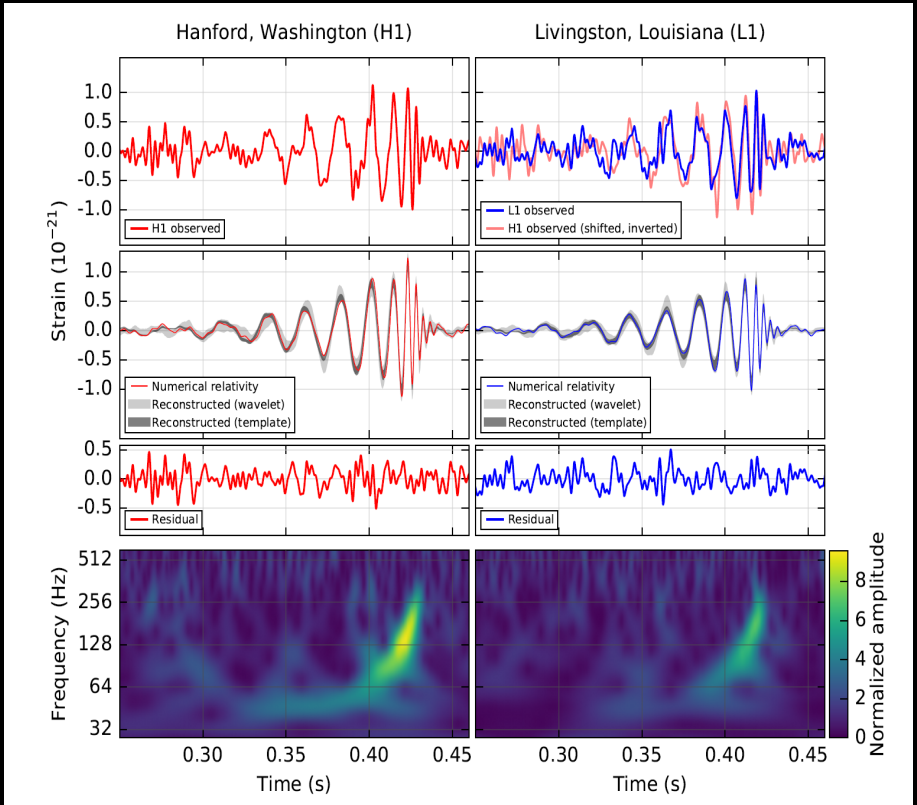
“From Einstein to Gravitational Waves”

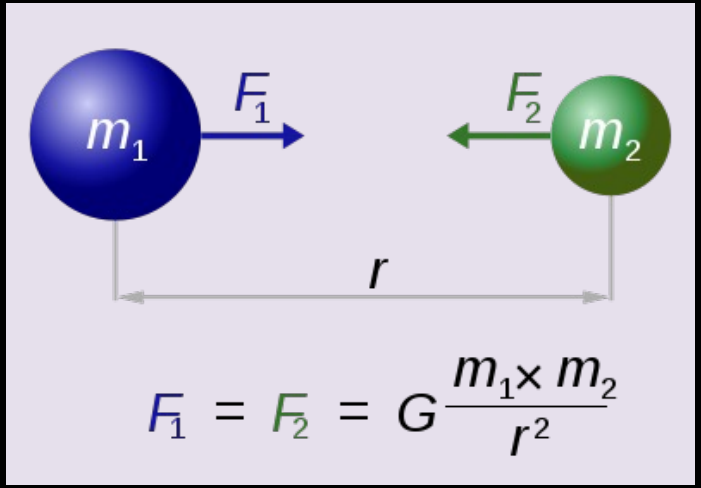


“The Onassis Foundation Science Lecture Series 2022 in Physics”

Barry C Barish
Caltech and UC Riverside

27-July-2022

Sir Isaac Newton



Universal Gravity: force between massive objects is directly proportional to the product of their masses, and inversely proportional to the square of the distance between them.

ISAACUS NEWTON EQ. AUR. &c.

PHILOSOPHIÆ NATURALIS PRINCIPIA MATHEMATICA.

AUCTORE

ISAACO NEWTONO, Eq. Aur.

Editio tertia aucta & emendata.

LONDINI

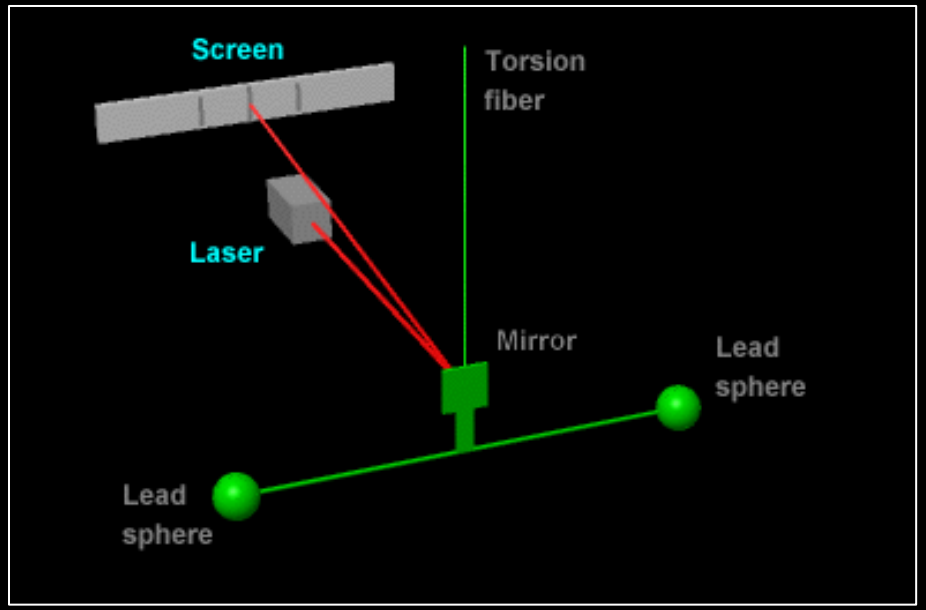
Apud Guil. & Joan. Innys, Regiæ Societatis typographos.

MDCCXXVI.

Henry Cavendish
(1731 – 1810)

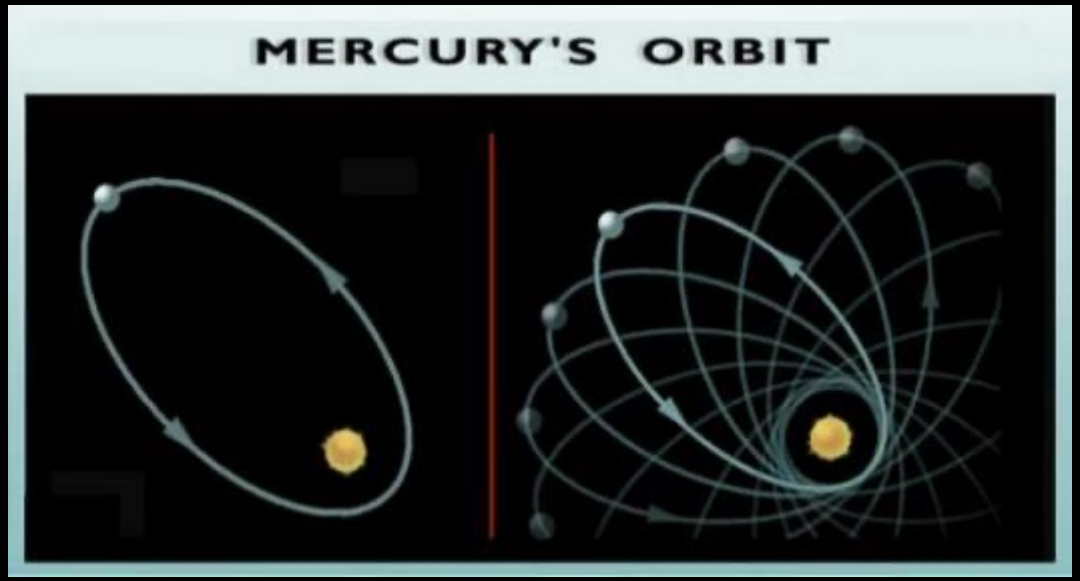
The Weight of the Earth

Torsion Balance



$$G = 6.67408 \times 10^{-11}\ N\ m^2\ Kg^{-2}$$

Only Observed Problem with Newton's Gravity by the time of Einstein - 1900s



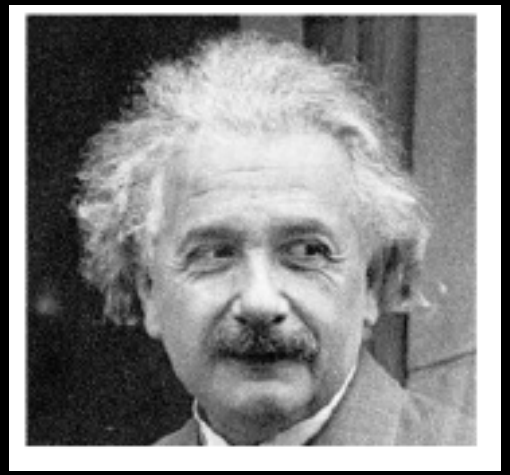
Mercury's elliptical path around the Sun. Perihelion shifts forward with each pass. (Newton 532 arc-sec/century vs Observed 575 arc-sec/century)
(1 arc-sec = 1/3600 degree).

General Relativity: Einstein's account of gravity

In 1915, Einstein reformed our understanding of gravity for the first time since Isaac Newton (1686).

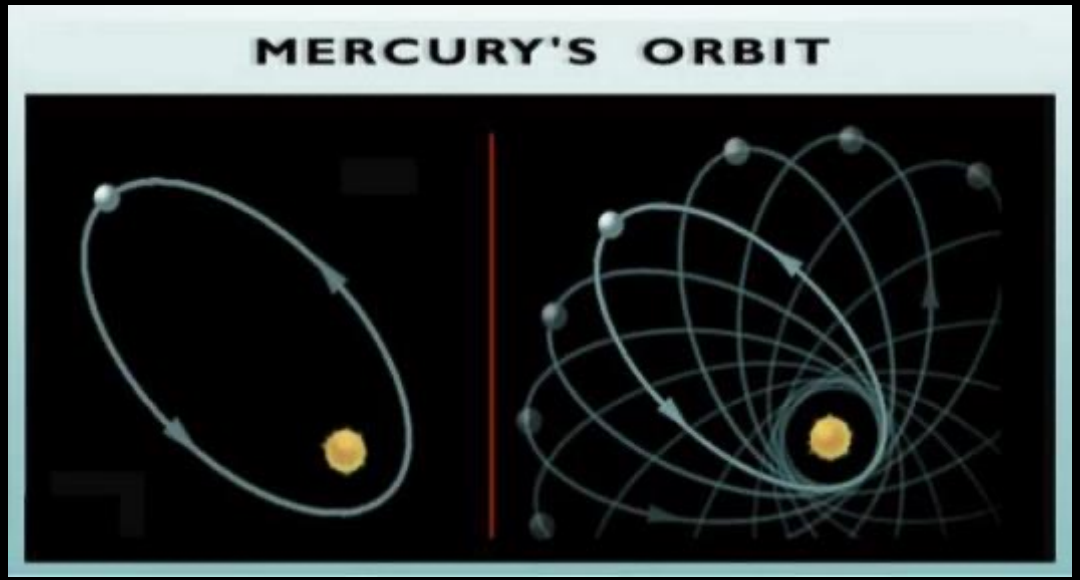
Gravity isn't a force that acts in space and time, but instead is built into the actual structure of space and time.

Space and time are *curved*; nothing can avoid feeling that curved structure. That is what makes gravity *universal*.



