Microlensing: Theory, Practice, Results, Future

Lecture 1

Nicholas James Rattenbury

JODRELL BANK CENTRE FOR ASTROPHYSICS
THE UNIVERSITY OF MANCHESTER

Brief Biography

PhD, The University of Auckland, New Zealand, 2003

“Detection of Extra-Solar Planets via High Amplification Microlensing Events”

Post-doctoral research associate, JBO, July 2004 - present

Current Research Interests

- Detection of planets via microlensing

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- Charactisation of microlensing planets (modelling)

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- Galactic structure and dynamics
- High Proper motion / nearby stars
- VLTI microlensing

Outline of Lectures

Lecture 1: Microlensing History and Theory

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- Background
- Motivation/Goals
- Early results
- Evolution of a field
- Basic microlensing theory

Outline of Lectures

Lecture 1: Microlensing History and Theory

Lecture 2: Beyond the single lens

Outline of Lectures

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Lecture 2: Beyond the single lens

- Finite source star
- Limb Darkening
- Blending
- Parallax
- Xallarap

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Lecture 2: Beyond the single lens

Lecture 3: Planetary Microlensing - I

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Lecture 1: Microlensing History and Theory

Lecture 2: Beyond the single lens

Lecture 3: Planetary Microlensing - I

- Binary lens microlensing
- Extreme mass ratio microlensing
- Theoretical tools of trade: caustics
- Planetary microlensing regiemes
- General rules

Outline of Lectures

Lecture 1: Microlensing History and Theory

Lecture 2: Beyond the single lens

Lecture 3: Planetary Microlensing - I

Lecture 4: Planetary Microlensing -II

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Lecture 3: Planetary Microlensing - I

Lecture 4: Planetary Microlensing -II

- Capabilities, detection limits
- Detection
- Modelling

Outline of Lectures

Lecture 1: Microlensing History and Theory

Lecture 2: Beyond the single lens

Lecture 3: Planetary Microlensing - I

Lecture 4: Planetary Microlensing -II

Lecture 5: Current and Future Operations

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Lecture 5: Current and Future Operations

- Survey (MOA and OGLE)
- Follow-up (PLANET, RoboNET, μFUN, etc)
- Instrumentation and Operations
- Image analysis / processing
- “Earth Hunter”
- Microlensing from space and Antarctica
- Autonomous observations

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Lecture 6: Miscellaneous

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Lecture 6: Miscellaneous

- Quasar microlensing
- Exotic microlensing
- Ancilliary science from microlensing surveys

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Lecture 6: Miscellaneous

A lot to get through - topics may shuffle depending on rate!

Outline of Workshops

- Workshop 1: Lightcurves - I

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  - Familiarisation with single and binary lens lightcurves
  - Recognition practice

Outline of Workshops

- Workshop 1: Lightcurves - I
- Workshop 2: Lightcurves - II

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- Workshop 1: Lightcurves - I
- Workshop 2: Lightcurves - II
    - Effect of finite source star size
    - Limb darkening
    - Lens rotation

Outline of Workshops

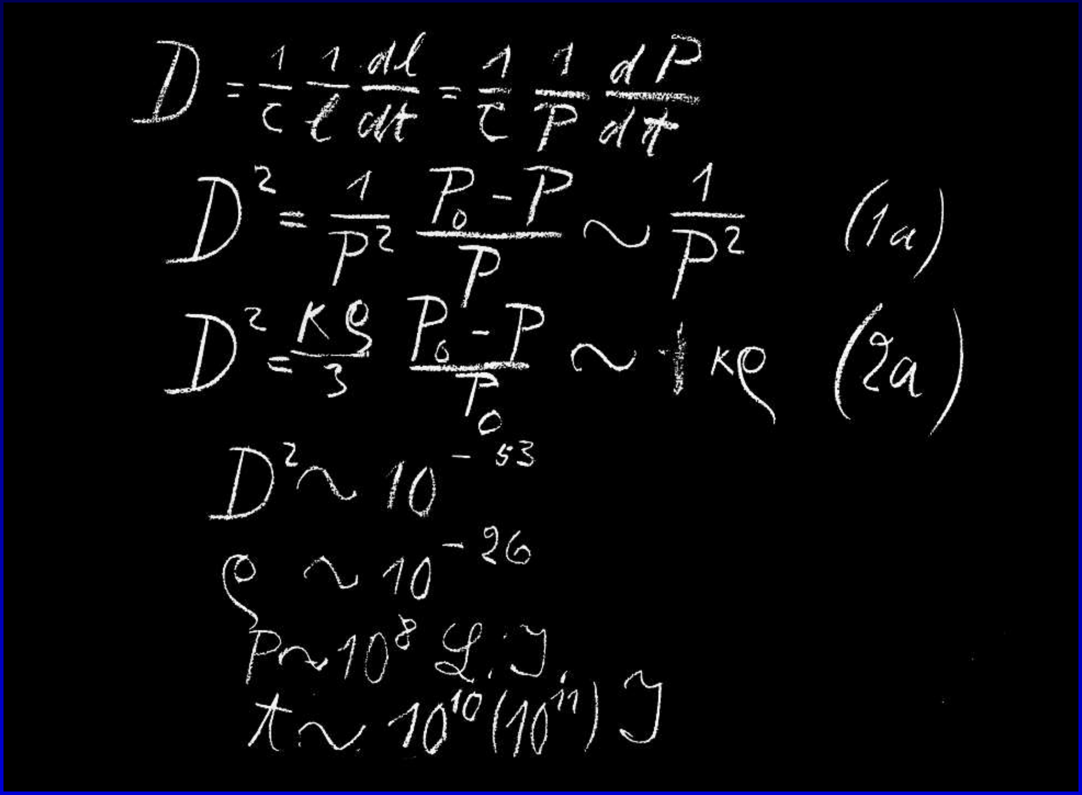
- Workshop 1: Lightcurves - I
- Workshop 2: Lightcurves - II
- Workshop 3: Modelling

Outline of Workshops

- Workshop 1: Lightcurves - I
- Workshop 2: Lightcurves - II
- Workshop 3: Modelling
  - Write basic MHMCMC code
  - Apply to basic model fitting

History

The General Theory of Relativity predicted that light would be deflected by a gravitational field.



