# LECTURE 6: PRINCIPLES OF SPACE AND TIME

- Coordinate systems and reference frames
- Galilean relativity
- Cosmological principle
- Cracks in Newton's theory
- The speed of light problem- if we have time

*This week: please finish Ch 6 of text and start Ch 7*

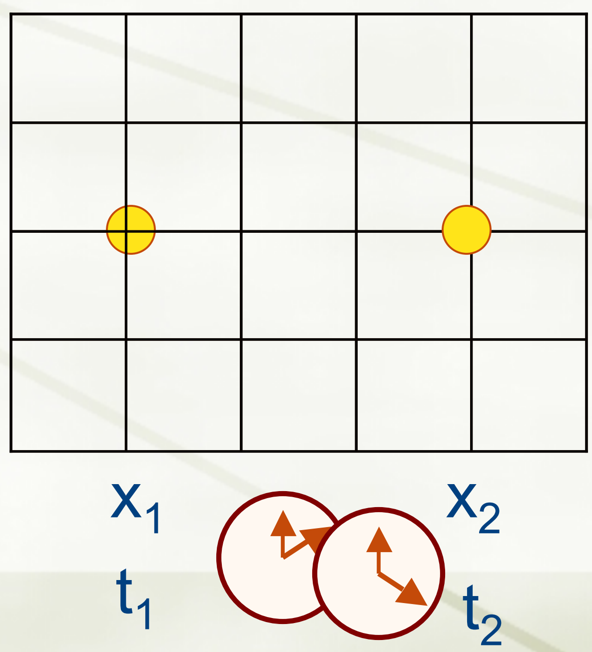
# *Coordinate systems*

- Scientific observations involve making measurements
- Fundamental measurements are always of events in terms of their coordinates in space and time
- Space-time coordinates are often written as $(x,y,z,t)$
- Coordinates are convenient labels, not fundamental attributes of space and time
  - We are free to choose whatever units we want (e.g. m, km, foot,…), and whatever coordinate origin we want
  - What matters is the *intervals* in time and space, not absolute numbers. For Event 1 at $(x_1,y_1,z_1,t_1)$ and Event 2 at $(x_2,y_2,z_2,t_2)$, the time interval is $\Delta t=t_2-t_1$ , and using the Pythagorean theorem generalized to 3D, the space interval (distance) is

$$\Delta s = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

# *Review- Velocities and accelerations*

- Velocities are rates of change of vector positions
- Accelerations are rates of change of vector velocities
- For motion in a *given* direction, the velocity is equal to the change in position $\Delta \underline{x} = x_2 - x_1$ divided by the corresponding change in time $\Delta t = t_2 - t_1$ : $\underline{v} = \Delta x / \Delta t$
- Similarly, $\underline{a} = \Delta \underline{v} / \Delta t$



# *Inertial and non-inertial frames of reference*

- Newton's laws are powerful. But they also lead to some puzzles, particularly relating to reference frames.
- We have already come across idea of frames of reference that move with constant velocity. In such frames, Newton's laws (esp. N1) hold. These are called **inertial frames of reference**.
- Suppose you are in an accelerating car looking at a freely moving object (i.e., one with no forces acting on it). You will see its velocity changing because you are accelerating! *In accelerating frames of reference, N1 doesn't hold* – this is a **non-inertial frame of reference**- and it can have 'fake' forces(last lecture: Coriolis, centrifugal forces) .

# *Real and fictitious forces*

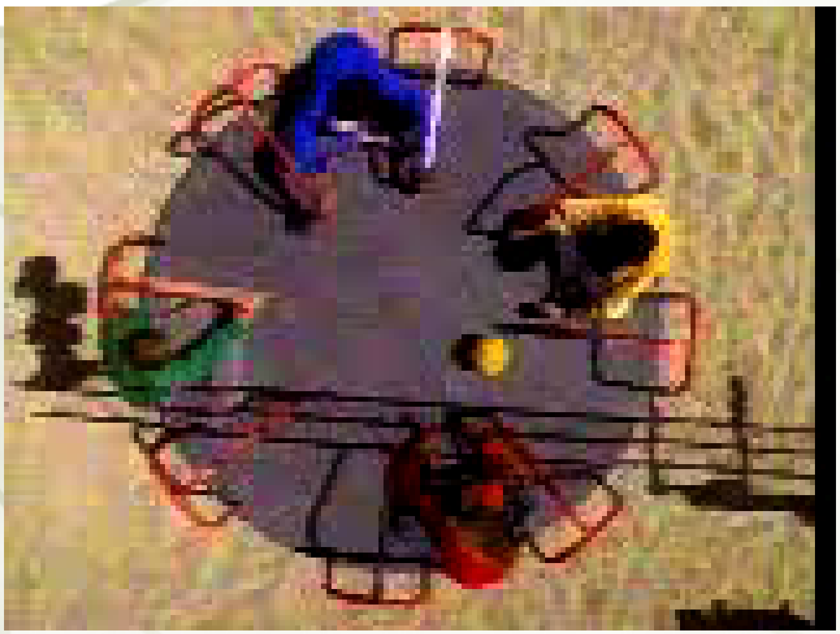
- In non-inertial frames you might be fooled into thinking that there were forces acting on free bodies, because velocities change.
- Such forces are call "fictitious forces". Examples –
  - G-forces in an accelerating vehicle.
  - Centrifugal forces in amusement park rides.
  - The Coriolis force on the Earth.
- Fictitious forces point opposite to the direction of acceleration measured in an inertial frame
- Fictitious forces are always proportional to the inertial mass of the body.

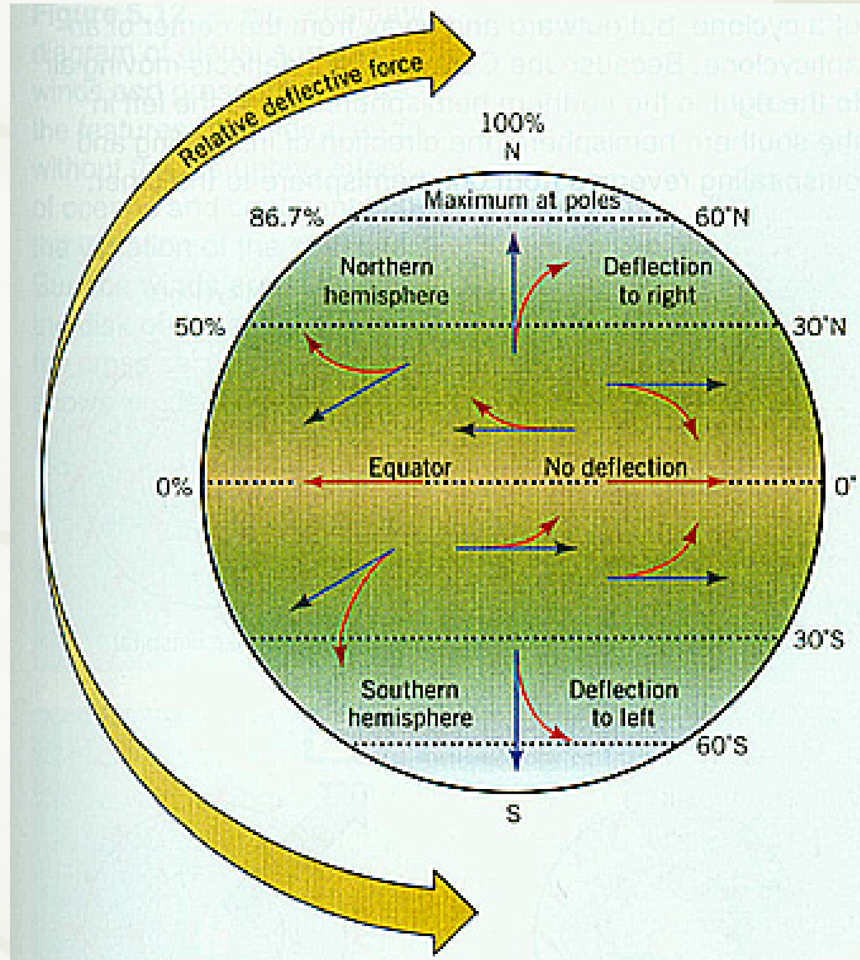
# *Coriolis force: a fictitious force*


Inertial frame


Noninertial frame

# Coriolis at work





# *Frames of reference, again*

- The frame of reference in which a measurement is made consists of the spatial coordinates (the grid) and time coordinate (the clock) that are used to make the measurement
- Note that in general, we use a "clock" that is attached to the spatial coordinate system we are using (why this matters will become apparent soon!)
- The reference frame may potentially have any arbitrary motion and/or acceleration. However, reference frames that have $\mathbf{a}\neq 0$ are fundamentally different from those with $\mathbf{a}=0$
- "Inertial frame" = unaccelerated frame
- "Non-inertial frame" = accelerated frame
- *How can an observer inside the frame tell the difference?*
  - In an inertial frame, a free particle (no forces acting) has constant velocity (including v=0 special case)
  - In a non-inertial frame, a free particle's velocity (speed and/or direction) varies
  - Note that for humans, even if we don't have a free particle handy for experiments, we can sense accelerations physiologically

