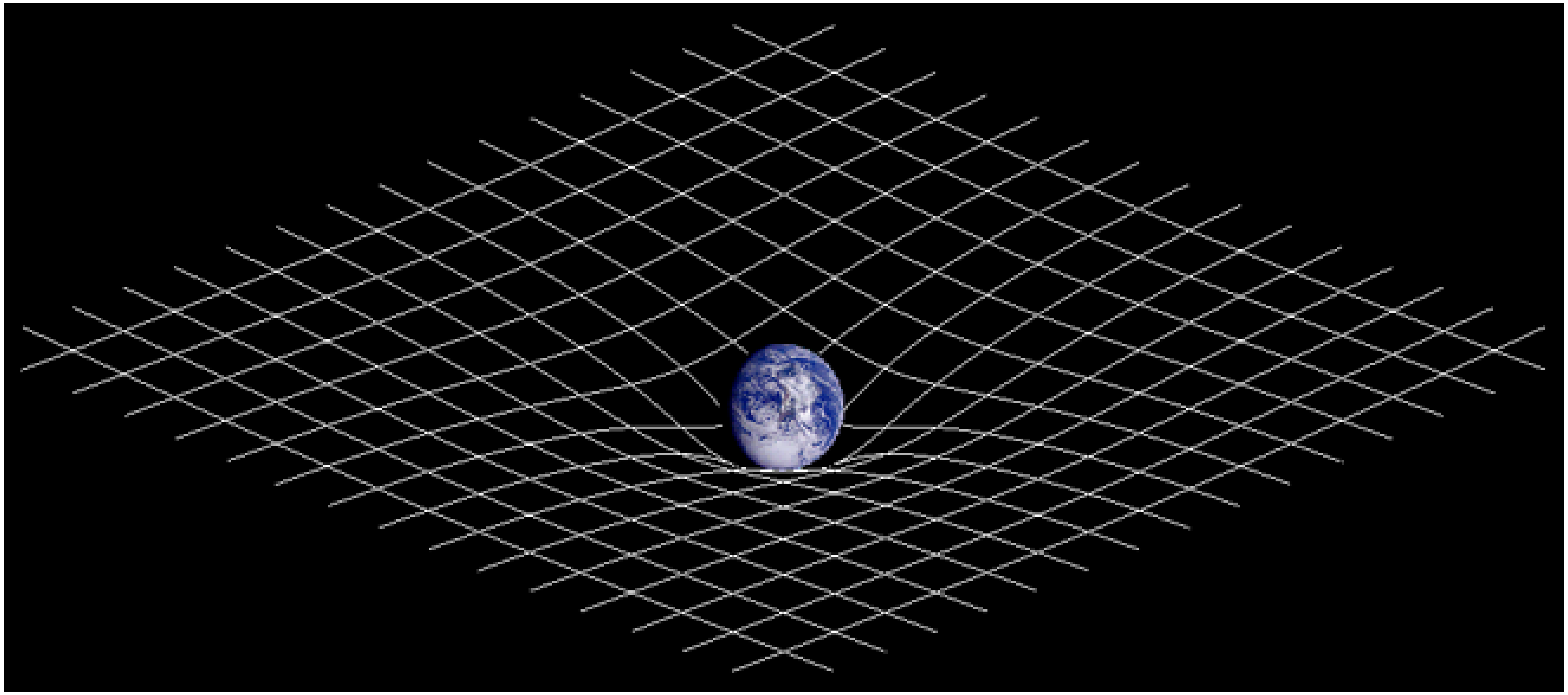
Misc

1. Final exam is scheduled for ***Monday, March 17, 1:30-3:30PM here in KPTC 106***.

2. Today, we are covering material of S 22-2, 26-1, 26-2

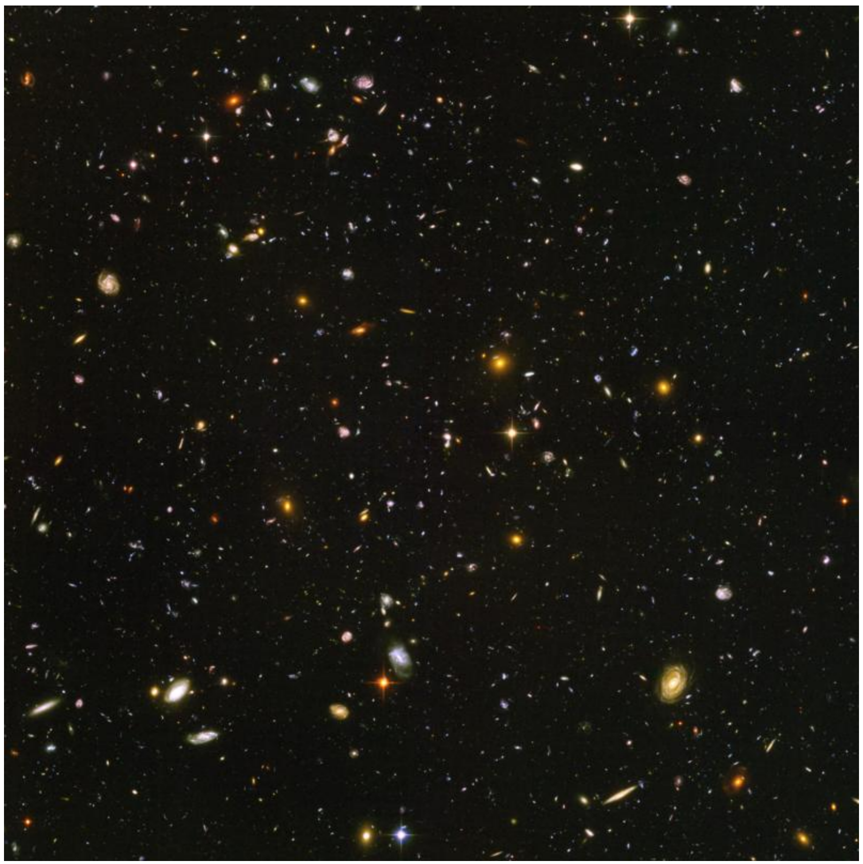
3. Next week, we will start SNIa lab (length 2 weeks), not the CMB lab as originally scheduled.

Lecture 11



Olbers paradox.
Einstein's theory of General Relativity.

The Big Questions of cosmology



Hubble Space Telescope Ultra Deep Field

- What is the origin of the Universe and how did it evolve?
- What is its structure?
- How large is it? Is it infinite?

The universe is in fact without limit of any kind,
for if it had it would have to have an outside.