$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

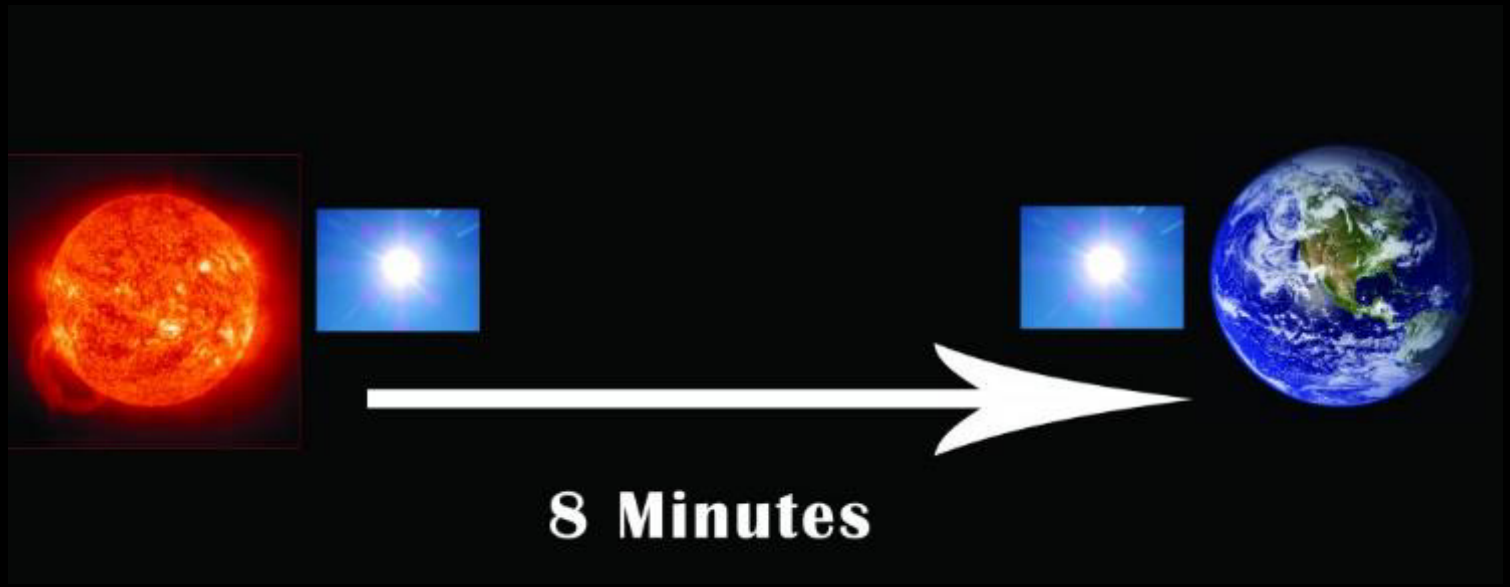
Einstein Solved the only Known Problem with Newton's Gravity



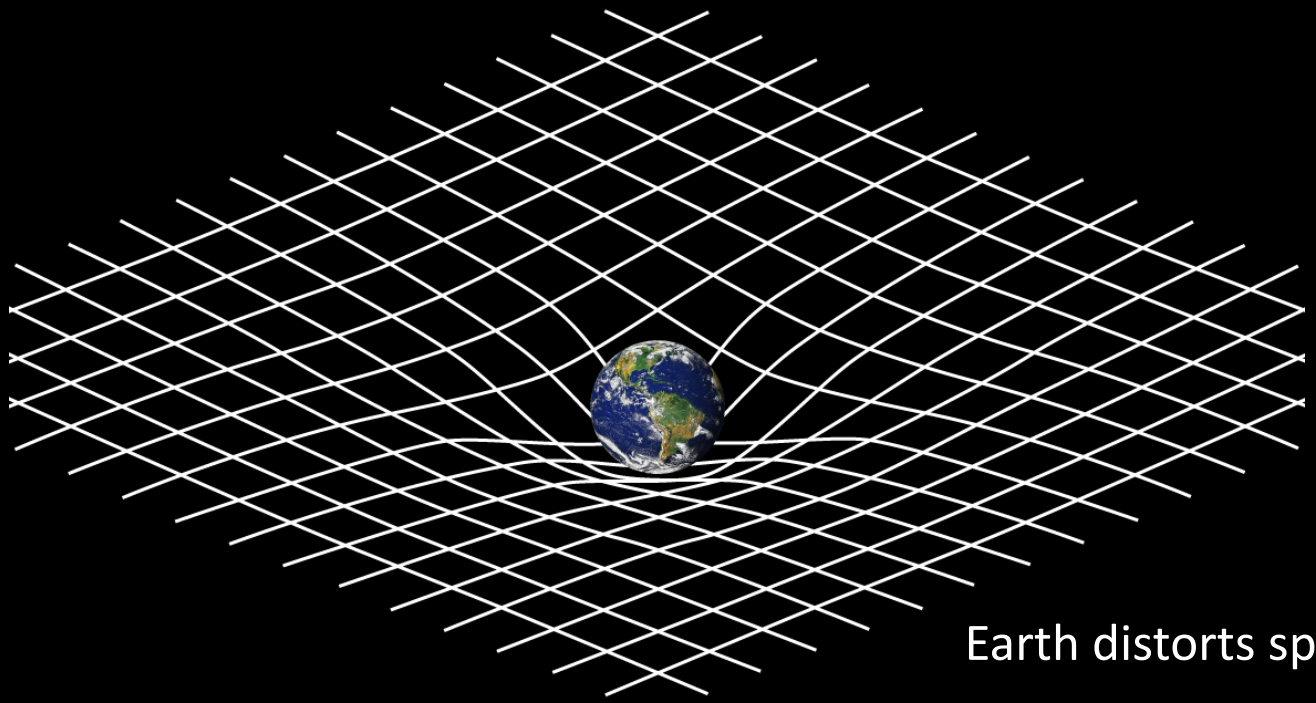
Mercury's elliptical path around the Sun. Perihelion shifts forward with each pass. (Newton 532 arc-sec/century vs Observed 575 arc-sec/century)
(1 arc-sec = 1/3600 degree).

Einstein Solved a Conceptual Problem with Newton's Theory of Gravity

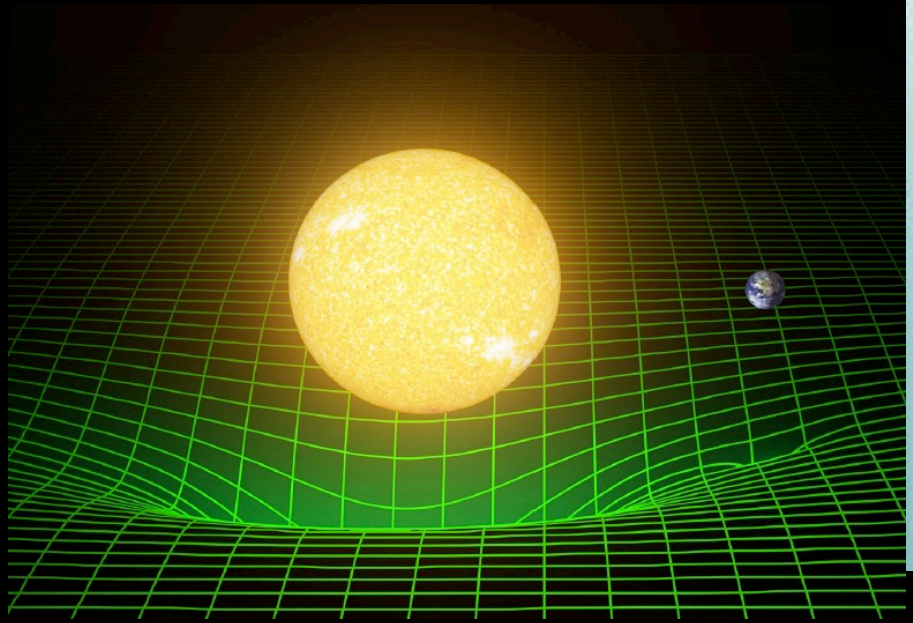
"Instantaneous Action at a Distance"

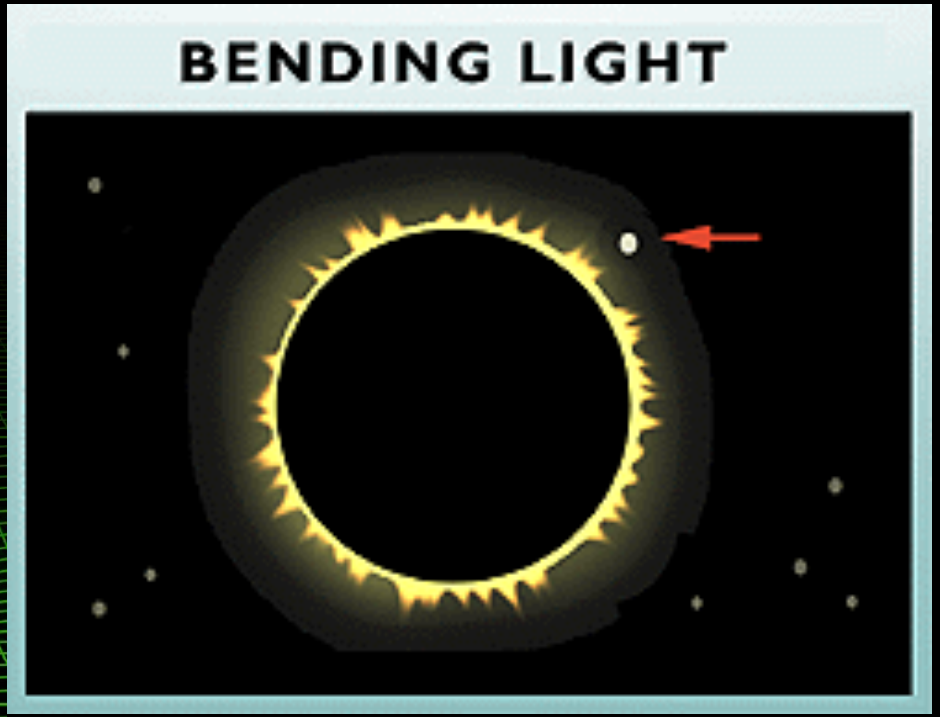


Einstein Explains WHY the apple falls!



Earth distorts spacetime





First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

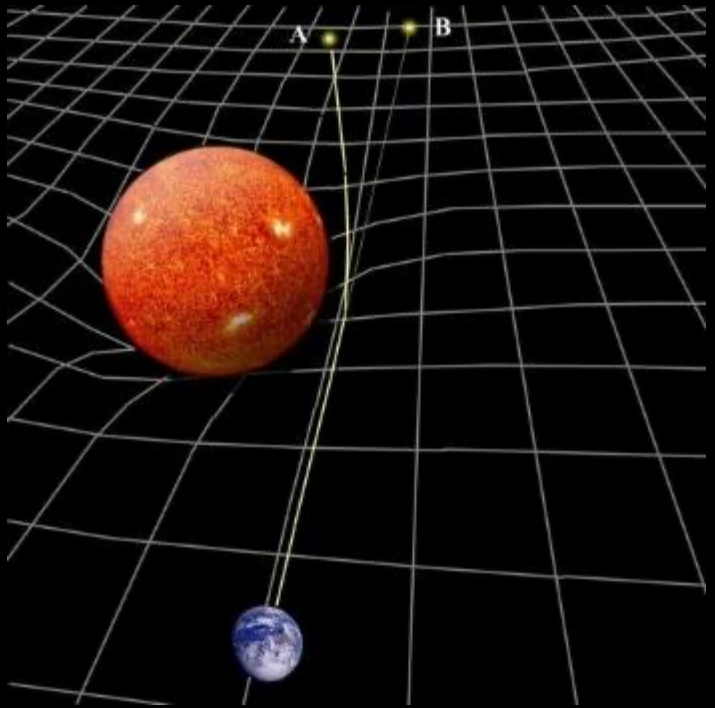
General Relativity

Einstein's equations have form similar to the equations of elasticity.

$P = Eh$ (P = stress, h = strain, E = Young's mod.)

$T = (c^4/8\pi G)h$ T = stress tensor, G = Curvature tensor and $c^4/8\pi G \sim 10^{42}$N is a space-time "stiffness" (energy density/unit curvature)

- Space-time can carry waves.
- They have very small amplitude
- There is a large mismatch with ordinary matter, so very little energy is absorbed (very small cross-section)



The New York Times.

