Microlensing of distant Quasars

Joachim Wambsganss
Zentrum für Astronomie der Universität Heidelberg (ZAH/ARI)

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Microlensing of distant Quasars

- What is **microlensing**?

  mass scales, angular scales, time scales

- Why is quasar **microlensing** relevant for astrophysics?

  lens/source, qualitative/quantitative, light/dark

- How can we observe quasar **microlensing**?

  photometrically, spectroscopically, astrometrically

- What are interesting results of quasar **microlensing**?

  no machos in 0957, dark matter fraction, transverse velocity ...

- The future of quasar **microlensing**?

  unique, useful, universal

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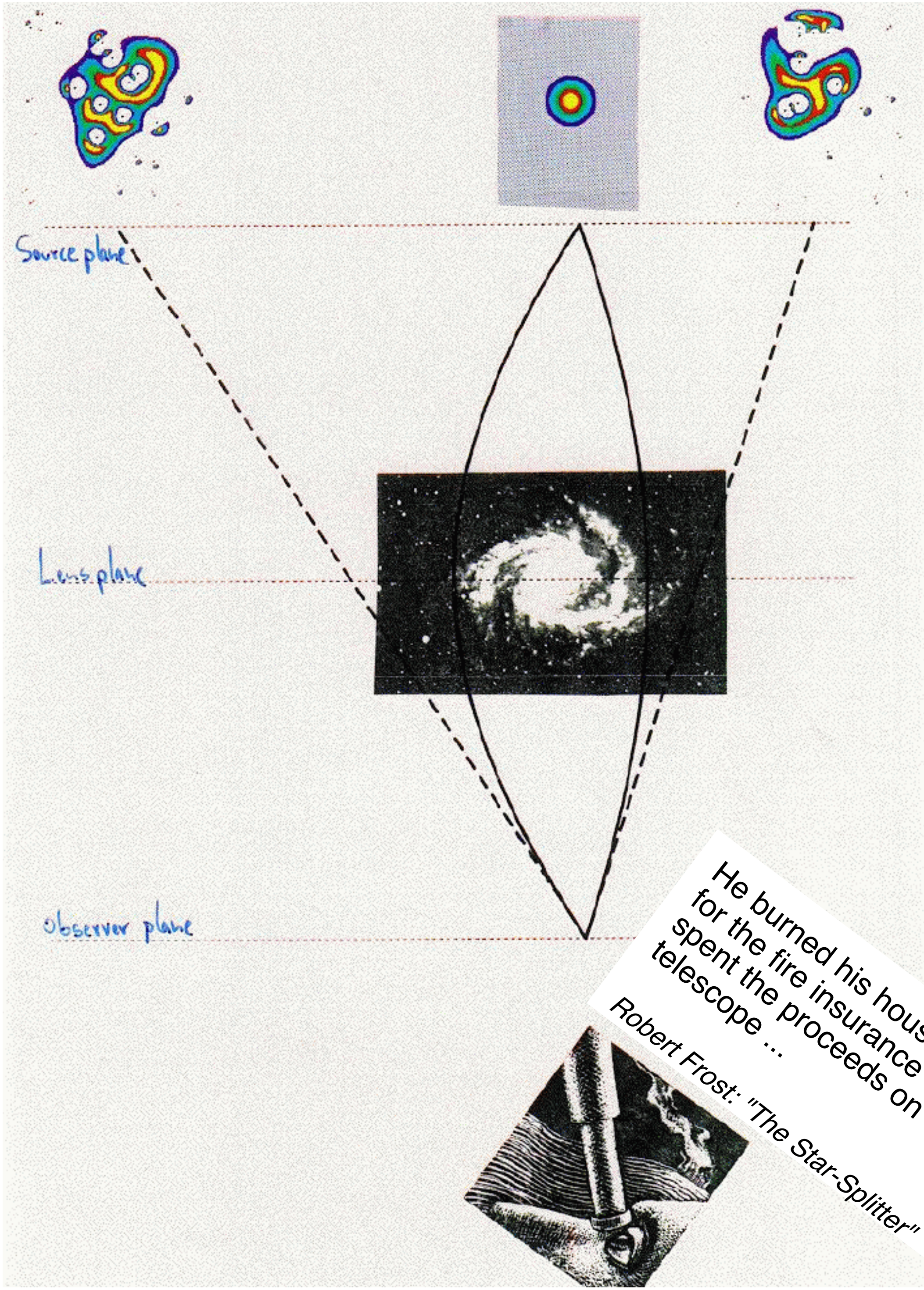
Basics of Lensing: Geometry



Basics of Gravitational Lensing

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

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 : $\mu = \dfrac{1}{\det \mathcal{A}}$

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

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

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

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

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

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

critical surface mass density:

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

What *is* Gravitational **Micro**lensing?

Gravitational microlensing is the action of **compact** objects of **small mass** along the line of sight to **distant sources**

what is "small mass" ?

$$\Rightarrow \quad 10^{-6} < M/M_{\odot} < 10^{3}$$

what is "compact" ?

⇒ (much) smaller than Einstein radius

what are the "distant sources"?

⇒ quasars, stars

(other regimes/names: nanolensing, mesolensing, millilensing)

Einstein Radii of Microlenses:

Overall scale in gravitational lensing: Einstein radius

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

Einstein radius for star in distant galaxy:

$$\theta_E \approx 1.8 \sqrt{\frac{M}{M_\odot}} \quad \text{microarcsec}$$

Einstein radius for star in Milky Way:

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

Quasar Microlensing: Angular Scale, **Time Scale**

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

angular Einstein radius: $$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}} \approx 1.8\sqrt{\frac{M}{M_\odot}}\quad \mathrm{microarcsec}$$

Einstein time: $$t_E = r_E/v_\perp \approx 15\sqrt{\frac{M}{M_\odot}}\; v_{600}^{-1}\ \mathrm{years}$$

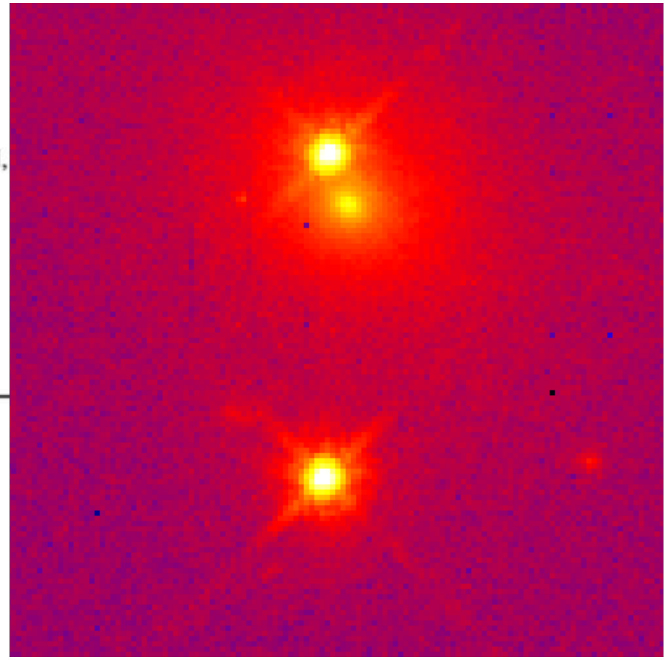
Crossing time: $$t_{cross} = R_{source}/v_\perp \approx 4R_{15}v_{600}^{-1}\ \ \mathrm{months}$$

(for $z_L = 0.5$, $z_S = 2.0$)

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.

article

Nature **282**, 561 - 564 (06 December 1979)

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

If the double QSO 0957 + 561 A, B is the result of gravitational lens actions by a massive galaxy, stars in its outer parts and close to the light paths may cause significant flux changes in one year. One star can split a QSO image into two to four images with angular separations of ~10^{-5} arc s.

Astron. Astrophys. 132, 168–178 (1984)

Star disturbances in gravitational lens galaxies

K. Chang and S. Refsdal

Hamburger Sternwarte, Gojenbergsweg 112, D-2050 Hamburg 80, Federal Republic of Germany

Received April 26, accepted October 19, 1983

Summary. Image splitting and flux changes caused by a single star in an extended gravitational lens galaxy are investigated. Earlier investigations (Chang and Refsdal, 1979) showed that an image can split into two or four sub-images. We here find, by a more general investigation, that the number of sub-images in some cases can be zero, so that one of the gravitational lens images of the equivalent "smoothed out" galaxy disappears completely due to the inhomogeneity represented by a star (or a globular cluster).

Why is microlensing relevant for astrophysics?
(background source: quasars)

1979 Chang & Refsdal: "Flux variations of QSO 0957+561 A, B and image splitting by stars near the light path"

1981 Gott: "Are heavy halos made of low mass stars? A gravitational lens test"

1986 Paczynski: "Gravitational microlensing at large optical depth"

1986 Kayser et al.: "Astrophysical applications of gravitational micro-lensing"

1987 Schneider/Weiss: "A gravitational lens origin for AGN-variability? Consequences of micro-lensing"

1989 Irwin et al.: "Photometric variations in the Q 2237+0305 system: first detection of a microlensing event"

How can we observe *micro*-lensing ?

Einstein angle ($\theta_E = 0.5 \sqrt{(M/M_\odot)}$ milliarcsec) << telescope resolution !

$\Rightarrow$ image splitting not directly observable!

However, microlensing affects:

- **apparent magnitude (magnification)**
- (emission/absorption line shape)
- center-of-light position

AND these effects change with time due to relative motion of source, lens and observer:

$\Rightarrow$ microlensing is a **dynamic** phenomenon! It is observable:

- **photometrically**
- (spectroscopically)
- astrometrically

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: ~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

Gravitational Microlensing:

	stellar, Galactic, Local Group microlensing	quasar, extragalactic, cosmological microlensing
main lenses:	stellar mass objects in Milky Way, SMC, LMC, M31, halo	stellar mass objects in lensing galaxy
sources:	stars @ kpc/Mpc	quasars (SNe) @ Gpc
Einstein angle:	0.5 milliarcsec	1 **micro**arcsec
Einstein time:	weeks-months	months-years
optical depth:	low: 10^{-6}	high: of order 1
proposed:	(Einstein 1936) Paczynski 1986a	Chang & Refsdal 1979, 1984 Gott 1981, Paczynski 1986b
first detected:	OGLE, MACHO, EROS 1993	Irwin et al. 1989
way of detection:	photometrically, spectroscopically, astrometrically	photometrically, spectroscopically, astrometrically
signal:	simple	complicated
good for:	machos, stars, **planets**, (moons?) stellar masses/profiles, structure	quasar sizes/profiles, machos, dark matter

How do I know that quasar variability is due to microlensing?

(... rather than a physical variation of the quasar ...)

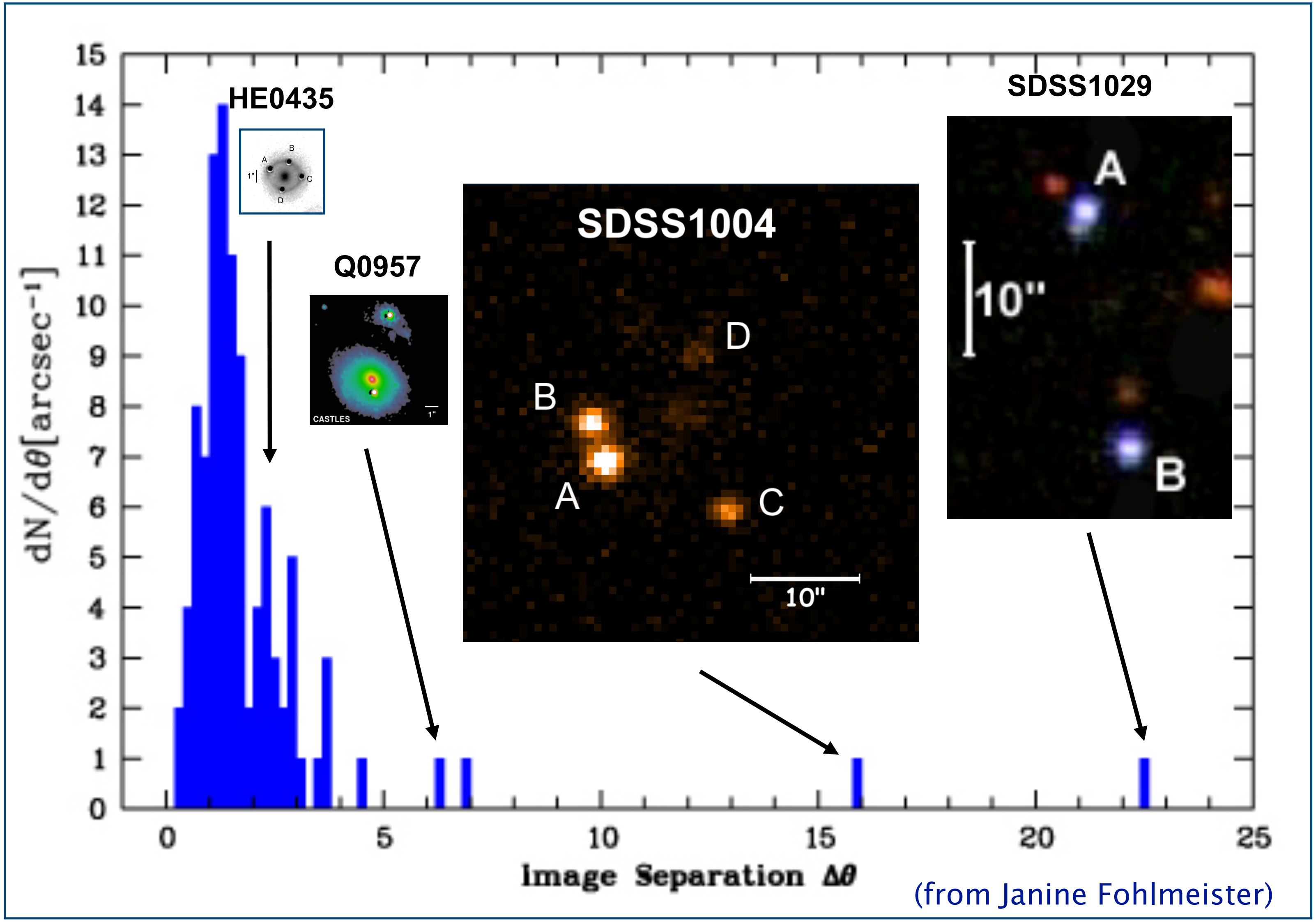
All quasars are variable (more or less ...)

- For an isolated quasar:
  - very difficult to distinguish "intrinsic" variability from "extrinsic" (i.e. microlens-induced) variability! (there some hints, though ...)
- For a double/multiple quasar:
  - intrinsic variability affects ALL images, after certain time delay!

