Outline

- Nature of dark matter
- Gravitational lensing
- Microlensing experiments
- Modified gravity

Dark Matter

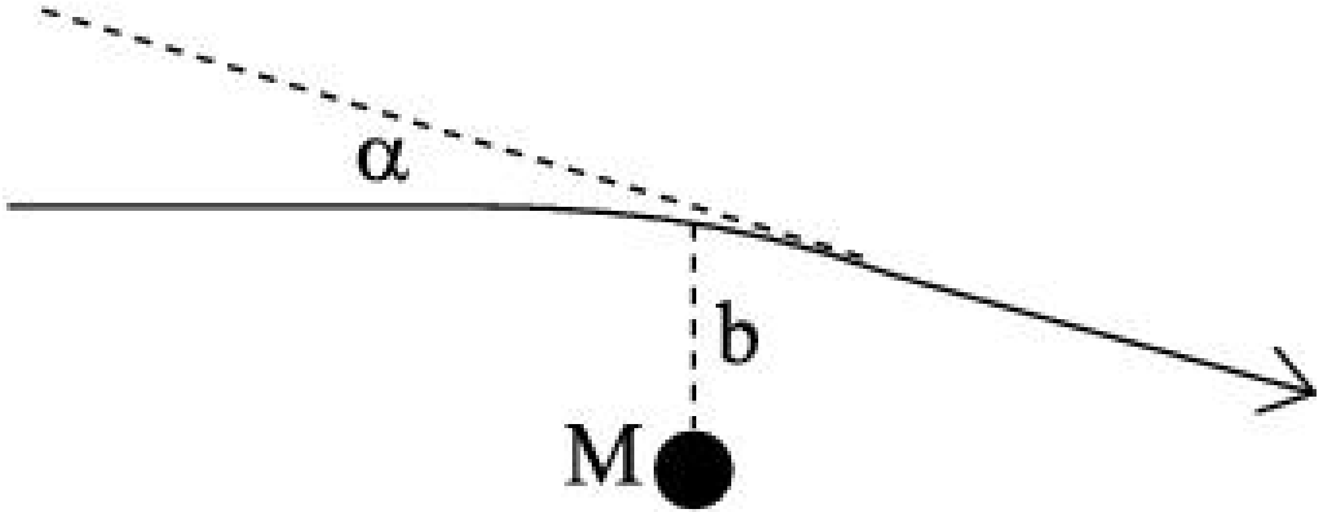
- Gas or dust?
  - Atomic gas – would emit 21 cm radiation
  - Molecular gas – would emit/absorb molecular lines (is ruled out)
  - Ionized gas – would emit UV/X-rays
  - Dust – would emit IR

Gas and dust are not really "dark".

Dark Matter

- Massive Compact Halo Objects (MACHOs) - these are gravitationally bound objects that are “star-like”, but do not produce or absorb significant amounts of radiation.
  - Normal stars – make light
  - Neutron stars – dim, if not accreting, but would see supernovae (or their aftermath) needed to form neutron stars
  - Black holes – possible issues with supernovae progenitors, would disrupt stellar binaries
  - White dwarfs – would see halos of red giant progenitors around distant galaxies (is ruled out)
  - Brown dwarfs and planets – need to go look. How?

Gravitational Deflection



- b = impact parameter – distance of closest approach
- If in "weak field limit", b >> Schwarzschild radius, then