VOL. LXIX. No. 21,694. NEW YORK, MONDAY, NOVEMBER 10, 1919. THIRTY-TWO PAGES. TWO CENTS

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

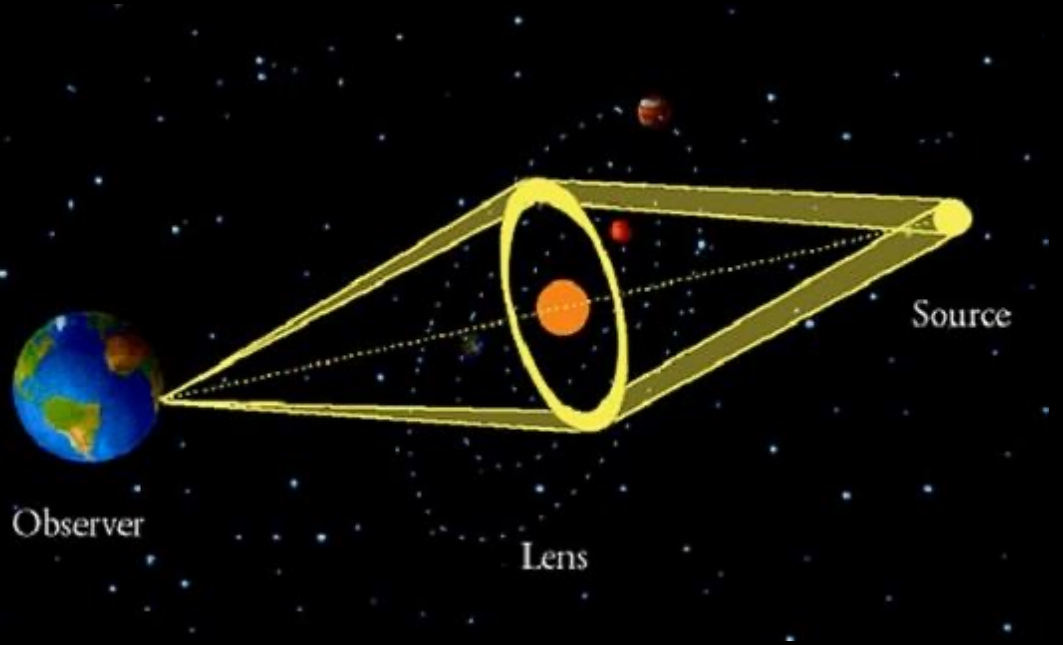
A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Thompson states that the difference between theories of Newton and those of Einstein are infinitesimal in a popular sense, and as they are purely mathematical and can only be expressed in strictly scientific terms it is useless to endeavor to detail them for the man in the street.

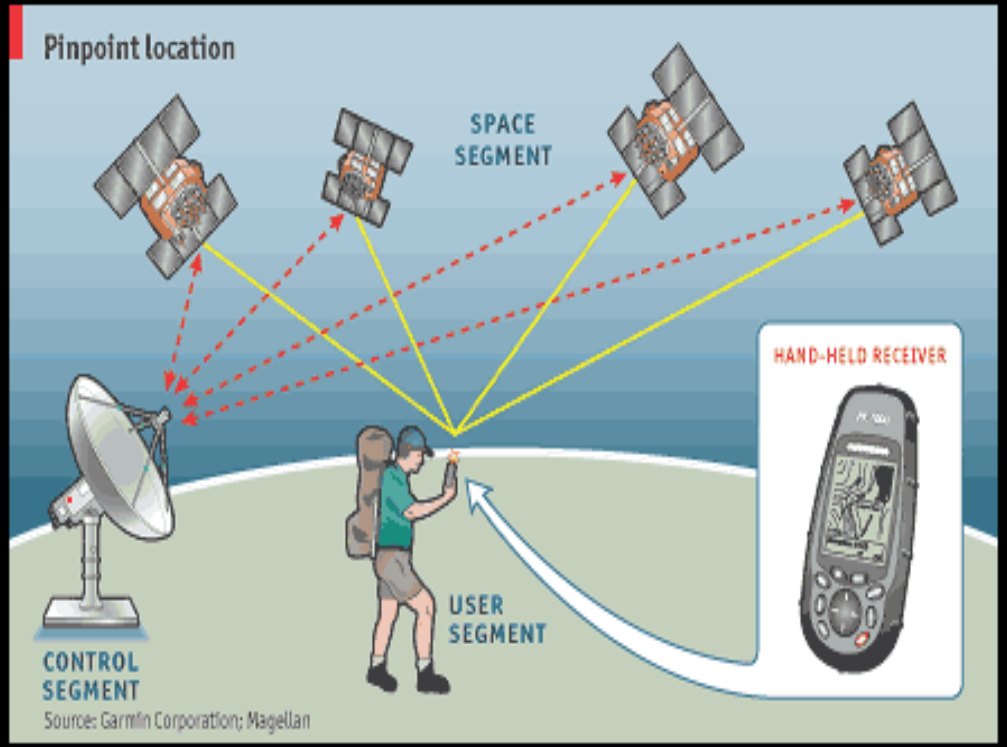
"What is easily understandable," he continued, "is that Einstein predicted the deflection of the starlight when it passed the sun, and the recent eclipse has provided a demonstration of the correctness of the prediction.

In Modern Astronomy: Gravitational Lensing



Einstein Cross

GPS: General Relativity in Everyday Life



Special Relativity

(Satellites v = 14,000 km/hour

"moving clocks tick more slowly"

Correction = - 7 microsec/day

General Relativity

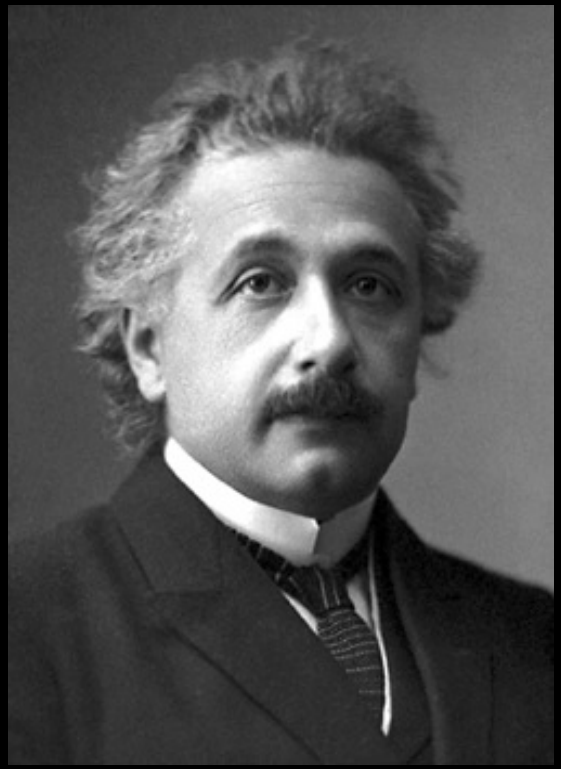
Gravity: Satellites = 1/4 x Earth

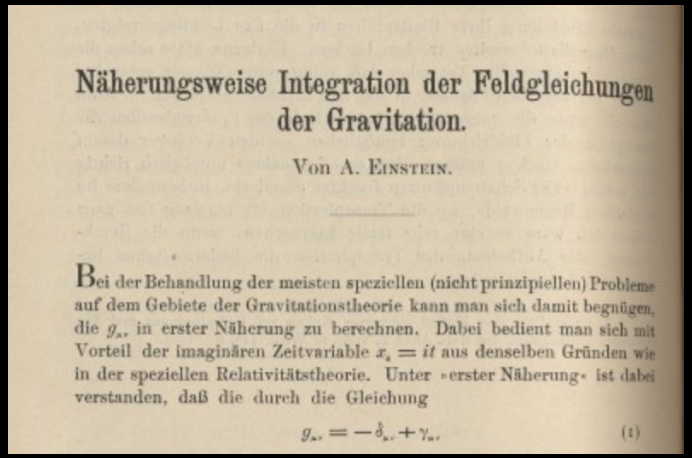
Clocks faster = + 45 microsec/day

GPS Correction = + 38 microsec/day

(Accuracy required ~ 30 nanoseconds to give 10 meter resolution

Einstein Predicted Gravitational Waves in 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

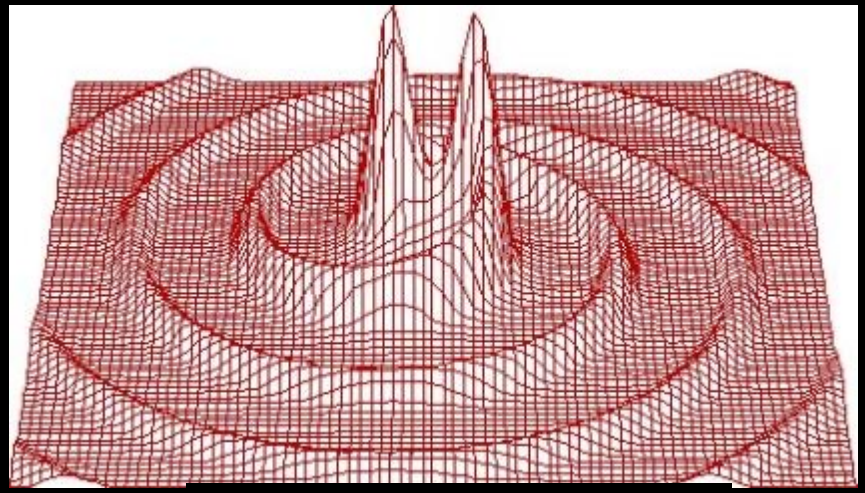
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

- 1st publication indicating the existence of gravitational waves by Einstein in 1916
  - Contained errors relating wave amplitude to source motions
- 1918 paper corrected earlier errors (factor of 2), and it contains the quadrupole formula for radiating source

Einstein's Theory Contains Gravitational Waves

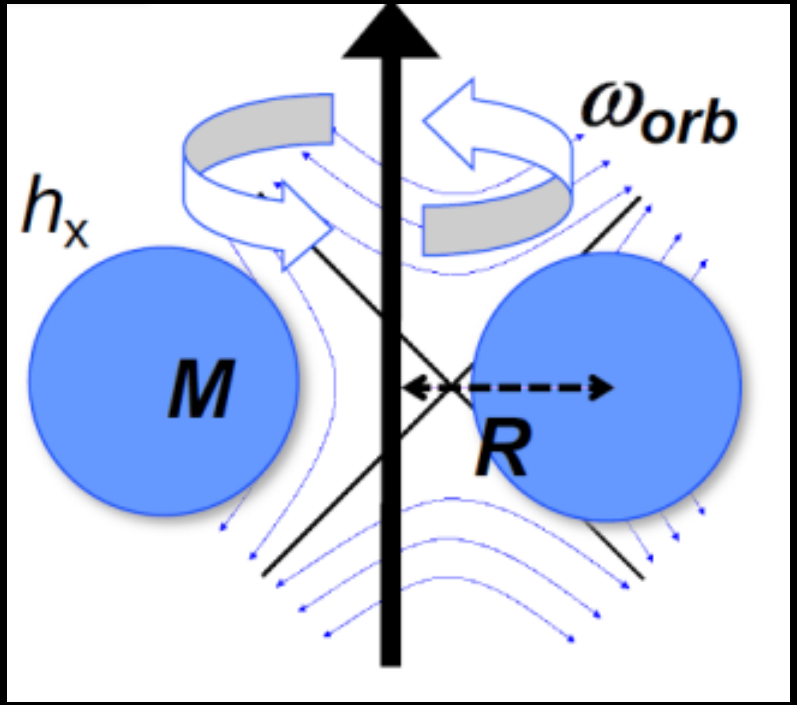
A necessary consequence of Special Relativity with its finite speed for information transfer

Gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light



gravitational radiation
binary inspiral
of
compact objects

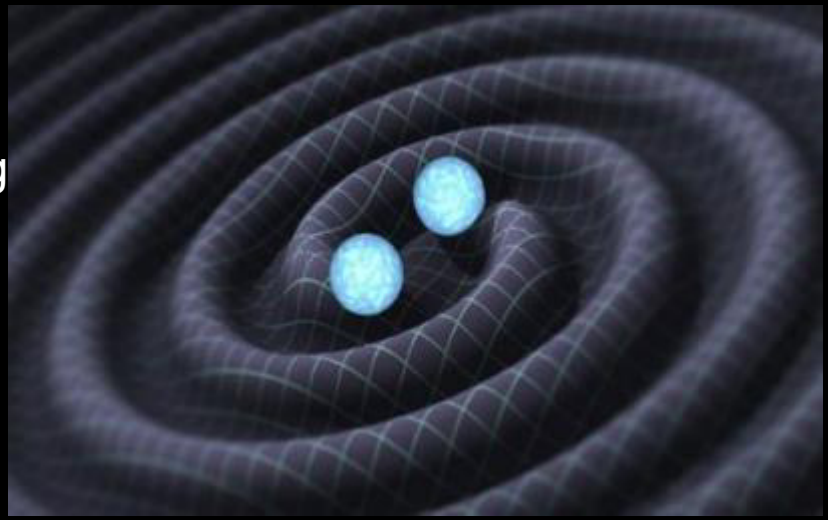
Making Gravitational Waves



- To make gravitational waves, you need something that dramatically changes the distribution of matter.
- Binary stars are a good example. The more massive the stars, the better. The faster they accelerate, the better.
- Binaries made of neutron stars are very good.
- Binaries made of black holes are best.
- In gravitational wave signals, we'd see these things in ways no ordinary telescope can rival.

