INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

100 Years of General Relativity

Albert Einstein's Revolution in Physics

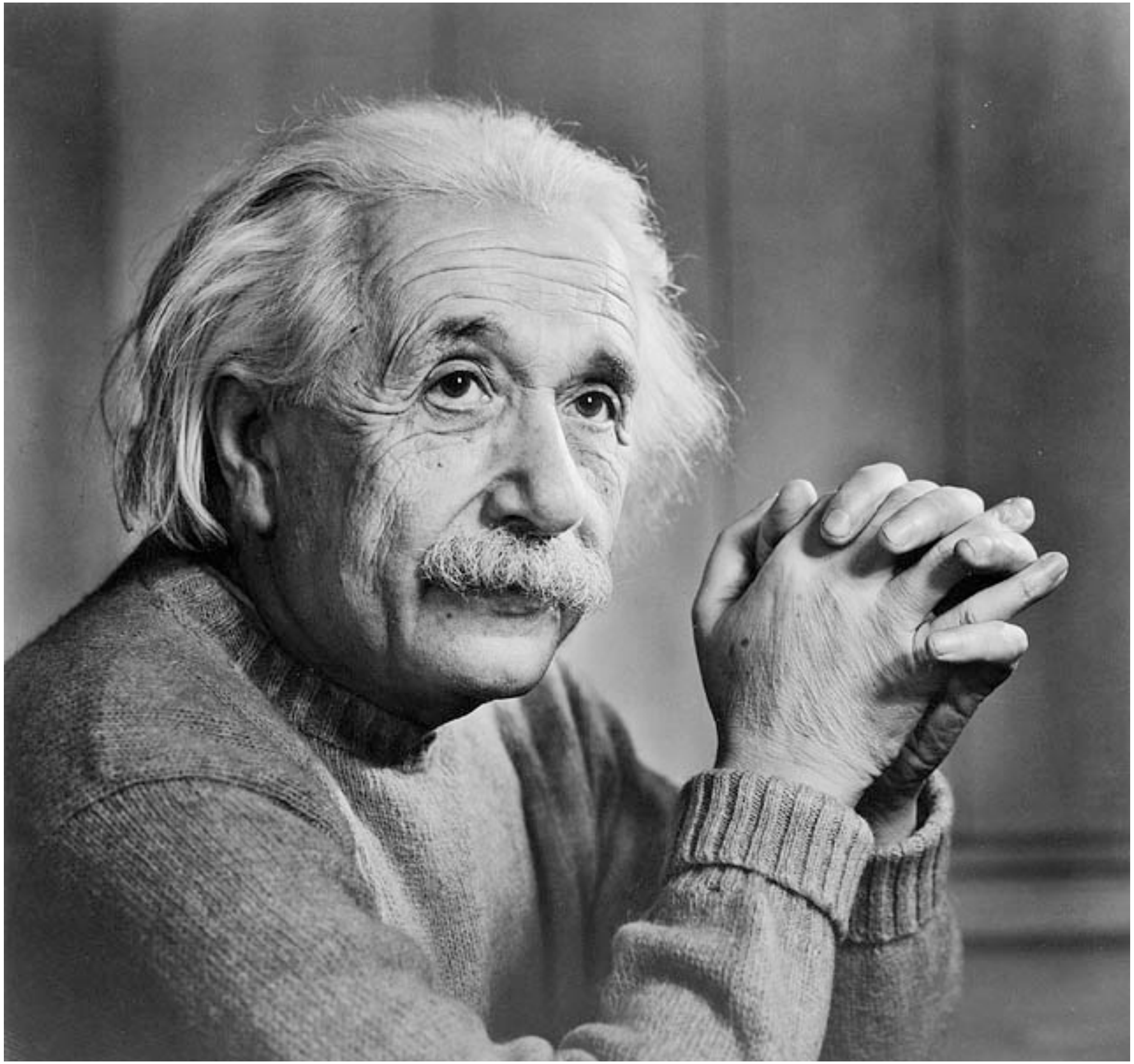
Spenta R. Wadia

International Centre for Theoretical Sciences,

Tata Institute of Fundamental Research, Bangalore

30 November 2015

Albert Einstein (1879-1955)



100 years ago in Berlin

- In 1915, in a series of weekly (Thursday) presentations to the Prussian Academy in Berlin, (Nov 4, Nov 11, Nov 18, Nov 25, 1915) Albert Einstein put forth his General Theory of Relativity.

- Nov 25, 1915 is significant because it is on this day the complete and correct equations were presented for the first time:

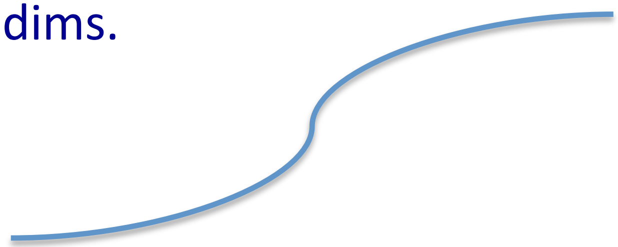
A. Einstein, Die Feldgleichungen der Gravitation. Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin) 1915, 844–847 (1915)

- GR overturned the Newtonian view where space is a static arena and time is absolute and unchanging. In GR space-time is a dynamic arena and gravitation is a consequence of the curvature of space- time.

- We will trace this incredible journey from Newton to Einstein and beyond.

Isaac Newton (Principia Mathematica 1687)
Birth of Theory in Science

Newton formulated the laws of motion in terms of the flow in time of the position of a point particle in 3-dims.



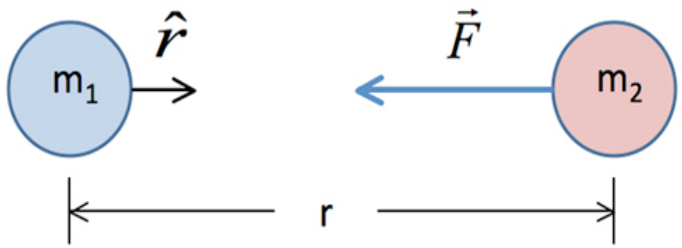
(x(t), y(t), z(t))

Time is absolute and the same for all observers. Coordinates may be rotated or moved with constant velocity.

Newton's law of motion:

Force = $m_{inertial}$ x **Acceleration**

Newton's law Universal Gravitation



$$\vec{F} = -\frac{Gm_1 m_2}{r^2}\hat{r}$$

Force acts instantaneously at a distance

Newton (1692): "That one body may act upon another at a distance through a vacuum without the mediation of anything else, by and through which their action and force may be conveyed from one another, is to me so great an absurdity that, I believe, no man who has in philosophic matters a competent faculty of thinking could ever fall into it."

Newton (1713) "I have not yet been able to discover the cause of these properties of gravity from phenomena and I feign no hypothesis. It is enough that gravity does really exist and acts according to the laws I have explained, and that it abundantly serves to account for all the motions of celestial bodies."

James Clerk Maxwell (1831-79)

Maxwell unified electricity and magnetism, predicted the existence of electromagnetic waves and identified light as an electromagnetic wave moving with a speed c (in vacuum):

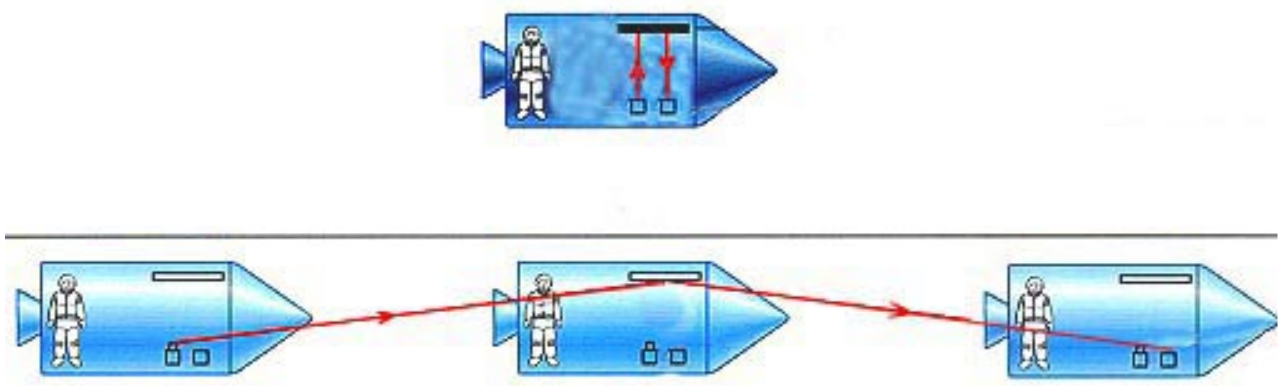
$c = 3.1 \times 10^5$ km/sec

Special Relativity (1905)

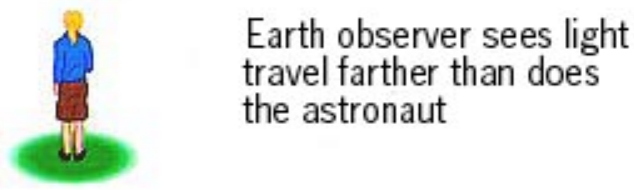
Implications of Maxwell's theory:

Speed of light is the same whether you run towards it or away from it. Space and time have to adjust themselves to ensure this!

