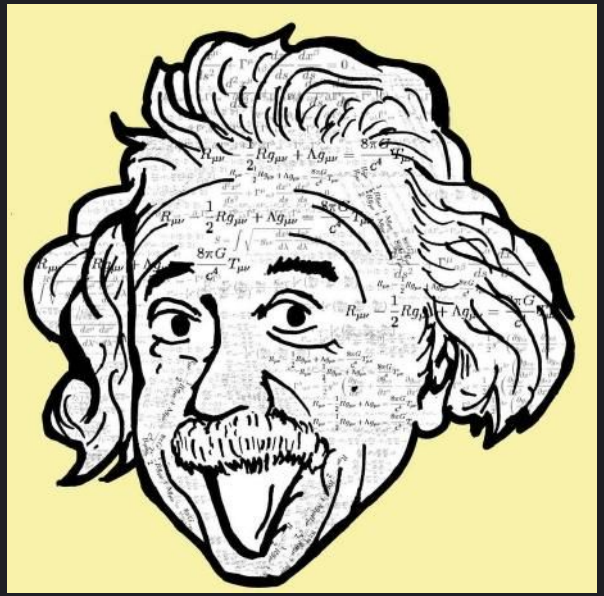
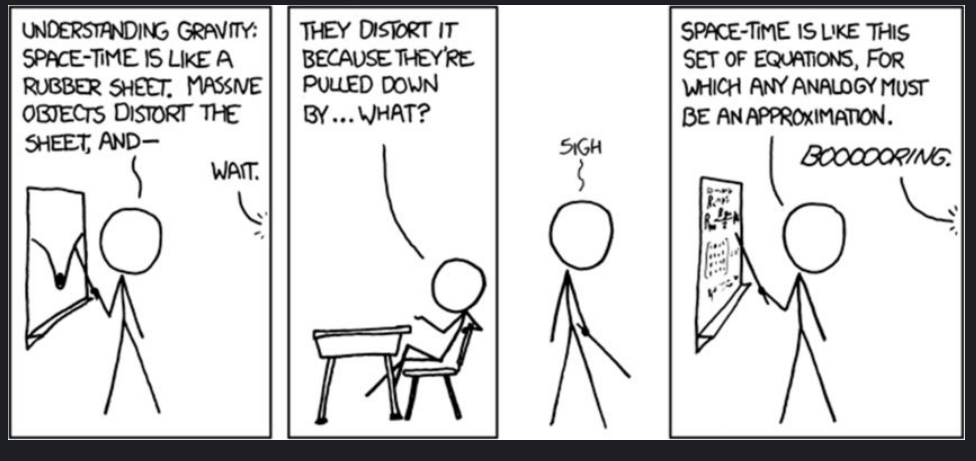
Module 3.1

Relativity and Cosmology

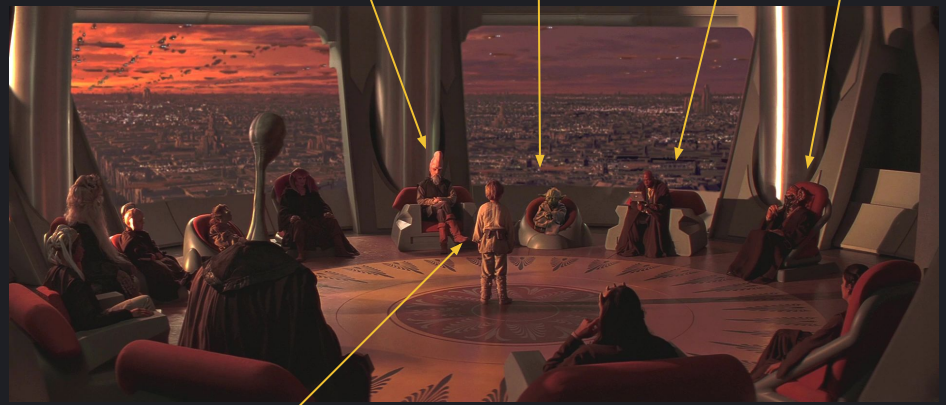
Horizon|CFI Summer School 2021





Goals for this module

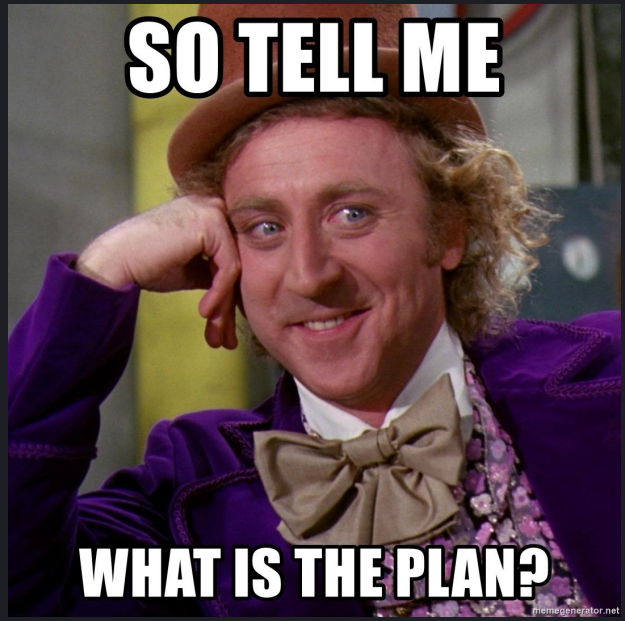
- A “brief” overview of the theory of **Special Relativity** and **General Relativity**.
- Also introduce to the field of **Cosmology**.



The council of Relativity

Module Plan

- 20th July - Part I (Special Relativity)
- 21st July - Part II (GR & Cosmology)
- 22nd July - Tutorial
- Tutorial sessions are optional but highly recommended.
- We will help you with the assignments. You can submit them on 23rd July (after Tutorial)



Special Relativity

Revising Newtonian Ideas 01.

Galilean Relativity, Postulates of Special Relativity

Historical Development 02.

Maxwell equations,

Postulates and Lorentz transformation 03.

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Consequences of Relativity 04.

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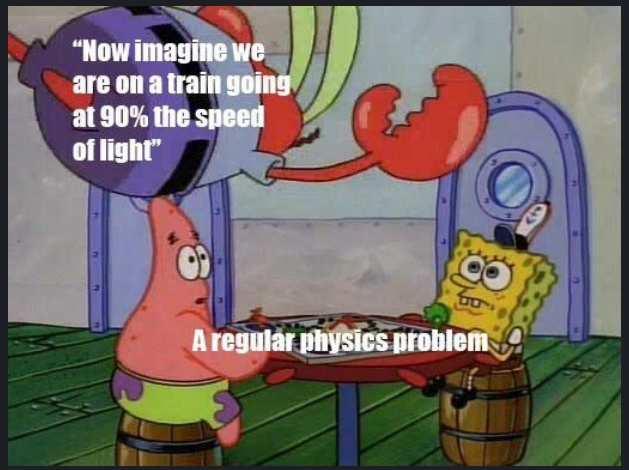

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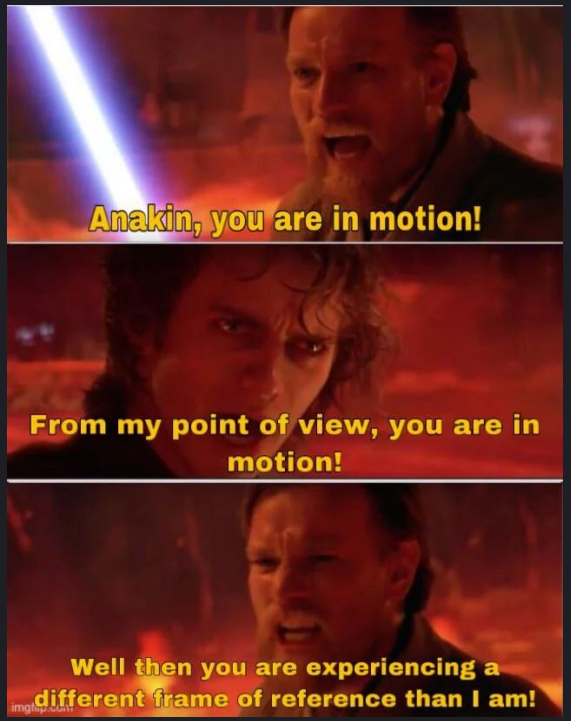

01.
Revising Newtonian ideas

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Reviewing Newtonian and Galilean ideas

- Newtonian mechanics assumes a particular idea of time called Absolute time and geometry of space
- According to Newton’s first law, particles move on a straight line
- Okay...But what geometry is this “Straight line” and what idea of time is given for “constant speed”
- Euclidean Geometry

$$ds^2 = dx^2 + dy^2 + dz^2$$

Black Board

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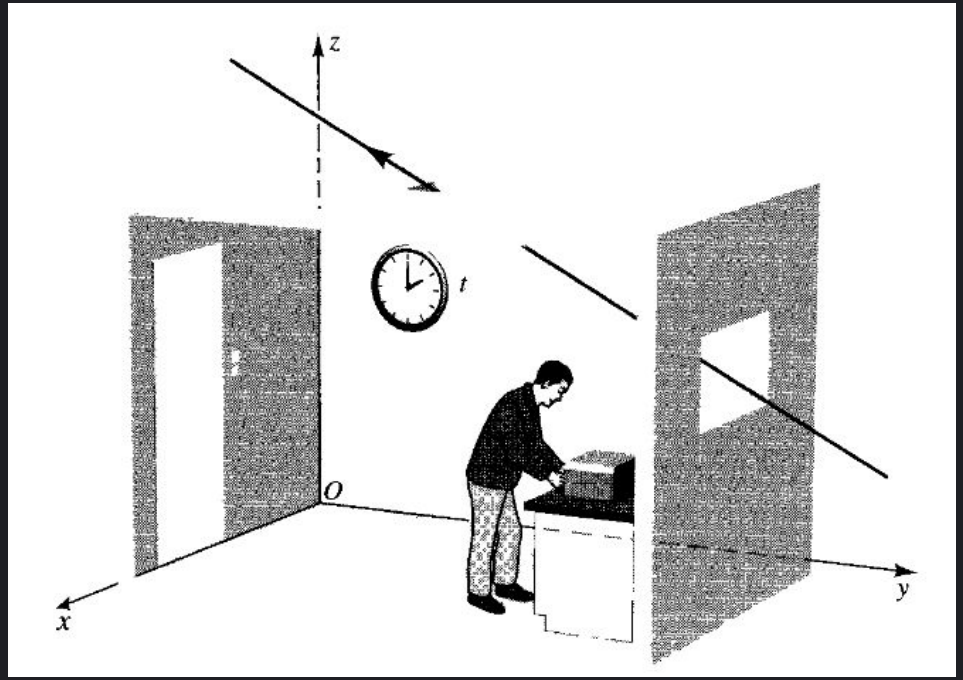
Frame of reference

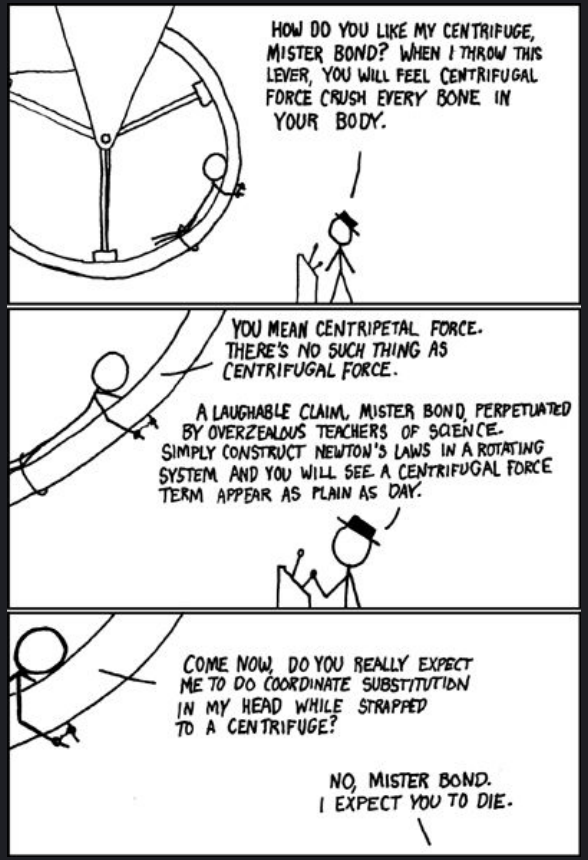
- Describe a frame of reference with cartesian coordinates (x,y,z) and a clock to measure the time
- Newton's laws take the simplest frames in **Inertial frames**

$$\frac{d^2x}{dt^2} = 0$$
$$\frac{d^2y}{dt^2} = 0$$
$$\frac{d^2z}{dt^2} = 0$$



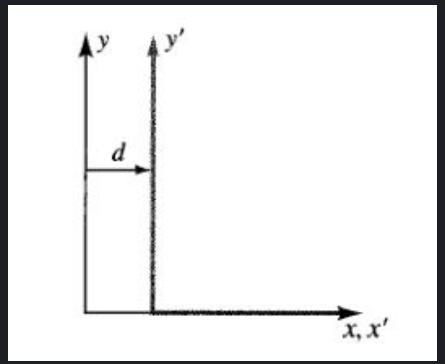
Inertial and Non-Inertial Frames

- Inertial frames could be defined as reference frames for which **Newton's equations hold**
- **Not every coordinate system is an inertial frame!**
- Even our Earth is not a perfect inertial frame!
- Equations of motion will include **Centrifugal and Coriolis** terms that results from Earth's rotation

