Gravitational Microlensing

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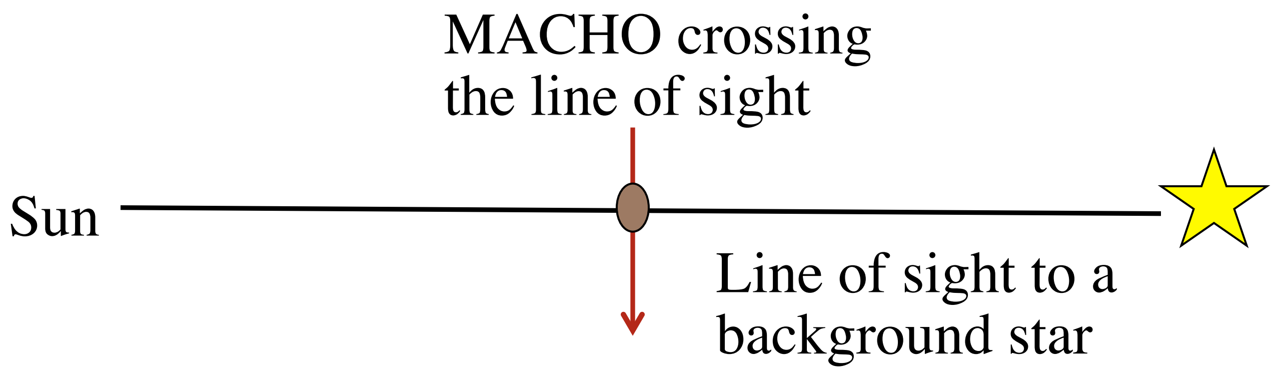
Lensing event occurs as a MAssive Compact (Halo) Object, MACHO (could be a main sequence star, white or brown dwarf, neutron star or black hole, or … ?), passes within an angular distance $\boldsymbol{q_E}$ of a background star:

- background star initially brightens
- eventually fades as the alignment is lost



Since the cross section for a strong lensing is small compared to interstellar separations, such events must be exceedingly rare

Expected Gravitational Microlensing Lightcurves:

The **peak magnification** depends on the lens alignment (impact parameter).

The **event duration** depends on the lens velocity.

