Einstein's theory of relativity

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Special relativity

- The ether and Maxwell's equations
- Einstein's two postulates
  - Laws of physics are the same in all inertial reference frames
  - Speed of light is constant
- Ground-breaking new ideas
  - Space and time is not independent (spacetime)
  - Simultaneous depends upon reference frames

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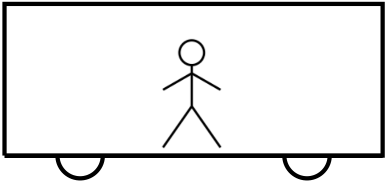

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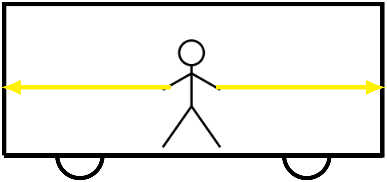

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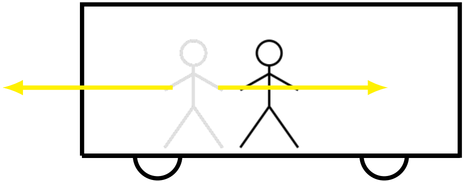


Lorentz transformation

The transformations between two inertial reference frames moving with a relative velocity v. At t'=t=0 the origins of the two cordinates systems are the same.

$$t' = \gamma(t - vx/c^2)$$

$$x' = \gamma(x - vt)$$

where :

$$c = \text{Speed of light}$$

$$\gamma = \frac{1}{\sqrt{(1 - v^2/c^2)}}$$

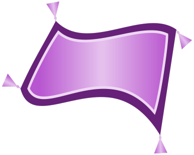
Consequences of special relativity

$v = 0.87c$

$\gamma = 2$

$x_1 =$ Back of the carpet

$x_2 =$ Front of the carpet



Flying on the magic carpet is the primed reference frame

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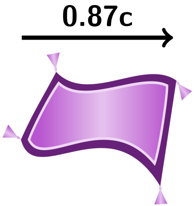

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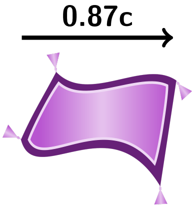

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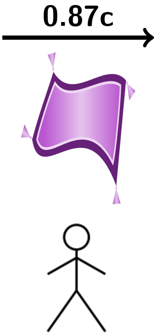

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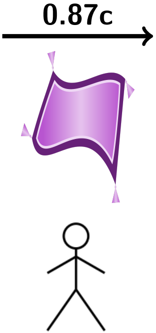

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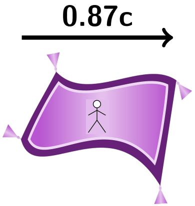

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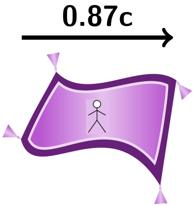

My two hour ride was only one hour(:

Flying on the magic carpet is the primed reference frame

In the real world

- Atomic clocks in flights
- Muons actually reach the earth
- Particle accelerators

Picture by Dave L. Jones

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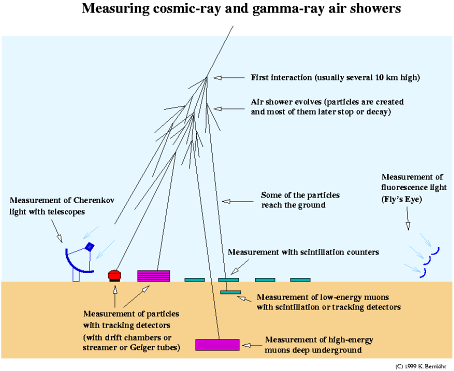

Figure by K.Bernkör

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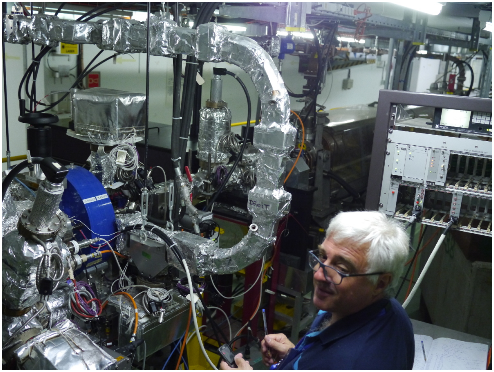

Photo by K.Sjøbæk

General relativity

Is gravity acceleration?

