Quasar Microlensing with **OGLE**

Joachim Wambsganss
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Quasar Microlensing with **OGLE**

- „The *other* microlensing“: What is quasar **microlensing**?

  similarities, differences

- A few historic remininscenes w/r to quasar **microlensing**

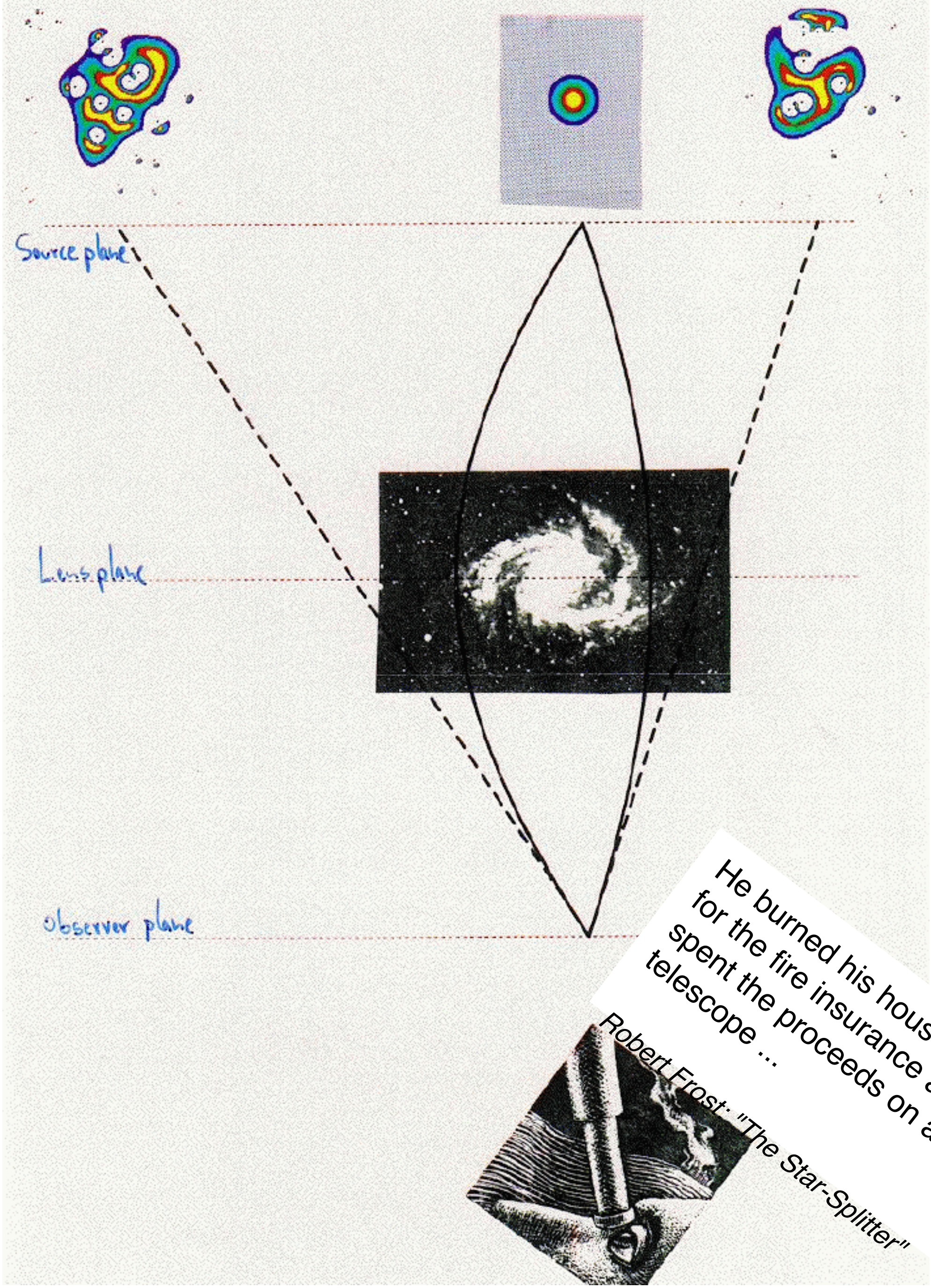
  Chang/Refsdal (1979, 1984), Gott (1981), Paczynski (1986a)

- Quasar **microlensing** and OGLE’s important contributions

  opening the time domain (!), quasar size, dark matter fraction

- Concluding remarks

Quasar Lensing: Geometry



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,
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Institute of Astronomy, Cambridge, UK
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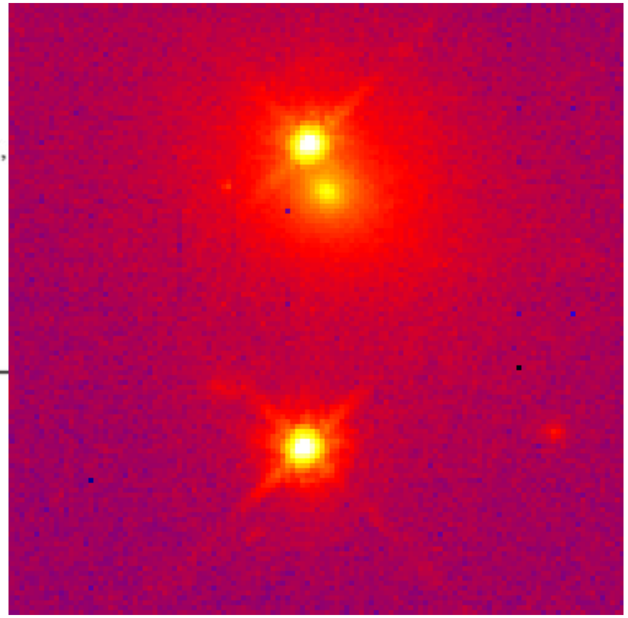
Steward Observatory, University of Arizona, Tucson, Arizona 85721

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.



1979 Chang & Refsdal:

Received 29 August; accepted 2 October 1979.

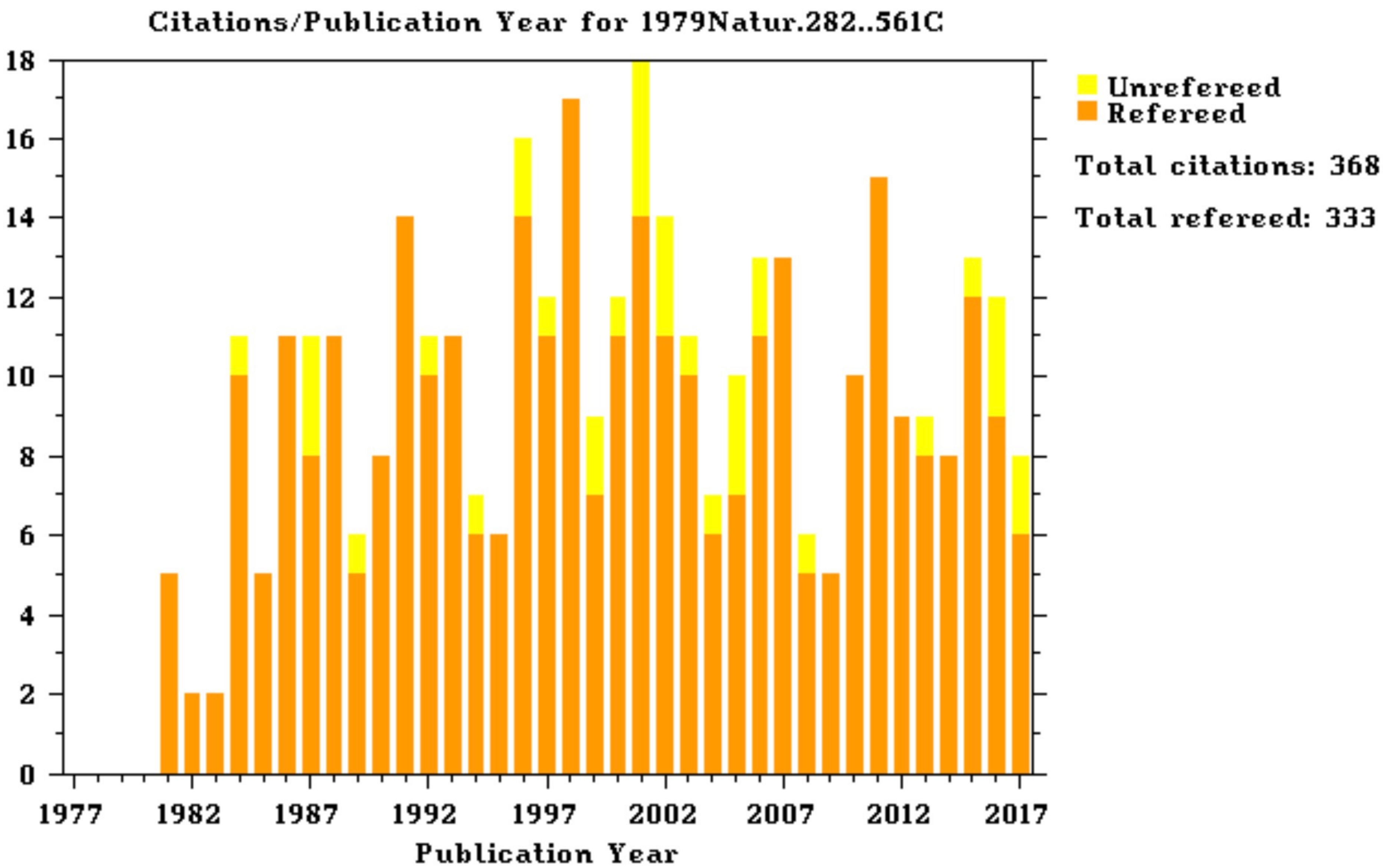
Nature Vol. 282 6 December 1979 561

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

K. Chang & S. Refsdal
Hamburger Sternwarte, Gojenbergsweg 112, D-2050 Hamburg 80, FRG

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 $\sim 10^{-5}$ *arc s.*

1979 Chang & Refsdal:



1984 Chang & Refsdal

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

ASTRONOMY AND ASTROPHYSICS

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). The missing third image in the double QSO 0957 + 561 A, B may be due to this effect.

Gott (1981)

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

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

J. RICHARD GOTT III[1]
Department of Astrophysical Sciences, Princeton University
Received 1980 April 21; accepted 1980 July 22

ABSTRACT

A test to determine whether the heavy halos of galaxies are made of low mass stars is proposed. A galaxy at intermediate redshift can act as a gravitational lens to produce a double image of a large-redshift QSO. The QSO 0957+561 A, B is almost certainly an example of this phenomenon. We show that in such a case if the intervening galaxy has a heavy halo made of low mass stars in the range $4 \times 10^{-4}\ M_{\odot}$ to $0.1\ M_{\odot}$, then these stars acting as individual gravitational lenses must produce fluctuations of order unity in the intensities of the QSO images on time scales of 1–14 years.

Paczyński (1986a)

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

GRAVITATIONAL MICROLENSING AT LARGE OPTICAL DEPTH

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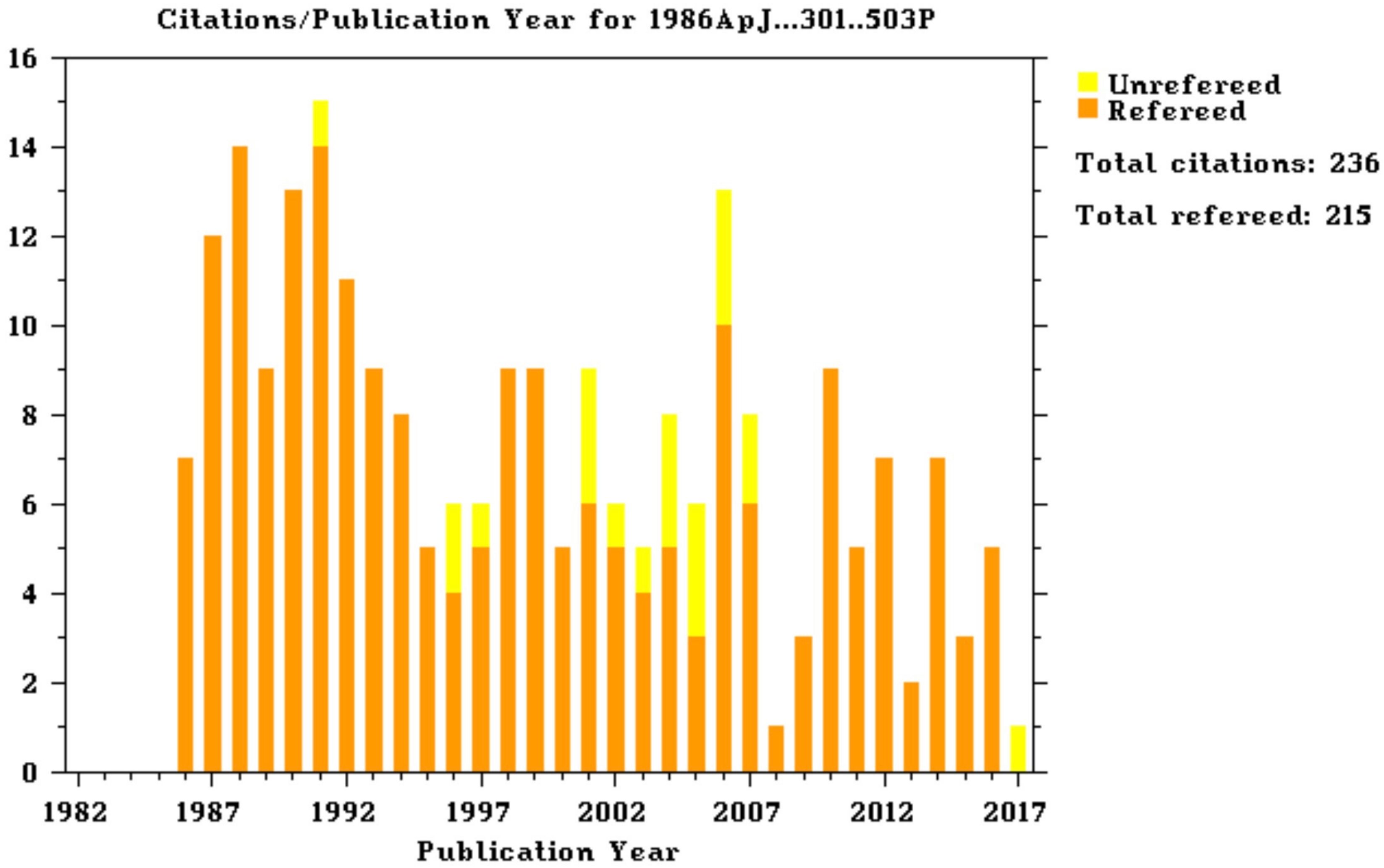
Princeton University Observatory
Received 1985 June 24; accepted 1985 August 20

ABSTRACT

A large number of numerical models of gravitational microlensing by stars in the lensing galaxy has been calculated, and properties of the models are described. The expected light intensity variations are more rapid when optical depth (i.e., the surface mass density expressed in proper units) to microlensing is large, but the time scale is a few years in the best cases, and much longer in a typical case. However, microlensing introduces considerable scatter, up to 2 or 3 orders of magnitude, to the intensity of macroimages expected at any given time, and this may considerably complicate the analysis of the observed lenses.