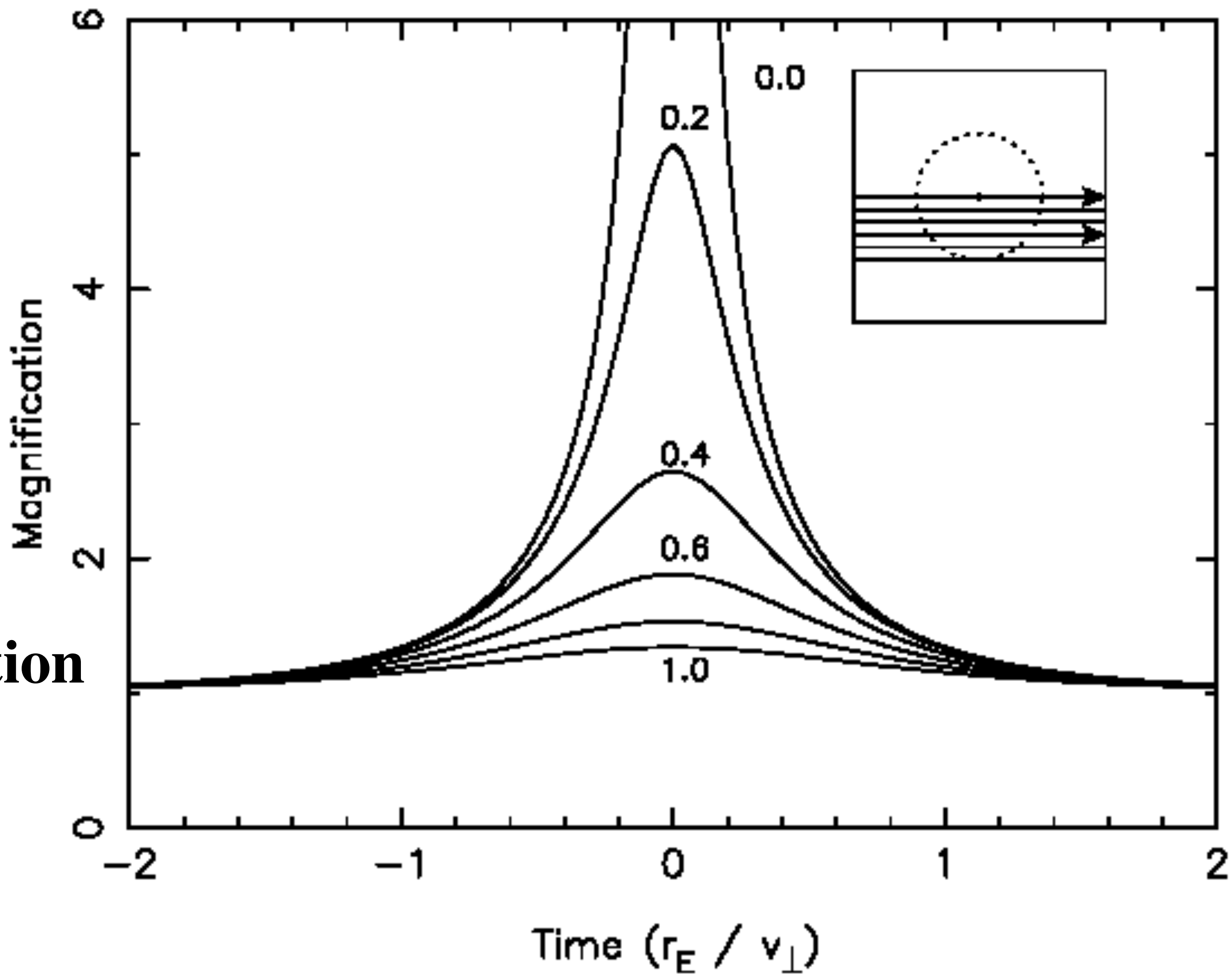
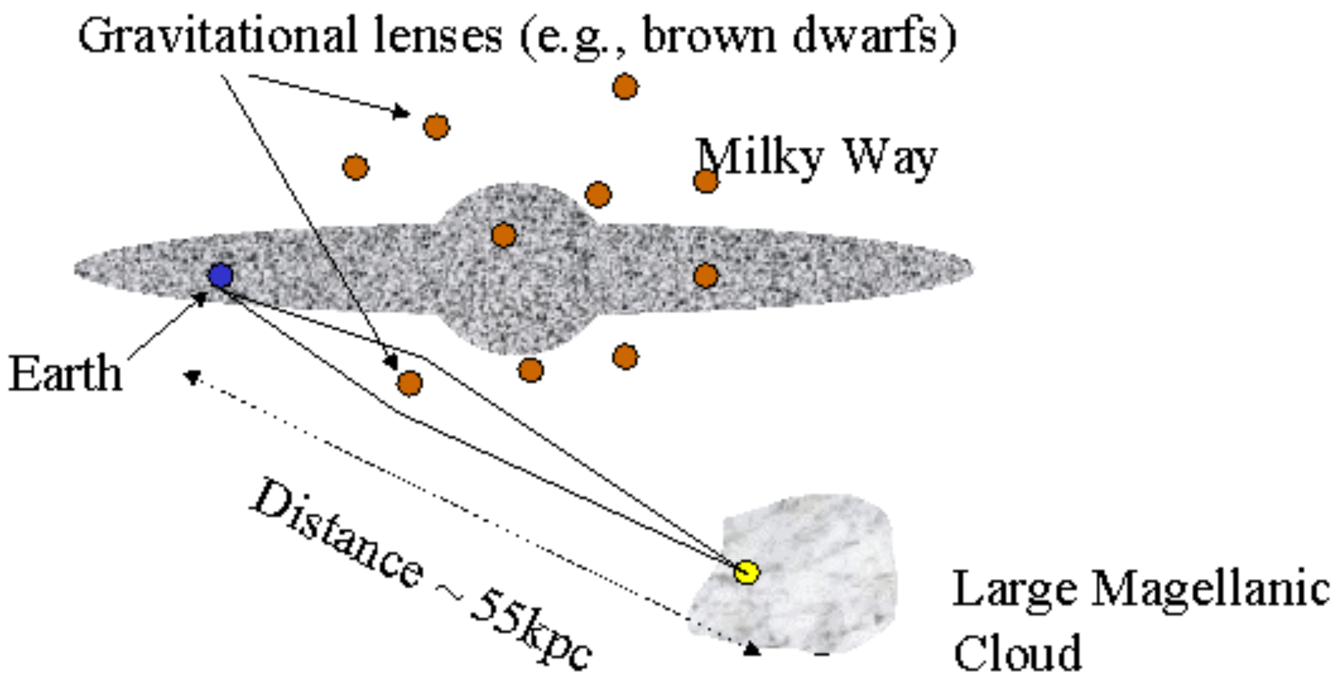


