AGNs and Quasars

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Thursday, November 8, 2012:

1) Intro to AGNs/Quasars and Quasar Lensing
2) Microlensing of Quasars: Size and Luminosity Profile

Friday, November 9, 2012:

3) Multiply Imaged Quasars: Time Delays and Hubble Constant
4) Microlensing of Quasars: Machos, Smooth Dark Matter and more

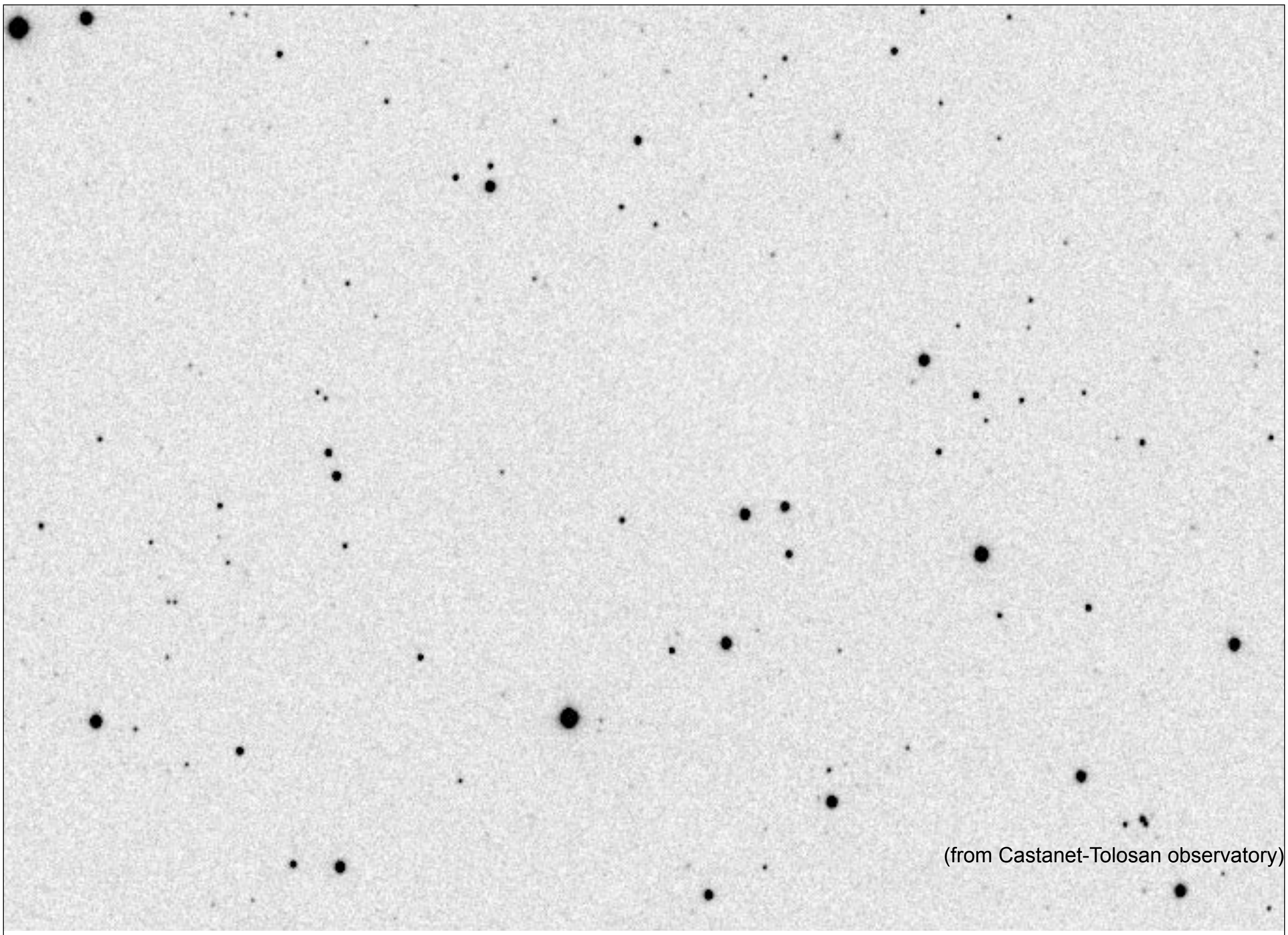
AGNs and Quasars

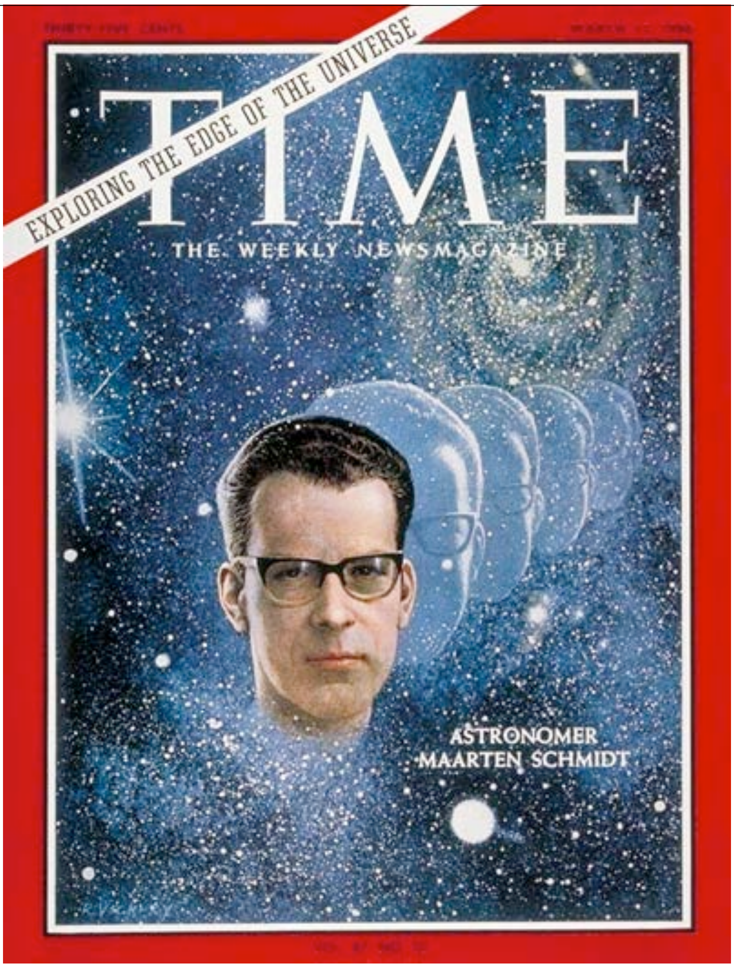
Joachim Wambsganss

1) Intro to AGNs/Quasars and Quasar Lensing

What are Quasars and AGNs?

- Discovered in 1960s as radio sources
- Counterparts in the visible light: unresolved, point-like blue-ish objects (looking similar to stars) ...
- ... with strange spectra, sometimes variable
- Energy production was discussed controversially
- After discovery/interpretation of “shifted” emission lines (Maarten Schmidt):
    - Quasars are extremely luminous objects at great distances
- A **qua**si-**st**e**llar** radio source (**“Quasar”**) is a very energetic and distant **active galactic nucleus** (**“AGN”**)


(from Castanet-Tolosan observatory)



What are Quasars and AGNs?

Consensus now:

- Very compact regions in centers of massive galaxies (light travel time AND discovery of quasar host galaxies)
- Supermassive black hole: (10^7 - 10^9 solar masses), surrounded by accretion disk, material accelerated, heated
- Among the most luminous, powerful, and energetic objects known in the universe: $L_{\text{quasar}} \simeq 100\ L_{\text{Milky Way}} \simeq 10^{40}$ J/sec
- Emission over the whole electromagnetic spectrum (vom radio through IR, visual, UV, X-ray and gamma-ray (peak at UV)
- Powered by accretion on a supermassive black hole with 10^7 - 10^9 solar masses: surrounded by accretion disk, material accelerated, heated,

---

What are Quasars and AGNs?

- 200 000 quasars known (mostly by Sloan Digital Sky Survey), redshift range $0.056 \lesssim z_{\text{quasar}} \lesssim 7.085$
- Quasars were more common in the past, peak at about $z_{\text{quasar}} \simeq 2$
- Quasars are variable: time scales years, months, weeks, days, even hours (“intra-day variability) → emission region must be very small: light days or light hours
- Emission of large amounts of power from a small region requires a power source far more efficient than the nuclear fusion
- release of gravitational energy by matter falling towards a massive black hole is the only process known that can produce such high power continuously: up to 10% of rest energy !!!
- Energy production: very efficient!

What are Quasars and AGNs?

- Quasar structure (from small to large):
    - Central Supermassive Black Hole (SMBH)
    - Continuum Emission Region (Accretion disk)
    - Broad Line Region (BLR)
    - Narrow Line Region (NLR)
    - Jets (occasionally “superluminal”)

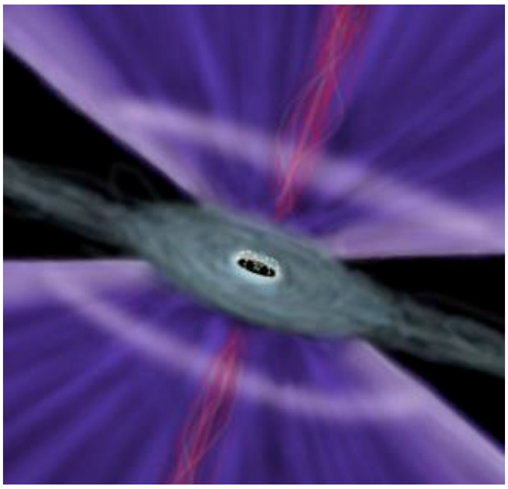
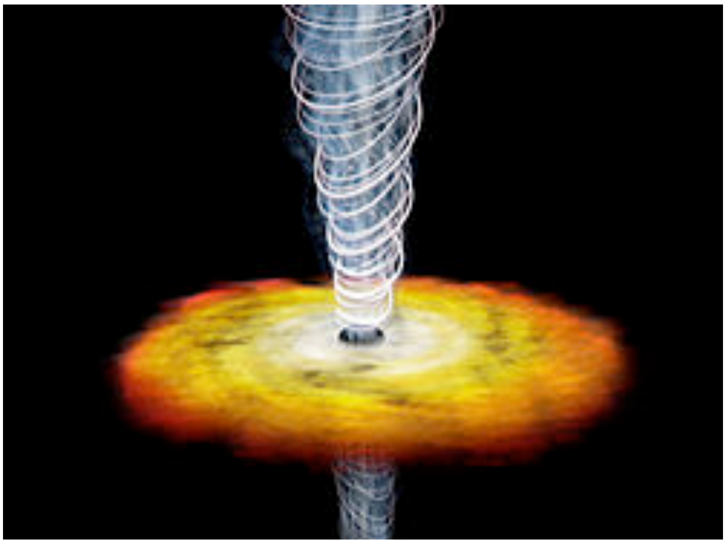
- Model for accretion disk: Shakura & Sunyaev (1973):
    - Thermal disk, temperature decreases outward like $T \propto R^{-3/4}$
    - With Wien’s law ($\lambda_{max} * T_{max}$ = const.): → $R \propto T^{-4/3} \propto \lambda^{4/3}$