Time intervals between events depend on your state of motion; things happen (according to us) more slowly for a moving observer than for us.



$$\Delta t' = \frac{\Delta t}{\sqrt{1 - v^2/c^2}}$$



4-dimensional Space-Time

Hemann Minkowski (1864-1909)

Introducing Geometry in Special Relativity

- *“Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.”*

- Time is a 4th component of a 4-dim. space-time $x_4 = ct$; a new geometry described by
  $ds^2 = (dx_4)^2 - (d\mathbf{x})^2$

- Recall Euclid’s geometry:
  $ds^2 = (dx_4)^2 + (d\mathbf{x})^2$

Two seemingly unrelated puzzles

- In Newton's law of gravitation the force of gravity acts instantaneously. Not consistent with Special Relativity! Like Newton Einstein would like to have the force of gravity communicated at the speed of light by a field analogous to the electro-magnetic field of Faraday and Maxwell.

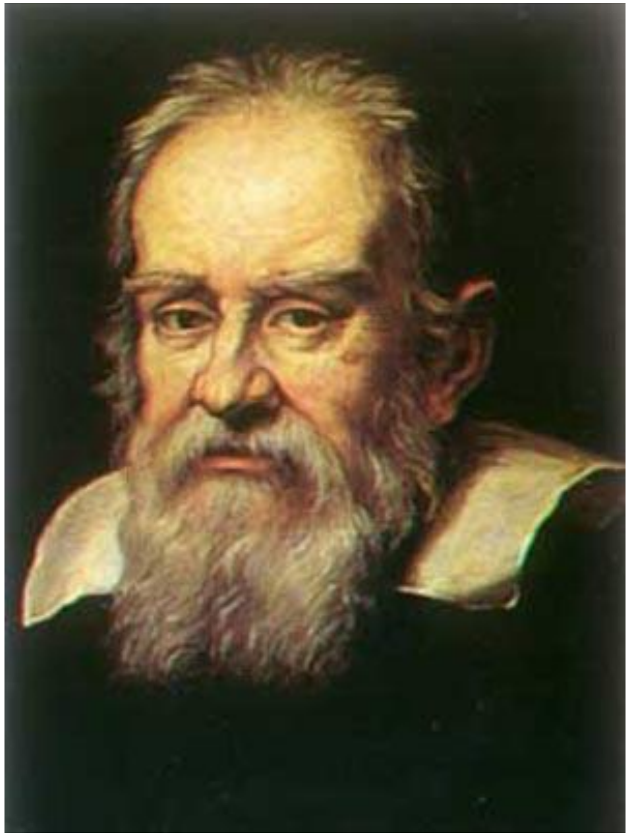
- Special Relativity is restricted to frames with relative constant velocity, but the laws of physics must be valid in any reference frame including those which are accelerating.

- A possible resolution occurred in 1907: **The Principle of Equivalence** *(Einstein: "the happiest/luckiest thought of my life").*

Galileo (1564-1642)

Pioneer of the modern scientific method

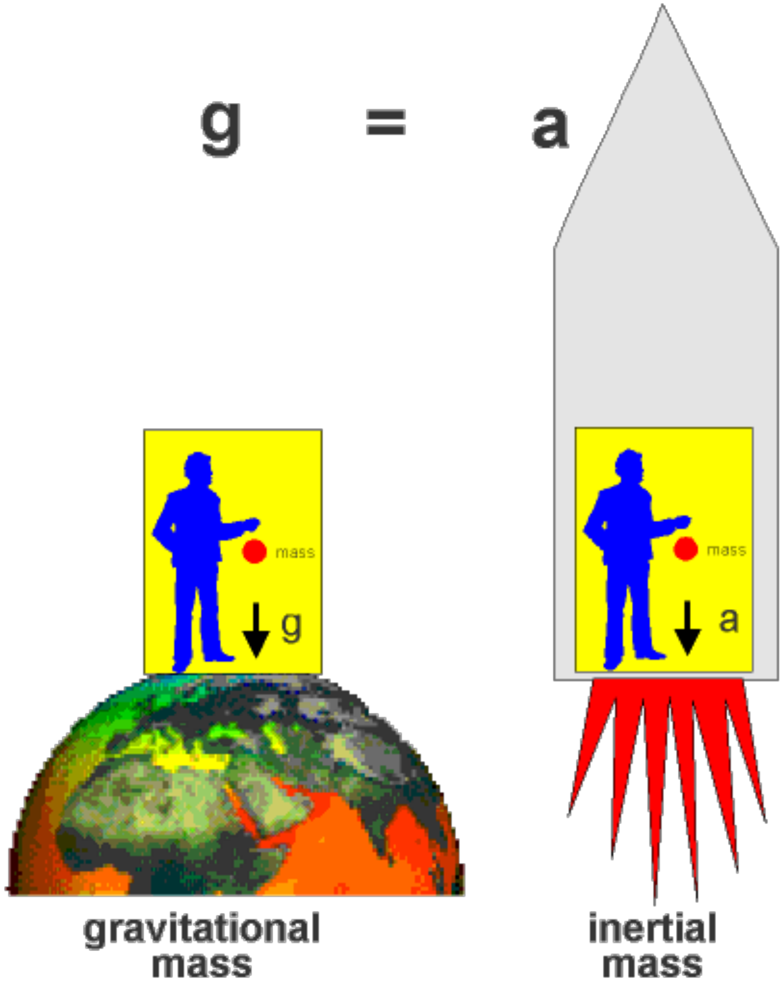
Discovered a new law of gravity



Gravity acts in the same way on all bodies: they all fall in the same way independent of their mass:

$m_{inertial} = m_{gravitational}$ ($1/10^{13}$ precision)

Principle of Equivalence



Einstein 1907:
"The effect of a constant gravitational field is equivalent to a uniformly accelerated frame"

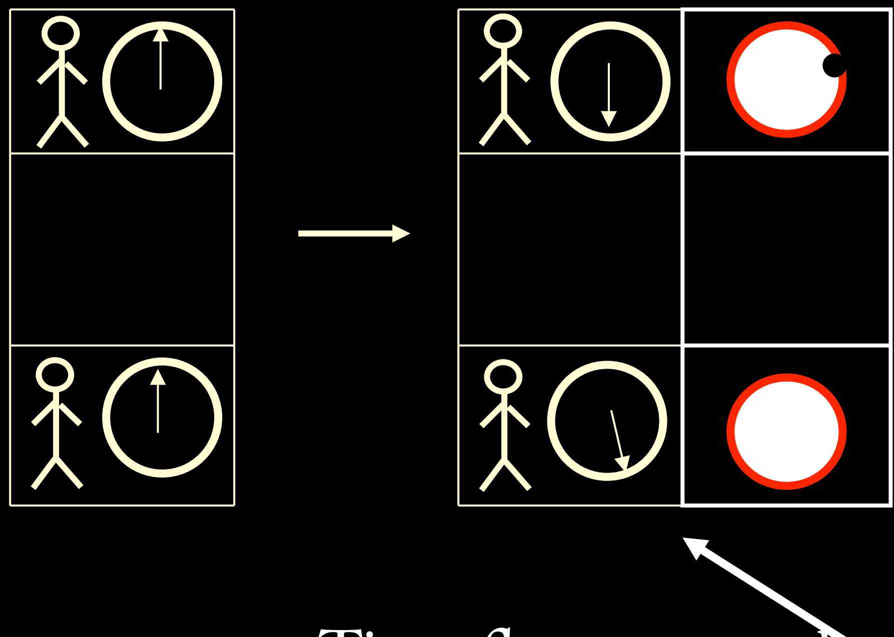
True over sufficiently small regions of space and times in a non-uniform gravitational field. Analogy with a `bug' crawling on a sphere.

Patching up such regions of space-time to construct the full space-time needed Riemannian geometry (curved space-time) and **Marcel Grossmann.** (1912, Zurich)

Equivalence Principle implies that time flows different for two observers in a gravitational field.