Figure 2. Microlensing event lightcurves (magnification versus time) for six values of the impact parameter $u_{\rm min} = 0.0, 0.2, \ldots, 1.0$ as labelled. Time is in units of the Einstein radius crossing time $r_{\rm E}/v_\perp$. The inset illustrates the Einstein ring (dotted circle) and the source paths relative to the lens (dot) for the six curves.

How Can We Detect MACHOs ?

- Problem: a probability of a distant star being lensed is maybe ~ 10^{-7} per year
- Solution: monitor ~ 10^{7} stars simultaneously!

Typically in the LMC or the Galactic Bulge



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)

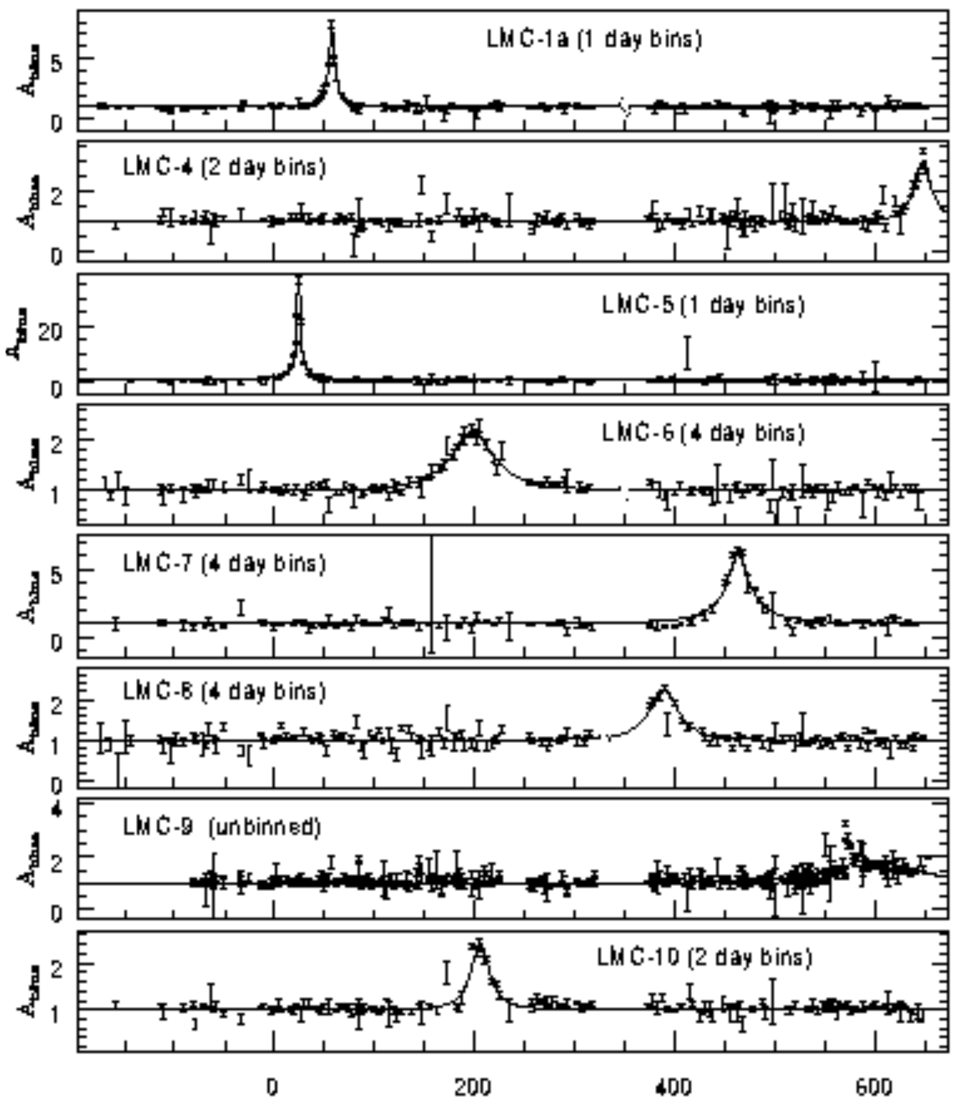
MACHO (Massive Compact Halo Object):

