Microlensing and Compact Objects in Galaxies

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“Applications of Gravitational Lensing”
KITP, Santa Barbara
October 4, 2006

Microlensing and Compact Objects in Galaxies

- What is **microlensing**?
  mass scales, angular scales, time scales
- Why is **microlensing** relevant for astrophysics?
  lens/source, qualitative/quantitative, light/dark, near/far, stellar/quasar
- How can we observe **microlensing**?
  photometric, spectroscopic, astrometric microlensing
- Which are the interesting **microlensing** results?
  - quasar microlensing: quasar size, compact (cold) dark matter
  - stellar microlensing: (no) machos, star structure, cool dark matter
- What is the future of **microlensing**?
  unique, useful, universal

What is Microlensing?

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" ?

$\Rightarrow$ (much) smaller than Einstein radius

what are the "distant sources"?

$\Rightarrow$ quasars, stars

What is Microlensing?

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:

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

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

1936 Einstein: "Lens-like action of a star by the deviation of light in the gravitational field”

1986 Paczynski: "Gravitational Lensing by the Galactic Halo"

1991 Mao & Paczynski: "Gravitational microlensing by double stars and planetary systems”

1993 Alcock et al. (MACHO team): "Possible gravitational microlensing of a star in the Large Magellanic Cloud”

1993 Aubourg et al. (EROS team): "Evidence for gravitational microlensing by dark objects in the Galactic halo”

1993 Udalski et al. (OGLE team): "The optical gravitational lensing experiment. Discovery of the first candidate microlensing event in the direction of the Galactic Bulge halo”

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"

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

How can we observe microlensing ?

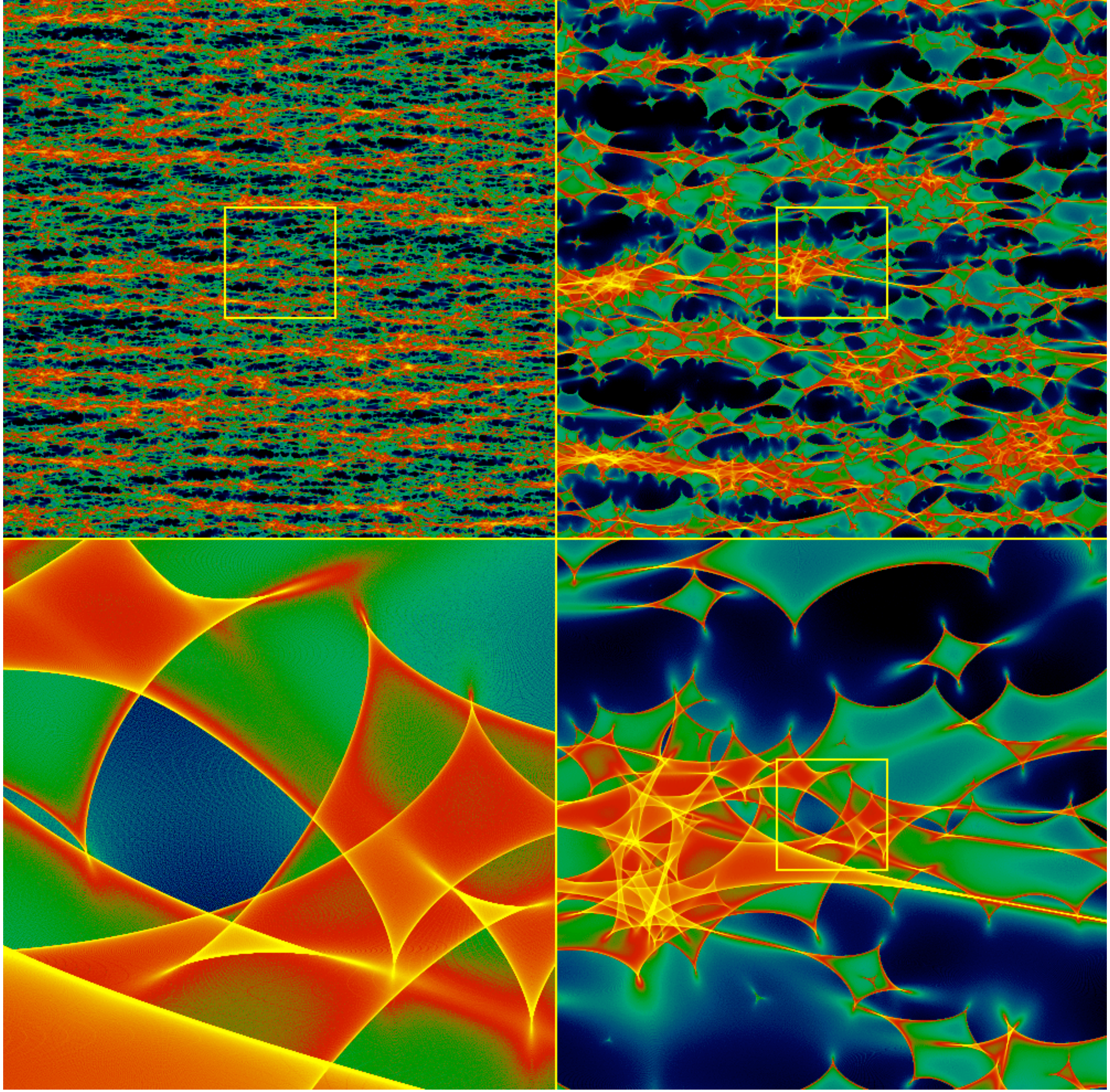
Direct imaging? impossible:

Einstein angle << telescope resolution; however:

- magnification, line shape, position change with time due to relative motion of source, lens and observer: microlensing is a **dynamic** phenomenon! Observable:
  - **photometrically**
  - spectroscopically
  - astrometrically
- what are the relevant time scales? ($z_L = 0.5$, $z_S = 2.0$)

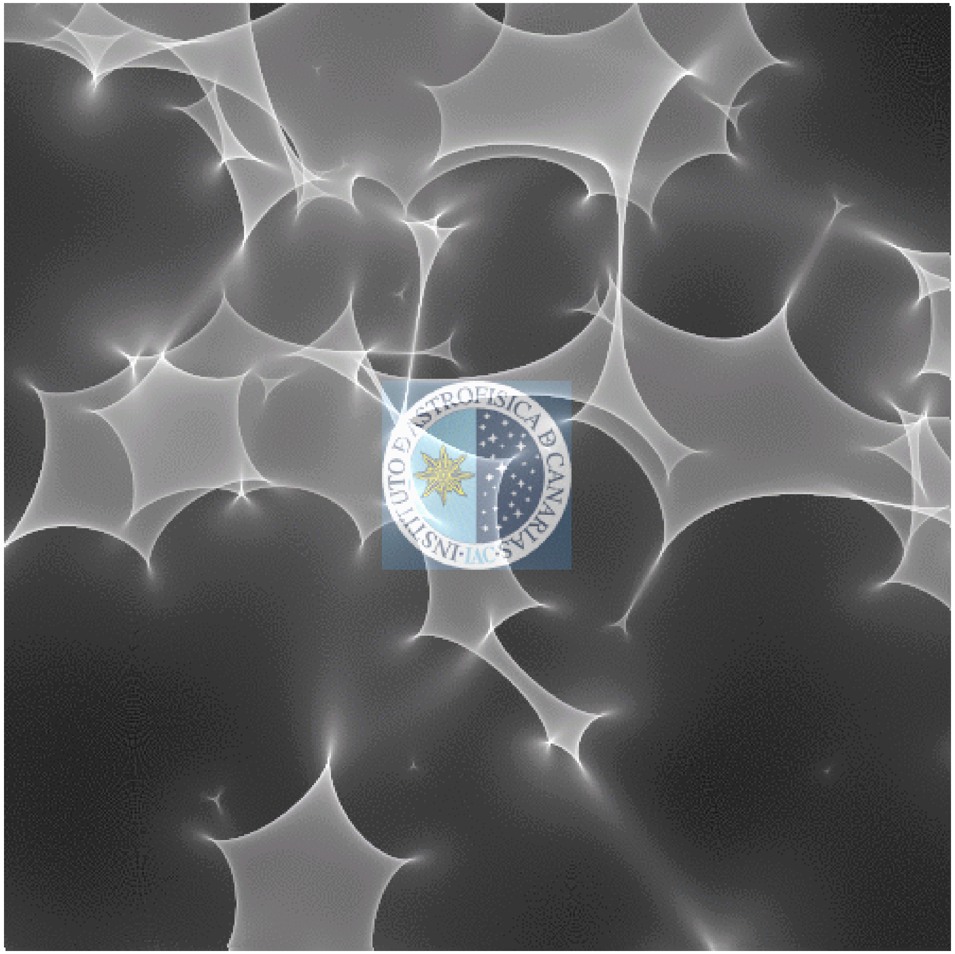
Einstein time: $$t_E = r_E / v_\perp \approx 15 \sqrt{\frac{M}{M_\odot}}\; v_{600}^{-1} \text{ years}$$

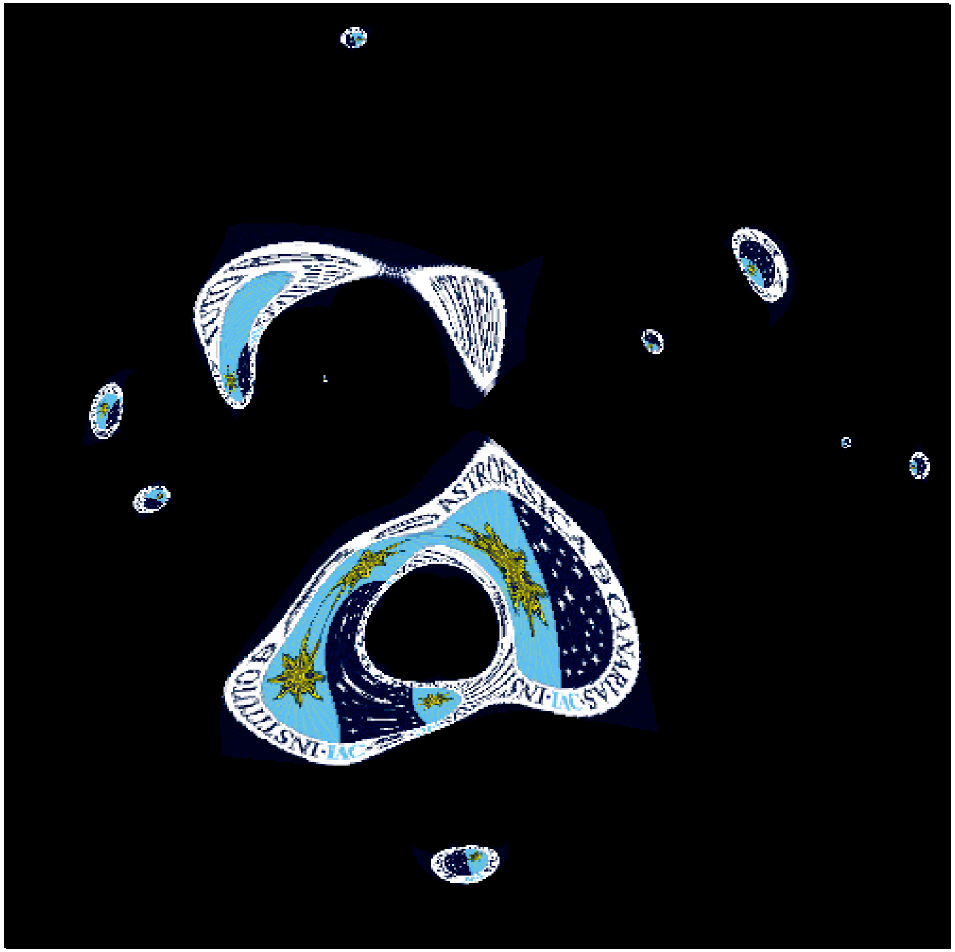
Crossing time: $$t_{cross} = R_{source} / v_\perp \approx 4 R_{15} v_{600}^{-1} \text{ months}$$



(from Wambsganss, Paczynski, Schneider 1990)

Quasar Microlensing





Quasar microlensing:

Quasar variability due to microlensing reveals:

- Effects of compact objects along the line of sight
- Size of quasar
- Two-dimensional brightness profile of quasar
- Mass (and mass function) of lensing objects
- Detection of smoothly distributed (dark) matter

Quasar microlensing

A few highlights:

– Quadruple Q2237+0305: source size, $v_{transverse}$

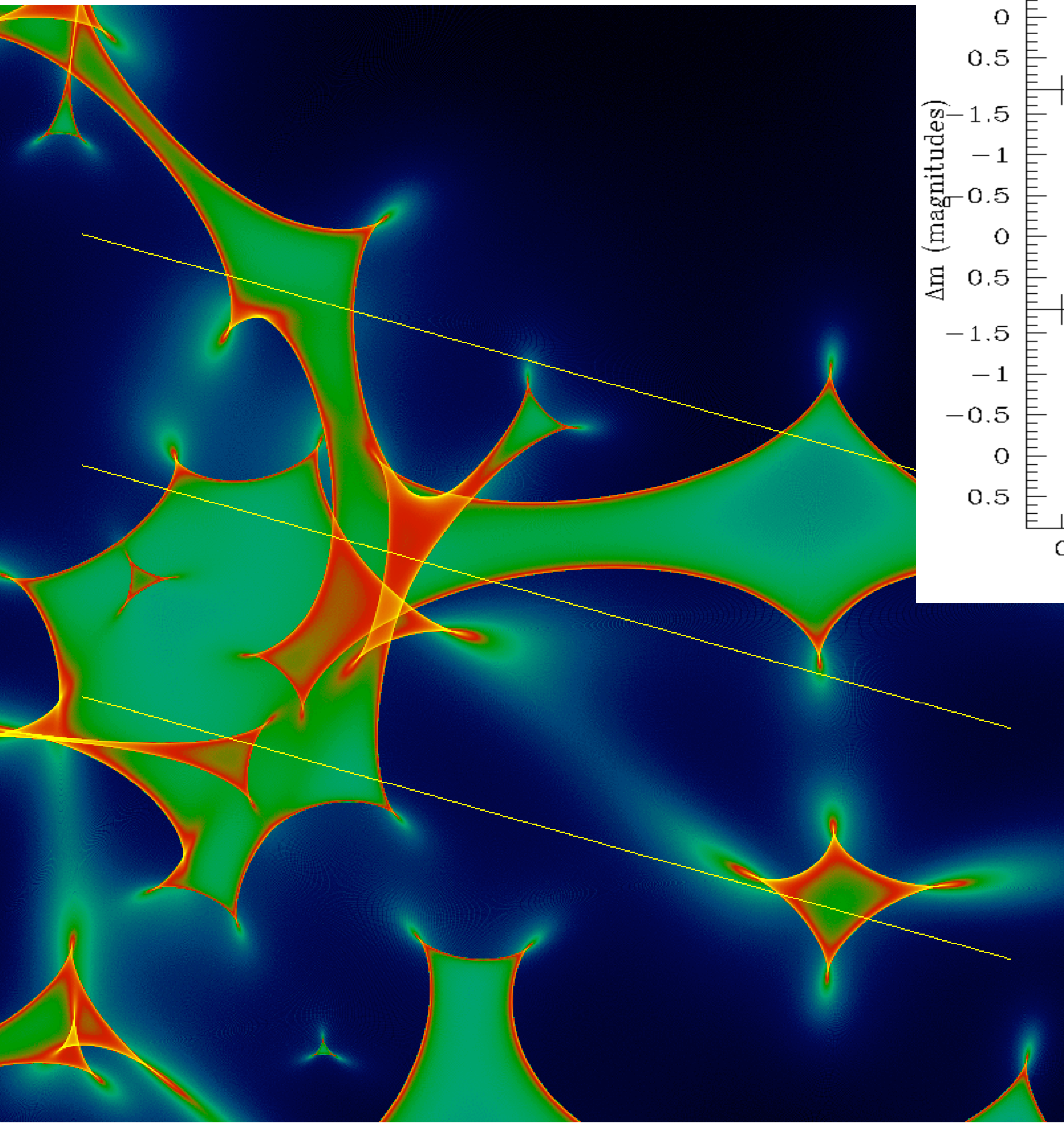
– Double Q0957+561: limits on machos

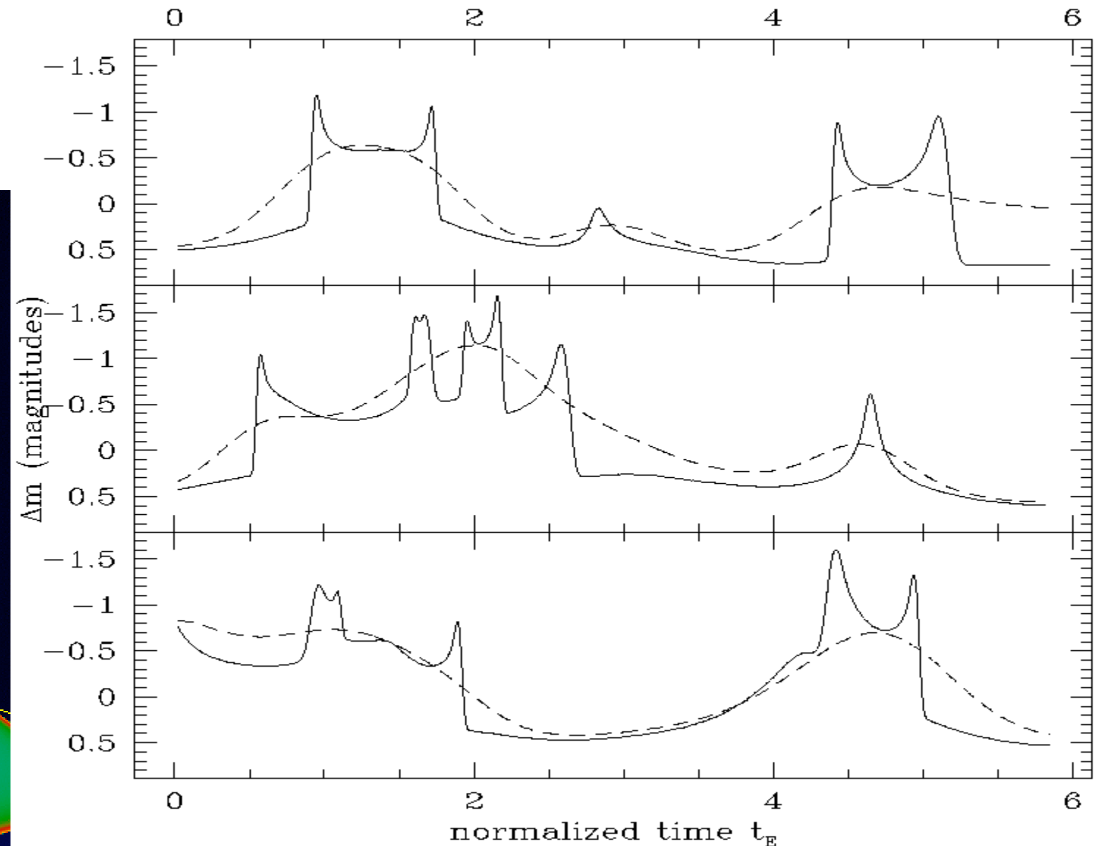
– Flux anomaly: Microlensing can do it

– “Odd” images

– Size is everything

Source size effect in quasar microlensing:





