Gravitational Lensing Theory and Applications:

Of Giant Luminous Arcs, Multiple Quasars and Extrasolar Planets

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KITP, Santa Barbara, September 28, 2006

Gravitational Lensing Theory and Applications

- Lensing history

  Soldner, Einstein, Zwicky, ...

- Lensing basics

  geometry, lens equation, Einstein radius

- Lensing phenomena

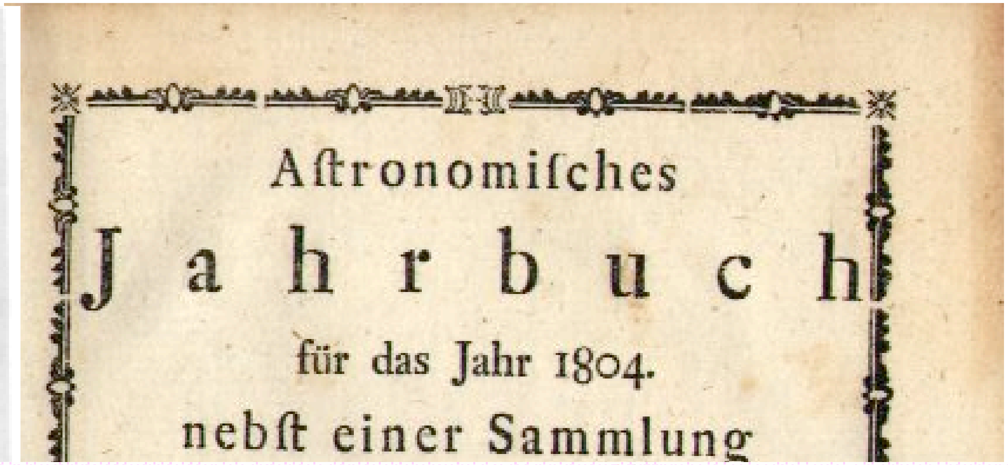
  strong/weak, macro/micro, near/far

- Lensing applications
  - cluster lensing: giant arcs, statistics, secondary matter
  - quasar (micro)lensing: Hubble constant, dark matter
  - stellar microlensing: exoplanets, icy matter

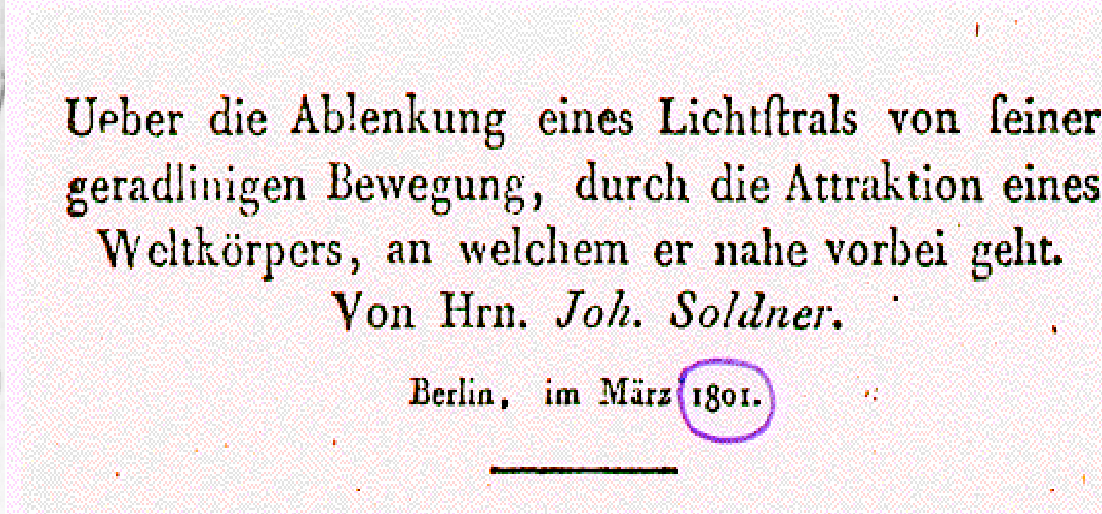
- Lensing summary

  unique, useful, universal

Johann Georg von Soldner
1776–1833



Aſtronomiſches
Jahrbuch
für das Jahr 1804.
nebſt einer Sammlung

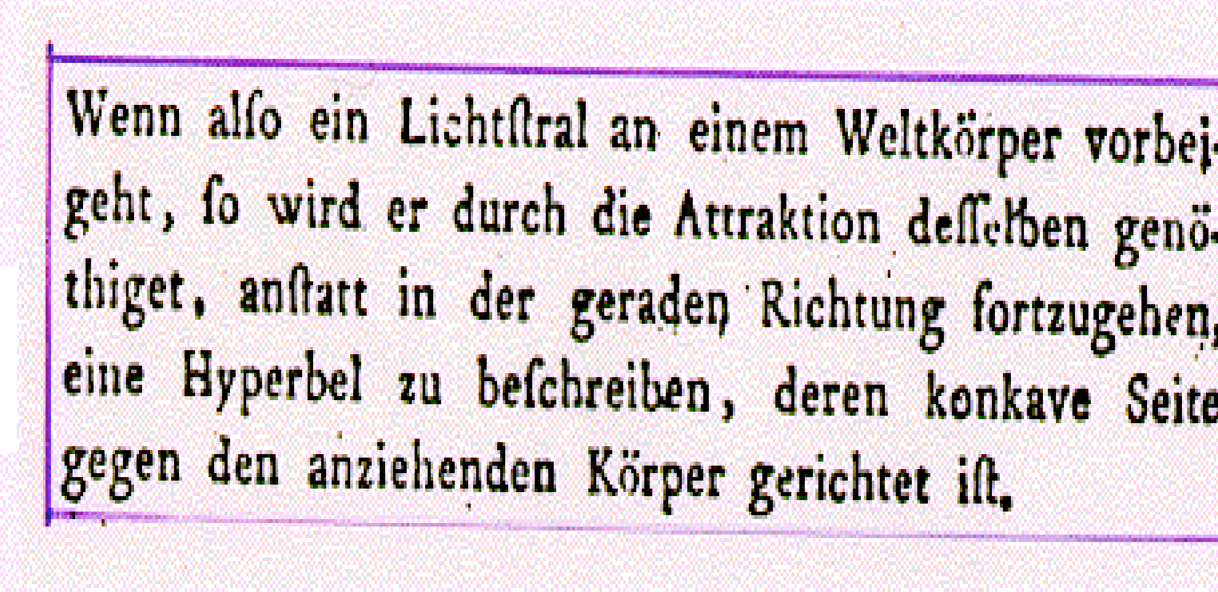


Ueber die Ablenkung eines Lichtſtrals von ſeiner geradlinigen Bewegung, durch die Attraktion eines Weltkörpers, an welchem er nahe vorbei geht.
Von Hrn. *Joh. Soldner.*

Berlin, im März 1801.

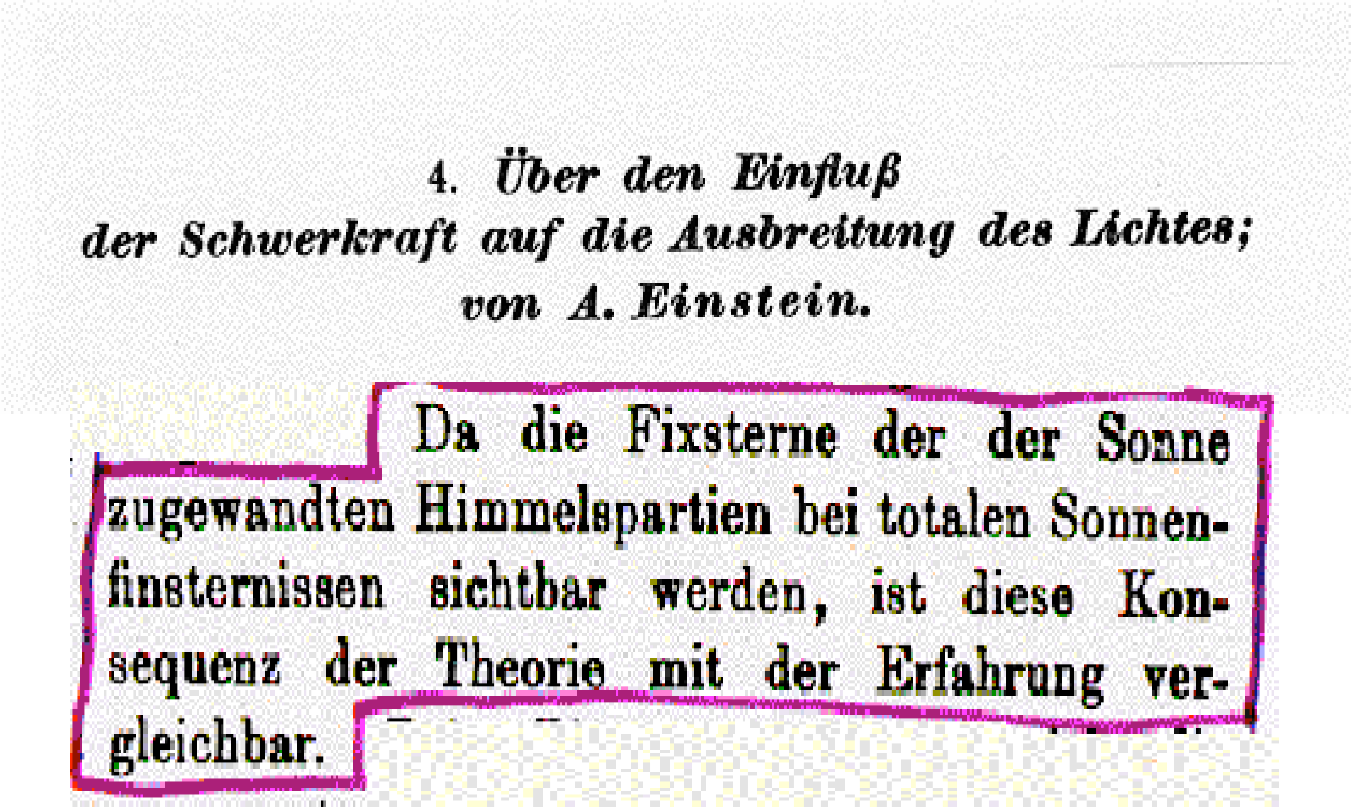
for solar limb:

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



Wenn alſo ein Lichtſtral an einem Weltkörper vorbei-geht, ſo wird er durch die Attraktion deſſelben genö-thiget, 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!

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 ...

A brief history of light deflection

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

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

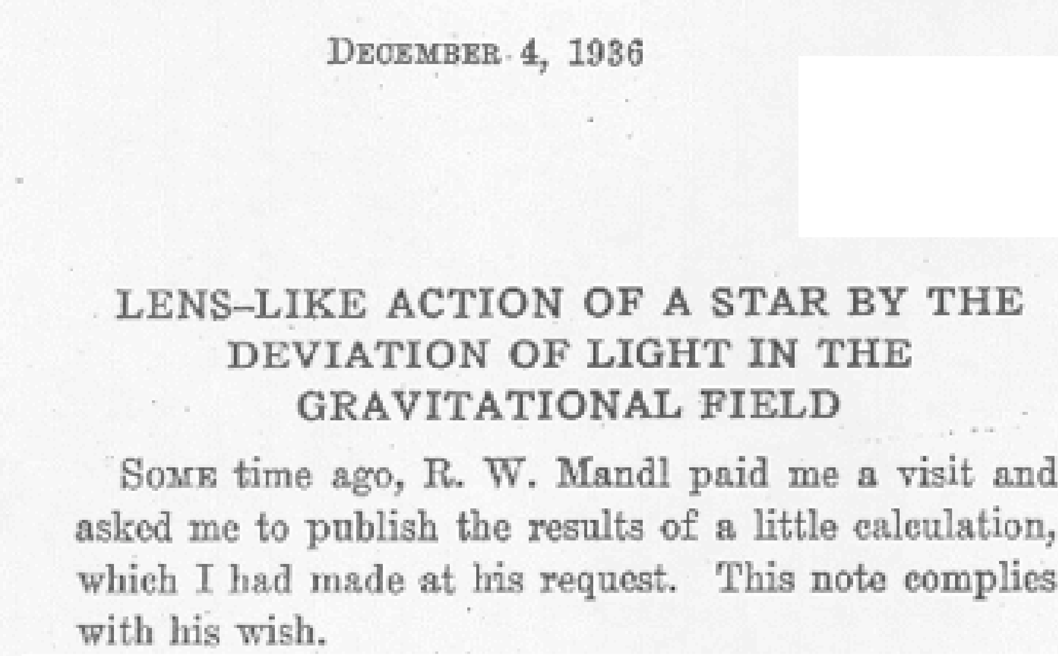
1915: General Relativity

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

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

A brief history of (micro)lensing (1)

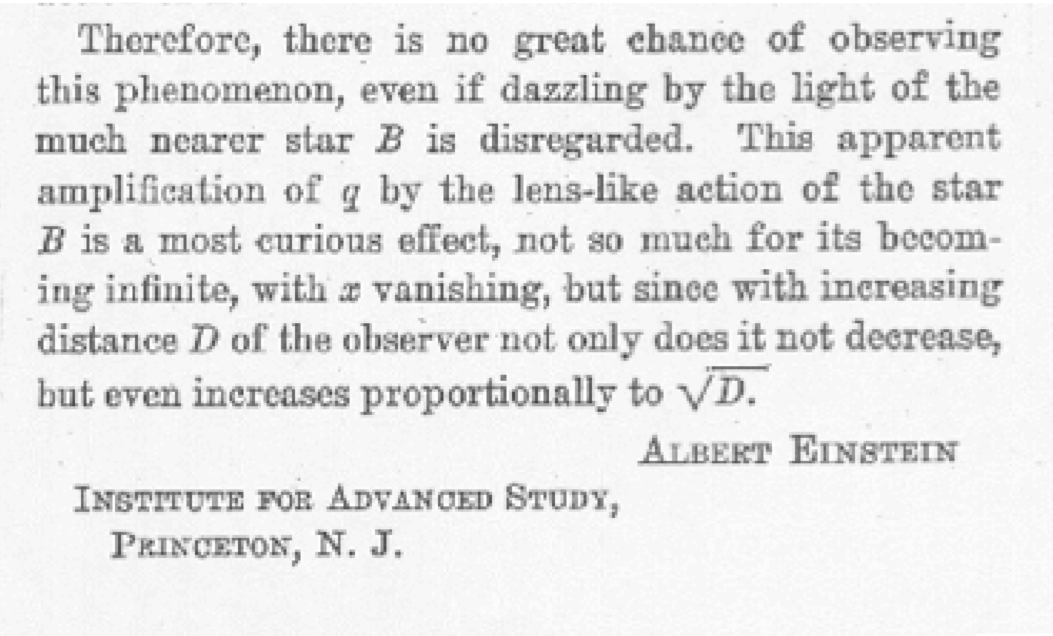
1936 **Einstein:**



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.



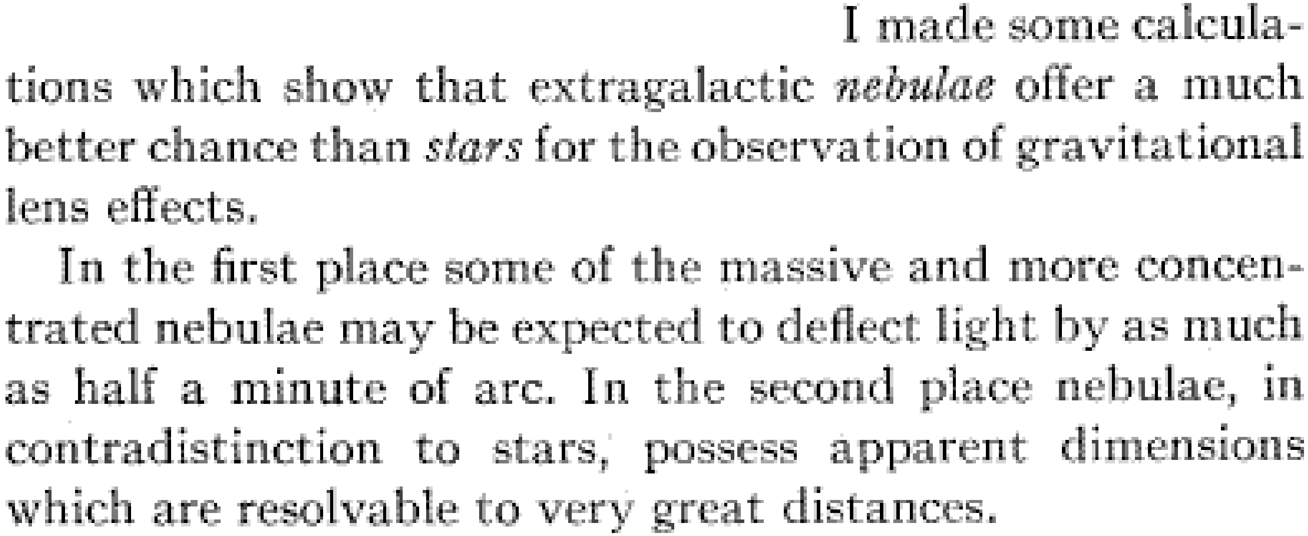
Therefore, there is no great chance of observing this phenomenon, even if dazzling by the light of the much nearer star B is disregarded. This apparent amplification of q by the lens-like action of the star B is a most curious effect, not so much for its becoming infinite, with x vanishing, but since with increasing distance D of the observer not only does it not decrease, but even increases proportionally to $\sqrt{D}$.

ALBERT EINSTEIN

INSTITUTE FOR ADVANCED STUDY,
PRINCETON, N. J.

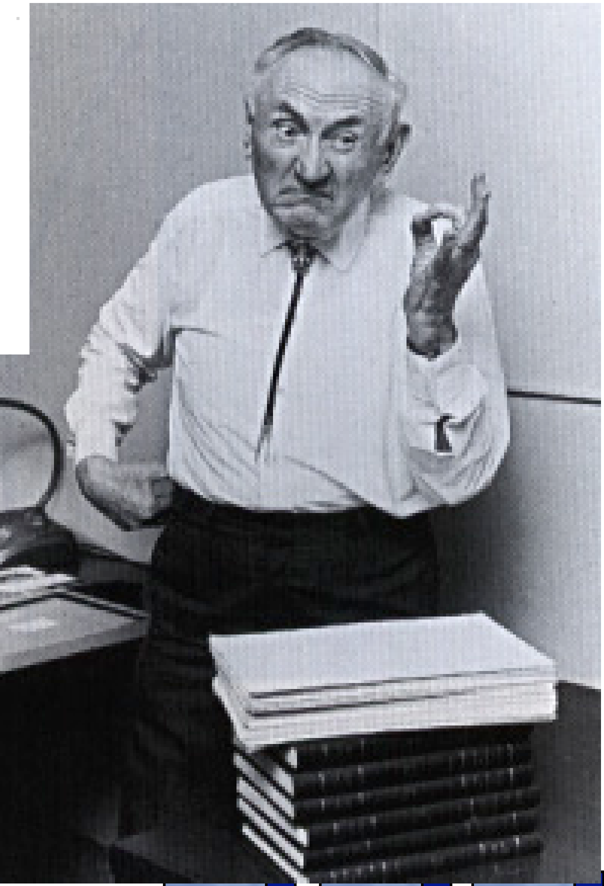
A brief history of (micro)lensing (2)

1937 Zwicky: "Nebulae as gravitational lenses"



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

In the first place some of the massive and more concentrated nebulae may be expected to deflect light by as much as half a minute of arc. In the second place nebulae, in contradistinction to stars, possess apparent dimensions which are resolvable to very great distances.



1) additional test for GR

2) "telescope": see fainter objects

3) measure masses: confirm large
masses of "nebulae" (i.e. dark matter)

A brief history of (micro)lensing (3)

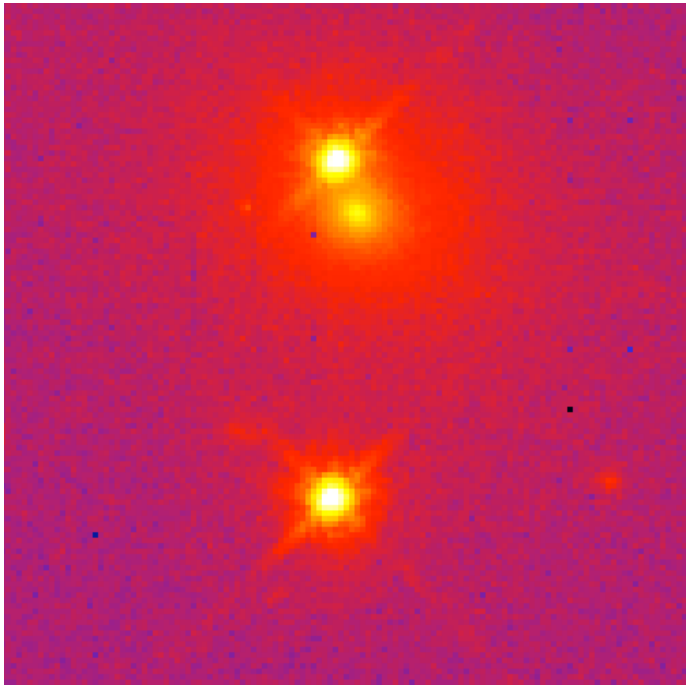
1967 Gunn:

"A fundamental limitation on the accuracy of angular measurements in observational cosmology"

“On the propagation of light in inhomogeneous cosmologies. I - Mean effects”

(*adding* to Einstein: weak/statistical lensing ...)

A brief history of (micro)lensing (4)

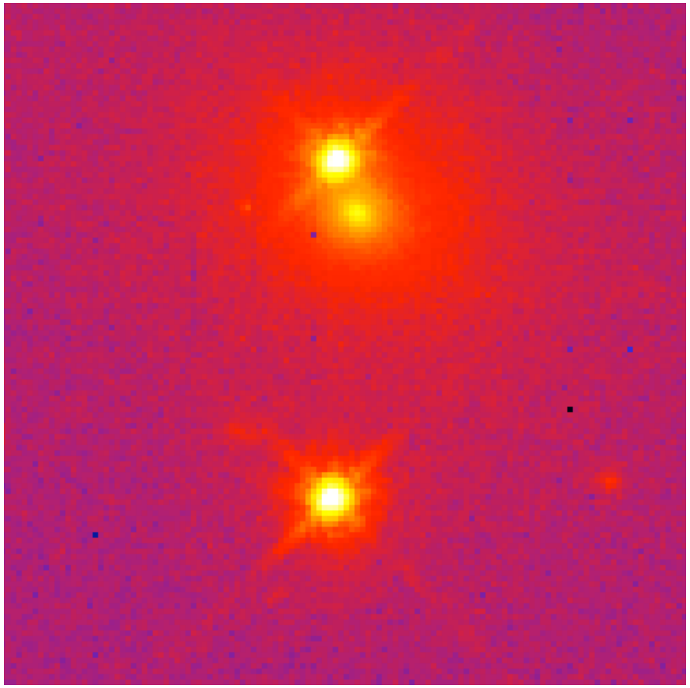


1979 Walsh, Carswell, Weyman:

"0957+561 A, B – Twin quasistellar objects or gravitational lens?"

(*proving* Zwicky right ...)

A brief history of (micro)lensing (4)



1979 Chang & Refsdal:

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

(*combining* Einstein with Zwicky: stars INSIDE nebulae ...)

A brief history of (micro)lensing (5)

1981 Gott:

"Are heavy halos made of low mass stars?
A gravitational lens test"

(*correcting* Einstein:

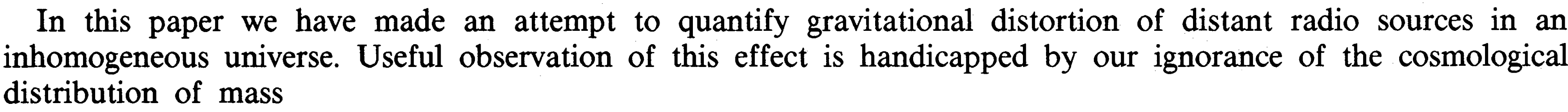
distant stellar microlensing IS observable ...)

A brief history of (micro)lensing (6)

1981 Blandford & Jaroszynski:

"Gravitational distortion of the images of distant radio sources in an inhomogeneous universe"

(*quantifying* statistical lensing ...)



In this paper we have made an attempt to quantify gravitational distortion of distant radio sources in an inhomogeneous universe. Useful observation of this effect is handicapped by our ignorance of the cosmological distribution of mass

A brief history of (micro)lensing (7)

1984 Turner, Ostriker, Gott:

“The statistics of gravitational lenses: the distributions of image angular separations and lens redshifts”

(*verifying* Zwicky: galaxy lensing IS real and useful ...)

A brief history of (micro)lensing (8)

1986 Paczynski:

"Gravitational Lensing by the Galactic Halo"

(*correcting* Einstein:

local stellar microlensing IS observable ...)

A brief history of (micro)lensing (9)

1991 Mao & Paczynski:

"Gravitational microlensing by double stars and planetary systems”

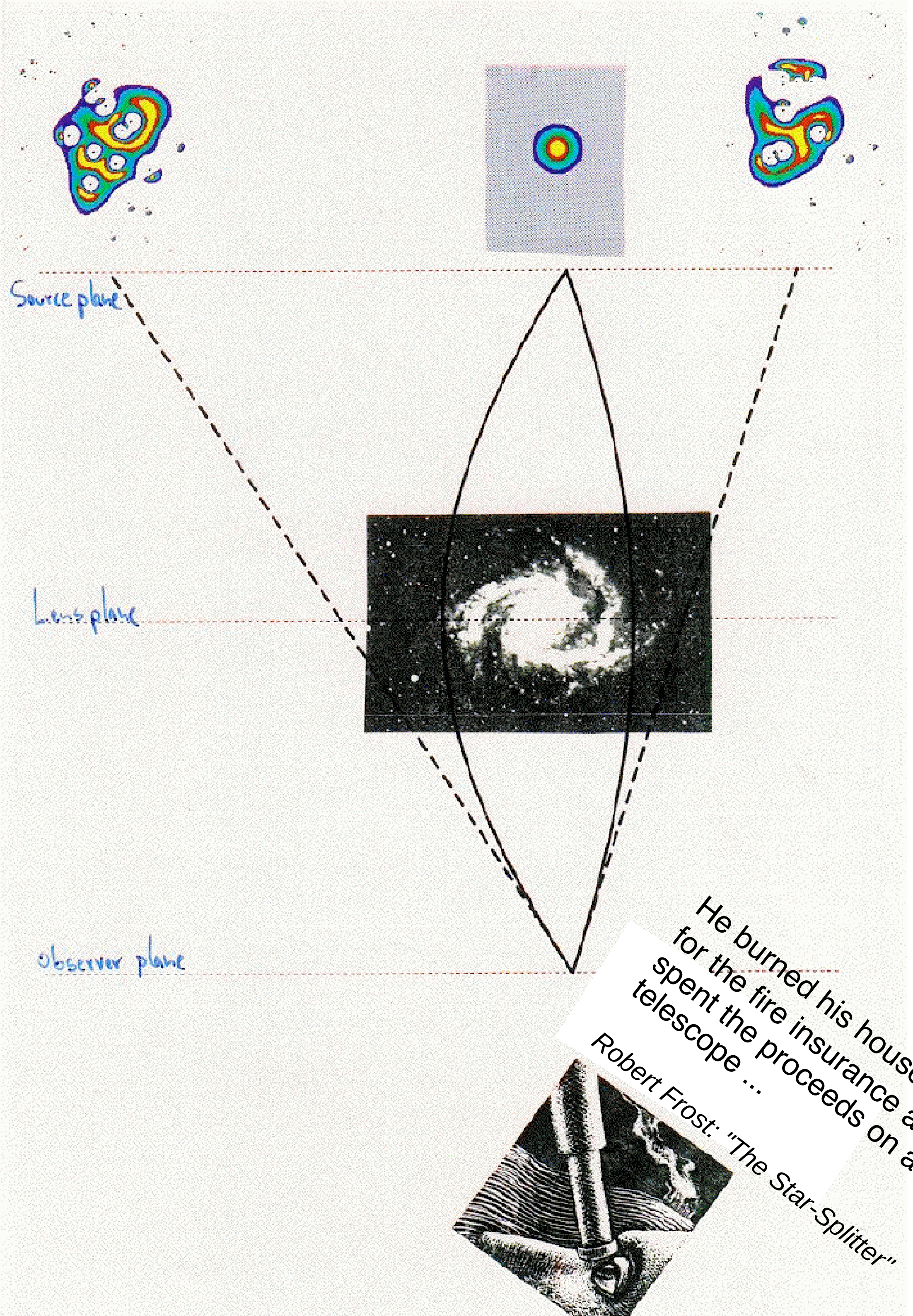
(*correcting* Einstein: even planetary microlensing is observable ...)

A brief history of light deflection

- 1920/30s: Chwolson, Einstein, Zwicky:
  ring images, double images, galaxy lenses
- 1960s: Refsdal: Hubble constant
- 1979: Walsh et al.: lensed quasar Q0957+561A,B
- 1979: Chang/Refsdal: Prediction of Microlensing
- 1986/7: Soucail et al., Lynds & Petrosian: Giant Arcs
- 1989: Irwin et al.: quasar microlensing Q2237+0305
- 1993: Alcock et al, Afonso et al, Udalski et al: stellar microlensing
- 1998: many authors: weak lensing, cosmic shear
- 2006: more than 3000 publications on
  gravitational lensing !?!

Basics of lensing:

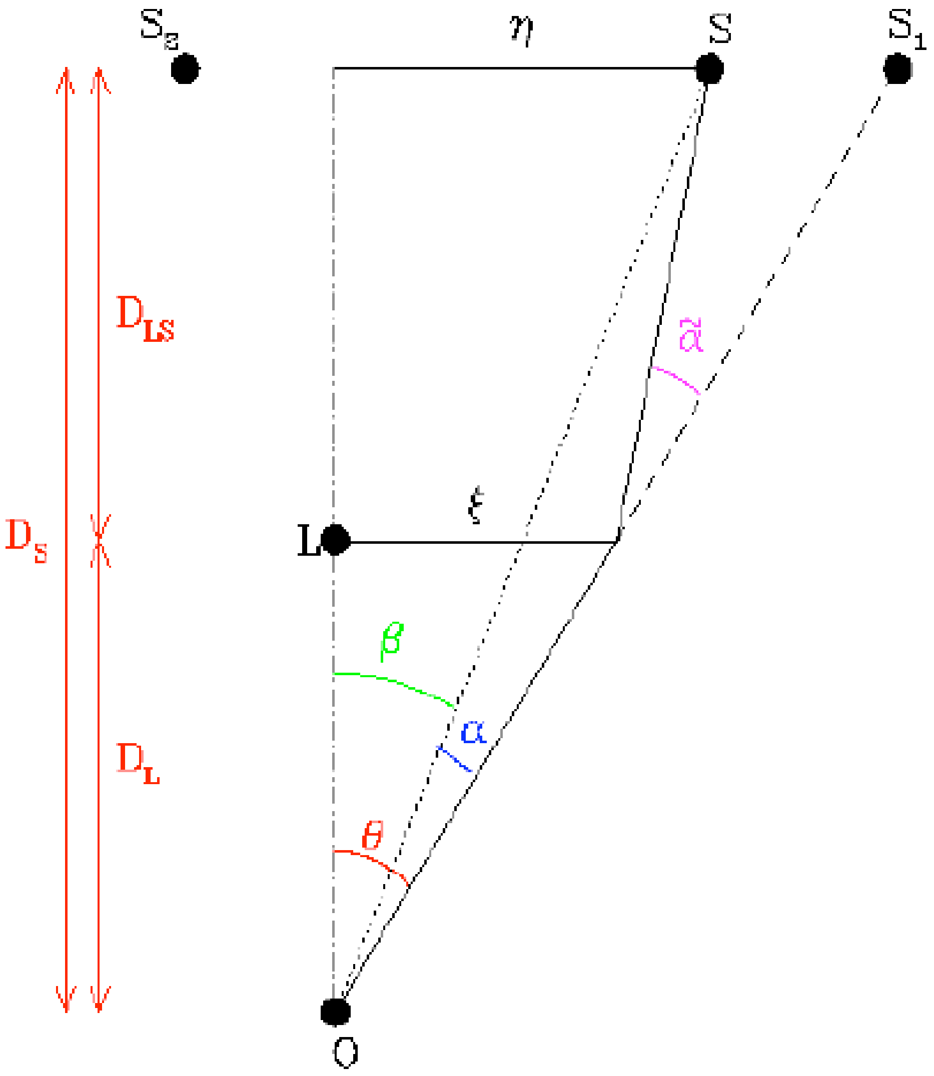
Geometry



He burned his house down for the fire insurance and spent the proceeds on a telescope ...

