General relativity, astronomy and the universe: *the first hundred years*

Cormac O'Raifeartaigh FRAS

Waterford Institute of Technology

Irish National Astronomy Meeting UCD 7-9/9/16

Overview

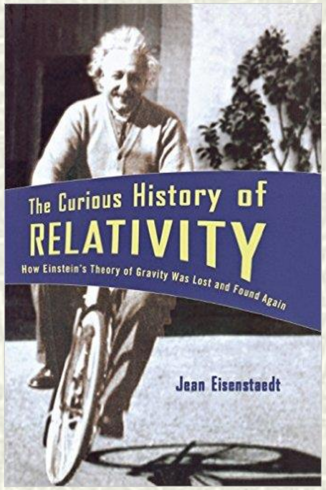
- **Relativity**
  The special theory of relativity
  The general theory of relativity

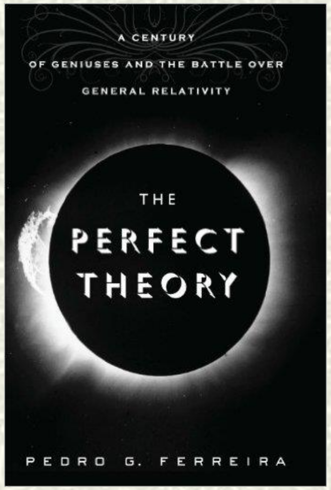
- **Three classic astronomical tests**
  The perihelion of Mercury; the bending of starlight
  The gravitational redshift

Einstein in Berlin (1916)

- **Three cosmological predictions**
  Black holes; gravitational waves
  The dynamic universe

- **The curious history of general relativity**
  Low watermark period (1930-60)
  Astronomy catches up - the golden period



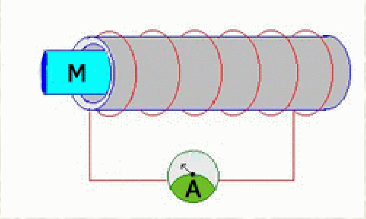


The special theory of relativity (1905)

- **Two principles**

  *Laws of **all** physics identical for observers in relative uniform motion*

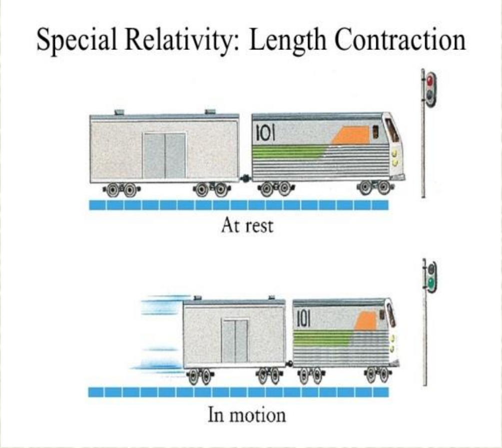
  Speed of light in vacuum identical for observers in relative uniform motion



- **Implications**

  Intervals in distance and time not universal

  Experienced differently by bodies in relative uniform motion



- **Predictions (high-speed bodies)**

  Length contraction : time dilation

  Mass increase; mass-energy equivalence

- **Space-time (Minkowski 1908)**

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2dt^2$$

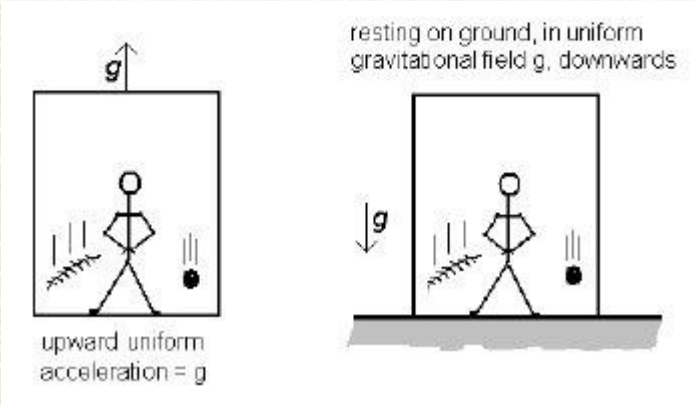
  Space-time invariant for observers in inertial frames

The general theory of relativity (1916)

- **Extending the special theory (1907-)**

  Relativity and gravity?

  Relativity and accelerated motion?