Paczyński (1986a)

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



It was a wonderful occasion and a great honor and pleasure for me to work with **Bohdan Paczyński** from 1987 onward:

- we wrote 13 joint papers (5 out of my first 10)
- Bohdan was incredibly influential for me, my career, my life
- Thank you, Bohdan!

Irwin et al. (1989)

THE ASTRONOMICAL JOURNAL VOLUME 98, NUMBER 6 DECEMBER 1989

PHOTOMETRIC VARIATIONS IN THE Q2237+0305 SYSTEM: FIRST DETECTION OF A MICROLENSING EVENT[a),b)]

M. J. IRWIN
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R. L. WEBSTER[c)]
Canadian Institute of Theoretical Astrophysics, 60 St. George Street, Toronto, Ontario MS5 1A1, Canada

P. C. HEWETT, R. T. CORRIGAN, AND R. I. JEDRZEJEWSKI
Institute of Astronomy, Madingley Road, Cambridge CB3 OHA, England
Received 18 April 1989; revised 27 June 1989

ABSTRACT

We present new photometric data for the gravitationally lensed quasar system 2237 + 0305, which shows unambiguous evidence for a change in brightness of one of the four component images. This represents the first detection of a microlensing event.

Irwin et al. (1989)

THE ASTRONOMICAL JOURNAL VOLUME 98, NUMBER 6 DECEMBER 1989

PHOTOMETRIC VARIATIONS IN THE Q2237+0305 SYSTEM: FIRST DETECTION OF A MICROLENSING EVENT[a),b)]

TABLE III. Published *R* band photometry for 2237 + 0305.

	r^1 1986 September 28	r^2 1987 September 25	R^3 1988 August 18	R^3 1988 September 16
A	17.58 ± 0.2	17.62 ± 0.02	17.03 ± 0.05	17.18 ± 0.05
B	17.48 ± 0.2	17.77 ± 0.03	17.56 ± 0.05	17.59 ± 0.05
C	17.91 ± 0.2	18.06 ± 0.04	18.17 ± 0.05	18.15 ± 0.05
D	18.41 ± 0.2	18.40 ± 0.06	18.40 ± 0.05	18.38 ± 0.05

[1]Schneider *et al.* (1988).
[2]Yee (1988).
[3]This paper.

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

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

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

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

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

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

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**

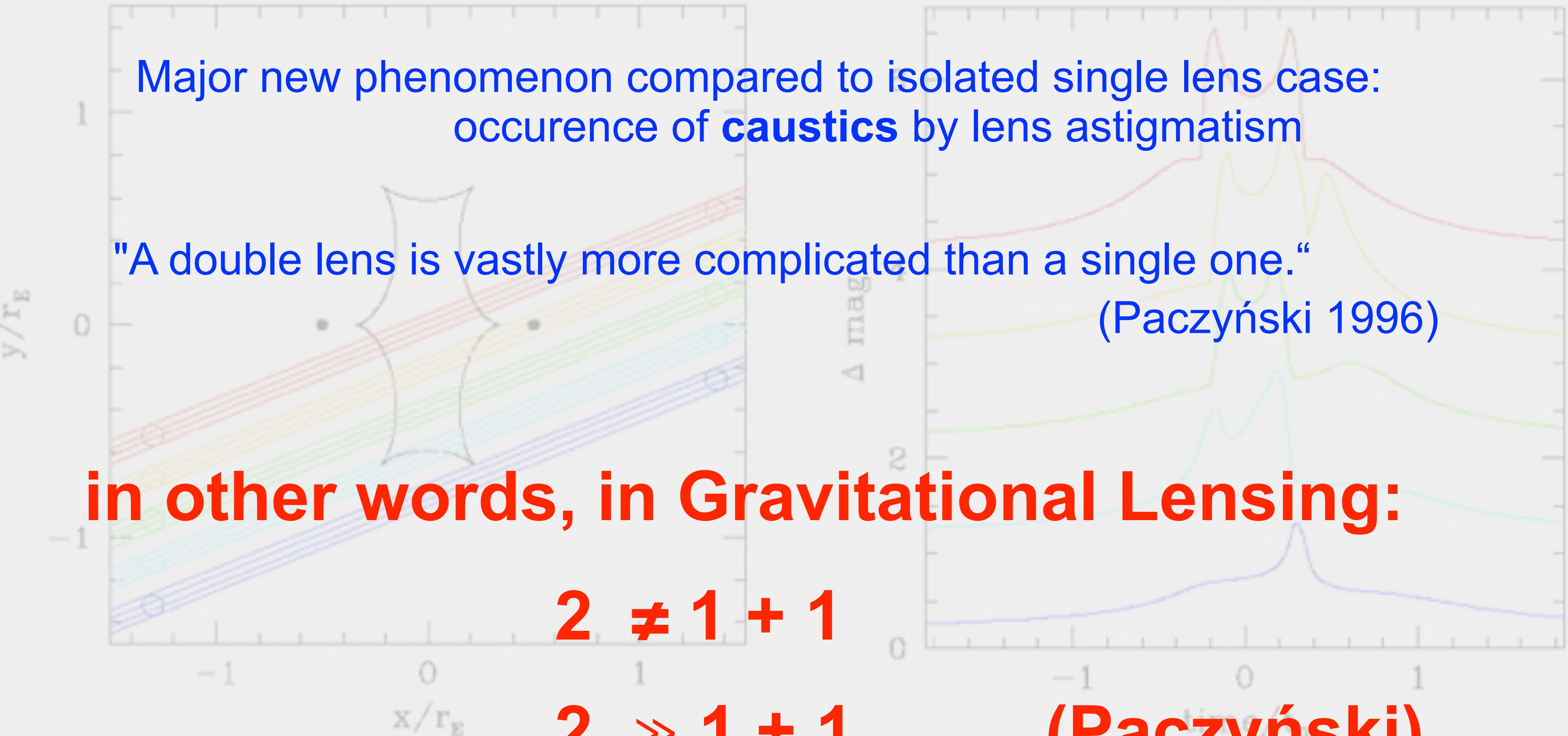
  quasar microlensing
  extragalactic microlensing
  cosmological microlensing
  optical depth: ~1

  far

Two regimes of 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 @ 10-100kpc	quasars (SNe) @ Gpc
Einstein angle:	0.5 milliarcsec	1 **micro**arcsec
Einstein time:	weeks-months	**weeks-months-years**
optical depth:	low: 10^{-6}	**high: of order 1**
proposed:	(Einstein 1936) Paczynski 1986b	Chang & Refsdal 1979, 1984 Gott 1981, Paczynski 1986a
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 structure: size/profile machos, dark matter**

Microlensing by Double Lenses
(Mao & Paczynski 1991, Sackett 1995):



Major new phenomenon compared to isolated single lens case:
occurence of **caustics** by lens astigmatism

"A double lens is vastly more complicated than a single one.“
(Paczyński 1996)

in other words, in Gravitational Lensing:

$2 \neq 1 + 1$

$2 \gg 1 + 1$ **(Paczyński)**

$n \ggg 1 + 1 + 1 +$

Three additional parameters:
1) mass ratio q,
2) separation d,
3) angle Φ

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

(... rather than intrinsic variability of the quasar ...)

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

→ yesterday by Laurent Eyer

→ next talk by Szymon Kozłowski

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

⇒ shift lightcurves in time (Δt) and magnitude (Δm):

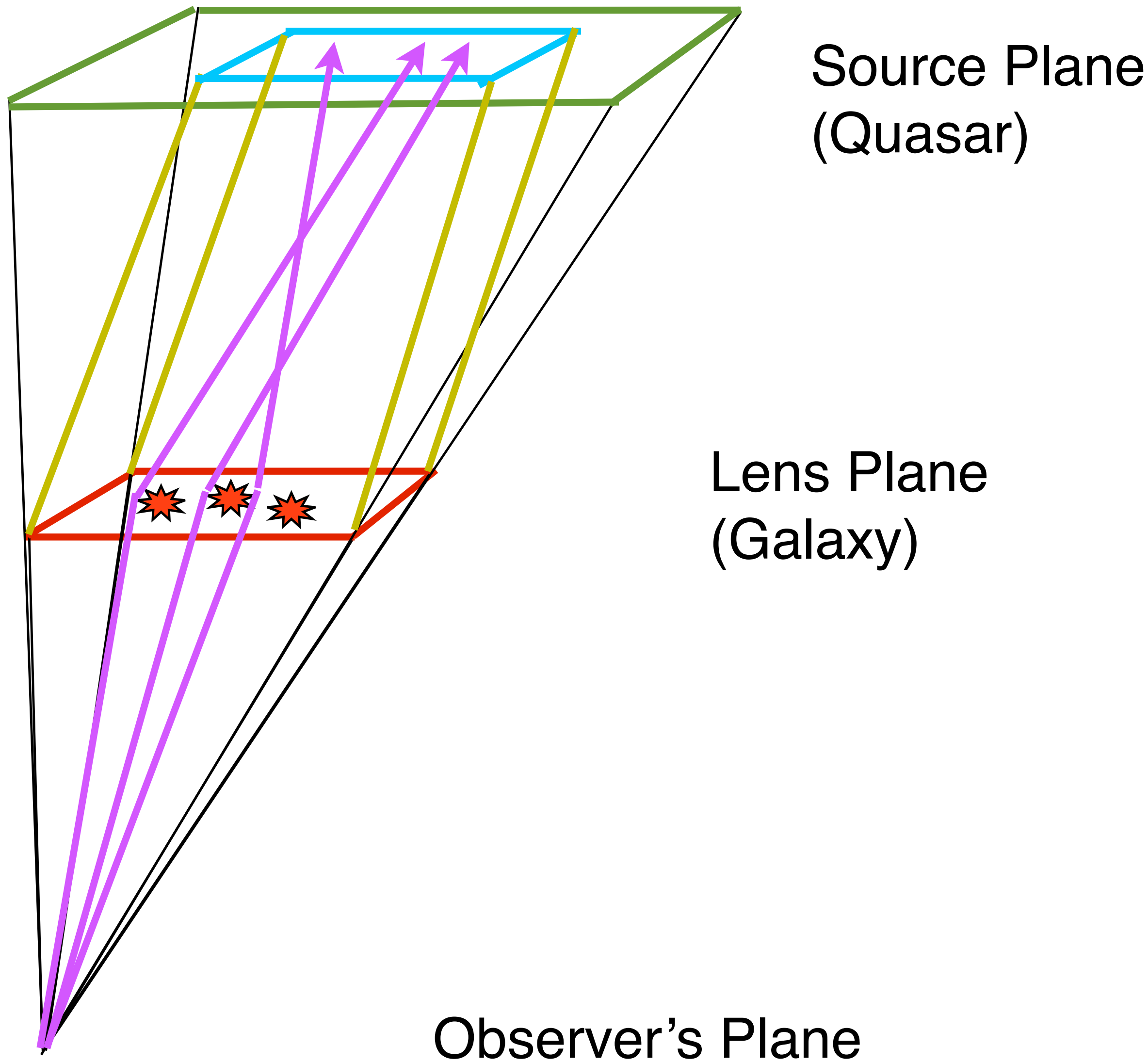
⇒ determine difference lightcurve:

- if flat → no microlensing
- if variable → microlensing

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

How to calculate quasar microlensing

Idea of “backward ray tracing”:



Efficient Inverse Ray Shooting: A Tree-Code Approach

(Wambsganss 1990, 1999)

Deflection angle for n lenses:

$$\tilde{\boldsymbol{\alpha}}_i = \sum_{j=1}^{n} \tilde{\boldsymbol{\alpha}}_{ji} = \frac{4G}{c^2} \sum_{j=1}^{n} M_j \frac{\boldsymbol{r}_{ij}}{r_{ij}^2}$$

Number of computational operations:

$$N_{\rm total} = N_{\rm op} \times N_{\rm pix} \times N_{\rm av} \times N_* \simeq 10 \times 2500^2 \times 500 \times 10^6 \approx 3 \times 10^{16}$$