Robert Frost: "The Star-Splitter"

Basics of lensing:



"Lens equation":

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

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

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

Basics of lensing:

Deflection angle (point mass):

$$\tilde{\alpha} = \frac{4GM}{c^2}\frac{1}{\xi}$$

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

$$\beta(\theta) = \theta - \frac{D_{LS}}{D_L D_S}\frac{4GM}{c^2}\frac{1}{\theta}$$

Hence lens equation:

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

Einstein radius:

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

Basics of lensing:

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:

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

Basics of lensing:

Lens mapping:

$$\mathcal{A} = \frac{\partial \vec{\beta}}{\partial \vec{\theta}} = \left(\delta_{ij} - \frac{\partial \alpha_i(\theta)}{\partial \theta_j} \right) = \left(\delta_{ij} - \frac{\partial^2 \psi(\vec{\theta})}{\partial \theta_i \partial \theta_j} \right)$$

magnification : $\mu = \frac{1}{\det \mathcal{A}}$

$$\psi_{ij} = \frac{\partial^2 \psi}{\partial \theta_i \partial \theta_j}$$

quasar images characterised by:
external shear γ and
dimensionless surface mass density κ

$$\kappa = \frac{\Sigma}{\Sigma_{\rm crit}}$$

$$\psi_{11} + \psi_{22} = 2\kappa = {\rm tr}\ \psi$$

$$\gamma_1(\vec{\theta}) = \frac{1}{2}(\psi_{11} - \psi_{22}) = \gamma(\vec{\theta}) \cos[2\varphi(\vec{\theta})]$$

$$\gamma_2(\vec{\theta}) = \psi_{12} = \psi_{21} \gamma(\vec{\theta}) \sin[2\varphi(\vec{\theta})]$$

critical surface mass density:

$$\Sigma_{\rm crit} = \frac{c^2}{4\pi G} \frac{D_S}{D_L D_{LS}} \approx 1 \text{ g cm}^{-2}$$

Basics of lensing

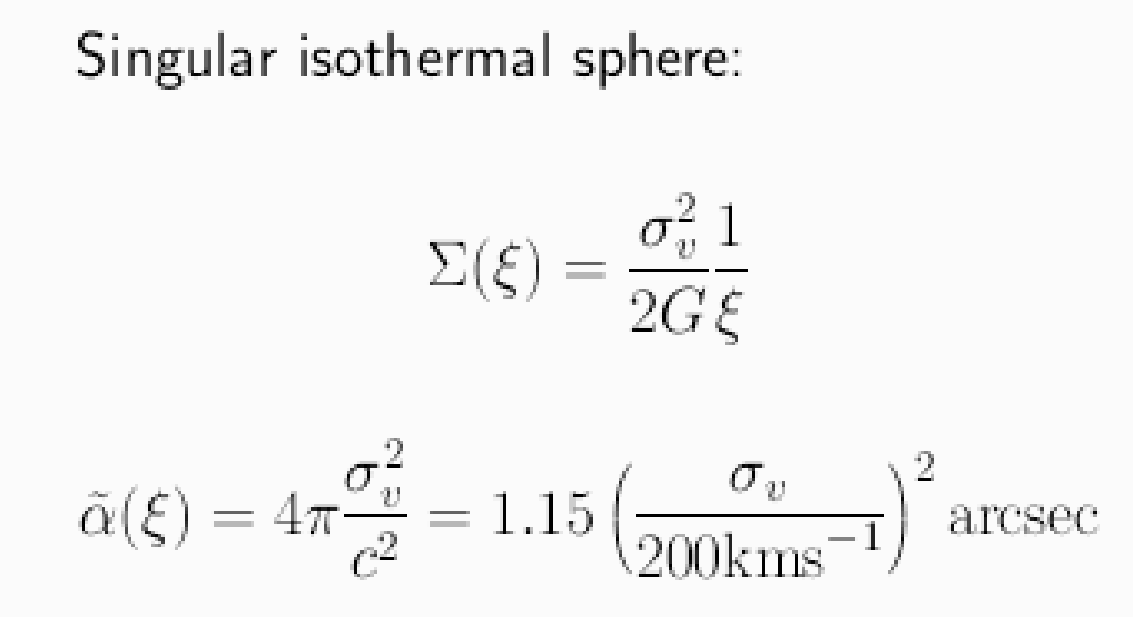
Point lens: magnification of two images (Einstein 1936):

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

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

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

Basics of lensing:

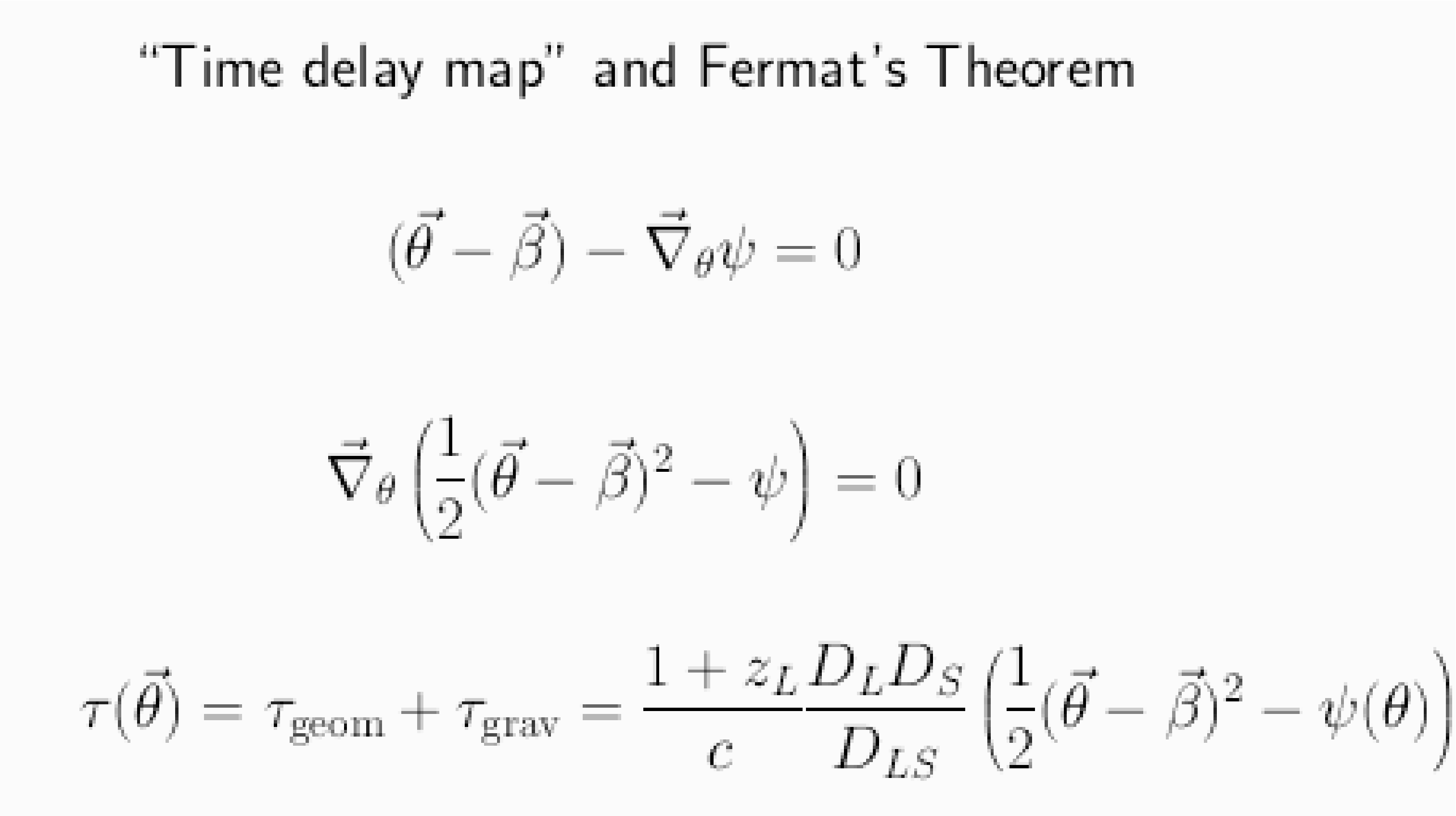


Singular isothermal sphere:

$$\Sigma(\xi) = \frac{\sigma_v^2}{2G}\frac{1}{\xi}$$

$$\tilde{\alpha}(\xi) = 4\pi\frac{\sigma_v^2}{c^2} = 1.15\left(\frac{\sigma_v}{200\mathrm{kms}^{-1}}\right)^2 \mathrm{arcsec}$$

Time delay / Hubble constant



"Time delay map" and Fermat's Theorem

$$(\vec{\theta} - \vec{\beta}) - \vec{\nabla}_\theta \psi = 0$$

$$\vec{\nabla}_\theta \left(\frac{1}{2} (\vec{\theta} - \vec{\beta})^2 - \psi \right) = 0$$

$$\tau(\vec{\theta}) = \tau_{\rm geom} + \tau_{\rm grav} = \frac{1 + z_L}{c} \frac{D_L D_S}{D_{LS}} \left(\frac{1}{2} (\vec{\theta} - \vec{\beta})^2 - \psi(\theta) \right)$$

Effects of gravitational lensing: strong and weak

- 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 luminous arcs

Lensing Phenomena:

- Two regimes of strength: strong ⇔ weak
- Two regimes of scales: macro ⇔ micro
- Two regimes of distance: near ⇔ far
-
- Two regimes of time: ancient ⇔ recent

How can we observe lensing phenomena?

Depends on (lens) mass scale:

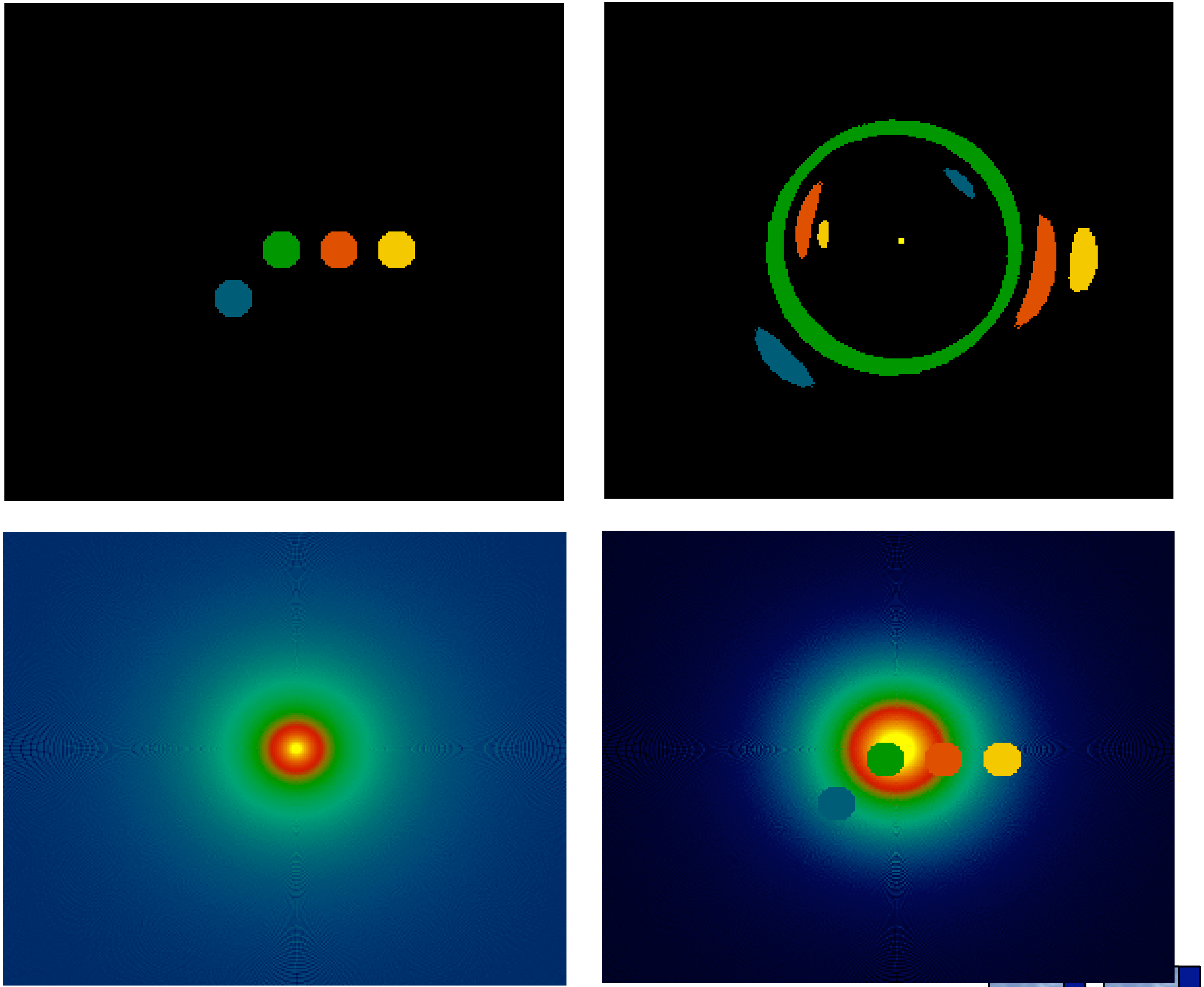
- "Statically":

  macrolensing: galaxy or galaxy cluster as a lens,
  Einstein angle > resolution of telescope!
  (time scale >> 100 years)
  do surveys for quasars or galaxy clusters (and be patient & lucky!):
  1 out of 500 quasars is multiply imaged ...

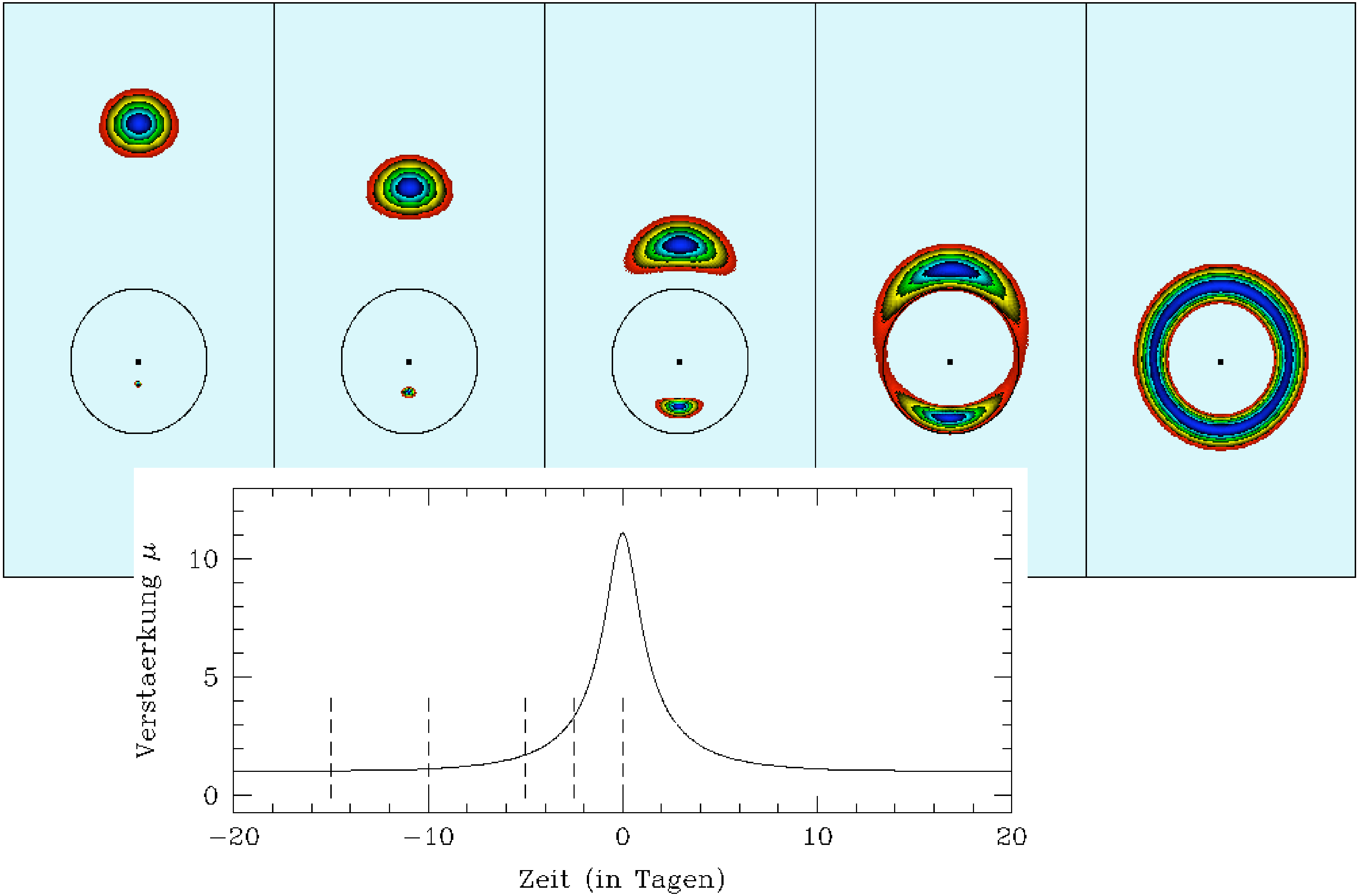
- "Dynamically":

  microlensing: stars as lenses,
  (Einstein angle << telescope resolution)
  time scale = Einstein radius/transverse vel ≈ months/years
  monitor known multiple quasars (and be patient & lucky!)

Simulation: Point lens and extended source

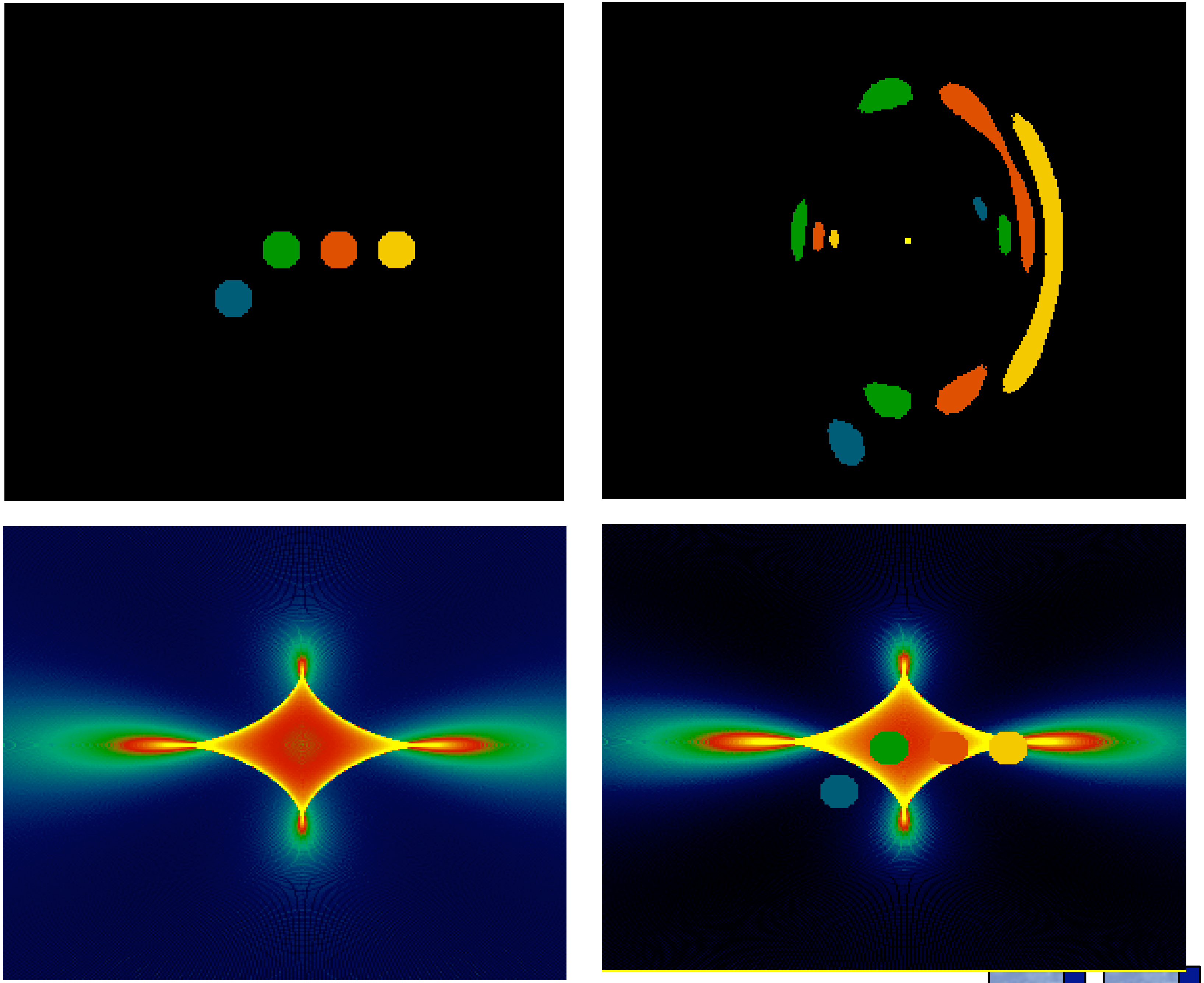


Simulation: Point lens and extended source

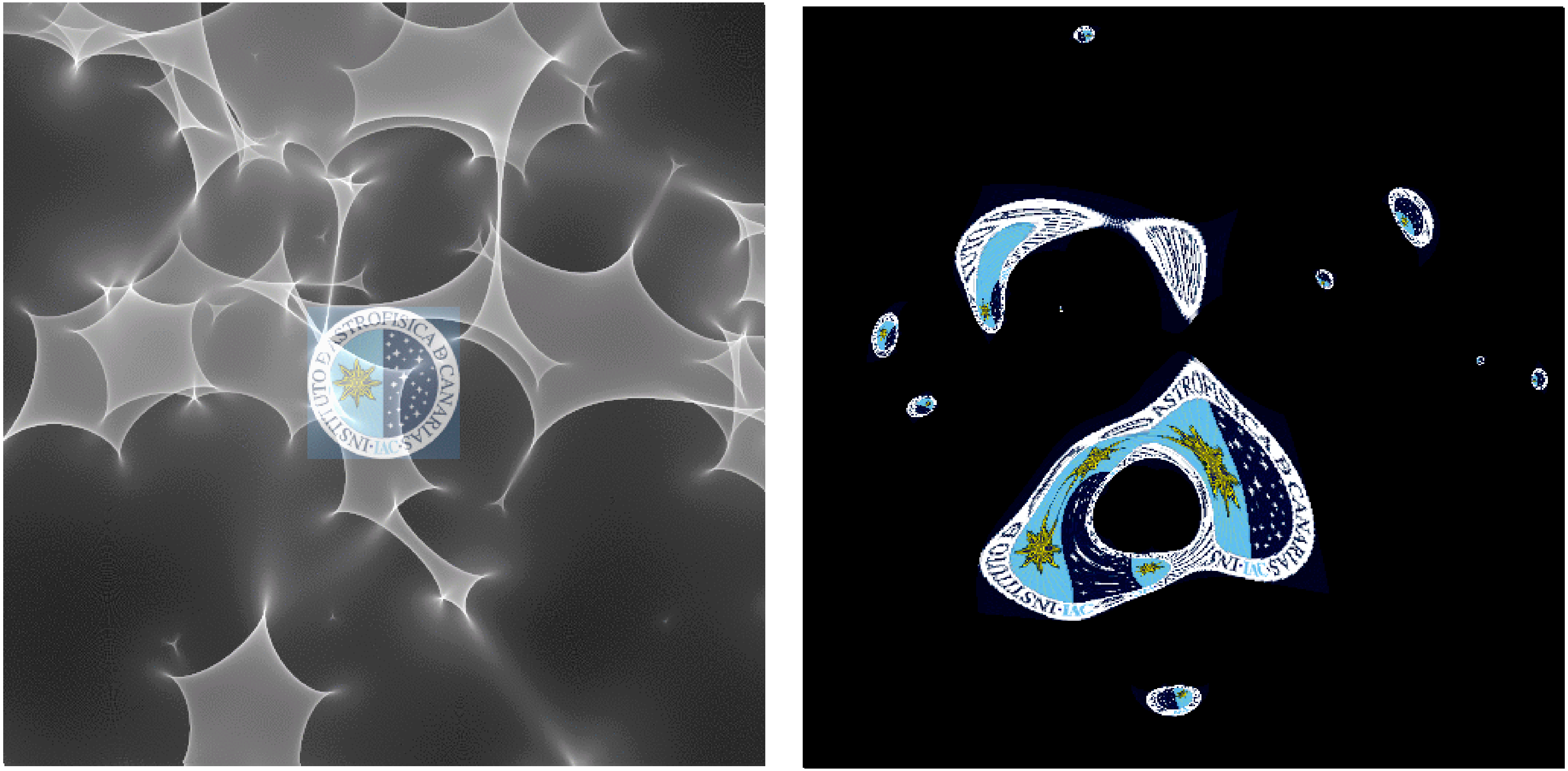


Introductory Lecture: “Gravitational Lensing Theory and Applications”
Joachim Wambsganss, KITP Santa Barbara, September 28, 2006

Simulation: Chang-Refsdal-Lens



Quasar Microlensing



Strong lensing phenomena:

- Double quasars:

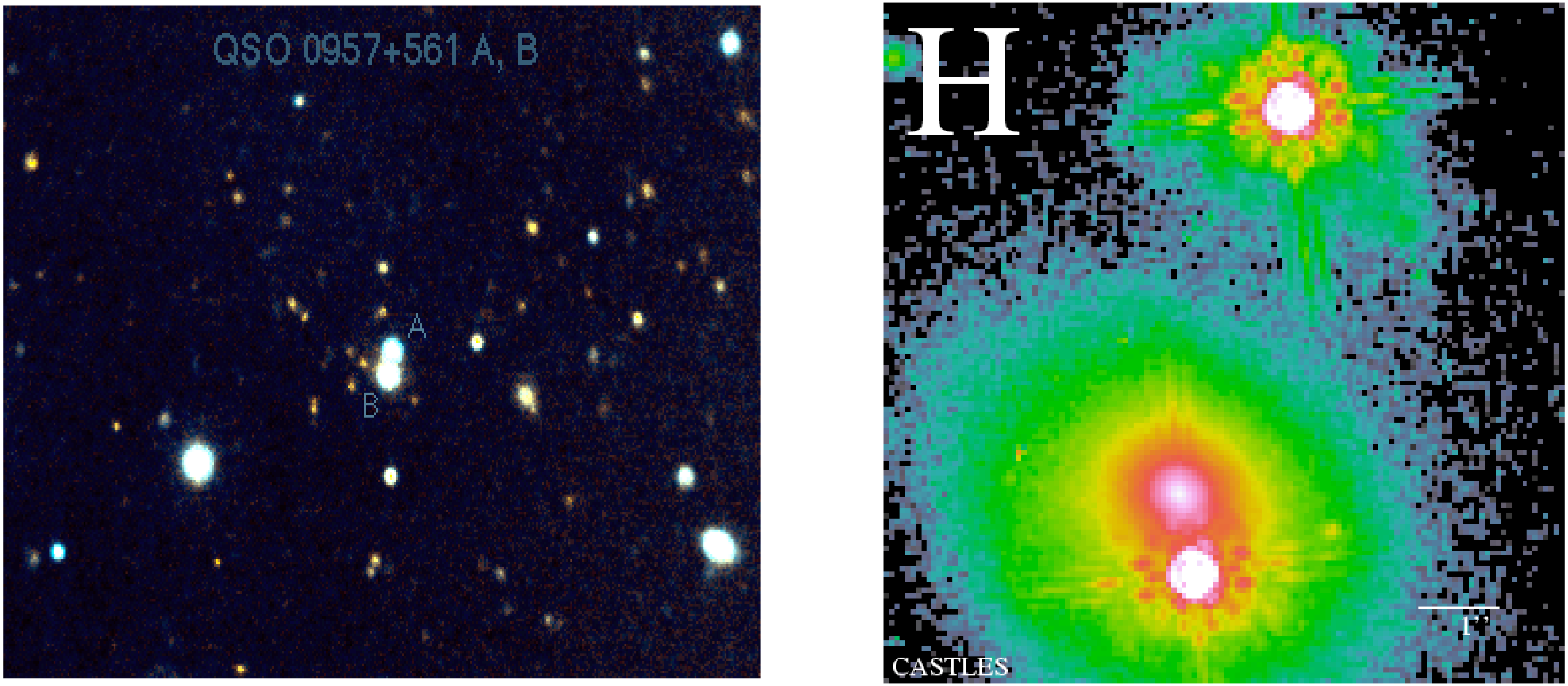
  Q0957+561 and HE 1104-1805
- Quadruple quasars:

  Q2237+0305 and PG1115+080
- Einstein ring:

  B1938+666
- Giant Luminous Arcs:

  Abell 2218

Double quasar Q0957+561A, B



Two quasar images, 6.1 arcseconds apart, z (quasar) = 1.41,   z(galaxy) = 0.36

(APO, HST, Falco et al., CASTLES)

When are two quasar images »illusions«?

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

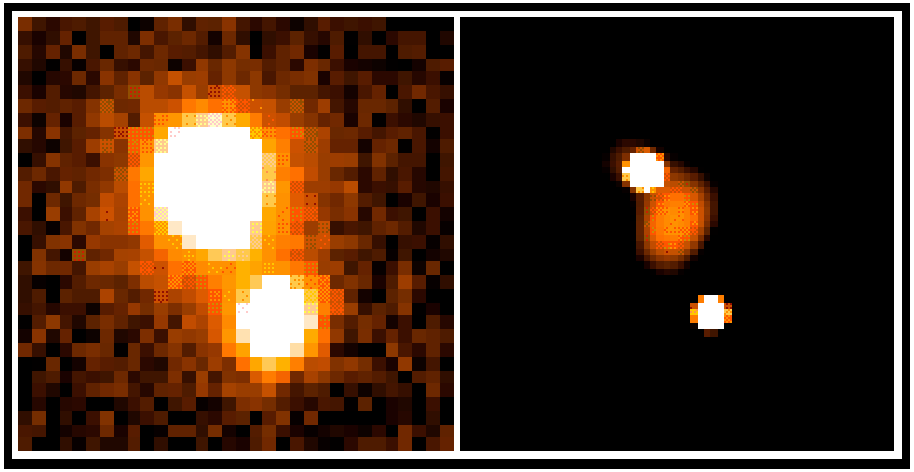
Criteria for gravitational lens candidates:

- 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 2006):

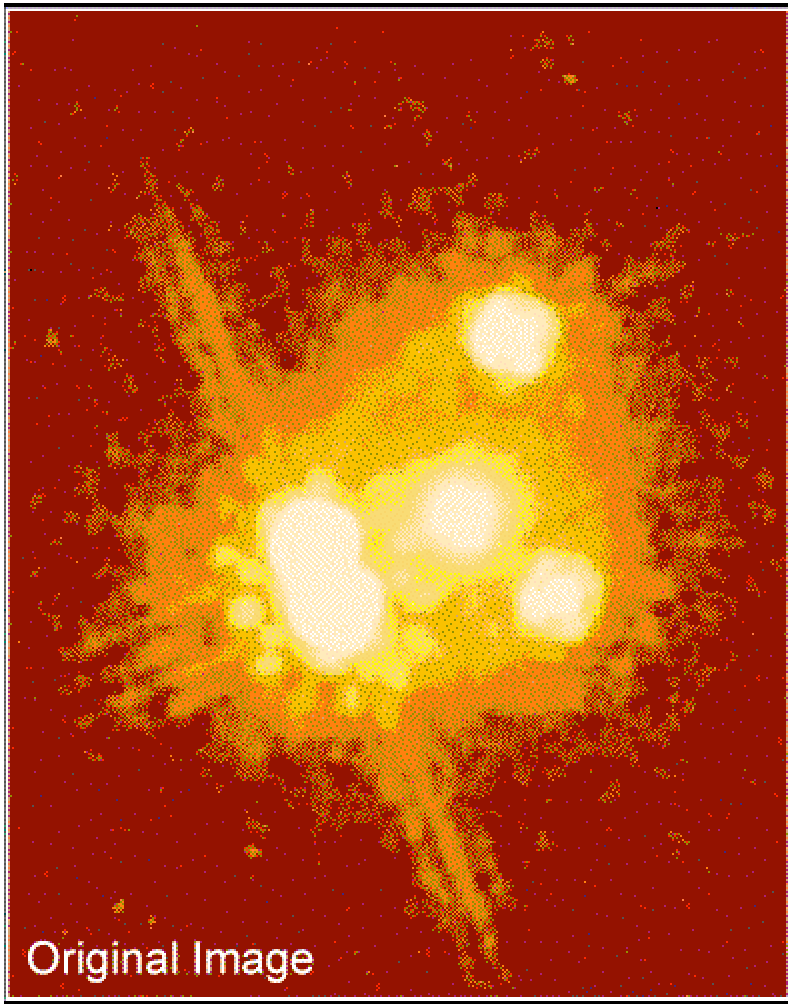
> 120 "accepted" multiple quasars systems!

