

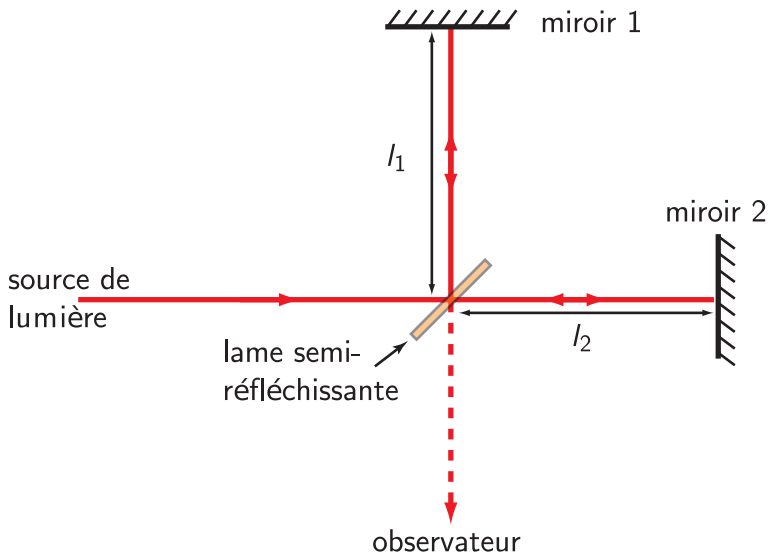
Relativité restreinte et générale

Alexandre Le Tiec

Laboratoire Univers et Théories
Observatoire de Paris / CNRS



Expériences de Michelson et Morley



Isotropie de la vitesse de propagation de la lumière

PRL 103, 090401 (2009)

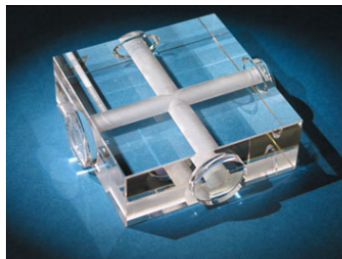
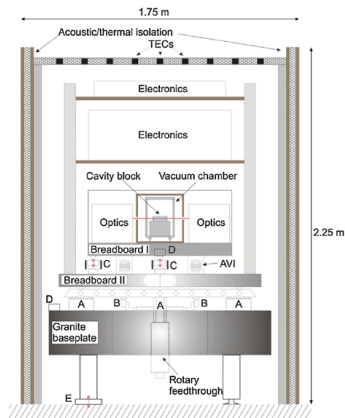
PHYSICAL REVIEW LETTERS

week ending
28 AUGUST 2009

Laboratory Test of the Isotropy of Light Propagation at the 10^{-17} Level

Ch. Eisele, A. Yu. Nevsky, and S. Schiller

Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
(Received 13 June 2008; revised manuscript received 7 August 2009; published 25 August 2009)



précision relative $\sim 10^{-17}$

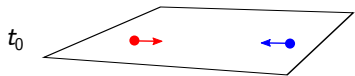
$$c = 1$$

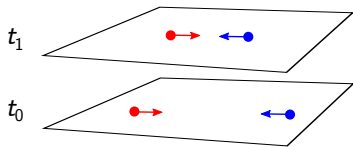
Plan de l'exposé

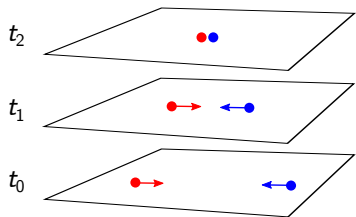
- 1 Espace, temps et espace-temps
- 2 Relativité de la simultanéité
- 3 Dilatation des durées
- 4 Relativité générale

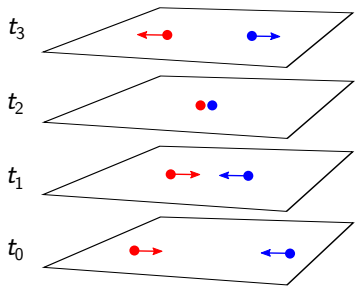
Plan de l'exposé

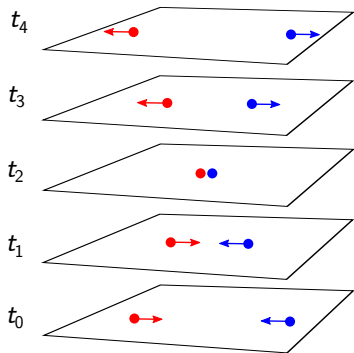
- 1 Espace, temps et espace-temps
- 2 Relativité de la simultanéité
- 3 Dilatation des durées
- 4 Relativité générale





