Physics 801: Instrumentations and Methods in Astroparticle Physics

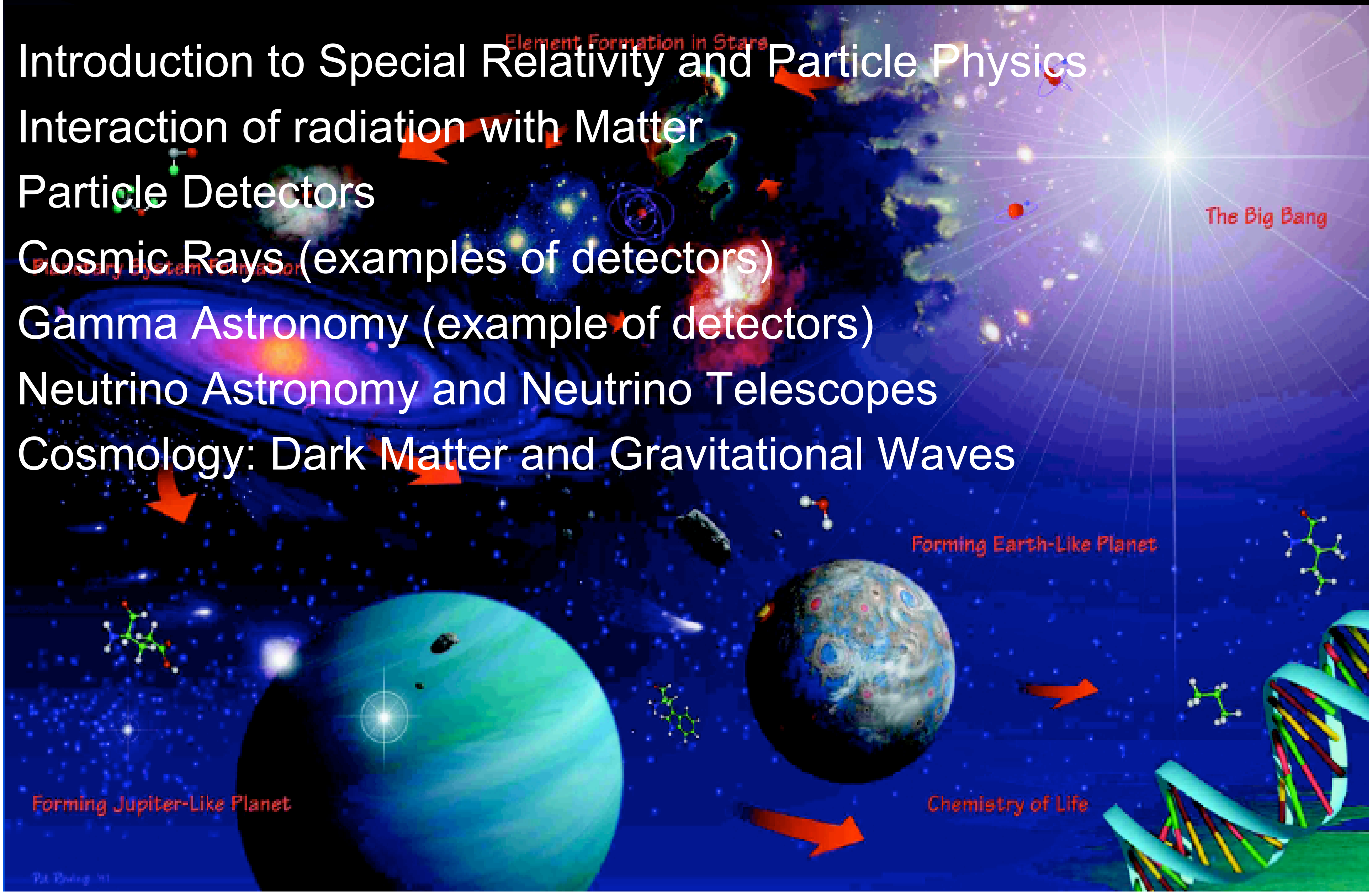
Prof. Teresa Montaruli
Chamberlin Hall, Room 4112
tmontaruli@icecube.wisc.edu
http://www.icecube.wisc.edu/~tmontaruli

Lectures: Tue-Thu 11:00-12:15

Office Hours: send me an email to fix a time or after lectures

Course Contents

Introduction to Special Relativity and Particle Physics
Interaction of radiation with Matter
Particle Detectors
Cosmic Rays (examples of detectors)
Gamma Astronomy (example of detectors)
Neutrino Astronomy and Neutrino Telescopes
Cosmology: Dark Matter and Gravitational Waves



Why Astroparticle?

