


Introduction to (Strong) Gravitational Lensing: Basics and History



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XIth School of Cosmology

September 17 - 22, 2012 — IESC, Cargèse

Introduction to (Strong) Gravitational Lensing: Basics and History

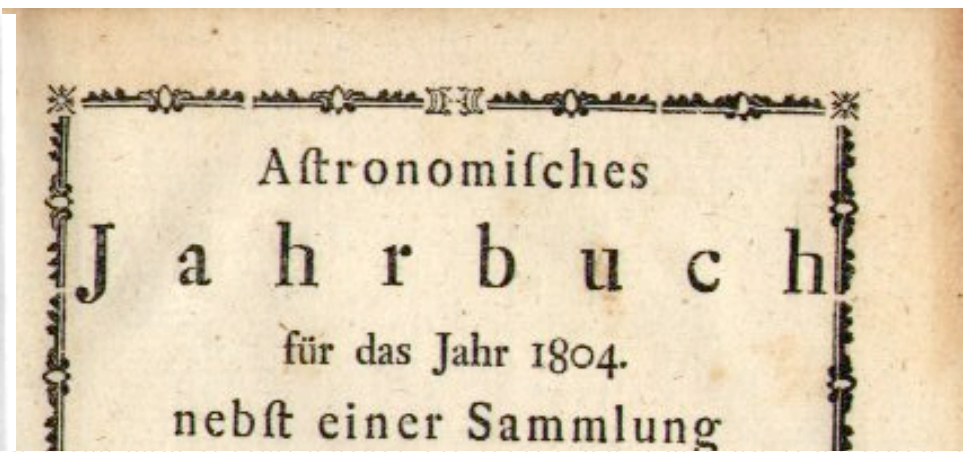
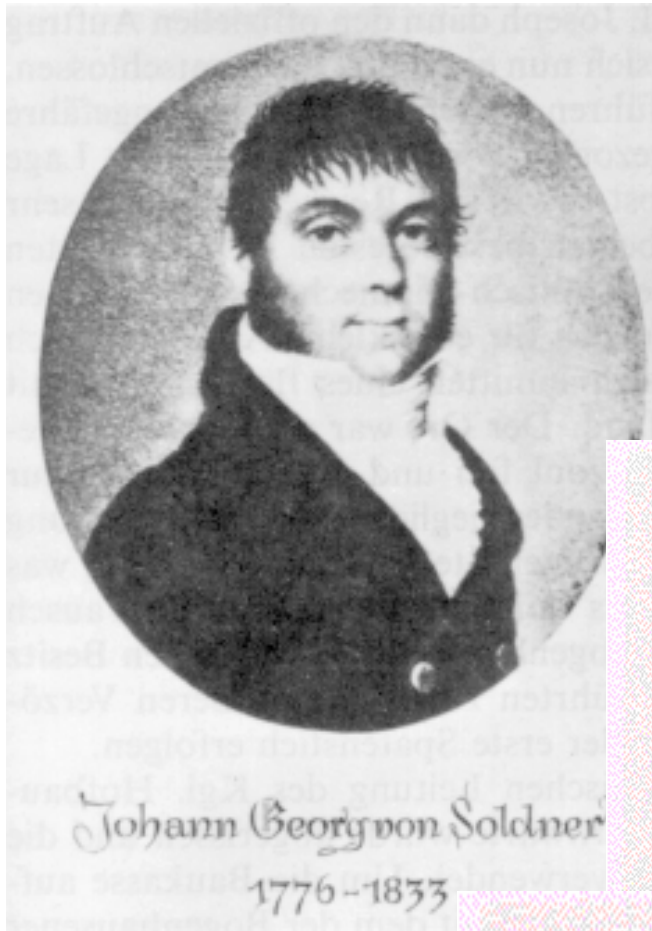
Joachim Wambsganss

- The **history** of gravitational lensing (pretty predictive ...)
 - Soldner, Einstein, Chwolson, Zwicky, Russell, Walsh, Refsdal, Paczynski, ...
- The **basics** of gravitational lensing (pretty simple ...)
 - mass scales, distance scales, angular scales
- A few **examples** of (strong) gravitational lensing (pretty diverse ...)
 - distant, nearby, imaging, monitoring



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Ueber die Ablenkung eines Lichtstrals von seiner geradlinigen Bewegung, durch die Attraktion eines Weltkörpers, an welchem er nahe vorbei geht.
Von Hrn. *Joh. Soldner*.

Berlin, im März 1801.

for solar limb:

$$\alpha_{\odot, \text{Soldner}} = 0.84''$$

Wenn also ein Lichtstral an einem Weltkörper vorbeigeht, so wird er durch die Attraktion desselben genöthiget, anstatt in der geraden Richtung fortzugehen, eine Hyperbel zu beschreiben, deren konkave Seite gegen den anziehenden Körper gerichtet ist.

A brief history of light deflection

4. *Über den Einfluß
der Schwerkraft auf die Ausbreitung des Lichtes;
von A. Einstein.*

Da die Fixsterne der der Sonne zugewandten Himmelspartien bei totalen Sonnenfinsternissen sichtbar werden, ist diese Konsequenz der Theorie mit der Erfahrung vergleichbar.

$$\alpha_{\odot, \text{Einstein 1911}} = 0.84''$$

1911: Light deflection at solar limb:

Einstein is only half correct!

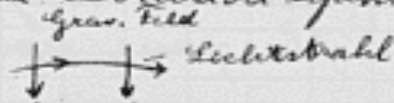


Zürich. 14. I. 13.

Aus

Hoch geehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.



An Sonnenrande misste diese Ablenkung $0,84''$ betragen und wie $\frac{1}{R}$ abnehmen ($R =$ Sonnenradius).
($R =$ Sonnenradius). - $20,84''$



Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnen-nähe ^{helle} Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.

Light on “curved” tracks: confirming Einstein’s prediction?

How? During a solar eclipse!

Who? Erwin Freundlich!

When? 21. August 1914!

Where? Crimean Peninsula!



... and off they went, the Potsdam expedition ...

30

prof einstein huberlandstrasse 5
berlin. =

22.9.19. 1-N
30

Telegramm Nr. _____

genommen den 22/9 1919
um 14 Uhr 26 Min.
von _____
durch _____

Telegraphie des  Deutschen Reichs.

Berlin, Haupt Telegraphenamts Zeitung Nr. 34

Befördert den _____
um _____
in Lit. _____ an _____
durch _____

Telegramm aus bln sgravenhage 0046 21/19 22/9 10.40 III = um _____ Uhr _____ Min.

eddington fand sternverscheidung am sonnenrand vorlaeufige gruss
zwischen neun zehntel sekunde und doppelt = Lorentz +

22. IX. 19

Liebe Mutter!

Heute eine freundige Nach-
richt. H. A. Lorentz hat mir
telegraphiert, dass die englischen
Expeditionen die Lichtablenkung
an der Sonne wirklich bewiesen
haben. Maja schreibt mir lie-



A brief history of light deflection

1911: Einstein only half correct!
Light deflection at solar limb:

$$\alpha_{\odot, \text{Einstein 1911}} = 0.84''$$

1915: General Relativity

$$\alpha_{\odot, \text{Einstein 1915}} = 1.74''$$

1919: Solar Eclipse Expedition
Eddington confirms:
Einstein fully correct!



Einstein, Science 84, 506 (1936)

DECEMBER 4, 1936

LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

SOME time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish.

The light coming from a star A traverses the gravitational field of another star B , whose radius is R_0 . Let there be an observer at a distance D from B and at a distance x , small compared with D , from the extended central line \overline{AB} . According to the general theory of relativity, let α_0 be the deviation of the light ray passing the star B at a distance R_0 from its center.

It follows from the law of deviation that an observer situated exactly on the extension of the central line \overline{AB} will perceive, instead of a point-like star A , a luminous circle of the angular radius β around the center of B , where

$$\beta = \sqrt{\alpha_0 \frac{R_0}{D}}$$

It should be noted that this angular diameter β does not decrease like $1/D$, but like $1/\sqrt{D}$, as the distance D increases.

Of course, there is no hope of observing this phenomenon directly.

ALBERT EINSTEIN

INSTITUTE FOR ADVANCED STUDY,
PRINCETON, N. J.

Über eine mögliche Form fiktiver Doppelsterne. Von O. Chwolson.