Gravitational Waves

- Gravity needs to obey the principle of relativity (no signals faster than light).
- What about gravity from rapidly accelerating stars? Their gravitational effects at large distances can't change instantaneously. (If they did, that would violate relativity.)
- Gravitational changes "ripple out" from an accelerating object. Those ripples in the structure of space-time, moving at the speed of light, are *gravitational waves*.



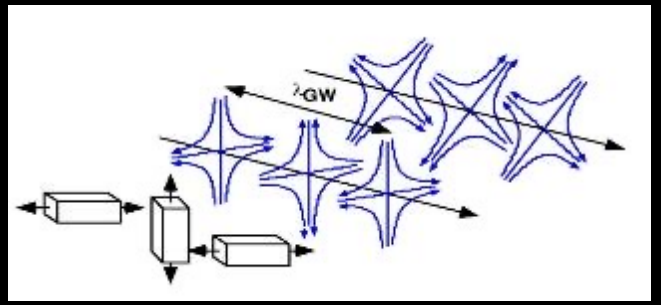
Einstein's Theory of Gravitation

Gravitational Waves

• Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

• The strain $h_{\mu\nu}$ takes the form of a plane wave propagating at the speed of light (c).



• Since gravity is spin 2, the waves have two components, but rotated by 45^0 instead of 90^0 from each other.

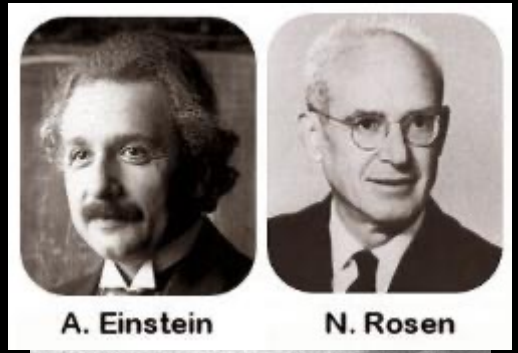
$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$

Einstein vs Physical Review

1936

Einstein and Rosen Submited an article to Physical Review

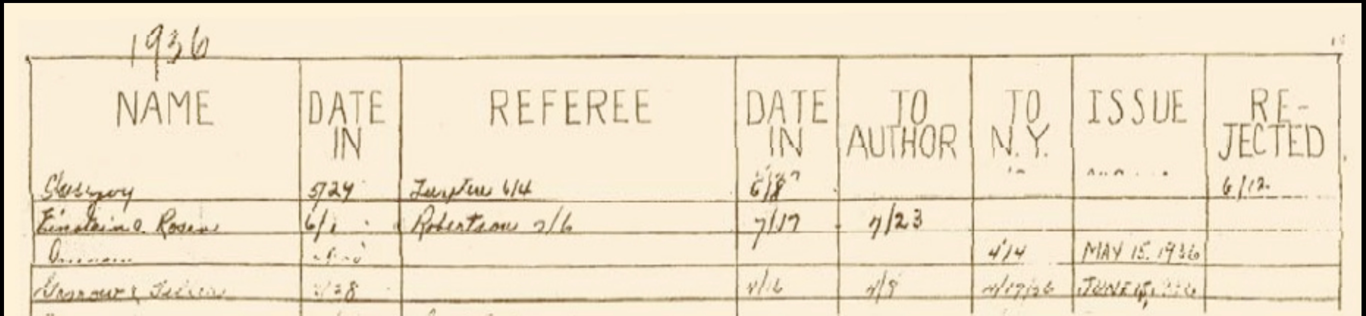
"Do Gravitational Waves Exist?"



John Tate sends the Paper for "Peer Review"

Howard Percy Robertson

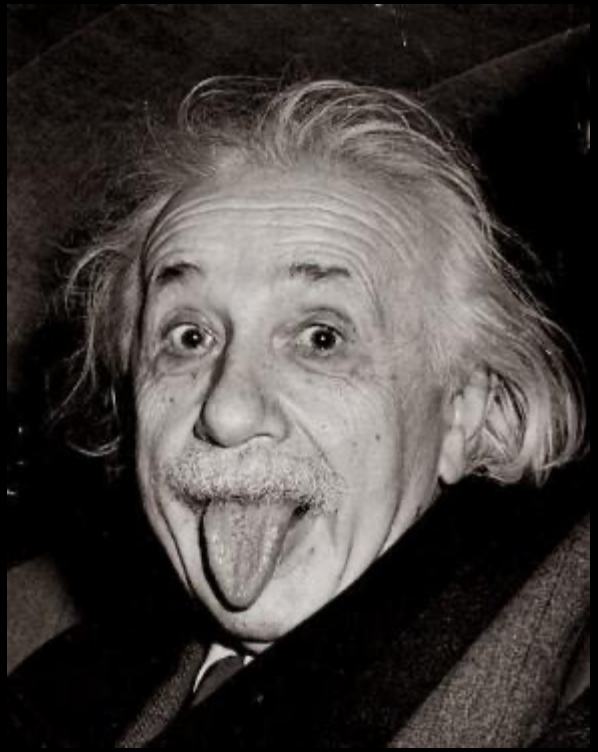
- Einstein/Rosen used a single coordinate system to cover all of space-time and encountered a singularity.
- Robertson found the error and showed that casting metric in cylindrical coordinates removed the difficulty.
- Tate sent Einstein a mild letter stating "would be glad to have (Einstein's) reaction to referee comments and criticisms".



1936

NAME	DATE IN	REFEREE	DATE IN	TO AUTHOR	TO N.Y.	ISSUE	RE-JECTED
Gregory	5/24	Tarpley 6/4	6/8				6/12
Einstein & Rosen	6/1	Robertson 7/6	7/17	7/23			
[illegible]	[illegible]				4/14	MAY 15, 1936	
[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	JUNE [illegible]	

Einstein's Reply to Tate



Dear Sir

We (Mr. Rosen and I) had sent you our manuscript for publication and had not authorized you to show it to specialists before it is printed. I see no reason to address the --- in any case erroneous --- comments of your anonymous expert. On the basis of this incident, I prefer to publish the paper elsewhere.

Respectfully,

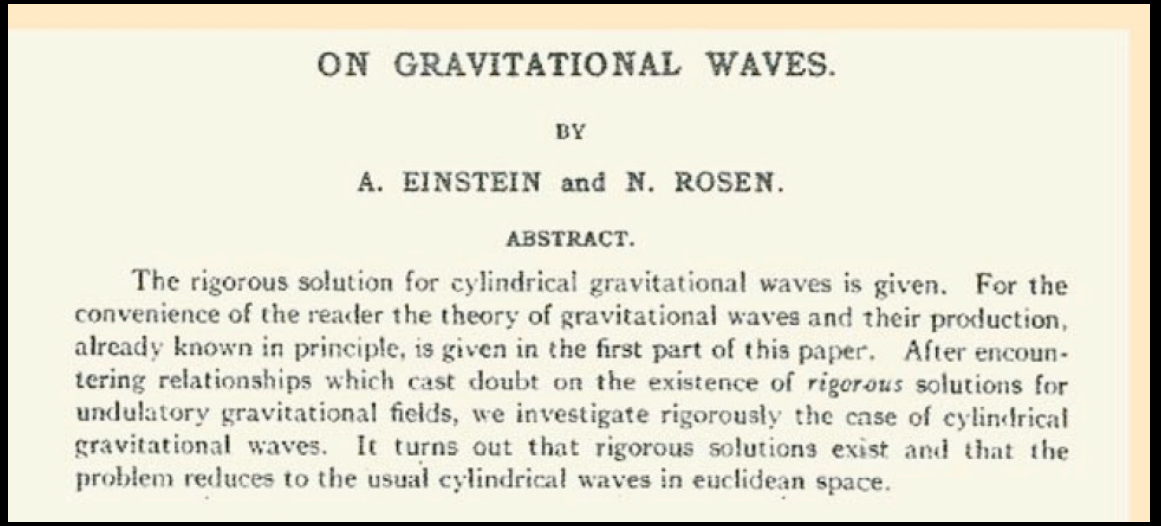
Einstein then Submitted to Franklin Institute Journal

Infeld

All's well that ends well …

- **Robertson returned from Caltech sabbatical a while later, struck up a friendship with Infeld. Robertson told Infeld he didn't believe Einstein's result, and went over Infeld's version of the argument. Robertson pointed out the error.**

- **Infeld reported to Einstein, and Einstein said he independently had found the error himself. He then completely modified the paper.**



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.

The Chapel Hill Conference

Could the waves be a coordinate effect only, with no physical reality? Einstein didn't live long enough to learn the answer.

In January 1957, the U.S. Air Force sponsored the *Conference on the Role of Gravitation in Physics*, a.k.a. the Chapel Hill Conference, a.k.a. GR1.

The organizers were Bryce and Cecile DeWitt. 44 of the world's leading relativists attended.

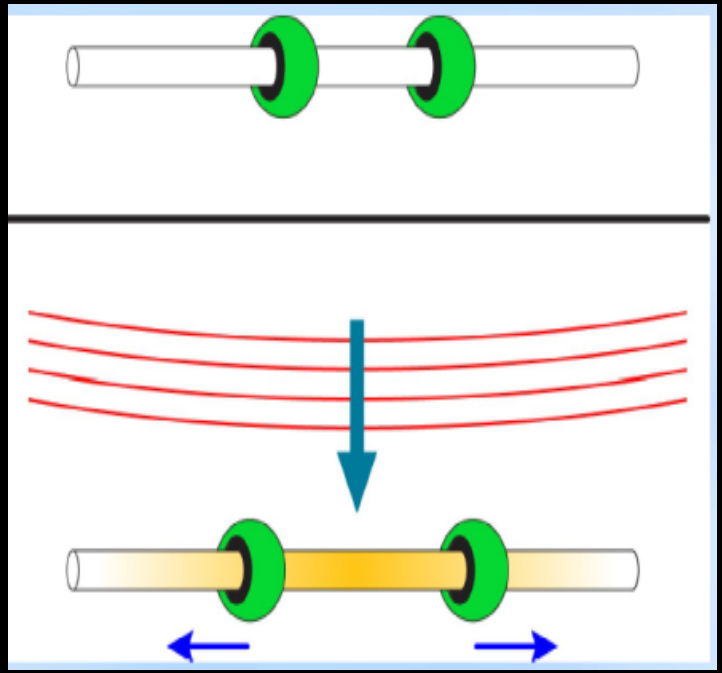
The "gravitational wave problem" was solved there, and the quest to detect gravitational waves was born.