Quasars HE1104-1805 and PG1115+080



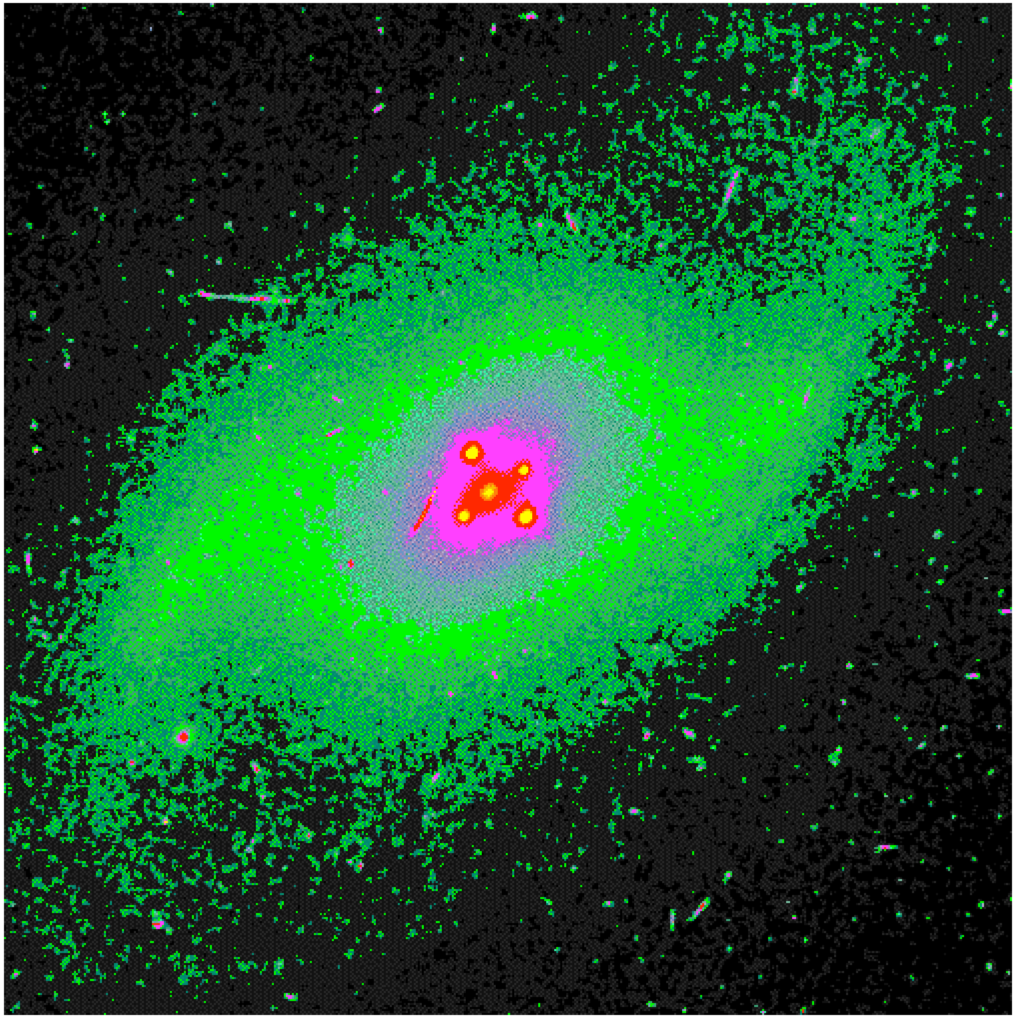
- Double quasar HE1104-1805
  - z(quasar) = 2.32
  - separation 3.2 arcsec
  - Courbin et al.

- Quadruple quasar PG1115-080
  - z(quasar) = 1.72
  - separation 2.4 arcsec
  - Impey et al.



Gravitational Lens and Quasar PG 1115

The quadruple quasar Q2237+0305

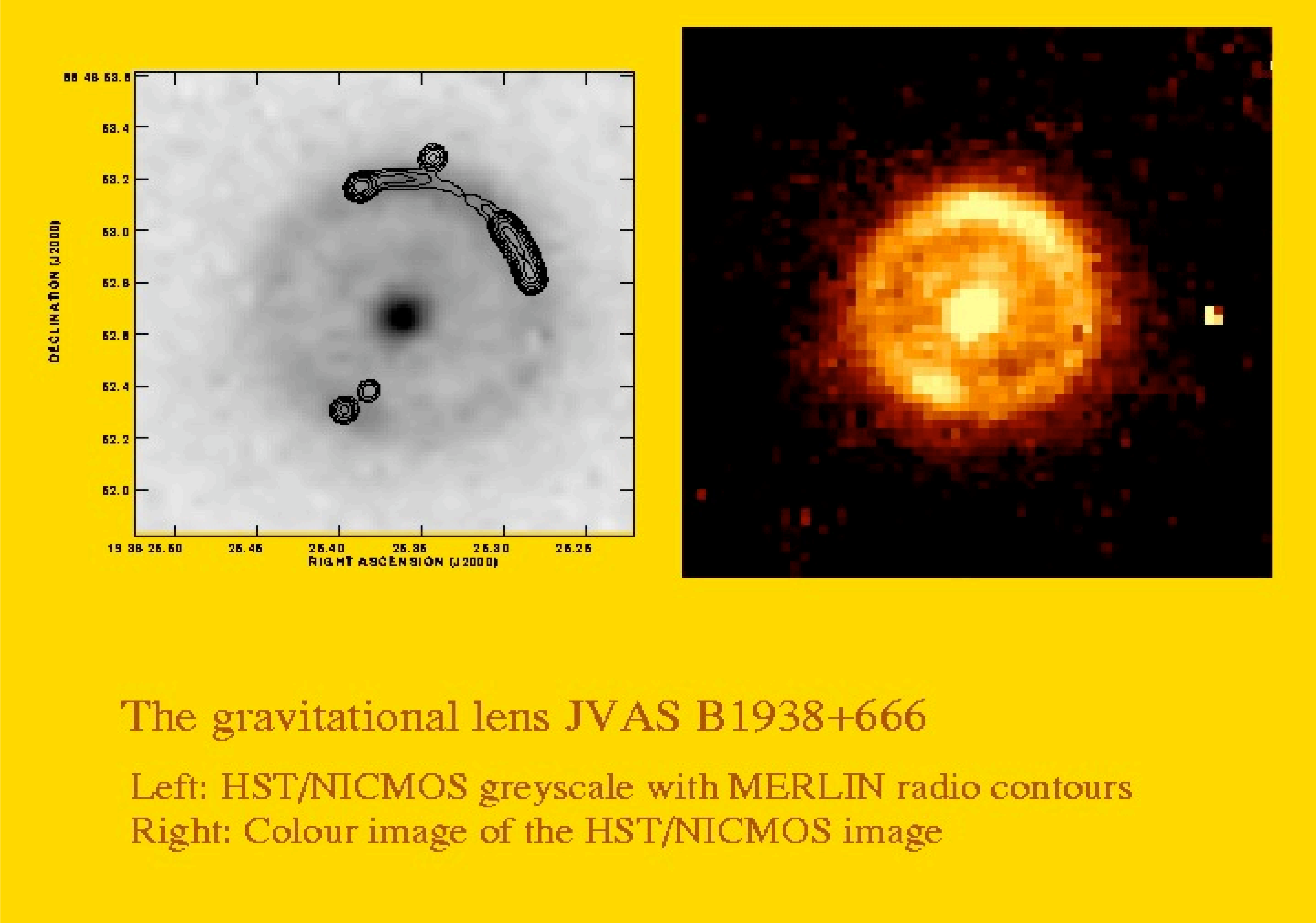


z(quasar) = 1.695, z(galaxy) = 0.039

image separation 1.7 arcsec

(HST)

Einstein ring B1938+666

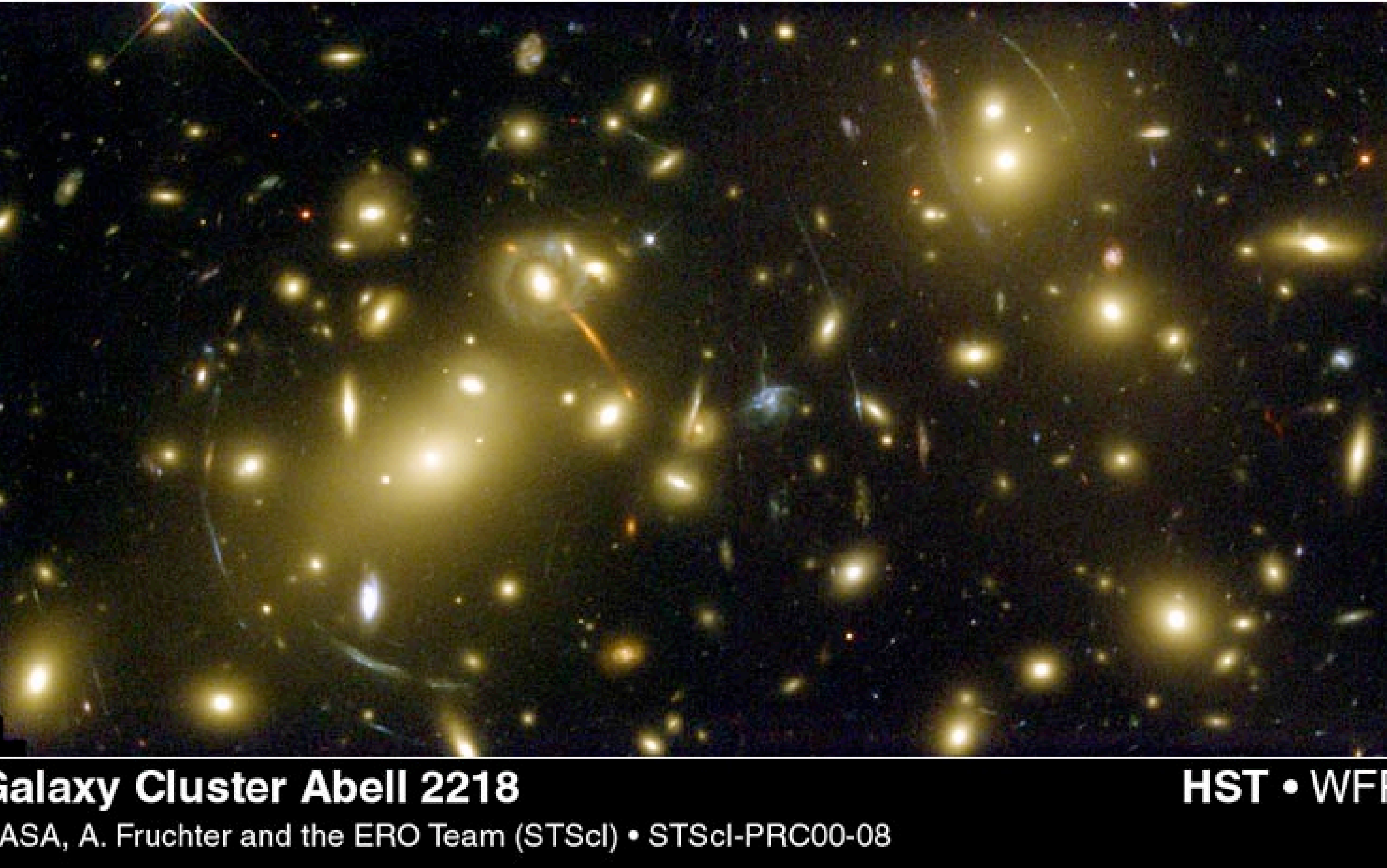


The gravitational lens JVAS B1938+666

Left: HST/NICMOS greyscale with MERLIN radio contours
Right: Colour image of the HST/NICMOS image

King et al. (1997)

Giant Luminous Arcs: Abell 2218

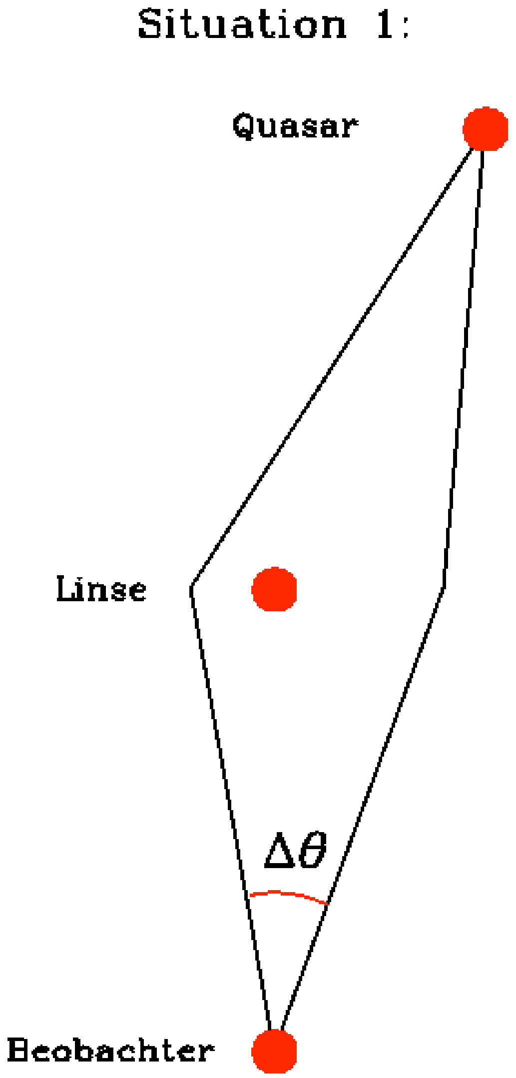


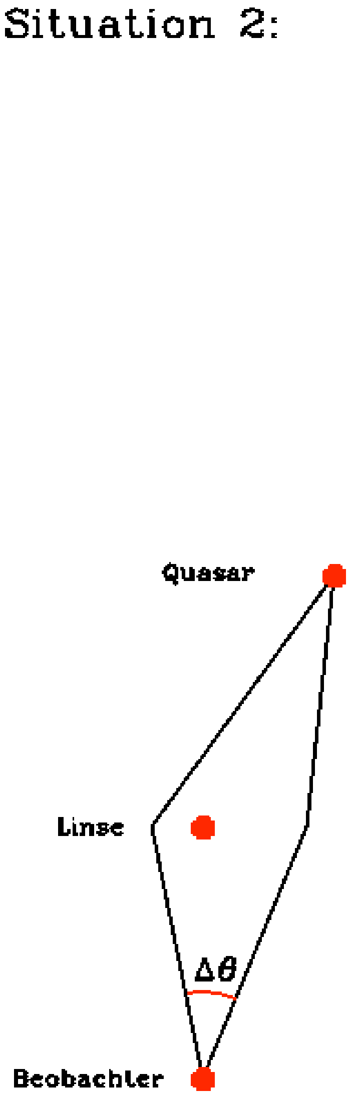
Lensing Applications

(selected with a strong lensing bias ...)

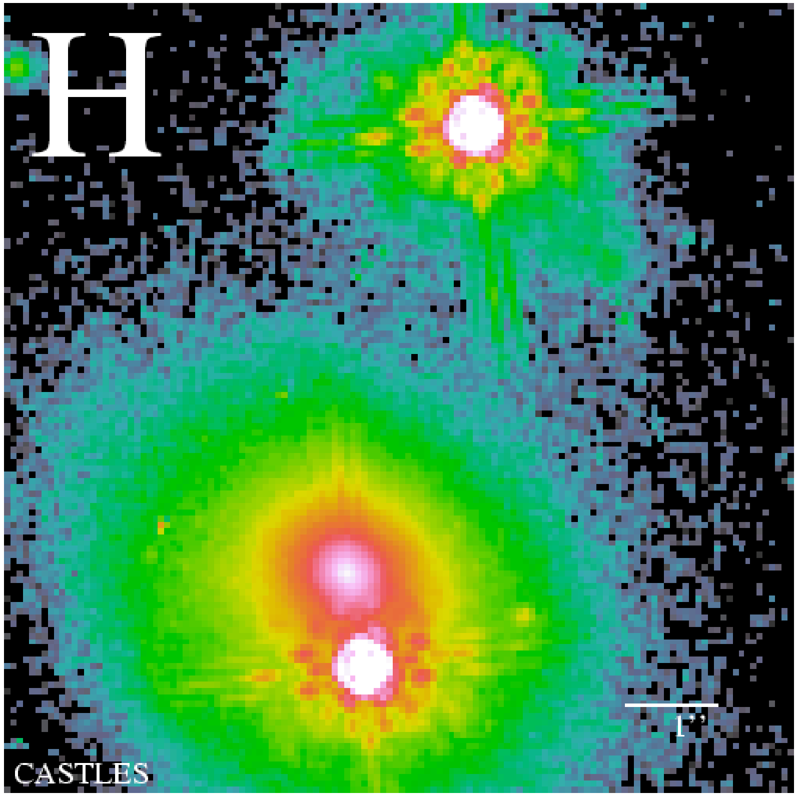
- how to measure the Hubble constant (strongly simplified ...)
- how many arcs out there (strongly magnified ...)
- how much dark matter (possibly demagnified ...)
- how to find cool planets (independently verified ...)

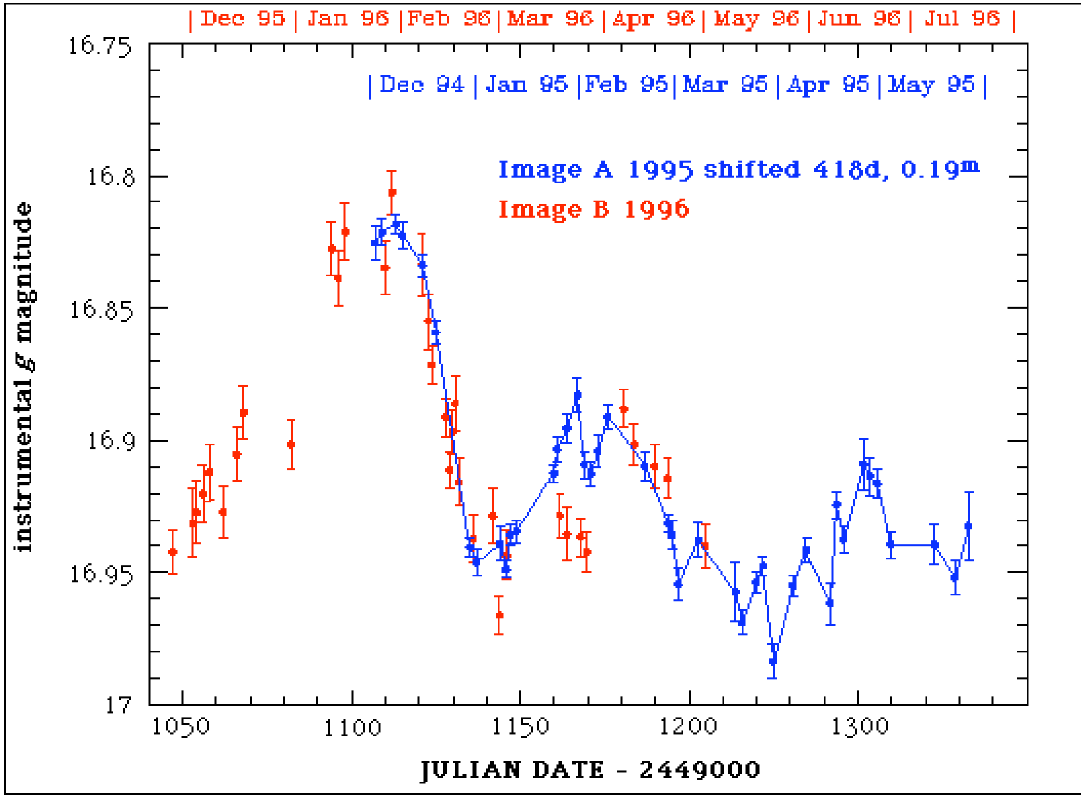
Time delay & Hubble constant from lensed quasars (Refsdal 1964):





Double quasar Q0957+56: Time Delay & Hubble constant





Time delay for double quasar Q0957+561:

$\Delta t_{Q0957+561} = 417 \pm 3$ days (Kundic et al. 1997)

Hubble constant (from Δt and lens model):

$$H_0 = 64 \pm 13 \text{ km/sec/Mpc} \quad (2\sigma)$$

Ensemble of 15 multiple quasars: Time Delay & Hubble constant

Oguri (yesterday, astro-ph/0609694):

> "We find that 15 published time delay quasars constrain the Hubble constant to be $H_0 = (70 \pm 3)$ km/s/Mpc."

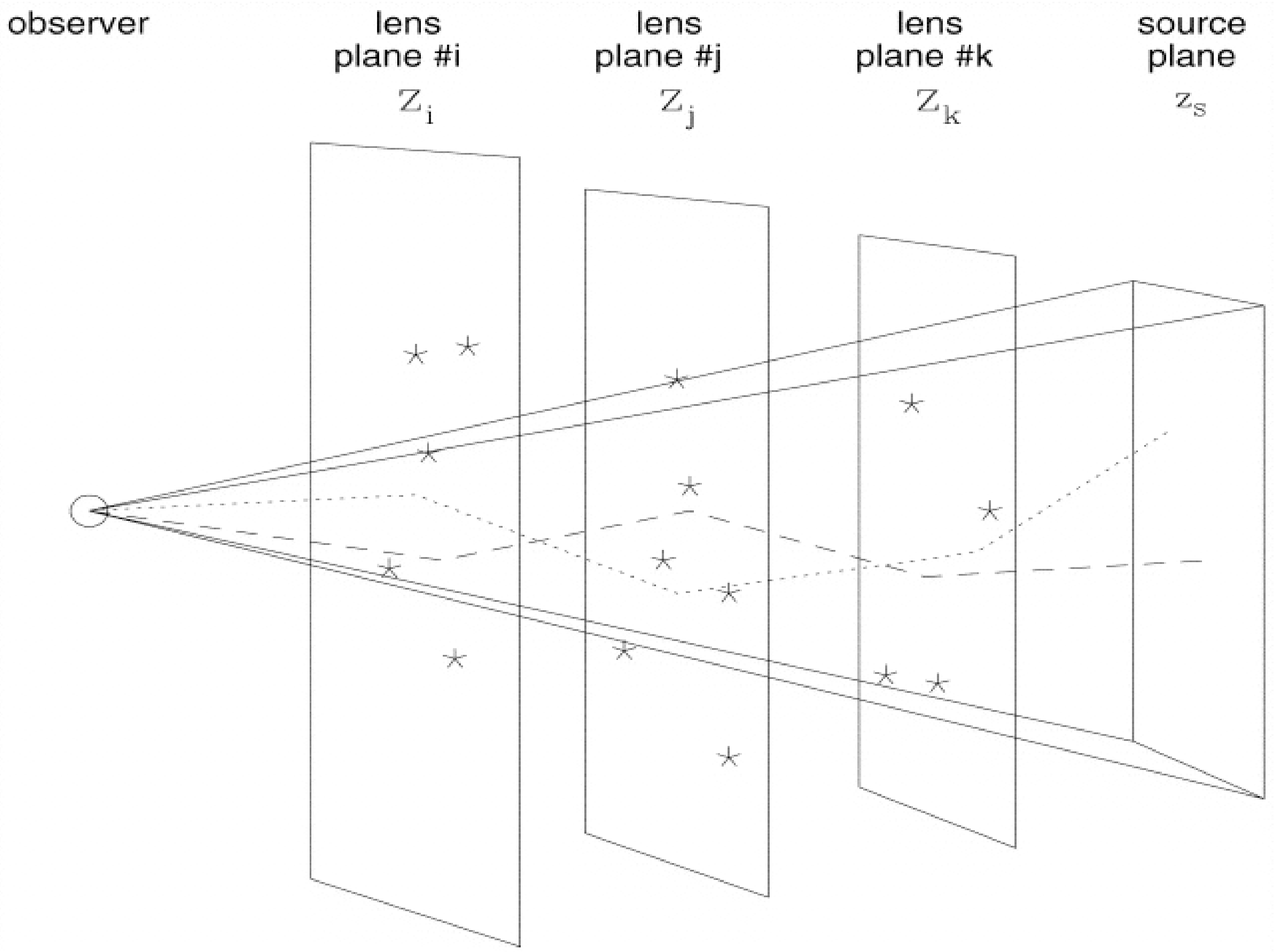
Strong lensing by galaxy clusters: arcs

Frequent approximation in cosmological scenario:
single lens plane, single cluster

However:
foreground/background are not entirely "empty"

→ multi-plane lensing with matter from n-body

Strong lensing by galaxy clusters: arcs



Multi lens plane lensing

Magnification at position x:

$$\mu(\vec{x}) = [\ \det A(\vec{x})\ ]^{-1} = [\ a_{11}(\vec{x})a_{22}(\vec{x}) - a_{12}(\vec{x})a_{21}(\vec{x})\ ]^{-1}$$

components of the shear $\vec{\gamma}(\vec{x}) = [\gamma_1(\vec{x}), \gamma_2(\vec{x})]$ are

$$\gamma_1(\vec{x}) = -0.5\ [\ a_{11}(\vec{x}) - a_{22}(\vec{x})\ ];$$

$$\gamma_2(\vec{x}) = -0.5\ [\ a_{12}(\vec{x}) + a_{21}(\vec{x})\ ].$$

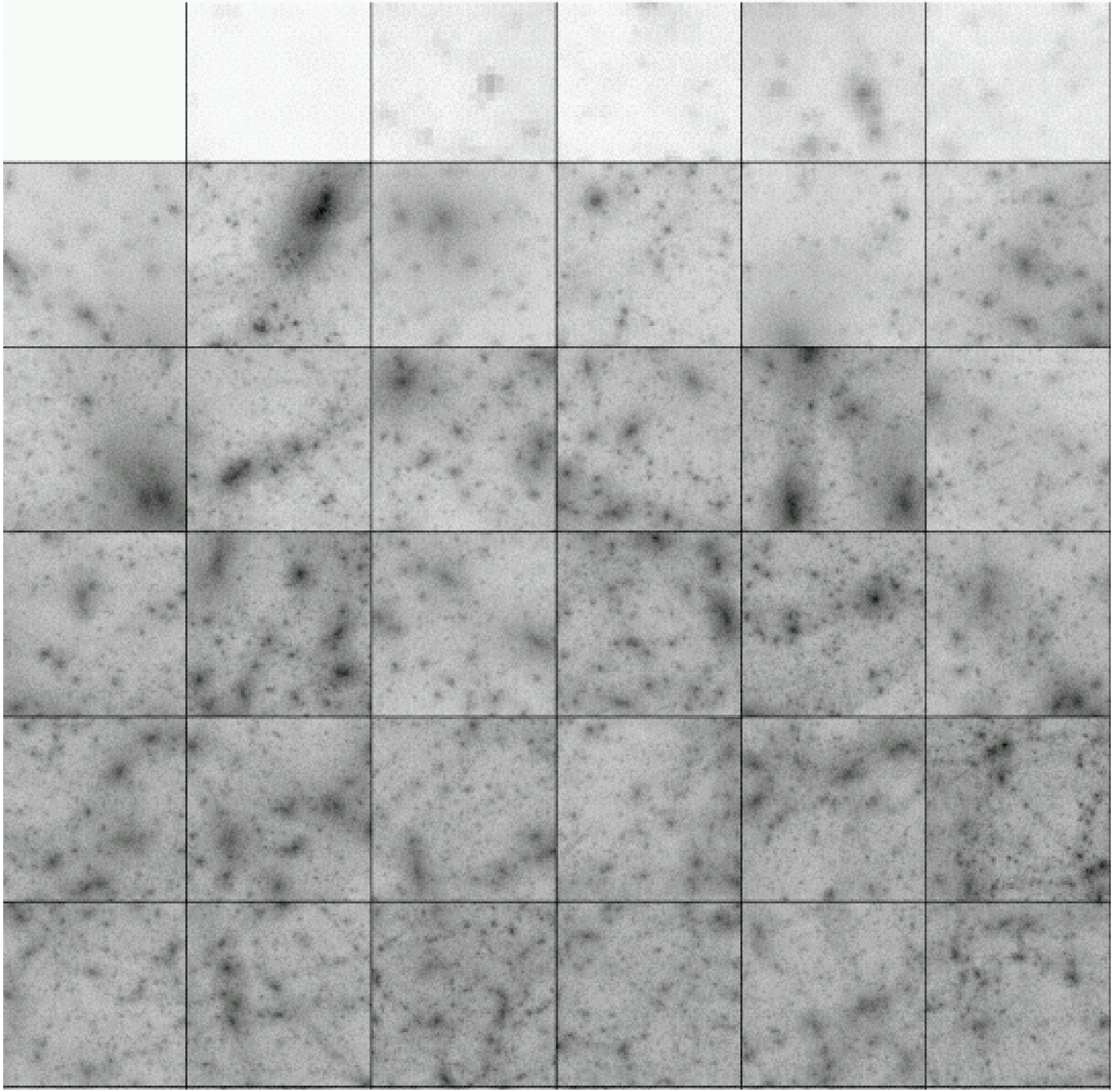
Ingredients for multi-lens plane approach:

n-body simulations with:

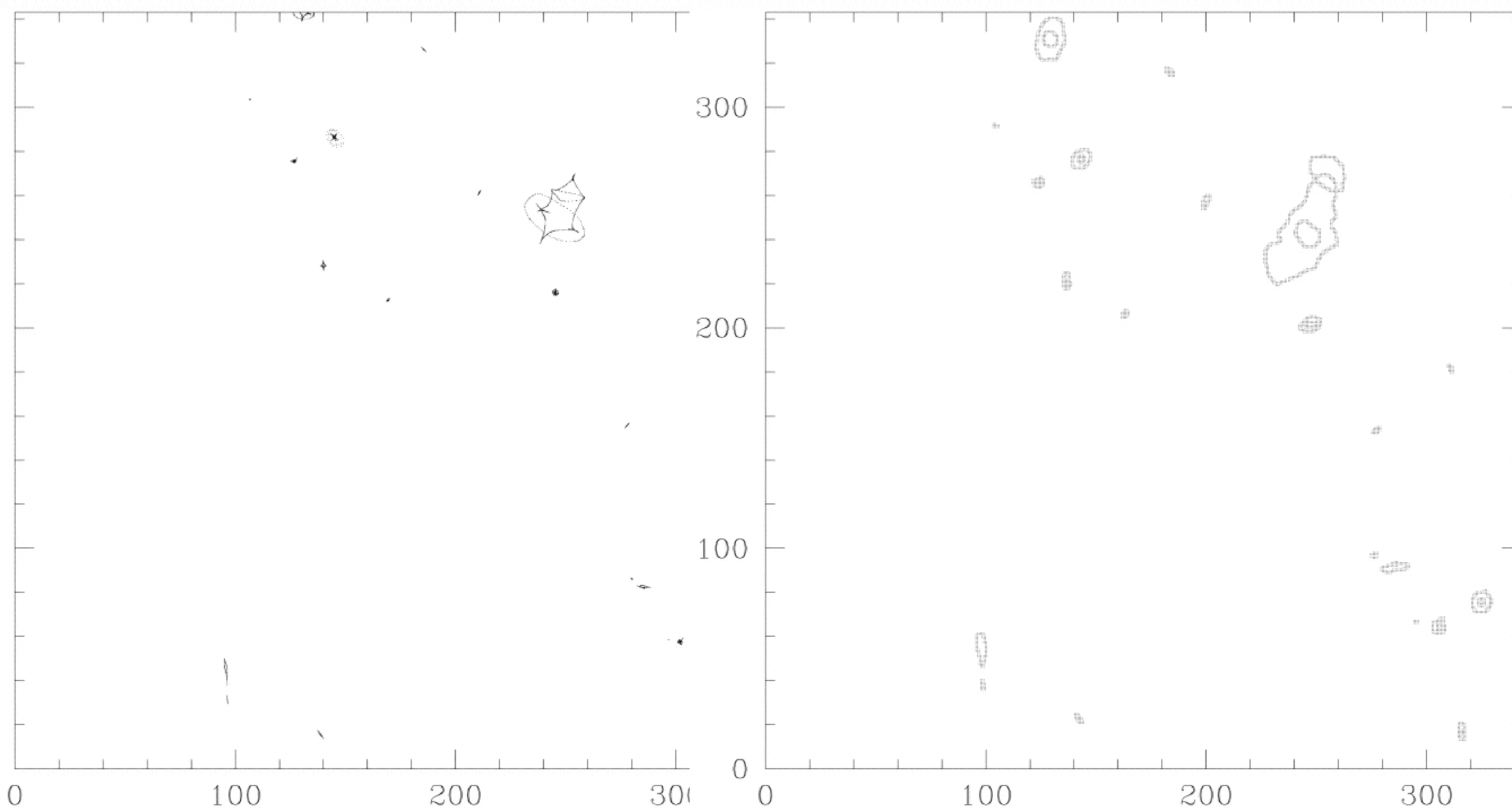
TPM (Tree-Particle-Mesh) code (with Ostriker, Bode)