$$D = \frac{1}{c}\frac{1}{l}\frac{dl}{dt} = \frac{1}{c}\frac{1}{P}\frac{dP}{dt}$$

$$D^2 = \frac{1}{P^2}\frac{P_0 - P}{P} \sim \frac{1}{P^2} \quad (1a)$$

$$D^2 = \frac{\kappa\rho}{3}\frac{P_0 - P}{P_0} \sim \frac{1}{3}\kappa\rho \quad (2a)$$

$$D^2 \sim 10^{-53}$$

$$\rho \sim 10^{-26}$$

$$P \sim 10^8 \ L.J.$$

$$t \sim 10^{10} (10^{11}) \ J$$

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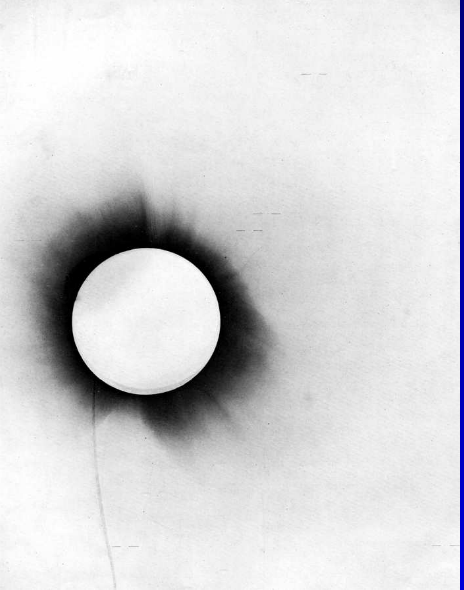

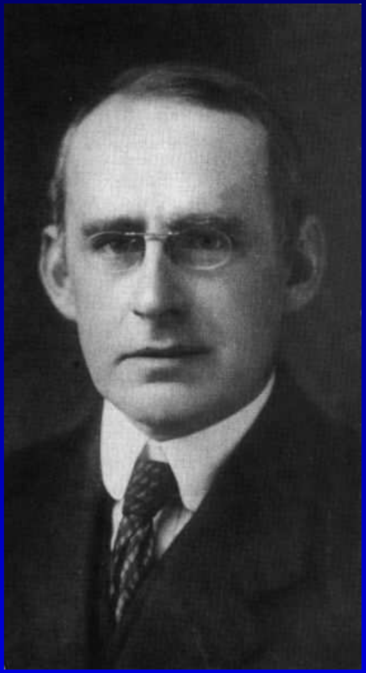

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Following prompting from R. W. Mandl, in 1936 Einstein considered the bending of light by stars other than the Sun.

He pointed out that, if two stars were lined up, as seen from Earth, then light from the more distant one would be bent by the gravitational field of the nearer one.

History

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In 1986, Bohdan Paczyński proposed that lensing by stars (microlensing) could be observed towards the Galactic Centre and Magellanic Clouds.

History Summary (pre-1993)

1979 - First discovery of gravitationally lensed quasar Q0957+561A,B (Walsh et al)

1979 - Action of individual stars on quasar lensing (Chang & Refsdal)

1981 - Simulation work by Gott, Young et al

1986-8 - Simulations by Paczynski; Kayser et al; Schneider & Weiss; Grieger et al

1989 - Discovery of microlensing in quadruple quasar (Irwin et al)

Compiled from J. Wambsganss

History

In 1993, the first detection of microlensing made.

Gravitational microlensing

Gravitational microlensing: a foreground object (usually a star) passes between us and a background star. The light from the background star is amplified in a characteristic way, changing with time as the lens star passes in front of it.

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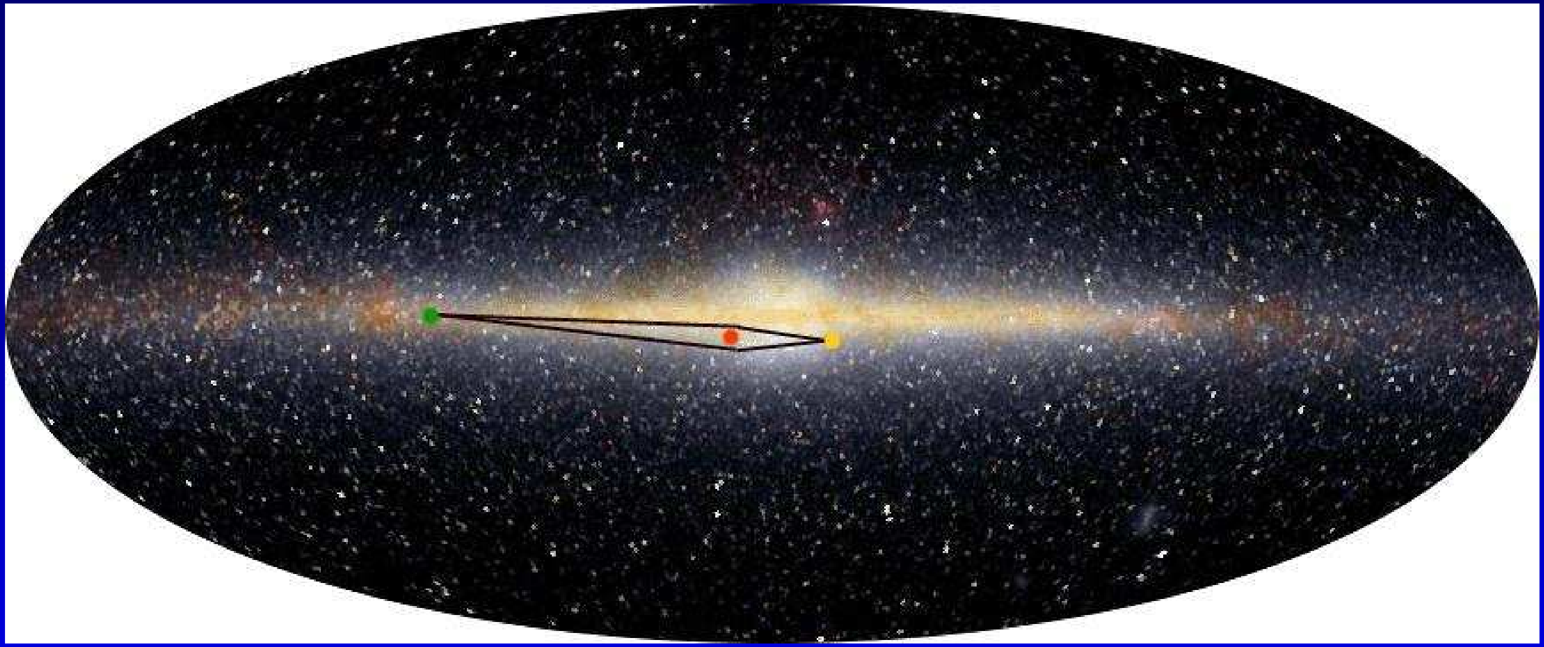