(Pirani, Feynman and Babson)

Agreement: Gravitational Waves are Real

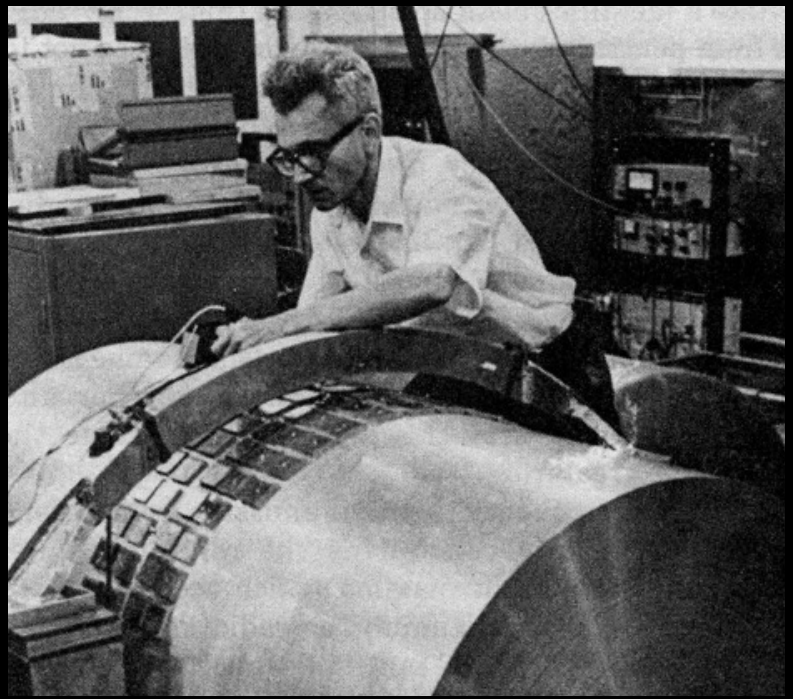
- Felix Pirani presentation: relative acceleraton of particle pairs can be associated with the Riemann tensor. The interpretation of the attendees was that non-zero components of the Riemann tensor were due to gravitational waves.

- Sticky bead argument (Feynman)
  - Gravitational waves can transfer energy?



The Experimental Search Begins

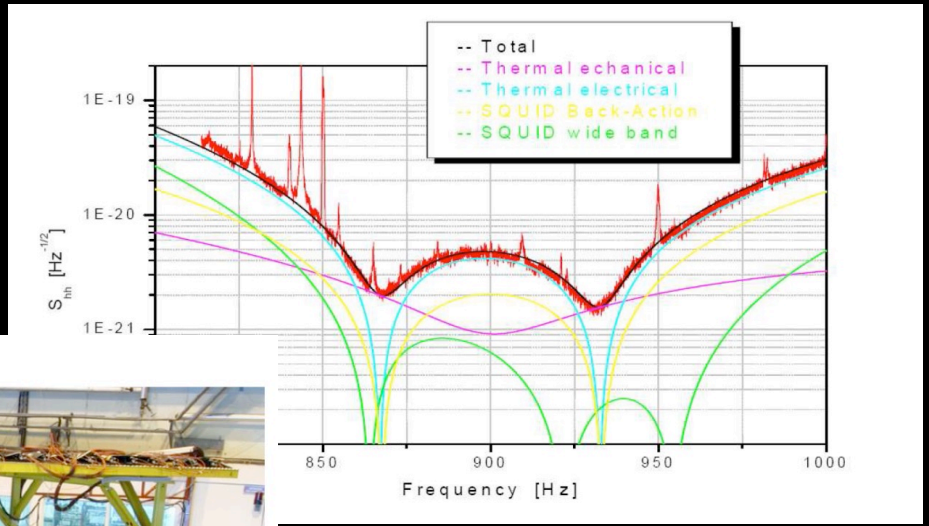
Joseph Weber

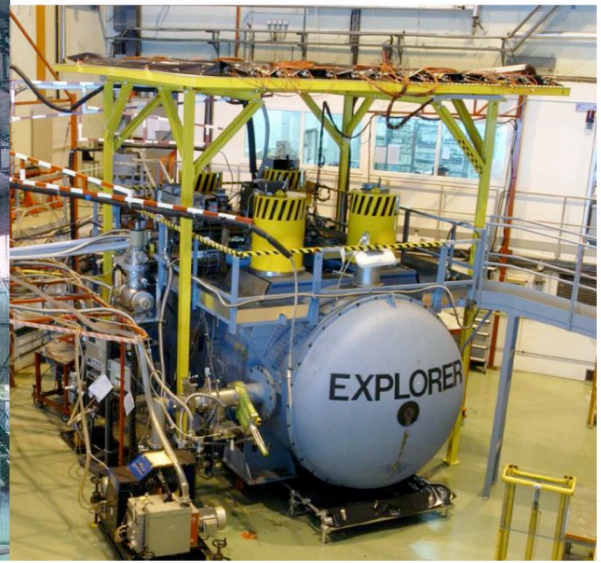


First Gravitational-wave experimental research began in 1960's using 'resonant bars"

A cylinder of aluminum - each end acts like a test mass. The center is like a spring. PZT's around the midline absorb energy to send to an electrical amplifier.

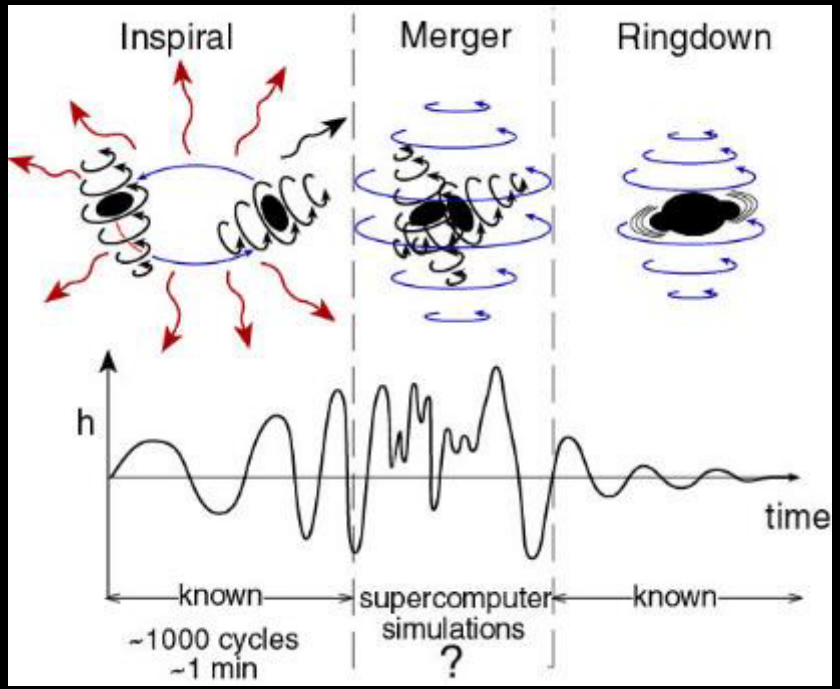
Resonant Bars "Evolution"



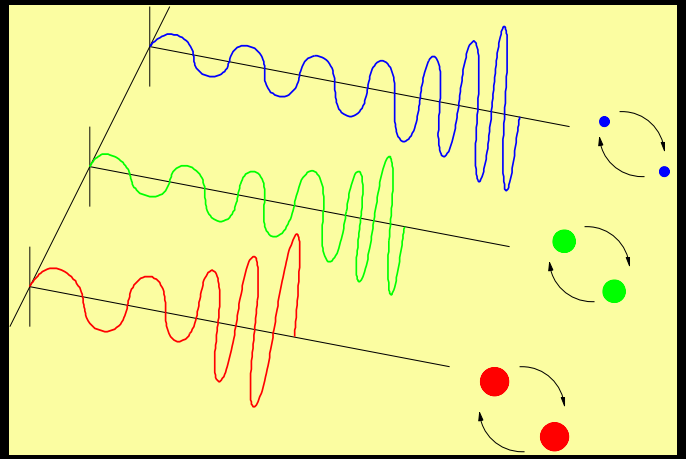


- **Cryogenic** – reduce termal noise
- **Network** – sky location
- Broader Band - ~ 100 Hz

Compact Binary Collisions



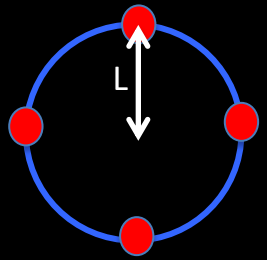
- Neutron Star – Neutron Star
  - **waveforms are well described**
- Black Hole – Black Hole
  - **Numerical Relativity waveforms**
- Search: *matched templates*

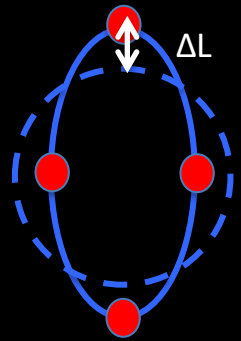


“chirps”

Detecting Gravitational Waves

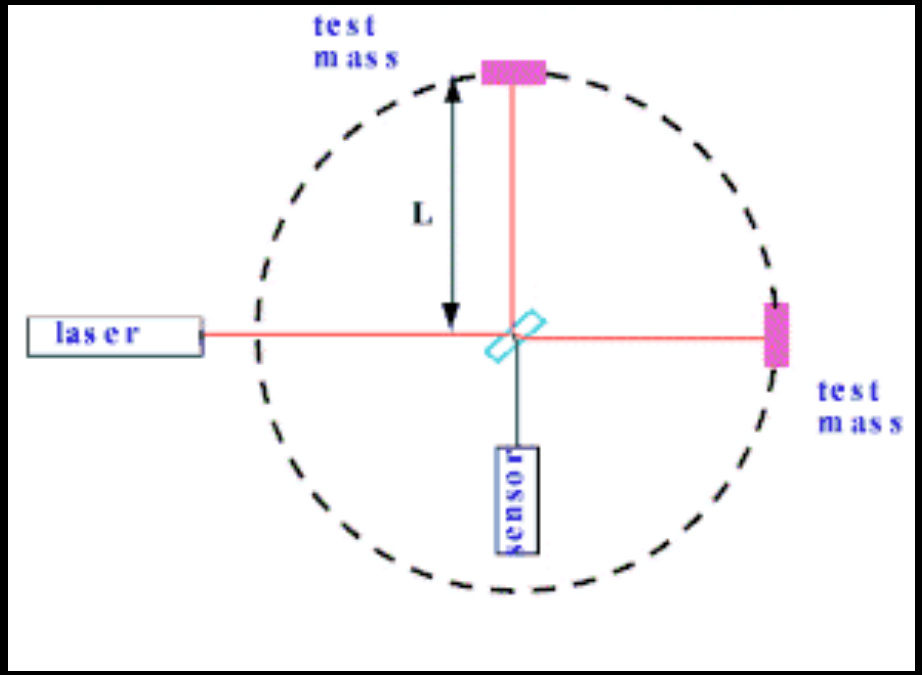
- Ripples of spacetime that stretch and compress spacetime itself
- The amplitude of the wave is $h \approx 10^{-21}$
- Change the distance between masses that are free to move by $\Delta L = h \times L$
- Spacetime is “stiff” so changes in distance are very small





$$\Delta L = h \times L = 10^{-21} \times 1\,\mathrm{m} = 10^{-21}\,\mathrm{m}$$

Suspended Mass Interferometry



$$h = \frac{\Delta L}{L} \leq 10^{-21}$$

$$L = 4\text{km} \quad \Delta L \leq 4 \text{x} 10^{-18} \text{ meters}$$

$\Delta L \sim 10^{-12}$ wavelength of light

$\Delta L \sim 10^{-12}$ vibrations at earth's surface

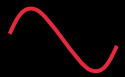
How Small is 10^{-18} Meter?