Upper floor

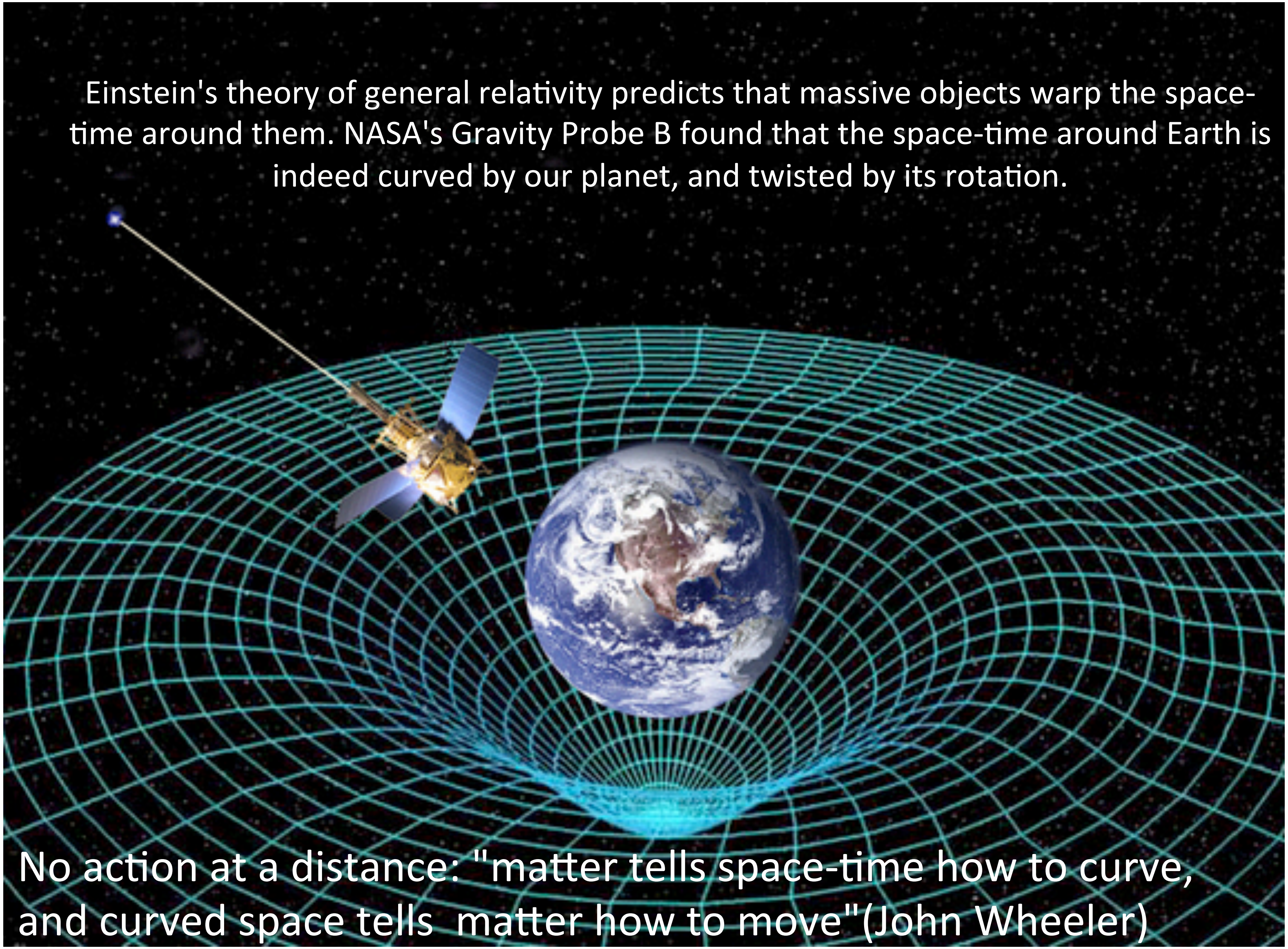
Lower floor



Time flows more slowly

(A part in 10^{15}) for a height of 100 mtrs.

This effect is relevant for GPS!


Einstein's theory of general relativity predicts that massive objects warp the space-time around them. NASA's Gravity Probe B found that the space-time around Earth is indeed curved by our planet, and twisted by its rotation.
No action at a distance: "matter tells space-time how to curve, and curved space tells matter how to move"(John Wheeler)

Equations of space-time geometry

- Einstein made the space-time grid `fluid', communicative and causal

- Just as the equations of fluid dynamics, describe the flow of fluids, the equations of GR describe the shape changes of the geometry or fabric of space-time caused by massive objects in which other objects move. This explains gravity without gravity.

- In fact `small' shape changes are communicated by `gravitational waves'…whose detection is a central experimental challenge of our times.

The gravitational field is described by the warping of the fabric of space-time (1915)

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

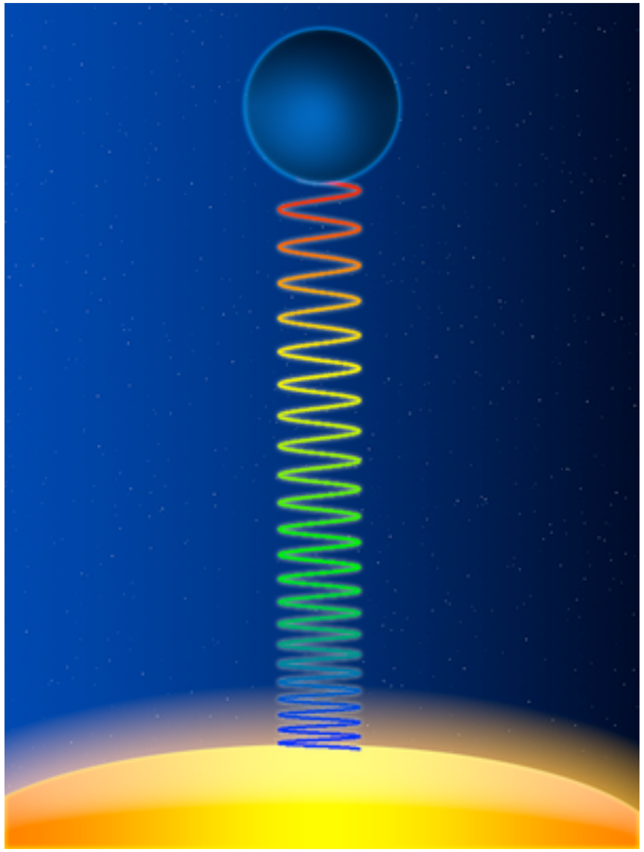
The lhs is related to the curvature of space-time and the rhs is the energy-momentum tensor

Law of motion of an object in a curved space-time: It follows a path that maximizes the time in the frame of the object (proper time).

In the following we will present the famous experimental tests of these equations and further predictions.

Tests of GR: 1. Gravitational Redshift

Wavelength of light shifts from blue (short) to red (long)



- $(\lambda_{obs}-\lambda_e)/\lambda_e = \Delta\lambda, \quad \Phi_d-\Phi_u = \Delta\Phi$

$$\Delta\lambda = \Delta\Phi/c^2$$

λ is wavelength and Φ is the gravitational potential

- First verified by Pound and Rebka in 1959 at Harvard

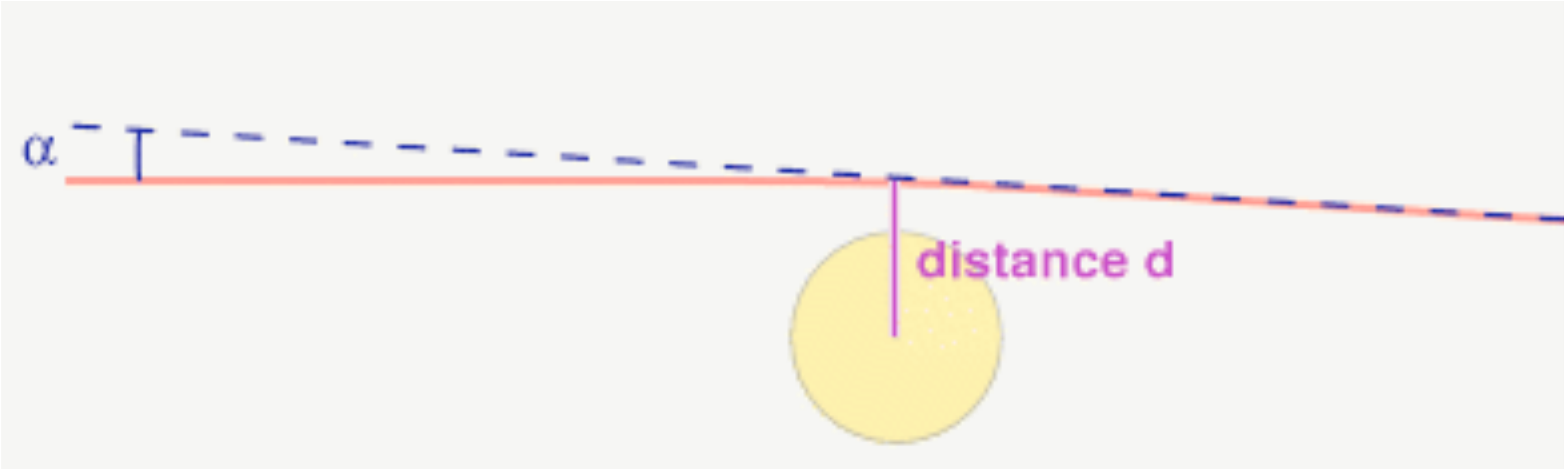
- Astrophysical tests:

Sun: $\Delta\lambda \approx 2\text{x}10^{-6}$

White Dwarf: $\Delta\lambda \approx 0.001$

Neutron Star: $\Delta\lambda \approx 0.1$

2. Bending of light by massive objects

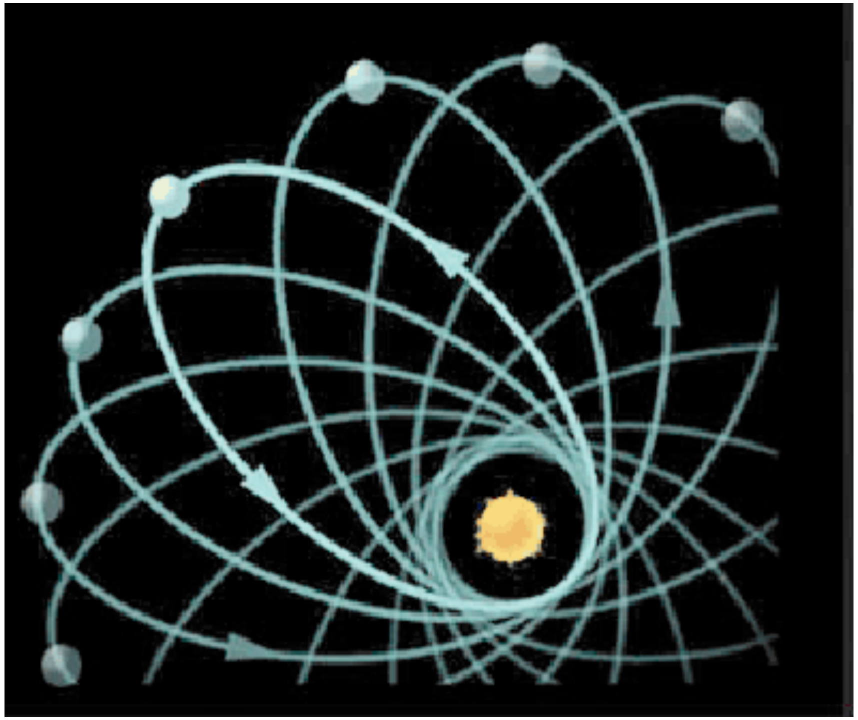


Newtonian theory $\alpha = 2GM/c^2d = 0.9$ arc seconds
Einstein theory $\alpha = 2 \times 0.9$ arc seconds, agrees with experiment.

Experiments carried out during a solar eclipse: **Eddington 1919**, Lick Observatory 1922, Yerkes Observatory 1953, U Texas 1973.
Long baseline radio interferometry 1960s gave the most accurate verification of the GR prediction.

When asked by an assistant if general relativity had not been confirmed by Eddington and Dyson in 1919, Einstein famously made the quip: "Then I would feel sorry for the dear Lord. The theory is correct anyway."

3. Perihelion of Mercury

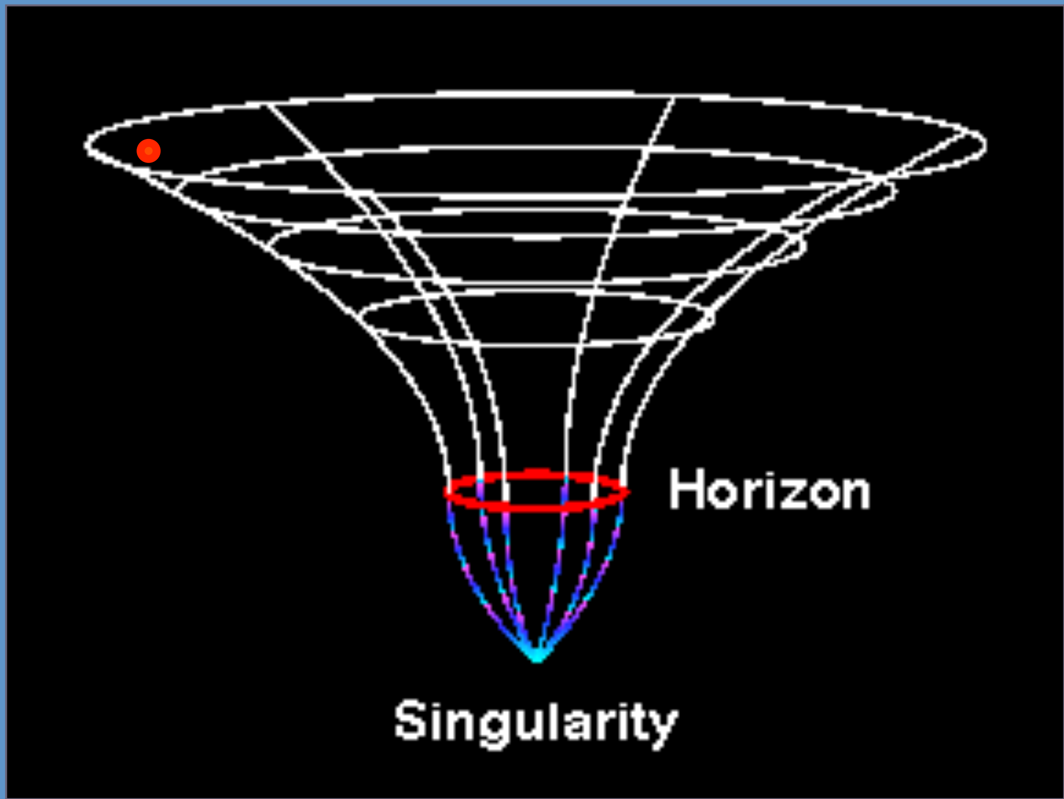


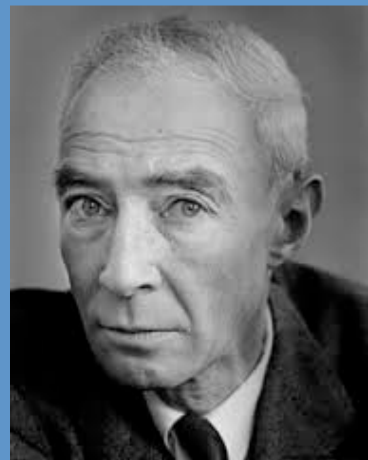
- 5600 seconds of arc per century (one second of arc=1/3600)
- Newton: predicts a precession of 5557 seconds of arc per century. **There is a discrepancy of 43 seconds of arc per century.**
- Einstein's theory accounts for this discrepancy, by taking into account that space-time is curved by the mass of the Sun.