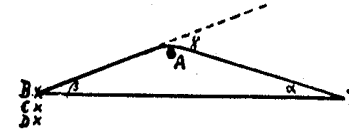
Es ist gegenwärtig wohl als höchst wahrscheinlich anzunehmen, daß ein Lichtstrahl, der in der Nähe der Oberfläche eines Sternes vorbeigeht, eine Ablenkung erfährt. Ist γ diese Ablenkung und γ_0 der Maximumwert an der Oberfläche, so ist $\gamma_0 \geq \gamma \geq 0$. Die Größe des Winkels ist bei der Sonne $\gamma_0 = 1''.7$; es dürften aber wohl Sterne existieren, bei denen γ_0 gleich mehreren Bogensekunden ist; vielleicht auch noch mehr. Es sei A ein großer Stern (Gigant), T die Erde, B ein entfernter Stern; die Winkeldistanz zwischen A und B , von T aus gesehen, sei α , und der Winkel zwischen A und T , von B aus gesehen, sei β . Es ist dann

$$\gamma = \alpha + \beta.$$

Ist B sehr weit entfernt, so ist annähernd $\gamma = \alpha$. Es kann also α gleich mehreren Bogensekunden sein, und der Maximumwert von α wäre etwa gleich γ_0 . Man sieht den Stern B von der Erde aus an zwei Stellen: direkt in der Richtung TB und außerdem nahe der Oberfläche von A , analog einem Spiegelbild. Haben wir mehrere Sterne B, C, D , so würden die Spiegelbilder umgekehrt gelegen sein wie in

Petrograd, 1924 Jan. 28.

einem gewöhnlichen Spiegel, nämlich in der Reihenfolge D, C, B , wenn von A aus gerechnet wird (D wäre am nächsten zu A).



Der Stern A würde als fiktiver Doppelstern erscheinen. Teleskopisch wäre er selbstverständlich nicht zu trennen. Sein Spektrum bestände aus der Übereinanderlagerung zweier, vielleicht total verschiedenartiger Spektren. Nach der Interferenzmethode müßte er als Doppelstern erscheinen. Alle Sterne, die von der Erde aus gesehen rings um A in der Entfernung $\gamma_0 - \beta$ liegen, würden von dem Stern A gleichsam eingefangen werden. Sollte zufällig TAB eine gerade Linie sein, so würde, von der Erde aus gesehen, der Stern A von einem Ring umgeben erscheinen.

Ob der hier angegebene Fall eines fiktiven Doppelsternes auch wirklich vorkommt, kann ich nicht beurteilen.

O. Chwolson.

Antwort auf eine Bemerkung von W. Anderson.

Daß ein Elektronengas einer Substanz mit negativem Brechungsvermögen optisch äquivalent sein müßte, kann bei dem heutigen Stand unserer Kenntnisse nicht zweifelhaft sein, da dasselbe einer Substanz von verschwindend kleiner Eigenfrequenz äquivalent ist.

Aus der Bewegungsgleichung

$$\varepsilon X = \mu \frac{d^2 x}{dt^2}$$

eines Elektrons von der elektrischen Masse ε und der ponderablen Masse μ folgt nämlich für einen sinusartig pendelnden Prozeß von der Frequenz ν die Gleichung

$$\varepsilon X = -(2\pi\nu)^2 \mu x.$$

Berücksichtigt man, daß εx das »Moment« eines schwingenden Elektrons ist, so erhält man für die Polarisation $p = n \varepsilon x$ eines Elektronengases mit n Elektronen pro Volumeneinheit

$$p = -\varepsilon^2 n / [\mu (2\pi\nu)^2] \cdot X.$$

Hieraus folgt, daß die scheinbare Dielektrizitätskonstante

$$D = 1 + 4\pi p / X = 1 - \varepsilon^2 n / (\pi \mu \nu^2)$$

ist. \sqrt{D} ist in diesem Falle der Brechungsexponent, also jedenfalls kleiner als 1. Es erübrigt sich bei dieser Sachlage, auf das Quantitative einzugehen.

Es sei noch bemerkt, daß ein Vergleich des Elektronengases mit einem Metall unstatthaft ist, weil die bei der elementaren Theorie der Metalle zugrundegelegte »Reibungskraft« bei freien Elektronen fehlt; das Verhalten der letzteren ist allein durch die Einwirkung des elektrischen Feldes und durch die Trägheit bedingt.

Berlin, 1924 April 15.

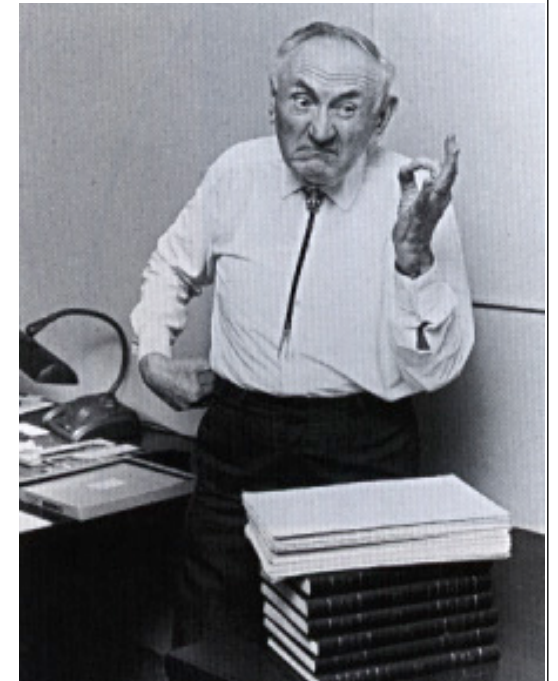
A. Einstein.

Fritz Zwicky: "Nebulae as gravitational lenses"

Phys. Rev. 51, 290 - 290 (1937)

I made some calculations which show that extragalactic *nebulae* offer a much better chance than *stars* for the observation of gravitational lens effects.

- 1) additional test for GR
- 2) "telescope": see fainter objects
- 3) measure masses: confirm large masses of "nebulae" (i.e. dark matter)
- 4) splittings of up to 30 arcseconds



Scientific American, Feb 1937:

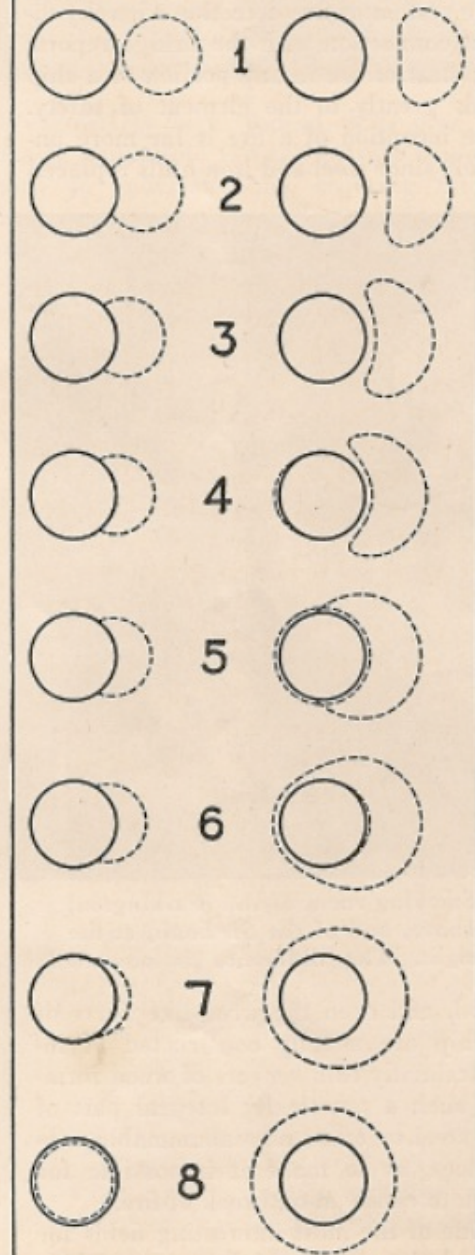
A RELATIVISTIC ECLIPSE

What Might be Seen from a Planet Conveniently Placed Near the Companion of Sirius . . . Perfect Tests of General Relativity that are Unavailable

By HENRY NORRIS RUSSELL, Ph. D.

Chairman of the Department of Astronomy and Director of the Observatory at Princeton University. Research Associate of the Mount Wilson Observatory of the Carnegie Institution of Washington. President of the American Astronomical Society.