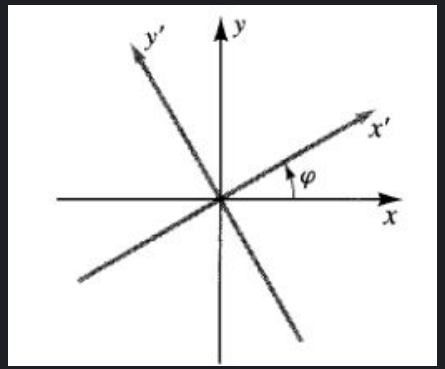


Going from one one inertial frame to another

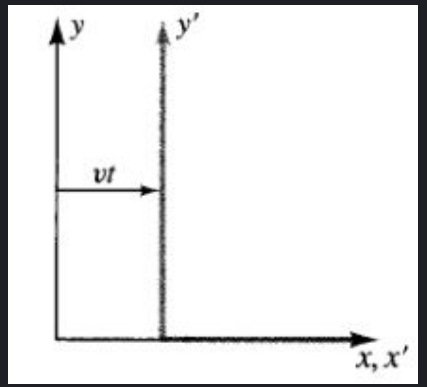
- Displacement



- Rotation



- Uniform motion



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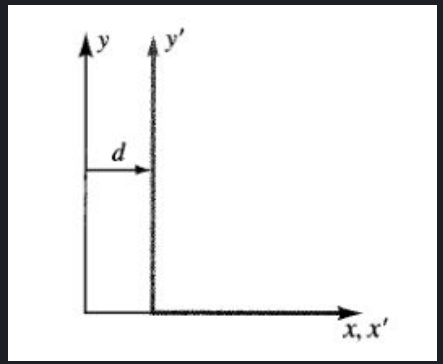
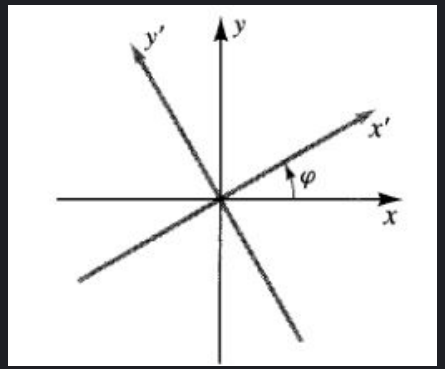
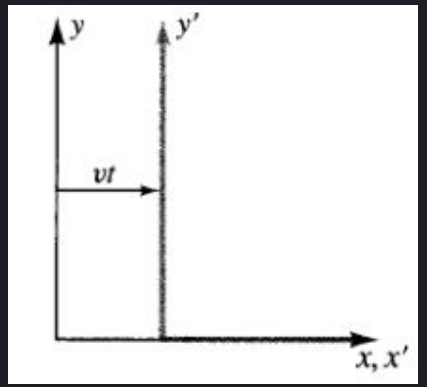
- Displacement



- Rotation



- Uniform motion



Galilean Transformation

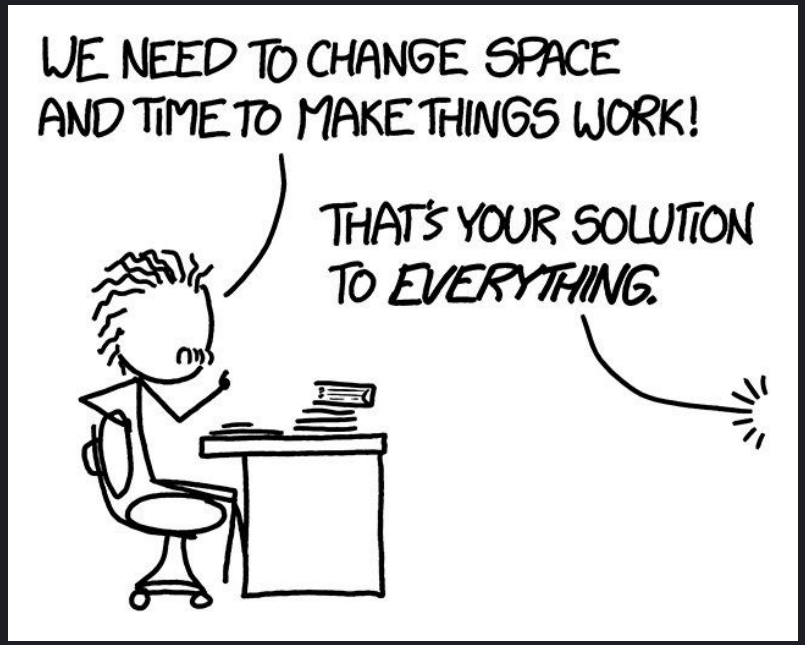
- Using t=t’ (idea of absolute team we can complete the idea of Galilean transformation
- This idea of **absolute time** is abandoned in special relativity

$$x' = x - vt$$

$$y' = y$$

$$z' = z$$

$$t' = t$$



02.

Historical Development

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Theory of Electromagnetism

- In 19th century, it was widely accepted that light travelled in a substance called **aether**
- **Maxwell** showed that electricity and magnetism, previously considered to be separate forces, were two aspects of one force.
- One of his key observations was that electromagnetic effects seemed to propagate at nearly light speed.

Theory of Electromagnetism

“This velocity is so nearly that of light that it seems we have strong reason to conclude that light itself (including radiant heat and other radiations, if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws.”

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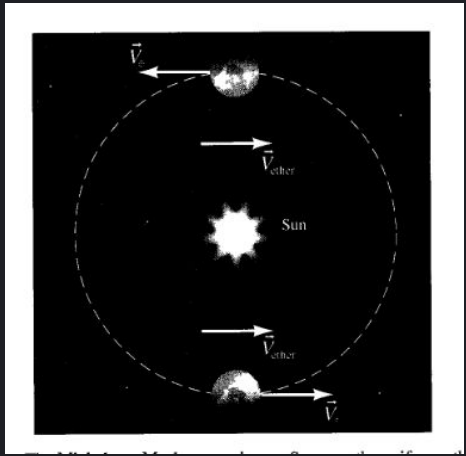
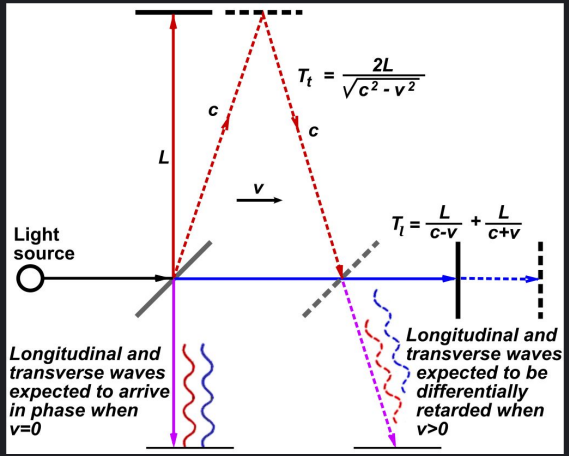
What about Aether ?

- If space were indeed full of an aether then the motion of objects through this aether should be detectable by measuring the velocity of light rays.
- In 1887 **Michelson and Morley** performed an 'interferometer' experiment to test whether the observed velocity of light is indeed the sum of the speed of light in the aether and the velocity of the observer
- Michelson and Morley discovered that the measured velocity of light **did not change with the velocity of the observer**.



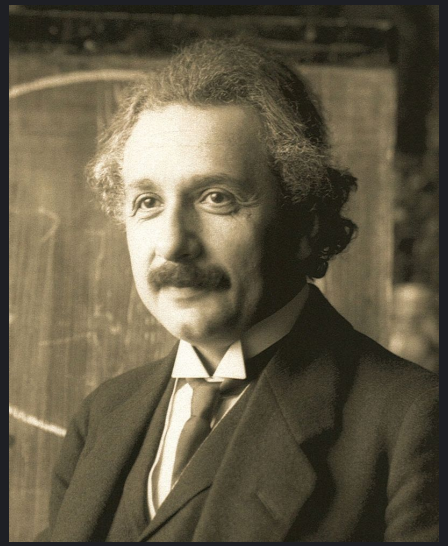


Speed of light (c)

- How could the speed of light in a vacuum be constant for all observers no matter how they are moving themselves?
- It was possible that Maxwell's theory was correct but the theory about the way that velocities add together (known as Galilean Relativity) was wrong.
- Alternatively it was possible that Maxwell's theory was wrong and Galilean Relativity was correct. However, the most popular interpretation at the time was that both Maxwell and Galileo were correct and something was happening to the measuring equipment!
- By the late nineteenth century it was becoming clear that aether theories of light propagation were problematic.

Einstein's Special Relativity

The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.



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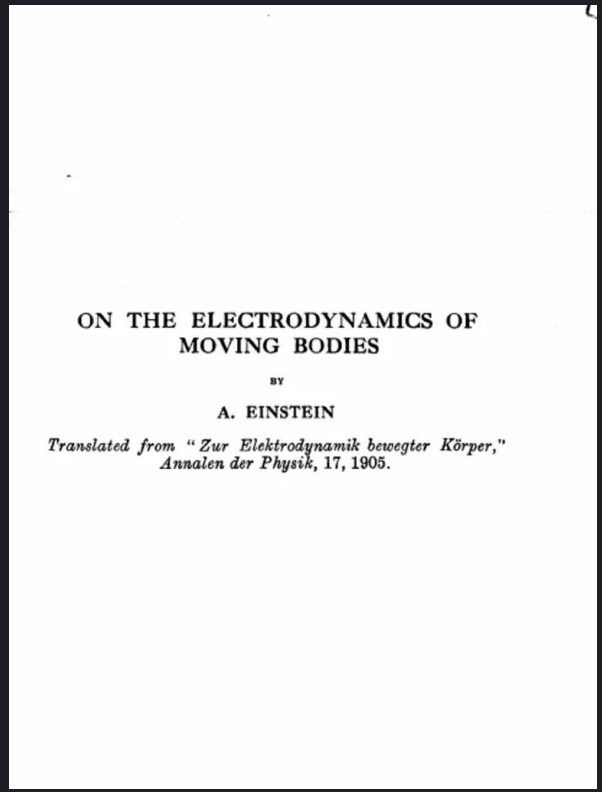
Einstein's Special Relativity

- In 1905 Albert Einstein realised that Maxwell's equations did not require an aether
- Einstein's remarkable achievement was to be the first physicist to propose that Galilean relativity might only be an approximation to reality. He came to this conclusion by being guided by the Lorentz Transformation Equations themselves and noticing that these equations only contain relationships between space and time without any references to the properties of an aether.



ON THE ELECTRODYNAMICS OF MOVING BODIES

BY

A. EINSTEIN

Translated from "Zur Elektrodynamik bewegter Körper," Annalen der Physik, 17, 1905.

03.

SR Postulates and Lorentz transformation

Here you can add a subtitle for the section if you need it

The Principle of Relativity

- Identical experiments carried out in different inertial frames give identical results.
- Maxwell's equations are correct but that classical velocity addition is wrong: **there is no preferred reference frame.**
- Informally: every physical theory should look the same mathematically to every inertial observer. Experiments in a physics laboratory in a spaceship or planet orbiting the sun and galaxy will give the same results, no matter how fast the laboratory is moving.

Speed of light is invariant

- **the speed of light in free space is a constant in all inertial frames of reference.**
- the speed of light in a vacuum, commonly denoted c, is the same for all inertial observers; is the same in all directions; and does not depend on the velocity of the object emitting the light

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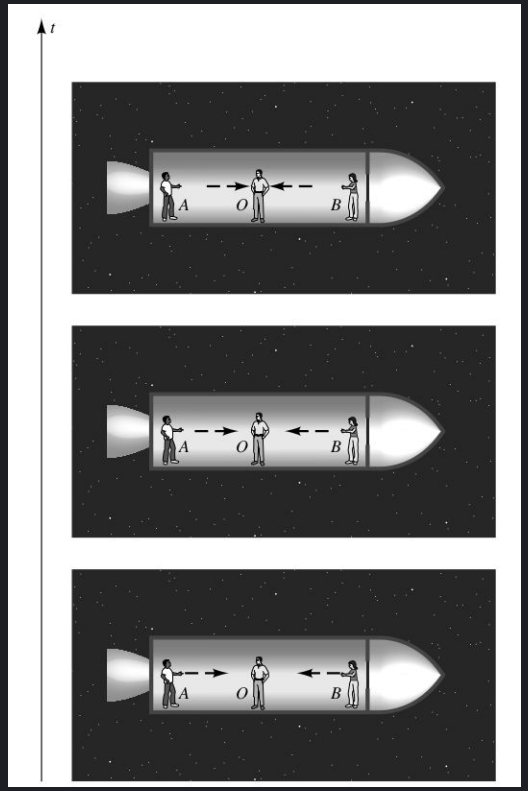
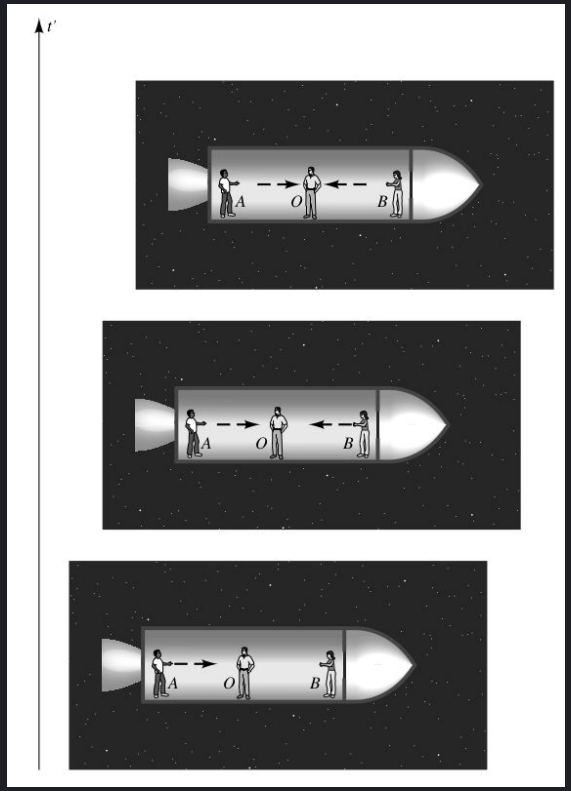
Speed of light is invariant





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Lorentz Transformation

- Einstein asked how the lengths and times measured by observes change if they find the speed of light was constant
- The result of this calculations gave us the Lorentz transformation equations

$$x' = \gamma\left(x - \frac{v}{c}ct\right)$$

$$y' = y$$

$$z' = z$$

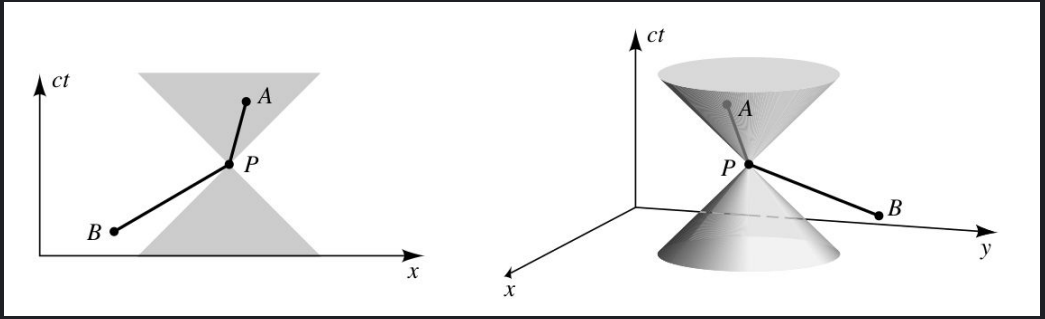
$$ct' = \gamma\left(ct - \frac{v}{c}x\right)$$

Lorentz Transformation : Blackboard

Lorentz invariant interval

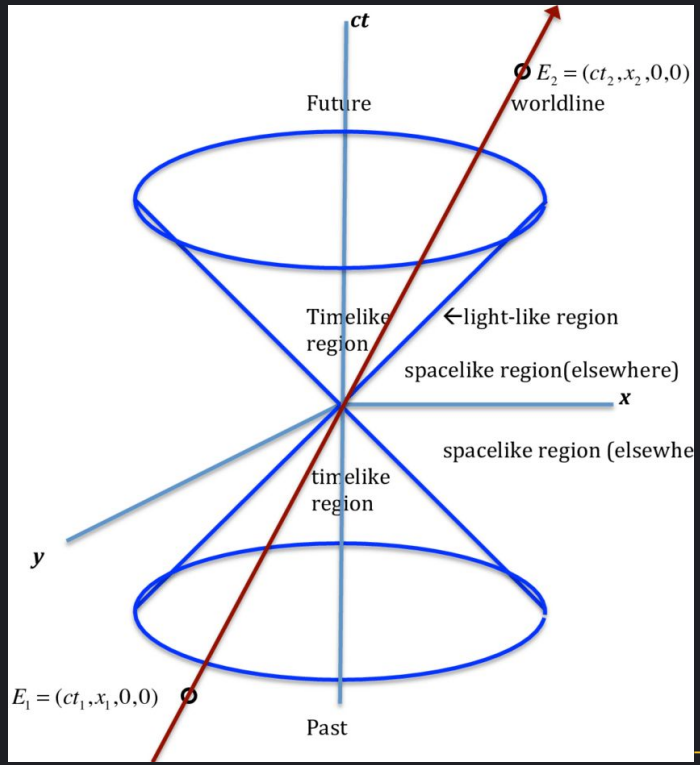
- The interval is a constant in all inertial frames
- The distance between points defining the spacetime geometry **must** be the same in all coordinate systems.

