Relativitat especial d'Einstein

Albert Bramon
Dept. de Física, UAB

"Cosmologia: origen i futur de l'univers".
UCE, Prada, 21 d'agost de 2012

Francesc Aragó, Estagell, 1798

Benjamin Thompson, 1753
Comte Rumford

$$c' = c \,?$$

$$E_0 = mc^2 \,?$$

c = 299 792 458 m/s

$$1 \text{ cal} \longleftrightarrow 4,5 \times 10^{-17} \text{ kg}$$

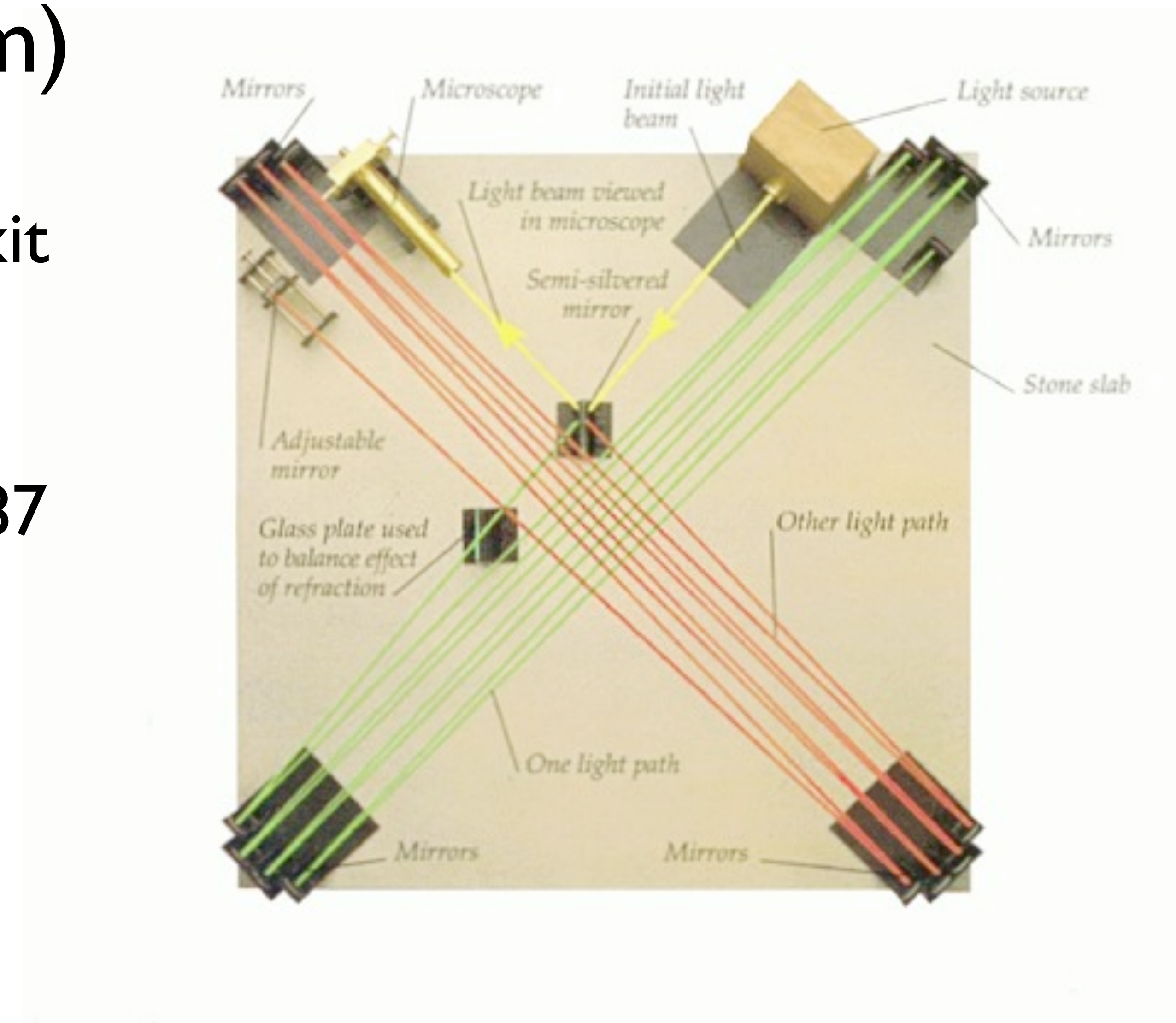
La velocitat de la llum al buit: c = 299 792 458 m/s

Absoluta i insuperable!

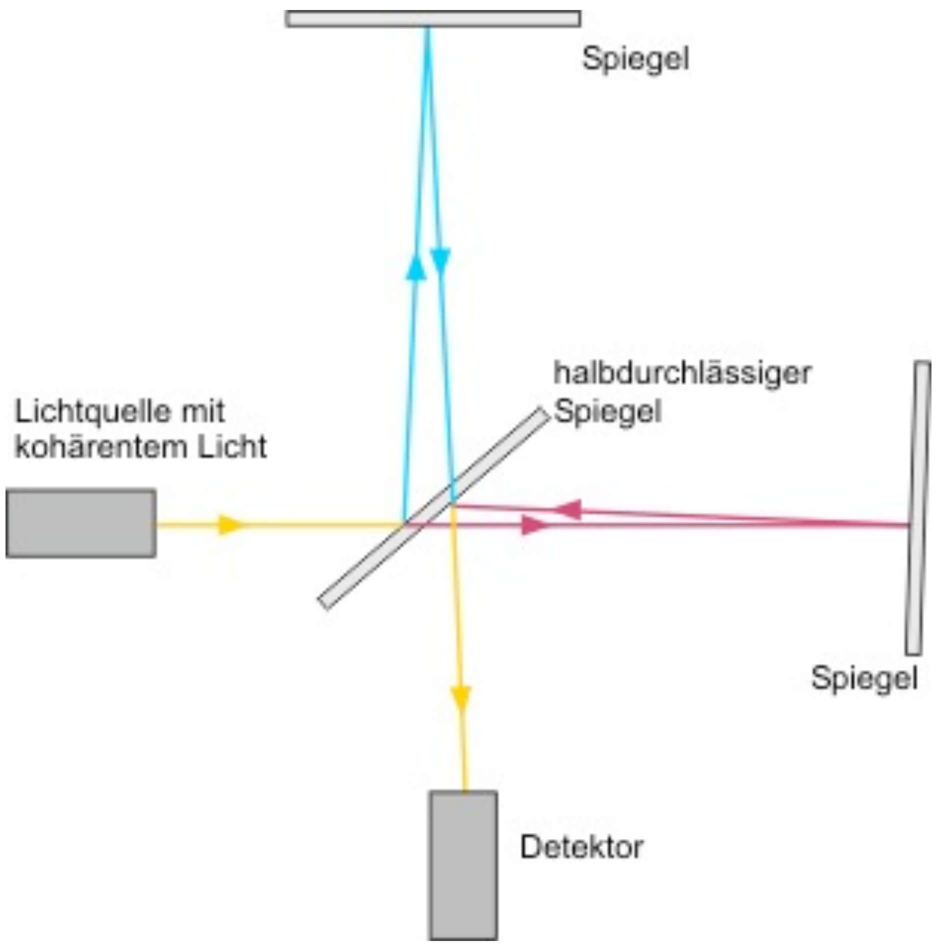
$$1\,\mathrm{m} \equiv c \times \frac{1}{299792458}\,\mathrm{s}$$

c = 299792458 m/s (tothom)

F. Arago 1810, idea brillant sense èxit



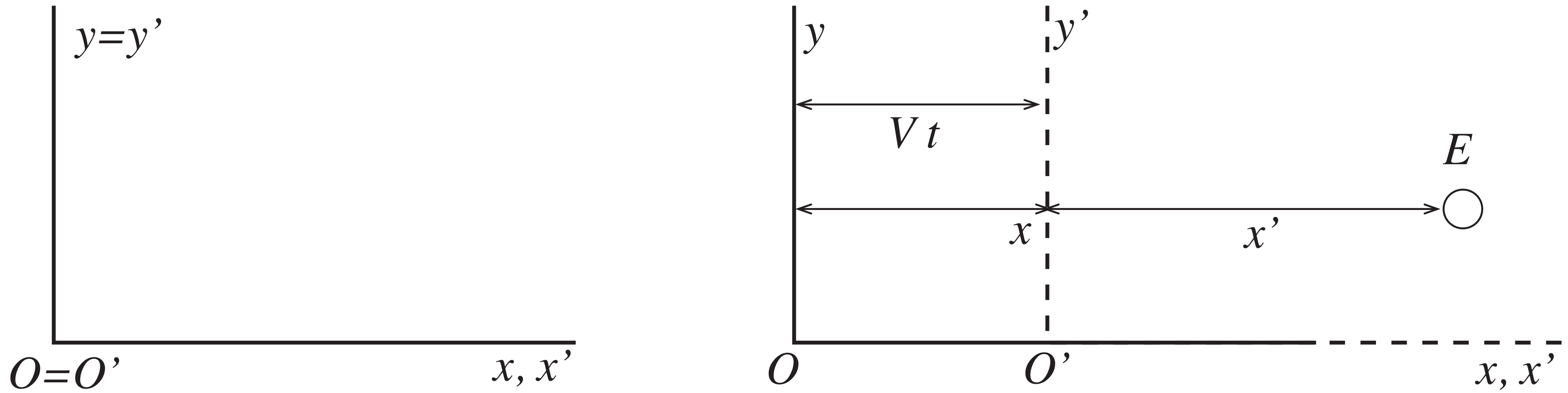
L'interferòmetre de Michelson i Morley, 1887



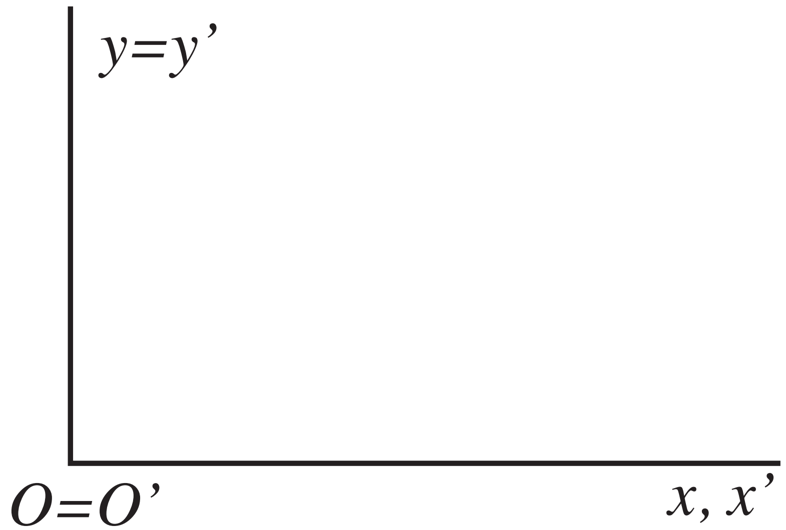
L'interferòmetre de Kennedy-Thorndike tenia els braços desiguals, 1932

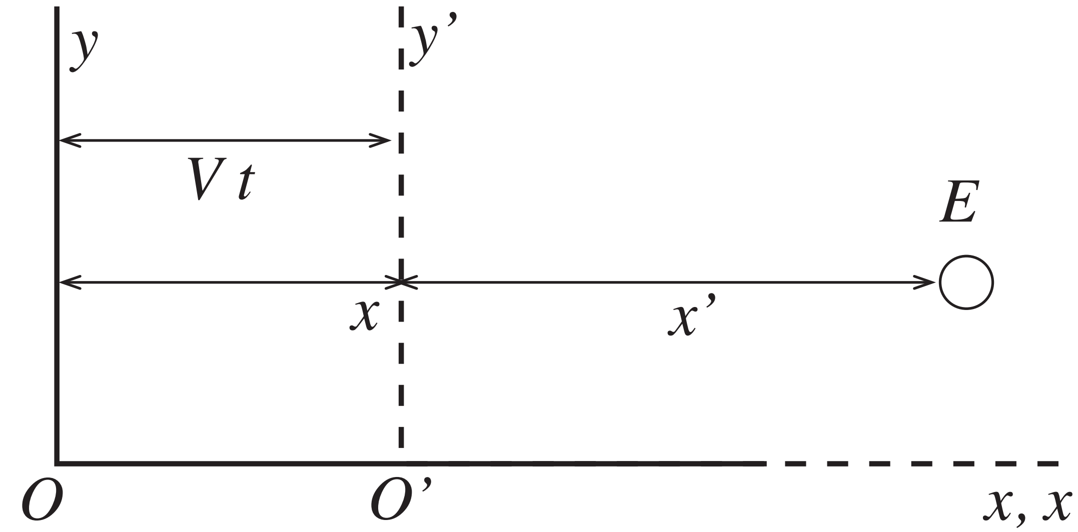
Galileu i l'experiment del vaixell

Configuració estàndard entre S i S’



Visions des d’S quan hi són les t=0 (esquerra) i quan hi són les t (dreta) i es produeix l’esdeveniment E. Mentrestant, els eixos del sistema S’ han avançat Vt





$$x' = x - Vt, \qquad y' = y, \qquad t' = t$$

$$v'_x = v_x - V$$

Velocitat relativa, depén des d'on es mesuri

Temps absolut, ningú se n'escapa del seu pas ...