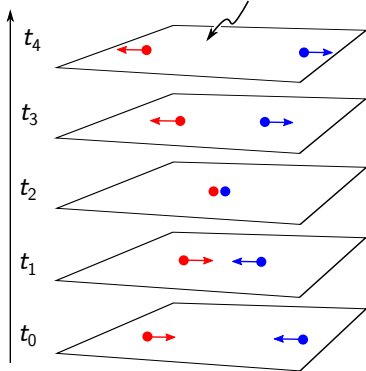






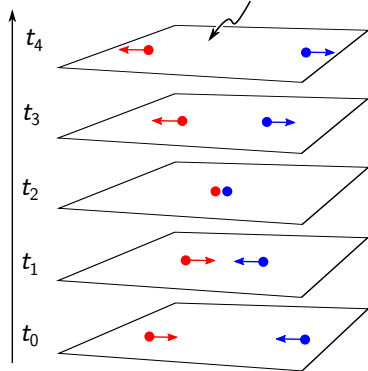
temps

espace

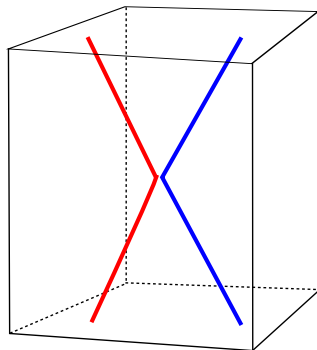


temps

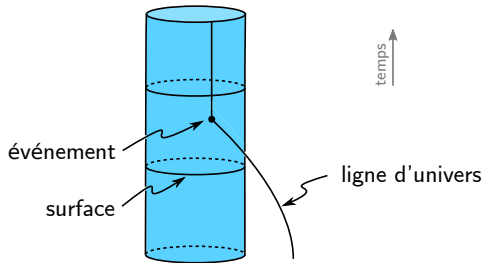
espace



espace-temps

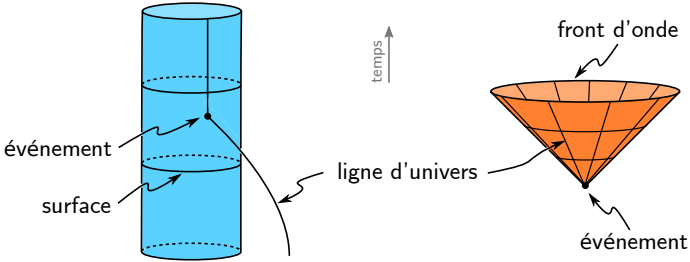


Notion d'événement



Accident de parachutisme

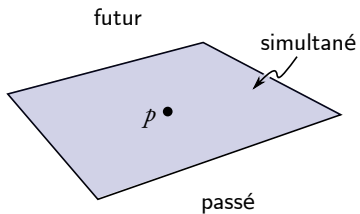
Notion d'événement



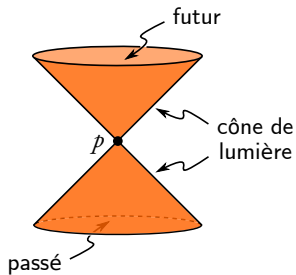
Accident de parachutisme

Émission d'un flash

Causalité

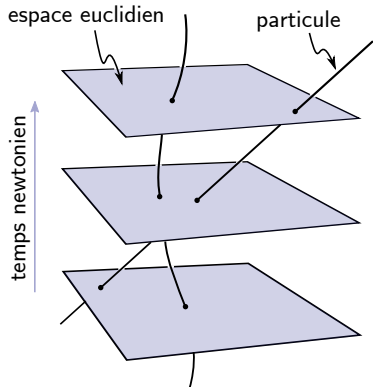


Physique pré-relativiste

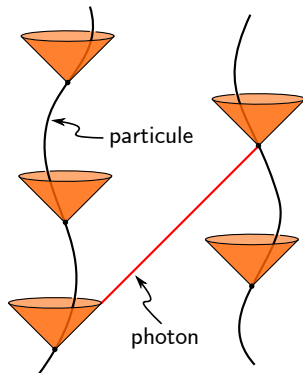


Relativité restreinte

Causalité



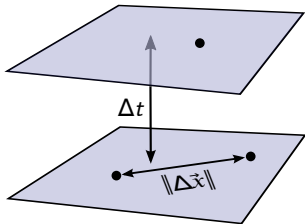
Physique pré-relativiste



Relativité restreinte

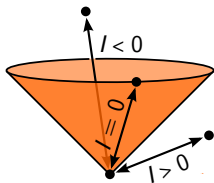
Invariants

$$\Delta t, \|\Delta\vec{x}\|$$



Physique pré-relativiste

$$I \equiv -(\Delta t)^2 + \|\Delta\vec{x}\|^2$$



Relativité restreinte

Invariants

$$\Delta t, \|\Delta\vec{x}\|$$

$$I \equiv -(\Delta t)^2 + \|\Delta\vec{x}\|^2$$

Groupe de Galilée

- Rotations spatiales
- Translations spatiales
- Translations temporelles
- Transformations de Galilée

$$t' = t$$
$$\vec{x}' = \vec{x} - \vec{v}t$$

Groupe de Poincaré

- Rotations spatiales
- Translations spatiales
- Translations temporelles
- Transformations de Lorentz

$$t' = \gamma (t - \vec{v} \cdot \vec{x}_{\parallel})$$
$$\vec{x}'_{\parallel} = \gamma (\vec{x}_{\parallel} - \vec{v}t)$$

Invariants

$$\Delta t, \|\Delta\vec{x}\|$$

$$I \equiv -(\Delta t)^2 + \|\Delta\vec{x}\|^2$$

Groupe de Galilée

- Rotations spatiales
- Translations spatiales
- Translations temporelles
- Transformations de Galilée

$$t' = t$$
$$\vec{x}' = \vec{x} - \vec{v}t$$

Groupe de Poincaré

- Rotations spatiales
- Translations spatiales
- Translations temporelles
- Transformations de Lorentz

$$t' = \gamma (t - \vec{v} \cdot \vec{x}_{\parallel})$$
$$\vec{x}'_{\parallel} = \gamma (\vec{x}_{\parallel} - \vec{v}t)$$

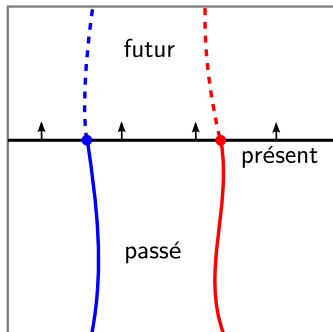
↑

$$1/\sqrt{1 - v^2}$$

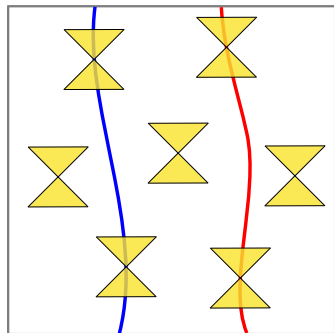
Plan de l'exposé

- 1 Espace, temps et espace-temps
- 2 Relativité de la simultanéité
- 3 Dilatation des durées
- 4 Relativité générale

Disparition du présent



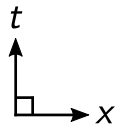
Physique pré-relativiste



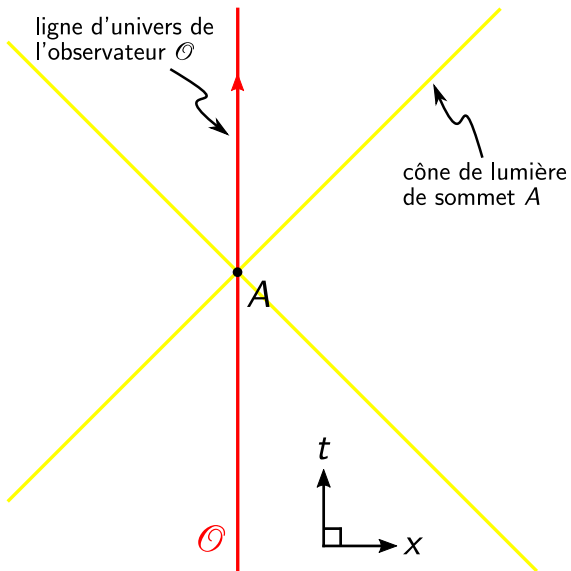
Relativité restreinte

Notion d'observateur

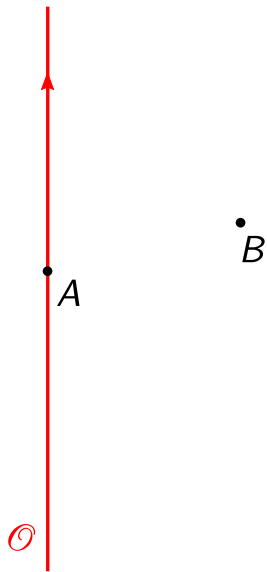
ligne d'univers de
l'observateur \mathcal{O}