- 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

The First MACHO Event Seen in the LMC Experiment →



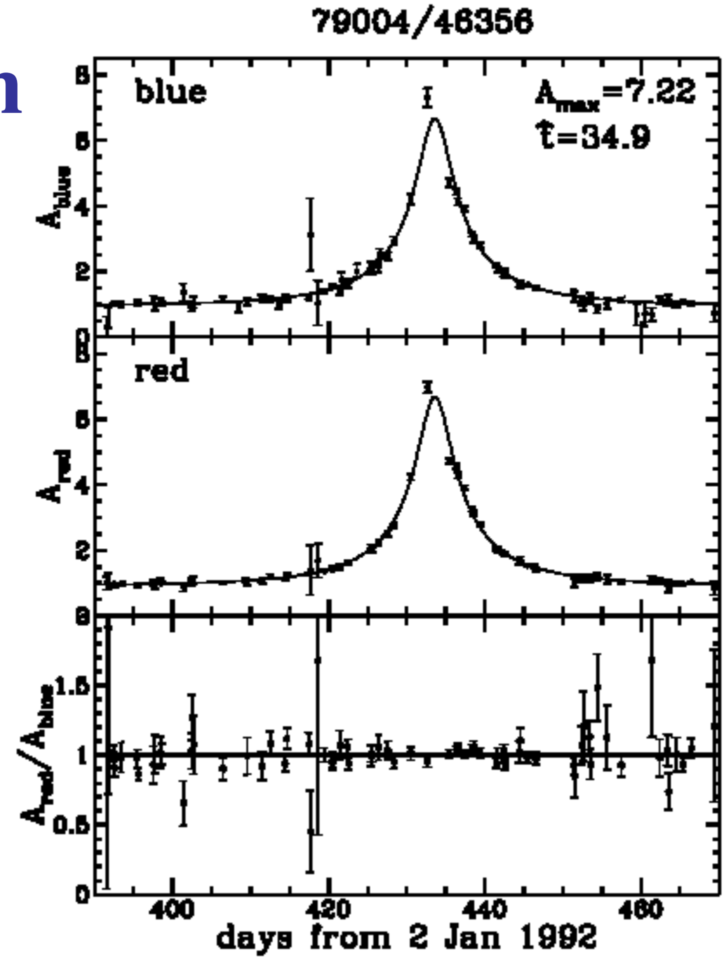


Figure 3. The first LMC microlensing candidate from the MACHO project. (Expanded view: 6 yr of constant data are

To date, hundreds (or more) of microlensing events have been detected by various groups.

The Einstein radius for a single lens of mass M, at distance $\boldsymbol{d_L}$,
observer-source distance is $\boldsymbol{d_S}$,
lens-source distance is $\boldsymbol{d_{LS} = d_S - d_L}$

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

Probability that this lens will magnify a given source is:

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

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:

- 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

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

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

$$\tau = \frac{4}{v_L c} \sqrt{\frac{G M d_L d_{LS}}{d_S}}$$

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:

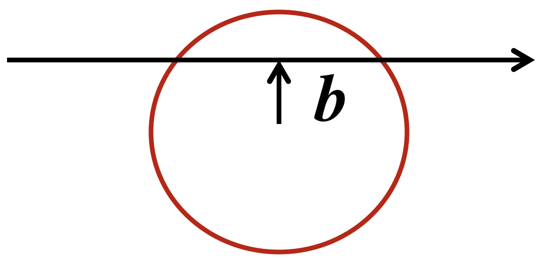
- $d_S = 8$ kpc, $d_L = d_{LS} = 4$ kpc
- $M = 0.3\ M_\odot$
- $v_L = 200$ km s^{-1}

