Gravity as a Relativistic Effect

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Contents

Problems with Newtonian gravity

- Consider two pointmasses m_1 and m_2 at resp. locations $\vec{r}_1$ and $\vec{r}_2$

  Gravity as described by Newton :

  Gravitational force $\vec{F}_{12}$ of m_1 exerted on m_2 at time t

$$|\vec{F}_{12}| = \frac{Gm_1m_2}{|\vec{r}_1(t) - \vec{r}_2(t)|^2} = \frac{Gm_1m_2}{(\Delta r)^2} \text{ with } \Delta t = 0$$

$*$ Clash with relativity : Δr and Δt are no absolute values

$\longrightarrow$ The above Newtonian formula is valid in only 1 inertial frame

$*$ Laws of physics should be identical in all inertial frames

$\longrightarrow$ New theory of gravity needed which is consistent with relativity

- Another puzzle : $\vec{F} = \dfrac{\mathrm{d}\vec{p}}{\mathrm{d}t} = (\text{constant inertial mass } m_I) = m_I \cdot \vec{a}$

  At the Earth surface $|\vec{a}|$=constant and $|\vec{F}_{grav}| = m_G \cdot \frac{GM_\oplus}{R_\oplus^2} = m_I \cdot |\vec{a}|$

  Why is gravitational mass m_G equal to the inertial mass m_I ?

  Or : How does gravity "know" how strong to pull to give all objects the same $\vec{a}$?

Einstein's insight

- Einstein : Observer in free fall to the earth $\longrightarrow$ No experience of the gravitational field

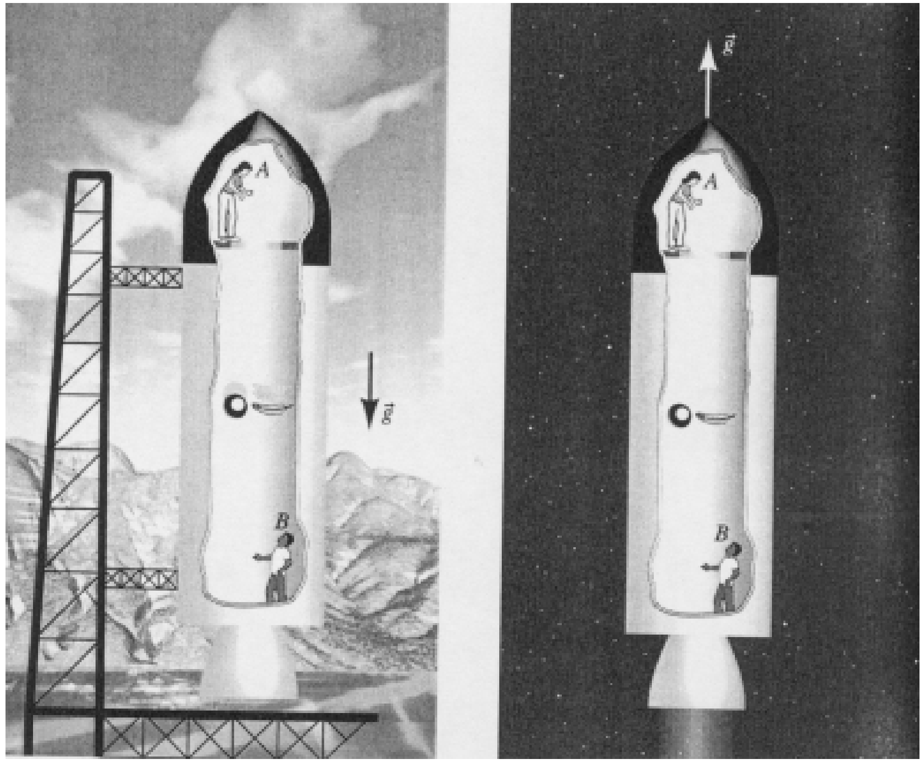
  $\longrightarrow$ An accelerated frame can transform gravity away

  Objects at rest close to the observer will stay at rest $\longrightarrow$ Local inertial frame

  $\longrightarrow$ The gravitational field has only a relative existence

$\ast$ Consequence : Gravity can be induced by accelerating the reference frame

The equivalence principle



Effects in a uniform gravitational field

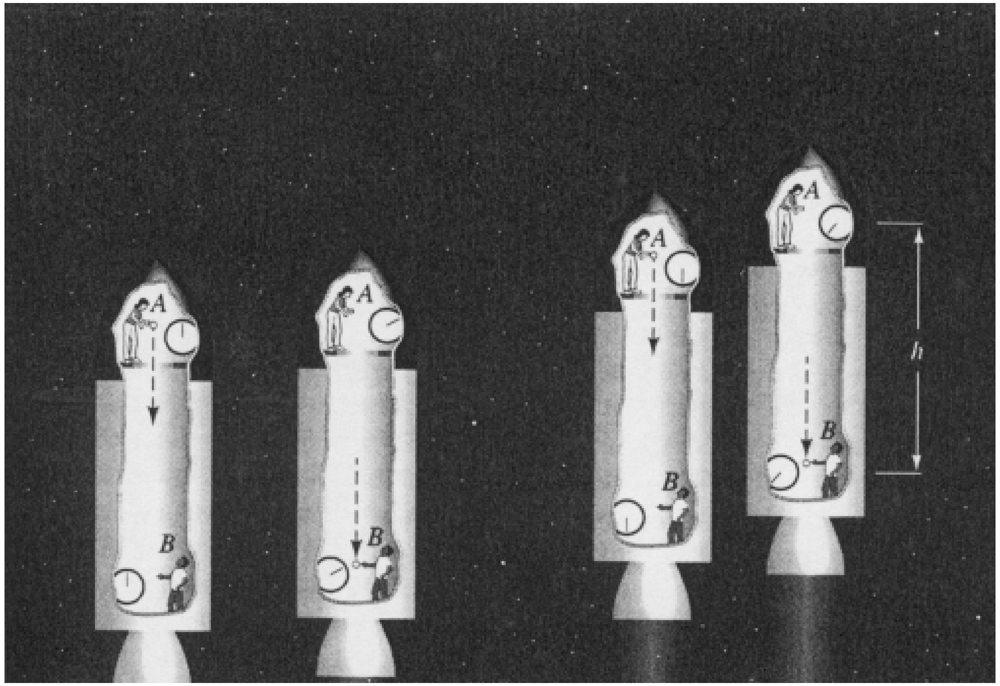
Gravitational time dilation

- Consider a rocket in empty space with constant vertical acceleration $g\,\hat{z}$

  Nose of the rocket : Observer A with clock A emitting light signals at intervals $\Delta\tau_A$

  Tail of the rocket : Observer B with clock B receiving light signals at intervals $\Delta\tau_B$

$\ast$ Distance A-B $\equiv h$: At what time intervals does observer B receive the signals ?