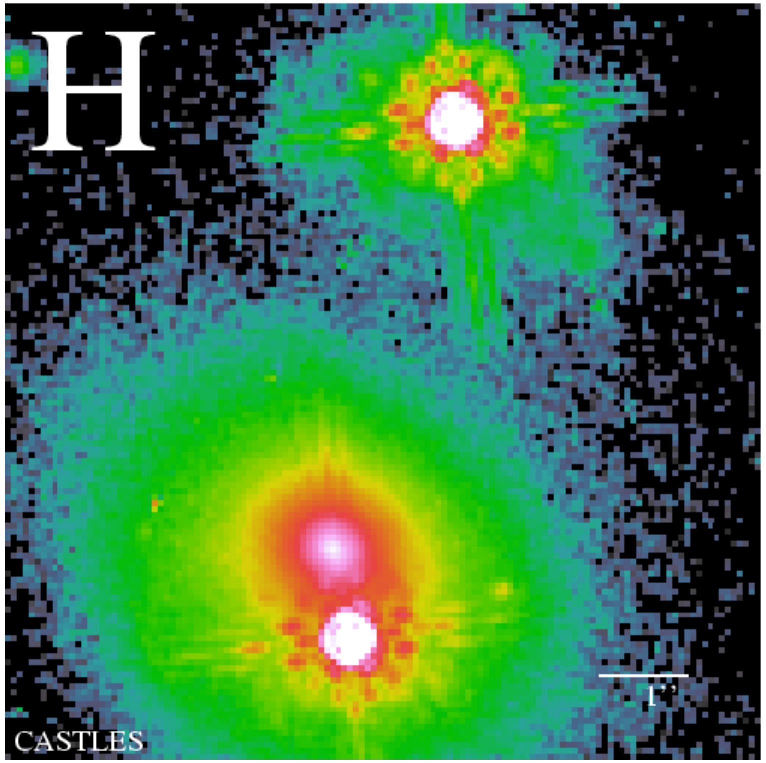
    $\Rightarrow$ shift lightcurves in time (Δt) and magnitude (Δm) :
    - obtain "difference" lightcurve:
      - if flat - no microlensing
      - if variable - microlensing

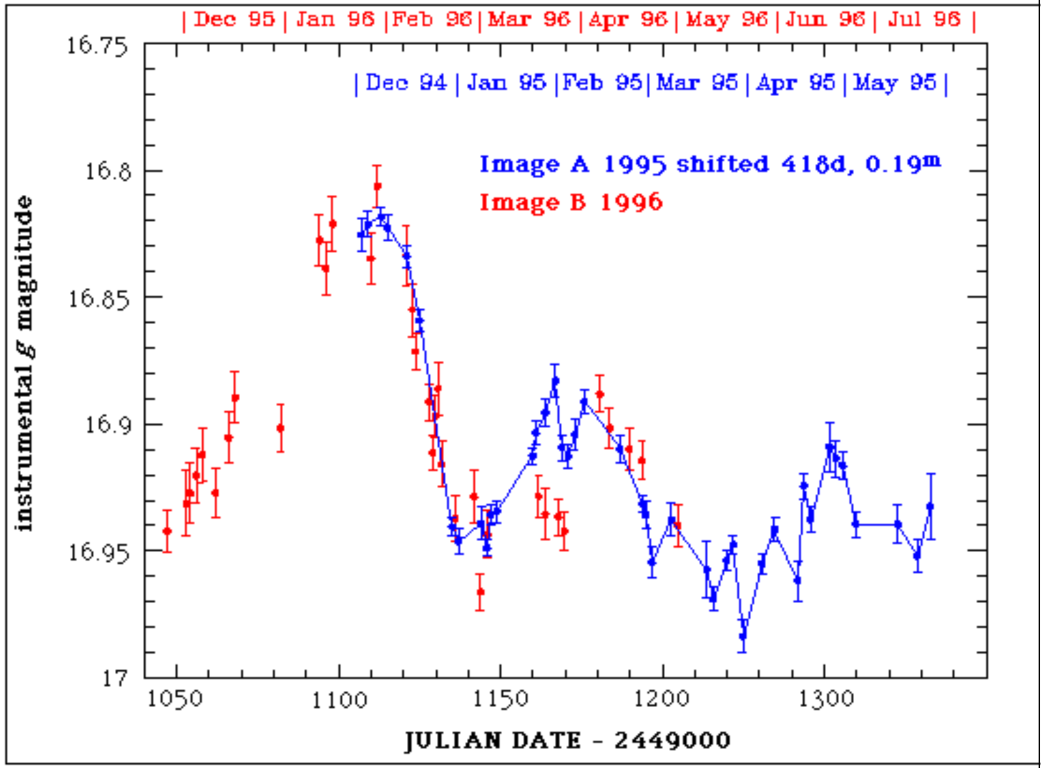
... one man's signal is another man's noise ... (Paul Schechter)

Image separations of known multiply imaged QSOs



Double quasar Q0957+56: Time Delay & Hubble constant





Time delay for double quasar Q0957+561:

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

Hubble constant (from Δt and lens model):

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

Ensemble of 16 multiple quasars: Time Delay & Hubble constant

May 2007: Oguri, ApJ 660, 1

“We find that 16 published time delay quasars constrain the Hubble constant to be H_0 = (70 ± 6) km/s/Mpc.”

...

“After including rough estimates of important systematic errors, we find H_0 = (68 ± 6 [stat.] ± 8 [syst.]) km/s/Mpc.”

How to calculate quasar microlensing:

Consider the deflection of (very) many stars close to the light bundle of a quasar (macro) image

→ follow the deflected light rays backward from observer through lens plane to source plane (inverse ray tracing)

→ collect the rays in "pixels"