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

Events with $\tau \sim 1$ day: $M <$ Jupiter mass ($\sim 10^{-3}\ M_\odot$)
Events with $\tau \sim 1$ year: $M \sim 25\ M_\odot$ (e.g. stellar black holes)

For each event, there are only two observables:

- Duration τ - 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



Define $u = \dfrac{b}{d_L \theta_E}$

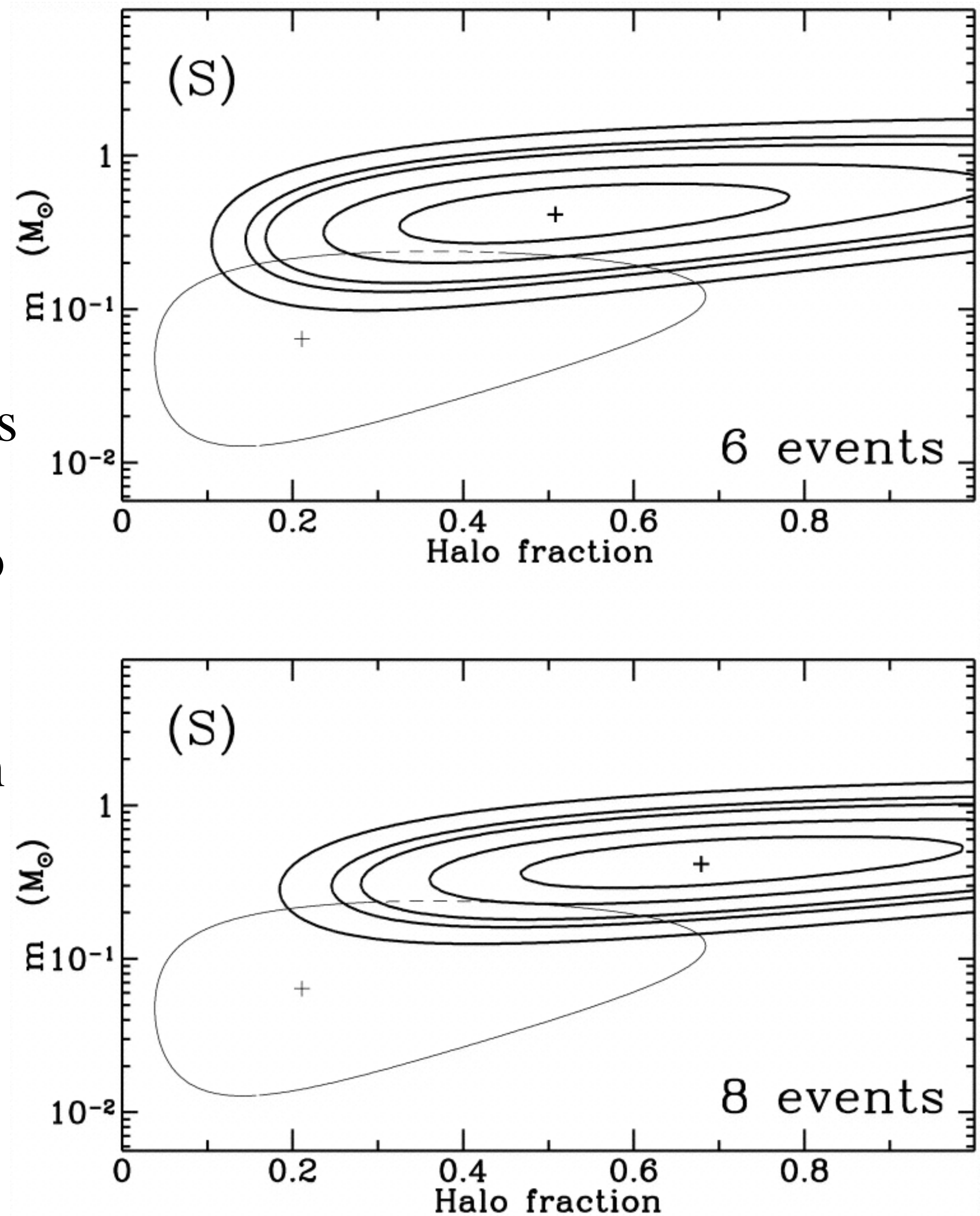
$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$$

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.