# *…does this seem familiar?*

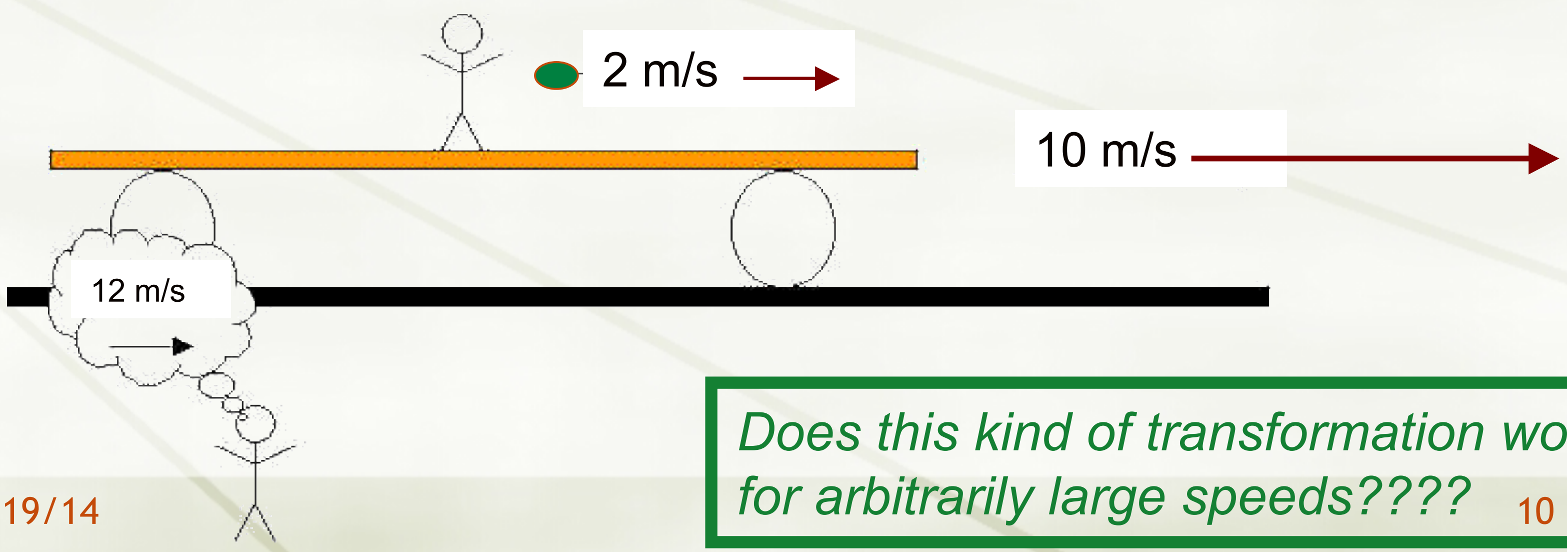
Recall that from weak equivalence principle, inertial mass=gravitational mass $\Rightarrow$ *gravitational force is proportional to inertial mass.*

**Maybe gravity is a fictitious force…**

**… and we live in an accelerating frame of reference???**

# Relativity

- "Relativity" refers in general to the way physical measurements made in a given inertial frame are related to measurements in another frame.
- An **inertial observer** is one whose rest frame is inertial
- A quantity is **invariant** if all inertial observers obtain the same value
- Under **Galilean relativity**, *measurements are transformed simply by adding or subtracting the velocity difference between frames:*
- $v_{ball}$(measured on ground)=$v_{train}$ (measured on ground)+$v_{ball}$(measured on train)
  12 m/s = 10m/s + 2 m/s
- $V_{ball}$(measured on train)=$v_{ground}$(measured on train)+ $v_{ball}$(measured on ground)
  2 m/s = –10m/s + 12 m/s




*Does this kind of transformation work for arbitrarily large speeds????*

# *Cosmological principle*

- The physical universe is described in terms of its properties in space and time- this seems obvious, but various cultures have included other attributes

- Confined to Earth, we are unable to *visit* all of space (or obtain information from all of time) **but** we can observe the universe far back in time and far away in space

- From Copernicus onward, it was realized that *Earth is not a special place; this is extended to include the solar system, our galaxy and to the idea that* no *place in the universe is special with respect to its position in space* (however with respect to time we have the initial singularity of the Big Bang).

# *Cosmological principle*

- In formulating cosmological models, we extend this idea to the much larger scale of the whole Universe
  - Fundamental principle is that any place in the Universe is "just about the same" as any other place. The Universe is essentially *uniform* (on large scales).

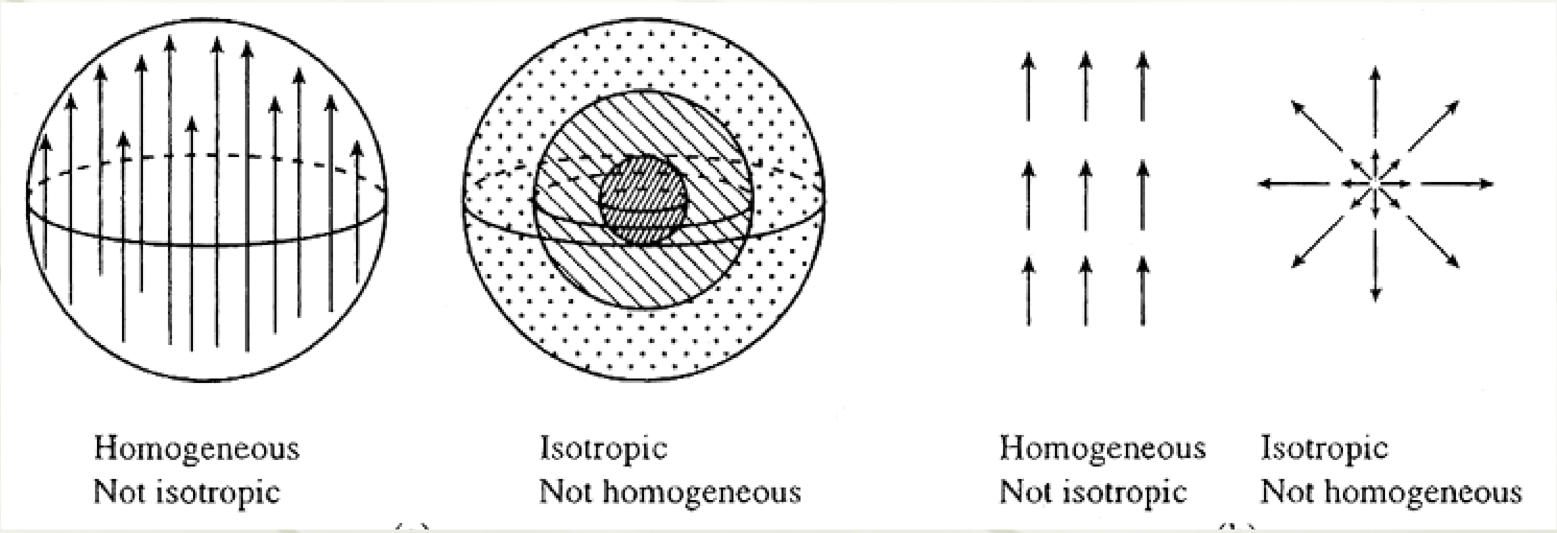
  or to phrase it differently

- On sufficiently large distance scales, there are no preferred directions or preferred *places* in the Universe.
  - The two testable structural consequences of the cosmological principle are homogeneity and isotropy.
  - *Isotropic:* Uniform in all *directions*