Nothing can have an outside unless there is something beyond it;
So the point can be seen at which it ceases to be
and beyond which the senses could not follow it.
There can be no such point for the whole creation;
If one thinks of the whole there can be nothing outside it,
it can have no limit or measure, you could not conceive it.
It does not matter what position you occupy,
space must stretch an infinite distance in every direction.

Titus Lucretius Carus "De Rerum Natura" (c. 99-55 BC)

The Olbers Paradox
or why the night sky is dark?

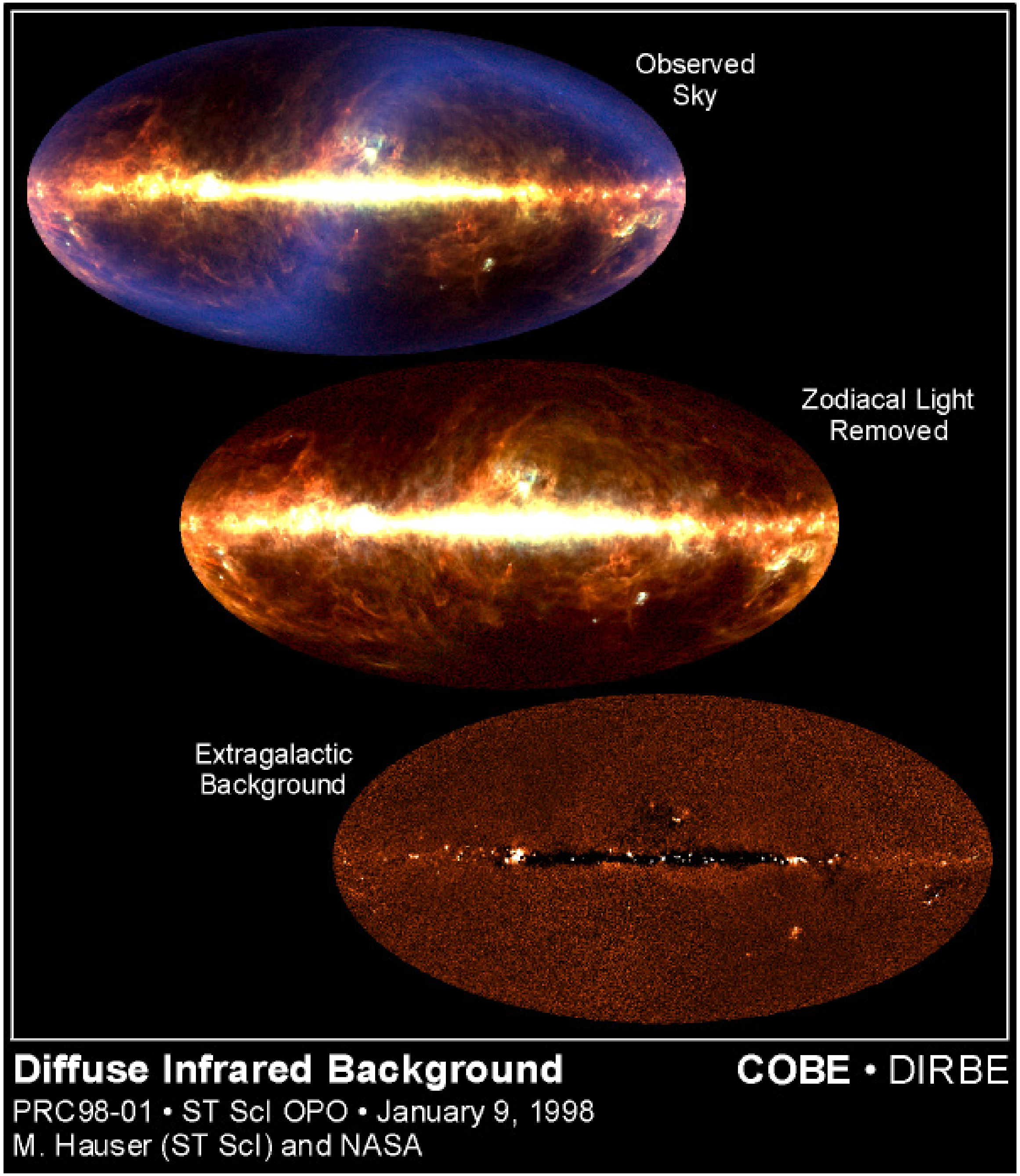
If the Universe is infinite should not every single line of sight on the sky intersect a surface of a star somewhere?