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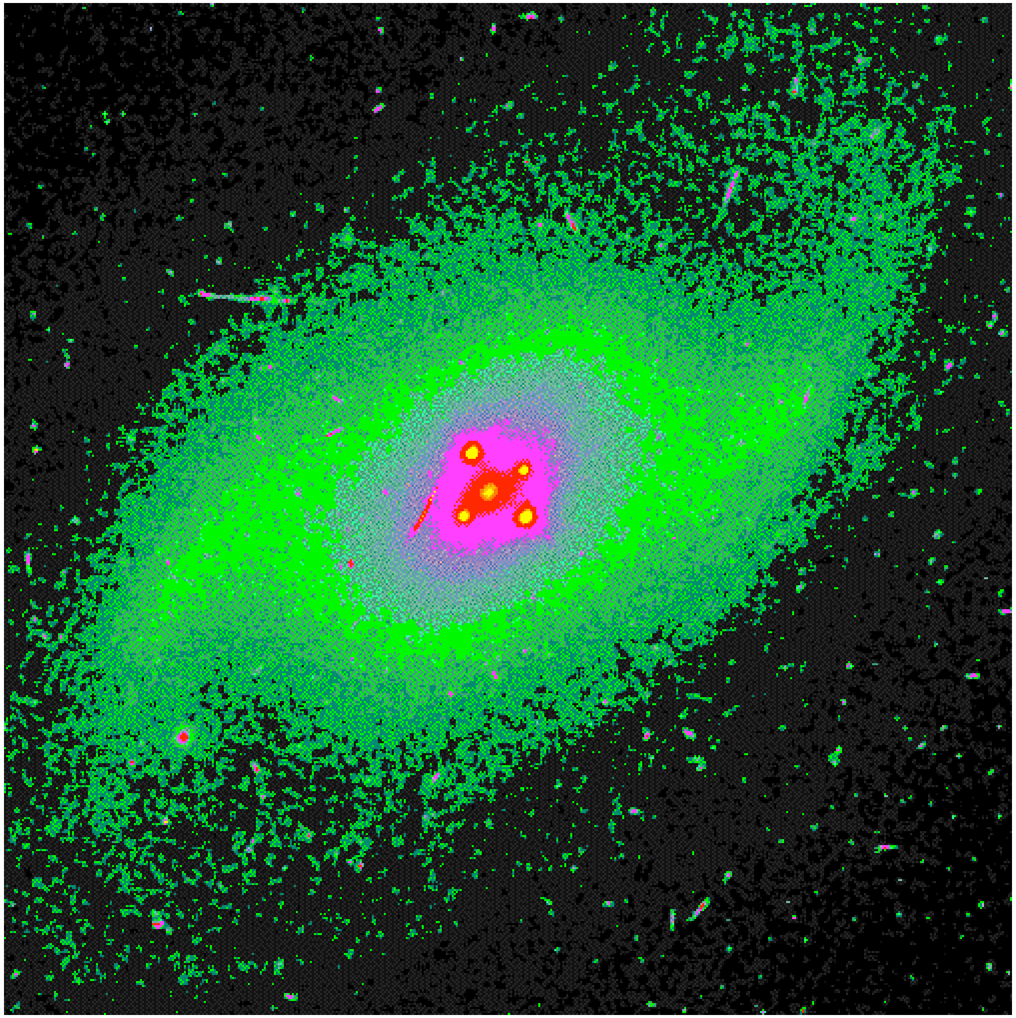
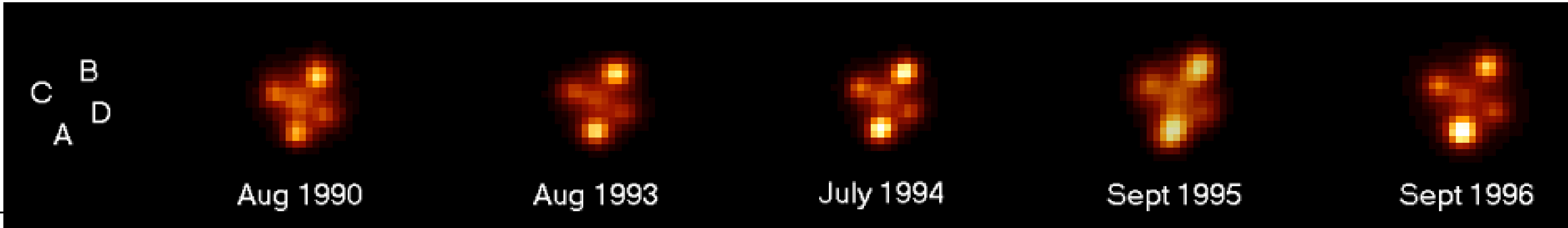
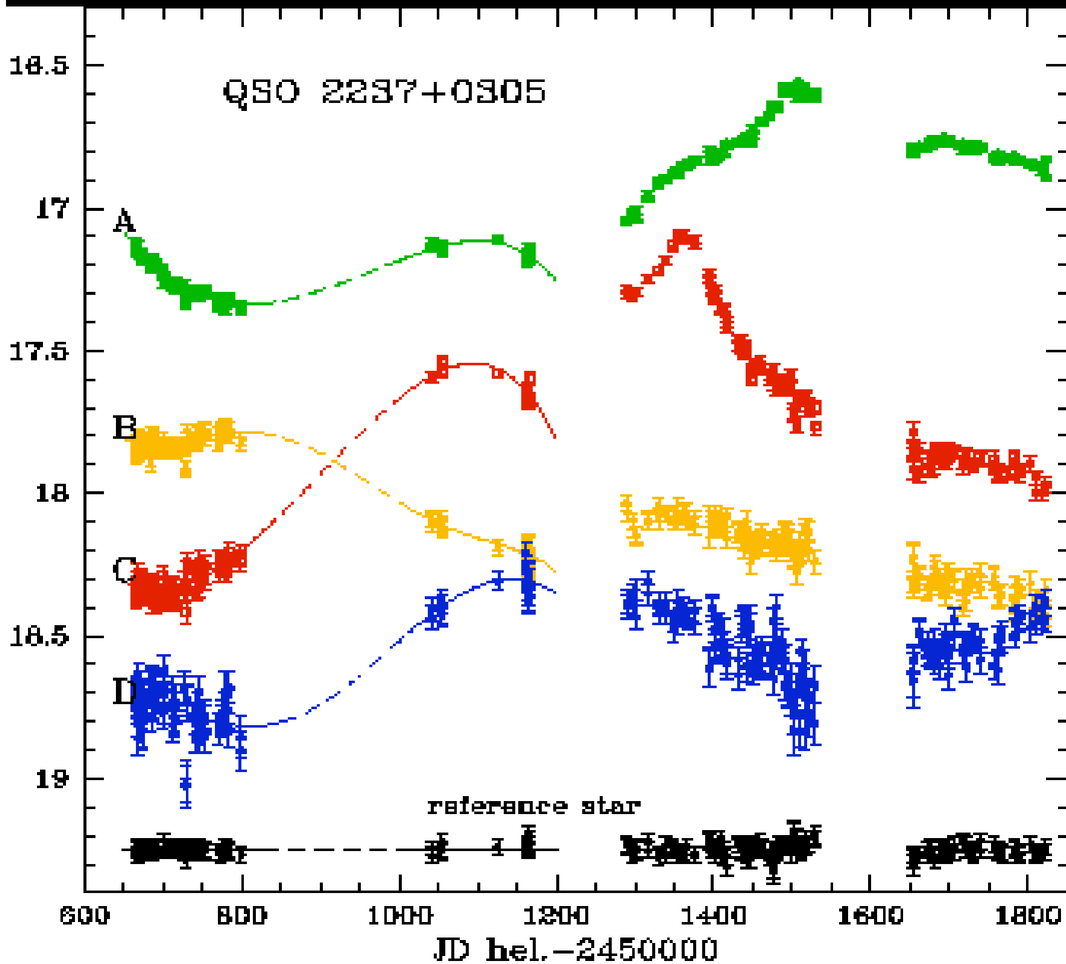
The quadruple quasar Q2237+0305



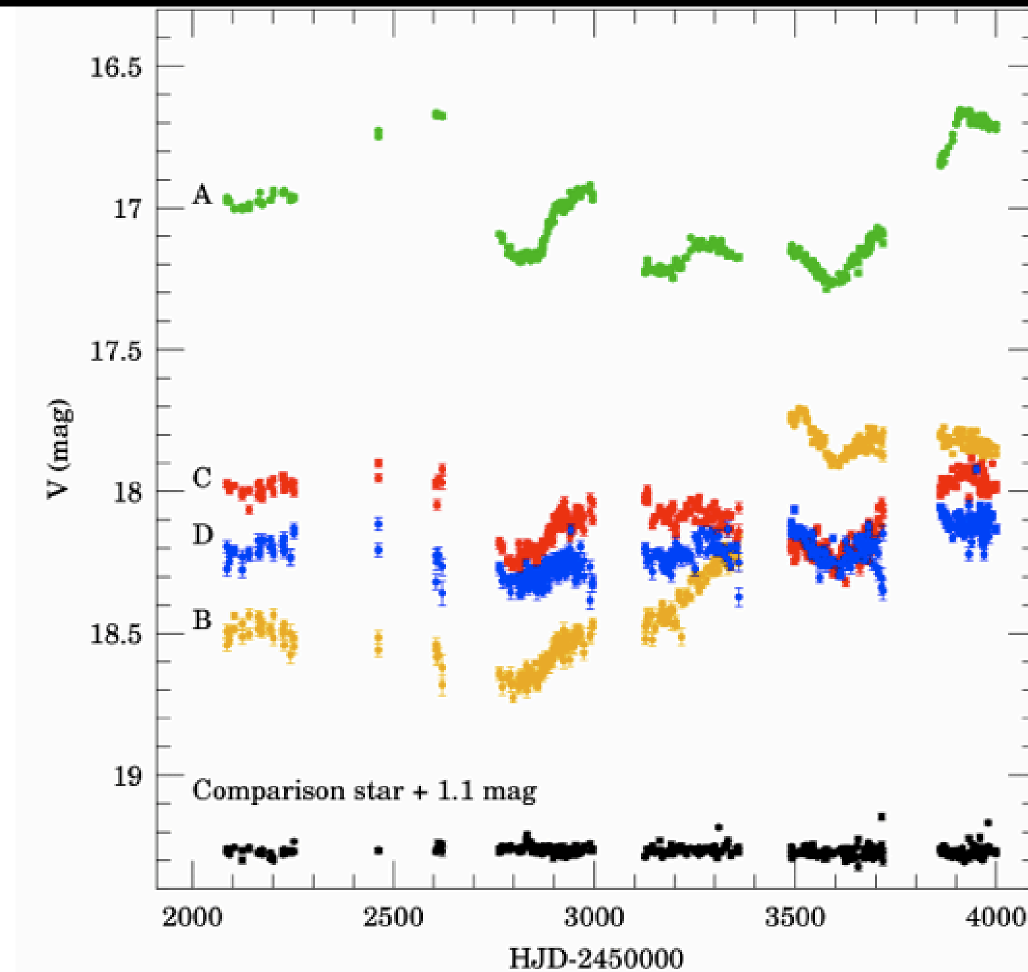
z(quasar) = 1.695, z(galaxy) = 0.039
image separation 1.7 arcsec (HST)

Quasar Microlensing: Q2237+0305





Wozniak et al. 2000 (OGLE)

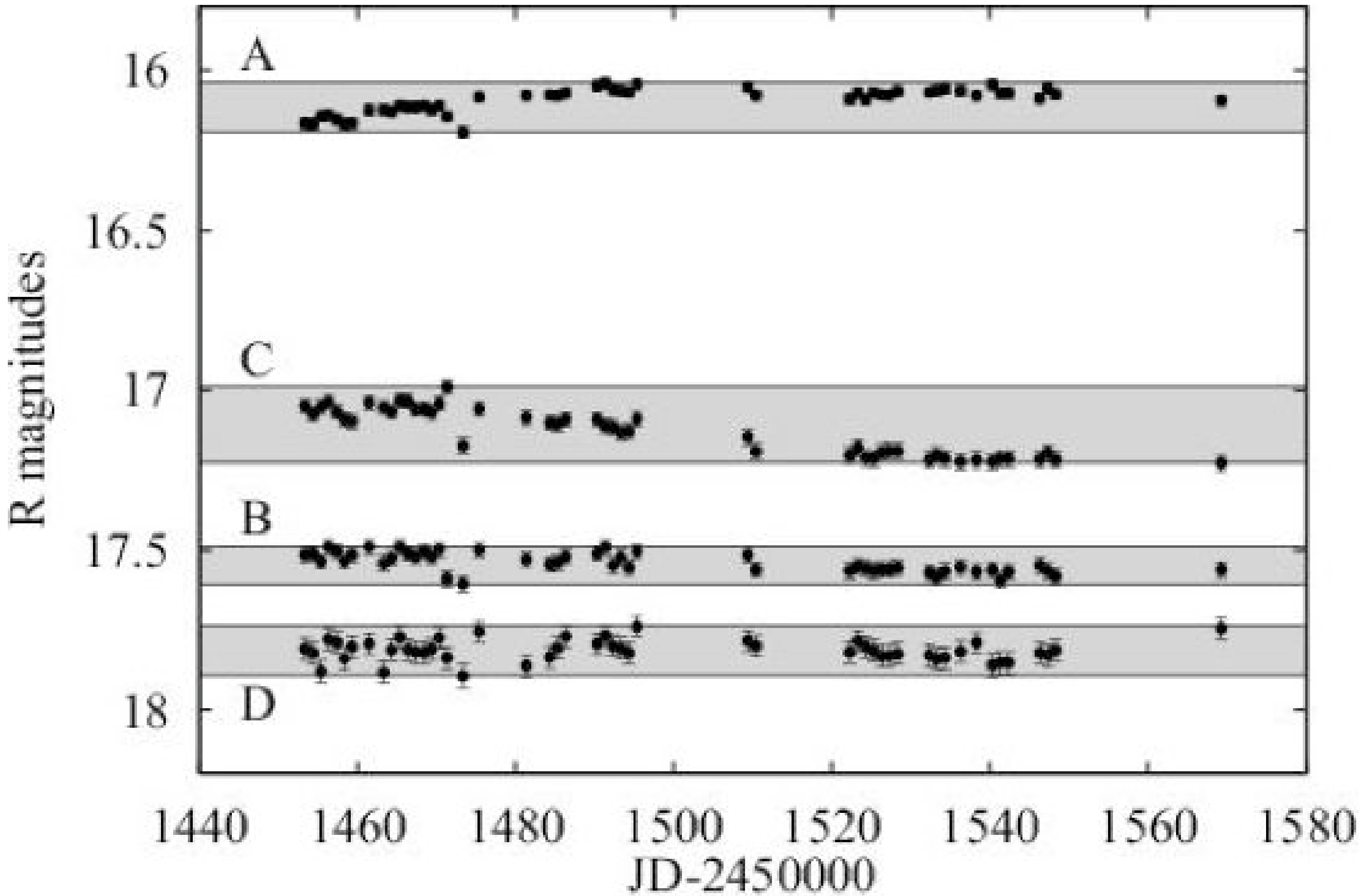


OGLE Web page

Quasar Microlensing: Q2237+0305

Monitoring campaign: 6 months in 2000

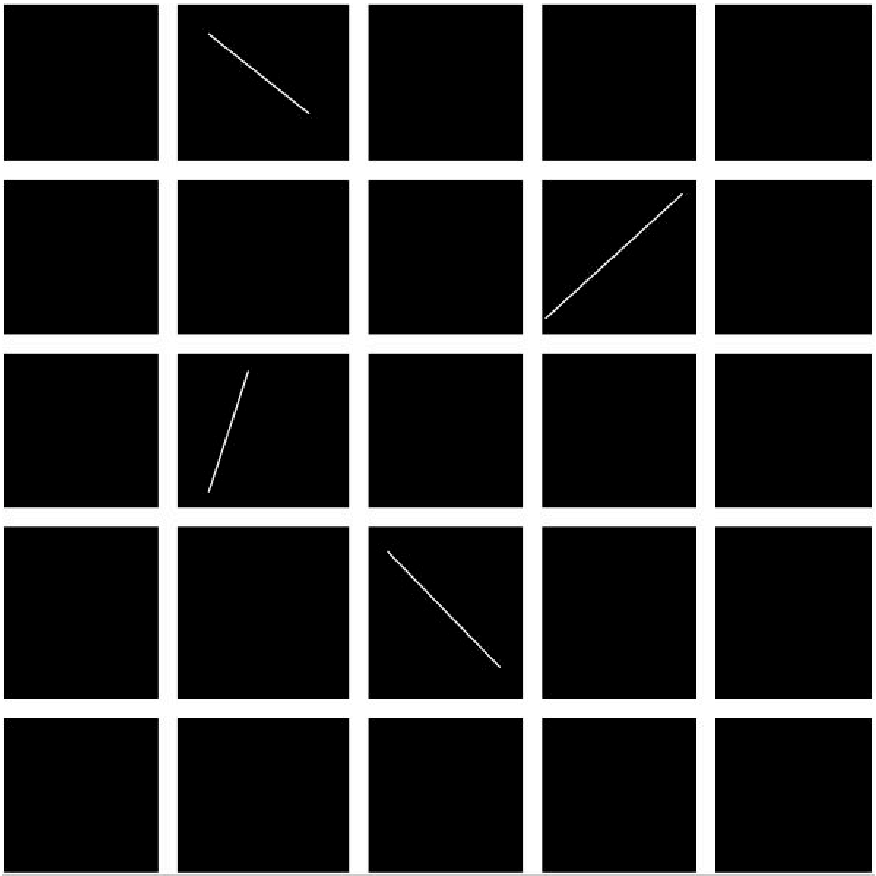
GLITP - Gravitational Lens International Time Project