La relatività d'Einstein
1905

Albert Einstein va nèixer a Ulm
el 14 de març de 1879

El retrat més antic d'Einstein

Emma Sallent i Antoni Roca, Revista de Física (de la SCF), número especial 2005

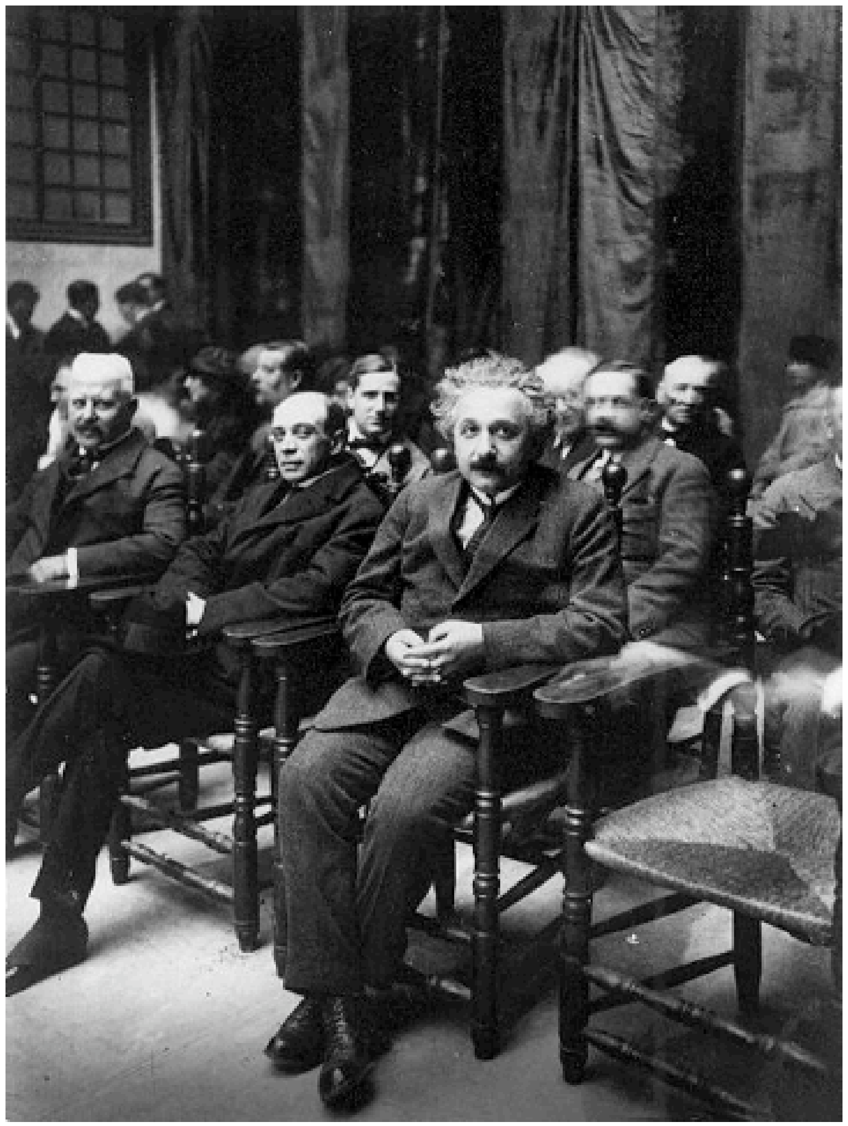


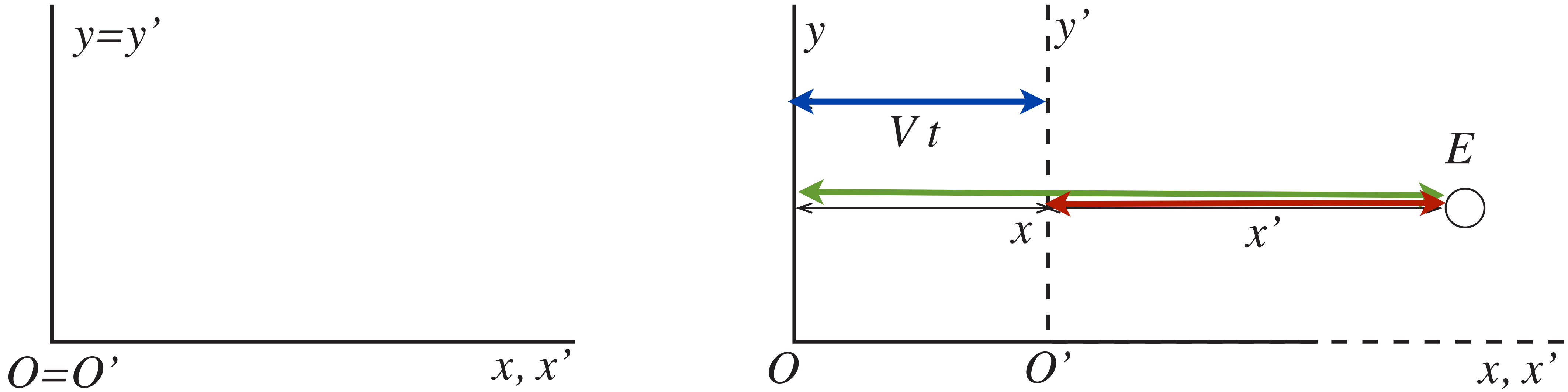
Figura 2: *Albert Einstein a l'Escola Industrial; al seu costat Pere Mias Codina, conseller de la Mancomunitat. Entre tots dos Carles Pi Sunyer*

Figura 1: *Albert Einstein a Poblet; a l'esquerra de la fotografia Rafael Campalans i a la dreta Bernat Lassaletta. Foto: C. Lana Sarrate, Mundo Gráfico 1923, número 592 (7 de març)*

Charlie Chaplin a Einstein:

"A mi tothom m'estima perquè comprenen tot el que dic
i a vostè tothom l'estima perquè no entenen res del que diu"

Un periodista: Vostè parla de res més que no sigui de física?
Einstein: Sí, però amb vostè no!



$$x' = x - Vt, \qquad y' = y, \qquad t' = t$$

Simultaneïtat relativa

$$x' = \frac{x - Vt}{\sqrt{1 - V^2/c^2}}, \quad y' = y, \quad t' = \frac{t - Vx/c^2}{\sqrt{1 - V^2/c^2}}$$

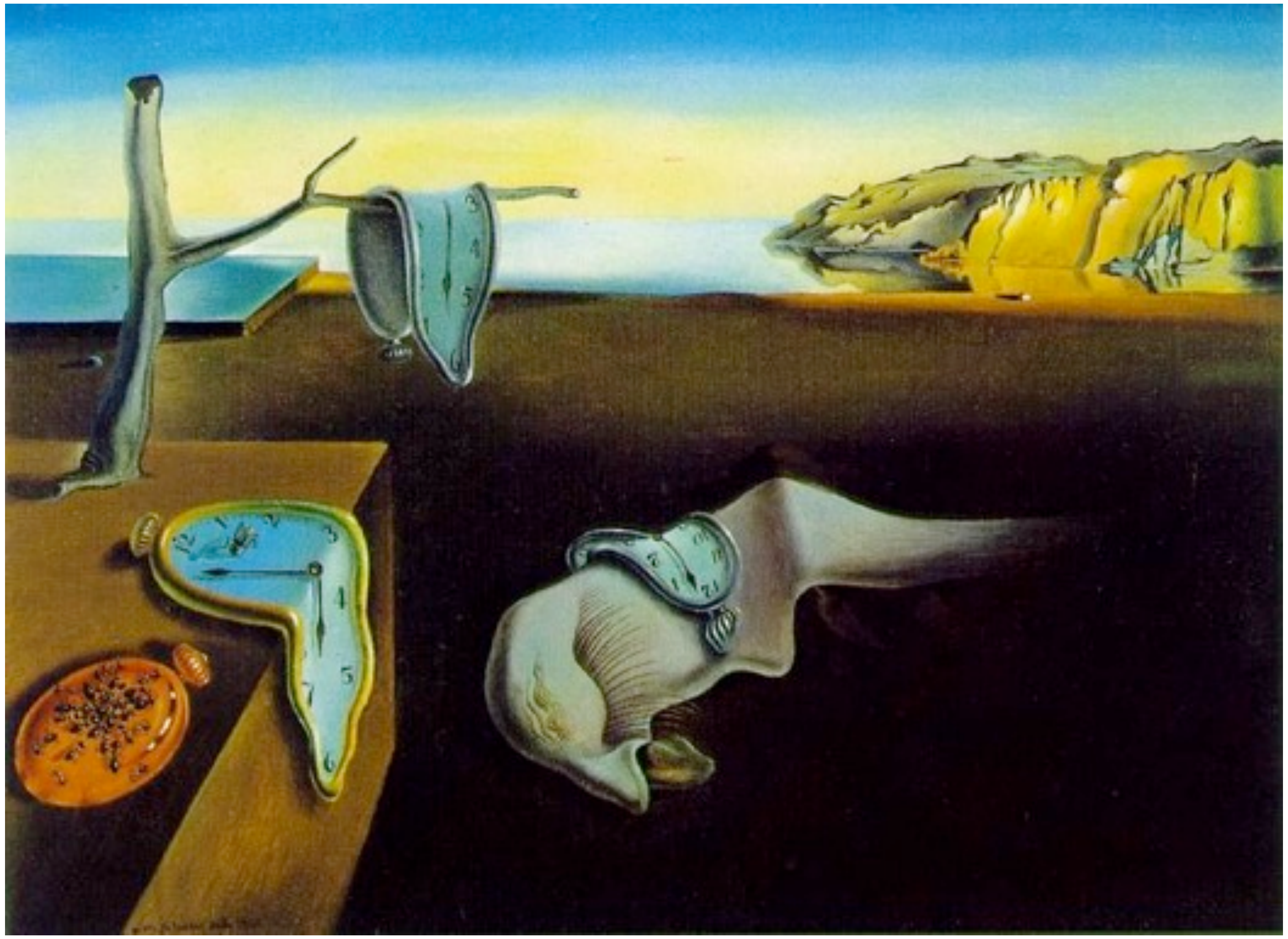
Contracció de longituds

Dilatació dels temps

Velocitat de la llum: absoluta i insuperable!

$c' = c$

Conseqüències de la invariància c:

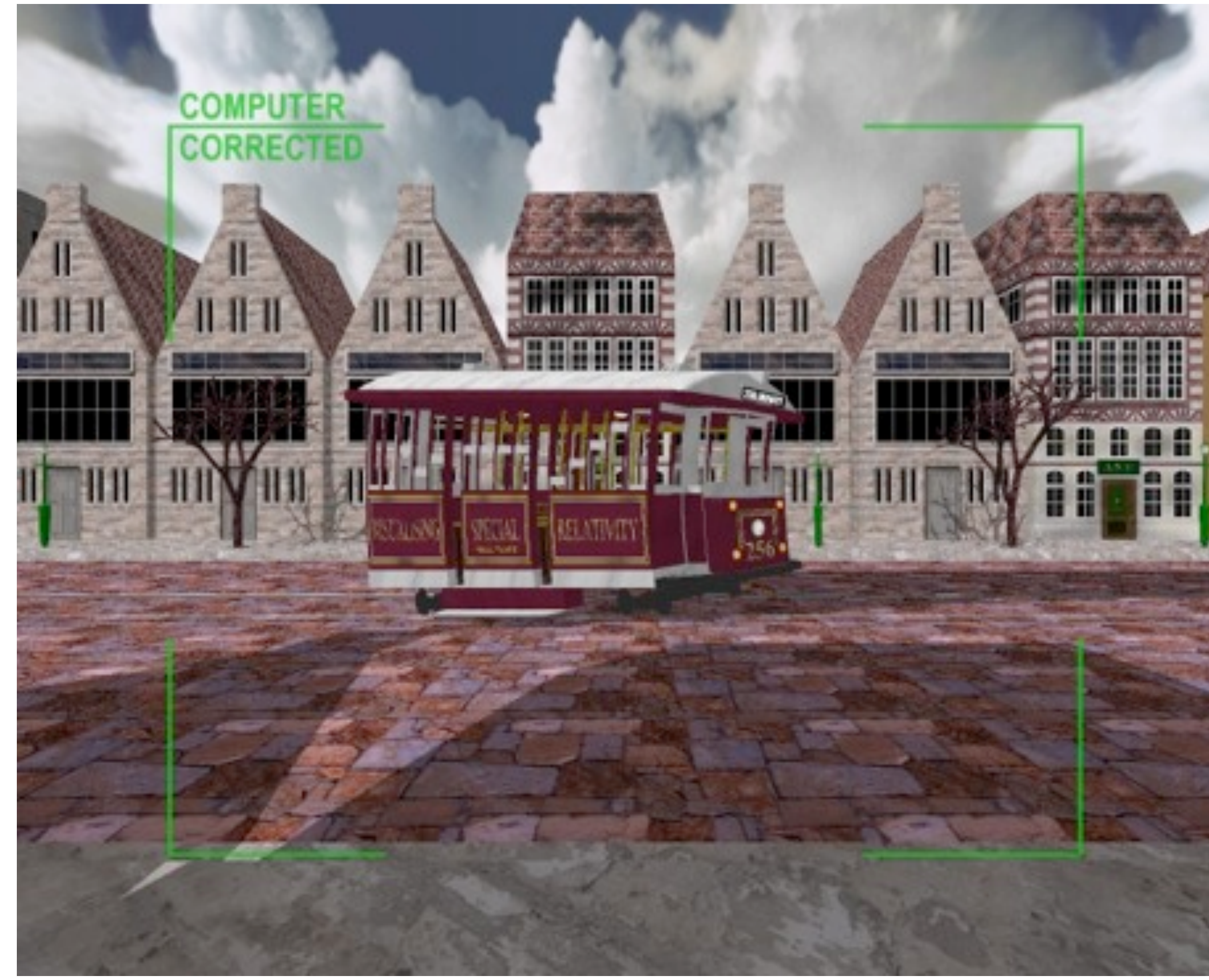


1. **No simultaneïtat**
2. **Dilatació de temps**
3. **Contracció longituds**

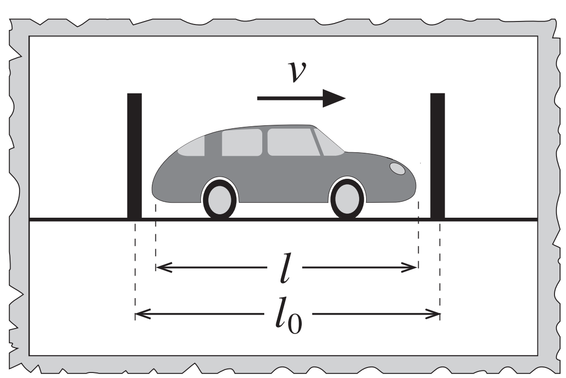
I. Temps: allò que es mesura amb rellotges

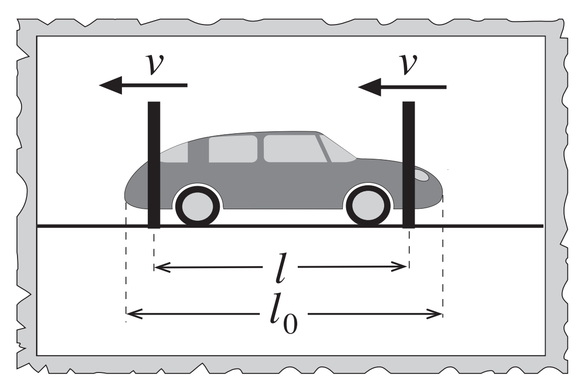
II. Espai: allò que es mesura amb regles

A fons ...