- 1) “Einstein effect” is **perfect (but unavailable) test for GR**: “effects conspicuous to the immediate gaze”
- 2) source is not point-like: “finite angular size”
- 3) image “appears to be enlarged vertically”, “bright crescent”, “image has developed pointed horns”
- 4) “most spectacular phenomena of the heavens”



My hearty thanks are due to Professor Einstein, who permitted me to see the manuscript of his note before its publication.—*Princeton University Observatory, December 2, 1936.*

Refsdal, MNRAS 128, 307 (1964)

ON THE POSSIBILITY OF DETERMINING HUBBLE'S PARAMETER AND THE MASSES OF GALAXIES FROM THE GRAVITATIONAL LENS EFFECT*

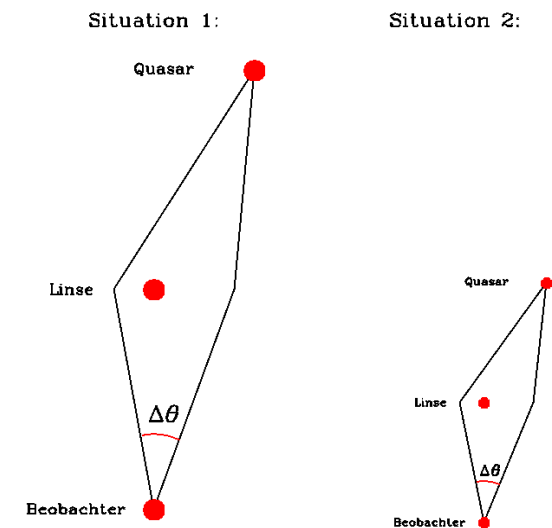
Sjur Refsdal

(Communicated by H. Bondi)

(Received 1964 January 27)

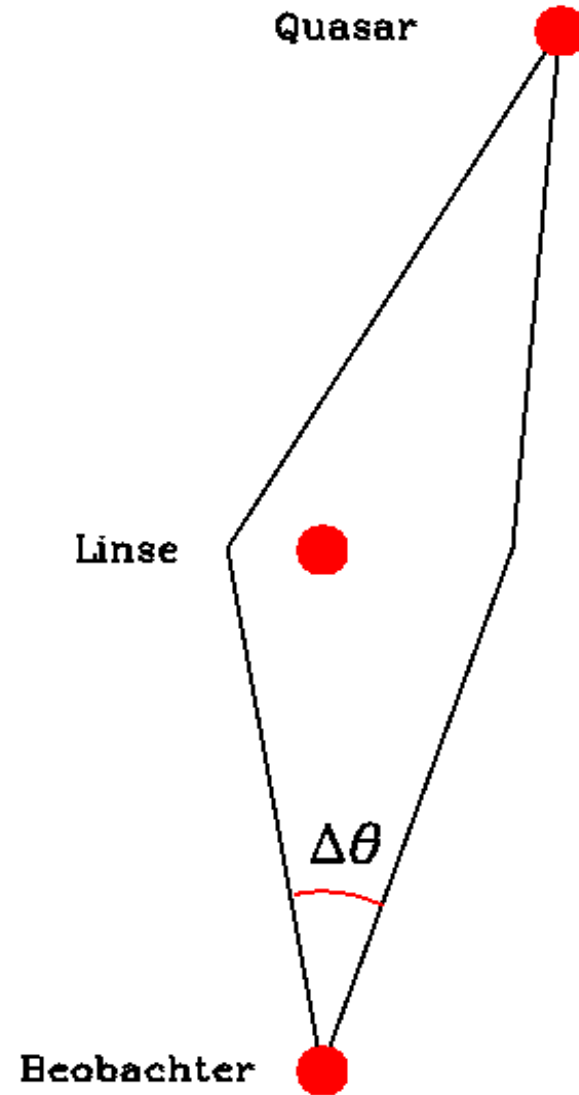
Summary

The gravitational lens effect is applied to a supernova lying far behind and close to the line of sight through a distant galaxy. The light from the supernova may follow two different paths to the observer, and the difference Δt in the time of light travel for these two paths can amount to a couple of months or more, and may be measurable. It is shown that Hubble's parameter and the mass of the galaxy can be expressed by Δt , the red-shifts of the supernova and the galaxy, the luminosities of the supernova "images" and the angle between them. The possibility of observing the phenomenon is discussed.

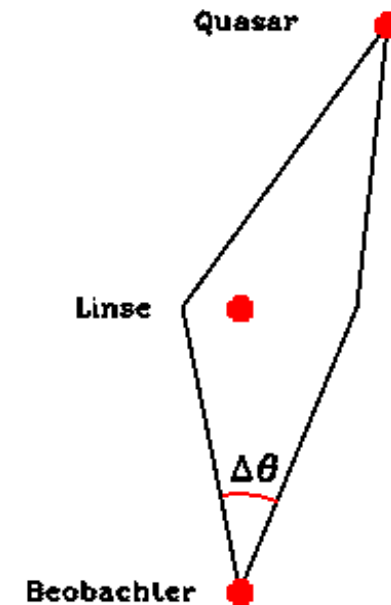


Refsdal, MNRAS 128, 307 (1964)

Situation 1:



Situation 2:



1979 Walsh, Carswell, Weymann:

Nature Vol. 279 31 May 1979

381

0957+561 A, B: twin quasistellar objects or gravitational lens?

D. Walsh

University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield,

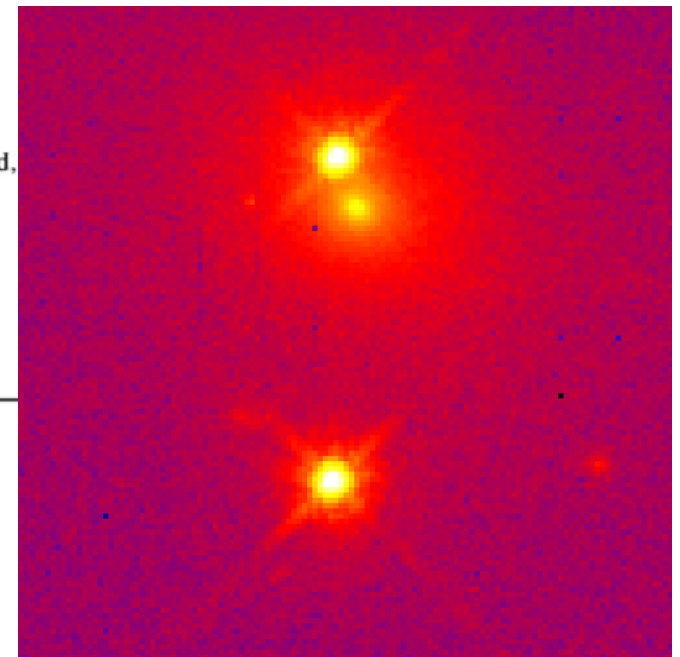
R. F. Carswell

Institute of Astronomy, Cambridge, UK

R. J. Weymann

Steward Observatory, University of Arizona, Tucson, Arizona 85721

0957+561 A, B are two QSOs of mag 17 with 5.7 arc s separation at redshift 1.405. Their spectra leave little doubt that they are associated. Difficulties arise in describing them as two distinct objects and the possibility that they are two images of the same object formed by a gravitational lens is discussed.



When are two quasar images »illusions«?

(... rather than a physical pair of quasars ...)

Criteria for gravitational lens candidates:

- two or more (point) images of same color
- identical (or very similar) redshifts
- identical (or very similar) spectra
- lensing galaxy between images visible
- change of brightness identical (or very similar) in all images, after certain time delay(s): "parallel" lightcurves

So far (September 2012):

> 200 "accepted" multiple quasars systems!

1979 Chang & Refsdal:

Nature Vol. 282 6 December 1979

561

Flux variations of QSO 0957 + 561 A, B and image splitting by stars near the light path

K. Chang & S. Refsdal

Hamburger Sternwarte, Gojenbergsweg 112, D-2050 Hamburg 80, FRG

1981 Gott:

THE ASTROPHYSICAL JOURNAL **243**:140–146, 1981 January 1

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ARE HEAVY HALOS MADE OF LOW MASS STARS? A GRAVITATIONAL LENS TEST

J. RICHARD GOTT III¹

Department of Astrophysical Sciences, Princeton University

Received 1980 April 21; accepted 1980 July 22

1984 Turner, Ostriker, Gott:

THE ASTROPHYSICAL JOURNAL, **284**: 1–22, 1984 September 1
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THE STATISTICS OF GRAVITATIONAL LENSES: THE DISTRIBUTIONS OF IMAGE ANGULAR SEPARATIONS AND LENS REDSHIFTS