If so, should not the sky be as bright as the surface of the Sun?

NO. If the Universe is not infinitely old, there will be a *finite* region of space from which light could have reached us.

Moreover, if the Universe is expanding, light from distant stars will be redshifted from optical to infrared wavelengths invisible to out eye making the sky darker.

So, such ordinary fact as darkness of the night sky can teach us quite a bit about the Universe…

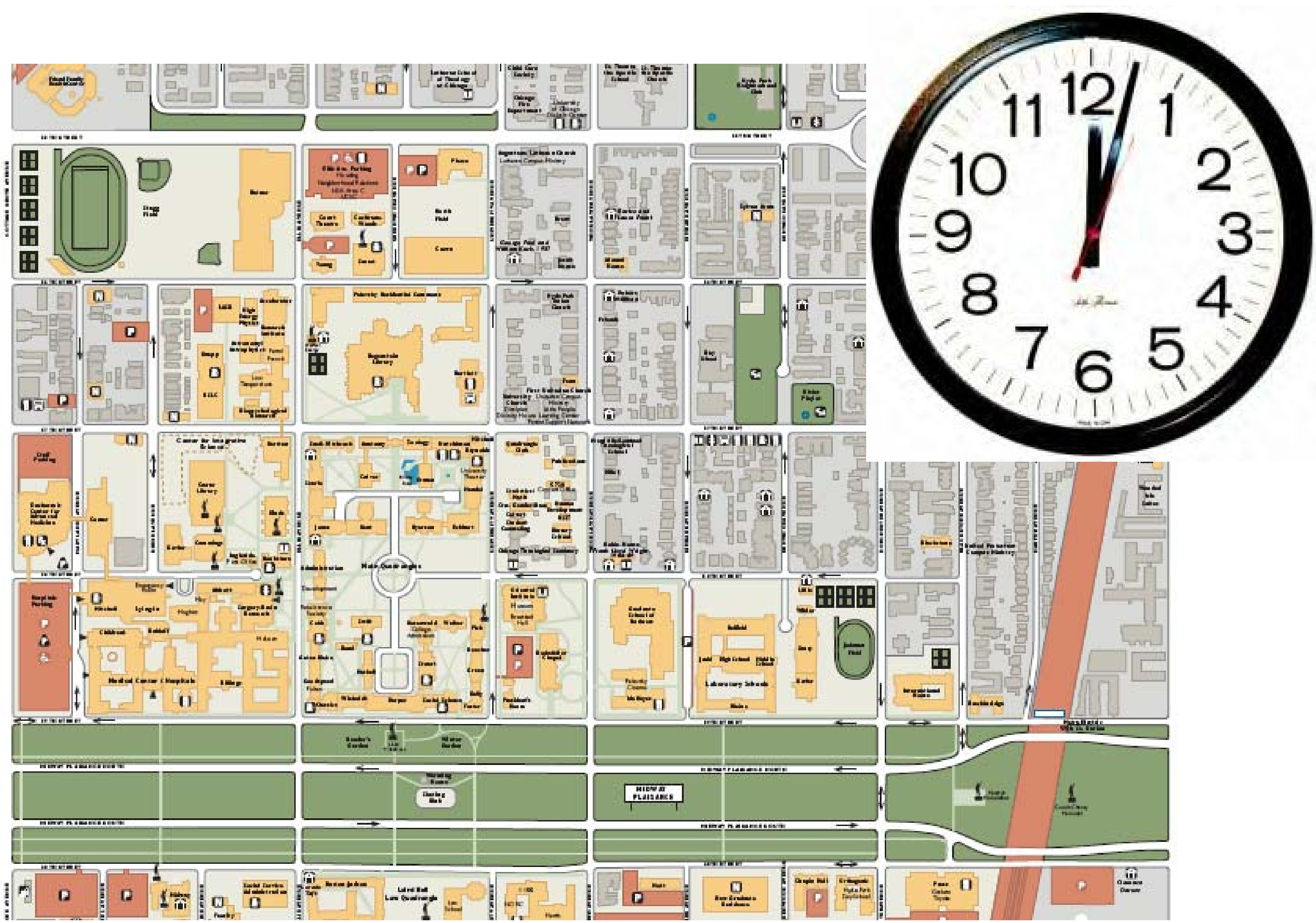


There are also so-called *backgrounds* – diffuse radiation filling the sky in infrared, X-ray wavelengths, etc.

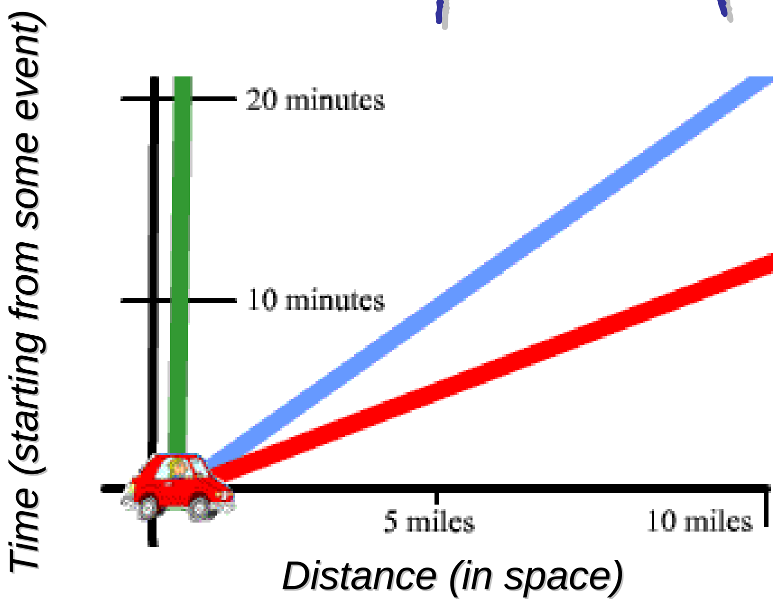
So the sky is shining in some sense…

it's just not shining as bright as the stars in visible light

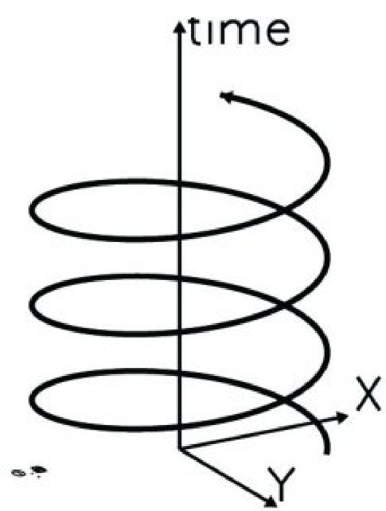
Concepts of Space and Time



Concepts of Space and Time



www.theory.caltech.edu/people/patricia/st101.html



Earth orbit in space-time

- ❑ Newton has put physics on solid mathematical footing, by developing calculus.

- ❑ Time and space are part of the mathematical equations. They become physical and mathematical concepts, not necessarily related to the human notion of time

- ❑ However, the question turned out to be more complicated. Space and time in the laws describing the physical Universe often behave counter to human intuition.

- ❑ In physics and cosmology the space and time are integral parts of the inseparable space-time that forms the fabric of the Universe

Inertial Reference Frames

- Newton's 2nd law of mechanics: ***F=ma***, ***m*** is the *inertial mass*. Inertia is an inherent property of physical bodies (hence the need for seatbelts!)