Effects in a uniform gravitational field

- Enable simple Newtonian mechanics by selecting an inertial frame such that

  Rocket velocity $V = 0$ at the first signal emission

  $\Delta V = g \cdot h/c \ll c \rightarrow$ No acceleration to relativistic V while light travels nose-tail

- Choose time and axis origin : First pulse emitted at $t \equiv 0$ and $z_B(t=0) \equiv 0$

  $V(t=0) \equiv 0 \rightarrow$ Observer locations : $z_B(t) = \frac{1}{2}gt^2 \qquad z_A(t) = h + \frac{1}{2}gt^2$

  First pulse emitted at $t = 0$ and received at $t = t_1$

  Second pulse emitted at $t = \Delta\tau_A$ and received at $t = t_1 + \Delta\tau_B$

- Distance traveled by first pulse : $z_A(0) - z_B(t_1) = ct_1$

  $\rightarrow h - \frac{1}{2}gt_1^2 = ct_1 \qquad (1)$

- Distance traveled by second pulse : $z_A(\Delta\tau_A) - z_B(t_1 + \Delta\tau_B) = c(t_1 + \Delta\tau_B - \Delta\tau_A)$

  $\rightarrow h + \frac{1}{2}g(\Delta\tau_A)^2 - \frac{1}{2}g(t_1 + \Delta\tau_B)^2 = c(t_1 + \Delta\tau_B - \Delta\tau_A) \qquad (2)$

- Combining (1)&(2) and neglecting higher orders of $\Delta\tau_A$ and $\Delta\tau_B$:

$$\rightarrow \Delta\tau_B = \frac{c\Delta\tau_A}{c + gt_1} \approx \frac{c\Delta\tau_A}{c + gh/c} = \frac{\Delta\tau_A}{1 + gh/c^2}$$

Effects in a uniform gravitational field

Equivalence principle : The same must happen in a uniform gravitational field

- Gravitational time dilation

$$\Delta\tau_B \approx \frac{\Delta\tau_A}{1 + gh/c^2}$$

Emission and reception rates ν :

$$\nu_B \approx \nu_A \, (1 + gh/c^2)$$

- In terms of the gravitational potential Φ :

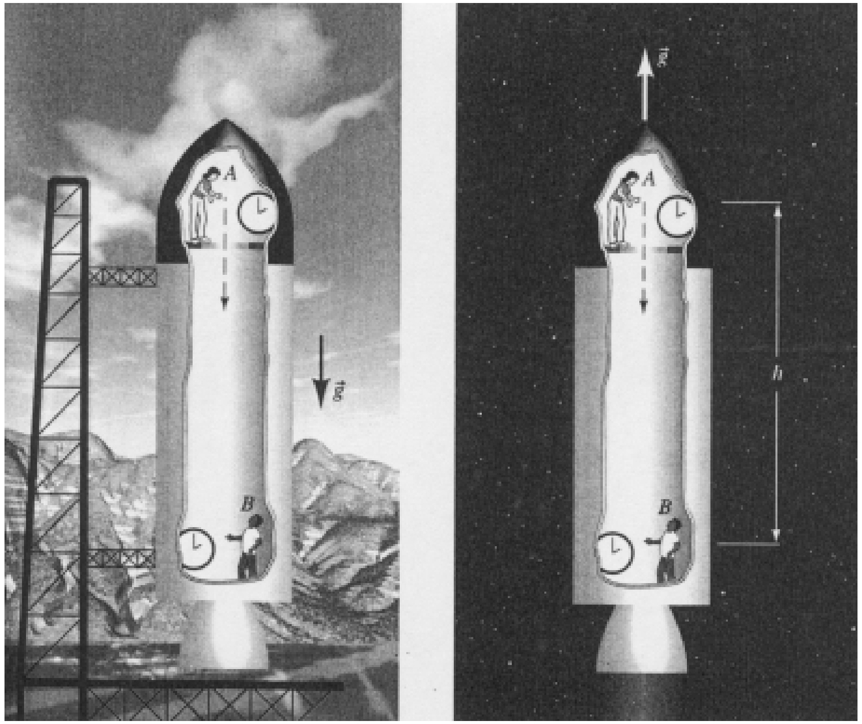
$$\boxed{\nu_B \approx \nu_A \left(1 + \frac{\Phi_A - \Phi_B}{c^2}\right)}$$

Also valid in non-uniform grav. fields

Gravitational red shift

$$z \equiv \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}} = \frac{\lambda_{obs}}{\lambda_{emit}} - 1$$

($z < 0 \rightarrow$ blue shift)



$*$ Exercise : Determine the redshift at $r = \infty$ for the light emitted from the edge of a white dwarf with mass $M = M_\odot$ and radius $R = 10^3$ km

Effects in a uniform gravitational field

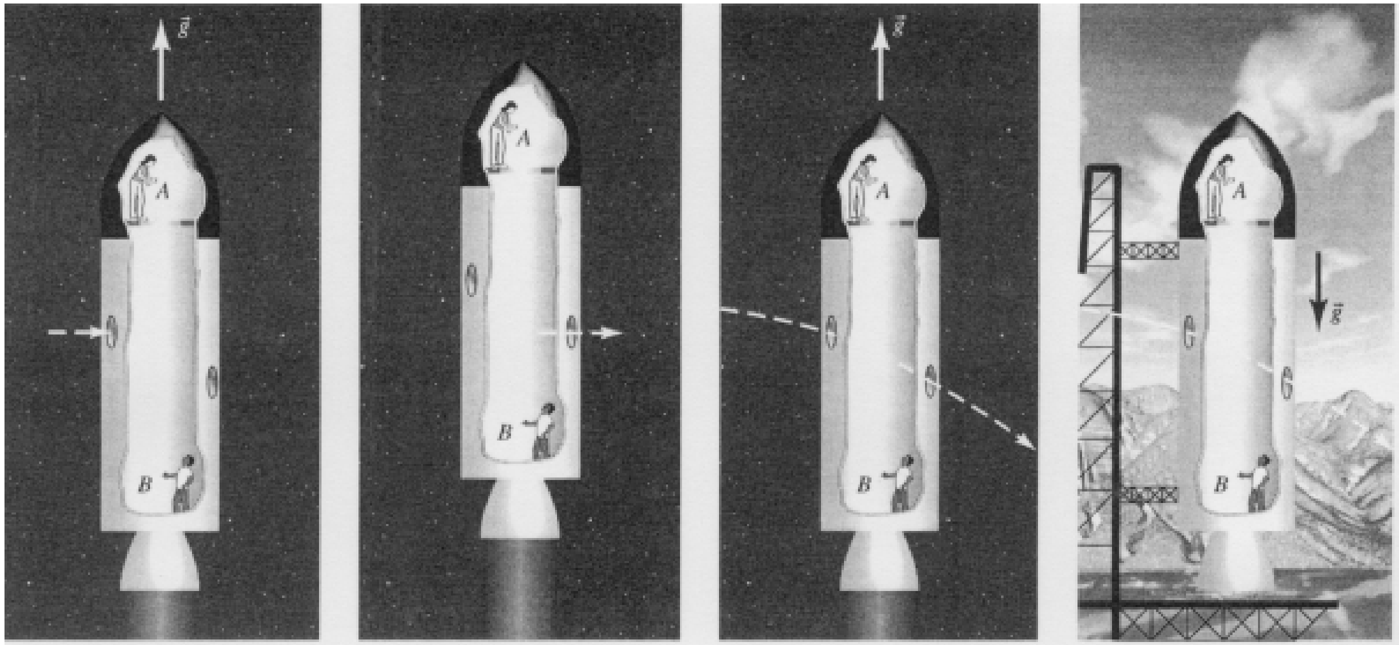
Gravitational deflection of light

- Consider a rocket in empty space with constant vertical acceleration $g\,\hat{z}$

  Light ray enters (upper window) and exits (lower window)

  Outside inertial frame : light ray describes straight path

  Accelerated rocket frame : light ray falls down with acceleration g



A light ray in a gravitational field must fall with the same acceleration as other objects

Gravity as a geometrical effect

- Deflection of light in a gravitational field

  Not corresponding to Newtonian gravity formula

  Ultimate proof that all particles experience the same $\vec{a}$ irrespective of m
- Einstein's idea concerning gravitational path deflection

  Consider a particle traveling in a straight line over a flat rubber sheet

  Put a heavy object on the rubber sheet $\longrightarrow$ sheet stretches and curves

  $\longrightarrow$ The particle will now follow a curved path on the sheet

  Gravitational path deflection is due to curvature of space
- Similar reasoning for the time coordinates