Space-Time diagram

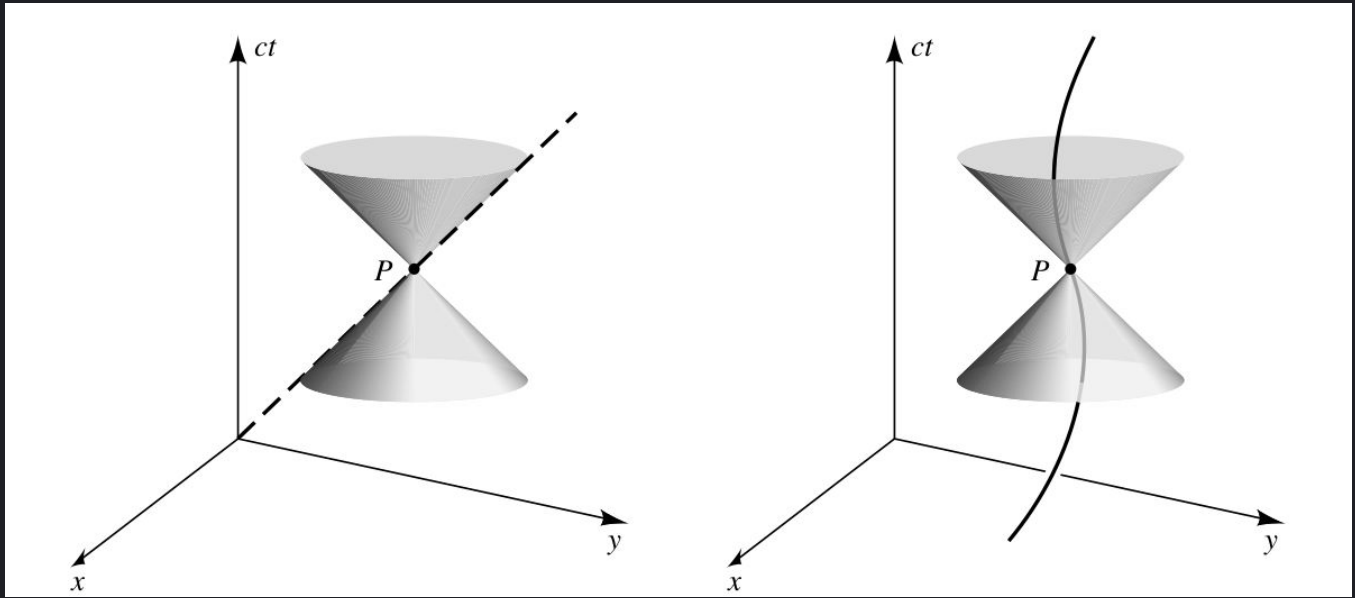


Blackboard: Spacetime Diagrams

- Timelike separated
- Spacelike separated
- Null-like separated



Blackboard : Space-Time diagram



Einstein Velocity Addition rule (Exercise)

- Consider a particle A in the frame B. Her velocity w.r.t frame B is Vab.
- Consider a frame C moving w.r.t B with Vcb.
- Then the velocity of A w.r.t C will be

$$v_{AC} = \frac{v_{AB} + v_{BC}}{1 + (v_{AB} v_{BC}/c^2)},$$

Blackboard

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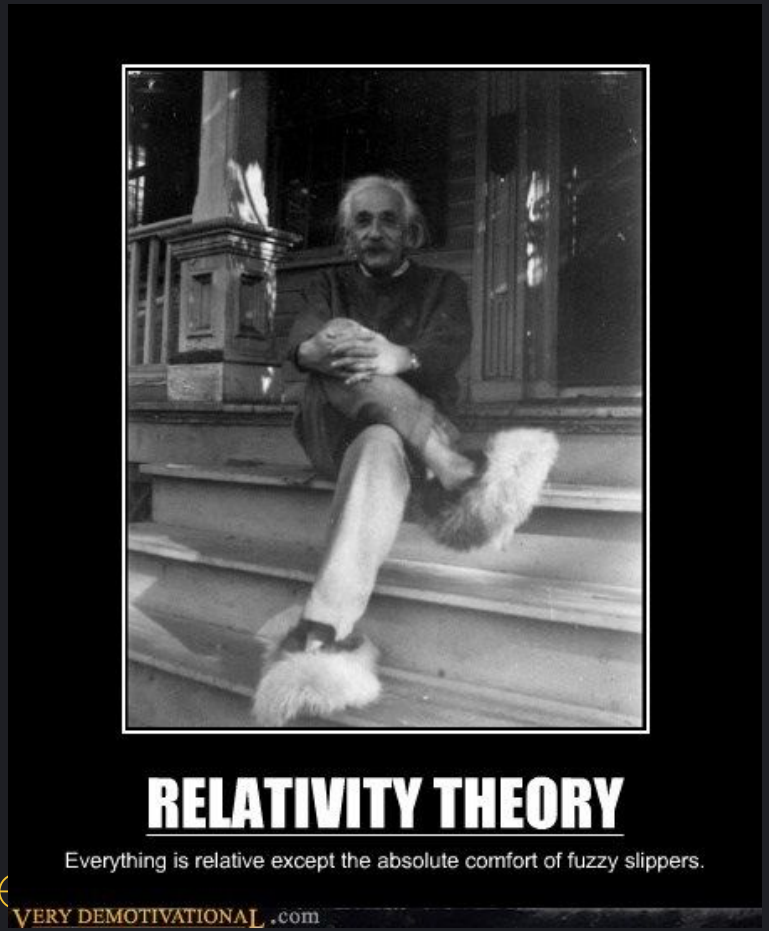
Take a break!



04.
Consequences of Relativity

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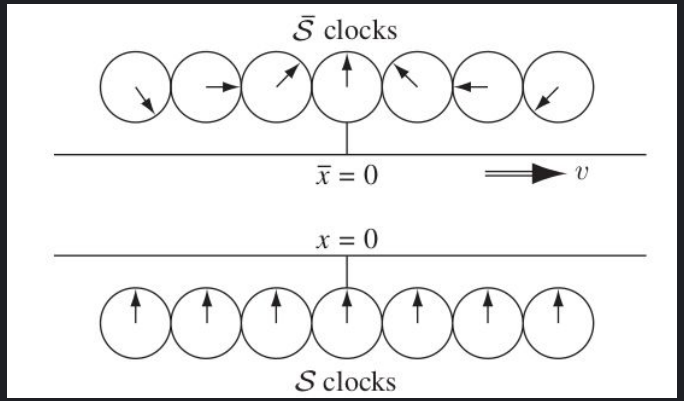
Simultaneity

- **Two events that are simultaneous in one inertial system are not, in general, simultaneous in another.**
- Suppose at time t=0 observer at S decides to examine all the clocks in S`. They read *different* times, depending on their location.

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



Time Dilation

- Suppose from S you focus on one close at rest in the S' frame (say at x' = a) and watches over some interval Δt
- So using $\Delta x' = 0$ on the lorentz transformation equation, we get $\Delta t' = \frac{\Delta t}{\gamma}$
- Thus the time on the moving frame moves slow!
- **Moving clocks run slow.**

Length Contraction

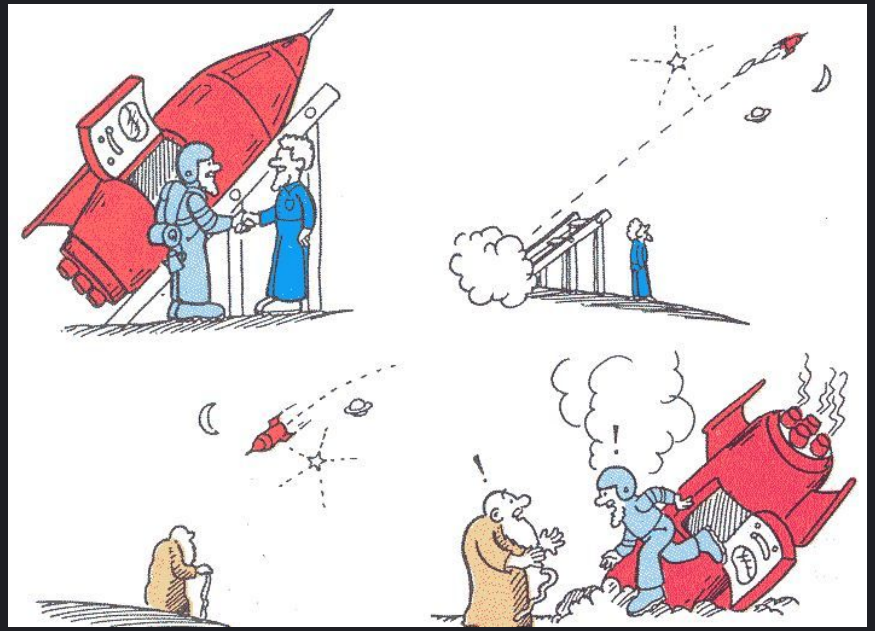
- Consider a stick of length at rest in S'. The rest length is $\Delta x'$
- If an observer in S were to measure the stick at time t, Δx
- Then using lorentz transformation, we get:

$$\Delta x = \frac{\Delta x'}{\gamma}$$

- **Moving objects are shortened.**

Twin Paradox

- On her 21st birthday, Alice takes off a spaceship at a speed of 12/13 c. After 5 years have elapsed on her watch, she turns around and heads back to earth to rejoin her twin brother. How old will be her brother Bob when she is finally back home ?

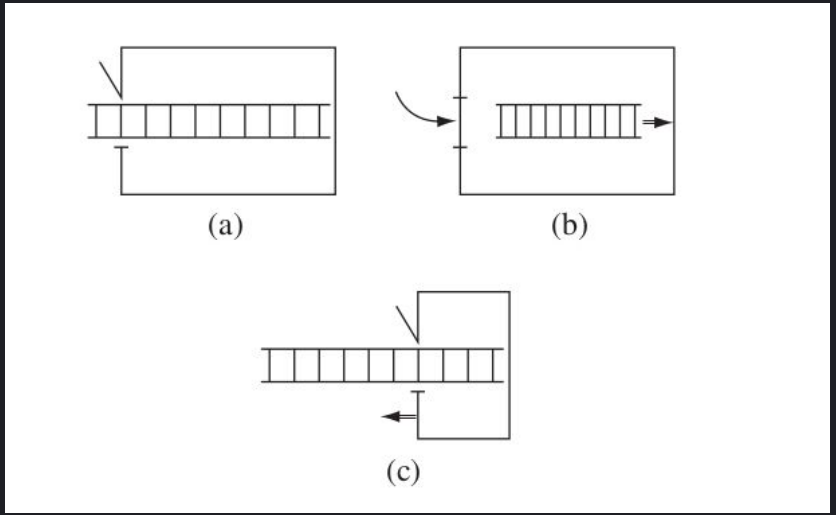


Twin Paradox

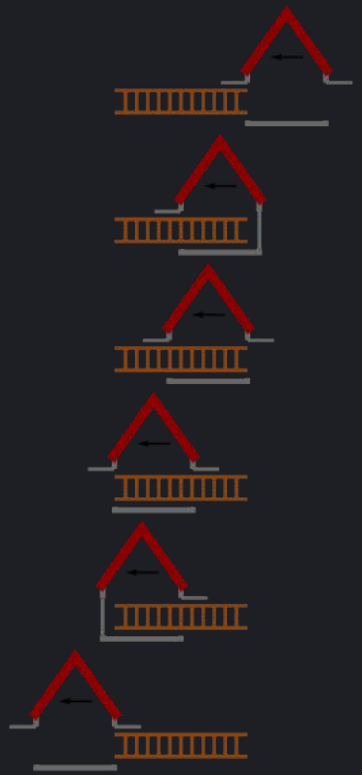
- On her 21st birthday, Alice takes off a spaceship at a speed of 12/13 c. After 5 years have elapsed on her watch, she turns around and heads back to earth to rejoin her twin brother. How old will be her brother Bob when she is finally back home ?
- But from Alice's perspective she is at rest and it appears earth is moving away from her at 12/13 c and hence it is he who should be younger at the reunion!
- The second analysis is wrong!
- The travelling twin's frame is accelerating therefore not inertial.

Barn and Ladder Problem

- There lived a farmer who had a ladder too long to fit into his barn. He was educated in relativity, and hence had a solution to his problem. He instructed his daughter to run with the ladder as fast as she could and using lorentz contraction, the ladder would easily fit in!