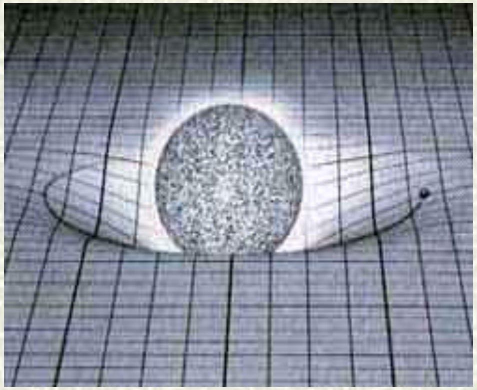
- **<u>The principle of equivalence</u>**

  Equivalence of gravity and acceleration

- **<u>Mach's principle</u>**

  Inertial mass defined relative to matter

  "No such thing as empty space"



- **A long road (1907-1915)**

  Curvilinear geometry, tensor algebra

Gravity = curvature of space-time

The field equations of GR (1915)

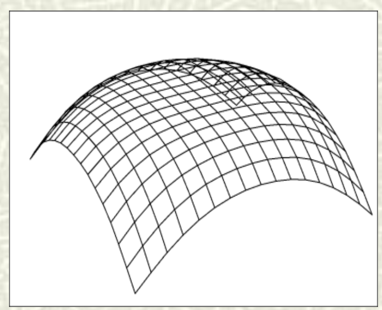
$$G_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

10 non-linear differential equations relating the spacetime metric to the density and flow of energy and momentum

SR $ds^2 = dx^2 + dy^2 + dz^2 - c^2dt^2$

$$ds^2 = \sum_{\mu,\nu=1}^{4} n_{\mu\nu} dx^\mu dx^\nu$$

$$n_{\mu\nu} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$



GR $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

$$ds^2 = \sum_{\mu,\nu=1}^{4} g_{\mu\nu} dx^\mu dx^\nu$$

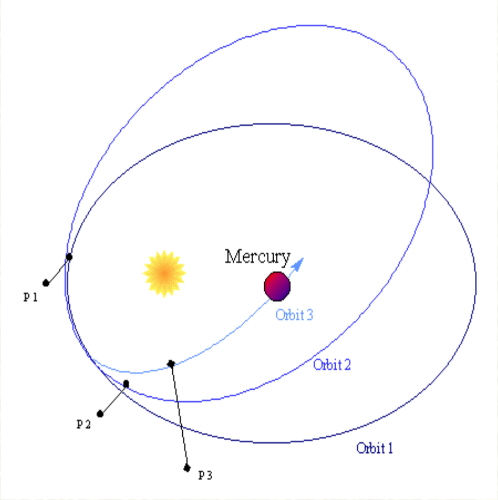
$g_{\mu\nu}$ *: variables determined by matter*

Three astronomical tests (Einstein, 1916)

- **Small deviations from Newton's gravity**

  Different in principle

- **The perihelion of Mercury**

  Well-known anomaly in Mercury's orbit (43" per century)

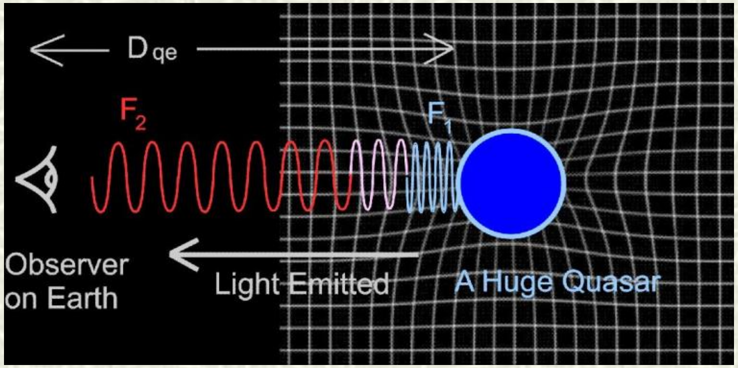
  Postdicted by GR (1916)

- **The bending of starlight by the sun** (1.7")

  Eclipse expeditions of Eddington and Dyson (1919)

