25 YEARS AFTER THE DISCOVERY: SOME CURRENT TOPICS ON LENSED QSOs
Santander (Spain), 15th-17th December 2004

25 Years of Quasar Microlensing

- Introduction -

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Santander, December 17, 2004

25 Years of Quasar Microlensing
- Introduction -

- microlensing is ubiquitous: in lensed quasars and at this meeting:
- 8 out of 30 talks here have “microlensing” in title
- in almost ALL talks, “microlensing” was mentioned (occasionally in the negative form “no microlensing” ...)

Quasar Microlensing

- What is (quasar) microlensing?
- What can be learned from microlensing?
  - attempts?
  - detections?
  - limits?
- What are the prospects for future detections?

What is microlensing?

- effects of **“compact”** objects with **“small”** masses along the line of sight to distant sources
  - what is **“compact”**?
  - what is **“small”**?

What is microlensing?

- effects of **“compact”** objects with **“small”** masses along the line of sight to distant sources
  - what is **“compact”**?
    much smaller than the Einstein radius!
  - what is **“small”**?
    Einstein radius below resolution limit!

What is microlensing?

- effects of "**compact**" objects with "**small**" masses along the line of sight to distant sources
  - what is "**compact**"?
    much smaller than the Einstein radius!
  - what is "**small**"?
    Einstein radius below resolution limit!

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:

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

- what mass range? $10^{-6} < m/M_\odot < 10^{6}$

(or: nanolensing, mesolensing, millilensing)

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

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

Problem: all quasars are variable (more or less ...)

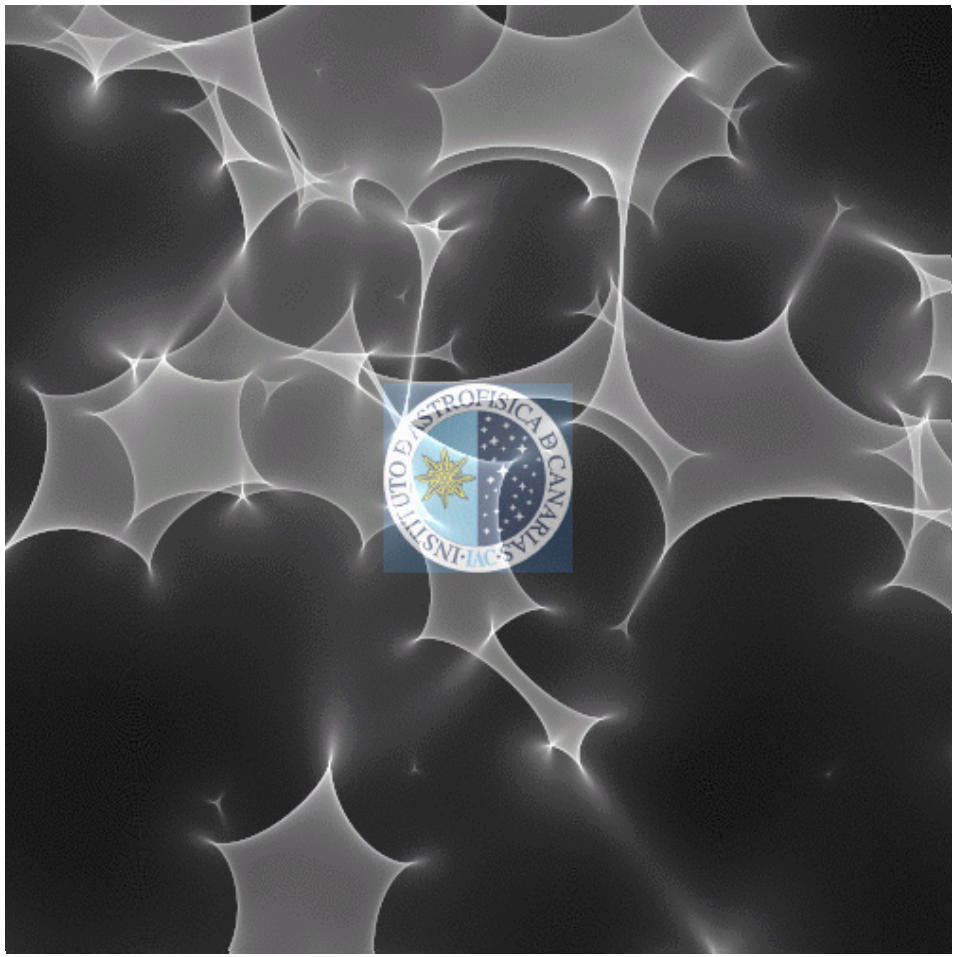
For an isolated quasar:

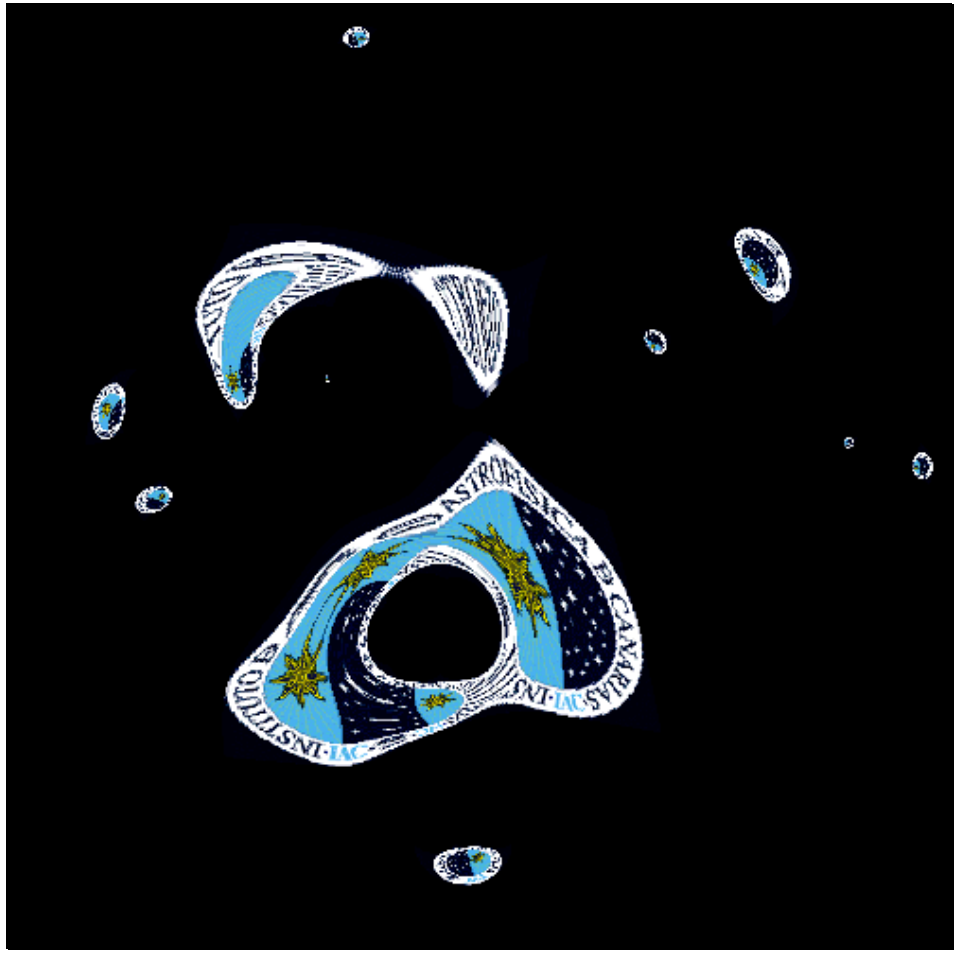
- (almost) impossible to distinguish "intrinsic" variability from "extrinsic" (i.e. microlens-induced) variability!

For a double/multiple quasar:

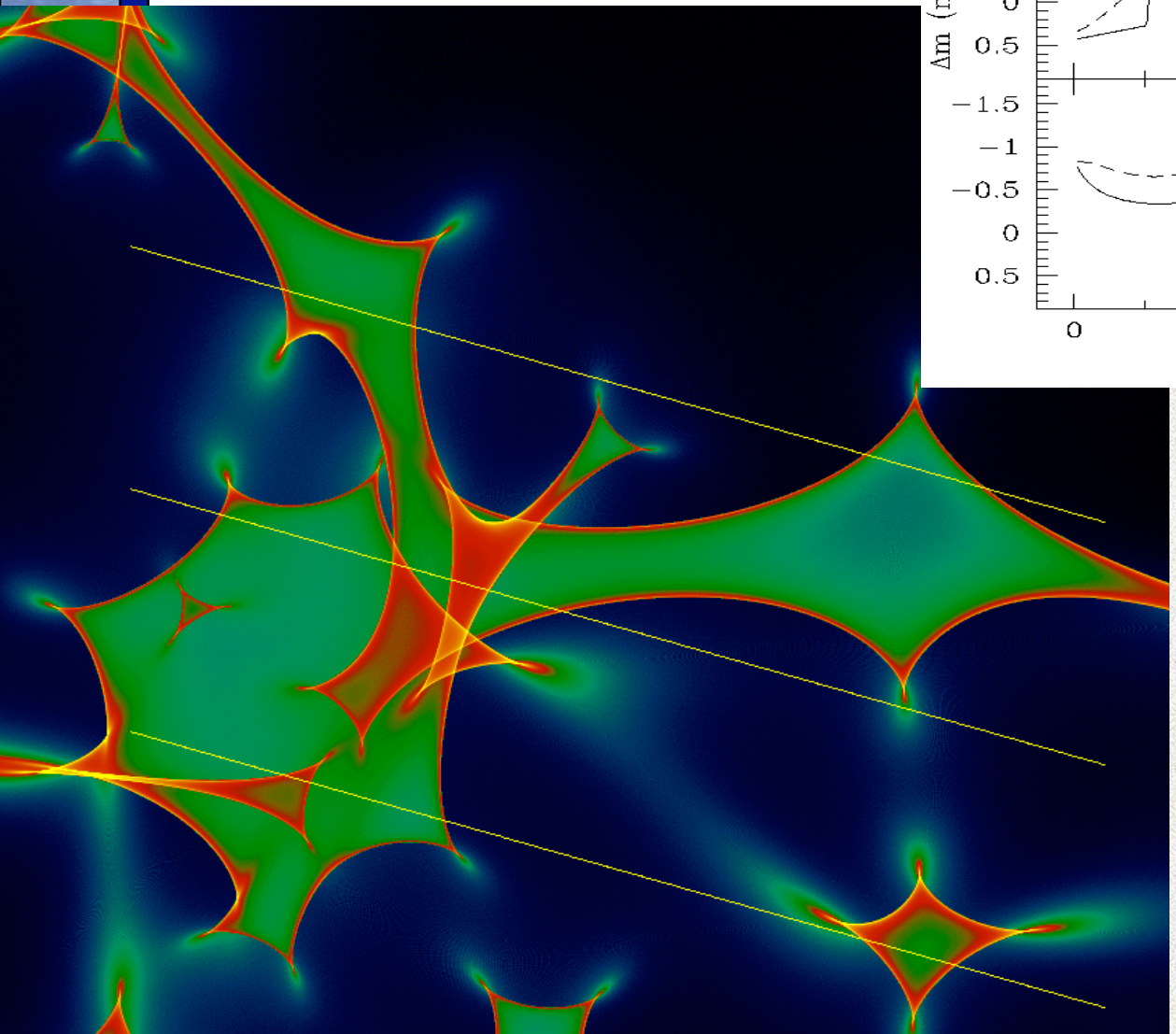
- intrinsic variability shows up in ALL images, after certain time delay!
  ⇒ shift and subtract lightcurves:
  "difference" lightcurve: flat - no microlensing
  variable - microlensing