- large box size L (in order to cover primordial fluctuations with large wavelength)
  L = 320 Mpc/h
- small "smoothing length" l (in order not to smooth small fluctuations)
  l = 3.2 kpc/h
- very large number of particles N (in order to resolve cores of individual galaxy mass halos)
  $N = 1024^3 = 1{,}073{,}741{,}824$

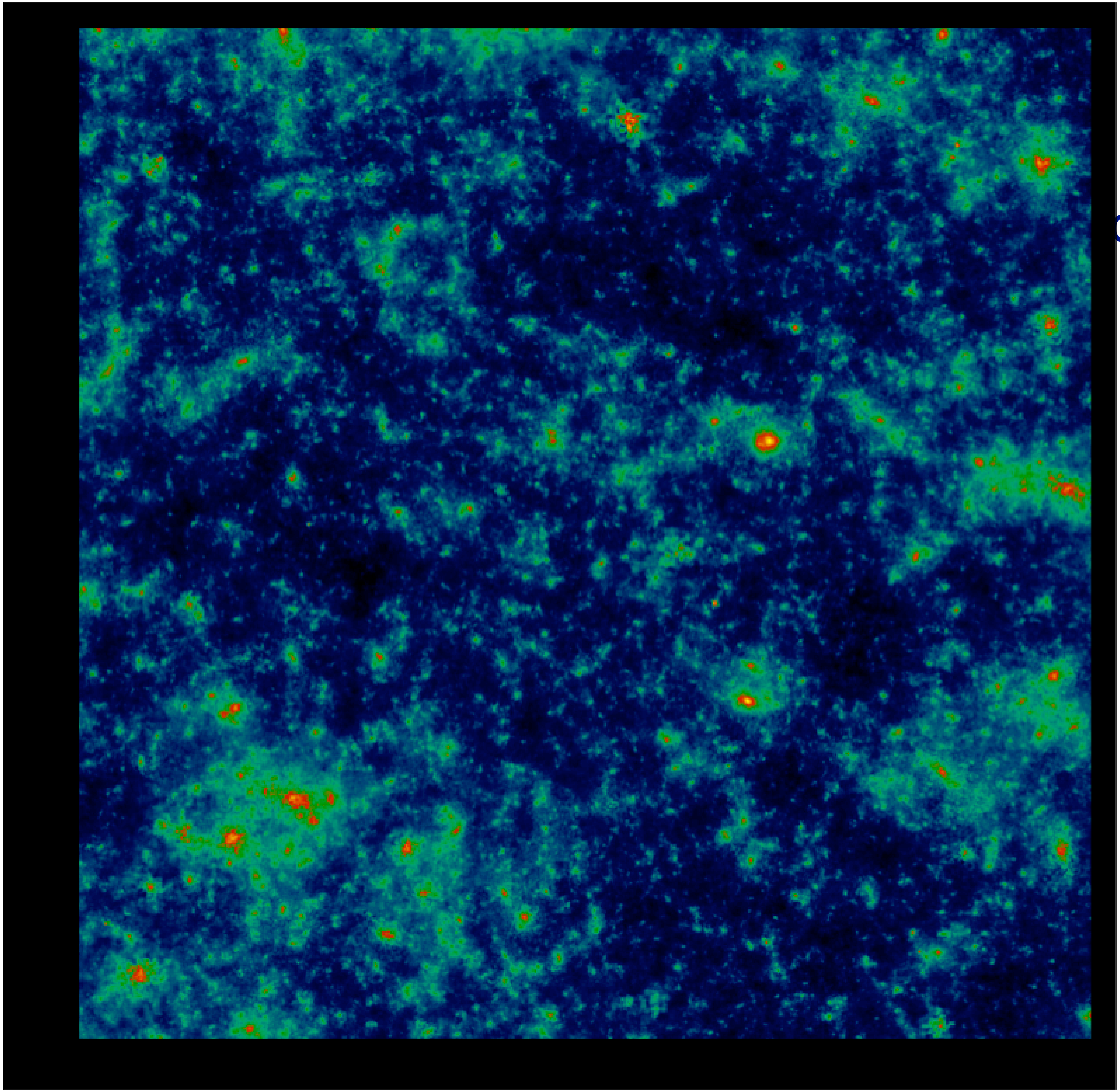
Example for lens planes as a function of redshift:



Example for regular source grid at high redshift:



Ray tracing simulations: matter & shear



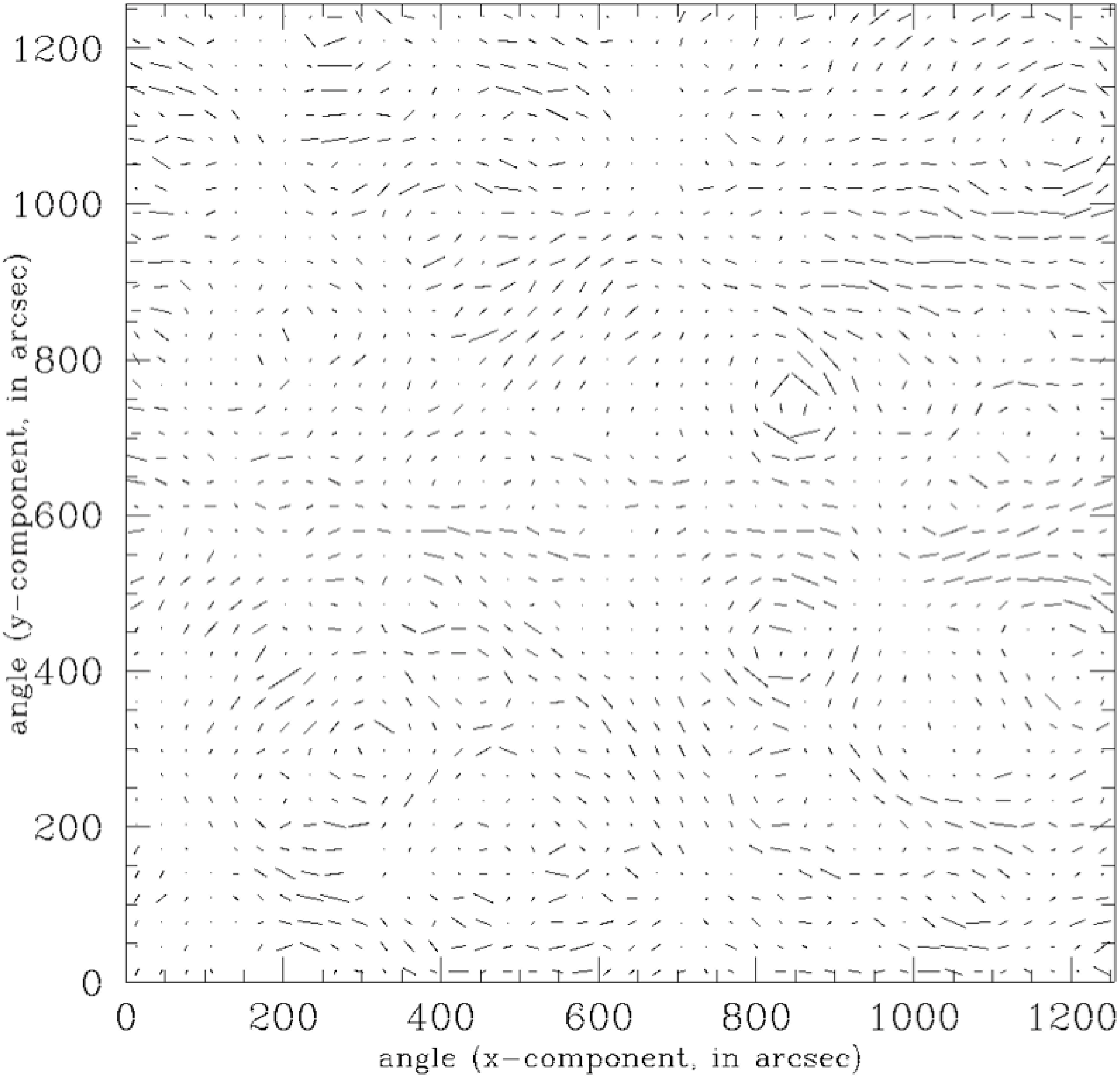
integrated
matter
distribution

plus

shear

Introductory Lecture: “Gravitational Lensing Theory and Applications”
Joachim Wambsganss, KITP Santa Barbara, September 28, 2006

Ray tracing simulations: matter & shear

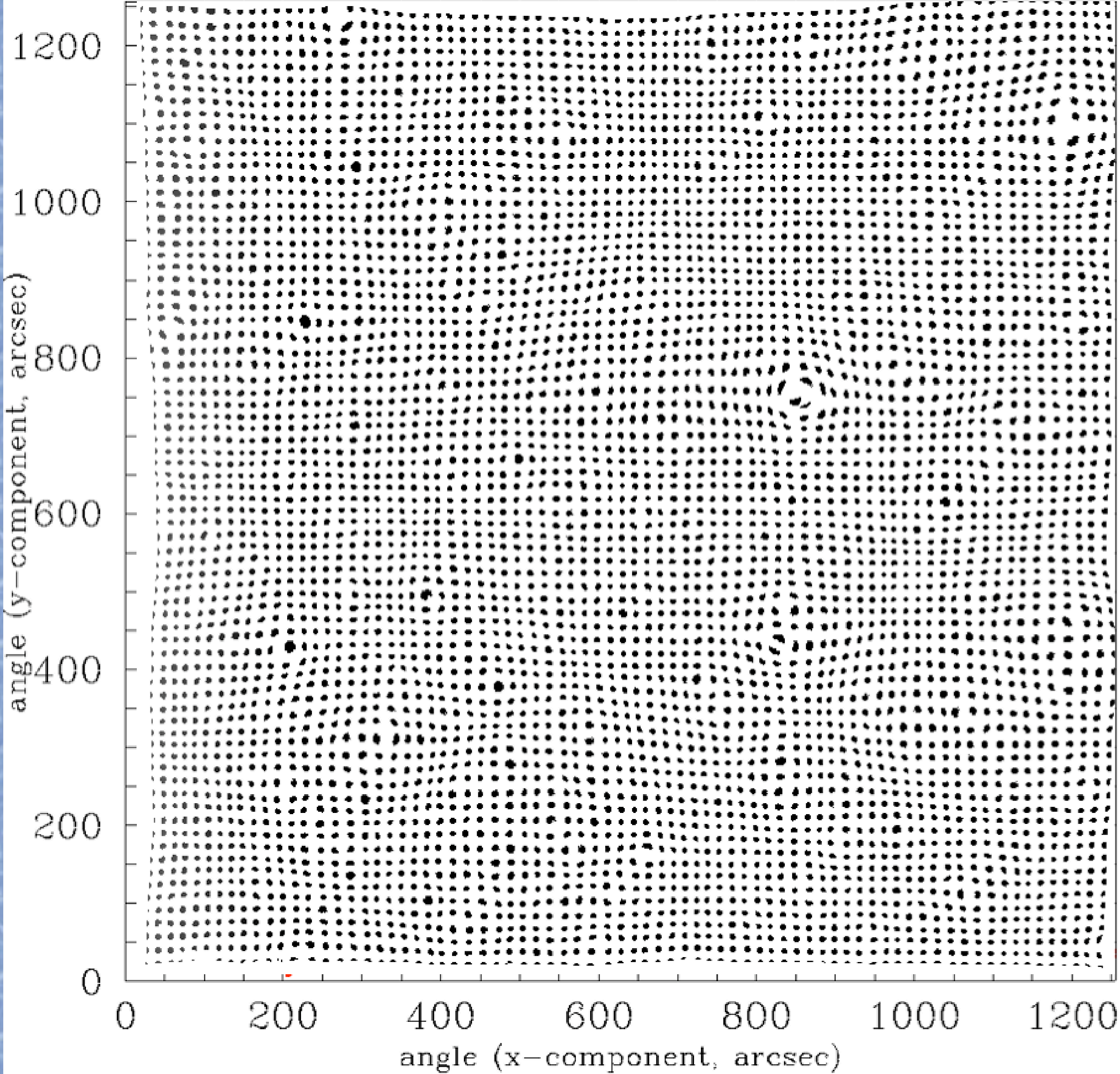


integrated
matter
distribution

plus

shear

Ray tracing simulations: critical lines & images

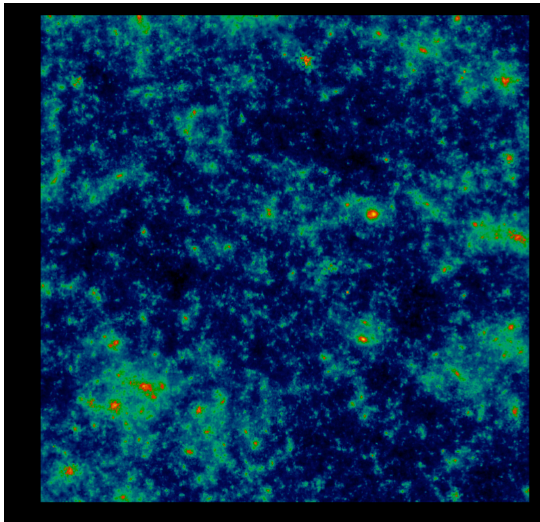


critical lines
in image plane

plus

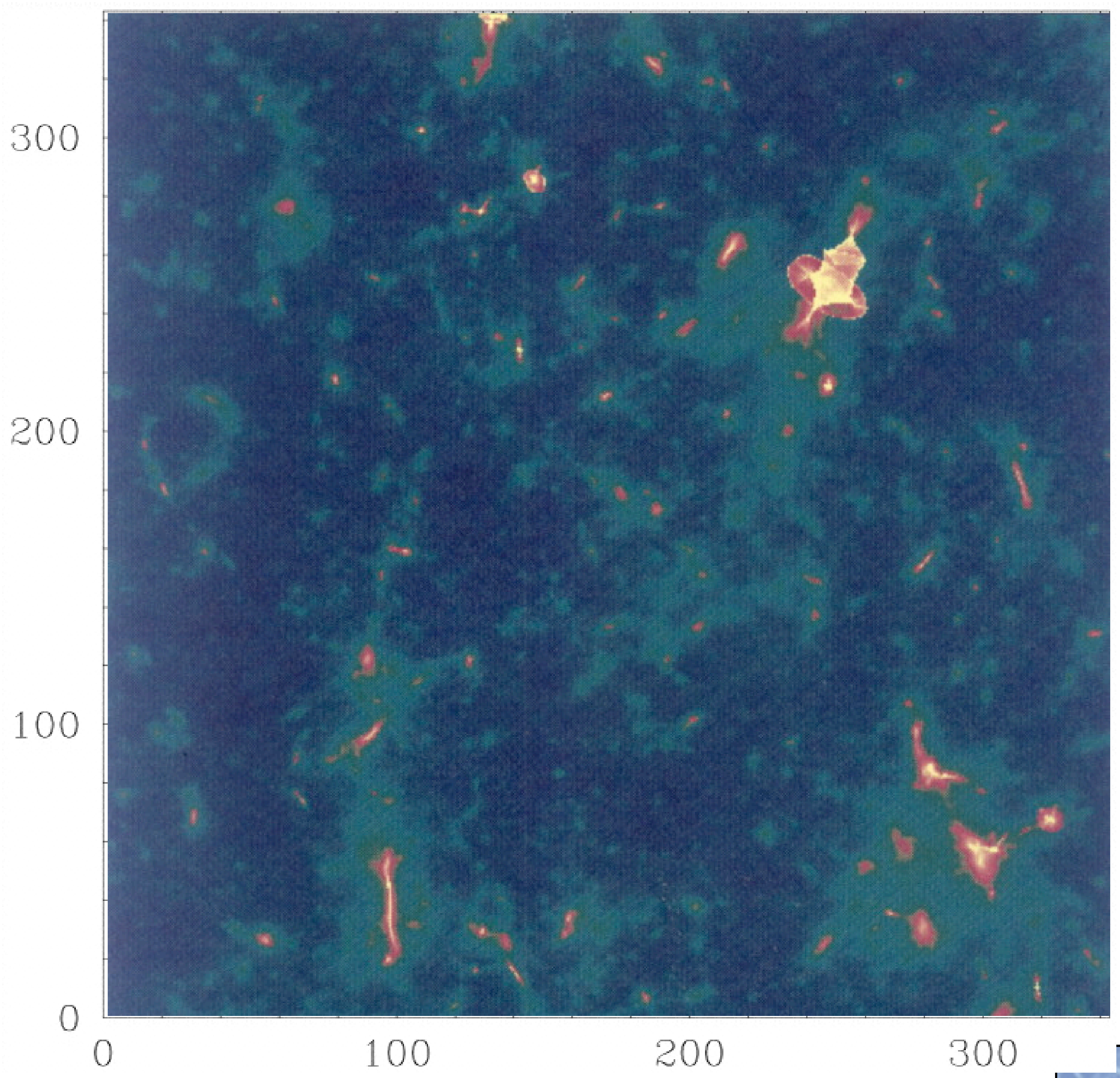
images

(for regular grid of circular sources at $z_s = 4.8$)

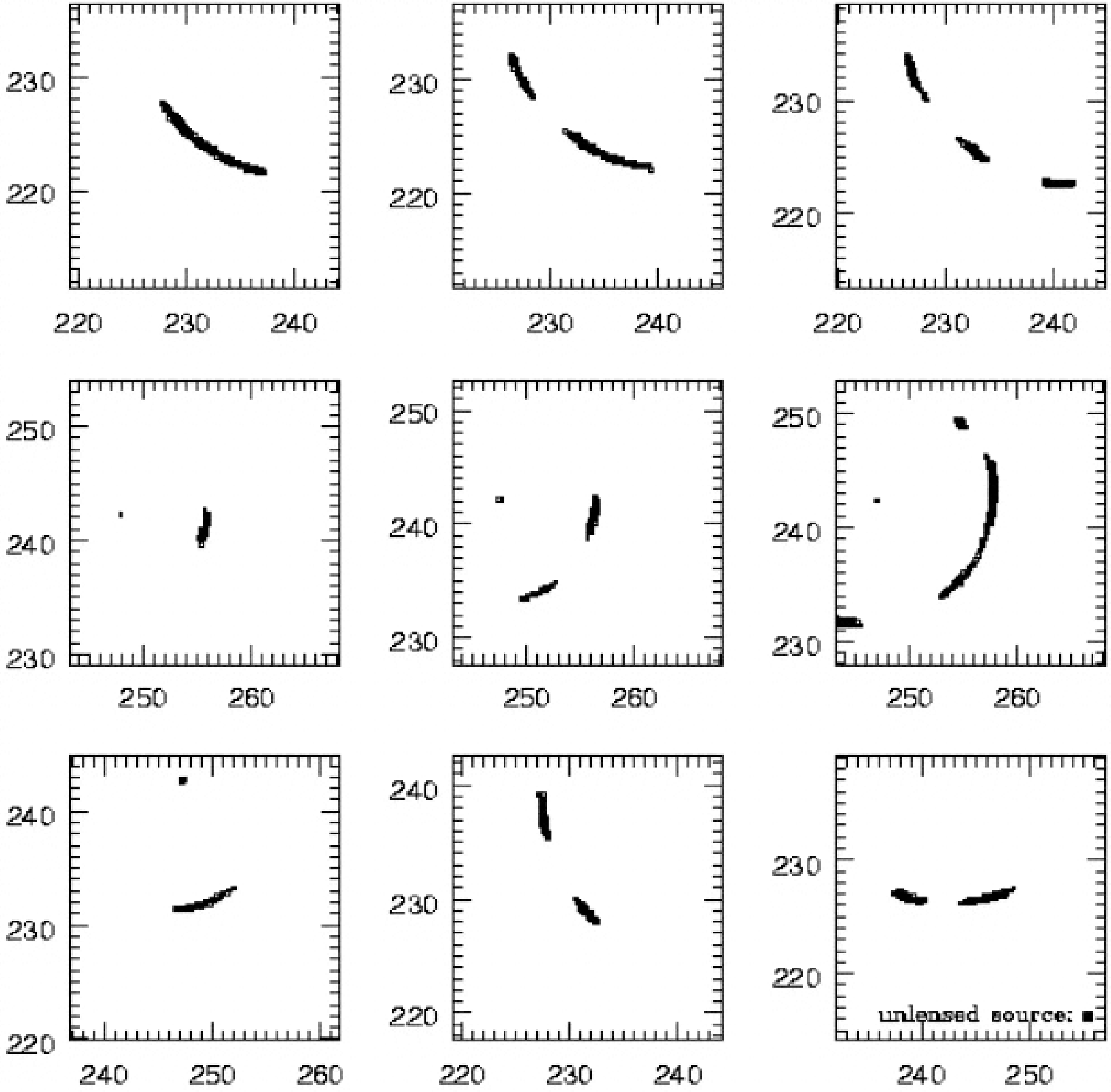


Introductory Lecture: “Gravitational Lensing Theory and Applications”
Joachim Wambsganss, KITP Santa Barbara, September 28, 2006

Magnification distribution in source plane:



Examples for arc-structures at high redshift:



Scientific questions which can be addressed with these gravitational lensing simulations:

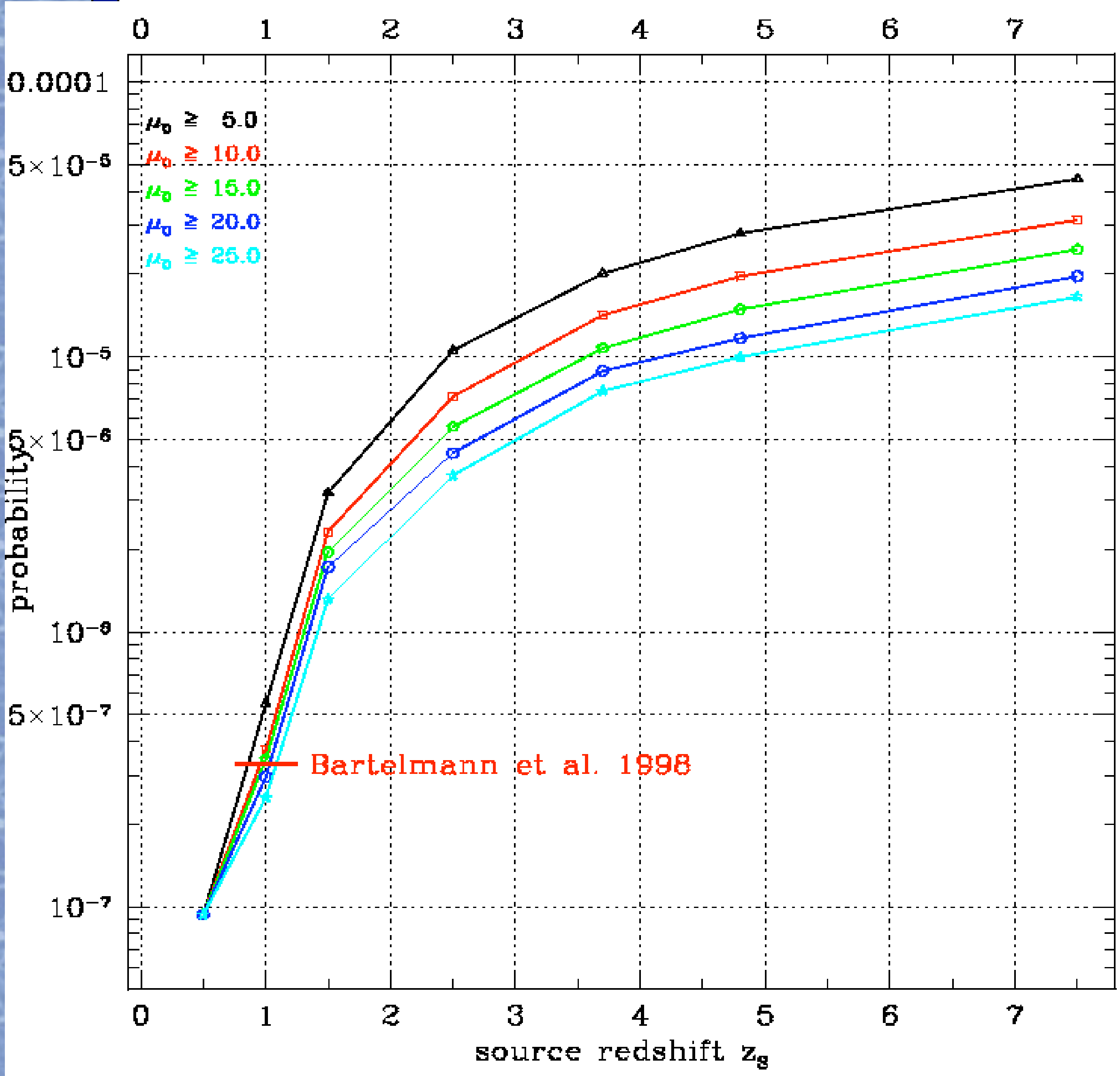
- Magnification distribution due to lensing as a function of source redshift:
  there are no standard candles!   not even high-z supernovae!

- Frequency and separation distribution of large separation multiple quasars:
  why aren't (weren't) there (m)any > 10 arcsec lensed quasars?

- Frequency of giant luminous arcs:
  in concordance with concordance cosmological model?

- Importance of secondary (tertiary, ...) lens planes:
  how frequently is strong lensing supported by sub-critical lens planes?

Frequency of giant luminous arcs:



Probability for the occurance of giant arcs:

strong function of source redshift!

Wambsganss, Bode, Ostriker (2004)

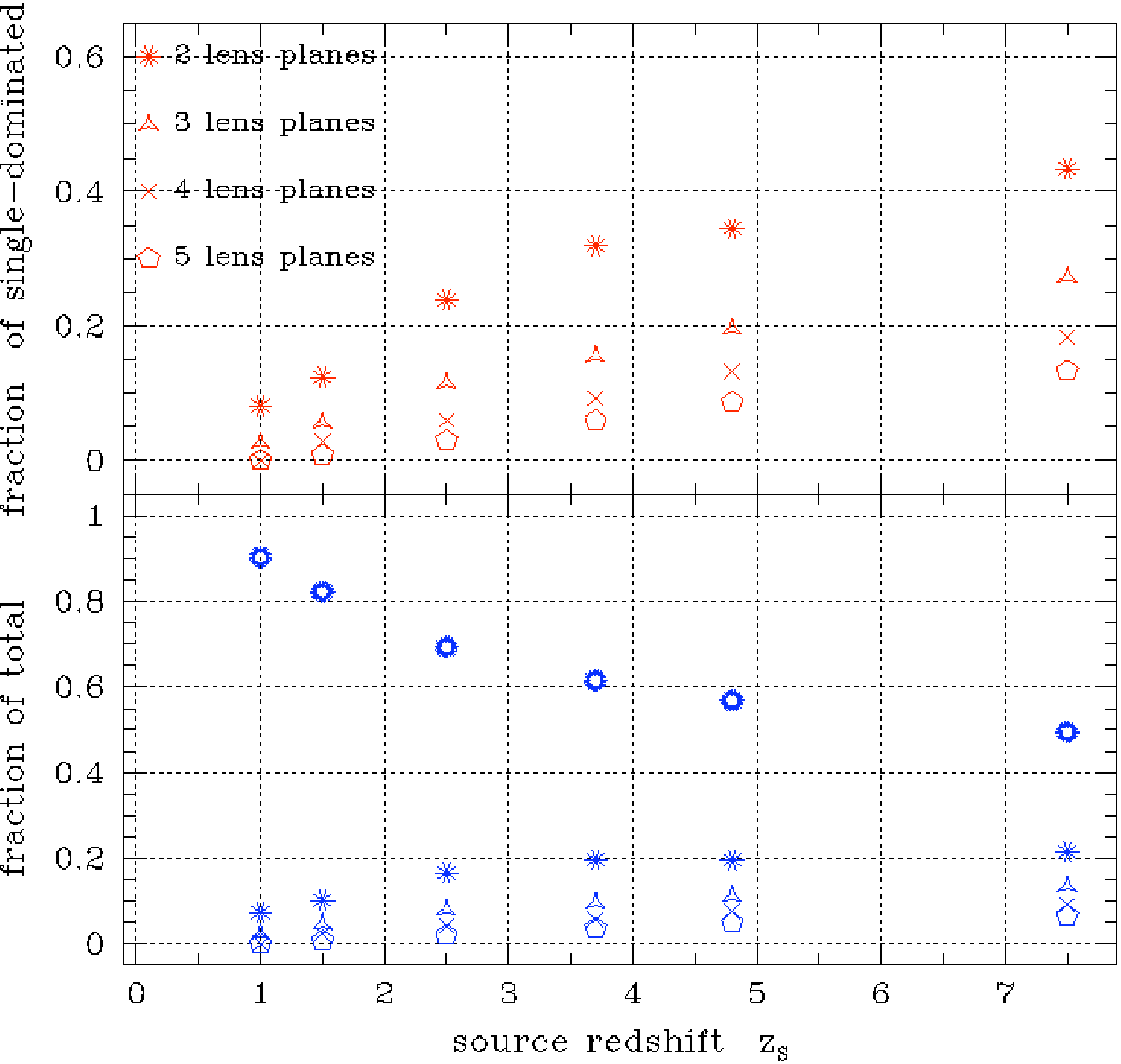
Importance of secondary (tertiary) lens planes:

how frequently is strong lensing supported by sub-critical lens planes?

Most strong lens systems are modelled assuming "thin" lens approximation: Is this always correct/justified?

For some multiple quasars: different redshifts for lensing galaxies measured statistically important?

Importance of secondary (tertiary) lens planes:

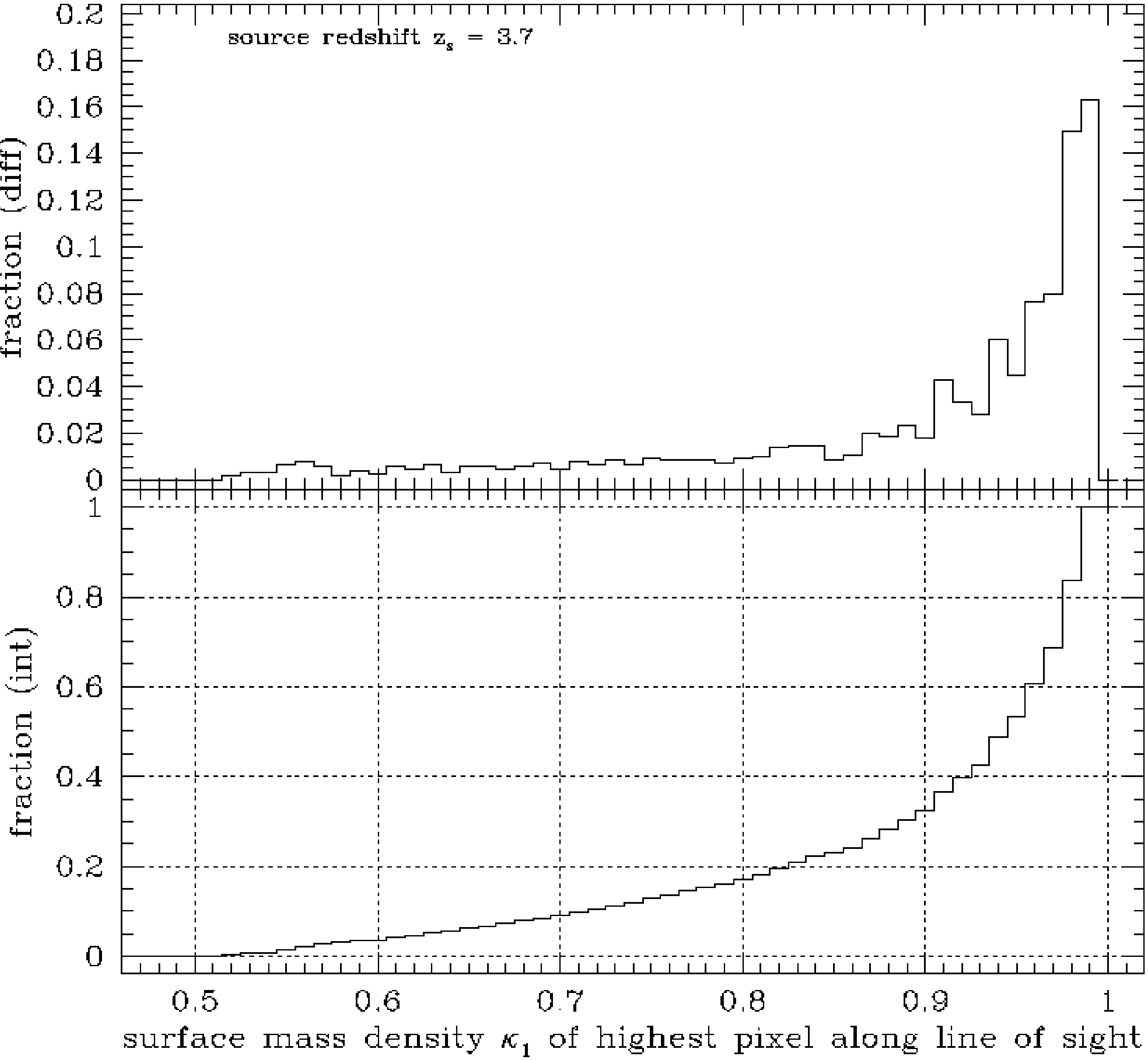


for increasing source redshift:

increasing importance of secondary, tertiary, ... lens planes!