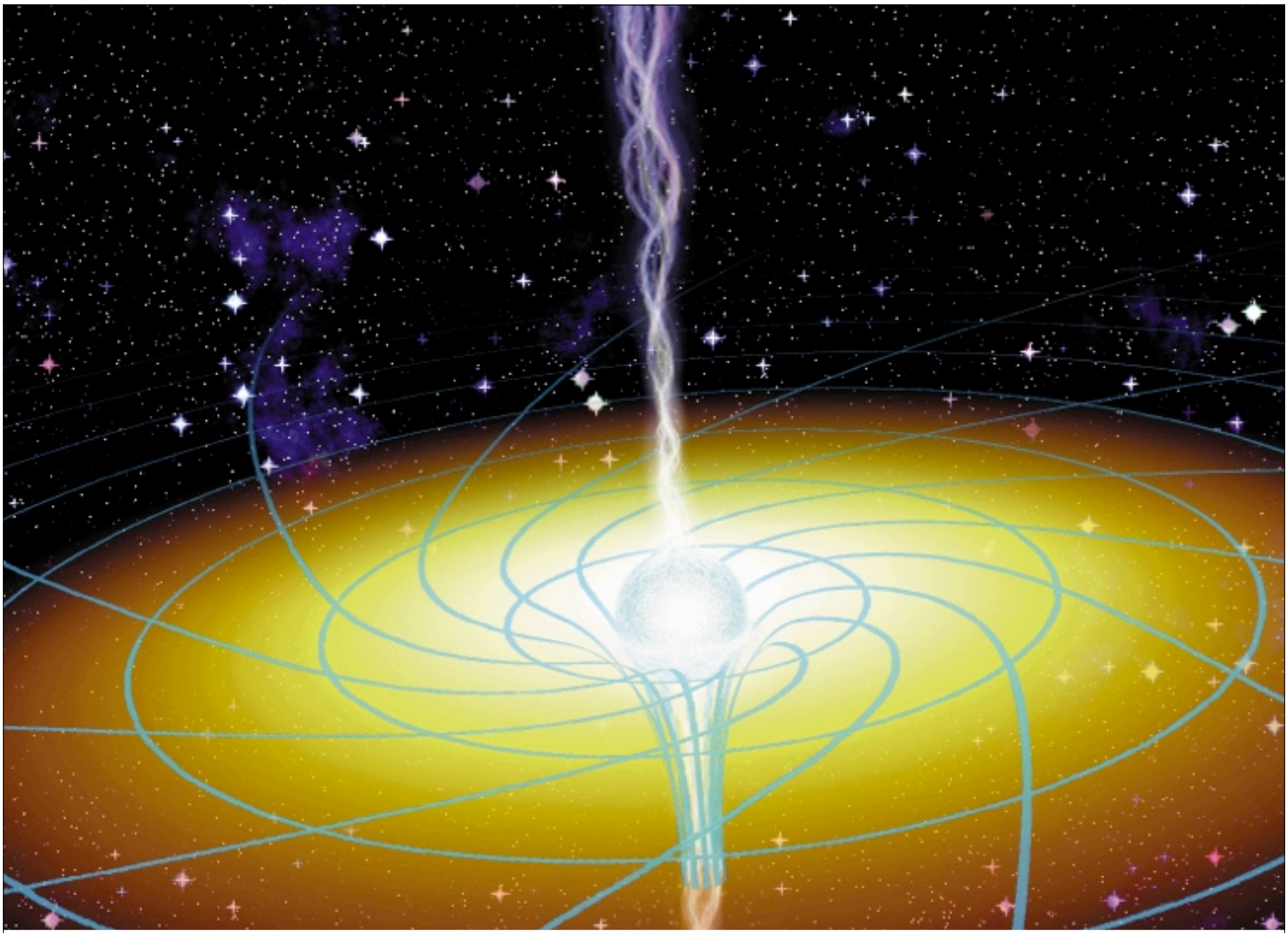
What are Quasars and AGNs?

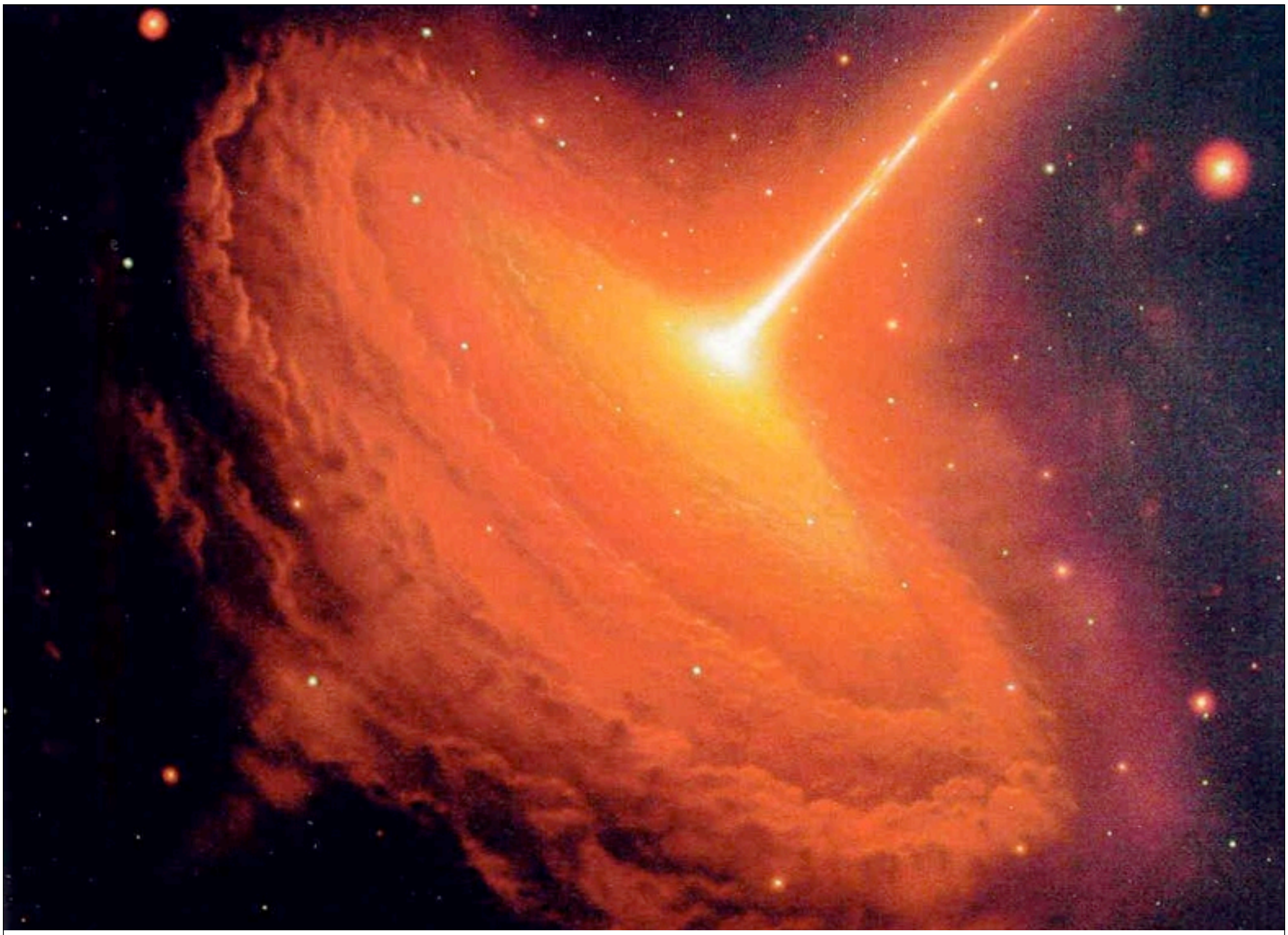
- For luminosity of 10^{47} erg/s = 10^{40} J/s: quasar has to devour 10 solar masses per year
- Are “active galaxies” a different class of galaxies (1 in a 1000), or is every galaxy in an active state for a small fraction of the time?
- “Active states” are switched on and off; after active phase, quasar turns into quiet ordinary galaxy again
- Only 10% of quasars are “radio-loud” → the name **QSO** for **quasi-stellar object** was coined comprising both types
- **Active Galaxies** or **Active Galactic Nuclei (AGN)** is the most general name, the particular form depends on the viewing angle

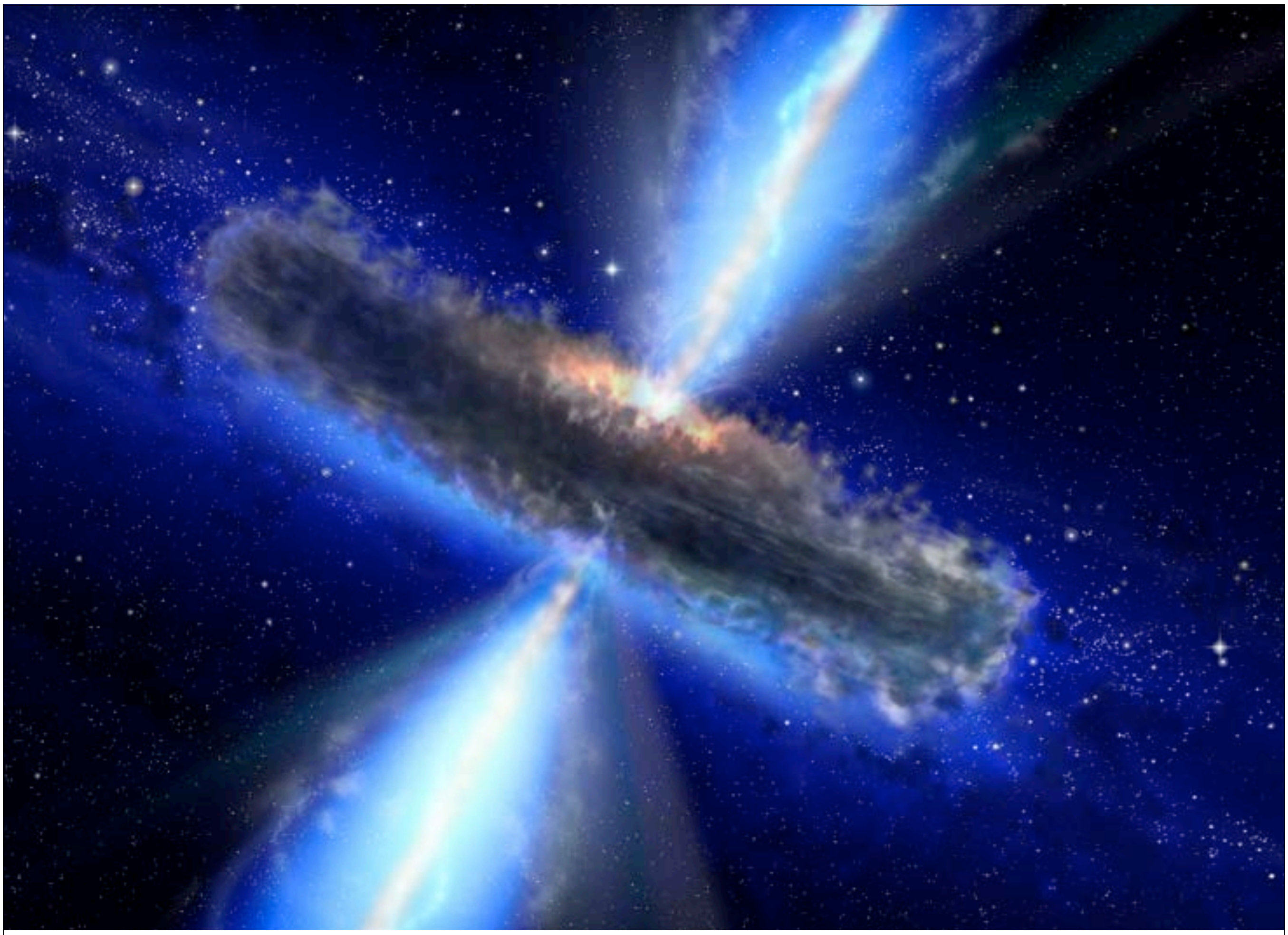
What are Quasars and AGNs?