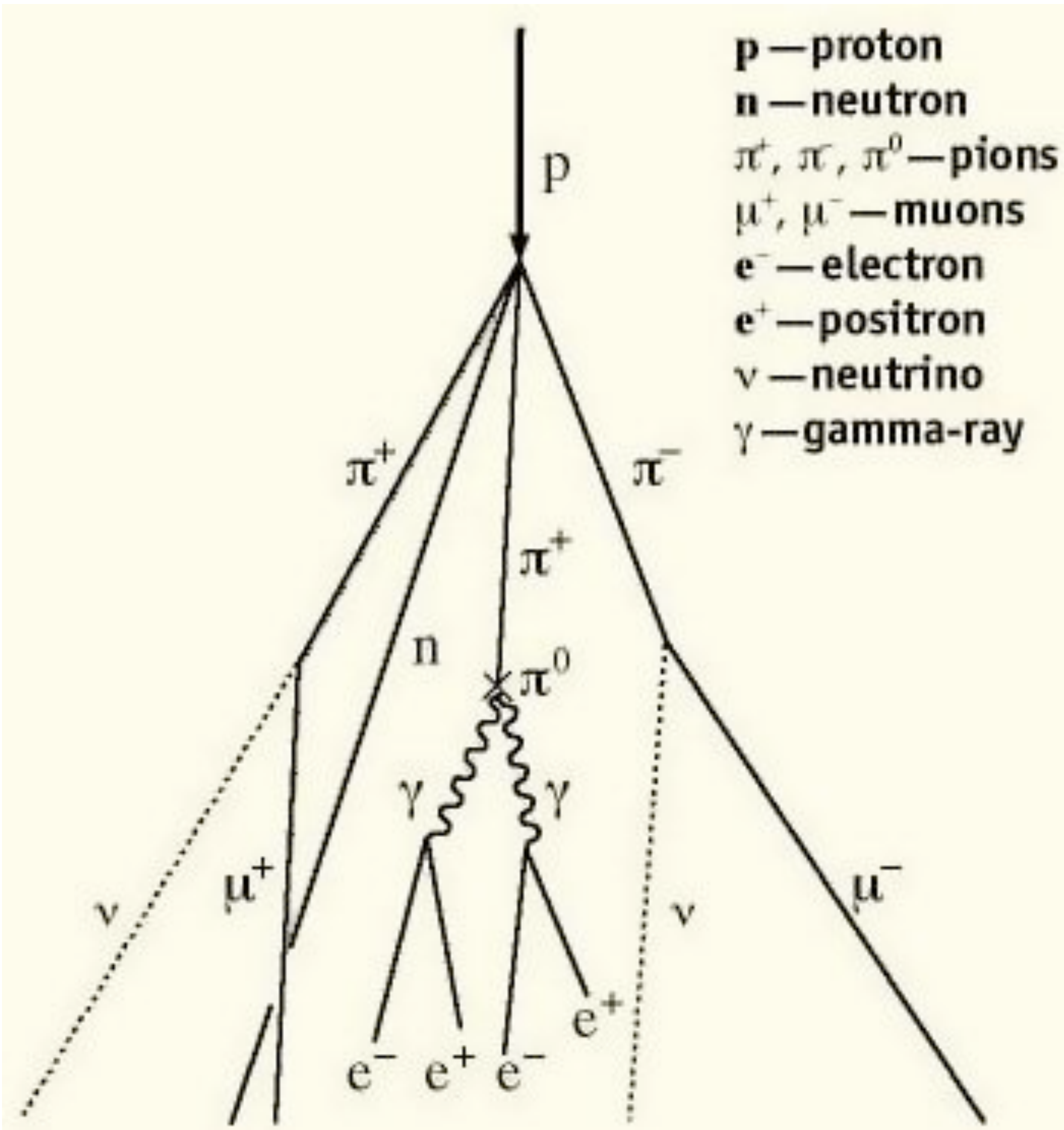


Terrell effect, contracció relativista de longituds paral.leles al moviment.

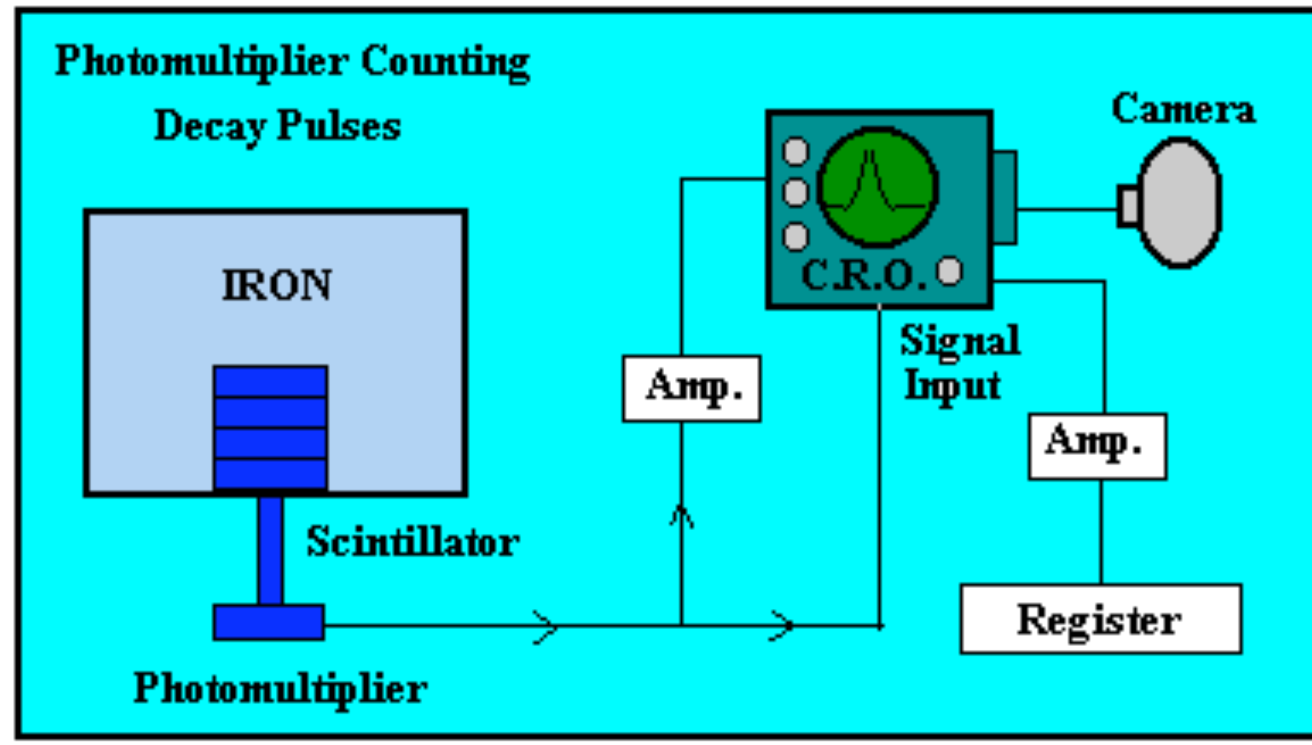




Si només s'il.luminés la cara que es veu



Producció de muons a l'alta atmosfera per raigs còsmics



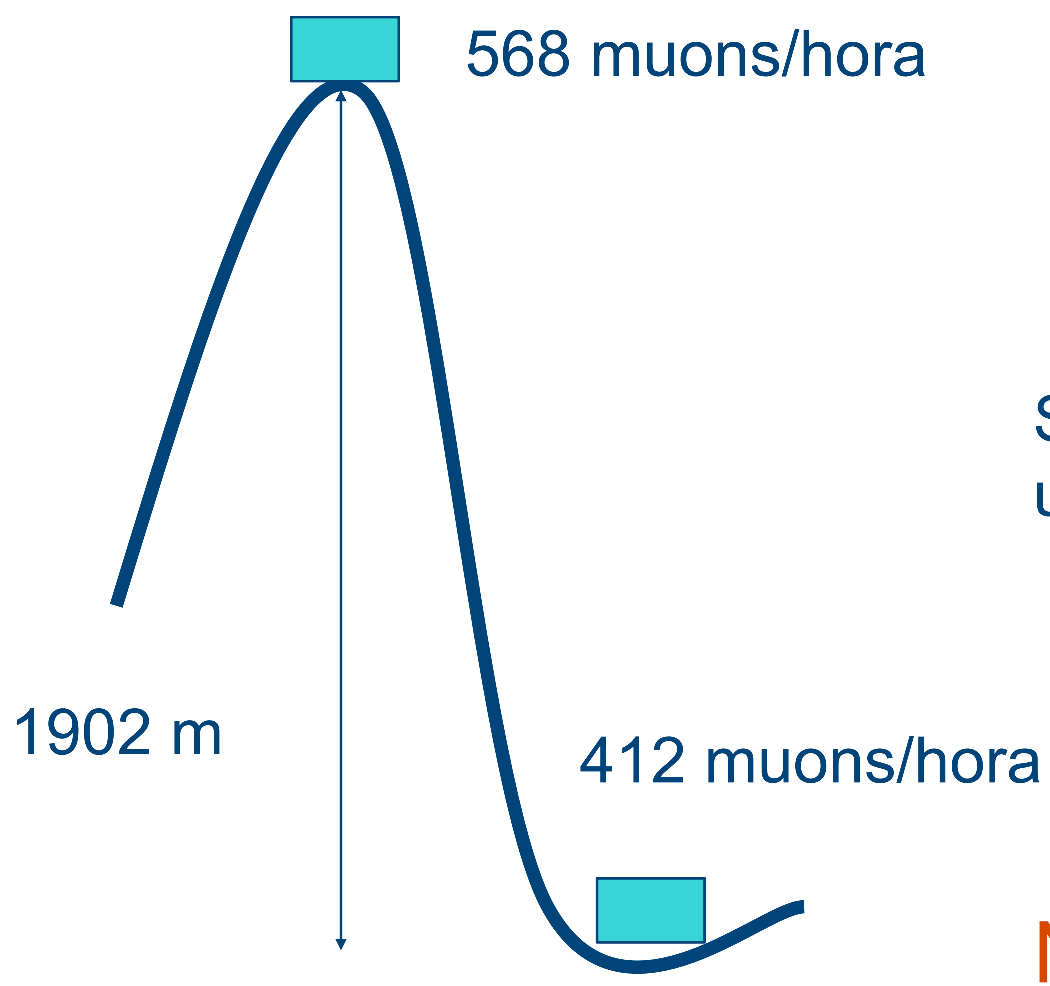
Captura de muons:
registres de senyal d'entrada i de desintegració

http://www.egglescliffe.org.uk/physics/

És realment així?

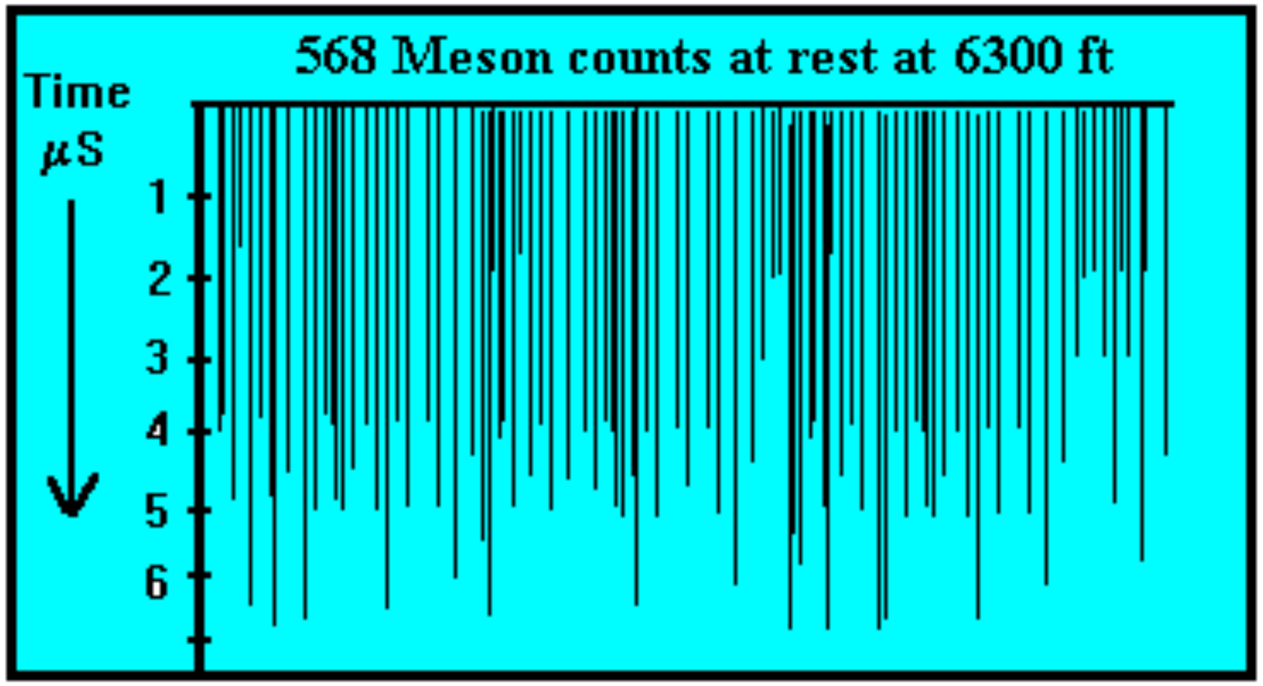
No importa quant maca sigui la teva teoria, quant intel.ligent siguis: si no coincideix amb l'experiment, està equivocada. *Richard Feynman*