→ determine the local magnification

→ convolve magnification with the source profile

→ evaluate for linear track

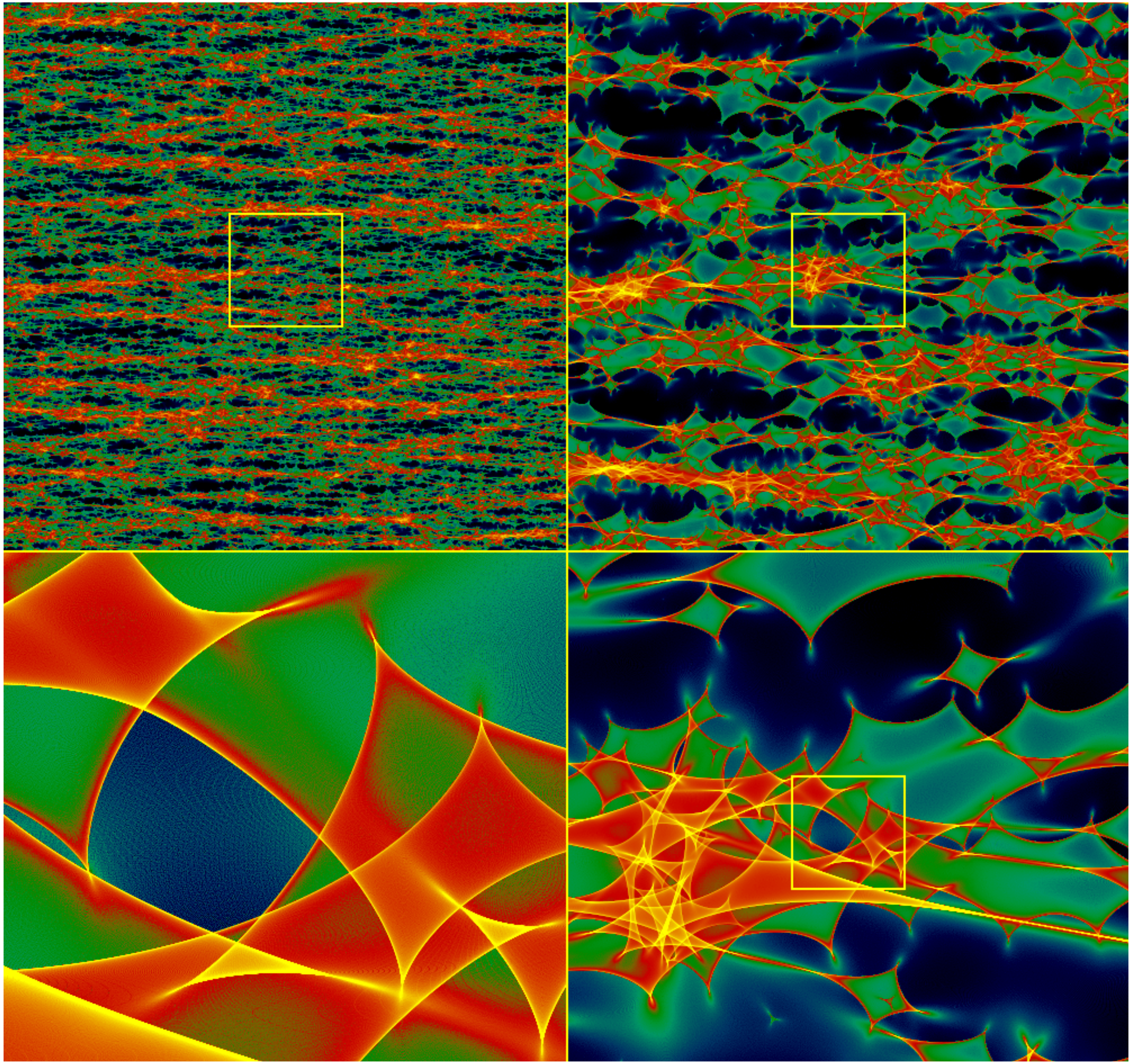
→ obtain microlensed lightcurve

→ **learn HOW to do it this afternoon, 4:30pm !**

Quasar microlensing: typical magnification patterns

L = 100 R_E

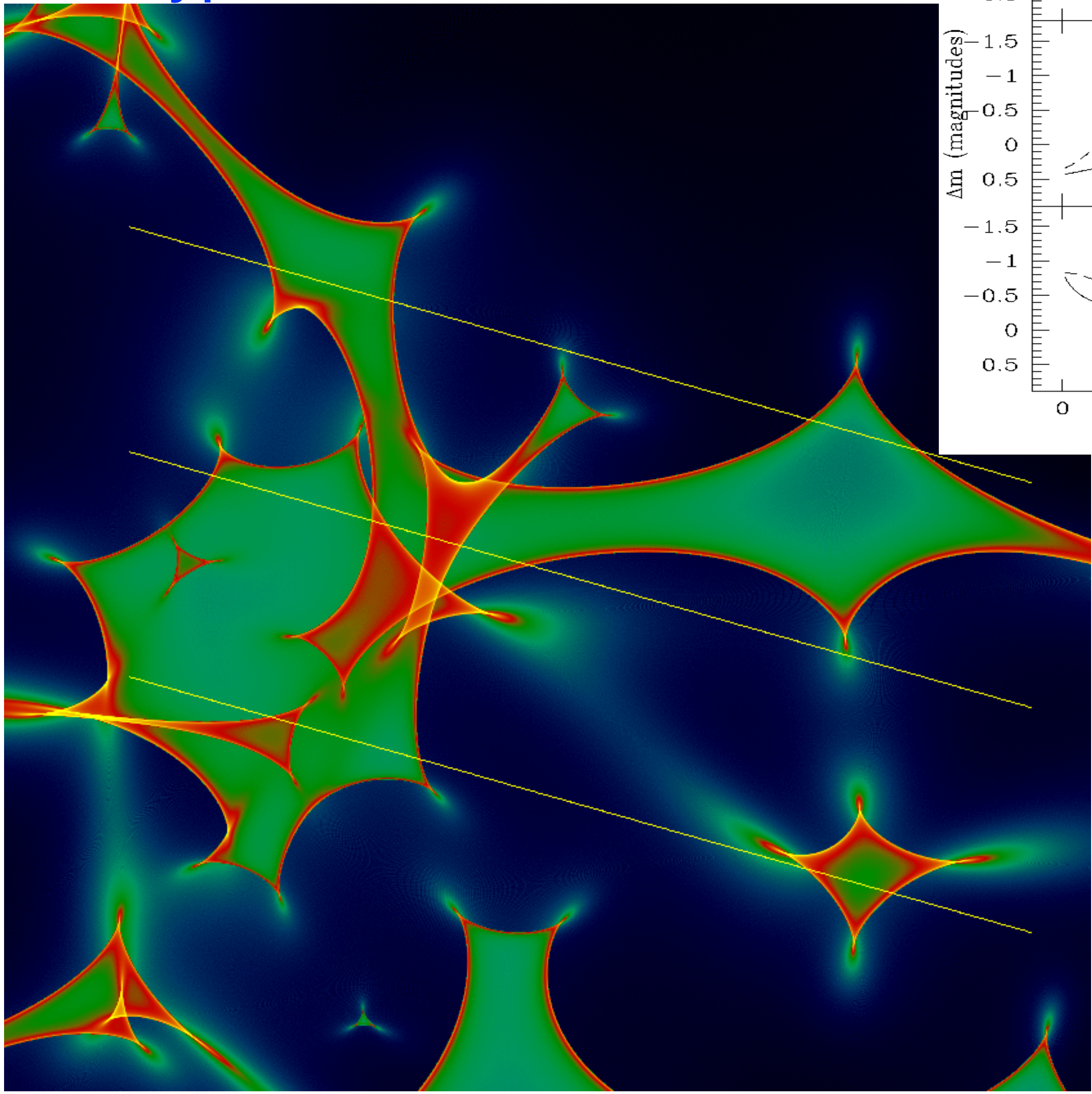
20 R_E

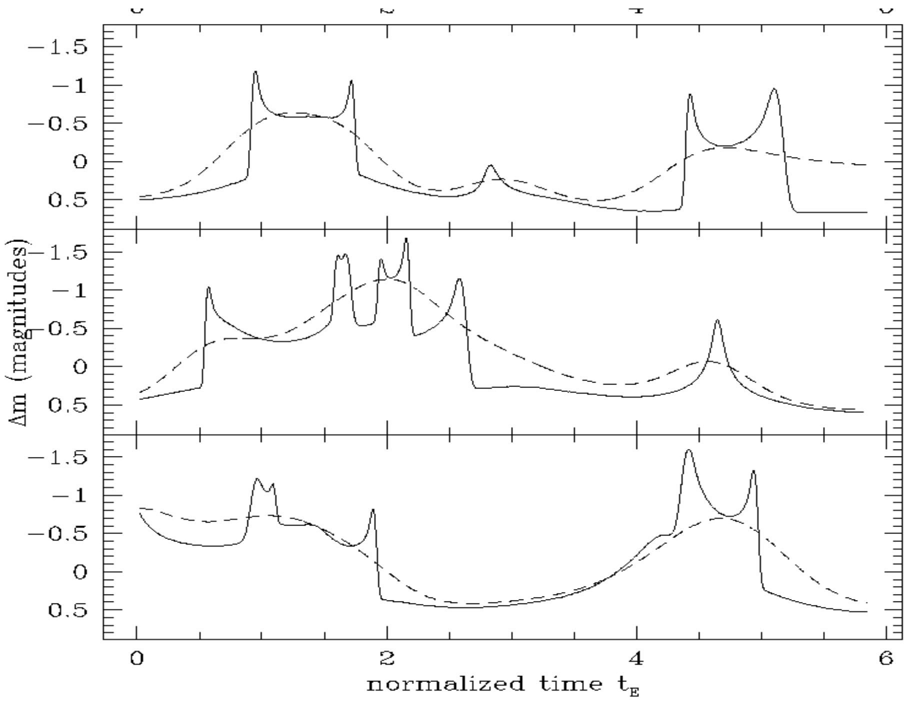


0.8 R_E

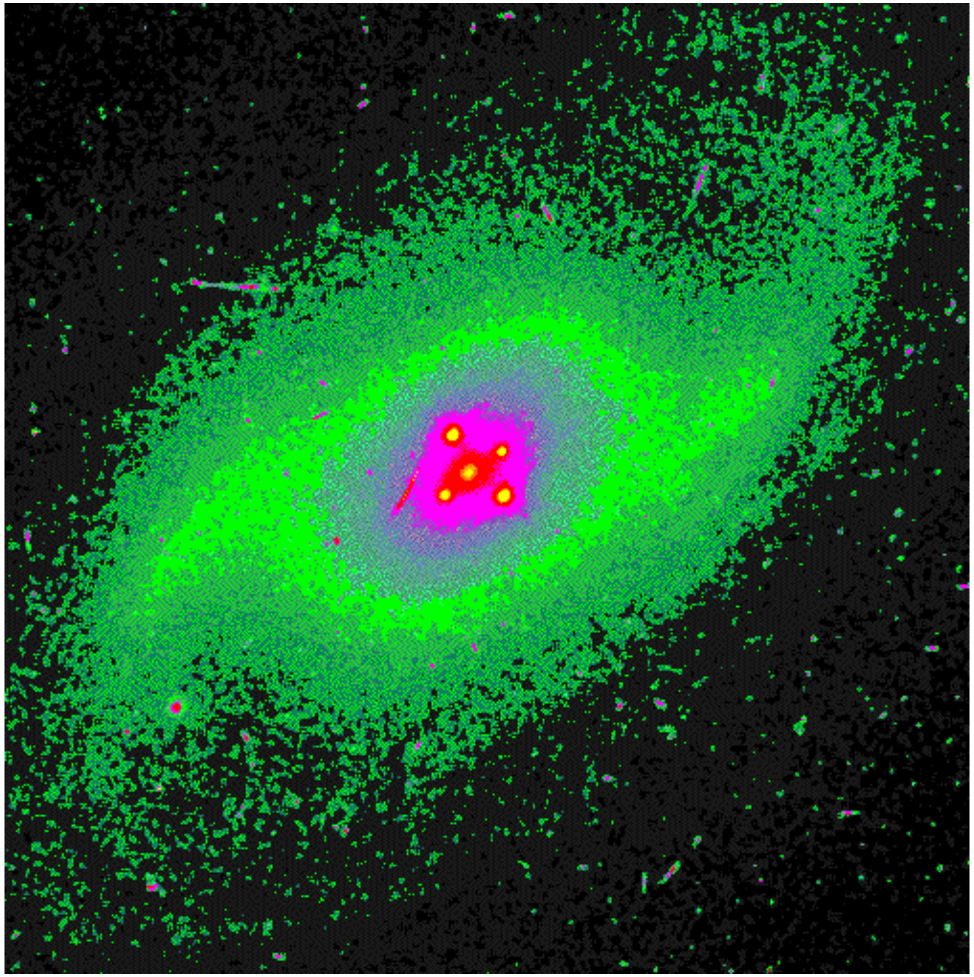
4 R_E

Quasar microlensing: typical simulations





The quadruple quasar Q2237+0305

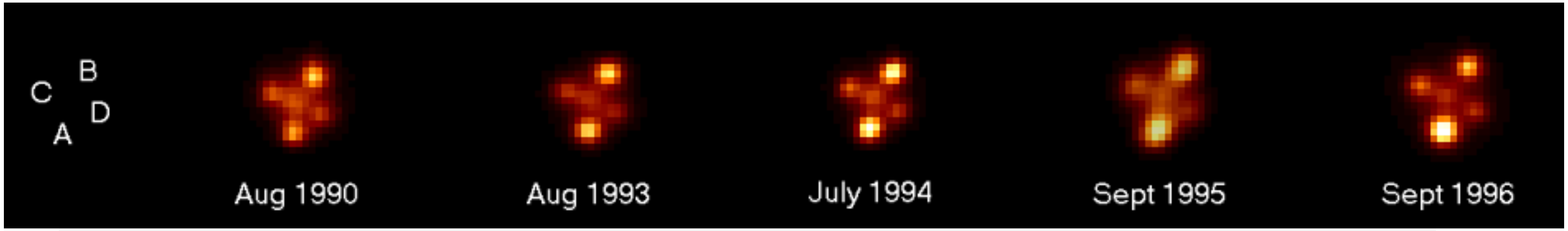


z(quasar) = 1.695, z(galaxy) = 0.039

image separation 1.7 arcsec

(HST)

Quasar Microlensing: Q2237+0305



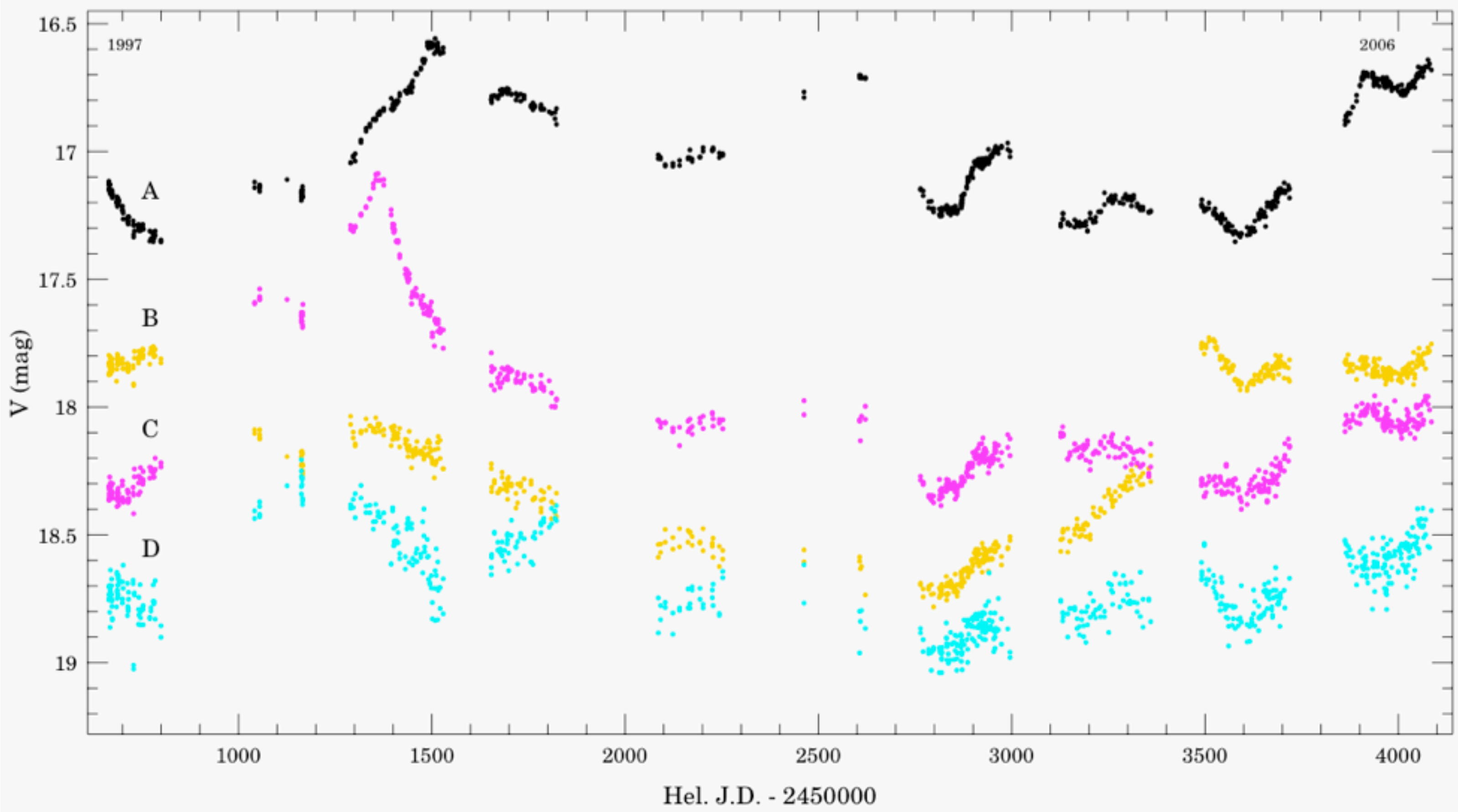


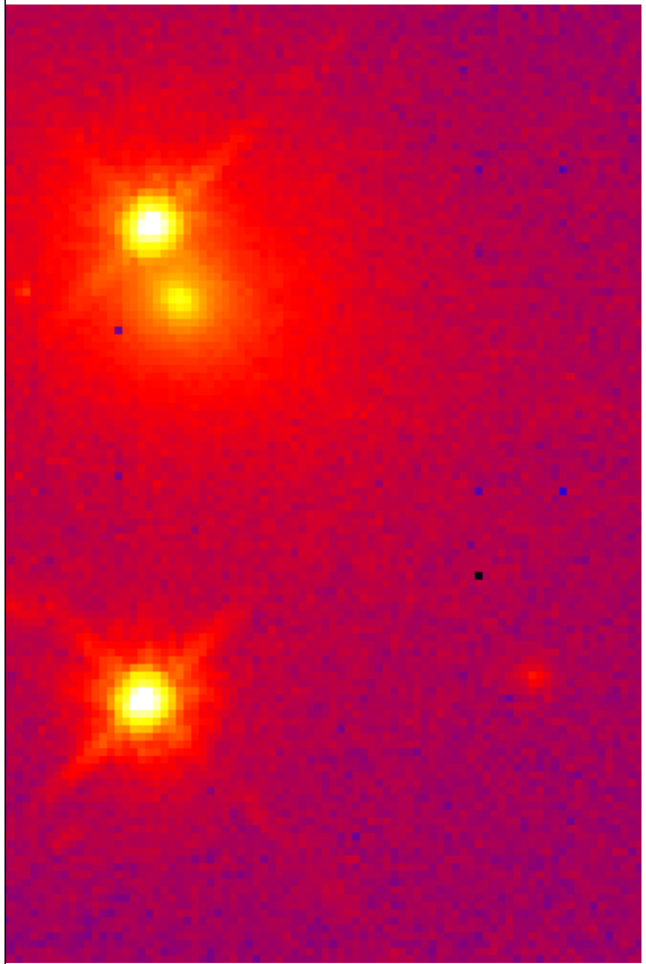
Fig. 4. OGLE light curve of the gravitational lens QSO 2237+0305 covering ten observing seasons 1997–2006.

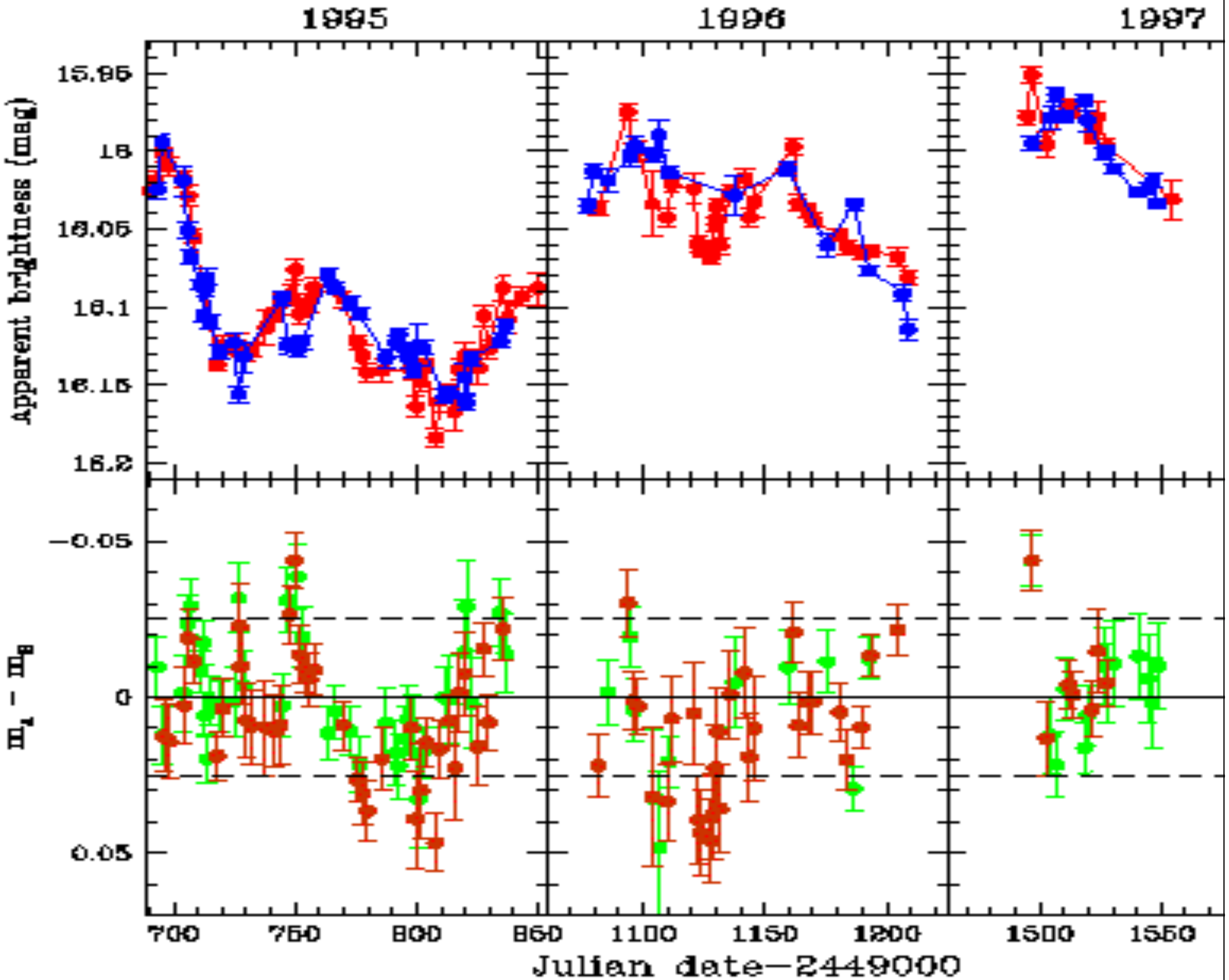
Udalski et al. 2006 (OGLE)

Six (plus one) Applications of Quasar Microlensing

- Double Quasar Q0957+56: no Machos
  Wambsganss & Schmidt (2000)
- Quadruple Q2237+0305: limits on transverse velocity
  Gil-Merino, Wambsganss et al. (2005)
- Size is everything: quasar profile does not matter much
  Mortonson, Schechter & Wambsganss (2005)
- Flux anomalies/“suppressed saddlepoints”: smooth dark matter
  Schechter & Wambsganss (2002)
- Determine Dark Matter fraction via microlensing
  Pooley et al. (2009)
- Measure the accretion disk profile
  Eigenbrod et al. (2008)
- Future accurate quasar positions: astrometric microlensing
  Treyer & Wambsganss (2004)