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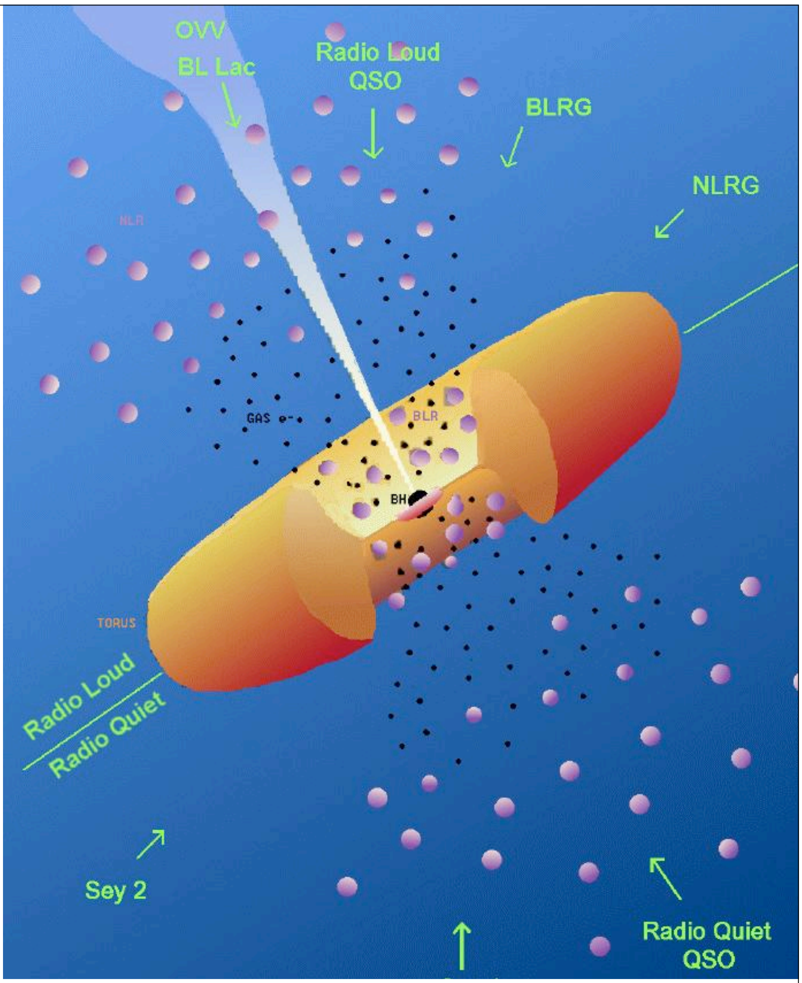
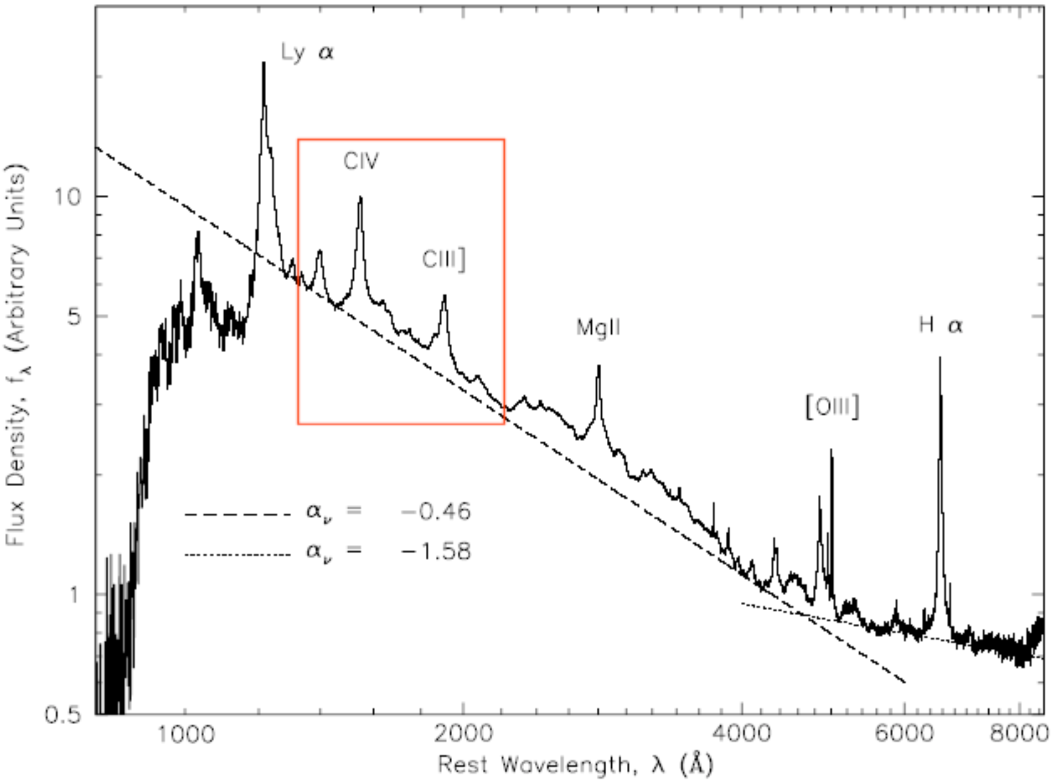
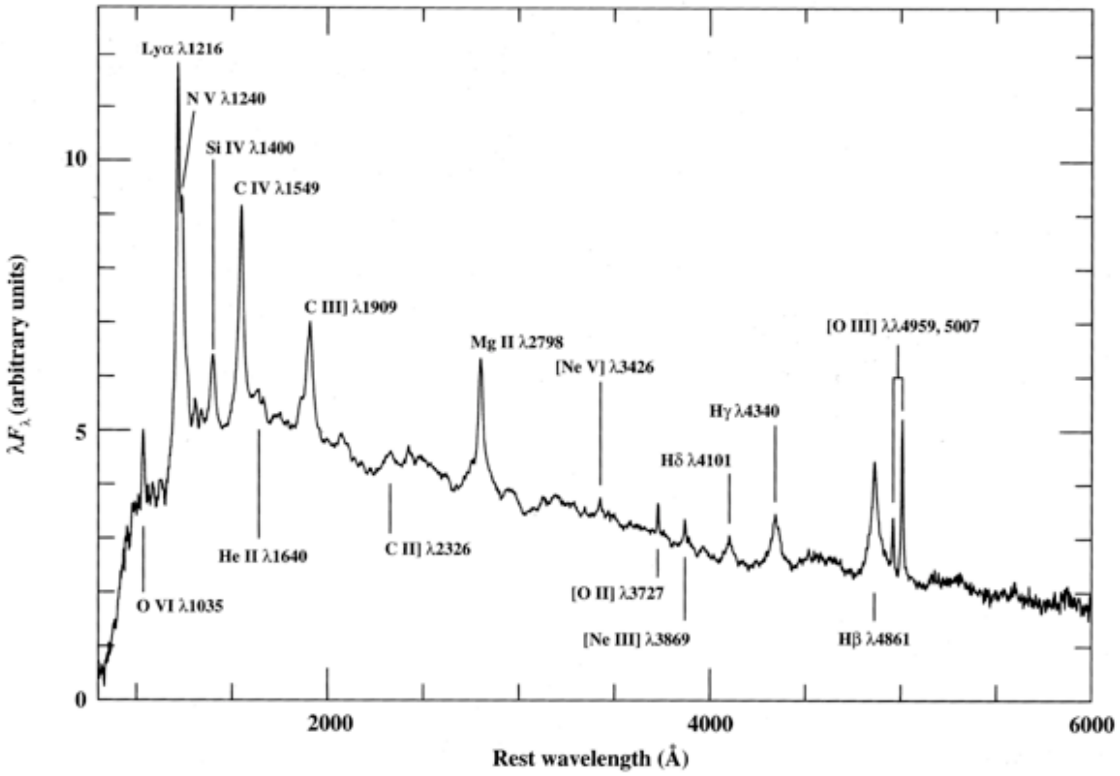


Non-thermal spectrum with broad and narrow emission lines:



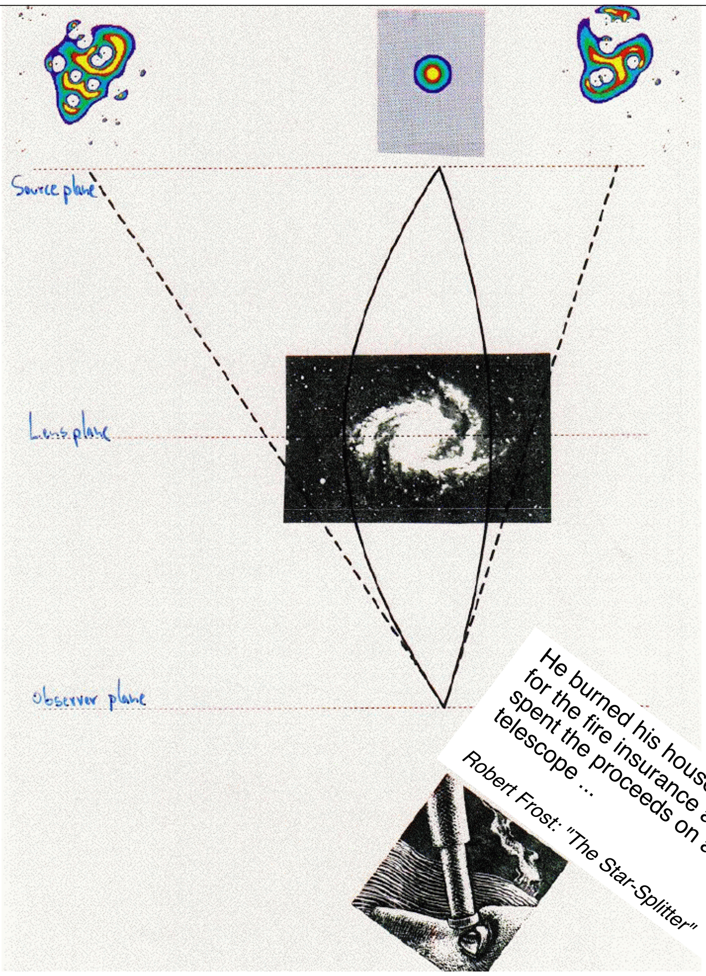
(composite quasar spectrum from D. Vanden Berk & all, AJ, 122, 549-564, 2001)