  Gravitational time dilation is due to curvature of time

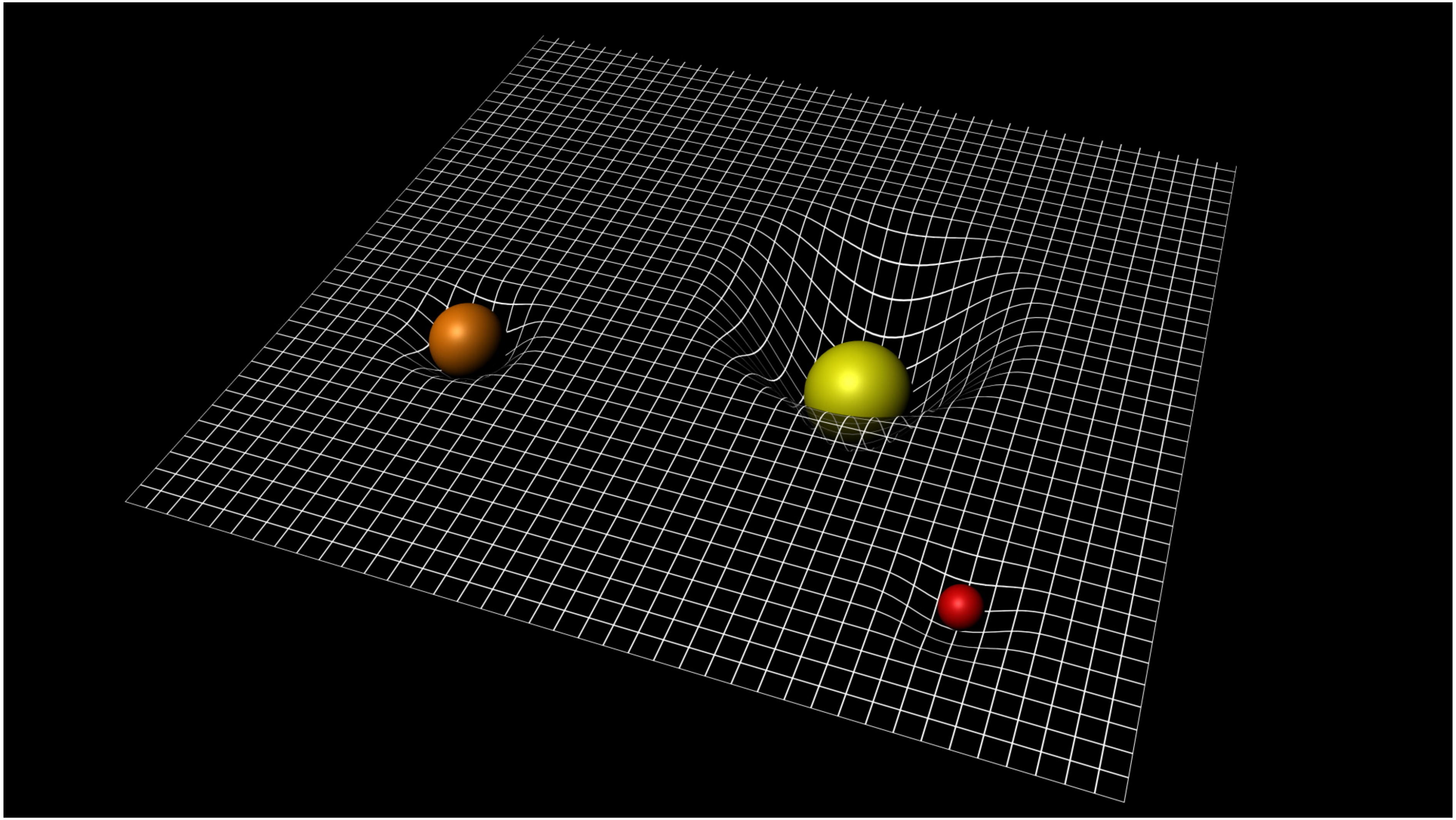
Relativistic viewpoint on gravity

Gravity is a geometric effect due to curvature of space-time

The presence of mass introduces a curvature in space-time

Gravity as a geometrical effect

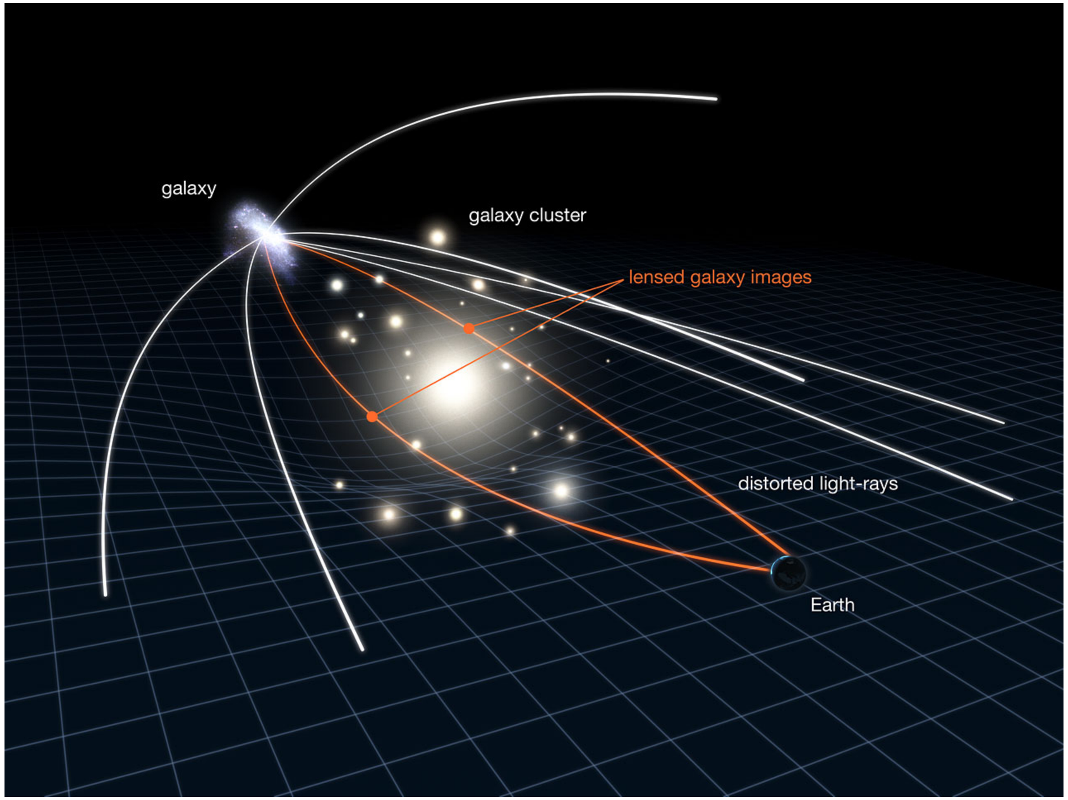
Curvature of space due to the presence of mass



