Microlensing experiments

Several experiments have searched for microlensing events:

- toward the Galactic Bulge (lenses are disk or bulge stars)
- toward the Magellanic Clouds (lenses could be stars in the LMC / SMC, or halo objects)

MACHO (Massive Compact Halo Object):

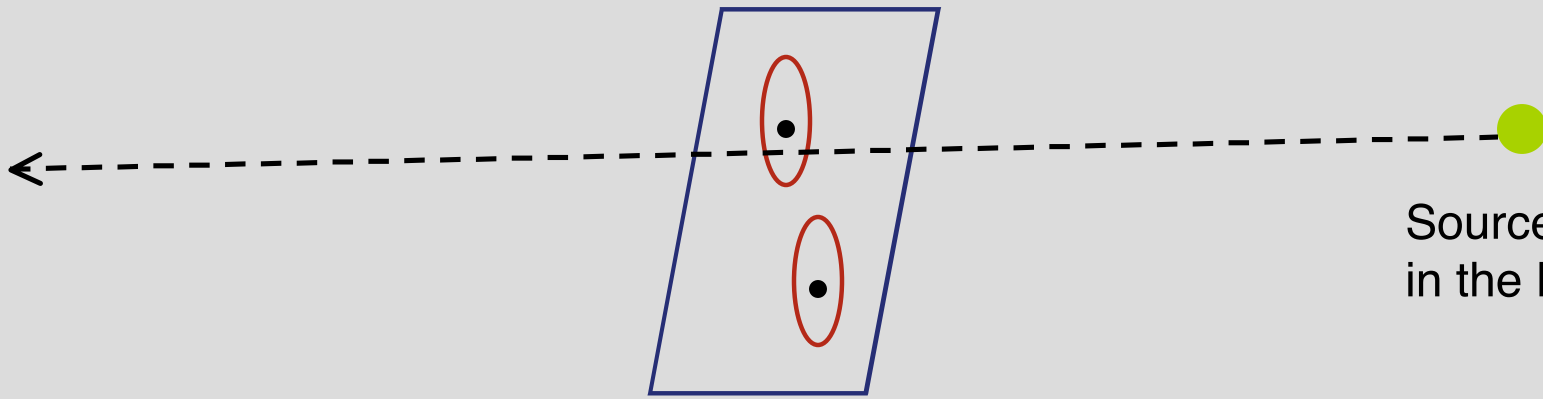
- observed 11.9 million stars in the Large Magellanic Cloud for a total of 5.7 years.

OGLE (Optical Gravitational Lensing Experiment):

- ongoing experiment
- presently monitor 33 millions stars in the LMC, plus 170 million stars in the Galactic Bulge.

Microlensing observables:

Suppose that between us and the Magellanic Clouds there are a large number of dark, compact objects.



At any one time, we will see a clear lensing event (i.e. the background star will be magnified) if the line of sight passes through the Einstein ring of one of the lenses.

Previously derived the angular radius of the Einstein ring on the sky θ_E. Area is $\pi\theta_E^2$.

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

Single lens of mass M, at distance d_L. Observer - source distance is d_S, lens - source distance is d_{LS} ($=d_S-d_L$)

Probability that this lens will magnify a given source is:

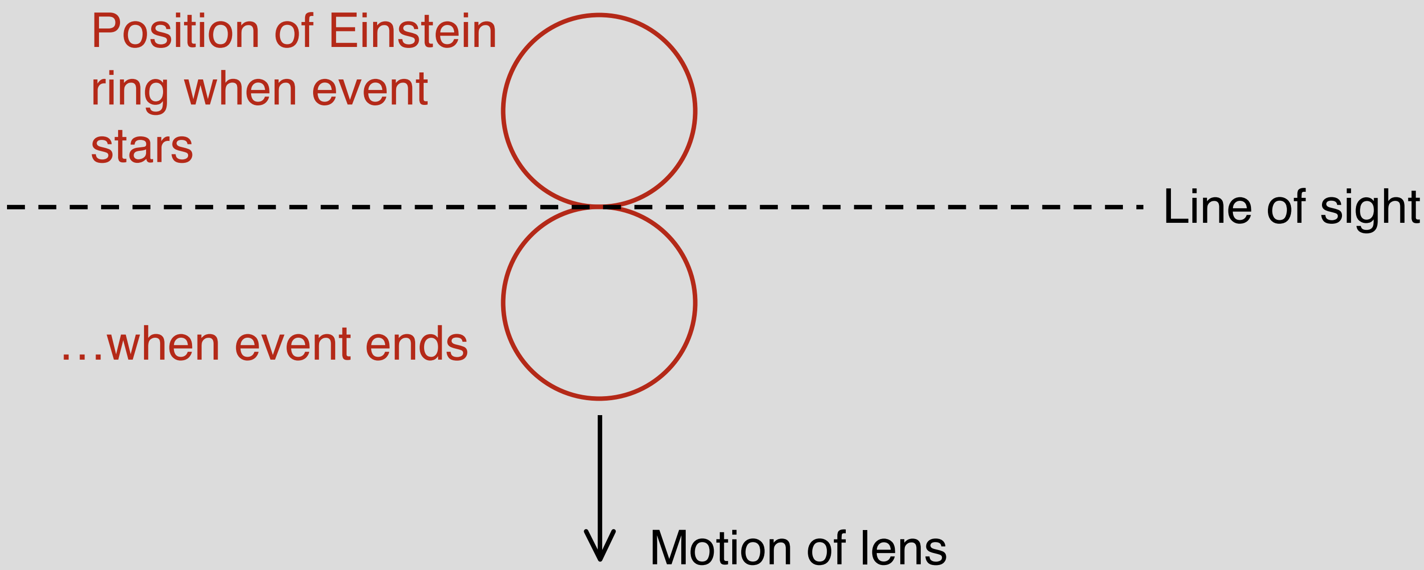
$$P \propto \theta_E^2 \propto \left(\frac{d_{LS}}{d_L d_S}\right) M$$

directly proportional to the mass of the lens

Same is obviously true for a population of lenses, with total mass M_{pop} - just add up the individual probabilities. Conclude:

- measuring the fraction of stars that are being lensed at any one time measures the **total mass** in lenses, independent of their individual masses
- geometric factors remain - we need to know where the lenses are to get the right mass estimate.

No way to determine from a single image whether a given star is being magnified by lensing. Need a series of images to see star brighten then fade as the alignment changes:



Lensing time scale: equals the *physical* distance across the Einstein ring divided by the relative velocity of the lens:

$$\tau = \frac{2 d_L \theta_E}{v_L}$$

$$\tau = \frac{4}{v_L c}\sqrt{\frac{GMd_L d_{LS}}{d_S}}$$

Time scale is proportional to the square root of the individual lens masses.

Put in numbers appropriate for disk stars lensing stars in the Galactic bulge:

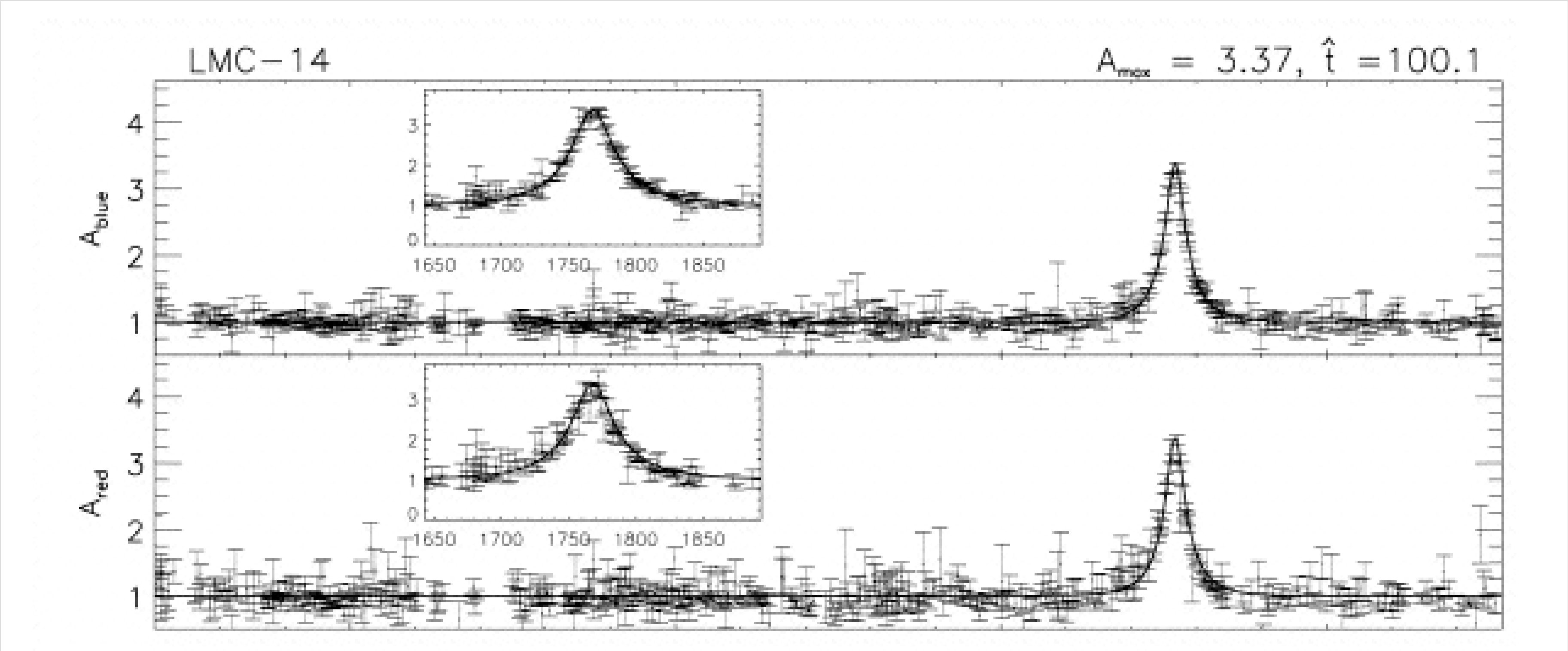
- d_S = 8 kpc, $d_L = d_{LS}$ = 4 kpc
- M = 0.3 M_{sun}
- v_L = 200 km s^{-1}