Non-thermal spectrum with broad and narrow emission lines:



(Adapted from B.M. Peterson, 1997))

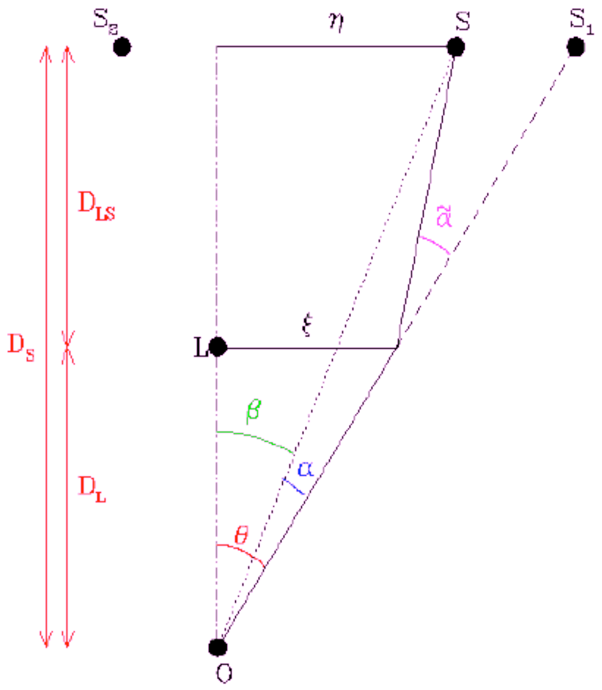
Basics of Lensing: Geometry



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



"Lens equation":

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

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

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

Basics: Lens Equation and Einstein Radius

Deflection angle (point mass):

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

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

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

Einstein radius:

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

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

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

Einstein Radius for distant galaxy:

$$\theta_E \approx 1.8 \sqrt{\frac{M}{10^{12} M_\odot}} \text{ arcsec}$$

Hence lens equation:

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

Basics: Magnification, Convergence and Shear

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

Convergence at position $\vec{x}$: $\kappa(\vec{x}) = 1 - 0.5\ [\ a_{11}(\vec{x}) + a_{22}(\vec{x})\ ]$

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

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

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

Convergence: Normalized surface mass density: $\kappa = \Sigma / \Sigma_{crit}$

$$\Sigma_{crit} = \frac{c^2}{4\pi G} \frac{D_s}{D_i D_{is}}$$

Basics: Caustics and Critical Lines

For positions x (in lens plane) with *det A(x)* = 0: magnification $\mu \longrightarrow \infty$

formally infinite magnification !!! **"Critical Lines"** ! !

Mapping these positions in source plane: **"Caustics"**

Caustics: Separate regions in source plane with different image multiplicity

Crossing a **caustic** increases or decreases the number of images by 2 !

New image pairs are (dis)appear at **critical lines**!

- Binary lens: Schneider & Weiss (1986; Astron. Astroph. 164, 237)

$$\det A = 1 - \left(\frac{\mu_1}{|\underline{r}-\underline{r}_0|^2} + \frac{\mu_2}{|\underline{r}+\underline{r}_0|^2}\right)^2 + \frac{16\mu_1\mu_2 X^2 r_2^2}{|\underline{r}-\underline{r}_0|^4\,|\underline{r}+\underline{r}_0|^4}$$

$$\cos^2\Phi = \frac{1}{4r^2X^2}\left[\frac{1}{2} + (r^2+X^2)^2 - \sqrt{\frac{1}{4}+2(r^4+X^4)}\right],$$

$$\sin^2\Phi = \frac{1}{4r^2X^2}\left[\sqrt{\frac{1}{4}+2(r^4+X^4)} - \frac{1}{2} - (r^2-X^2)^2\right].$$

The conditions $\sin^2\Phi \leqq 1$ and $\sin^2\Phi \geqq 0$ lead to the following constraints on r:

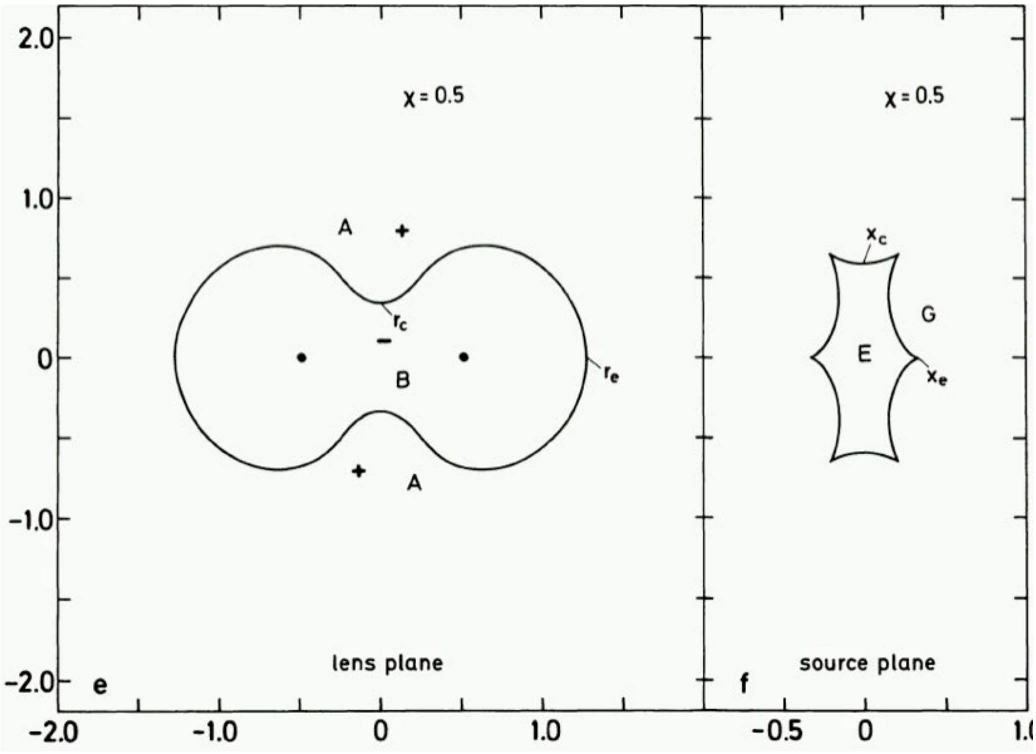
$$|r^2-X^2| \leqq (r^2+X^2)^2$$

and

$$r^2+X^2 \geqq (r^2-X^2)^2 .$$

Here: one of three Cases: $1/8 \leqq X^2 \leqq 1$

- Binary lens: Schneider & Weiss (1986; Astron. Astroph. 164, 237)



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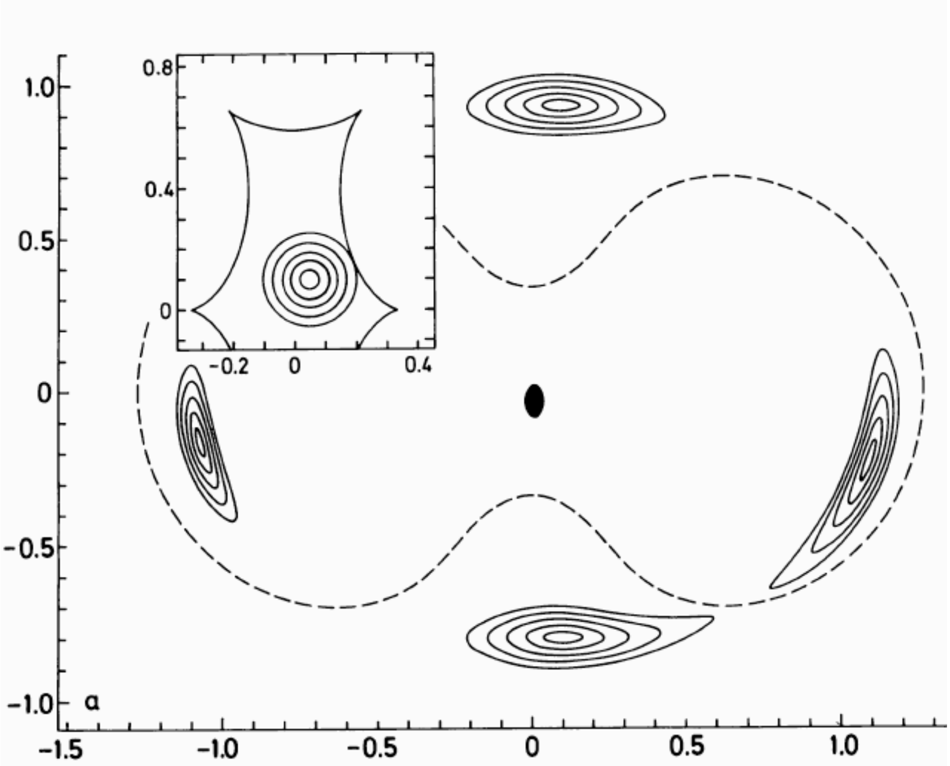

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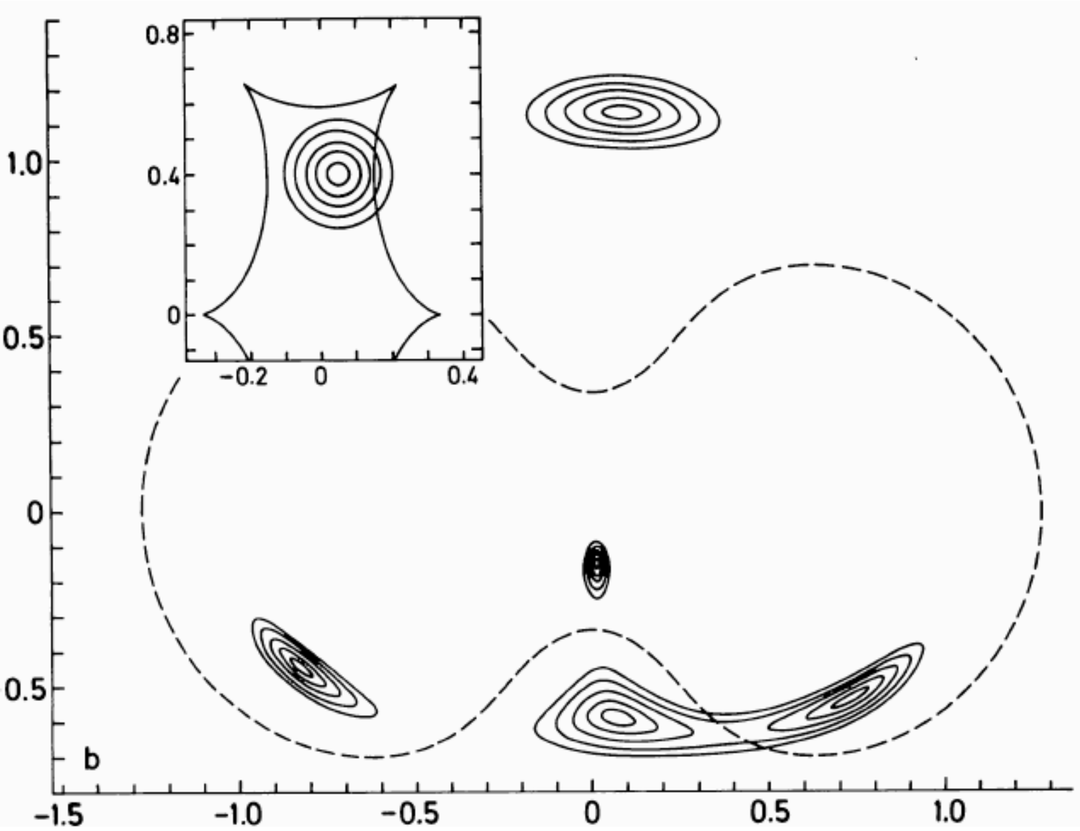