Astroparticle: cross-disciplinary area (astrophysics, high energy particle physics, plasma physics) . Meeting point between

Physicists: extended understanding of matter down to quark level that compose neutrons and protons and leptons (electrons, muons, taus and their neutrinos partners) and described how forces shape matter

Astronomers: observed

- Expansion of the Universe
- Cosmic Microwave Background Radiation: the echo of the big bang that provides a snapshot of the universe when it was 1/2 million yrs old
- measured the relative abundance of light elements in the Universe (H, Li, ^{2}H, He) produced in nuclear reactions in the first seconds of the universe life in the quantity predicted by the Big Bang
- globular clusters and some radioactive isotopes do not seem to exceed an age 13-14 billion of yrs from now

Open questions

All questions address to the understanding of the Universe.

Existing models describe its evolution down to 10^{-43} seconds

Physicists are building the largest collider LHC at CERN (10^{11} particles/bunch, 600 million collisions/s at 7 TeV in CM, 10 times more powerful than Tevatron and LEP) which will bring protons/ions in head on collisions reproducing the conditions of the early universe 10^{-11} s after the Big Bang. They will discover new particles, possibly composing the **dark matter and complete the understanding of building blocks of matter**. Other fundamental questions: **neutrino mass and Majorana/Dirac**. Still one familiar interaction, **gravitation, that is not formulated as a relativistic quantum field theory**

Astronomers have found that the Universe is speeding up in its expansion after the Big Bang due to the **mysterious Dark Energy**. What is it? Why there is **much less antimatter than matter**? What is the **Dark matter**?

You are lucky! Will see the re-birth of Physics

The building blocks of Matter and interacting Forces

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electri charg
g gluon	0	0

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Notions of Special Relativity

Inertial frames: a body not subject to any force remains at rest or in steady rectilinear motion

Two postulates:

1) **The laws of physics have the same form in any inertial frame**
2) **The velocity of light in vacuum c = 2.99793 × 10^8 m/s has the same value in all inertial frames**

Space-time coordinates: $x^\mu = (ct,x,y,z) = (ct,\mathbf{r})$ (4-vectors)

From 2) if we consider the same light ray in the 2 ref systems K and K' and look at the time difference Δt, Δt' of its passage through the distance |Δ**r**|, |Δ**r**'|, the velocity of light must be the same

$$c = \frac{|\Delta\mathbf{r}|}{\Delta t} = \frac{|\Delta\mathbf{r}'|}{\Delta t'}$$

Hence the combination (the line element)

$$\Delta s^2 = c^2\Delta t^2 - |\Delta\mathbf{r}|^2 = c^2\Delta t^2 - \Delta x^2 - \Delta y^2 - \Delta z^2$$

is invariant in 2 different reference frames

In analogy to rotations that leave invariant the length of a vector **x**, namely also its square $x^2+y^2+z^2$, the quantity $s^2 = c^2t^2 - x^2 - y^2 - z^2$ is an invariant.

This suggests that x,y,z,t can form a 4 vector in this 4-dimensional space that transforms according to Lorentz transformations with

$x_0 = ct$, $x_1 = x$, $x_2 = y$, $x_3 = z$

Casual structure of space-time

$$\Delta s^2 = c^2\Delta t^2 - |\Delta \mathbf{r}|^2 = c^2\Delta t^2 - \Delta x^2 - \Delta y^2 - \Delta z^2$$