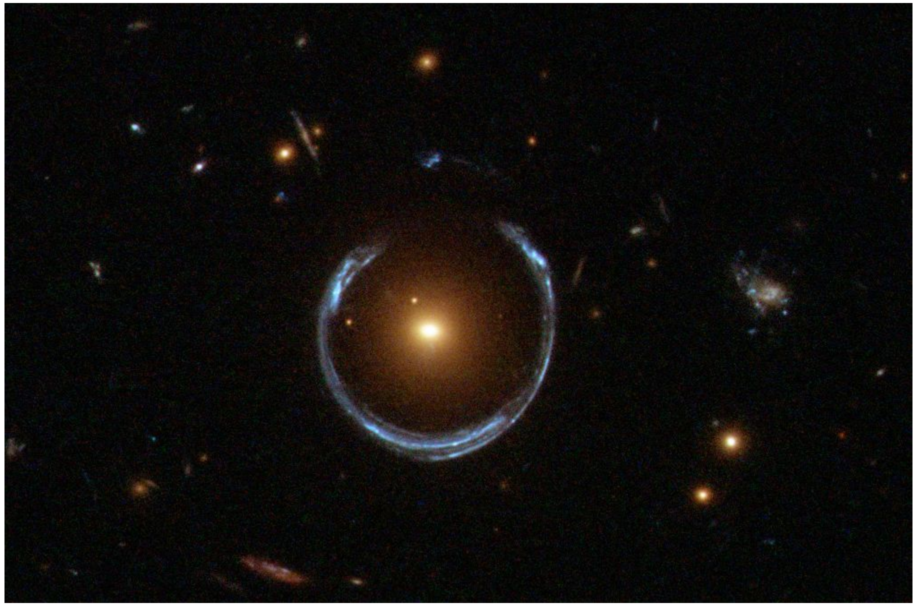
Gravity as a geometrical effect

Gravitational lensing

The principle



An observation



Gravitational Waves

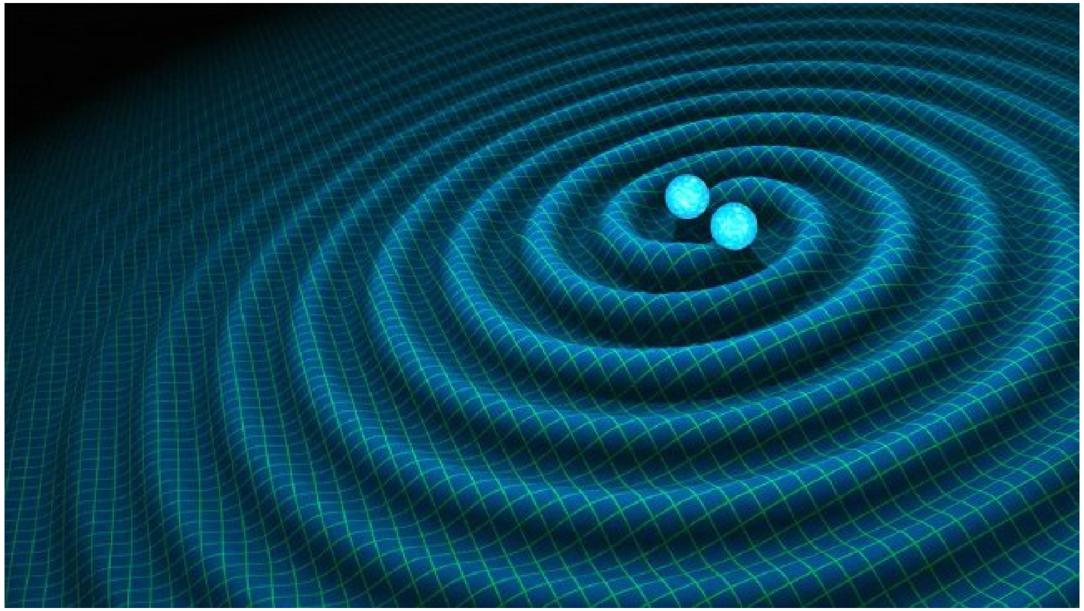
- Consider 2 heavy objects rotating closely around each other

  Time dependent space-time deformations cause ripples (e.g. a water surface)

  $\longrightarrow$ These are called gravitational waves

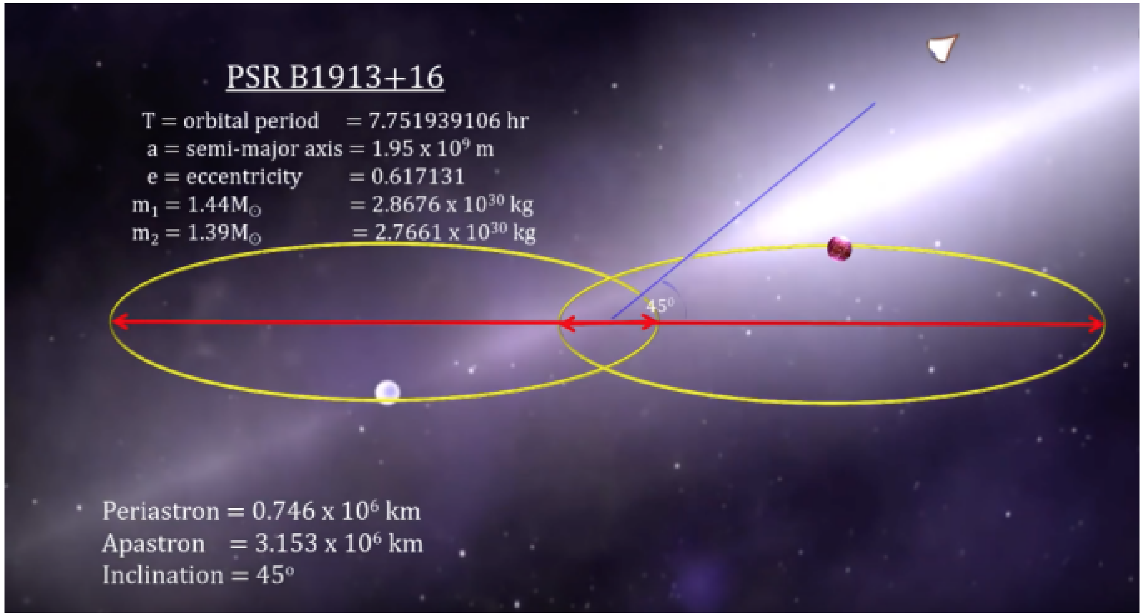
- Frequency of the gravitational wave is related to the orbital period

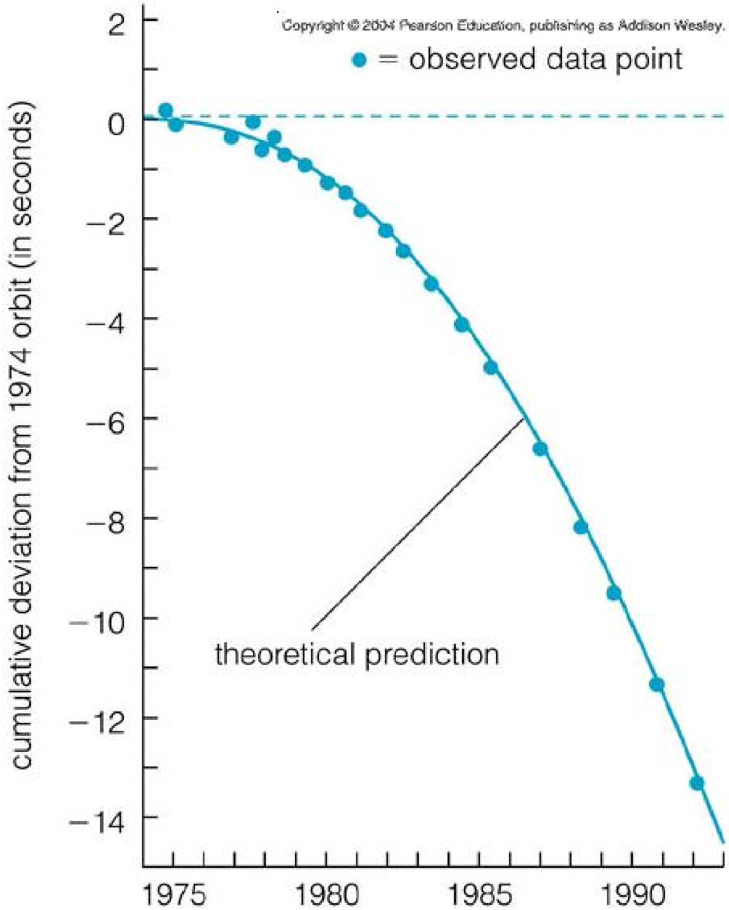
  Shorter orbital period $\longrightarrow$ Higher frequency (shorter wavelength)



Gravity as a geometrical effect

A first indication : The binary pulsar PSR B1913+16





- In case of emission of gravitational waves
  - $\longrightarrow$ Loss of energy
  - $\longrightarrow$ Change of orbital period
- Observe a decrease of the orbital period ?