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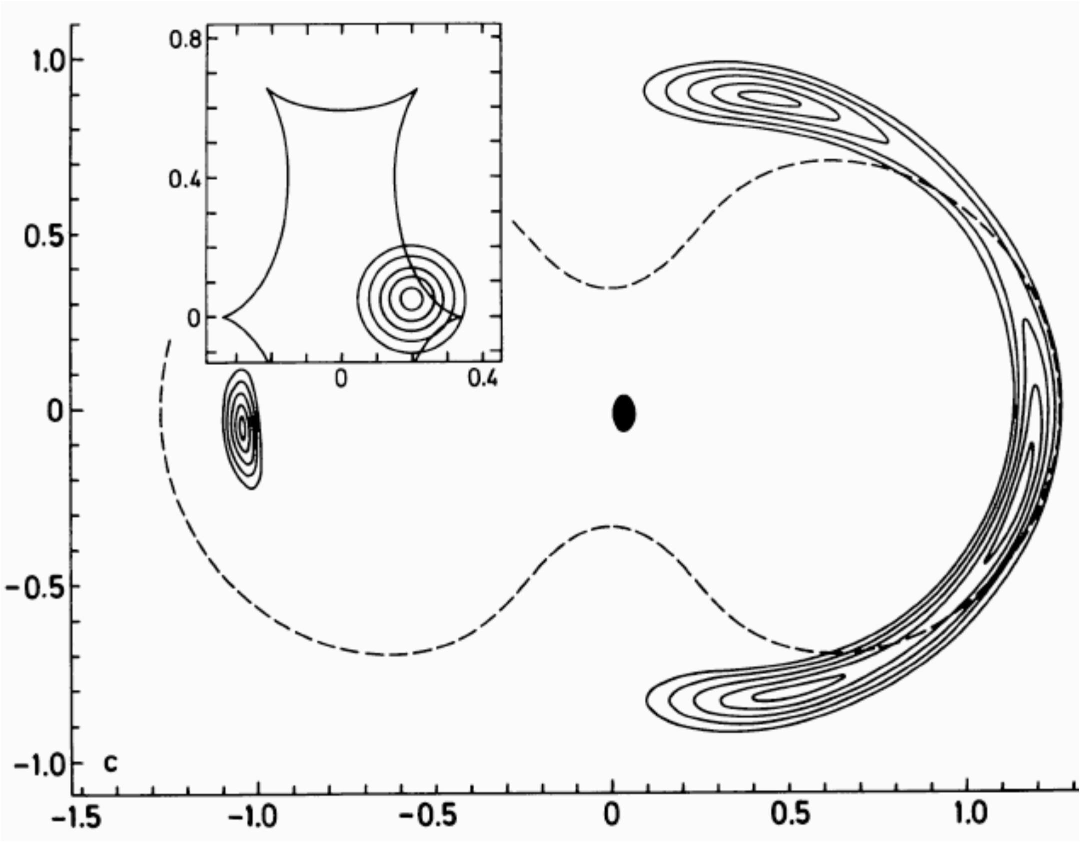


How can we observe (strong) lensing phenomena?

Depends on (lens) mass scale!

- "Statically" (images):
    - macrolensing: massive object as a lens ($\geq 10^6 M_\odot$)
    - Einstein angle > resolution of telescope
    - morphological (multiplicity, shapes)
- "Dynamically" (brightness, positions):
    - microlensing: stars as lenses ($\approx 1 M_\odot$)
    - Einstein angle << resolution of telescope
    - time scale = Einstein radius/transverse velocity ≈ years
    - variability (lightcuves, positions)

Basics of Lensing: Scales

mass scales:

- few Earth mass planets (10^{-5} M⊙) to galaxy clusters (10^{15} M⊙):
  ⇒ 20 orders of magnitude (and counting ...)

angular scales:

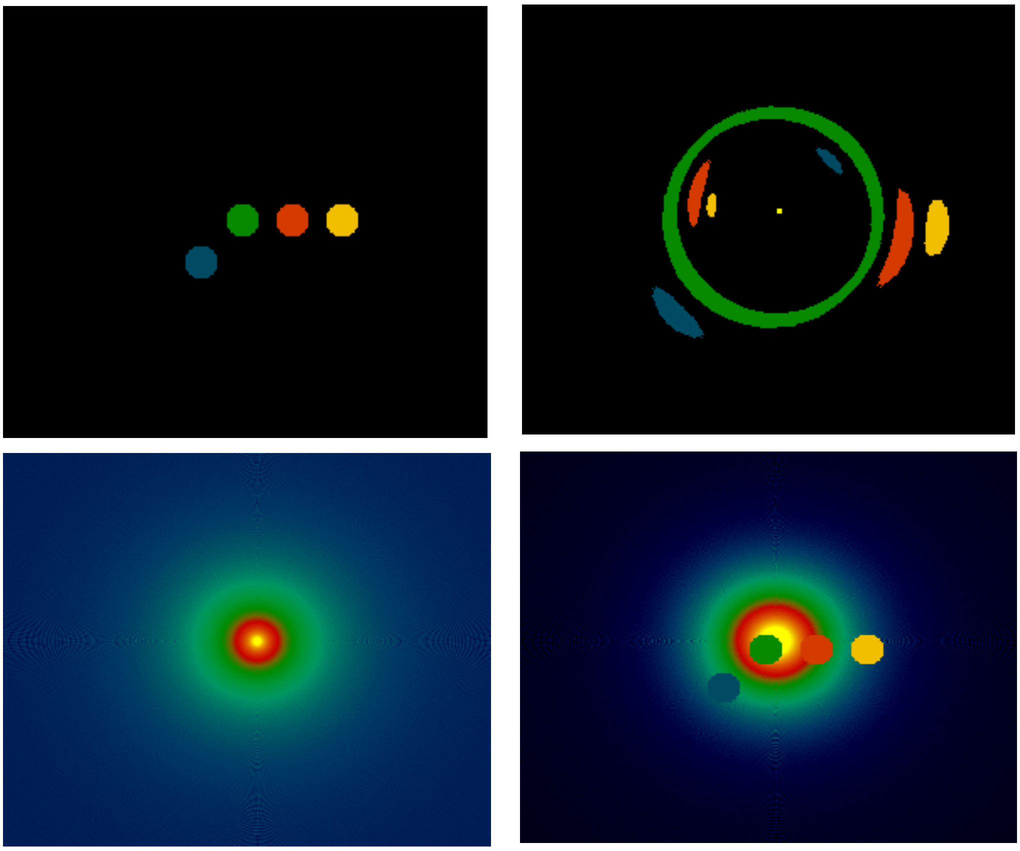
- quasar microlensing (10^{-6} arcsec) to giant arcs (100 arcsec)
  ⇒ 8 orders of magnitude

distance scales

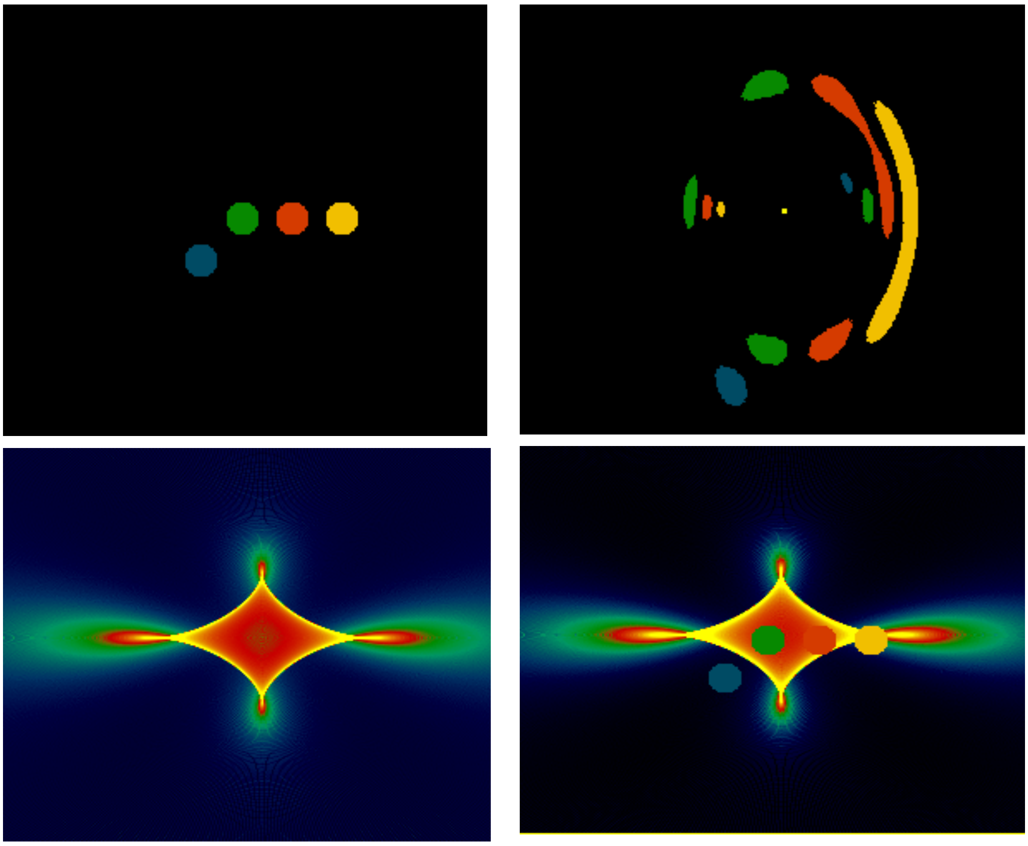
- Milky Way stars (few kpc) to most distant quasars (few Gpc)
  ⇒ 6 orders of magnitude