For a light ray: **$\Delta s^2 = 0$ light-like separation**

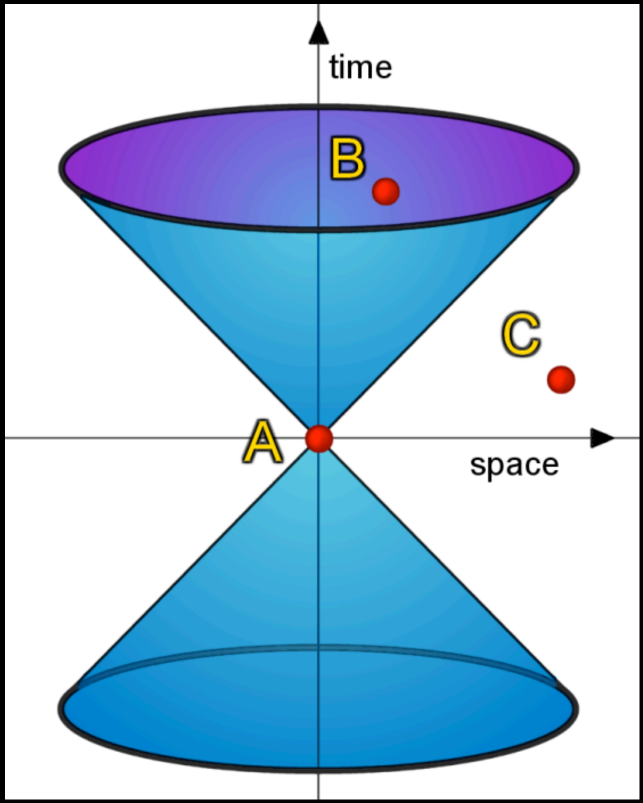
A system in which 2 events happen at the same time ($\Delta t=0$) can be found only if **$\Delta s^2<0$ space-like separation**

A system in which 2 events happen at the same place can be found only if **$\Delta s^2>0$ time-like separation**

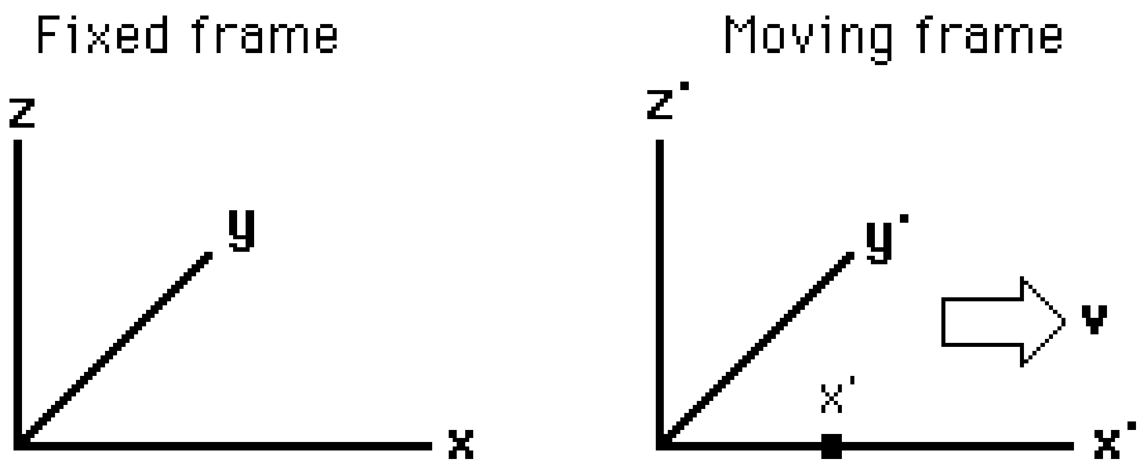
The light cone respect to an event A in the origin of an inertial ref frame at time t=0 is defined by $\Delta s^2 = 0$ (Δs is the distance respect to another event)

Points in the light cone (B) have $\Delta s^2 > 0$ and are casually connected to the observer since $c\Delta t>|\Delta \mathbf{r}|$ so that they can be connected by signals traveling at speed <c

Events outside (C) the light cone $\Delta s^2<0$ are casually disconnected and $c\Delta t<|\Delta r|$



Galilean transformations



Galilean Transformation

$$x' = x - vt$$
$$y' = y$$
$$z' = z$$
$$t' = t$$

The primed frame moves with velocity v in the x direction with respect to the fixed reference frame.

The reference frames coincide at $t=t'=0$.

The point x' is moving with the primed frame.

The Galilean transformation gives the coordinates of the point as measured from the fixed frame in terms of its location in the moving reference frame.