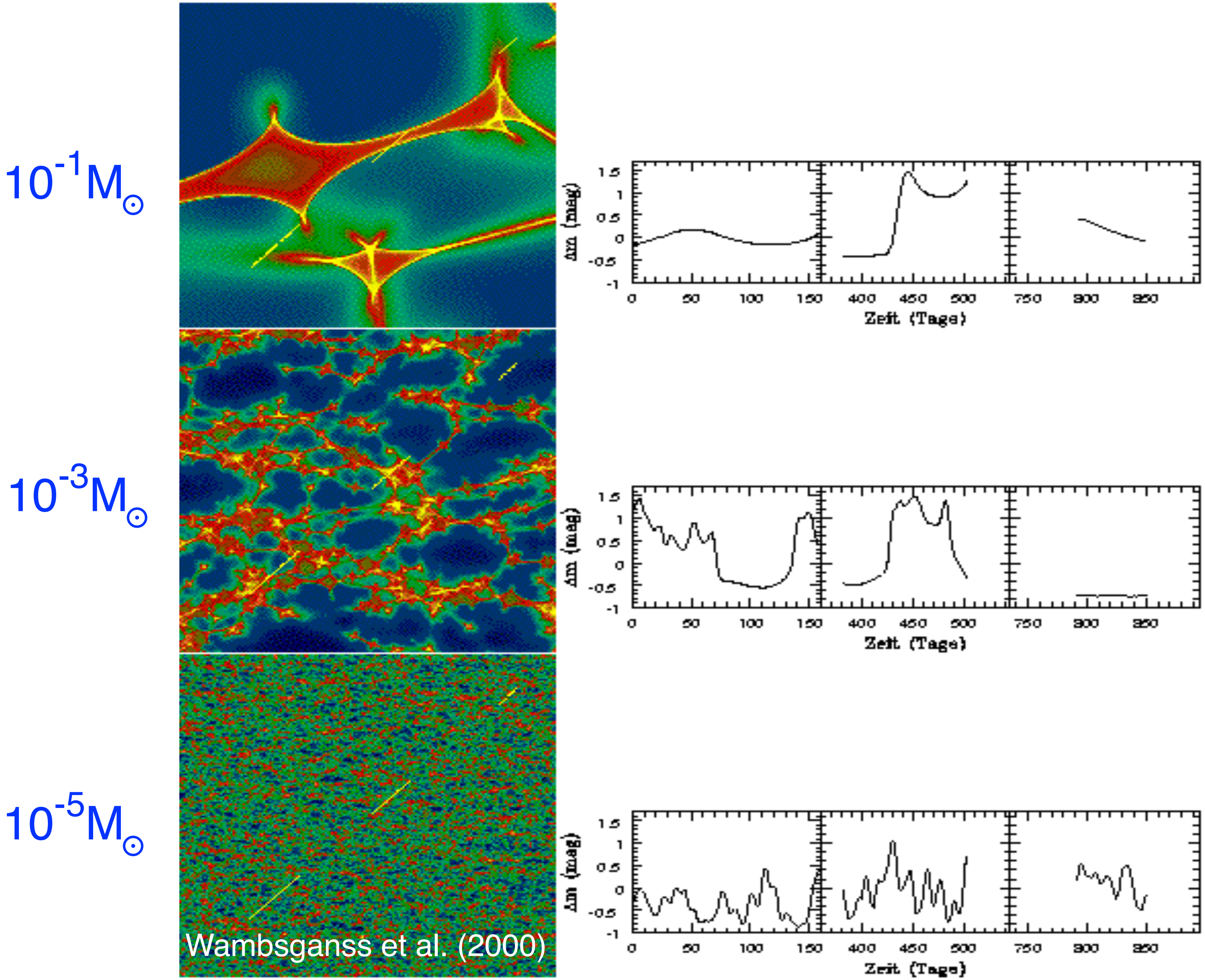
Quasar Microlensing? Q0957+561



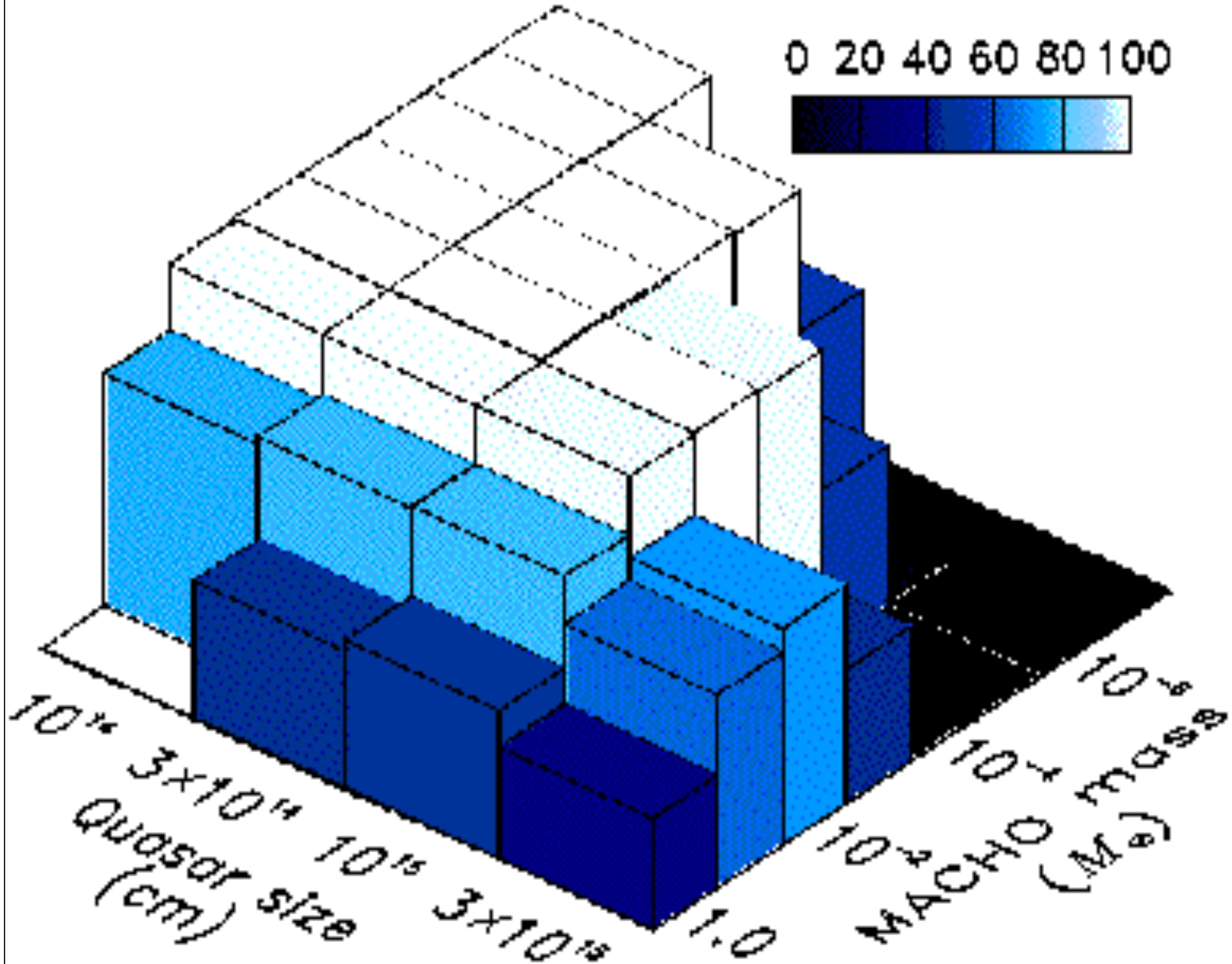


Falco et al. (1998); Kundic et al. (1997)

Quasar Microlensing Simulation: Q0957+561



Quasar Microlensing Results: Q0957+561



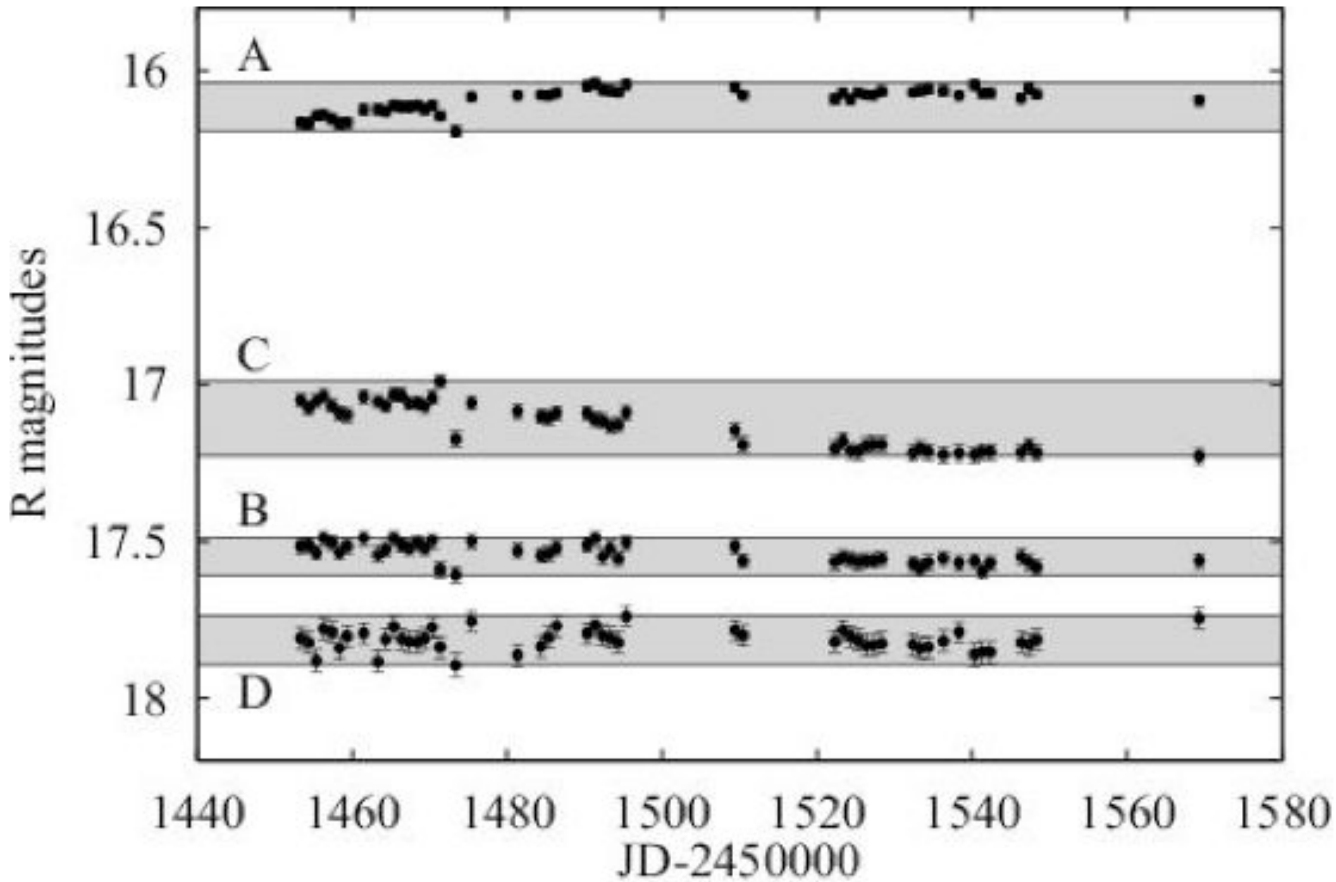
Halo of lensing galaxy cannot consist entirely of compact objects (MACHOs) in certain mass ranges
(Wambsganss et al. 2000)

More systems, longer baseline
⇒ better constraints!

Quasar Microlensing: Q2237+0305

Monitoring campaign: 6 months in 2000

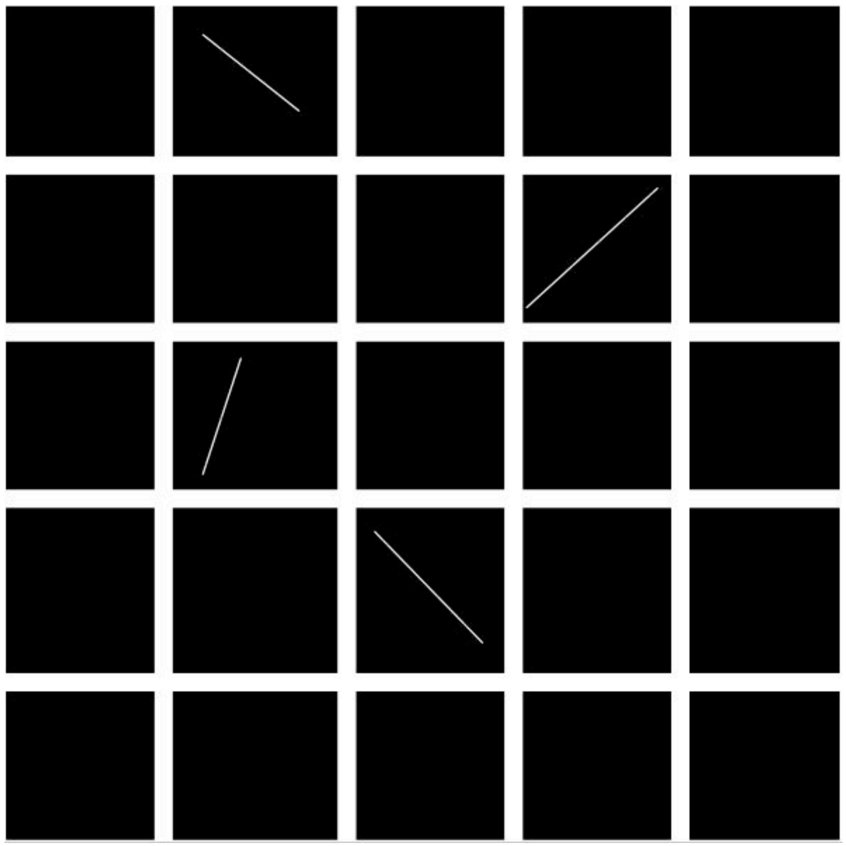
GLITP - Gravitational Lens International Time Project

