave

July 11, 2013

Leggo My LIGO : Feud Between Two Key Researchers Rattles $250-Million Gravity-Wave Project; Officials Say It Is Still 'On Track'

April 28, 1993 | MARK A. STEIN | TIMES SCIENCE WRITER

A $250-million project to detect gravity waves has been rattled by two California Institute of Technology scientists who have been making waves of a different kind by feuding over how to manage the National Science Foundation program.

Researchers familiar with the project said program manager Rochus Vogt at one point locked gravity-wave expert Ronald Drever out of his Pasadena office and denied him access to computers after an exchange over the need to keep the project on schedule versus a desire to do more research.

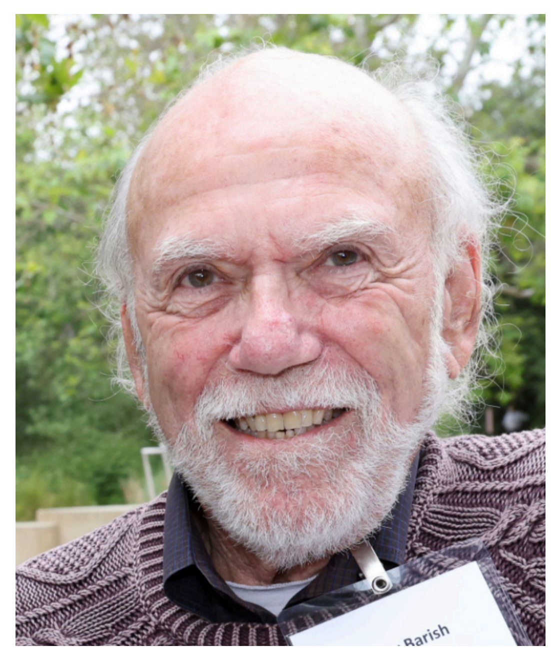
David Berley, the NSF official in charge of the program, said it is now "on track and functioning well."

Vogt was out of the country Tuesday, and Drever declined to comment. University administrators said policy forbids discussion of personnel matters, but they emphasized that "all concerned parties are working hard toward the goals of the . . . project."

But Lew Allen, chairman of a faculty oversight committee established last December to keep the project on track, indicated Tuesday that the professional disagreement that dates back at least to last summer has not yet been fully resolved.

1996: Breaking Ground

And they were built!