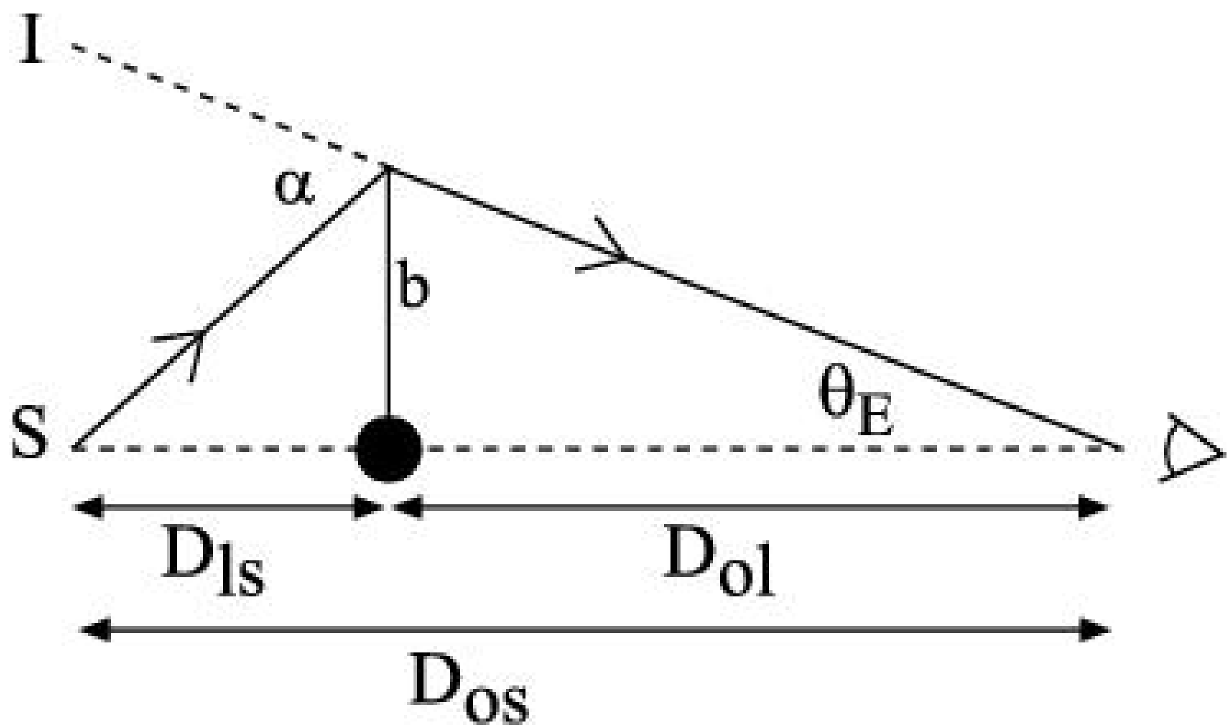
  deflection $\alpha = 2r_s/b = 4GM/bc^2$

- For light ray at limb of the Sun, $b = 7\times10^{10}$ cm, $r_s = 3\times10^5$ cm,

  deflection $\alpha = 8.6\times10^{-6}$ radians = 1.8 arcsec

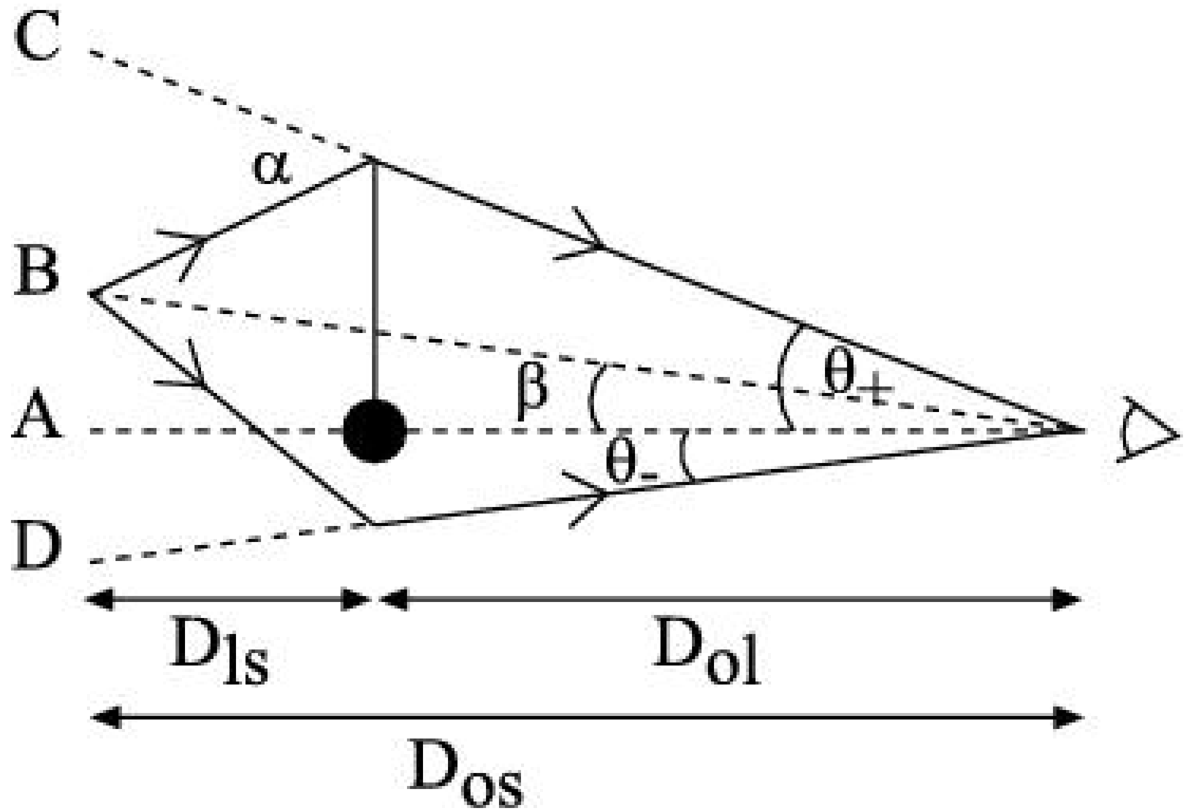
- Measured by Eddington in 1919.