    *e.g., surface of a sphere is isotropic, surface of a cylinder is anisotropic*
  - *Homogeneous:* Similar conditions at all *locations*
  - Notes:
    1. isotropy as seen from every location implies homogeneity
    2. Homogeneity everywhere need not imply isotropy; e.g. surface of smooth, infinitely long cylinder is homogeneous but not isotropic

# Cosmological principle

- Isotropy : there are no special directions to the Universe (e.g. no center)
- Homogeneous : there are no special places in the Universe.
  1. isotropy as seen from every location implies homogeneity
  2. Homogeneity everywhere need not imply isotropy; e.g. surface of smooth, infinitely long cylinder is homogeneous but not isotropic




http://abyss.uoregon.edu/~js/cosmo/lectures/lec05.html

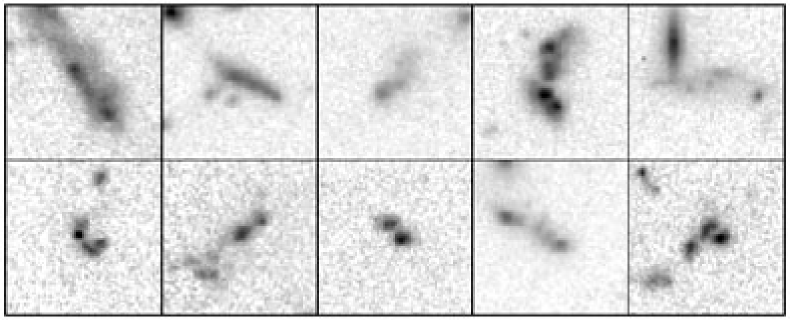
# *To Beat a Dead Horse*

- :
  - Imagine that the whole universe is an infinitely large field with one perfectly symmetrical hill, which you are seated atop. Look around: you see an isotropic universe, since the hill is equally green and equally steep in all directions. But the universe is not homogeneous: it has a hill! http://curious.astro.cornell.edu/question.php?number=508

- These concepts are important-
  - most modern cosmology is based on the "cosmological principle," it is assumed that, on large scales, the universe is both homogeneous and isotropic. Studies of large-scale structure in the universe and analysis of the microwave background radiation help confirm that this assumption is justified.

# *Perfect Cosmological Principle*

- The Perfect Cosmological Principle, that the Universe is homogenous and isotropic in space and time. That is, the universe looks the same everywhere (on the large scale), the same as it always has and always will- **This is not true**
- **The universe was different in the past**



Galaxies in the distant universe are very different than galaxies today

# *Some Tests of Isotropy and (Homogenity)*

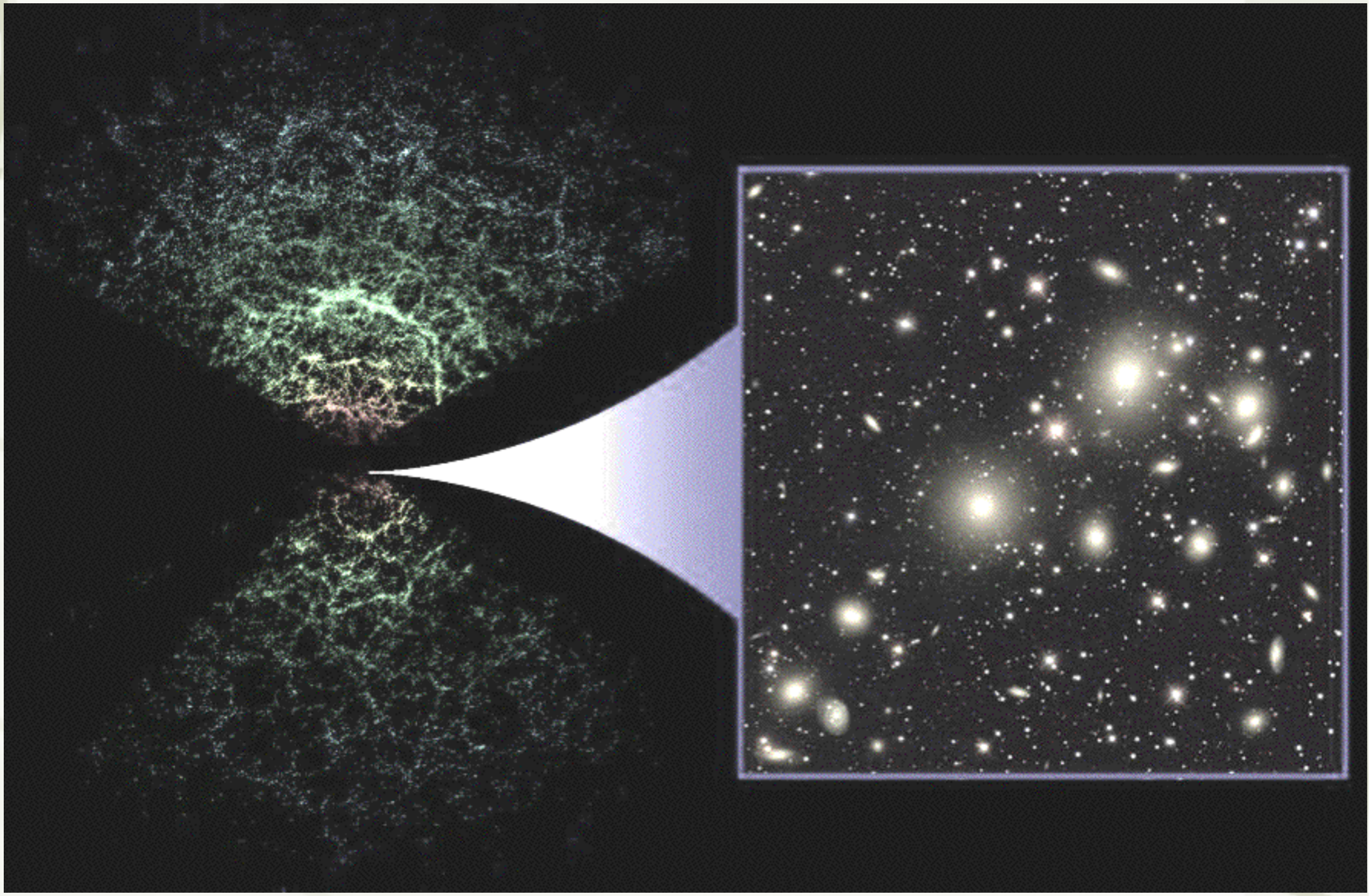
- (i) the large scale spatial distribution of galaxies,appears to be a *randomly* tangled web of clusters and voids up to around 400 megaparsecs* in width.
- ii) the distribution of radio galaxies, which are *randomly* distributed across the entire sky.
- (iii) the cosmic microwave background radiation, the relic radiation produced by the expansion and cooling of the early universe, constant temperature in **all** directions to one part in $10^5$
- (iv) spatial distribution of gamma-ray bursts, objects at cosmological distances

Homogenity is very difficult to test since the universe is evolving- use consistency relations between distances and expansion rates: a bit messy to show