- Els materials radioactius són rellotges naturals

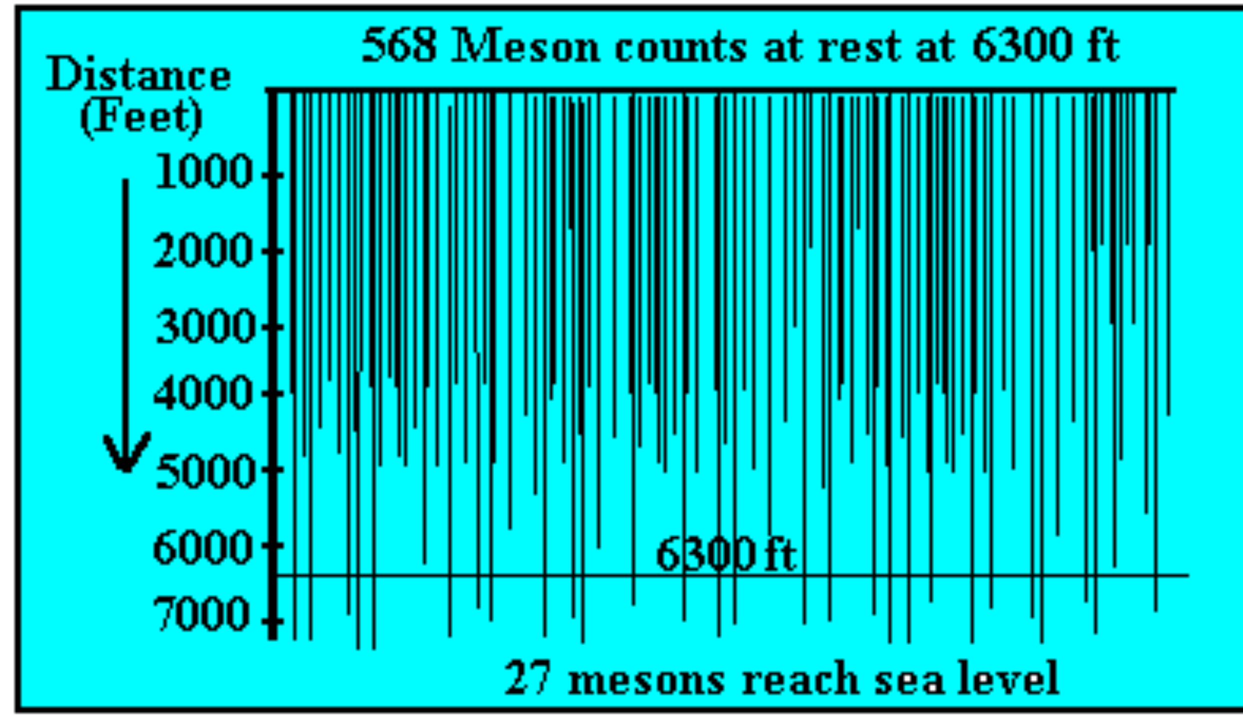


Segons els càlculs clàssics haurien d'arribar uns 27 muons/hora

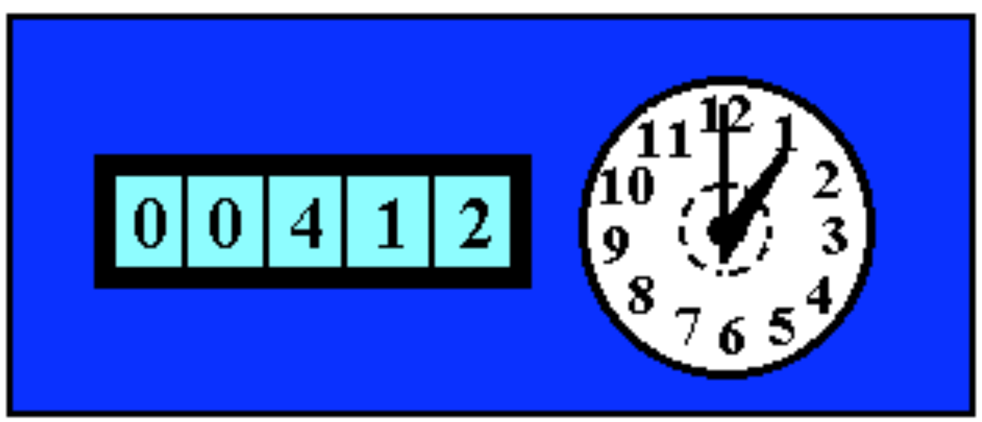
N'arriben molts més perquè ha passat menys temps per a ells



Vida mitjana dels muons: 2.2 microsegons,



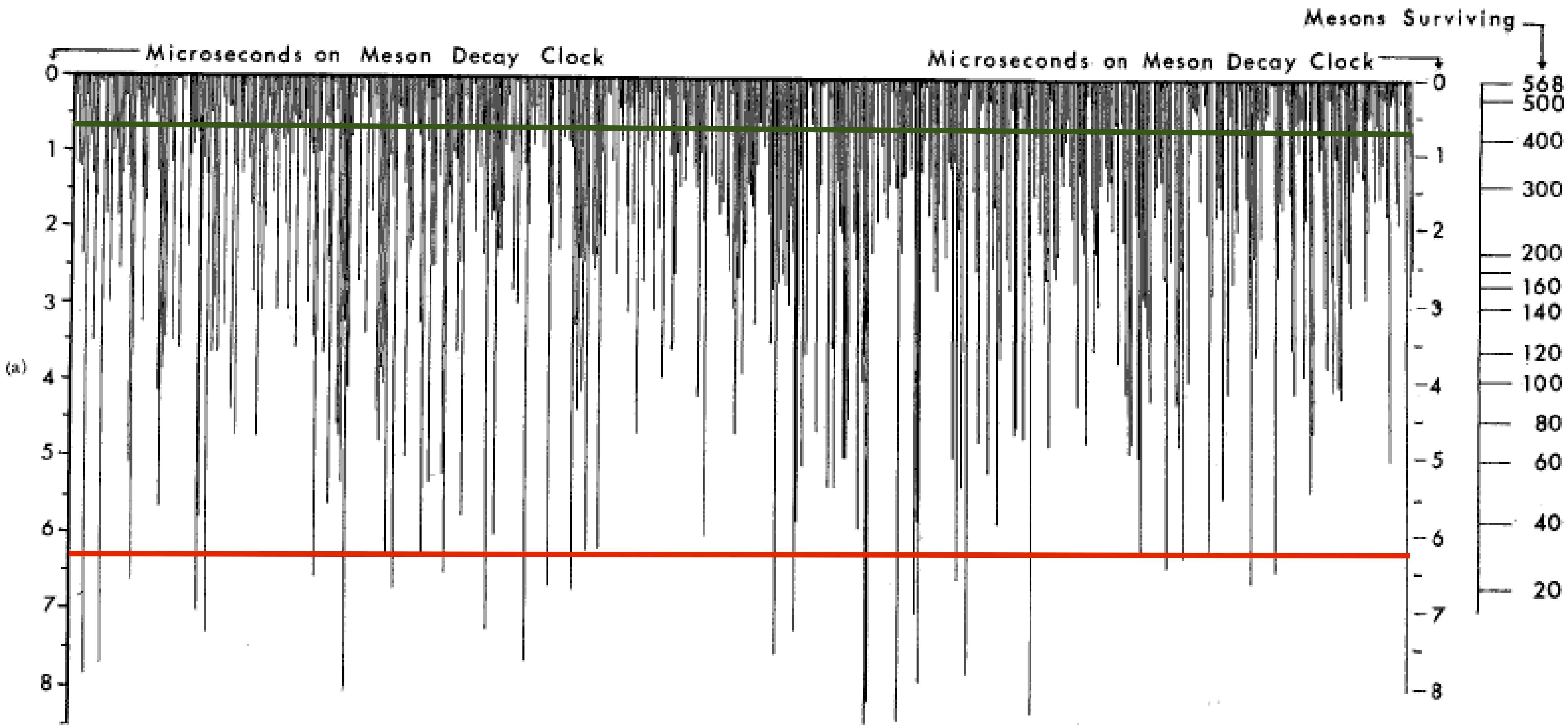
Vida de cada muó (esquemàtica)
Quants sobreviuen 6300 peus = 2 km més avall?
Clàssicament: uns 27. Relativísticament: uns 405



El veredicte experimental

Per a muons que veiem viatjar a la velocitat de 0.994c
el temps hi passa unes 9 vegades més lentament que per a nosaltres. Equivalentment, els muons veuen la distància de 6300 peus reduida a la novena part, uns 700 peus.
Uns 405 sobreviuran, molts més dels 27 clàssics.

L'experiment dels muons



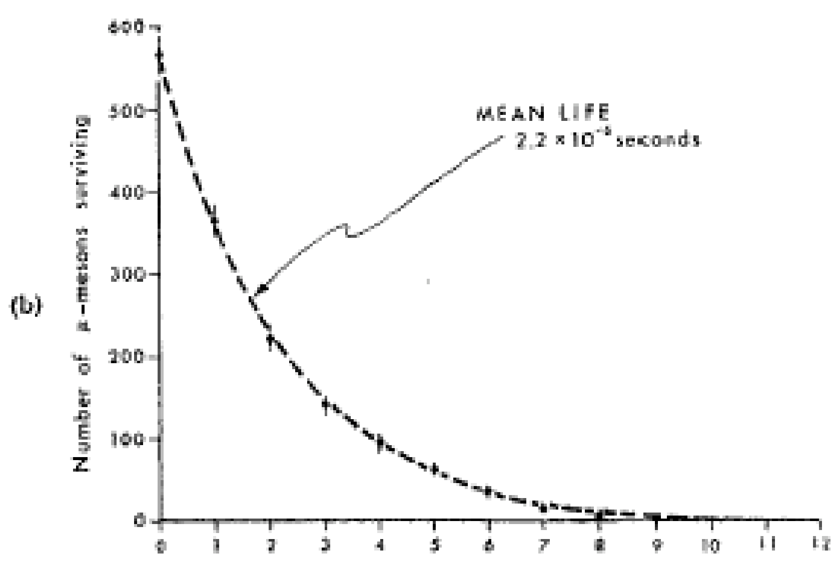
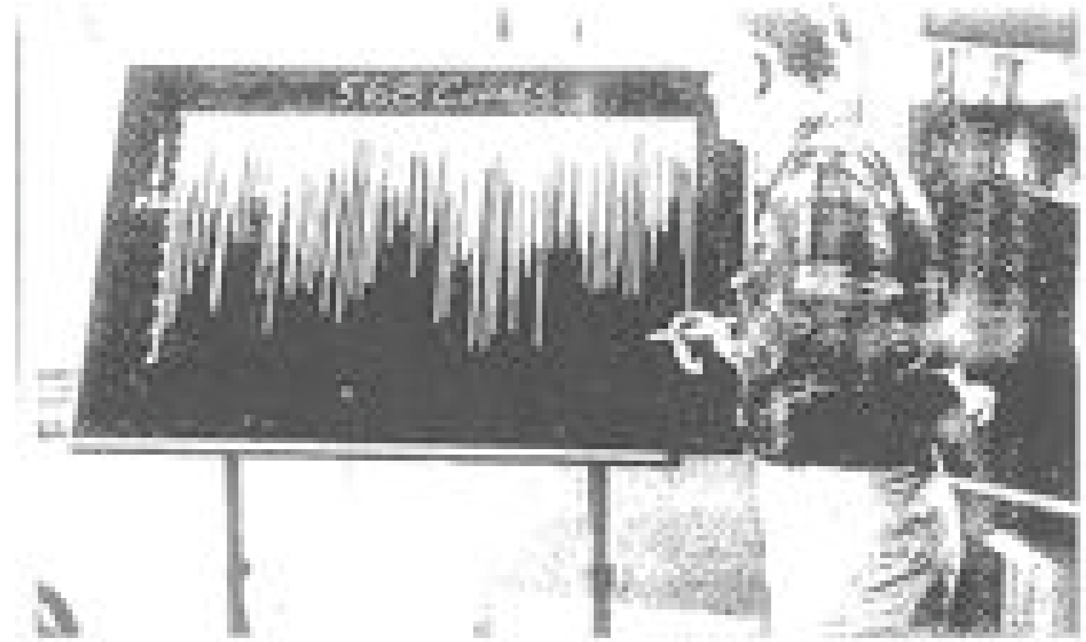


FIG. 6. (a) This is a reproduction of the chart used, in the film, to display the data from a 1-h run on top of Mt. Washington. The decay time of each μ-meson is represented by a vertical line, the length of which is proportional to the decay time. The lines (decay times) of 568 μ-mesons are displayed side-by-side across the chart. (b) The data are obtained from the chart in Fig. 6(a). The dashed curve is for a theoretical mean life of 2.2 μsec.

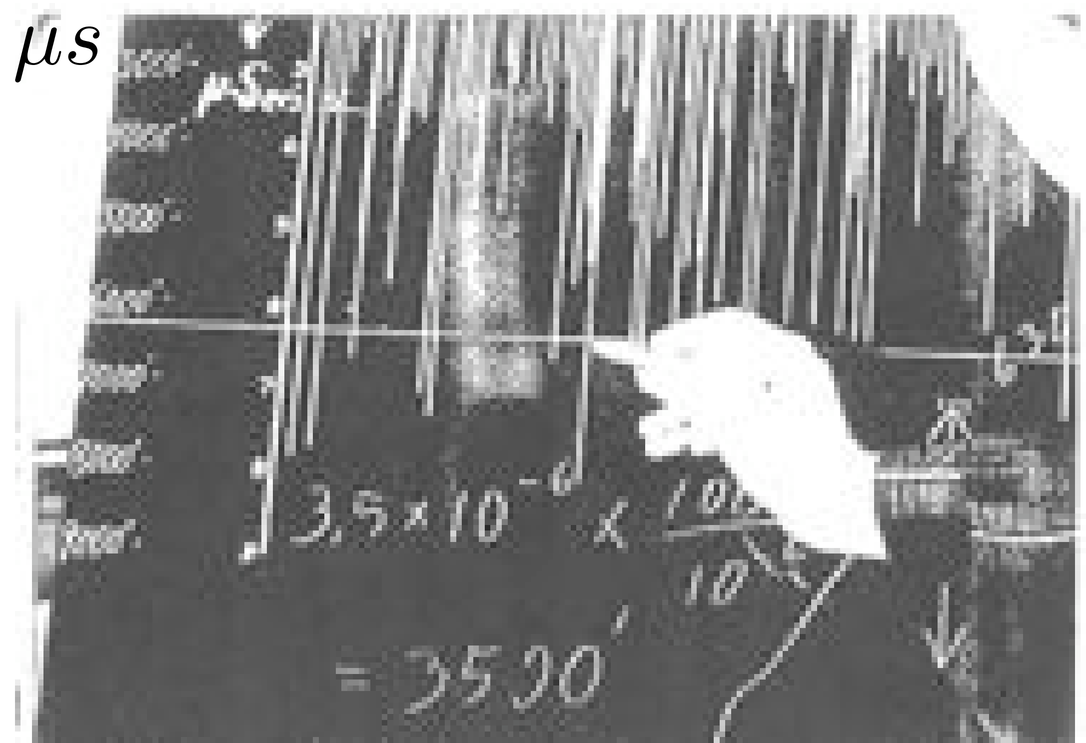
L'experiment dels muons

$$v \simeq 0,994\ c$$

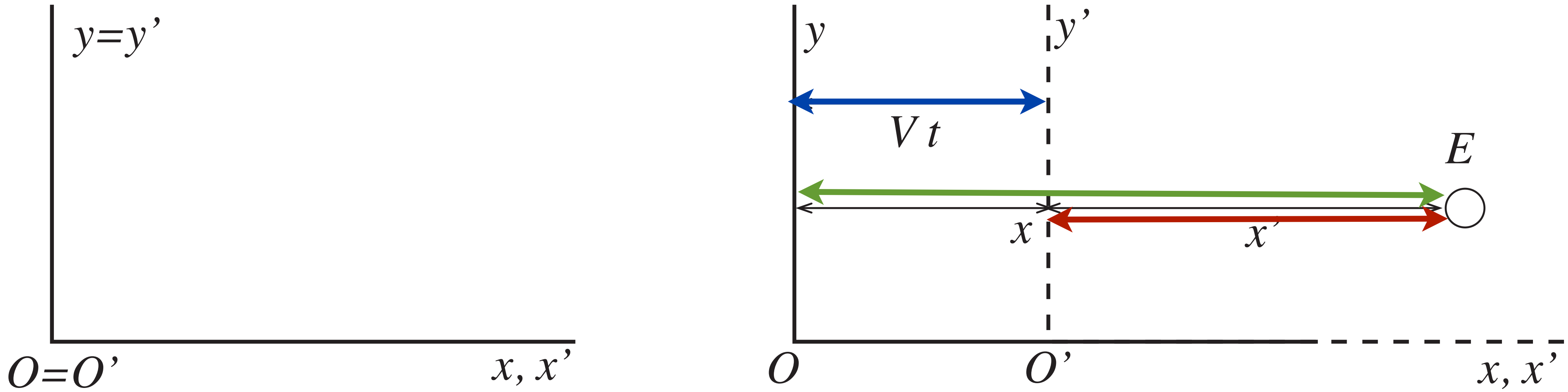
$$\gamma \simeq 9$$



$$6300\ ft \simeq 2000\ m \rightarrow 6,3/9 \simeq 0,7\ \mu s$$



$$6300\ ft \simeq 2000\ m \rightarrow 6,3\ \mu s$$



$$x' = x - Vt, \qquad y' = y, \qquad t' = t$$

$$x' = \frac{x - Vt}{\sqrt{1 - V^2/c^2}}, \quad y' = y, \quad t' = \frac{t - Vx/c^2}{\sqrt{1 - V^2/c^2}}$$

$$\sqrt{1 - V^2/c^2} < 1, \qquad c = 299\,792\,458 \text{ m/s}$$

"My goodness, it's 12:15:0936420175! Time for lunch." © 1993 by Sidney Harri

Déu meu, ja són les 12:130936420175, l'hora d'anar a dinar!