EDWIN L. TURNER,¹ JEREMIAH P. OSTRIKER, AND J. RICHARD GOTT III

Princeton University Observatory

Received 1984 January 12; accepted 1984 March 19

1986 Paczyński:

THE ASTROPHYSICAL JOURNAL, **301**:503–516, 1986 February 15

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GRAVITATIONAL MICROLENSING AT LARGE OPTICAL DEPTH

BOHDAN PACZYŃSKI¹

Princeton University Observatory

Received 1985 June 24; accepted 1985 August 20

THE ASTROPHYSICAL JOURNAL, **304**:1–5, 1986 May 1

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GRAVITATIONAL MICROLENSING BY THE GALACTIC HALO

BOHDAN PACZYŃSKI¹

Princeton University Observatory

Received 1985 August 1; accepted 1985 October 23

Microlensing by Planets (Mao & Paczynski 1991):

THE ASTROPHYSICAL JOURNAL, 374:L37-L40, 1991 June 20
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GRAVITATIONAL MICROLENSING BY DOUBLE STARS AND PLANETARY SYSTEMS

SHUDE MAO AND BOHDAN PACZYŃSKI

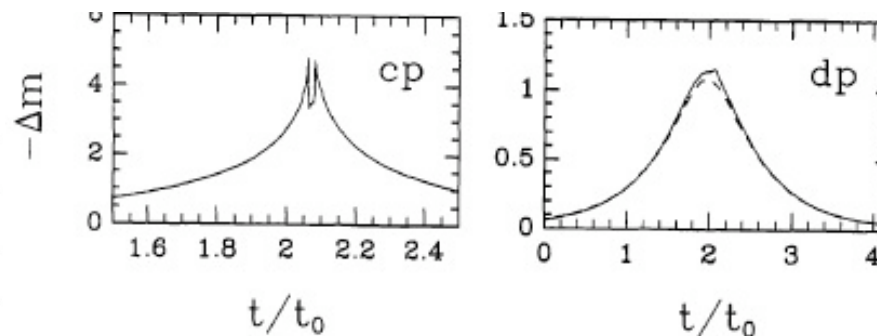
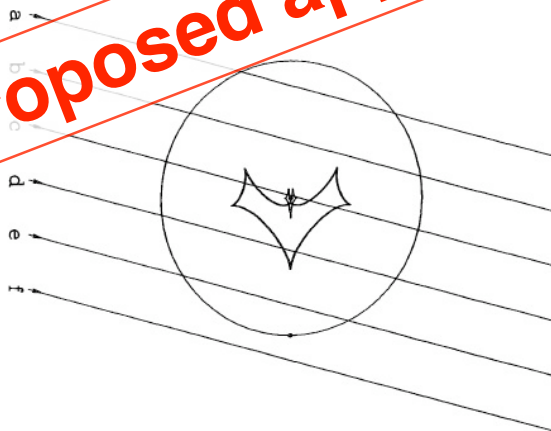
Princeton University Observatory, Princeton, NJ 08544

Received 1991 March 12; accepted 1991 April 2

ABSTRACT

Almost all stars are in binary systems. When the separation between the two components is comparable to the Einstein ring radius corresponding to the combined mass of the binary acting as a gravitational lens, then an extra pair of images can be created, and the light curve of a lensed source becomes complicated. We estimate that $\sim 10\%$ of all lensing episodes of the Galactic bulge stars will strongly display the binary nature of the lens. The effect is strong even if the companion is a planet. A massive search for microlensing of the Galactic bulge stars may lead to discovery of the first extrasolar planetary systems.

“The proposed approach is difficult, but not hopeless.”



Introduction to (Strong) Gravitational Lensing: Basics and History

Joachim Wambsganss

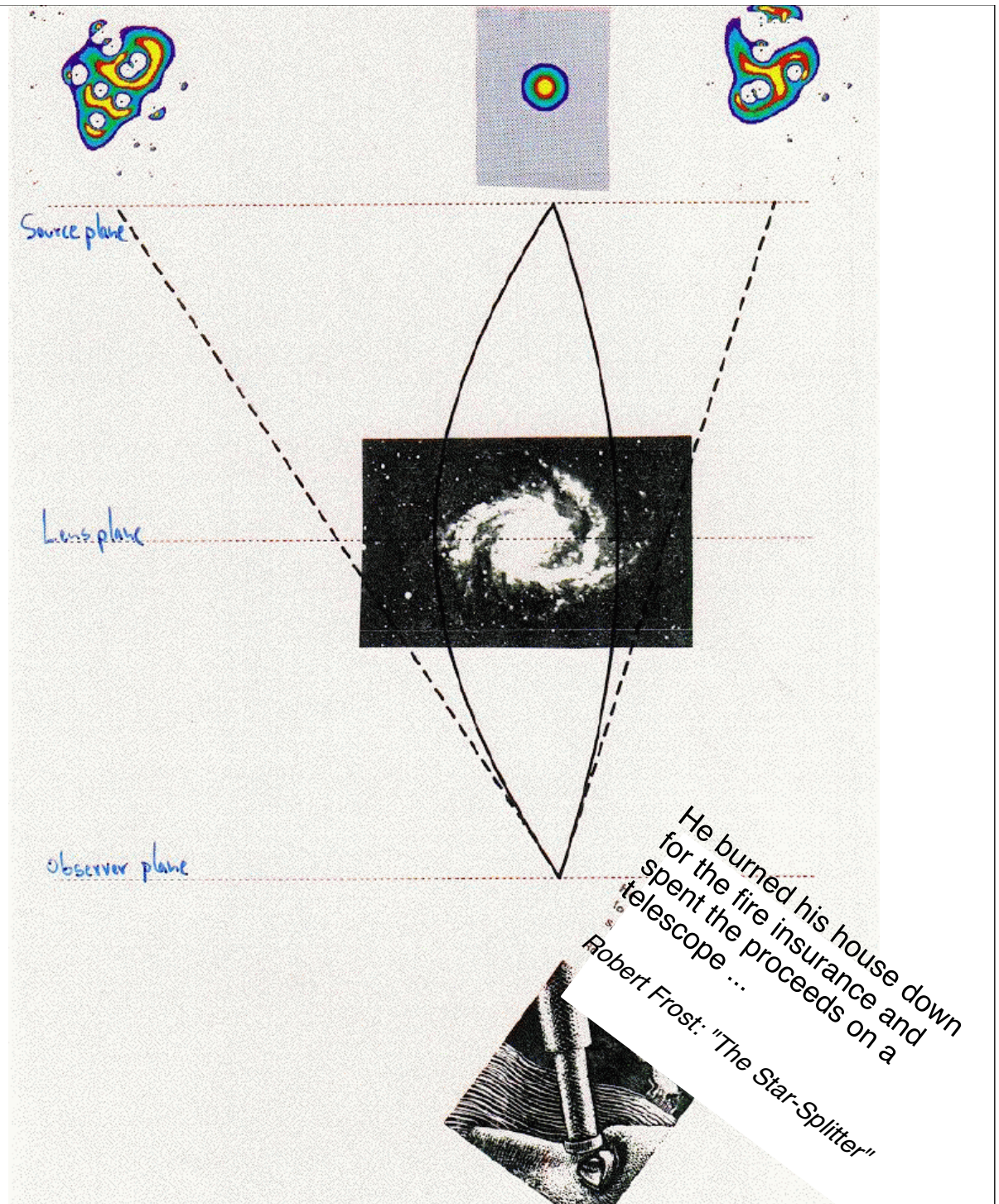
- The **history** of gravitational lensing (pretty predictive ...)
 - Soldner, Einstein, Chwolson, Zwicky, Russell, Walsh, Refsdal, Paczynski, ...
- The **basics** of gravitational lensing (pretty simple ...)
 - mass scales, distance scales, angular scales
- A few **examples** of (strong) gravitational lensing (pretty diverse ...)
 - distant, nearby, imaging, monitoring