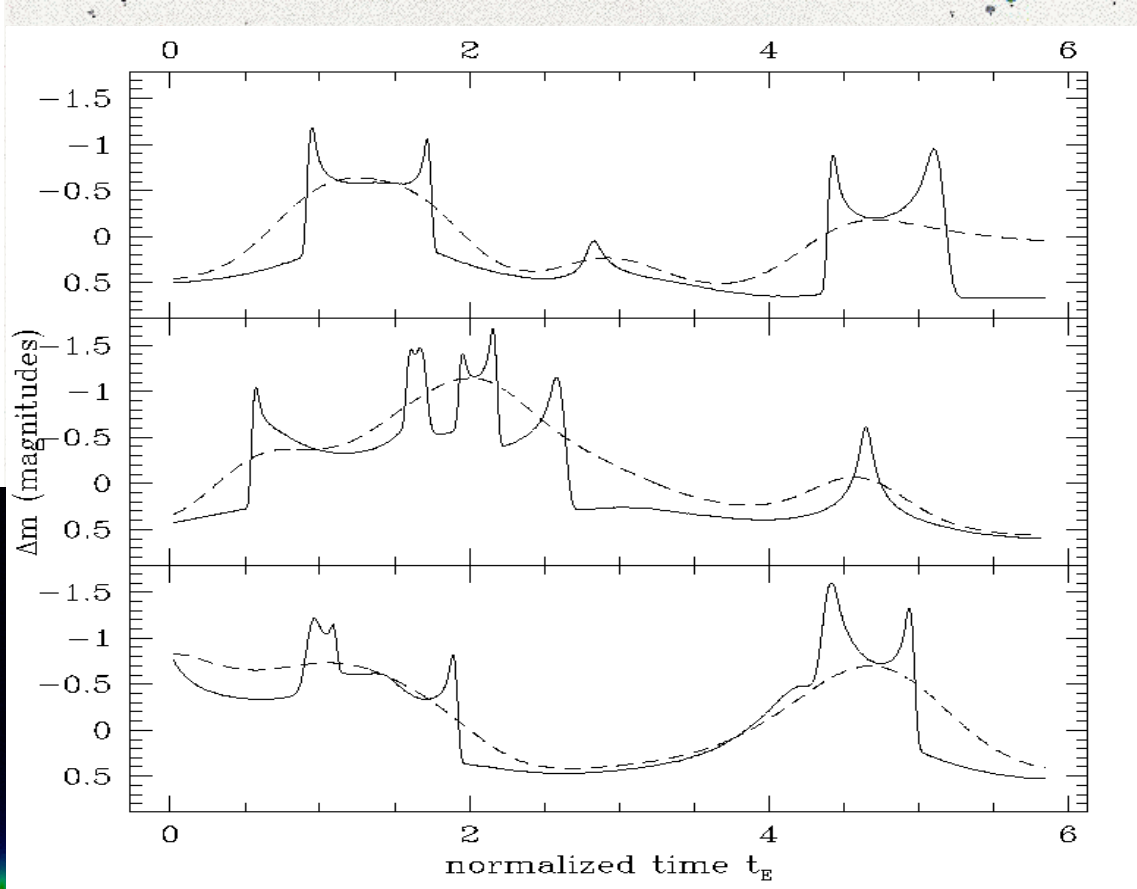
Quasar Microlensing

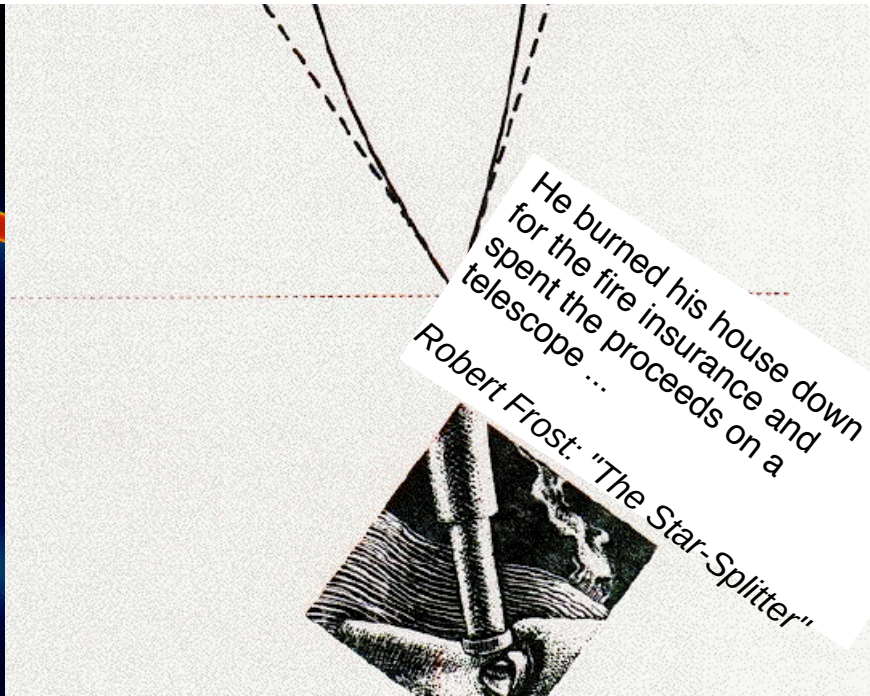




Quasar microlensing







How to detect microlensing?

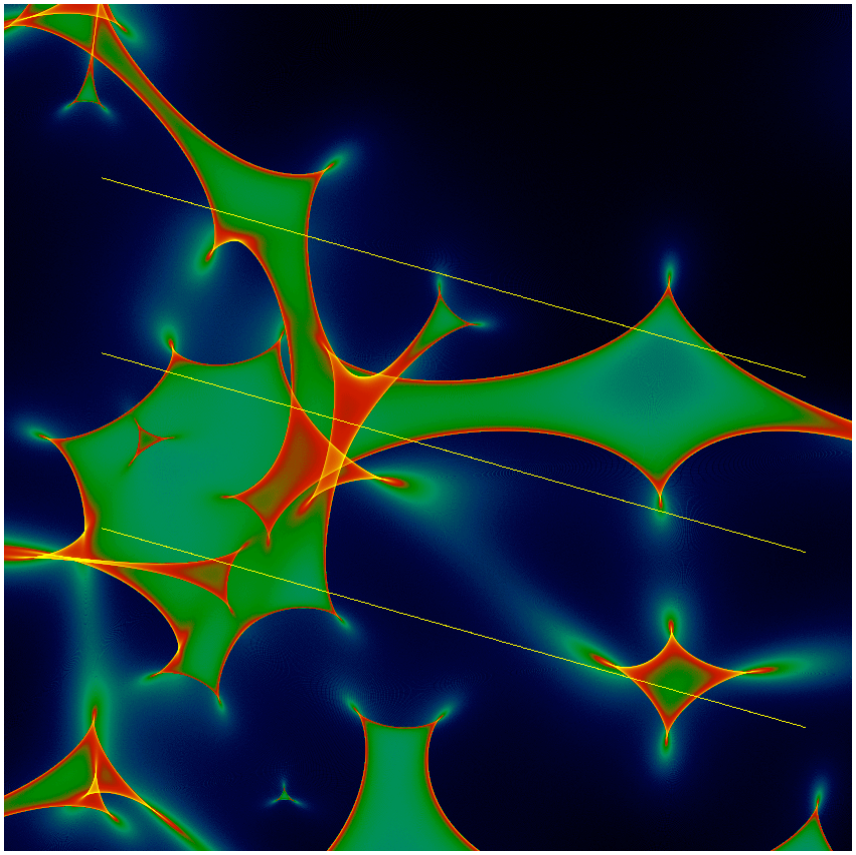
- Statically
  - Intensity ratios in optical disagree with models and/or those of radio/ emission lines
- Dynamically
  - non-intrinsic variability
  - apparent motion of light centroid
-
  - Generic problem / very important:
    - for detection/understanding of microlensing: time delay must be measured, or known (!) to be very small (compared to time scale of measured fluctuations)

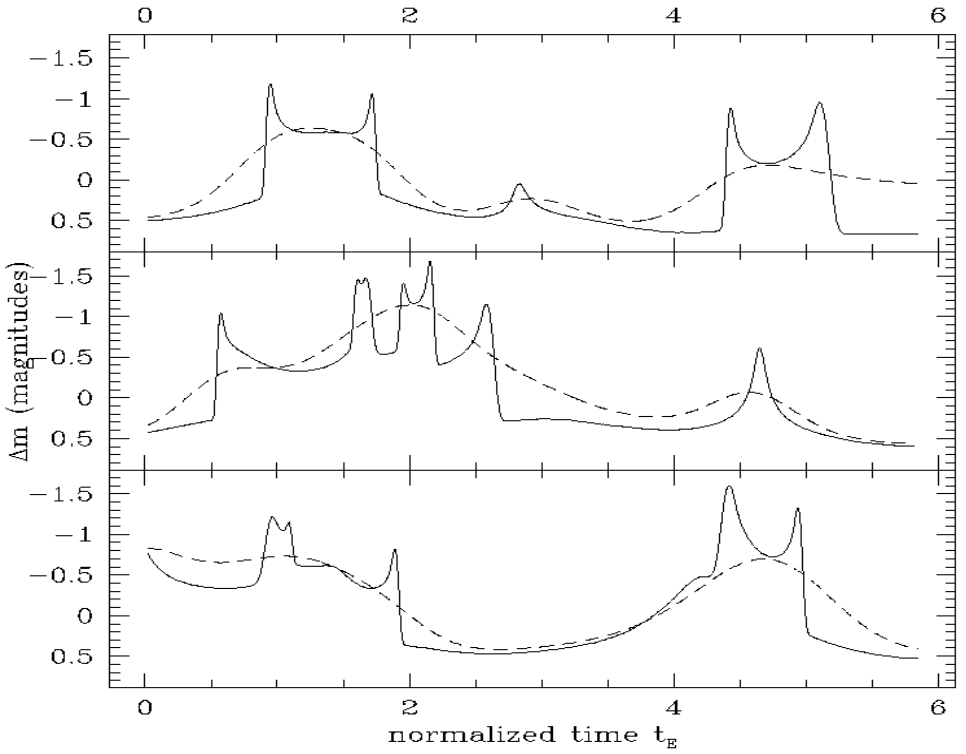
"One man's signal is another man's noise!"
(Paul Schechter)

How can we observe 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 expected 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:

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

The (pre)history of quasar microlensing

- (1979 Walsh et al.: Discovery of first gravitationally lensed quasar Q0957+561A,B)
- **1979 Chang & Refsdal: Suggestion of action of individual stars on magnification of quasar**
- 1981 Young et al.; Gott: Simulations, suggestions
- 1986/87/88 Paczynski; Kayser, Refsdal, Stabel; Schneider & Weiss; Grieger et al.: More s(t)imulations
- **1989 Irwin et al.; Vanderiest et al.: Discovery of microlensing in quadruple quasar Q2237+0305 and in double quasar Q0957+561!**

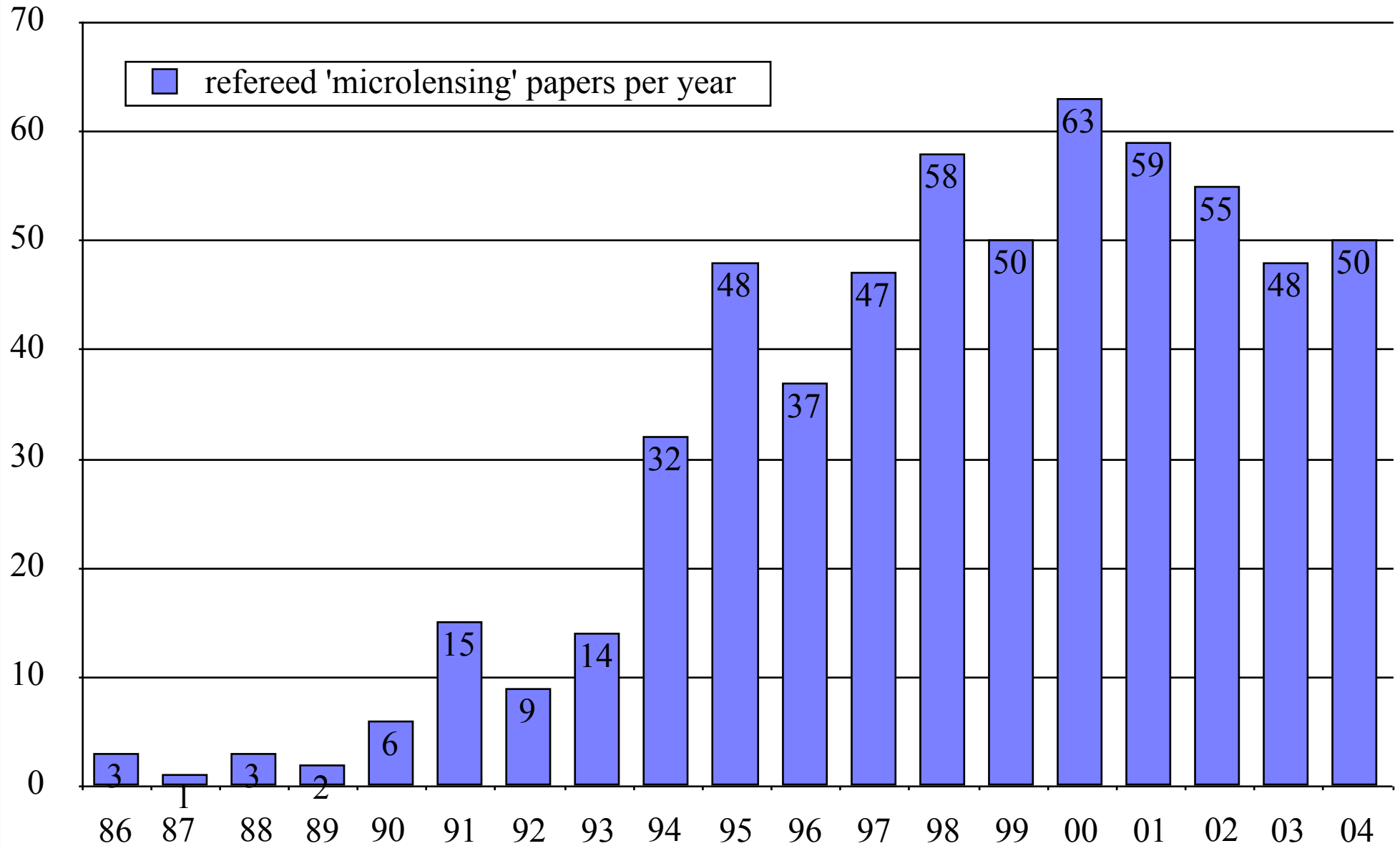
Citations of Refsdal's papers:

1	1964MNRAS.128..307R Refsdal, S.	213.000	00/1964	A	F G		R C	S	U
		On the possibility of determining Hubble's parameter and the masses of galaxies from the gravitational lens effect							
2	1964MNRAS.128..295R Refsdal, S.	201.000	00/1964	A	F G		R C		U
		The gravitational lens effect							
3	1986A&A...166...36K Kayser, R.; Refsdal, S.; Stabell, R.	189.000	09/1986	A	F G		R C	S N	U
		Astrophysical applications of gravitational micro-lensing							
4	1979Natur.282..561C Chang, K.; Refsdal, S.	186.000	12/1979	A		C			U
		Flux variations of QSO 0957+561 A, B and image splitting by stars near the light path							
5	1984A&A...132..168C Chang, K.; Refsdal, S.	116.000	03/1984	A	F G		R C	S N	O U
		Star disturbances in gravitational lens galaxies							

Citations of microlensing papers based on Chang/Refsdal 1979:

1	1986ApJ...304....1P Paczynski, B.	514.000	05/1986	A	F G	R C		L
	Gravitational microlensing by the galactic halo							
2	1986A&A...166...36K Kayser, R.; Refsdal, S.; Stabell, R.	189.000	09/1986	A	F G	R C	S N	
	Astrophysical applications of gravitational micro-lensing							
3	1989AJ.....98.1989I Irwin, M. J.; Webster, R. L.; Hewett, P. C.; Corrigan, R. T.; Jedrzejewski, R. I.	163.000	12/1989	A	F G	R C	S N	
	Photometric variations in the Q2237 + 0305 system - First detection of a microlensing event							
4	1991ApJ...374L..37M Mao, Shunde; Paczynski, Bohdan	160.000	06/1991	A	F G	R C		
	Gravitational microlensing by double stars and planetary systems							
5	1986ApJ...301..503P Paczynski, B.	151.000	02/1986	A	F G	R C		
	Gravitational microlensing at large optical depth							
6	1987A&A...171...49S Schneider, P.; Weiss, A.	145.000	01/1987	A	F G	R C	S N	
	A gravitational lens origin for AGN-variability? Consequences of micro-lensing							
7	1981ApJ...244..756Y Young, P.	123.000	03/1981	A	F G	R C	S N	
	Q0957+561 - Effects of random stars on the gravitational lens							
8	1986A&A...164..237S Schneider, P.; Weiss, A.	122.000	08/1986	A	F G	R C		
	The two-point-mass lens - Detailed investigation of a special asymmetric gravitational lens							
9	1996ARA&A..34..419P Paczynski, Bohdan	121.000	00/1996	A E F		R C	S	
	Gravitational Microlensing in the Local Group							
10	1984A&A...132..168C Chang, K.; Refsdal, S.	116.000	03/1984	A	F G	R C	S N	
	Star disturbances in gravitational lens galaxies							
11	1981ApJ...243..140G Gott, J. R., III	116.000	01/1981	A	F G	R C		
	Are heavy halos made of low mass stars - A gravitational lens test							
12	1990A&A...236..311W Witt, H. J.	102.000	09/1990	A	F G	R C	S	
	Investigation of high amplification events in light curves of gravitationally lensed quasars							

”Microlensing” Papers:



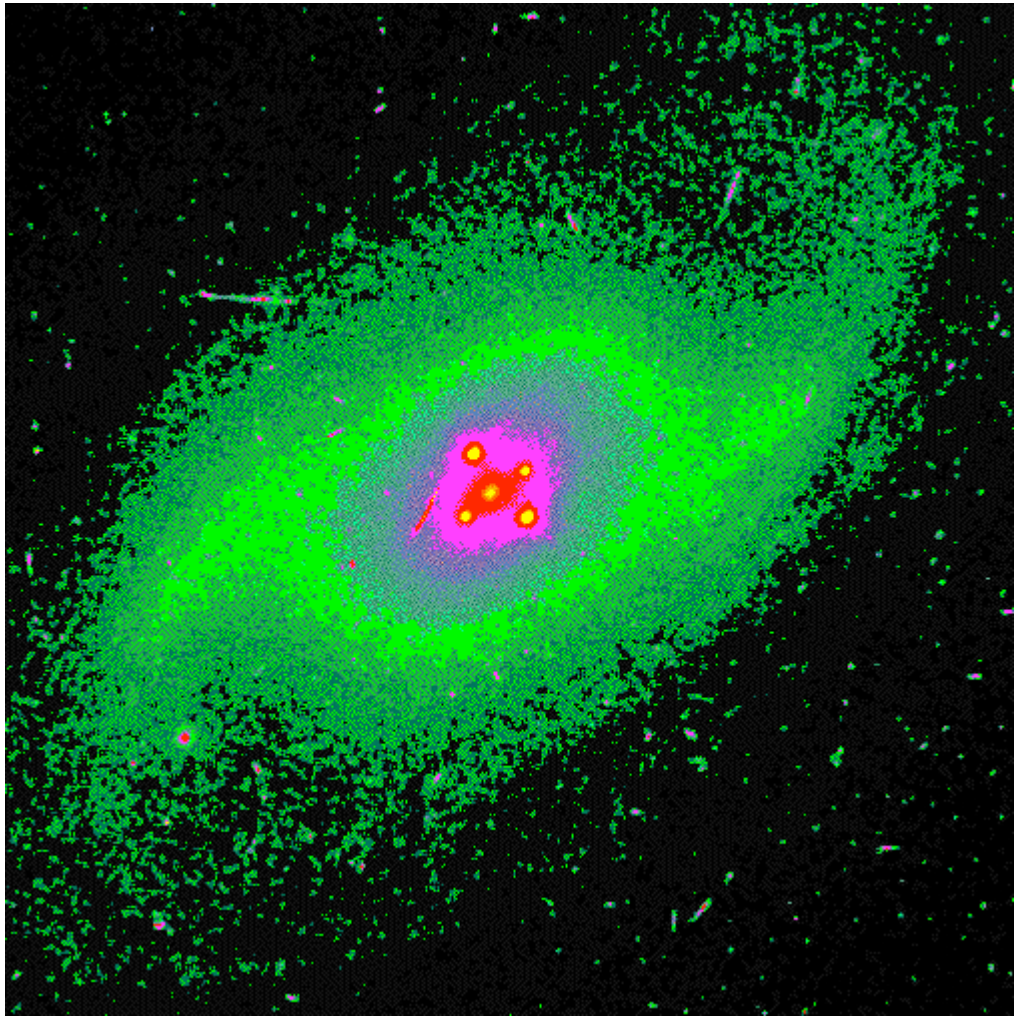
Quasar microlensing: The goals

- Quasar variability due to microlensing reveals:
  - Effects of compact/smooth matter along line of sight
  - Size of quasar
  - Two-dimensional brightness profile of quasar
  - Mass (and mass function) of lensing objects

Quasar microlensing: The goals

- Quasar variability due to microlensing reveals:
  - Effects of compact/smooth matter along line of sight
    detected!
  - Size of quasar
    partly!
  - Two-dimensional brightness profile of quasar
    not at all!
  - Mass (and mass function) of lensing objects
    some limits!