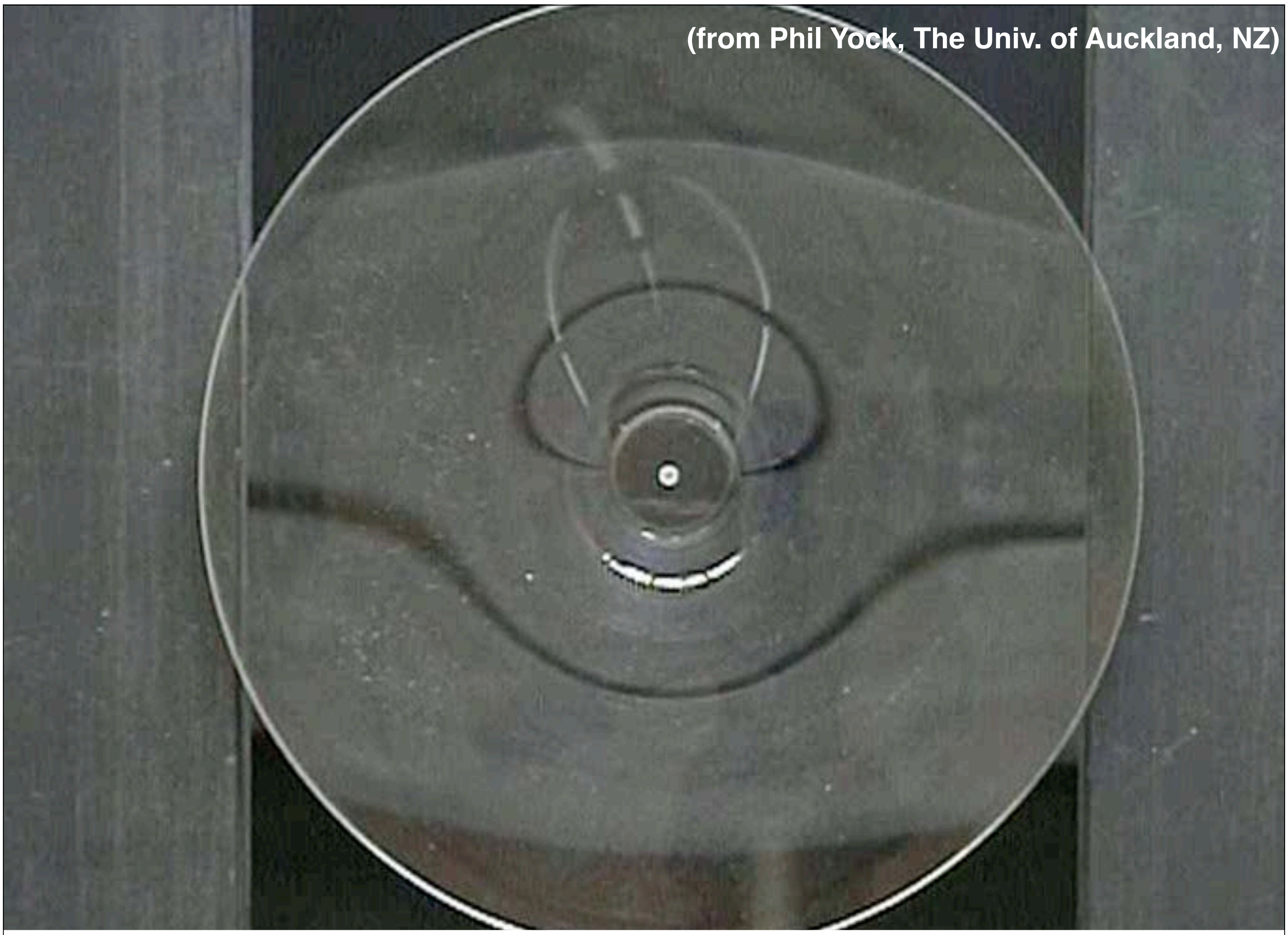
(or even 15, if you're ready to include a nearby star at a distance of a couple of microparsecs ...)

Simulation: Point lens and extended source

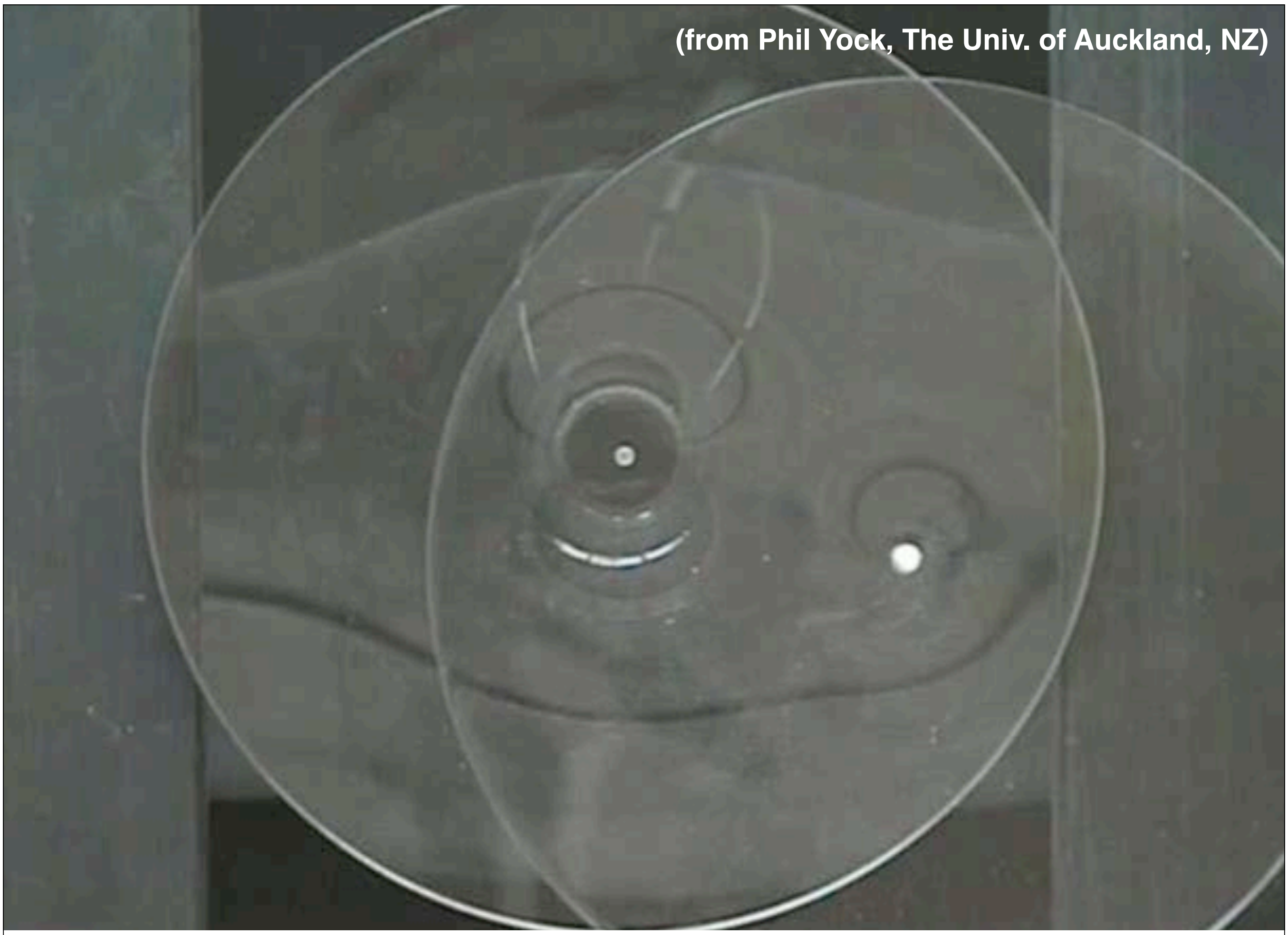


Simulation: Chang-Refsdal-Lens (point lens plus shear)





(from Phil Yock, The Univ. of Auckland, NZ)