Around-the-World Atomic Clocks: Relativistic Time Gains. Hafele and Keating

Science 177 (1972) p. 166 and p. 168

Typical time differences per day:

$$24\,\mathrm{h} \rightarrow 24\,\mathrm{h} \pm 0.1\,\mu\mathrm{s}$$

Around-the-World Atomic Clocks: Predicted Relativistic Time Gains

Hafele + Keating Science 177 (1972) 166.

Abstract. *During October 1971, four cesium beam atomic clocks were flown on regularly scheduled commercial jet flights around the world twice, once eastward and once westward, to test Einstein's theory of relativity with macroscopic clocks. From the actual flight paths of each trip, the theory predicts that the flying clocks, compared with reference clocks at the U.S. Naval Observatory, should have lost 40 ± 23 nanoseconds during the eastward trip, and should have gained 275 ± 21 nanoseconds during the westward trip. The observed time differences are presented in the report that follows this one.*

One of the most enduring scientific debates of this century is the relativistic clock "paradox" (*1*) or problem (*2*), which stemmed originally from an alleged logical inconsistency in predicted time differences between traveling and reference clocks after a round trip. This seemingly endless theoretical debate, which has flared up recently with renewed vigor (*2, 3*), begs for a convincing empirical resolution with macroscopic clocks. A simple and direct experimental test of the clock problem with portable atomic clocks is now possible because of the unprecedented stability achieved with these clocks (*4*).

In this first of two reports, we present relativistic time differences calculated from flight data for our recent around-the-world flying clock experiments. The theory predicts a detectable effect with cesium beam clocks if they are flown around the world at typical jet aircraft speeds (*4*). Moreover, it predicts an interesting asymmetry in the time difference between the flying clocks and a ground reference clock, depending on the direction of the circumnavigation (*4*). Predicted time differences are compared with our observed time differences in the following report.

A brief elementary review of the theory seems appropriate, particularly because of some confusion about the capacity of such experiments to produce meaningful results (*5*). Special relativity predicts that a moving standard clock will record less time compared with (real or hypothetical) coordinate clocks distributed at rest in an inertial reference space. For low coordinate speeds ($u^2 \ll c^2$), the ratio of times recorded by the moving and reference coordinate clocks reduces to $(1 - u^2/2c^2)$, where c is the speed of light. Because the earth rotates, standard clocks distributed at rest on the

... bla, bla ...

Table 1. Predicted relativistic time differences (nsec). 1 nsec = 10^{-9} sec

Effect	Direction: East	Direction: West
Gravitational	144 ± 14	179 ± 18
Kinematic	−184 ± 18	96 ± 10
Net	−40 ± 23	275 ± 21

Around-the-World in 24 h

$V = \frac{40\times10^6 m}{24\times3600 s} = 463 m/s$

$\tau(24h) = 24h + 103 ns$ $(0.103\times10^{-6} s)$

$\beta \equiv \frac{V}{c} = 1.54\times10^{-6} \rightarrow \gamma = \frac{1}{\sqrt{1-\beta^2}} \simeq 1 + 1.2\times10^{-12}$

Around-the-World Atomic Clocks: Observed Relativistic Time Gains

Abstract. *Four cesium beam clocks flown around the world on commercial jet flights during October 1971, once eastward and once westward, recorded directionally dependent time differences which are in good agreement with predictions of conventional relativity theory. Relative to the atomic time scale of the U.S. Naval Observatory, the flying clocks lost 59 ± 10 nanoseconds during the eastward trip and gained 273 ± 7 nanoseconds during the westward trip, where the errors are the corresponding standard deviations. These results provide an unambiguous empirical resolution of the famous clock "paradox" with macroscopic clocks.*

In science, relevant experimental facts supersede theoretical arguments. In an attempt to throw some empirical light on the question of whether macroscopic clocks record time in accordance with the conventional interpretation of Einstein's relativity theory (*1*), we flew four cesium beam atomic clocks around the world on commercial jet flights, first eastward, then westward. Then we compared the time they recorded during each trip with the corresponding time recorded by the reference atomic time scale at the U.S. Naval Observatory, MEAN(USNO) (*2*). As was expected from theoretical predictions (*1*), the flying clocks lost time (aged slower) during the eastward trip and gained time (aged faster) during the westward trip. Furthermore, the magnitudes of the time differences agree reasonably well with predicted values, which were discussed in the preceding report (*1*). In this second report, we present the time difference data for the flying ensemble, and explain the methods by which the relativistic time differences were extracted.

The development of compact and portable cesium beam atomic clocks (*3*) permits a terrestrial test of relativity theory with flying clocks. The fundamental unit of time interval, the second, is now by definition equal to 9,192,631,770 accumulated periods of the frequency of the atomic transitions of an "ideal" cesium beam frequency standard (*2, 3*). Because these clocks are regulated by the frequency of a natural atomic transition, a particularly well defined hyperfine transition in the ground state of the ^{133}Cs atom, they

... bla, bla ...

Table 1. Observed relativistic time differences from application of the correlated rate-change method to the time intercomparison data for the flying ensemble. Predicted values are listed for comparison with the mean of the observed values; S.D., standard deviation.

Clock serial No.	$\Delta\tau$ (nsec) Eastward*	$\Delta\tau$ (nsec) Westward
120	− 57	277
361	− 74	284
408	− 55	266
447	− 51	266
Mean ± S.D.	− 59 ± 10	273 ± 7
Predicted ± Error est.	− 40 ± 23	275 ± 21

OK!

* Negative signs indicate that upon return the time indicated on the flying clocks was less than the time indicated on the MEAN(USNO) clock of the U.S. Naval Observatory.

6ii)

Time flies

LAST UPDATED: 1 Feb 2011 + **CATEGORY:** News

In June 2010 one of NPL's atomic clocks was flown around the world as part of a rare experiment to test Einstein's theories of Relativity. The results demonstrate that Einstein's theories are correct, as NPL was able to measure a clear time-shift of 230 ± 20 nanoseconds between the two clocks involved in the experiment. This agrees with the time-shift predicted by Einstein.

Testing Relativity

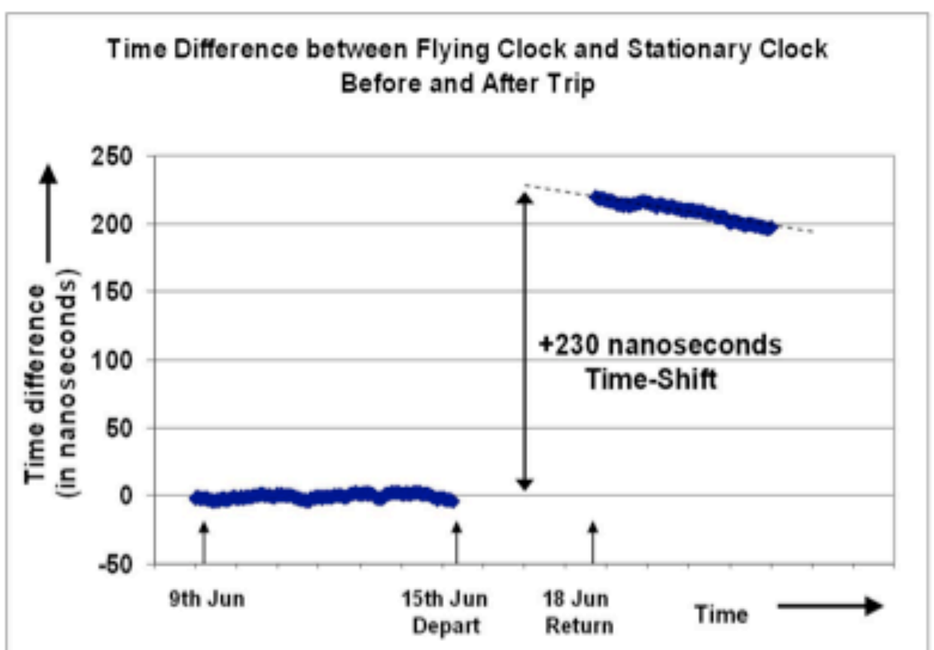
The experiment was a repeat of the famous Hafele-Keating experiment and revealed the time dilation effects predicted by Einstein's theories of Relativity.

To reveal these effects, you need two highly accurate atomic clocks, calibrated to check that they are perfectly in sync with each other - ticking down the nanoseconds (that's one billionth of a second: 0.000 000 001 seconds) in complete unison. Then, one clock is taken on a trip around the world, whilst the other one stays at NPL.

Did you know?
NPL can measure time to the accuracy of
0.000 000 000 1 seconds

NPL's Setnam Shemar with Bang Goes the Theory presenter, Dallas Campbell, and the atomic clock. This photo was taken outside NPL before Dallas and the clock set off on their round the world trip

When the two clocks are reunited, according to Einstein's theories, they should no longer be in sync - the clock that travelled around the world should be ahead of the stationary clock by a significant amount. In this case, the time-shift was predicted to be 246 ± 3 nanoseconds after taking account of the aircraft speed and height for the different flights taken in the journey. The actual measured result using the clocks was 230 ± 20 nanoseconds, which agrees (to within the measurement error) with the prediction.



The BBC1 science programme, *Bang Goes the Theory*, approached NPL in late 2009 to ask if it would be possible to use two of our atomic clocks to perform this experiment, which saw one of them fly from London - LA - Auckland - Hong Kong - London.

Dr Setnam Shemar, one of NPL's Time scientists, was pleased to oblige:

"This is a rare and exciting experiment - a full round-the-world trip like this hadn't been attempted since 1971, so we were absolutely delighted to be a part of it. It was great to have non-scientists [the BBC crew] so closely involved with the fieldwork aspect of the experiment - as they're the ones that accompanied the clock on the flights."

Einstein's theories are split into 'Special', and 'General' Relativity. Special Relativity deals with the effects caused by the relative motion of objects (e.g. the motion of the flying clock relative to the stationary clock). Whilst General Relativity deals with how gravity affects the shape of space-time (e.g. space-time curves around massive objects, like the Earth).

El GPS

El Global Positioning System (GPS) necessita correccions relativistes.

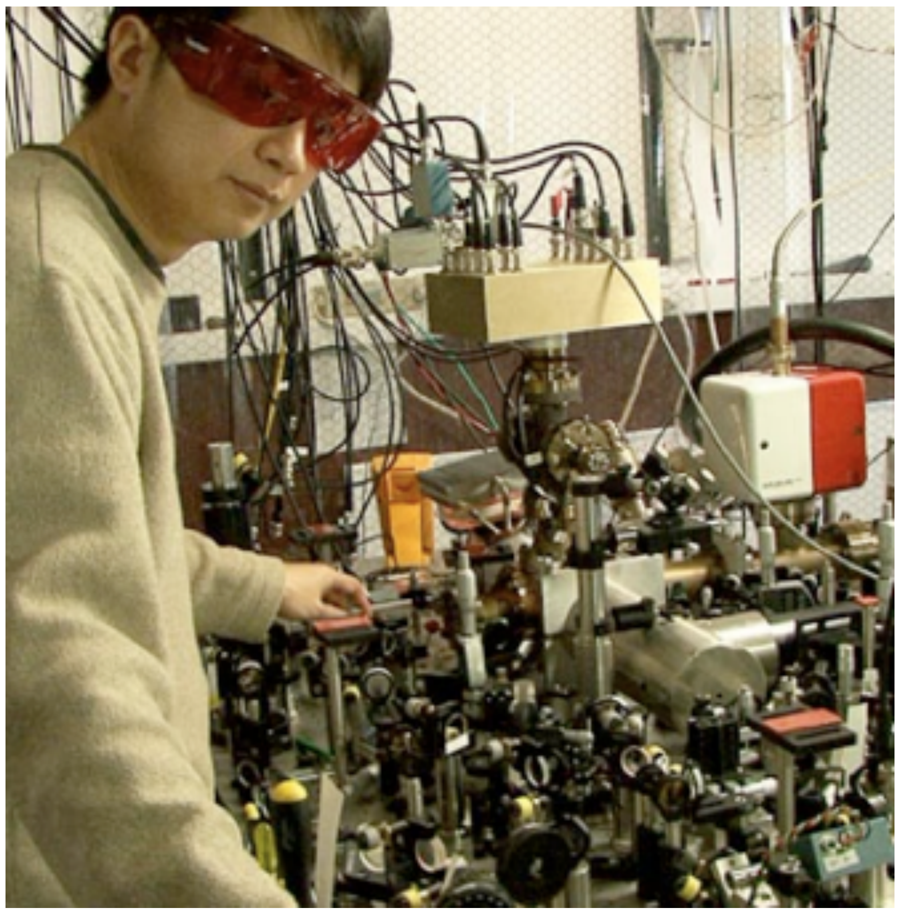
Radi de les òrbites i velocitat: R= 26 600 km i v = 3,9 km/s.