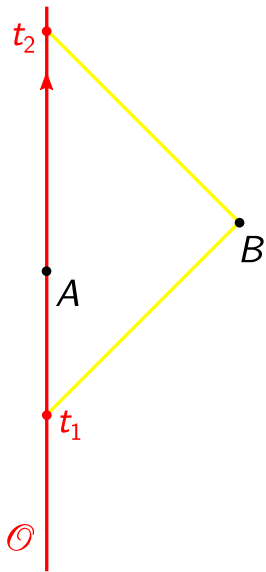
Notion d'observateur



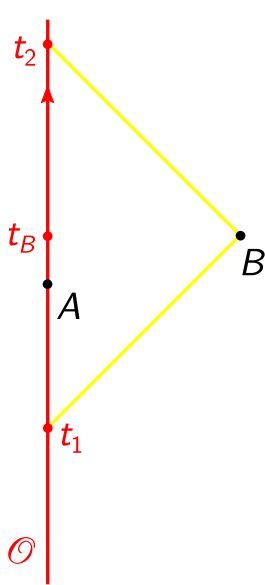
Simultanéité d'Einstein-Poincaré



Simultanéité d'Einstein-Poincaré

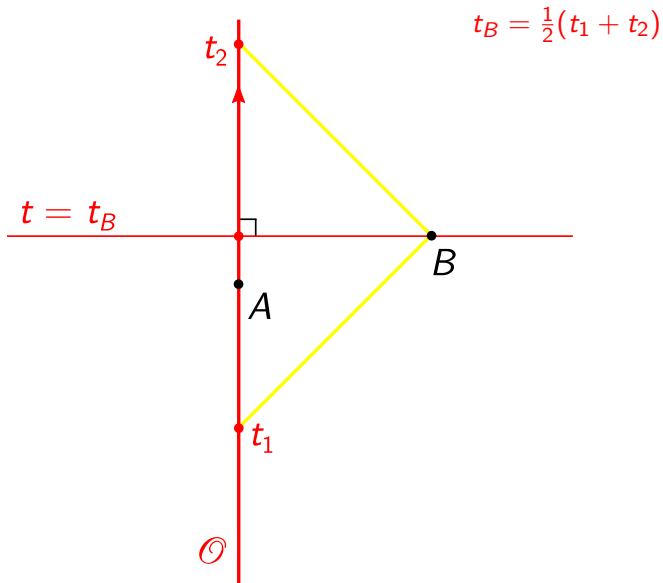


Simultanéité d'Einstein-Poincaré

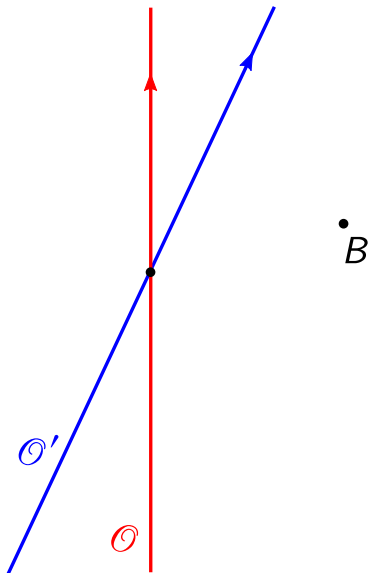


$$t_B = \frac{1}{2}(t_1 + t_2)$$

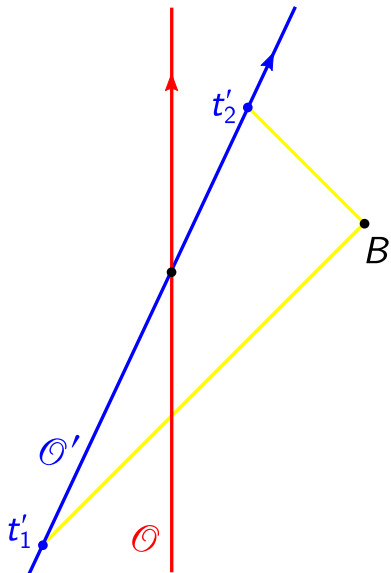
Simultanéité d'Einstein-Poincaré



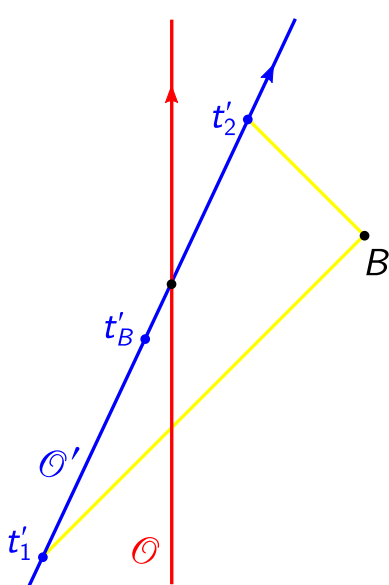
Simultanéité d'Einstein-Poincaré



Simultanéité d'Einstein-Poincaré

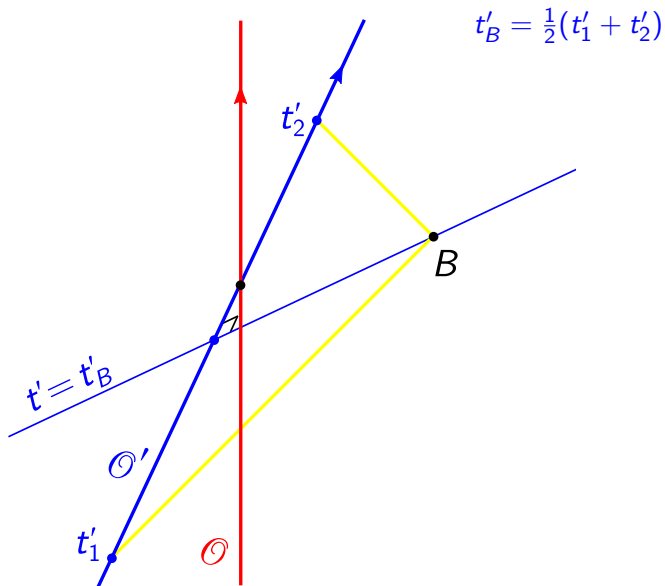


Simultanéité d'Einstein-Poincaré

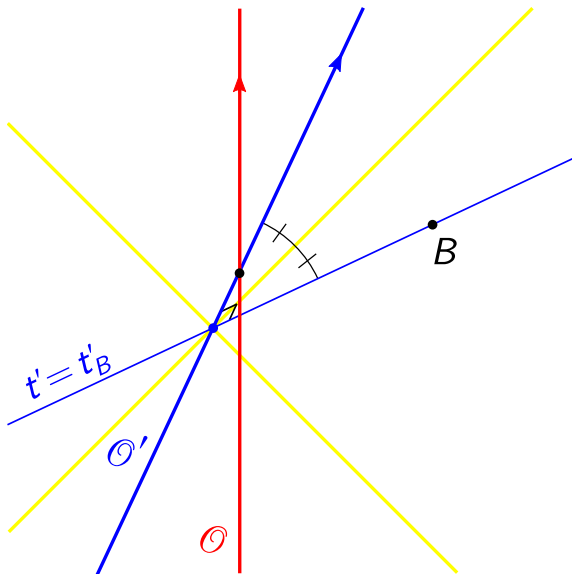


$$t'_B = \frac{1}{2}(t'_1 + t'_2)$$

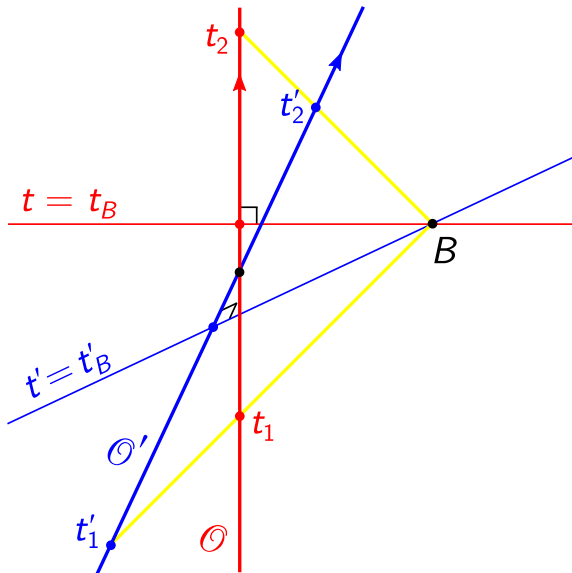
Simultanéité d'Einstein-Poincaré



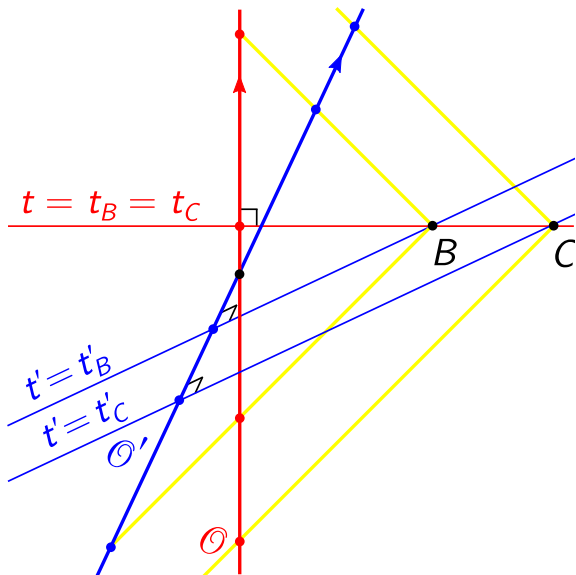
Simultanéité d'Einstein-Poincaré



Relativité de la simultanéité



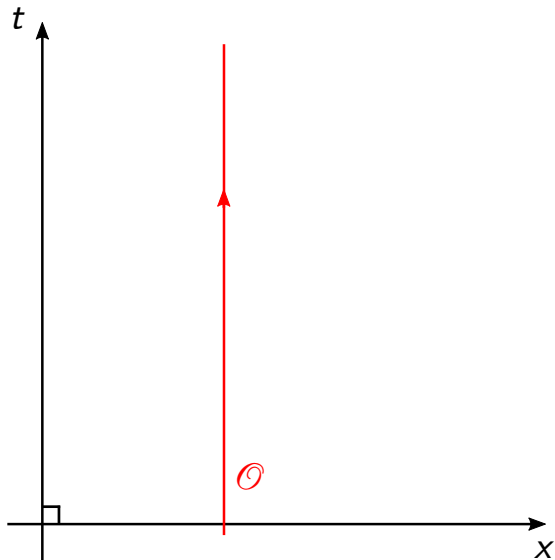
Relativité de la simultanéité



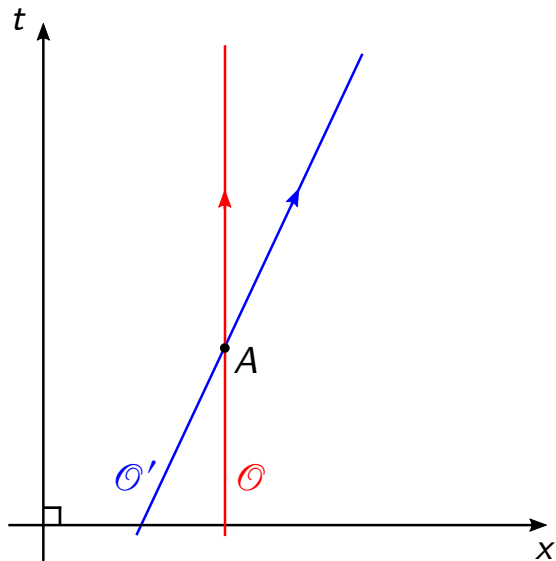
Plan de l'exposé

- 1 Espace, temps et espace-temps
- 2 Relativité de la simultanéité
- 3 Dilatation des durées**
- 4 Relativité générale