Barn and Ladder Problem



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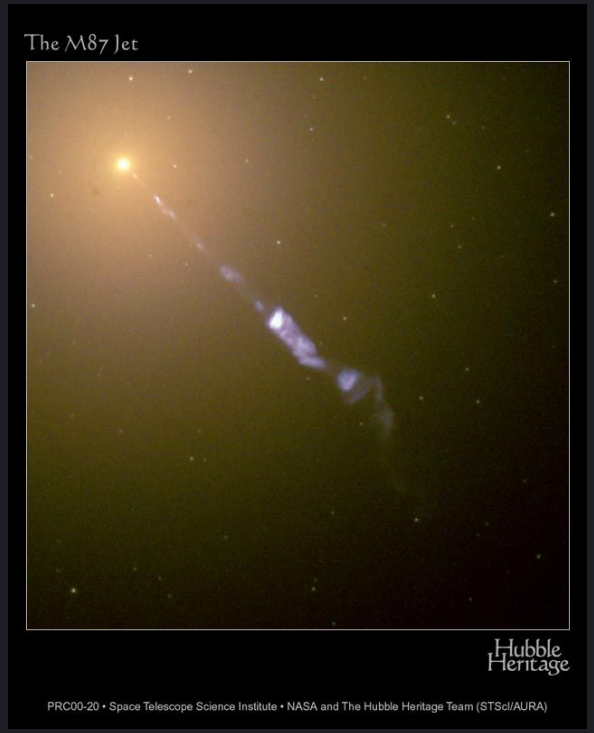
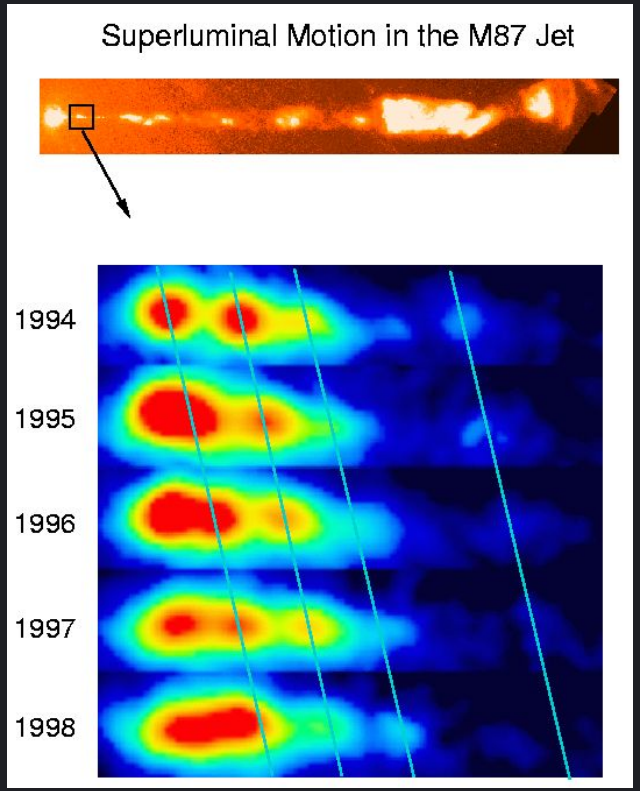
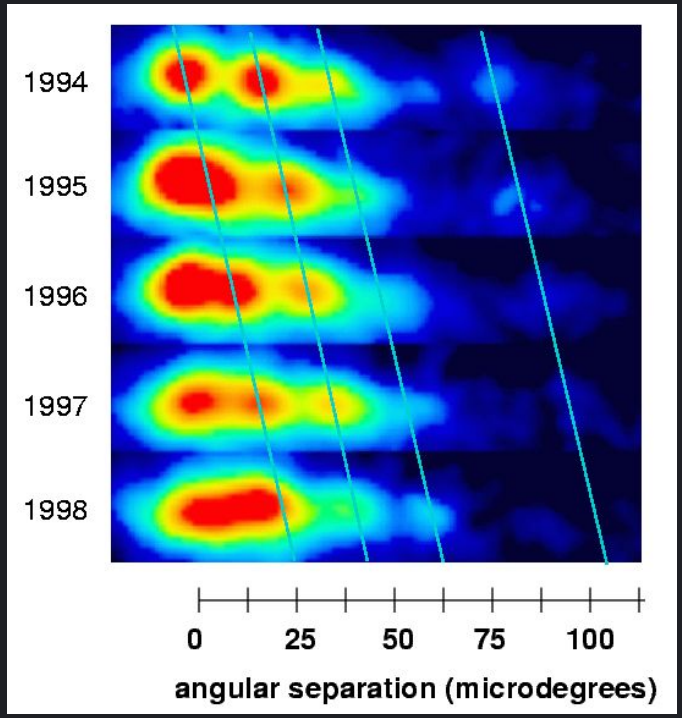
EXERCISE (Superluminal Motion)

- Astronomers observed radio galaxies moving with velocities exceeding the velocity of c!
- M87 is an example in the Virgo cluster
- The distance to this galaxy, M87, is about D = 62 million light years. One can use this distance to convert angular separations into linear separations across the line of sight.

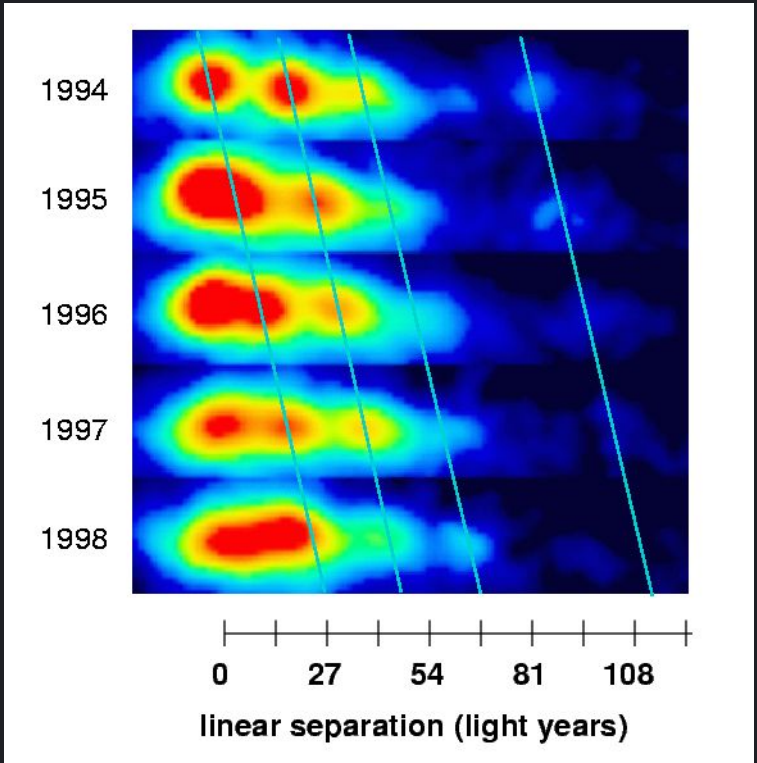


EXERCISE (Superluminal Motion)





EXERCISE (Superluminal Motion)



- Now, look at one of the blobs: the innermost one, which appears most clearly in 1996 and 1997.
- Calculate the velocity of the blob. It looks like it is moving more than 10 c!
- Hold on a minute! Isn't this against special relativity postulate 2 ?

BONUS exercise (Relativistic Doppler Effect)

$$\nu = \sqrt{\frac{c+v}{c-v}}\nu_0$$

General Relativity

Some Tools for Relativity 01.

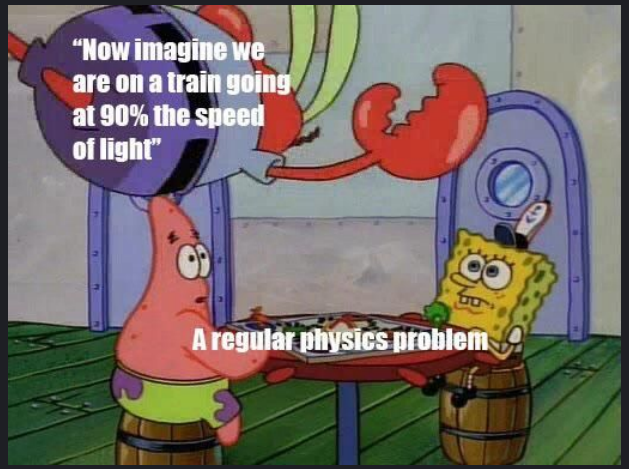
Galilean Relativity, Postulates of Special Relativity

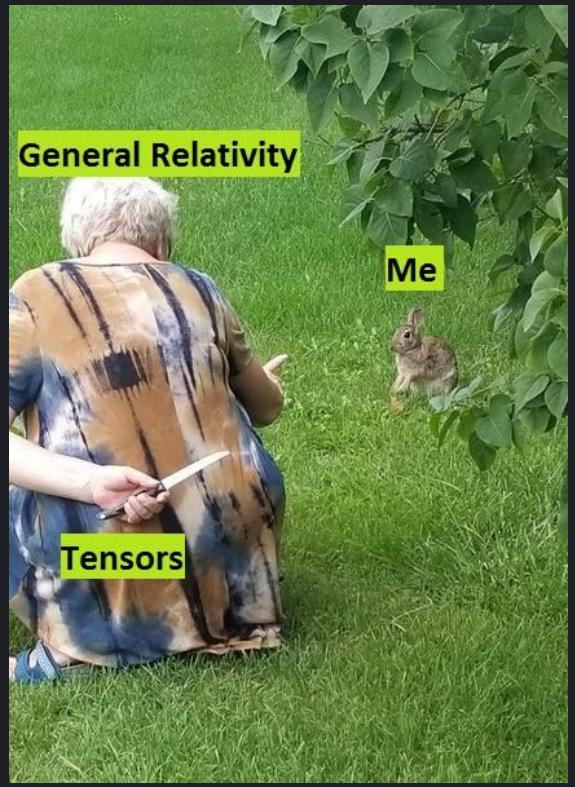
Towards GR 02.

Maxwell equations,

Einstein Equations 03.

You can describe the section here





01.

Some Tools for Relativity

Here you can add a subtitle for the section if you need it

Scalars, Vectors and Tensors

- Scalars, vectors and tensors differ in the way they are transformed under a coordinate transformation

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Four Vectors

- We will denote it using Greek indices like:

$$X^{\mu}$$

$$\mu = 0, 1, 2, 3$$

$$x^0 \equiv ct$$

$$x^1 \equiv x$$

$$x^2 \equiv y$$

$$x^3 \equiv z$$

Four Vectors

- We can now rewrite the lorentz transformation equations using the four vectors in a matrix form.

$$\bar{x}^{\mu} = \sum_{\nu=0}^{3} \Lambda^{\mu}_{\nu} \, x^{\nu}$$

$$\begin{pmatrix} \bar{x}^0 \\ \bar{x}^1 \\ \bar{x}^2 \\ \bar{x}^3 \end{pmatrix} = \begin{pmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma\beta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Four Vectors

- We can define a **4-vector** in the same way we defined for (x0,x1,x2,x3) that transforms the same way under Lorentz transformations
- We can define a dot product of two four vectors :

$$\mathbf{A} \cdot \mathbf{B} = -a^0 b^0 + a^1 b^1 + a^2 b^2 + a^3 b^3$$

Minkowski Metric

- There is a difference between lower index and upper index
- We can lower the index of a four vector we can use a second rank tensor

$$a_\mu = (a_0, a_1, a_2, a_3) = (-a^0, a^1, a^2, a^3)$$

$$a_\mu = \sum_{\mu=0}^{3} g_{\mu\nu} a^\nu$$

- g_{mu nu} is called the metric. Here it is the **Minkowski Metric**

Minkowski Metric

$$g_{\mu\nu} \equiv \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- This metric describes a flat spacetime
- Metric is a very important quantity in general relativity
- It tells you a lot about the geometry and as a result gravity!

Einstein Summation Rule

- Arguably Einstein’s biggest contribution to physics!

$$a_\mu = g_{\mu\nu} a^\nu$$

02.

Towards GR

Here you can add a subtitle for the section if you need it

Fundamental Postulates of GR

- The **Equivalence Principle** which poses the **equivalence of gravity and acceleration**
- The **Principle of Covariance**, which extended relativity to say that **the form of laws of physics should be the same in all inertial an accelerating frames**
- In this new context of GR, gravity **is not a forced,** but rather in the **differential gravitational acceleration of nearby local free falling inertial observers.**
- This relative acceleration is interpreted as the curvature of the spacetime.

Equivalence Principle

- Einstein observed a simple thing: In a gravitational field, **all things fall to the ground at the same rate of acceleration.**
- **Weak Equivalence Principle**
- m = inertial mass
- M = gravitational mass
-

$$a = \frac{M}{m} g$$

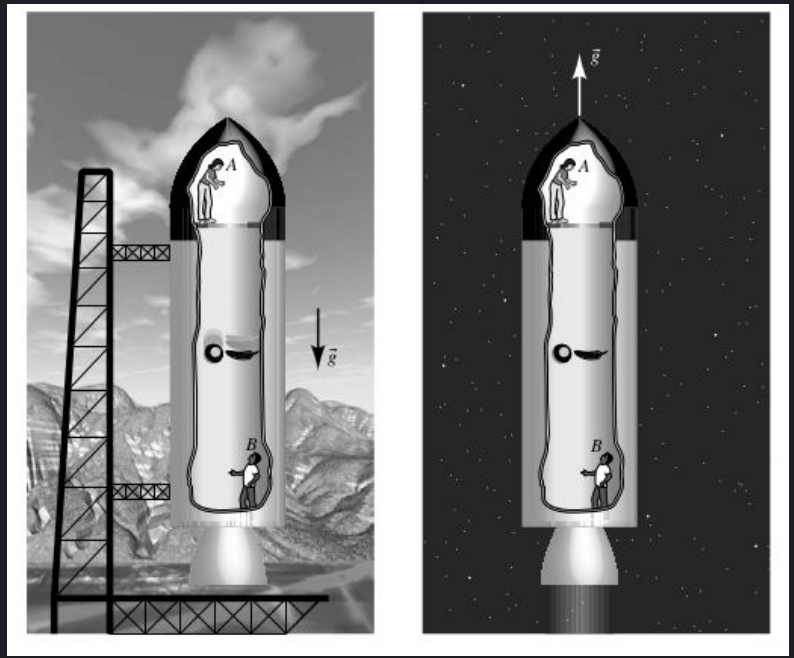
Equivalence Principle

"There then occurred to me the 'glückischste Gedanke meines Lebens,' the happiest thought of my life, in the following form. The gravitational field has only a relative existence. . . . Because for an observer falling freely from the roof of a house there exists—at least in his immediate surroundings—no gravitational field. Indeed, if the observer drops some bodies then these remain relative to hi in a state of rest or uniform motion, independent of their particular chemical or physical nature (in this consideration air resistance is, of course, ignored). The observer has the right to interpret his state as 'at rest."