Calculation of deflection angle for N* lenses split into two parts:

$$\tilde{\boldsymbol{\alpha}} = \sum_{i=1}^{N_*} \tilde{\boldsymbol{\alpha}}_i \approx \sum_{j=1}^{N_{\rm L}} \tilde{\boldsymbol{\alpha}}_j + \sum_{k=1}^{N_{\rm C}} \tilde{\boldsymbol{\alpha}}_k =: \tilde{\boldsymbol{\alpha}}_{\rm L} + \tilde{\boldsymbol{\alpha}}_{\rm C}.$$

The N's denote the following:

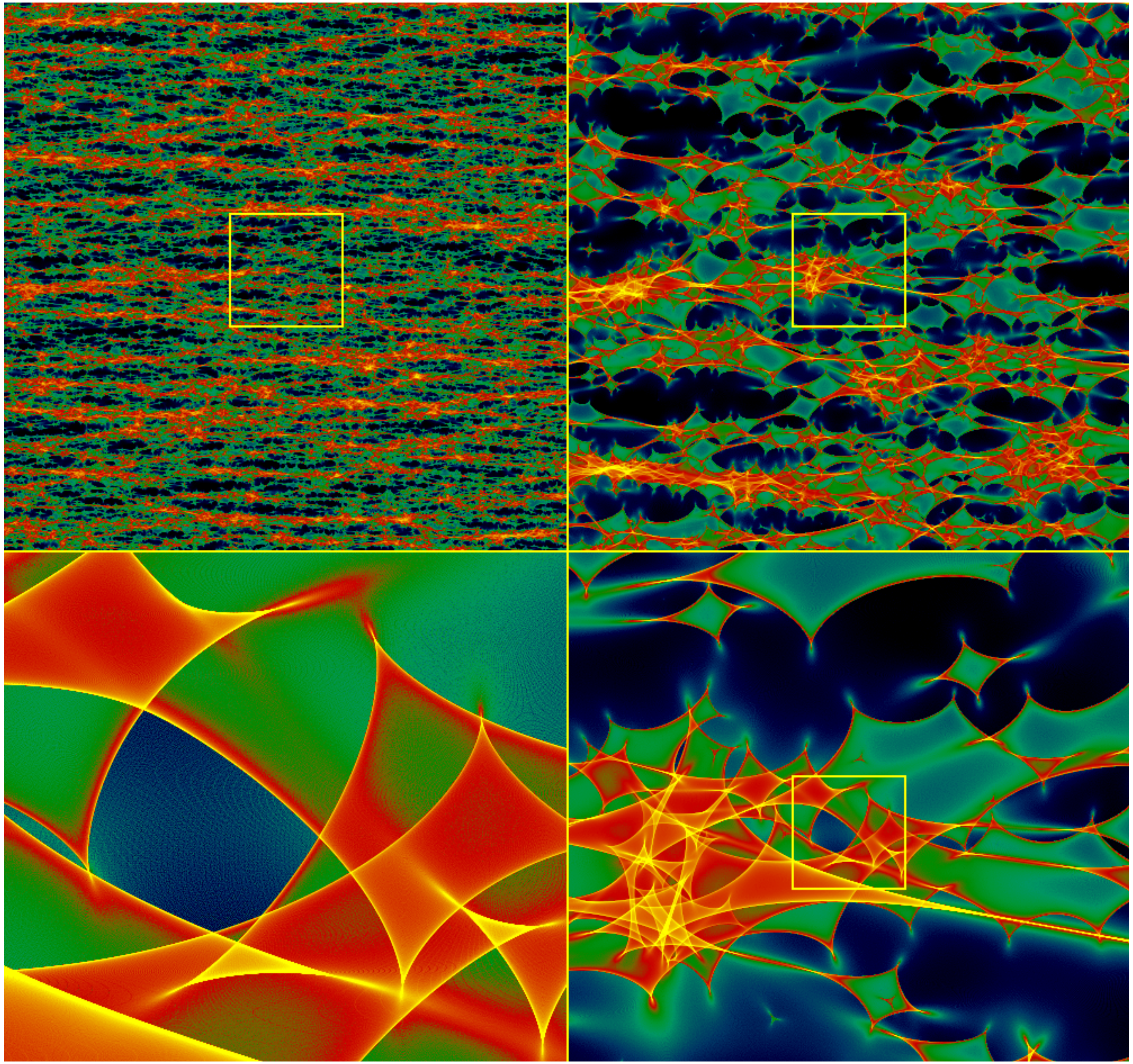
- N_* is the number of all lenses,
- $N_{\rm L}$ the number of lenses to be included directly,
- $N_{\rm C}$ the number of cells (= pseudo-lenses) to be included.

→ suggested to me by Bohdan Paczyński in 1987

Quasar microlensing: typical magnification patterns

L = 100 R_E

20 R_E

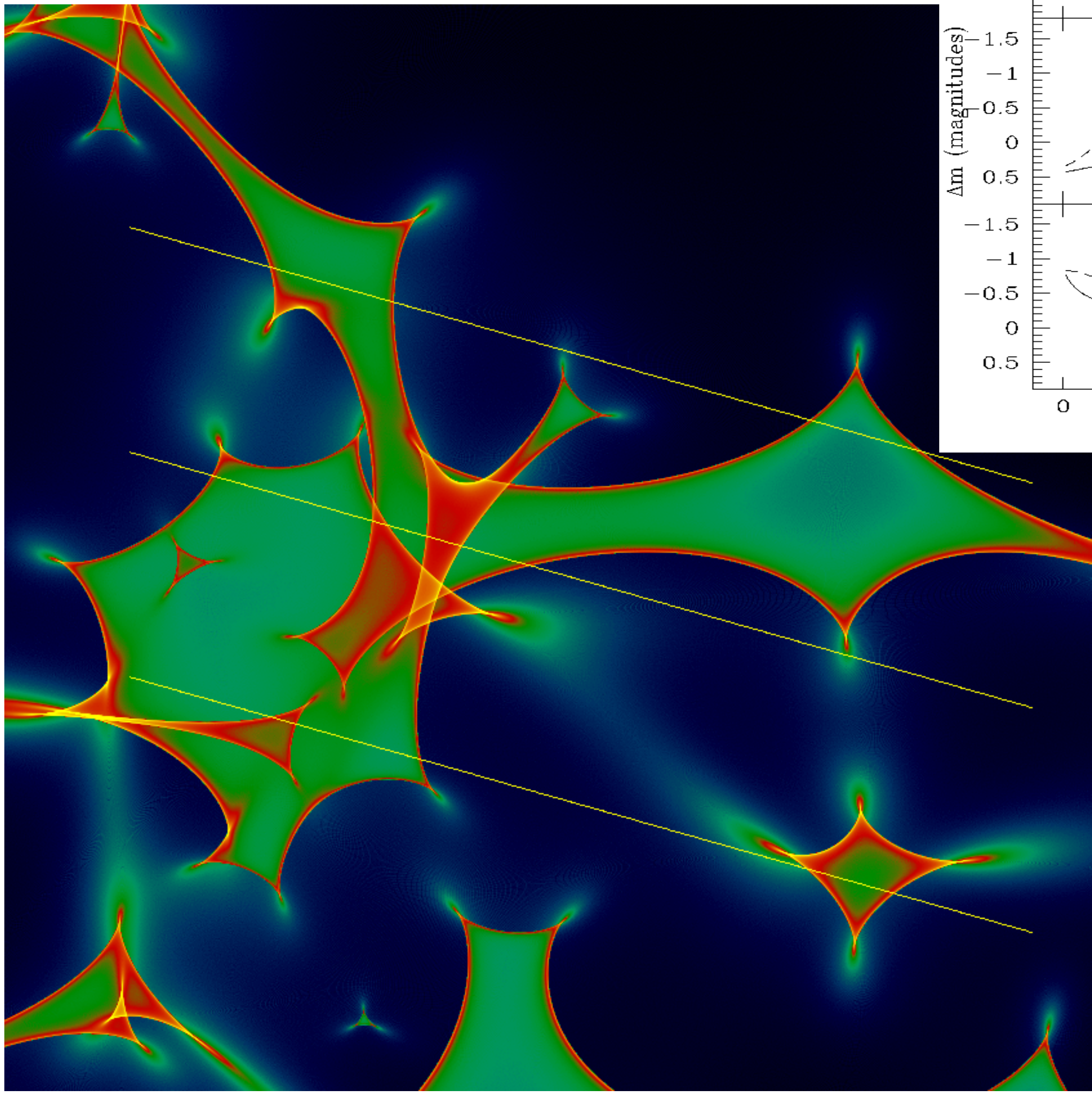


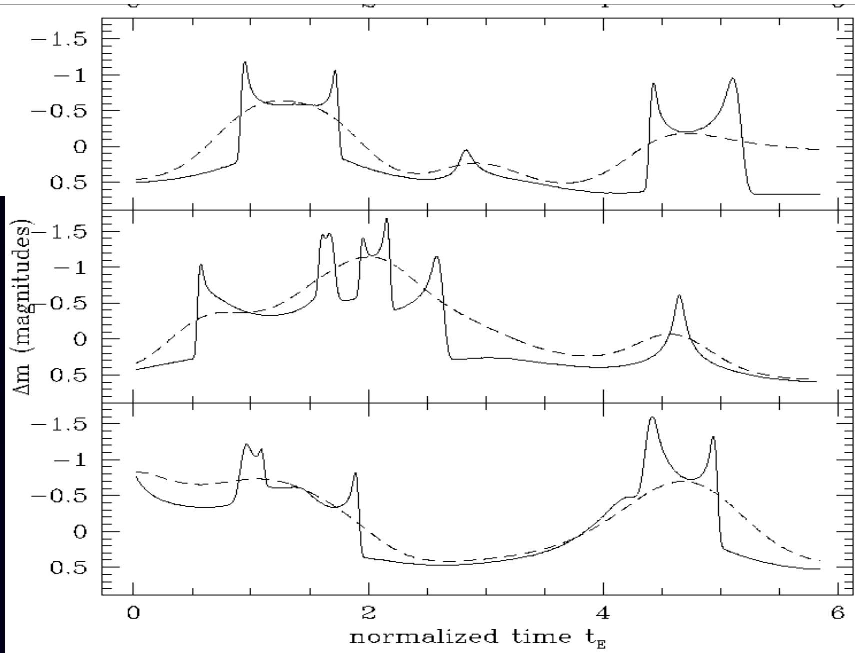
0.8 R_E

4 R_E

from Wambsganss, Paczyński, Schneider (1990)

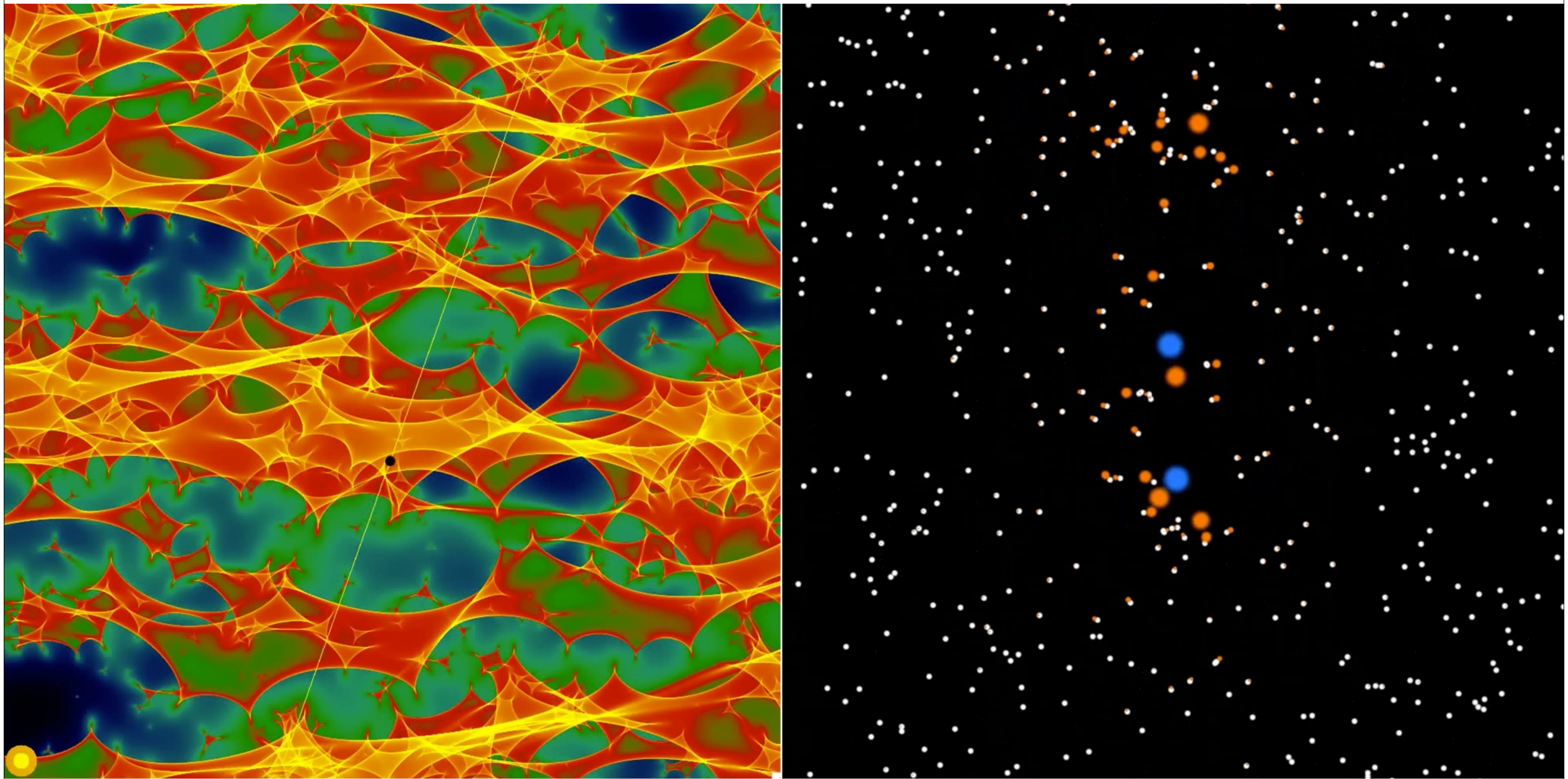
Quasar microlensing: typical simulations