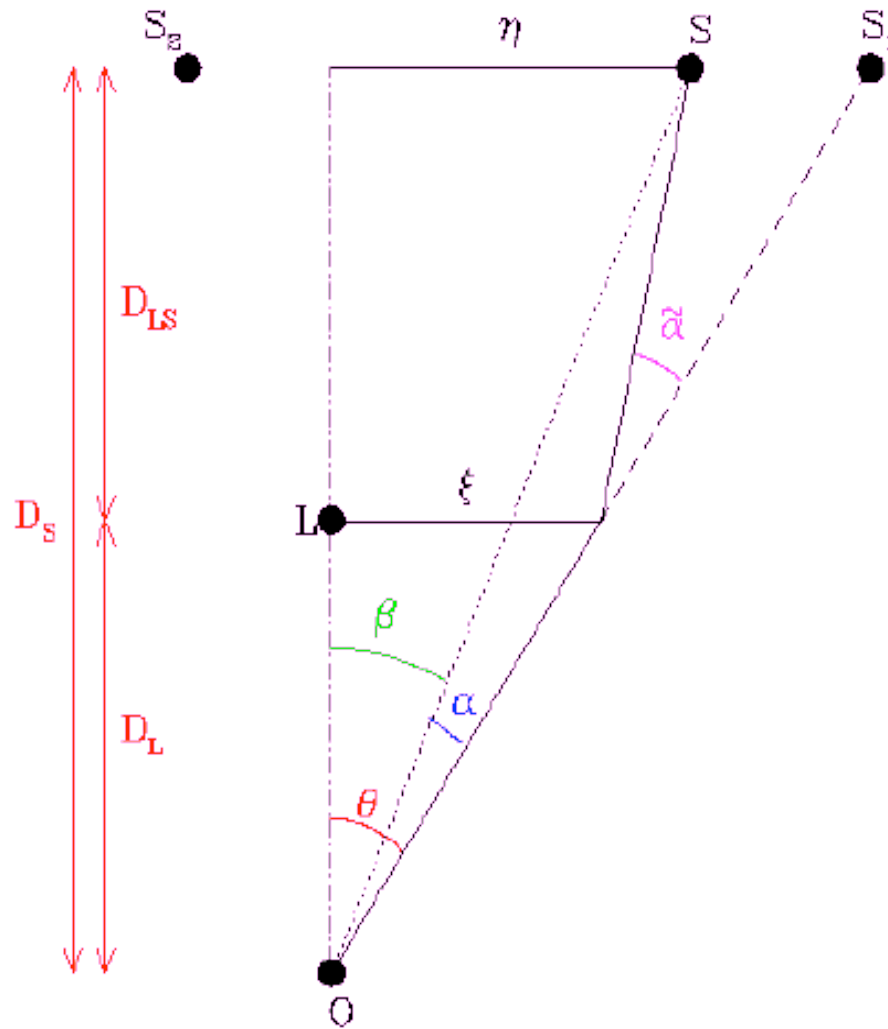
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Basics of Lensing: Geometry



Basics of Lensing: Lens Equation



“Lens equation”:

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

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

$$\text{(with } \vec{\alpha} = \vec{\alpha} \times D_{LS}/D_S)$$

Basics of Lensing: Einstein Radius

Deflection angle (point mass):

$$\tilde{\alpha} = \frac{4GM_1}{c^2 \xi}$$

$$\vec{\beta} = \vec{\theta} - \tilde{\alpha}(\vec{\theta})$$

(with $\vec{\alpha} = \tilde{\alpha} \times D_{LS}/D_S$)

Point lens (with $\xi = D_L \theta$):

$$\beta(\theta) = \theta - \frac{D_{LS}}{D_L D_S} \frac{4GM_1}{c^2 \theta}$$

Hence lens equation:

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

Einstein radius:

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

Einstein Radius for distant galaxy:

$$\theta_E \approx 1.8 \sqrt{\frac{M}{10^{12} M_\odot}} \text{ arcsec}$$

Einstein radius for star in Milky Way:

$$\theta_E \approx 0.5 \sqrt{\frac{M}{M_\odot}} \text{ milliarcsec}$$

How can we observe (strong) lensing phenomena?

Depends on (lens) mass scale!

- "Statically" (images):
 - **macrolensing**: massive object as a lens ($\geq 10^6 M_{\odot}$)
 - Einstein angle $>$ resolution of telescope
 - morphological (multiplicity, shapes)
- "Dynamically" (brightness, positions):
 - **microlensing**: stars as lenses ($\approx 1 M_{\odot}$)
 - Einstein angle \ll resolution of telescope
 - time scale = Einstein radius/transverse velocity \approx years
 - variability (lightcurves, positions)

Basics of Lensing: Scales

mass scales:

- few Earth mass planets ($10^{-5} M_{\odot}$) to galaxy clusters ($10^{15} M_{\odot}$):
⇒ 20 orders of magnitude (and counting ...)

angular scales:

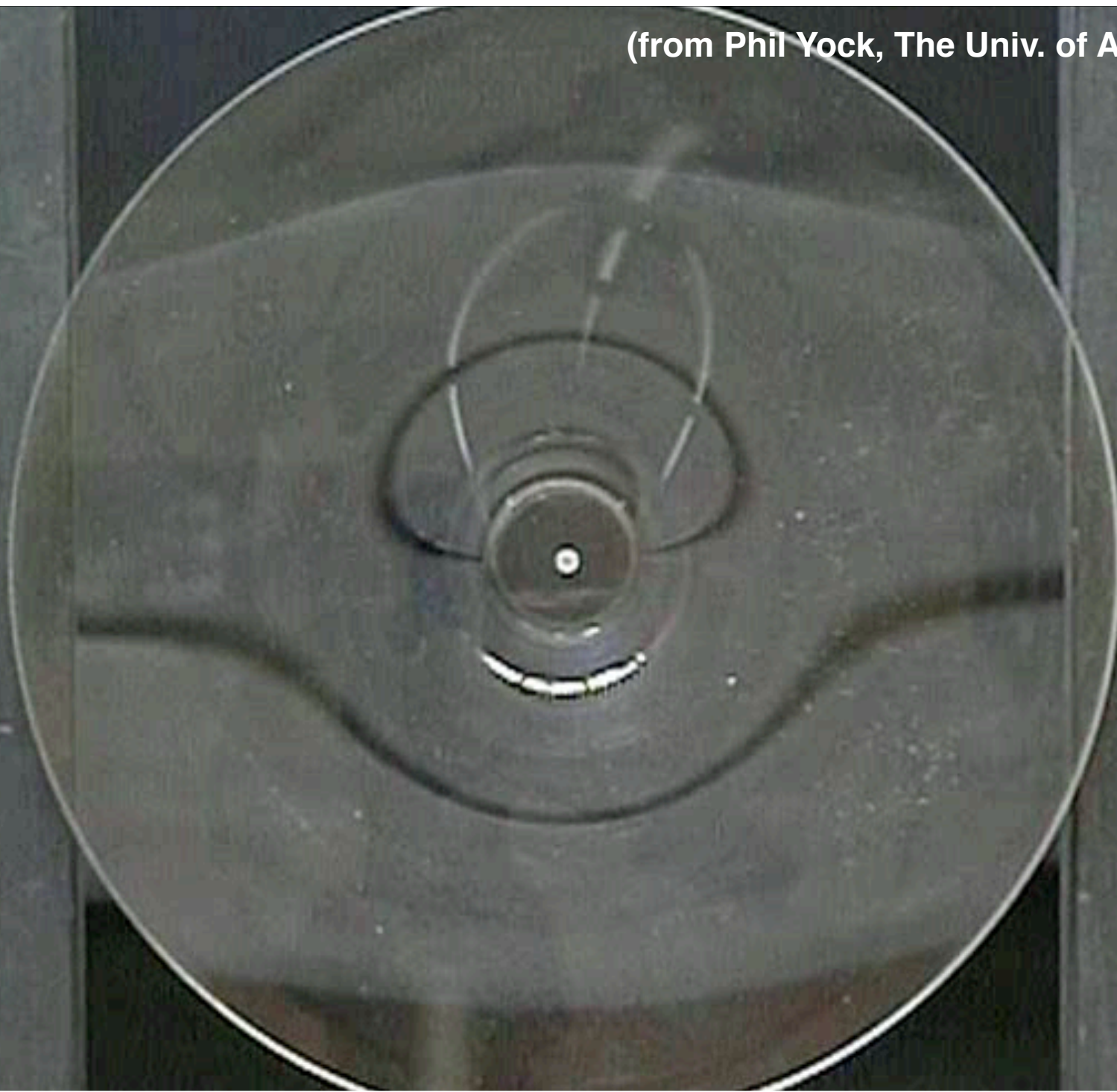
- quasar microlensing (10^{-6} arcsec) to giant arcs (100 arcsec)
⇒ 8 orders of magnitude