If all bodies with the same initial conditions fall along the same curve independent of their composition, then that curve can be a property of the geometry of spacetime and not of a force acting on the body.

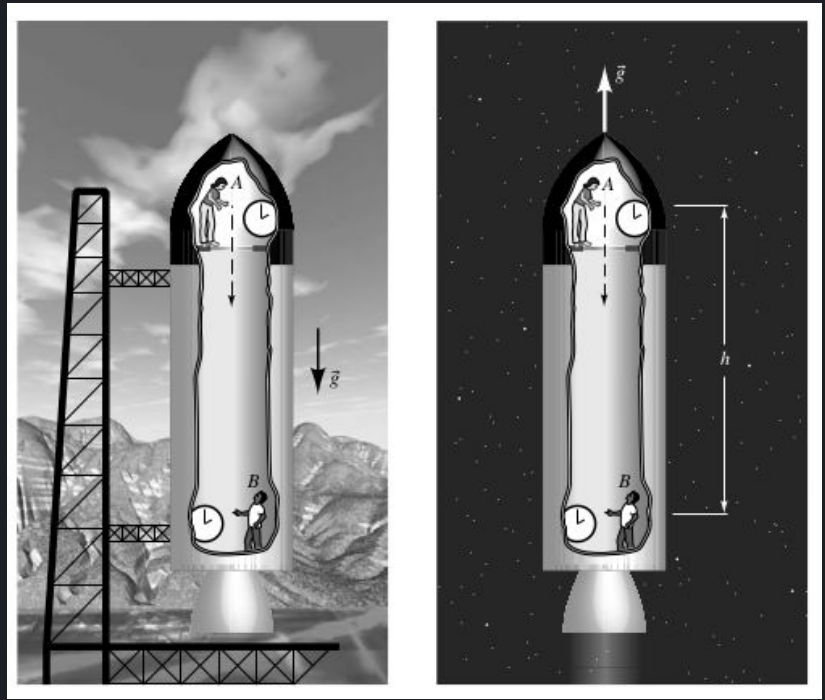
Equivalence Principle

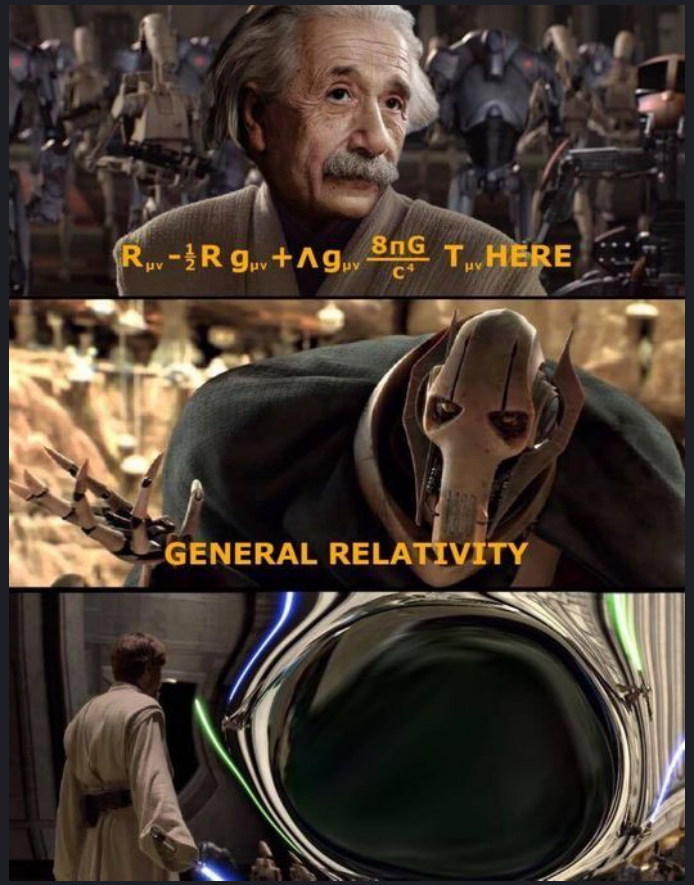
- The equivalence principle also implies that gravitational field can be eliminated by **acceleration**
- Consider the same experiment in an uniform accelerated and a frame with uniform gravitational field.
- **An observer inside wouldn’t be able to distinguish between these two frames.**



Clocks in gravitational field (in Tutorial)

Alice is at a height h above Bob in a uniform gravitational field inside a rocket that is stationary. Alice emits light signals at equal intervals DTa. At what intervals DTb does Bob receive the signals as measured by a clock at his height ? Use equivalence principle to view this in space then you may conclude that **Bob receive the signals at faster rate than they are emitted.**





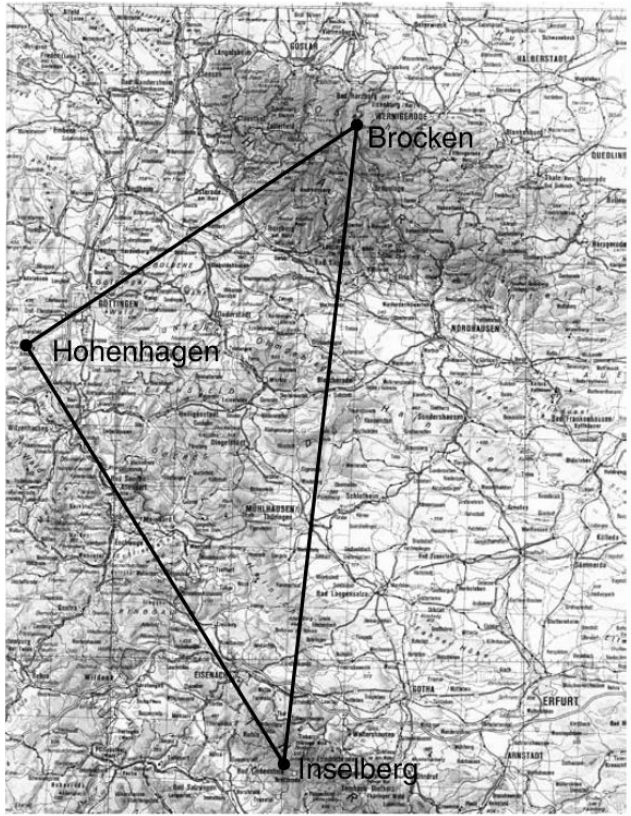
03.

Spacetime is Curved

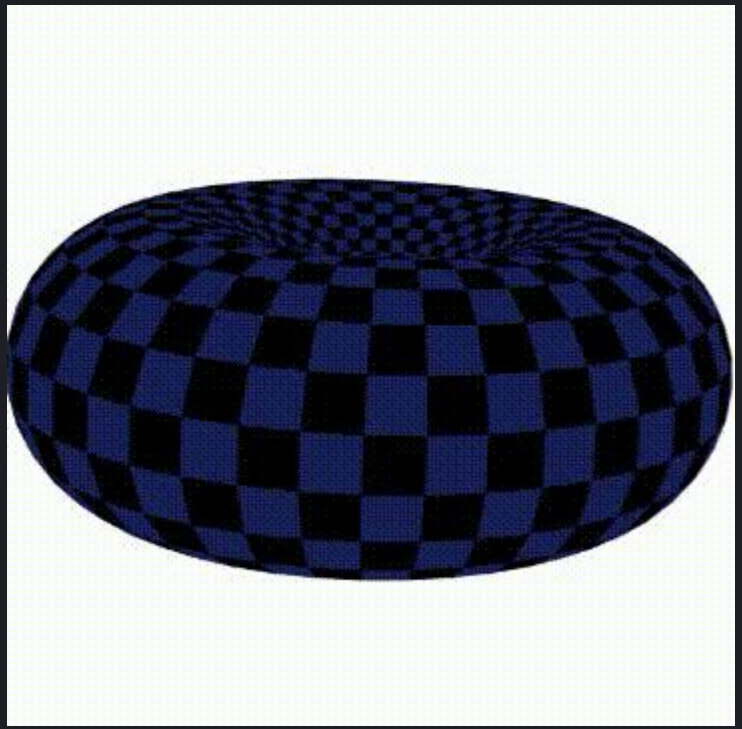
Here you can add a subtitle for the section if you need it

Curvature

- Sum of interior angles in a euclidean geometry ?
- Sum of interior angles in a non-euclidean geometry ?



Geodesics



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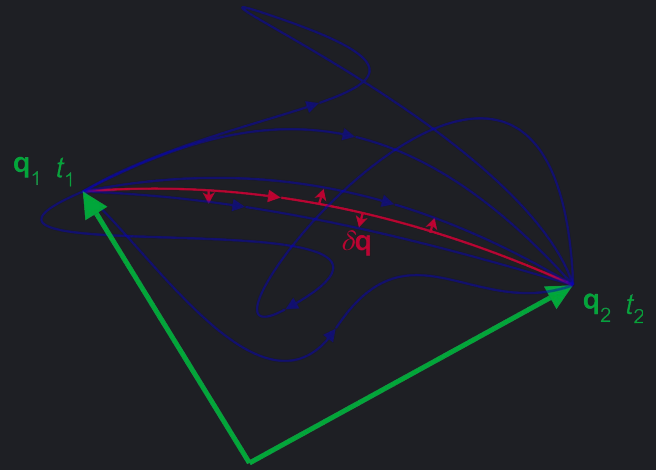
Physics is where the action is

- **Principle of least action** is a fundamental principle that yields the equations of motion for a system

$$S[q(t)] = \int_{t_1}^{t_2} L(q(t), \dot{q}(t), t)dt$$



Geodesic Equation

$$S = \int ds$$

$$ds = -\sqrt{g_{\mu\nu} dx^\mu dx^\nu}$$

$$S = \int \sqrt{-g_{\mu\nu} \frac{dx^\mu}{d\lambda} \frac{dx^\nu}{d\lambda}} d\lambda$$

$$\delta S = 0$$

Geodesic Equation

$$S = \int ds$$

$$ds = -\sqrt{g_{\mu\nu} dx^\mu dx^\nu}$$

$$S = \int \sqrt{-g_{\mu\nu} \frac{dx^\mu}{d\lambda} \frac{dx^\nu}{d\lambda}} d\lambda$$

$$\delta S = 0$$

Geodesic Equation

$$\frac{d^2x^\beta}{d\tau^2} + \Gamma^\beta_{\alpha\nu}\frac{dx^\alpha}{d\tau}\frac{dx^\nu}{d\tau}$$

$$\Gamma^\beta_{\alpha\nu} = \frac{1}{2}g^{\mu\beta}(\partial_\alpha g_{\mu\nu} + \partial_\nu g_{\mu\alpha} - \partial_\mu g_{\alpha\nu})$$

Blackboard

$$\frac{d^2x^\beta}{d\tau^2} + \Gamma^\beta_{\alpha\nu}\frac{dx^\alpha}{d\tau}\frac{dx^\nu}{d\tau}$$

$$\Gamma^\beta_{\alpha\nu} = \frac{1}{2}g^{\mu\beta}(\partial_\alpha g_{\mu\nu} + \partial_\nu g_{\mu\alpha} - \partial_\mu g_{\alpha\nu})$$

The Minkowski Metric

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2$$

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu$$

$$\eta_{\mu\nu} = \eta^{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Exercise for Minkowski metric

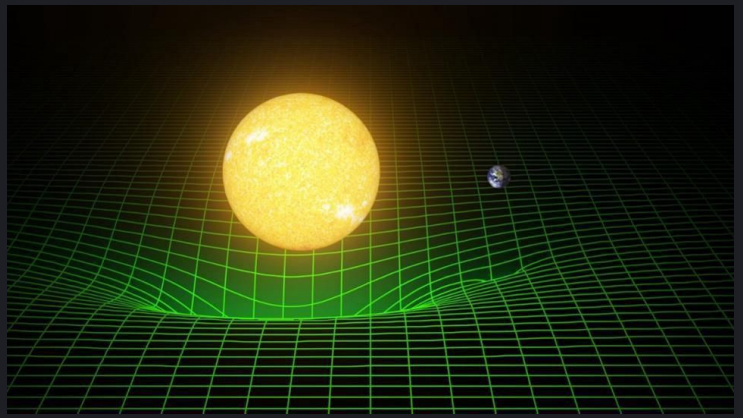
- Do a coordinate transformation from (t,x,y,z) to spherical polar coordinates (t,r,\theta,\phi).
- Show that the metric looks different in this coordinate system

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2 \sin^2\theta \end{pmatrix}$$

Gravity is Geometry

- The central content of GR is just one equation : **The Einstein Equation**
- Essentially the equation tells us how the **presence of matter** produces **spacetime curvature**

$$\begin{pmatrix}\text{a measure of local}\\ \text{spacetime curvature}\end{pmatrix} = \begin{pmatrix}\text{a measure of}\\ \text{matter energy density}\end{pmatrix}$$



Einstein Equation

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

Einstein Equation (Blackboard)

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

GR: The Big picture

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

Cosmology

History 01.

The cosmological principle, Hubble’s law

Basic cosmology 02.

The Friedmann equations, the distance ladder

21 cm physics 03.

The hyperfine transition, reionization, structure formation

Observational surveys 04.

Gaia, COBE, SKA and others

What is cosmology?

Cosmology is the study of the universe as a whole, i.e. at its largest scales.

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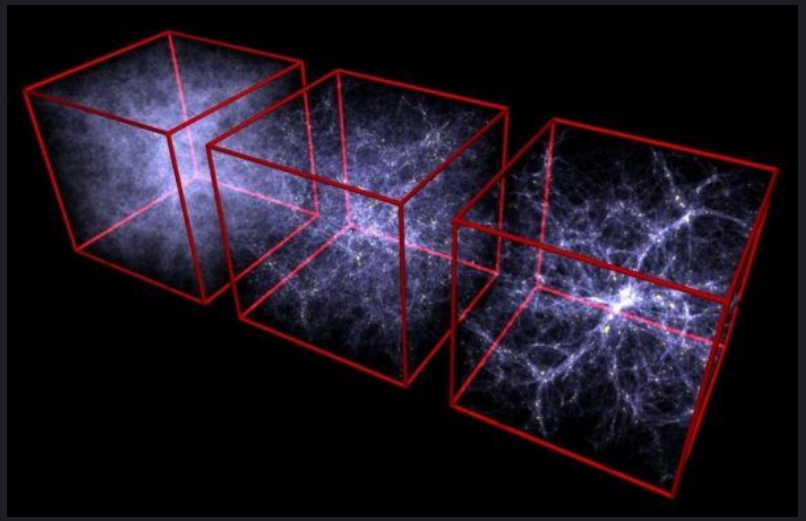


01.