Russel Hulse and Joe Taylor
Nobel prize 1993

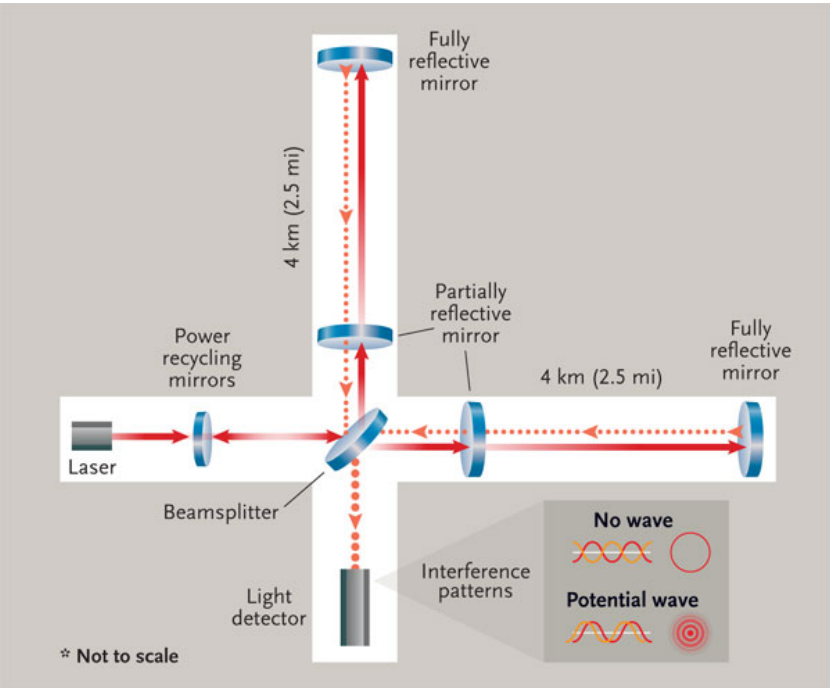
Gravity as a geometrical effect

The discovery of gravitational waves (2015)

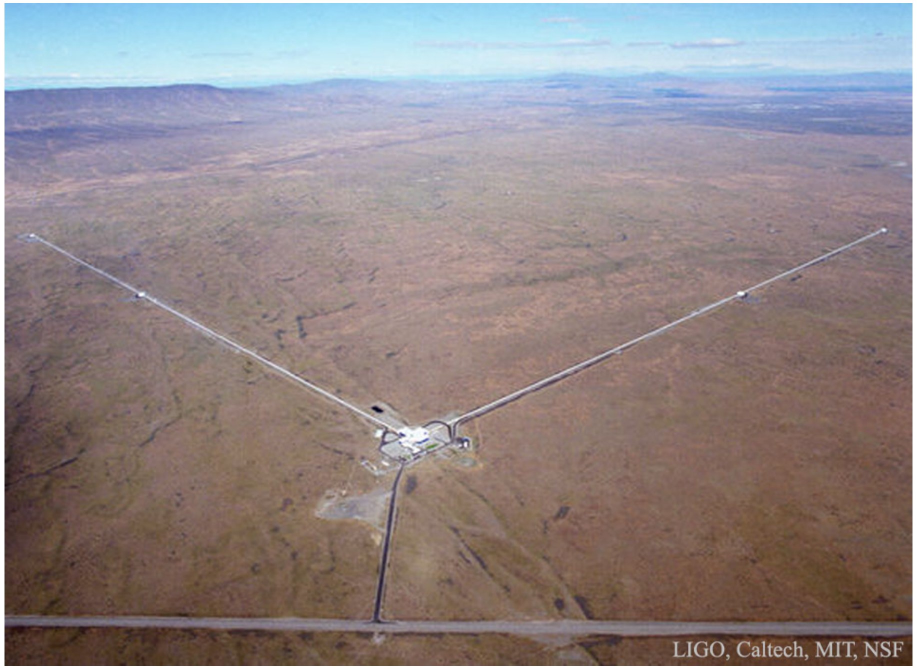
- Gravitational wave deforms space

  $\longrightarrow$ Temporary change ΔL
- Example : 2 corks at a water surface

The detection principle



The Ligo and Virgo interferometers

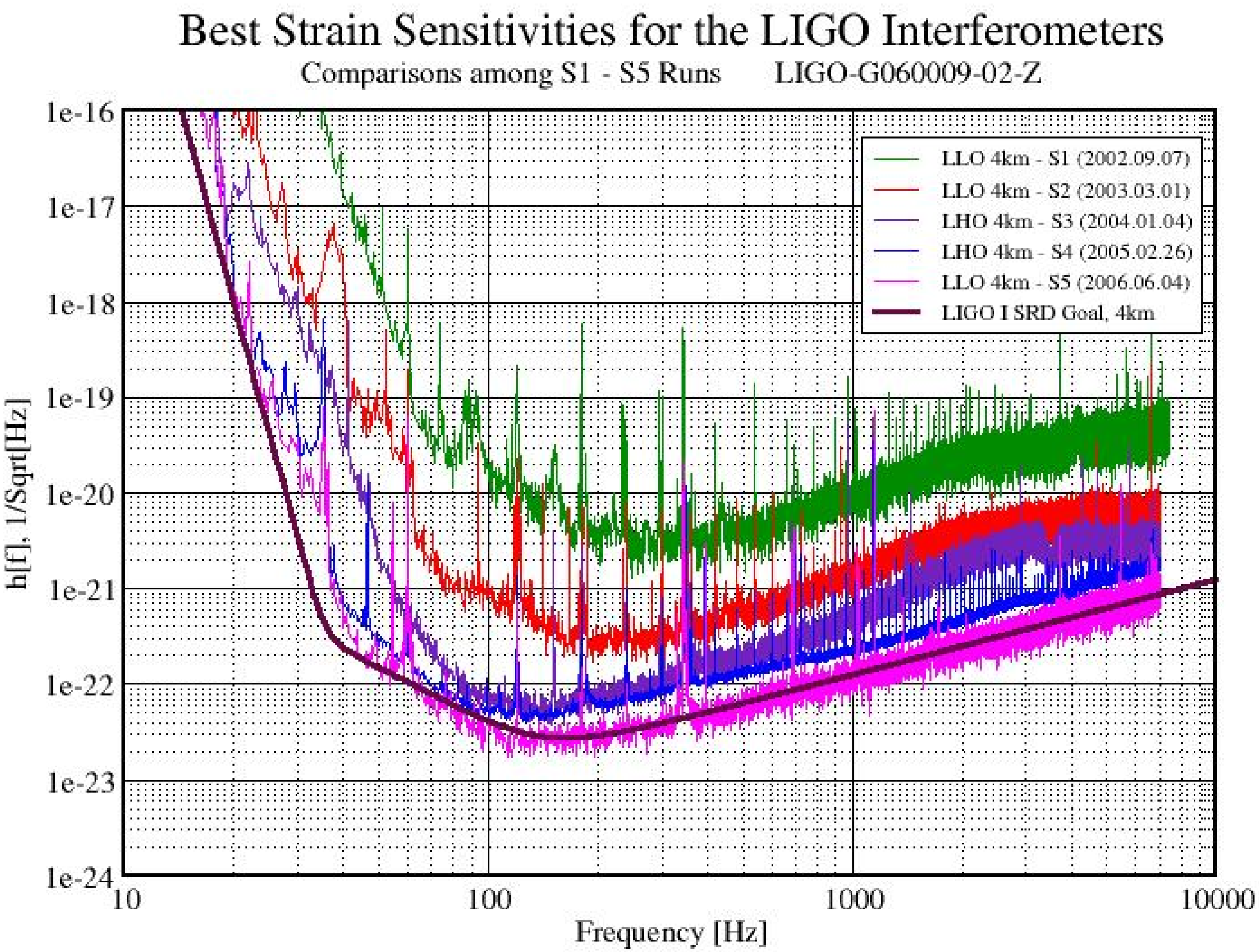


Ligo: Hanford (WA), Livingston (LA)