One meter

÷10,000

Human hair, about 100 microns

÷100



Wavelength of light, about 1 micron

÷10,000

Atomic diameter, 10^{-10} meter

÷100,000

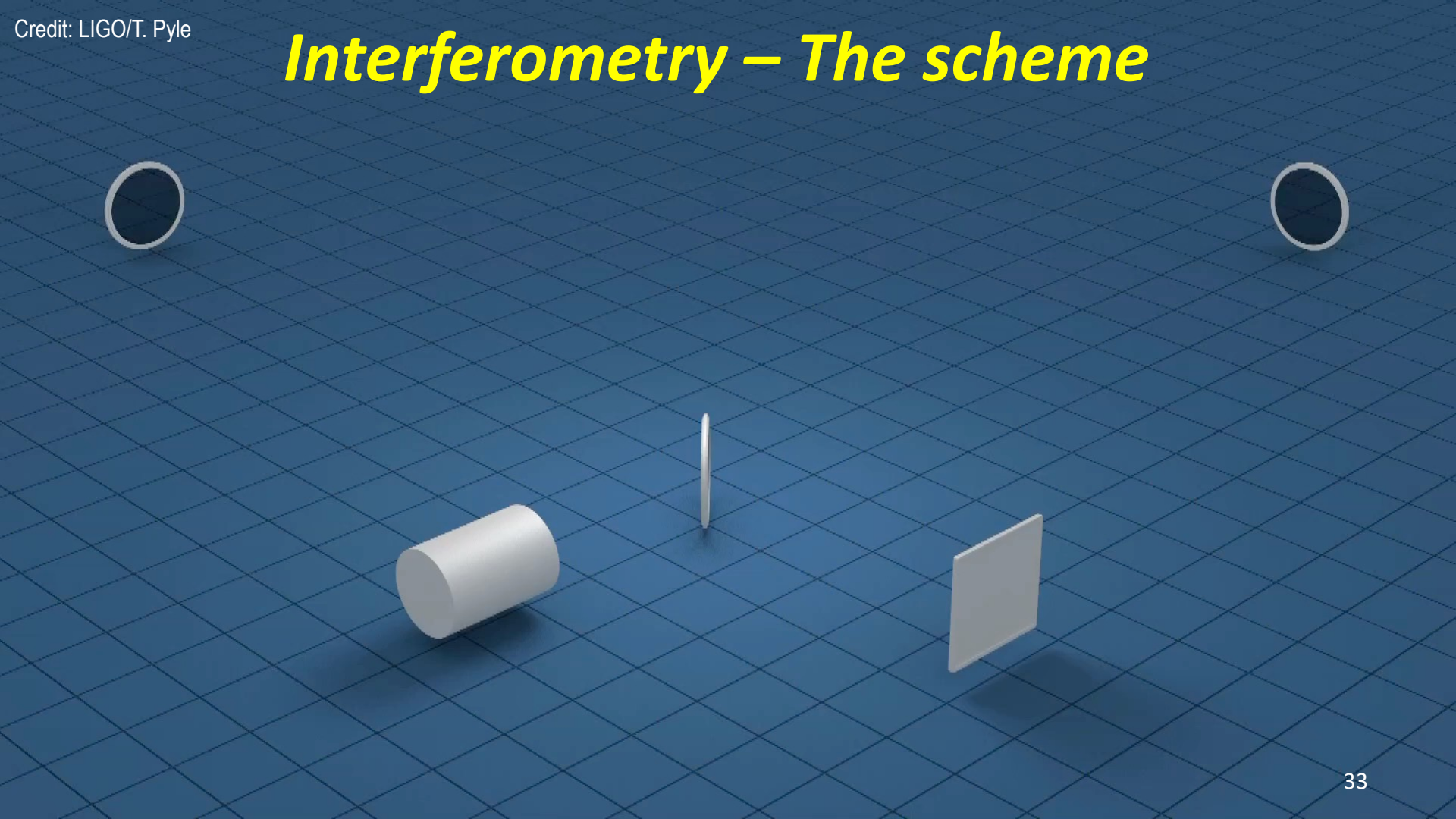
Proton diameter, 10^{-15} meter

÷1,000

LIGO sensitivity, 10^{-18} meter

Credit: LIGO/T. Pyle

Interferometry – The scheme



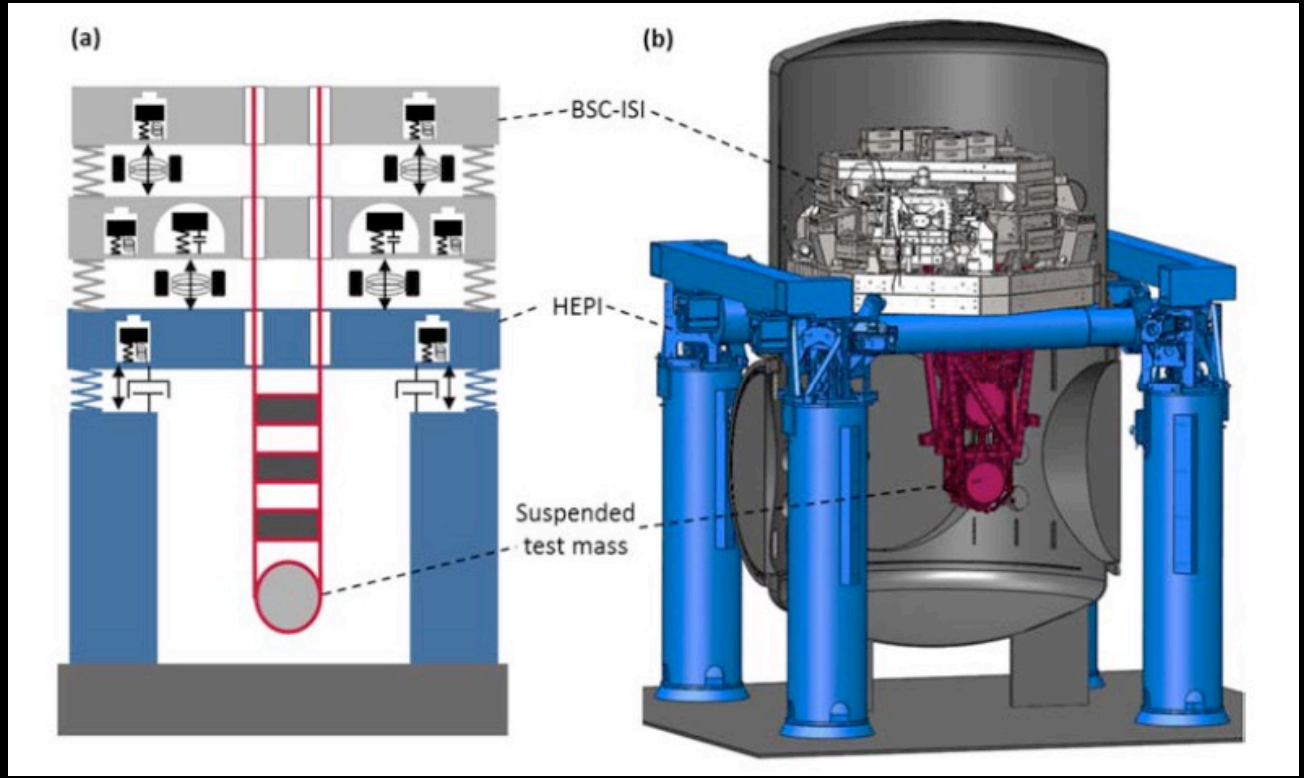
LIGO Interferometers

Hanford, WA

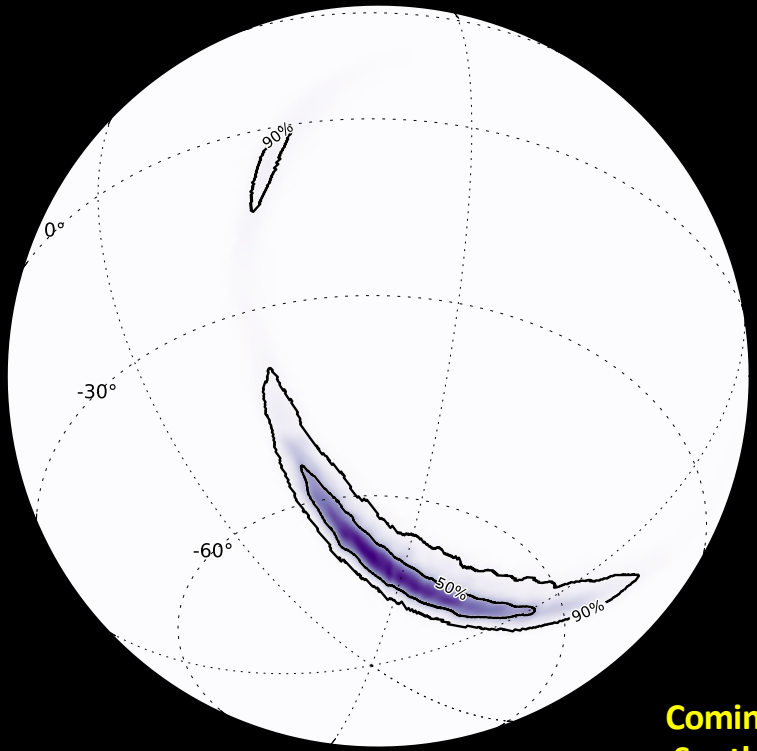
Livingston, LA


LIGO Interferometer Infrastructure

Seismic Isolation
Passive / Active Multi-Stage

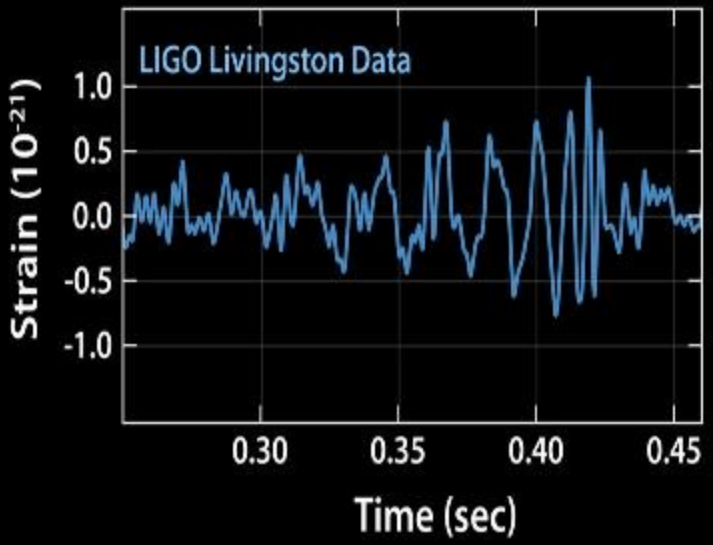


Sept 14, 2015

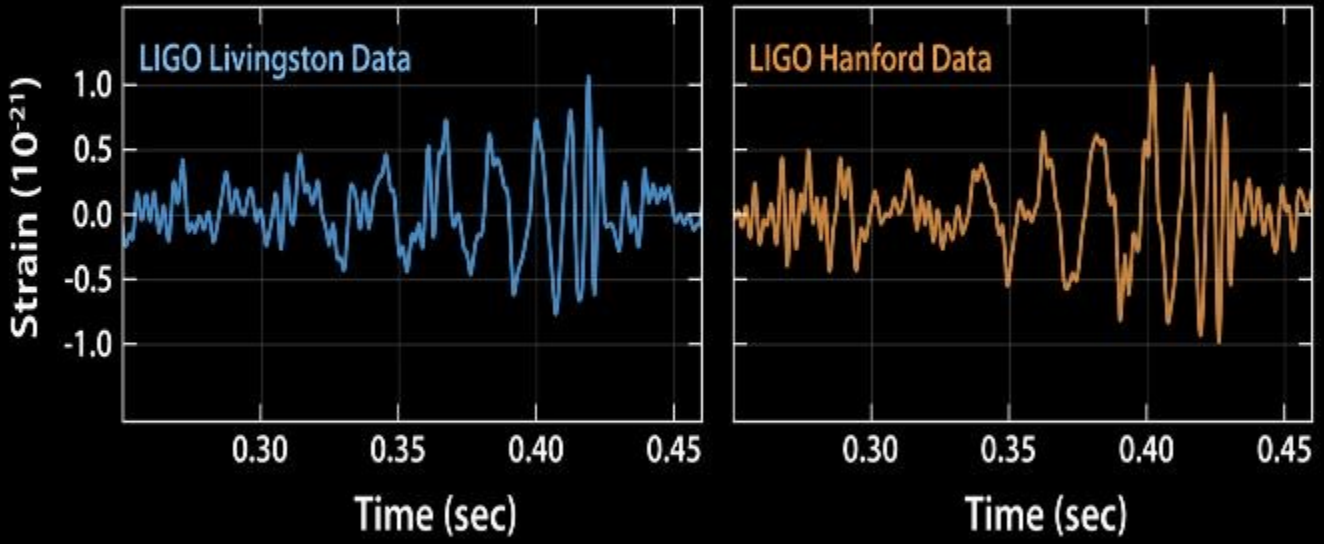