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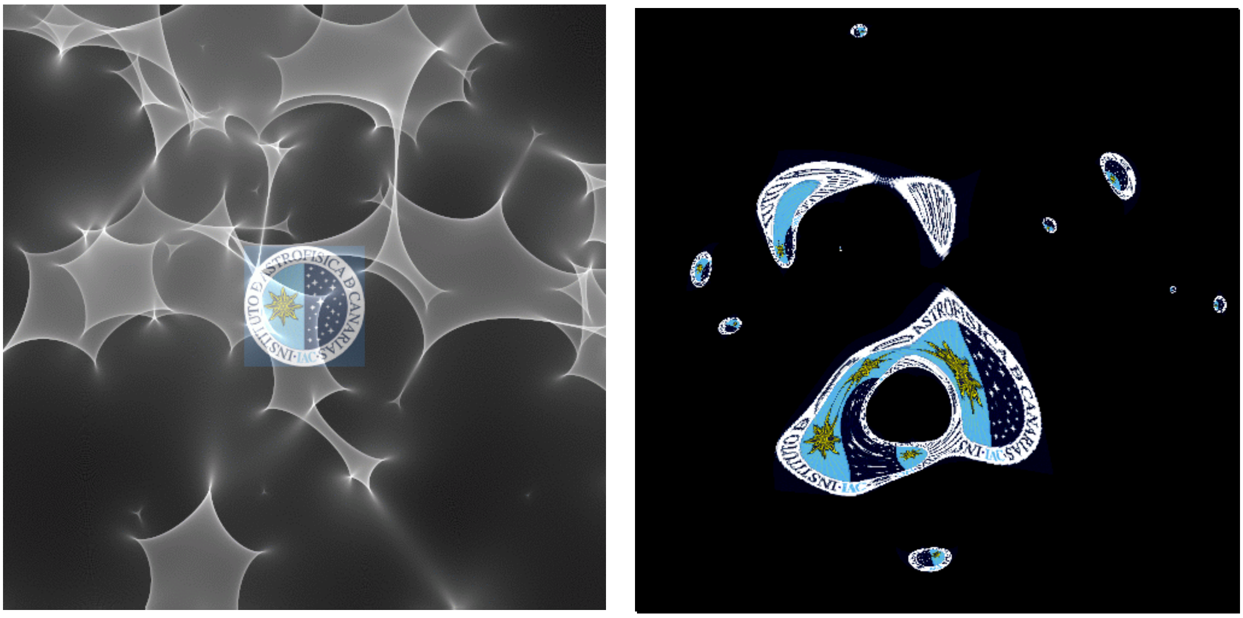
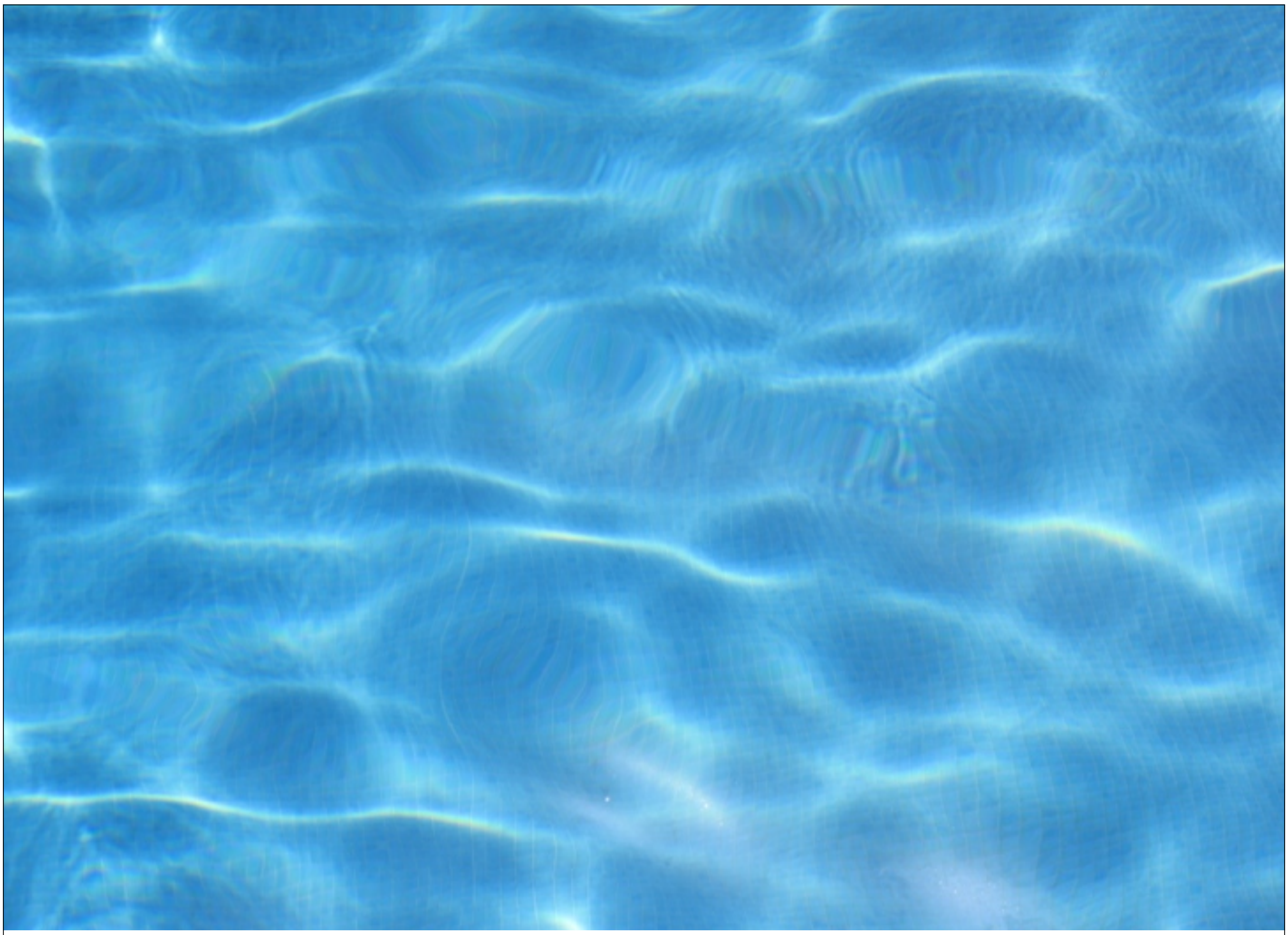
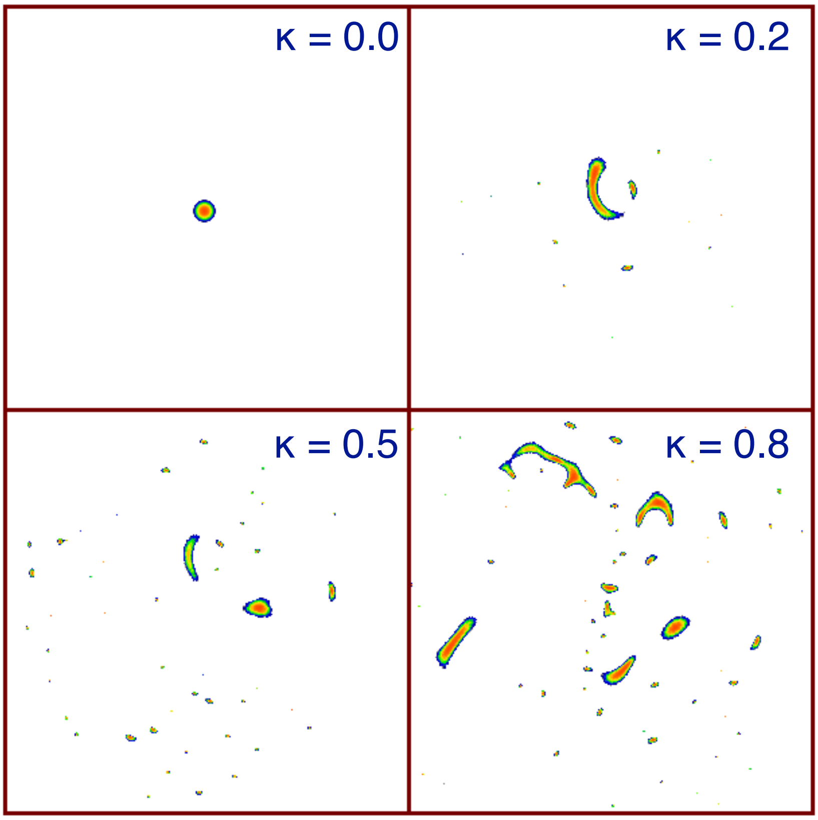
Many Lenses: Quasar Microlensing





(Unresolvable) Image Configurations in Microlensing ...



... as a function of the surface mass density κ (“kappa”)

here: external shear γ (“gamma”) = 0

Lensing Phenomena:

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

Lensing Phenomena:

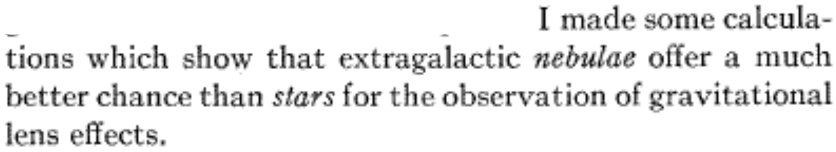
- Two regimes of strength: **strong** ⇔ weak
- Two regimes of scales: **macro** ⇔ **micro**
- Two regimes of distance: near ⇔ **far**

Effects of Lensing

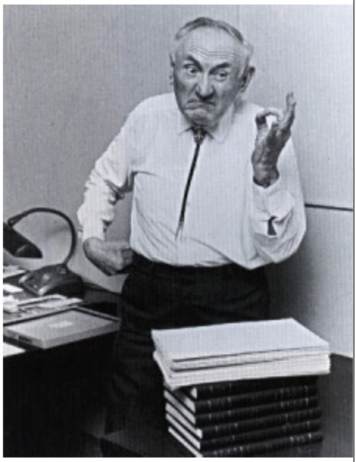
- change of position
  - first confirmation of GR: offset at solar limb
  - »normally« not observable: astrometric microlensing
- distortion
  - extended sources: arclets, arcs, Einstein rings, ...
- (de)magnification
  - point sources: brighter/fainter: no standard candles!
  - galaxies: larger/smaller: arcs
- multiple images
  - most dramatic effect! multiple quasars, giant arcs

Fritz Zwicky: "Nebulae as gravitational lenses"

Phys. Rev. 51, 290 - 290 (1937)



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



Fritz Zwicky (1898 - 1974)

1) additional test for GR

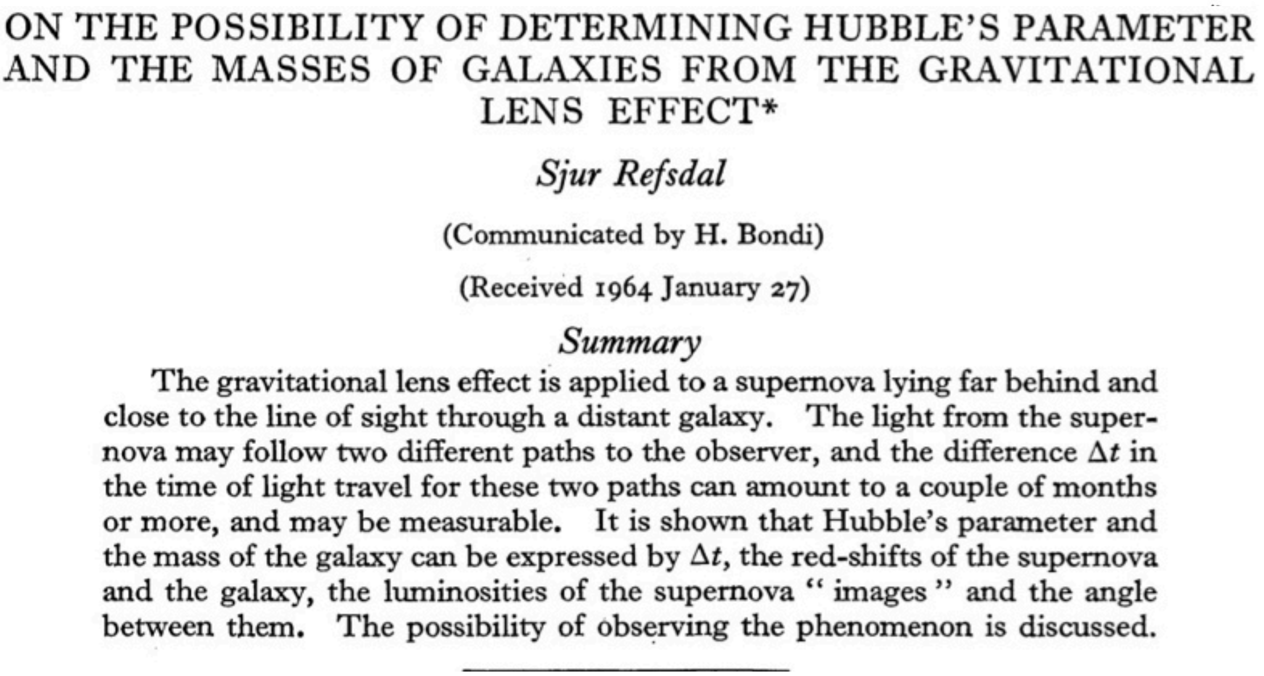
2) "telescope": see fainter objects

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

4) splittings of up to 30 arcseconds

Sjur Refsdal
(1935 - 2009)

MNRAS 128, 307 (1964)