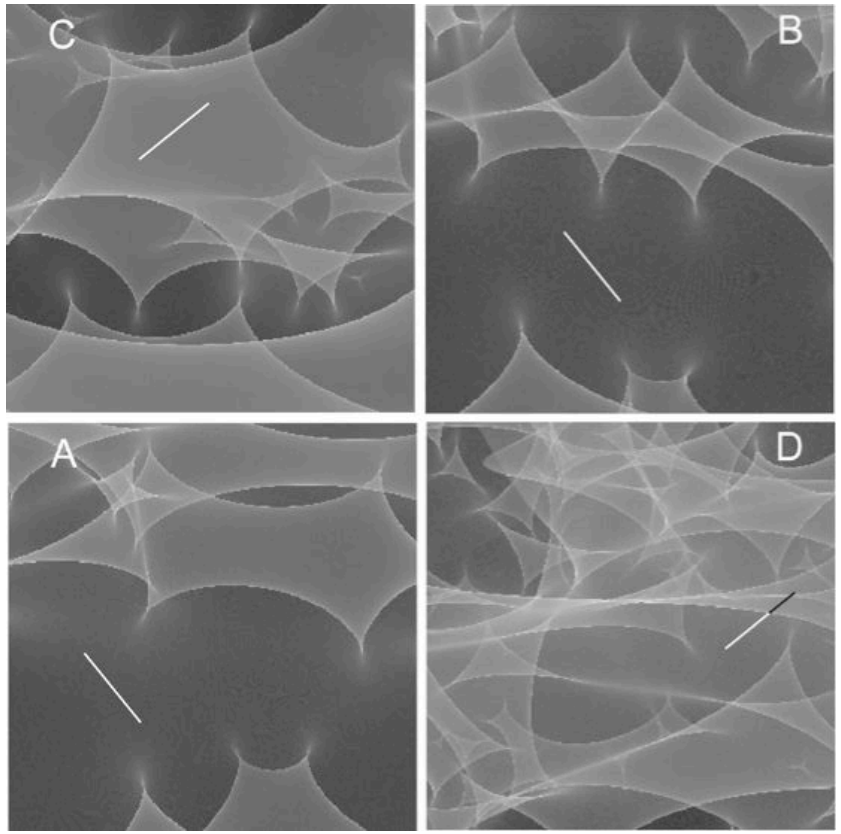


Quasar Microlensing: Q2237+0305

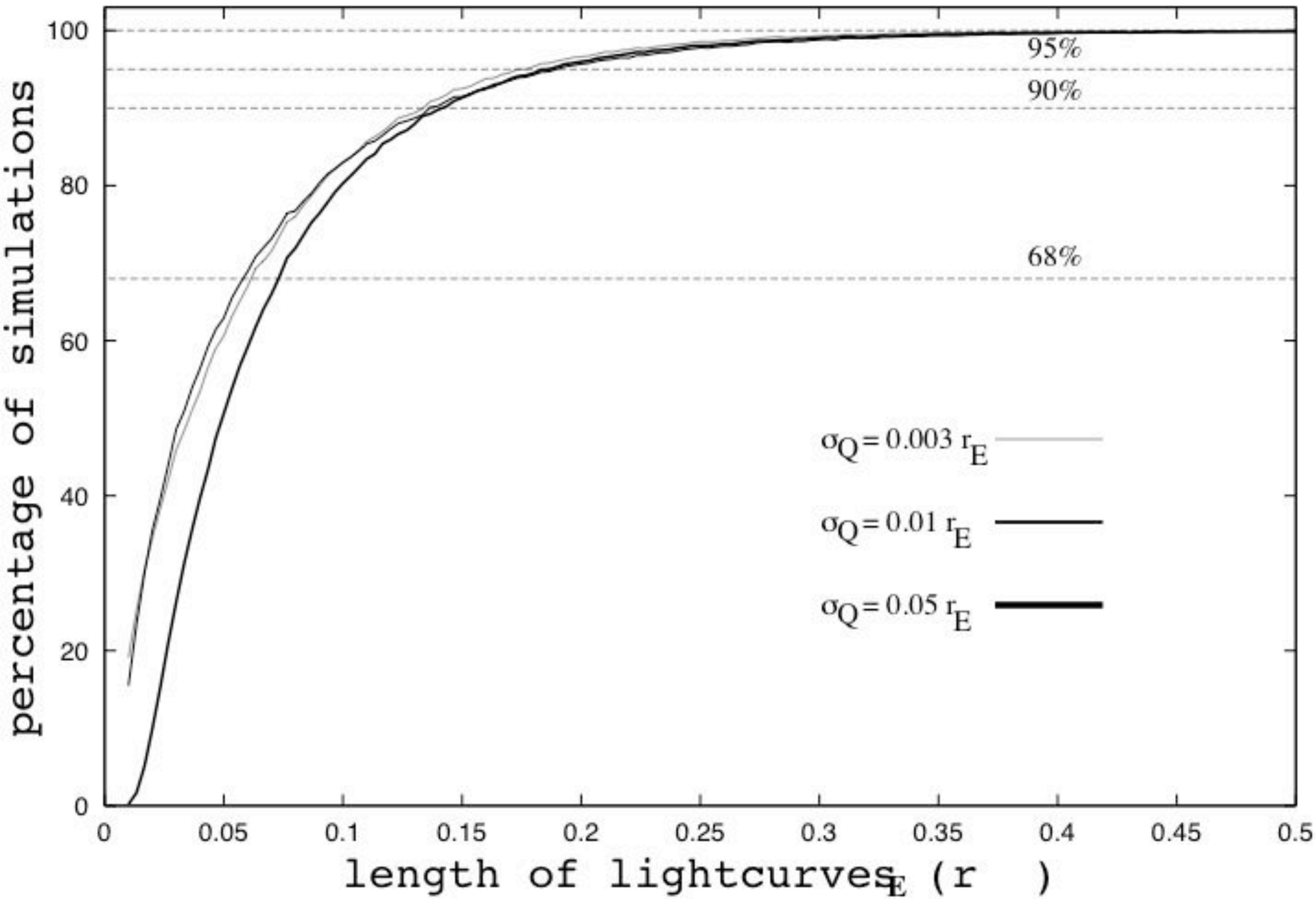
Limits on transverse velocity of lensing galaxy:

Idea: "typical" distance between caustics
$\Rightarrow$ due to effective transverse motion:
$\Rightarrow$ typical time scale between maxima!





Quasar Microlensing: Q2237+0305



Quasar Microlensing: Q2237+0305

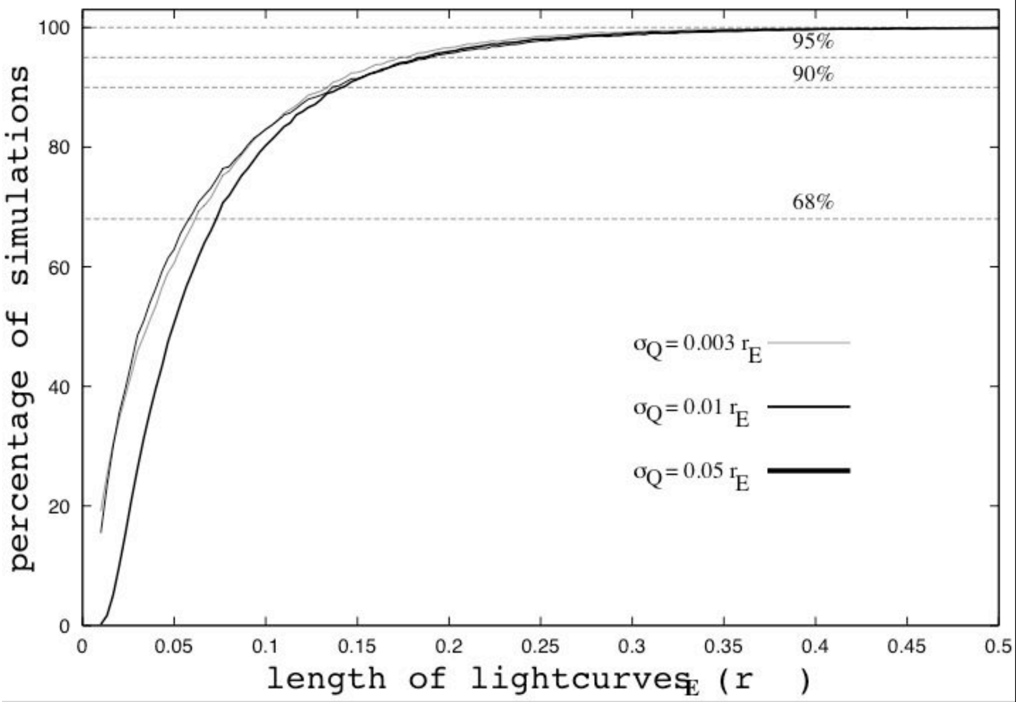
limits on V_{trans}:

<u>$M = 1\ M_\odot$:</u>

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

<u>$M = 0.1\ M_\odot$:</u>

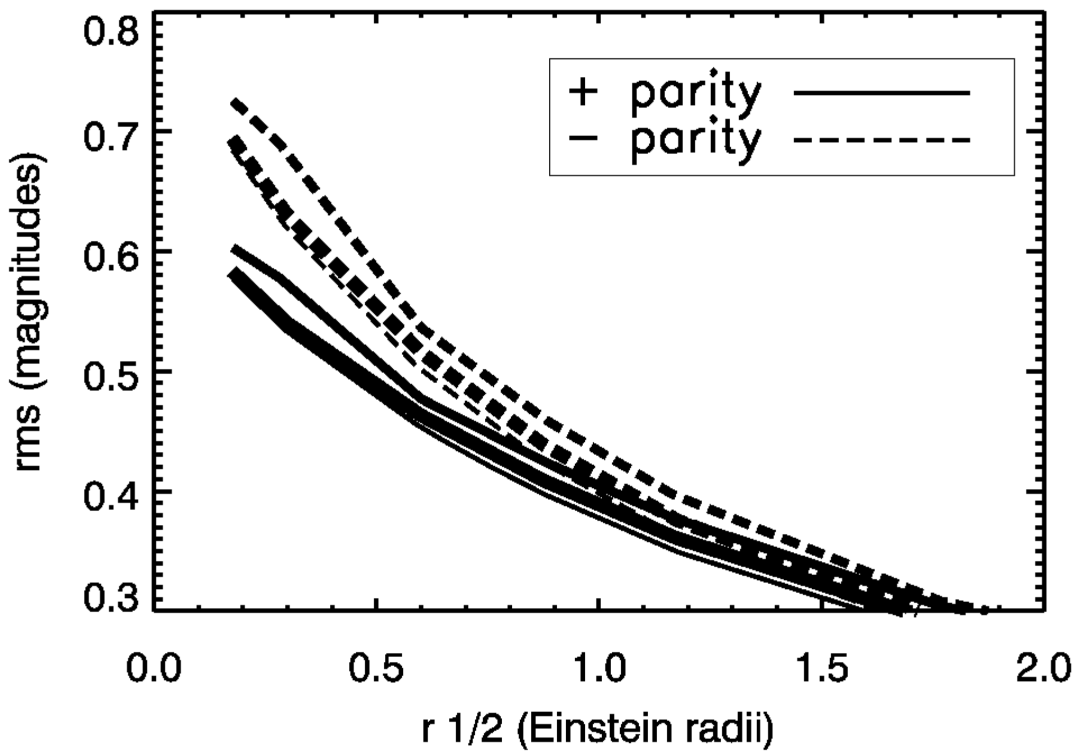
$V_{trans,\ 90\%} \leq$ 630 km/sec
$V_{trans,\ 95\%} \leq$ 872 km/sec



Gil-Merino, Wambsganss et al. (2005)

“Size is everything”:

Investigation of quasar luminosity profiles on microlensing fluctuations:
Uniform disks, Gaussian disks, “cones”, Shakura-Sunyaev models:

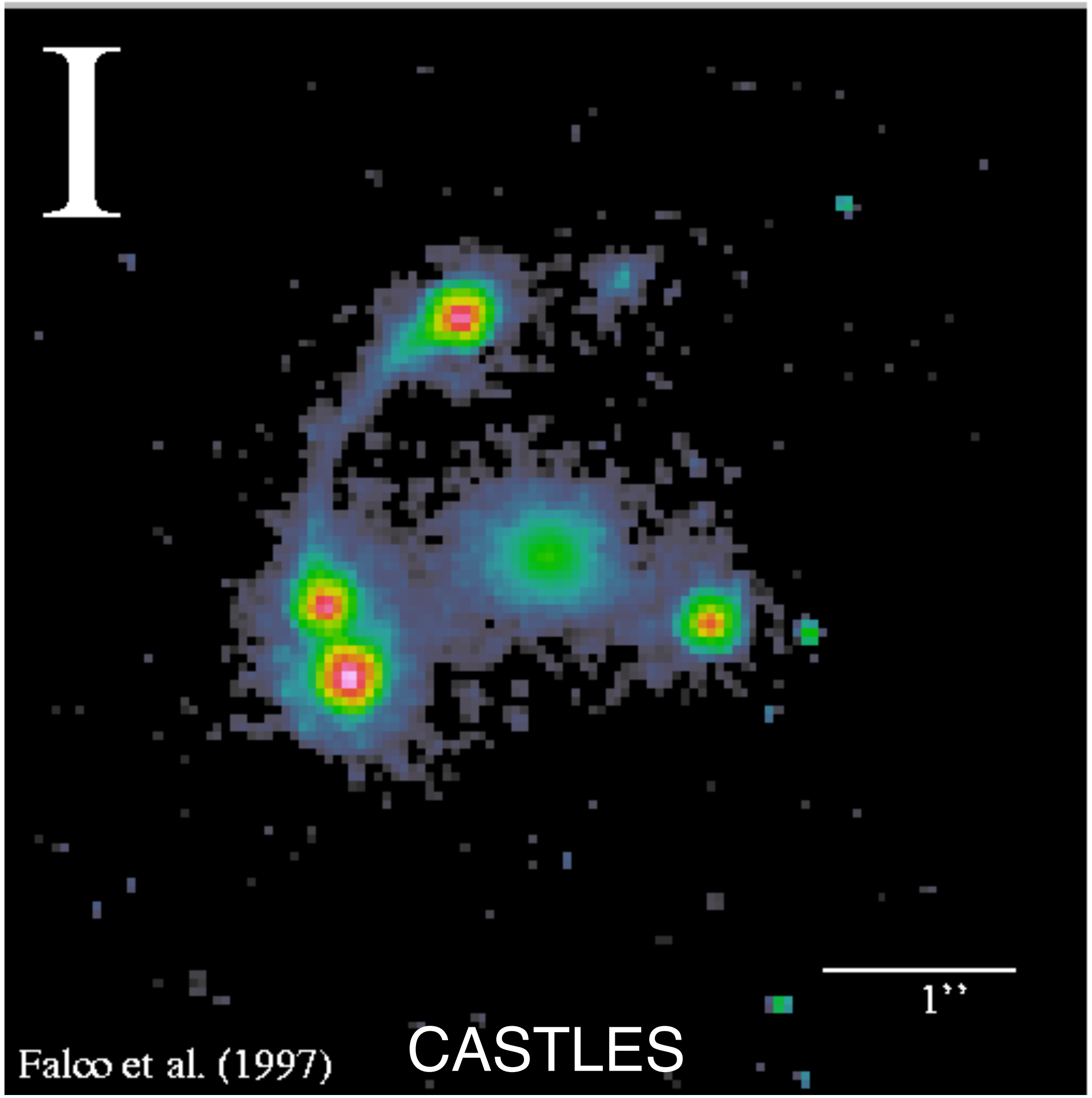


for circular disk models:

microlensing fluctuations are relatively insensitive to all properties of the models except the **half-light radius of the disk**

(Mortonson, Schechter & Wambsganss 2005)

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



MG0414+0534:

close pairs of bright images:

should be about equal in brightness

they are not!