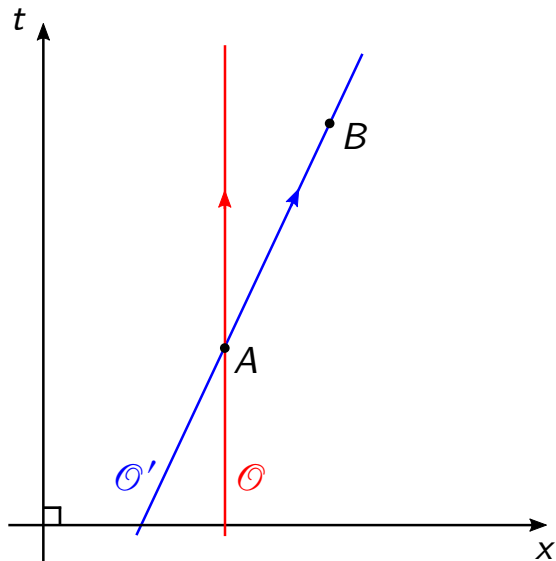
Mesurer des durées



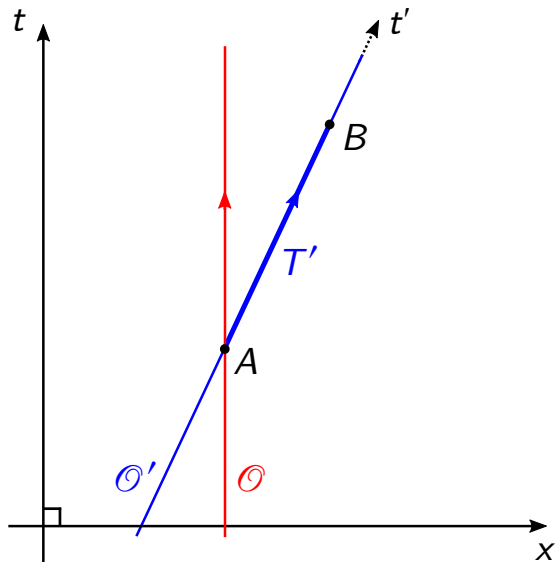
Mesurer des durées



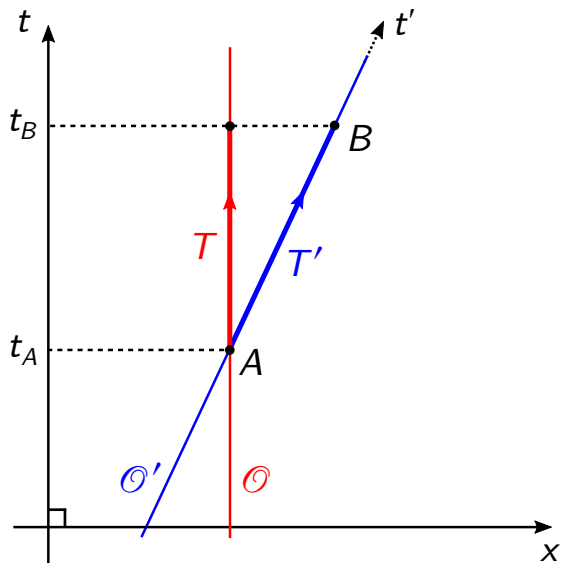
Mesurer des durées



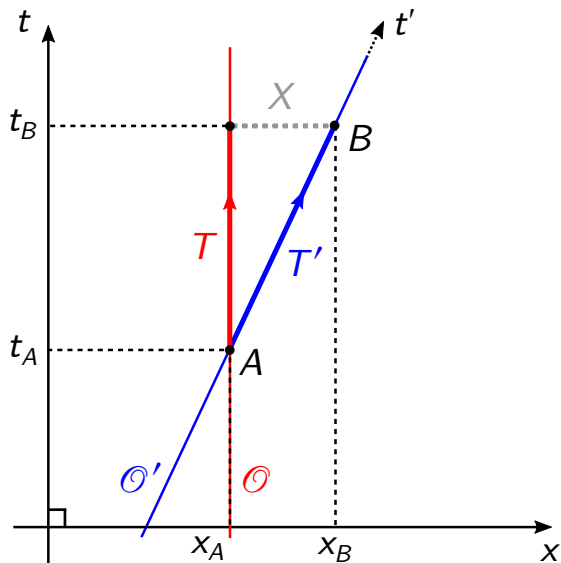
Mesurer des durées



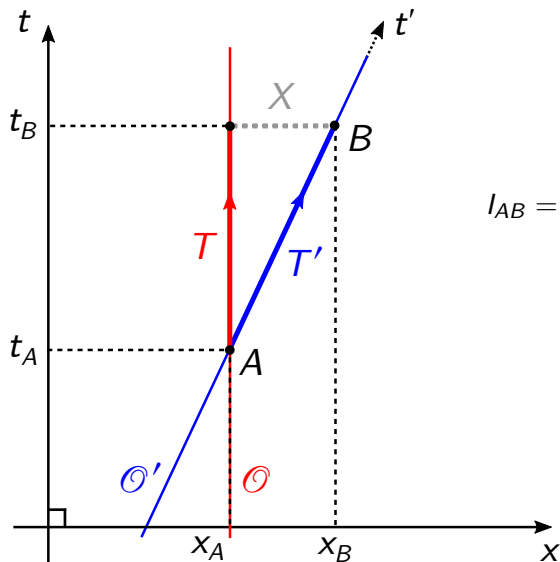
Mesurer des durées



Mesurer des durées

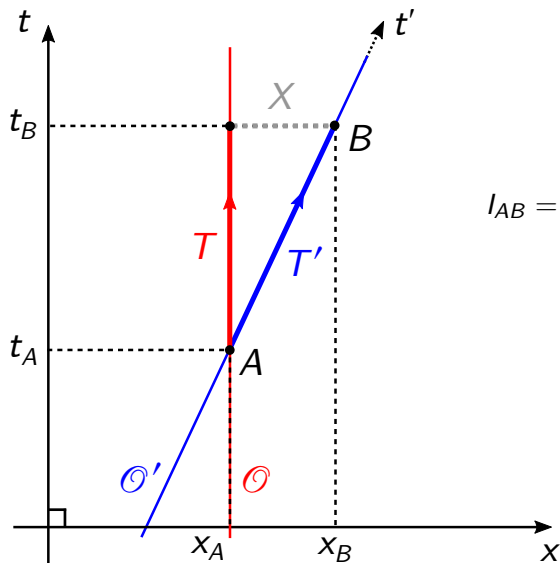


Invariance de l'intervalle



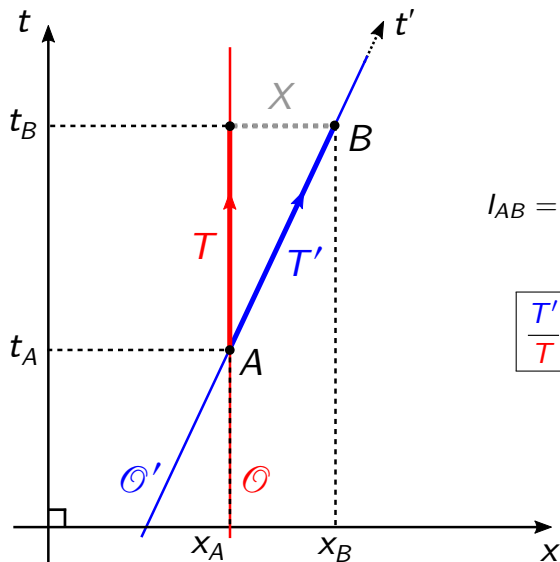
$$I_{AB} = -T^2 + X^2$$

Invariance de l'intervalle



$$I_{AB} = -T^2 + X^2 = -T'^2 + X'^2$$

Invariance de l'intervalle

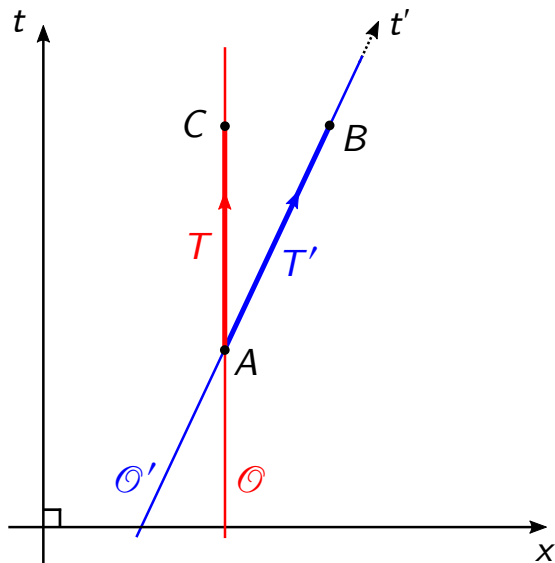


$$I_{AB} = -T^2 + X^2 = -T'^2$$