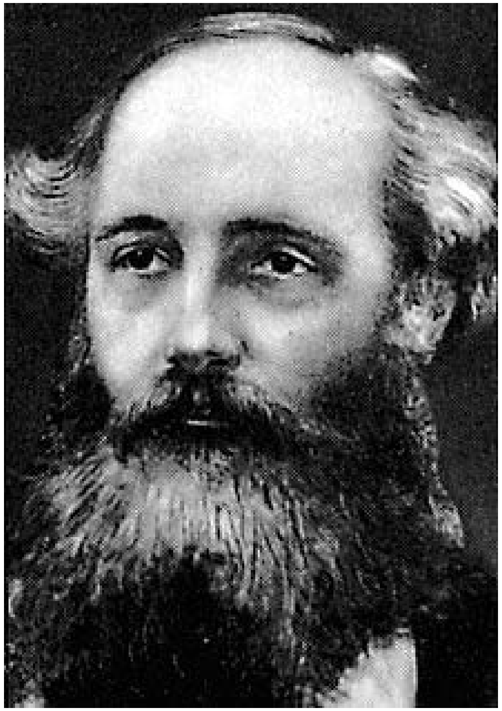
- Unaccelerated motion (a=0) is called *inertial motion*

- Frame of reference in inertial motion is called *inertial reference frame.* A particle on which no forces act, will move uniformly in an inertial frame

- Spatial distances and time are *relative,* but Newton's laws of motion will be the same (or *invariant*) in all inertial frames. This is called the *Galilean Principle of Relativity*

Q: Is the Earth inertial reference frame?

Maxwellian theory of Electromagnetism



James Clerk Maxwell
(1831-1879)

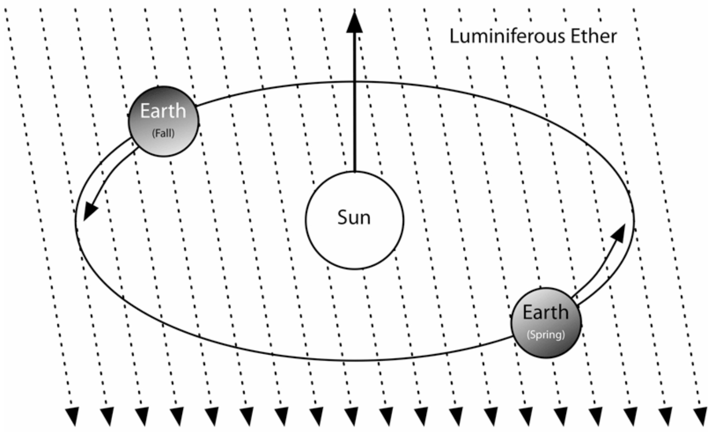
- 1860s. Maxwell developed his theory of electromagnetism that explained electric and magnetic forces as part of the same phenomenon. Prediction of electromagnetic waves propagating with the speed of light. Later identified with the light itself.

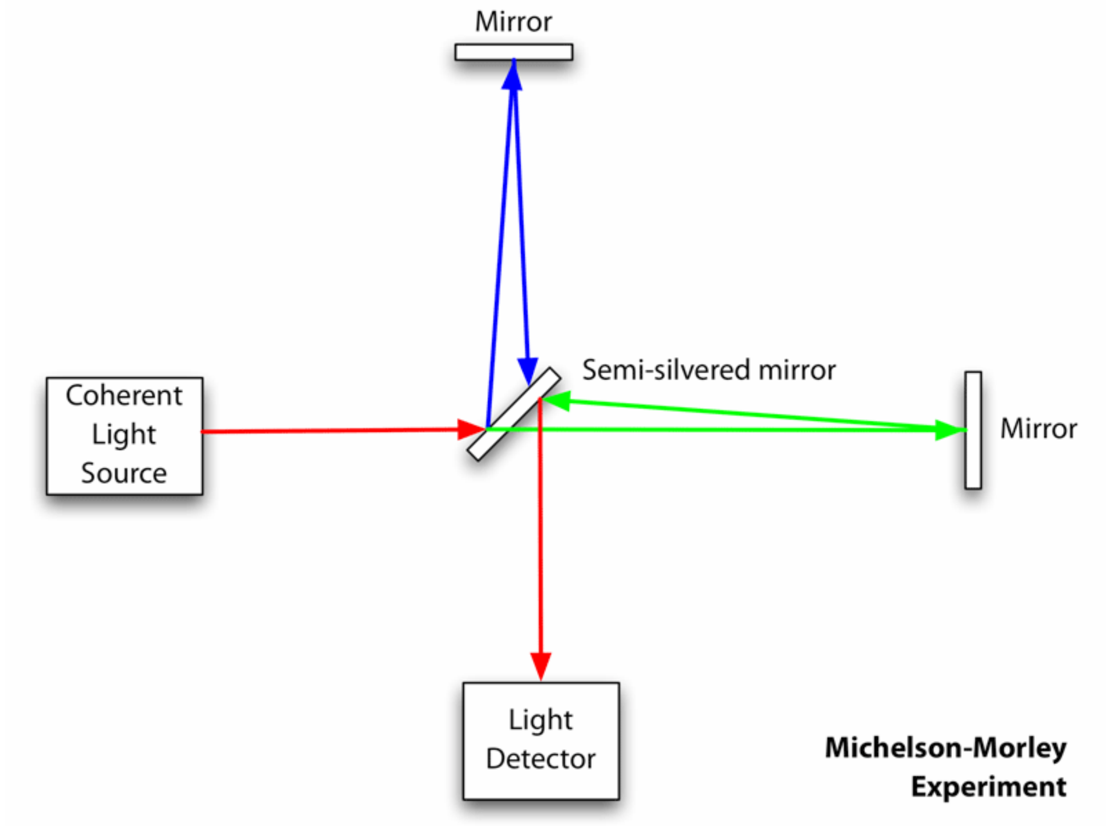
- Maxwell equations depend on the speed of light *c.* If the velocity is relative, is the speed of light relative? If so, Maxwell equations would be different in different inertial reference frames.