What Are MACHOs?

Analysis of the LMC microlensing experiments suggest that MACHO masses are ~ 0.5 $M_{\odot}$: too heavy for brown dwarfs. Old halo white dwarfs?? (There are problems with that…)



(Alcock et al. 1997)

MACHO Results

Based on the number and duration of MACHO events,
if the lenses are objects in the Galactic Halo:

• 20% of the mass of the Galactic halo (inferred from the Galactic rotation curve) is in the form of MACHOs; the idea that ***all*** the mass in the halo is MACHOs is definitely ruled out

• Typical mass is between 0.15 $M_\odot$ and 0.9 $M_\odot$

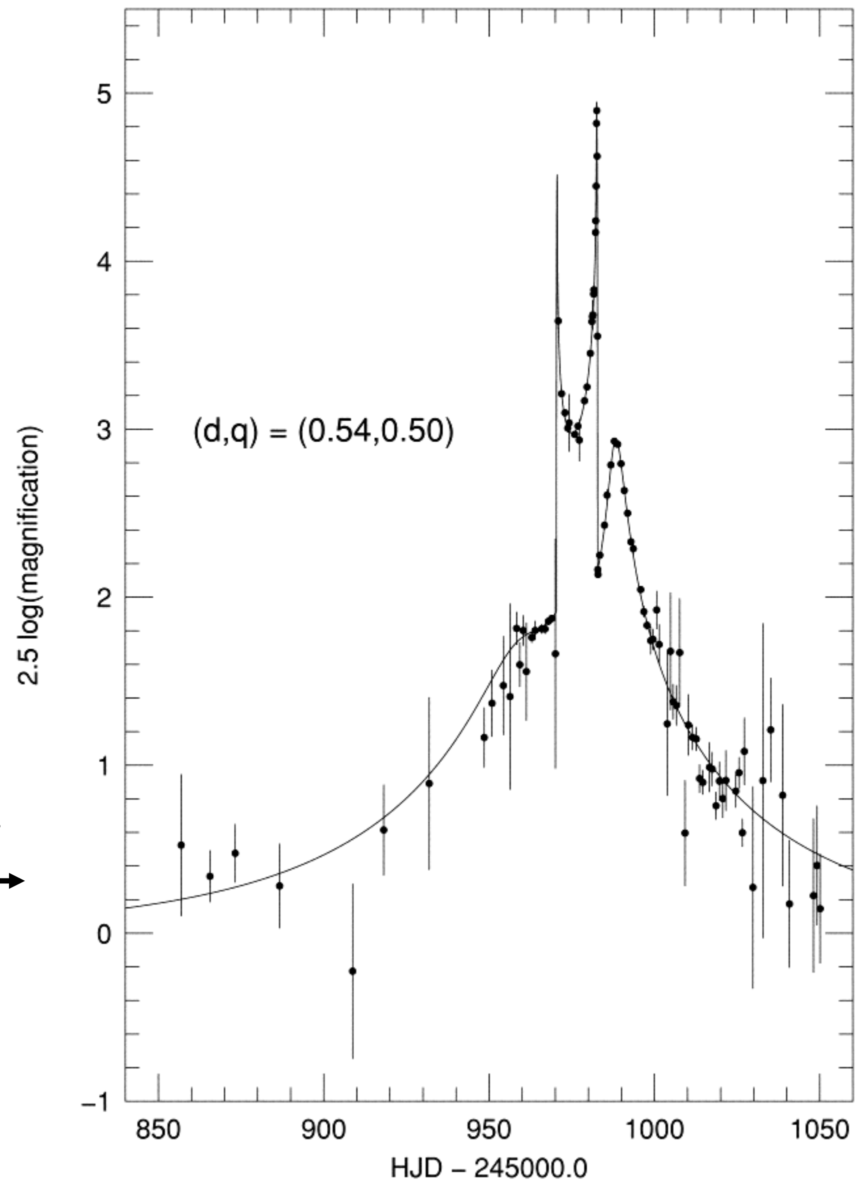
One interpretation of these results is that the halo contains a much larger population of white dwarf stars than suspected. This poses other problems: requires a major epoch of early star formation to generate these white dwarfs - but what about the corresponding metals?