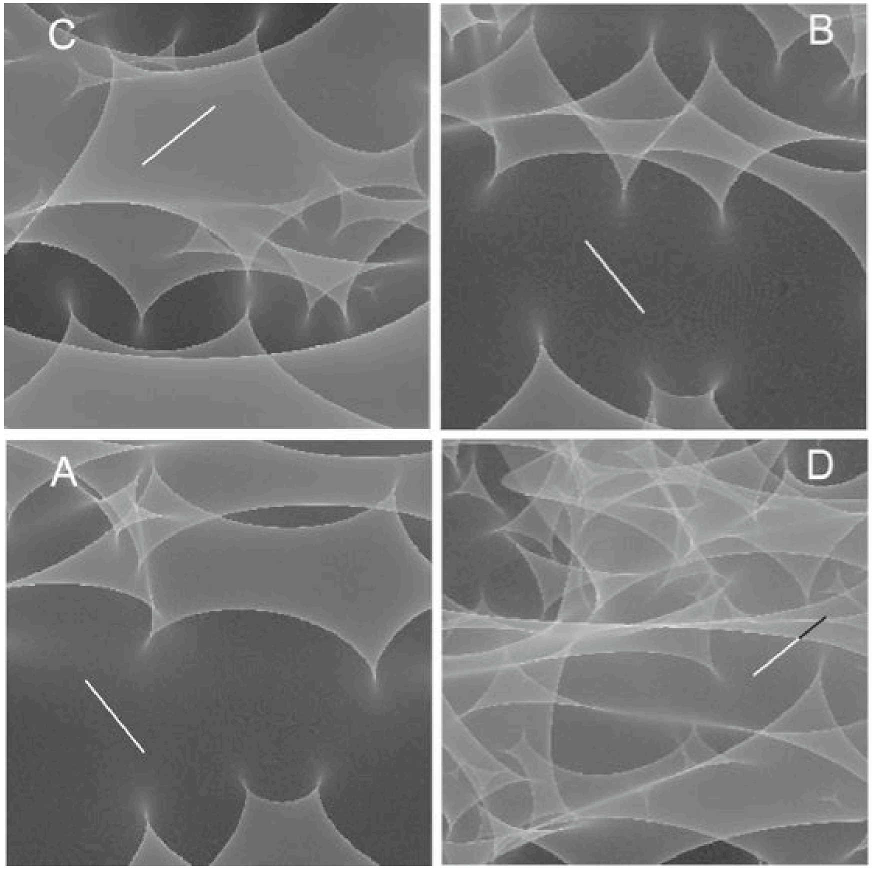


Quasar Microlensing: Q2237+0305

Limits on transverse velocity of lensing galaxy:

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





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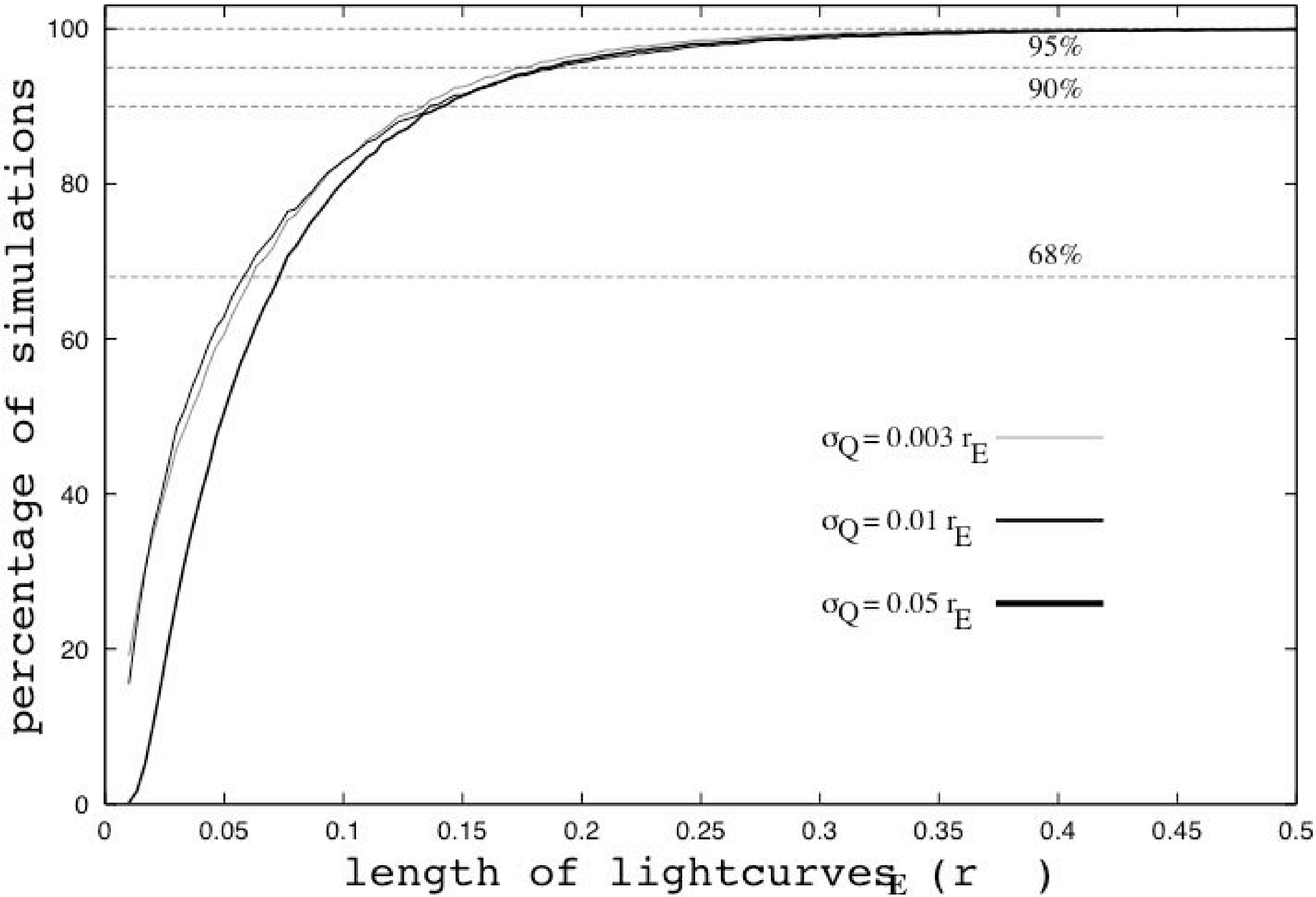
Quasar Microlensing: Q2237+0305



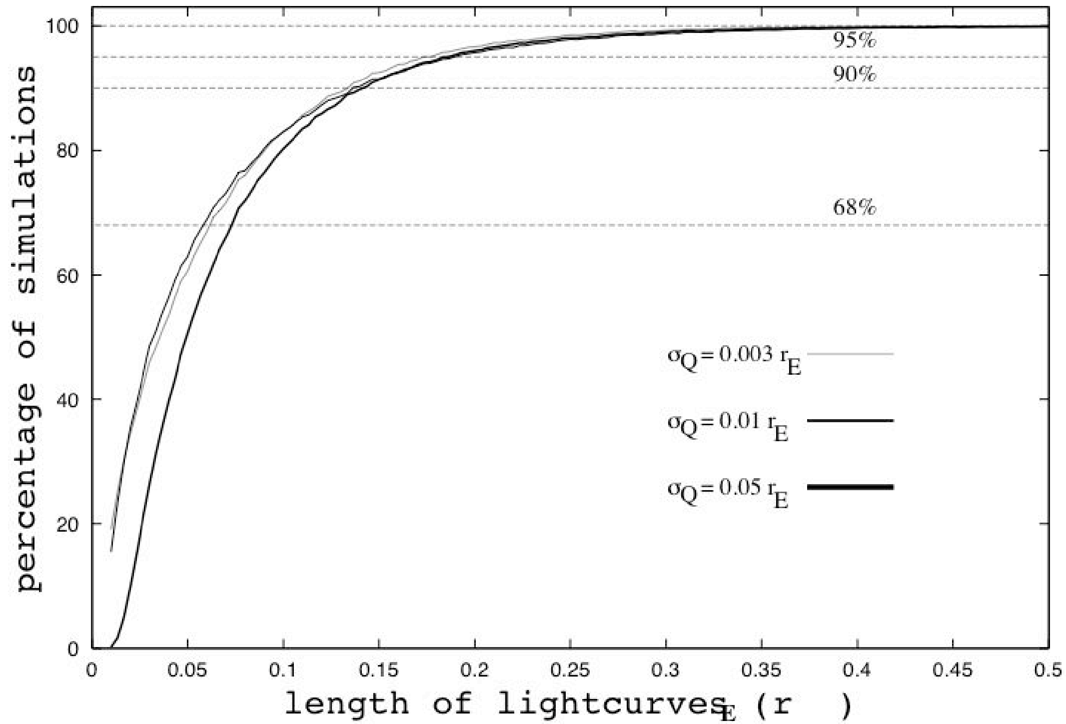
Gil-Merino, Wambsganss et al. (2005)

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

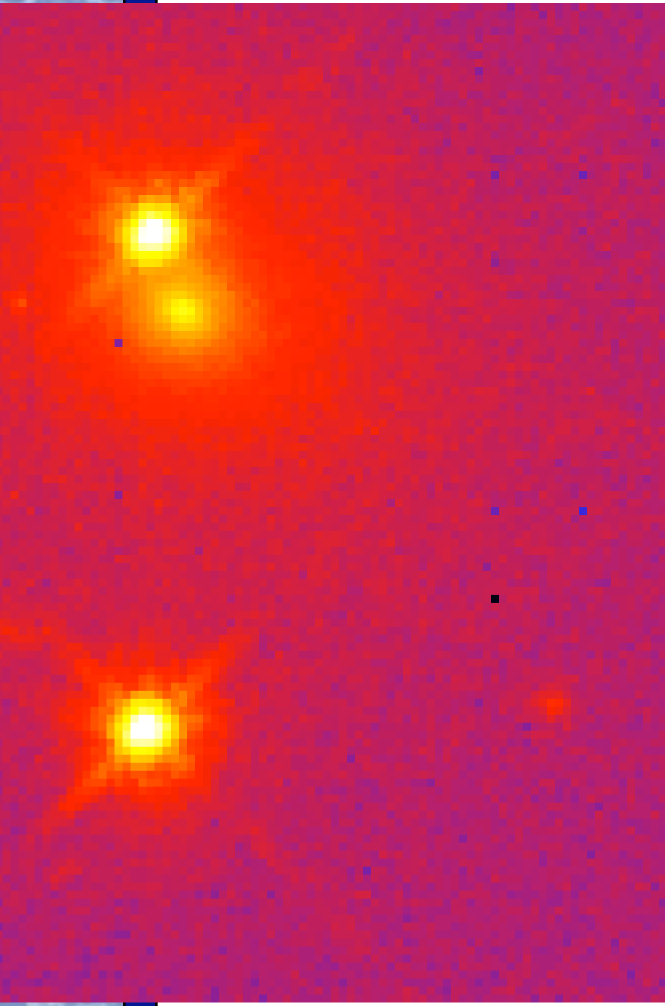


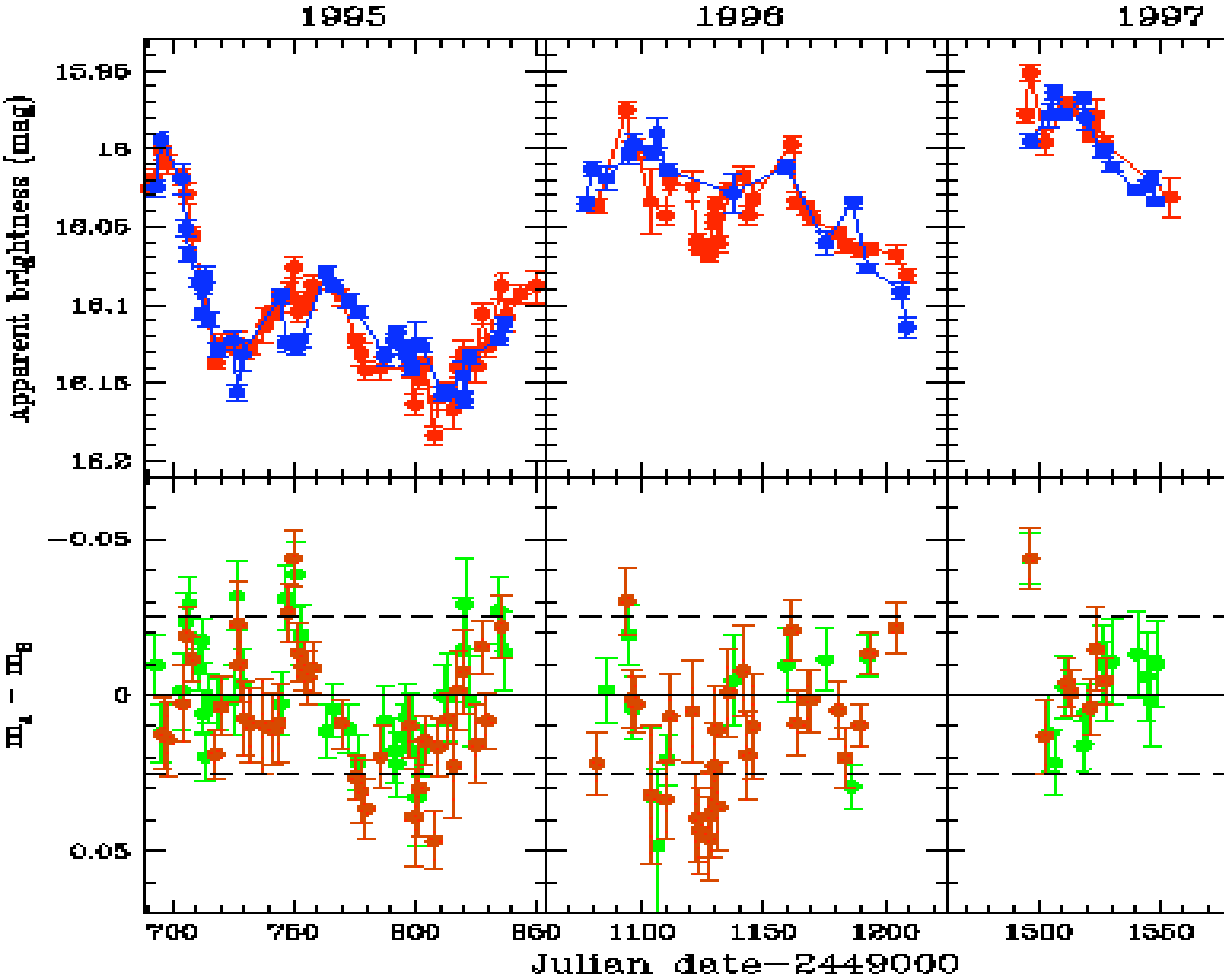
<u>$M = 0.1\,M_\odot$:</u>

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

Gil-Merino, Wambsganss et al. (2005)