- In 1907 Einstein had the "happiest thought of his life"
- Equivalence principle
- Continuation of the the universality of free fall

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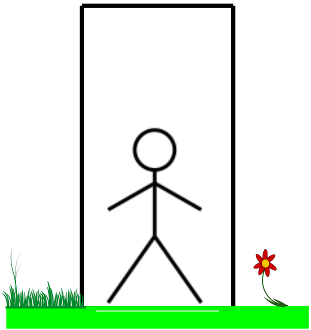

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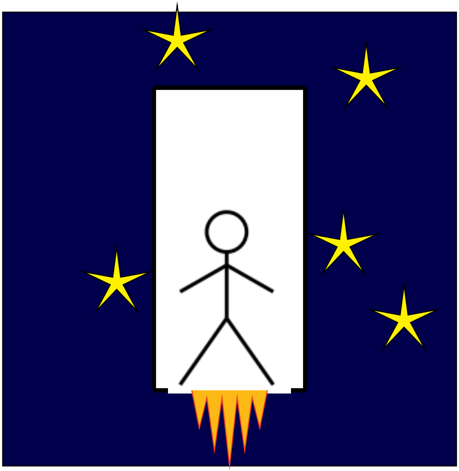

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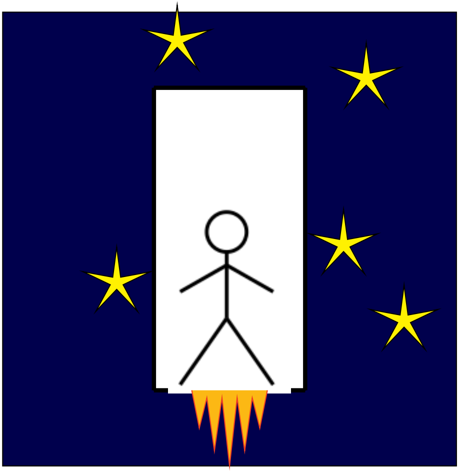

Is gravity a geometrical effect?

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- Globally there is tidal forces
- Can gravity be a geometrical effect

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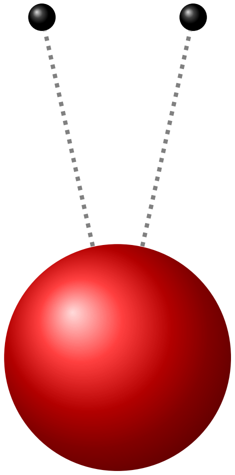

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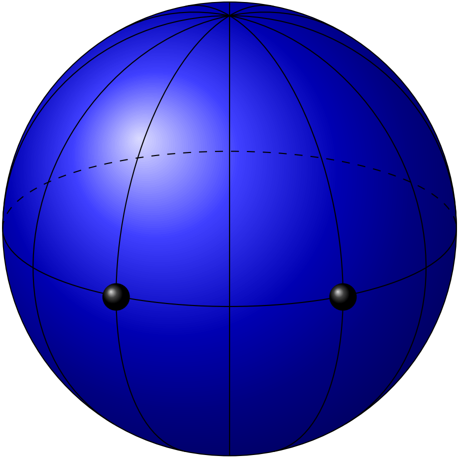

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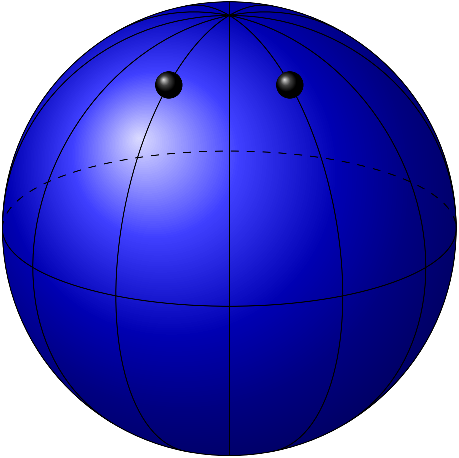

A geometrical model for gravity

- General relativity describes spacetime as a manifold
- A manifold can describe a space that locally is flat, but is curved on larger scale
- The surface of a sphere:
  - Curved on larger scale
  - Locally flat
- Spacetime according to general relativity
  - Locally it a free falling coordinate system, the weak equivalence principle holds
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- Describing spacetime as a manifold gave the theory a mathematical framework (tensor analysis)

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Einstein's field equations

- Curvature of space on left side
- Content of space on right side
- The metric $= g_{\mu\nu}$
- Only analytically solvable in special cases, for instance the Schwarzschild solution

Field equations

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

$$\begin{aligned} R_{\mu\nu} &= \text{Ricci curvature tensor}(f(g_{\mu\nu})) \\ g_{\mu\nu} &= \text{The metric} \\ \Lambda &= \text{Cosmological constant} \\ T_{\mu\nu} &= \text{Stress-energy tensor} \end{aligned}$$

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$$\frac{d^2 x^\mu}{ds^2} + \Gamma^\mu{}_{\beta\alpha} \frac{d^2 x^\alpha}{ds^2} \frac{d^2 x^\beta}{ds^2} = 0$$

