Lecture 15
Doppler shift or how the police finds you speeding or how astronomers find galaxies moving

Einstein’s new relativity

- Galileo:
  - The laws of mechanics are the same in all inertial frames of reference
  - time and space are the same in all inertial frames of reference
- Einstein:
  - The laws of physics are the same in all inertial frames of reference
  - the speed of light in the vacuum is the same in all inertial frames of reference

$\Rightarrow$ time spans and distances are relative

Consequences

- breakdown of simultaneity:
  whether or not two events happen simultaneously depends on the speed at which you are moving with respect to the events
- time dilation

$$\Delta t_R = \frac{\Delta t_P}{\sqrt{1-\frac{v^2}{c^2}}}$$

- length contraction

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

Boost factor

- Boost factor:

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

- time dilation: $\Delta t_R = \Gamma \times \Delta t_P$

- length contraction: $d_P = d_R / \Gamma$

This is messy, so let's clean up a bit

- proper time: time measured by a clock at rest with respect to a specific observer
  ⇒ clock at the fastest possible rate
- proper length: length of an object as measured in its own rest frame
  ⇒ largest possible length
- time and length in other inertial frames can be calculated by the so-called Lorentz transformation (i.e. multiplying with or dividing by the boost factor Γ)

So c + c=c ?   yes, sort of ...

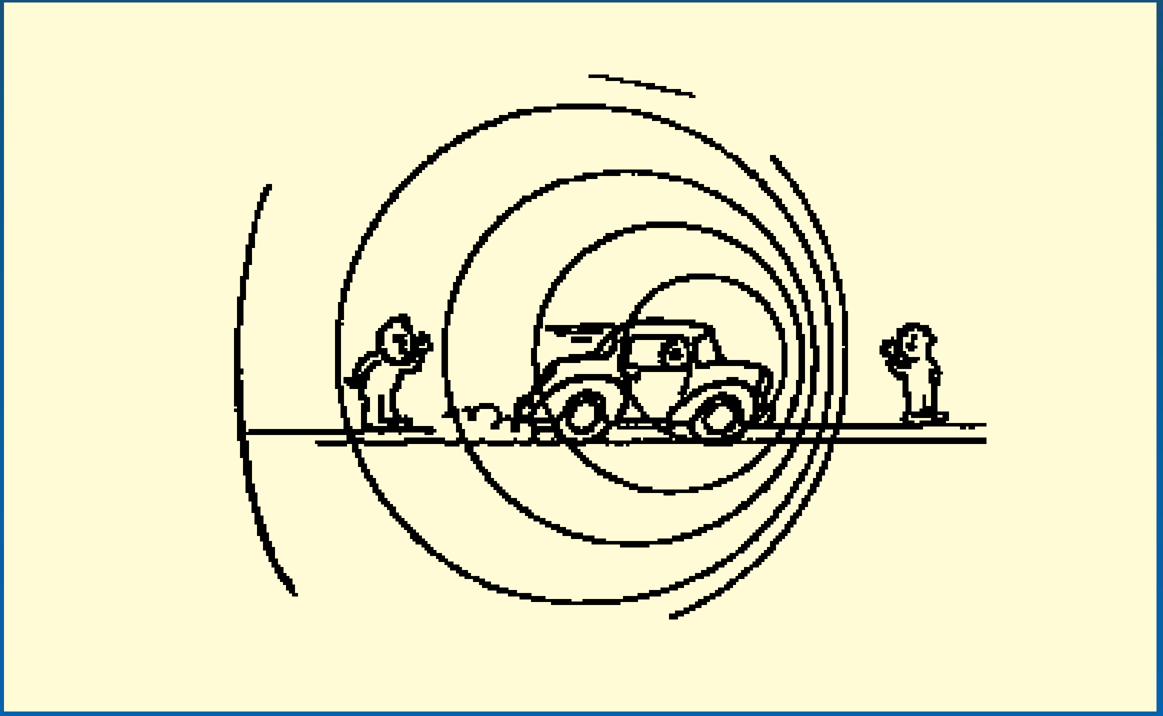
- Q: So how do we add velocities ?
  A: by properly applying Lorentz transforms:

$$v_{tot} = \frac{v_1 + v_2}{1 + \frac{v_1 \times v_2}{c^2}}$$

- Example: shoot a torpedo (v_2=0.5c) from the Enterprise, moving at v_1=0.5c
  outside observer: $v_{torpedo}$= 0.8c