FAPESP Advanced School, Sao Paulo, May 30, 2023

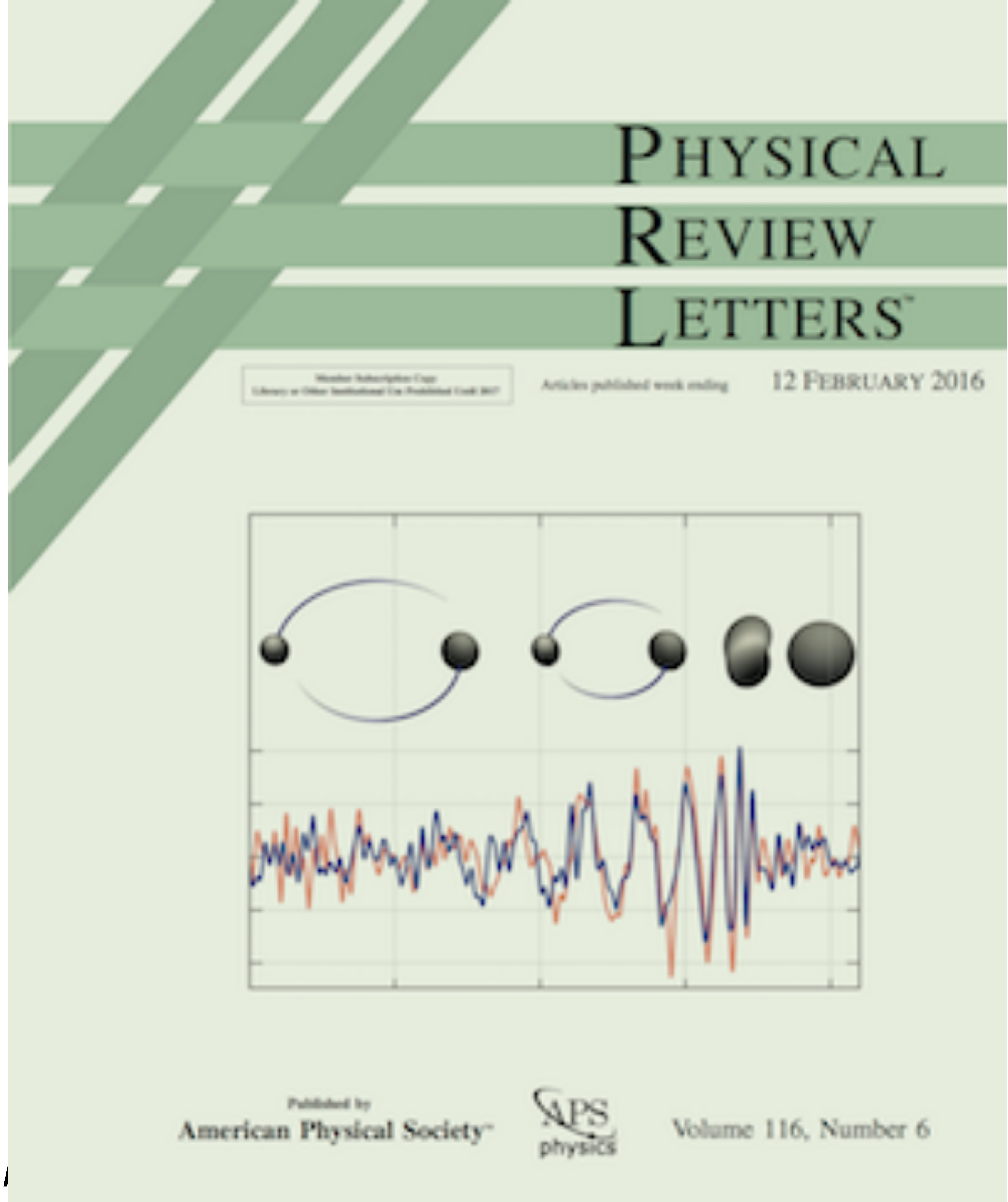
Numerical Relativity

- ADM formalism (1950s).
- Hahn and Lindquist (1964), first attempt.
- L. Smarr Eppley (1965).
- Richard Stark and Tsvi Piran (1980) -rotating collapse-.
- Binary Black Hole Grand Challenge Alliance, first head on collision.
- Lazarus project late early 2000.