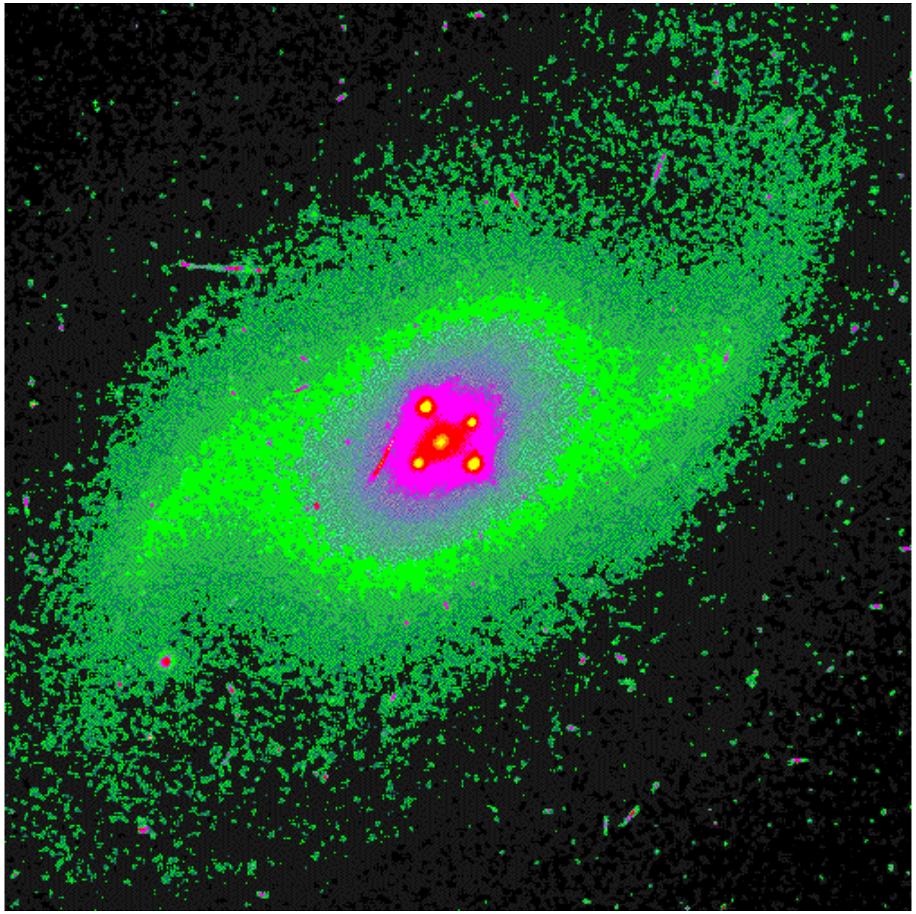
"Chromatic Microlensing":

Due to source size effect,
→ Wambsganss & Paczyński (1991)



Movie made by Luke Weisenbach (student of Paul Schechter @ MIT)

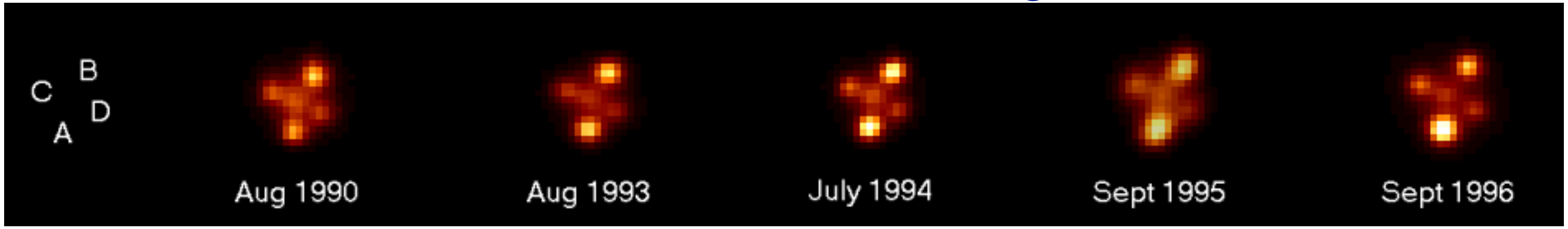
The quadruple quasar Q2237+0305
(also known as „Einstein Cross“ or „Huchra’s lens“)



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

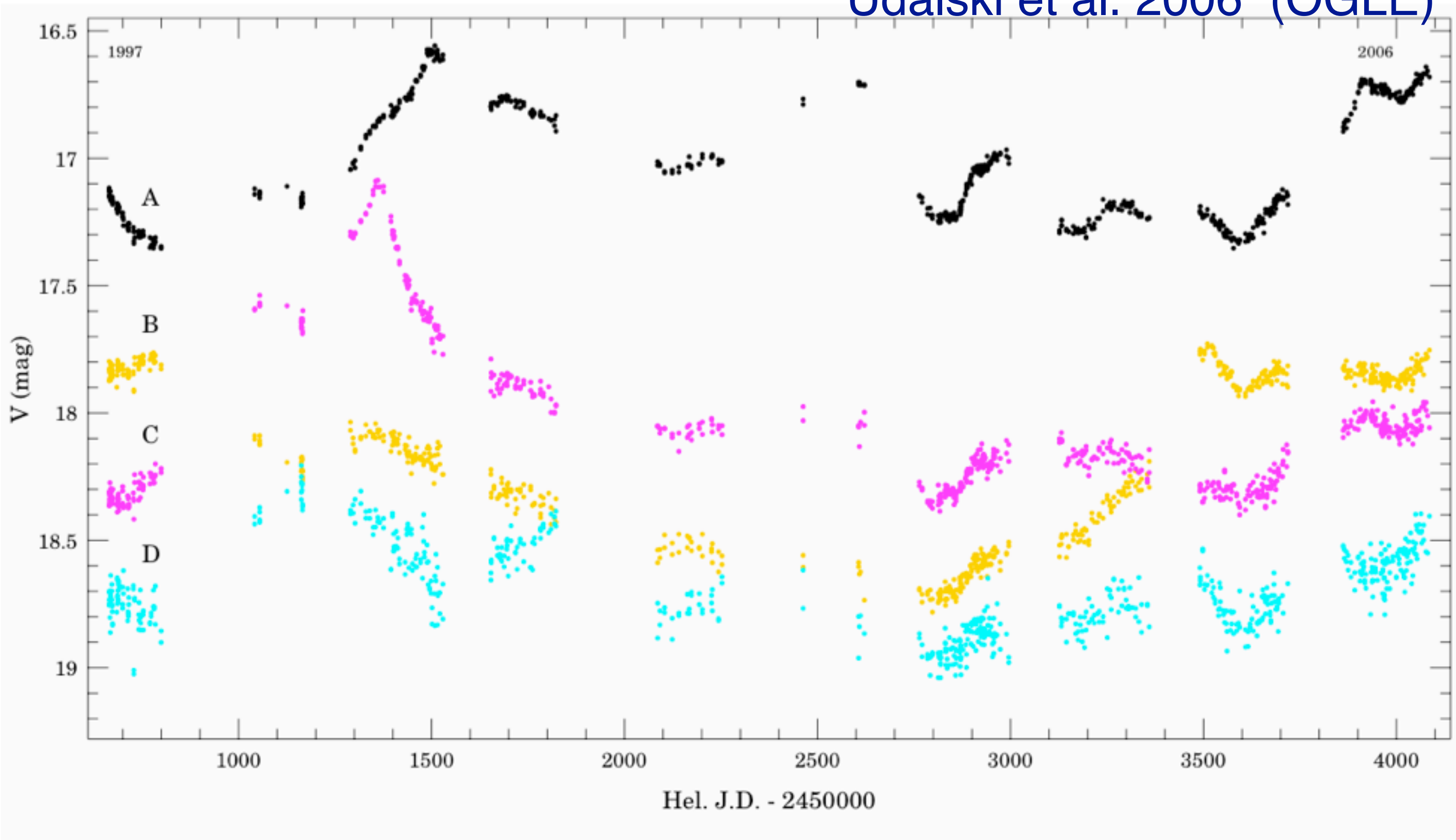
image separation   1.7 arcsec   (HST)

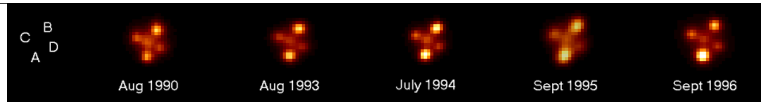
Pre-OGLE Quasar Microlensing: Q2237+0305



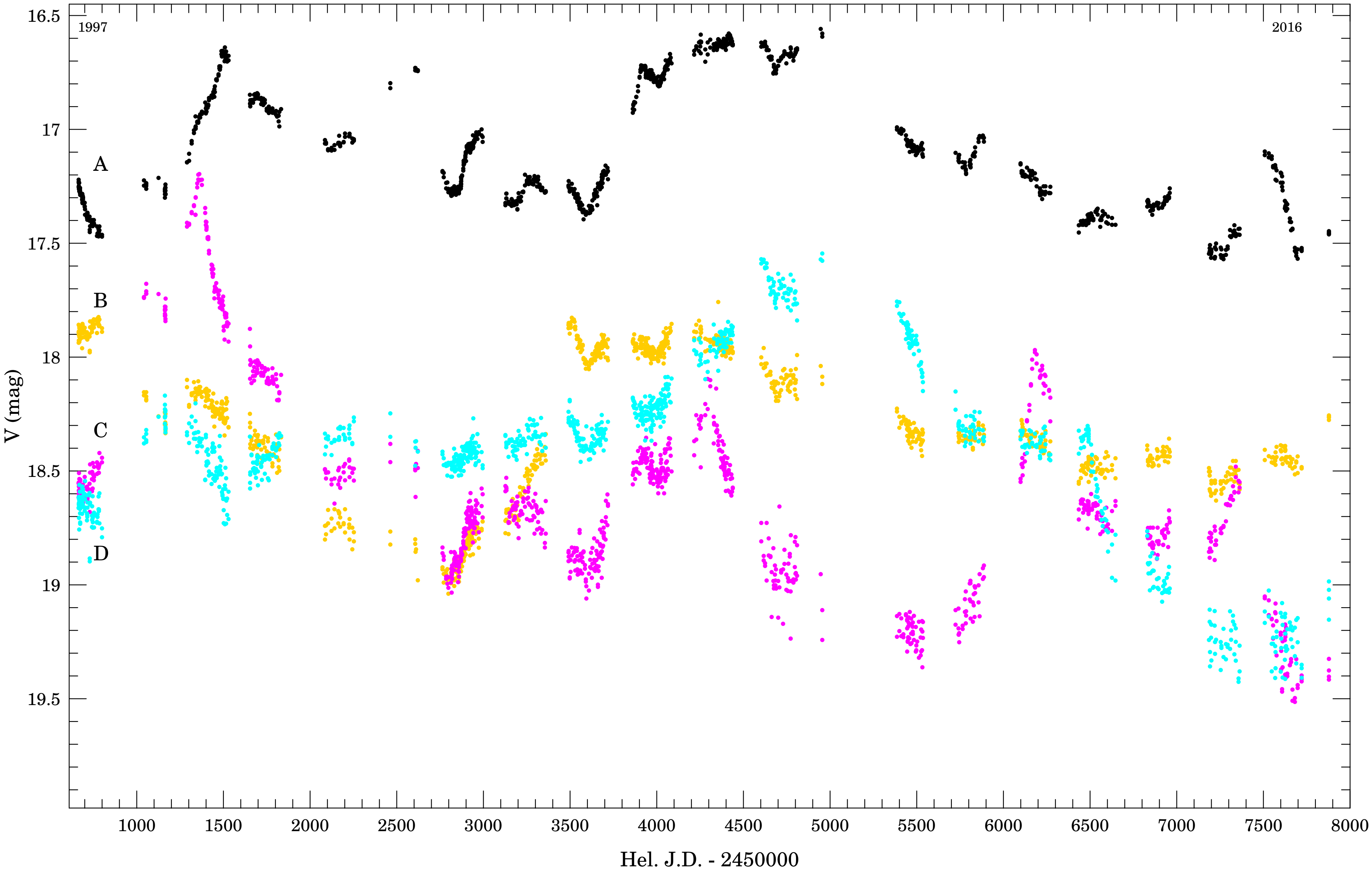
enter OGLE:

Udalski et al. 2006 (OGLE)



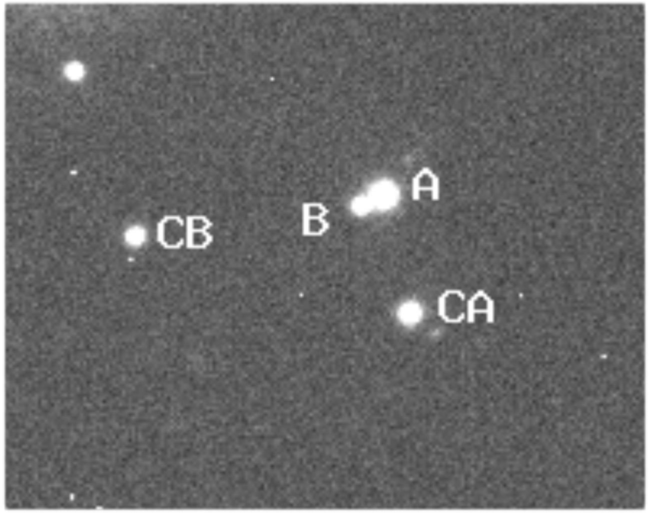


QSO 2237+0305 (EINSTEIN CROSS)