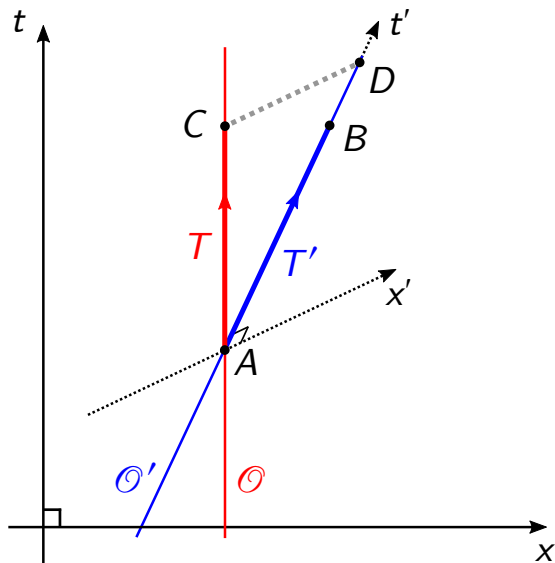
↓

$$\frac{T'}{T} = \sqrt{1 - v^2} < 1$$

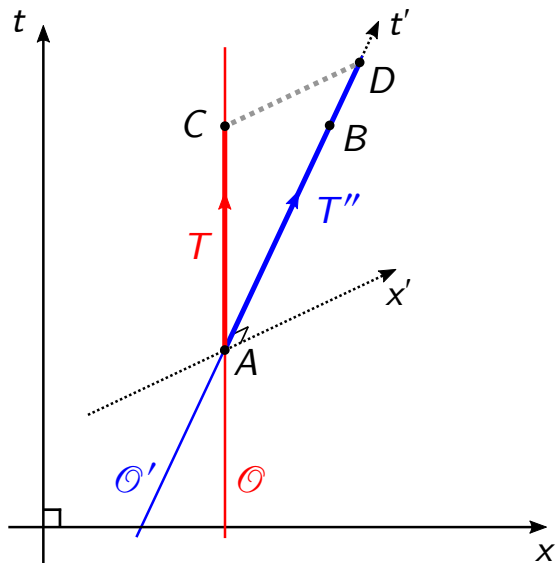
Point de vue de l'observateur \mathcal{O}'



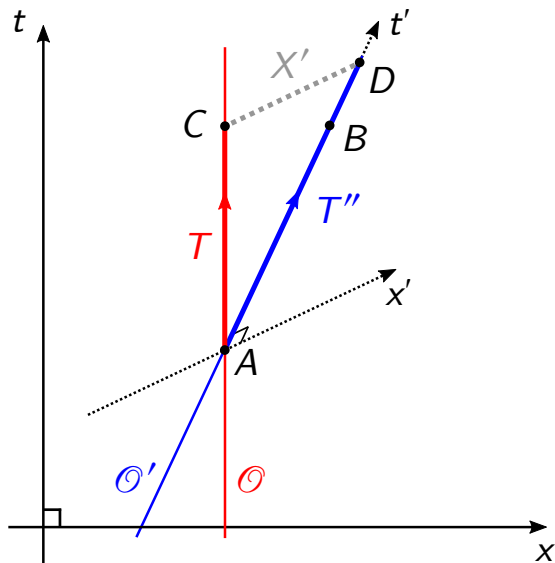
Point de vue de l'observateur \mathcal{O}'



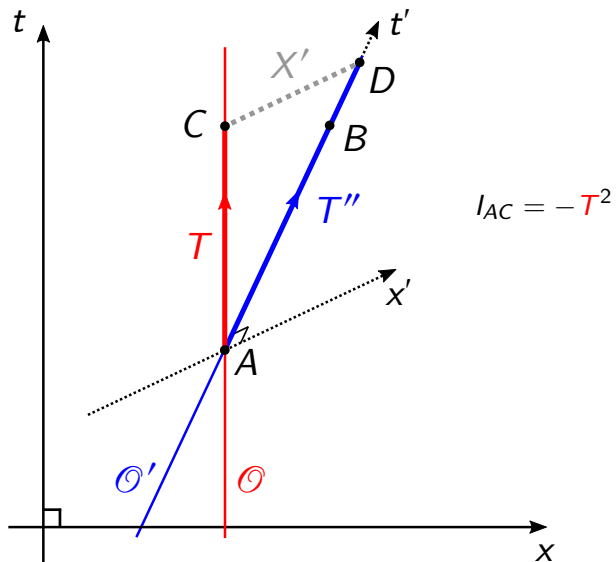
Point de vue de l'observateur \mathcal{O}'



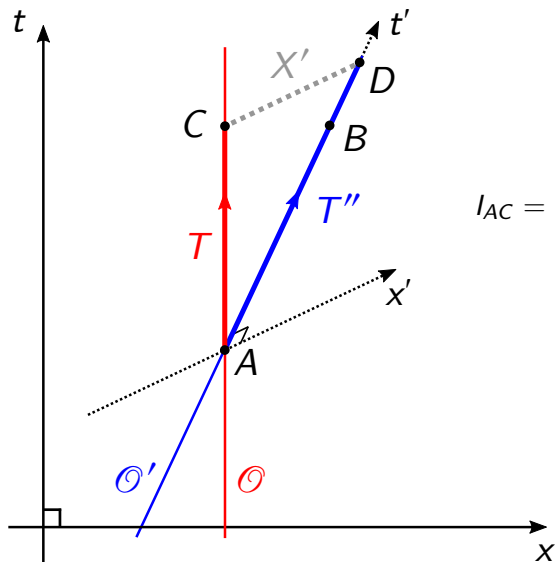
Point de vue de l'observateur \mathcal{O}'



Point de vue de l'observateur \mathcal{O}'

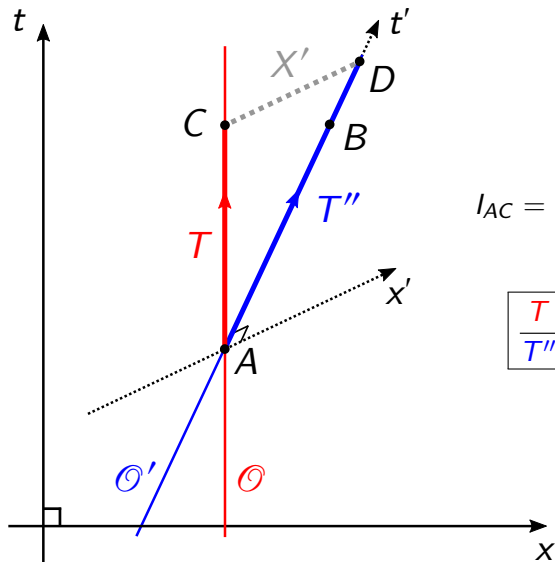


Point de vue de l'observateur \mathcal{O}'



$$I_{AC} = -T^2 = -T''^2 + X'^2$$

Point de vue de l'observateur \mathcal{O}'