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The light from the background source star is split into several images by the gravitational potential of the foreground lens star. Normal terrestrial optical telescopes cannot resolve the individual images (hence microlensing), but we note an apparent time-dependent brightening of the source star.

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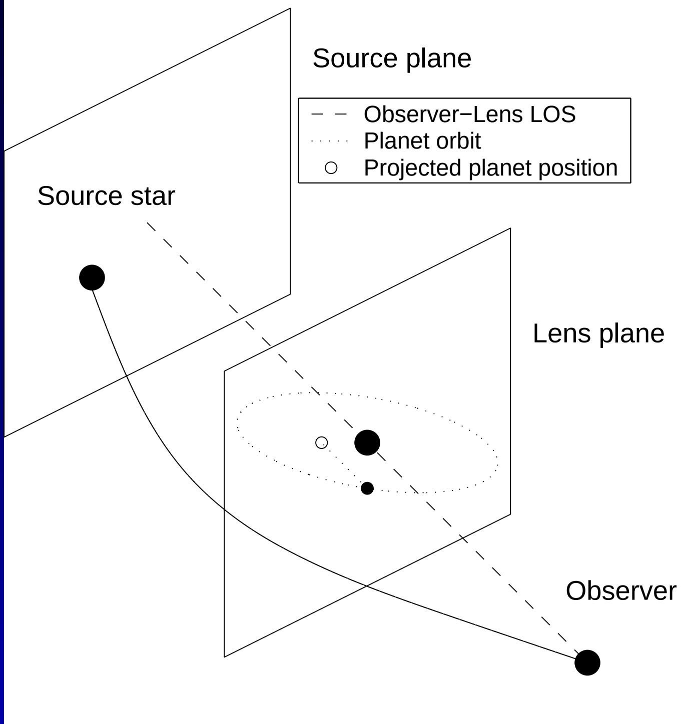
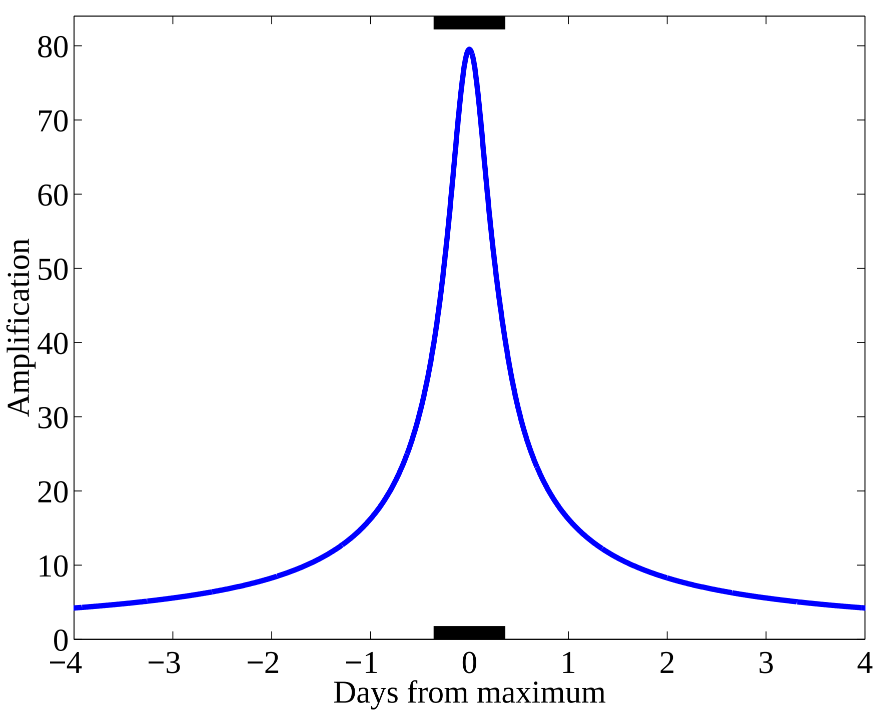
We record the amount of light observed from the background star as a microlensing event light curve. Analysis of these light curves is a unique window on the study of low-mass extra-solar planets, the structure of our Galaxy and occasionally the background(source) stars.

Microlensing Lightcurves





Relative motion of source, observer and lens gives time-dependent amplification of source.