Udalski/OGLE, Schechter, J.W. et al. (in prep)

OGLE observations of the double quasar HE1104-1805



ACTA ASTRONOMICA
Vol. **53** (2003) pp. 229–240

The Optical Gravitational Lensing Experiment. Optical Monitoring of the Gravitationally Lensed Quasar HE1104–1805 in 1997–2002*

by

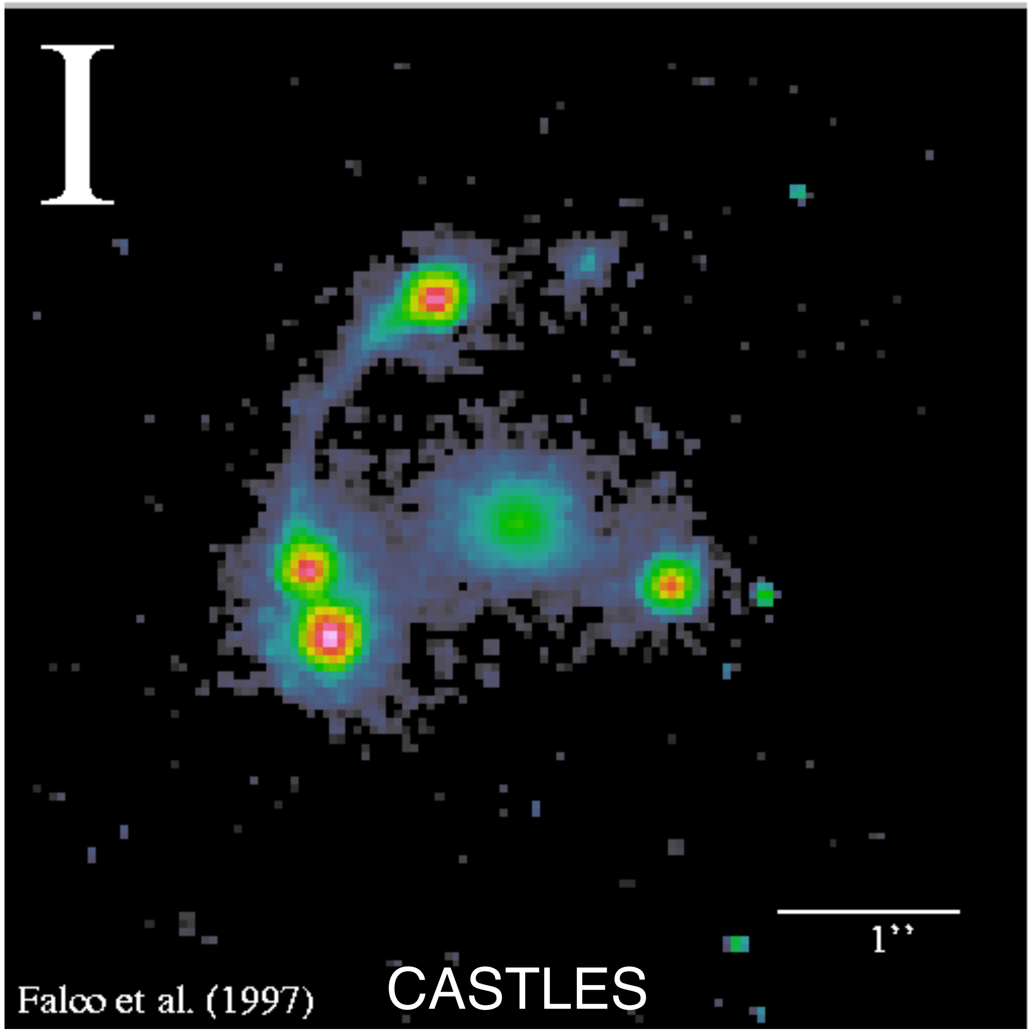
Ł. Wyrzykowski[1], A. Udalski[1], P.L. Schechter[2],
O. Szewczyk[1], M. Szymański[1], M. Kubiak[1],
G. Pietrzyński[1], I. Soszyński and K. Żebruń[1]

THE ASTROPHYSICAL JOURNAL, 584:657–663, 2003 February 20

MICROLENSING OF RELATIVISTIC KNOTS IN THE QUASAR HE 1104–1805 AB

PAUL L. SCHECHTER,[1,2] A. UDALSKI,[3] M. SZYMAŃSKI,[3] M. KUBIAK,[3] G. PIETRZYŃSKI,[3,4] I. SOSZYŃSKI,[3] P. WOŹNIAK,[5]
K. ŻEBRUŃ,[3] O. SZEWCZYK,[3] AND Ł. WYRZYKOWSKI[3]
(THE OGLE COLLABORATION)

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!

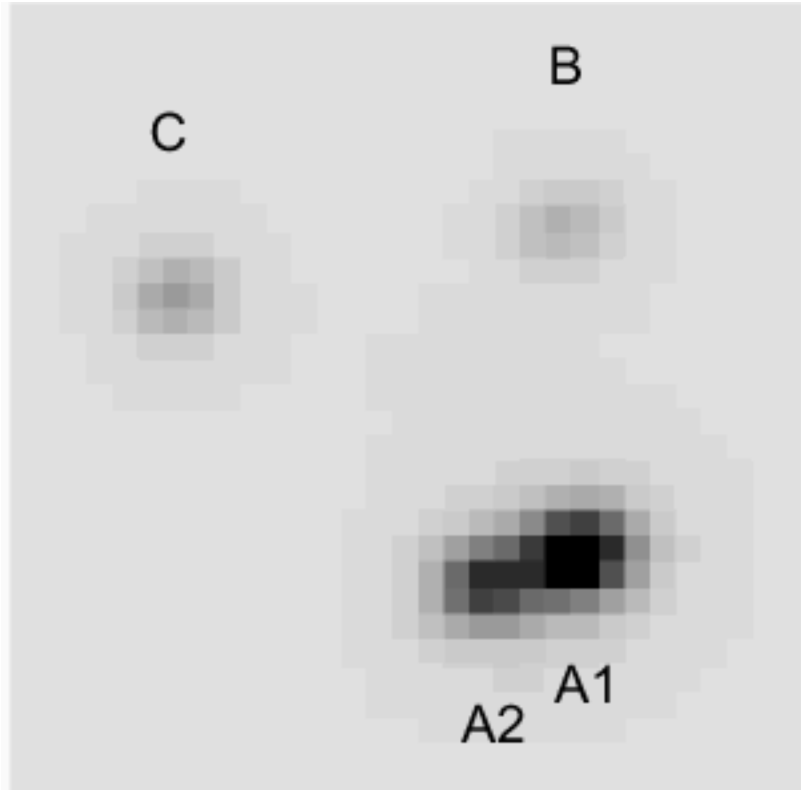
at least 4 similar systems

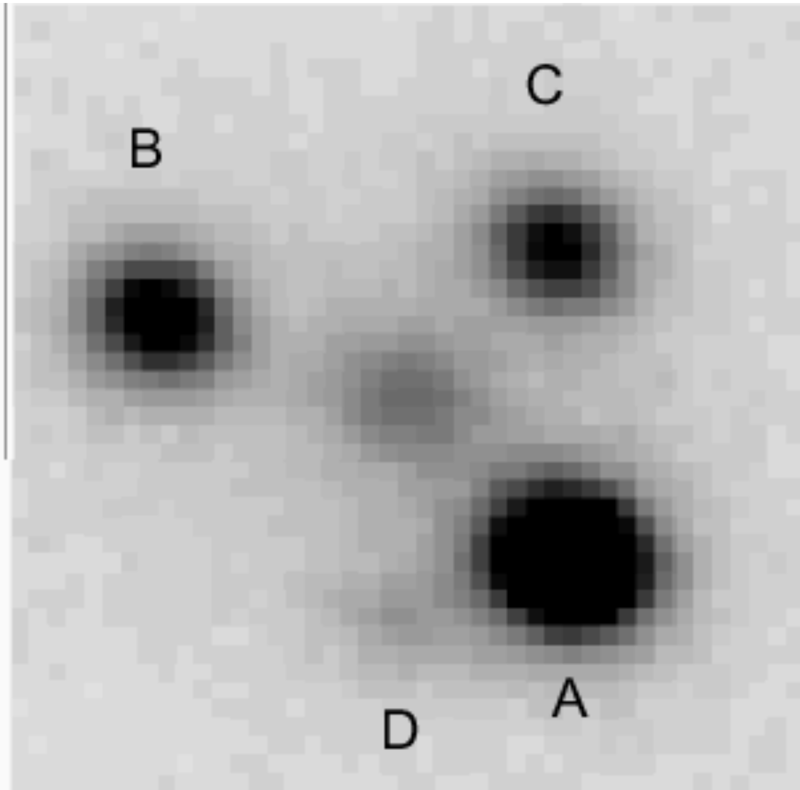
what's going on?!?

microlensing? substructure? DM ?

(Schechter & Wambsganss 2002)

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)

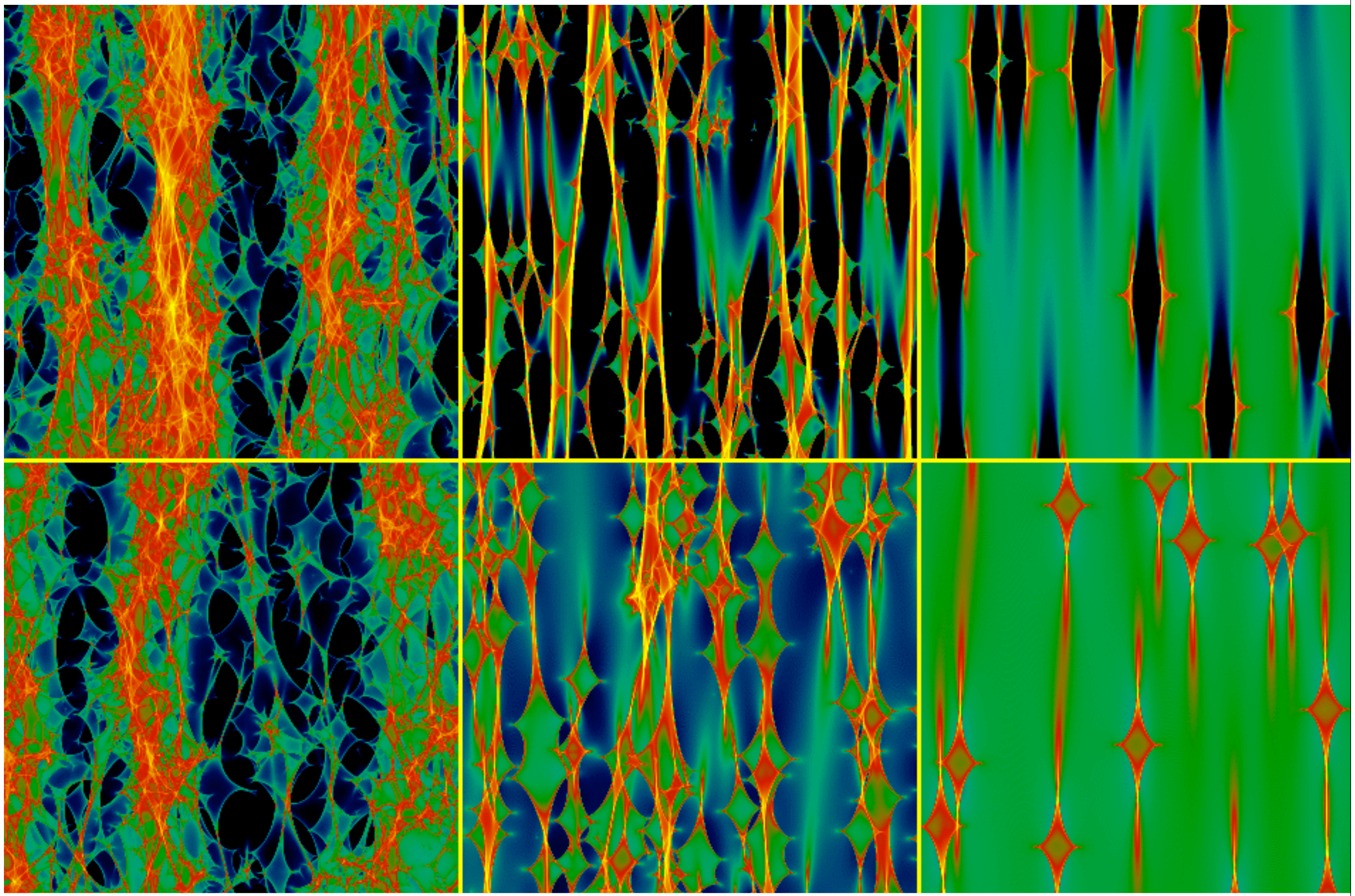
Quasar Microlensing at high magnification: suppressed saddlepoints and the role of dark matter (Schechter & Wambsganss 2002)

