Dark matter in the Galactic Halo

Rotation curve (i.e. the orbital velocity V of stars and gas as a function of distance to the Galactic Center r) of the disk of the Milky Way is measured:

- for the inner Galaxy by looking at the Doppler shift of 21 cm emission from hydrogen
- for the outer Galaxy by looking at the velocity of star clusters relative to the Sun.

(details of these methods are given in Section 2.3 of Sparke & Gallagher…)

Fact that V(r) ~ constant at large radius implies that the Galaxy contains more mass than just the visible stars and gas.

Extra mass - the dark matter - normally assumed to reside in an extended, roughly spherical halo around the Galaxy.

Possibilities for dark matter include:

- molecular hydrogen gas clouds
- very low mass stars / brown dwarfs
- stellar remnants: white dwarfs, neutron stars, black holes

} **baryonic dark matter** - made (originally) from ordinary gas

- primordial black holes

- elementary particles, probably currently unknown - **non-baryonic** dark matter

The Milky Way halo probably contains *some* baryonic dark matter - brown dwarfs + stellar remnants accompanying the known population of low mass stars.

This uncontroversial component of dark matter is not enough - is the remainder baryonic or non-baryonic?

On the *largest scales* (galaxy clusters and larger), strong evidence that the dark matter has to be non-baryonic:

- Abundances of light elements (hydrogen, helium and lithium) formed in the Big Bang depend on how many baryons (protons + neutrons) there were.

  ➡ light element abundances + theory allow a measurement of the number of baryons

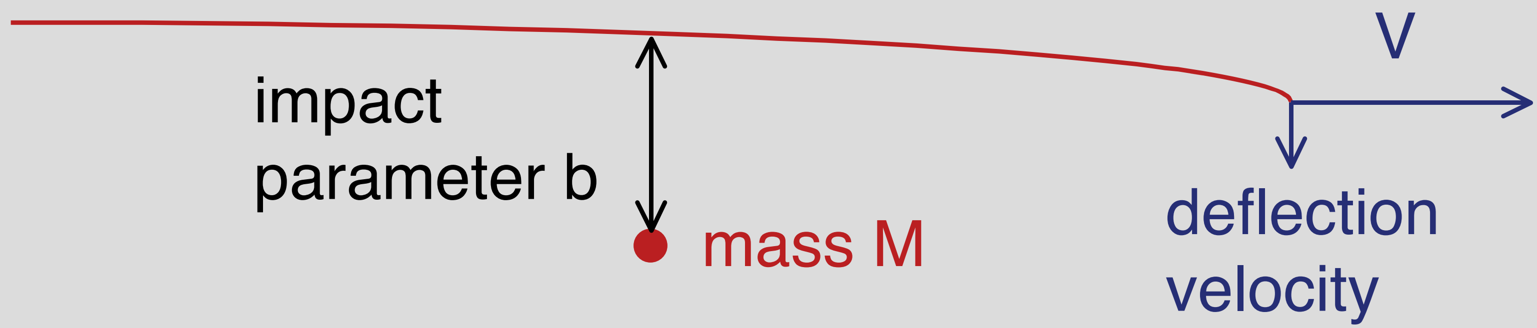
- observations of dark matter in galaxy clusters suggest there is too much dark matter for it all to be baryons, must be largely **non-baryonic**.

On galaxy scales no such simple argument exists. Individual types of dark matter can be constrained using various indirect arguments, but only direct probe is via **gravitational lensing**.

Gravitational lensing

Photons are deflected by gravitational fields - hence images of background objects are distorted if there is a massive foreground object along the line of sight.

Bending of light is similar to deflection of massive particles - e.g. if a star passes by a massive body at velocity V with an impact parameter (distance of closest approach) b its path is deflected:



Fairly easy to show that the transverse velocity imparted due to the gravitational acceleration during the flyby is:

$$\Delta V_{\perp} = \frac{2GM}{bV}$$ (textbook 3.2.2)

The deflection angle is: $\alpha = \frac{\Delta V_{\perp}}{V} = \frac{2GM}{bV^2}$

General relativity predicts that for **photons**, the bending is exactly twice the Newtonian value:

$$\alpha = \frac{4GM}{bc^2} = \frac{2R_s}{b}$$

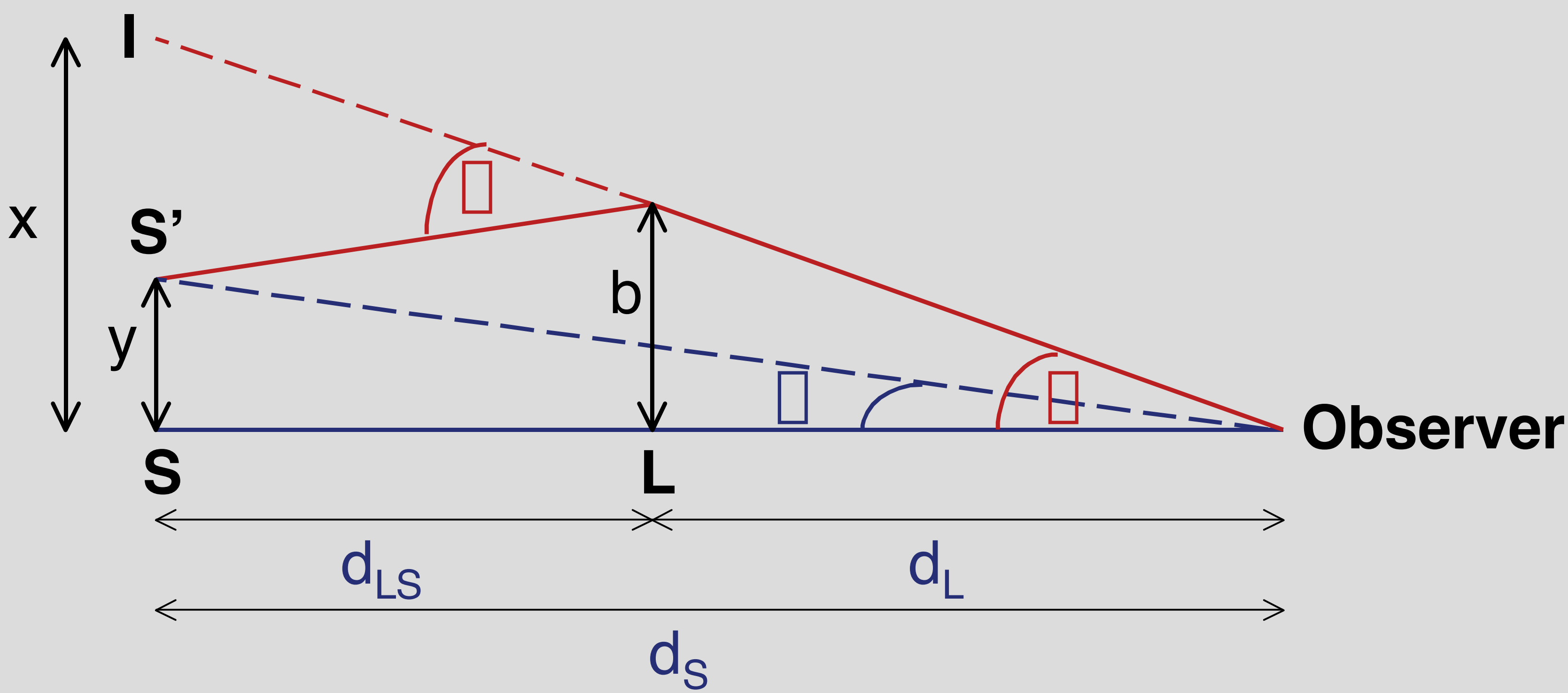
…where R_s is the Schwarzschild radius of a body of mass M.

Formula is valid provided that $b >> R_s$:

- Not valid very close to a black hole or neutron star
- Valid everywhere else
- Implies that deflection angle α will be small

Geometry for gravitational lensing

Consider sources at distance d_S from the **observer O.**
A point mass **lens L** is at distance d_L from the observer:



Observer sees the image I of the source S' at an angle □ from line of sight to the lens. In the absence of deflection, *would* have deduced an angle □.

Recall that all the angles - θ, β, α - are **small**:

$$\theta = \frac{b}{d_L} = \frac{x}{d_S}, \quad \beta = \frac{y}{d_S}, \quad \alpha = \frac{x - y}{d_{LS}}$$

Substitute these angles into expression for deflection angle:

$$\frac{x - y}{d_{LS}} = \frac{4GM}{bc^2}$$

$$\theta d_S - \beta d_S = \frac{4GM}{bc^2} d_{LS}$$

$$\theta - \beta = \frac{1}{\theta} \frac{4GM}{c^2} \underbrace{\frac{d_{LS}}{d_S d_L}}$$

Geometric factors

Quadratic equation for the apparent position of the image, θ, given the `true' position β and knowledge of the mass of the lens and the various distances.

Simplify this equation by defining an angle θ_E, the **Einstein radius** of the lens:

$$\theta_E = \frac{2}{c}\sqrt{\frac{GMd_{LS}}{d_L d_S}}$$

Equation for the apparent position then becomes:

$$\theta^2 - \beta\theta - \theta_E^2 = 0$$

Solutions are:

$$\theta_{\pm} = \frac{\beta \pm \sqrt{\beta^2 + 4\theta_E^2}}{2}$$

For a source exactly behind the lens, $\beta = 0$. Source appears as an **Einstein ring** on the sky, with radius θ_E.

For $\beta > 0$, get two images, one inside and one outside the Einstein ring radius.