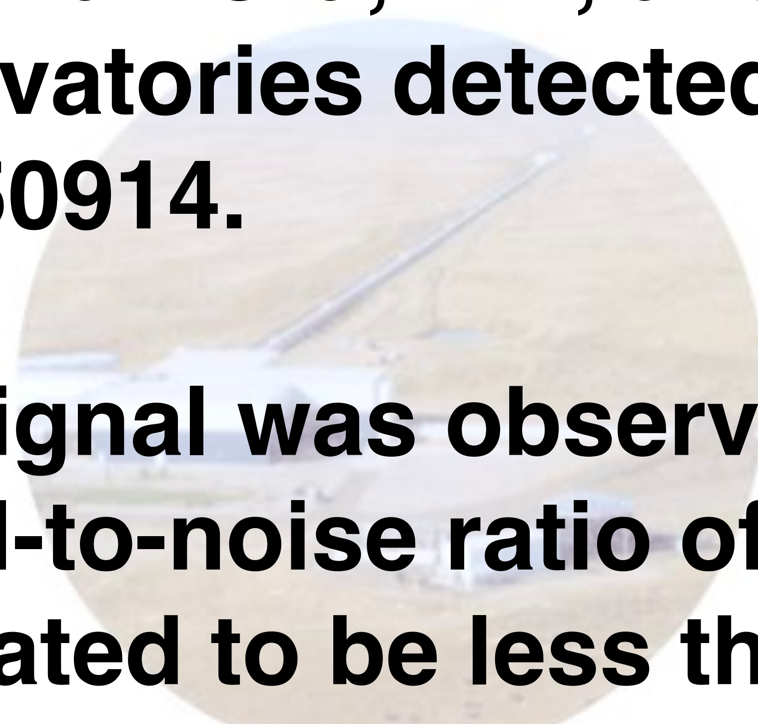
Full evolution

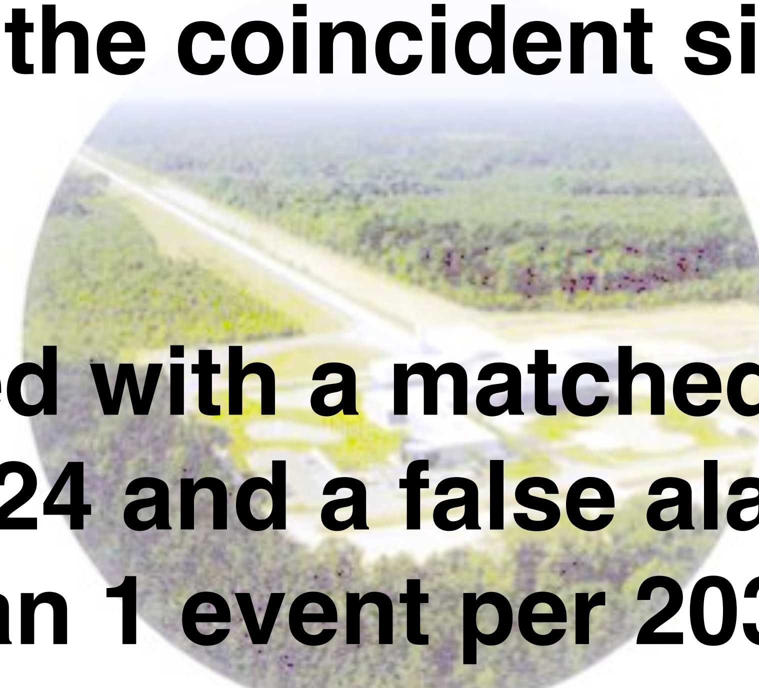
- M. Campanelli, C.O. Lousto, P. Marronetti, and Y. Zlochower: "Accurate Evolutions of Orbiting Black-Hole Binaries without Excision", Phys. Rev. Lett. 96, 111101 (2006)
- John G. Baker, Joan Centrella, Dae-Il Choi, Michael Koppitz, and James van Meter: "Gravitational-Wave Extraction from an Inspiraling Configuration of Merging Black Holes", Phys. Rev. Lett. 96, 111102 (2006)

The end of a long journey: GW150914



The end of History: Detection





- **On September 14, 2015 at 09:50:45 UTC, the LIGO Hanford, WA, and Livingston, LA, observatories detected the coincident signal GW150914.**

- **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.**

Physical Parameters

- One $36^{+5}_{-4} M_\odot$ BH, the other $29^{+4}_{-4} M_\odot$. One final BH $62^{+4}_{-4} M_\odot$
- Luminosity distance 410^{+180}_{-160} Mpc. Equivalent to a $z = 0.09^{+0.03}_{-0.04} M_\odot$
- $3.0^{+0.5}_{-0.5} M_\odot$ radiated away in gravitational waves.
- Final BH spin $0.67^{+0.05}_{-0.07}$