- A possible solution: existence of an absolute reference frame defined by the *ether*,
In which electromagnetic waves propagate.
Maxwell equations would be applicable to the reference frame defined by the ether.

Michelson-Morley experiment

Showed no evidence for ether as motion of the Earth seemed to create no preferred direction and speed of light was measured to be the same independent of direction





Special Relativity Theory

Albert Einstein
In 1905

- 1905 (Einstein's Miracle Year). Albert Einstein published the Special Theory of Relativity

Postulates of the theory:

- All laws of nature are the same (invariant) in all inertial reference frames (this is called *the relativity principle*)

- The speed of light is constant in all inertial frames (this leads to the Lorentz transformation, which Einstein argued supersedes Galilean transformation)

Simple… but many surprising consequences: Dilation of time, contraction of length

Chapter 22 describes many of the interesting implications and paradoxes

Lorentz transformation
and the need for a new theory of gravity

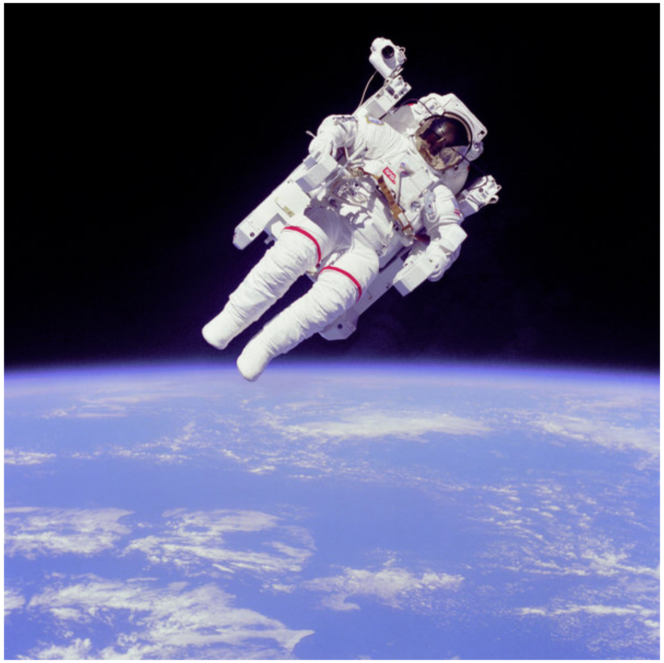
- Einstein's conviction that the relativity principle is correct and the lack of Galilean invariance of the Maxwell equations, led him to abandon absolute space and time and the Galilean invariance and to adopt Lorentz transformation.

- If you think about it, there is no truly inertial force-free frame of reference because Universe is filled with matter and its gravity should be omnipresent. The inertial frames should be very *special* indeed.

- A direct consequence of special relativity is that spatial distances are relative (depend on the reference frame), but Newtonian gravity requires distance to calculate the force. If distance is relative -> so is the Newton's law of gravitation!

Therefore, we need a new, more *general* theory of gravity consistent with special relativity. Without it we cannot fully describe the Universe!

? On the orbit around the Earth, astronauts in the Space Shuttle feel no gravity: they float around, move objects many times their own mass with one finger, etc. Does it mean that there is no gravity in the outer space?



When a space mission is launched, astronauts feel several ‘g’ – a force of gravity much stronger than usual. Why? Does gravity become stronger somehow?

Concept of inertial frame

- Concept of inertial frame and effects of gravity are intricately linked.

- For example, weightlessness astronauts experience on a space shuttle. This weightlessness is present for any object free-falling in a gravitational field.

- Conversely, the feeling of gravity is present in an accelerating frame. For example, rotating frame of reference gives perception of a gravity-like force. Such forces in accelerating frames are called inertial forces.