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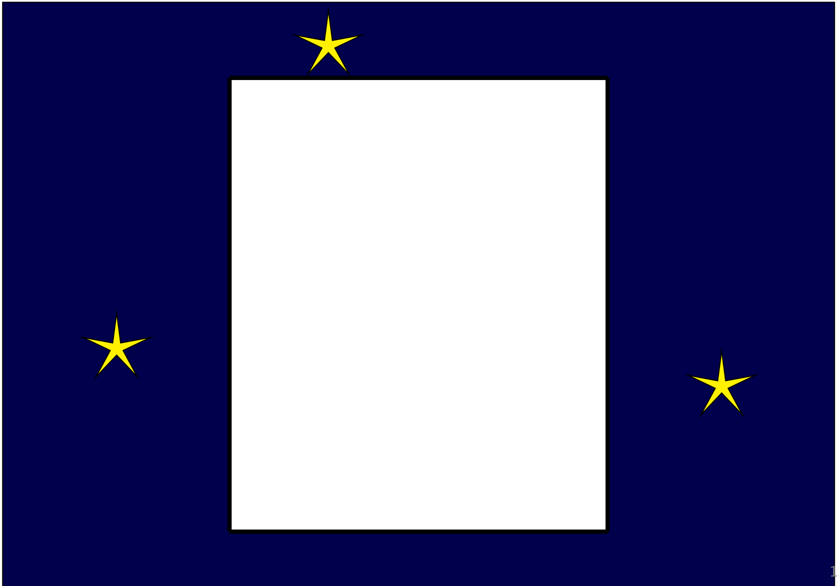

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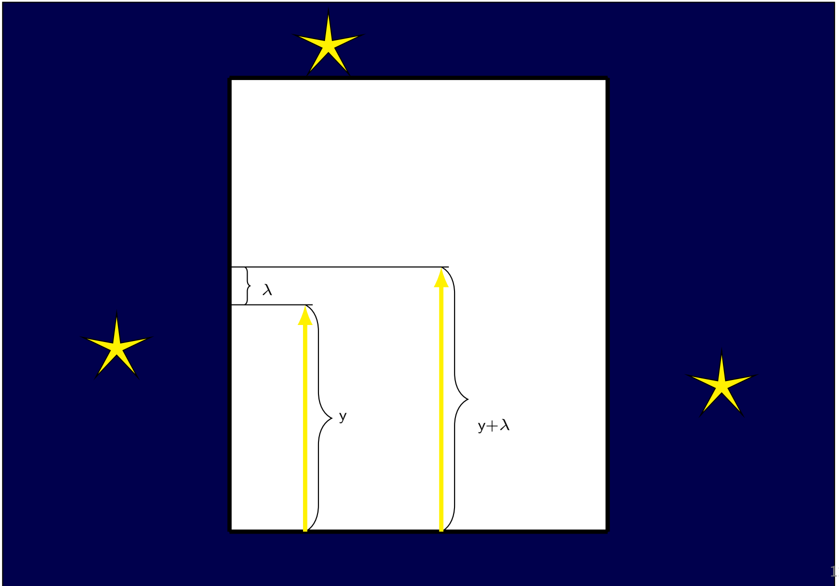

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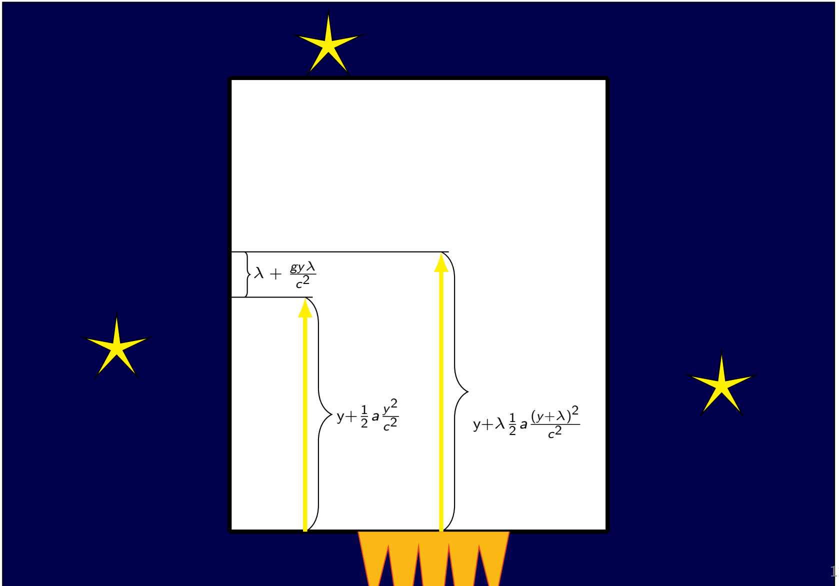