Historic result

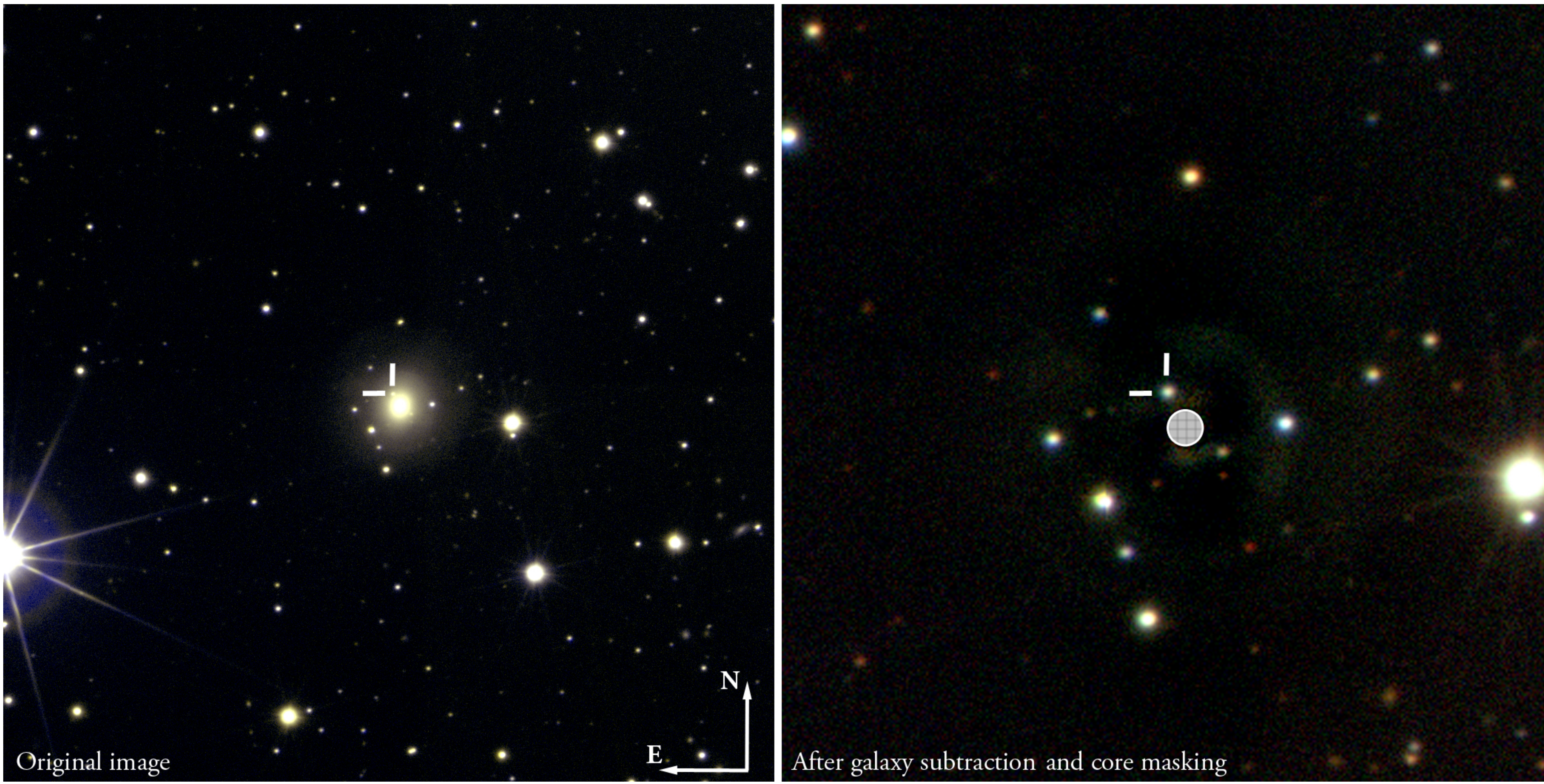
- All uncertainties define 90% credible intervals.
- These observations demonstrate the existence of binary stellar-mass black hole systems.
- This is the first direct detection of gravitational waves and,
- the first observation of a binary black hole merger.

Multi-messenger Astronomy

Dismissing our Sun for its domesticity (Davis, 1968) only three clear events so far:

- SN1987A (Hirata et al, 1987).
- GW170817-GRB170817A-AT2017gfo (Abbott et al. , 2017).
- Blazar TXS 0506+056 Flaring, IceCube-170922, (Aartsen et al. 2018).