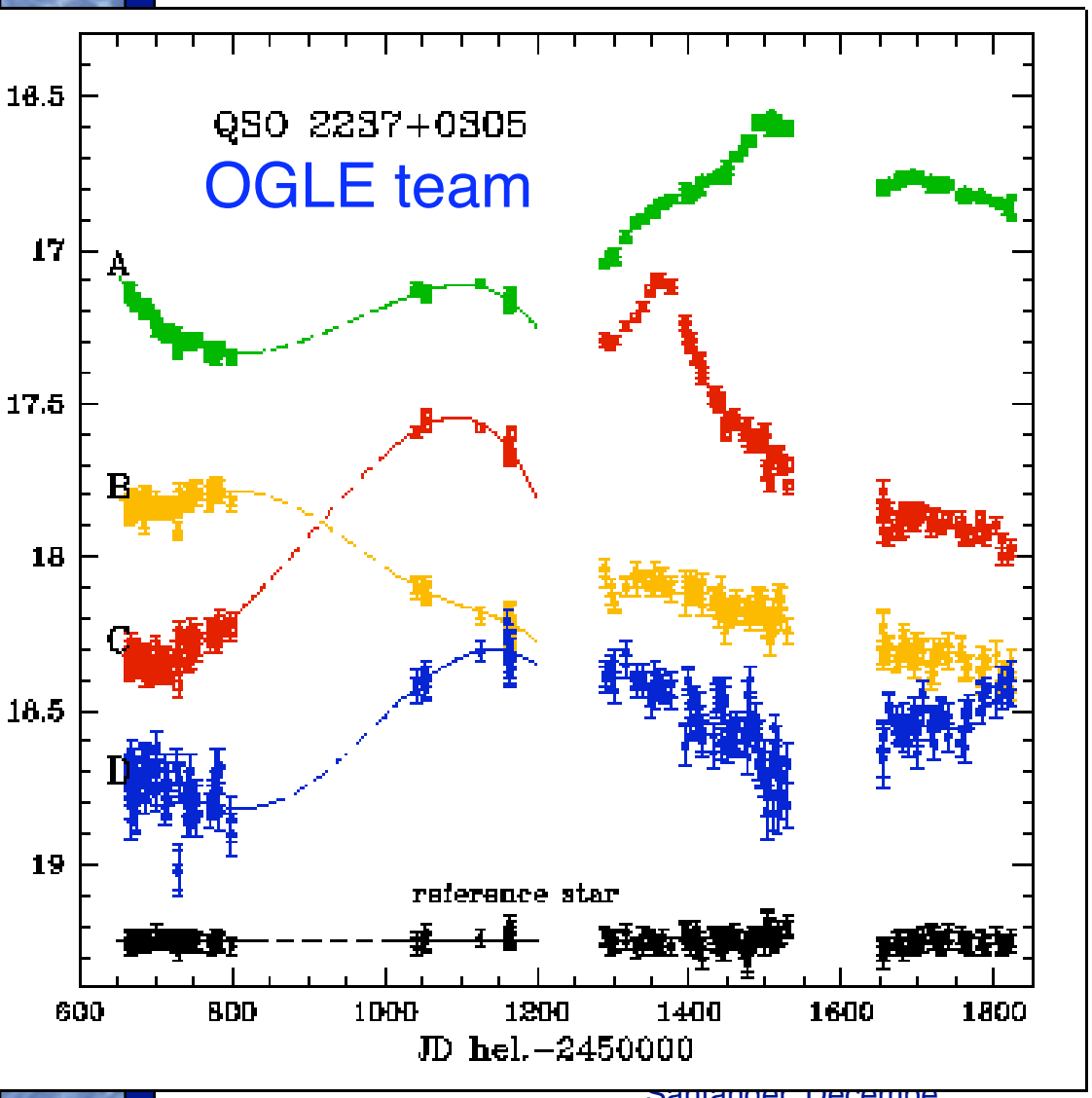
The quadruple quasar Q2237+0305



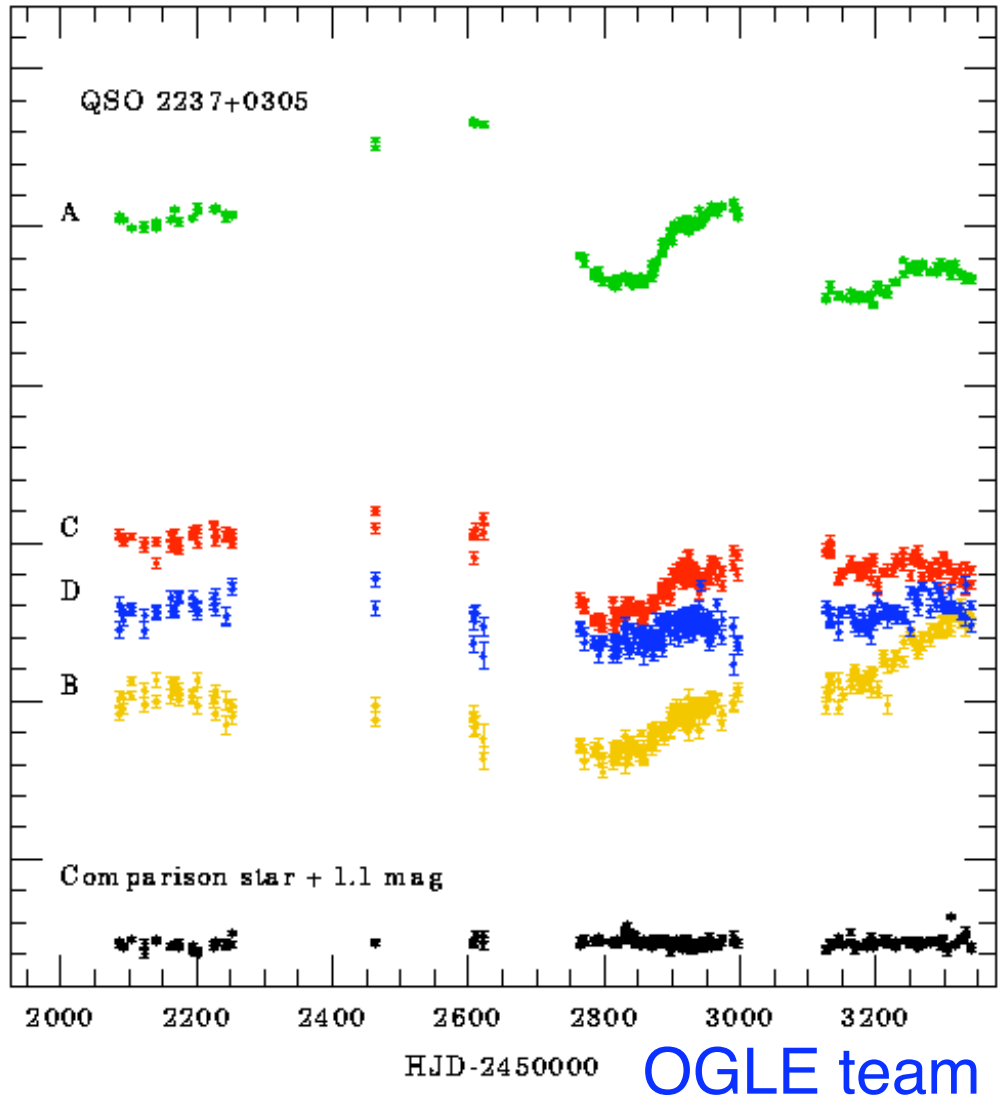
z(quasar) = 1.695, z(galaxy) = 0.039

image separation 1.7 arcsec (HST)

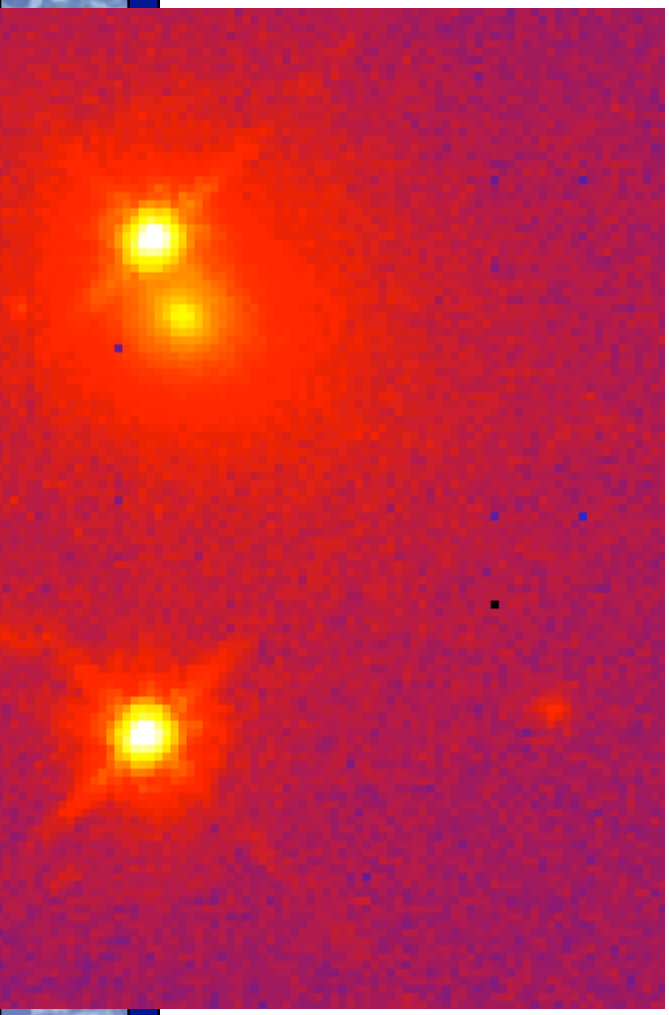
Quasar Microlensing: Q2237+0305

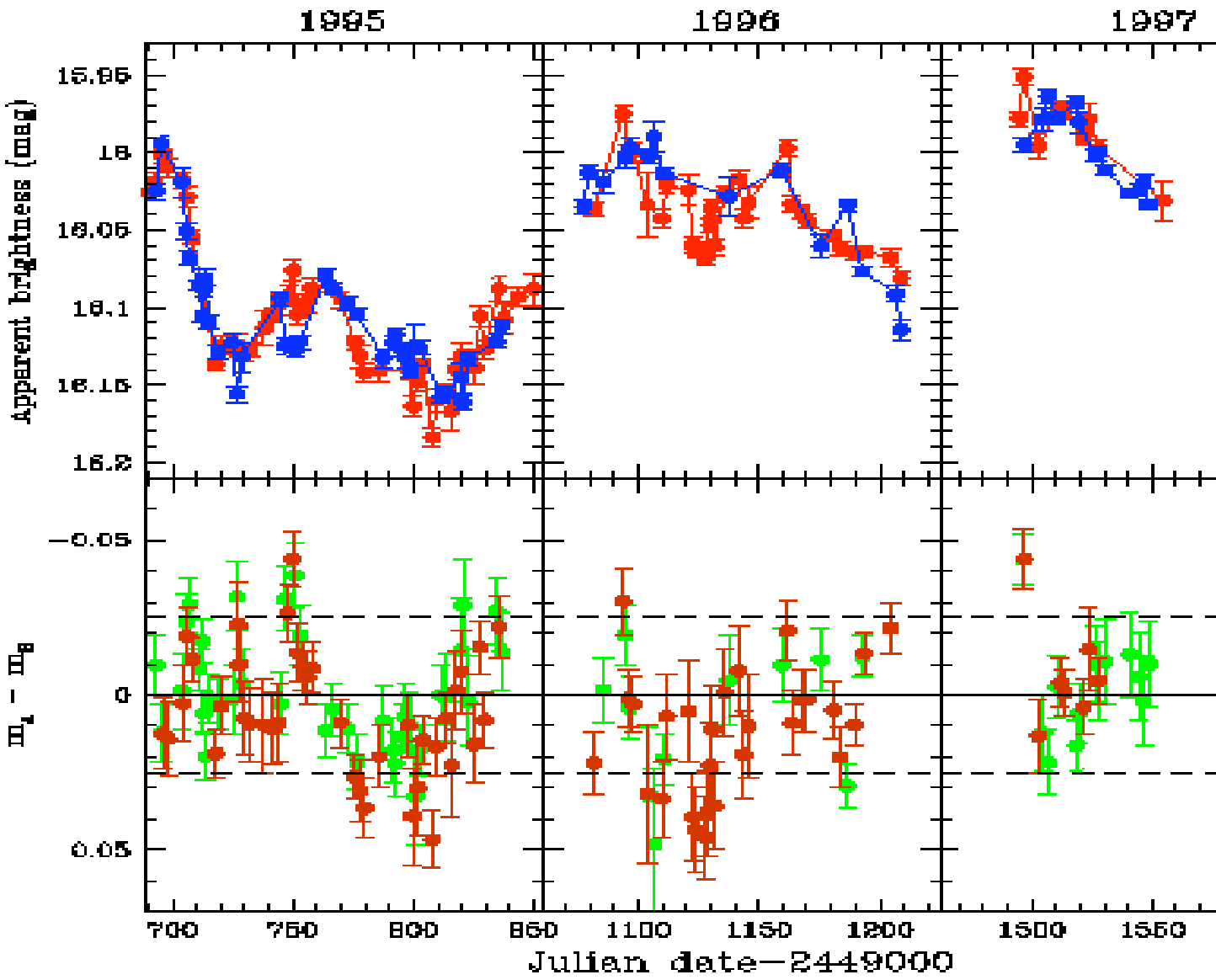


HUCHRA's LENS



Quasar Microlensing? Q0957+561





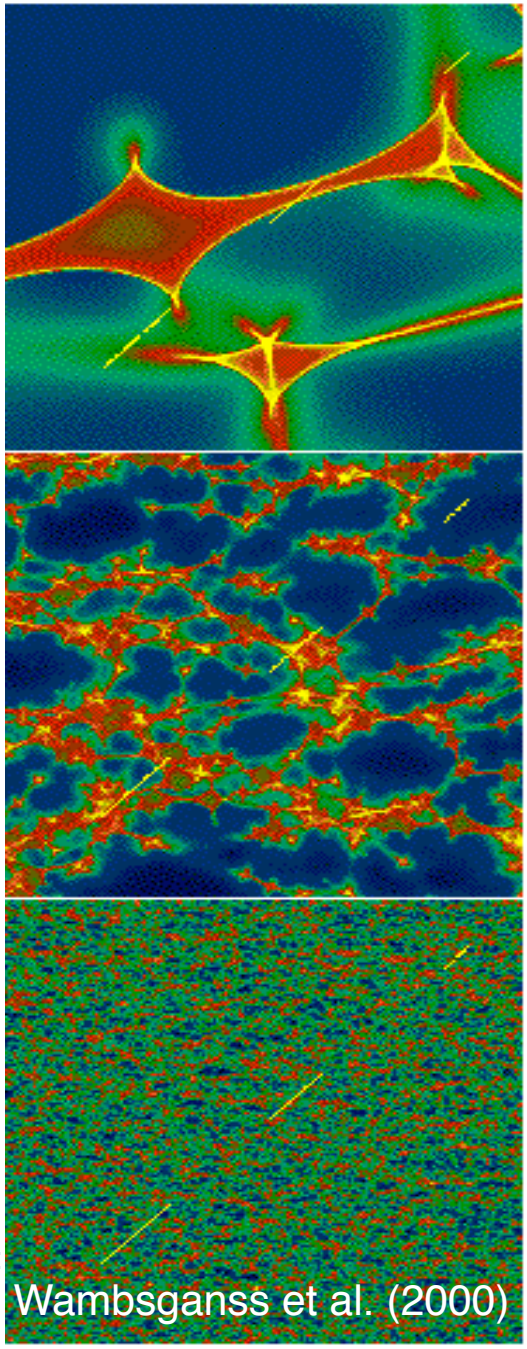
Kundic et al. (1997), Wambsganss et al. (2000)

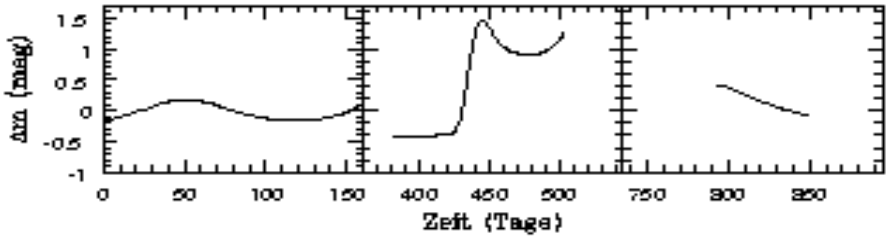
Quasar Microlensing Simulation: Q0957+561