- Weightlessness on a shuttle is due to the fact that the shuttle is in free-fall on an orbit around the Earth. The shuttle, astronauts, and all objects free-fall at the same rate.

Equivalence Principle

Newton's (weak) equivalence principle: *inertial and gravitational masses are equivalent. Consequently, inertial and gravitational forces are equivalent.*

The gravity and inertial forces cancel out for an object on a circular orbit. Hence, the weightlessness.

Mechanical equivalence of inertial frames with free-falling frames hints at something deeper. Namely, at the

Einstein's (strong) equivalence principle: *all inertial and free-falling frames of reference are equivalent and there is no experiment that would distinguish them.*

Applies to all physical laws, not just to mechanics. This is why it's called strong.

Facing the consequences...

- Equivalence Principle sounds innocent, but it has several immediate interesting implications.

- Consider, for example, a laser shooting horizontal pulse in a free-falling elevator. Equivalence principle implies that for a person in the elevator, the laser beam will appear straight. But the elevator is falling, so by the time the pulse reaches the opposite wall, elevator moves down. In order *to appear* straight for an observer in the elevator, the light beam must follow *curved* path!

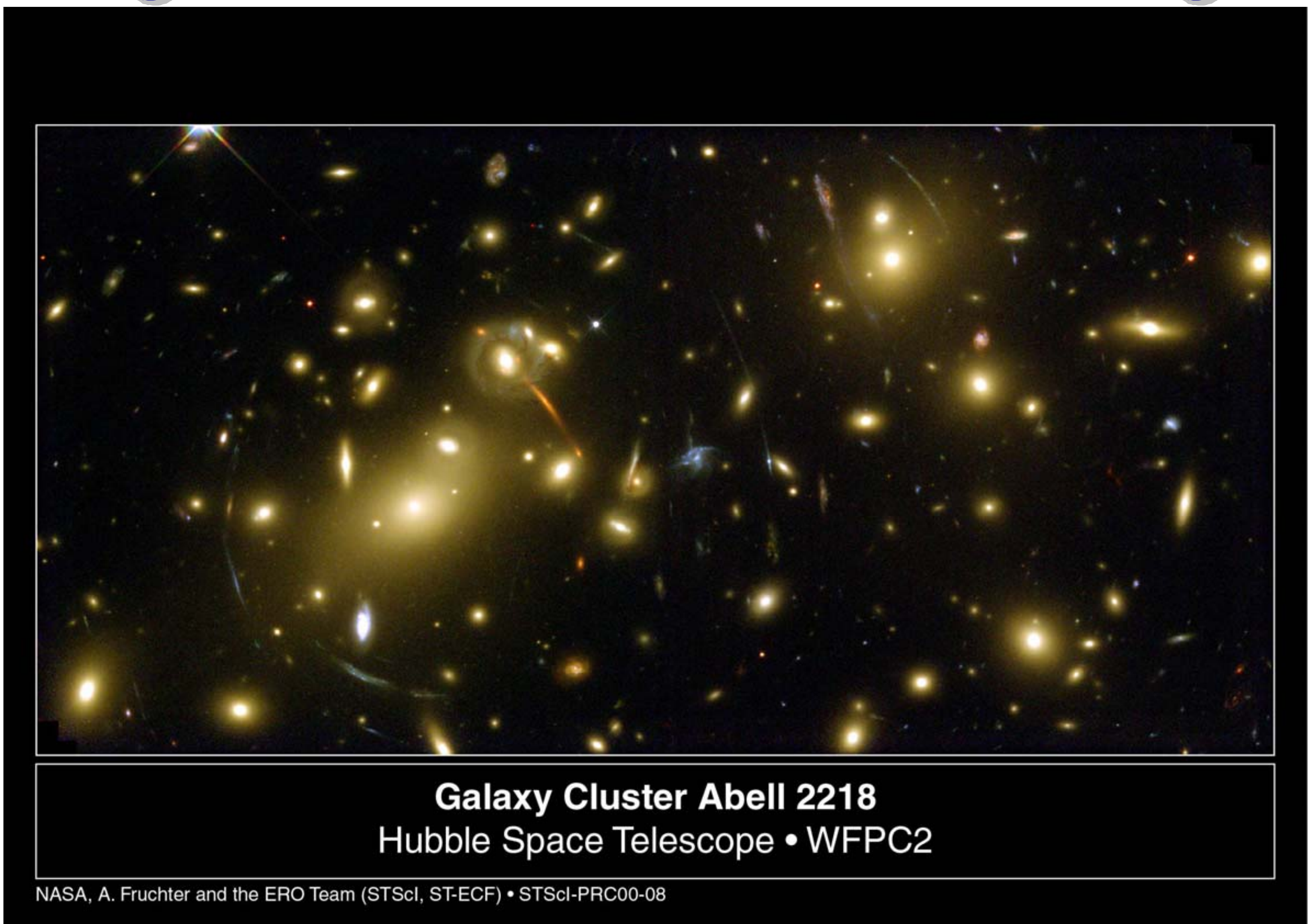
Thus, light follows curved path in the presence of gravity!