distance scales

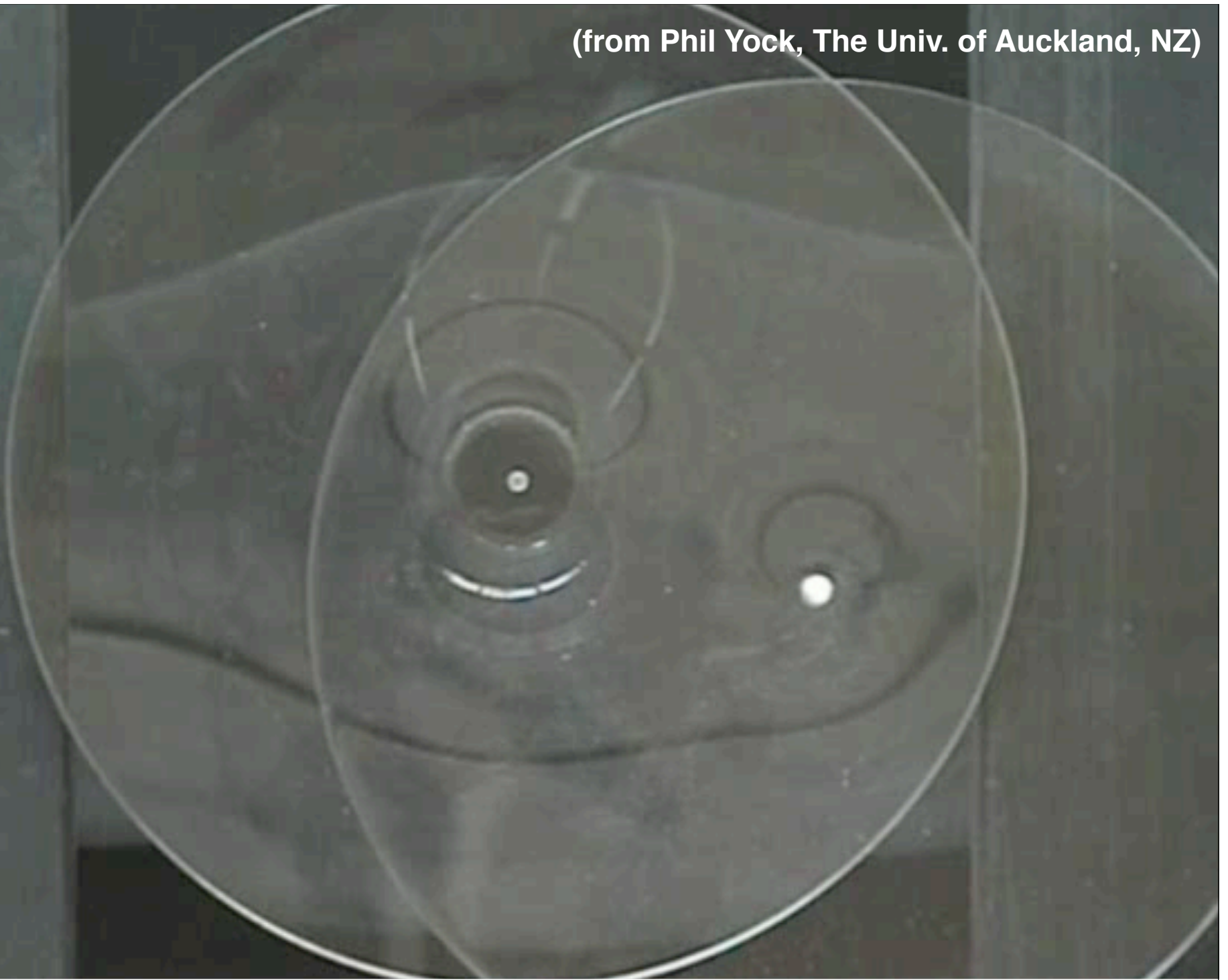
- Milky Way stars (few kpc) to most distant quasars (few Gpc)
⇒ 6 orders of magnitude

(or even 15, if you're ready to include a nearby star at a distance of a couple of microparsecs ...)

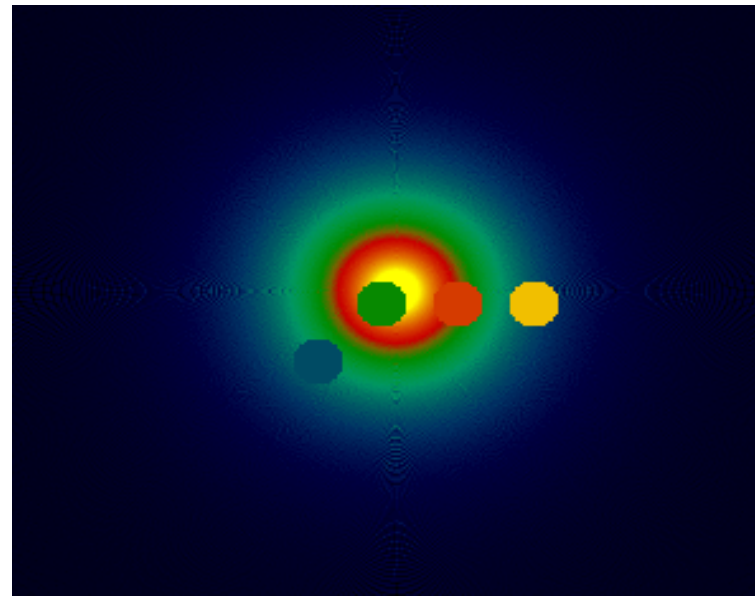
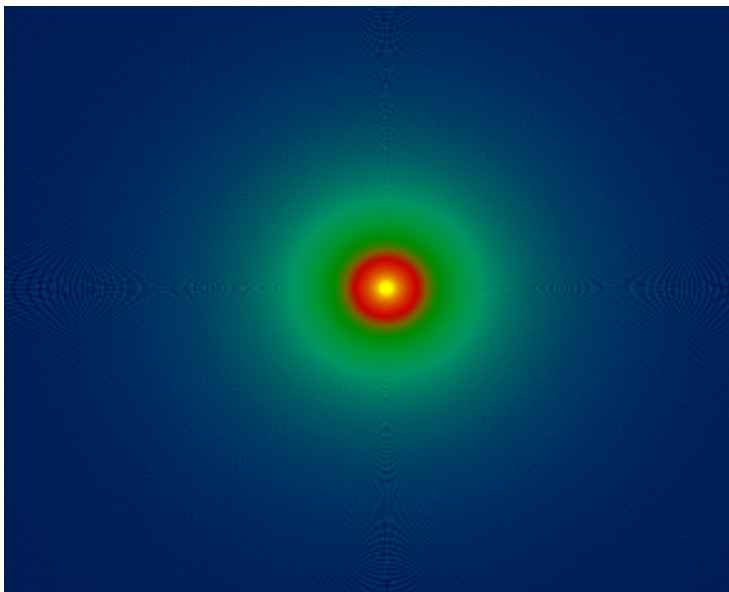
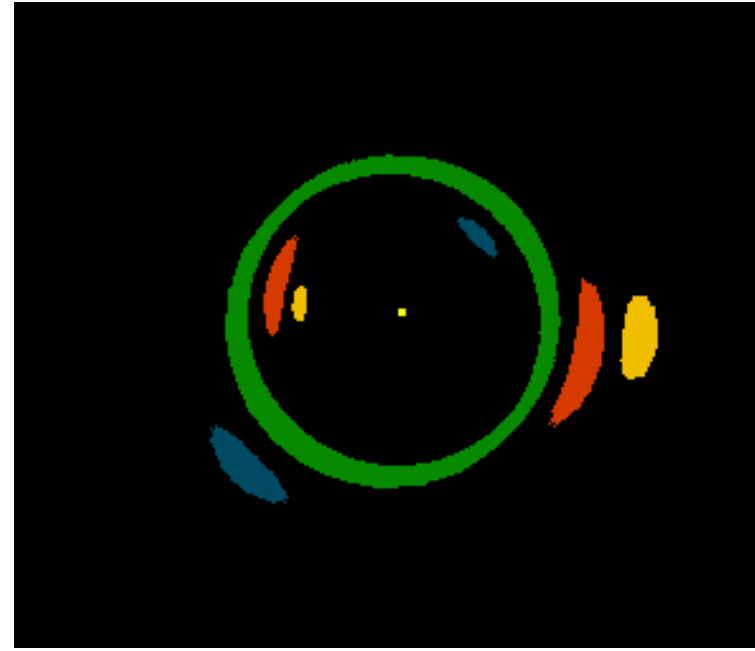
(from Phil Yock, The Univ. of Auckland, NZ)