Quasar Microlensing? Q0957+561





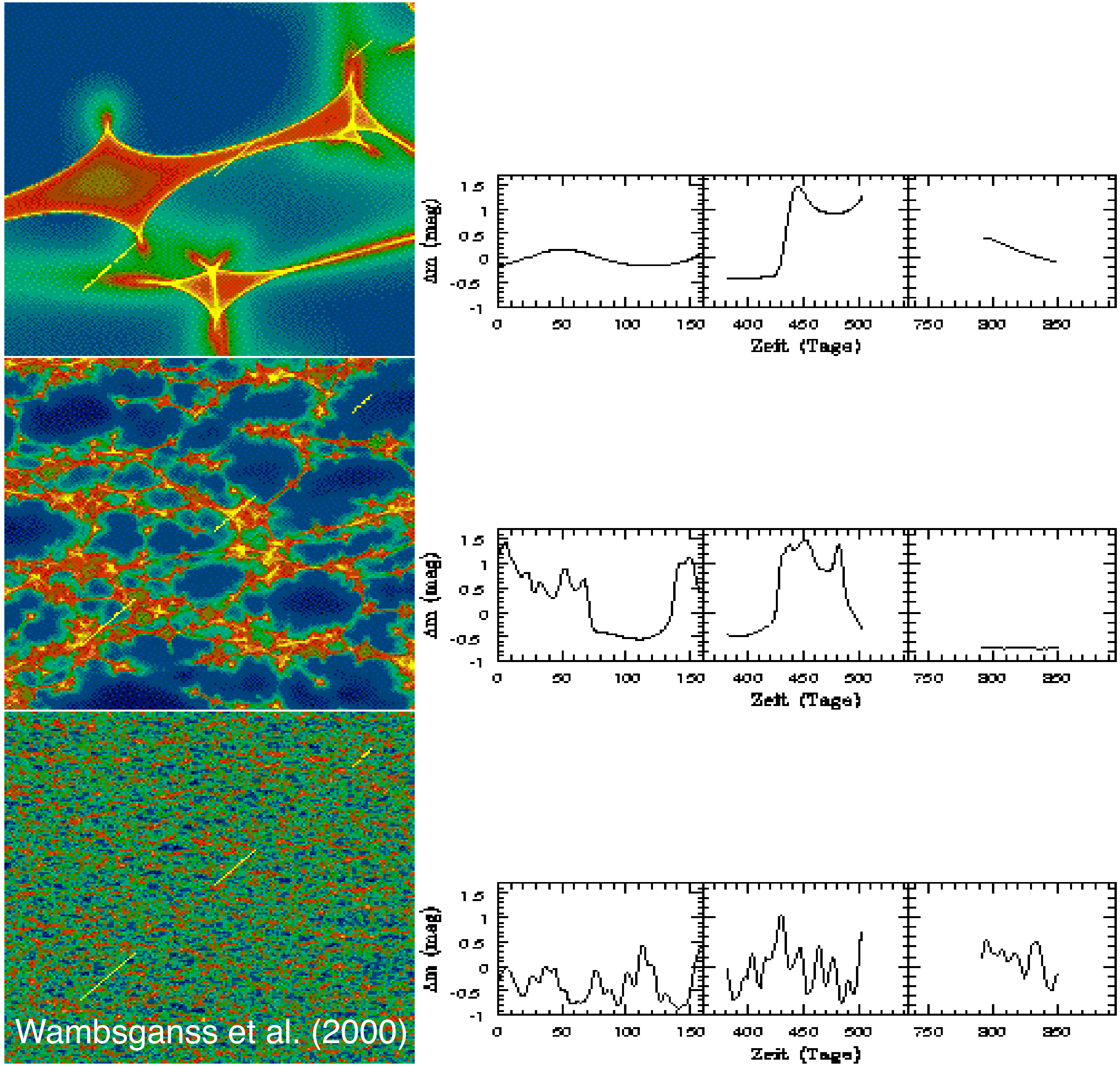
Falco et al. (1998); Kundic et al. (1997)

Quasar Microlensing Simulation: Q0957+561

$10^{-1} M_\odot$

$10^{-3} M_\odot$

$10^{-5} M_\odot$



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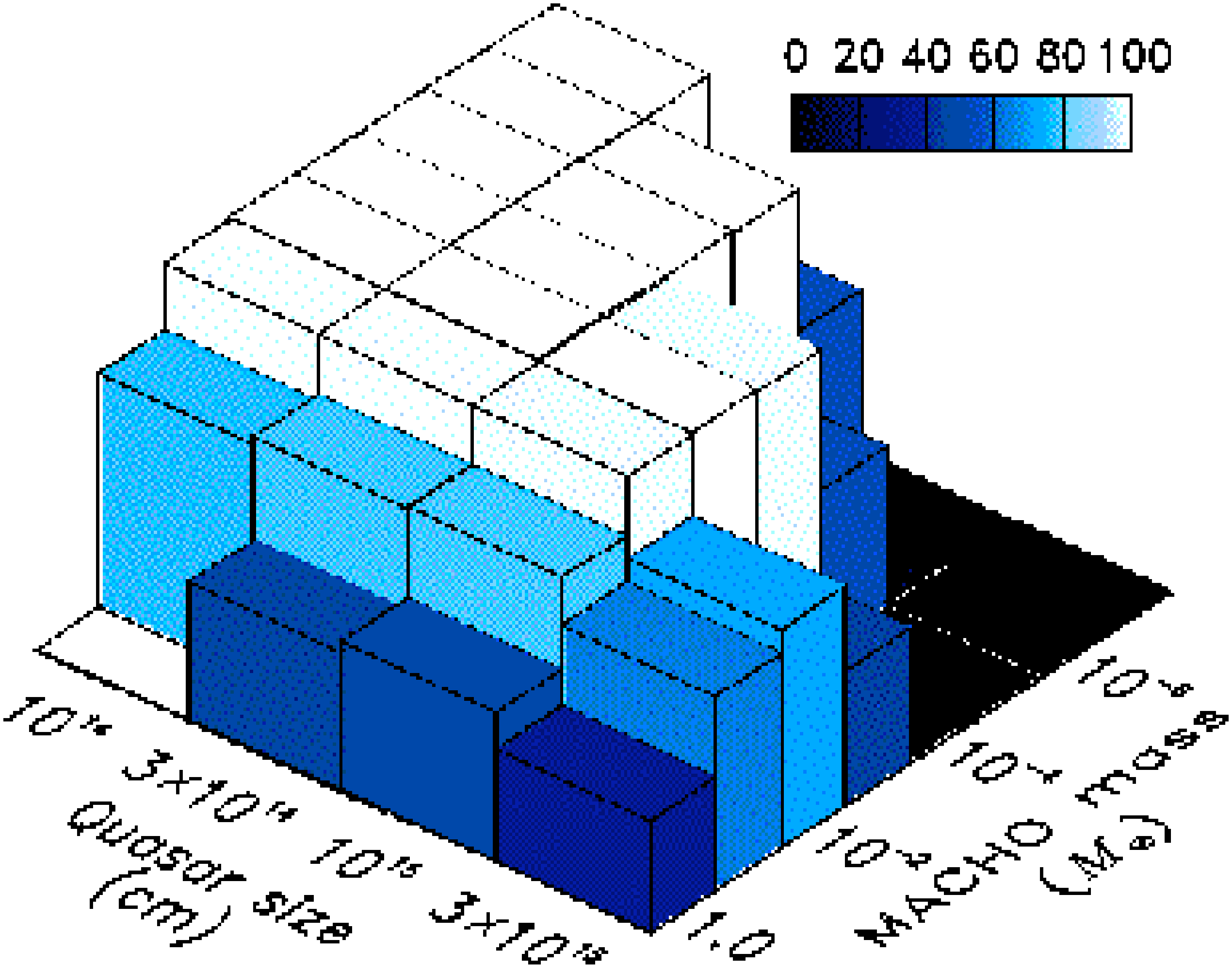
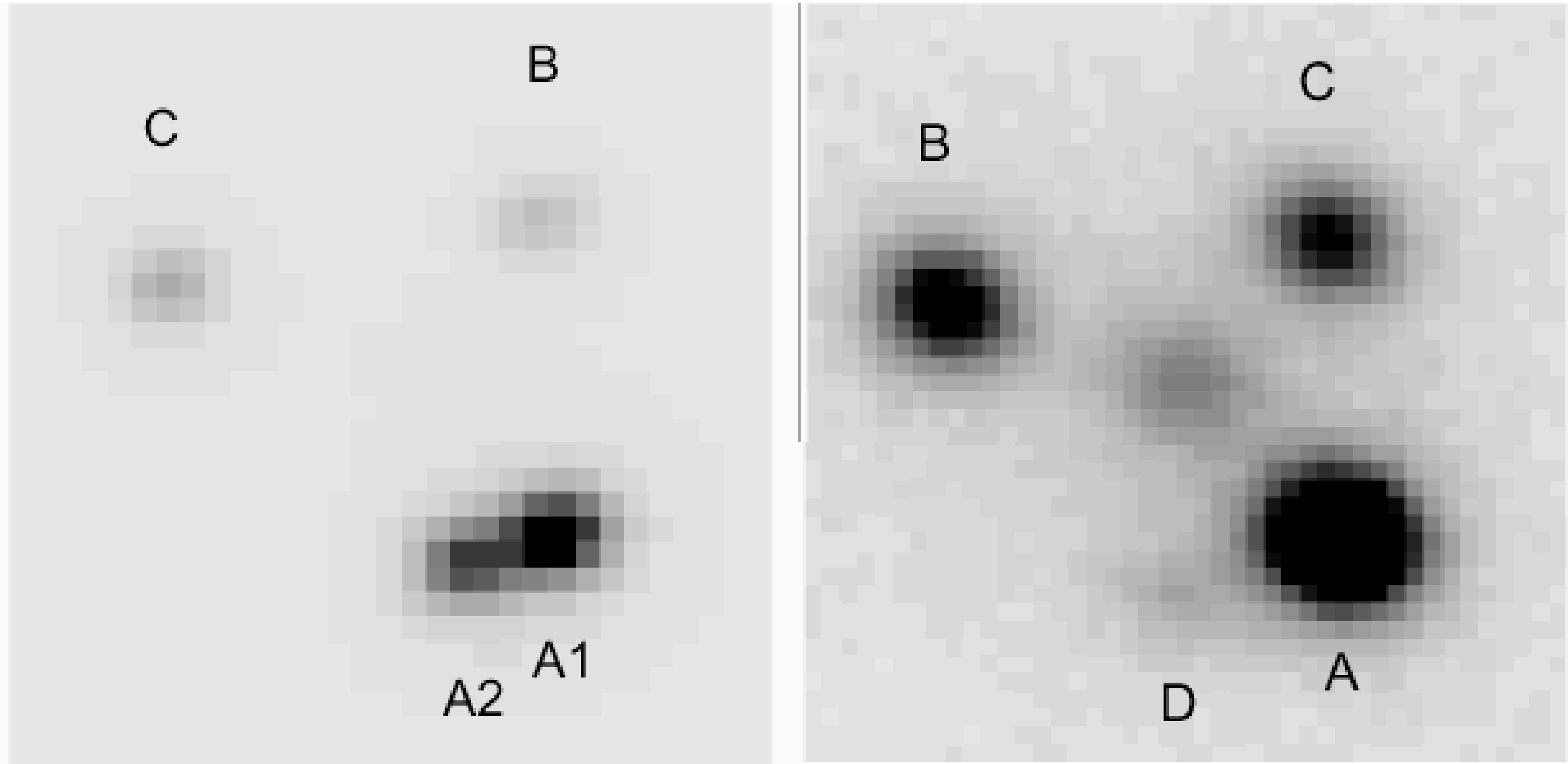
Quasar Microlensing Results: Q0957+561



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!

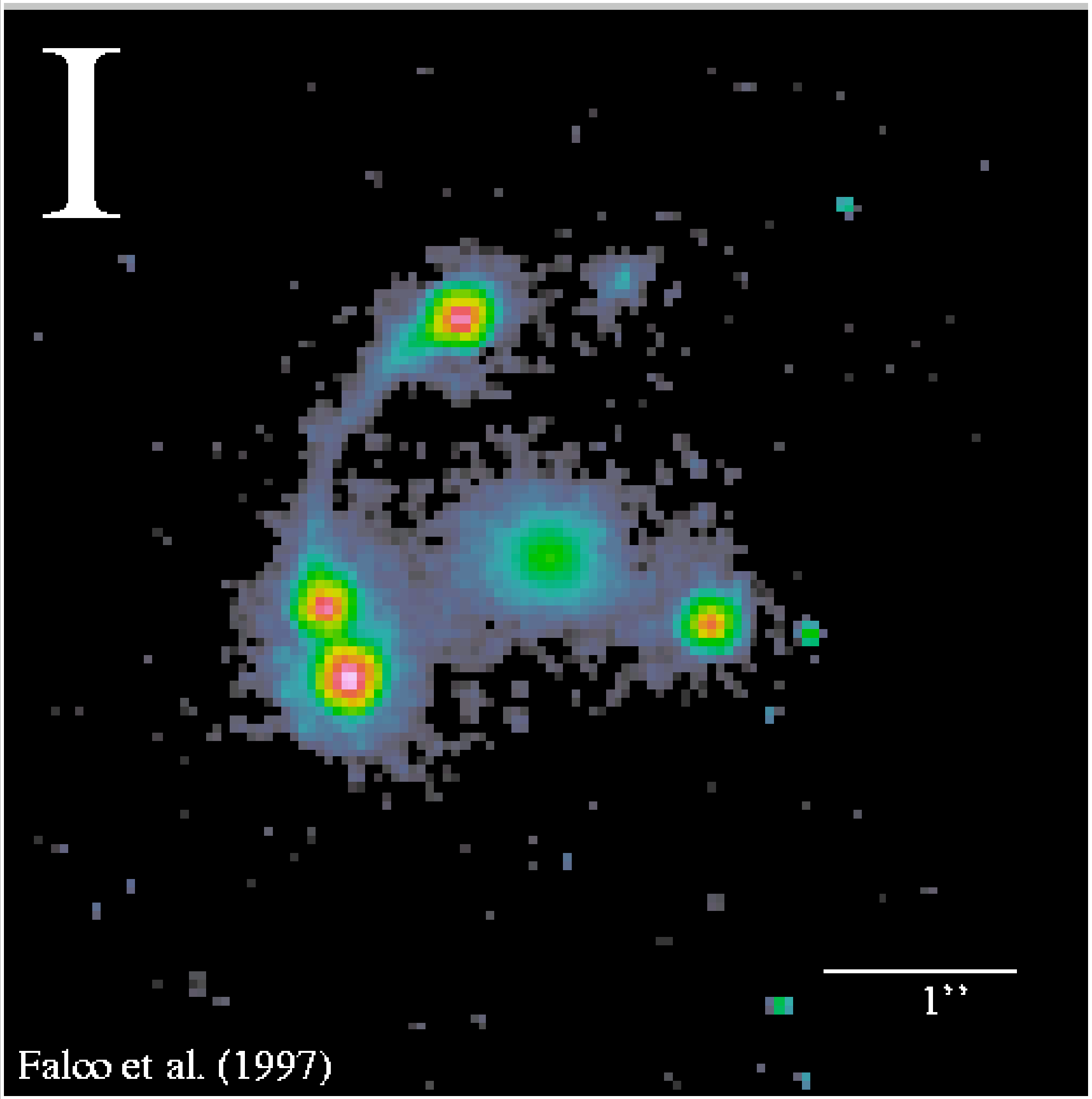
Quasar Microlensing:
"**suppressed saddlepoints**" and the role of dark matter



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:
"**suppressed saddlepoints**" and the role of dark matter



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 ?

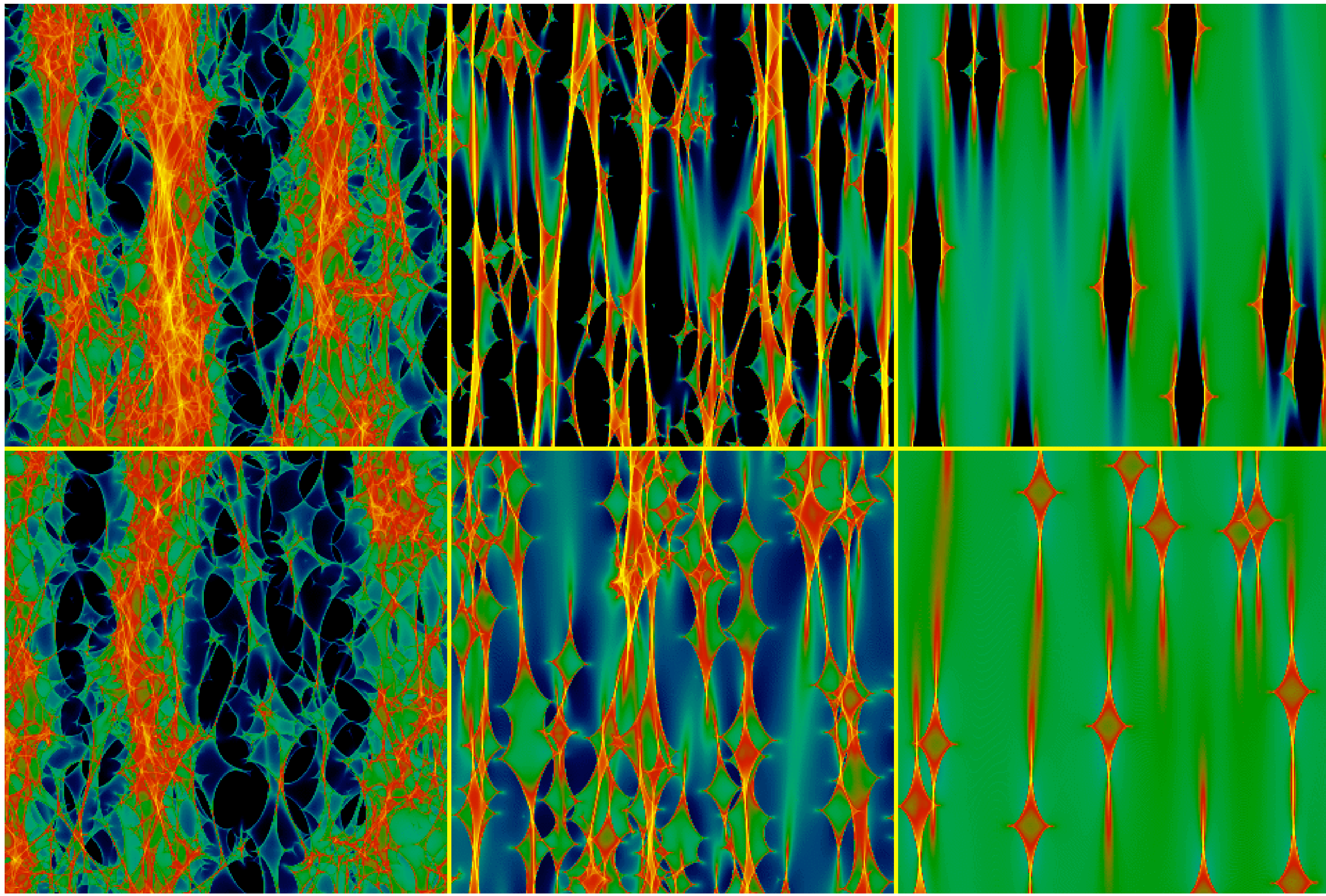
Quasar Microlensing: “**Suppressed saddlepoints**” and the role of dark matter (Schechter & Wambsganss 2002)