Virgo: Cascina (Italie)

Gravity as a geometrical effect

Sensitivity is expressed as strain $\Delta L/L$



Gravity as a geometrical effect

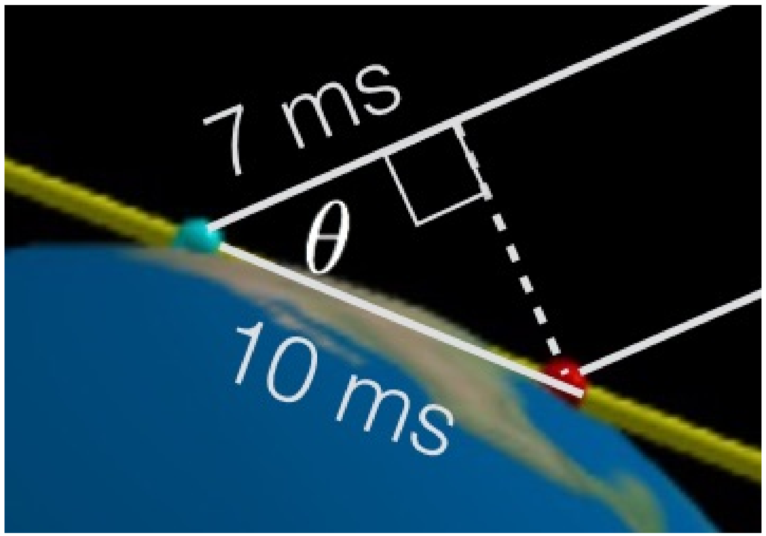
A subtle interplay

Noise reduction and arrival direction

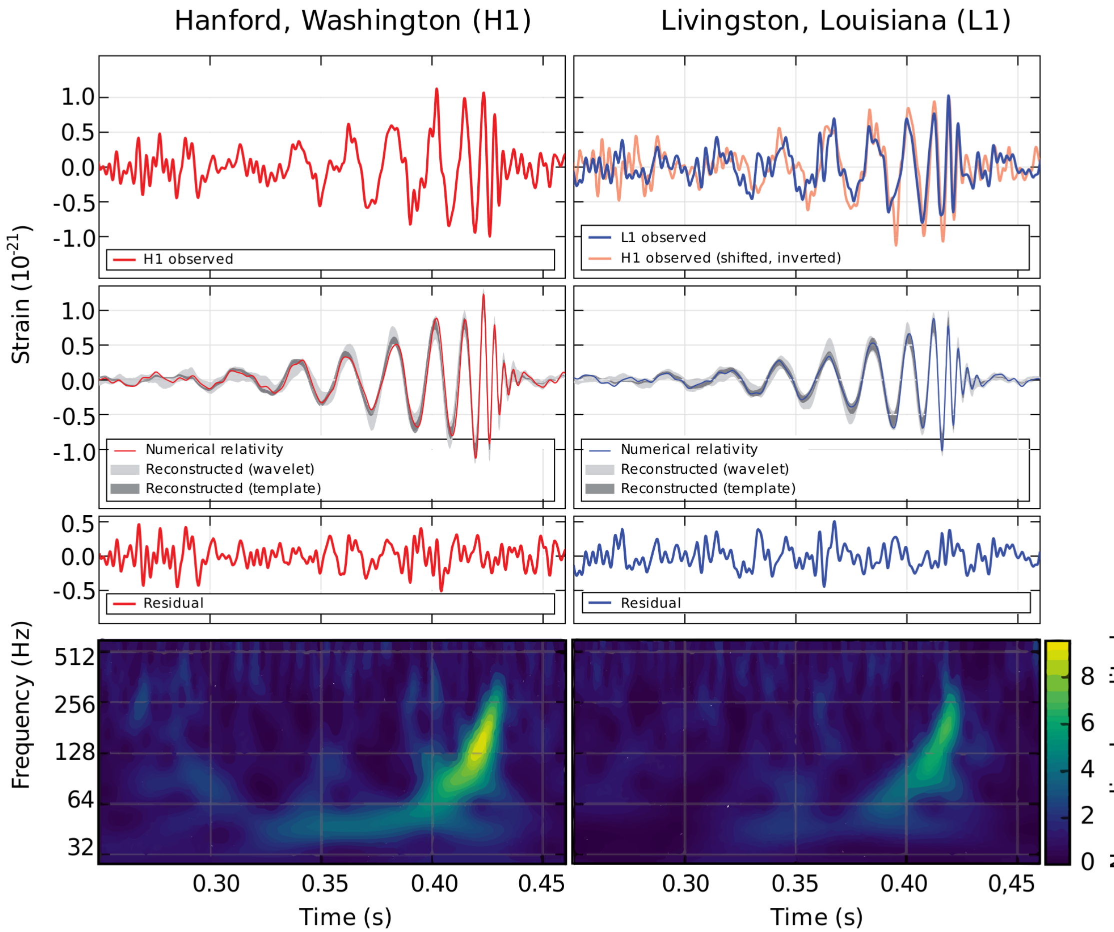
- Hanford-Livingston: ∼3000 km
- Grav. wave moves with light speed
- Timing of the coincidence

  → Reduces noise

  → Provides arrival direction



The discovery (GW150914)



Gravity as a geometrical effect

Analysis of GW150914

- Try to describe the observed pattern on basis of theoretical templates

  $\rightarrow$ 2 Black Holes with $M_1 \approx 30M_\odot \quad M_2 \approx 35M_\odot$ and $M_{end} \approx 62M_\odot$

  $\rightarrow$ An energy equivalent of $3M_\odot c^2$ has been emitted in a fraction of a second !

  $P_{max} \approx 3.6 \cdot 10^{49}$W $\rightarrow$ More than all stars in the visible Universe !
- Distance ca. 440 Mpc ($\sim 1.3 \cdot 10^9$ light year)

$\boxed{\text{Nobel prize 2017 for the discovery of gravitational waves}}$

(Barry Barish, Kip Thorne en Rainer Weiss)

Gravity as a geometrical effect

How to introduce curvature in space-time in accordance with observations ?