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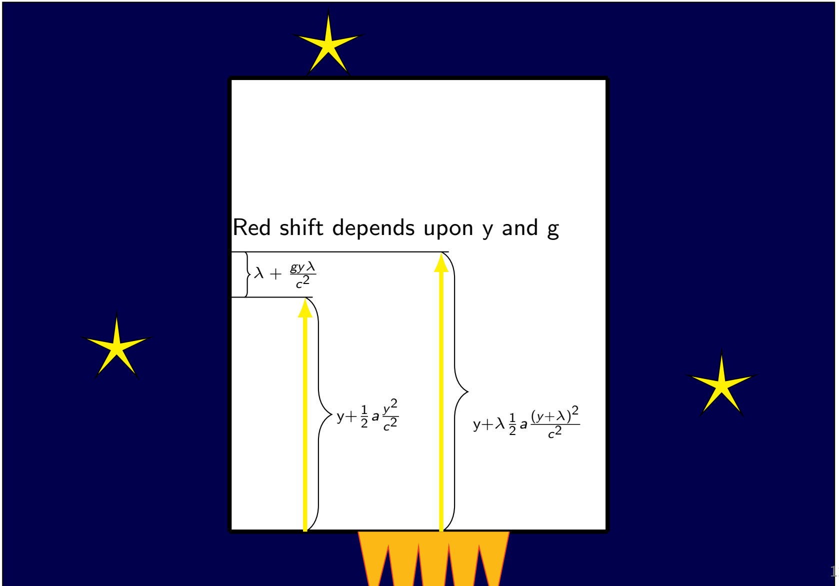
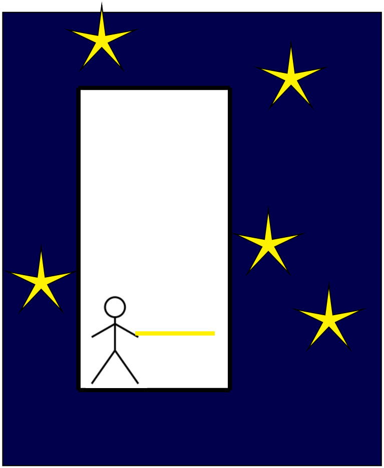


Gravity and light

- Light is being bent by gravitational fields



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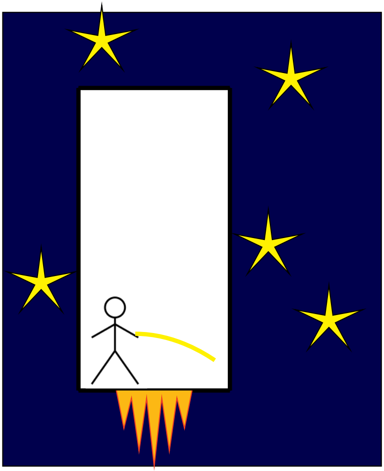

Testing the theory 1919

- Bending of light by the sun might alter the apparent position of stars
- Solar eclipse 1919 was the ultimate test
- Three possible outcome
  - No bending
  - Newton bending
  - Bending of light predicted by general relativity
- Turned out that Einstein was right

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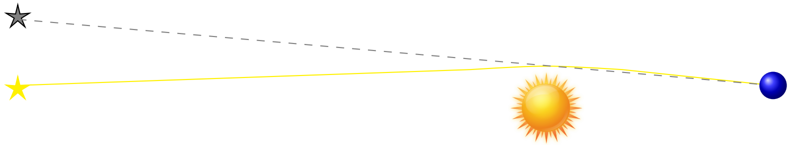

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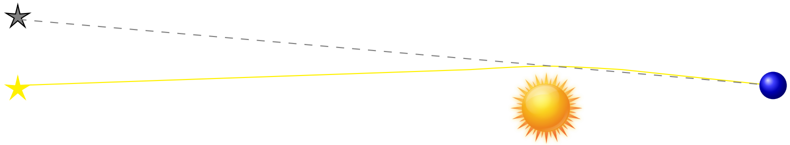

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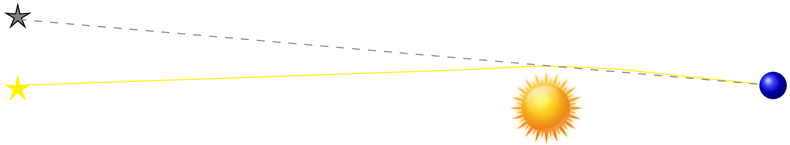

Testing the theory 2015

Photo credit: LIGO / Caltech / MIT

Conclusion

- Alter how we see the world
- The equivalence principle is central
- Well tested theory