New predictions (solutions) of GR

- Black holes
- Standard model of cosmology
- Gravitational waves

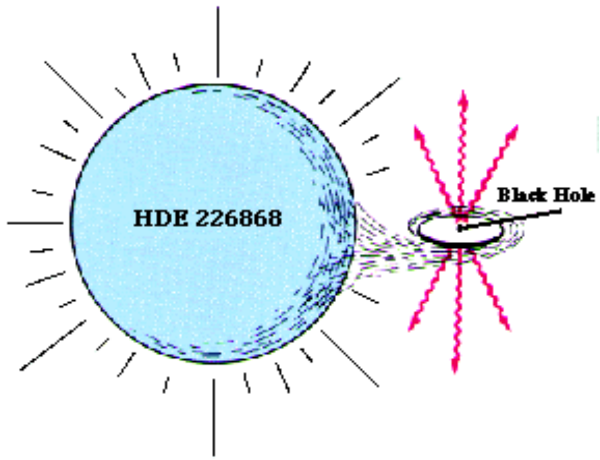
Einstein's theory predicts Black Holes

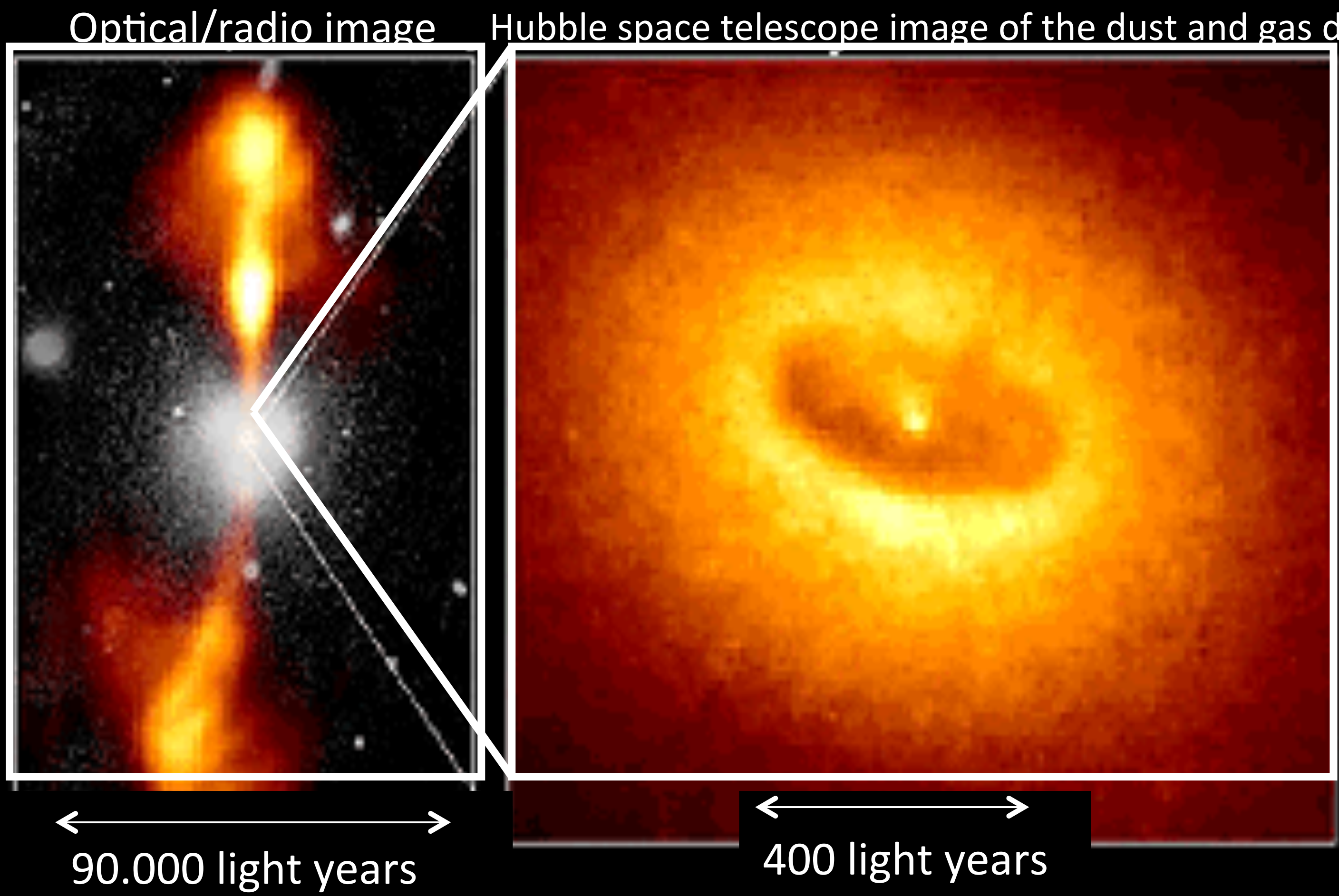




Black holes can be observed

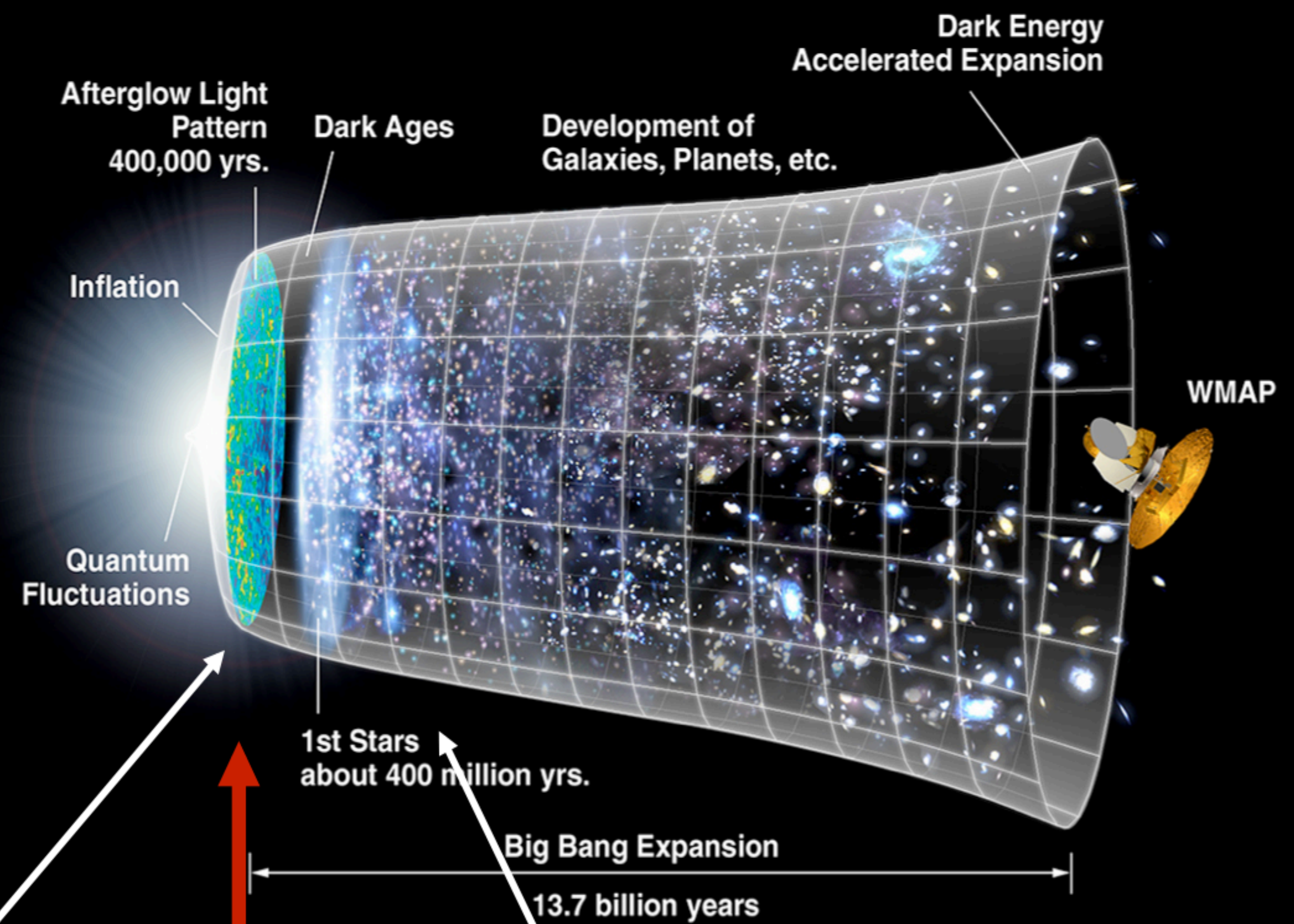
- Black holes, like a lens, bend the light coming from stars behind them. In this way we can `see' them.
- Radiation from a companion star's material falling into a black hole has characteristic signatures which can be measured by astronomers, e.g. by instruments on board India's ASTROSAT satellite.





Many galaxies similar to ours have these black holes at the center.