Aquestes dades permeten calcular una pèrdua (retardament) d'unes 7,2 milionèsimes de segon diaris respecte als rellotges de la Terra que cal corregir (junt amb altres efectes de Relativitat General).

$$\gamma \times (24h) \simeq 24h + 7,2\mu s$$

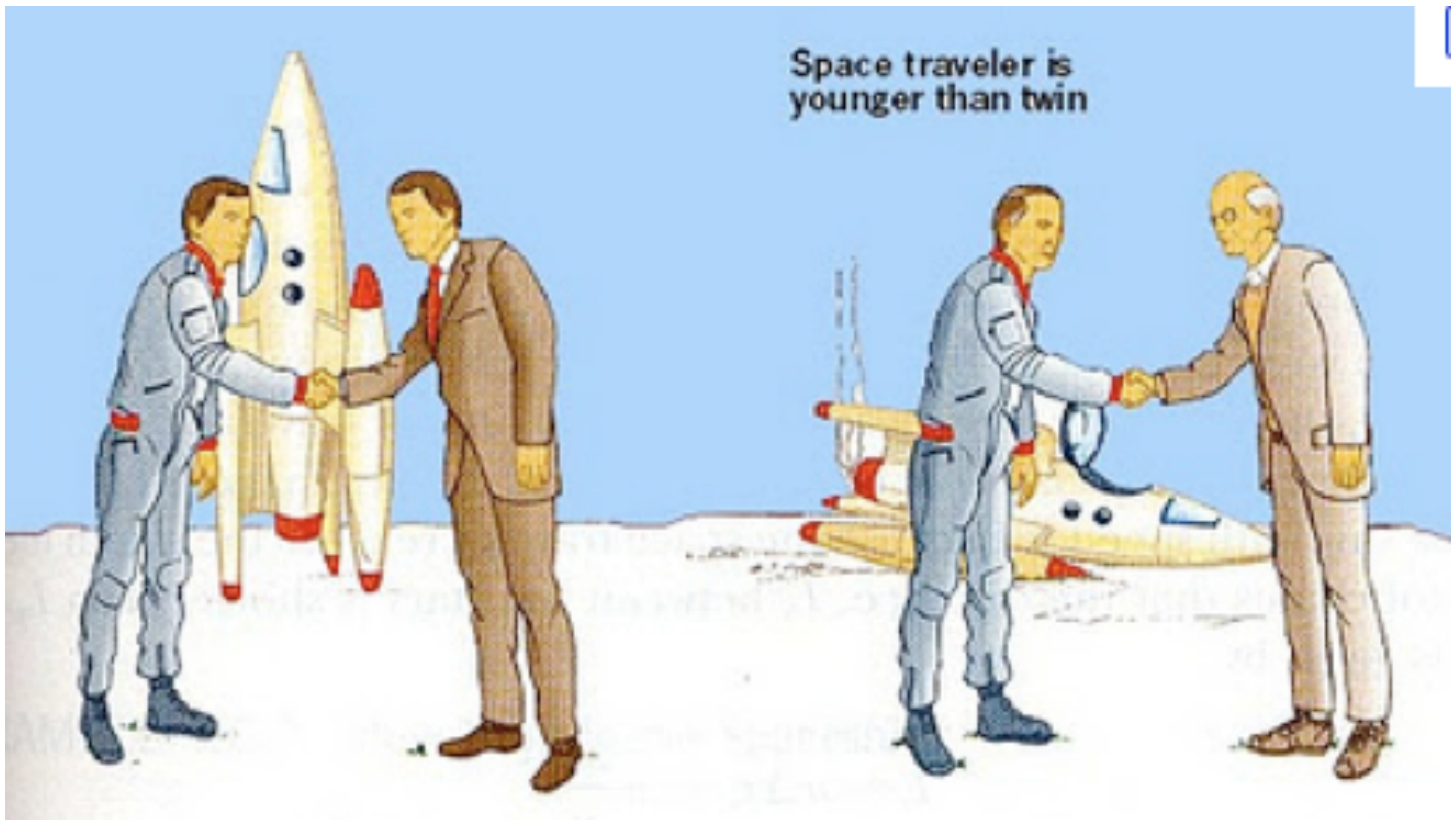
$$\gamma \equiv 1/\sqrt{1 - v^2/c^2} \simeq 1 + v^2/2c^2 \simeq 1 + 8,5 \times 10^{-11}$$

J. Chin-Wen Chou et al. (NIST), Science 329 (2010) p. 1630



Clock accuracy:
1 s in 3.8 Gy

La paradoxa dels bessons:
de la Terra a Alfa-Centauri
a 240.000 km/s

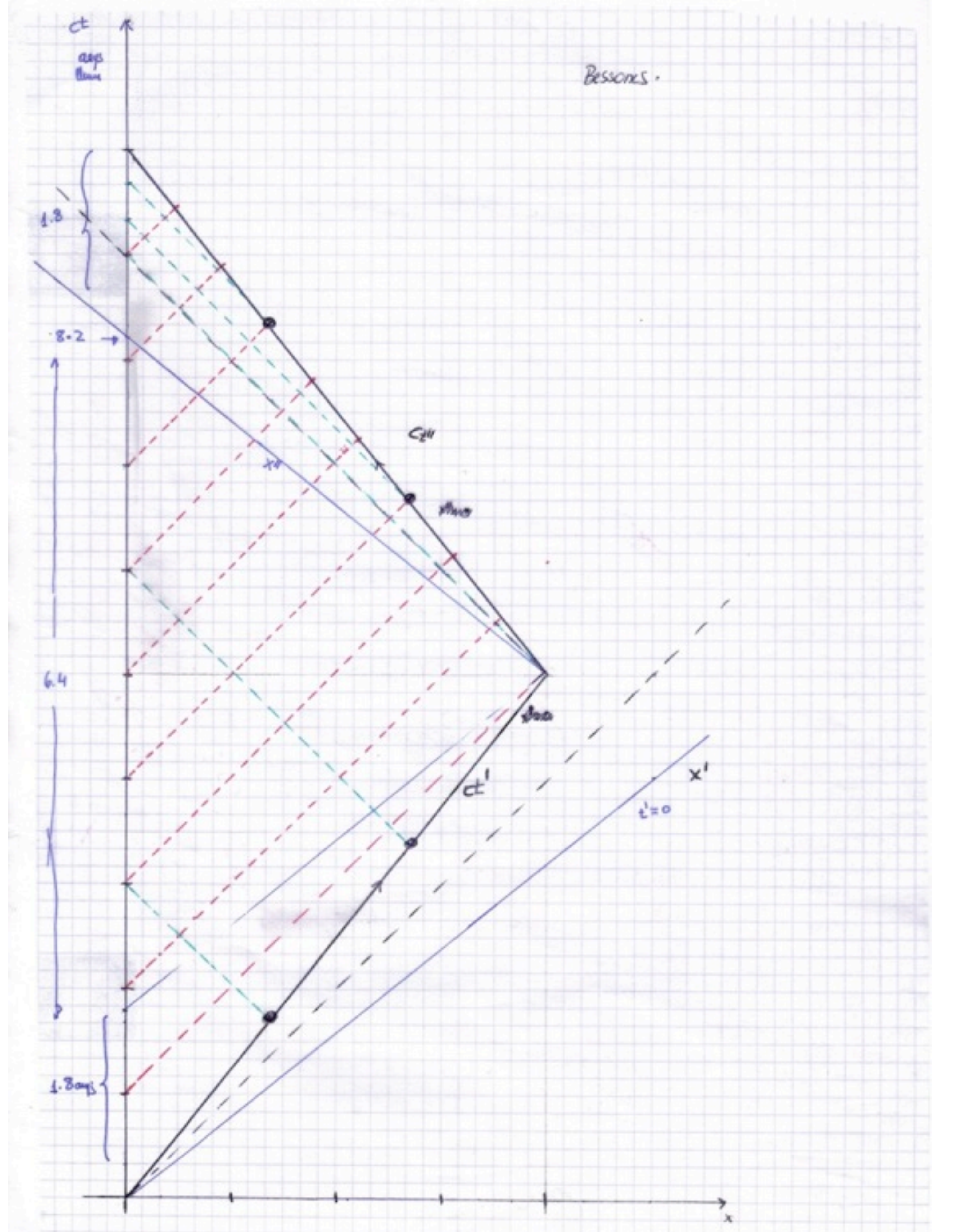


40 anys 46 i 50 anys

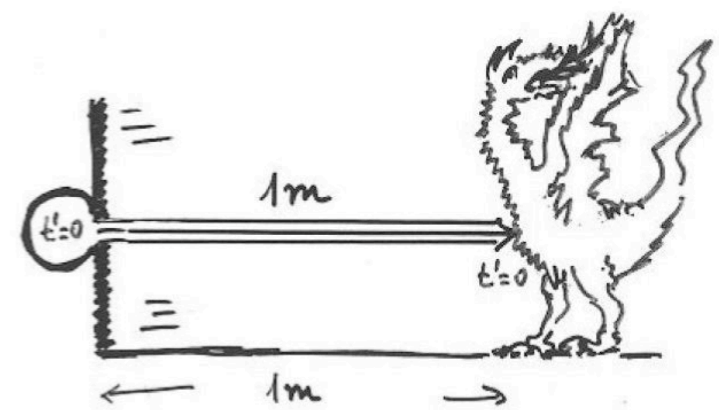
La paradoxa dels bessons en un diagrama d'espai temps.

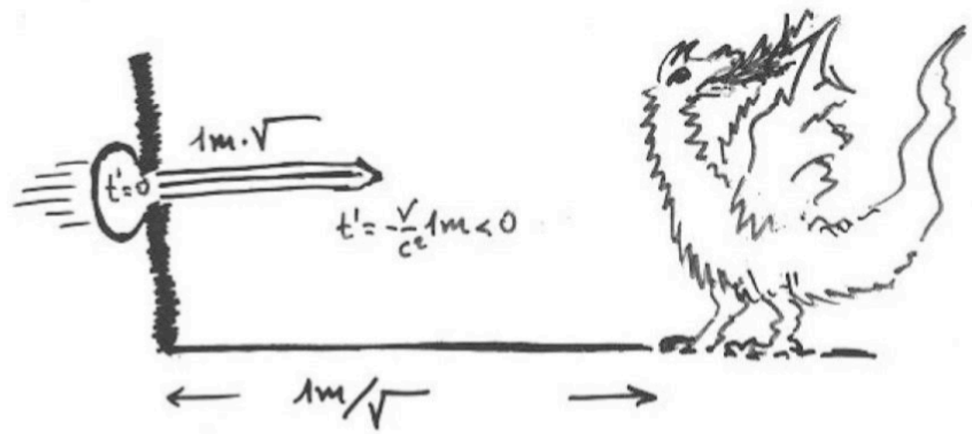
Línees negres: anada i tornada d'A,
línees vermelles: missatges de B a A,
línees verdes: missatges d'A a B.

L'efecte Doppler diu que
mentre s'allunyin (s'apropin)
el ritme de recepció de
senyals ràdio és
un terç (el triple) del d'emissió



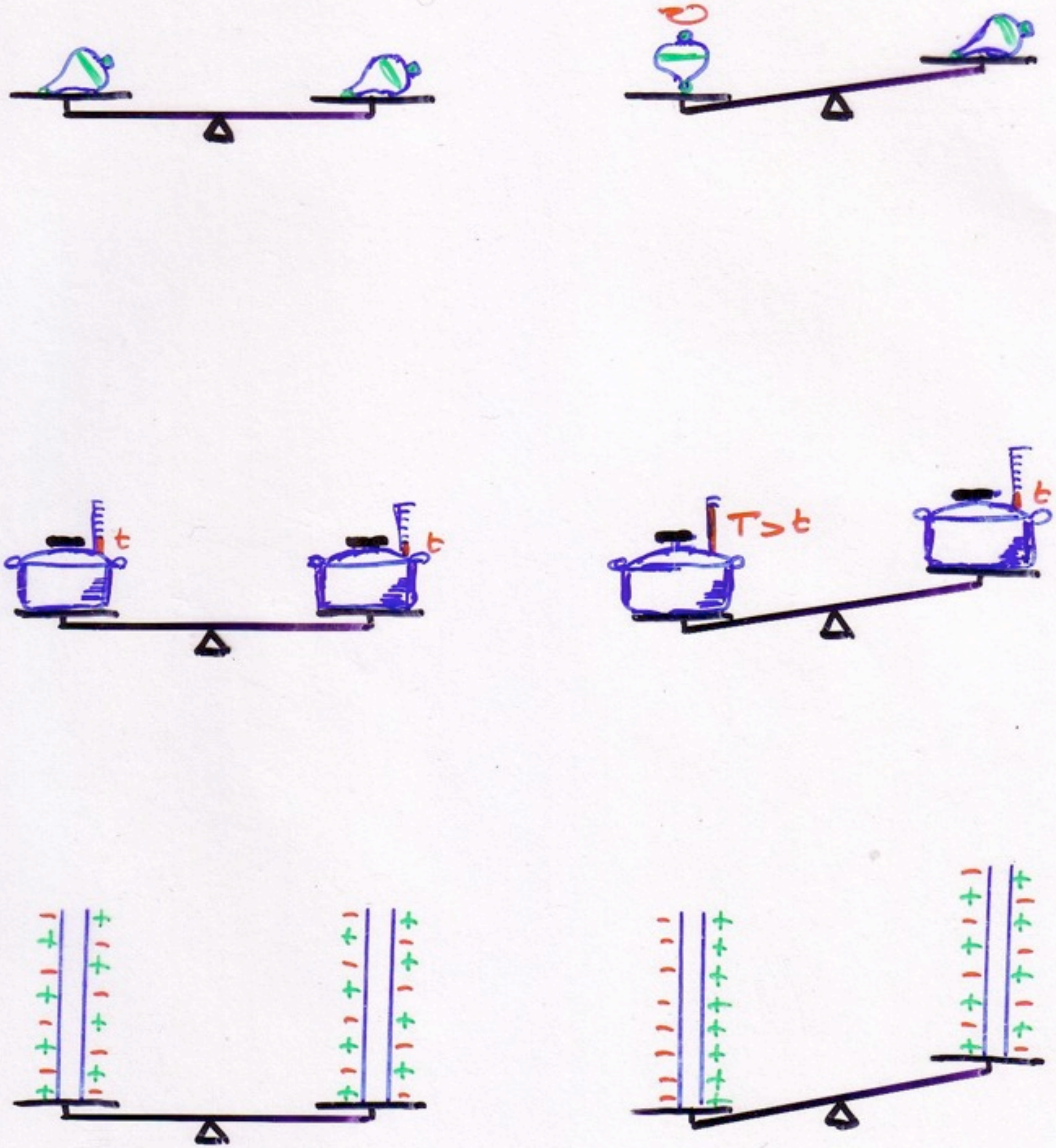
$$1m \quad vs \quad 1m/\sqrt{1-v^2/c^2} > 1m$$