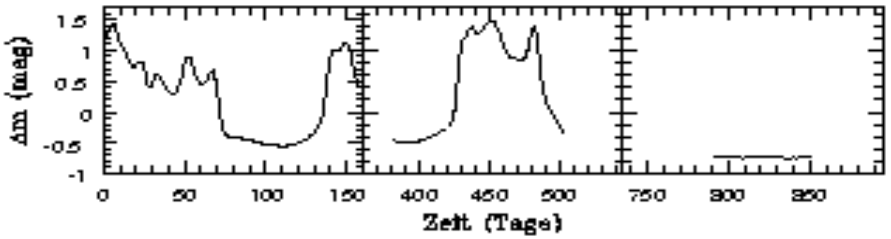
$10^{-1} M_\odot$

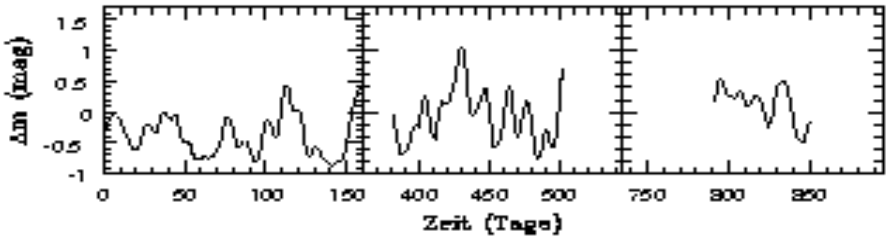
$10^{-3} M_\odot$

$10^{-5} M_\odot$



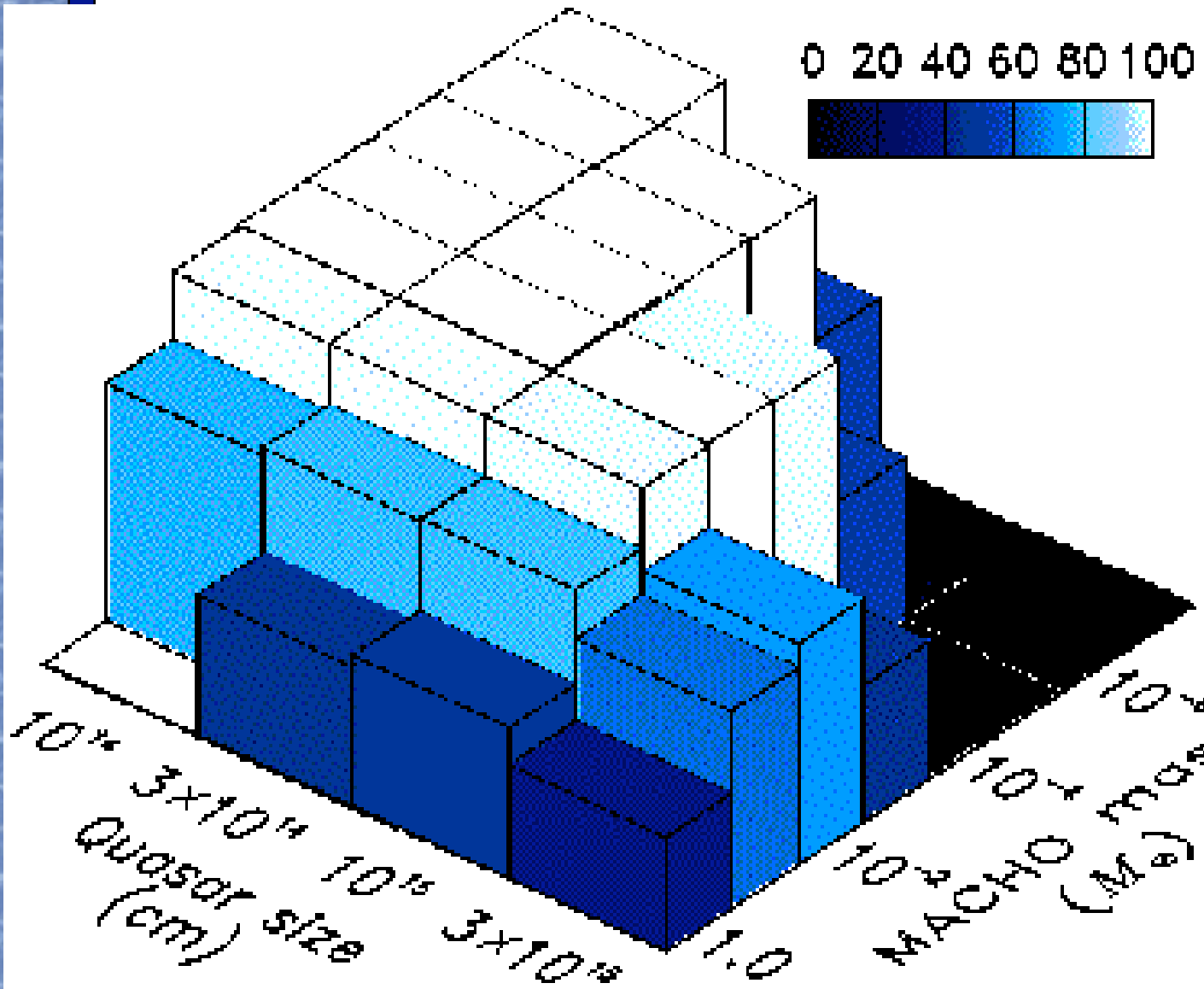






in: Wambsganss et al. (2000)

Quasar Microlensing Results: Q0957+561

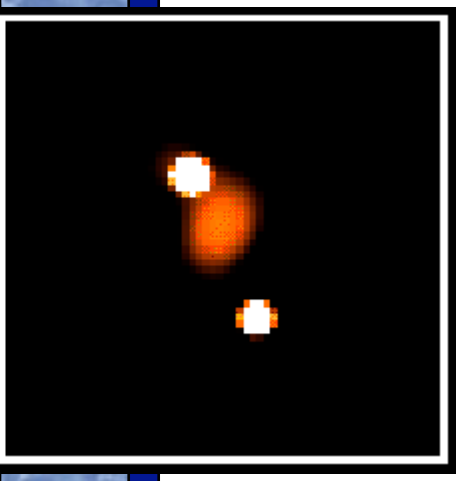


Halo of lensing galaxy cannot consist entirely of compact objects (MACHOs) in certain mass ranges
(Wambsganss et al. 2000)

More systems, longer baseline
⇒ better constraints!

OGLE monitoring of HE1104-1805: Microlensing of (relativistically moving) knots

(Schechter et al. 2003)



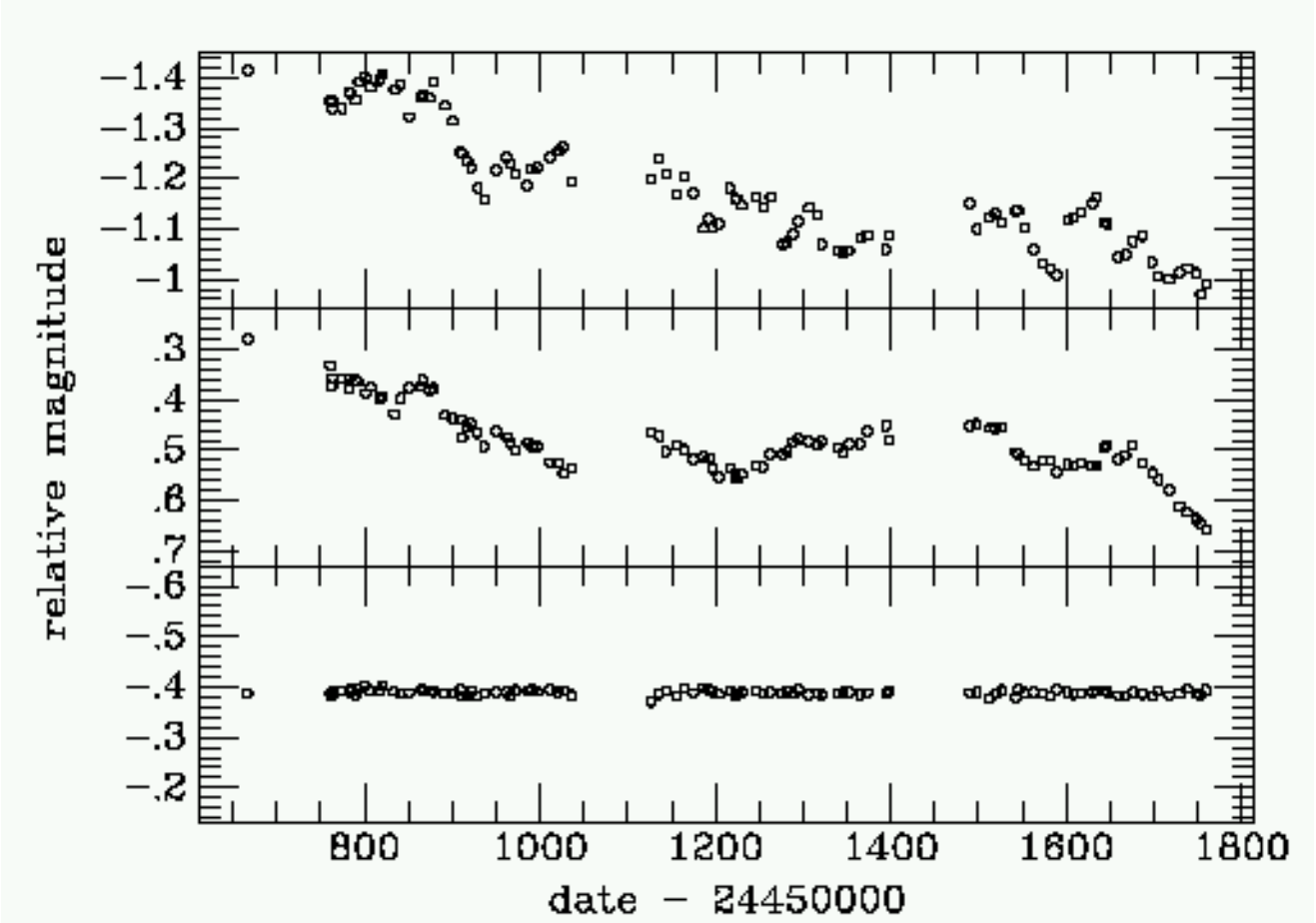


FIG. 2.—Light curves for QSO components A (*top*) and B (*middle*) and for comparison star CA (*bottom*).

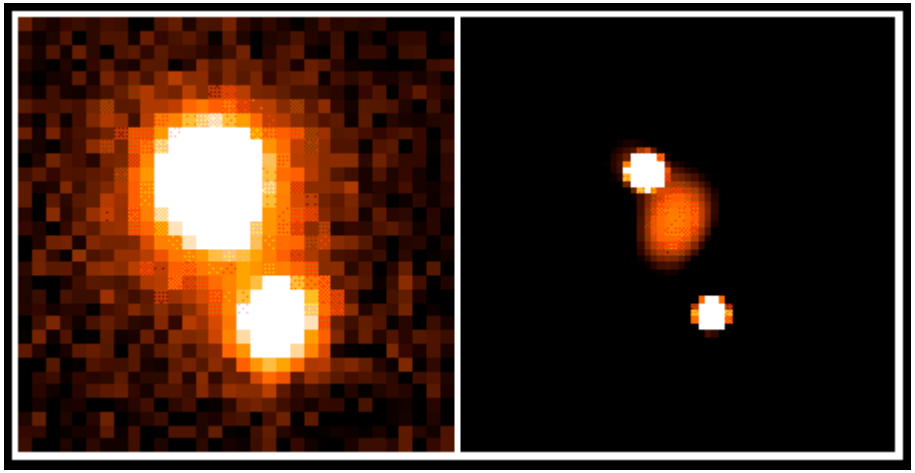
OGLE monitoring of HE1104-1805: Microlensing of (relativistically moving) knots

(Schechter et al. 2003)

data points for 102 separate nights in three years:

both images show fluctuations, but with substantial differences when correcting for time delay

short time scale (4 weeks) requires relativistic motion of one or more components of source (knots?)



dark matter? not necessarily ...

HE1104-1805 (Courbin et al.)

Microlensing by cosmologically distributed lensing objects of stellar mass?!

Dalcanton et al. (1994):

- microlensing of objects between 0.001 $M_\odot$ and 100 $M_\odot$

  will MAGNIFY continuum regions of quasars

  ⇒ reduce apparent equivalent widths (EW)

  ⇒ increase of small EW quasars with z

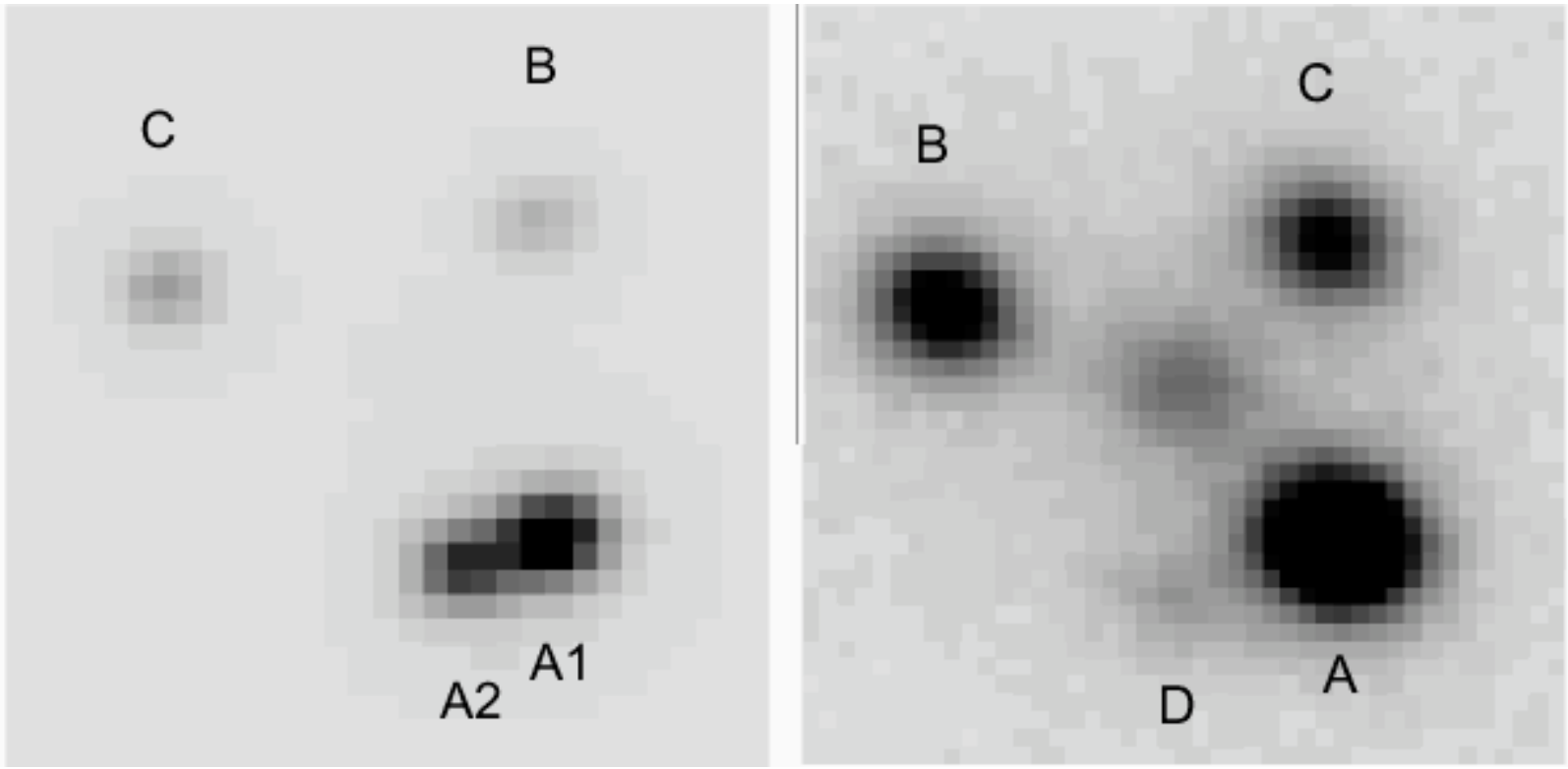
  ⇒ test: 200 QSOs

- effect NOT observed ⇒ limits on Omega, no significant DM

  $\Omega\,(0.001\ M_\odot - 20\ M_\odot) < 0.1$

- needs to be REDONE!!!