The Standard Model of Cosmology

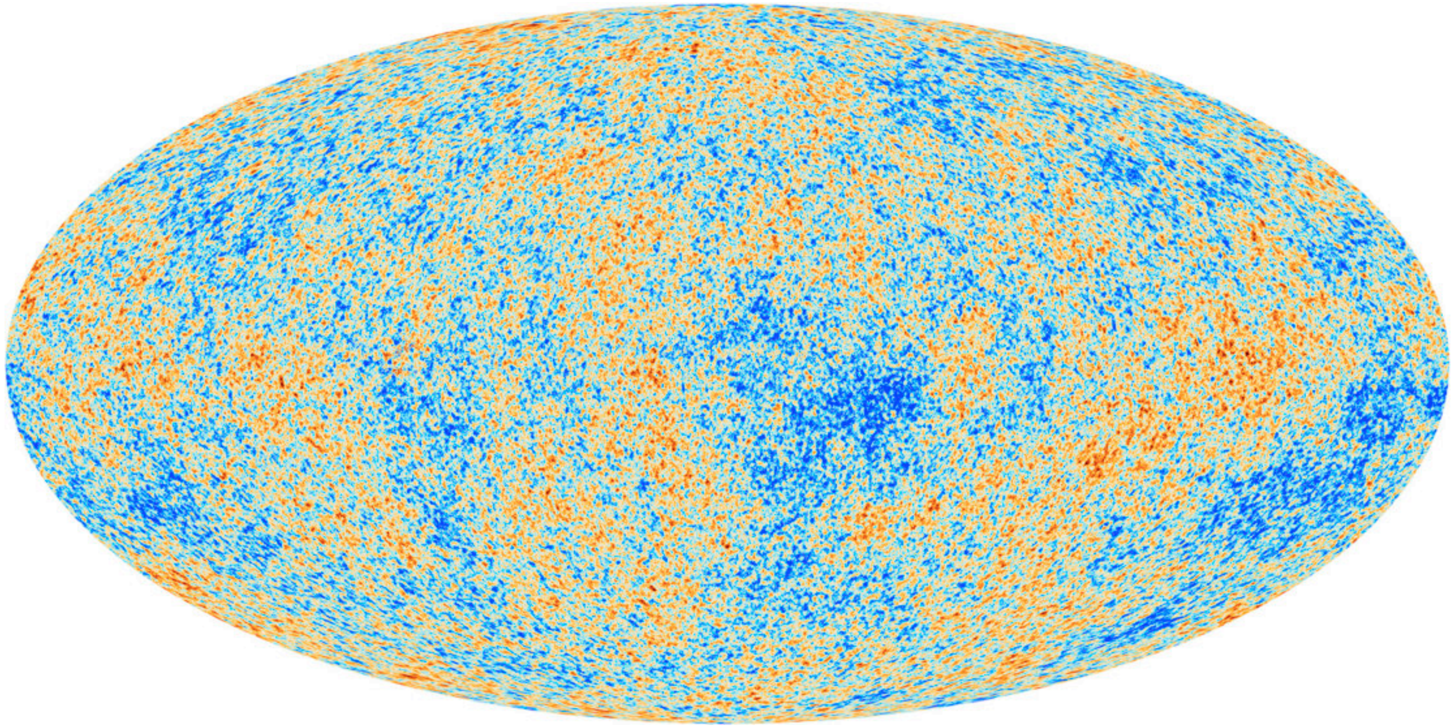


Surface of last scattering
at "decoupling."

"Reionization"

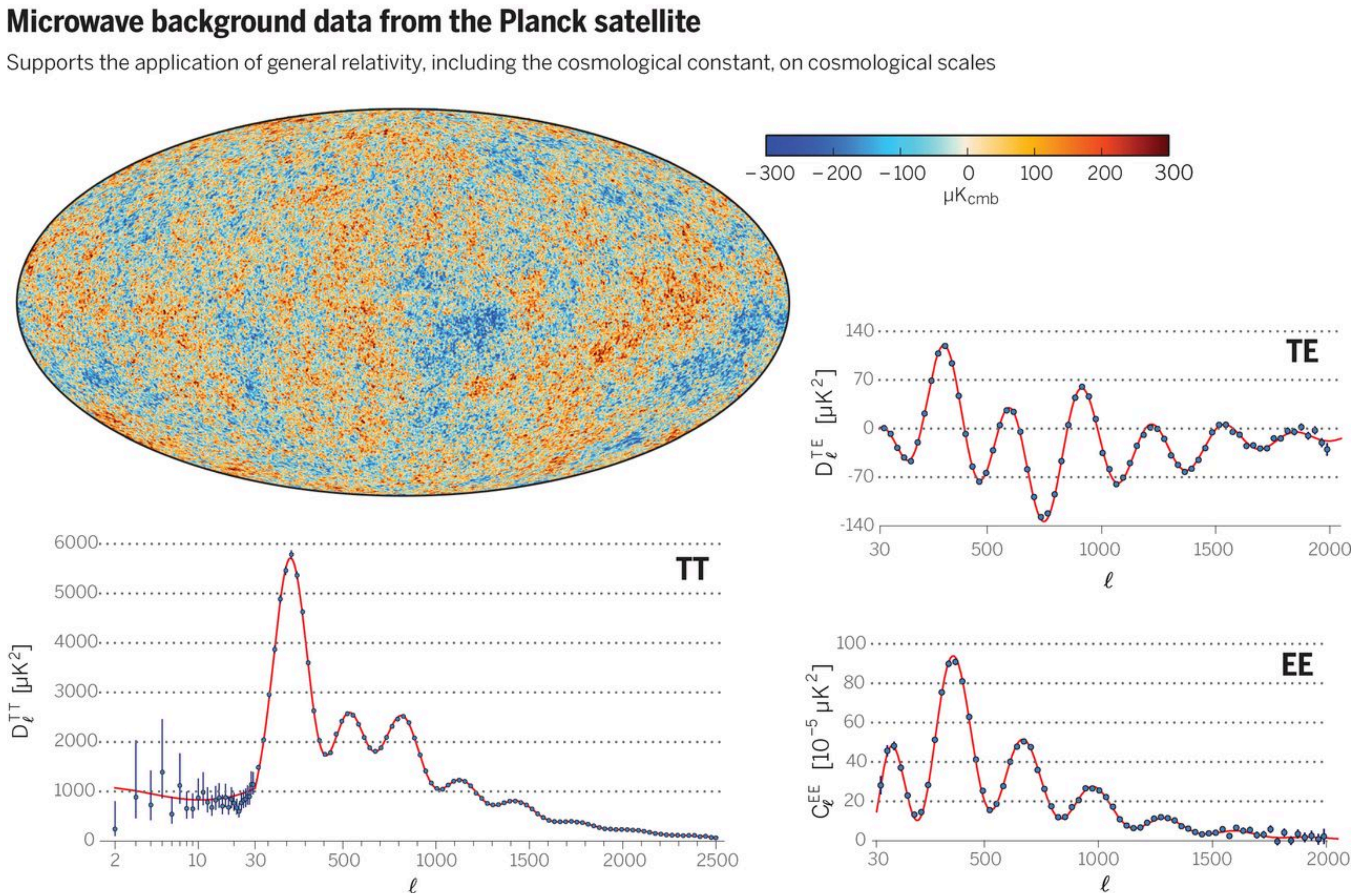
Cosmic Microwave Background (CMB) map of the early universe

(Planck Experiment of ESA)



CMB – the relic radiation left over from the Big Bang gives astronomers insight into the evolution since the birth of our Universe, nearly 14 billion years ago. Density fluctuations seed the galaxies.

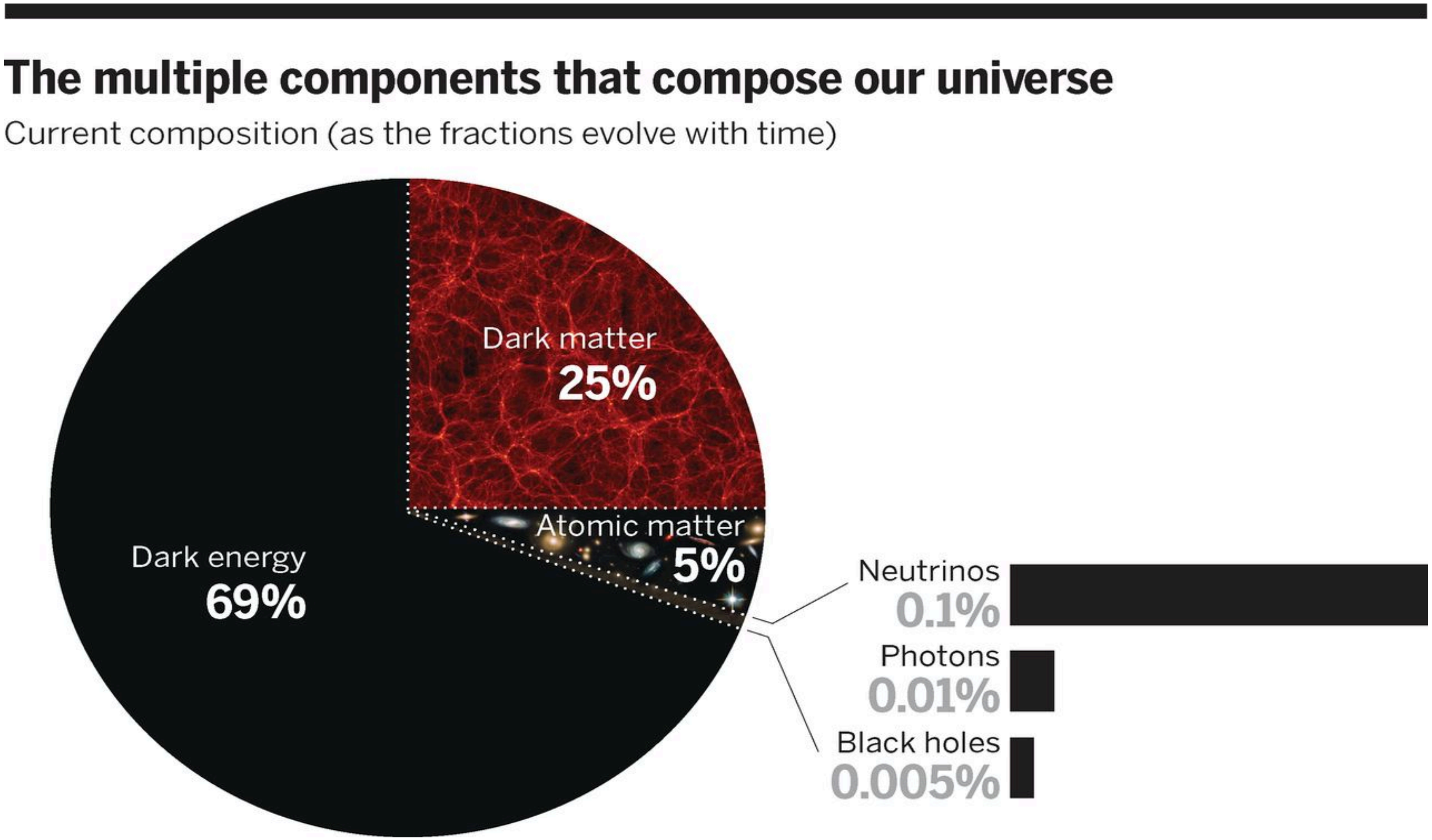
Recent microwave background data from the Planck satellite.(Top left) The best fitting map of the temperature fluctuations.