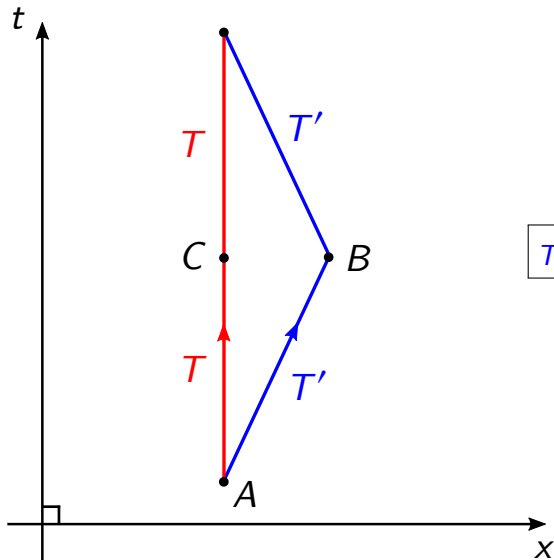


$$I_{AC} = -T^2 = -T''^2 + X'^2$$

↓

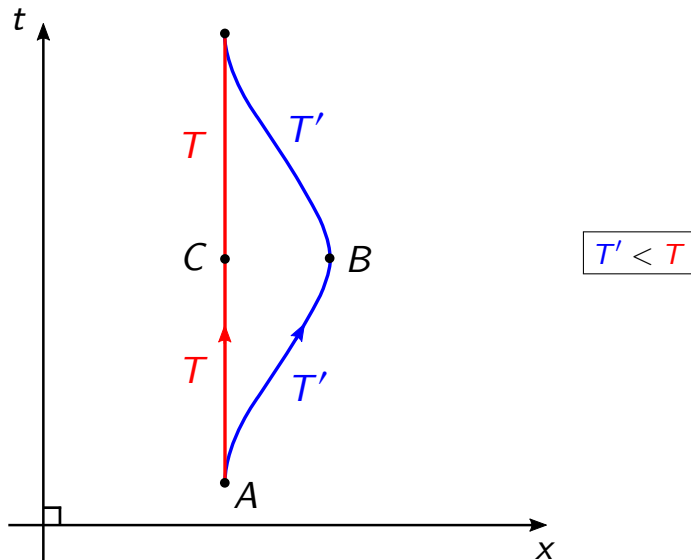
$$\boxed{\frac{T}{T''} = \sqrt{1 - v^2} < 1}$$