- Detailed look at the equivalence principle

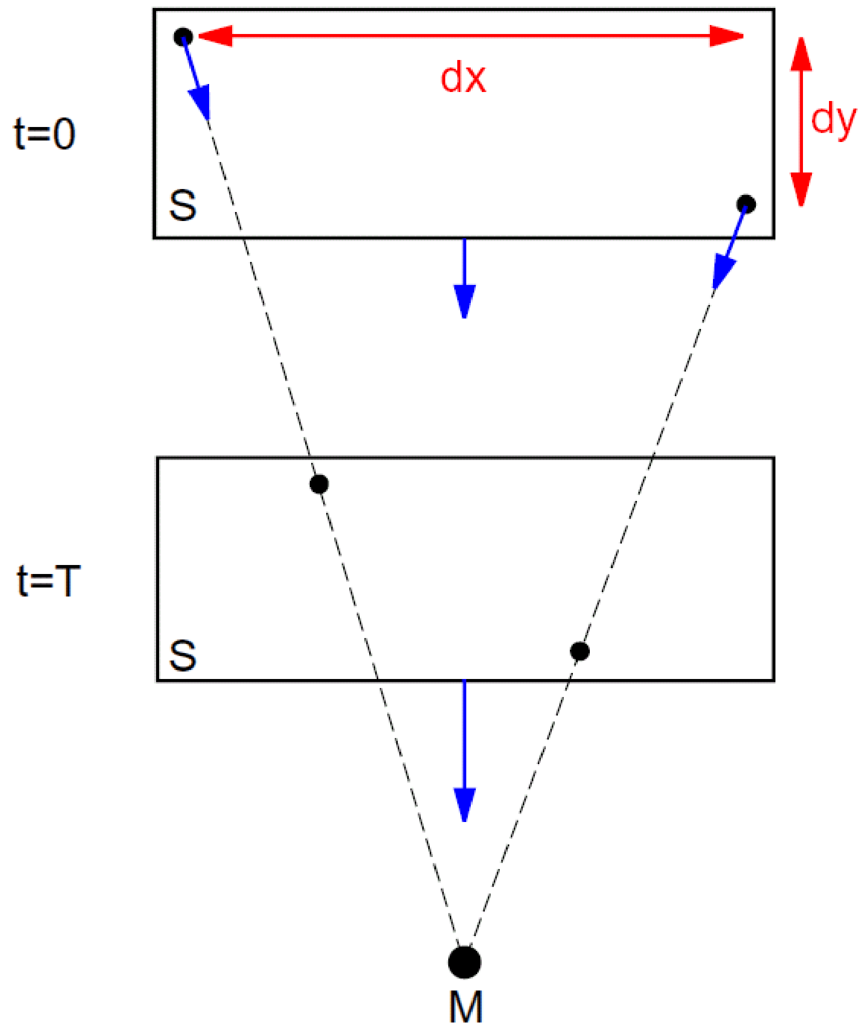
  Frame S in free fall with two objects at rest

$*$ Can the earth gravity stay "hidden" ?

  $|\vec{g}|$ must be constant in $S \rightarrow \mathrm{d}y$ small

  g_x must be small $\rightarrow \mathrm{d}x$ small

  Observation time T must be small



The Equivalence Principle

Experiments performed in a sufficiently small freely falling laboratory, over a sufficiently short time, yield results that are indistinguishable from those of the same experiments performed in an inertial frame in empty space.

Gravity as a geometrical effect

Linking the Equivalence Principle with relativity

- Relativistic description of an inertial frame

  It's all included in the metric

  $\mathrm{d}s^2 = (c\mathrm{d}t)^2 - \mathrm{d}\vec{r}^{\,2}$

  As 4-vectors : $\mathrm{d}s^2 = \eta_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu$

  with $\eta_{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$

- In the presence of gravity :

  Freely falling frame is only locally inertial

  $\longrightarrow$ All other locations in space-time have :

  $$\mathrm{d}s^2 = g_{\mu\nu}(\tilde{x})\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu$$

  $\tilde{x} \equiv$ location in space-time

Description of space-time curvature

Introduce metric tensor $g_{\mu\nu}(\tilde{x})$ of which the components depend on the location in space-time

- Equivalence Principle : $S \rightarrow S'$

  $g_{\mu\nu}(\tilde{x}) \rightarrow g'_{\mu\nu}(\tilde{x}\,') = \eta_{\mu\nu}$

- Consequences :

  $g_{\mu\nu}(\tilde{x})$ must be a symmetric 4x4 matrix

  Always 1 time and 3 space coordinates

$\ast$ This is the basis of General Relativity

What are the components of $g_{\mu\nu}(\tilde{x})$?

$\longrightarrow$ Need to investigate curvature

Curvature in space

- Investigate spatial curvature by considering familiar 2-dim. surfaces

  Can be looked upon as embedded in 3-dim. space $\rightarrow$ easy to catch the picture

$*$ 2-dimensional plane : Obviously flat

$*$ Surface of a sphere : probably curved

  Can't coincide with a plane without stretching or tearing

$*$ Surface of a cylinder : probably flat

  Can be unrolled onto a plane without distortion

- Gauss : The curvature of a surface can be determined intrinsically

  Make measurements and apply the theorems of Euclidean plane geometry

  In case of contradiction : Geometry is non-Euclidean $\rightarrow$ curved surface

$*$ Example : Triangle in a plane $\rightarrow$ sum of the angles adds up to 180^0

  Triangle on surface of a sphere : sum of angles $> 180^0$ $\rightarrow$ spherical surface is curved

- Need for a precise definition of curvature

  Use distance $\mathrm{d}s$ between any 2 points on the surface

Curvature in space

• Curvature in a 2-dim. plane : Cartesian grid $\quad x_1 \equiv x \quad x_2 \equiv y$

$\mathrm{d}s^2 = (\mathrm{d}x)^2 + (\mathrm{d}y)^2 = (\mathrm{d}x_1)^2 + (\mathrm{d}x_2)^2 \rightarrow g_{\mu\nu} = \text{diag}(1,1)$ No curvature

∗ Use polar coordinates in the same plane : $\quad x_1 = r \quad x_2 = \varphi$

$\mathrm{d}s^2 = (\mathrm{d}r)^2 + (r\mathrm{d}\varphi)^2 = (\mathrm{d}x_1)^2 + (x_1)^2(\mathrm{d}x_2)^2 \rightarrow g_{\mu\nu} = \text{diag}(1,(x_1)^2)$

If started with polar coord., how would we know whether the surface is curved or not ?

Try to find a coord. trafo such that $g_{\mu\nu} \rightarrow \text{diag}(1,1)$

Obviously such a trafo is : $(x_1)' = x_1 \cos(x_2) \quad (x_2)' = x_1 \sin(x_2)$

• Curvature on the surface of a cylinder with radius R : Cyl. coordinates (r, φ, z)

$\mathrm{d}s^2 = (R\mathrm{d}\varphi)^2 + \mathrm{d}z^2$ where R is a constant $\rightarrow$ Use $\quad x_1 = R\varphi \quad x_2 = z$

$\mathrm{d}s^2 = (\mathrm{d}x_1)^2 + (\mathrm{d}x_2)^2 \rightarrow g_{\mu\nu} = \text{diag}(1,1)$ No curvature

• Curvature on the surface of a sphere with radius R : Spherical coordinates (r, θ, φ)

$\mathrm{d}s^2 = (R\mathrm{d}\theta)^2 + (R\sin(\theta)\mathrm{d}\varphi)^2$ where R is a constant $\rightarrow$ Use $\quad x_1 = \theta \quad x_2 = \varphi$

$\mathrm{d}s^2 = R^2(\mathrm{d}x_1)^2 + R^2\sin^2(x_1)(\mathrm{d}x_2)^2 \rightarrow g_{\mu\nu} = \text{diag}(R^2, R^2\sin^2(x_1))$

No trafo possible to get $g_{\mu\nu} = \text{diag}(1,1) \rightarrow$ Spherical surface is intrinsically curved

Curvature in space

The curvature formula of Gauss

- From the previous : The curvature is contained in $g_{\mu\nu}$

  $\rightarrow$ The curvature K is an invariant quantity for a certain metric $g_{\mu\nu}$

  It should be possible to obtain the curvature K from the tensor $g_{\mu\nu}$
- The recipe provided by Gauss to determine the curvature (limited to 2-dim. surfaces)

$$K = \frac{1}{2g_{11}g_{22}} \left\{ \frac{-\partial^2 g_{11}}{(\partial x_2)^2} + \frac{-\partial^2 g_{22}}{(\partial x_1)^2} + \frac{1}{2g_{11}} \left[\frac{\partial g_{11}}{\partial x_1} \cdot \frac{\partial g_{22}}{\partial x_1} + \left(\frac{\partial g_{11}}{\partial x_2} \right)^2 \right] + \frac{1}{2g_{22}} \left[\frac{\partial g_{11}}{\partial x_2} \cdot \frac{\partial g_{22}}{\partial x_2} + \left(\frac{\partial g_{22}}{\partial x_1} \right)^2 \right] \right\}$$

$*$ For the surface of a sphere with radius R this yields : $K = 1/R^2$

- Higher dimensional surfaces : Can't be embedded in 3-dim. space $\rightarrow$ imagination fails

  Equivalent of curvature K for higher dim. surfaces involves a curvature tensor $R_{\alpha\beta\gamma\delta}$

$*$ General treatment of Einstein's theory $\rightarrow$ Tensor calculus

  Our cases contain symmetries $\rightarrow$ we can avoid tensor calculus and use K instead

Curvature in space-time : The Schwarzschild metric

- Consider an isolated point mass M at the origin O in empty space

∗ Two effects of curvature in space-time

Time is distorted by the gravitational time dilation

3-dim. position space becomes curved due to the presence of the mass M

- Isolated point mass M in O $\rightarrow$ Space is isotropic w.r.t. O $\rightarrow$ Use spherical coord.