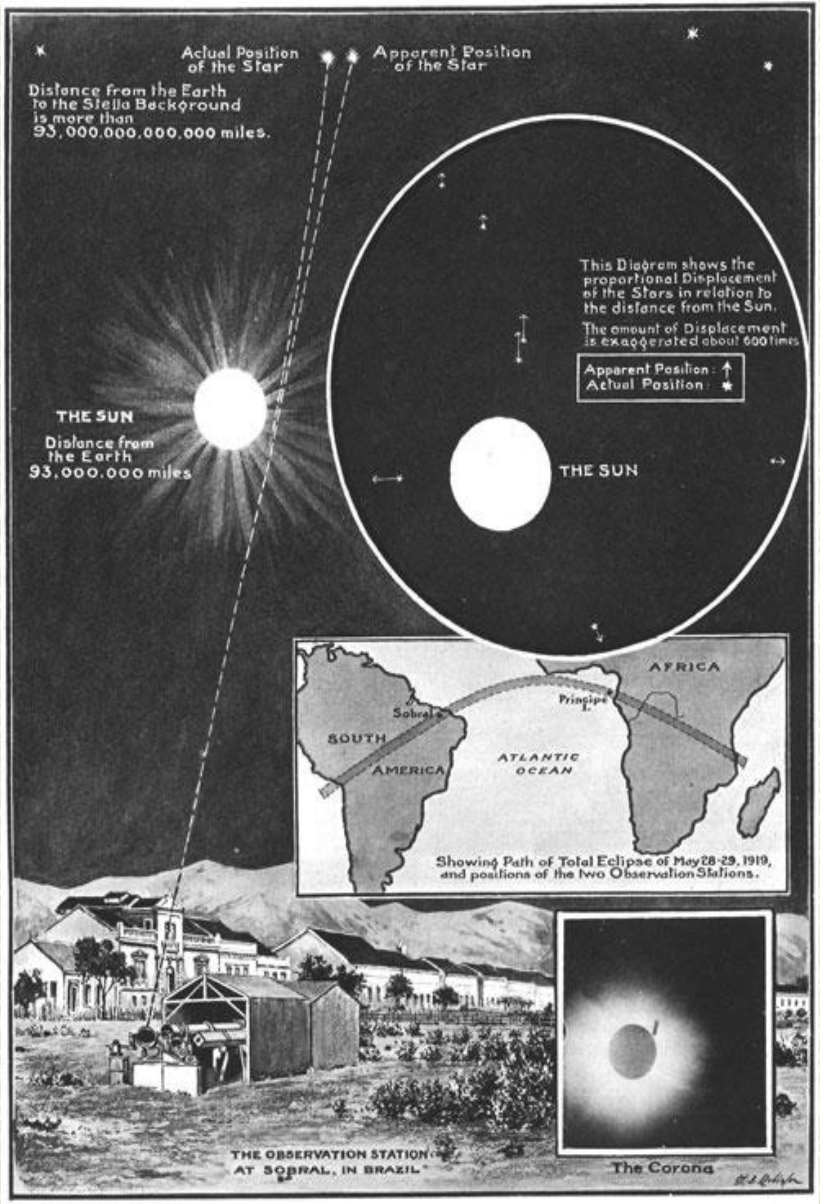
  Successful measurement (large error margin)

- **Gravitational redshift**

  Time dilation in strong gravitational field

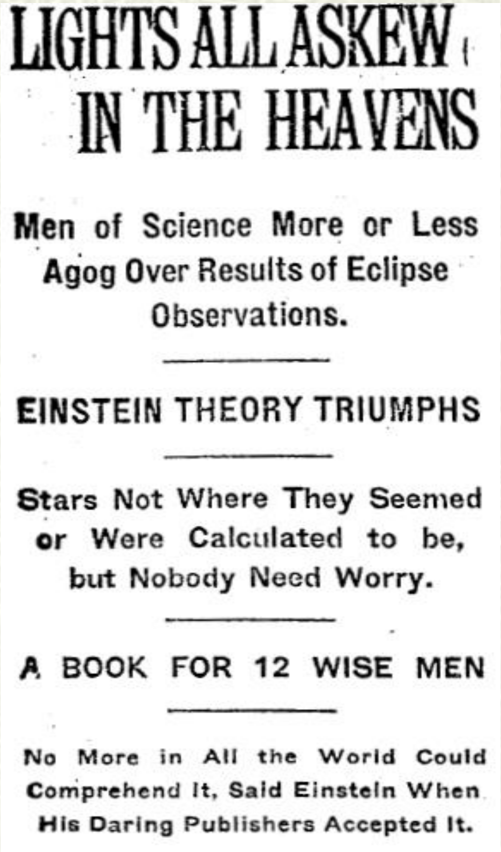
  Light from a massive star redshifted?



Eclipse Results (1919)

Sobral: 1.98" +/- 0.16
Principe: 1.7" +/- 0.4

Einstein famous (1919)



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.

Asymmetric controversy (Collins and Pinch 1970s)

Claim of bias; rebutted by astronomers (RAS)

Einstein's reaction

Albert Einstein, The Times (Nov 28th 1919)

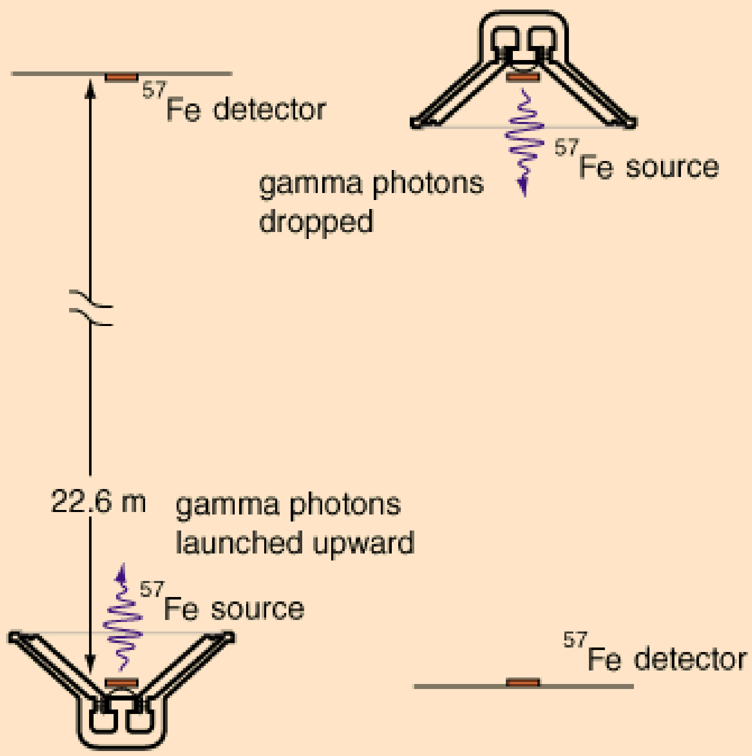
The new theory of gravitation diverges considerably, as regards principles, from Newton's theory. But its practical results agree so nearly with those of Newton's theory that it is difficult to find criteria for distinguishing them which are accessible to experience. Such have been discovered so far:

1. In the revolution of the ellipses of the planetary orbits round the sun (confirmed in the case of Mercury).
2. In the curving of light rays by the action of gravitational fields (confirmed by the English photographs of eclipses).
3. In a displacement of the spectral lines toward the red end of the spectrum in the case of light transmitted to us from stars of considerable magnitude (unconfirmed so far).*

Let no one suppose, however, that the mighty work of Newton can really be superseded by this or any other theory. His great and lucid ideas will retain their unique significance for all time as the foundation of our whole modern conceptual structure in the sphere of natural philosophy.

3. Gravitational redshift (1959)

Harvard Tower Experiment



In just 22.6 meters, the fractional gravitational red shift given by

$$\nu = \nu_0\left[1 + \frac{gh}{c^2}\right]$$

is just 4.92 x 10^-15 , but the Mossbauer effect with the 14.4 keV gamma ray from iron-57 has a high enough resolution to detect that difference. In the early 60's physicists Pound, Rebka,and Snyder at the Jefferson Physical Laboratory at Harvard measured the shift to within 1% of the predicted shift.

- Sirius B (Adams, 1925)
- Gravity Probe A (1970s)

Cosmic prediction I: Black Holes

- **Schwarzschild (1916)**

  Exact solution for the field equations

  Body of spherical symmetry

- **Enigma**

  Solution becomes singular at $r = 2GM/c^2$

  Space closed up around mass?

- **Rejected**

  Co-ordinate problem (Eddington)

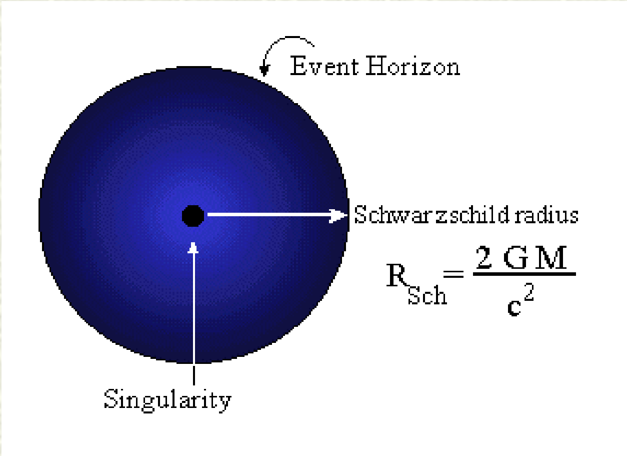
  Prevented by internal pressure (Einstein 1922)

- **Physical reality?**

  Collapse of sun? Anderson (UCG)

  Collapse of large stellar ensemble : Lodge (Liverpool)

Karl Schwarzschild (1873–1916)



The physics of black holes

- **Chandrasekhar (1931)**

  The physics of white dwarf stars (quantum degeneracy)

  SR: collapse to infinite density for $M > 1.4\ M_{\odot}$

  Rejected by Eddington, community

- **Oppenheimer (1939,40)**

  GR: Continued stellar collapse for $M > 3\ M_{\odot}$

  Rejected by Einstein (1939)

- **Wheeler, Thorne, Zeldovitch (1960s)**

  Numerical solutions of the field equations

  Simulation of stellar collapse

- **Penrose (1965)**

  No avoiding BH singularity

Black Holes: Observation

- **Compact astronomical objects (1960s)**

  Quasars: small, distant sources of incredible energy (1963)

  Pulsars: rapidly rotating neutron stars (1967)

- **X-ray binaries**

  Cygnus X-1 (1964)

  Matter pulled from star into massive companion emits X-rays

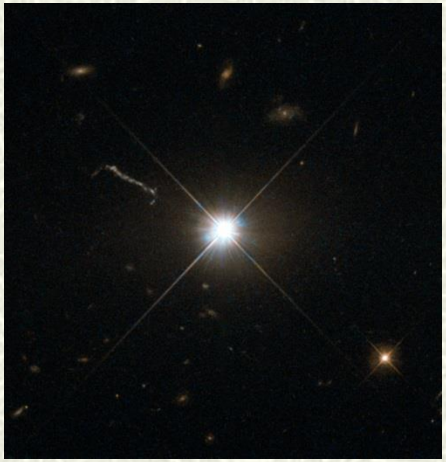
- **Orbit studies**

  Supermassive BH at centre of MW? (1990s)