The Galilean transformation is the common sense relationship which agrees with our everyday experience.

Lorentz transformations

Transformations between reference systems: K' moves at velocity v = const respect to K. Due to its invariance:

$$\Delta s^2 = -(\Delta x^2 + \Delta y^2 + \Delta z^2 - c^2\Delta t^2) = -(\Delta x'^2 + \Delta y'^2 + \Delta z'^2 - c^2\Delta t'^2)$$

$$\Delta s^2 = -(\Delta x^2 + \Delta y^2 + \Delta z^2 + \Delta \tau^2) = -(\Delta x'^2 + \Delta y'^2 + \Delta z'^2 + \Delta \tau'^2)$$ with $\tau = ict$ with $i^2 = -1$

Transformations leaving Δs^2 invariant are rotations (let's consider the rotation in $x\tau$ plane – y,z stay constant). The transformation must be of the form

$$\begin{cases} x = x'\cos\alpha - \tau'\sin\alpha \\ \tau = x'\sin\alpha + \tau'\cos\alpha \end{cases}$$

To determine α: we are in K and observe the origin of K' (x'=0) moving at velocity v along x (x = vt)

$$\begin{cases} x = -\tau'\sin\alpha \\ \tau = \tau'\cos\alpha \end{cases} \Rightarrow \frac{x}{\tau} = \frac{v}{ic} = -\tan\alpha \equiv -i\beta \Rightarrow \beta = \frac{v}{c}$$

$$\cos\alpha = \frac{1}{\sqrt{1+\tan^2\alpha}} = \frac{1}{\sqrt{1-\beta^2}} \equiv \gamma$$

$$\sin\alpha = \frac{\tan\alpha}{\sqrt{1+\tan^2\alpha}} = \frac{i\beta}{\sqrt{1-\beta^2}} \equiv i\beta\gamma$$

Lorentz transformations

$$\begin{cases} x = x'\gamma - i\beta\gamma(ict') = \gamma(x' + \beta ct') \\ ict = x'i\beta\gamma + ict'\gamma \Rightarrow ct = \gamma(ct' + x'\beta) \end{cases}$$

$$\begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \gamma & \beta\gamma & 0 & 0 \\ \beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} ct' \\ x' \\ y' \\ z' \end{pmatrix}$$

Lorentz transformations

$$\begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \gamma & \beta\gamma & 0 & 0 \\ \beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} ct' \\ x' \\ y' \\ z' \end{pmatrix}$$

The primed frame moves with velocity v in the x direction with respect to the fixed reference frame. The reference frames coincide at t=t'=0. The point x' is moving with the primed frame.

$$t' = \gamma t - \gamma \frac{vx}{c^2}$$

$$x' = \gamma x - \gamma v t$$

$$x' = \frac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$y' = y$$

$$z' = z$$

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

$$x = \frac{x' + vt'}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad t = \frac{t' + \frac{vx'}{c^2}}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\beta = \frac{v}{c}$$

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

Lorentz contraction: given a rod of a length Δx in the frame at rest its length in the moving frame Δx' looks contracted

Similarly, time dilation: in the equation for t', t is multiplied by γ in the comoving frame: this is interpreted as time proceeding slower when an object is moving relative to another frame of reference (the twin paradox: 1 of 2 twin brothers undertakes a long space journey with a high speed rocket at almost the spped of light while the other stays on Earth. When the traveler returns to hearth he is younger than the twin who stayed. A Einstein 1911)