R. D. Blandford Science 2015;347:1103-1108

Published by AAAS

The multiple components that compose our universe. Dark energy comprises 69% of the mass energy density of the universe, dark matter comprises 25%, and “ordinary” atomic matter makes up 5%.



David N. Spergel Science 2015;347:1100-1102

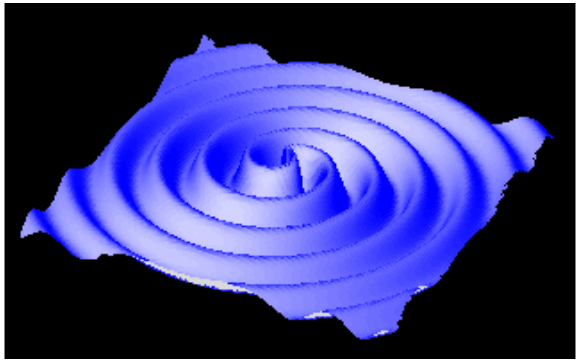
Published by AAAS

Gravitational waves: a new probe of astronomy

- The existence of gravitational waves (GWs), ripples in the fabric of space-time, is one of the most intriguing predictions of the GR.
- Indirect observation in binary pulsar (Hulse & Taylor, 1974)
- GW astronomy is a new frontier that will profoundly influence our knowledge of the universe and its past…it will see what `light' cannot.

accelerating charges (time-varying dipole moment) → electromagetc waves

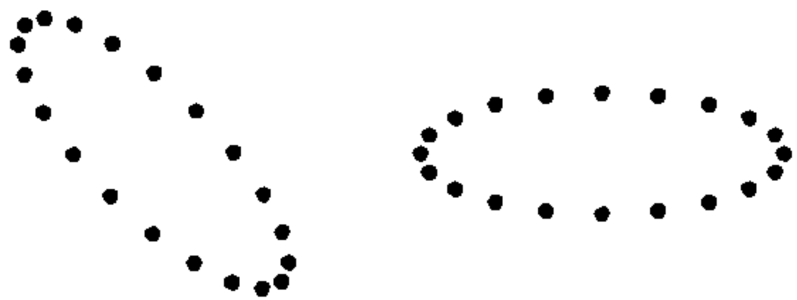
accelerating masses (time-varying quadrupole moment) → gravitational waves



Direct detection of gravitational waves

- GW signals from the last stages of the inspiral (and merger) could be detected using GW observatories on the Earth.
- When GWs pass through earth, they change the geometry of the spacetime.
- These changes can be detected with the help of laser interferometers.

Effect of GWs on a ring of test particles

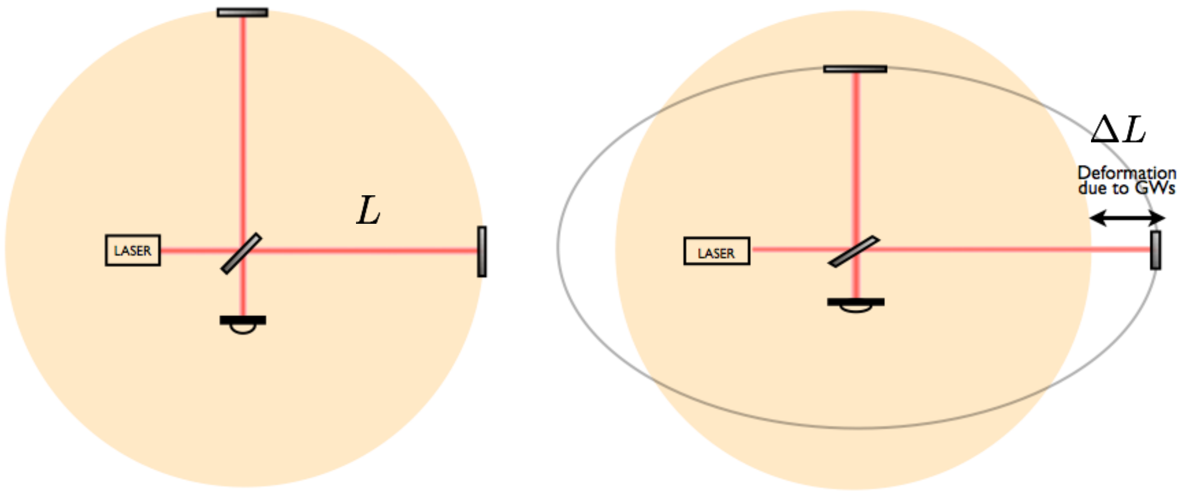


"x" polarisation

"+" polarisation

Direct detection of gravitational waves

- **Experimental challenge** Expected distortions are tiny!



Expected distortions: GW strain $h = \frac{\Delta L}{L} \sim 10^{-21}$

Required displacement sensitivity of interferometers (L ~ 1 km) $10^{-18}\,\mathrm{m}$

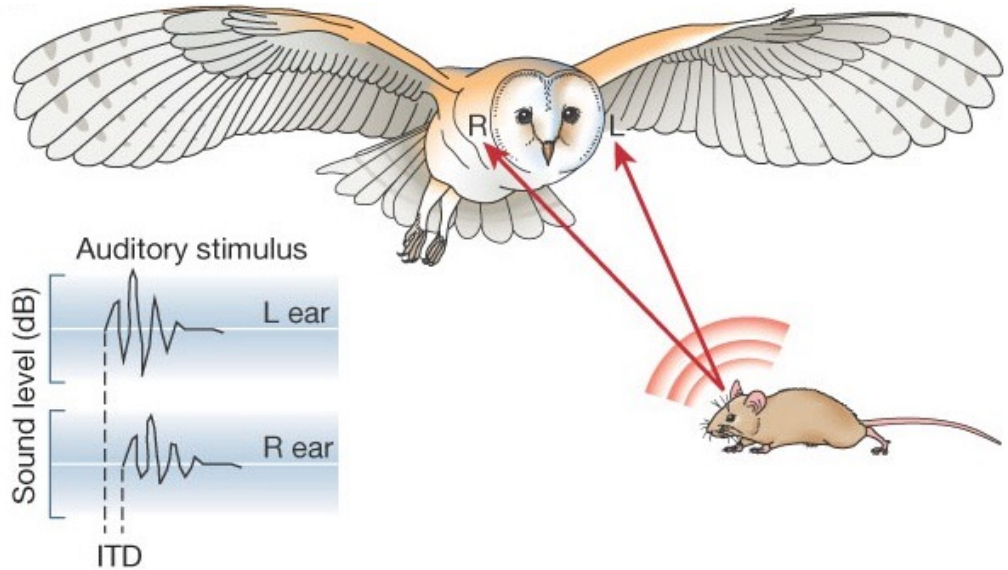
(1/1000 size of nucleus)

Direct detection of gravitational waves

- A worldwide network of ground-based detectors has started an exciting search for GWs.

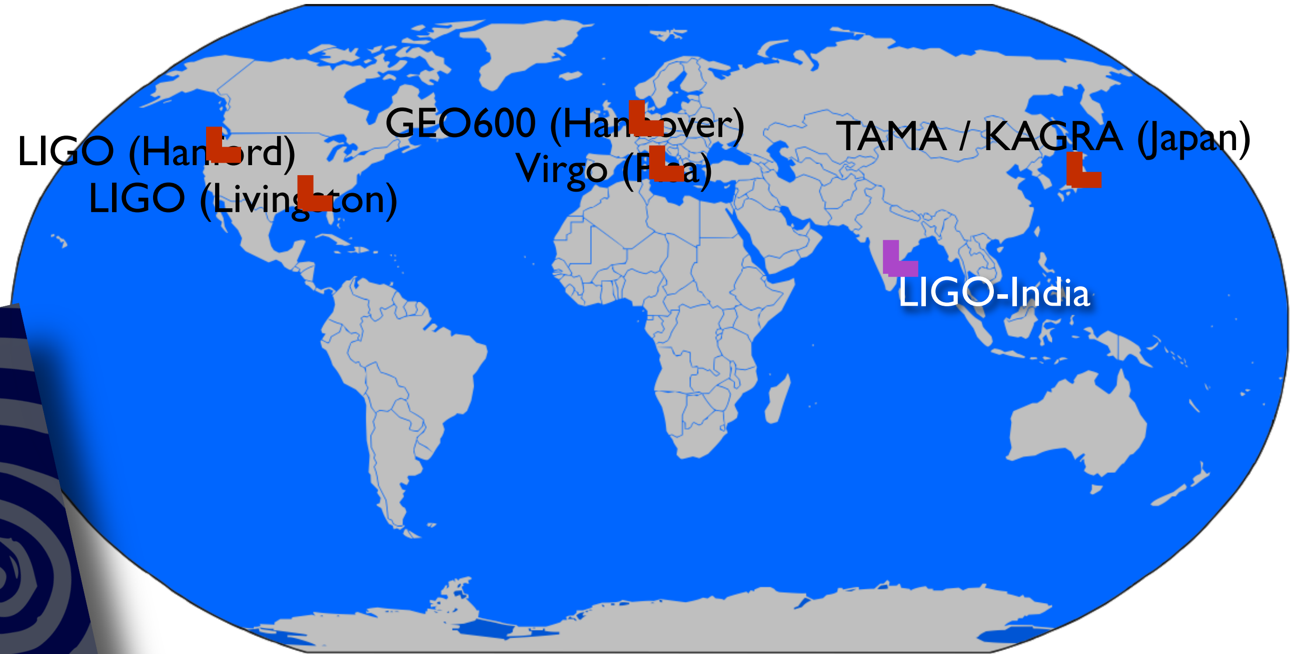
LIGO Observatories in Hanford and
Livingston, USA