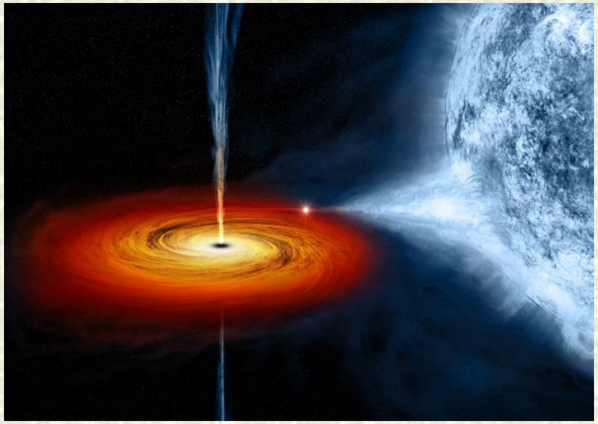
  Supermassive BH at centre of many galaxies (2000-)

- **2015-16**

  Gravitational waves from binary BH system!

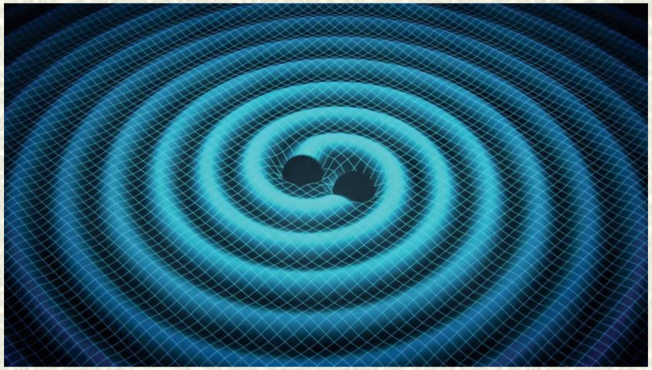


Quasar 3C273



Cygnus X-1 (1964)

Cosmic prediction II: gravitational waves



- **Einstein (1916, 18)**

  Linearized wave-like solutions of GFE

  Cosmic events cause tiny ripples in spacetime?

- **Einstein and Rosen (1936, 37)**

  Cylindrical wave solutions - no gravitational waves (1936)

  Corrected with assistance from HP Robertson (1937)

- **Wheeler (1960s)**

  Numerical wave solutions

- **Weber bars (1960s)**

  Reports signal of gravitational waves

  Not reproduced, not accepted by community

Joseph Weber

Gravitational Waves: Observation

- **Binary pulsar PSR1913+16**

  Hulse-Taylor (1974)

  Decrease in orbital period exactly as predicted

- **Direct measurement?**

  Interferometers: 1980-

  Interferometers with 4 km arms (LIGO, VIRGO)

- **Advanced LIGO (2015)**

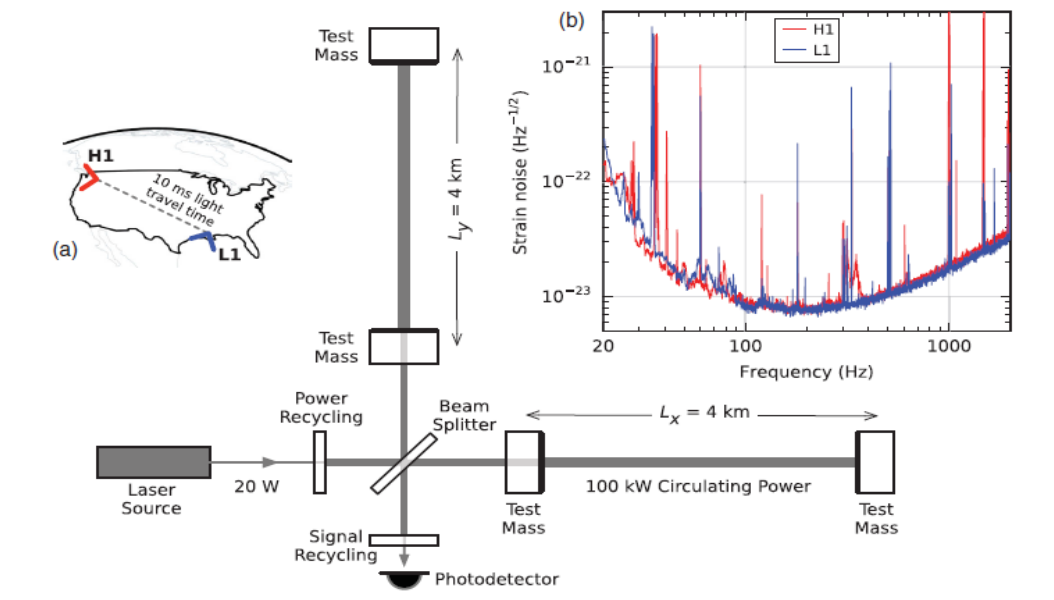
  Clear signal (September 2015)