* megaparsec= $10^6$pc=$3.0856 \times 10^{22}$ m

# *Large Scale distribution of normal galaxies*

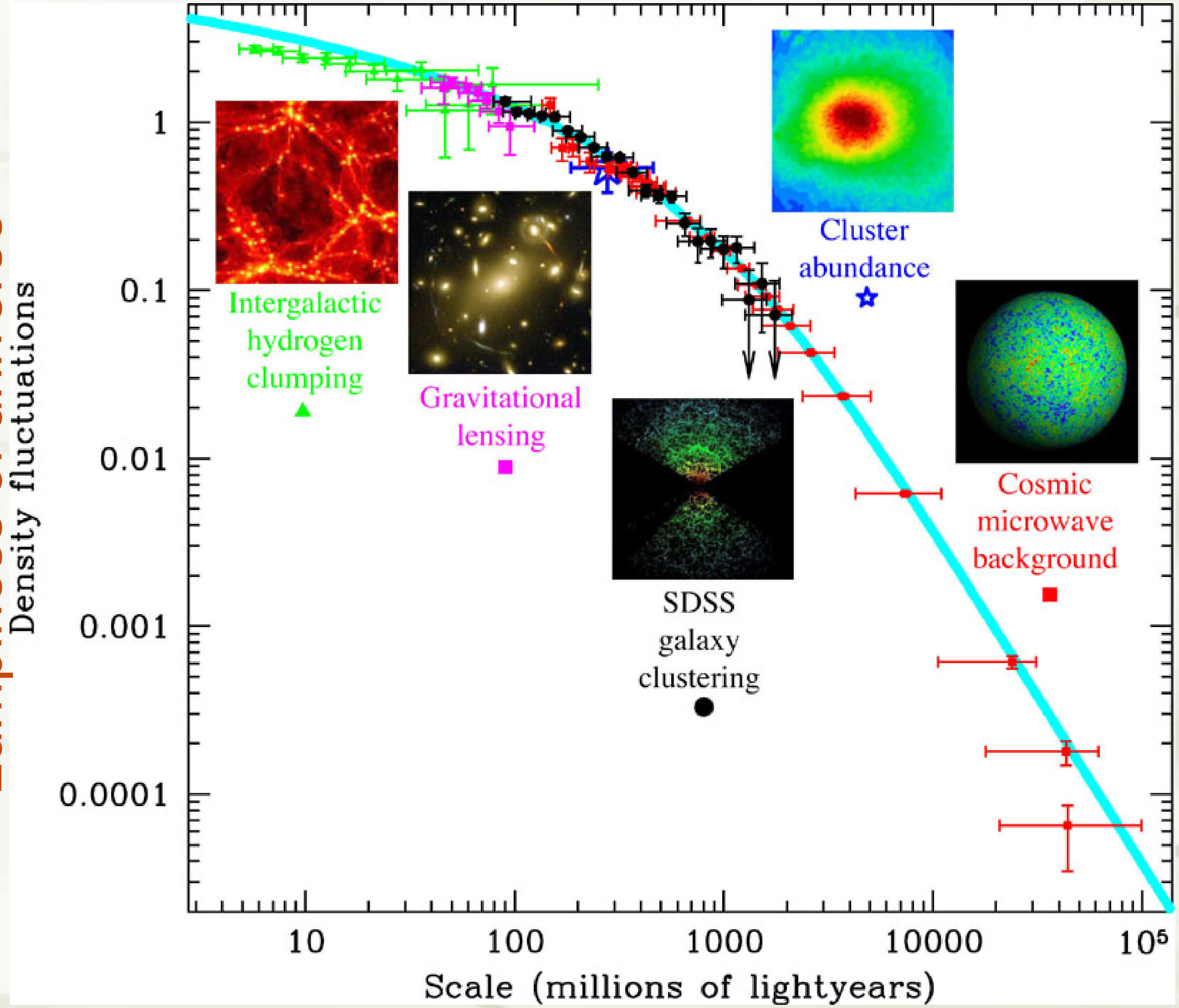
- On scales $<10^8$pc the universe is 'lumpy'- e.g. non-homogenous
- On larger scales it is homogenous- and isotropic



Sloan Digital Sky Survey- http://skyserver.sdss3.org/dr8/en/

- As one goes to larger scales the universe gets less lumpy (on average)

Lumpiness of universe



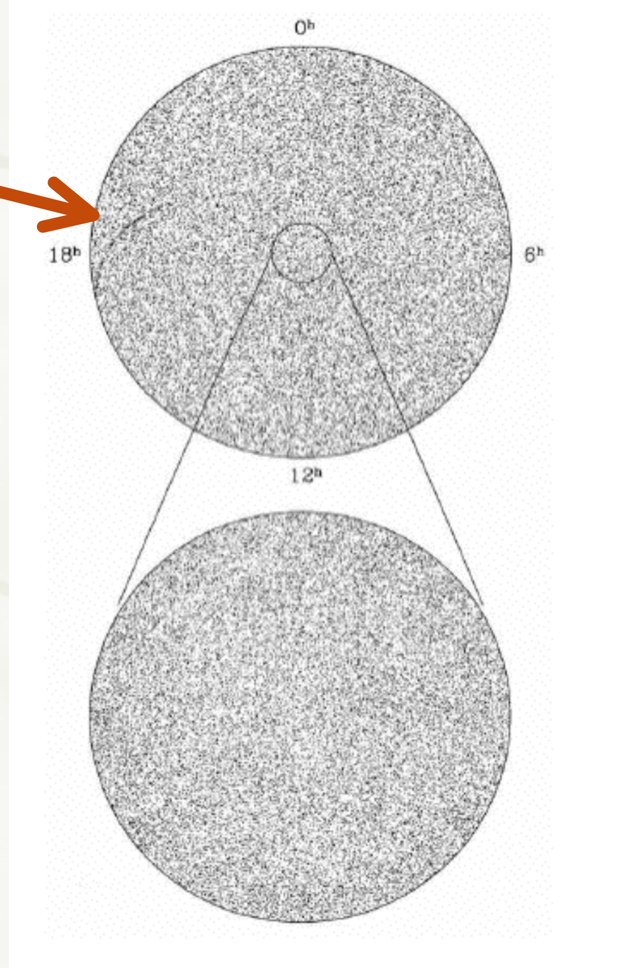

Tegmark 2004

size of box

# *Distribution of Radio Galaxies**

- Position of 40,000 brightest radio sources in northern sky
- 40,000 brightest sources near celestial north pole
- Mean distance between sources is ~$10^7$ pc- probe very large distances up to when universe was only 2 billion years old

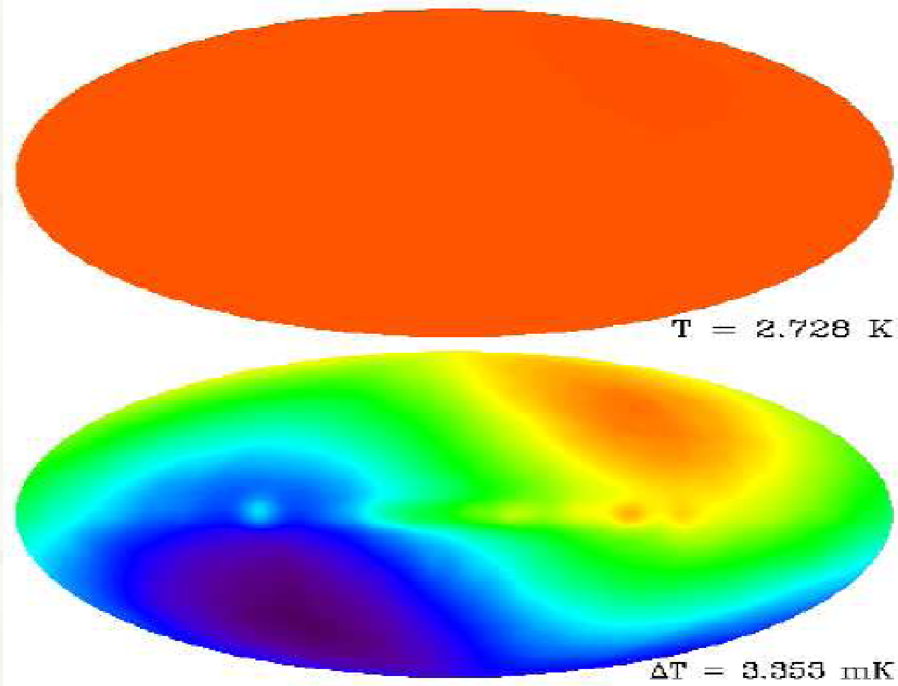
Condon 1999 PNAS97,4756

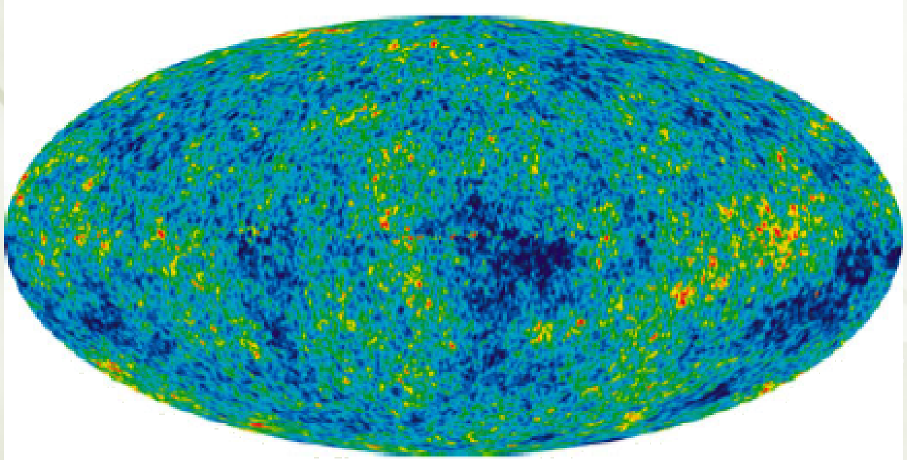



*radio galaxies are a special type of galaxy whose radio luminosity is produced by a supermassive black hole