Wambsganss, Bode, Ostriker (2005)

Importance of secondary (tertiary) lens planes:

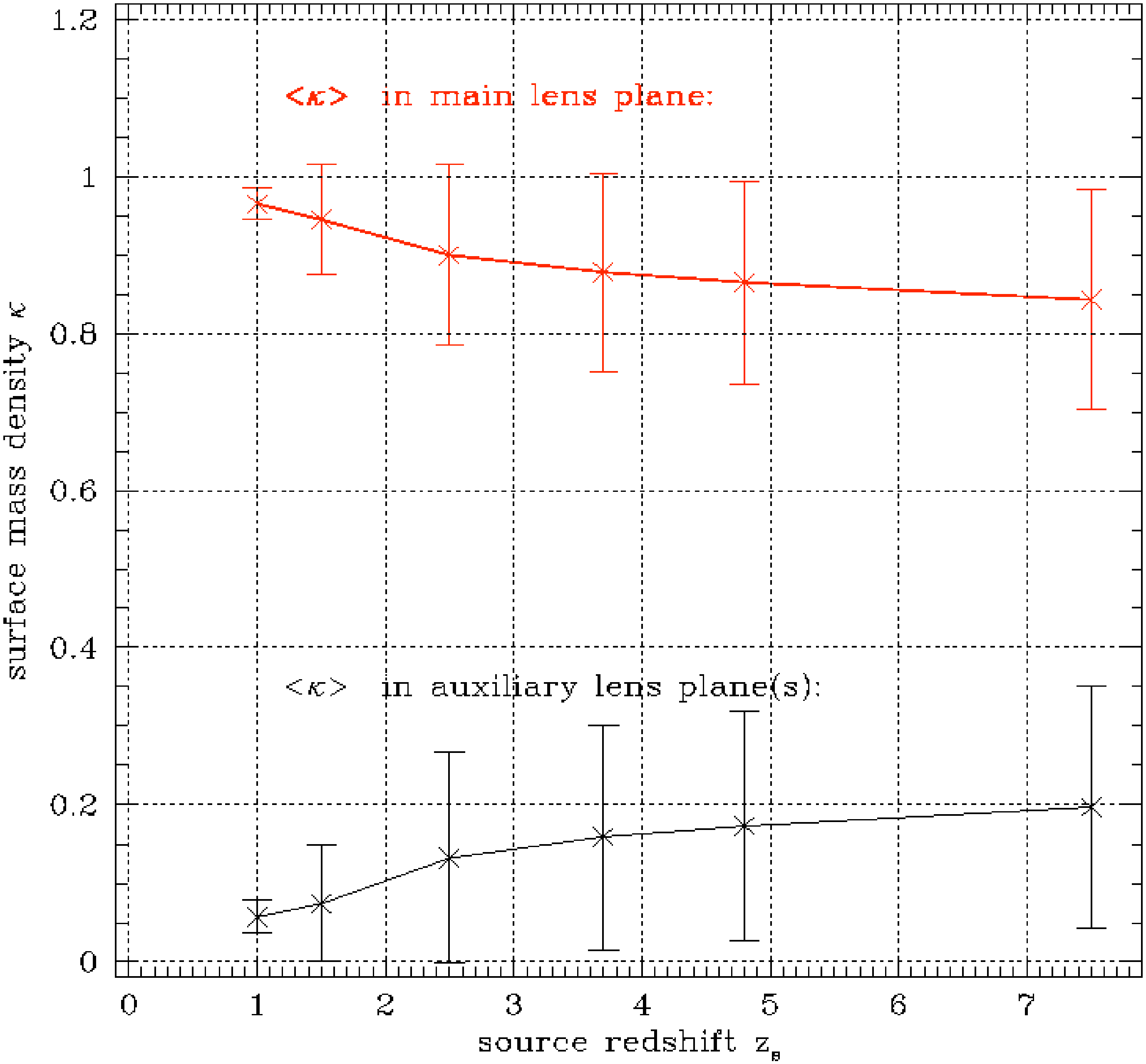


For two lens planes:
  heavily dominated by ONE lens plane,

secondary contribution
  "minor"

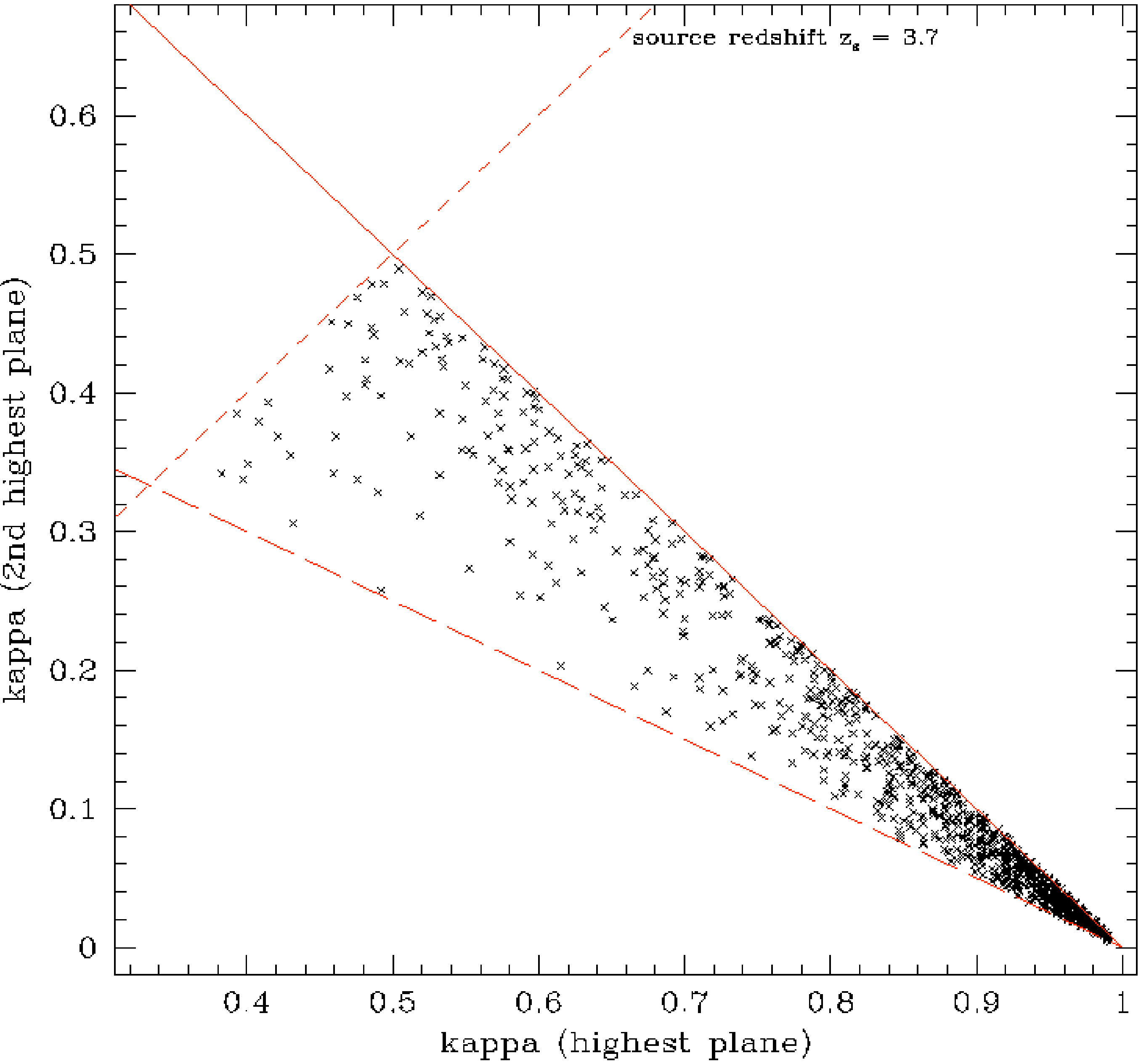
Wambsganss, Bode, Ostriker (2005)

Importance of secondary (tertiary) lens planes:



Wambsganss, Bode, Ostriker (2005)

Importance of secondary (tertiary) lens planes:



For three lens planes:

mostly dominated by
one lens plane

Wambsganss, Bode,
Ostriker (2005)

The two regimes of microlensing:

- compact objects in the **Milky Way**, or its halo, or the local group acting on **stars** in the Bulge/LMC/SMC/ M31:

  stellar microlensing
  Galactic microlensing
  local group microlensing
  optical depth: $\sim 10^{-6}$

  near

- compact objects in a **distant galaxy**, or its halo acting on even more distant (multiple) **quasars**

  quasar microlensing
  extragalactic microlensing
  cosmological microlensing
  optical depth: ~ 1

  far

Quasar Microlensing

- how can we observe quasar microlensing?
  - changing magnification, line shape, position;
    due to relative motion of source, lens and observer:
    microlensing is a **dynamic** phenomenon!
    - **photometrically**
    - spectroscopically
    - astrometrically
- what are the time scales?
- Einstein time: $$t_E = r_E/v_\perp \quad 15\sqrt{M/M_\odot}\, v_{600}^{-1} \ \text{years}$$
  ($z_L = 0.5$, $z_S = 2.0$)
- Crossing time: $$t_{cross} = R_{source}/v_\perp \approx 4 R_{15} v_{600}^{-1} \ \text{months}$$

Why "Micro"-lensing? The Scalings

Einstein radius:
($z_L = 0.5$, $z_S = 2.0$)

$$r_E = \sqrt{\frac{4GM}{c^2}\frac{D_S D_{LS}}{D_L}} \approx 4 \times 10^{16} \sqrt{M/M_\odot}\ \mathrm{cm}$$

Einstein angle:
($z_L = 0.5$, $z_S = 2.0$)

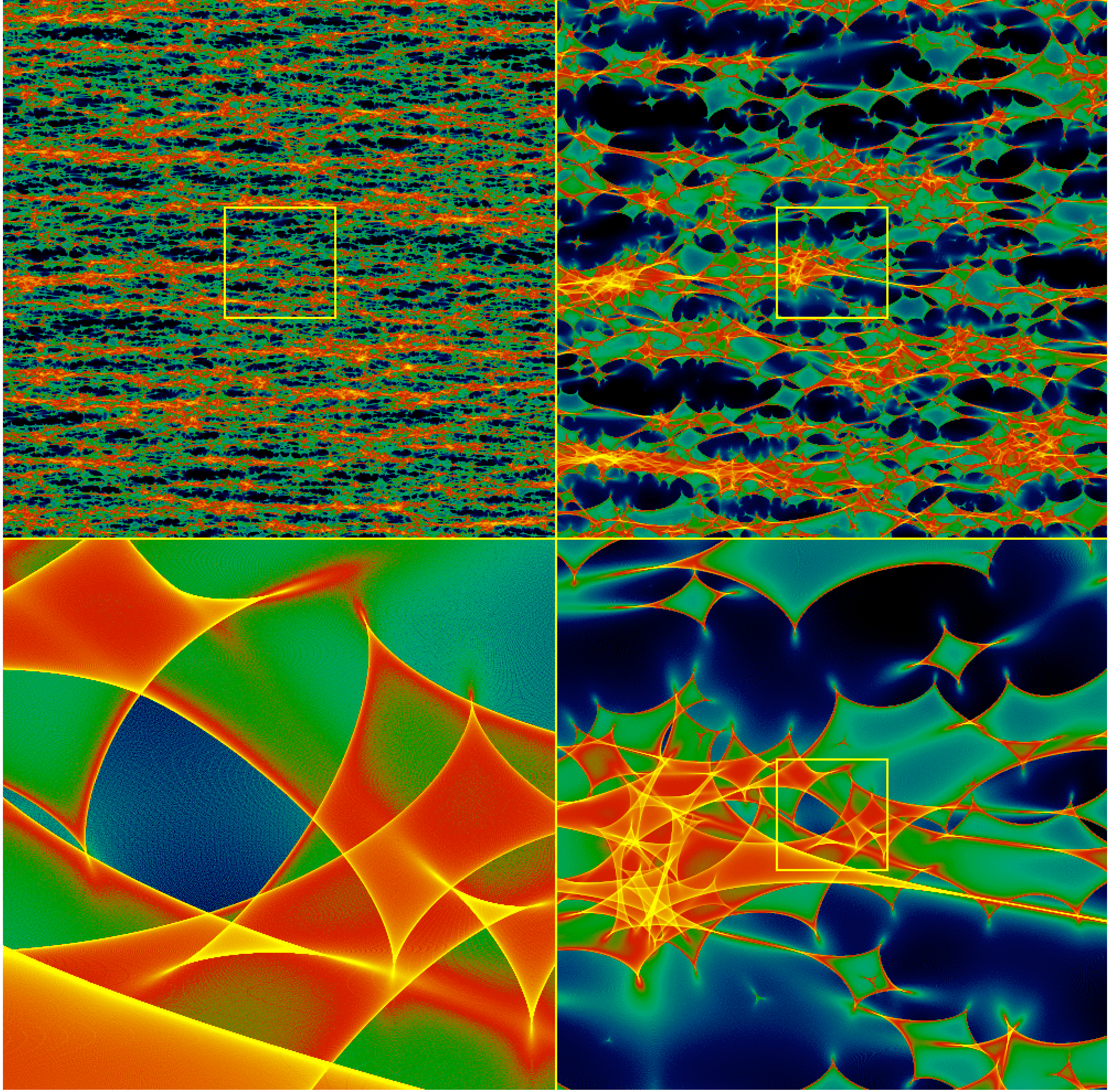
$$\theta_E = r_E/D_S \approx 10^{-6} \sqrt{M/M_\odot}\ \text{arcsec}$$

Einstein time:
($z_L = 0.5$, $z_S = 2.0$)

$$t_E = r_E/v_\perp \quad 15\sqrt{M/M_\odot}\, v_{600}^{-1}\ \text{years}$$

Crossing time:
($z_L = 0.5$, $z_S = 2.0$)

$$t_{cross} = R_{source}/v_\perp \approx 4 R_{15} v_{600}^{-1}\ \text{months}$$



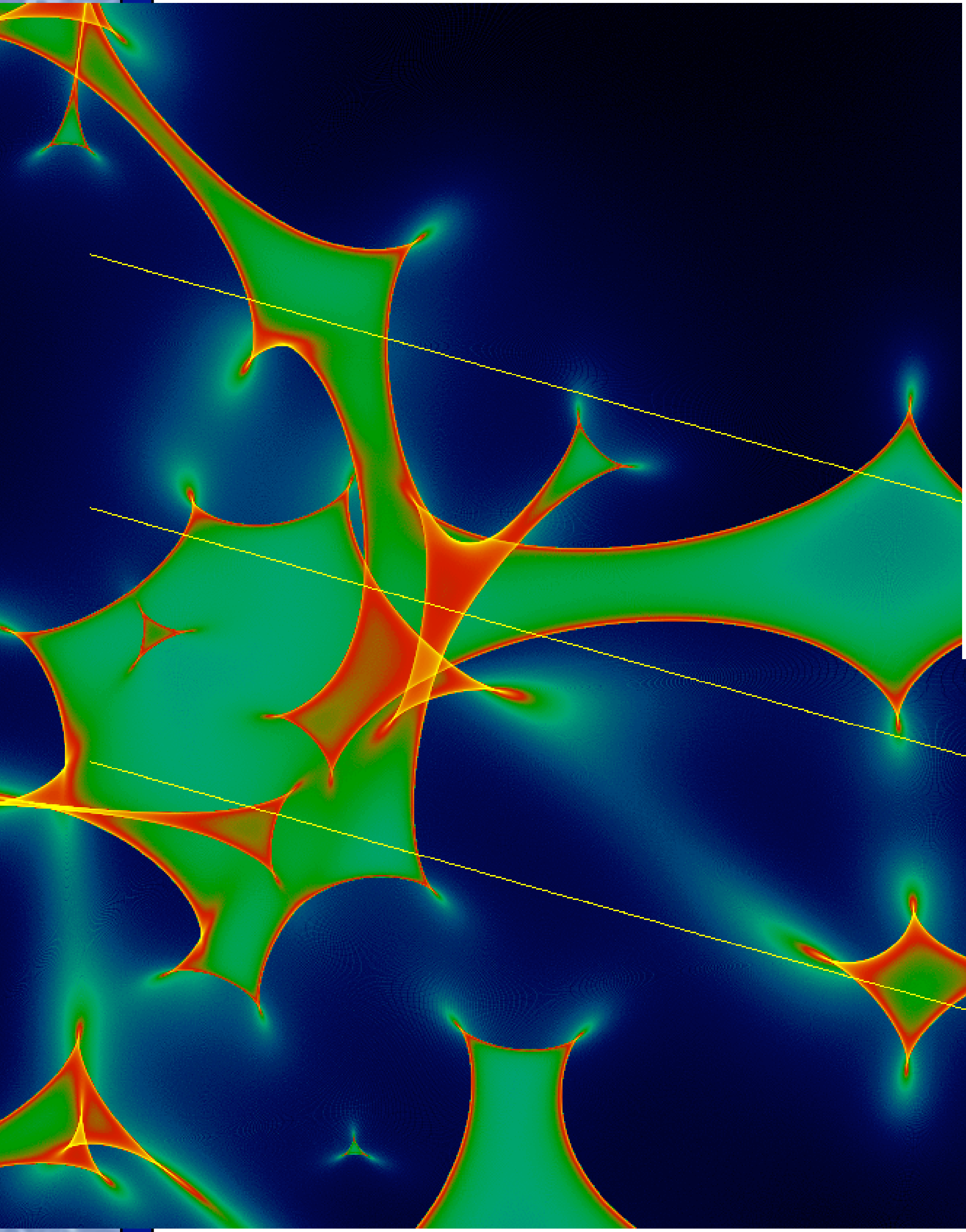
L =
100 R_E

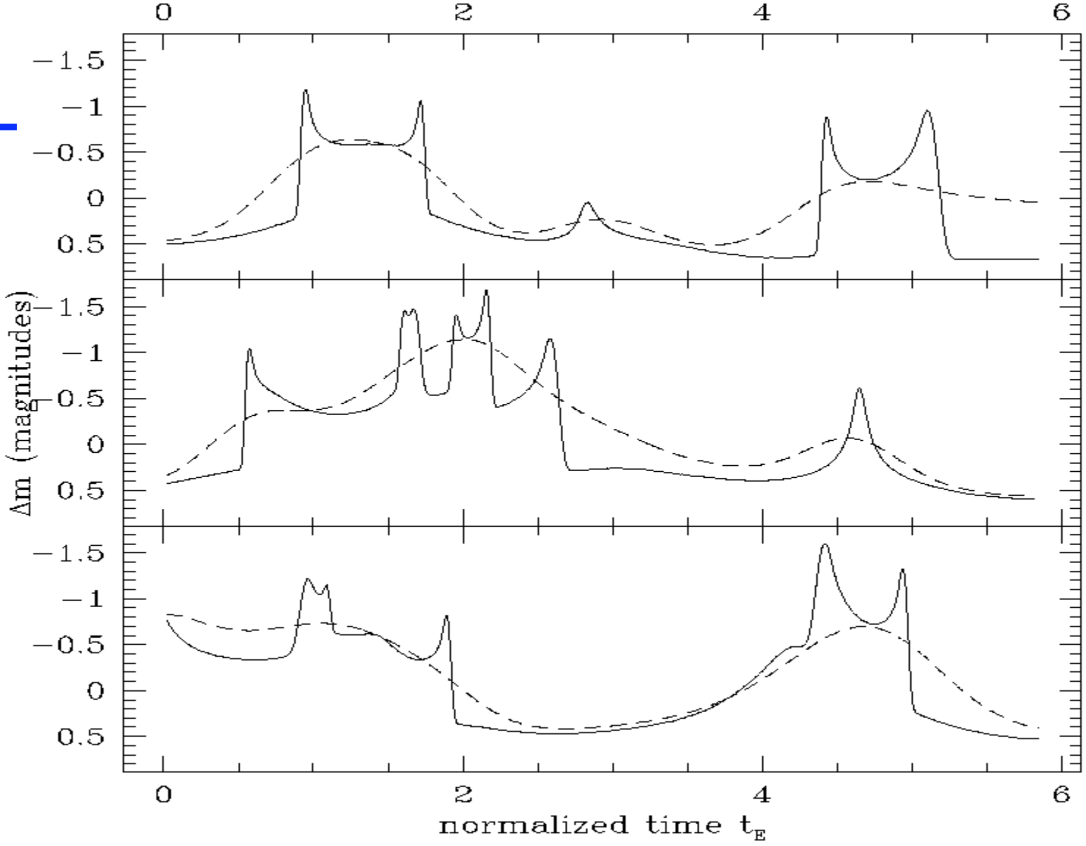
20 R_E

0.8 R_E

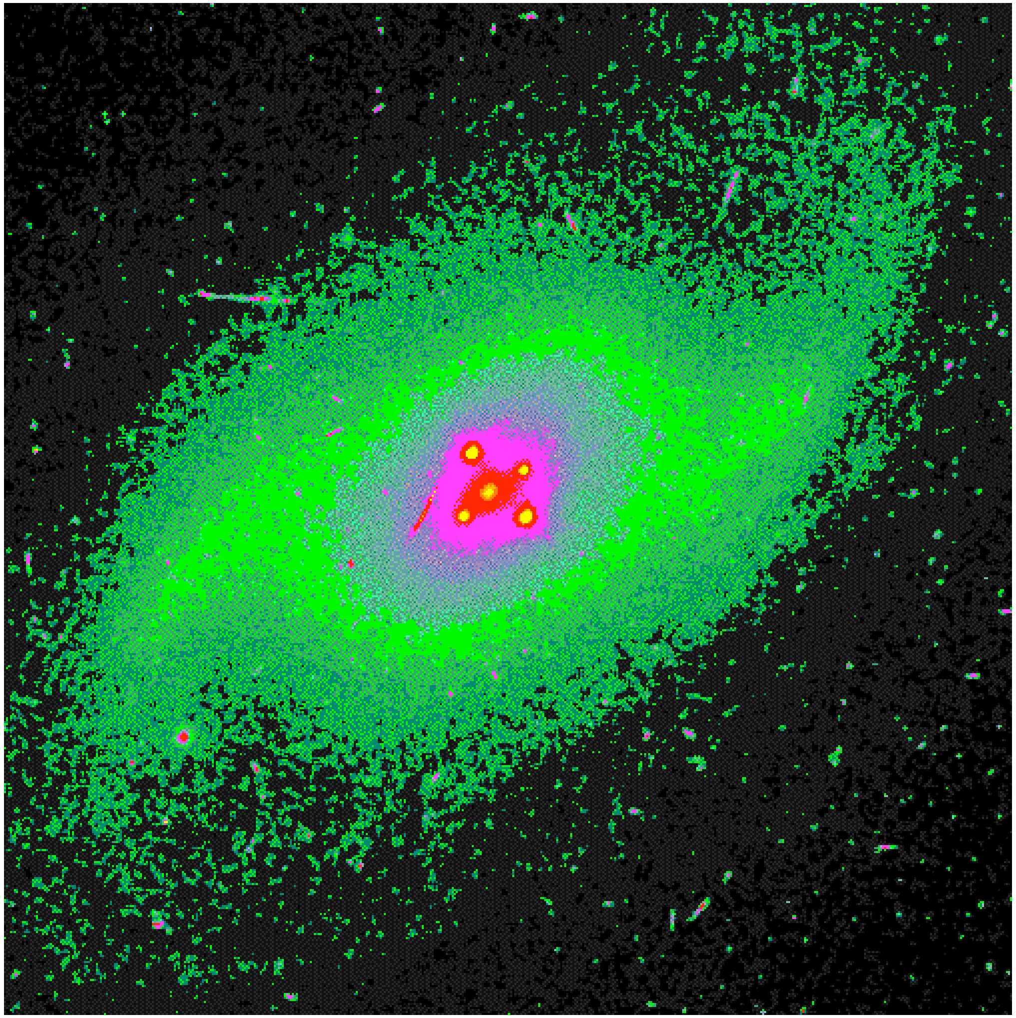
4 R_E

The two regimes of microlensing: quasar ML



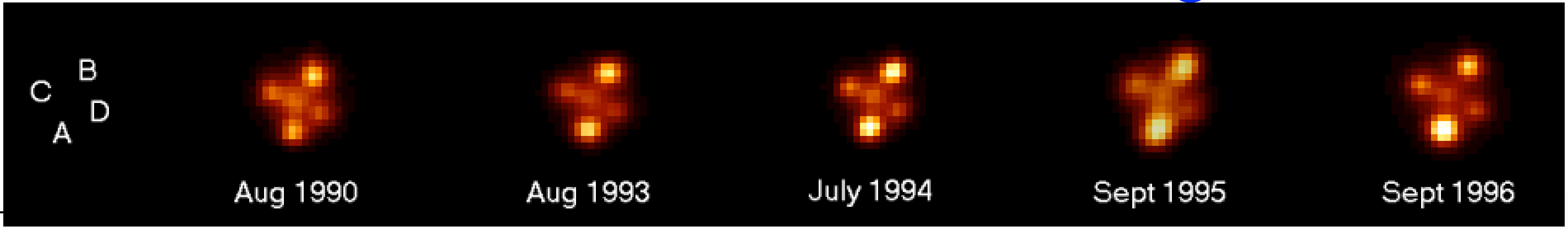


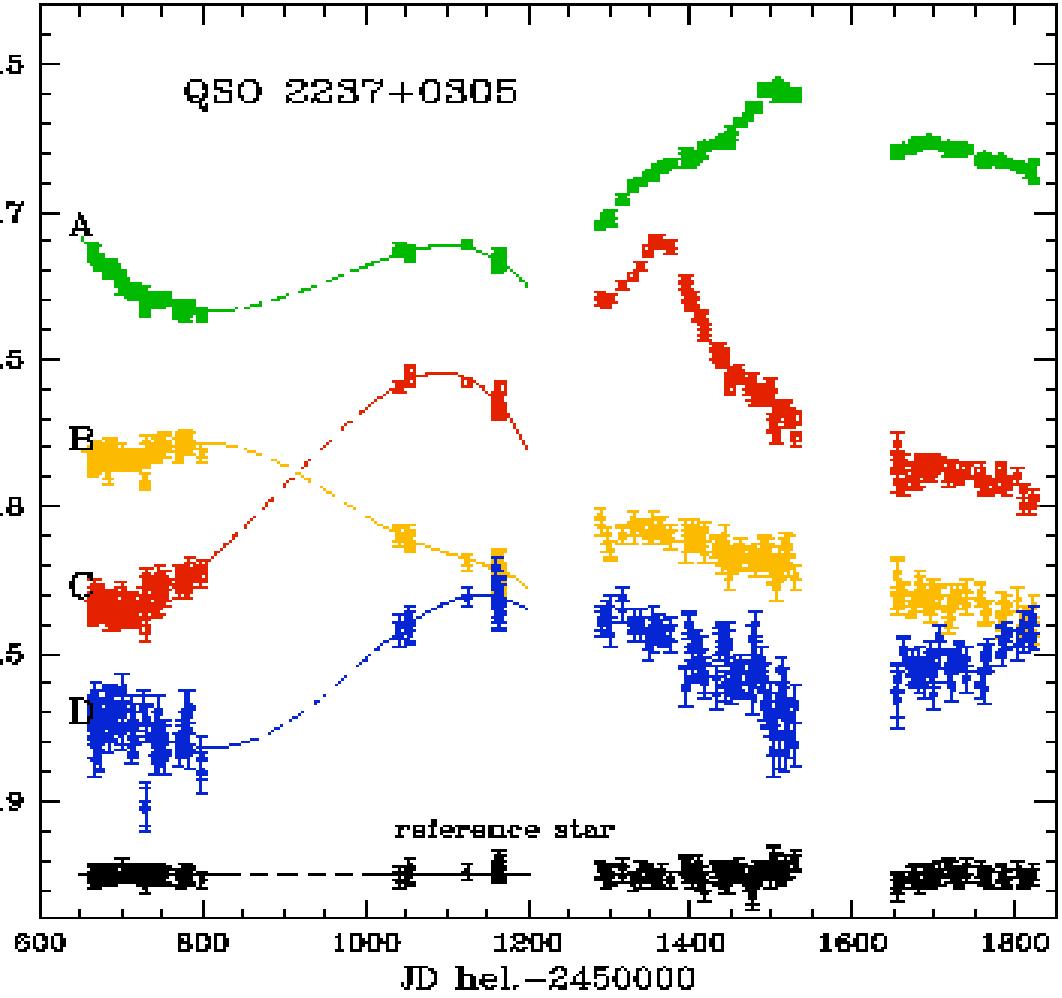
The quadruple quasar Q2237+0305

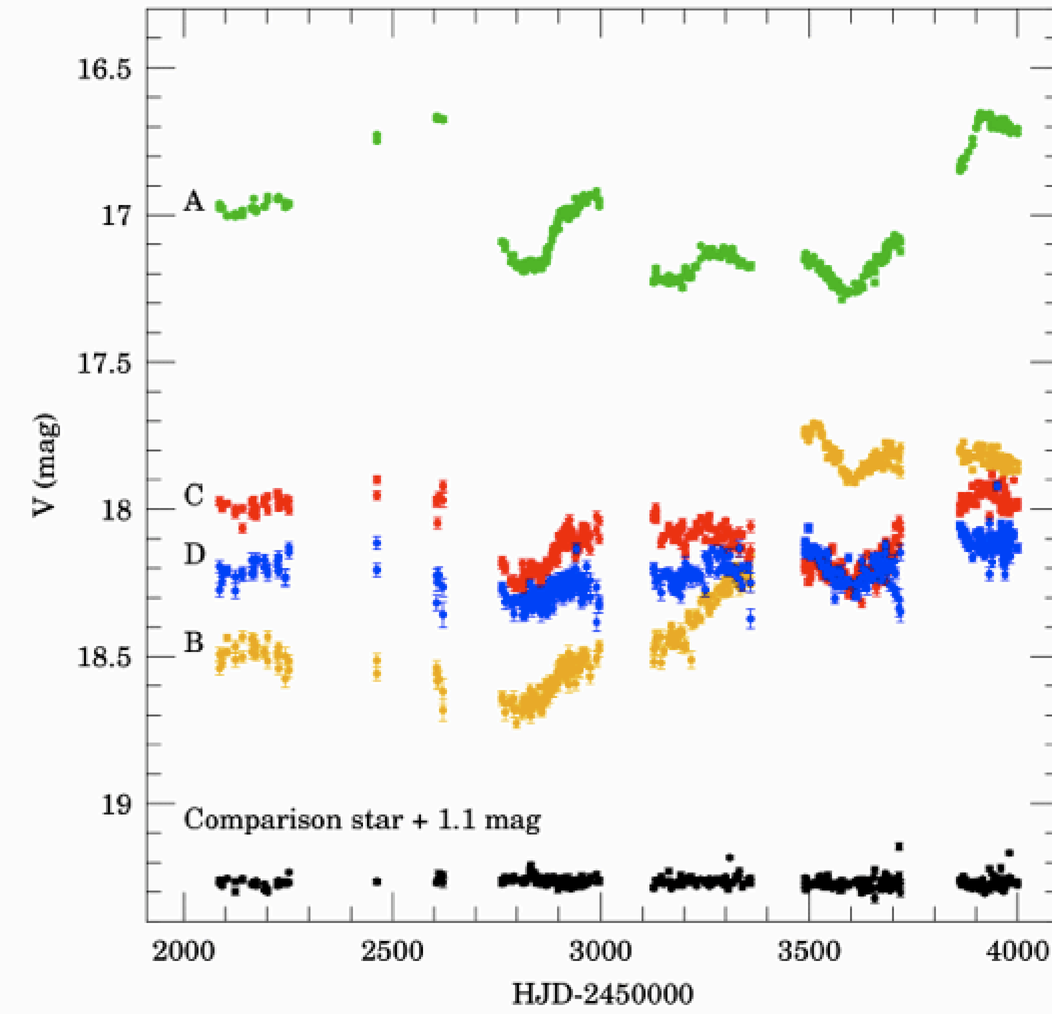


z(quasar) = 1.695, z(galaxy) = 0.039
image separation 1.7 arcsec (HST)