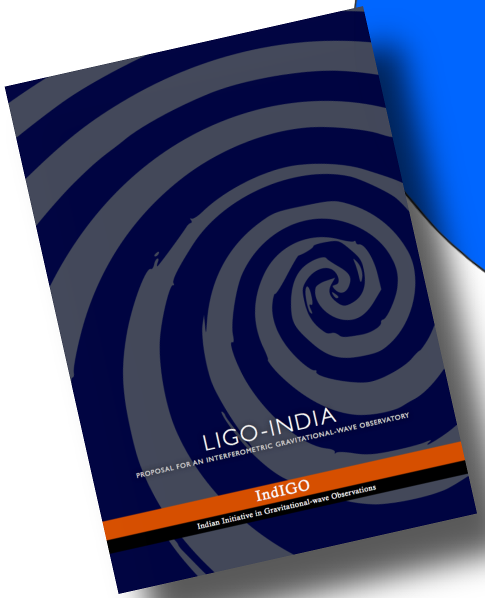
GW astronomy requires a worldwide network of observatories



- Interferometric GW detectors are nearly omnidirectional antennas. Sky-localization of the source is achieved by combining data from multiple, geographically separated detectors.

GW astronomy requires a worldwide network of observatories





http://www.gw-indigo.org/ligo-india

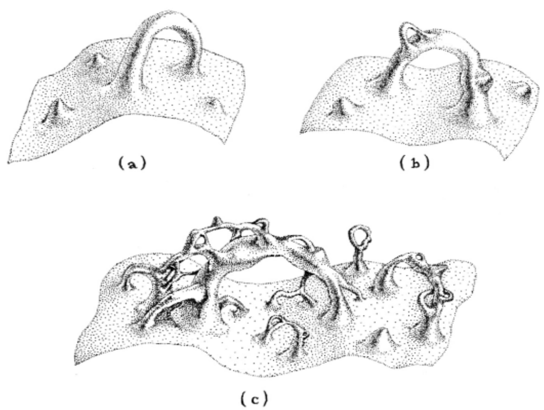
"General Relativity is now, I think, routinely accepted as the foundation of our description of the universe at large, which we call cosmology; of black holes, of neutron stars and of small corrections to the orbits of planets and spacecraft in our own solar system." (Science Magazine, March 2015)

Roger Blandford

Kavli Institute for Particle Astrophysics and Cosmology, Stanford University

The Future: GR and Quantum Mechanics

- QM (the uncertainty principle) implies that the fabric of space-time cannot be smooth at Planck space-time scales, and the Einstein theory breaks down at extremely short distances (10^{-33} cm) and short times (10^{-44} s) Quantum fluctuations (jitters) do not allow sensible calculations.



The quest to find a complete theory that includes GR at long wavelengths has occupied physicists for the last several decades.

Black Holes and new degrees of freedom of space-time

- String theory which has an infinite tower of states is a natural candidate and leads to calculable answers

- The smooth space-time of our experience is an approximate description of an underlying structure that is needed for a complete (quantum) description of gravity.

- In string theory quantum mechanics of black holes points to a revolutionary fact that space-time has more degrees of freedom that the metric. This fact leads to intriguing connections of string theory with different parts of physics and mathematics.

- **It also has the tenet to present a unified theory of the physical world.**

- This is a subject of intense current research in string theory…

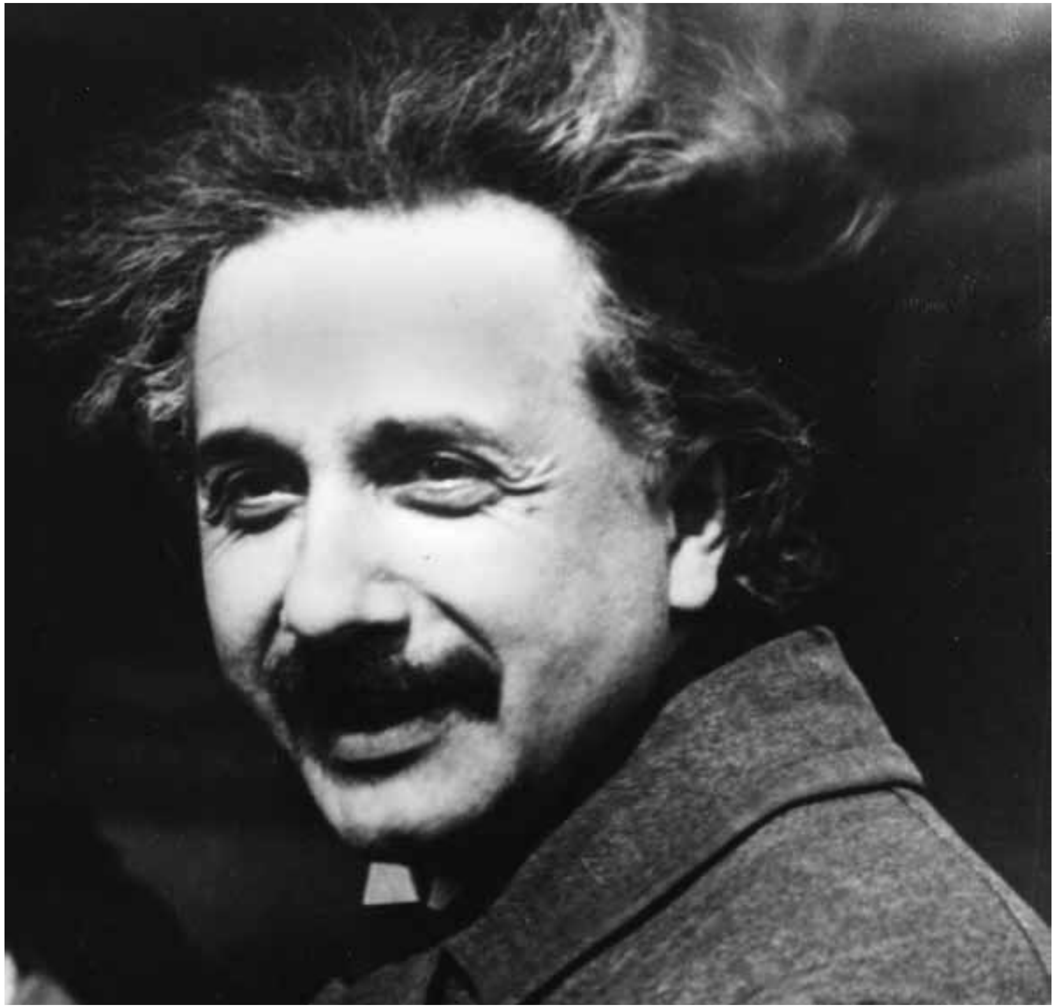
The Legacy of Einstein for Theoretical Physics

i) The fundamental role of symmetry in the formulation of the laws of physics. This was an important motivation in arriving at the gauge principle which is at the foundation of the standard model of elementary particles.

ii) The discovery of the laws of nature by **logical invention based on general principles**, which can subsequently meet the test of experiment. e.g. the Dirac equation for the electron.

iii) String theory carries forward the legacy of Albert Einstein. Its goal is to present a unify theory of all the physical laws that govern our universe (or even other universes!)

Thank You



Acknowledgement

- P. Ajith (ICTS-TIFR) for slides pertaining to gravitational wave astronomy.

- Juan Maldacena (IAS Princeton) for the animation about black holes and red shift.

- Various sources, including `Einstein Online’ of MPI, Albert Einstein Institute for illustrations.