Einstein Ring



- Now put source directly behind lens at appropriate distance so that we see gravitationally lensed radiation from the source.
- Work out geometry.

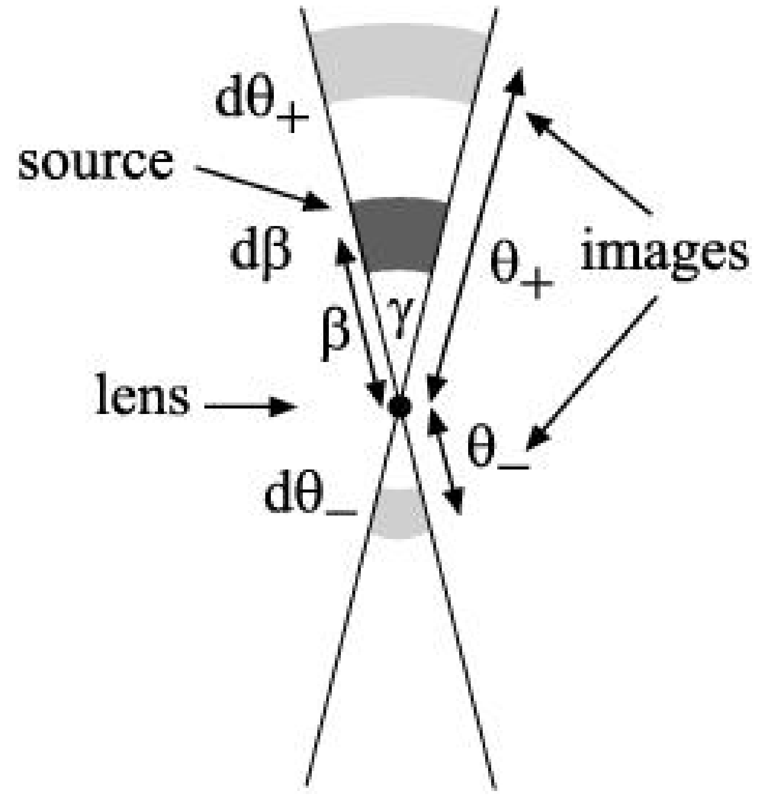
Gravitational Lens



- Now allow source to be at arbitrary position.
- Work out geometry.