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History

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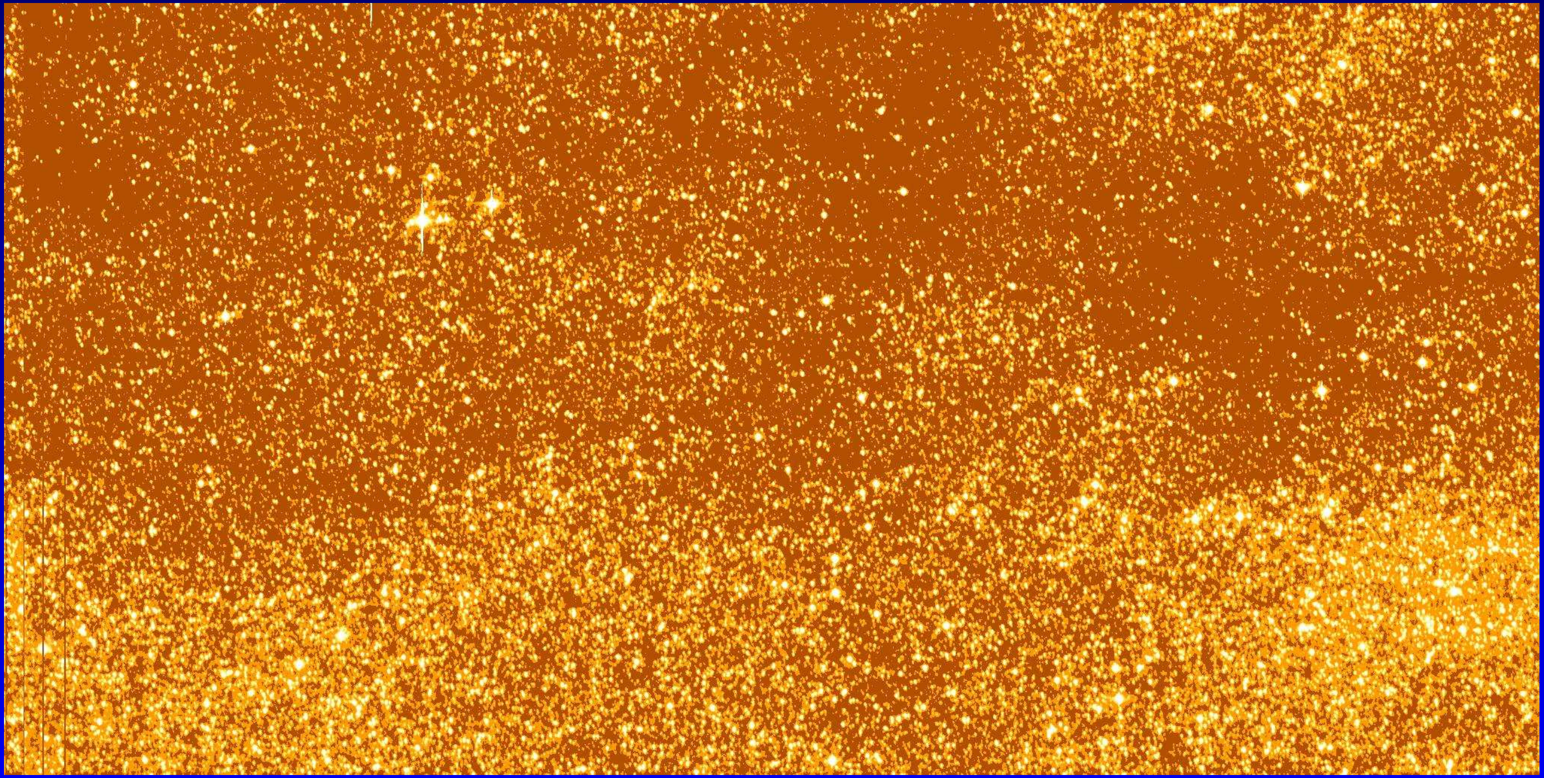
Playing the odds

The probability of a star being microlensed is very slight: $\sim 10^{-6}$. In order to detect a reasonable number of events in a given time, millions of stars have to be monitored simultaneously.



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When Einstein made his comment that lensing by stars was so unlikely as to be virtually impossible, the power of today's instrumentation and computing would have been the purest fantasy.

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Currently detecting ~ 1000 events per year.

Motivation - Dark Matter

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MACHOs were theorised to be objects like brown dwarfs or planets.

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Survey observations were begun by the US/Australian collaboration MACHO in June 1992, monitoring the Galactic Bulge and the Magellanic Clouds with the 50” Great Melbourne telescope atop Mt Stromlo, Canberra, Australia.

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and the OGLE (1992-) and MOA (1993-) collaborations from Las Campanas and New Zealand, respectively.

Results - Dark Matter

The results from the MACHO and EROS search for compact dark matter show that MACHOs do not comprise a significant fraction of the Galactic halo.

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- Alcock et al (2001): MACHO results consistent with 20% contribution of dark matter to halo
- Sahu (2003): MACHO results consistent with 0–5% contribution of dark matter to halo
- Tisserand (2006): EROS results consistent with 8% contribution of dark matter to halo

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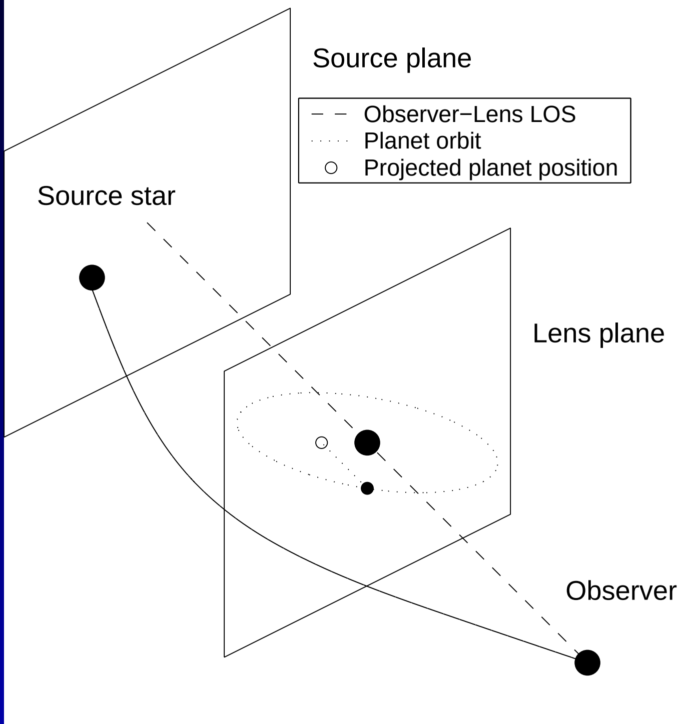
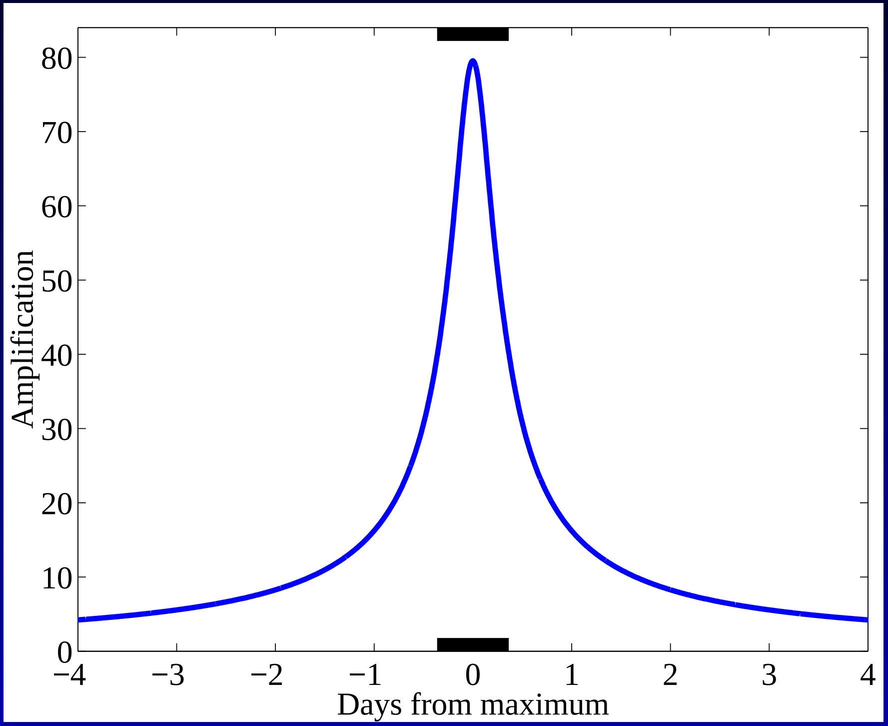
Microlensing Theory