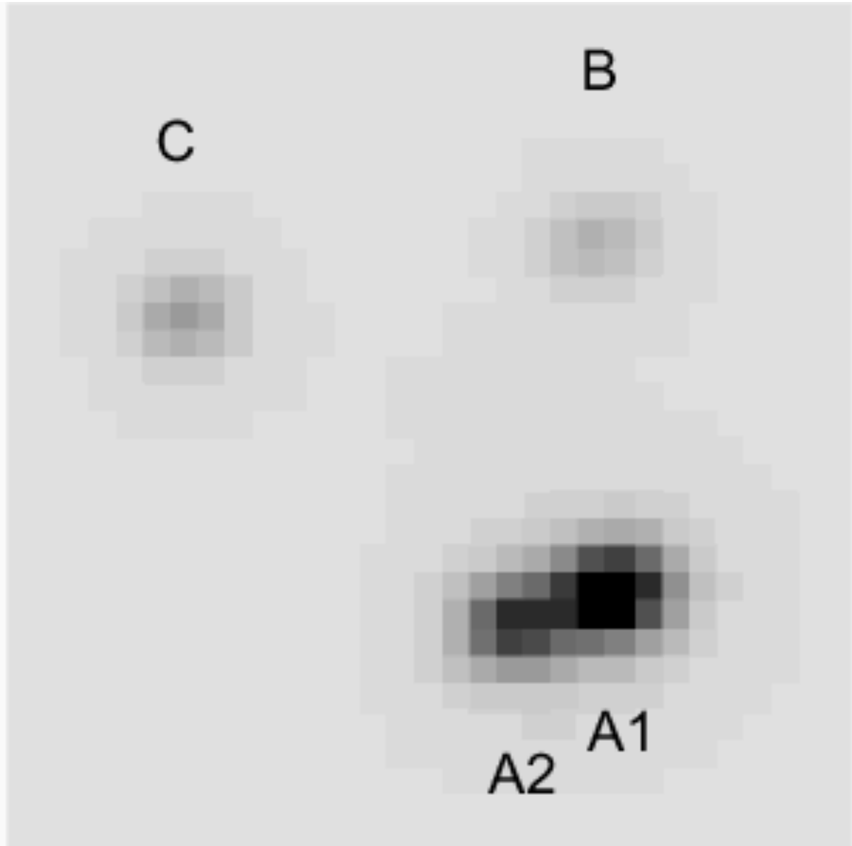
saddle point image demagnified!

at least 4 similar systems

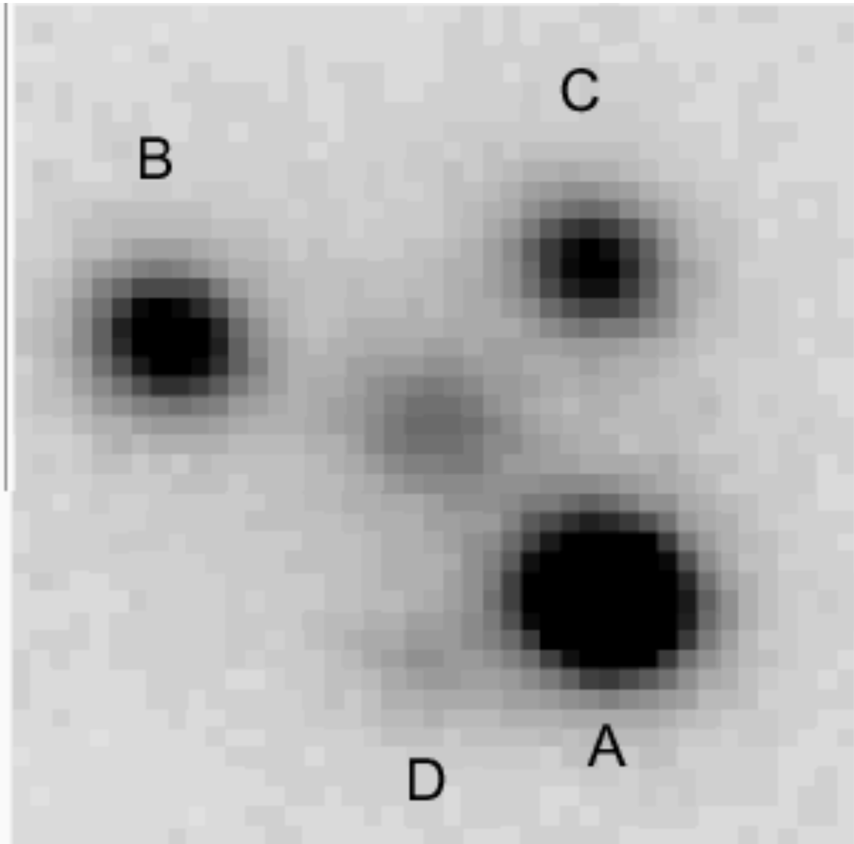
what's going on?!?

microlensing? substructure? DM ?

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)

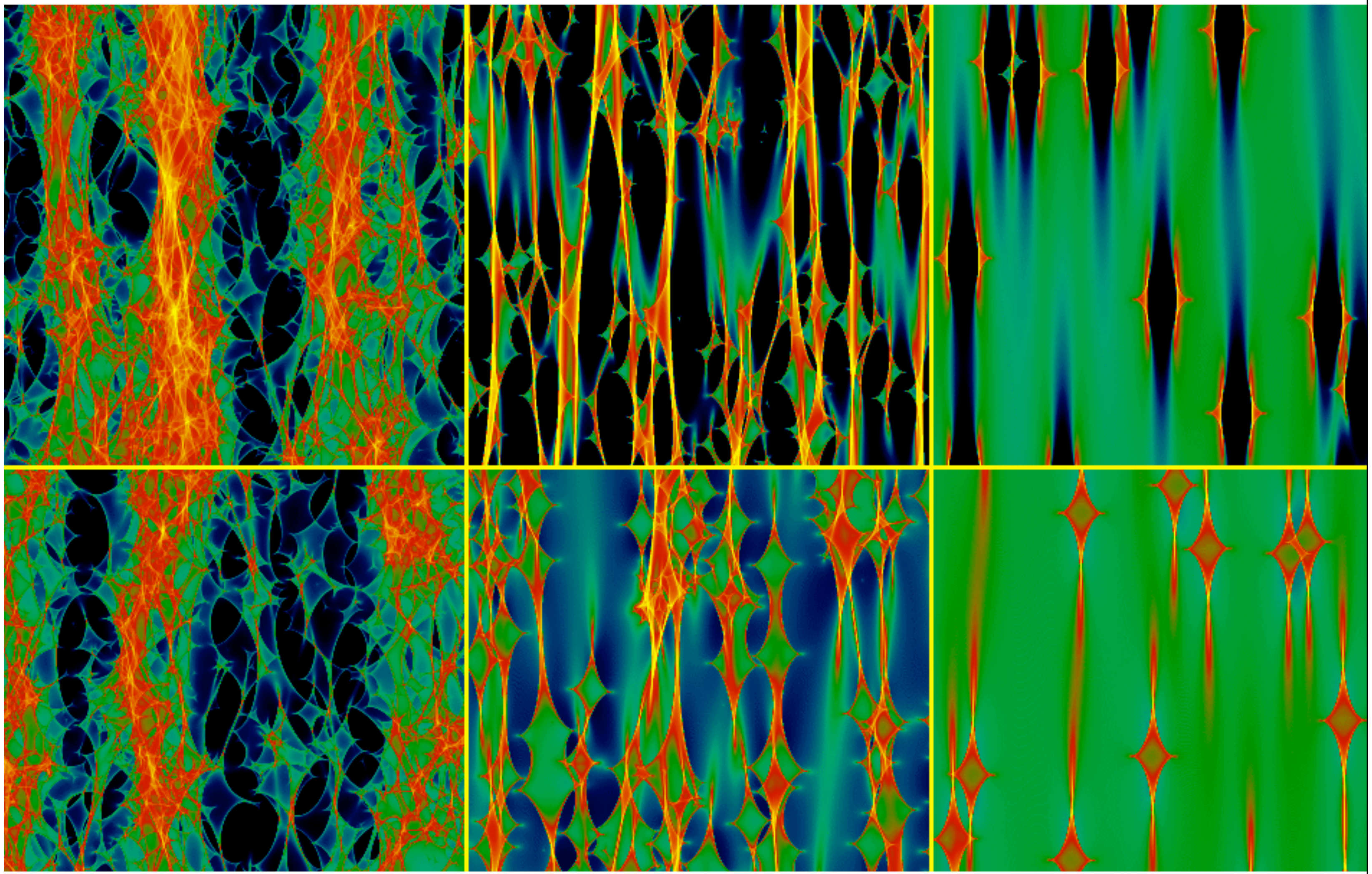
Quasar Microlensing at high magnification: suppressed saddlepoints and the role of dark matter (Schechter & Wambsganss 2002)

κ_{tot} = constant in horizontal rows

κ_{smooth} = 0% = 85% = 98%

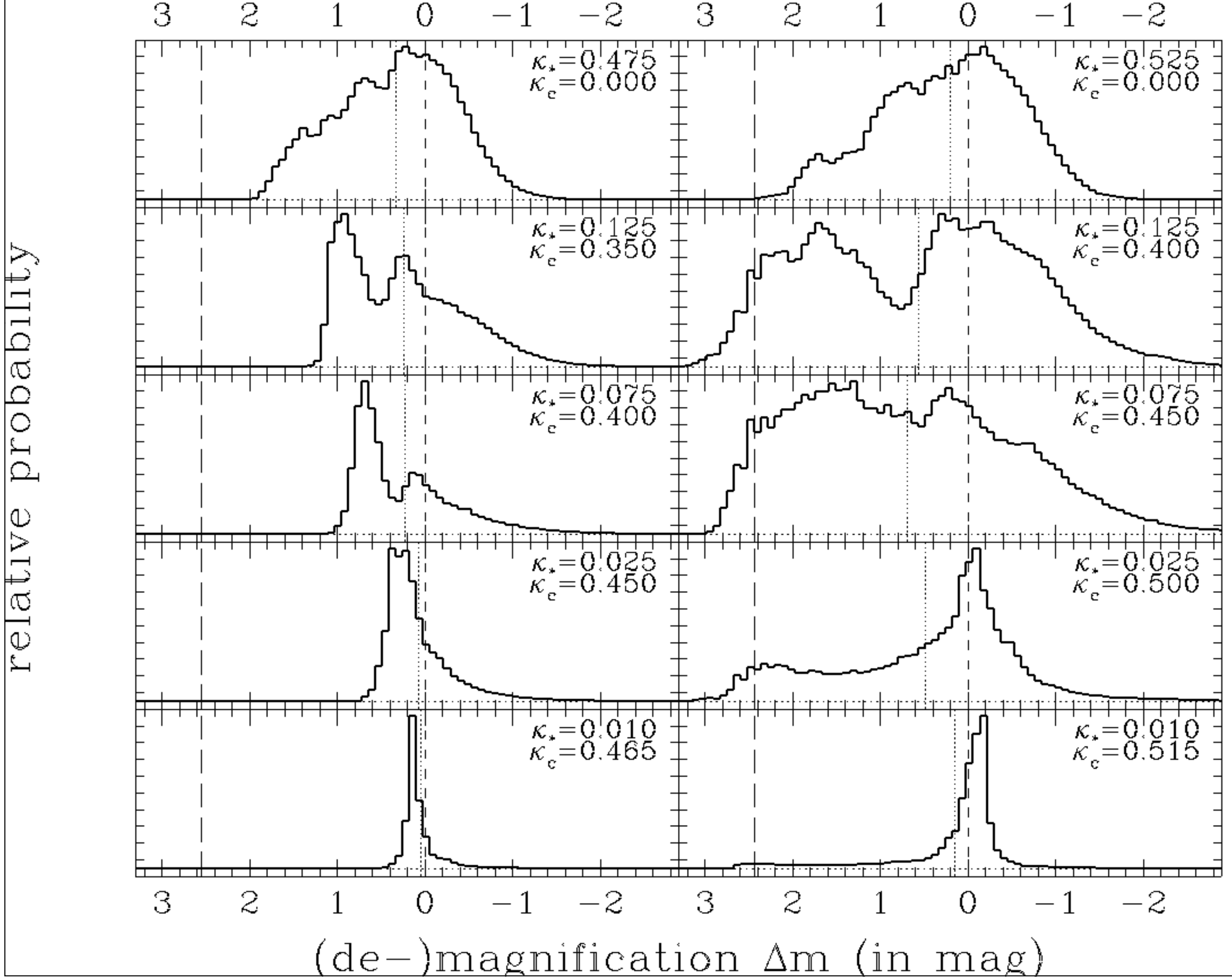
saddle point image:

minimum image:



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

minimum: saddle: κ_{tot} = const in columns



κ_{smooth} = 0%

= 85%

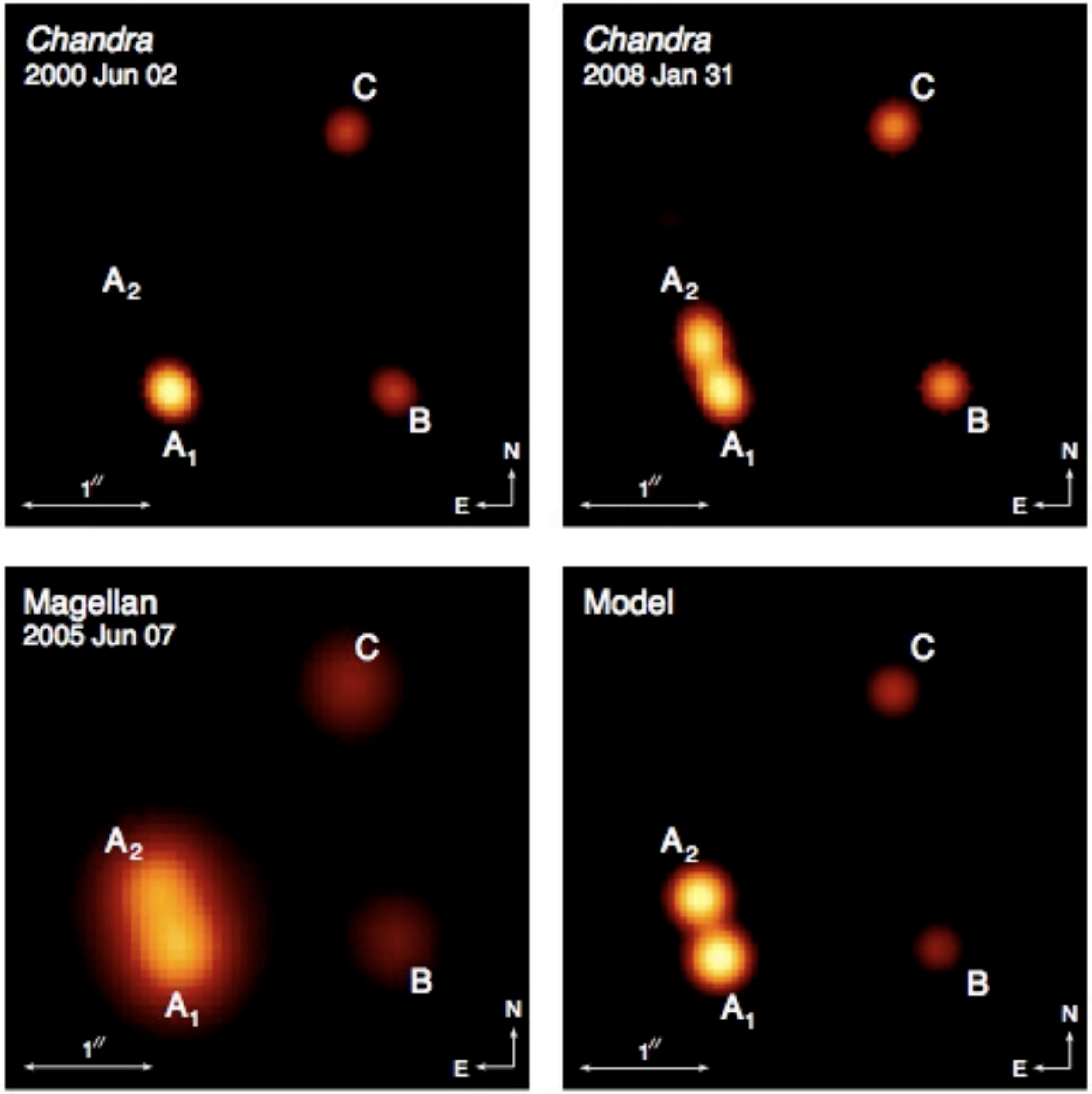
= 98%

The Dark-Matter Fraction in the Elliptical Galaxy Lensing the Quasar PG 1115+080

Pooley, Rappaport, Blackburne, Schechter, Schwab, Wambsganss; ApJ 697, 1892 (2009)