Coming up from Southern Hemisphere

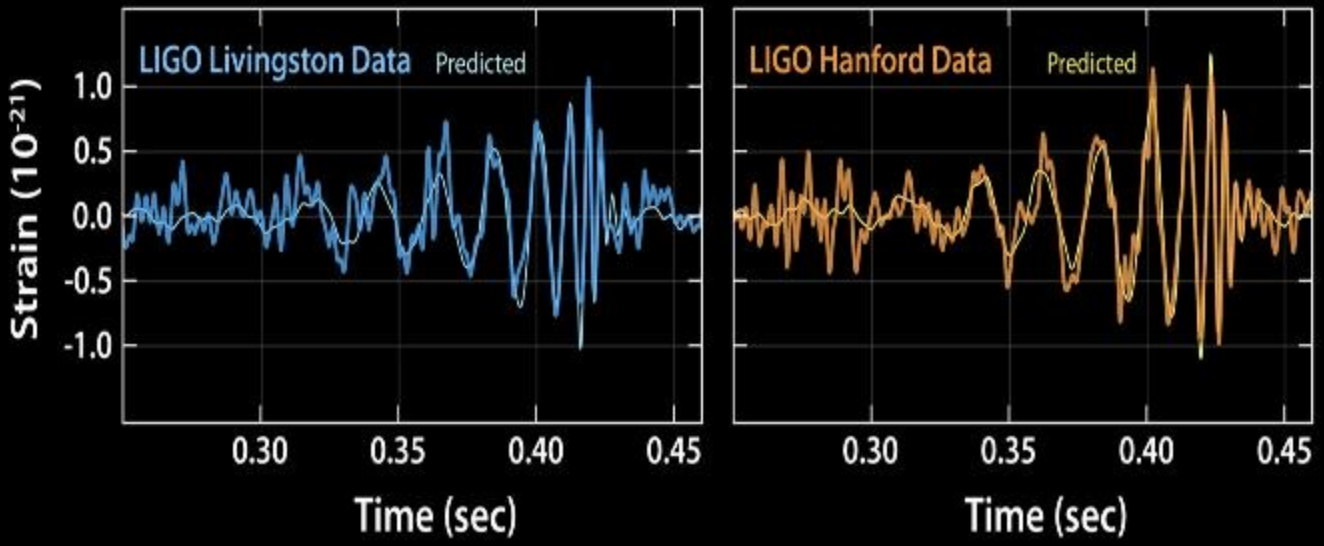
~ 20 msec later



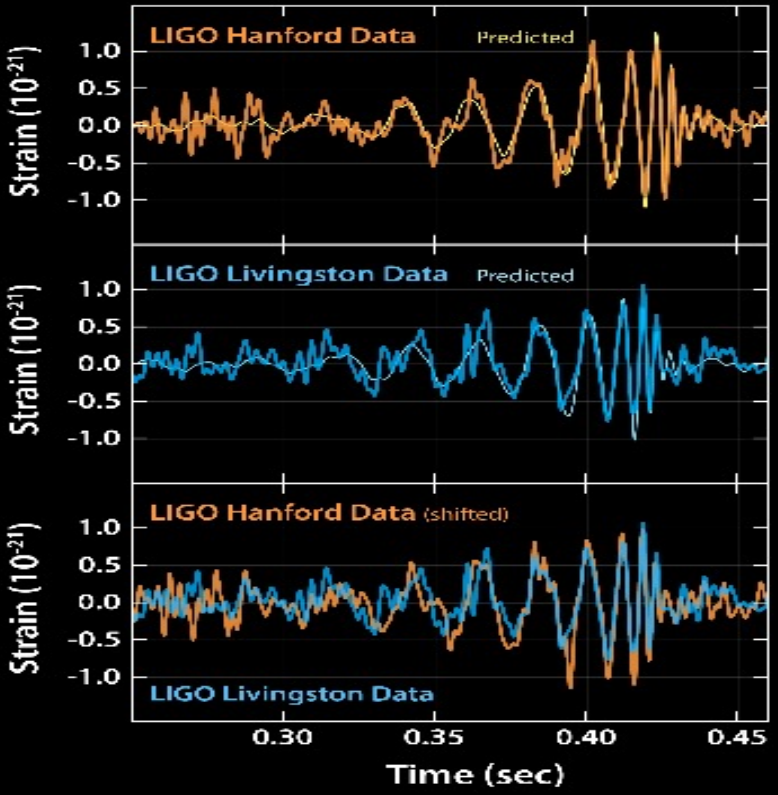
After another 7 msec

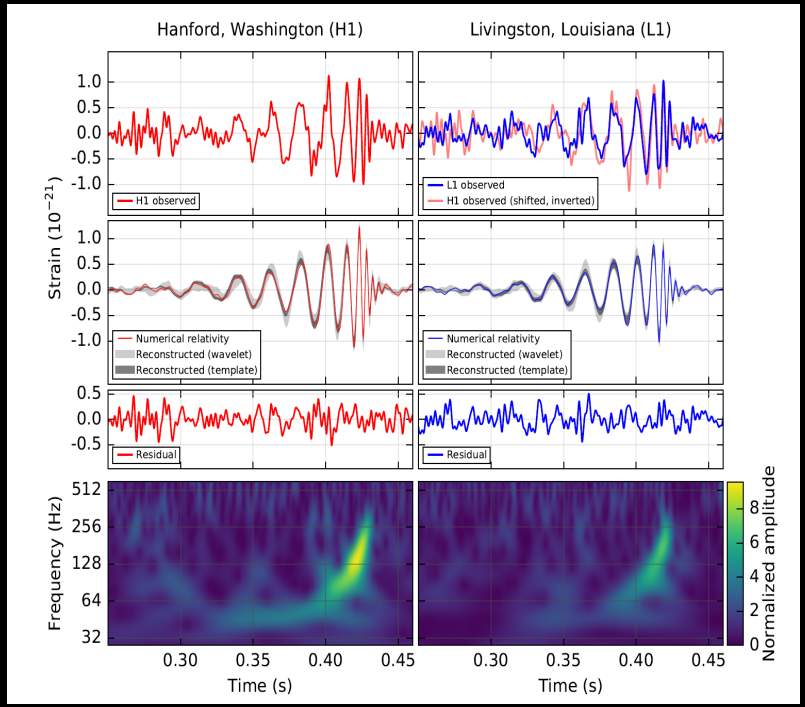


GR Prediction for BH merger



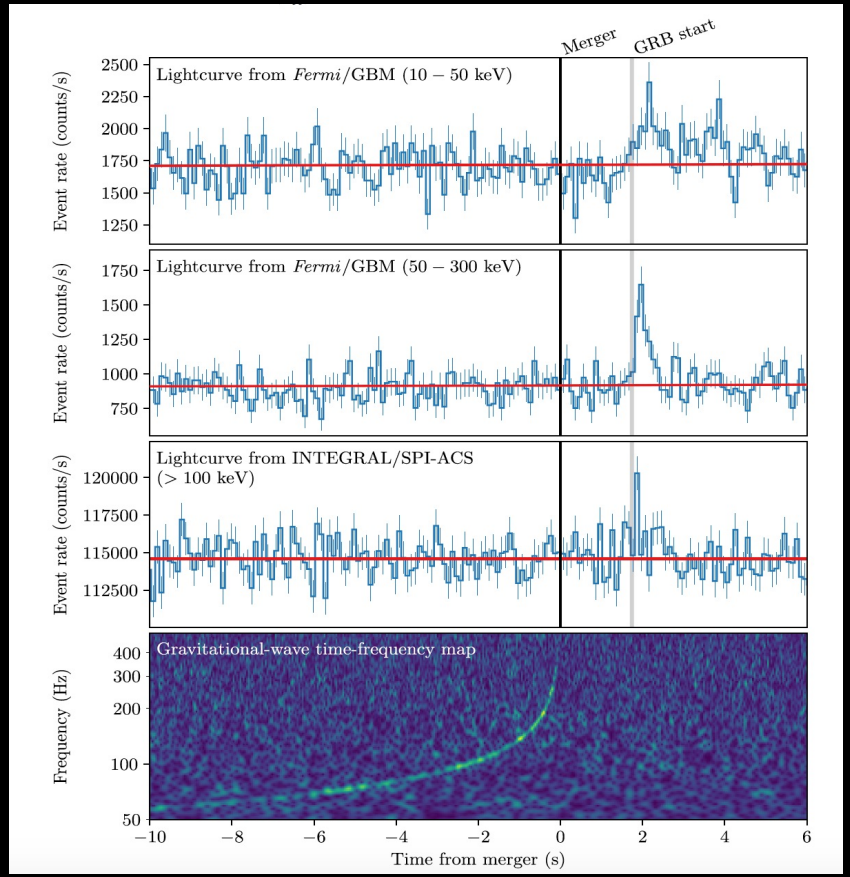
Black Hole Merger: GW150914

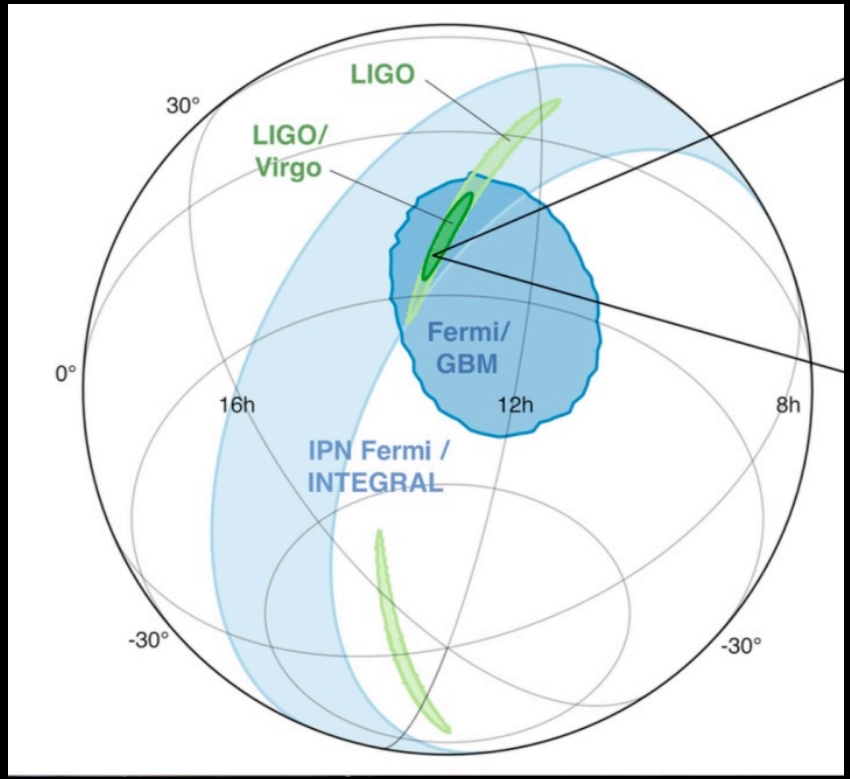




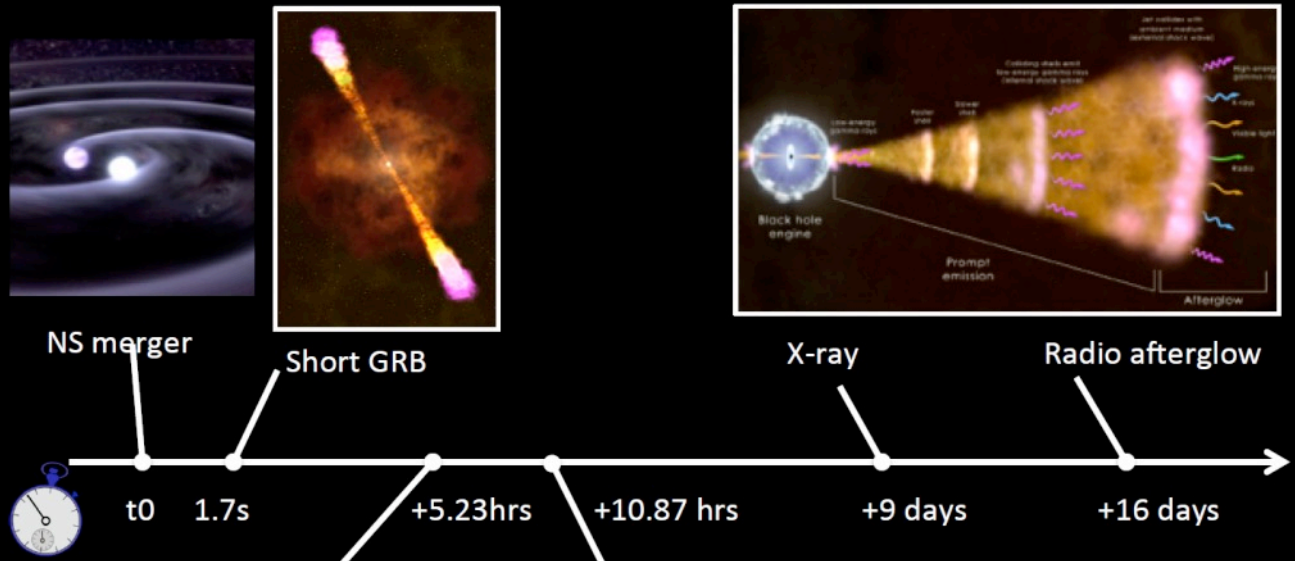

Cover stars
DER NOBELPREIS-
CODE
VICTORIA & CO

Fermi Satellite GRB detection 2 seconds later



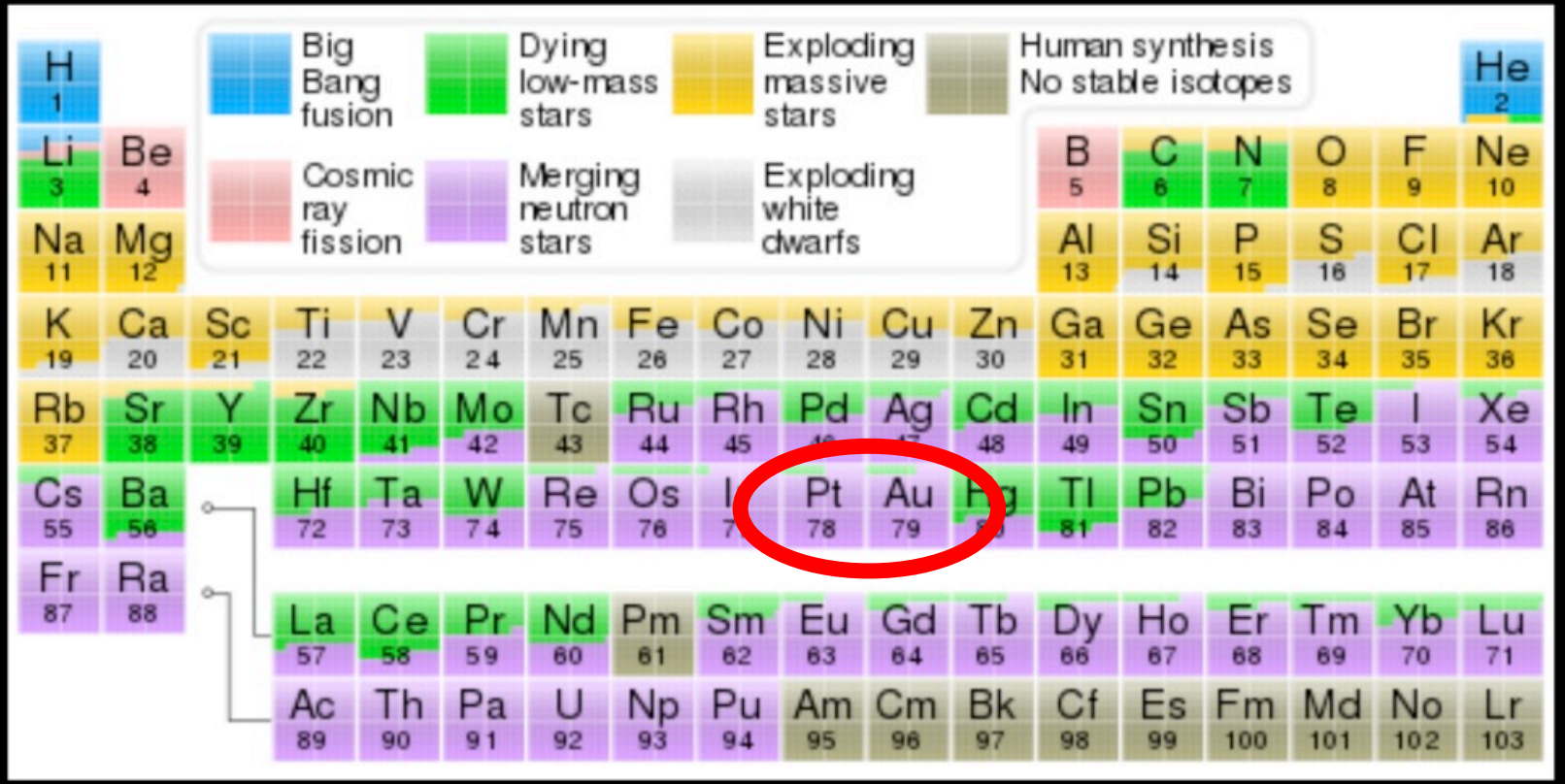


170817A" Astrophys. J. Lett., 848:L13, (2017)



LVC + astronomers, ApJL, 848, L12

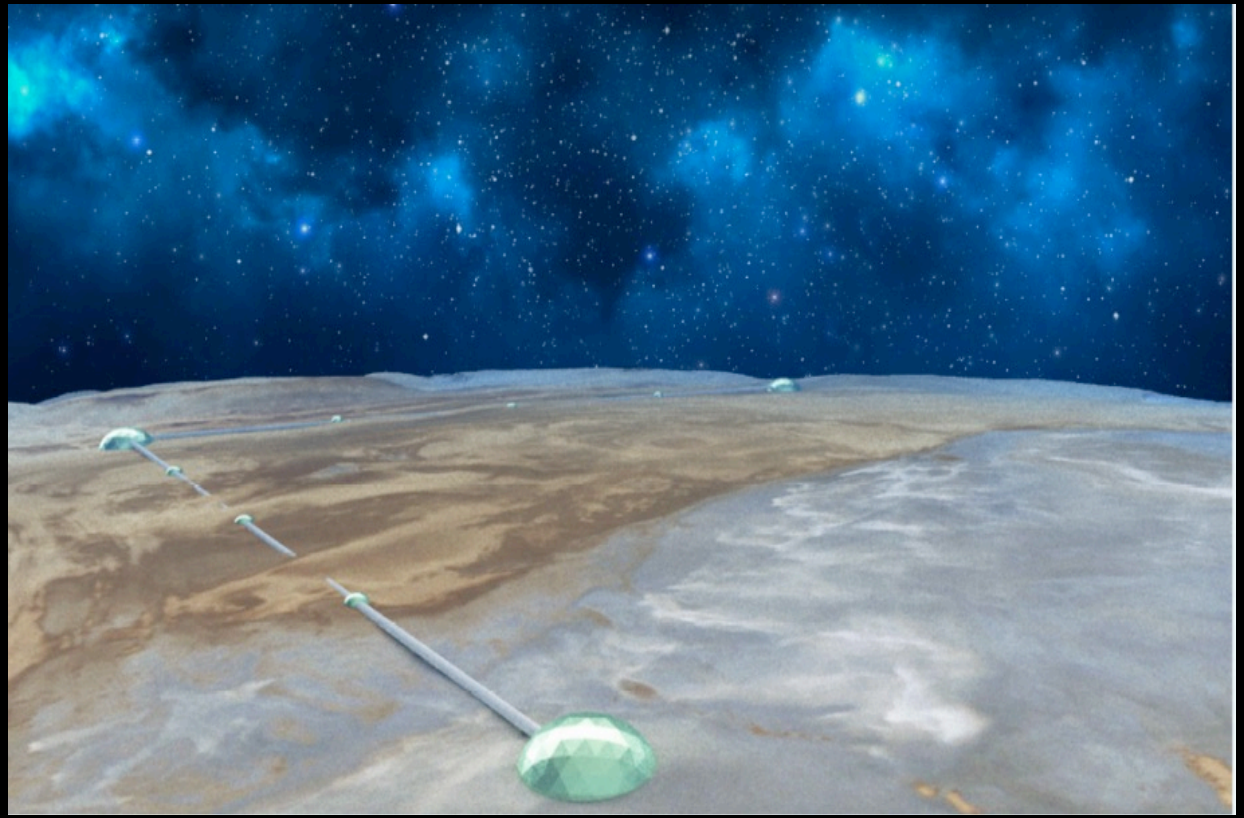