## *Microwave Background- relic of the big bang*

- CMB probes whole universe at 300,000 yrs after Big Bang
  - isotropic to $\Delta T/T \sim 10^{-5}$

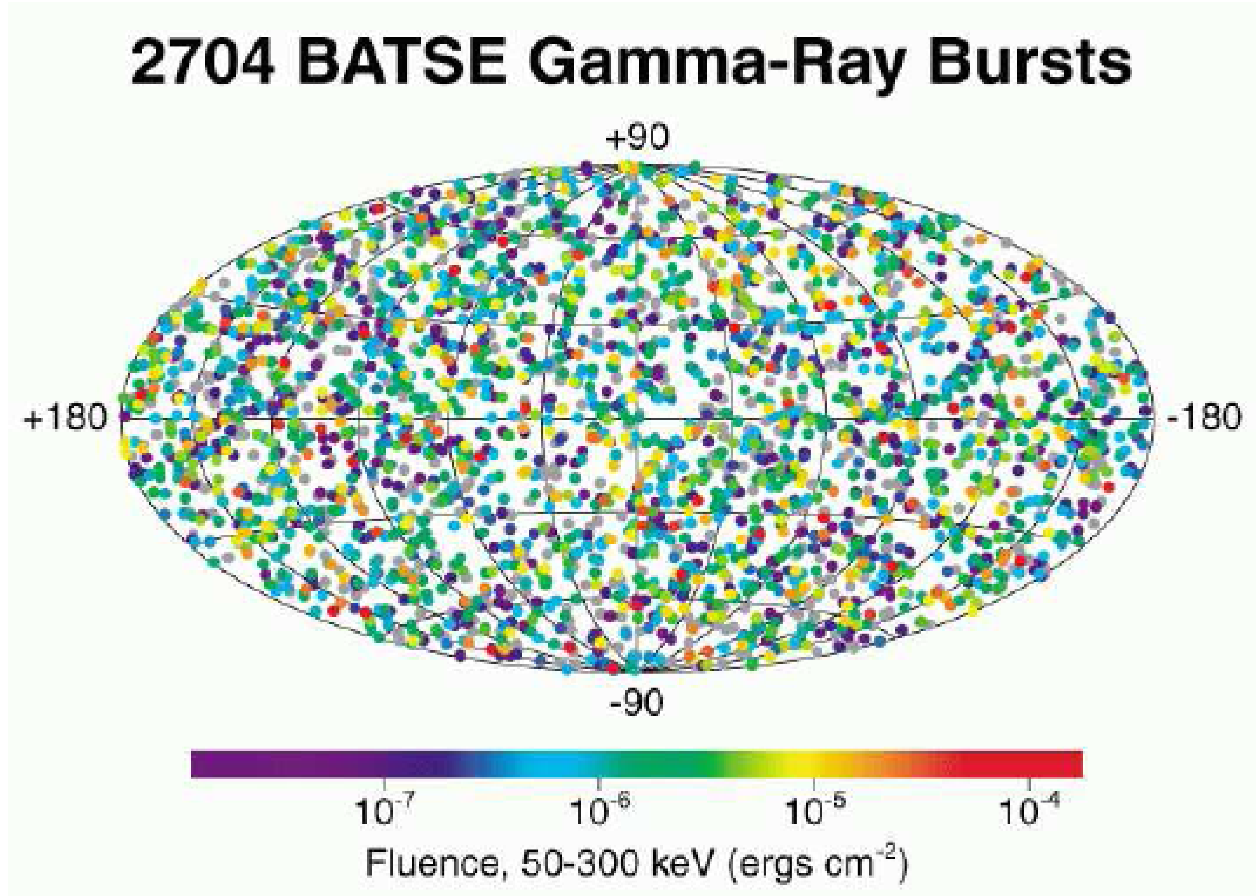


CMB temperature map from WMAP showing anisotropies at level of $10^{-5}$

# *Gamma-Ray Bursts*

- Gamma-ray bursts come from very far away, on average
- The mean redshift is z~1 (half the 'age' of the universe)- very isotropic




Position of γ-ray bursts on the sky in galactic coordinates derived from the Gamma-ray observatory satellite BATSE experiment- color is proportional to brightness of burst

- Cosmological principle → physical laws are assumed to be the same everywhere (can now measure atomic transitions in objects at redshifts ~6 when Universe is 1 billion years old and verify that quantum mechanics is the same )
- The cosmological principle of isotropy and homogeneity, like other scientific hypotheses, is testable by confrontation with data.
- So far, observations support this hypothesis

# NEWTON'S WORRIES

- Newton himself had concerns about his theory
  - Gravity is "action at a distance" – i.e. gravitation force somehow (mysteriously) reaches across large distances.
    - Newton was very suspicious of this.
    - How is information *communicated* from one gravitating body to another?
  - Problems with a static universe
    - Newton imagined that the Universe was infinite and full of stationary stars, each exerting a gravitational force on the others.
    - this configuration (and any other that Newton could think of) is unstable… the smallest disturbance and it will collapse in on itself! (takes a long time tho)
    - What prevents this collapse?

# *Physics after Newton and Before Einstein: Electromagnetic waves*

- The physics of electricity and magnetism:
  - In the late 1700's to mid 1800's scientists like Coulomb, Oerstead, Ampere, Faraday, Gauss developed ideas of how electricity and magnetism 'worked'-like Kepler and Brahe before Newton
- These quantitative theories of electricity and magnetism were formulated in terms of forces acting at a distance, analogous to Newton's law of gravitation.
- The fields of electromagnetism and understanding of light *were* unrelated and treated as separate branches having no connection.

# Physics after Newton and Before Einstein  electromagnetic waves

- James Clerk Maxwell (1831-1879)
  - Developed theory of electromagnetic fields in the 1860's (Maxwell's equations)
  - These unify the electric and magnetic forces in a single theory

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{E} = \rho$$

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$$

$$\nabla \times \mathbf{B} = 4\pi \mathbf{J} / c + (1/c) \partial \mathbf{E} / \partial t$$

These vector equations are just written out for 'fun'… you do not need to know them!

Notice that the speed of light 'c' enters explicitly

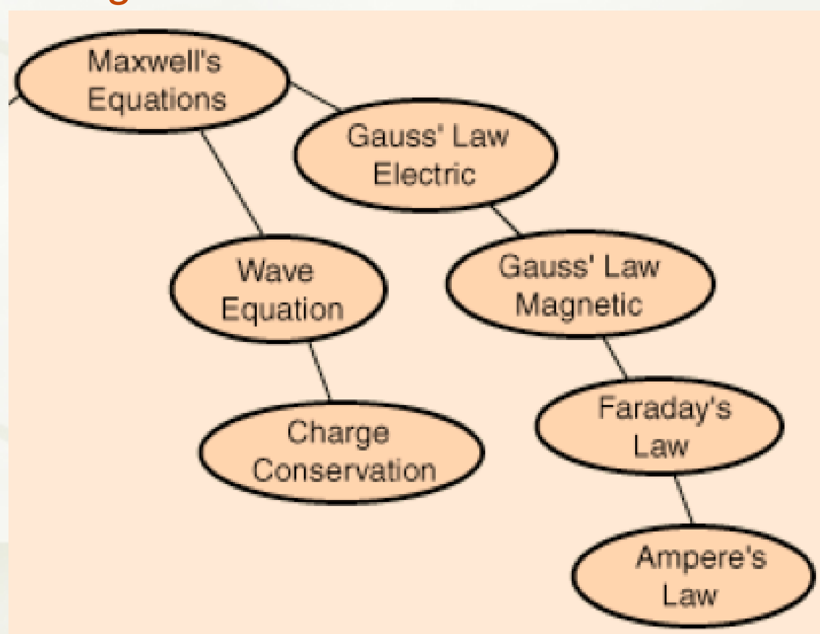
# A little bit more detail

- Maxwell discovered a speed equal to the speed of light from a purely theoretical argument based on experimental determinations of forces **between currents in wires and forces between electrostatic charges.**
- This led to the realization that light is an electromagnetic <u>*wave.*</u> (and that there must be other such waves with different wavelengths).
- Hertz detected other waves, of much longer wavelengths, experimentally, and this led directly to radio, tv, radar, cellphones

Maxwell's equations are an elegant and concise ways to state the fundamentals of electricity and magnetism.