Quasar Microlensing







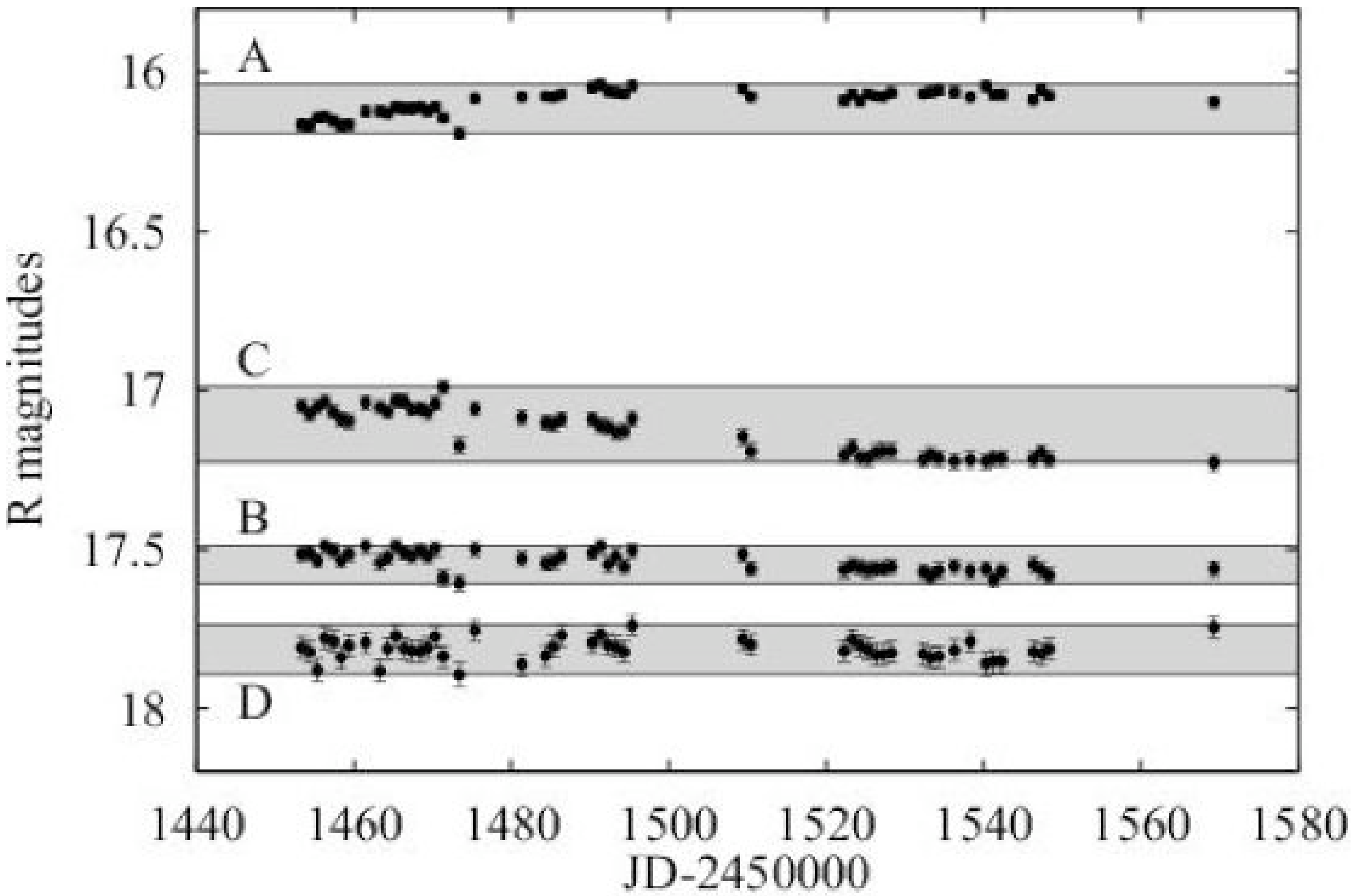
Wozniak et al. 2000 (OGLE)

OGLE Web page

Quasar Microlensing: Q2237+0305

Monitoring campaign: 6 months in 2000

GLITP - Gravitational Lens International Time Project



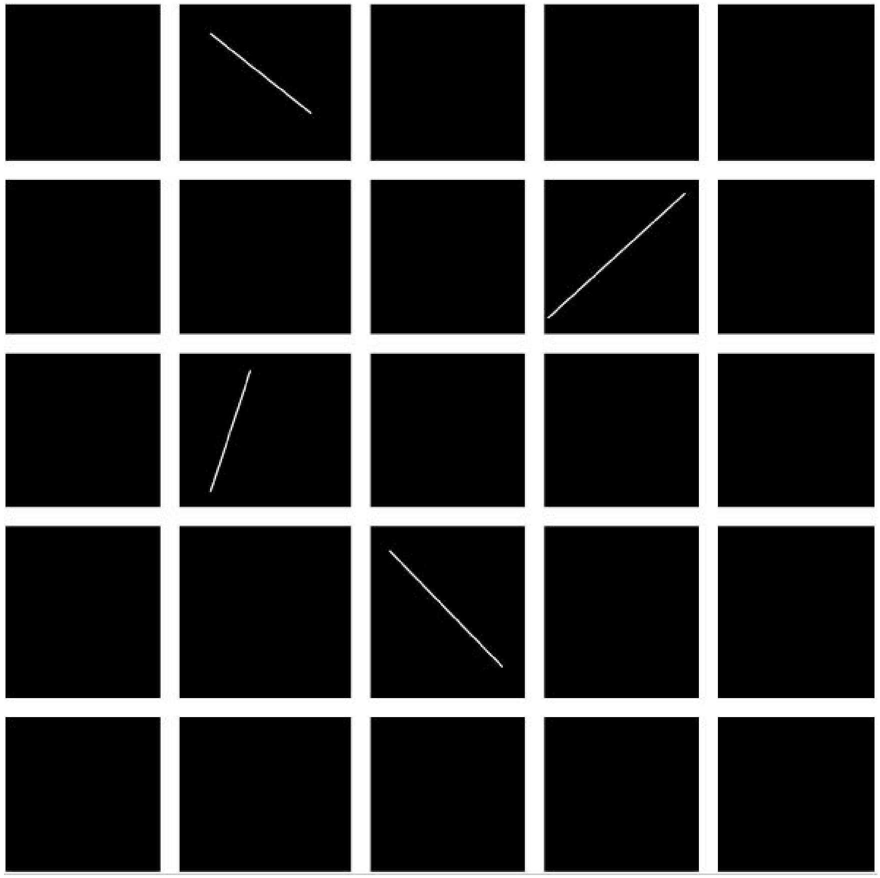
Quasar Microlensing: Q2237+0305

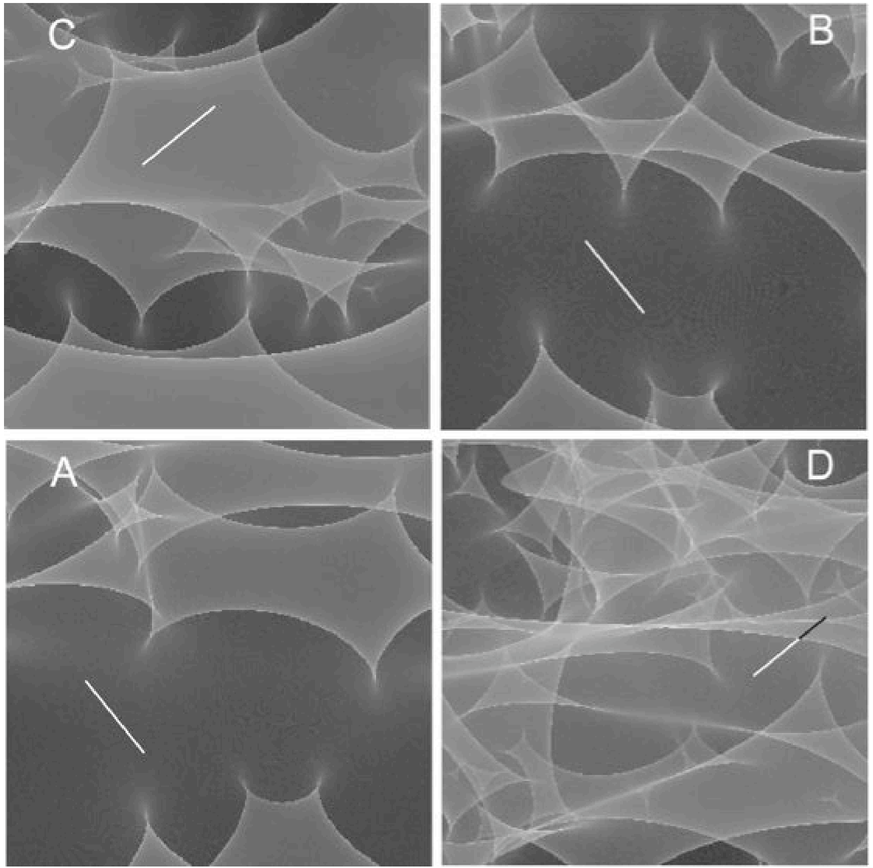
Limits on transverse velocity of lensing galaxy:

Idea: "typical" distance between caustics

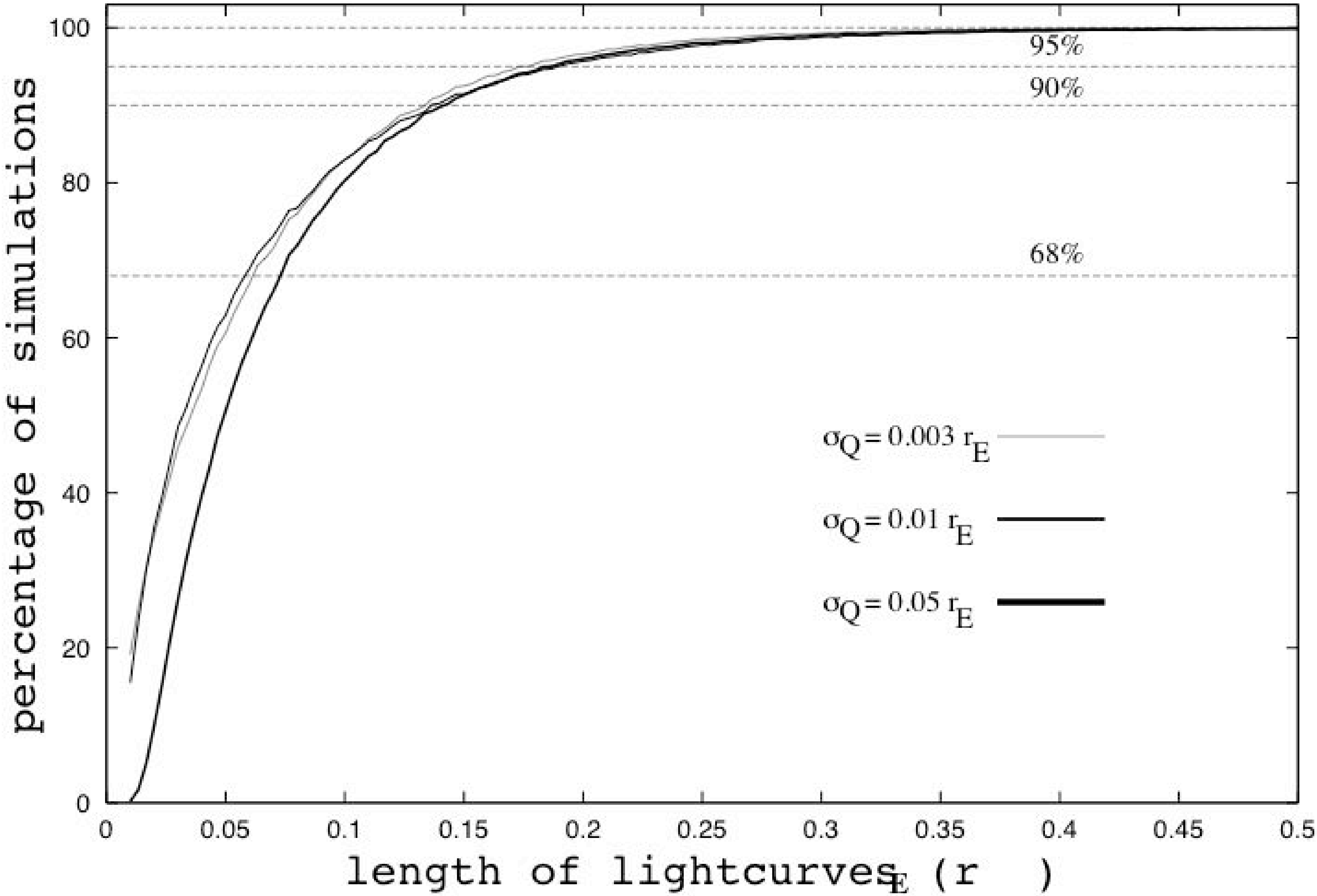
⇒ due to effective transverse motion:

⇒ typical time scale between maxima!

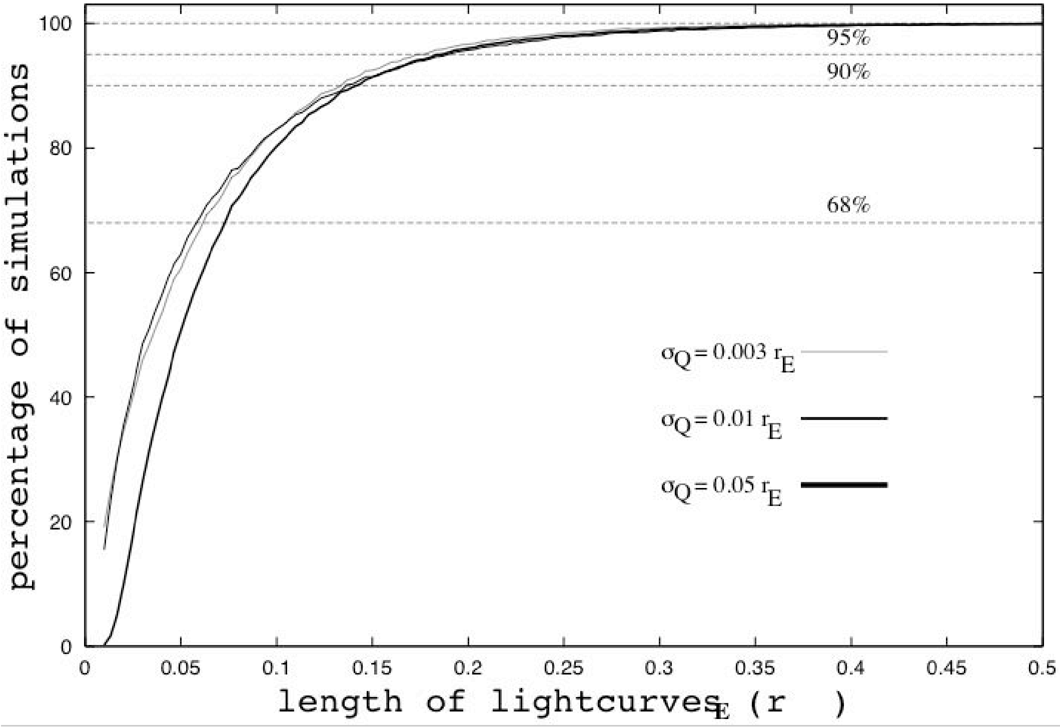




Quasar Microlensing: Q2237+0305



Quasar Microlensing: Q2237+0305



limits on V_{trans}:

$M = 1 M_\odot$:

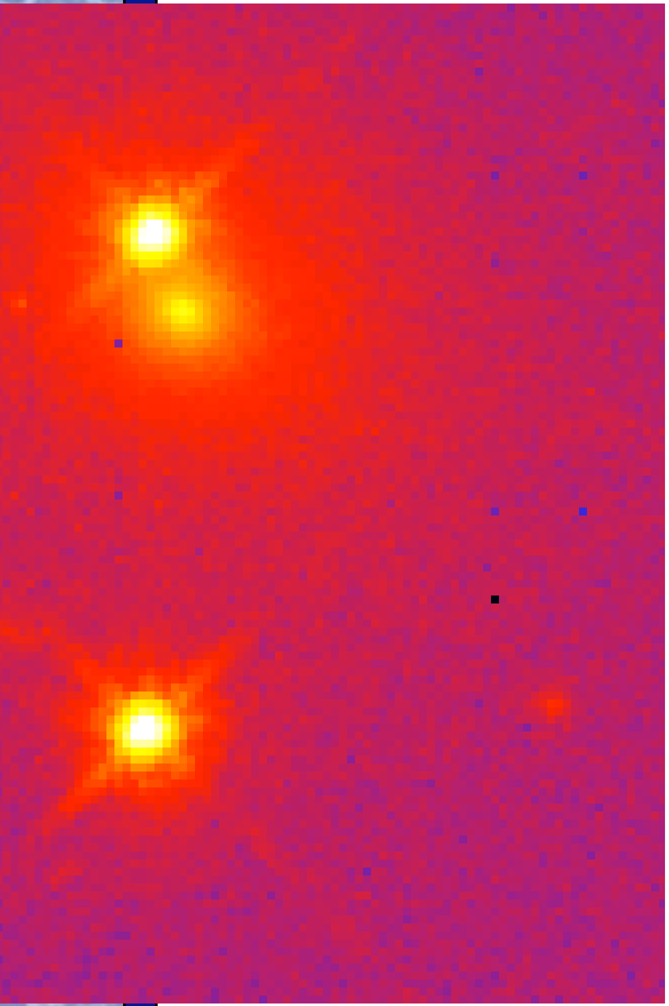
$V_{trans,\ 90\%} \leq$ 2160 km/sec
$V_{trans,\ 95\%} \leq$ 2820 km/sec

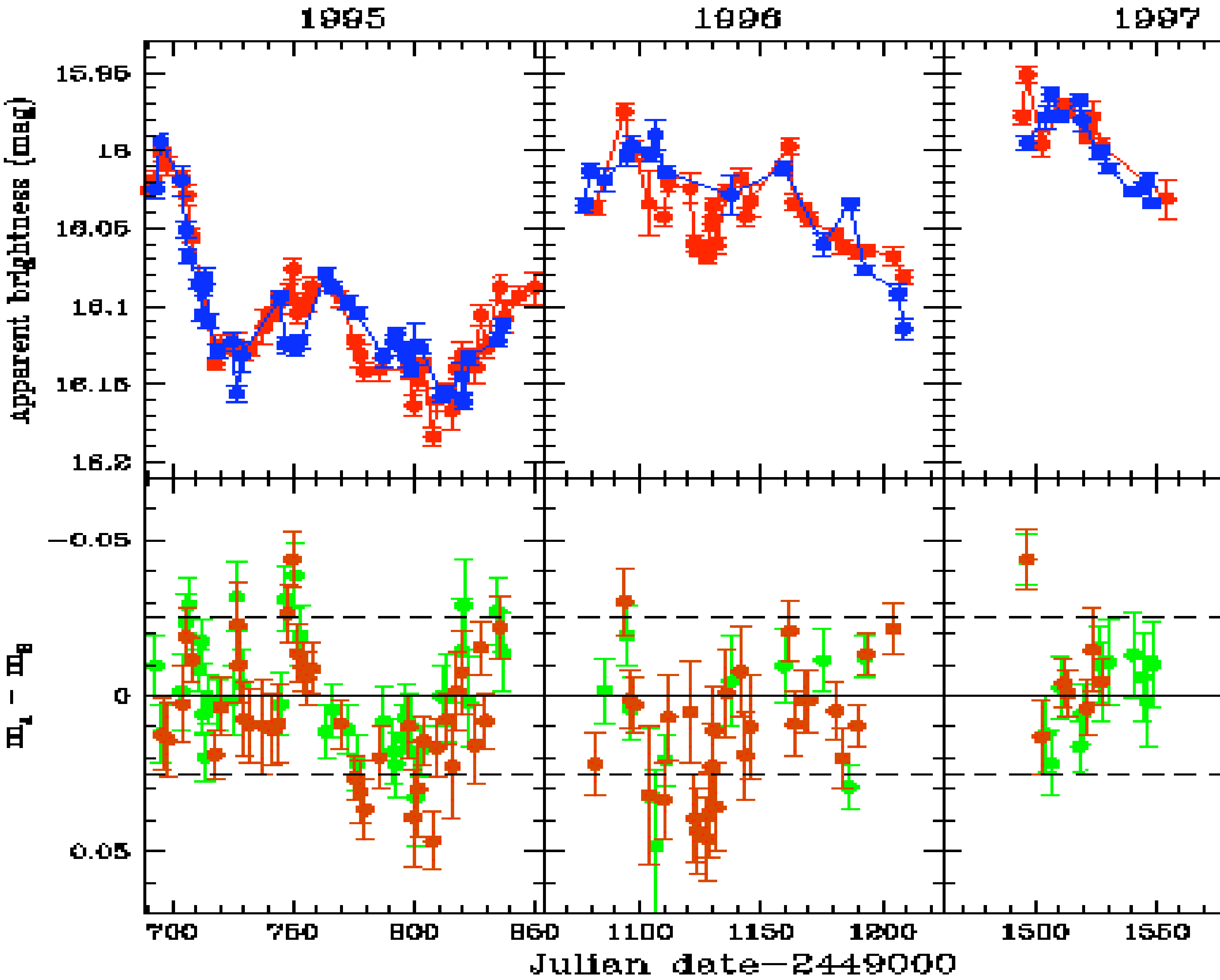
$M = 0.1 M_\odot$:

$V_{trans,\ 90\%} \leq$ 630 km/sec
$V_{trans,\ 95\%} \leq$ 872 km/sec

Gil-Merino,
Wambsganss
et al. (2005)

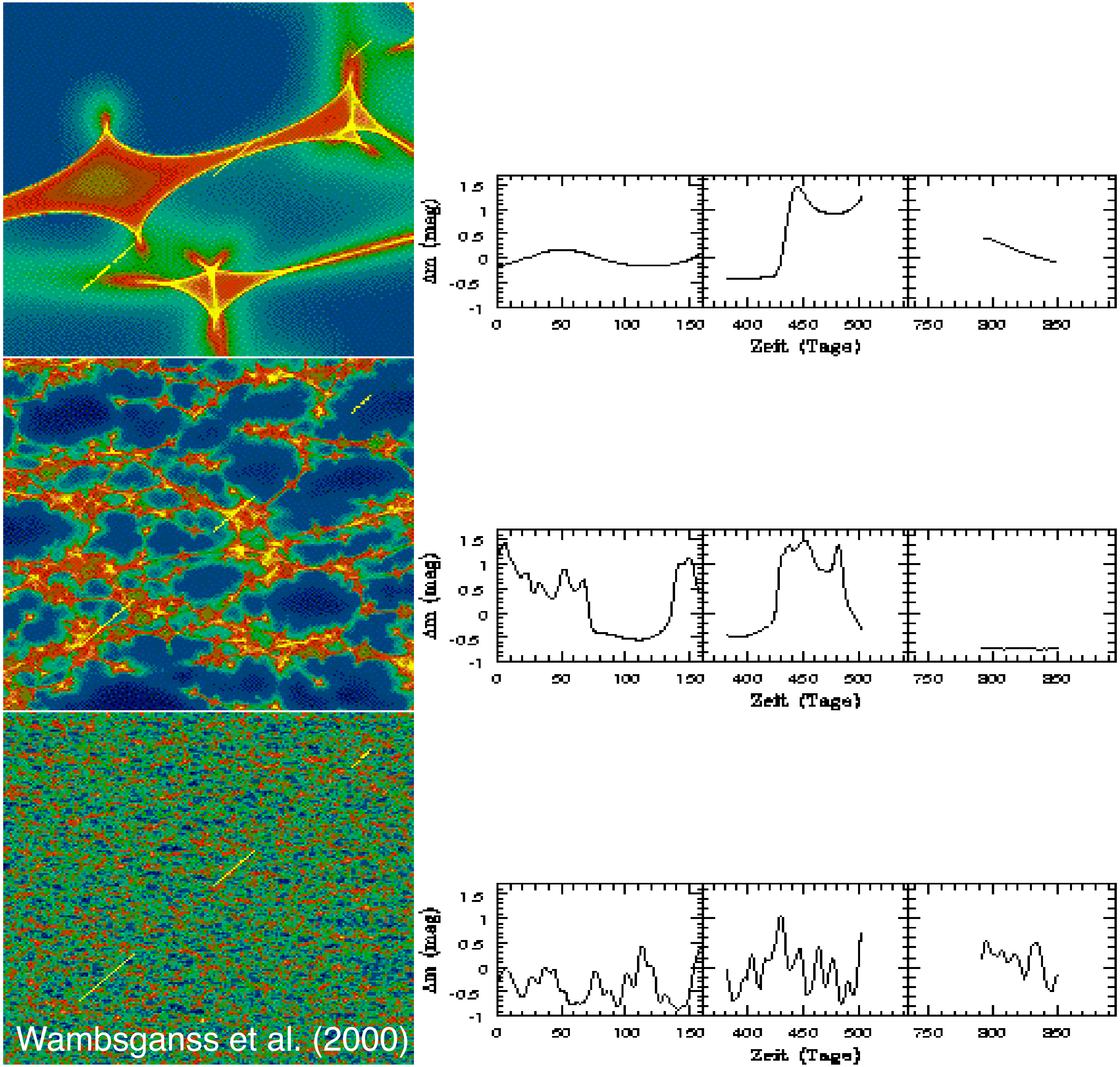
Quasar Microlensing? Q0957+561





Falco et al. (1998); Kundic et al. (1997)

Quasar Microlensing Simulation: Q0957+561



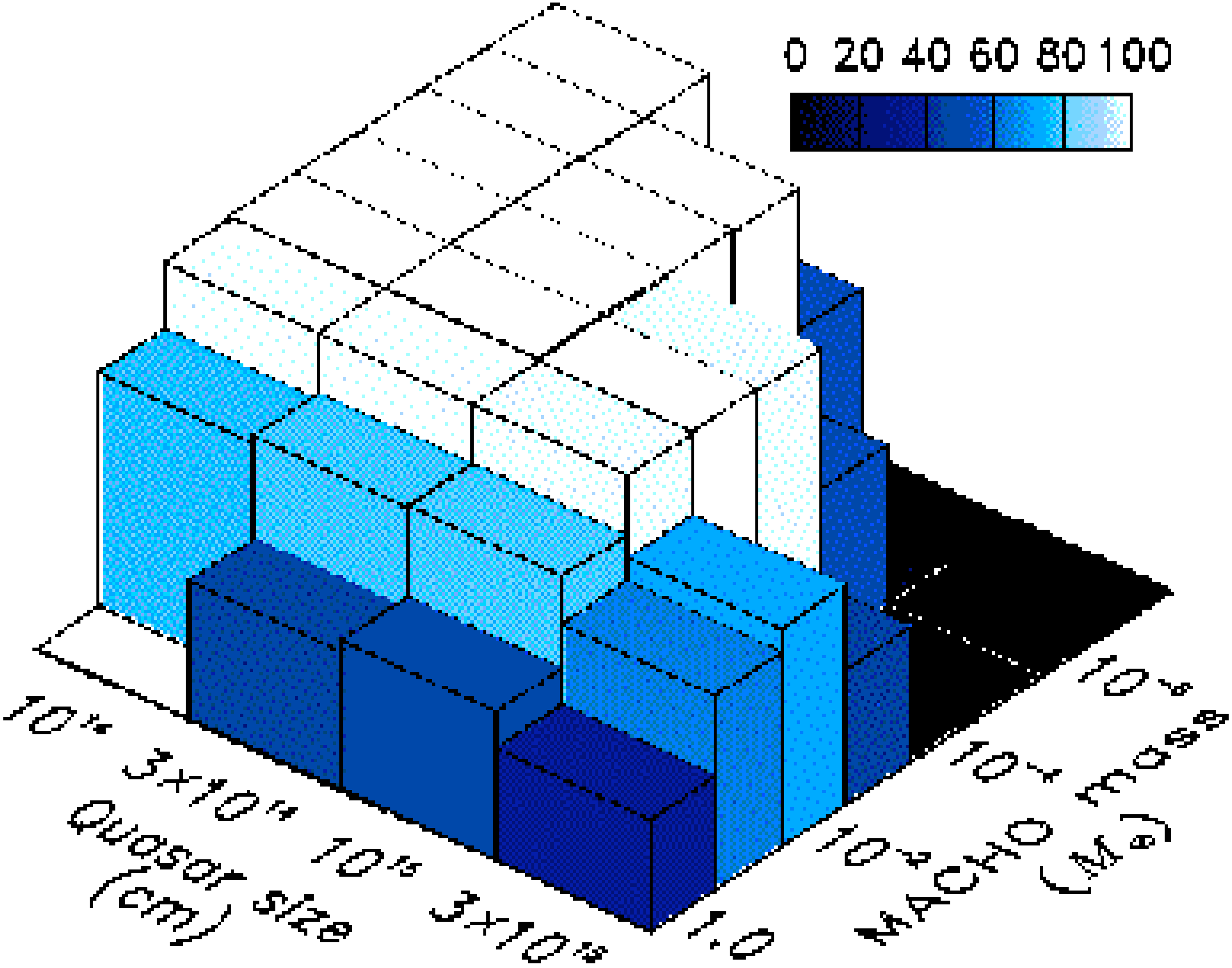
$10^{-1} M_\odot$

$10^{-3} M_\odot$

$10^{-5} M_\odot$

Wambsganss et al. (2000)

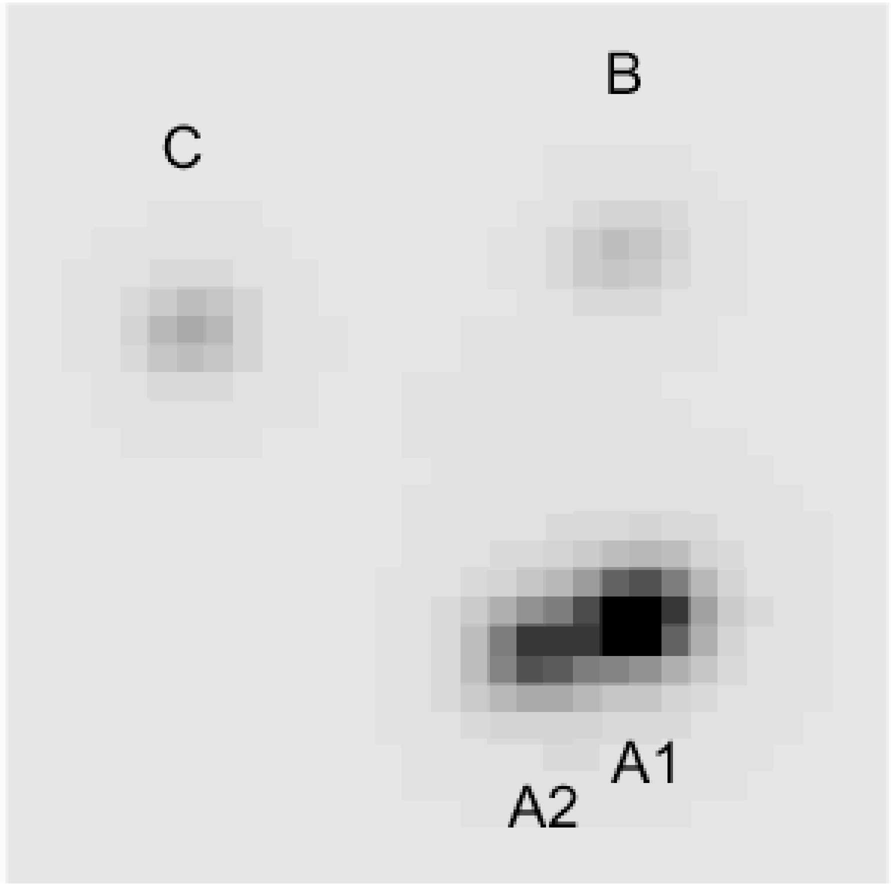
Quasar Microlensing Results: Q0957+561



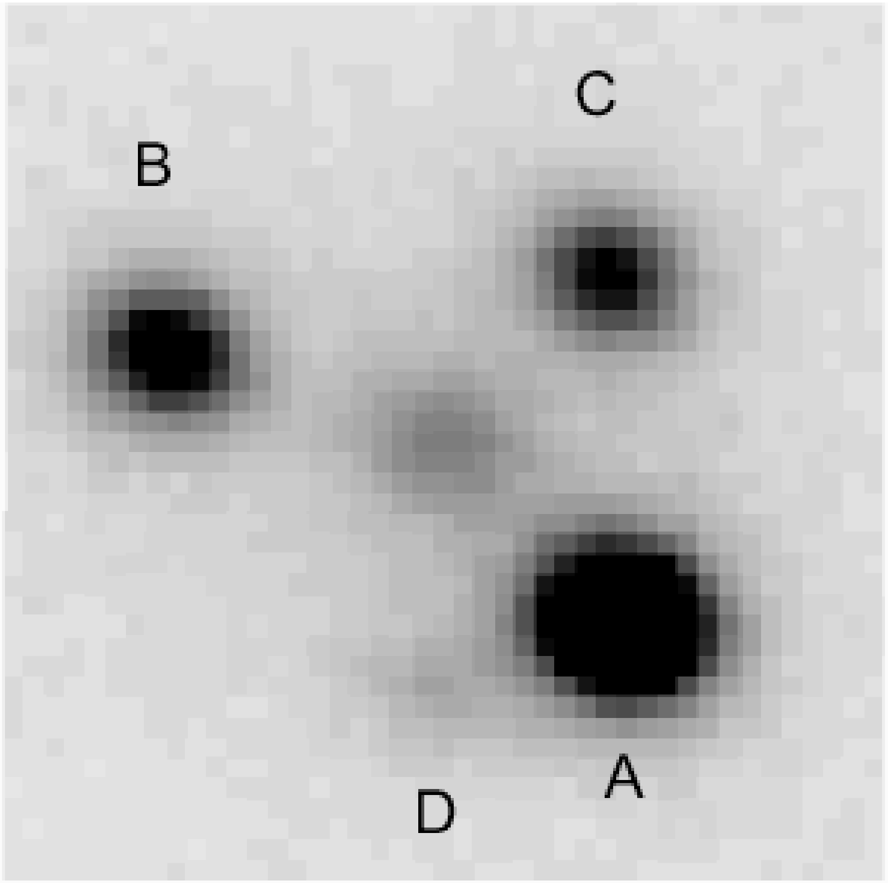
Halo of lensing galaxy cannot consist entirely of compact objects (MACHOs) in certain mass ranges
(Wambsganss et al. 2000)

More systems, longer baseline
⇒ better constraints!