Determination of most likely dark-matter fraction in elliptical galaxy lensing quasar PG 1115+080:

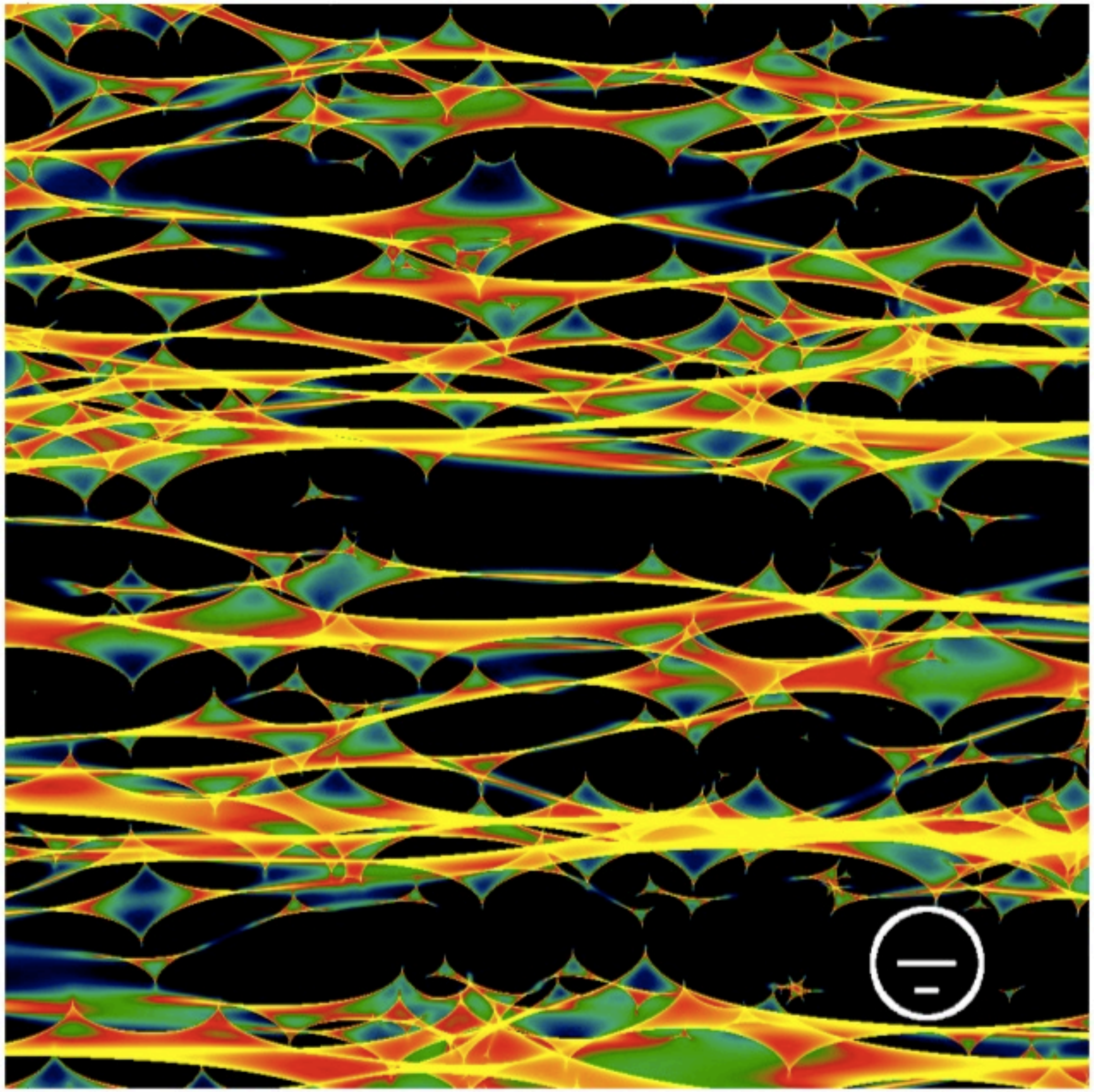
based on analyses of the X-ray fluxes of individual images in 2000 and 2008:



The Dark-Matter Fraction in the Elliptical Galaxy Lensing the Quasar PG 1115+080

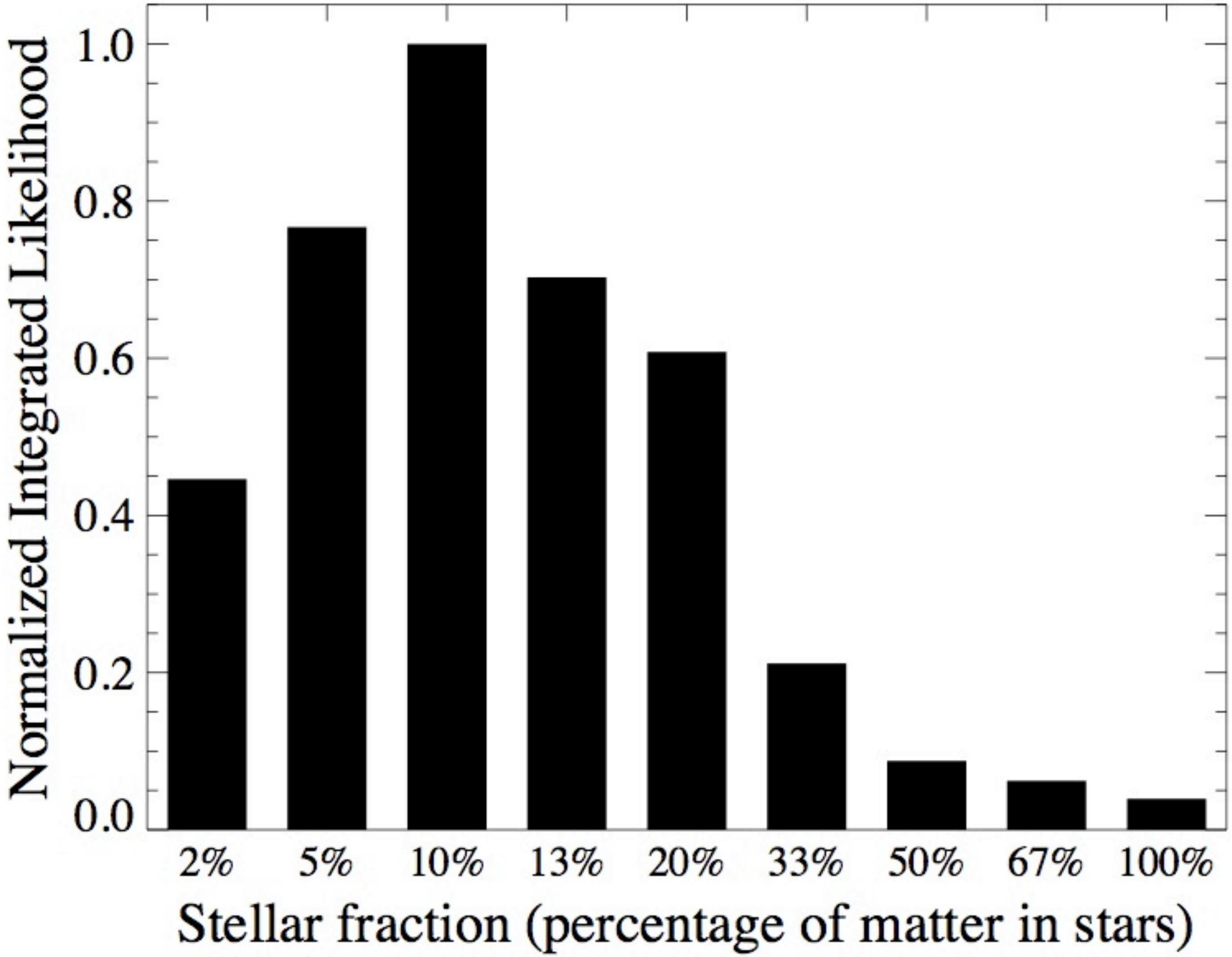
Pooley, Rappaport, Blackburne, Schechter, Schwab, Wambsganss; ApJ 697, 1892 (2009)

Microlensing magnification map for image A_2



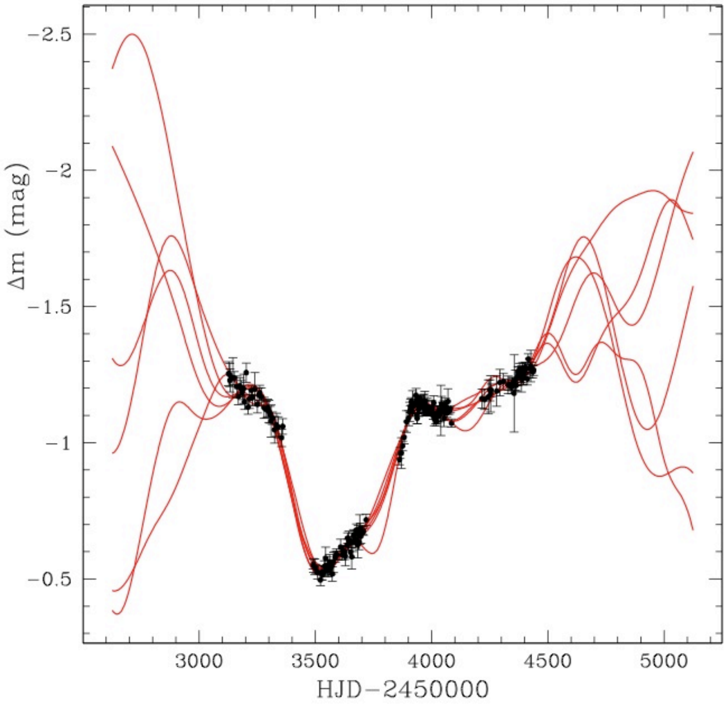
The Dark-Matter Fraction in the Elliptical Galaxy Lensing the Quasar PG 1115+080

Pooley, Rappaport, Blackburne, Schechter, Schwab, Wambsganss; ApJ 697, 1892 (2009)

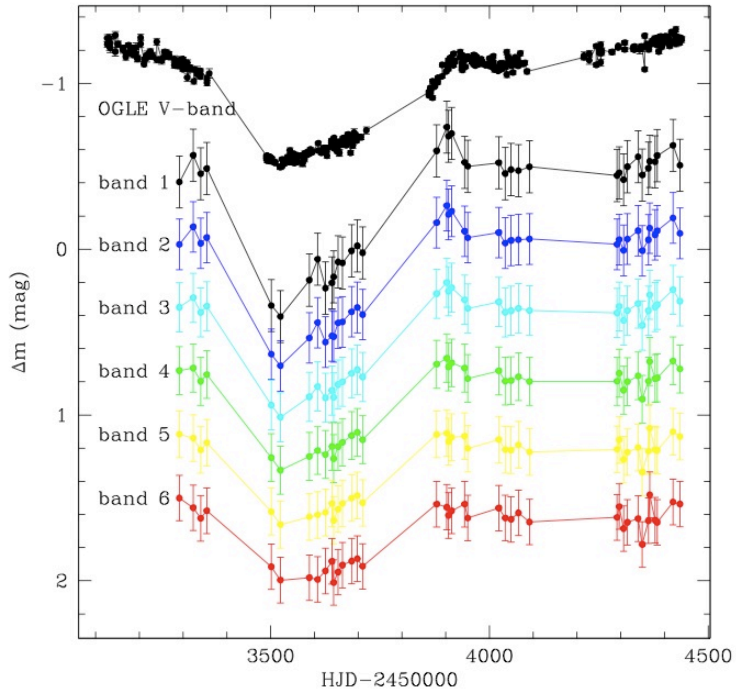


Accretion disk profile from quasar microlensing
(Eigenbrod et al. 2008)

studying chromatic variations in the UV/optical continuum of quadruple quasar Q2237+0305, images A and B,