History of Cosmology

Ancient astronomy, the Renaissance period, modern cosmology

Spherical Earth, cycles, epicycles...

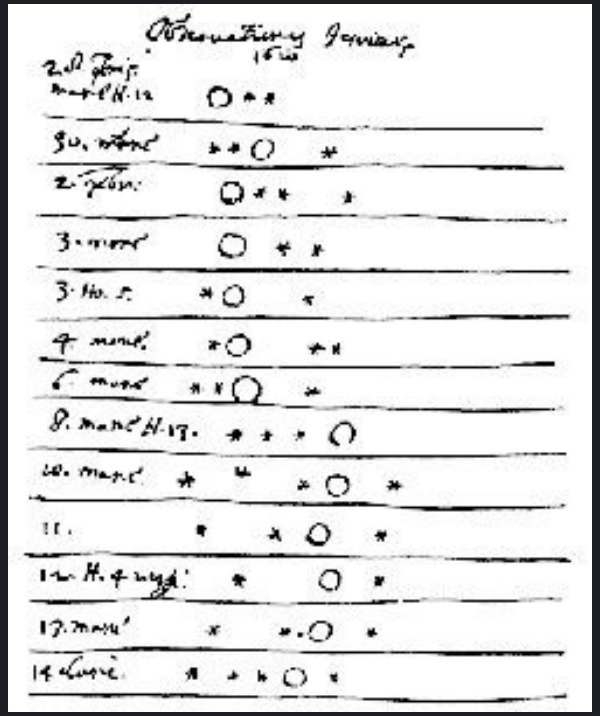
10^4

- **Circumference of the Earth** was first estimated to be ~64000 km (280-195 BC).
- Prevalent model - **geocentric model**
- Everything fixed on a celestial sphere that rotates about Earth.
- Stars move in **circles,** planets and satellites move in **epicycles**.

The Heliocentric Model

$$10^4 \rightarrow 10^8$$

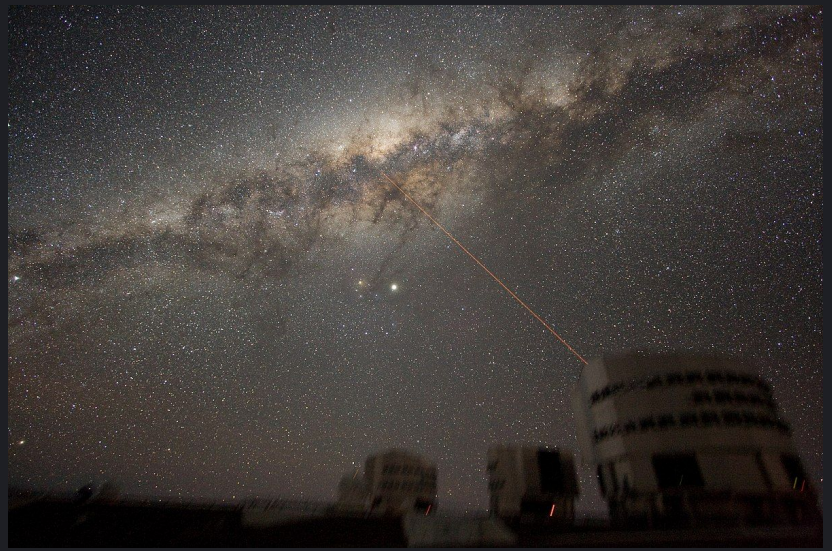
- *On the Revolution of Heavenly Spheres* (Copernicus, 1543) - **the heliocentric model**
- Galileo Galilei observed Jupiter and its moons using a **telescope.**
- *Philosophiae Naturalis Principia Mathematica* (Newton, 1687) - **universal law of gravitational attraction.**
- Kepler put forth his **laws of planetary motion.**



Outer planets and the Milky Way

$$10^4 \rightarrow 10^8 \rightarrow 10^{11} \rightarrow 10^{18}$$

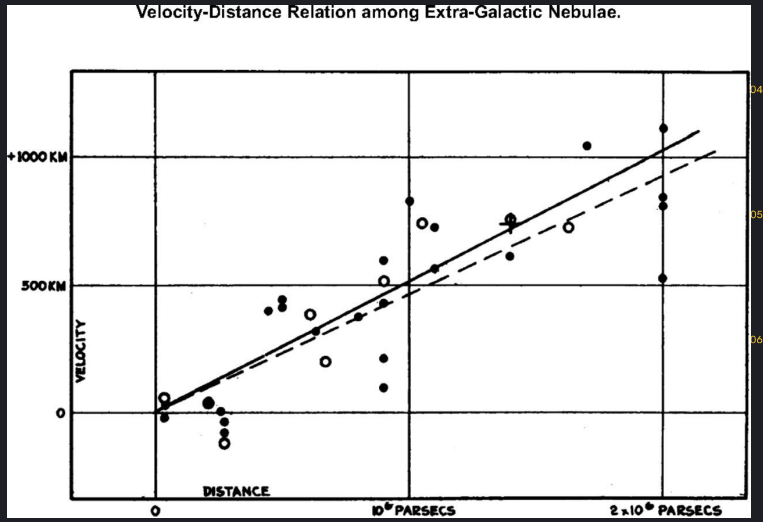
- William Herschel observed **Uranus** for the first time.
- Observations of **faint stars** in the galaxy - Galileo Galilei, William Herschel, Immanuel Kant
- **The Great Debate** - Harlow Shapley and Heber Curtis



Cepheid variables and Hubble's Law

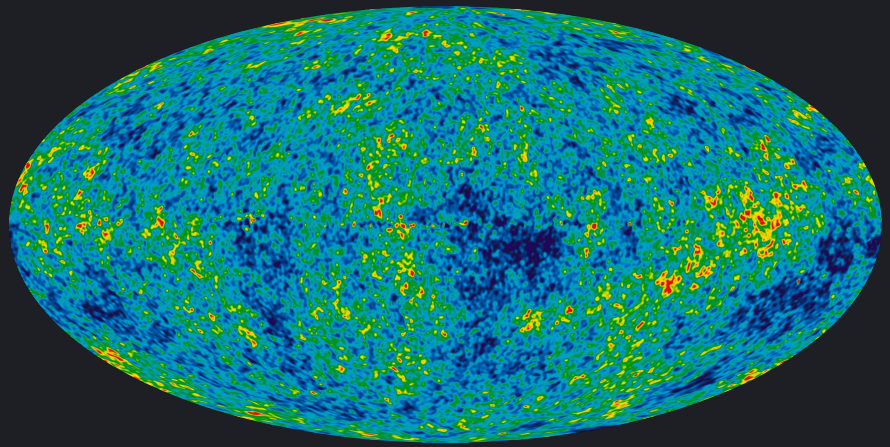
$$10^4 \rightarrow 10^8 \rightarrow 10^{11} \rightarrow 10^{18} \rightarrow 10^{20}$$

- Henrietta Leavitt discovered **Cepheid variables - period-luminosity relation**
- Cepheid variables used to infer Hubble's law, i.e. the **universe is expanding** (Lemaitre - 1927, Hubble - 1930).
- Led to the idea of the **Big Bang model.**

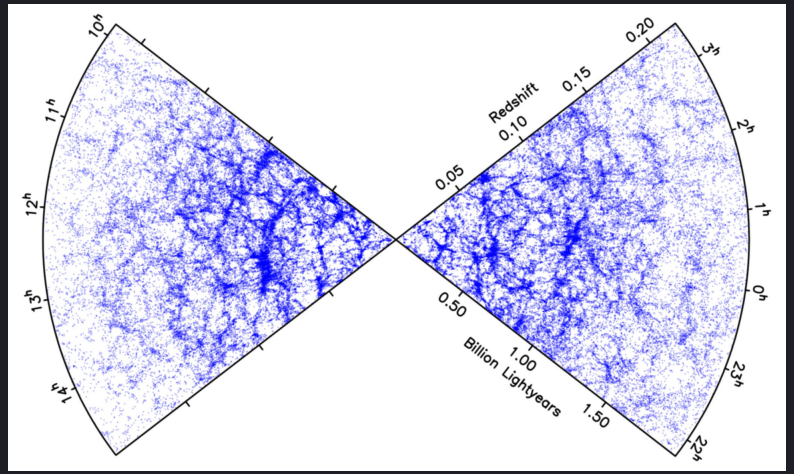


The observable universe

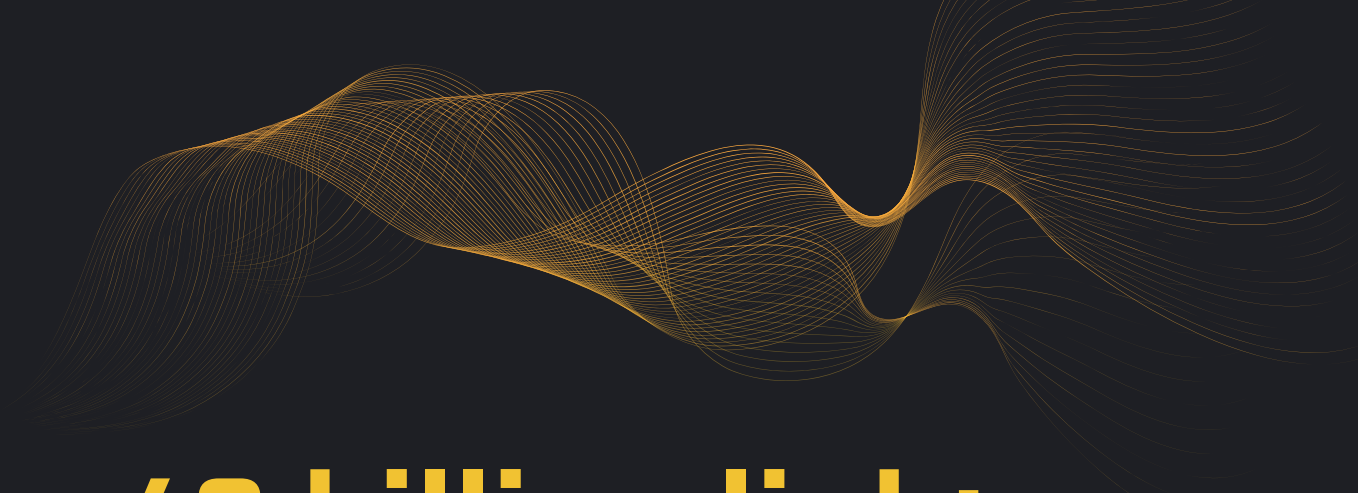
$$10^4 \rightarrow 10^8 \rightarrow 10^{11} \rightarrow 10^{18} \rightarrow 10^{20} \rightarrow 10^{24}$$



The Cosmic Microwave Background



The 2dF Galaxy Redshift Survey



46 billion light years

is the estimated radius of the observable universe.

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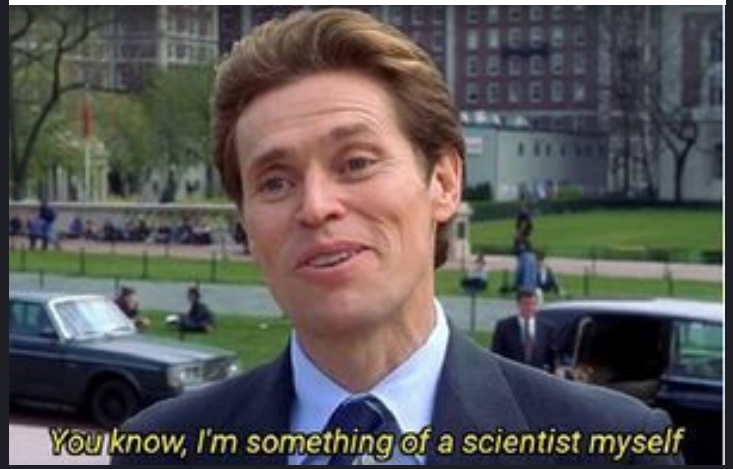
The audience after understanding basic cosmology:



02.

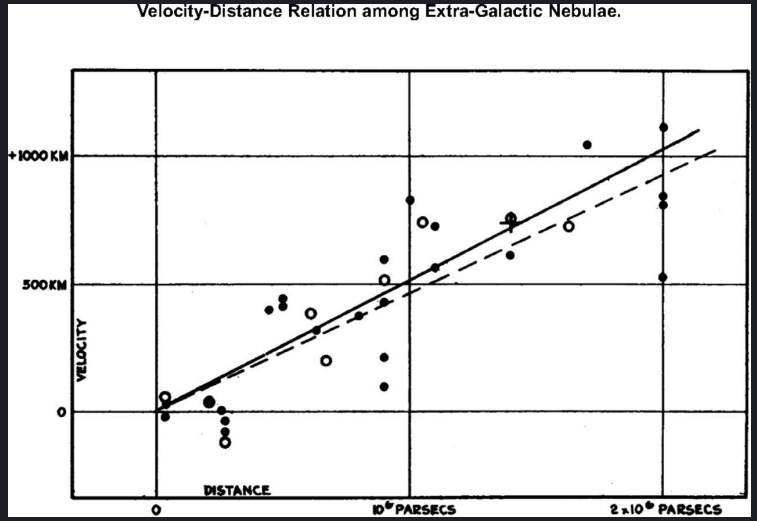
Basic Cosmology

The “universe is expanding” stuff, Friedmann equations, the distance ladder

Hubble's law once again

$$v = H_0 D$$

- v is the receding velocity of the galaxy.
- H_0 is the Hubble constant at present.
- D is the distance to the galaxy.



Comoving coordinates and the scale factor (blackboard)

The Friedmann equations

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} + \frac{\Lambda}{3} - \frac{k}{a^2}$$ → curvature

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$ → cosmological constant

These equations govern the expansion of space in a homogeneous and isotropic universe. One can obtain the fluid equation by using the above mentioned equations.