Les jumeaux de Langevin

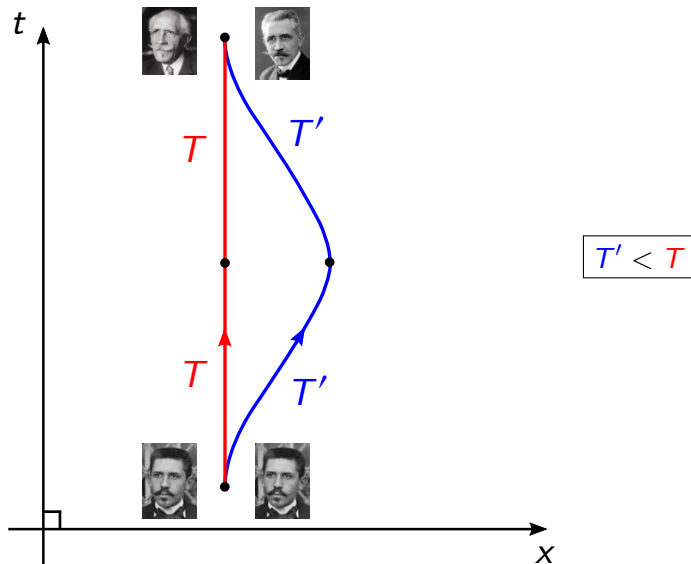


$$T' = T\sqrt{1 - v^2}$$

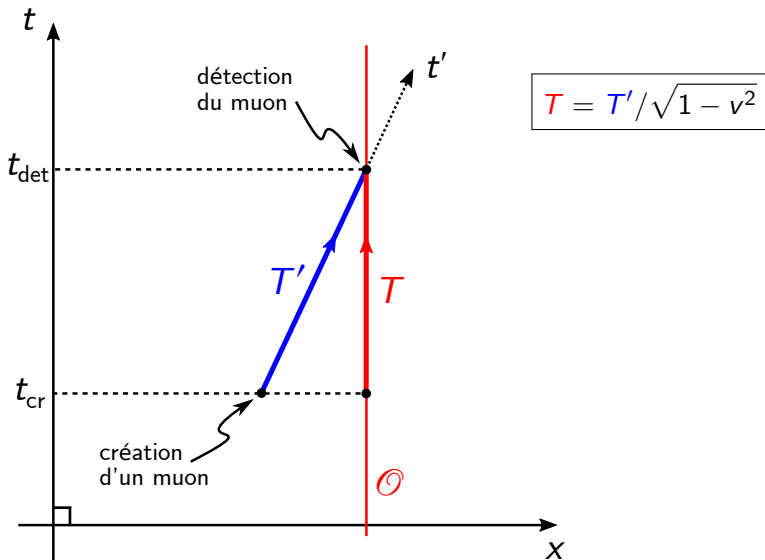
Les jumeaux de Langevin



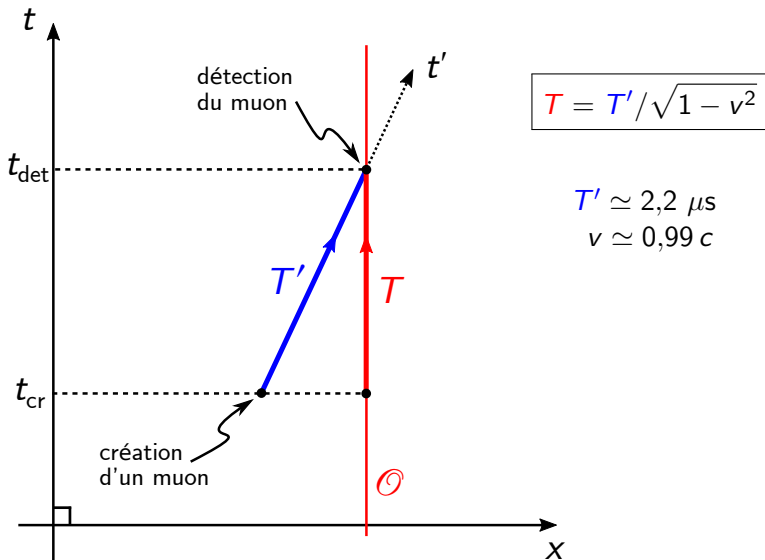
Les jumeaux de Langevin



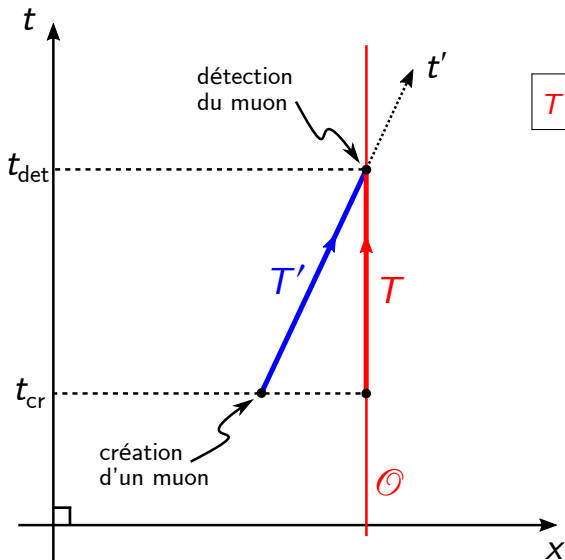
Désintégration des muons atmosphériques



Désintégration des muons atmosphériques



Désintégration des muons atmosphériques



$$T = T' / \sqrt{1 - v^2}$$

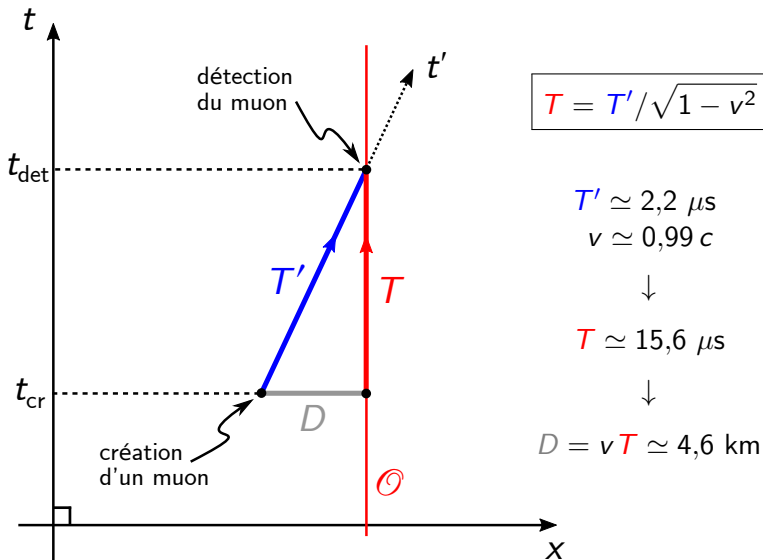
$$T' \simeq 2,2 \mu s$$

$$v \simeq 0,99 c$$

↓

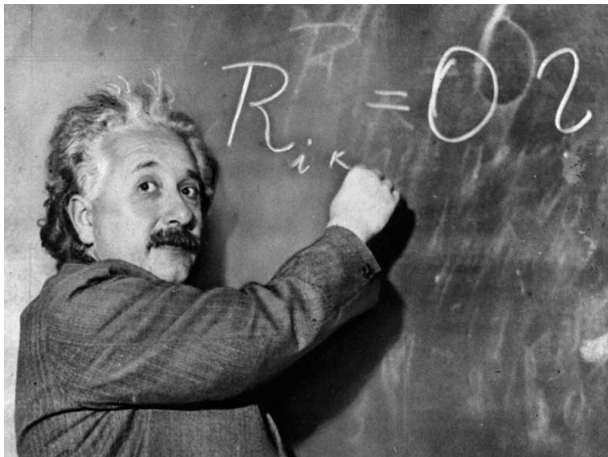
$$T \simeq 15,6 \mu s$$

Désintégration des muons atmosphériques



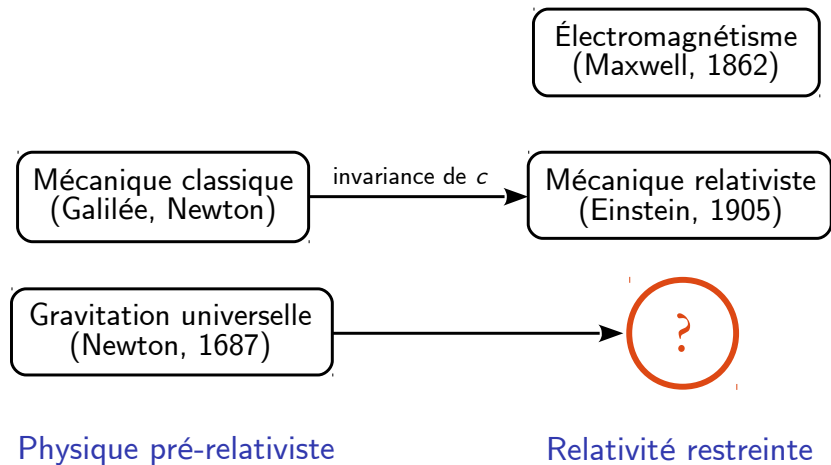
Plan de l'exposé

- 1 Espace, temps et espace-temps
- 2 Relativité de la simultanéité
- 3 Dilatation des durées
- 4 Relativité générale

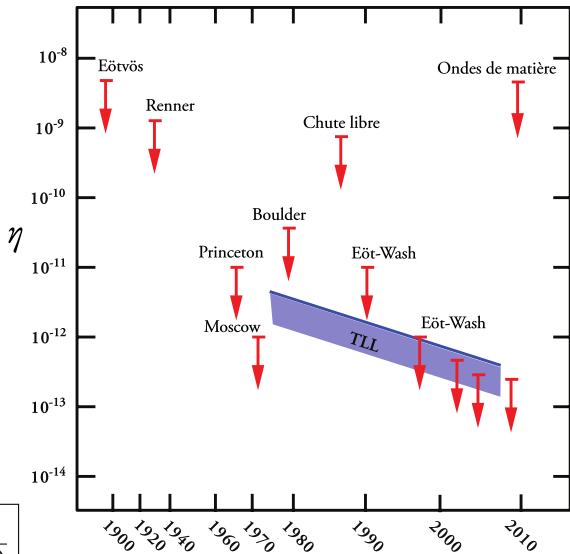


La *relativité générale* est la théorie de l'**espace**, du **temps** et de la **gravitation** formulée par Albert Einstein en 1915

Relativité et gravitation

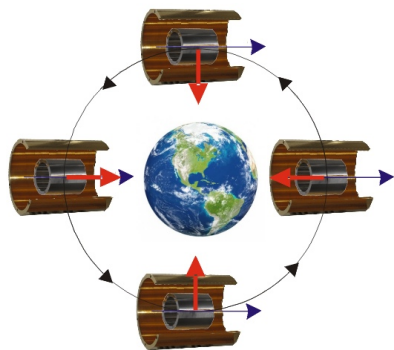


Universalité de la chute libre



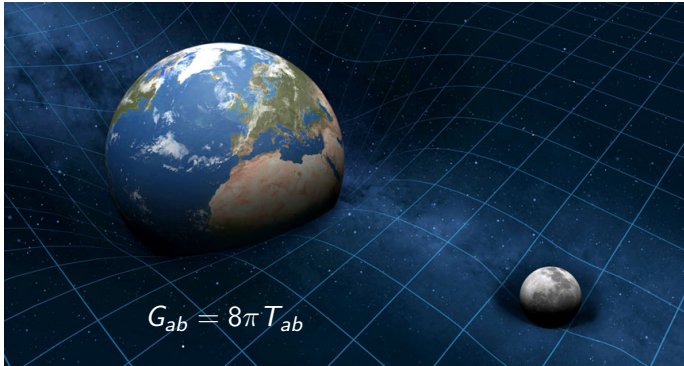
$$\eta \equiv \frac{|a_1 - a_2|}{\frac{1}{2}(a_1 + a_2)}$$

La mission MICROSCOPE



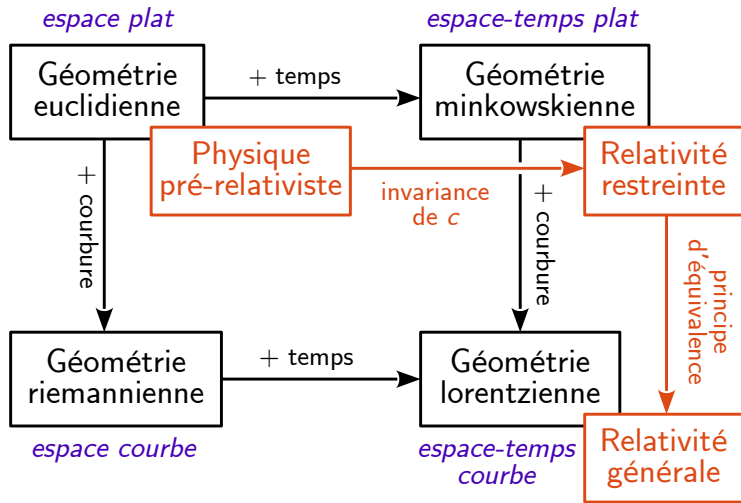
$$\eta < 10^{-15}$$

L'espace-temps est courbe

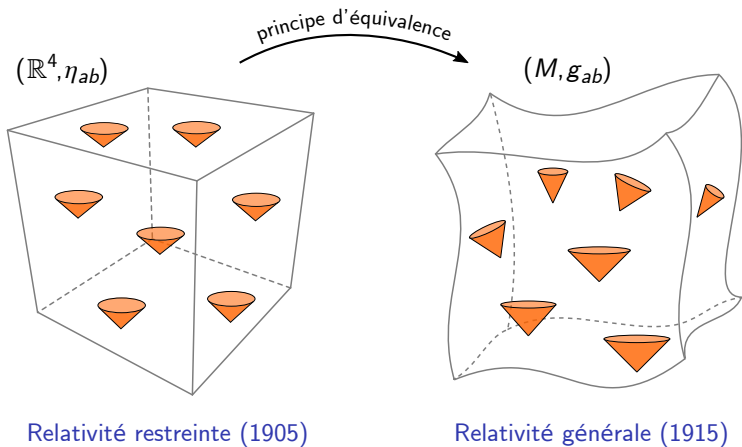


La gravitation est la manifestation de la **courbure de l'espace-temps** par la masse et l'énergie de la matière