κ_{tot} = constant in rows

κ_{smooth} = 0% = 85% = 98%

saddle point image:

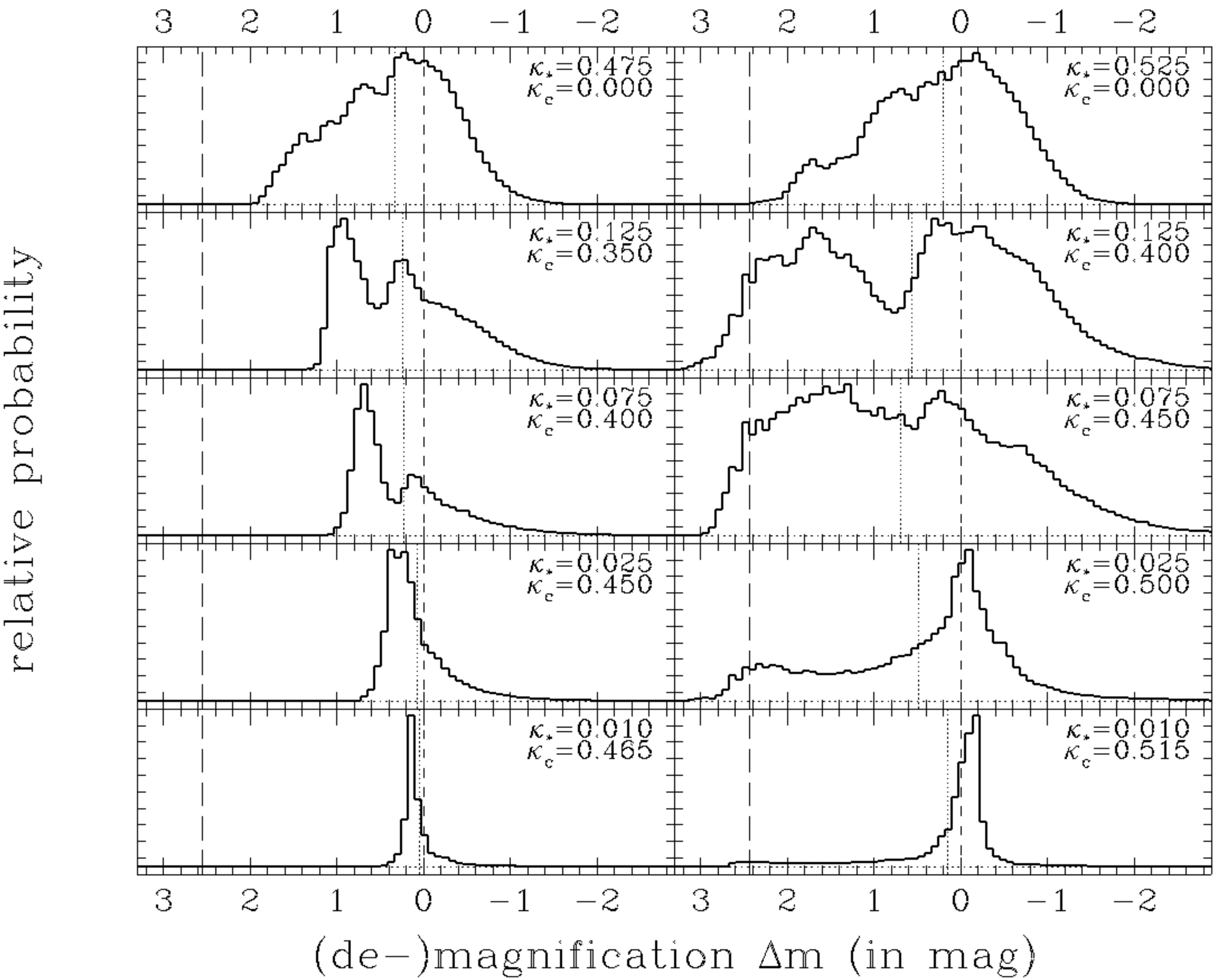
minimum image:



Quasar Microlensing:
"**suppressed saddlepoints**" and the role of dark matter
(Schechter & Wambsganss 2002)

minimum: saddle:

κ_{tot} = const in columns

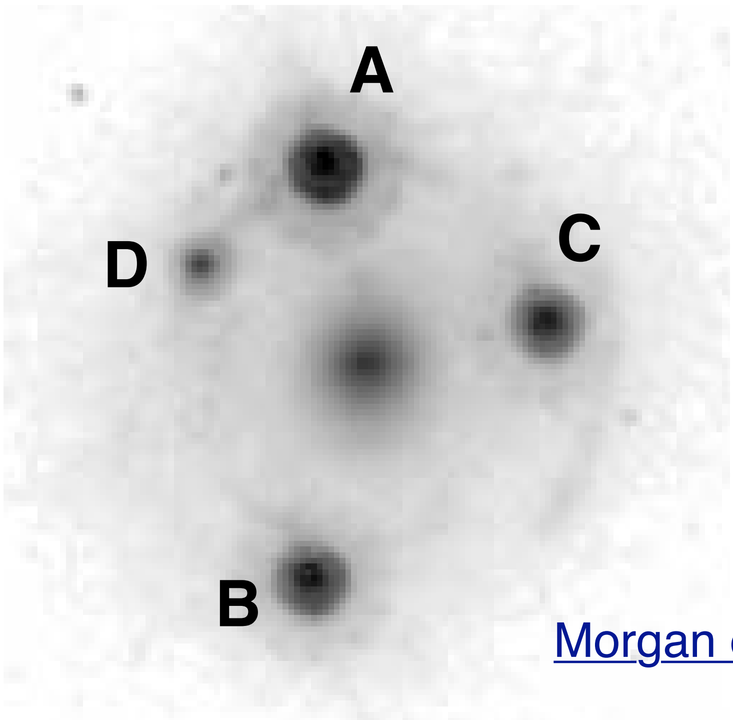


κ_{smooth} = 0%

= 85%

= 98%

“Most anomalous lensed quasar”: SDSS J0924+0219



Keeton et al. (2006):

image D factor 10-20 “too faint”; anomaly present in continuum & broad emission line flux

variability detected ⇒ microlensing!

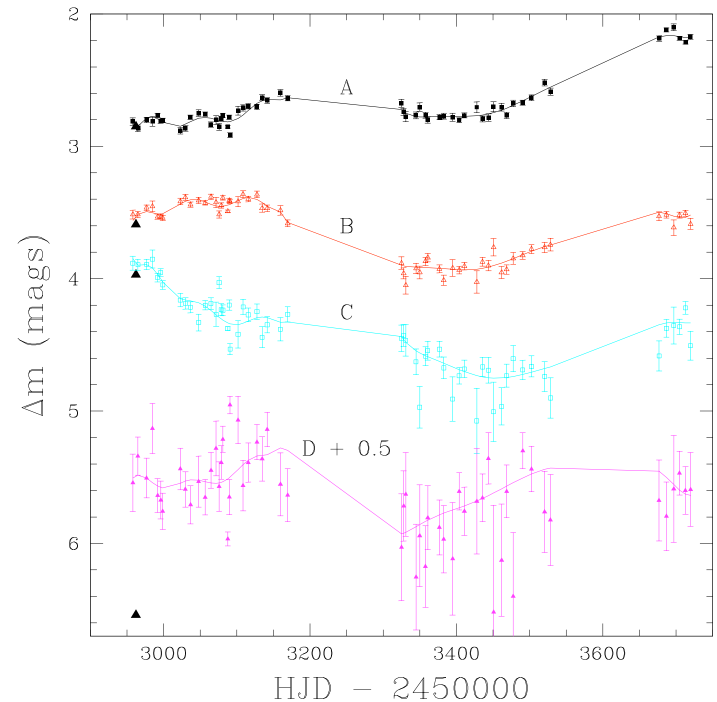
⇒ $R_{BLR} \leq 0.4 \; R_E$

⇒ stars contribute ≤ 15-20% of surface mass density

Morgan et al. (2006):

more variability ⇒ microlensing!

predictions: images C & D brighten

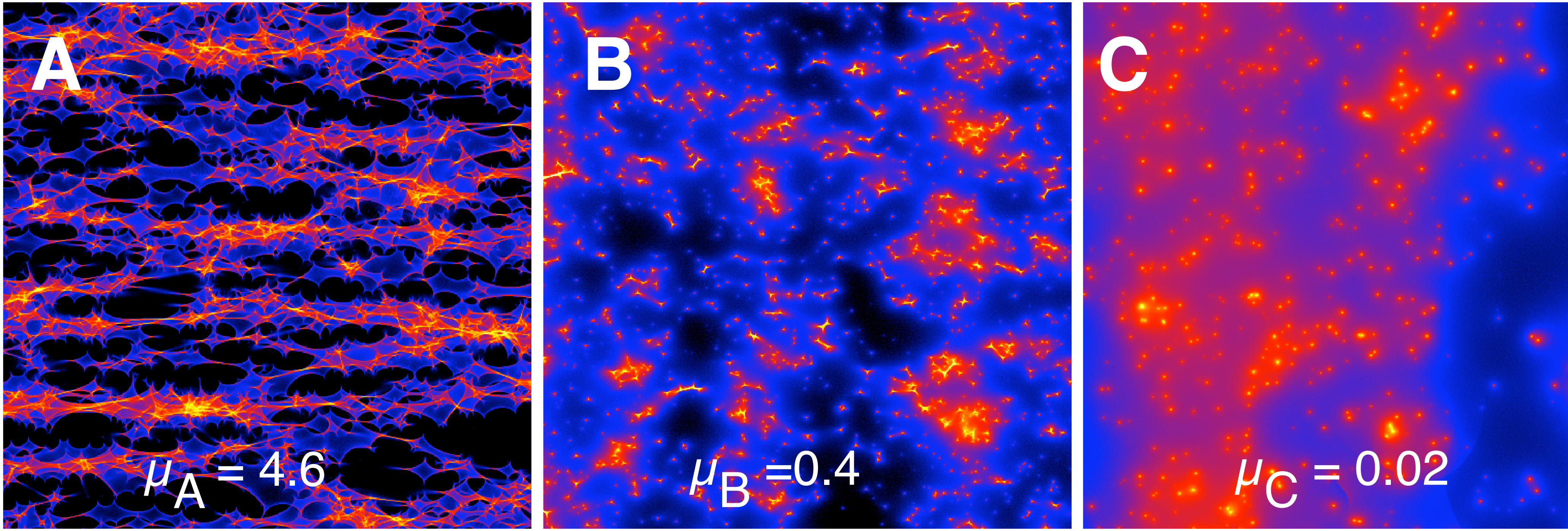


Keeton et al. (2006) & Morgan et al. (2006):
microlensing can explain the flux ratio anomaly

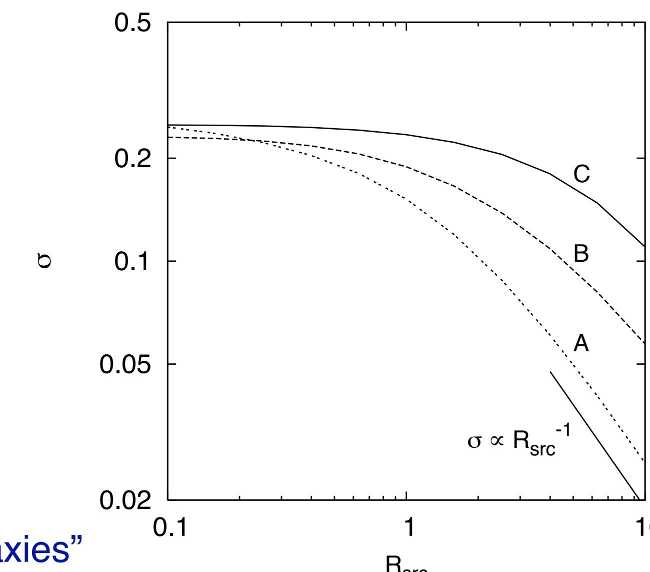
Maccio, Moore et al. (2006):
substructure cannot explain the flux ratio anomaly

"Odd Images": Microlensing Magnification Maps for PMN J1632-0033

(Winn et al. 2002, 2003, 2004)

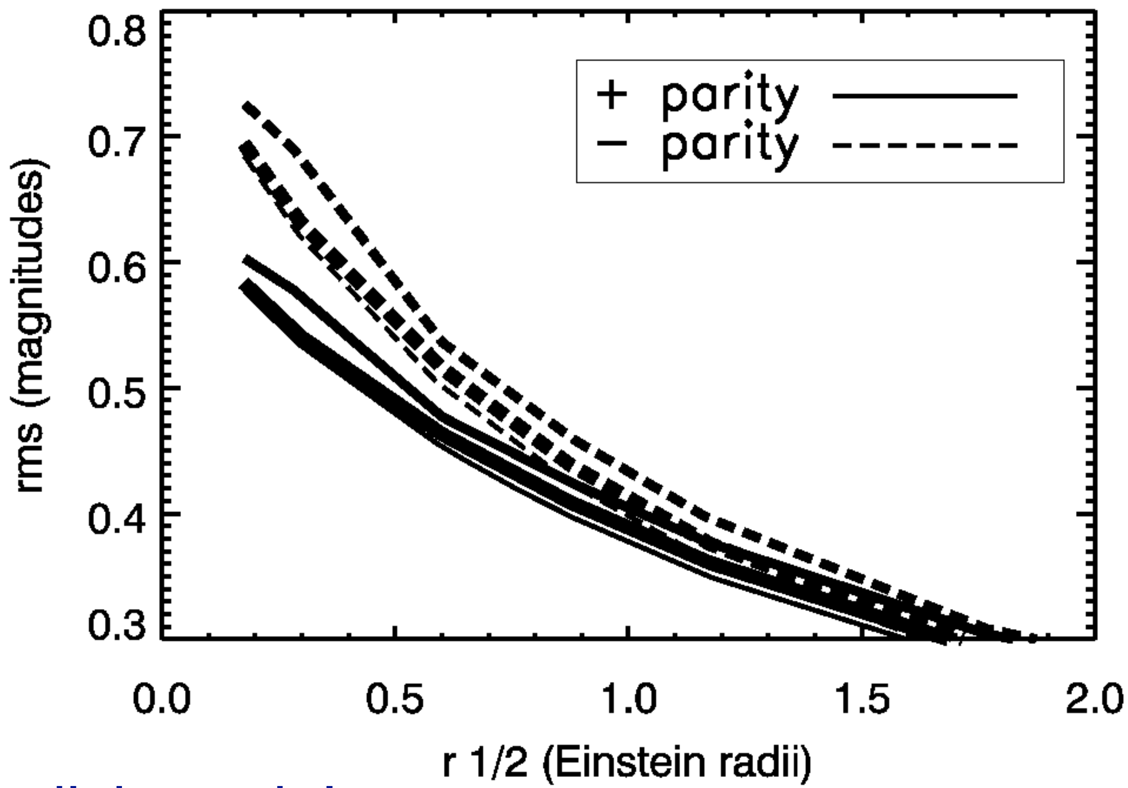


Dobler, Keeton & Wambsganss (2006)



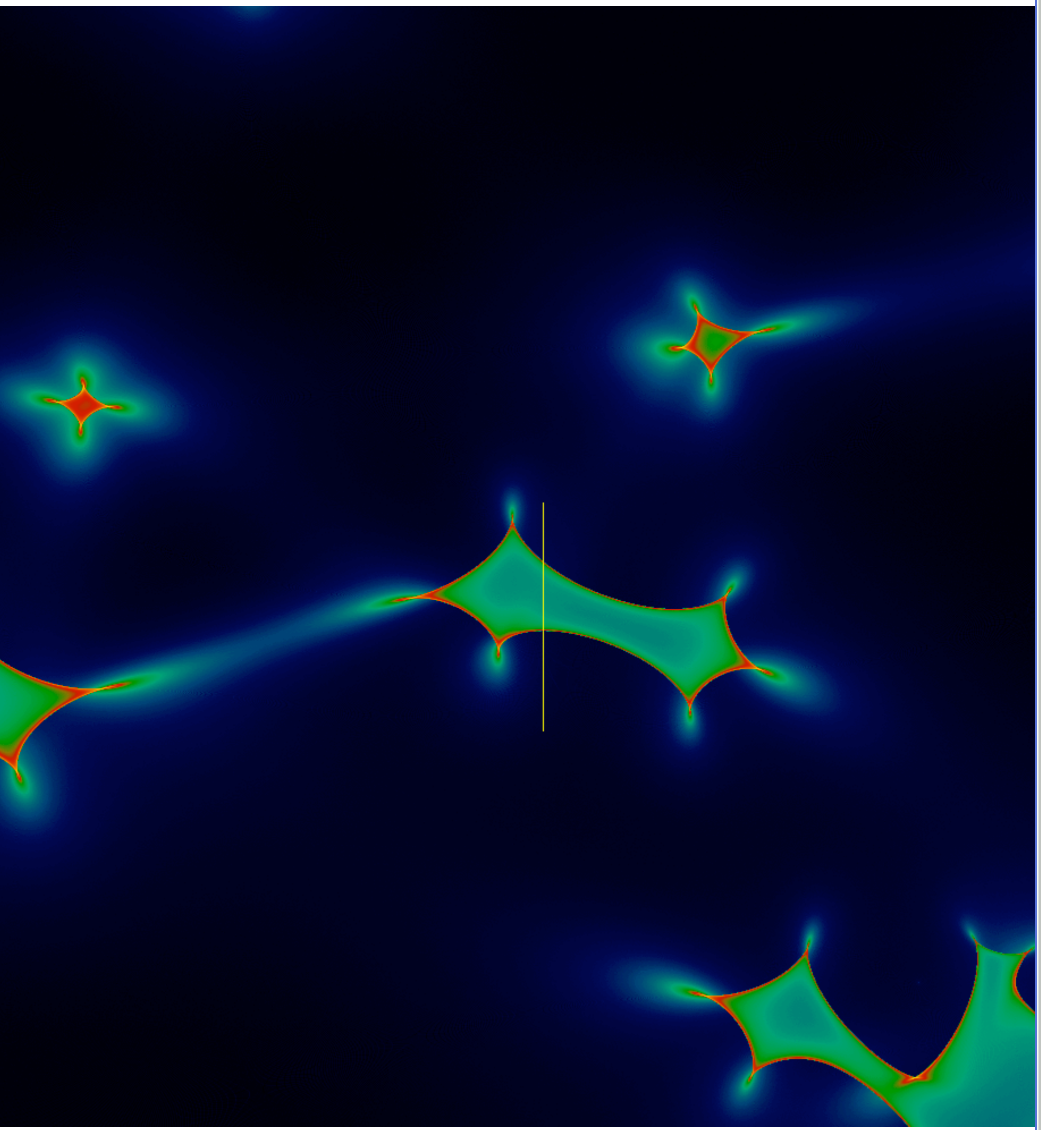
“Size is everything”:
Investigation of quasar luminosity profiles on microlensing fluctuations