They are core to an understanding of electricity, magnetism and light. but require a level of mathematical sophistication to understand

The speed of light is related to 2 constants that come out of the laws describing electric and magnetic forces



# THE SPEED OF LIGHT PROBLEM

- Maxwell's equations:
  - Predict "waves" of electromagnetic energy – and it was quickly realized that these are light waves!
  - The speed of light "c" appears as a **fundamental constant** in the equations.
  - c = 299,792.458 km/s (**$3x10^5$ km/s** )- in vacuum*
  - **BUT, what frame of reference is this measured relative to???**
  - If Light is a Wave, What is Waving?

*speed of light is slower in air ,water and in other mediums but is never faster!

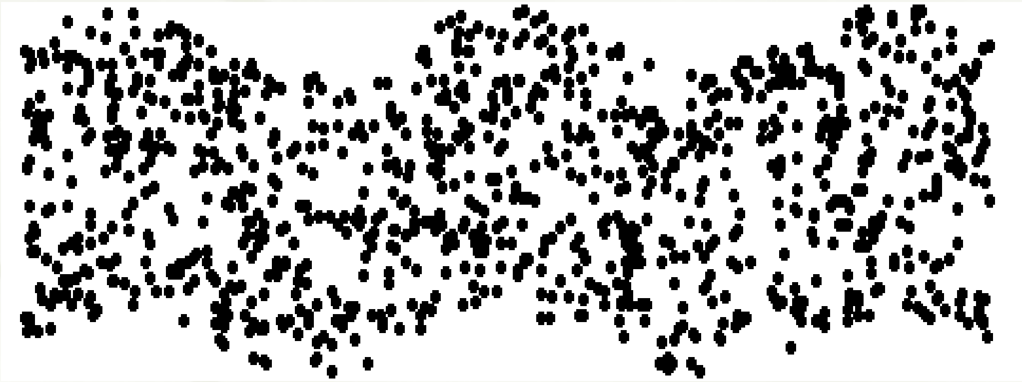
Known to greater accuracy than length of meter

# *Ether and light waves*

- Luminiferous Ether (19th century)
  - Hypothetical substance that fills space - provides a “medium” through which light can travel.
  - Idea was that Maxwell’s equations would apply only in frame of ether
  - This would explain why the speed of wave propagation “c” is a constant in the equations
  - If speed of light in aether is “c” , and *if Galilean relativity holds*, **then speed of light measured in other frames would be different from “c”**
  - Albert Michelson & Edward Morley attempted (1887) to measure motion of Earth through ether…

# Waves

- Before Maxwell all waves (sound, pressure waves in earthquakes etc) were known to be disturbances in the substance (water, air) through which they traveled and are generally not accompanied by a motion of the medium occupying this space as a whole
- sound waves propagate via air molecules bumping into their neighbors

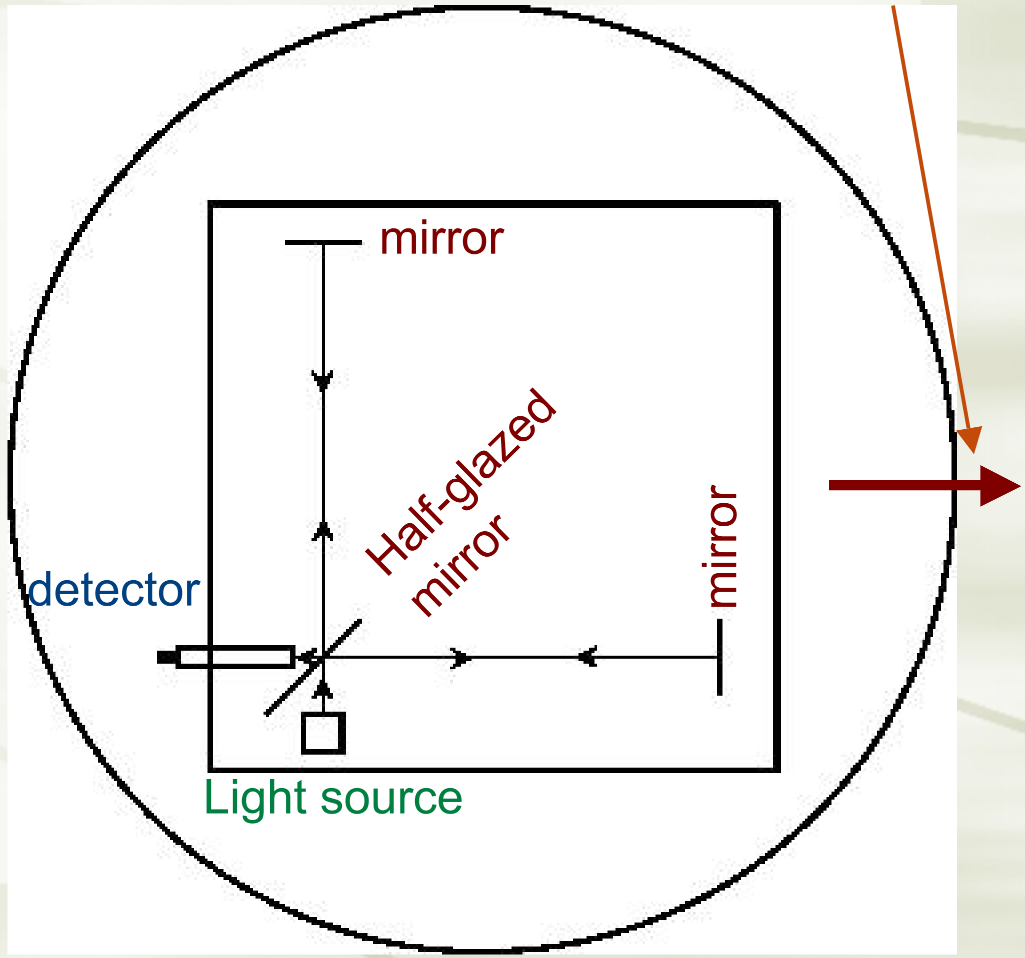


http://www.kettering.edu/physics/drussell/Demos/waves/wavemotion.html

# *Michelson-Morley Experiment*

- Light leaves source, and is partly reflected/partly transmitted at half-glazed mirror
- Light returning from both paths is collected at detector
- Path length of light along either “arm” of apparatus is the same
- **If one arm is along Earth’s motion through ether, and the other arm is perpendicular to motion through ether, then light travel time was expected to be shorter for perpendicular arm**

Motion of earth



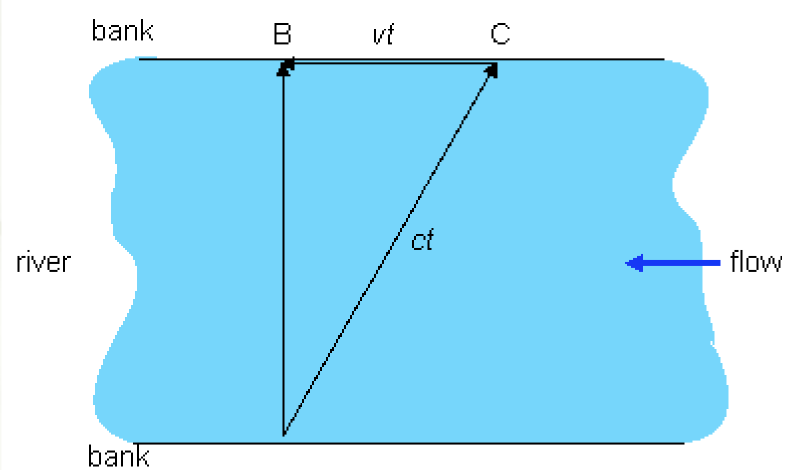
# Michelson-Morley Experiment

- Travel time difference was measured using interference fringes of light from two paths
- Apparatus could be rotated to make sure no effects from set-up
- Repeated at different times of year, when Earth's motion differs; Earth's speed around the Sun is ~30 km/s
- Experiment performed in 1887

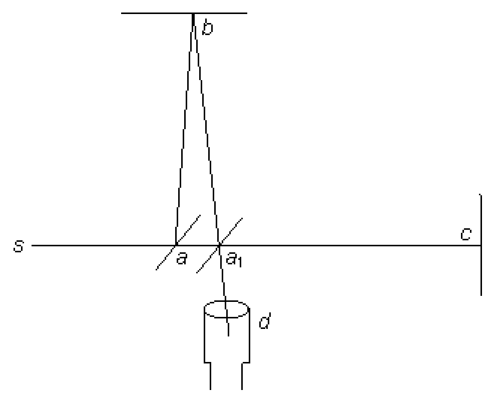
- Results
  - M-M showed that speed of light was same in any direction to within 5 km/s
  - Modern versions of the experiment show constancy to better than $10^{-6}$ m /s
- So, what's going on??