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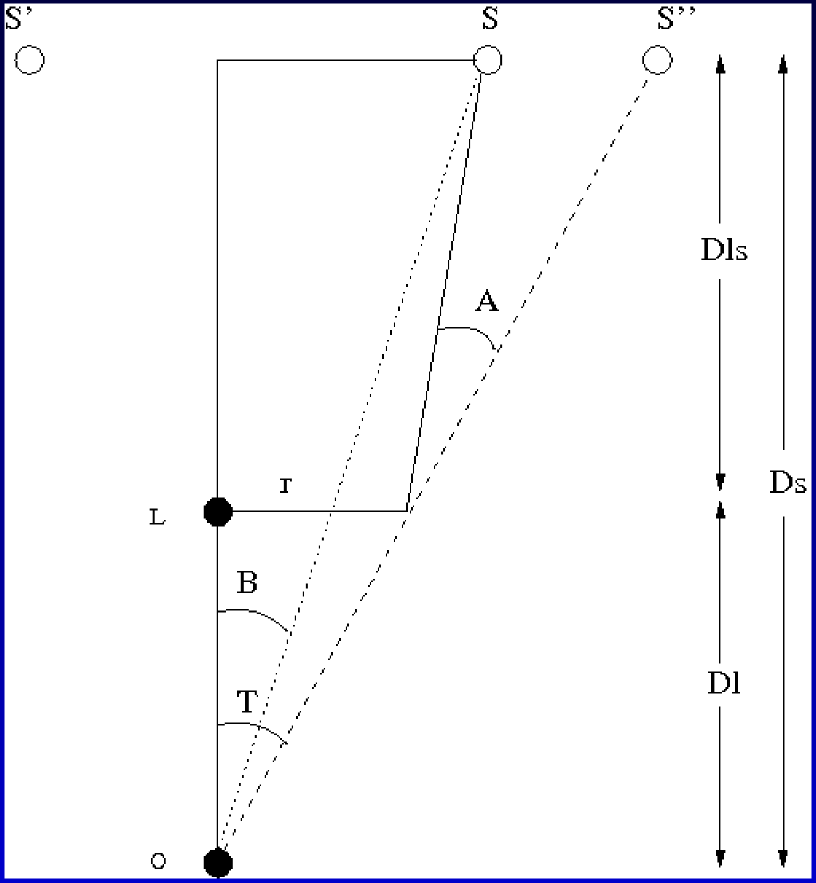
Microlensing Theory

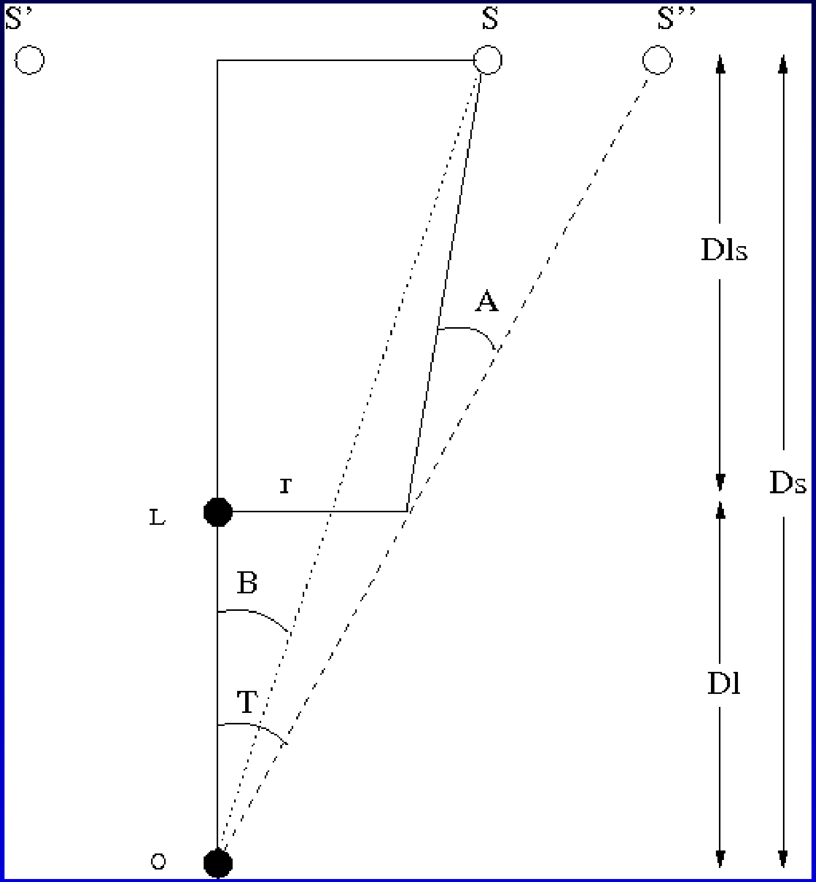


Light from a background source, S, is deflected through an angle, α, by the gravitational field of a lens object, L.