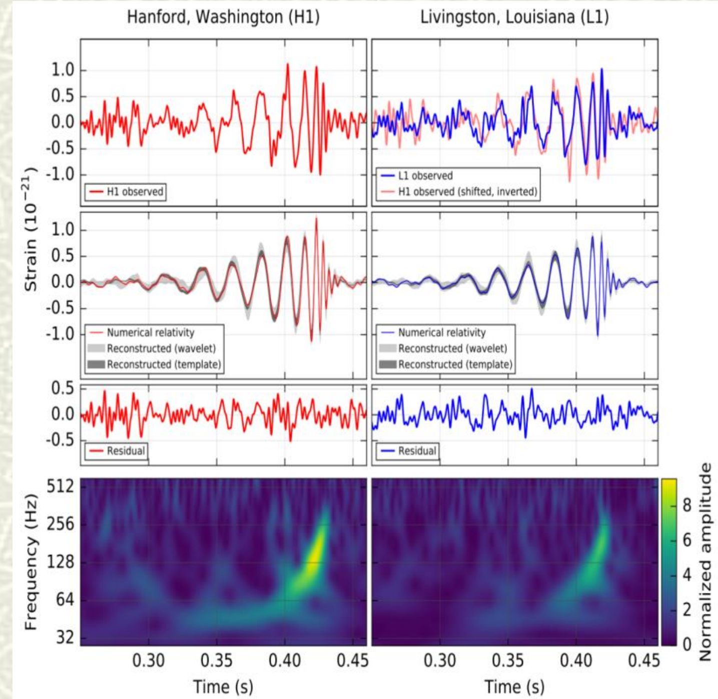
- **Double whammy**

  Exact match with merging BHs

  29 $M_{\odot}$, 36 $M_{\odot}$; *1.3 billion LY away*

Hulse-Taylor pulsar





Selected for a Viewpoint in *Physics*
, 061102 (2016) PHYSICAL REVIEW LETTERS week 12 FEBRU

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

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

1. ***Shape of waveform***
2. ***Frequency of orbit***

BBH !

Cosmic prediction III: The expanding universe

- **Einstein: apply GR to the Universe (1917)**

  Ultimate test for new theory of gravitation

Doc. 43

Cosmological Considerations in the General Theory of Relativity

This translation by W. Perrett and G. B. Jeffery is reprinted from H. A. Lorentz et al., *The Principle of Relativity* (Dover, 1952), pp. 175–188.

IT is well known that Poisson's equation

$$\nabla^2\phi = 4\pi K\rho \quad . \quad . \quad . \quad . \quad (1)$$

in combination with the equations of motion of a material point is not as yet a perfect substitute for Newton's theory of action at a distance. There is still to be taken into account the condition that at spatial infinity the potential ϕ tends

- **Assumptions**

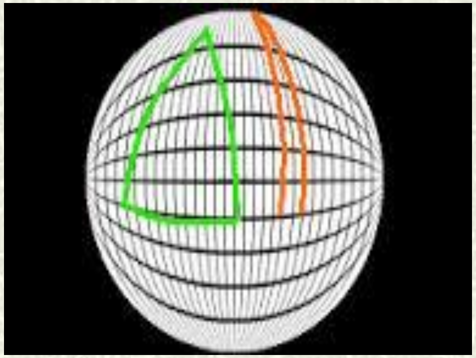
  Static, uniform distribution of matter

  Mach's principle: metric tensor to vanish at infinity

- **Boundary problem**

  Assume cosmos of closed curvature

  But…no consistent solution



- **New term in field equations!**

  Cosmic constant - anti-gravity term

  Radius and density defined by λ

$$G_{\mu\nu} = -\kappa T_{\mu\nu}$$

$$G_{\mu\nu} + \lambda g_{\mu\nu} = -\kappa T_{\mu\nu}$$

$$\lambda = \frac{\kappa\rho}{2} = \frac{1}{R^2}$$

The dynamic universe (theory)

- **Alexander Friedman (1922)**

  Allow time-varying solutions for the cosmos

  Two differential equations for R

- **Evolving universe**

  Time-varying radius and density of matter

  Distrusted by Einstein

- **Georges Lemaître (1927)**

  Theoretical universe of expanding radius

  Agreement with emerging astronomical data

  Also rejected by Einstein

$$\frac{3R'^2}{R^2}+\frac{3c^2}{R^2}-\lambda=\kappa c^2\rho,$$

$$\frac{R'^2}{R^2}+\frac{2RR''}{R^2}+\frac{c^2}{R^2}-\lambda=0.$$

$$\frac{1}{c^2}\left(\frac{\mathrm{d}R}{\mathrm{d}t}\right)^2=\frac{A-R+\frac{\lambda}{3c^2}R^3}{R}$$

Alexander Friedman (1888 -1925)

Georges Lemaître (1894-1966)

The watershed

Edwin Hubble (1889-1953)