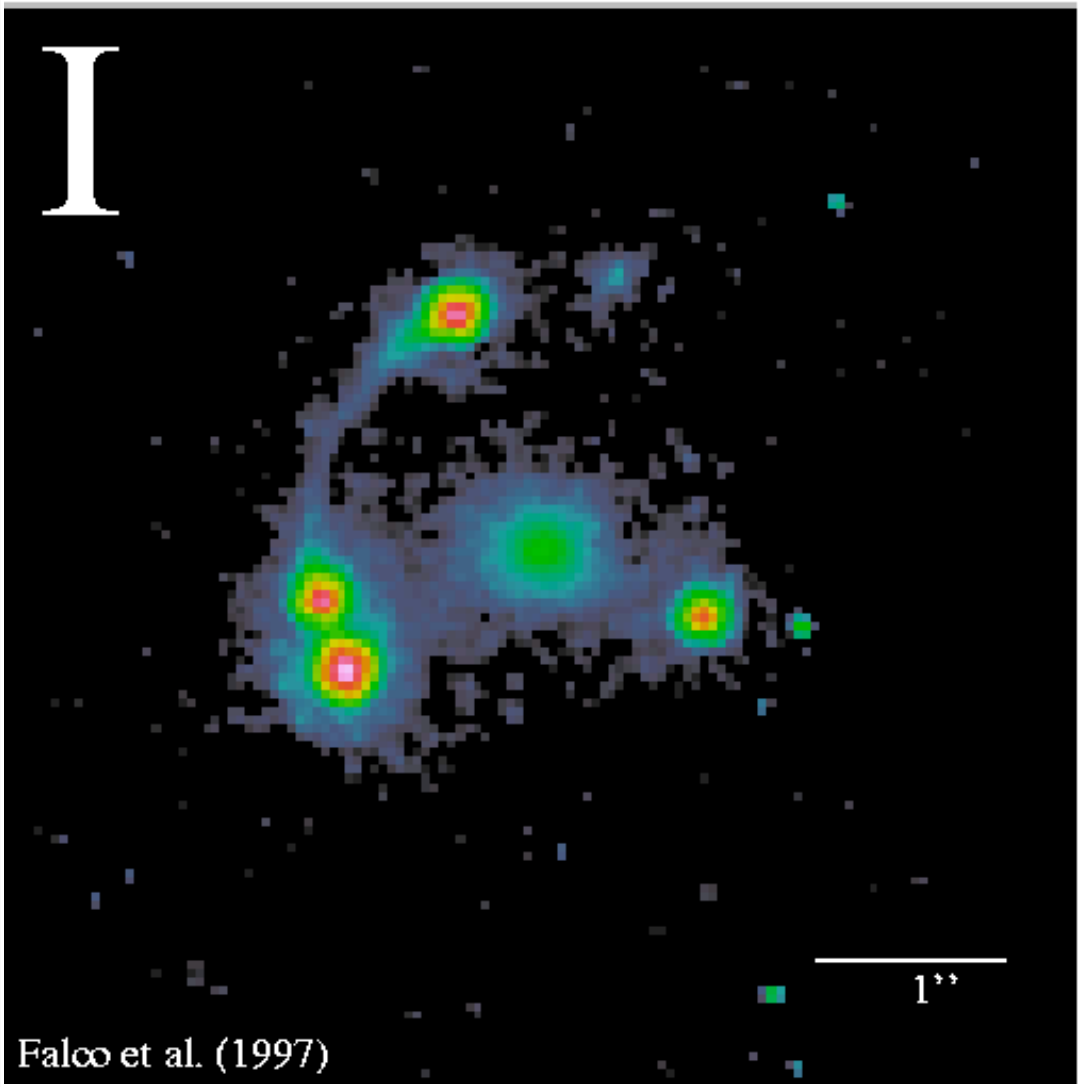
Quasar Microlensing at high magnification: suppressed saddlepoints and the role of dark matter



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



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

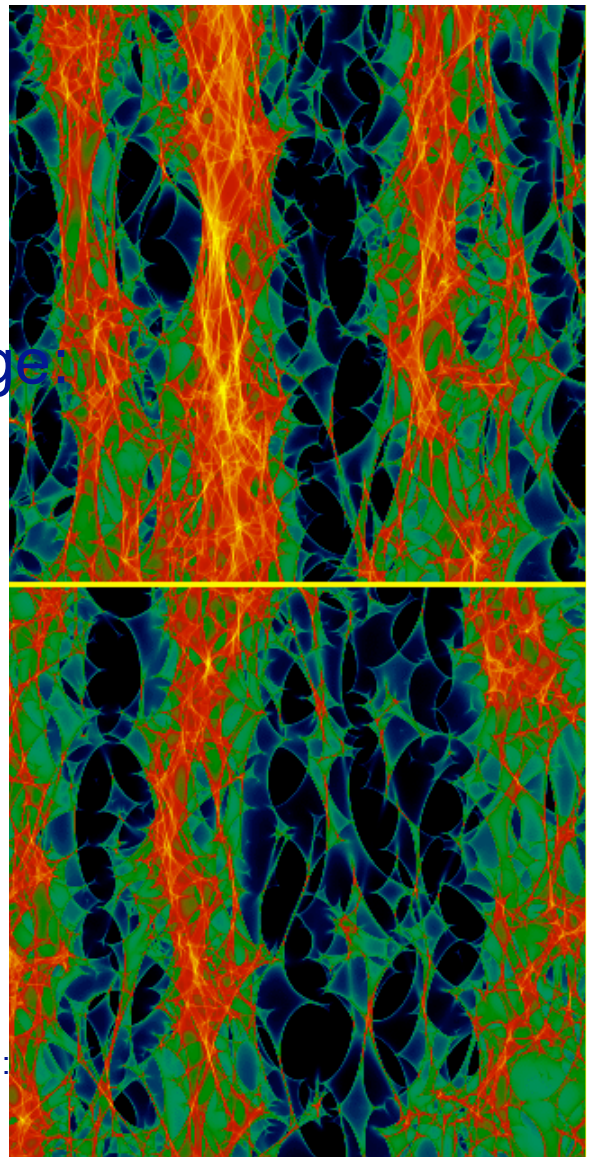
what's going on?!?

ML, substructure, DM ?

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

κ_{tot} =

κ_{smooth} = 0%



minimum image:

saddle point image:

in:

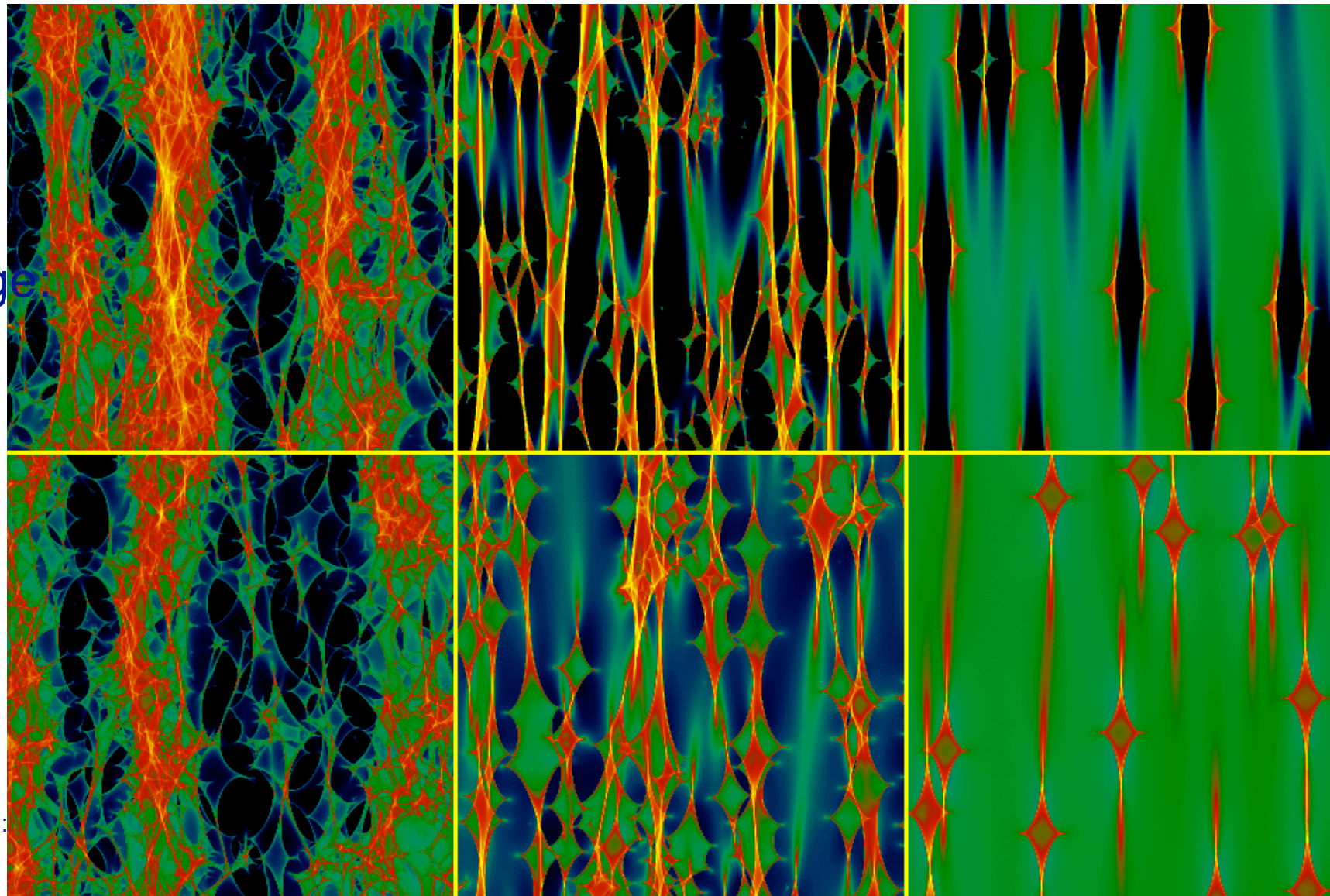
Quasar Microlensing at high magnification: suppressed saddlepoints and the role of dark matter (Schechter & Wambsganss 2002)

κ_{tot} = constant in horizontal rows

κ_{smooth} = 0% = 85% = 98%

minimum image:

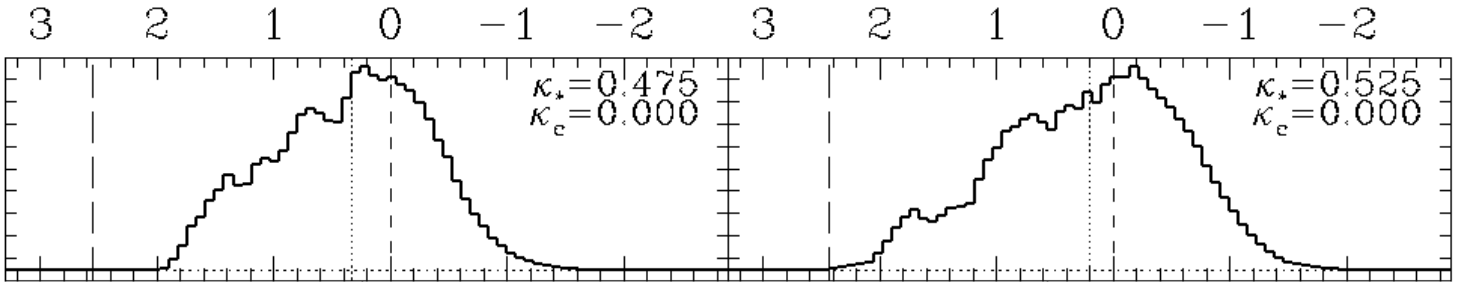
saddle point image:



in:

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%

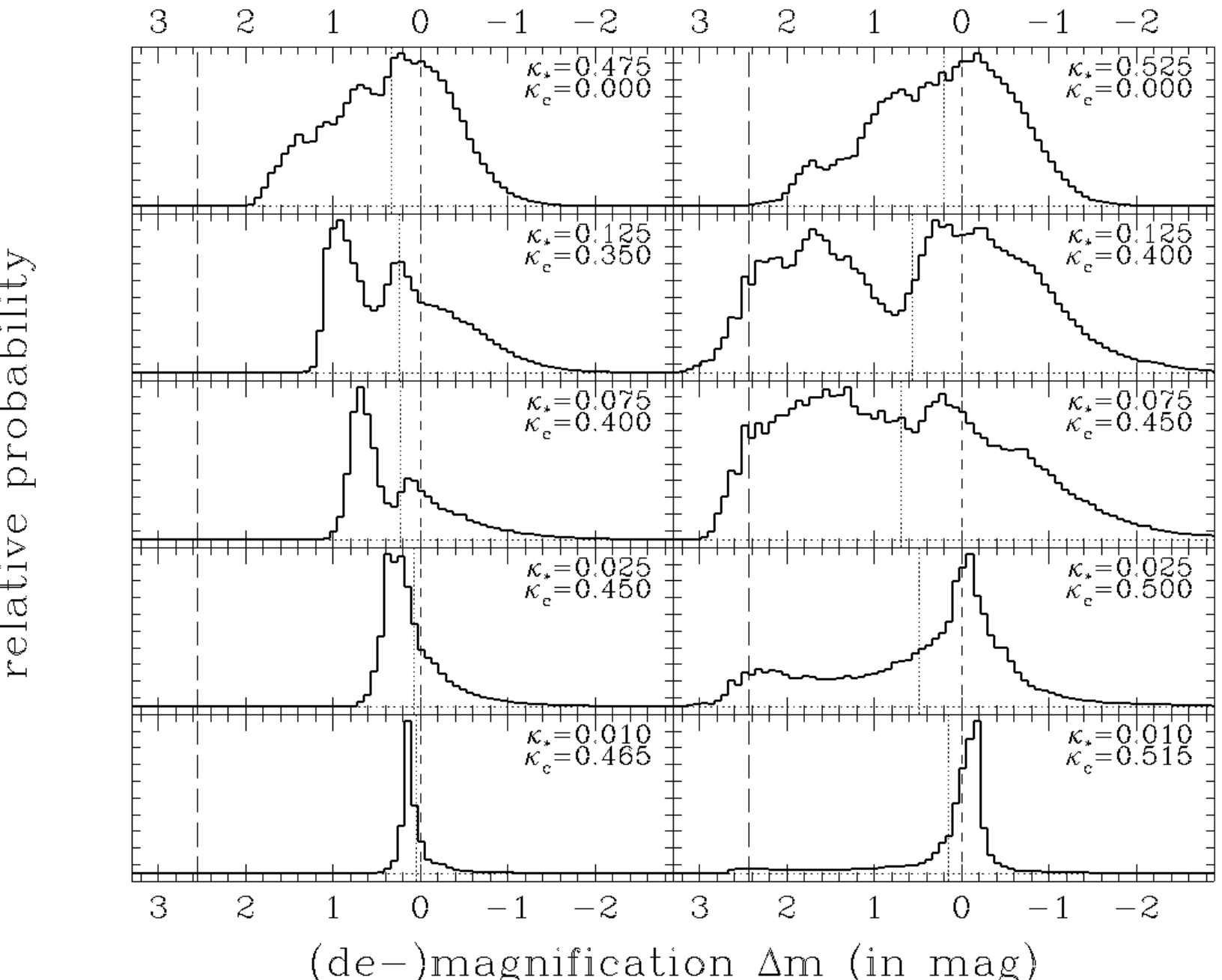
= 98%

relative probability

3 2 1 0 −1 −2 3 2 1 0 −1 −2

(de−)magnification Δm (in mag)

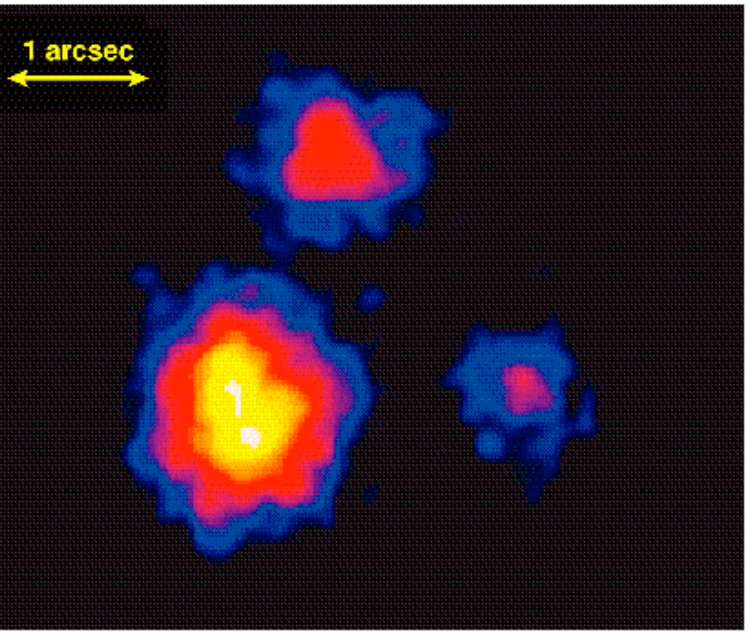
Quasar Microlensing at high magnification: suppressed saddlepoints and the role of dark matter (Schechter & Wambsganss 2002)

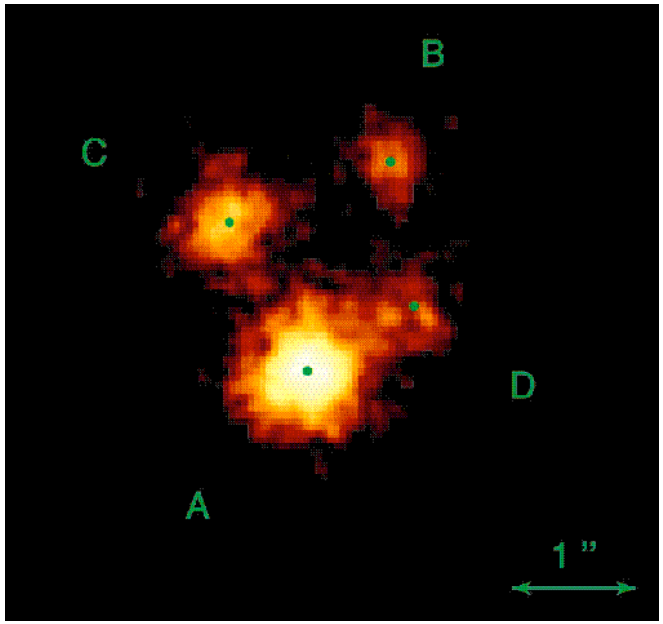


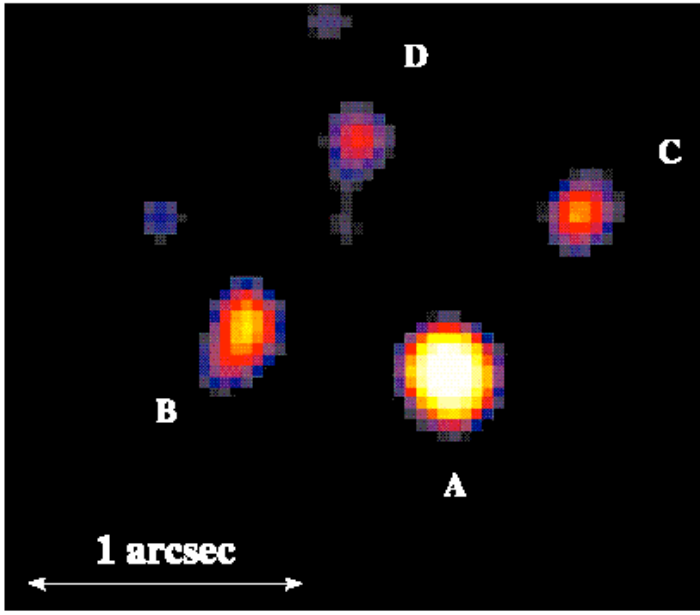
New window on microlensing: The X-rays

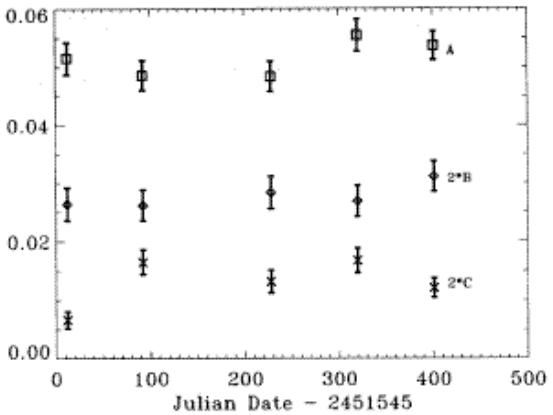
Chatras et al. (2002, 2004), Dai et al. (2003):

- Chandra observations of MG0414+0534, Q2237+0305, H1413+117



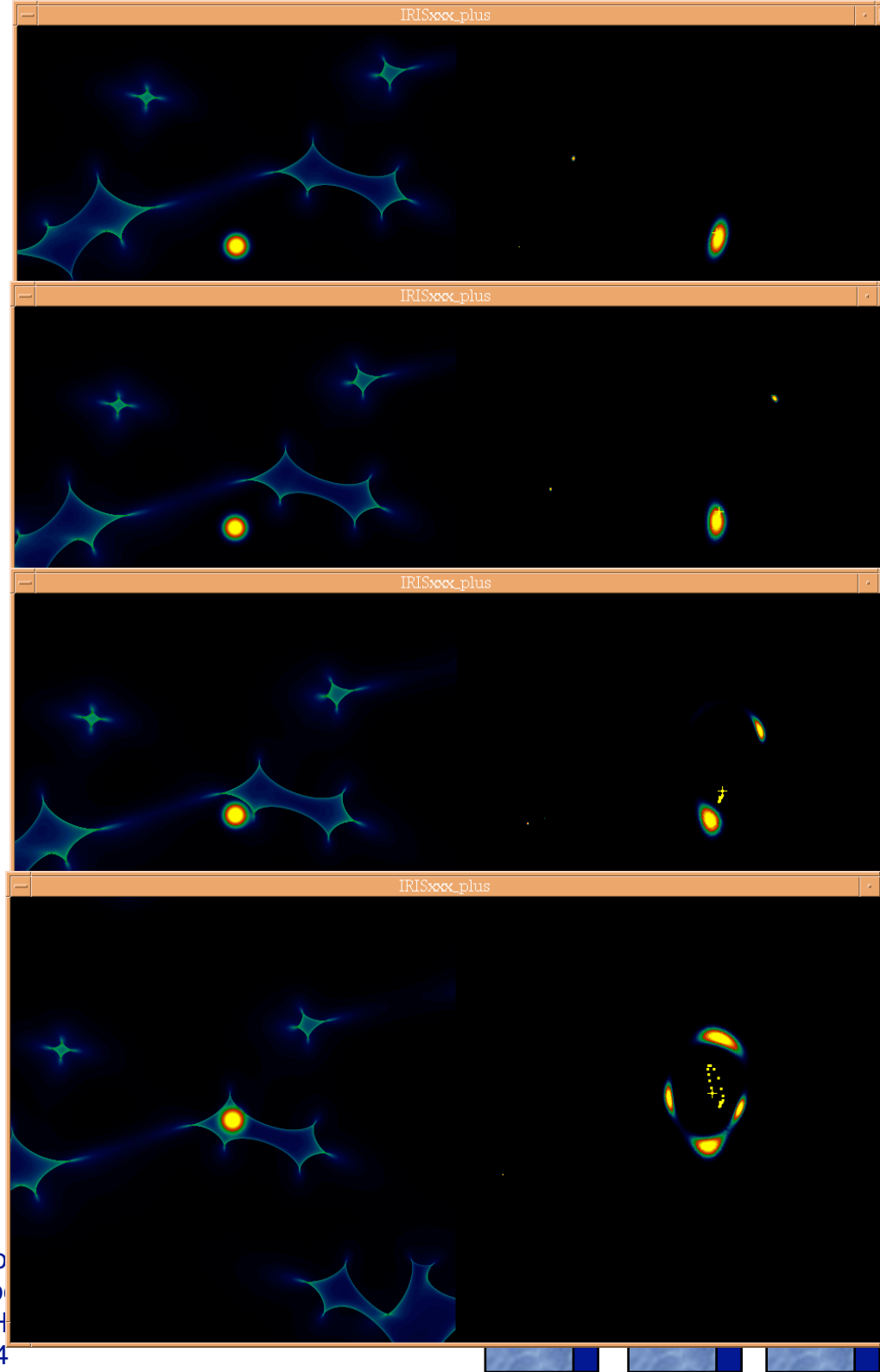






preliminary evidence for microlensing ...