August 17, 2017



Díaz et al, 2017

GW170817-GRB170817A-AT2017gfo

- Two neutron stars in the galaxy NGC4993 collided about 140 million years ago. Gravitational and electromagnetic waves travel from the big explosion reaching our earth on August 17 2017.
- GWs first detected by AdLIGO and AVIRGO (Abbott et al. 2017), GRB 170817A by Fermi and INTEGRAL (Goldstein et al. , Savchenko et al. , 2017)
- Then AT2017gfo (Coulter et al. 2017;, Valenti et al. 2017;, Tanvir et al. 2017, Lipunov et al. 2017, Soares-Santos et al. 2017, Arcavi et al. 2017)

GW170817: Multimessenger Astronomy

The End

Credit: Caltech-LIGO-NSF

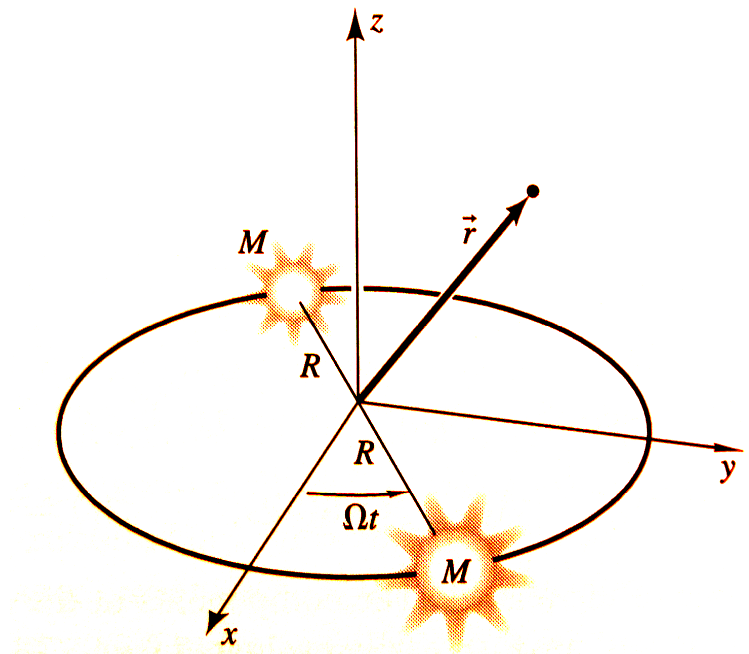
Extra slides

Binary systems

$$I_{\mu\nu} = \int dV \left(x_\mu x_\nu - \frac{1}{3}\delta_{\mu\nu} r^2\right) \rho(\vec{\mathbf{r}})$$

The associated metric perturbation is:

$$h_{\mu\nu} = \frac{2G}{Rc^4} \ddot{I}_{\mu\nu}$$



$$I_{xx} = 2Mr_o^2[\cos^2(2\pi f_{orb}t) - \frac{1}{3}]$$

$$I_{yy} = 2Mr_o^2[\sin^2(2\pi f_{orb}t) - \frac{1}{3}]$$

$$I_{xy} = I_{yx} = 2Mr_o^2 \cos(2\pi f_{orb}t)\sin(2\pi f_{orb}t)$$

$$I_{zz} = -\frac{1}{3}Mr_o^2$$

$$h_{xx} = -h_{yy} = \frac{32\pi^2 G}{Rc^4} M r_o^2 f_{orb}^2 \cos[2(2\pi f_{orb})t]$$

$$h_{xy} = h_{yx} = \frac{32\pi^2 G}{Rc^4} M r_o^2 f_{orb}^2 \sin[2(2\pi f_{orb})t]$$

$$f_{orb}^2 = \frac{GM}{16\pi^2 r_o^3}$$

With this estimation of the angular frequency

$$|h| \simeq \frac{r_{s_1} r_{s_2}}{r_o R} \rightarrow h = |h_{\mu\nu}| \simeq 1x10^{-21}$$