κ_{tot} = constant in horizontal rows

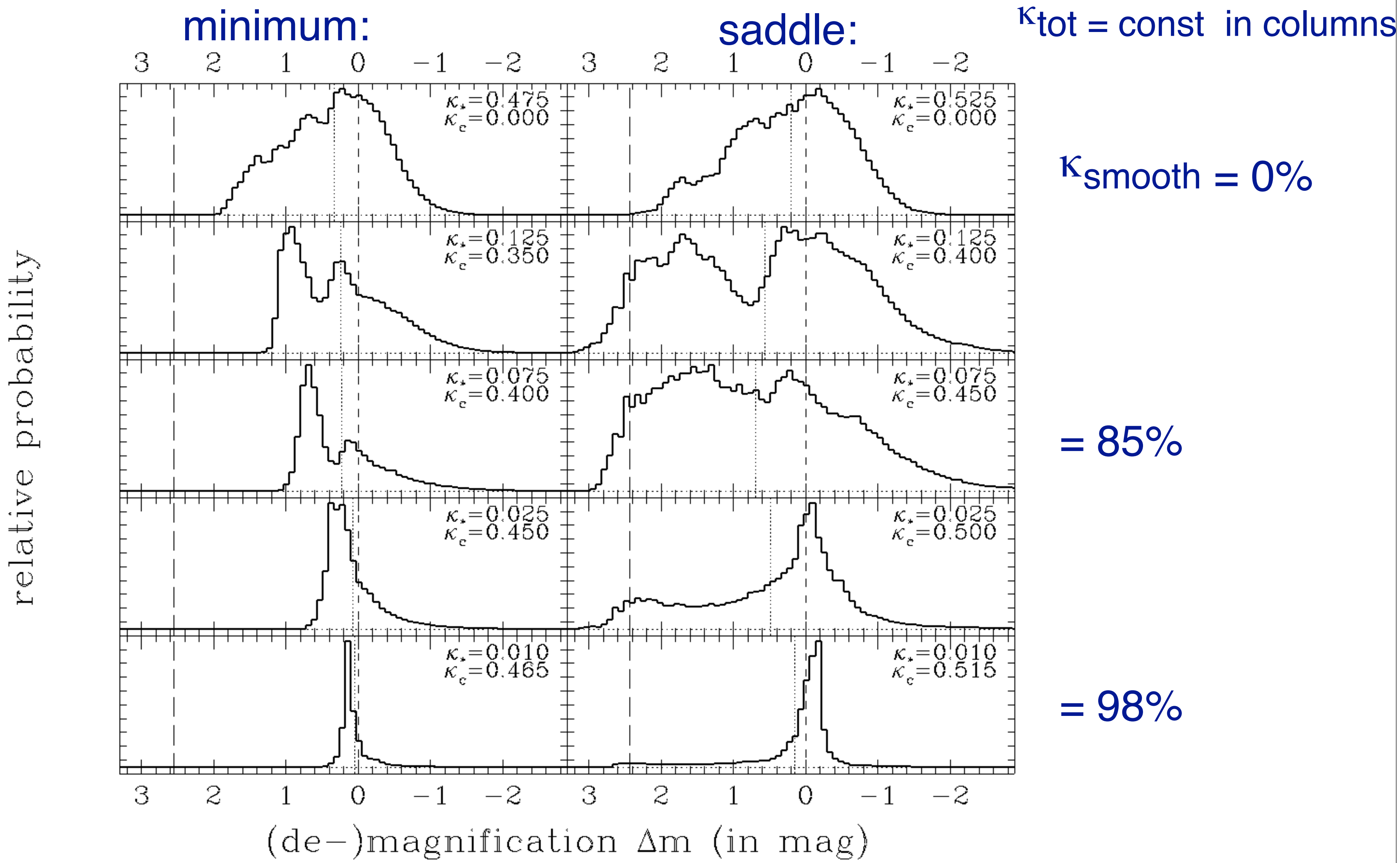
κ_{smooth} = 0% = 85% = 98%

saddle point image:

minimum image:



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

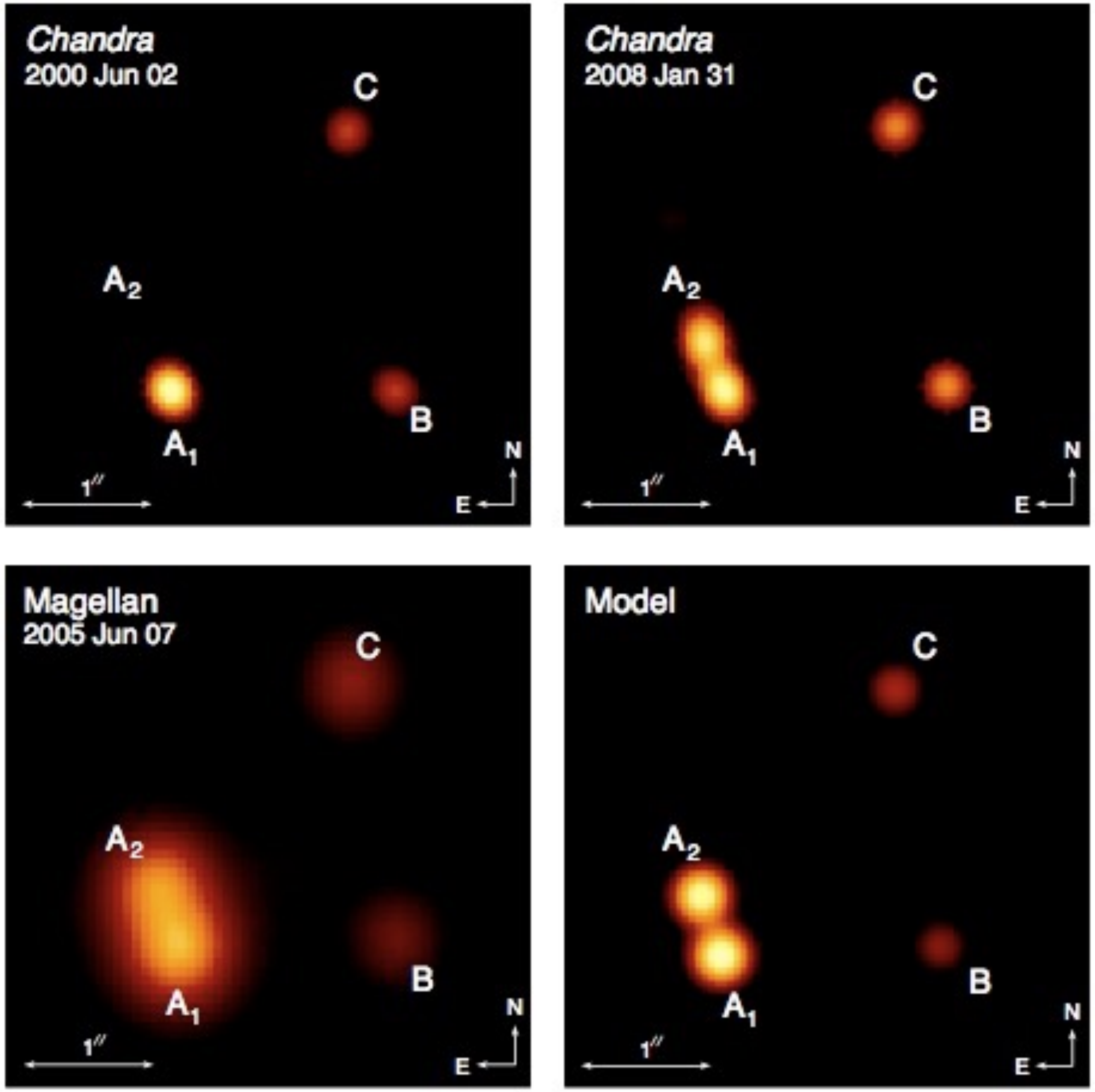


The Dark-Matter Fraction in the Elliptical Galaxy Lensing the Quasar PG 1115+080

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:

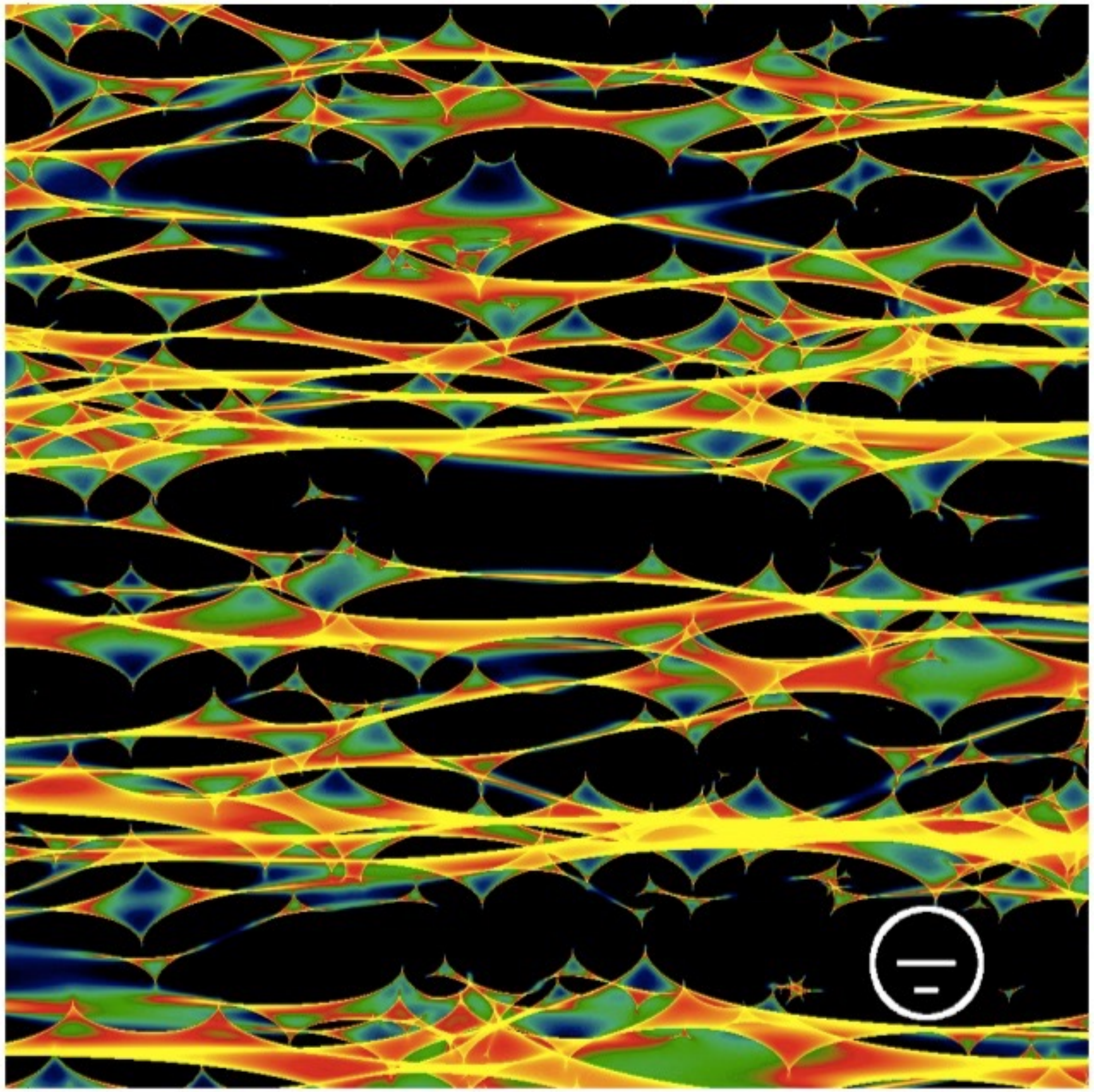
based on analyses of the X-ray fluxes of individual images in 2000 and 2008:



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

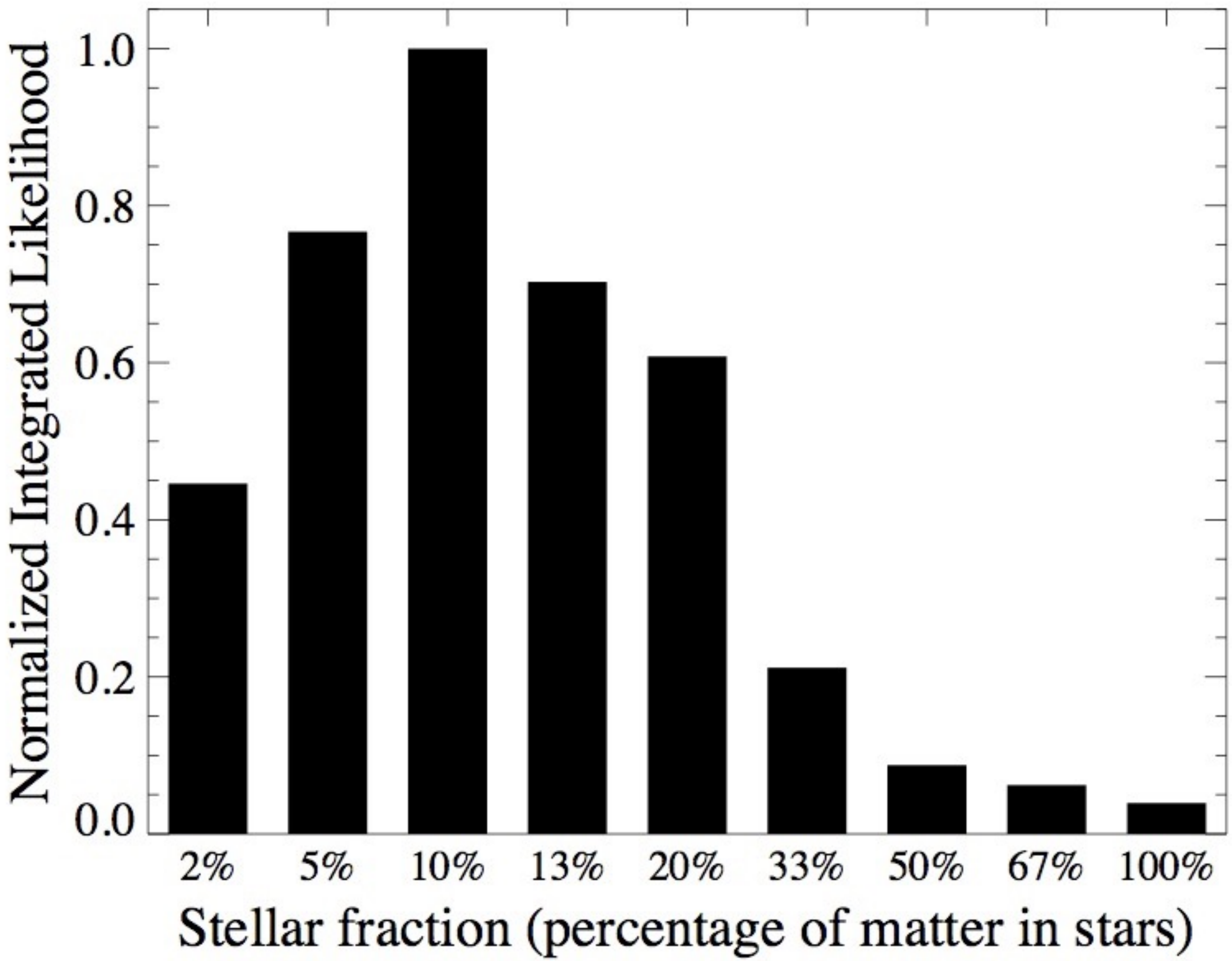
Pooley, Rappaport, Blackburne, Schechter, Schwab, Wambsganss; ApJ 697, 1892 (2009)