Magnification

- γ = original angular size of source tangential to lens plane
- $d\beta$ = original angular size of source in lens plane

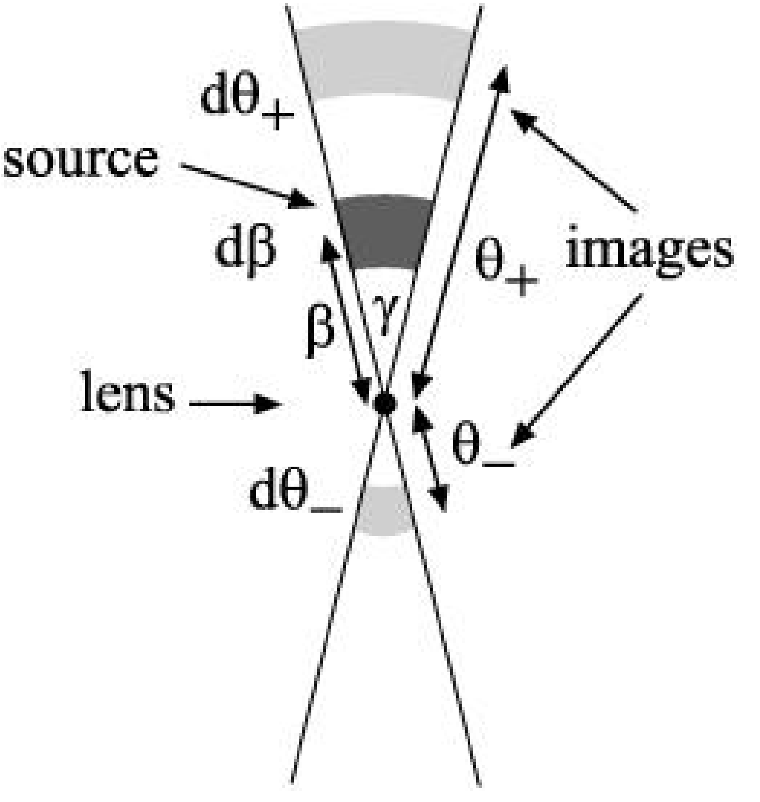


- Lensing:
- γ is multiplied by factor $\theta_{\pm}/\beta$
- $d\beta$ is multiplied by factor $d\theta_{\pm}/d\beta$
- Total angular size is multiplied by factor $a_{\pm} = (\theta_{\pm}/\beta)(d\theta_{\pm}/d\beta)$

Magnification = Amplification

- "Surface brightness is conserved by gravitational lensing".
- Image will larger surface area will have more total light.
- Total amplification a = $a_+ + a_-$

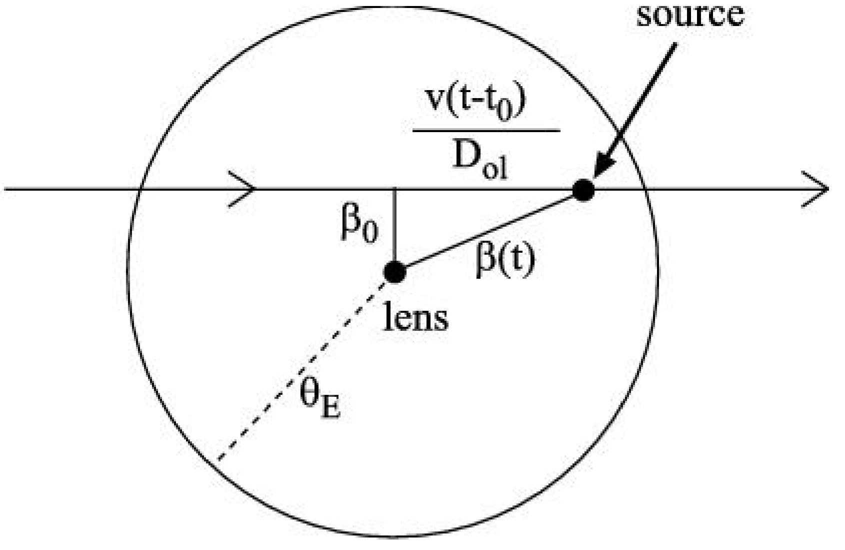
$$a = \frac{u^2+2}{u\left(u^2+4\right)^{1/2}} \quad \text{where} \quad u = \frac{\beta}{\theta_E}$$



