Doppler Effect : observer ⟵ source (v)

$$\Delta t_a = \Delta t_p + v\,\Delta t_p \qquad c = 1$$

- Δt_a: interval between wavefronts arriving at observer
- Δt_p: wavefronts being produced
- $v\,\Delta t_p$: extra travel due to source moving

↖ in observer's frame

period of wavefronts in source's frame

$$T = \Delta t_p' = \frac{1}{\gamma}\Delta t_p$$

$$T_{observed} = (1+v)\gamma\, T_{source}$$

$$T_{obs} = \frac{1+v}{\sqrt{1-v^2}}\, T_{src}$$

$$f_{obs} = \frac{\sqrt{1-v^2}}{1+v}\, f_{src} \longleftarrow \frac{\sqrt{(1-v)(1+v)}}{\sqrt{(1+v)(1+v)}}$$

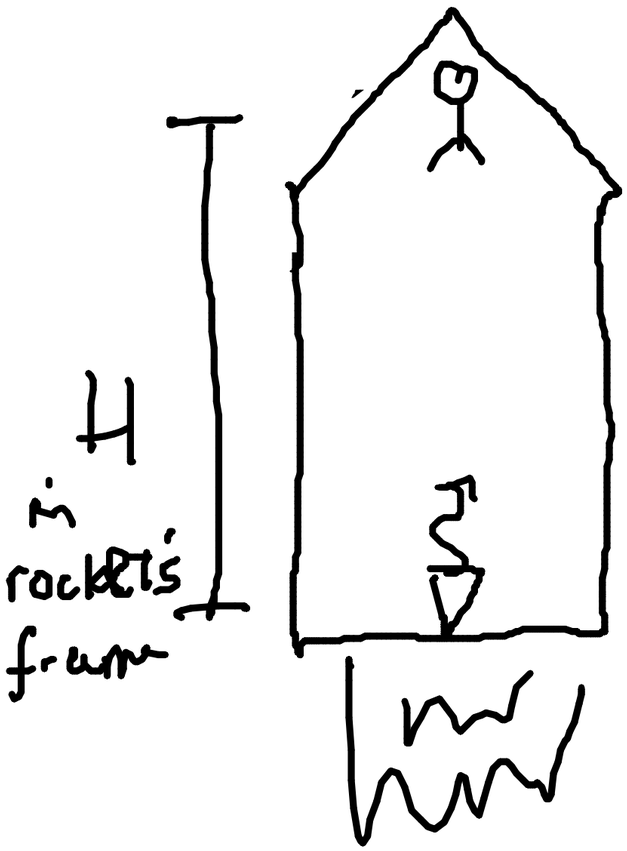
$$\boxed{f_{obs} = \sqrt{\frac{1-v}{1+v}}\, f_{src}}$$

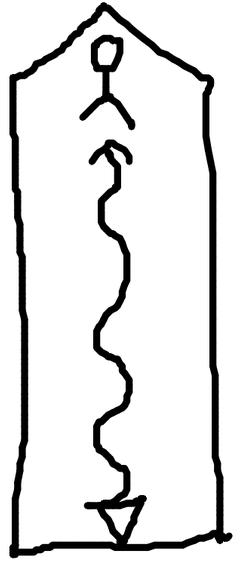
$v > 0$: away from each other

If $v > 0$ (away), $f_{obs} < f_{src}$ redshifted

$v < 0$, $f_{obs} > f_{src}$ blueshifted

Universe redshifted → universe expanding





At time t,

$v = at$,

$t = \frac{H}{c}$

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

At $t=0$,
$v=0$

Light left source when $v=0$

reaches observer when $v = \frac{aH}{c}$

Doppler effect

$$f_{obs} = f_{src}\sqrt{\frac{1-aH}{1+aH}}$$

$c=1$

General Relativity

mass plays two different roles in physics

- gravitational $F = G\frac{mM}{r^2}$ or mg
- inertial $F = ma$

no reason they should be the same

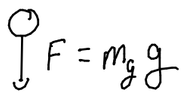
but they are (to 1 part in 10^{12} at most)

no discrepancy found

What if they were different?

Falling object

no air resistance



Newton's 2nd Law: $F = m_i a$

$$m_g g = m_i a$$

$$a = \frac{m_g}{m_i} g$$

e.g.

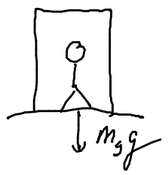
person feel a pseudoforce

$F_1 + F_2 + \ldots = ma$ (you think you're inertial)

$F_1 + F_2 + \ldots + ma = 0$

pseudoforce

If person on Earth



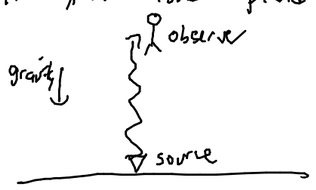
if $m_i = m_g$,

these two situations are indistinguishable

General relativity: gravity is indistinguishable from acceleration

~~free fall is indistinguishable from no gravity~~

e.g. in gravitational field



is equivalent to the accelerating rocket from earlier

∴ Therefore, light is redshifted as it leaves a gravitational field

Small effect but GPS satellites do take it into account

Objects in a gravitational well, are time dilated compared to outside.