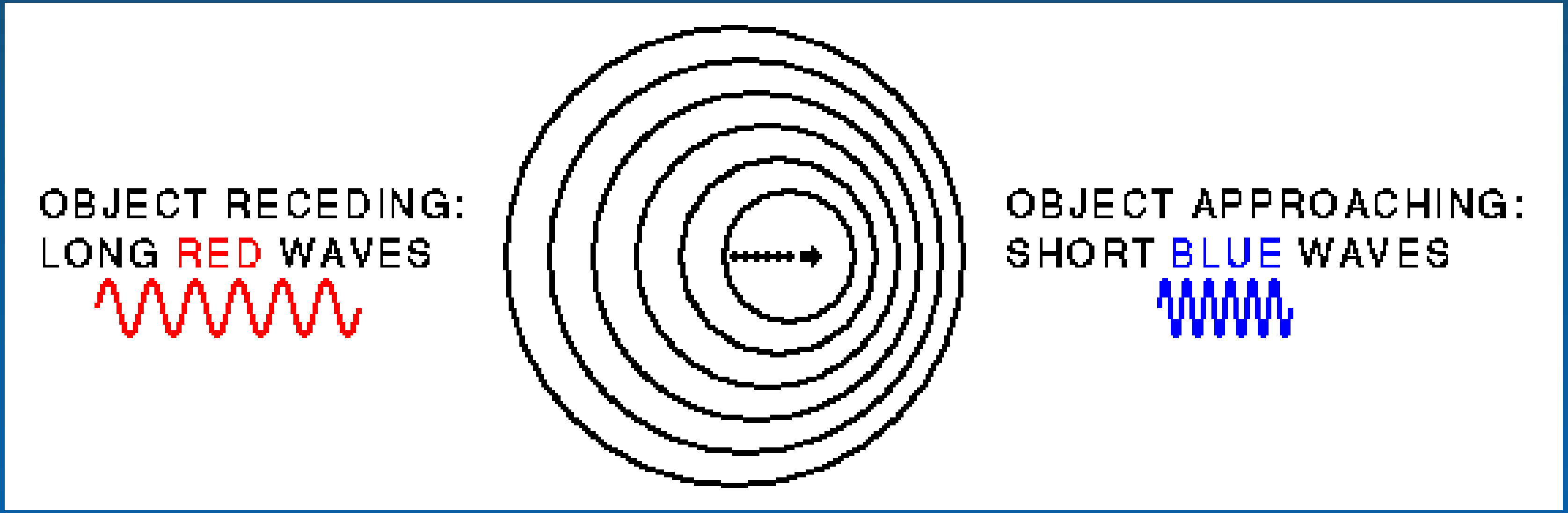
Doppler effect (for sound)

The pitch of an approaching car is higher than that of a car moving away.



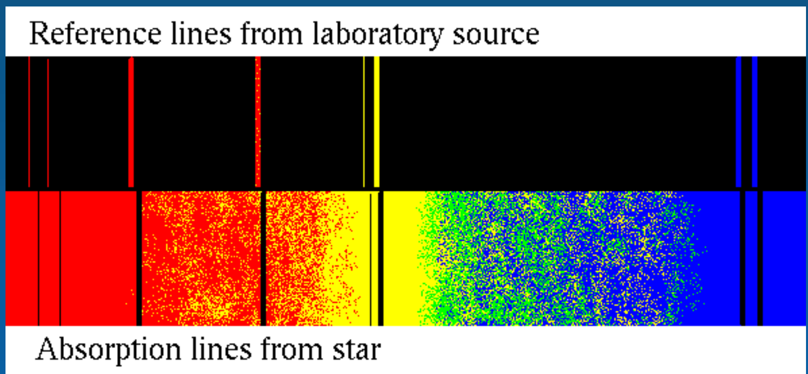
Doppler effect (for light)

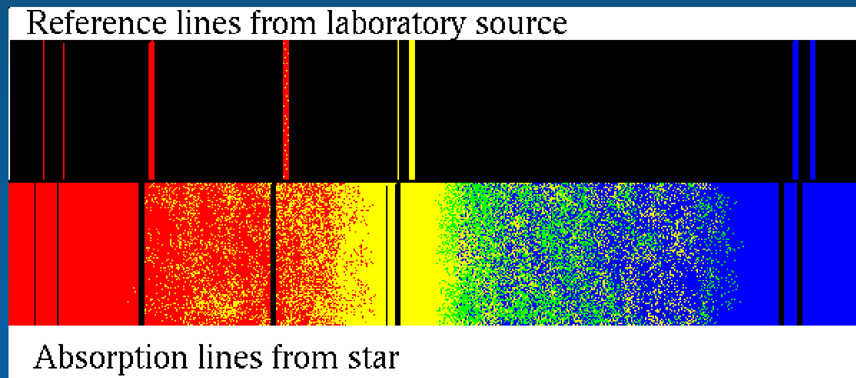
The light of an approaching source is shifted to the blue, the light of a receding source is shifted to the red.