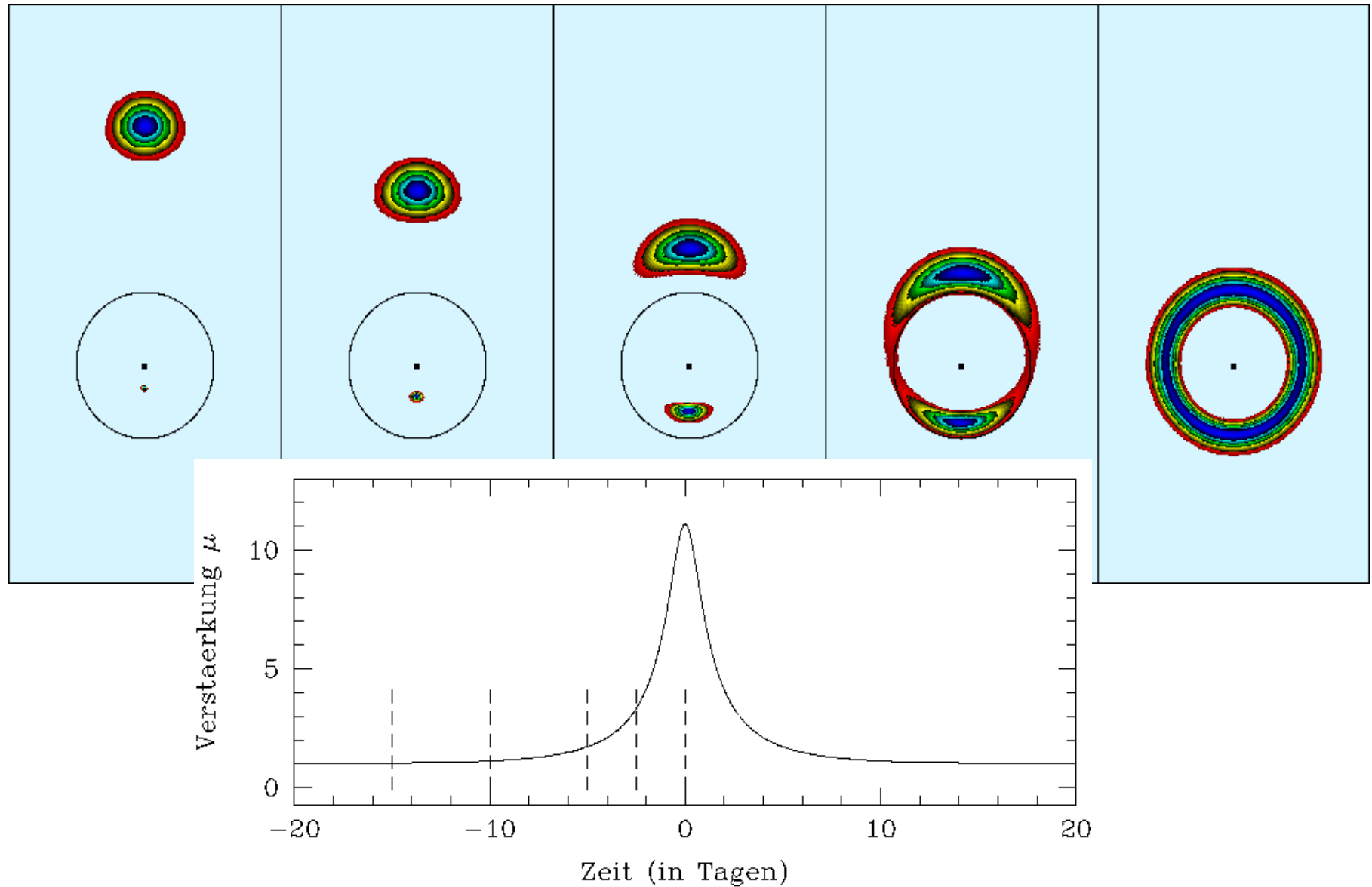
(from Phil Yock, The Univ. of Auckland, NZ)



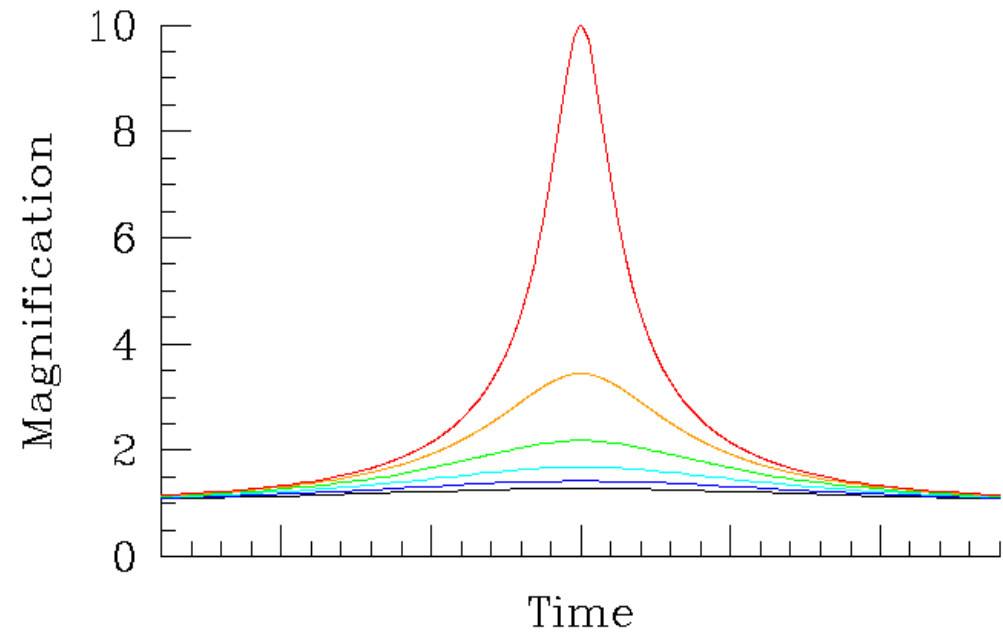
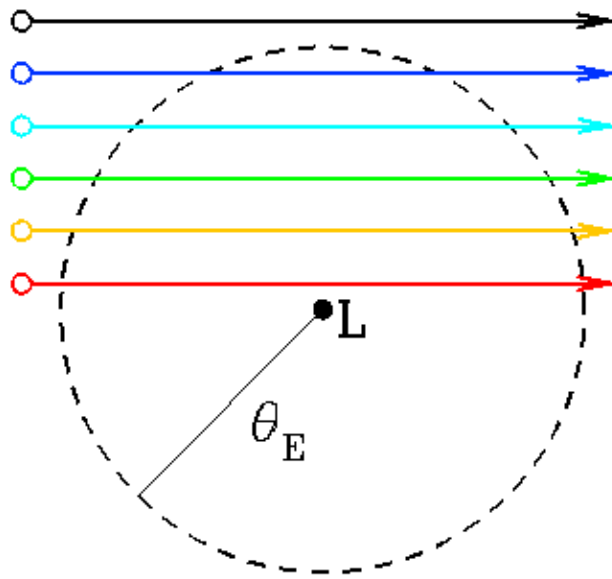
Simulation: Point lens and extended source



Simulation: Point lens and extended source



Micro lensing Lightcurve: Single Star as a Lens



Paczynski (1986): MACHO, EROS, OGLE, ...

(from Sackett 1999)

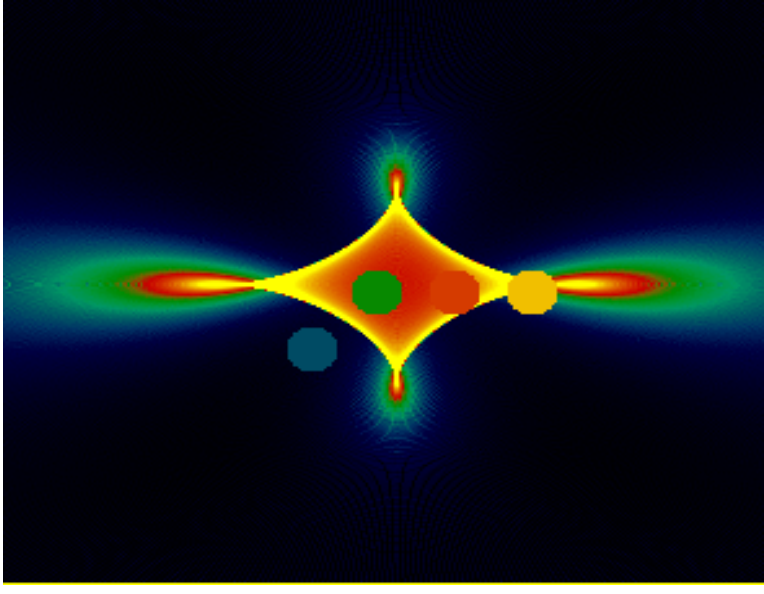
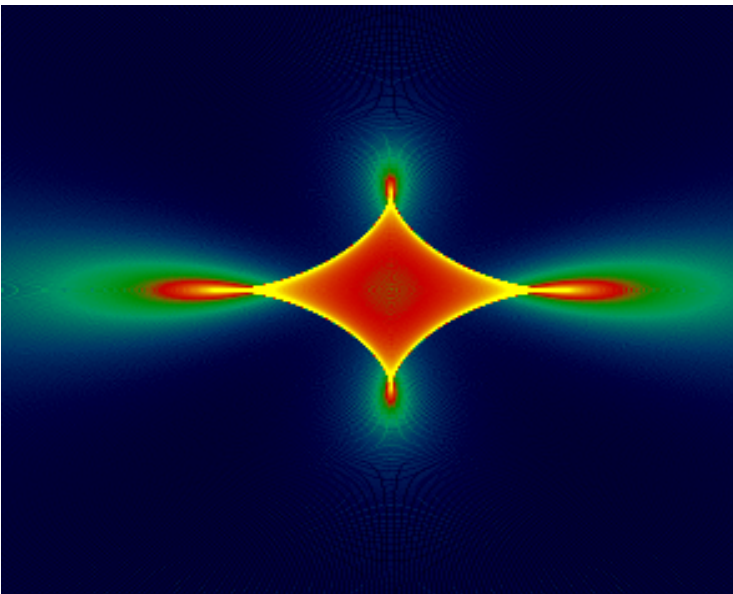
$$\mu_{1,2} = \left(1 - \left[\frac{\theta_E}{\theta_{1,2}} \right]^4 \right)^{-1} = \frac{u^2 + 2}{2u\sqrt{u^2 + 4}} \pm \frac{1}{2}$$