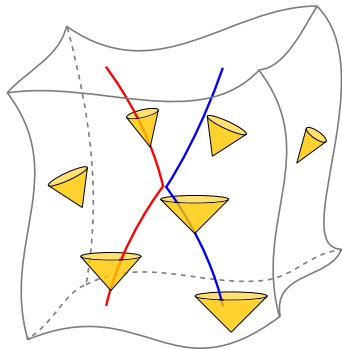
Gravitation et géométrie



Relativité restreinte \rightarrow Relativité générale

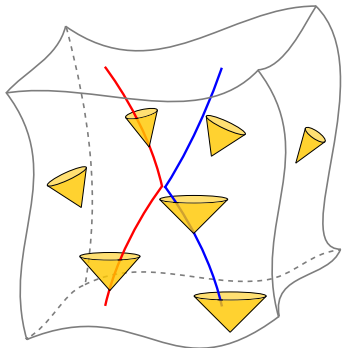


L'espace-temps est courbe



espace-temps

L'espace-temps est courbe

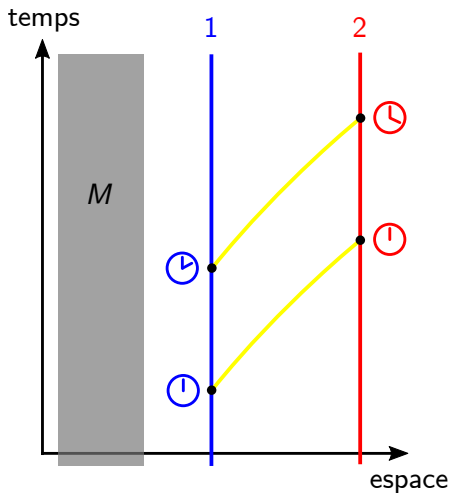


espace-temps



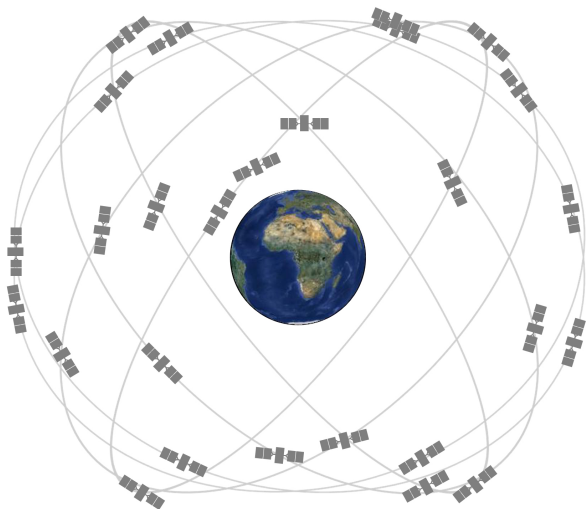
dessert anglais

Décalage vers le rouge gravitationnel



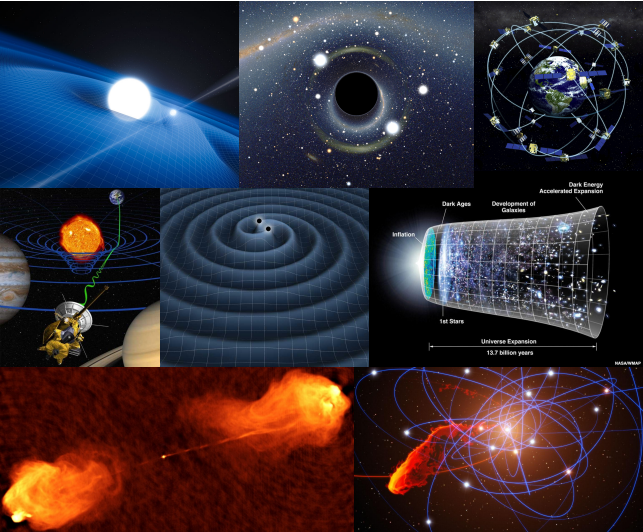
$$\frac{\Delta T_1}{\Delta T_2} = \sqrt{\frac{1 - 2GM/(c^2 r_1)}{1 - 2GM/(c^2 r_2)}} < 1$$

Application à la géolocalisation



$h \simeq 2 \times 10^4$ km \rightarrow décalage de $\simeq 46$ μ s/jour

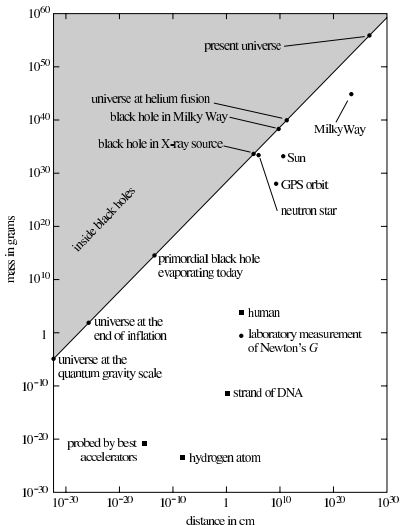
Relativité générale et astrophysique



Domaine d'application de la théorie

$$\text{Compacité} \equiv \frac{G}{c^2} \frac{M}{R}$$

Systeme	Compacité
Proton	$\sim 10^{-39}$
Terre	$\sim 10^{-9}$
Soleil	$\sim 10^{-6}$
Naine blanche	$\sim 10^{-3}$
Étoile à neutrons	$\sim 0,2$
Trou noir	$\sim 0,5$
Univers	$\sim 0,5$



Ouvrages de vulgarisation

- A. Riazuelo, *Les trous noirs*, Vuibert, 2016
- J. Levin, *Black hole blues*, Bodley Head, 2016
- P. Binétruy, *À la poursuite des ondes gravitationnelles*, Dunod, 2015
- N. Deruelle, *De Pythagore à Einstein, tout est nombre*, Belin, 2015
- N.&J. Delabrouille, *Les nouveaux messagers du cosmos*, Seuil, 2011
- J.-P. Lasota, *La science des trous noirs*, Odile Jacob, 2010
- D. Kennefick, *Traveling at the speed of thought*, U. Princeton, 2007
- T. Damour, *Si Einstein m'était conté*, Le Cherche Midi, 2005
- K. Thorne, *Trous noirs et distorsions du temps*, Flammarion, 1997
- R. Geroch, *General relativity from A to B*, U. Chicago Press, 1981

Ouvrages techniques

- N. Deruelle & J.-P. Uzan, *Théories de la relativité*, Belin, 2014
- P. Spagnou, *De la relativité au GPS*, Ellipses, 2012
- D. Langlois, *Introduction à la relativité*, Vuibert, 2011
- E.ourgoulhon, *Relativité restreinte*, EDP Sciences, 2010
- J.-P. Pérez, *Relativité et invariance*, Dunod, 2005

MOOC

- *Gravité!*, Université Paris Diderot
- *Peser l'Univers*, Observatoire de Paris

Plate-forme France université numérique : **www.fun-mooc.fr**