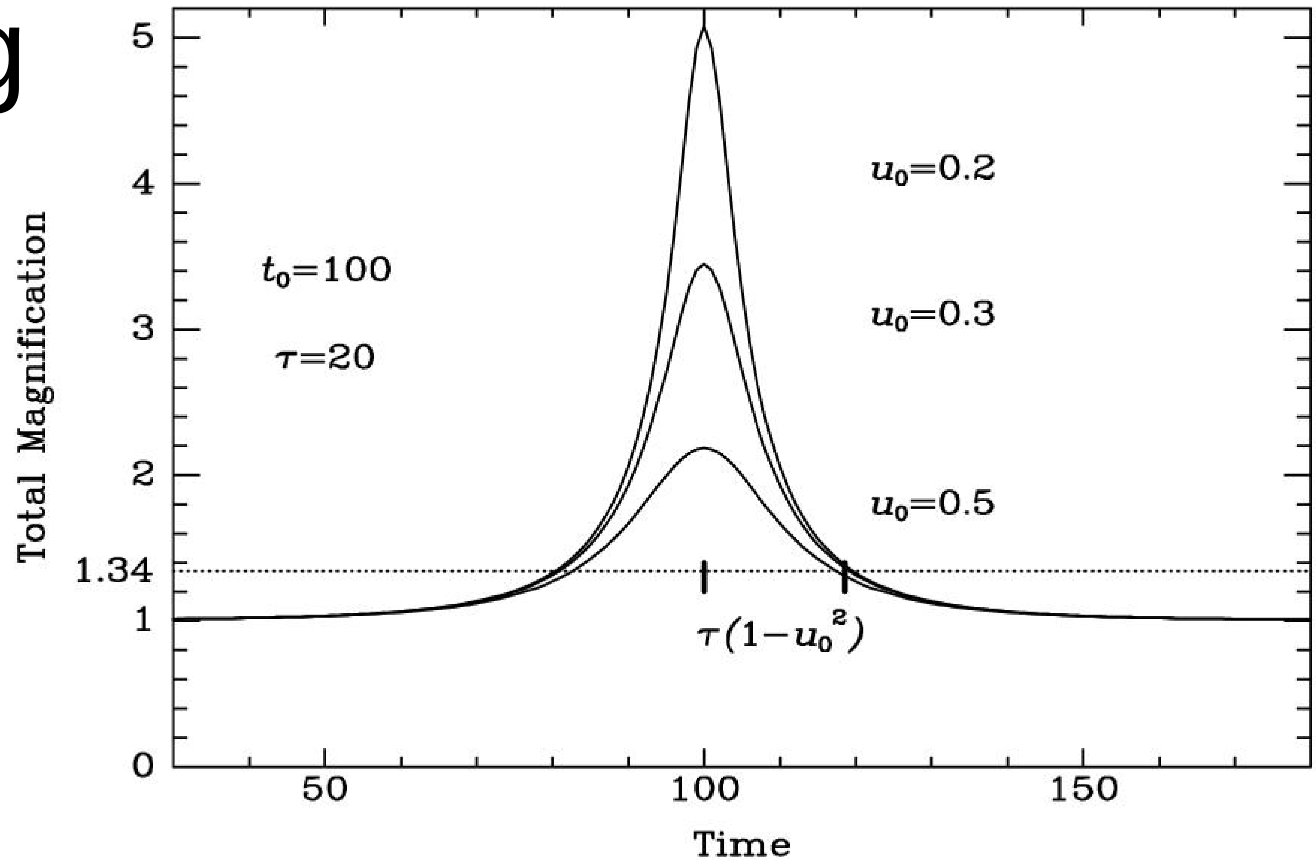
- For $u \gg 1$, find a = 1.
- For u = 1, find a = 1.34.
- For $u \ll 1$, find a → ∞. Why?

Microlensing event

- Assume lens is fixes and source moves with constant velocity.
- Does it matter if the source moves?
- Then β will change as a function of time depending on
  - β_0 = angle of closest approach
  - v = relative velocity of source and lens
- Can calculate $\beta(t)$, then $u(t)$, then $a(t)$.
- Can observe $a(t)$ by looking at a background source and watching to see if it brightens then dims.