Ambiguity in the distance to the lenses is the main problem!

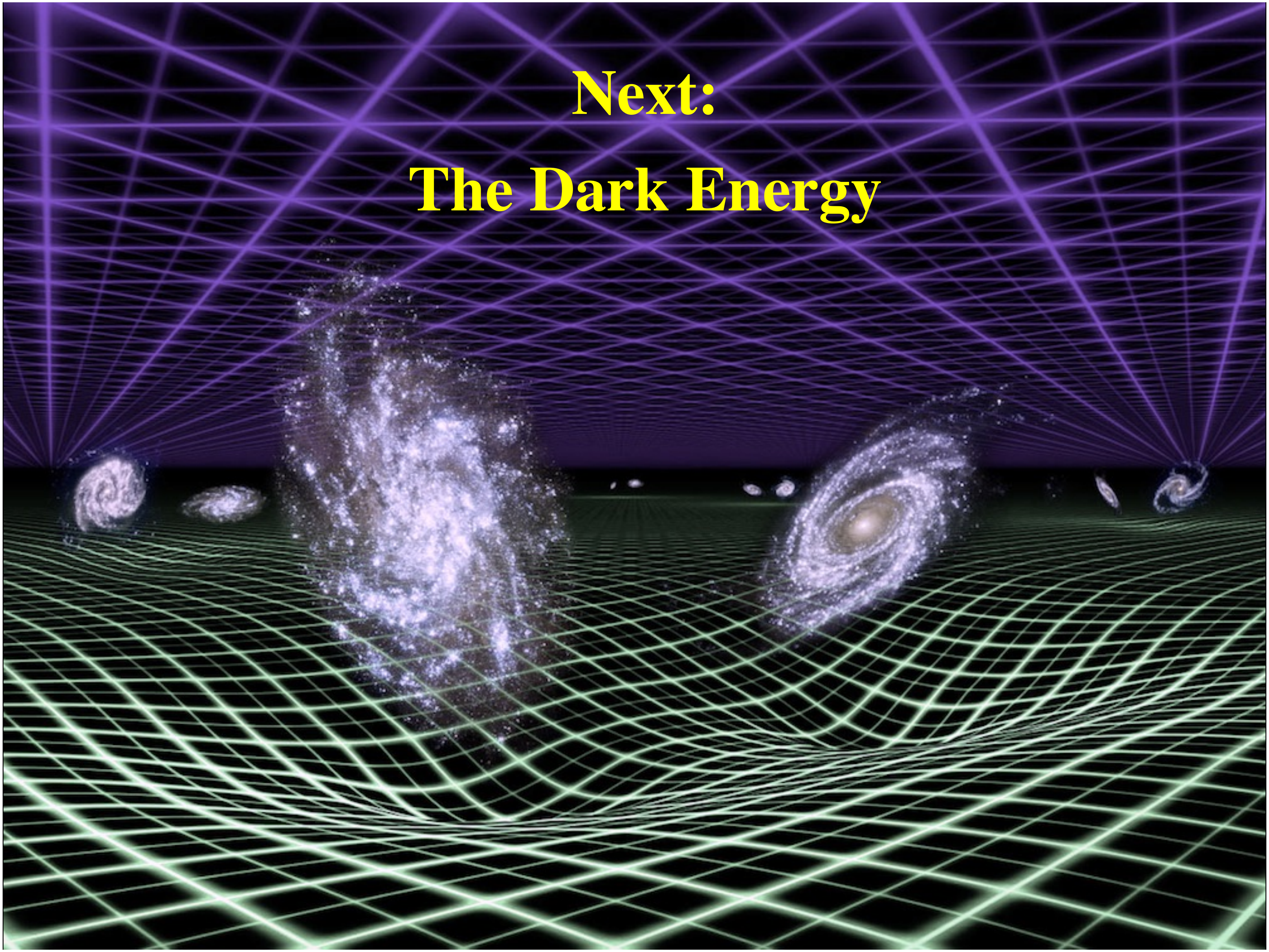
Distance ambiguity can be resolved in a few special cases:

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.



This provides more information about the event. (This one was close to the SMC)


Next:
The Dark Energy