Curvature can only depend on r and should vanish when $r \rightarrow \infty$

- General expression for a curved isotropic metric in spherical coordinates :

$$\mathrm{d}s^2 = \alpha(r)(c\,\mathrm{d}t)^2 - [f(r)(\mathrm{d}r)^2 + (r\mathrm{d}\theta)^2 + (r\sin(\theta)\mathrm{d}\varphi)^2]$$

∗ Determination of the time distortion $\alpha(r)$ using $\mathrm{d}s = c\,\mathrm{d}\tau$ when $\mathrm{d}\vec{r} = \vec{0}$

From before we have seen : $\mathrm{d}\tau_{obs} \approx \mathrm{d}\tau_{emit} \left(1 + \frac{\Phi_{emit} - \Phi_{obs}}{c^2}\right)^{-1}$

Putting the emitter at coordinates $(t, r, 0, 0)$ and the receiver at $(t, \infty, 0, 0)$ we obtain :

$$\frac{(\mathrm{d}\tau_{emit})^2}{(\mathrm{d}\tau_{obs})^2} = \frac{\alpha(r)(\mathrm{d}t)^2}{\alpha(\infty)(\mathrm{d}t)^2} = \alpha(r) \approx \left(1 + \frac{\Phi_{emit}}{c^2}\right)^2 \approx \left(1 + \frac{2\Phi_{emit}}{c^2}\right)$$

Curvature in space-time : The Schwarzschild metric

- Using $\Phi_{emit} = \dfrac{-GM}{r}$ directly yields $\alpha(r) = \left(1 - \dfrac{2GM}{c^2 r}\right)$

  The same result is obtained from a rigorous treatment of Einstein's equations !

∗ Determination of the spatial deformation $f(r)$

  Spatial curvature can only depend on $r \rightarrow K(r)$ and $K(\infty) \equiv 0$

- Let's try to "guess" the most simple form of $K(r)$

  $K(r) \rightarrow 0$ when $r \rightarrow \infty \Rightarrow K(r) \propto r^{-n}$

  Intuition : $K \propto M$ and also G should be in the game

  Use c to get dimensions right and use $\lambda = \pm 1$ to allow positive and negative curvature

- Intuitive guess : $K(r) = \lambda M G^k c^m r^{-n}$

  $\rightarrow$ Dimensionless for $(k, m, n) = (1, -2, 3)$

  Spherical surface : $K = 1/R^2 > 0 \rightarrow$ mass M : "rubber sheet" gets $K < 0$

∗ So, for the simplest form we obtain $K(r) = \dfrac{-GM}{c^2 r^3}$

  The same result is obtained from a rigorous treatment of Einstein's equations !

Curvature in space-time : The Schwarzschild metric

- Determination of $f(r)$ from the Gauss curvature formule using our metric and $K(r)$

  Go 2-D in (r, φ) by using $\theta \equiv \pi/2 \to \mathrm{d}\theta = 0 \quad \sin(\theta) = 1$ and of course $\mathrm{d}t \equiv 0$

  This yields : $\mathrm{d}s^2 = f(r)(\mathrm{d}r)^2 + r^2(\mathrm{d}\varphi)^2 \to K(r) = \dfrac{1}{2r f^2(r)} \cdot \dfrac{\mathrm{d}f(r)}{\mathrm{d}r}$

  Using our curvature $K(r) = \dfrac{-GM}{c^2 r^3}$ we obtain $\dfrac{1}{f^2(r)}\dfrac{\mathrm{d}f(r)}{\mathrm{d}r} = \dfrac{-2GM}{c^2 r^2}$

* Solution of this differential equation : $\dfrac{-1}{f(r)} = \dfrac{2GM}{c^2 r} + C \quad (C = \text{constant})$

  Boundary condition : $f(r = \infty) = 1 \to C = -1 \Rightarrow f(r) = \left(1 - \dfrac{2GM}{c^2 r}\right)^{-1}$

- The final metric we obtain is called the Schwarzschild metric

$$\mathrm{d}s^2 = \left(1 - \frac{2GM}{c^2 r}\right)(c\,\mathrm{d}t)^2 - \left[\frac{(\mathrm{d}r)^2}{\left(1 - \frac{2GM}{c^2 r}\right)} + (r\mathrm{d}\theta)^2 + (r\sin(\theta)\mathrm{d}\varphi)^2\right]$$

Curvature in space-time : The Schwarzschild metric

- The Schwarzschild metric describes the space-time around an isolated point mass M

$\rightarrow$ Prediction of worldlines of test bodies which can be experimentally verified

$*$ Special case when $\left(1 - \frac{2GM}{c^2 r}\right) = 0 \quad \rightarrow g_{00} = 0 \quad g_{11} = -\infty$

Define the Schwarzschild radius $R_s = 2GM/c^2$

- Consider a material body at rest at $r > R_s \rightarrow \mathrm{d}s^2 > 0 \quad \Rightarrow$ normal (timelike) situation

At $r < R_s$ the $\mathrm{d}s^2 > 0$ means the body HAS to move $\rightarrow$ it falls into M

- Consider observation of a light ray emitted radially from r_{emit} to $r = \infty$

Schwarzschild metric : $\nu_{obs} = \nu_{emit} \left(1 - \frac{R_s}{r_{emit}}\right)^{1/2}$

If $r_{emit} > R_s \rightarrow$ light is redshifted $\Rightarrow$ normal situation

At $r_{emit} = R_s$ the redshift becomes $\infty \rightarrow$ No light is observed (infinite time dilation)

At $r = R_s \rightarrow$ infinite time dilation $\Rightarrow$ Events are observed as "frozen"

$*$ Mass M contained within a sphere of radius $R_s \rightarrow$ Nothing can escape the surface

An object which is smaller than its Schwarzschild radius is called a Black Hole

Exercises

• Consider an isolated point mass M with Schwarzschild radius R_s, located at the origin O

From a distance $r_e > R_s$ a light ray is radially emitted and observed at a distance $r_o > r_e$

∗ Show that the exact formula for the gravitational redshift z is given by :

$$z = \sqrt{\frac{1 - R_s/r_o}{1 - R_s/r_e}} - 1$$

• Consider a proton as a spherical object with a radius of 1 fm.

∗ Determine from this the density of normal nuclear matter in GeV/fm^3

• The mass of the Earth is $M = 5.975 \cdot 10^{24}$ kg

∗ Determine the Schwarzschild radius R_s of the Earth

• Imagine that all the mass of the Earth is concentrated in a sphere with radius R_s

∗ Determine the density in GeV/fm^3 of this "Earth black hole" object

For comparison : QGP phase transition is expected to happen at about 3 GeV/fm^3