$$\left.\begin{array}{l} t=0 \\ x=1m\cdot\sqrt{\;} \end{array}\right\} \; t' = \frac{t - vx/c^2}{\sqrt{\;}} = -\frac{v}{c^2}1m\frac{\sqrt{\;}}{\sqrt{\;}} \Rightarrow t' = -\frac{v}{c^2}1m.$$

$$\frac{\frac{1m}{\sqrt{\;}} - 1m\cdot\sqrt{\;}}{\frac{v}{c^2}\cdot 1m\cdot\frac{1}{\sqrt{\;}}} = \frac{1-1+v^2/c^2}{v/c^2} = v$$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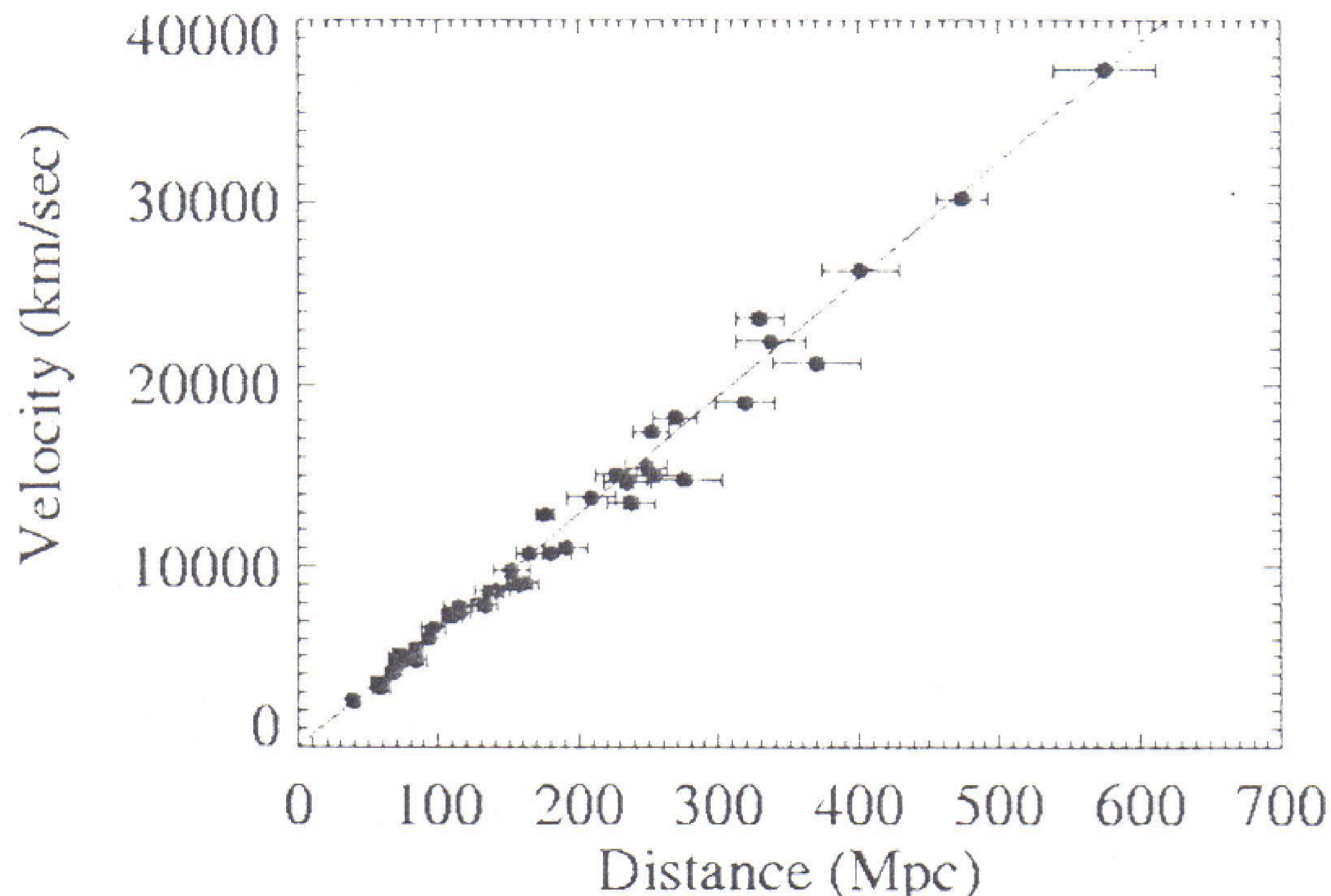
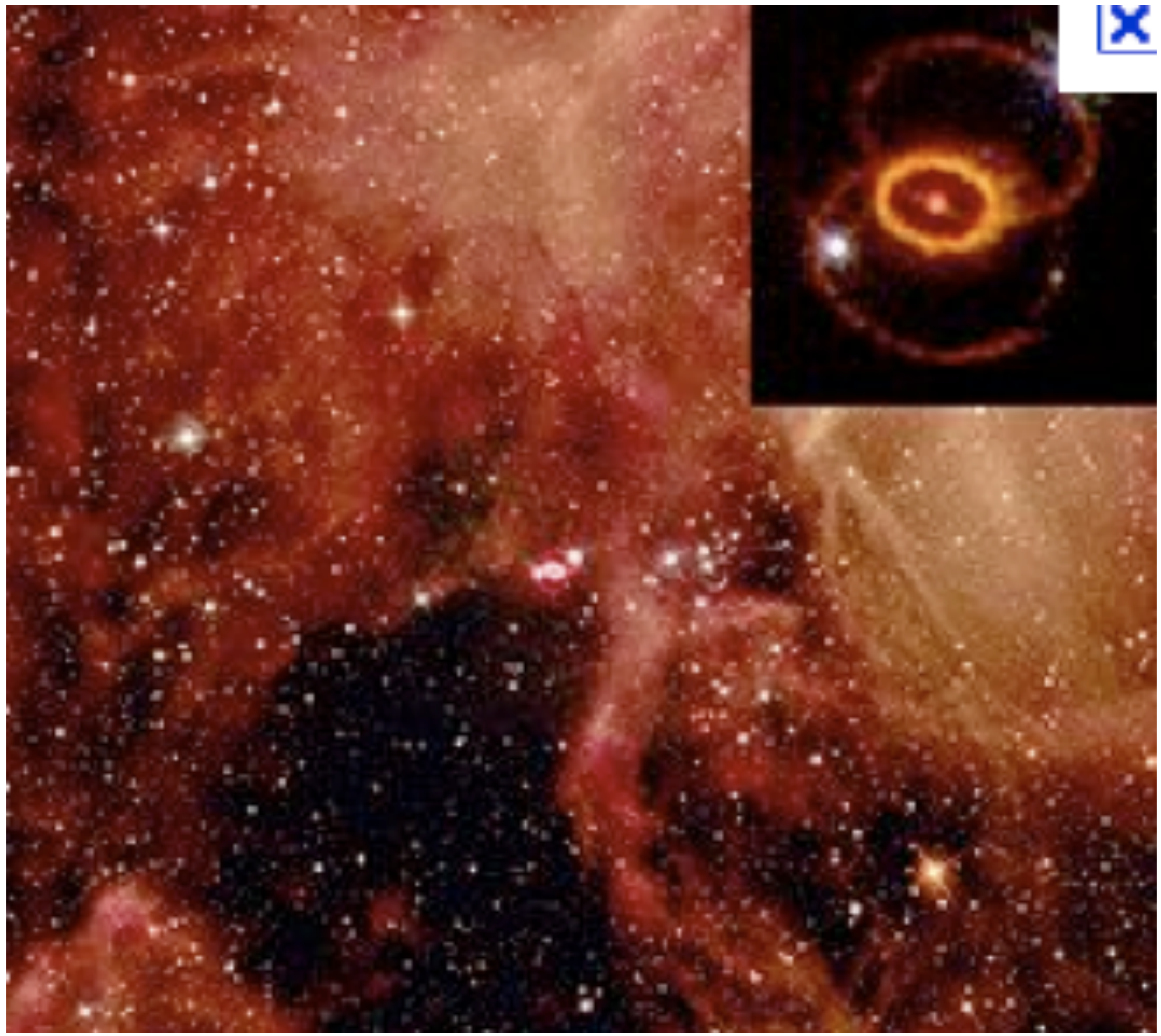


$1\,Mpc \approx 31 \times 10^{18}\,km$

Figure 15.1: The distance–redshift diagram illustrates the expansion of the Universe. This "Hubble diagram" with linear axes is derived from a sample of type Ia supernovae and $H_0 = 65 \pm 2\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ (error purely statistical; figure courtesy of Adam Riess).



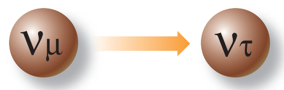
SN1987a

168 000 anys-llum

L'esperimento CNGS (Cern Neutrinos to Gran Sasso)

Obiettivo

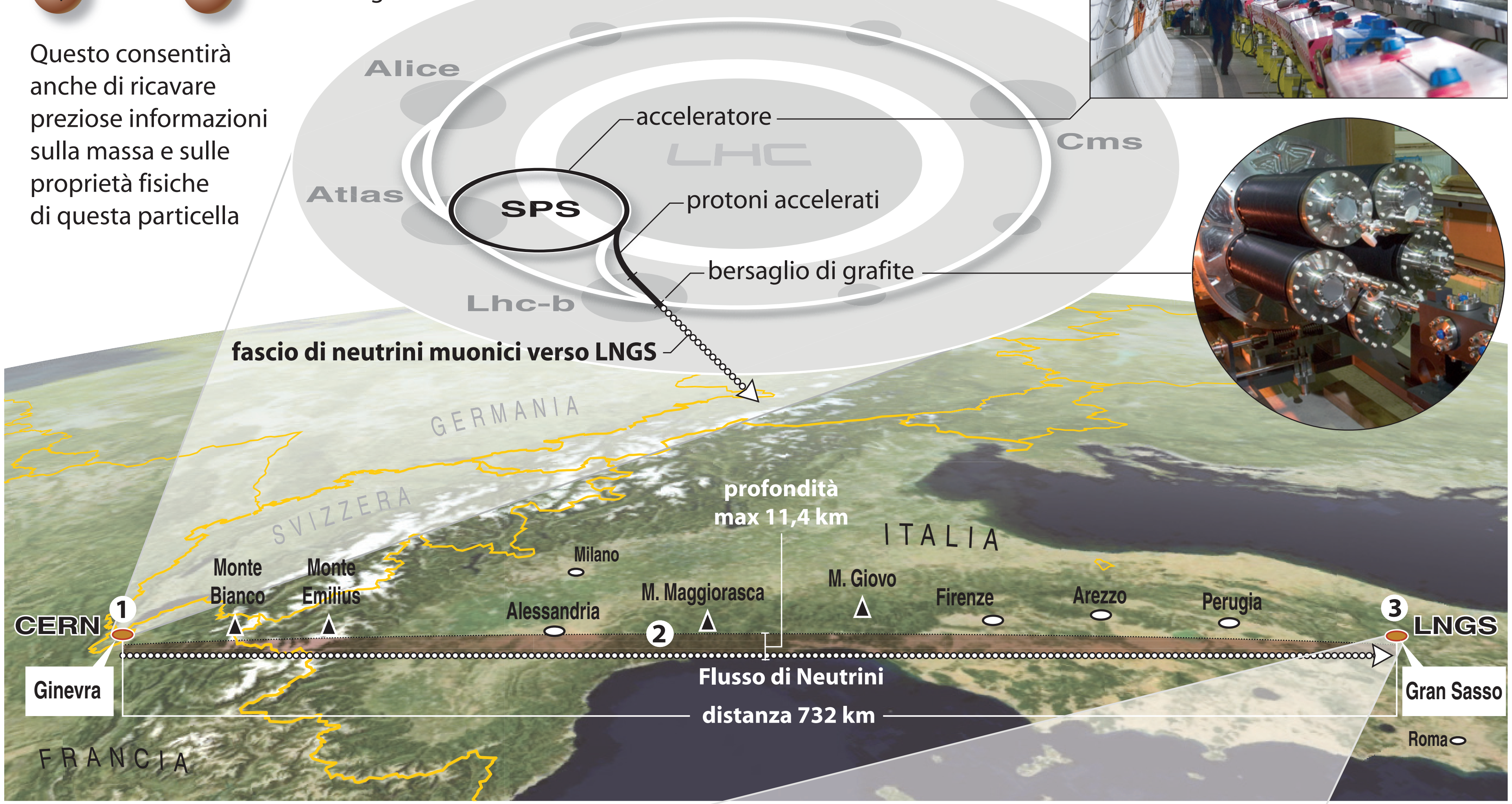
Osservare per la prima volta in modo diretto l'**oscillazione del neutrino.**



Questo consentirà anche di ricavare preziose informazioni sulla massa e sulle proprietà fisiche di questa particella

Come funziona

1 Al **CERN** di Ginevra, un fascio di neutrini muonici puntato verso i Laboratori Nazionali del Gran Sasso (LNGS) dell'Istituto Nazionale di Fisica Nucleare (INFN) viene prodotto facendo scontrare dei protoni accelerati contro un bersaglio di grafite



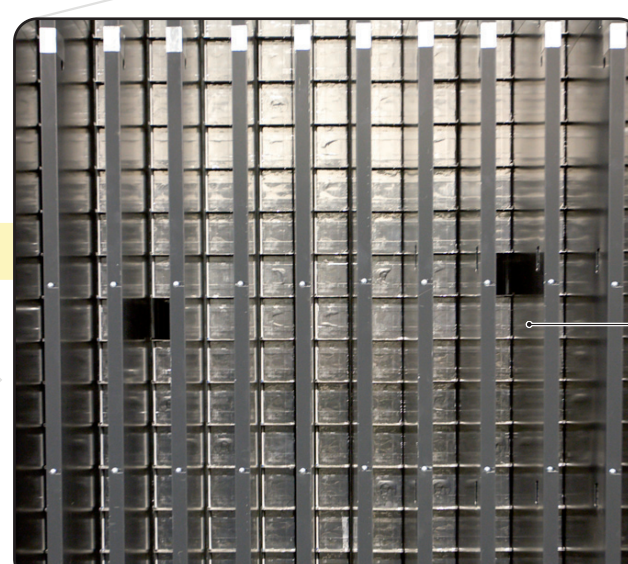
2 I neutrini attraversano la crosta terrestre per **732 km** e, viaggiando quasi alla **velocità della luce** giungono a destinazione dopo **2,4 millisecondi**

INFN Istituto Nazionale di Fisica Nucleare

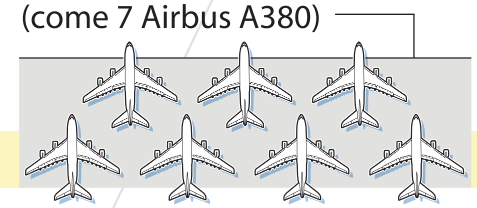
OPERA

3 Ad attenderli ai **LNGS** c'è **OPERA** che fotografa i prodotti della loro interazione con i nuclei del piombo di cui è composto il rivelatore.