Microlensing magnification map for image A_2



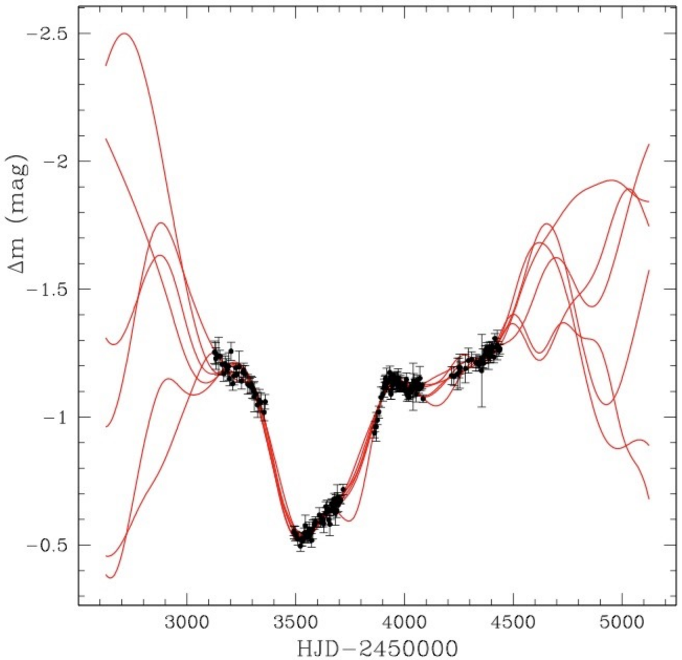
The Dark-Matter Fraction in the Elliptical Galaxy Lensing the Quasar PG 1115+080

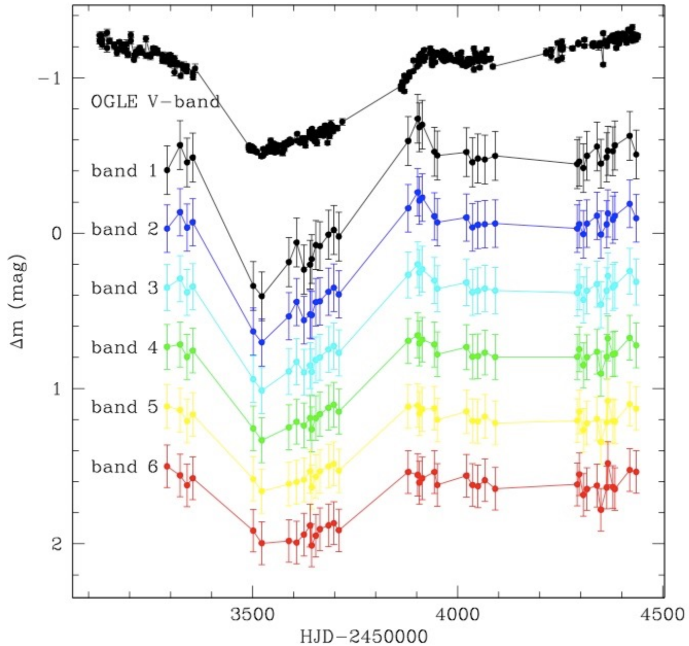
Pooley, Rappaport, Blackburne, Schechter, Schwab, Wambsganss; ApJ 697, 1892 (2009)



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,



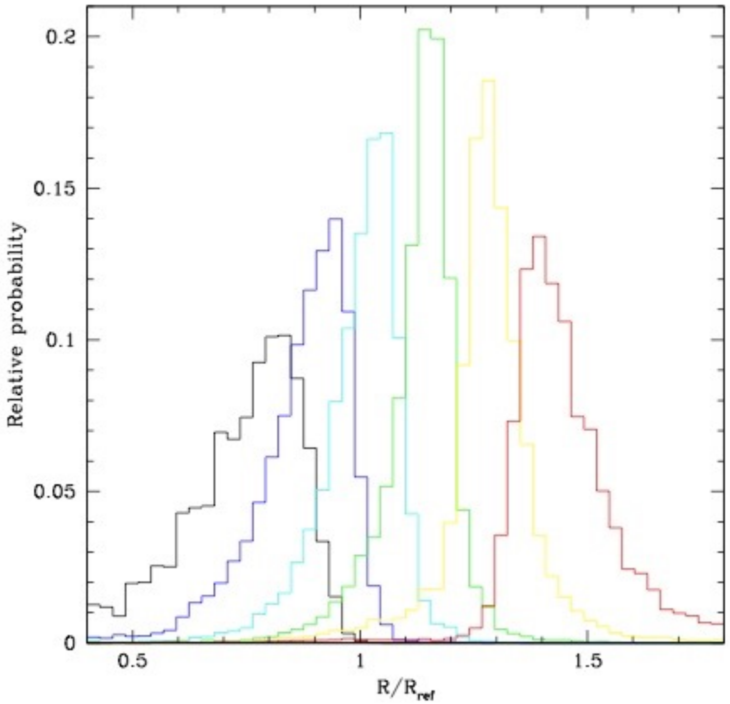


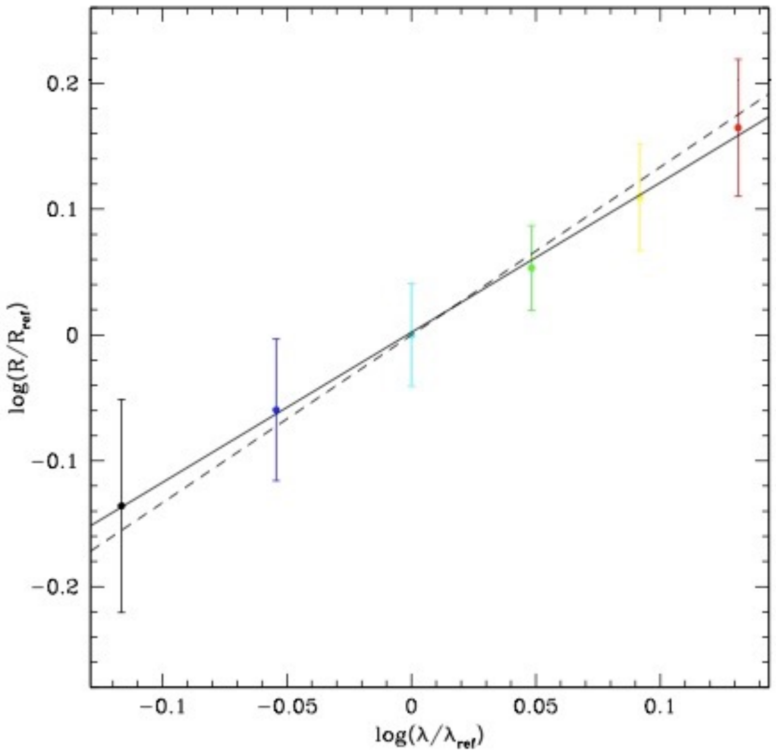
OGLE V-band data, fitted with different microlensing lightcurves

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 $\lambda_i / \lambda_{ref}$



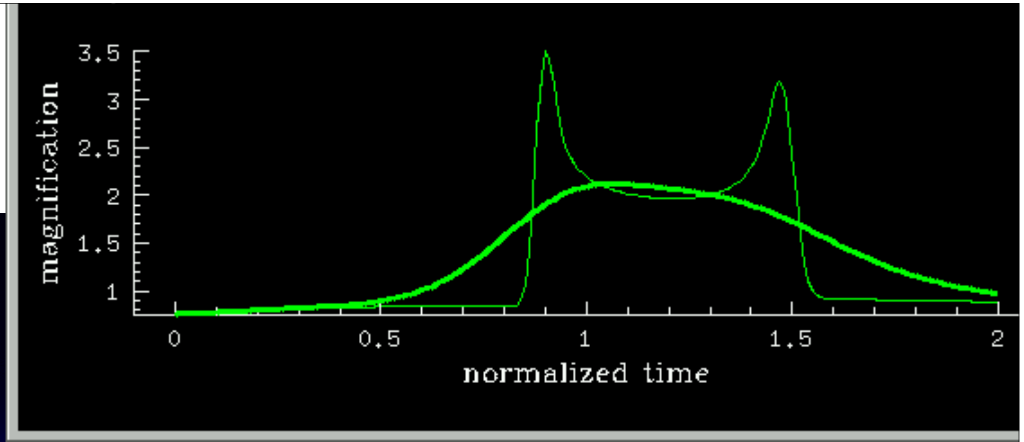


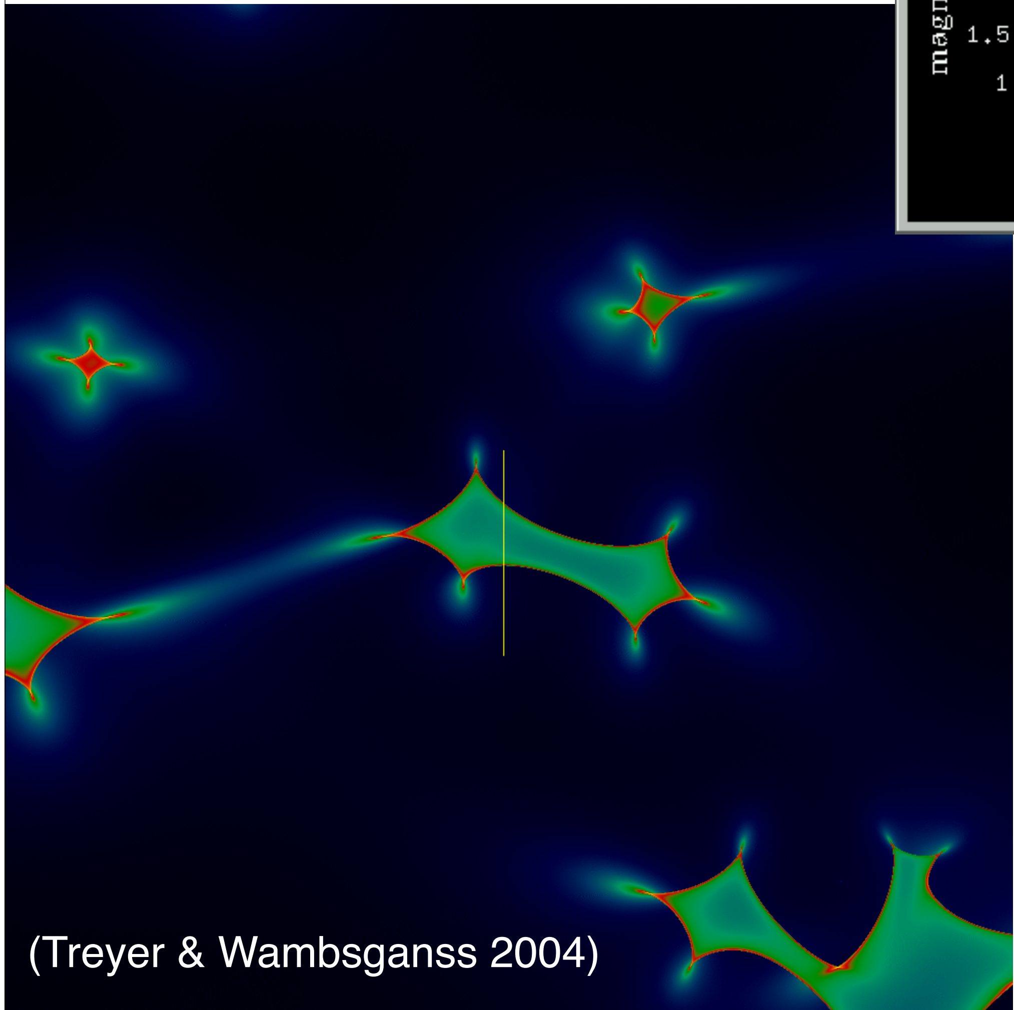
Dashed line relation for the standard optically thick & geometrically thin accretion disk model (Shakura-Sunyaev)