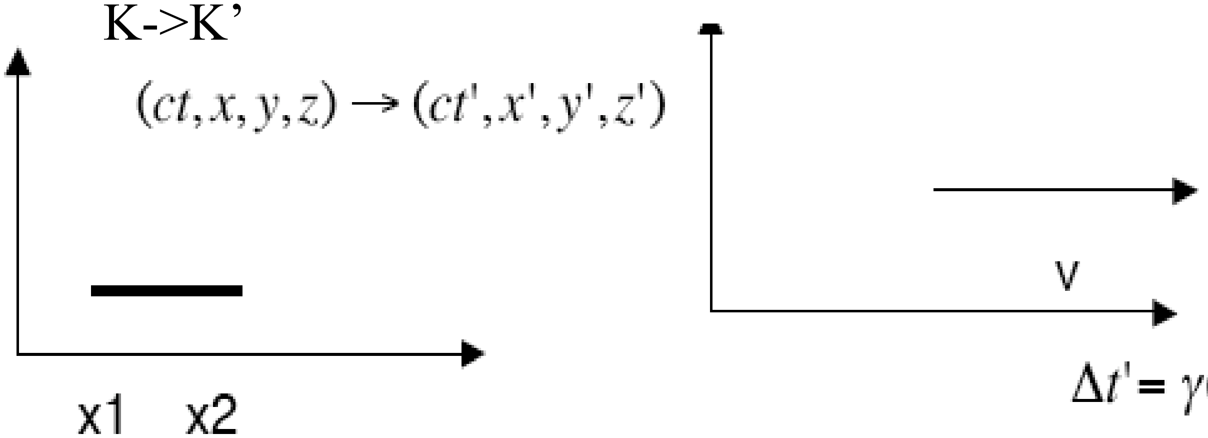
Length Contraction

$$t' = \gamma t - \gamma \frac{vx}{c^2}$$
$$x' = \gamma x - \gamma vt$$

Let us measure the length of the rod Δx' in the moving frame K':

K->K'

$$(ct, x, y, z) \rightarrow (ct', x', y', z')$$



$$\Delta t' = \gamma(t_2 - t_1) - \gamma\beta(x_2 - x_1)/c$$
$$\Delta x' = \gamma(x_2 - x_1) - \gamma\beta c(t_2 - t_1)$$

The simultaneous observation takes place in S' where Δt' = 0. We can eliminate Δt from

$$\Delta t' = 0 = \gamma\Delta t - \gamma\beta\Delta x / c \Rightarrow \Delta t = \beta\Delta x / c$$

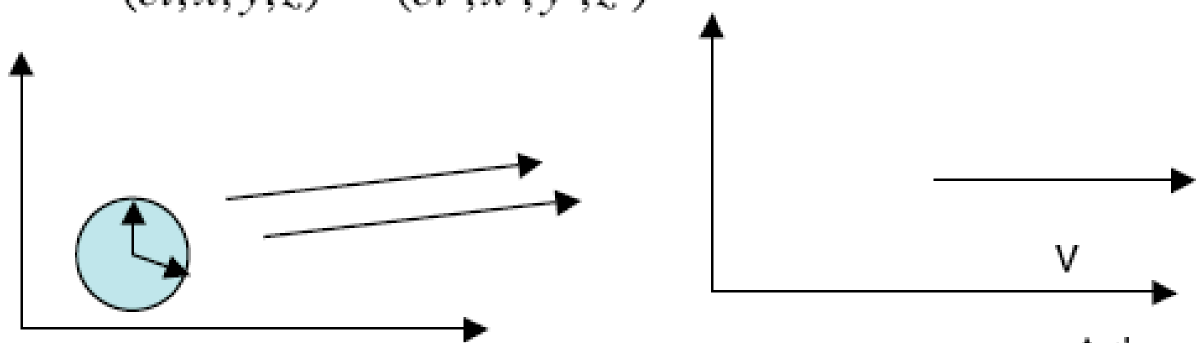
$$\Delta x' = \gamma\Delta x - \gamma\beta c\Delta t = \gamma\Delta x - \gamma\beta^2\Delta x = \gamma(1-\beta^2)\Delta x = \frac{\gamma}{\gamma^2}\Delta x$$

Δx'=Δx/γ

γ>1 length contraction

Time dilation

$$(ct, x, y, z) \rightarrow (ct', x', y', z')$$



x1=x2, T=t2-t1

$$\Delta t' = \gamma(t_2 - t_1) - \gamma\beta(x_2 - x_1)/c$$

$$\Delta x' = \gamma(x_2 - x_1) - \gamma\beta c(t_2 - t_1)$$

The observation takes place in S'. The timing signals are sent from the clock at rest in S: $\Delta x=0$. (Note that $\Delta x' \neq 0$!)

The result is:

$$\Delta t' = \gamma \Delta t$$

The time dilatation is the same in either direction. if we measure a clock in S, which is moving with S' we see a dilatation, too.