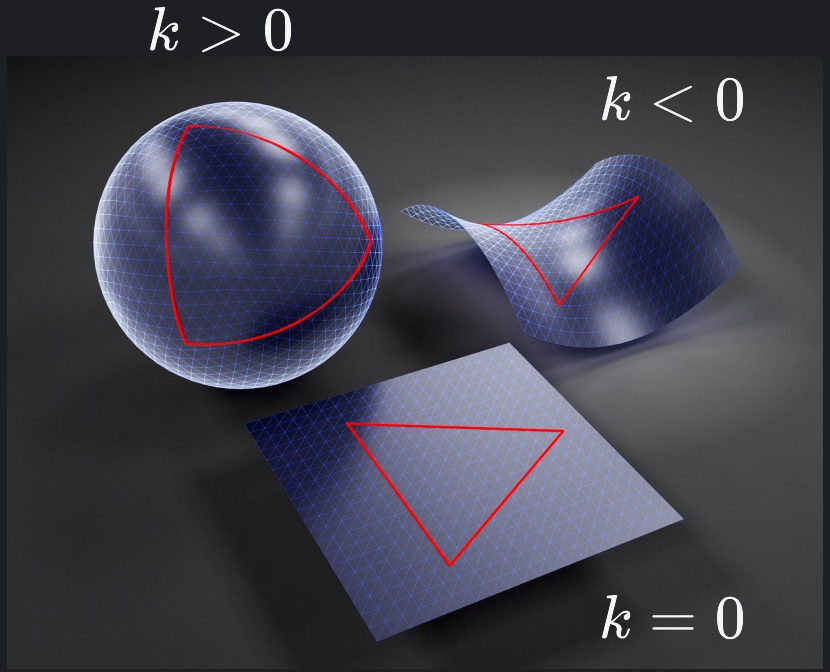
Exercise!

Derive the Friedmann equations (and the fluid equation) from Newtonian principles.

Geometry of the Universe

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} + \frac{\Lambda}{3} - \frac{k}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$



Equation of State (EoS) (blackboard)

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} + \frac{\Lambda}{3} - \frac{k}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

Some components in the Universe

Baryonic matter

The gravitationally attracting stuff we know

Dark matter

The gravitationally attracting stuff we don’t know

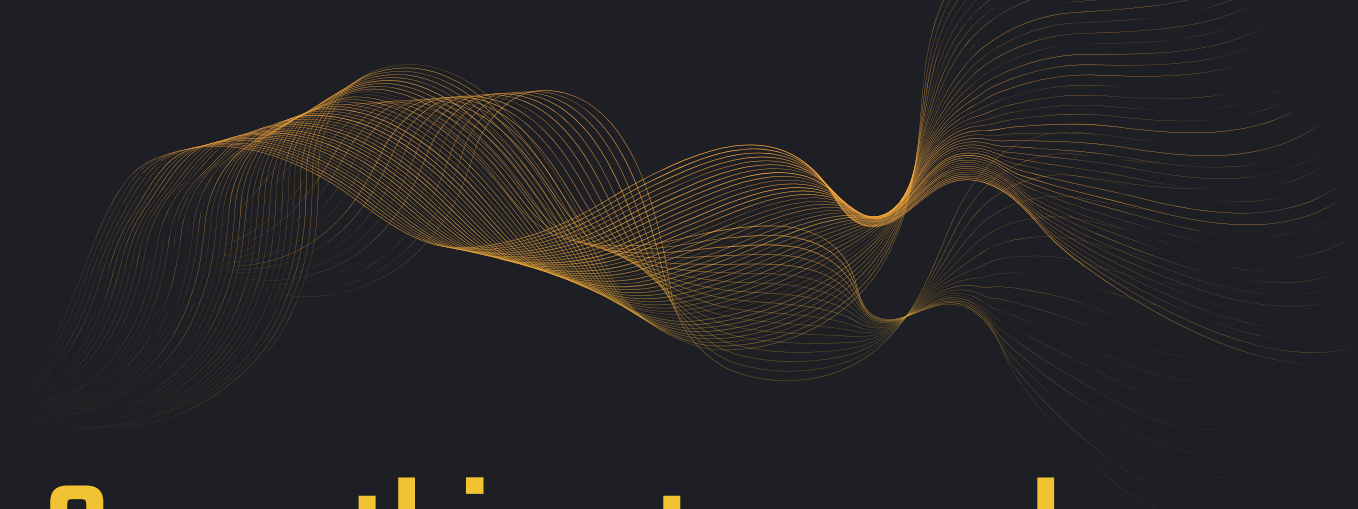
Dark energy

The cosmological constant

Non-relativistic matter

All forms of radiation

How to estimate the densities of these quantities?



Something to ponder over

In a cosmological context, what do the different components in the universe represent?

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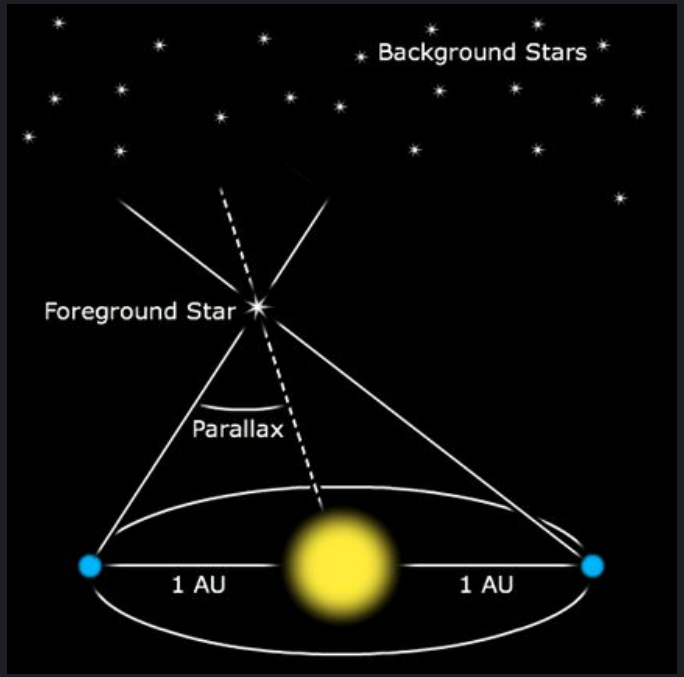
Take a break!

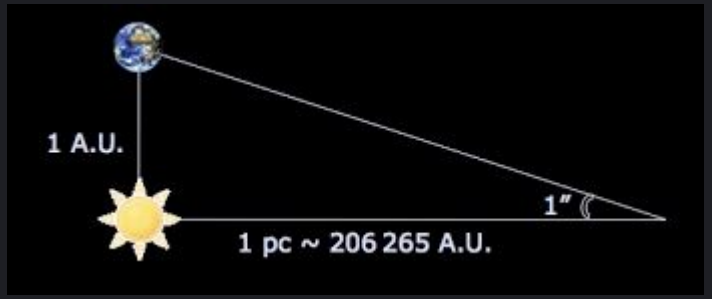
The Cosmic Distance Ladder

A set of methods to estimate distances to various objects in the universe

- Direct measurements
- Parallax
- Standard candles
  1. Cepheid variables
  2. Spiral galaxies
  3. Type 1a supernovae

Stellar parallax

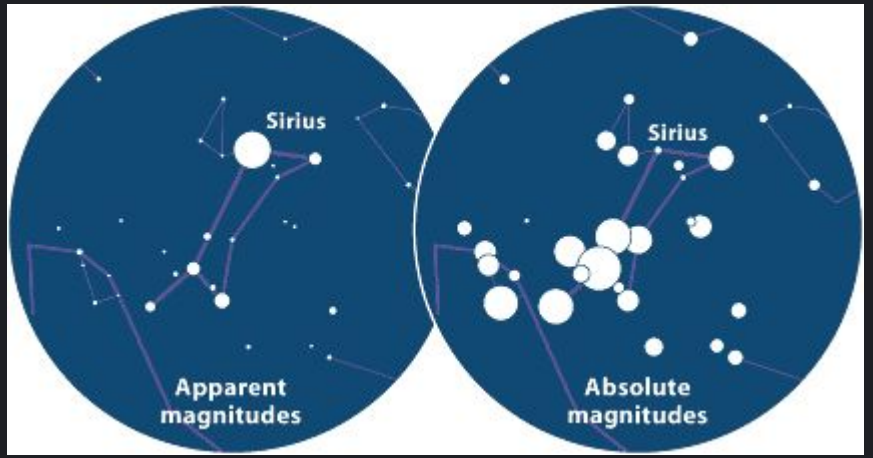




Definition of a parsec

Luminosity and flux (absolute and apparent magnitudes)

- **Luminosity** is the energy emitted per unit time.
- **Flux** is the energy emitted per unit time per unit area.

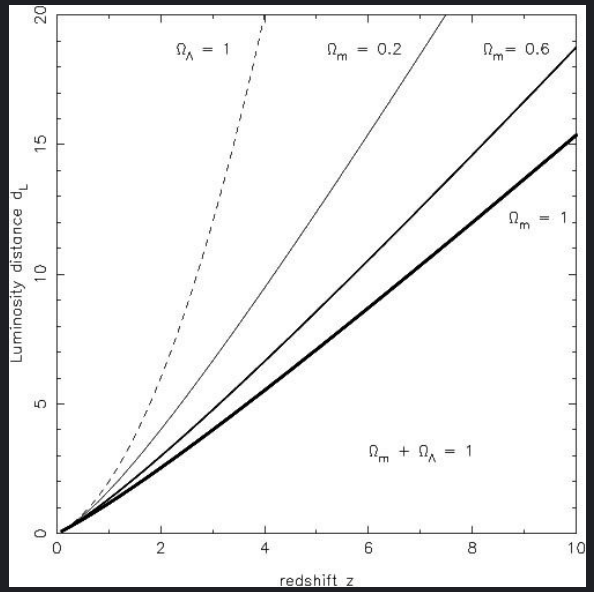


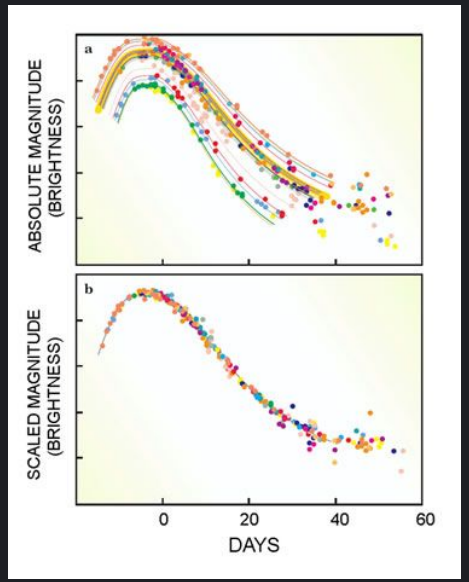
Luminosity distance and standard candles

- **Luminosity distance** is obtained from the known values of luminosity and flux of the object.
- A **standard candle** is an object with a known luminosity.

Type 1a supernovae

- Occur due to white dwarf stars accreting matter from the companion star and exceeding the Chandrasekhar limit.





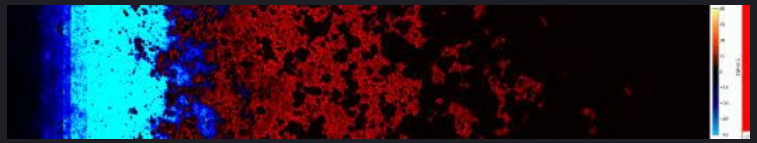
The Tully-Fisher relation

- Relates the rotational velocity of a spiral galaxy to its intrinsic luminosity.

$$L = Av_{rot}^{\beta}$$

- How do you measure the rotational velocity of a galaxy?

03.

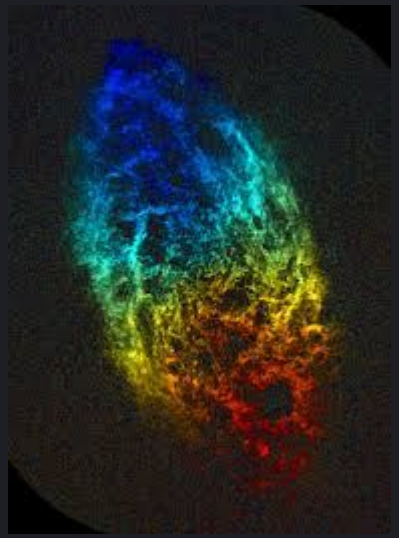


21 cm physics

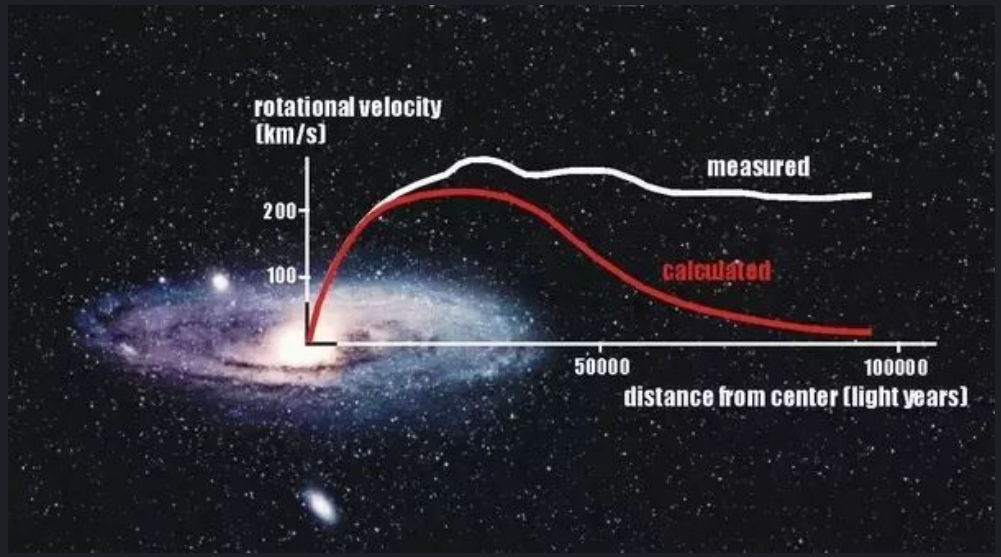
A fancy observational tool to probe the early universe

The 21 cm line and velocity measurements

- Radiation with wavelength **21 cm (1420 MHz)** is released wherever there is **neutral hydrogen (H1)**.