Doppler effect

The light of an approaching source is shifted to the blue, the light of a receding source is shifted to the red.





blue shift

red shift

Doppler effect

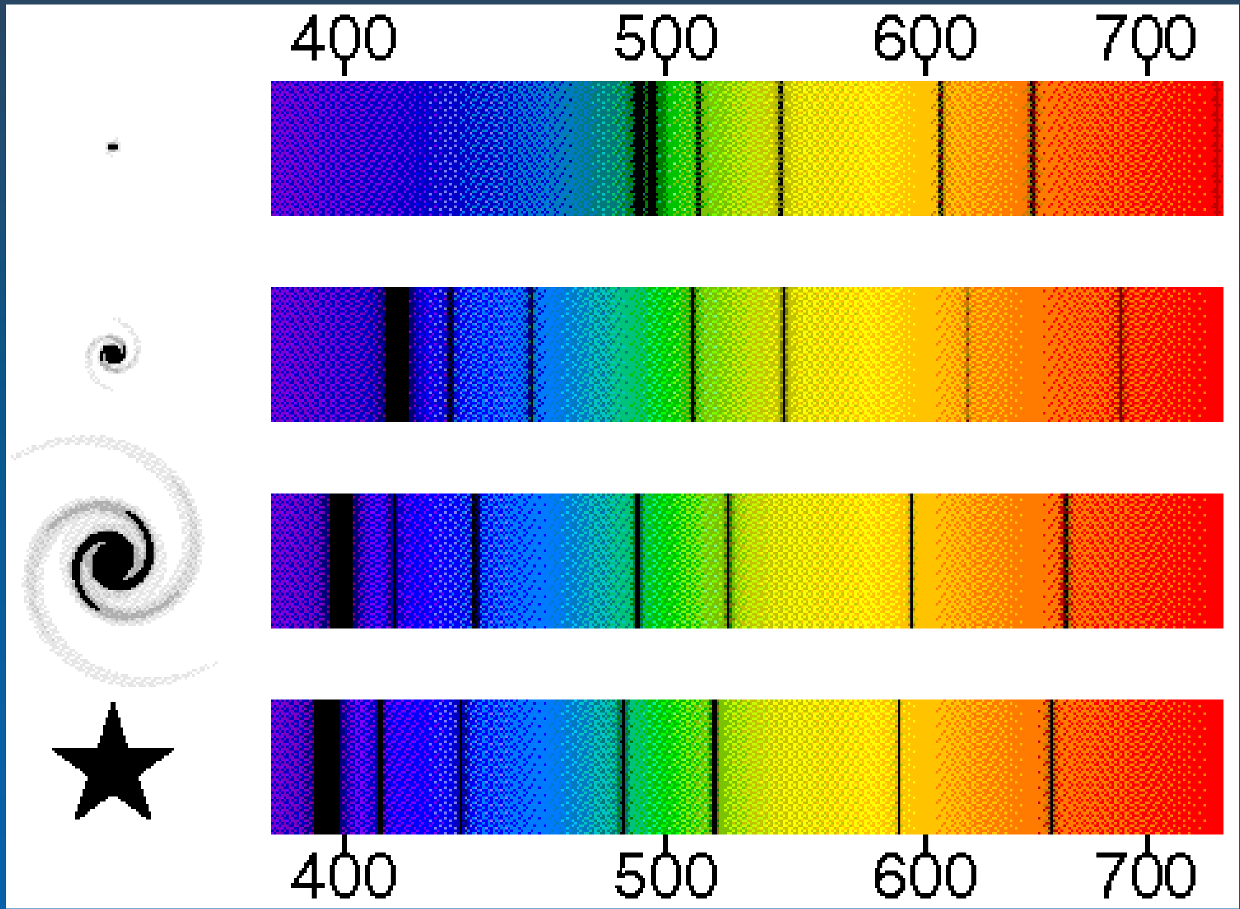
redshift:

$$1+z=\sqrt{\frac{1+v/c}{1-v/c}}$$

z=0: not moving

z=2: v=0.8c

z=∞: v=c



Energy

- Energy: the capacity to do work
- total energy is conserved, i.e. it is only transformed from one form of energy into another.
  - breaks: transform energy of motion (kinetic energy) into heat
  - falling body: transform gravitational energy into kinetic energy

Energy

- Newton:
  - kinetic energy: $E_{kin} = ½\, m\, v^2$
  - $v=0 \Rightarrow E_{kin} = 0$
- Einstein:
  - $E = \Gamma\, m_0\, c^2$
  - $v=0 \Rightarrow E = m_0\, c^2$ "rest energy"
  - $E_{kin} = (\Gamma-1)\, m_0\, c^2$
- Example:

  energy required to accelerate 1kg of mass to v=0.87c ⇒ equivalent of 20 megatons of TNT