Quasar Microlensing at high magnification: suppressed saddlepoints and the role of dark matter

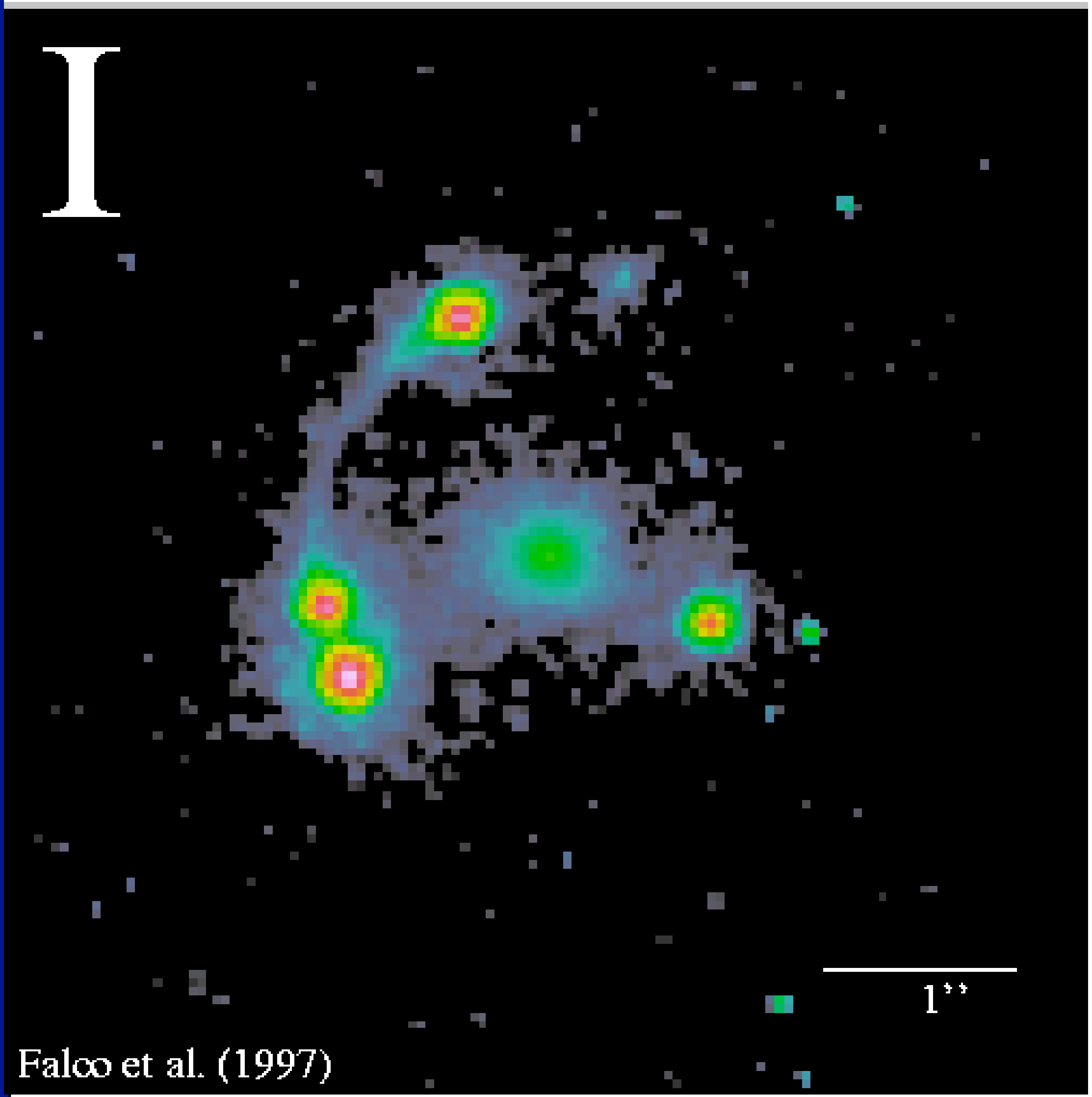


PG1115+080:
0.48", Δm = 0.5 mag
(Weymann et al. 1980)



SDSS0924+0219:
0.66", Δm = 2.5 mag
(Inada et al. 2003)

Quasar Microlensing at high magnification: suppressed saddlepoints and the role of dark matter



Falco et al. (1997)

CASTLES

MG0414+0534:

close pairs of bright images:

they should be "about" equal in brightness

they are not!

saddle point image demagnified!

at least 4 similar systems

what's going on?!?

ML, substructure, DM ?

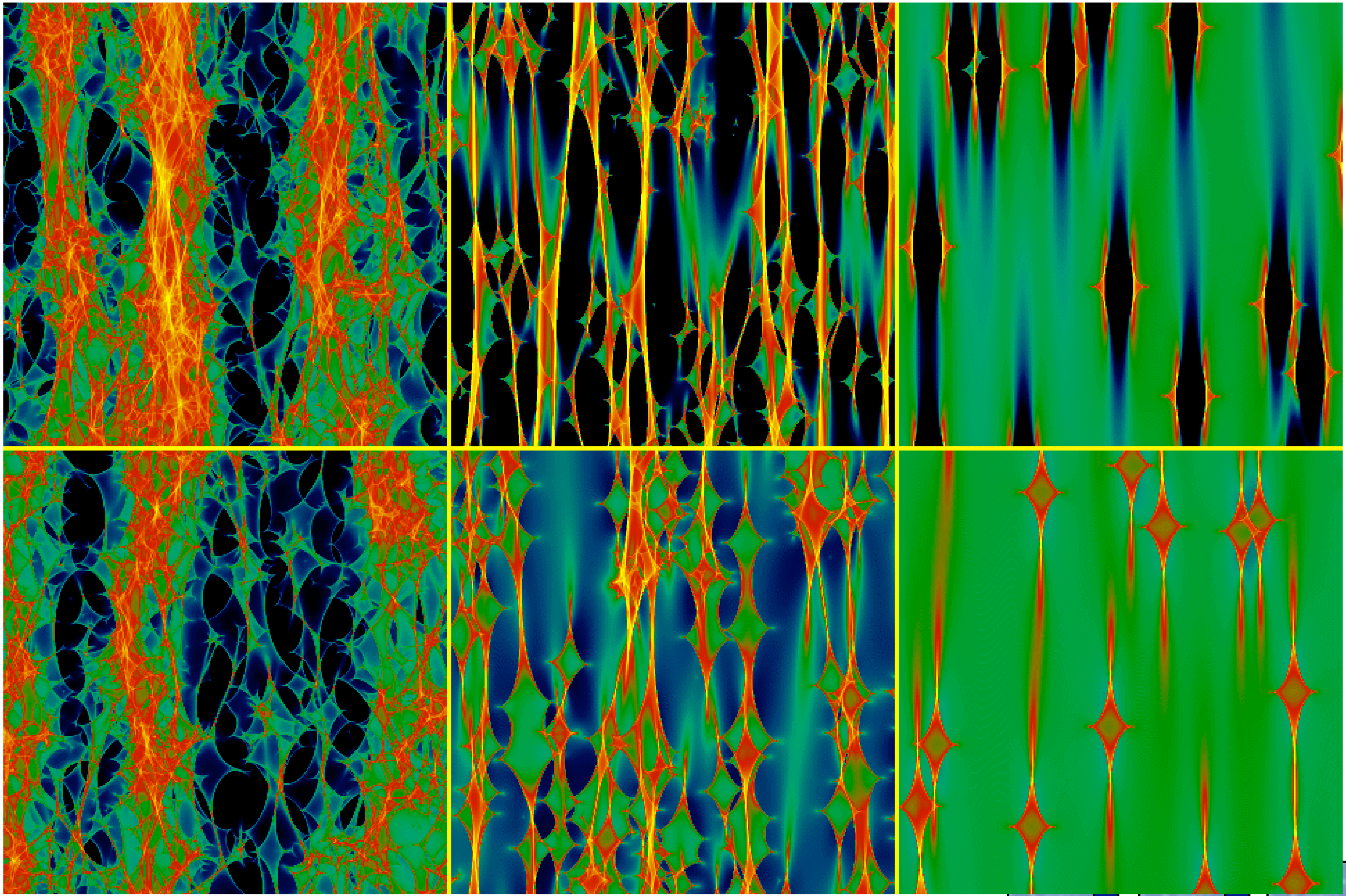
Quasar Microlensing at high magnification: suppressed saddlepoints and the role of dark matter (Schechter & Wambsganss 2002)

κ_{tot} = constant in horizontal rows

κ_{smooth} = 0% = 85% = 98%

saddle point image:

minimum image:



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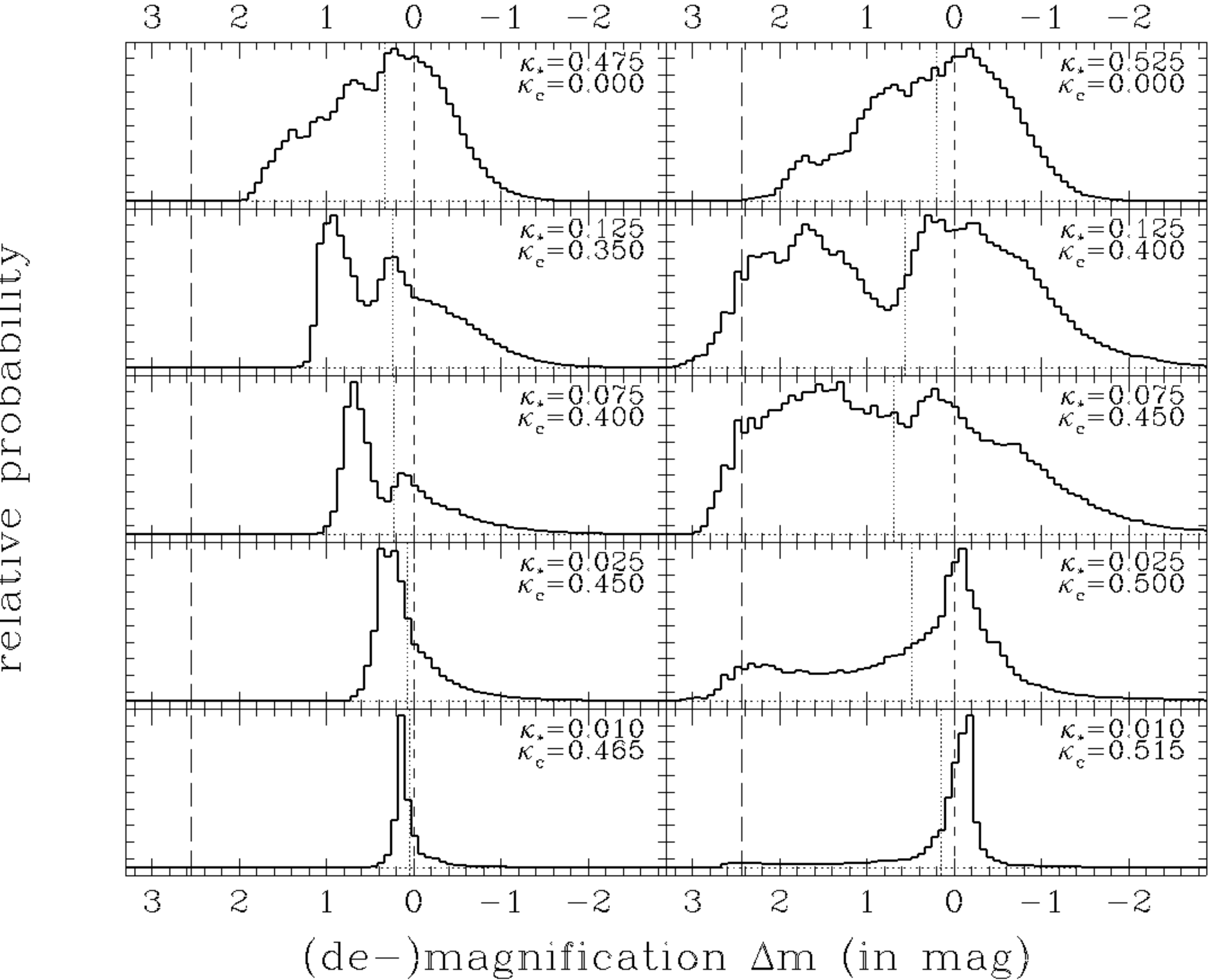
Quasar Microlensing at high magnification: suppressed saddlepoints and the role of dark matter (Schechter & Wambsganss 2002)

κ_{tot} = const in columns

minimum:

saddle:

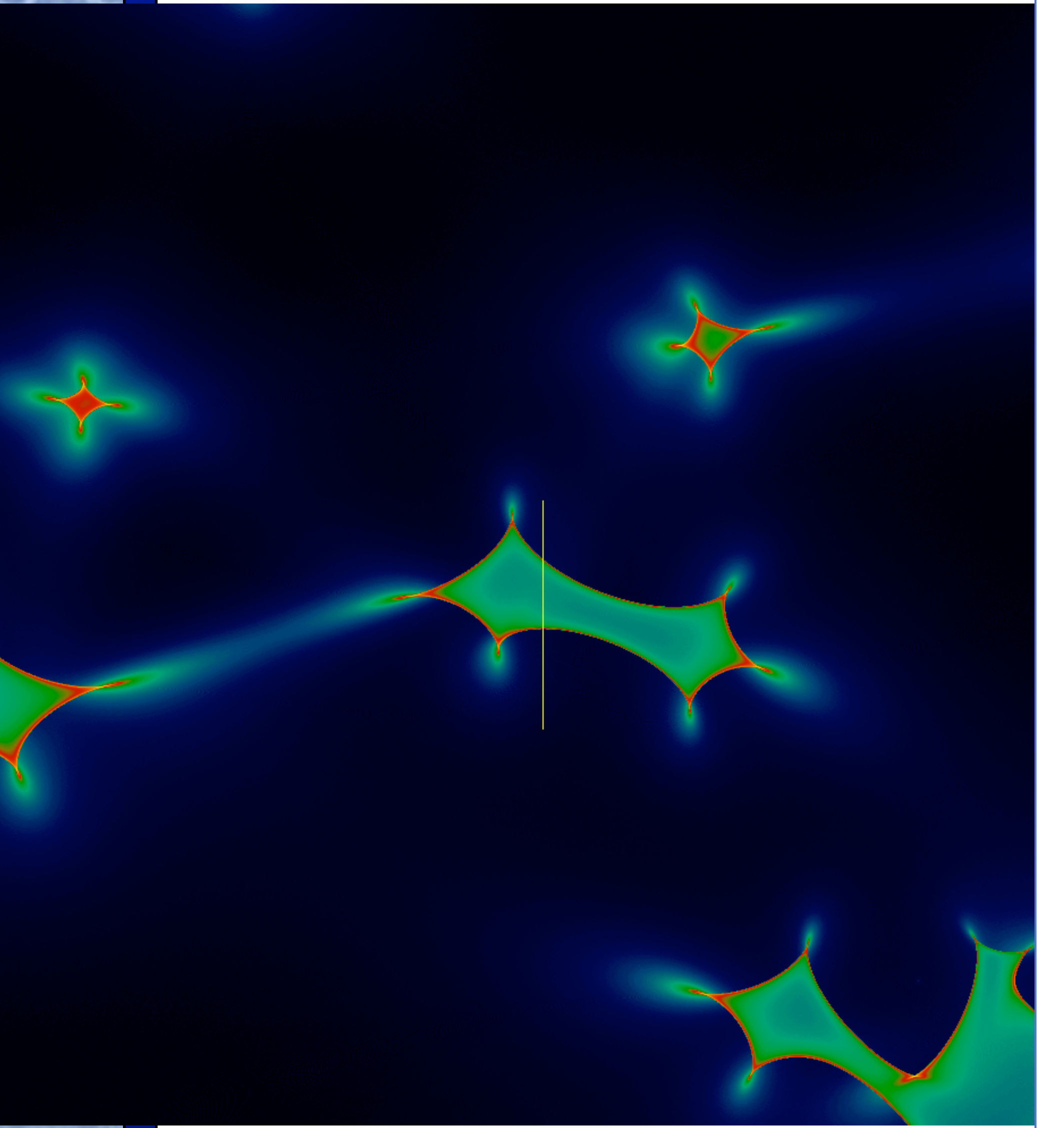


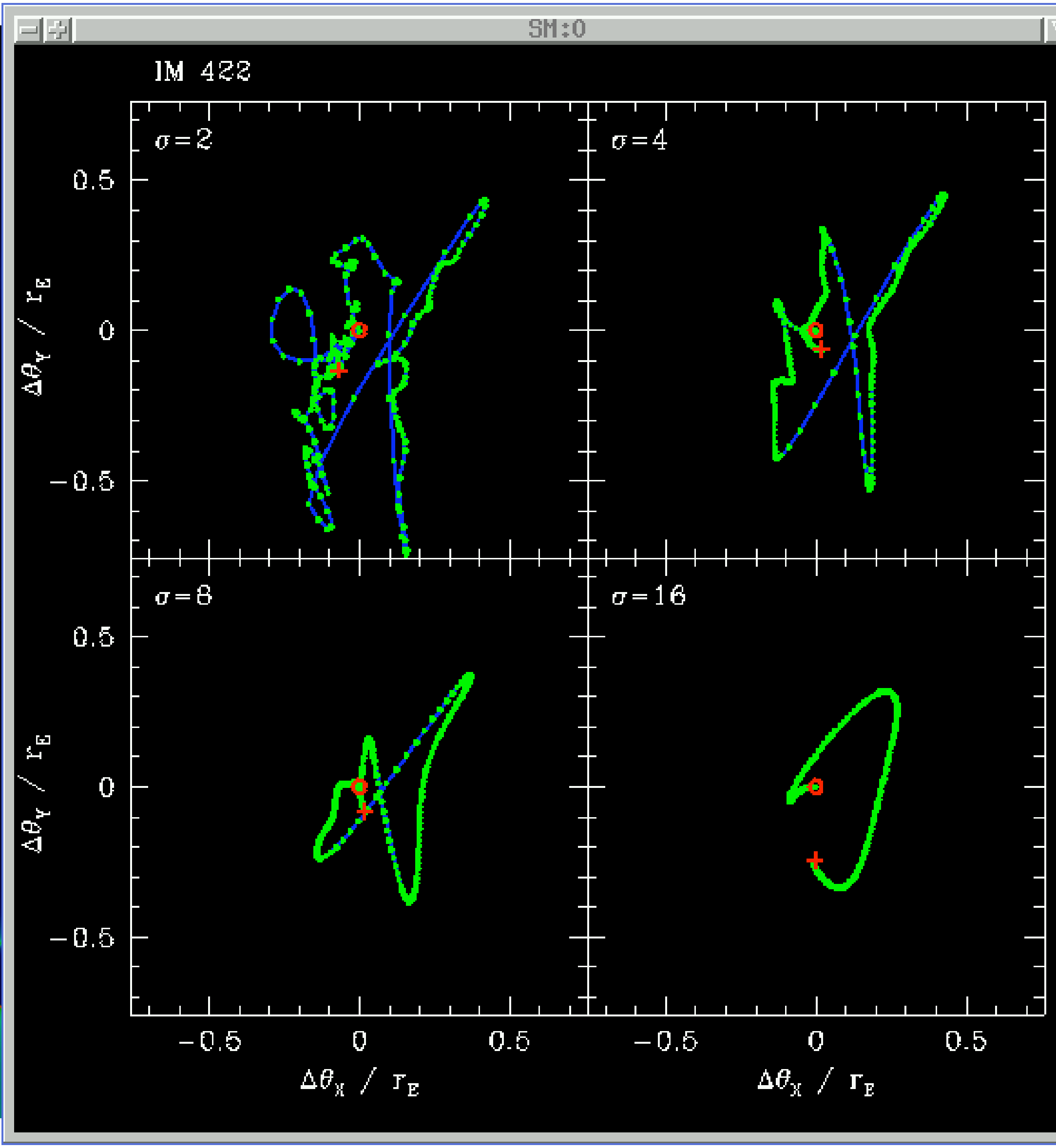
κ_{smooth} = 0%

= 85%

= 98%

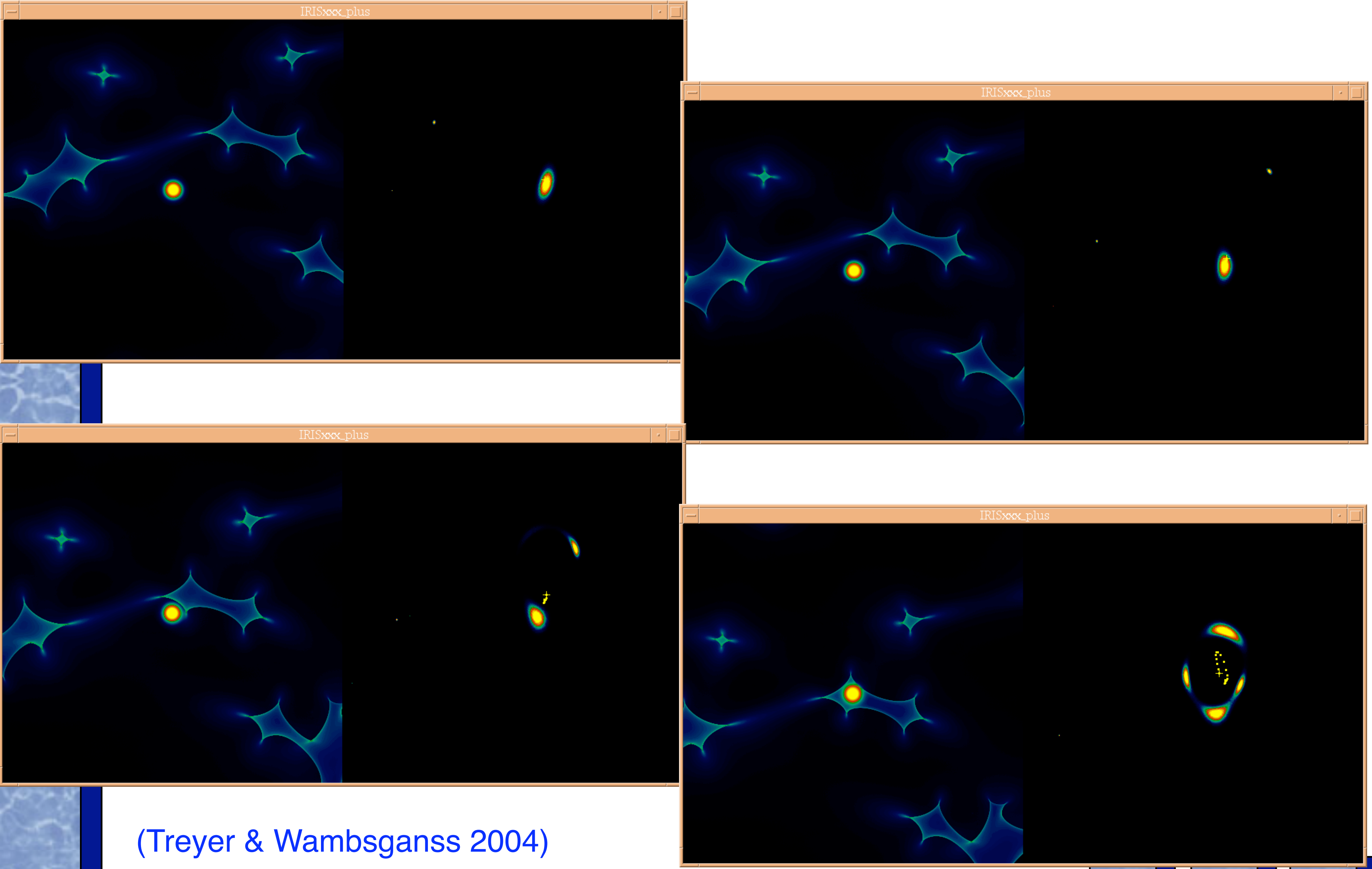
Astrometric microlensing of quasars





(Treyer & Wambsganss 2004)

Astrometric microlensing of quasars:

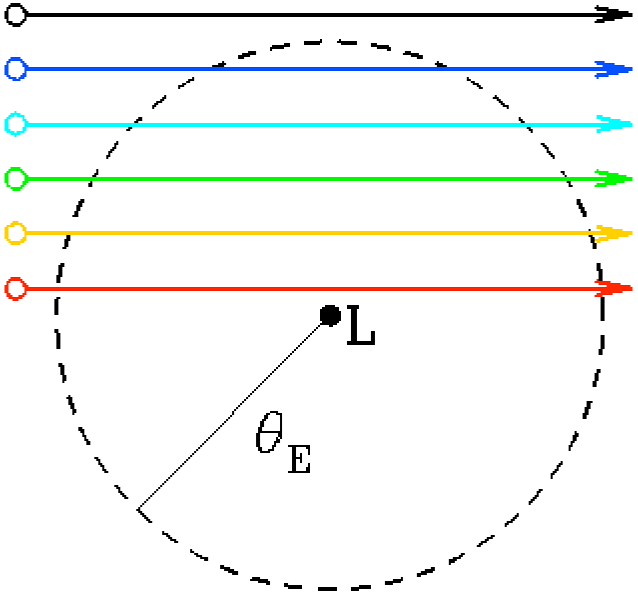


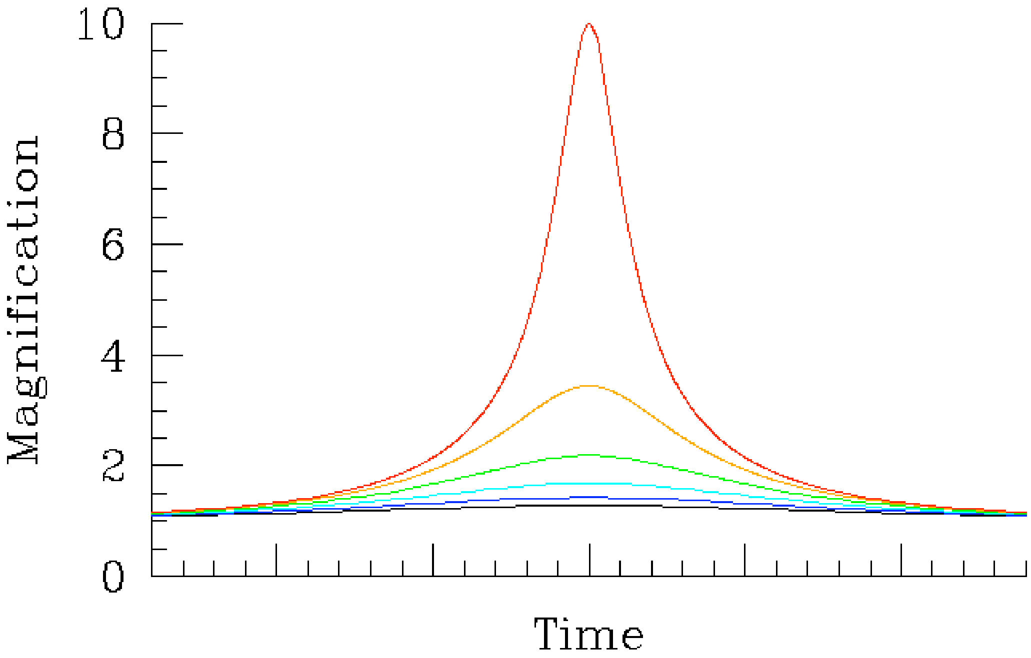
(Treyer & Wambsganss 2004)

Stellar Microlensing

- Microlensing by stars in the Milky Way (Halo):
  proposed by Paczynski (1986) as a test for compact dark matter
- Idea:
  - monitor (background) stars in LMC or Milky Way Bulge
  - occasionally a random (foreground) star passes in front and magnifies background star in characteristic way
  - problem: **very** small probability for stellar ML events (of order $\mathbf{10^{-6}}$)

“Near”: Stellar Microlensing





(from Sackett 1999)

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

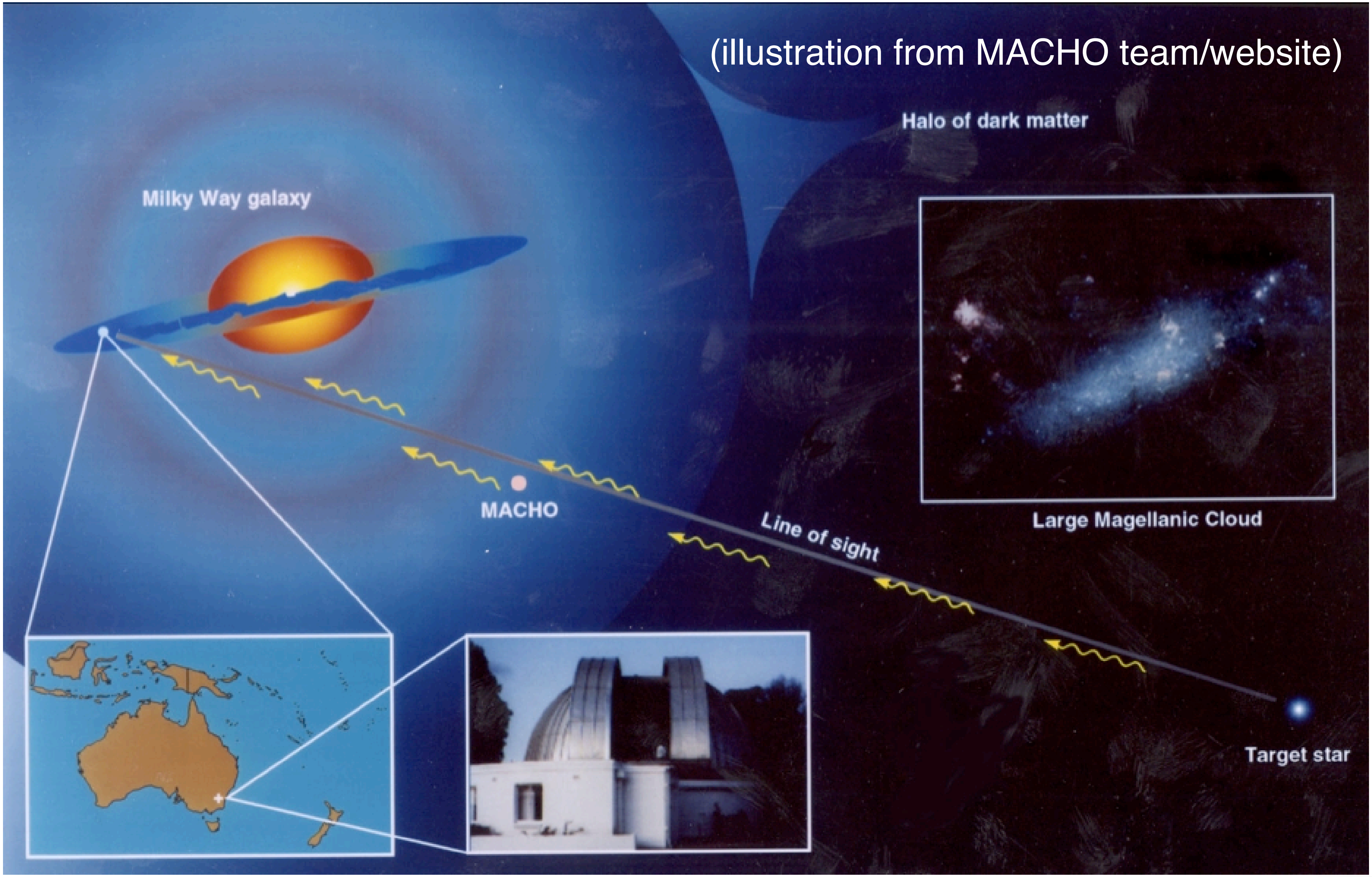
$$\mu_{1,2} = \left(1 - \left[\frac{\theta_E}{\theta_{1,2}}\right]^4\right)^{-1} = \frac{u^2+2}{2u\sqrt{u^2+4}} \pm \frac{1}{2}$$

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

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

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

“Near”: stellar microlensing towards the LMC/SMC


(illustration from MACHO team/website)

Macho Experiments: Dark Matter Detection?