Images of the background source appear at S' and S''. The distances from the observer, O, to the lens and source are D_L and D_S respectively.

After Wambsganss 1998.

Microlensing Theory



$$\theta D_S = \beta D_S + \alpha D_{LS}$$

Using $r = D_L\theta$, this becomes:

$$\beta(\theta) = \theta - \frac{D_{LS}}{D_L D_S}\frac{4GM}{c^2\theta}$$

In the case where the source, lens and observer are collinear, $\beta = 0$ and the light from the source is seen to be a circular image. The angular radius of this image (the Einstein ring) is called the Einstein radius, R_E

After Wambsganss 1998.

Microlensing Theory

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}}$$

In the lens plane, the Einstein ring has a radius $\theta_E D_L$. Setting $d = \frac{D_L}{D_S}$ we get:

$$\begin{aligned} R_E &= \sqrt{\frac{4GM}{c^2} D_S (1-d) d} \\ &= 6.61 \times 10^{11} \sqrt{\frac{M}{0.3 M_\odot}} \sqrt{\frac{D_S}{8\mathrm{kpc}}} \sqrt{(1-d)d} \quad \mathrm{m} \end{aligned}$$

Microlensing Theory

The Einstein ring crossing time $t_E = R_E / v_\perp$ is the natural time unit for microlensing and can be shown to be:

$$t_E = 38.25\,\mathrm{days}\left(\frac{M_L}{0.3M_\odot}\right)^{1/2}\left(\frac{D_S}{8\,\mathrm{kpc}}\right)^{1/2}((1-d)d)^{1/2}$$

if the transverse velocity of the lens is taken to be $v_\perp = 200\ \mathrm{km\,s^{-1}}$.

Microlensing Theory

The lens equation can be re-written as:

$$\beta = \theta - \frac{\theta_E^2}{\theta}$$

Solving this equation for θ, the image position, gives two solutions:

$$\theta_{1,2} = \frac{1}{2}\left(\beta \pm \sqrt{\beta^2 + 4\theta_E^2}\right)$$

Thus, for a point lens mass, two images of the background source will be produced.

Microlensing Theory

The gravitational lens potential produces distorted images. The surface brightness of the source is conserved by the lensing action. The magnification of a source image is defined as the ratio between the solid angles of the source and image:

$$\mu = \frac{\theta}{\beta}\frac{d\theta}{d\beta}$$

Microlensing Theory

The magnification can be expressed as:

$$\mu_{1,2} = \left(1 - \left[\frac{\theta_E}{\theta_{1,2}}\right]^4\right)^{-1} = \frac{u^2+2}{2u\sqrt{u^2+4}} \pm \frac{1}{2}$$

where $u = \frac{\beta}{\theta_E}$ is defined as the impact parameter: the angular separation of the lens and source scaled by the Einstein radius.

Microlensing Theory

The sum of the two image magnifications yields the total measurable magnification:

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

In the special case where the source, lens and observer are collinear ($\beta = 0$), the magnification is formally infinite. However, since most source objects have a finite size, and because a fuller treatment would use wave optics, infinite image magnifications are not found in reality.

Microlensing Properties

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- The angular spread of the Einstein ring in this situation is $\simeq 0.3$ mas.
- The separate images of the source star are not resolvable, but the amplification of the source by the lens is detectable as an apparent brightening of the source.

Microlensing Lightcurves

- Since the lens object, observer and source star are all in relative motion, the projected impact parameter changes with time.

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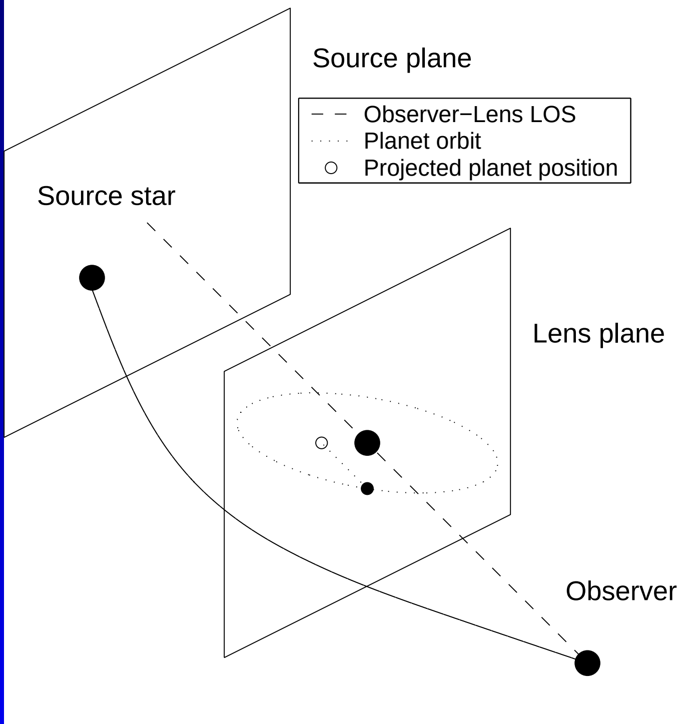