- OPERA ha fotografato all'arrivo una particella tau: prova che un **neutrino muonico si è trasformato in neutrino del tau** nel tragitto dal CERN ai LNGS



OPERA volume totale: **2.000 m³**
peso totale: **4.000 tonnellate**
(come 7 Airbus A380)



- Il rivelatore principale è costituito da **150.000 mattoncini.** Ogni mattoncino pesa **8,3 kg** ed è costituito da **56 lastre di piombo** alternate a emulsioni fotografiche ultrasensibili.

Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

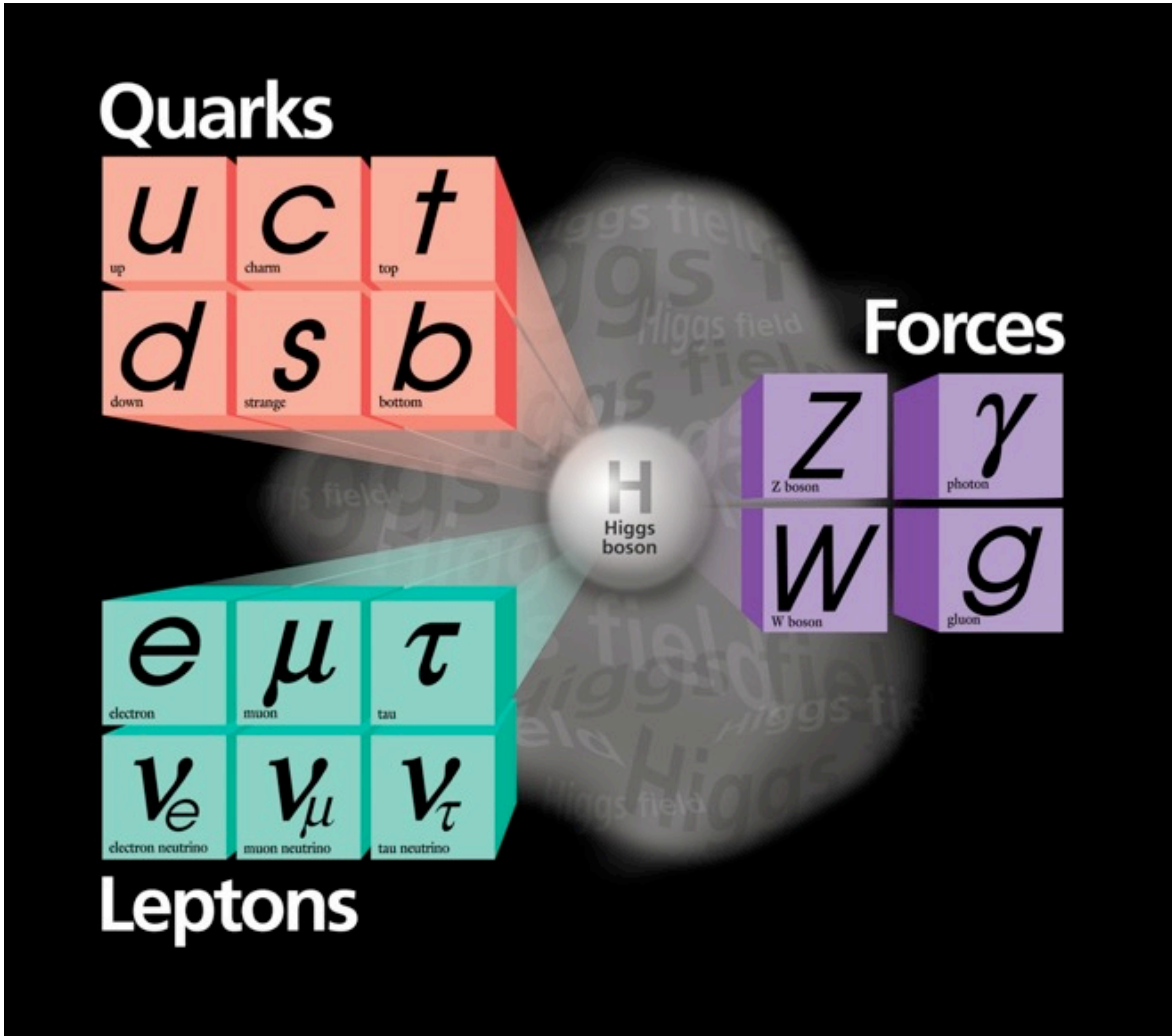
Abstract

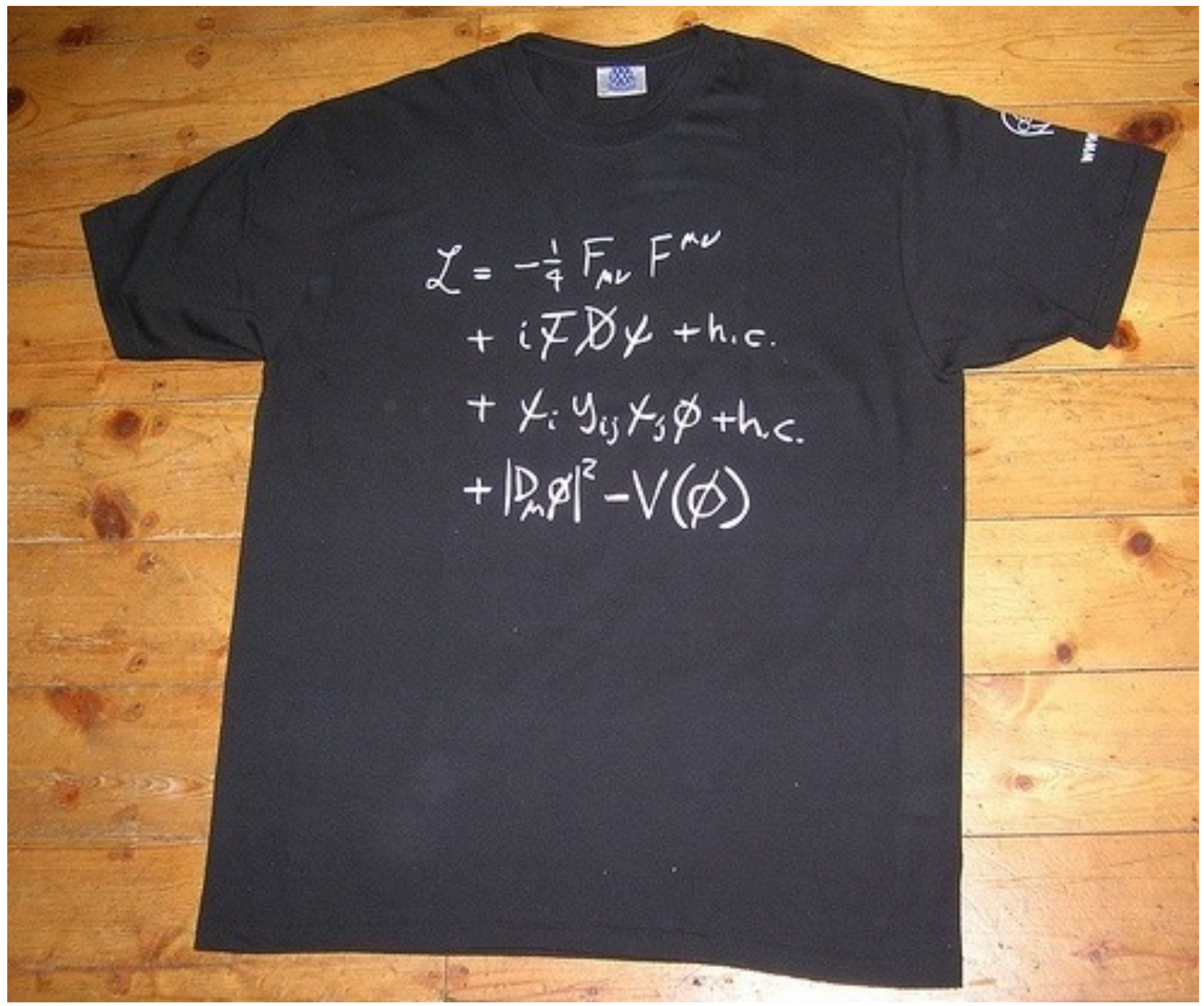
The OPERA neutrino experiment at the underground Gran Sasso Laboratory has measured the velocity of neutrinos from the CERN CNGS beam over a baseline of about 730 km with much higher accuracy than previous studies conducted with accelerator neutrinos. The measurement is based on high-statistics data taken by OPERA in the years 2009, 2010 and 2011. Dedicated upgrades of the CNGS timing system and of the OPERA detector, as well as a high precision geodesy campaign for the measurement of the neutrino baseline, allowed reaching comparable systematic and statistical accuracies. An early arrival time of CNGS muon neutrinos with respect to the one computed assuming the speed of light in vacuum of (60.7 ± 6.9 (stat.) ± 7.4 (sys.)) ns was measured. This anomaly corresponds to a relative difference of the muon neutrino velocity with respect to the speed of light $(v-c)/c = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}$.

$$730\,534,61 \pm 0,20 \text{ m}$$

$$v = \left(1 + (2,48 \pm 0,42) \times 10^{-5}\right) c$$

Model stàndard de partícules elementals




$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

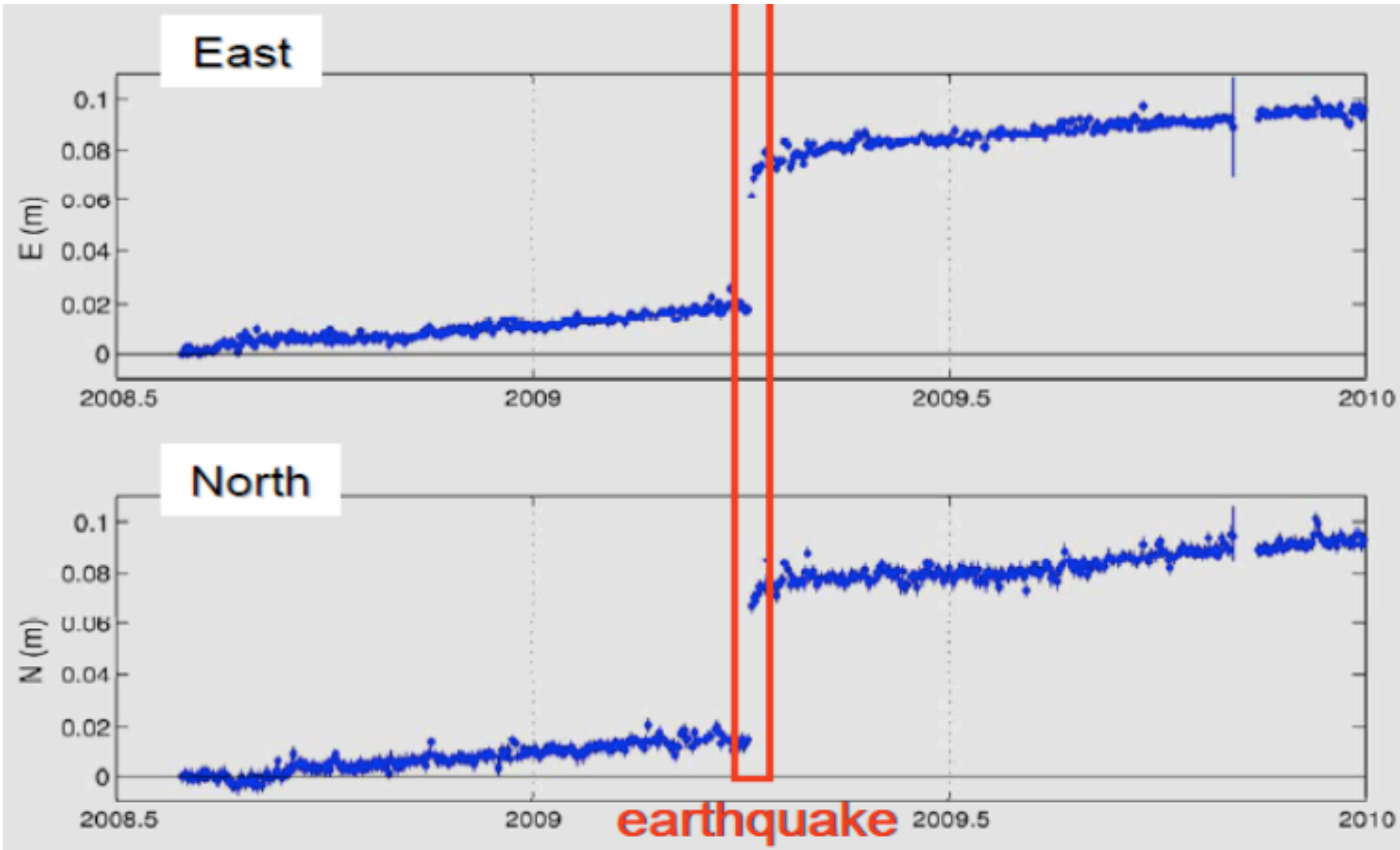


Fig. 7: Monitoring of the PolaRx2e GPS antenna position at LNGS, showing the slow earth crust drift and the fault displacement due to the 2009 earthquake in the L'Aquila region. Units for the horizontal (vertical) axis are years (meters).

Disharmony at OPERA?

The claim by a team of researchers in Italy that neutrinos can travel faster than the speed of light will require extra checks before being submitted to a peer-reviewed journal. That is the position of a number of researchers in the OPERA collaboration, which announced on 23 September that it had observed superluminal neutrinos travelling from the CERN particle-physics lab near Geneva to the Gran Sasso underground lab in central Italy.

The announcement made headlines around the world, since it appears to contradict Einstein's special theory of relativity. However, not everyone within OPERA was happy to release the results publicly, with several of the 30 group leaders within the 160-strong collaboration being opposed to the release of a paper on the *arXiv* preprint server and the accompanying seminars and press release without further tests of possible systematic errors being carried out. Now, a larger fraction of the group leaders is concerned about the paper being submitted to a research journal. One member of OPERA, who does not wish to be named, says there is a "lot of tension" within the collaboration and that up to half of the members are opposed to an immediate submission.