- **Hubble's law (1929)**

  A redshift/distance relation for the galaxies

  Linear relation: $h = 500\ kms^{-1}Mpc^{-1}$

- **Evidence of cosmic expansion?**

  RAS meeting (1930): Eddington, de Sitter

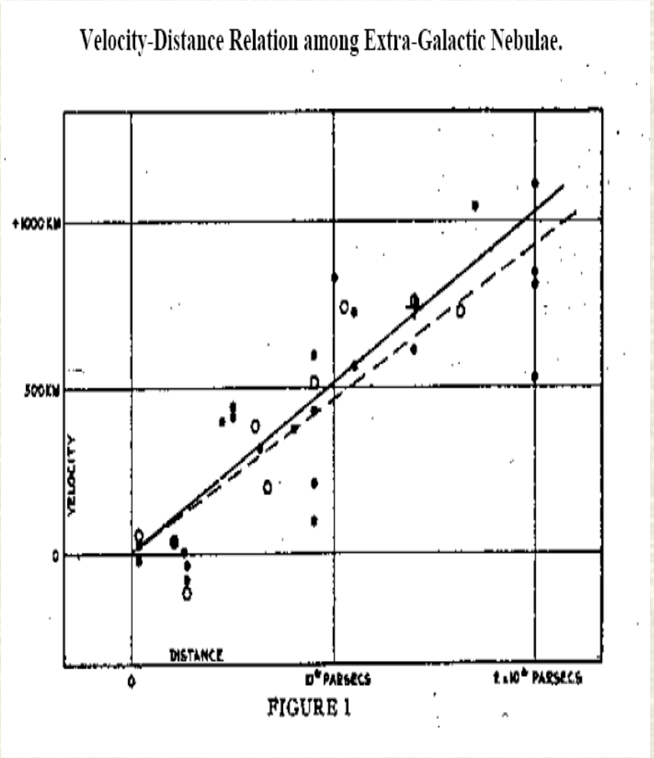
- **Friedman-Lemaître models circulated**

  Time-varying radius and density of matter

- **Einstein apprised**

  Sojourn at Cambridge (June 1930)

  Sojourn at Caltech (Spring 1931)



The expanding universe (1930 -)

- **Eddington (1930, 31)**

  On the instability of the Einstein universe

  Expansion caused by condensation?

- **Tolman (1930, 31)**

  On the behaviour of non-static models

  Expansion caused by annihilation of matter ?

- **de Sitter (1930, 31)**

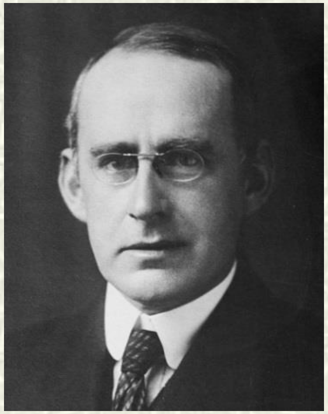
  Further remarks on the expanding universe

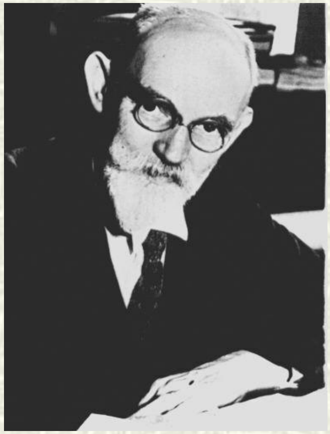
  Expanding universes of every flavour

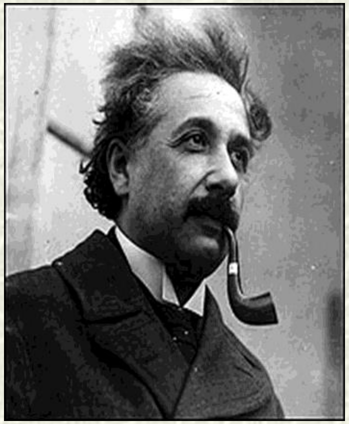
- **Einstein (1931, 32)**

  Friedman-Einstein model $k = 1,\ \lambda = 0$

  Einstein-de Sitter model $k = 0,\ \lambda = 0$







Expanding models

No mention of origins

Cosmic prediction IV: the big bang

Fr *Georges Lemaître*

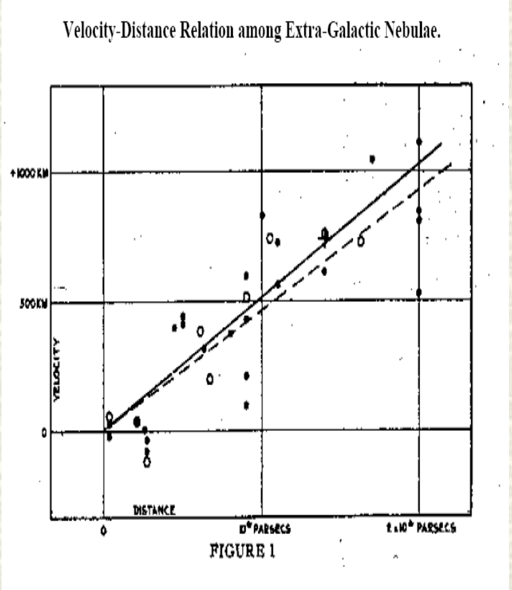
- **Lemaître 1931**: expanding *U* smaller in the past

- <u>Extrapolate</u> to very early epochs

- Extremely dense, extremely hot

- Expanding and cooling ever since

- <u>‘Fireworks beginning’ at *R* = 0?</u>



Not endorsed by community (1930-60)

Simplified models: timescale problem

Later called <u>***‘The big bang’***</u>

The steady-state universe (1948)

- **Expanding but unchanging universe**

  Perfect cosmological principle?