Origin of the Heavy Elements



NS Mergers are Incredible Gold Factories

LIGO observed Neutron Star Merger produced ~ 100 Earth Masses of Gold

Proposed 3rd Generation Detectors



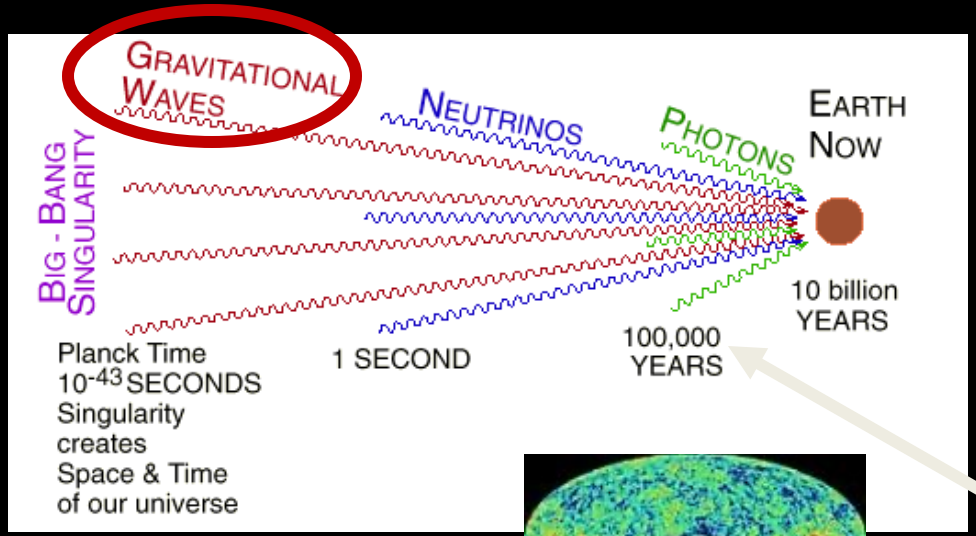
Cosmic Explorer 40 km

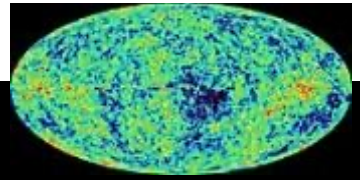
The Einstein Telescope: x40 aLIGO

- On the Earth‘s Surface
- 40 km arms
- L - shape
- Cryogenic (2nd generation)
- Multiple Detectors for Multi-messenger Astronomy

Signals from the Early Universe

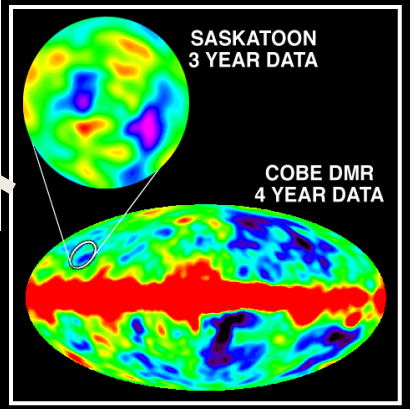
stochastic background





WMAP

Cosmic Microwave background



The Birth of a New Astronomy