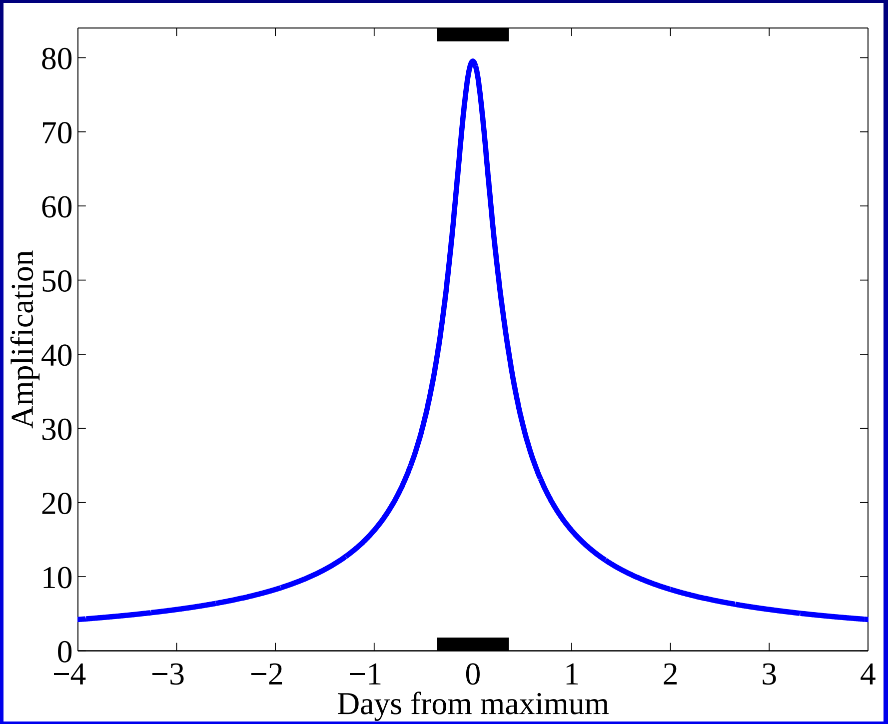

Co-ordinate system

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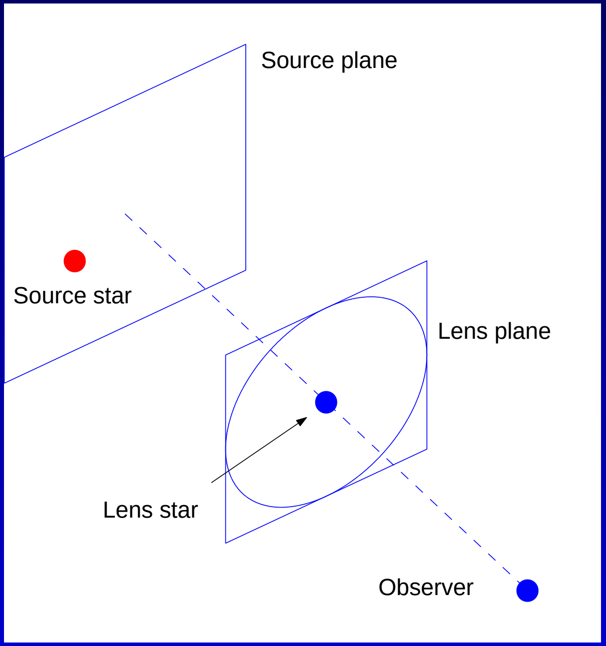

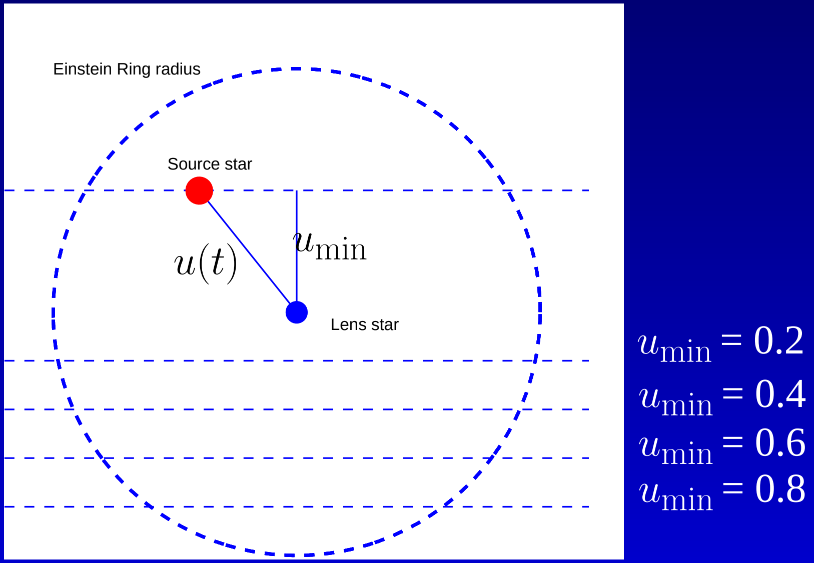

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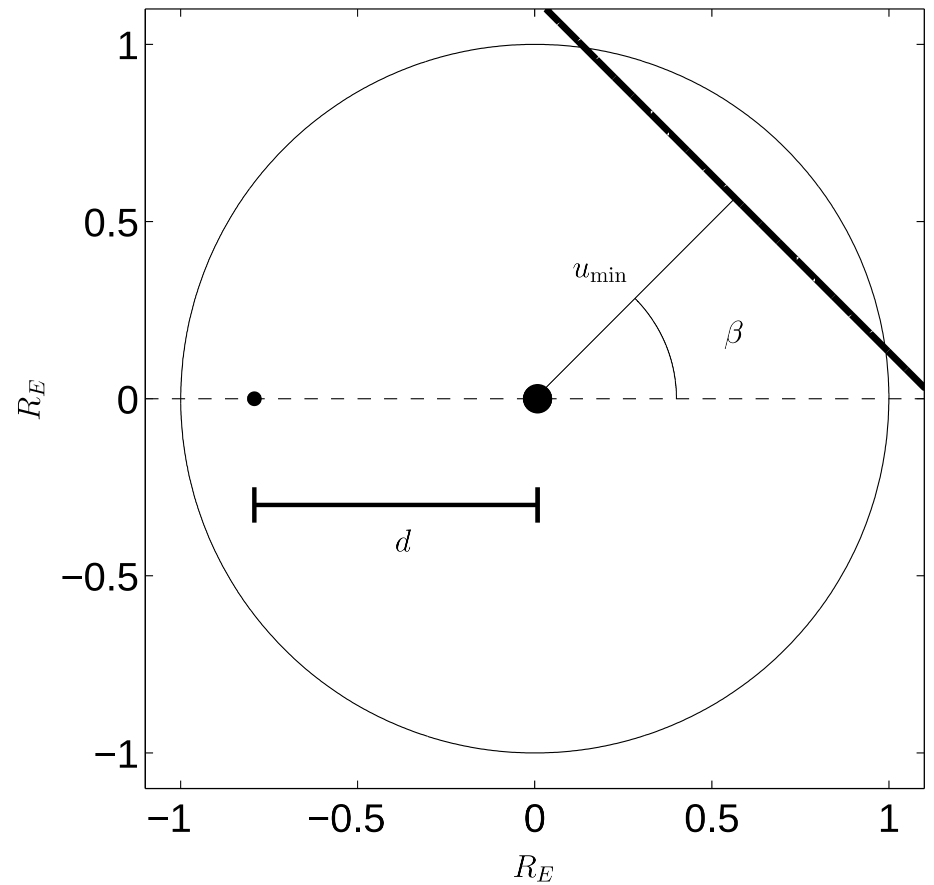

Single lens lightcurve

The amplification of the source star, at any time t is found using the time-dependent impact parameter:

$$u(t) = \left[{u_{\min}}^2 + \left(\frac{v_\perp \cdot (t - t_0)}{R_E} \right)^2 \right]^{\frac{1}{2}}$$

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

Here $v_\perp$ is the lens transverse velocity with respect to the observer-lens line of sight. $u_{\min}$ is the minimum impact parameter in units of the Einstein radius and t_0 is the time of maximum amplification.