Evidence for dark matter



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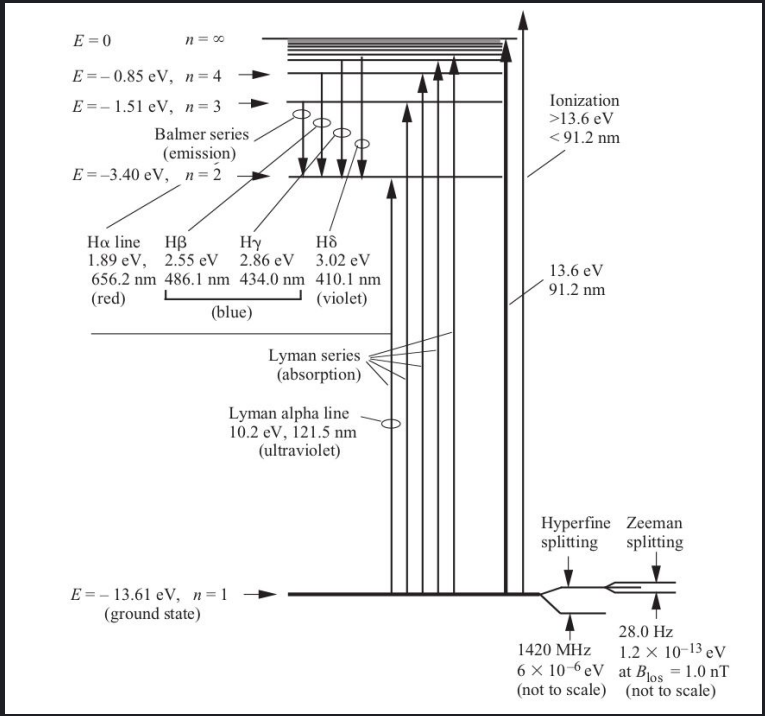
But what exactly is the 21 cm line?

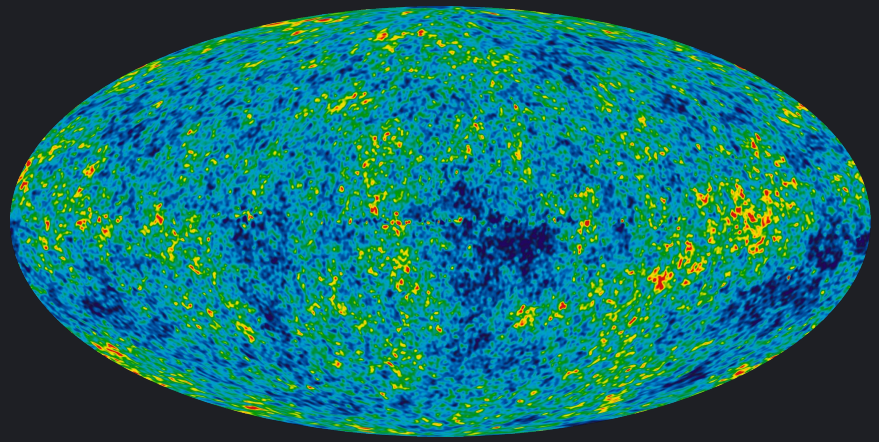
The hyperfine transition

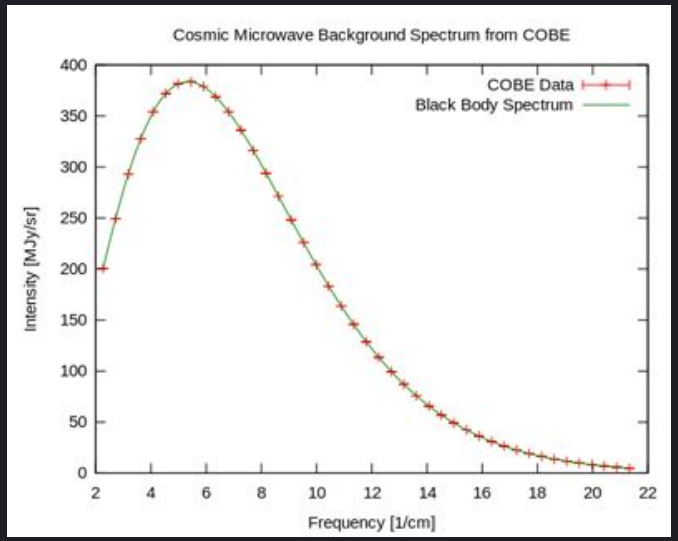


What causes the hyperfine transition?

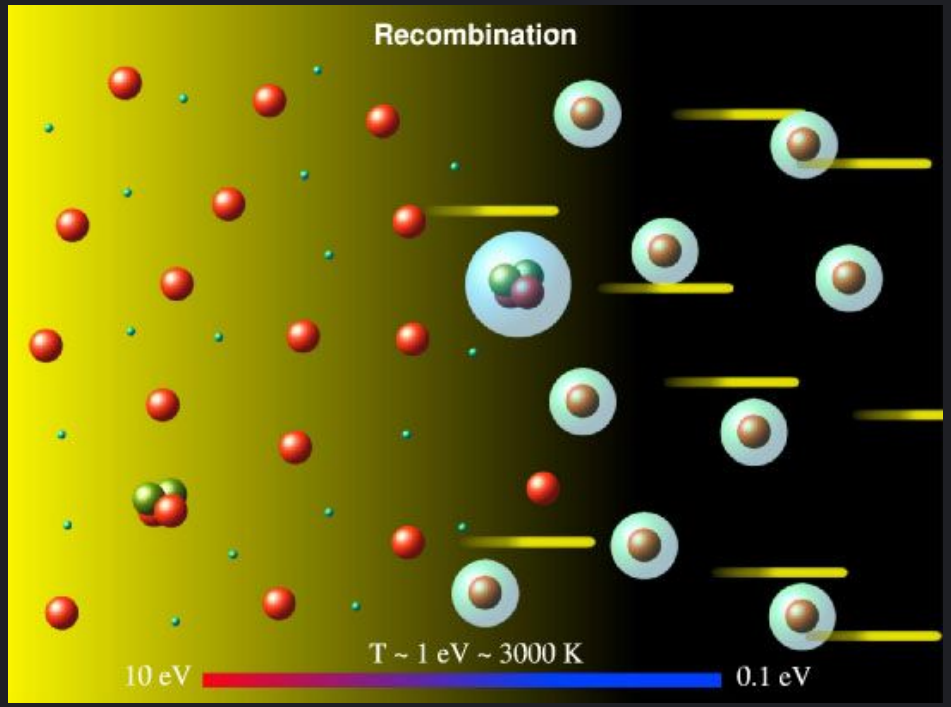
The Cosmic Microwave Background (CMB)

- It is radiation leftover from the Big Bang, currently in the microwave regime due to cosmological redshift.
- It is a **blackbody** corresponding to a temperature of around 2.725 K.

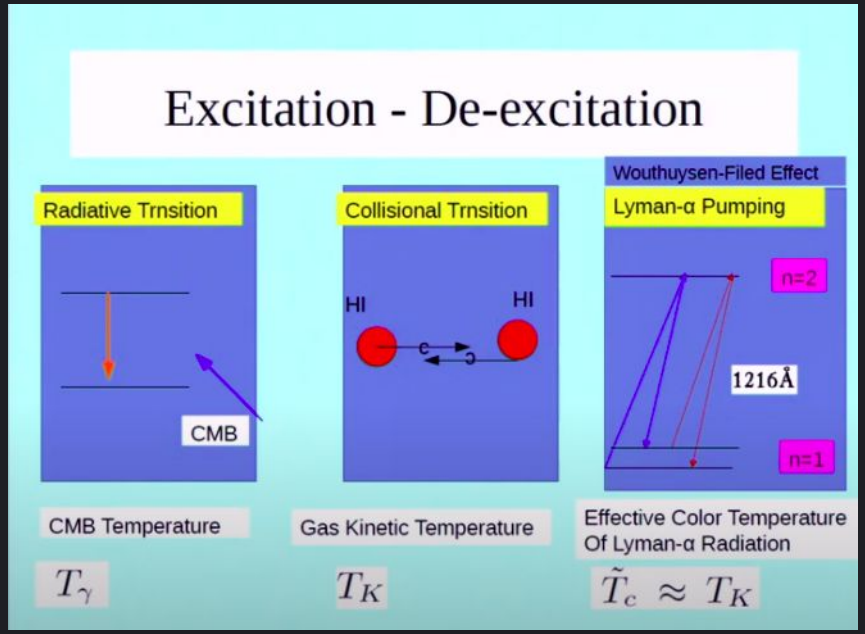




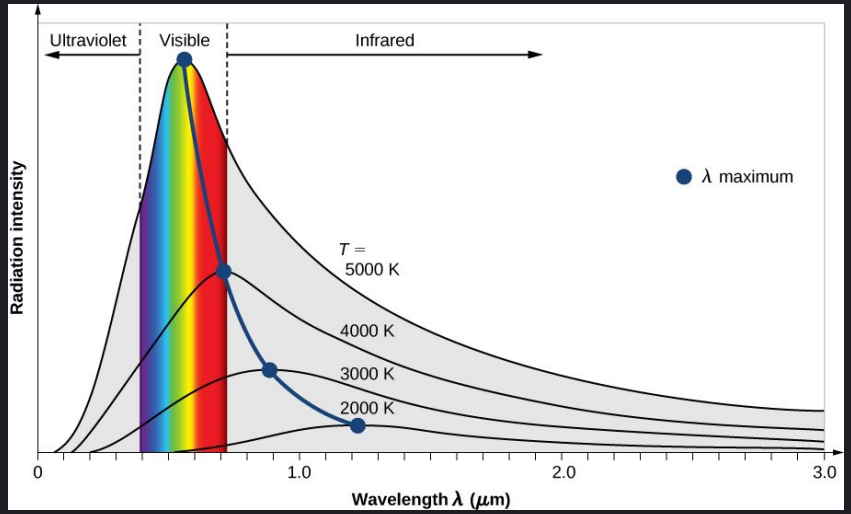
The last scattering surface



CMB, collisions and Lyman-alpha pumping

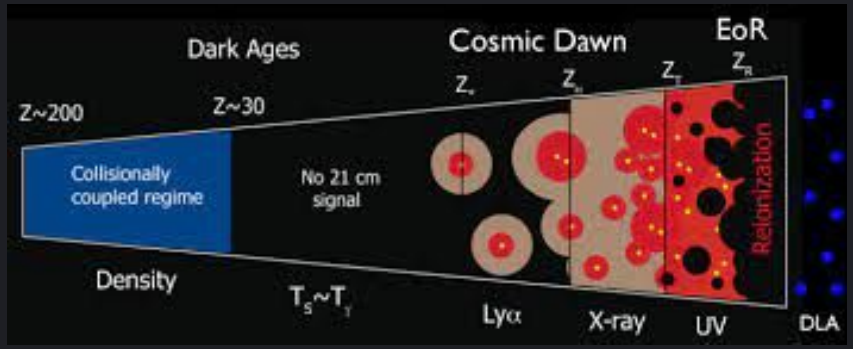


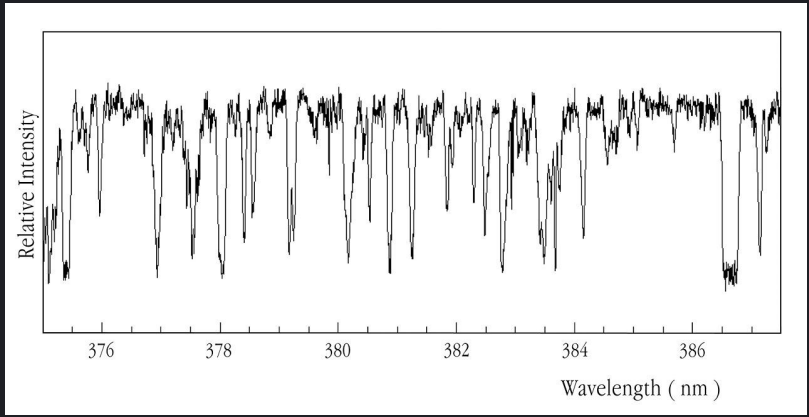
Brightness and spin temperatures



Blackbody radiation: $$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{KT}} - 1}$$

The dark ages and reionization



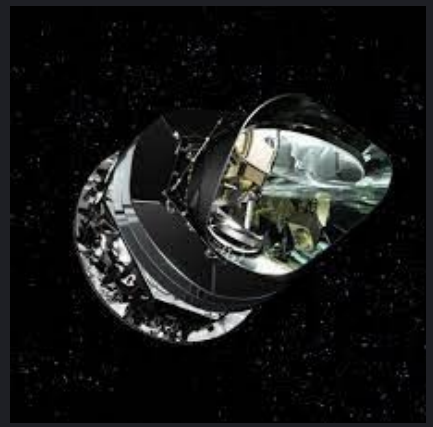


04.

Observational surveys

of various interesting stuff

Planck and COBE



- Measured the CMB and its anisotropies to the highest levels of accuracy, tested theories of the early universe and the origin of structure.
- Provided accurate measurements of standard cosmological parameters.
- More information available at: https://science.nasa.gov/missions/cobe, https://www.cosmos.esa.int/web/planck

Radio interferometry

- Large radio telescopes required in order to resolve the object properly. Recall $\theta = \frac{1.22\lambda}{D}$
- Thus, one resorts to **radio interferometry** by using a large number of telescopes in an **array**, spread over a large area.

The Square Kilometer Array (SKA)

- Largest radio telescope ever to be built with a total collecting area of over 1 sq. km.
- Spread across two continents with 14 member countries.
- Posed to answer many questions such as the nature of dark energy, galaxy formation and evolution, the search for alien life and perform tests for general relativity.
- More about it here: https://www.skatelescope.org/

THANKS

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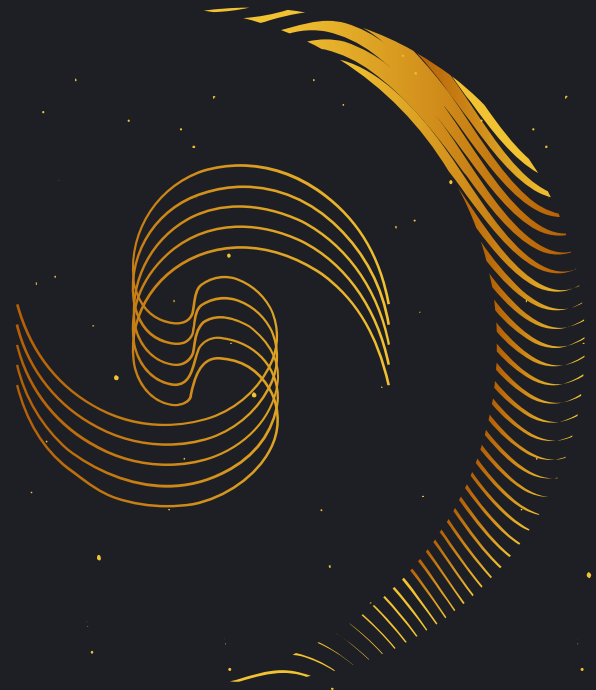
Rahul : rahulpriyadarshan19@gmail.com



Further Reading

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THANK YOU

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