$$\tau \approx 40\sqrt{\frac{M}{0.3M_{sun}}}\ \text{days}$$

Weak dependence on mass is very convenient observationally, if we observe every night can detect:

- events with τ ~ 1 day: M < Jupiter mass (10^{-3} M_{sun})
- events with τ ~ 1 year: M ~ 25 Solar masses (e.g. stellar mass black holes)
- + everything in between…

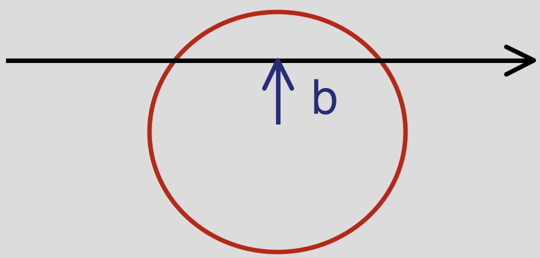
MACHO project detected 13-17 microlensing events toward the LMC in just under 6 years of operation, compared to only 2-4 expected on the basis of known stellar populations.



Lensing events are expected to be **achromatic** (same light curve in different wavebands), which helps distinguish them from variable stars.

For each event, there are only two observables:

- duration □- if we know the location of the lens along the line of sight this gives the lens mass directly
- peak amplification A: this is related to how close the line of sight passes to the center of the Einstein ring



$$\text{Define } u = \frac{b}{d_L \square_E}$$

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$$

(we won't try to prove this formula)

Note: amplification tells us nothing useful about the lens.

Additionally, observing many events gives an estimate of the probability that a given source star will be lenses at any one time (often called the *optical depth to microlensing*). This measures the total mass of all the lenses, if their location is known.

Based on the number and duration of MACHO events:

<u>If the lenses are objects in the Galactic Halo</u>

- 20% of the mass of the Galactic halo (inferred from the Galactic rotation curve) is in the form of compact objects
- Typical mass is between 0.15 M_{sun} and 0.9 M_{sun}
- Idea that **all** the mass in the halo is MACHOs is definitely ruled out

One interpretation of these results is that the halo contains a much larger population of white dwarf stars than suspected.

Other authors suggest the lenses may not be our halo at all, but rather reside in the Magellanic Clouds. If correct, implies that none of the halo is in the form of planetary mass to ~10 M_{sun} compact objects.