# Michelson-Morley

- Michelson's critical idea was to construct a race for pulses of light, with the aether wind playing the part of the river.
- expected difference in time is ~ $2(\text{pathlength}/c) \times (v^2/2c^2)$ - where v is the velocity of the aether




In time *t*, the swimmer has moved *ct* relative to the water, and been carried downstream a distance *vt*.




This is also from the original paper, and shows the expected path of light relative to the aether with an aether wind blowing.

Tried to measure annual effect effect to due rotation of earth and at different altitudes-nothing seem

http://galileoandeinstein.physics.virginia.edu/home.html

# Michelson-Morley Extra Slide

- Michelson's explanation of his experiment to his children
- Suppose we have a river of width w (say, 100 feet), and two swimmers who both swim at the same speed v feet per second (say, 5 feet per second). The river is flowing at a steady rate, say 3 feet per second. The swimmers race in the following way: they both start at the same point on one bank. One swims directly across the river to the closest point on the opposite bank, then turns around and swims back. The other stays on one side of the river, swimming upstream a distance (measured along the bank) exactly equal to the width of the river, then swims back to the start. Who wins?

- The algebra for deciding which swimmer goes the fastest (each swimmer can swim at 5 ft per sec)
- Consider the swimmer going upstream and back. Going 100 feet upstream, the speed relative to the bank is 2 feet per second, takes 50 seconds. Coming back, the speed is 8 feet per second, takes 12.5 seconds, total time of 62.5 seconds.
- the 2nd swimmer must aim upstream at the correct angle. Thus, the swimmer is going at 5 feet per second, at an angle, relative to the river, and being carried downstream at a rate of 3 feet per second. If the angle is correctly chosen so the movement is directly across, in one second the swimmer must have moved four feet across: the distances covered in one second will form a 3,4,5 triangle. So, at a crossing rate of 4 feet per second, the swimmer gets across in 25 seconds, and back in the same time, for a total time of 50 seconds. The cross-stream swimmer wins

Taken from http://galileo.phys.virginia.edu/classes/109N/lectures/michelson.html

see http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/mmexpt6.htm for nifty graphics

# Attempts to deal with M-M results

- Maybe the ether "sticks" to the Earth?
  - Gets "dragged" as Earth spins and orbits Sun…
  - Possibility at the time, but no-longer viable.
- Maybe the ether squeezes the arms of the M-M experiment and distorts the result? "Fitzgerald contraction" (1889)?
  - A contraction (in the direction parallel to motion through ether) would change the light travel time to compensate for the difference expected due to different speed of light

$$L = L_0\sqrt{1 - V^2 / c^2}$$

- Major mystery ("crisis") in 19th century physics – two highly successful theories seemed incompatible!
  - Mechanics – Galilean Relativity and Newton's laws
  - Electromagnetism – Maxwell's equations

# Next time…

Apparently light is not like sound, with a definite speed relative to some underlying medium. However, it is also not like bullets, with a definite speed relative to the source of the light. When one measure its speed always get the same result. How can all these facts be interpreted in a simple consistent way?

*Einstein to the rescue!-*

*Read Chapter 7*

*Homework #2 to be handed out*

# Albert Einstein

- Over a 15 year period (1905-1920) came the most explosive ideas of the century. They were catalysts that set in motion a reappraisal of every premise and postulate of modern natural science, a physical revolution whose end is far from sight.
- His ideas, like Newton's and Darwin's, reverberated beyond science, influencing modern culture from painting to poetry.
- Read more: http://www.time.com/time/magazine/article/0,9171,993017,00.html#ixzz1YQbS5kcK

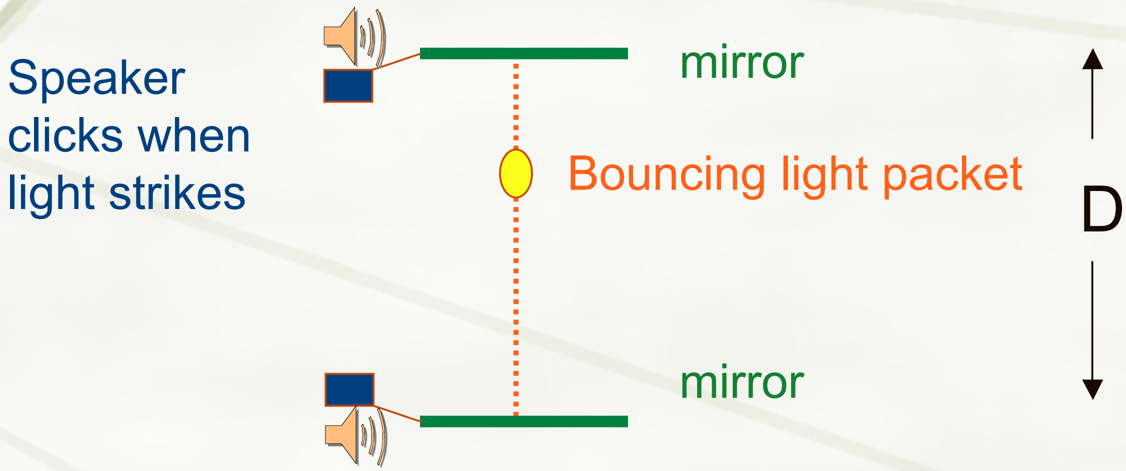
# *II : Einstein's Postulates of Special Relativity*

- Albert Einstein
  - Didn't like idea of Aether
  - Threw away the idea of Galilean Relativity
  - Came up with the two "Postulates of Relativity"

- **Postulate 1** – The laws of nature are the same in all inertial frames of reference
- **Postulate 2** – The speed of light in a vacuum is the same in all inertial frames of reference.

# III: TIME DILATION

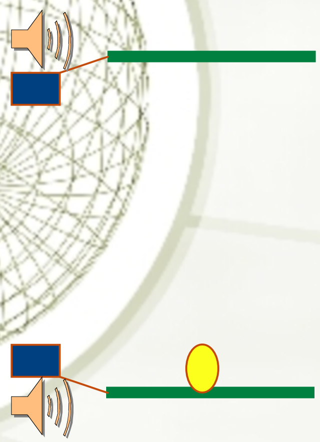
- Imagine building a clock using mirrors and a light beam.




- One "tick" of the clock is the time it takes for light to travel from one mirror to the other mirror.