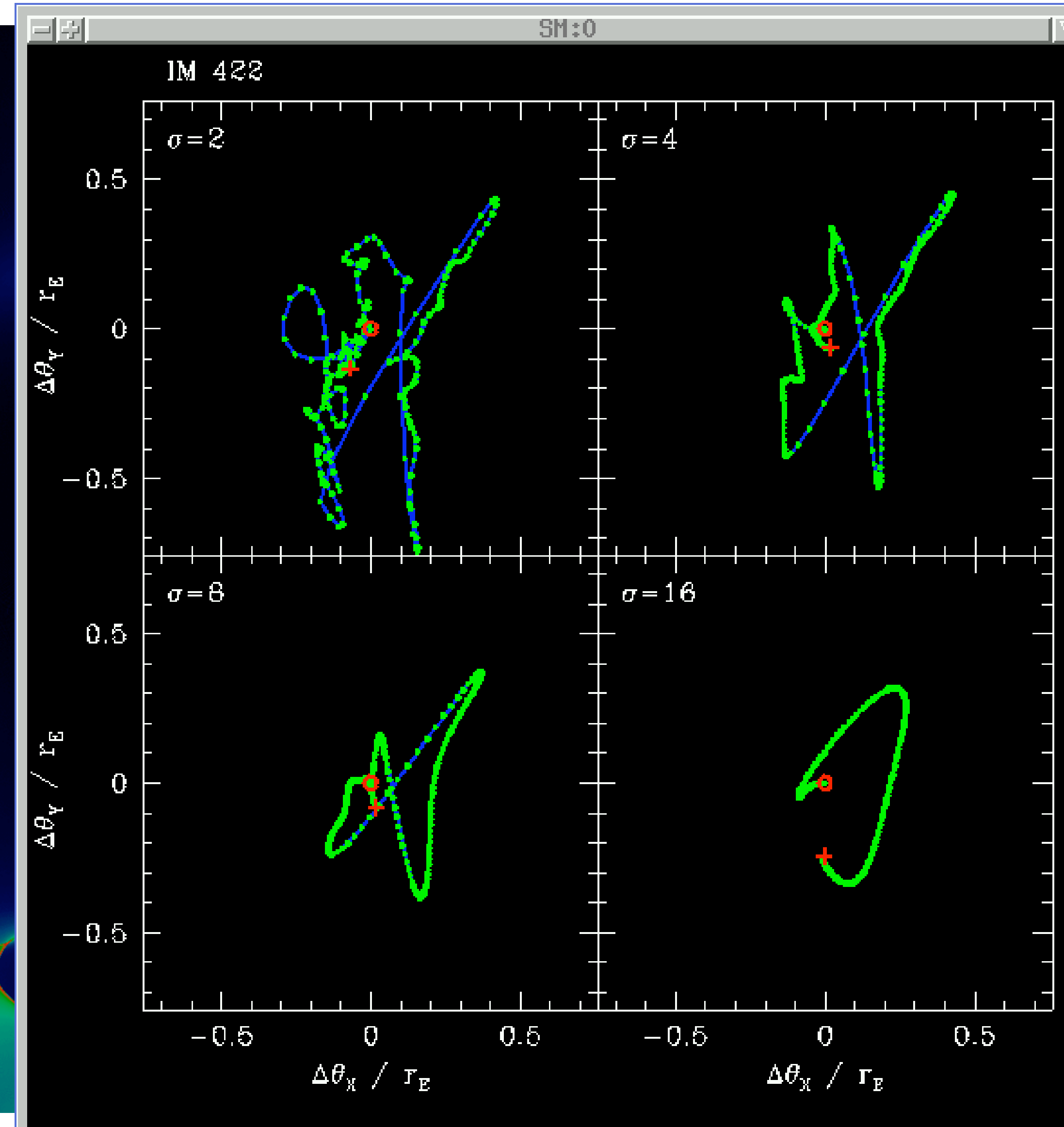
Uniform disks, Gaussian disks, “cones”, Shakura-Sunyaev models:



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)

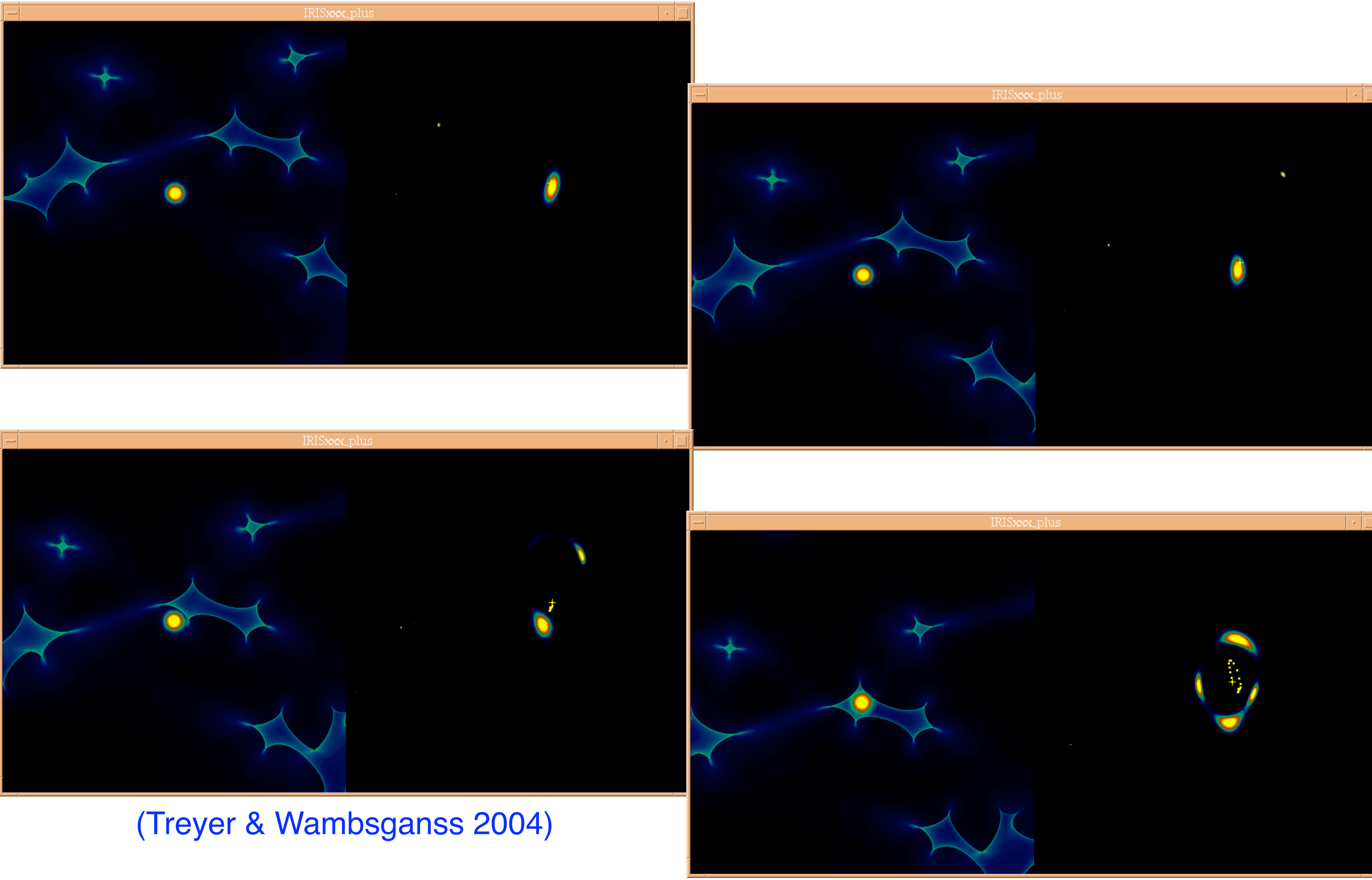
Astrometric microlensing of quasars





(Treyer & Wambsganss 2004)

Astrometric microlensing of quasars:



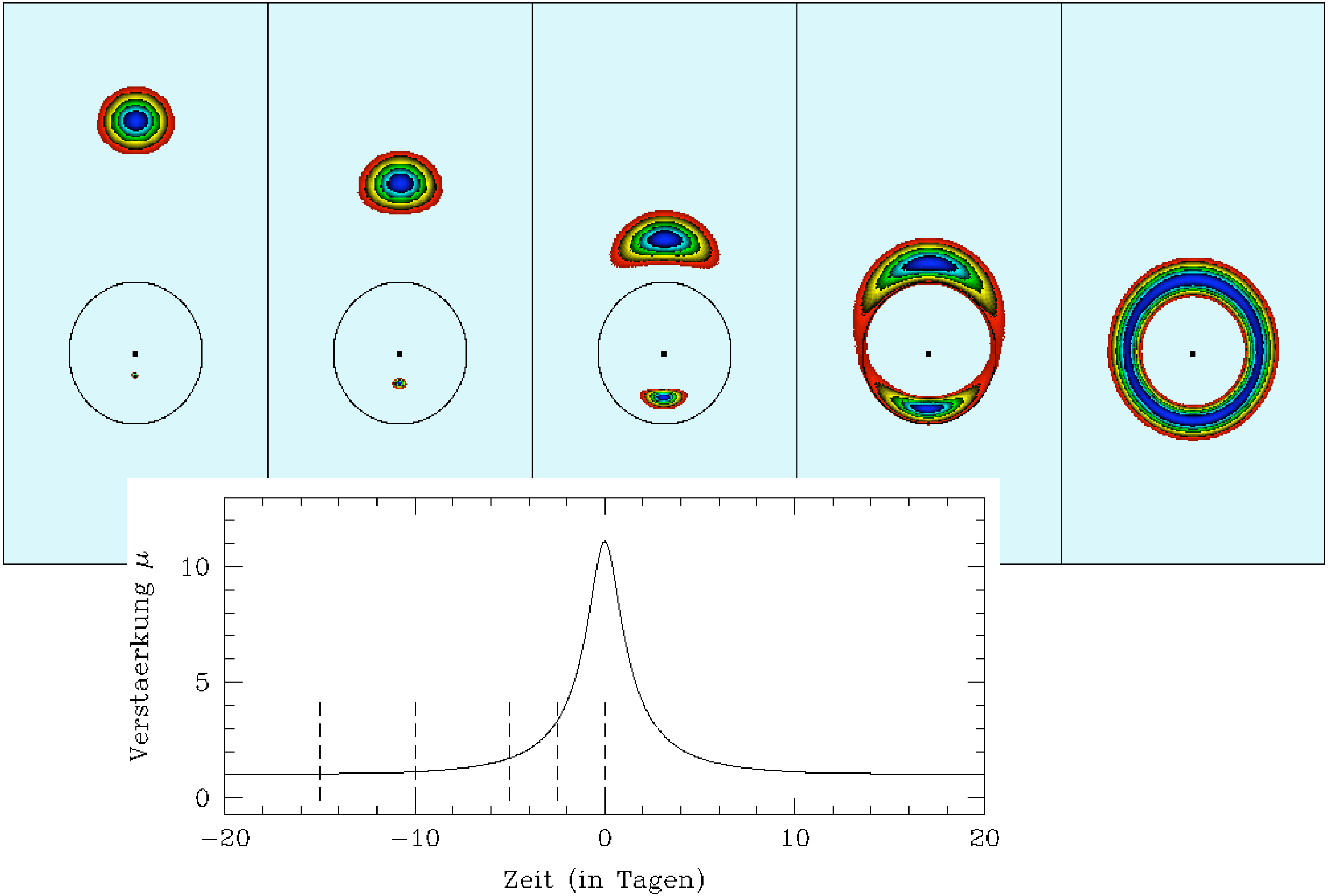
(Treyer & Wambsganss 2004)

Quasar microlensing:
The current achievements

Quasar variability due to microlensing reveals:

- Effects of compact objects along the line of sight
  YES!
- Size of quasar
  PARTLY!
- Two-dimensional brightness profile of quasar
  NOT AT ALL!
- Mass (and mass function) of lensing objects
  SOME LIMITS!
- Detection of smoothly distributed (dark) matter
  STRONG HINTS!

Stellar Microlensing: Point lens and extended source



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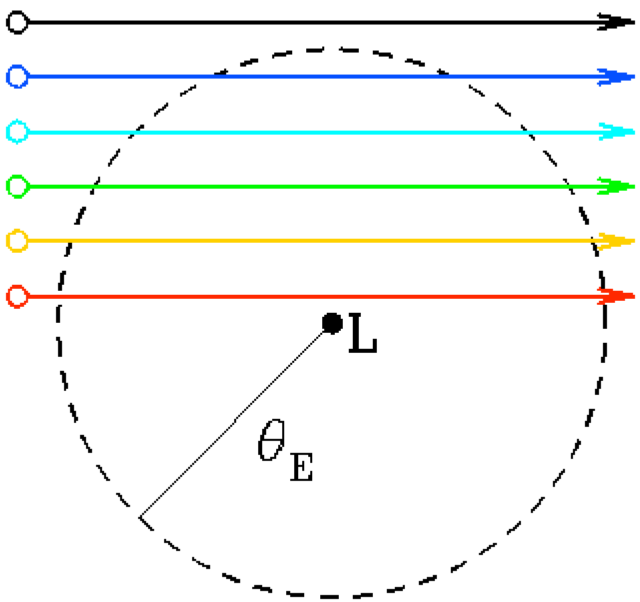
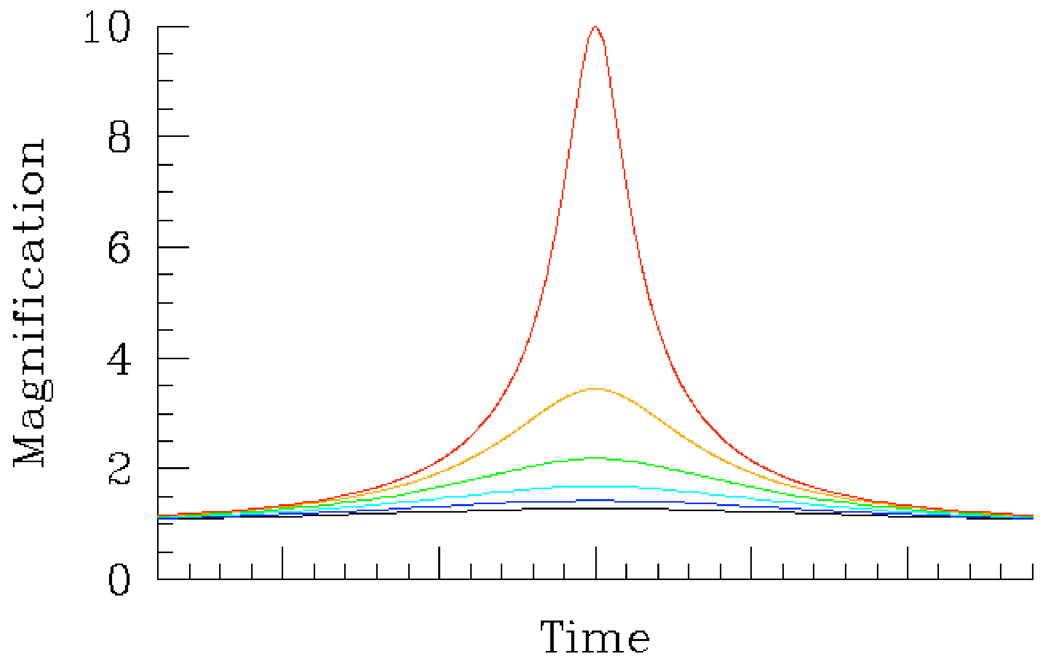
“Near”: Stellar Microlensing





(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 $u = \beta/\theta_E$)

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

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

Stellar microlensing:

Stellar variability due to microlensing reveals:

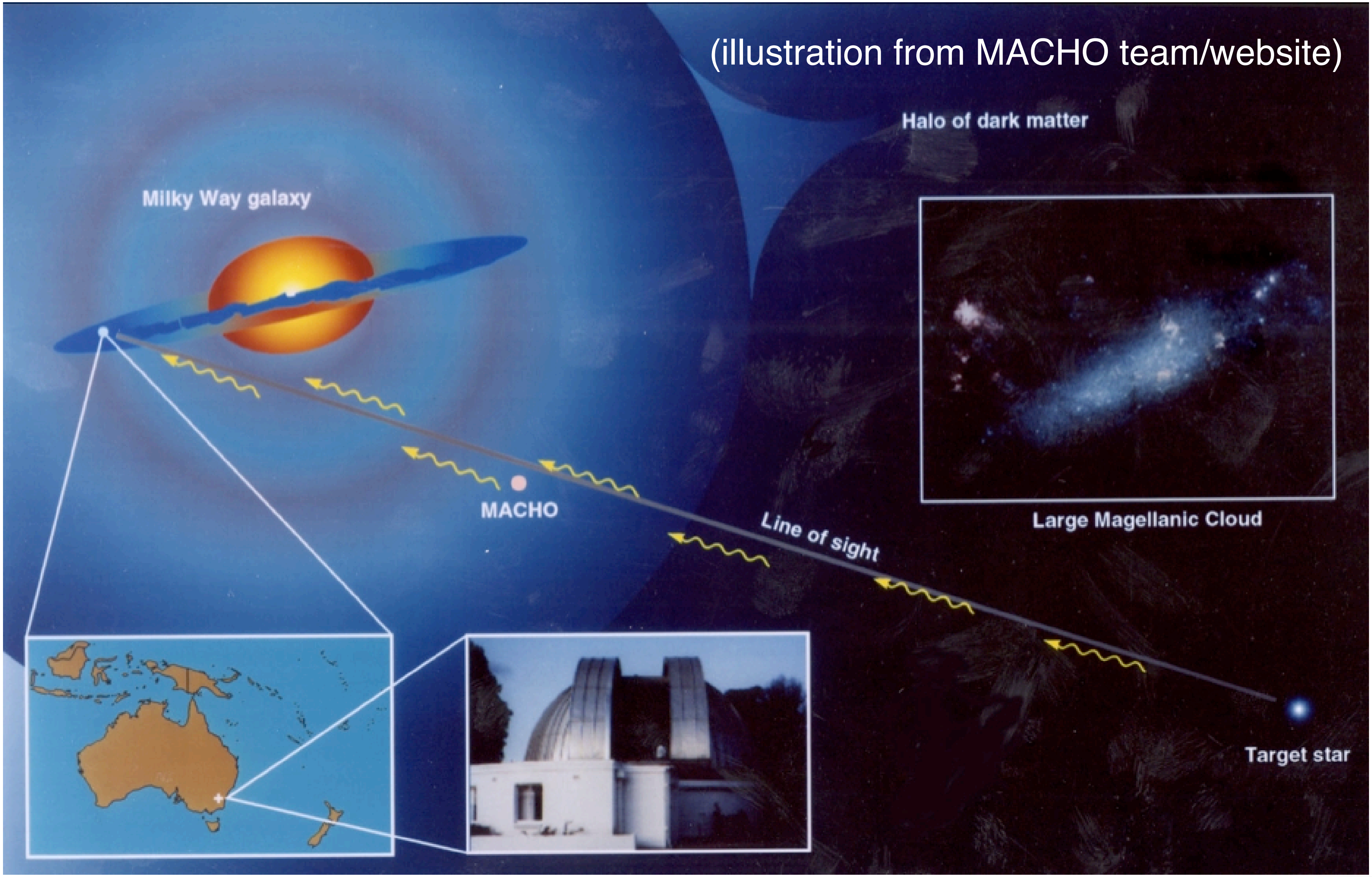
- Effects of Machos in Milky Way/galaxy halos
- Stars in the Milky Way disk/bulge/bar
- Mass measurement of lensing stars
- Surface brightness profile of distant stars
- Cool dark matter

Stellar microlensing

A few highlights:

- results on Macho determination
- results on stellar mass measurements
- results on stellar surface structure
- results on planet searching

Stellar microlensing towards the LMC/SMC



Stellar microlensing towards the LMC/SMC Dark Matter Detection?

MACHO 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),0.36×10^{-7}

OGLE results (see also poster by Wyrzykowski):

- macho contribution is low, optical depth: $(0.45\pm0.2)\times10^{-7}$

Little (or no?) evidence for dark matter!

Stellar microlensing towards the Galactic 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:

masses, stellar surface structure, exo-planets

Stellar Microlensing: mass determination

Jiang et al. (2004): "OGLE-2003-BLG-238: Microlensing Mass Estimate of an Isolated Star"

– microlensing is only known direct method to measure the masses of stars that lack visible companions

– required: measurement of both the angular Einstein radius θ_E and the projected Einstein radius r_E

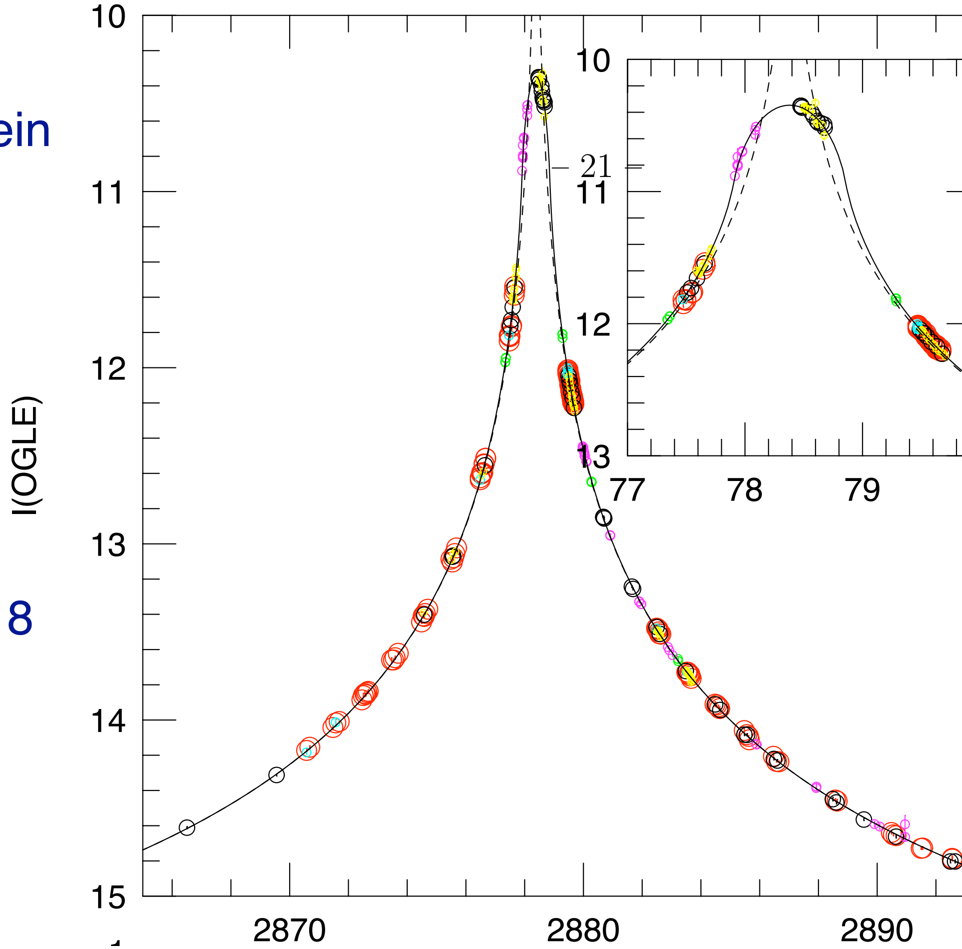
– simultaneous measurement of these two parameters is extremely rare

– for OGLE-2003-BLG-238 (μ_{max} = 170) with finite source effects: θ_E = 650 μas, t_E = 38 days

– constraints on microlens parallax: $4.4 < r_E /AU < 18$

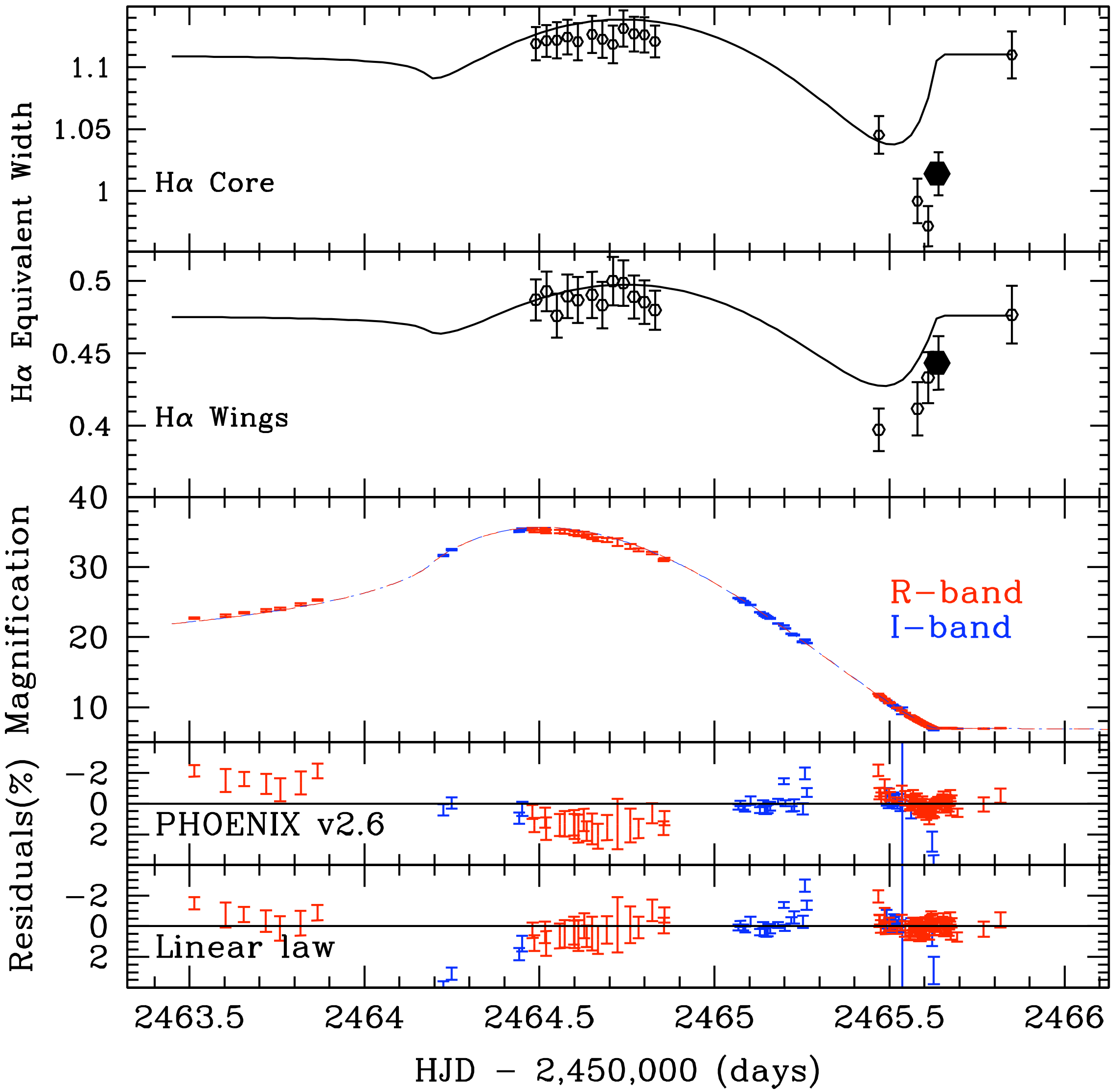
– lens mass: $0.36\ M_\odot < M < 1.48\ M_\odot$

– estimate rather crude, however, demonstrates viability of technique



Stellar Microlensing: Studying Stellar Atmospheres

Cassan et al. (2004): "Probing the atmosphere of the bulge G5III star OGLE-2002-BLG-069 by analysis of microlensed Hα line"



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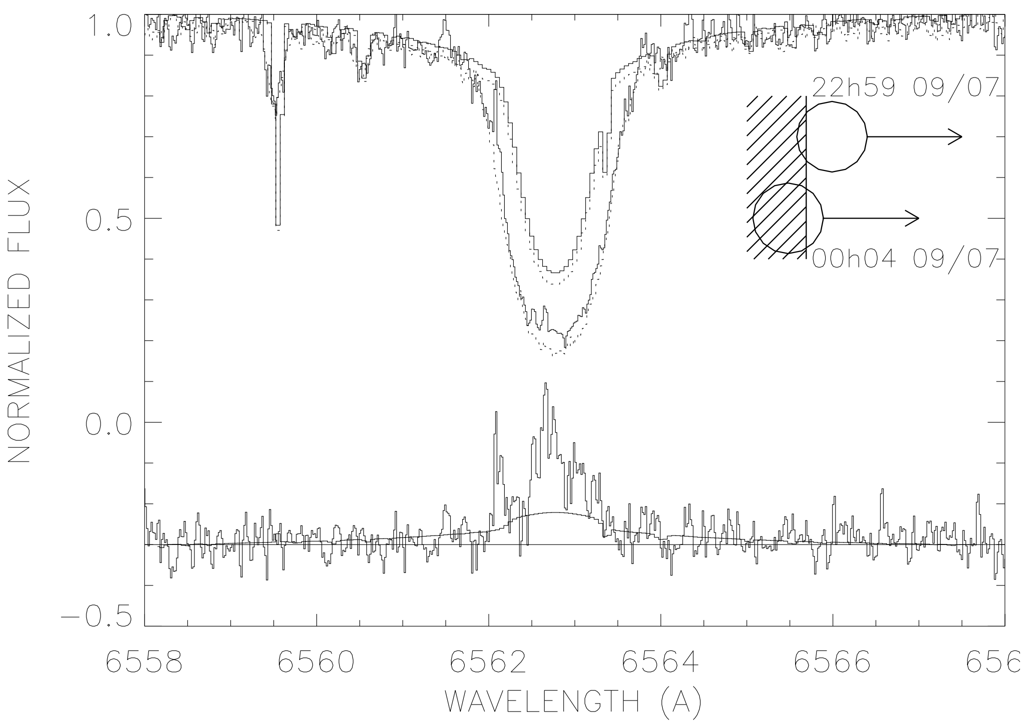

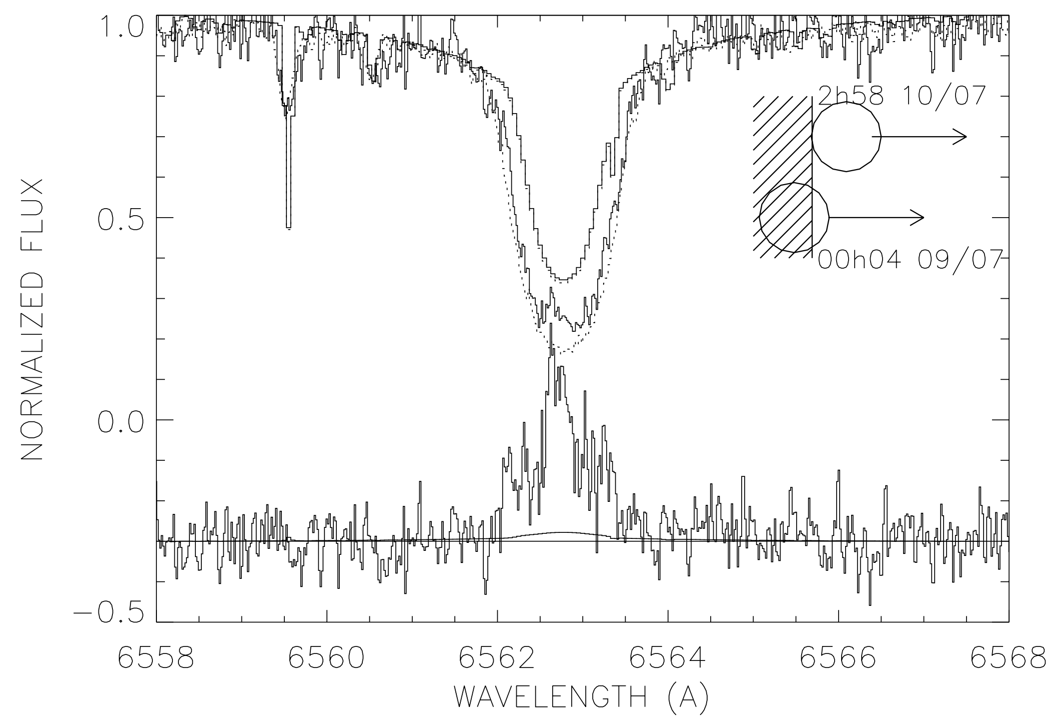

Stellar Microlensing: Studying Stellar Atmospheres

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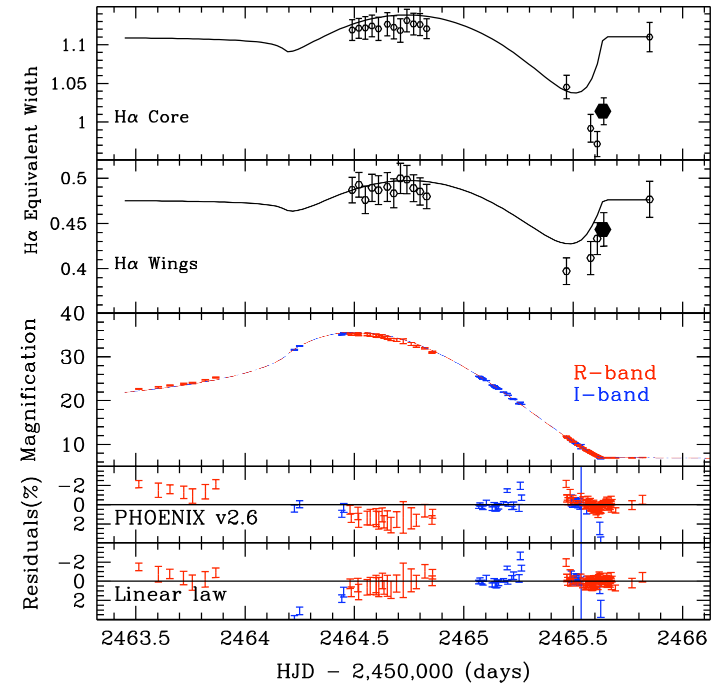
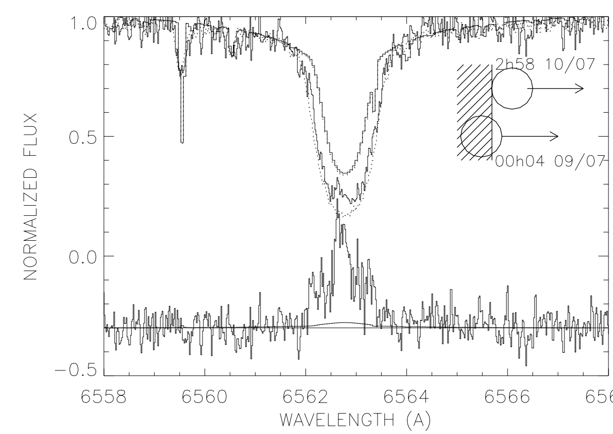
High-resolution, time-resolved spectra of caustic exit of OGLE-2002-BLG-069 (UVES/VLT):