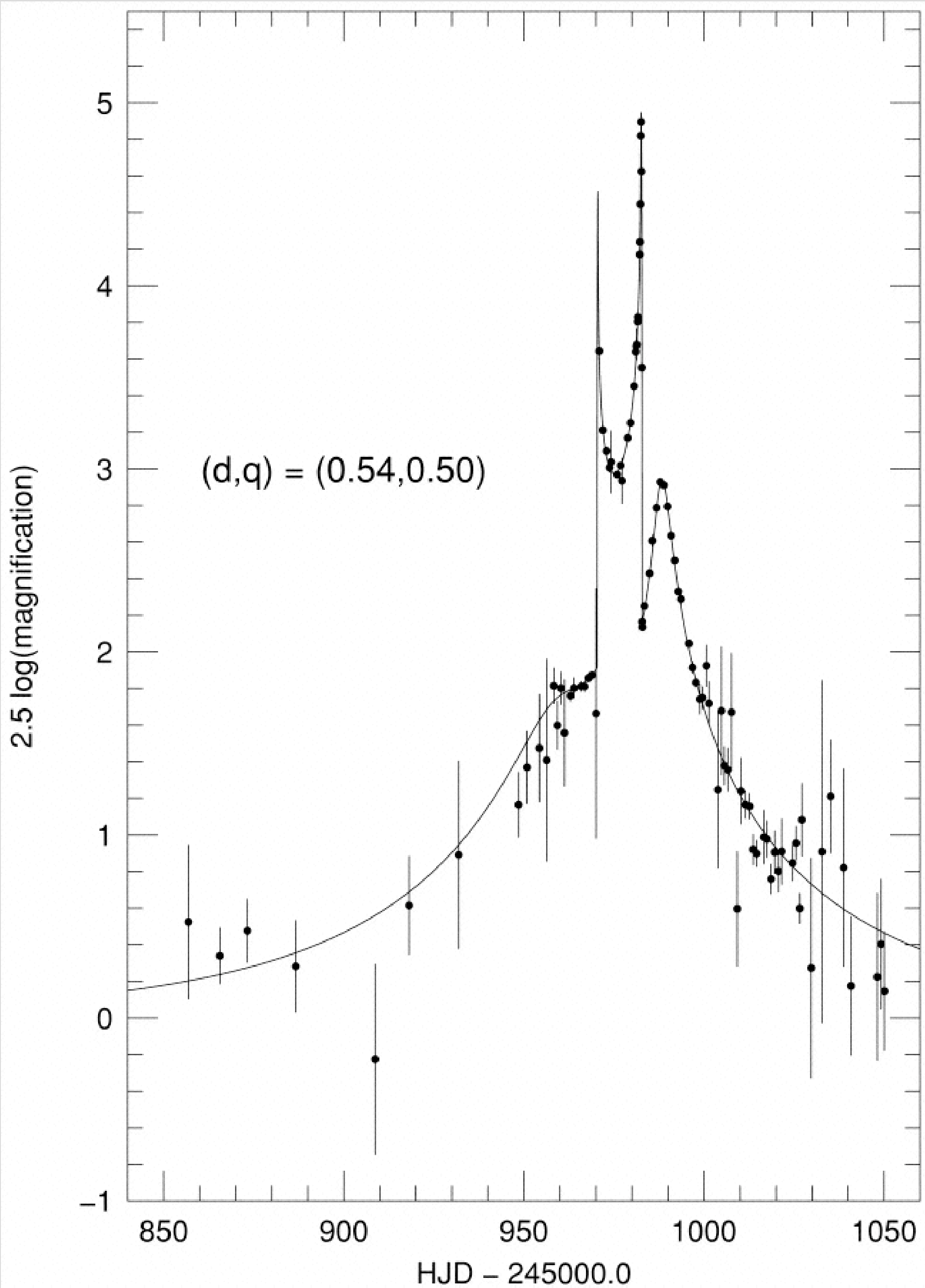
Ambiguity in the distance to the lenses is the main problem. Can be resolved in a few special cases:

a) If distortions to the light curve caused by the motion of the Earth around the Sun can be detected (`parallax events')

b) If the lens is part of a binary system. Light curves produced by binary lenses are much more complicated, but often contain sharp spikes (`caustic crossings') and multiple maxima. Provide more information about the event.

One event seen toward the Small Magellanic Cloud was a binary event, and it is known to lie close to the SMC.

My guess is therefore that the majority of the lenses are not in the Galactic halo, which is probably made up of elementary particle dark matter instead…



Observed binary lensing event.

Note: a star with an orbiting planet is just a special case of a binary system with a large difference in masses.

Much more numerous events toward the Bulge are being monitored for signs of any planets, so far without any definite detections…