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

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

Astrometric Microlensing of Quasars

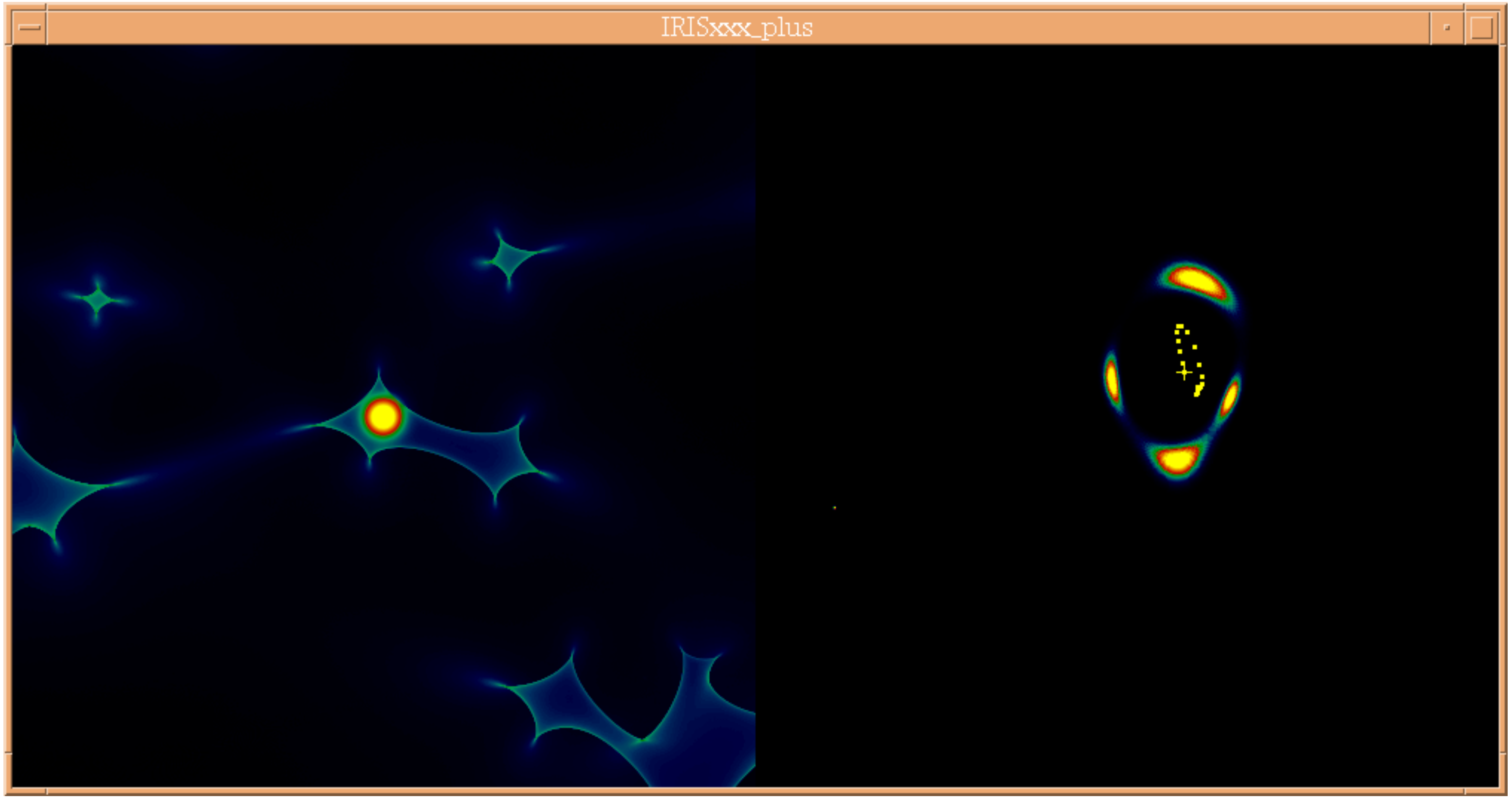




(Treyer & Wambsganss 2004)

Astrometric microlensing of quasars:

(Treyer & Wambsganss 2004)



Summary

Quasar microlensing has developed into a very useful astrophysical tool in the last 38 years …

- determination of size/temperature structure of quasar: optical/X-ray accretion disk, BLR
- prime candidate: Q2237+0305 (aka „Einstein Cross“, „Huchra’s lens“)
- measuring effects (masses, motions) of compact objects along line of sight
- detection and quantification of smoothly distributed dark matter

… and OGLE played a key role in last 20 years!

The unbelievable effectiveness of OGLE quasar monitoring:

OGLE monitoring of Q2237+0305 & HE1104 –1805: two data points per week

➜ about 0.2% of observing time (10 min per week) !

➜ 5(+1) papers: Wozniak+ (2000a,b); Udalski+ (2006)
Wyrzykowski+ (2003); Schechter+ (2003)

➜ more than 250 citations !

extreme extrapolation exercise:

0.2% of time	monitor 2 lensed quasar	5 papers	250 citations
1% of time	monitor 10 lensed quasars	25 papers	1,250 citations
10% of time	monitor 100 lensed quasars	250 papers	12,500 citations
100% of time	monitor 1,000 lensed quasars	2,500 papers	125,000 citations

OGLE

The Optical Gravitational Lens Experiment

ogle defined for English-language learners:

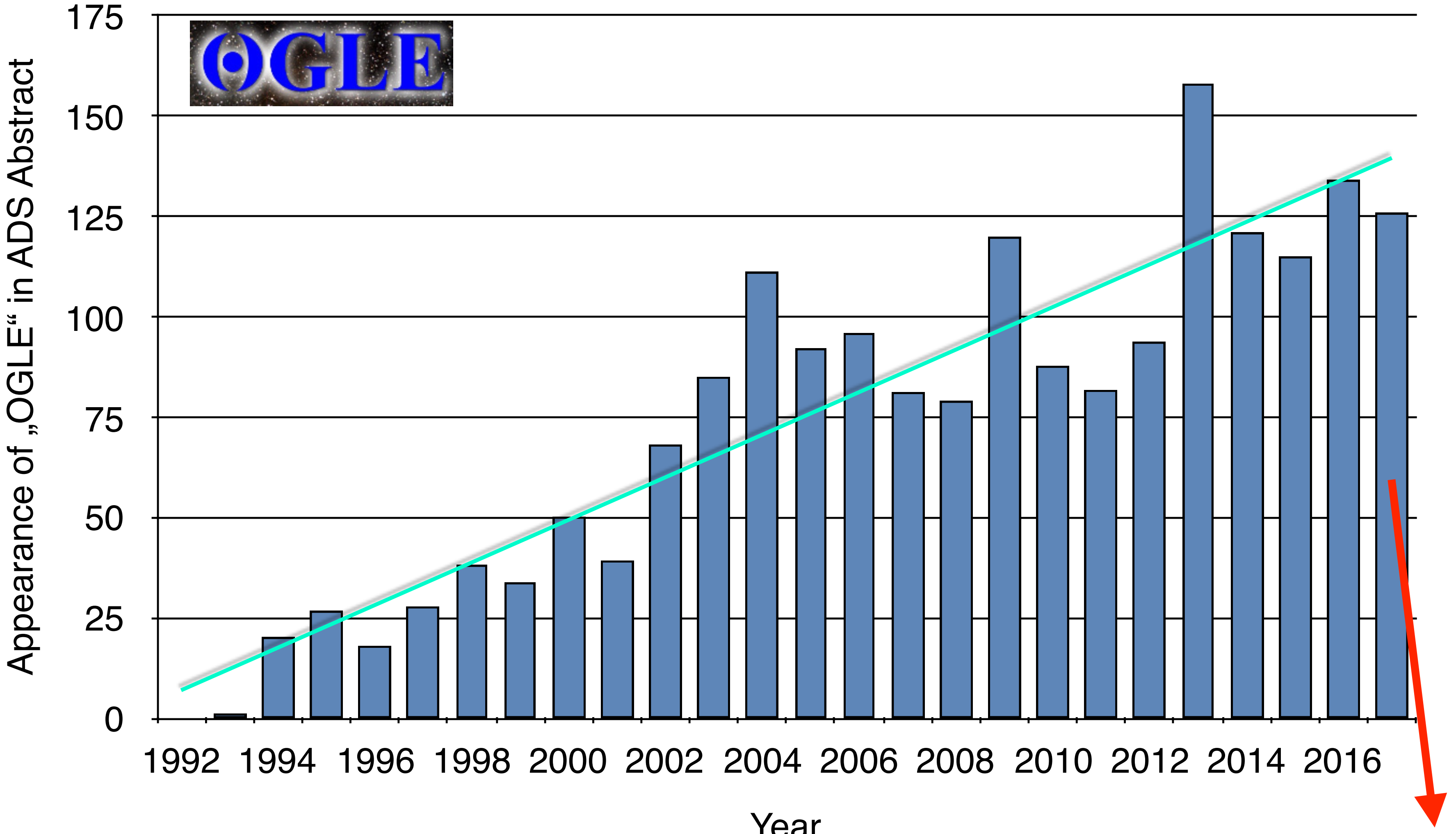
to look at (something) in a way that suggests strong interest or desire
(Merriam-Webster, Learners' Dictionary)

ogle defined for kids:

to look at in a flirting way or with unusual attention or desire
(Merriam-Webster, Word Central)

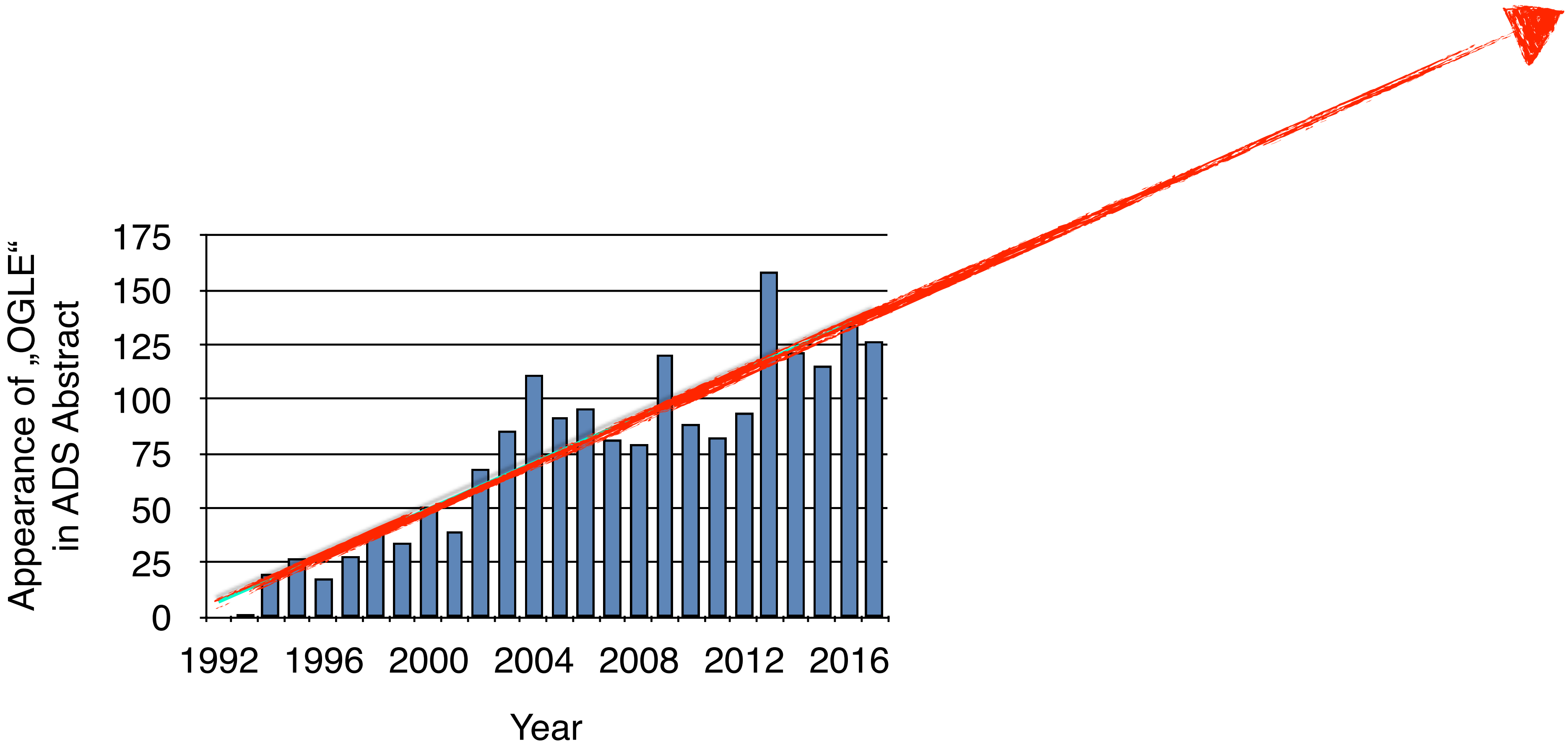
of papers per year with „OGLE“ in ADS Abstract

→ more than 1850 papers in total !!!



for year 2017:
2 x (# of papers up to June 30)

of papers per year with „OGLE“ in ADS Abstract



My personal connection with OGLE (since 2004):

50 (!) joint papers of J.W.
with Andrzej Udalski, Michal Szymański (and OGLE members)

I congratulate

Andrzej Udalski, Michał Szymański, **OGLE** team !

I thank

Andrzej Udalski, Michał Szymański, **OGLE**, Bohdan Paczyński !

I bow in admiration and adoration and appreciation:

OGLE

what a wonderful, unbelievable, incredibly successful project!

I congratulate

Andrzej Udalski, Michał Szymański, **OGLE** team !

I thank

Andrzej Udalski, Michał Szymański, **OGLE**, Bohdan Paczyński !

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