- source G5III giant in Galactic bulge
- strong differential magnification resolves stellar surface
- PHOENIX model lightcurve compared with photometric data and H_α equivalent width
- agreement on gross features, discrepancies in details: excess amplified chromospheric emission after star’s trailing limb outside caustic

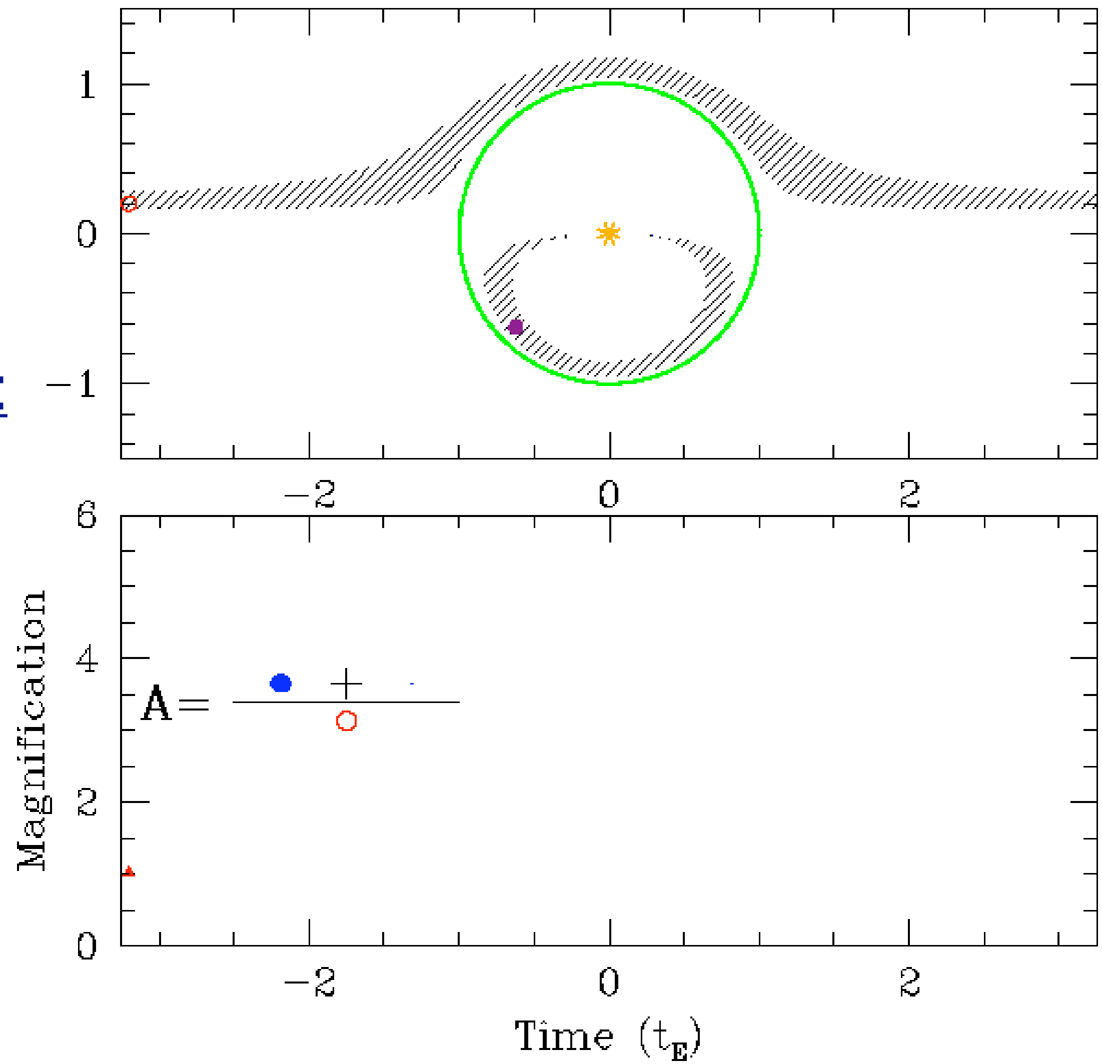




Stellar Microlensing: Searching for extrasolar planets

simulation by Scott Gaudi:

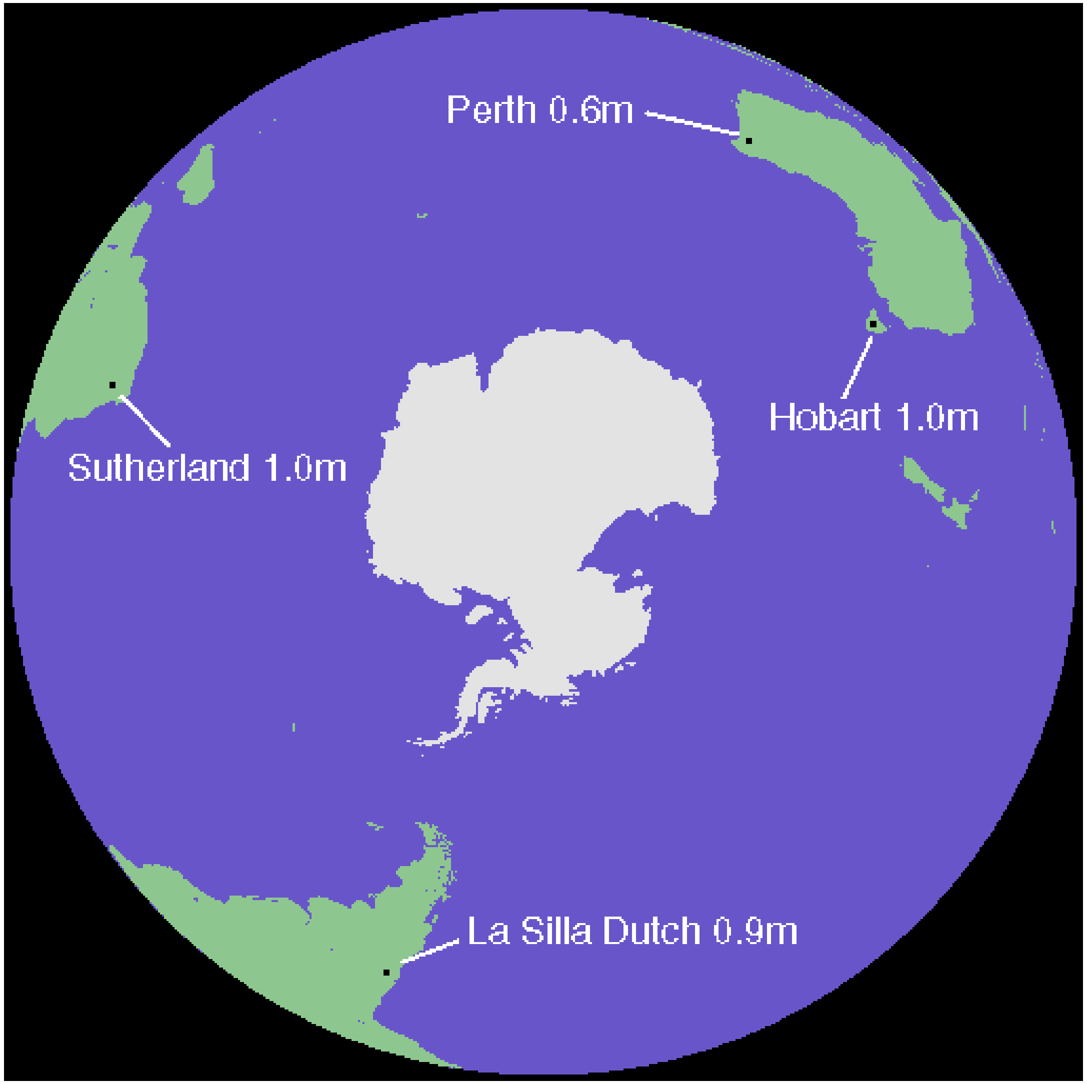
star-plus-planet lens



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

Stellar Microlensing: Searching for extrasolar planets

The 24 hour night shift: PLANET telescope sites



PLANET -
Probing
Lens
Anomaly
NETwork

Stellar Microlensing: Finding extrasolar planets

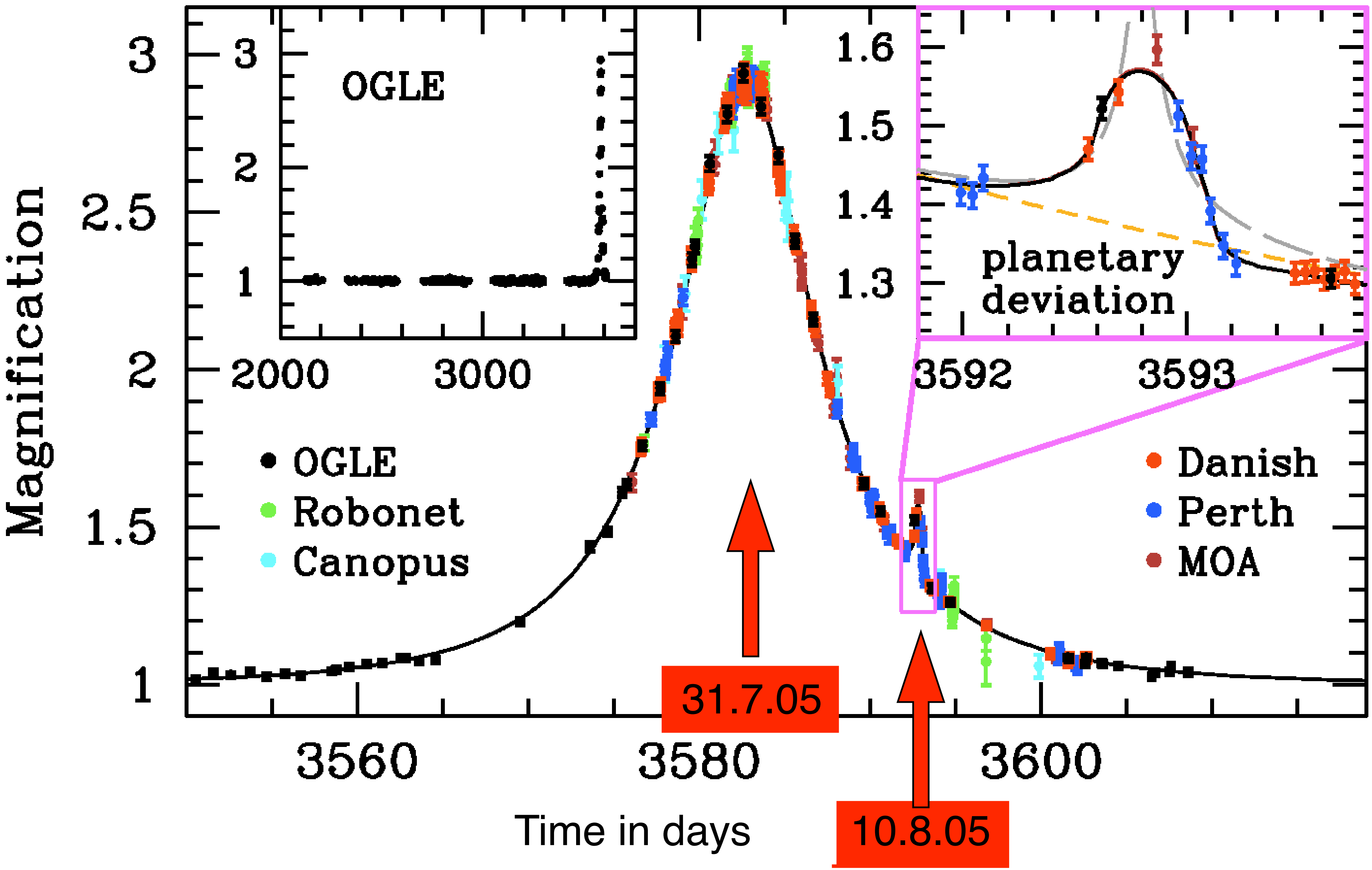
Vol 439|26 January 2006|**doi:10.1038/nature04441** nature

LETTERS

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

J.-P. Beaulieu[1,4], D. P. Bennett[1,3,5], P. Fouqué[1,6], A. Williams[1,7], M. Dominik[1,8], U. G. Jørgensen[1,9], D. Kubas[1,10], A. Cassan[1,4], C. Coutures[1,11], J. Greenhill[1,12], K. Hill[1,12], J. Menzies[1,13], P. D. Sackett[1,14], M. Albrow[1,15], S. Brillant[1,10], J. A. R. Caldwell[1,16], J. J. Calitz[1,17], K. H. Cook[1,18], E. Corrales[1,4], M. Desort[1,4], S. Dieters[1,12], D. Dominis[1,19], J. Donatowicz[1,20], M. Hoffman[1,19], S. Kane[1,21], J.-B. Marquette[1,4], R. Martin[1,7], P. Meintjes[1,17], K. Pollard[1,15], K. Sahu[1,22], C. Vinter[1,9], J. Wambsganss[1,23], K. Woller[1,9], K. Horne[1,8], I. Steele[1,24], D. M. Bramich[1,8,24], M. Burgdorf[1,24], C. Snodgrass[1,25], M. Bode[1,24], A. Udalski[2,26], M. K. Szymański[2,26], M. Kubiak[2,26], T. Więckowski[2,26], G. Pietrzyński[2,26,27], I. Soszyński[2,26,27], O. Szewczyk[2,26], Ł. Wyrzykowski[2,26,28], B. Paczyński[2,29], F. Abe[3,30], I. A. Bond[3,31], T. R. Britton[3,15,32], A. C. Gilmore[3,15], J. B. Hearnshaw[3,15], Y. Itow[3,30], K. Kamiya[3,30], P. M. Kilmartin[3,15], A. V. Korpela[3,33], K. Masuda[3,30], Y. Matsubara[3,30], M. Motomura[3,30], Y. Muraki[3,30], S. Nakamura[3,30], C. Okada[3,30], K. Ohnishi[3,34], N. J. Rattenbury[3,28], T. Sako[3,30], S. Sato[3,35], M. Sasaki[3,30], T. Sekiguchi[3,30], D. J. Sullivan[3,33], P. J. Tristram[3,32], P. C. M. Yock[3,32] & T. Yoshioka[3,30]

Stellar Microlensing: Finding extrasolar planets

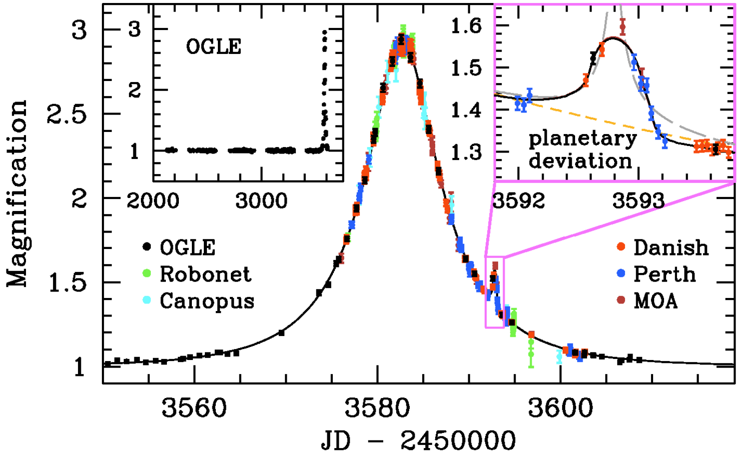


Joachim Wambsganss: “Microlensing and Compact Objects in Galaxies”
at: “Applications of Gravitational Lensing”, KITP, Santa Barbara, October 4, 2006

Stellar Microlensing: Finding extrasolar planets

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



Stellar microlensing:
The current achievements

Stellar variability due to microlensing reveals:

- Effects of Machos in Milky Way/galaxy halos
  Few (if any) dark compact objects in MW halo!
  [Few (if any) dark compact objects in G0957 halo!]
- Stars in the Milky Way disk/bulge/bar
  Plenty! and binaries!
- Mass measurement of lensing stars
  yes, very accurately!
- Surface brightness profile of distant stars
  yes!
- Cool dark matter
  yes, 4 planets so far (cool!)

Summary

The future of gravitational **microlensing** ...

- ... for measuring the surface brightness profiles of quasars as a function of wavelength ...
- ... for determining the mass scale, mass function, dark matter content of lensing objects in the galaxies ...
- ... for detecting compact objects in the Milky Way, in particular extrasolar planets ...

... is bright!

"... **from a curiosity into a tool** ..."

(Kochanek et al., September 2006)