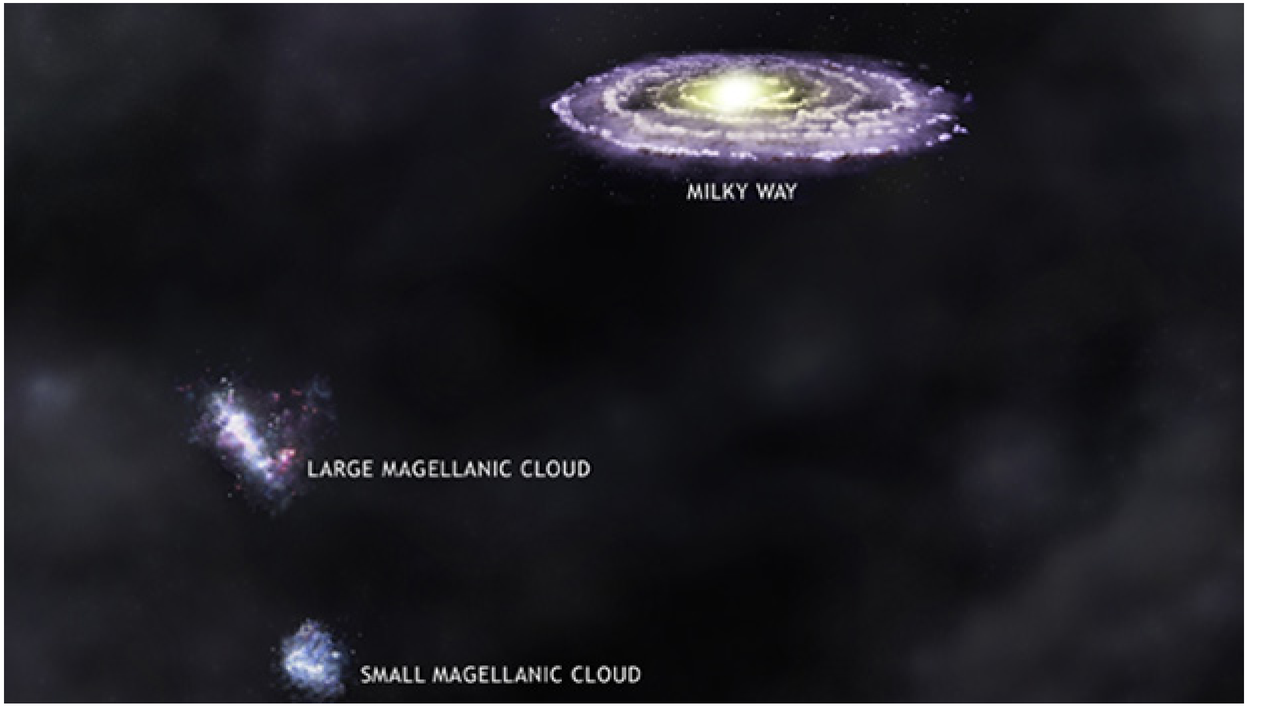


Microlensing event



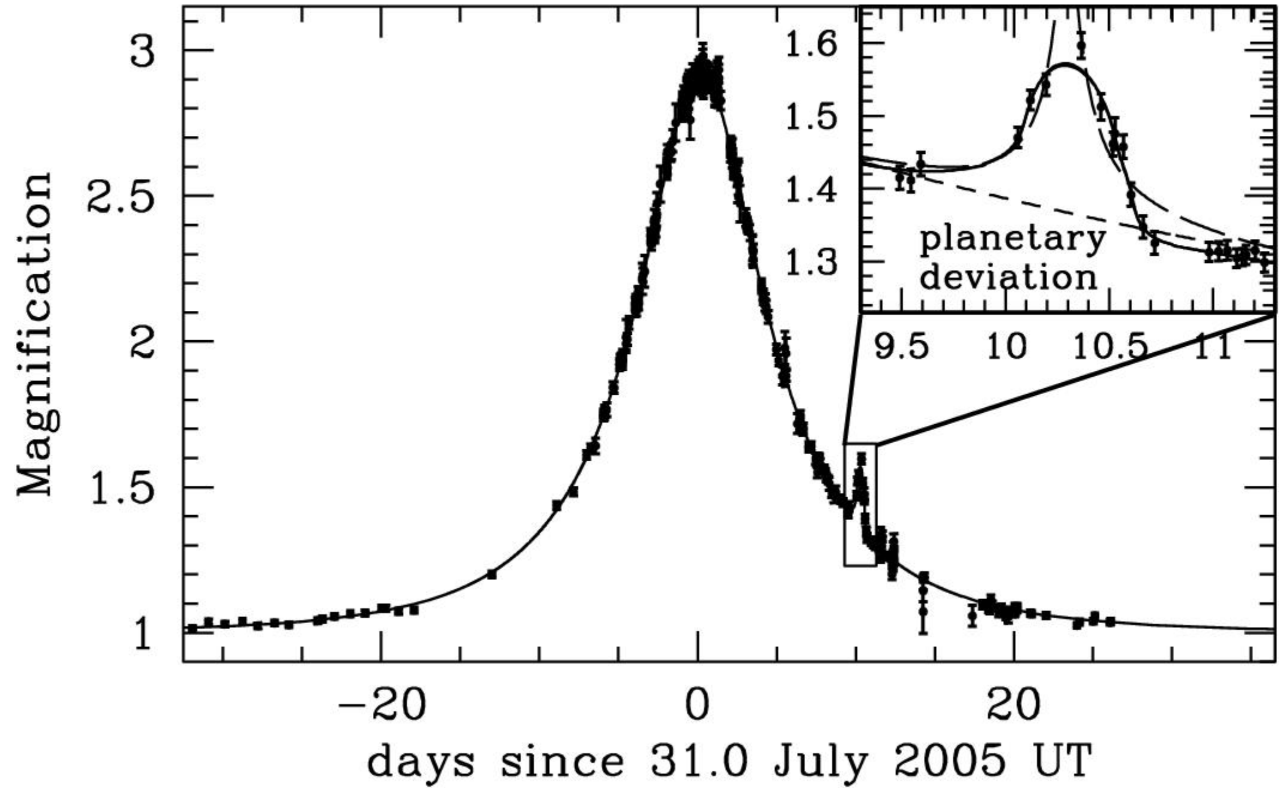
- $u_0 = \beta_0/\theta_E$ determines maximum magnification.
- $\tau = \theta_E D_{ol}/v$ determines time scale of event
- t_0 = time of maximum light.
- Knowing D_{ol} and v, you can find the mass of the lens by measuring τ.

Magellanic Cloud Microlensing



- Look at a star in the LMC.
- If a MACHO passes in front, then the star will brighten and dim with the characteristic time profile of a microlensing event.
- How many stars do you need to look at in order to have a good chance of catching a MACHO?