(where $u = \beta/\theta_E$)

$$\mu = \mu_1 + \mu_2 = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$$

$$t_0 = \frac{R_E}{v_{\perp}} \approx 0.214 \text{ yr} \sqrt{\frac{M}{M_{\odot}}} \sqrt{\frac{D_L}{10 \text{ kpc}}} \sqrt{1 - \frac{D_L}{D_S}} \left(\frac{v_{\perp}}{200 \text{ km/sec}} \right)^{-1}$$

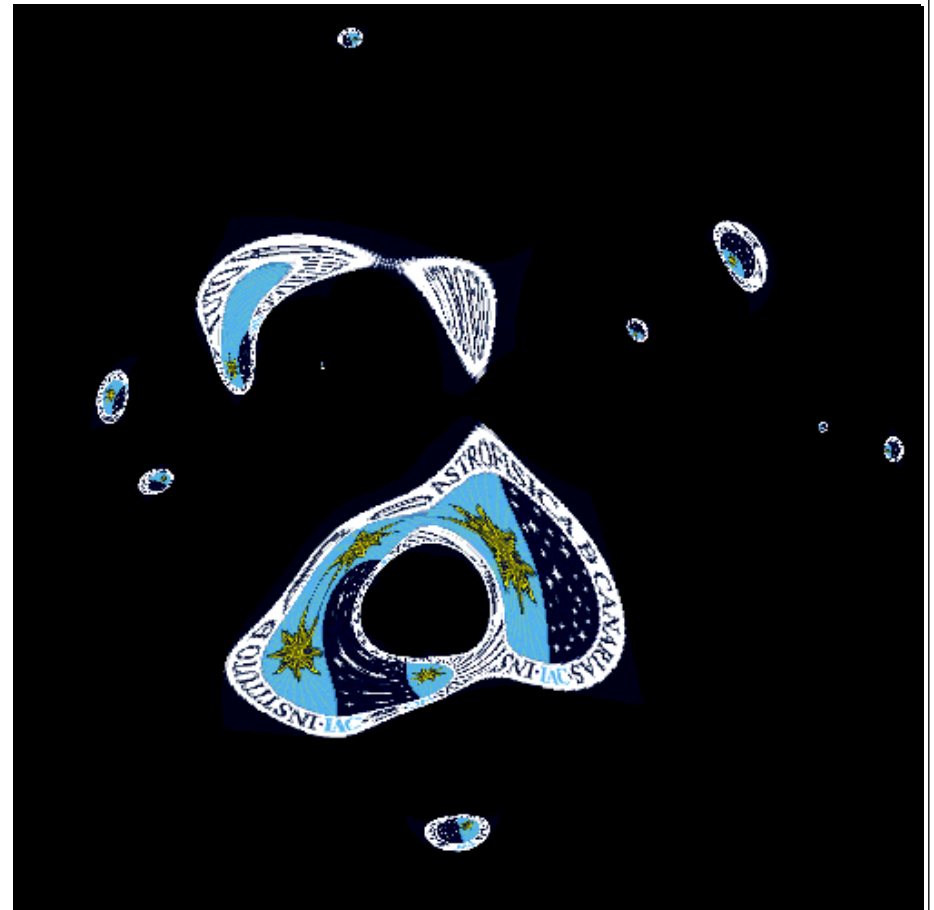
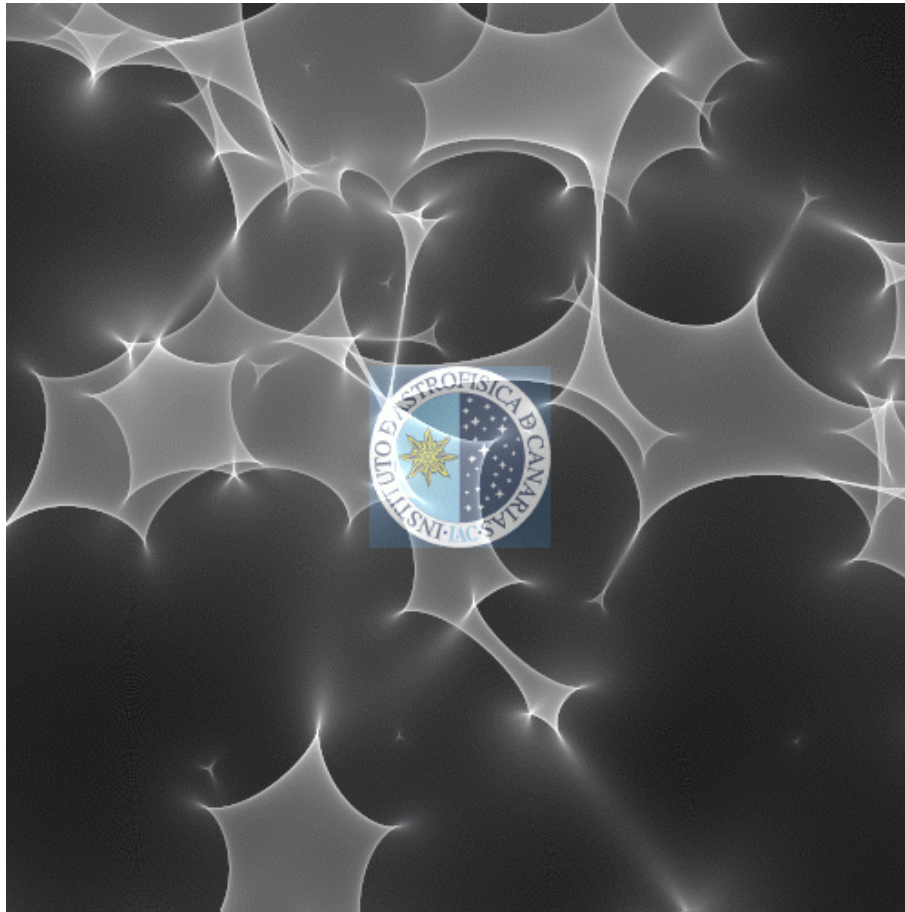
Simulation: Chang-Refsdal-Lens (point lens plus shear)



Effects of Lensing

- change of position
 - first confirmation of GR: **offset at solar limb**
 - »normally« not observable: **astrometric microlensing**
- distortion
 - extended sources: **arclets, arcs, Einstein rings, ...**
- (de)magnification
 - point sources: brighter/fainter: **no standard candles!**
 - galaxies: larger/smaller: **arcs**
- multiple images
 - most dramatic effect! **multiple quasars, giant arcs**

Many Lenses: Quasar Microlensing



Lensing Phenomena:

- Two regimes of strength: strong \Leftrightarrow weak
- Two regimes of scales: macro \Leftrightarrow micro
- Two regimes of distance: near \Leftrightarrow far



OBJECTS IN THE COSMOS ARE
DIFFERENT FROM HOW THEY APPEAR

Introduction to (Strong) Gravitational Lensing: Basics and History

In the course of the last 33 years:

Gravitational Lensing has developed from a curiosity to a **very useful astrophysical tool** on large range of mass, distance and angular scales

Cosmological Applications:

- Giant arcs, weak lensing and cosmic shear / cluster lenses and LSS
- Multiple quasars, Einstein rings, galaxy-galaxy lensing / galaxy lenses
- Quasar microlensing / stellar lenses



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