Similarly, one can deduce that

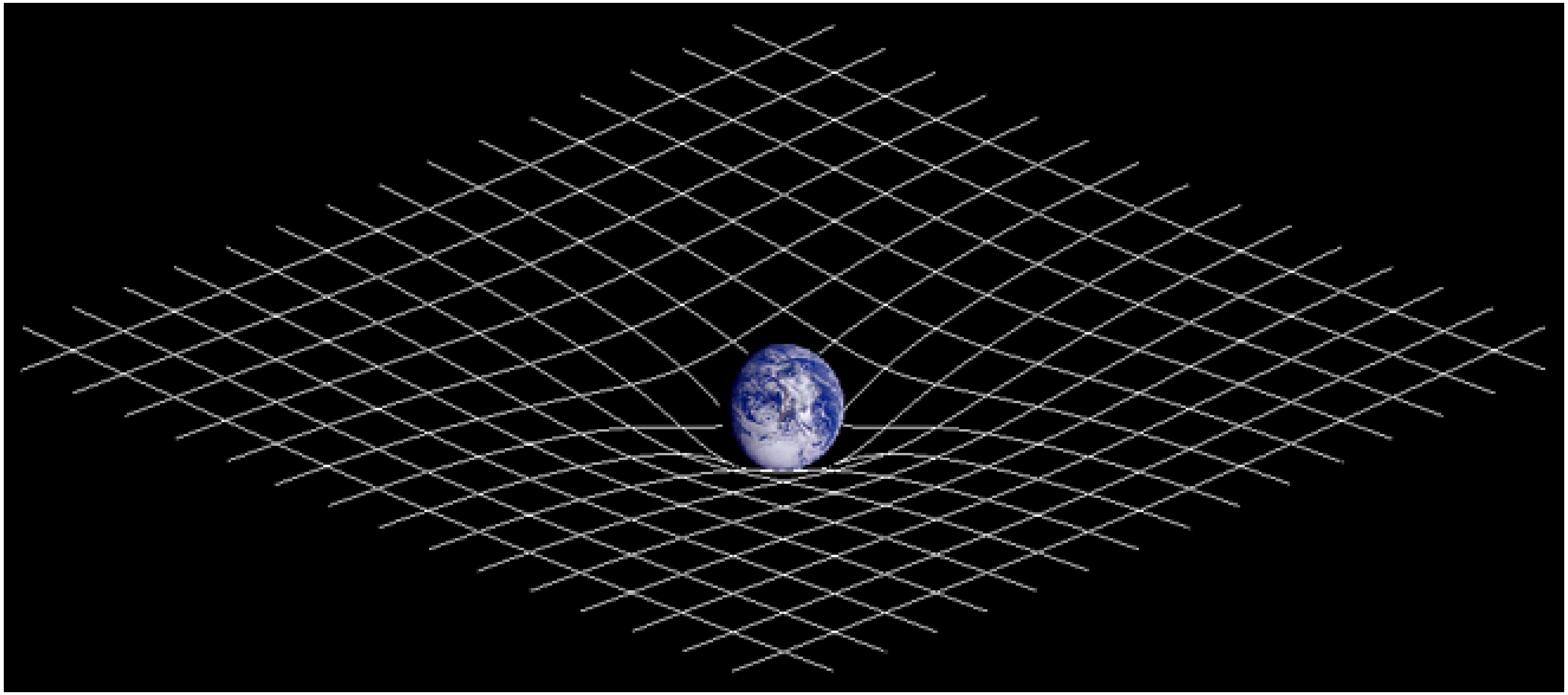
- Time runs slower in a stronger gravitational field (this has to be accounted for in the GPS system, for example).

- Light looses energy (red-shifted) when it moves away from a gravitating mass.

Light bending: gravitational lensing



An analogy…



“Spacetime grips mass, telling it how to move, and mass grips spacetime, telling it how to curve” – John Archibald Wheeler.

Theory of General Relativity

"The theory appeared to me then, and still does, the greatest feat of human thinking about nature, the most amazing combination of philosophical penetration, physical intuition, and mathematical skill. But its connections with experience were slender. It appealed to me like a great work of art, to be enjoyed and admired from a distance. – Max Born

The famous equation of Einstein's general relativity can be written simply as:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$GEOMETRY = MATTER + ENERGY$$

Where geometry refers to a measure of how curved the space is

Unfortunately, in practice the mathematical description of curvature and of matter content and energy is quite involved…