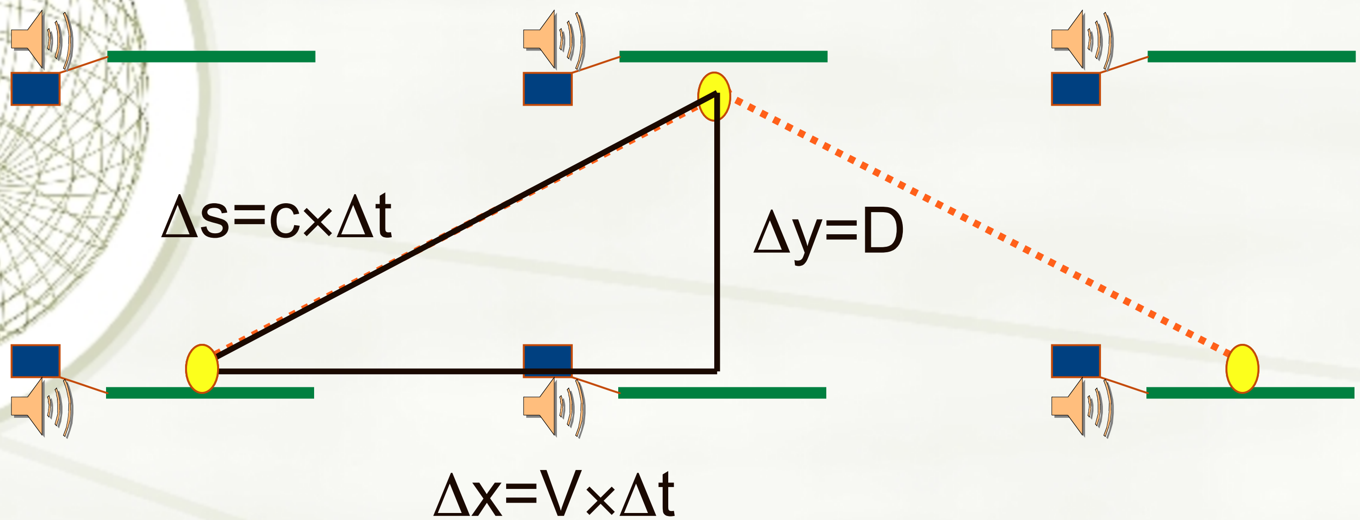
$$\Delta T = \frac{D}{c}$$

# *Moving clock*



- Now suppose we put the same "clock" on a spaceship that is cruising (at constant velocity, V) past us.
- How long will it take the clock to "tick" when we observe it in the moving spacecraft? Use Einstein's postulates…
- Total distance traveled by light beam is $\Delta s = c \times \Delta t$
- Therefore time $\Delta t = \Delta s / c$
- By Pythagorean theorem, $\Delta s = c\Delta t = \sqrt{\Delta x^2 + \Delta y^2} = \sqrt{(V\Delta t)^2 + D^2}$
- Can solve to obtain $\Delta t = (D/c) \div (1 - V^2/c^2)^{1/2} > D/c$
- Clock appears to run more slowly!!

# *Moving clock*

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- Clock appears to run more slowly!!

# *Now change the point of view…*

- For ground-based observer, clock on spaceship takes longer to "tick" than it would if it were on the ground
- But, suppose there's an astronaut in the spacecraft
  - the inside of the spacecraft is also an inertial frame of reference – Einstein's postulates apply…
  - So, the astronaut will measure a "tick" that lasts

$$\Delta T = \frac{D}{c}$$

  - This is just the same time as the "ground" observers measured for the clock their own rest frame
- So, different observers see the clock going at different speeds!

## So time is not absolute!!

It depends on your point of view…

# *Time dilation*

- This effect called **Time Dilation.**
- Clock always ticks most rapidly when measured by observer in its own rest frame
- Clock slows (ticks take longer) from perspective of other observers
- When clock is moving at V with respect to an observer, ticks are longer by a factor of

$$\Delta t \div \Delta T = \frac{D/c}{\sqrt{1-V^2/c^2}} \div \frac{D}{c} = \frac{1}{\sqrt{1-V^2/c^2}}$$

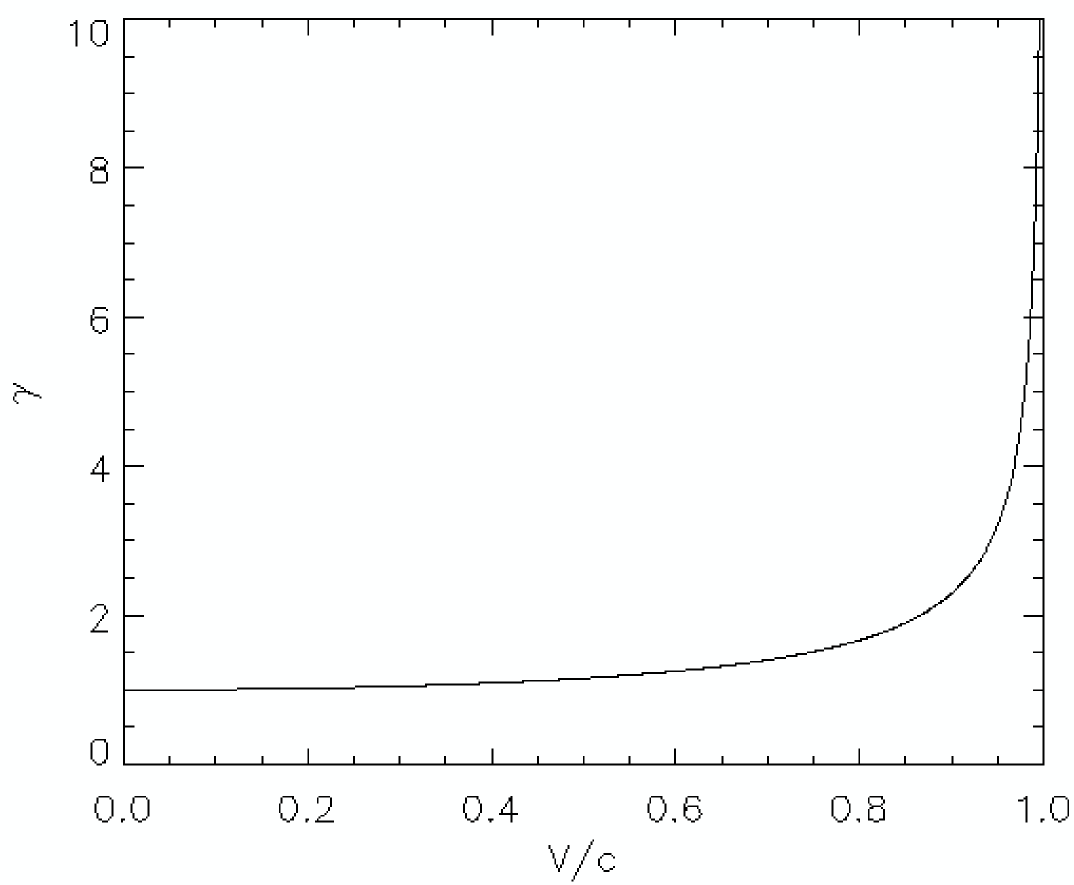
- This slowing factor is called the **Lorentz factor,** $\gamma$

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

# Clocks and time

- Does this "time dilation" effect come about because we used a funny clock?
- No, any device that measures time  would give the same effect!
- The time interval of an event as measured in its own rest frame is called the ***proper time***
- Note that if the astronaut observed the same "light clock" (or any clock) that was at rest on Earth, it would appear to run slow by the same factor $\gamma$ , because the dilation factor depends on *relative speed*
- This is called the ***principle of reciprocity***

# *Lorentz factor*




A 1% effect at v = 0.14 *c*, or about 42,000,000 m/s

Lorentz factor goes to infinity when V→c!

But it is very close to 1 for V/c small

# Why don't we ordinarily notice time dilation?

Some examples of speeds in m/s

- 0.0055m/s world record speed of the fastest snail in the Congham,UK
- 0.080 m/s the top speed of a sloth (= 8.0 cm/s)
- 1 m/s a typical human walking speed
- 28 m/s a car travelling at 60 miles per hour (mi/h or mph) or 100 kilometres per hour (km/h); also the speed a cheetah can maintain
- 341 m/s the current land speed record, which was was set by ThrustSSC in 1997.
- 343 m/s the approximate speed of sound under standard conditions, which varies according to air temperature
- 464 m/s Earth's rotation at the equator.
- 559 m/s the average speed of Concorde's record Atlantic crossing (1996)
- 1000 m/s the speed of a typical rifle bullet
- 1400 m/s the speed of the Space Shuttle when the solid rocket boosters separate.
- 8000 m/s the speed of the Space Shuttle just before it enters orbit.
- 11,082 m/s  High speed record for manned vehicle, set by Apollo 10
- 29,800 m/s Speed of the Earth in orbit around the Sun (about 30 km/s)
- 299,792,458 m/s the speed of light (about 300,000 km/s)

# Examples of time dilation

- The Muon Experiment
  - Muons are created in upper atmosphere from cosmic ray hits
  - Typical muon travel speeds are 0.99995×c, giving $\gamma$=100
  - Half-life of muons in their own rest frame (measured in lab) is $t_h$= 2 microseconds =0.000002s
  - Traveling at 0.99995×c for $t_h$=0.000002s, the muons would go only 600 m
  - But traveling for $\gamma\times t_h$= 0.0002s, the muons can go 60 km
  - *They easily reach the Earth's surface, and are detected!*
  - *Half-life can be measured by comparing muon flux on a mountain and at sea level; result agrees with* $\gamma\times t_h$