Single lens lightcurve

Generally, the maximum amplification of a source star in a microlensing event with a single lens is:

$$A_{\mathrm{max}} \simeq \frac{1}{u_{\mathrm{min}}}$$

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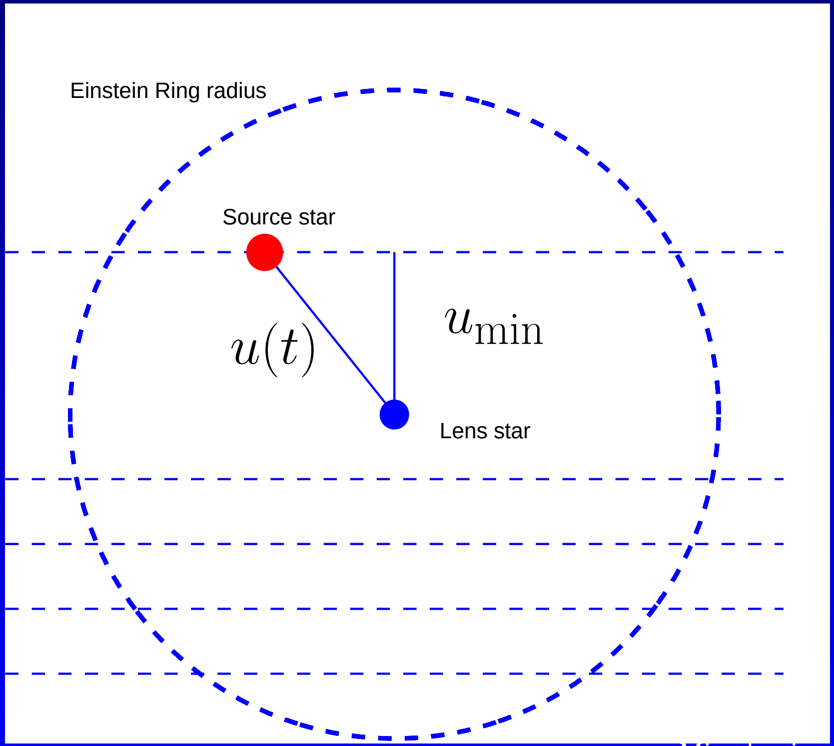

$u_{\mathrm{min}} = 0.2$

$u_{\mathrm{min}} = 0.4$

$u_{\mathrm{min}} = 0.6$

$u_{\mathrm{min}} = 0.8$

Single lens lightcurve

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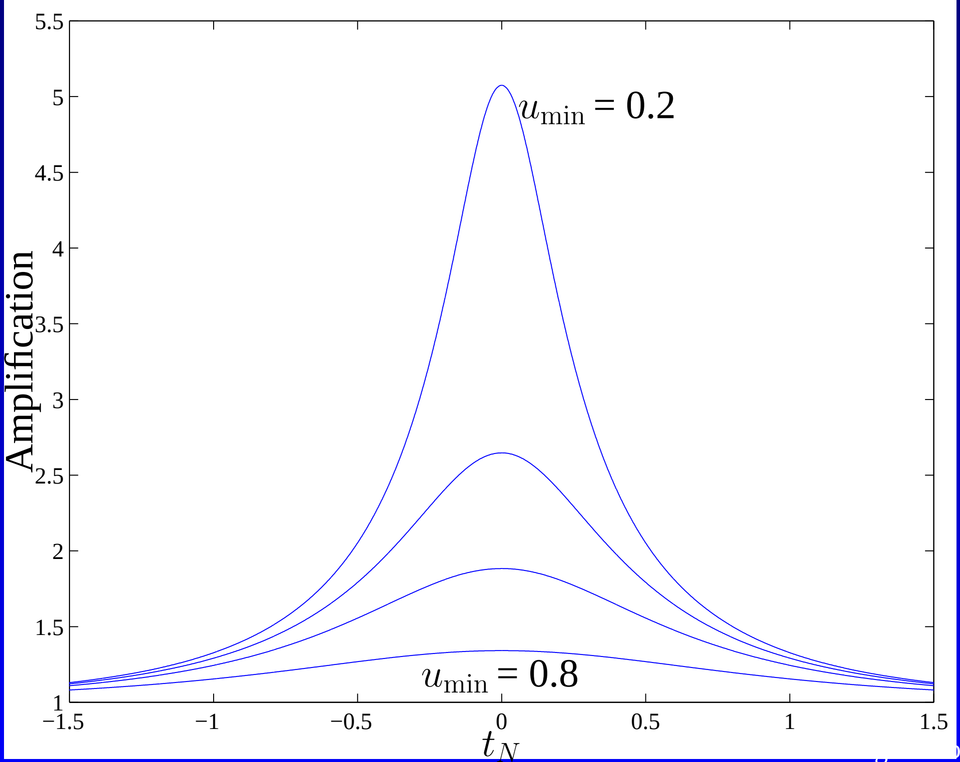

Single lens lightcurve

Single lens microlensing:

- Has three parameters: t_0, t_E, $u_{\rm min}$.
- Usually assume D_L= 6 kpc, D_S= 8 kpc for Galactic microlensing.
- Usually assume $v_\perp$ = 220 km/s for Galactic lenses.
- Degeneracies exist between lens mass, distance, and velocity.
- Only observable is t_E.

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