OGLE V-band data, fitted with different microlensing lightcurves

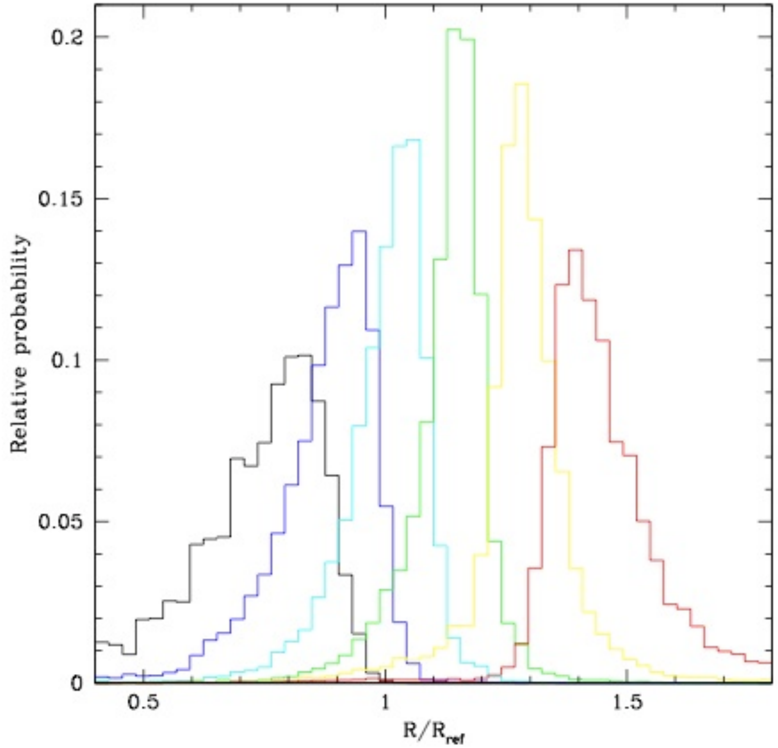


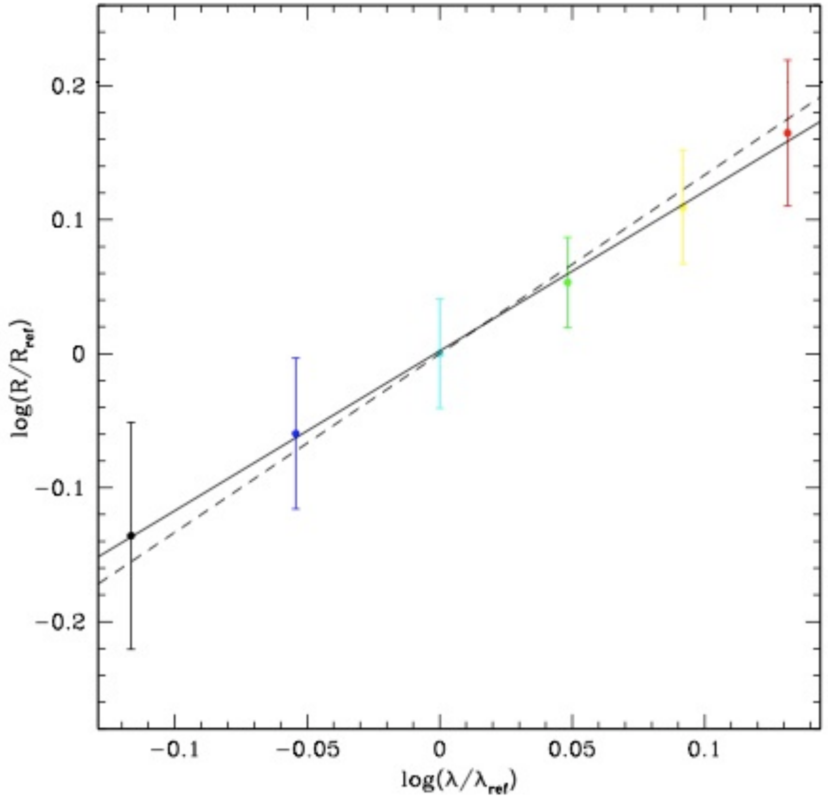
our spectroscopic data, reproduced as 6 “filters”:

39 epochs of spectrophotometric monitoring

Accretion disk profile from quasar microlensing
(Eigenbrod et al. 2008)

source FWHM ratio R_i / R_{ref} as a function of $\lambda_i / \lambda_{ref}$



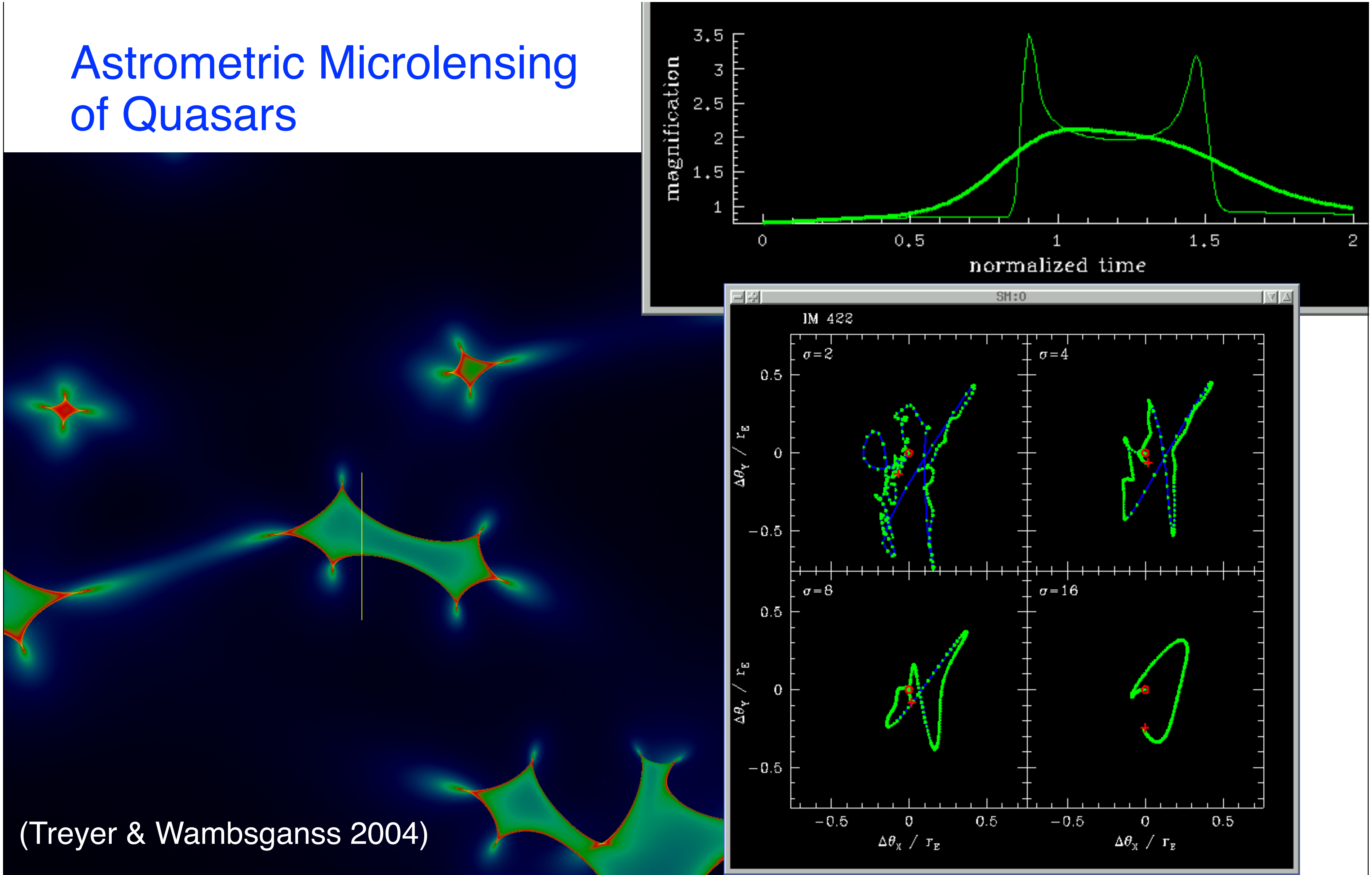


Dashed line relation for the standard optically thick & geometrically thin accretion disk model (Shakura-Sunyaev)

$$T \propto R^{-3/4} \rightarrow R \propto T^{-4/3} \propto \lambda^{4/3}$$

our best fit for: $R \propto \lambda^{\zeta} \rightarrow \zeta = 1.2 \pm 0.3$

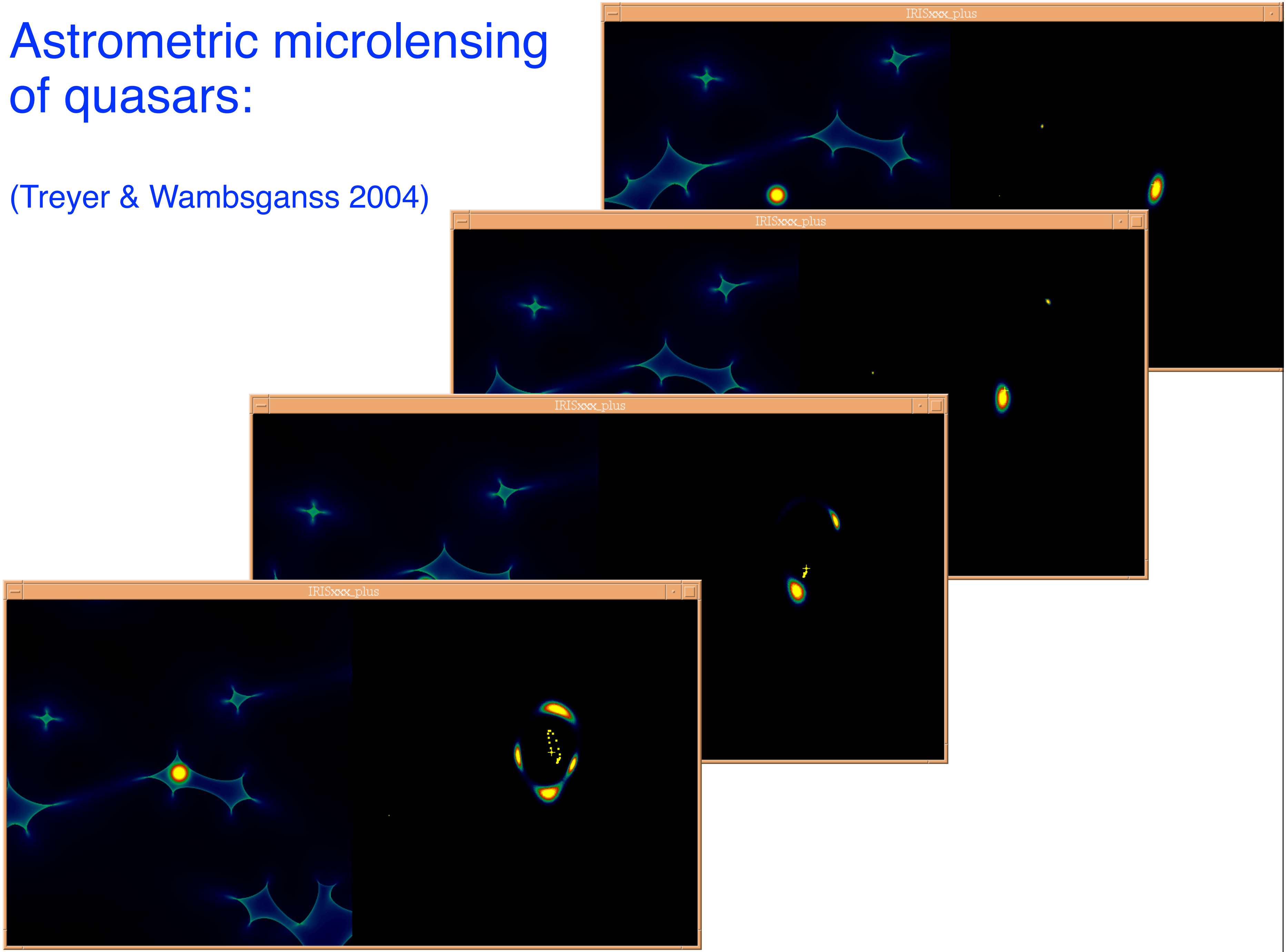
Astrometric Microlensing of Quasars



(Treyer & Wambsganss 2004)

Astrometric microlensing of quasars:

(Treyer & Wambsganss 2004)



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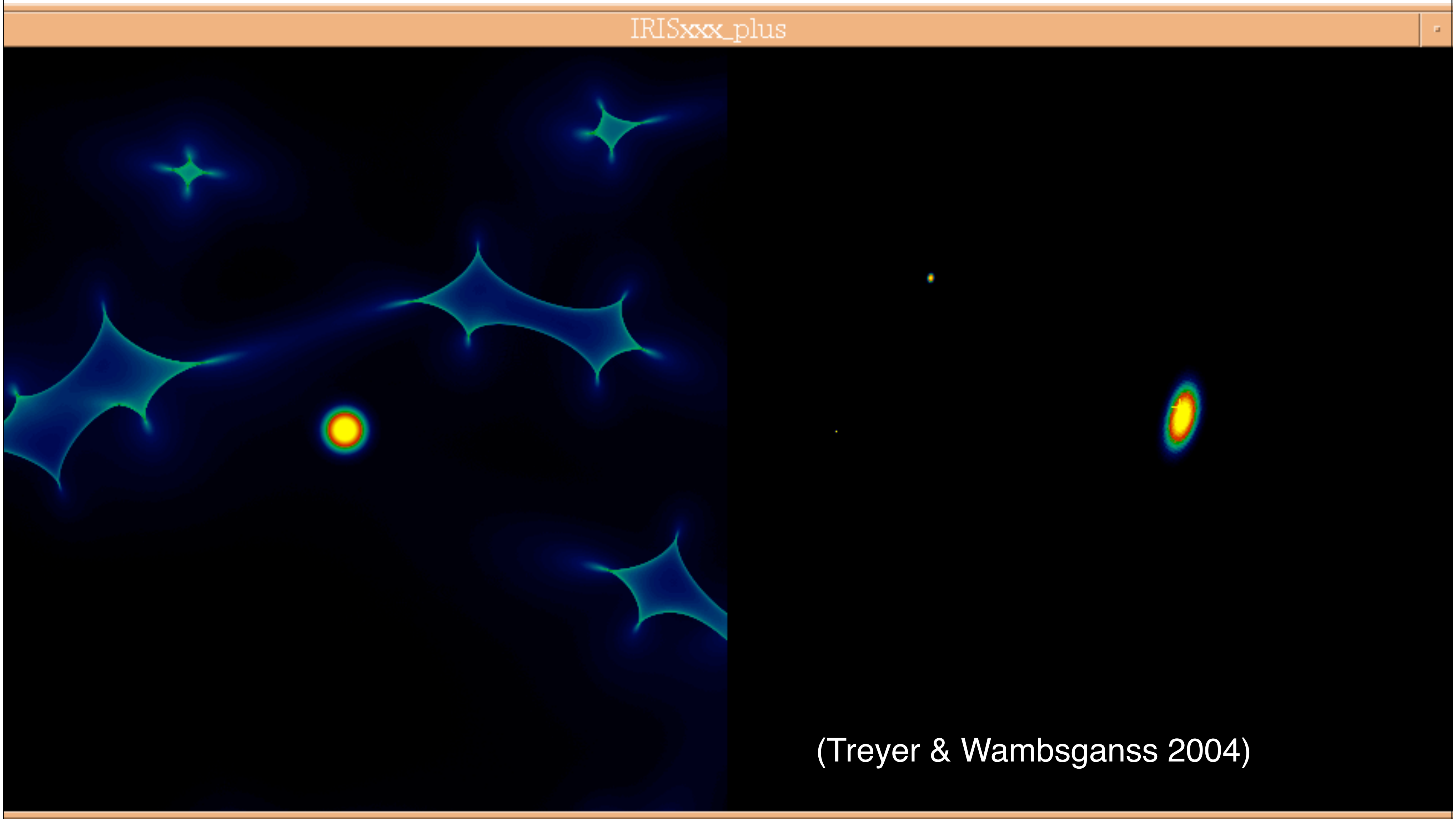

Microlensing of distant Quasars: Summary

Joachim Wambsganss

Quasar microlensing has developed into a very useful astrophysical tool for exploring:

- size and surface structure of quasar accretion disk
- effects (masses, motions) of compact objects along line of sight
- detection and quantification of smoothly distributed (dark) matter