Magellanic Cloud Microlensing



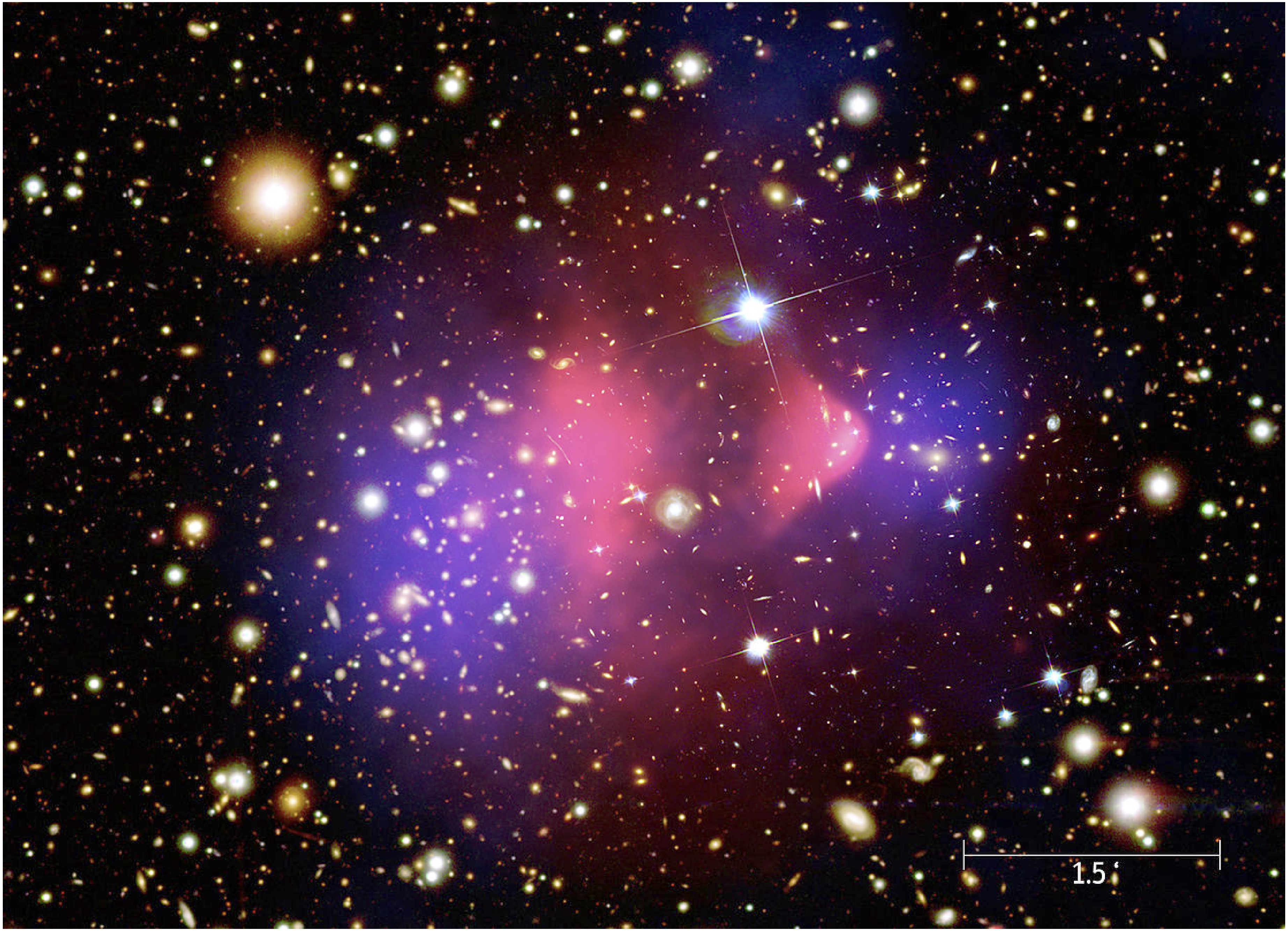
- Experiments followed 10^7 stars in LMC for ~ 6 years.
- Used 1 meter telescope with CCD camera with many pixels.
- Found only ~15 lensing events while ~100 would be predicted if MACHOs constitute the majority of the dark matter.
- Place limit that <20% of dark matter is in form of MACHOs.
- Event shown is from monitoring stars in bulge of MW. Event is due to a dim star with a planet passing in front of a bulge star.

Dark Matter

- Elementary particles
  - Neutrinos – can calculate number of expected neutrinos from cosmology, analogous to cosmic microwave background. Neutrinos do not contribute sufficient mass unless the individual particles are massive. Recent suggestions of 3.5 keV X-ray line from clusters of galaxies suggesting 7 keV neutrino.
  - Weakly interacting massive particles (WIMPs) – WIMPs of in GeV to TeV mass range solve both dark matter problem and explain mass of Higgs boson. Searching for at LHC and in direct detection experiments (LUX, Xenon1T).
  - Axions – predicted to solve problem in QCD. Convert to photons with sufficient strong magnetic field. Searching for at Axion Dark Matter Experiment.

Dark Matter

- Modified gravity – maybe Newton's laws are incorrect at large distances or very low accelerations.
- Milgrom suggested "Modified Newtonian Dynamics" (MOND) in which $F = ma$ is replaced by $F = ma^2/a_0$ for $a < a_0 = 10^{-8}$ cm/s^2.
- MOND "predicts" flat rotation curves and does remarkably well in explaining the properties of many galaxies.
- Thought to be ruled out by Bullet cluster – a collision between two galaxies in which X-rays show baryons are concentrated at center, while gravitational lensing shows most of the mass is on the outer edges.



Total mass is in blue, X-ray emitting baryonic matter is in red.

Homework

- For next class:
  - Problem 6-3