MACHO team results (Alcock et al. 2001):

- 13 - 17 events in 5.7 years
- consistent with ≤ 20% macho contribution to dark matter halo
  (still being debated what "≤" means: Sahu (2003), Belokurov & Evans (2005), Griest et al. (2005) ...)

EROS results (Milsztajn et al. 2000, Afonso et al. 2003):

- macho contribution ≤ 3% (95% confidence level)

Little (or no?) evidence for dark matter!

Microlensing towards the Bulge: OGLE and MOA

Microlensing events galore: more than 3000 events
(> 600 this season by OGLE and MOA!):

most single lens, many double lens/caustic crossing

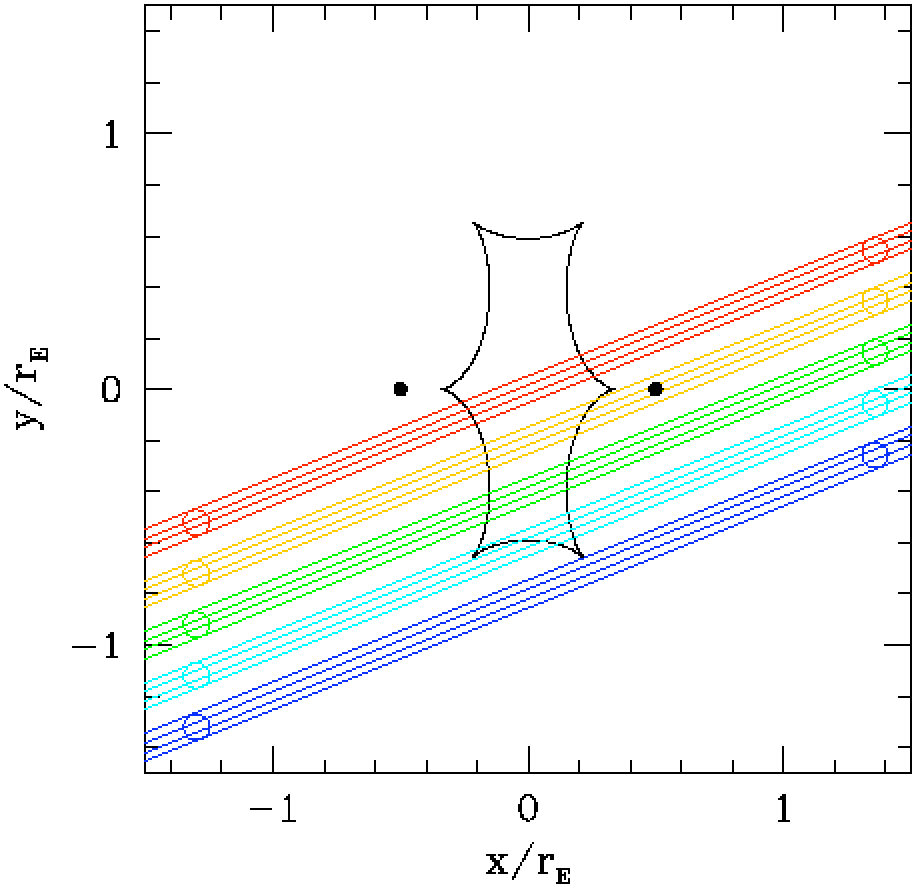
normal stars (binaries) acting as lenses!

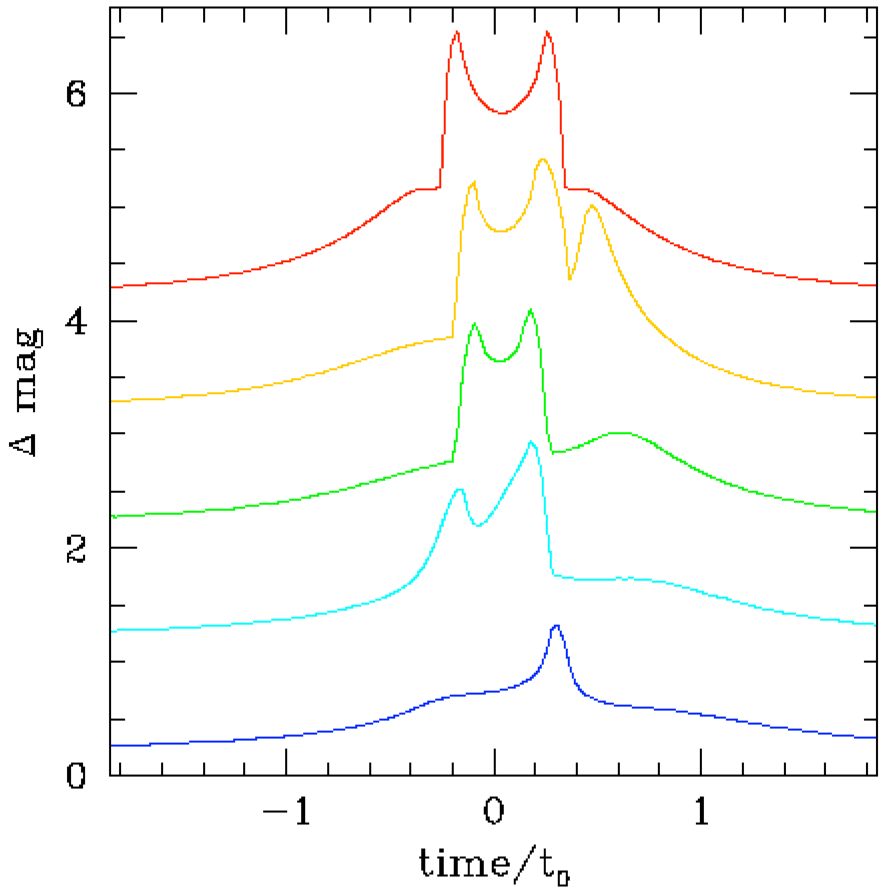
lots of interesting stellar/Galactic astrophysics:
here: results on planet searching

Stellar Microlensing

- Microlensing by stars in the Milky Way (Halo):
  proposed by Paczynski (1986) as a test for compact dark matter
- Idea:
  - monitor (background) stars in LMC or Milky Way Bulge
  - occasionally a random (foreground) star passes in front and magnifies background star in characteristic way
  - problem: **very** small probability for stellar ML events (of order **10^{-6}**)
-
- Mao & Paczynski (1992) propose:
  - about 10% of cases will be binary lenses
  - star-planet systems can/will act as lenses as well: probability smaller by at least factor 100 ... !

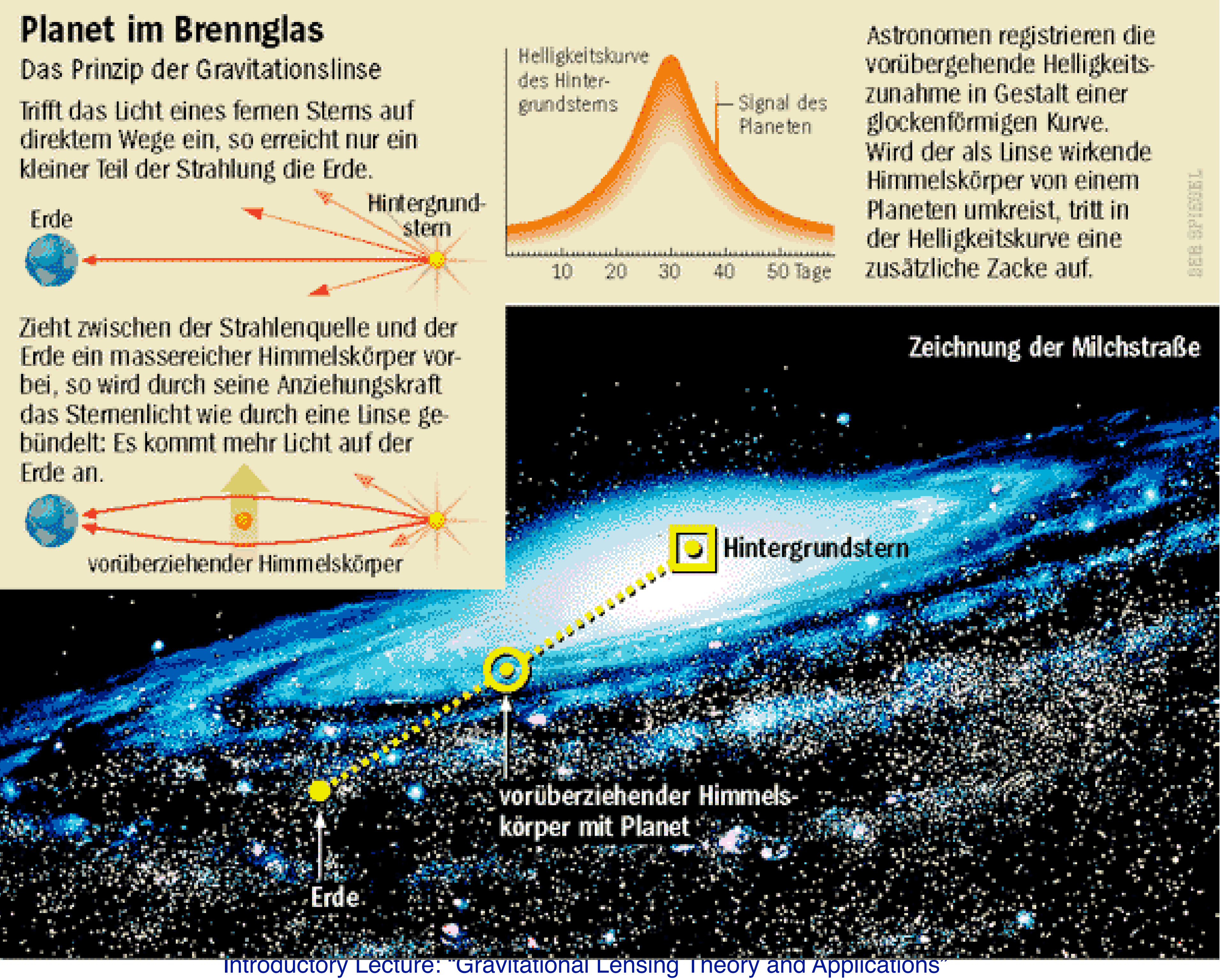
the method, the history





double lens: lightcurves can get very diverse; 3 additional parameters:

- mass ratio: $q = 1 \ldots 10^{-6}$; lensing effect $\propto q^{0.5}$
- projected separation: $d = 1 \ldots 5$ AU
- angle of motion relative to connecting line: φ



Planet im Brennglas

Das Prinzip der Gravitationslinse

Trifft das Licht eines fernen Sterns auf direktem Wege ein, so erreicht nur ein kleiner Teil der Strahlung die Erde.

Zieht zwischen der Strahlenquelle und der Erde ein massereicher Himmelskörper vorbei, so wird durch seine Anziehungskraft das Sternenlicht wie durch eine Linse gebündelt: Es kommt mehr Licht auf der Erde an.

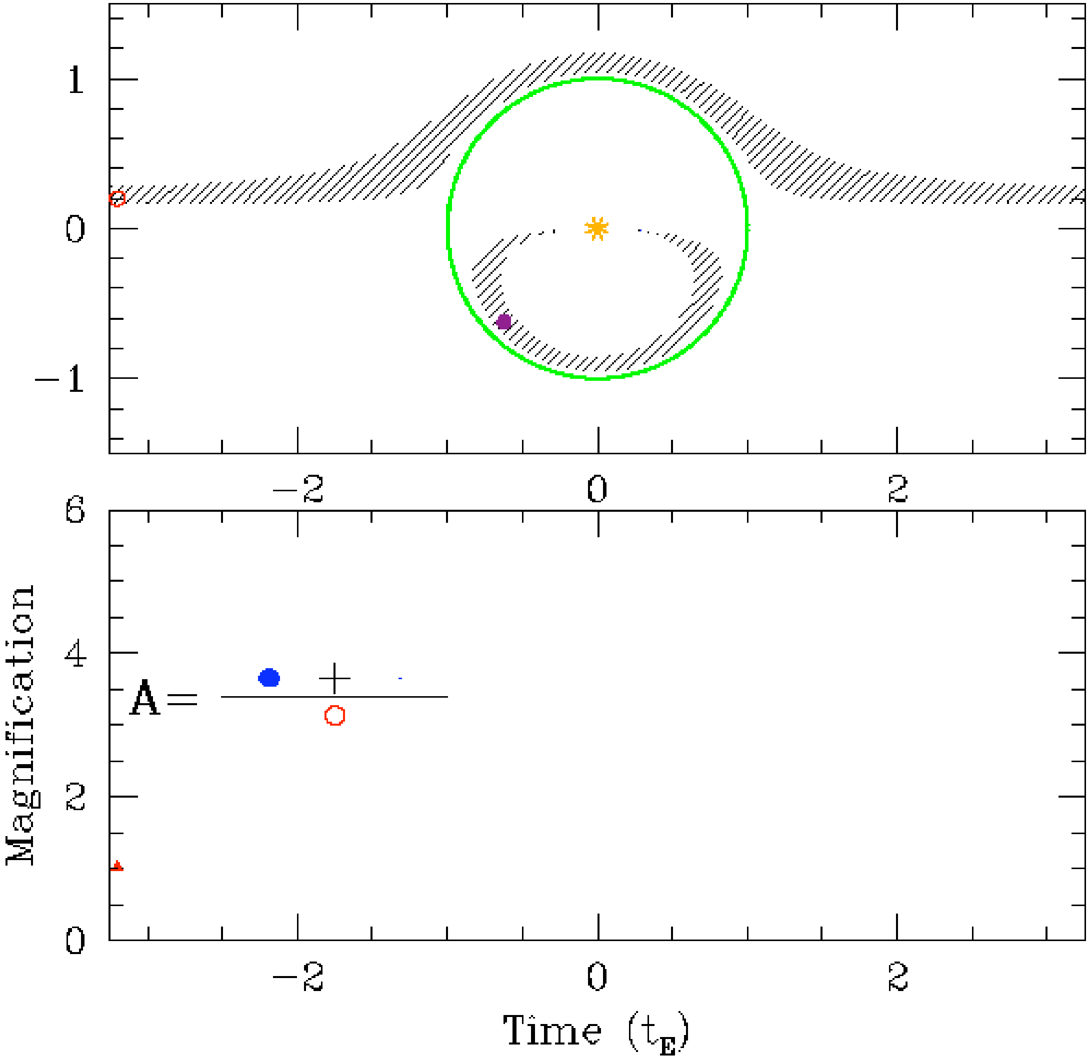
Astronomen registrieren die vorübergehende Helligkeitszunahme in Gestalt einer glockenförmigen Kurve. Wird der als Linse wirkende Himmelskörper von einem Planeten umkreist, tritt in der Helligkeitskurve eine zusätzliche Zacke auf.

Microlensing by Planets:

Scott Gaudi’s Simulations/Animations

time sequence:

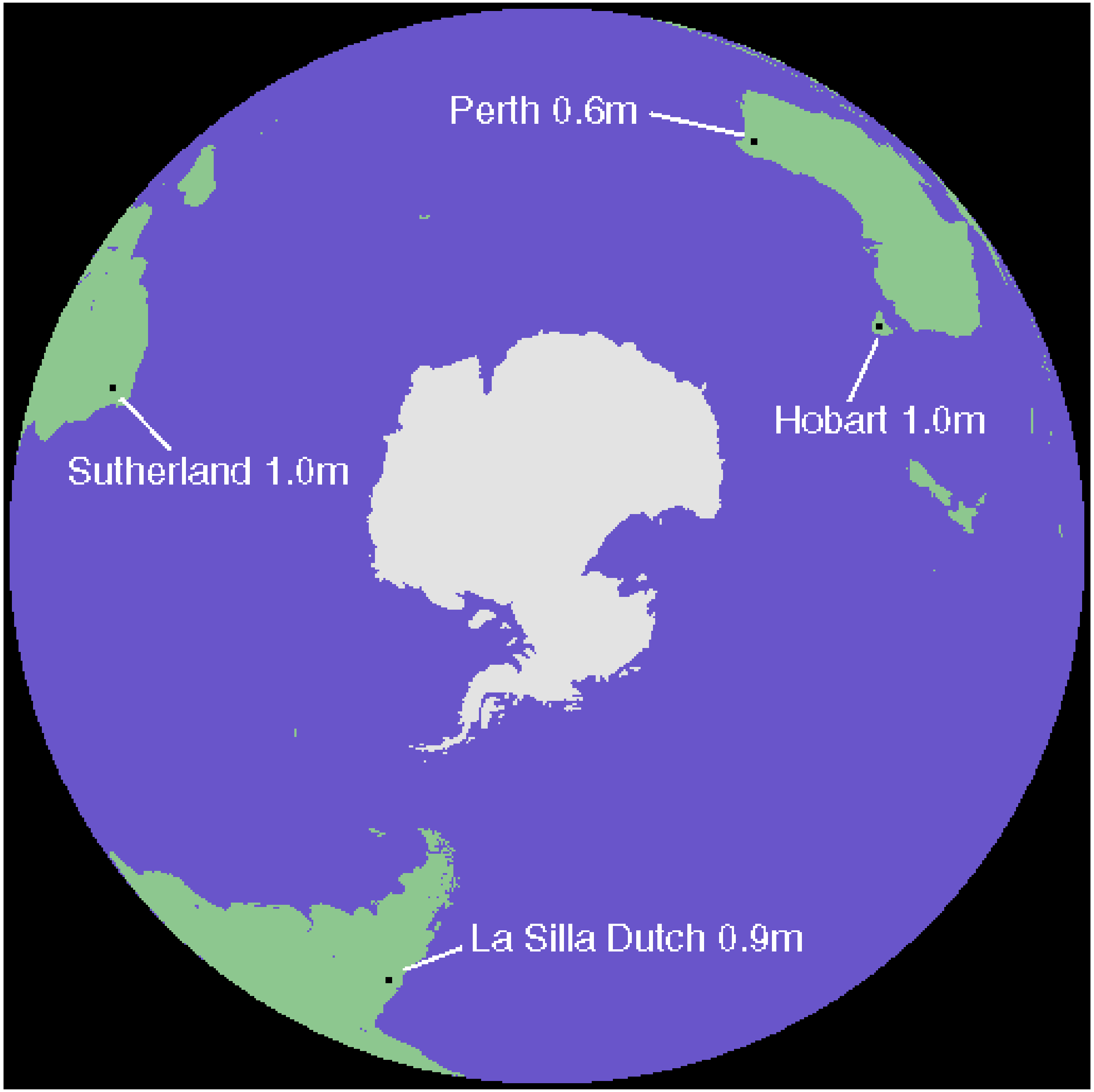
star-plus-planet



http://cfa-www.harvard.edu/~sgaudi/Movies

The 24 hour night shift:

Sites of the PLANET-Telescopes



PLANET -

Probing
Lens
Anomaly
NETwork

Third Microlensing Planet

Vol 439|26 January 2006|**doi:10.1038/nature04441**

nature

LETTERS

Discovery of a cool planet of 5.5 Earth masses through gravitational microlensing

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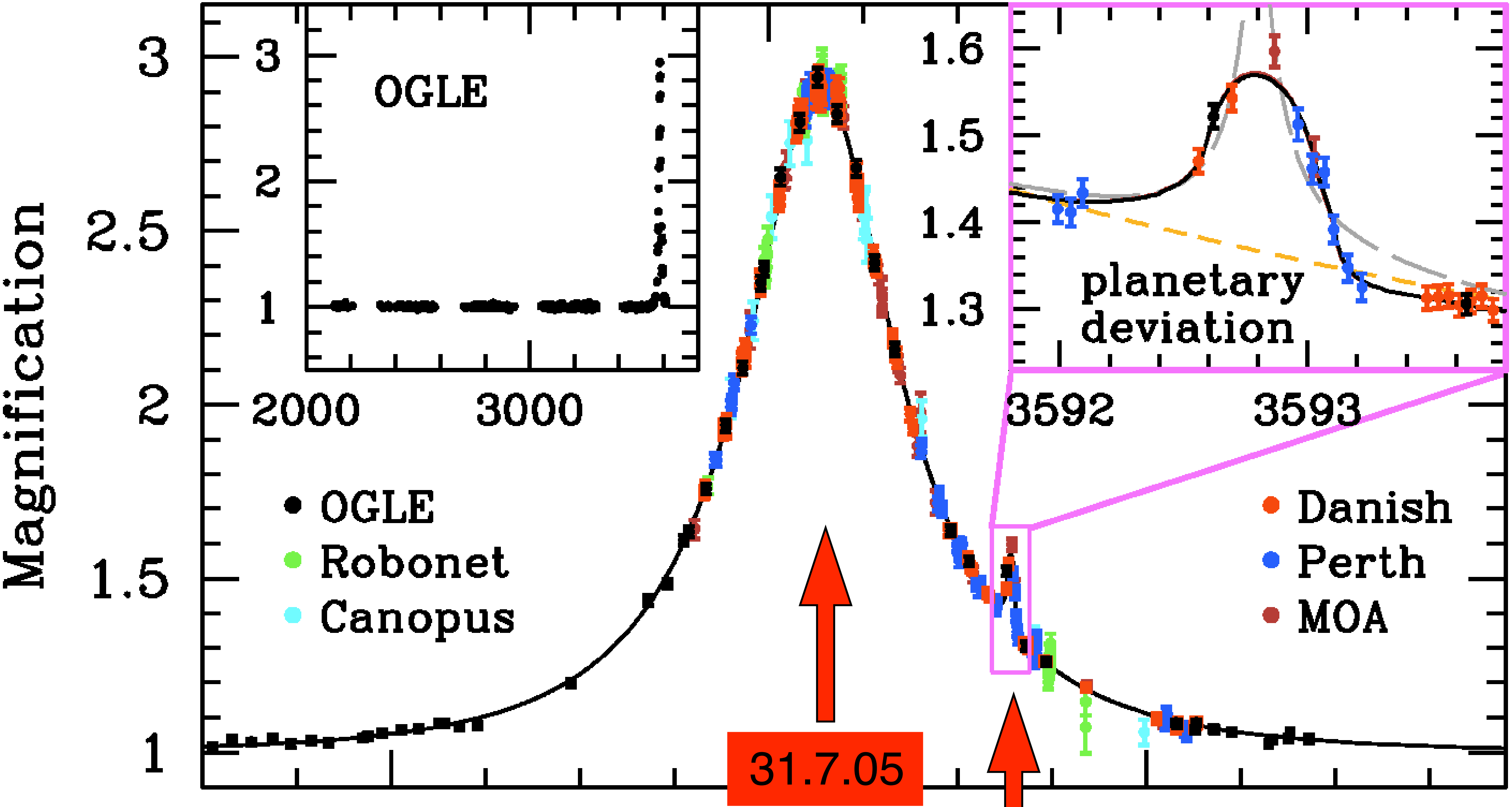
Third Microlensing Planet

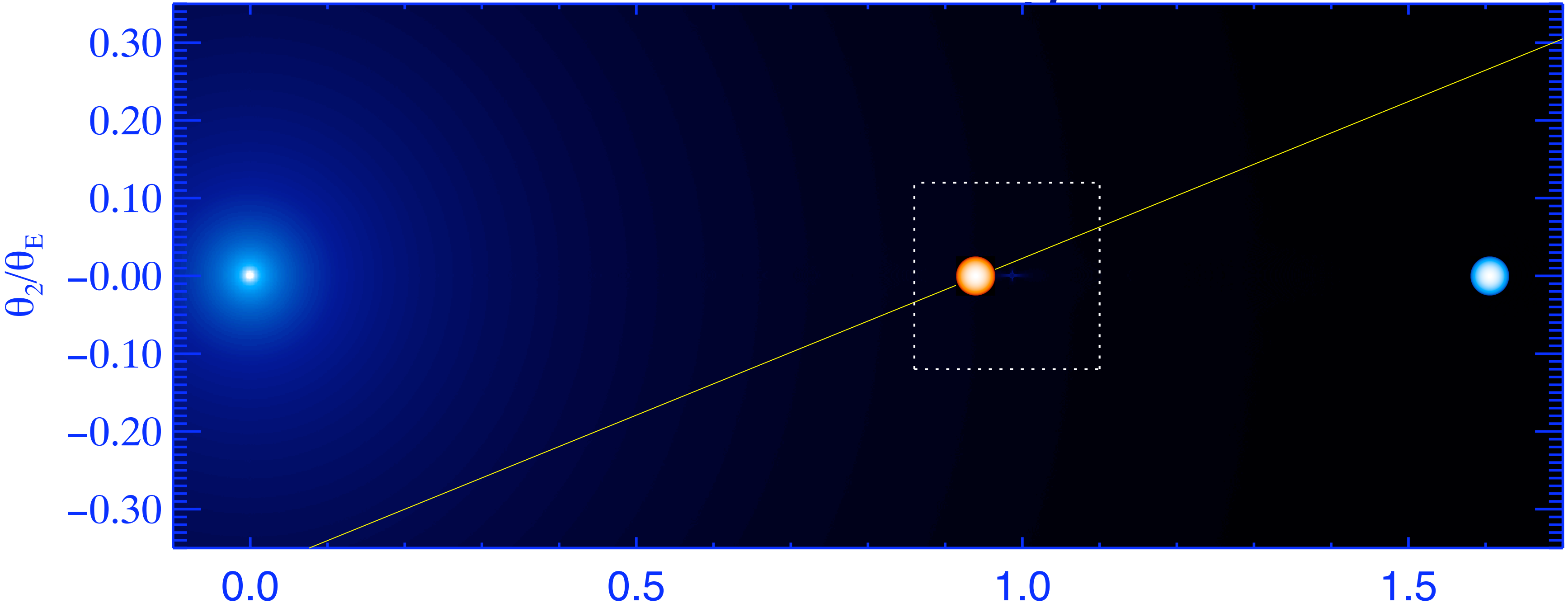


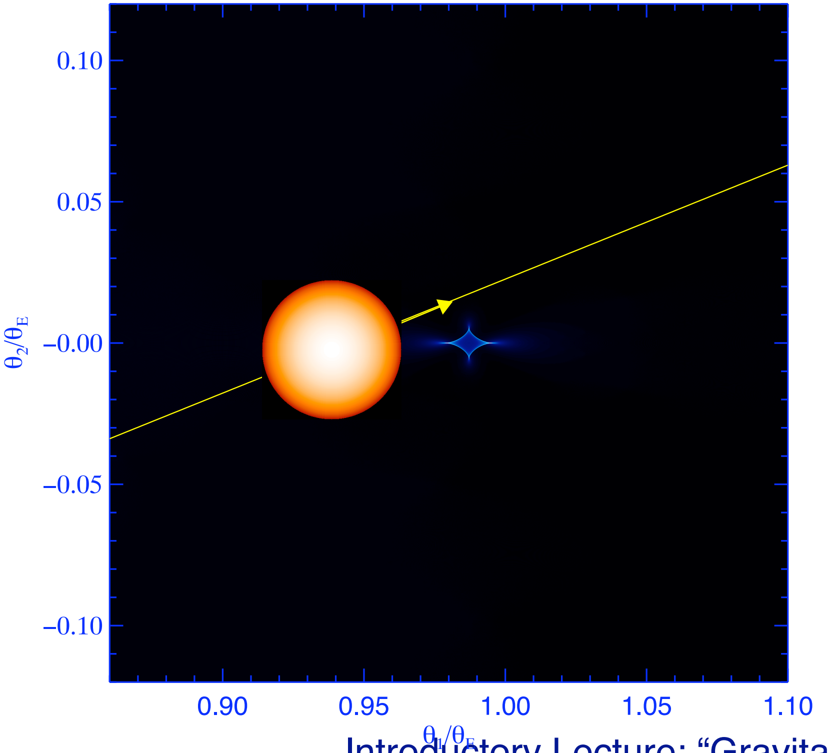
Time in days

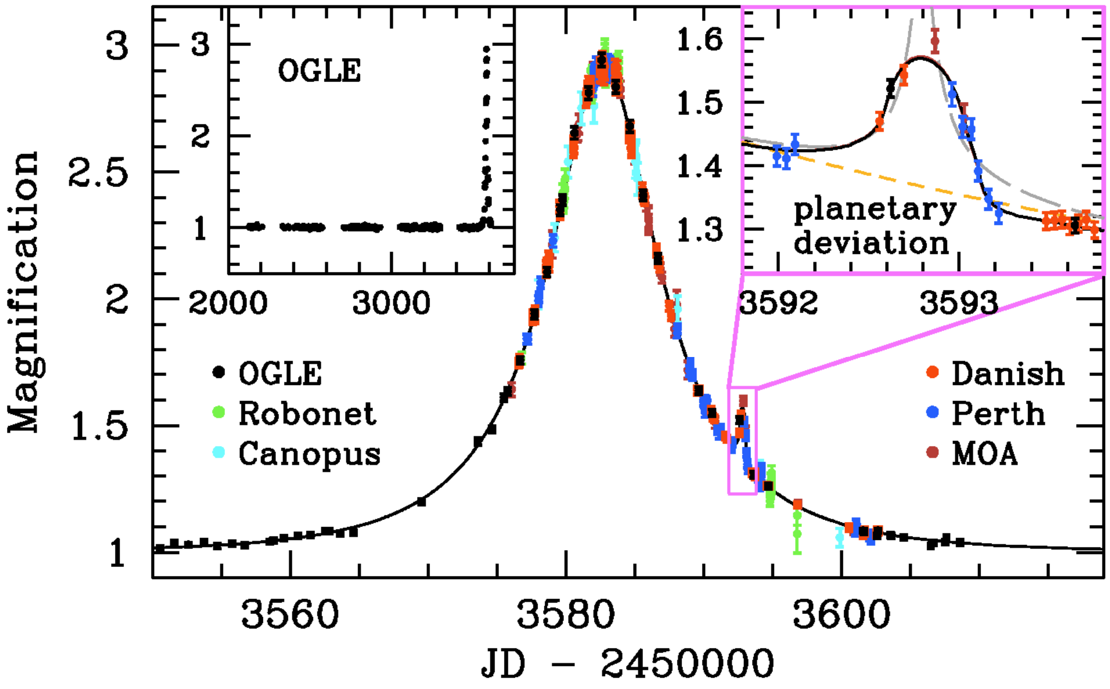
31.7.05

10.8.05

Third Microlensing Planet







Third Microlensing Planet

Microlensing event OGLE-2005-BLG-390:

- produced by star-plus-planet system with **mass ratio 7×10^{-5}**
-
- most likely (with model of Milky Way):
  - star of 0.2 solar masses
  - planet of 5.5 Earth masses
  - (instantanous) separation 2.6 AU
  - orbital period 10 years

Summary

Gravitational Lensing ...

- ... is unique as a geometrical tool for exploring the cosmos ...
- ... is useful on a wide range of mass and angular scales ...
- ... is universally applicable in many areas of astrophysics and cosmology ...

... and hence has a very bright future!