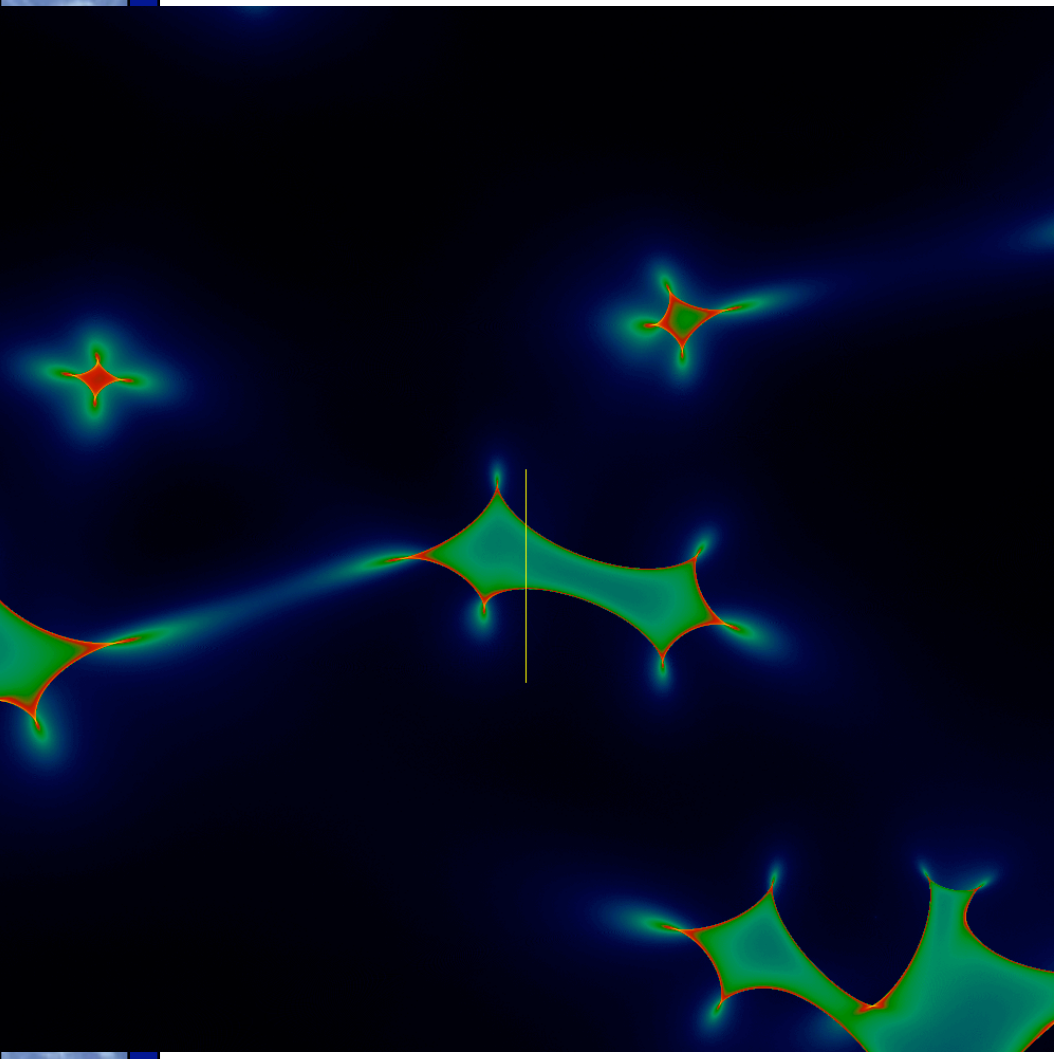
Astrometric microlensing of quasars:

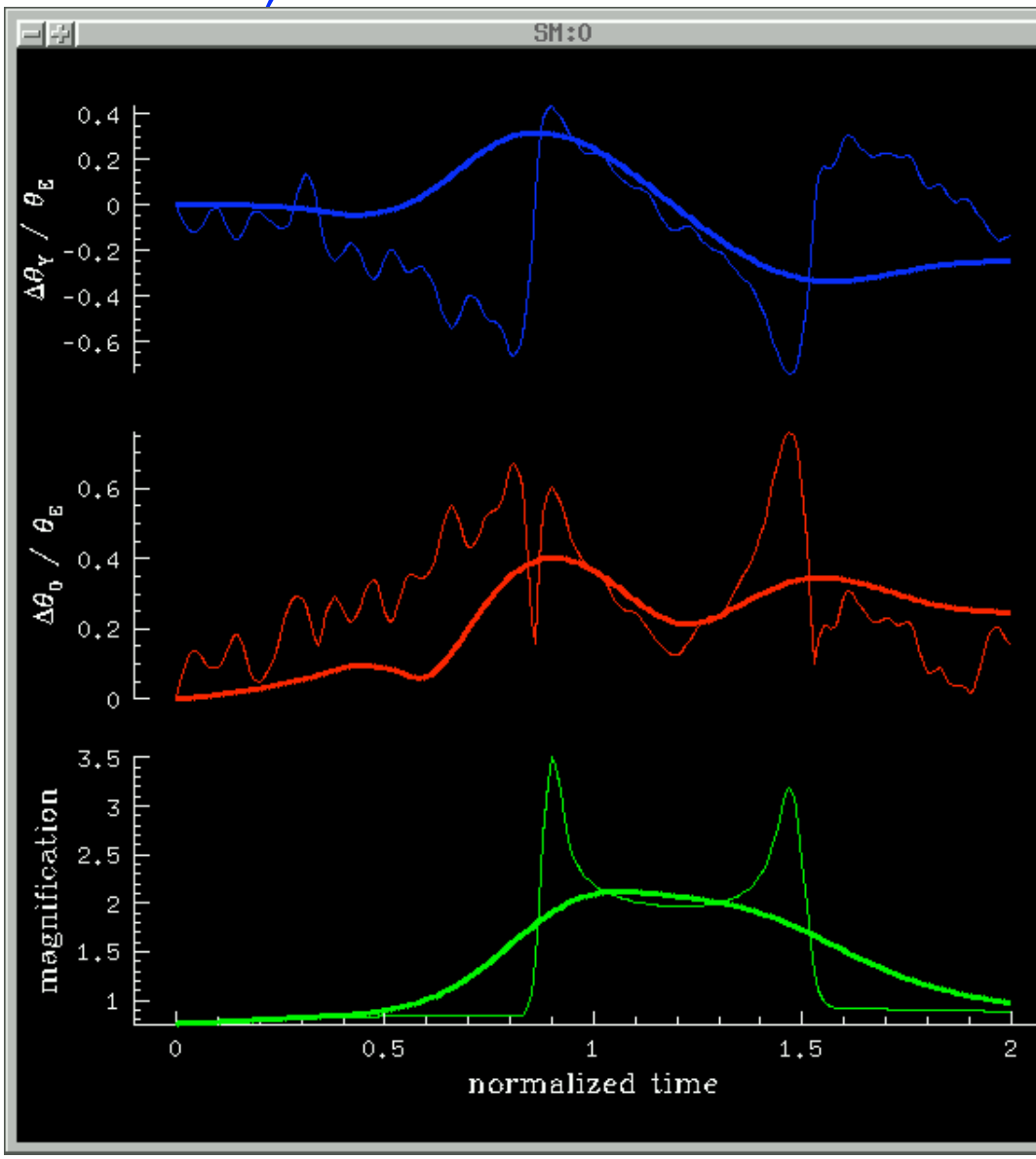


(Treyer & Wambsganss 2004)

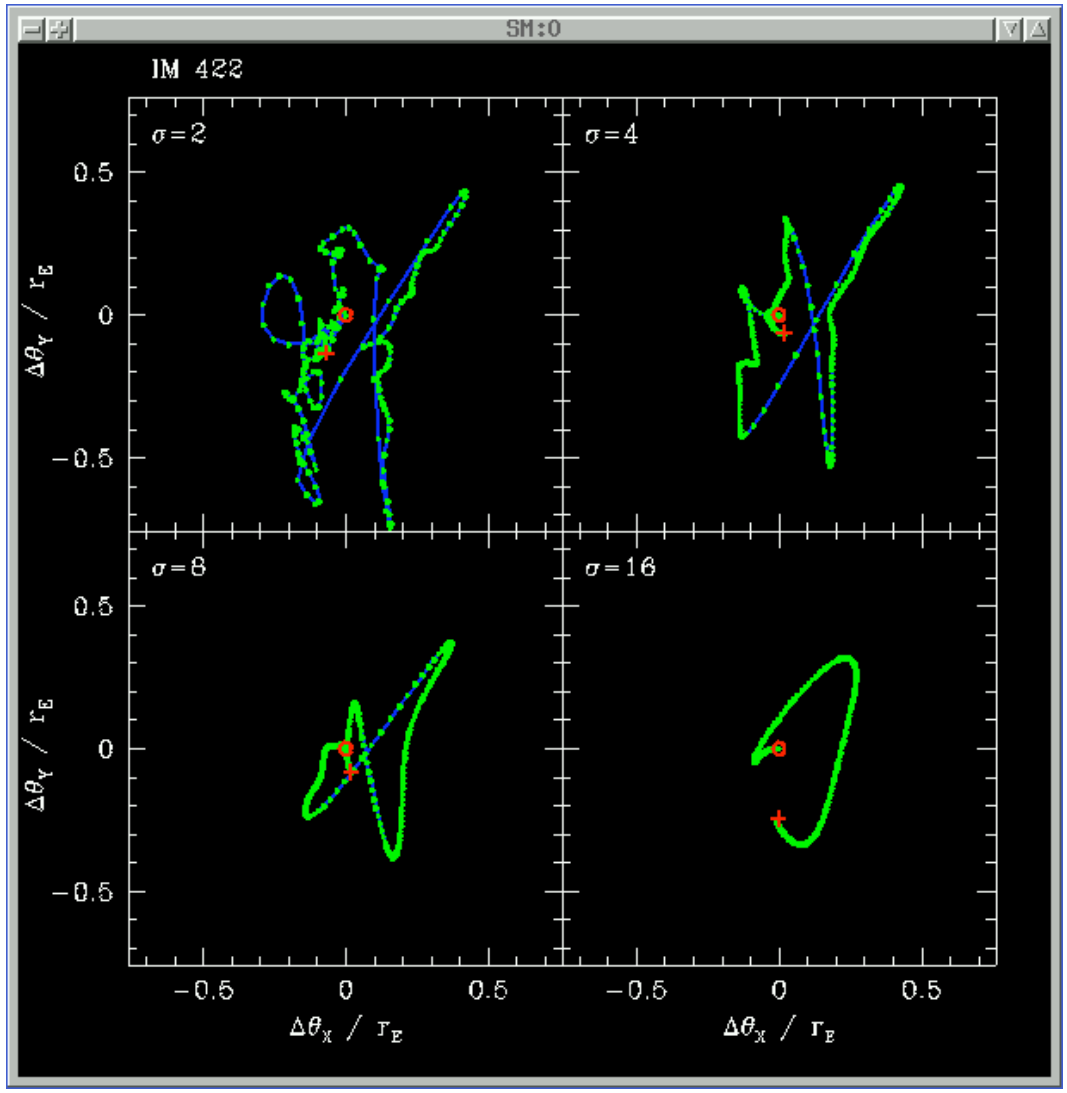
Astrometric microlensing of quasars

(Treyer & Wambsganss 2004)





Astrometric microlensing of quasars
(Treyer & Wambsganss 2004)



Astrometric microlensing of quasars
(Treyer & Wambsganss 2004)

- center-of-light of quasars moves during microlensing event:
  - effect depends on size of quasar ⇒ measurable
  - effect depends on mass of lenses ⇒ measurable
  - ... and on surface mass density/external shear: strongest for "interesting cases" with $\kappa = \gamma \approx 0.4$
- this centroid shift is correlated with magnification changes
- the "jumps" can easily reach few Einstein radii, for Q2237+0305 this is of order 15 to 35 microarcsec
- great opportunity for detection with SIM, VLTI, GAIA in not-to-distant future !

Quasar microlensing: The future goals

- Quasar variability due to microlensing reveals:
  - Effects of compact/smooth matter along line of sight
  - Size of quasar
  - Two-dimensional brightness profile of quasar
  - Mass (and mass function) of lensing objects

Quasar microlensing: The future goals

- Quasar variability due to microlensing reveals:
  - Effects of compact/smooth matter along line of sight
    Detect/monitor ML in more systems!
  - Size of quasar
    Go for it!
  - Two-dimensional brightness profile of quasar
    ML is unique tool for this!
  - Mass (and mass function) of lensing objects
    Just do it!