  No extrapolation to early epochs

  No beginning, no timescale paradox

Hoyle, Bondi, Gold (1948)

- **Requires continuous creation of matter**

  Very little matter required

- **Replace λ with creation term** (Hoyle)

$$G_{\mu\nu} + C_{\mu\nu} = -k\, T_{\mu\nu}$$

- **Improved version (1962)**

$$G_{\mu\nu} + \lambda g_{\mu\nu} = k\, T\,(C_{\mu} + C_{\nu})$$

Hoyle and Narlikar (1962)

Steady-state vs big bang (1950-70)

- **Optical astronomy (1950s)**

  Revised distances to the nebulae (Baade, Sandage)

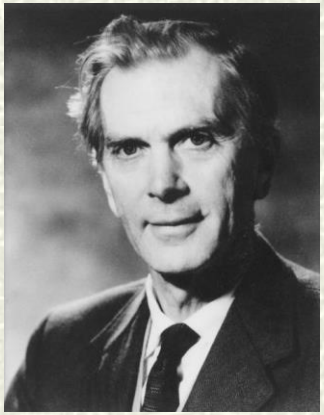
  Timescale problem resolved

Allen Sandage

- **Radio-astronomy (1960s)**

  Galaxy distributions at different epochs

  Cambridge 3C Survey (Ryle)



Martin Ryle

- **Nucleosynthesis of light elements**

  Alpher, Hermann and Gamow (1948)

- **Cosmic microwave background (1965)**

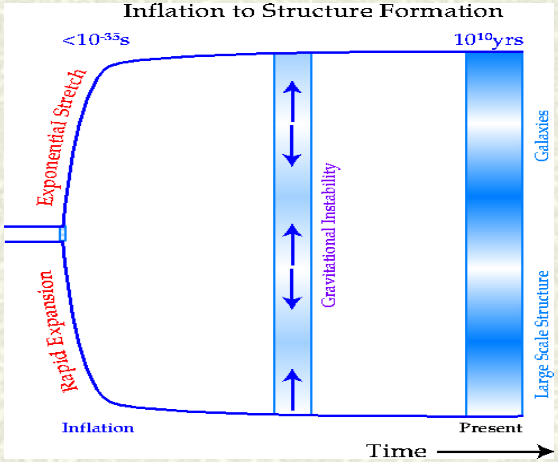
  Microwave frequencies

  Remnant of young, hot universe

Big bang puzzles

- **Characteristics of background radiation**

  Homogeneity, flatness, galaxy formation?(1970-80)



- **The theory of inflation (1981)**

  Exponential expansion within first second?

  Which model of inflation?

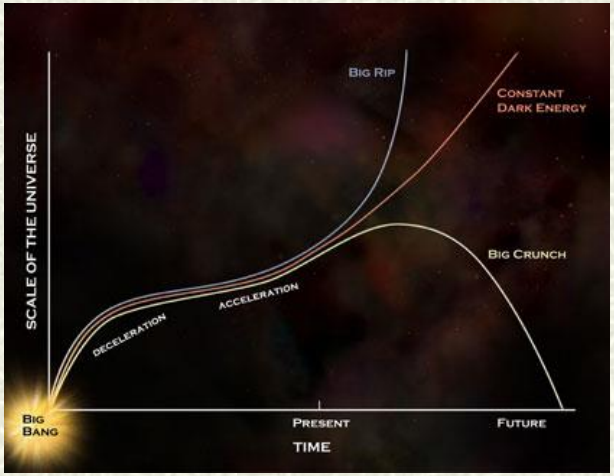
  Initial conditions?

- **Dark energy (1998)**

  Observation of accelerated expansion

  The return of the cosmological constant

  Problems of interpretation



$$\boldsymbol{G}_{\mu\nu} + \lambda g_{\mu\nu} = -\kappa\, \boldsymbol{T}_{\mu\nu}$$

Nature of DE unknown

Gelativity, astronomy and the universe: the first 100 years

- **Published 1915, 1916**

  A new theory of gravity

- **Classic predictions supported by observation**

  Perihelion of Mercury: bending of light by a star

  Gravitational redshift

- **Cosmological predictions supported by observation**

  Black holes: gravitational waves

  The expanding universe: the big bang

- **Relevant today**

  Modifications of theory?

Skeptical of extrapolations