ON THE POSSIBILITY OF DETERMINING HUBBLE'S PARAMETER AND THE MASSES OF GALAXIES FROM THE GRAVITATIONAL LENS EFFECT*

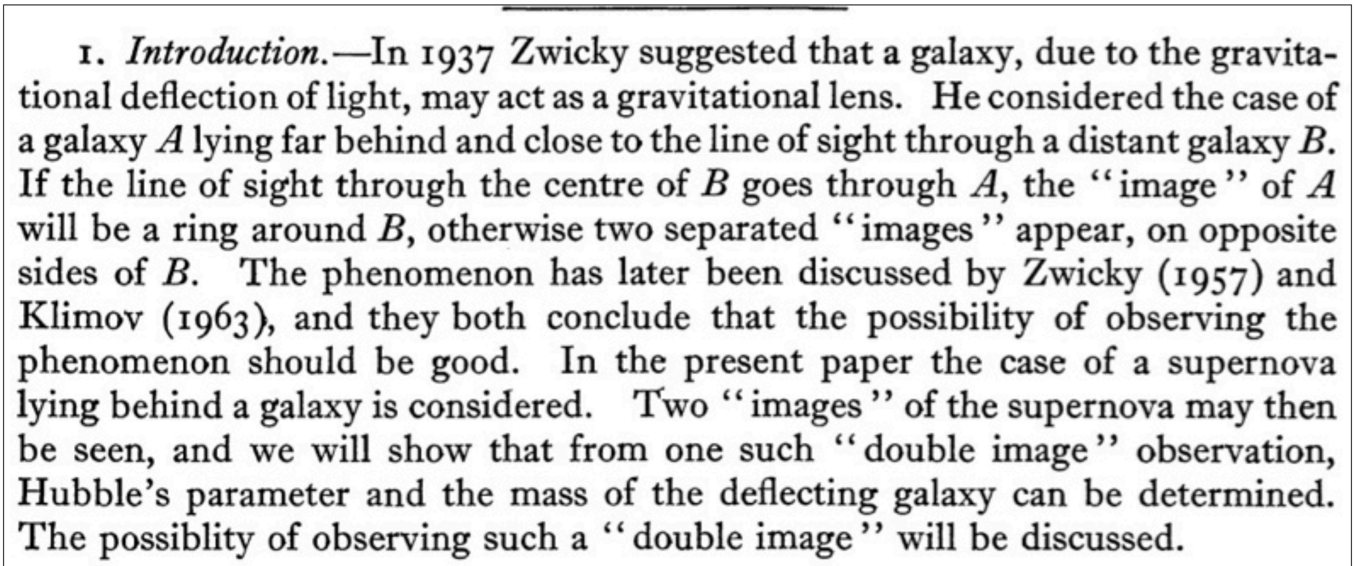
Sjur Refsdal

(Communicated by H. Bondi)

(Received 1964 January 27)

Summary

The gravitational lens effect is applied to a supernova lying far behind and close to the line of sight through a distant galaxy. The light from the supernova may follow two different paths to the observer, and the difference Δt in the time of light travel for these two paths can amount to a couple of months or more, and may be measurable. It is shown that Hubble's parameter and the mass of the galaxy can be expressed by Δt, the red-shifts of the supernova and the galaxy, the luminosities of the supernova "images" and the angle between them. The possibility of observing the phenomenon is discussed.



1. *Introduction.*—In 1937 Zwicky suggested that a galaxy, due to the gravitational deflection of light, may act as a gravitational lens. He considered the case of a galaxy *A* lying far behind and close to the line of sight through a distant galaxy *B*. If the line of sight through the centre of *B* goes through *A*, the "image" of *A* will be a ring around *B*, otherwise two separated "images" appear, on opposite sides of *B*. The phenomenon has later been discussed by Zwicky (1957) and Klimov (1963), and they both conclude that the possibility of observing the phenomenon should be good. In the present paper the case of a supernova lying behind a galaxy is considered. Two "images" of the supernova may then be seen, and we will show that from one such "double image" observation, Hubble's parameter and the mass of the deflecting galaxy can be determined. The possiblity of observing such a "double image" will be discussed.

Sjur Refsdal, MNRAS 128, 307 (1964)

Sjur Refsdal, MNRAS 128, 307 (1964)

Star-like objects with intense emission both in the radio range and the optical range have recently been discovered (Greenstein 1963). Their absolute visual luminosity are of order −24, and it is possible that flashes occur in the optical region, lasting about one month, and with an amplitude about 0·5$^{\mathrm{m}}$.

If so, observations at greater distances than with supernova will be possible. The distances may be so great that we can no longer assume Z to be small. The result of our calculations will then depend on the cosmological model we choose, giving a possibility of testing the different models. This will be discussed in a subsequent paper.

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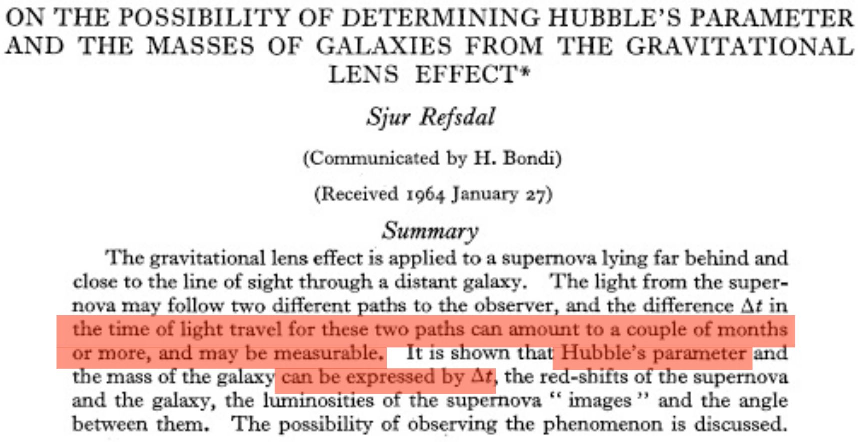
Active Galactic Nuclei (AGN), Quasars

Refsdal, MNRAS 128, 307 (1964)



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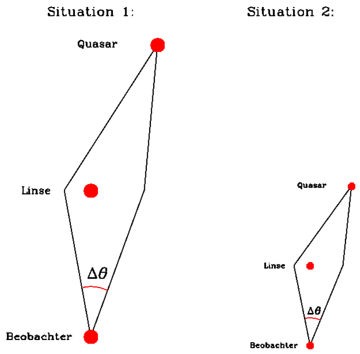
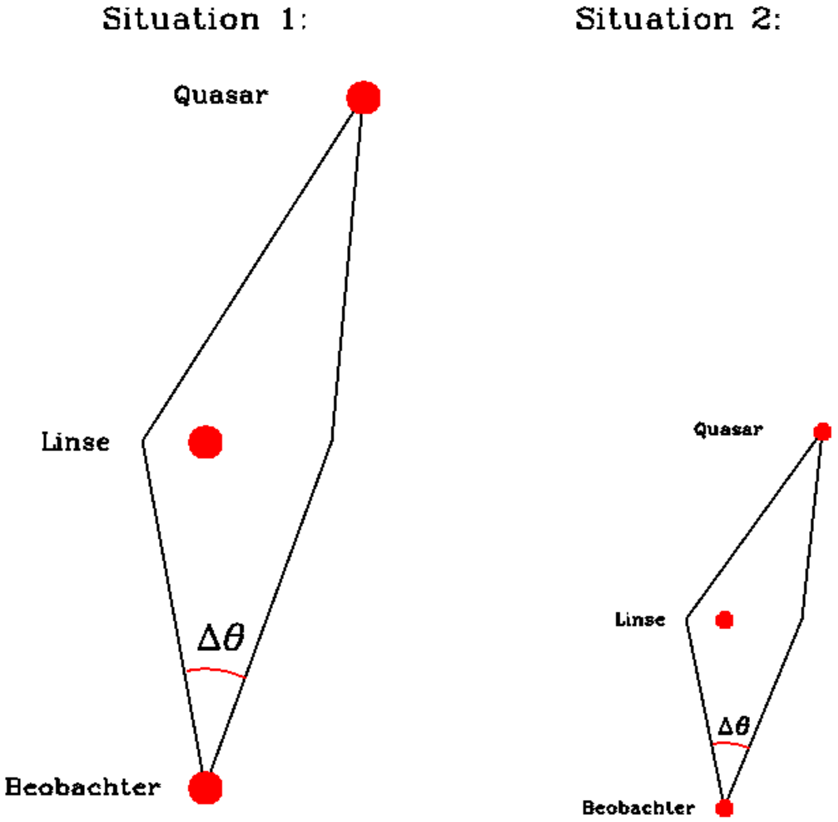


Refsdal, MNRAS 128, 307 (1964)



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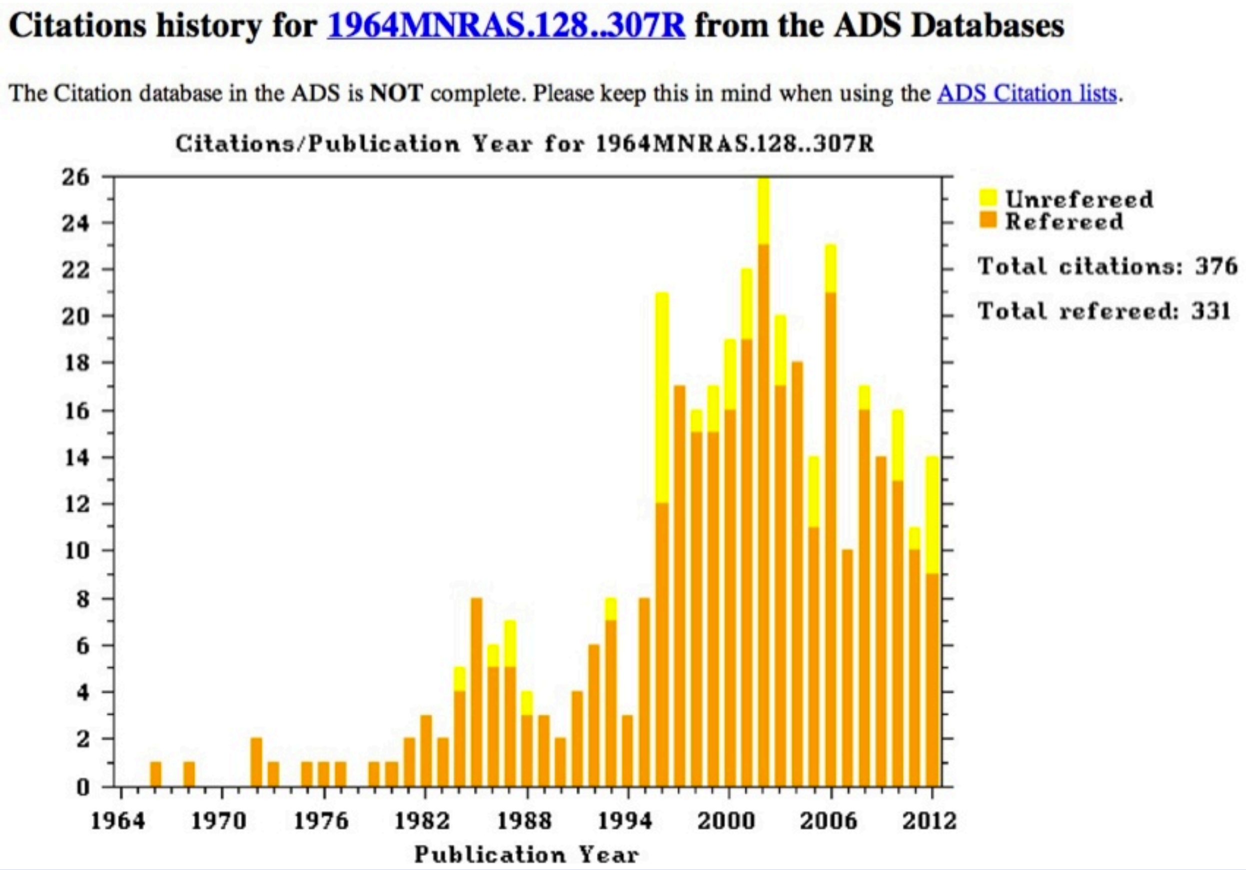

Citations history for 1964MNRAS.128..307R from the ADS Databases

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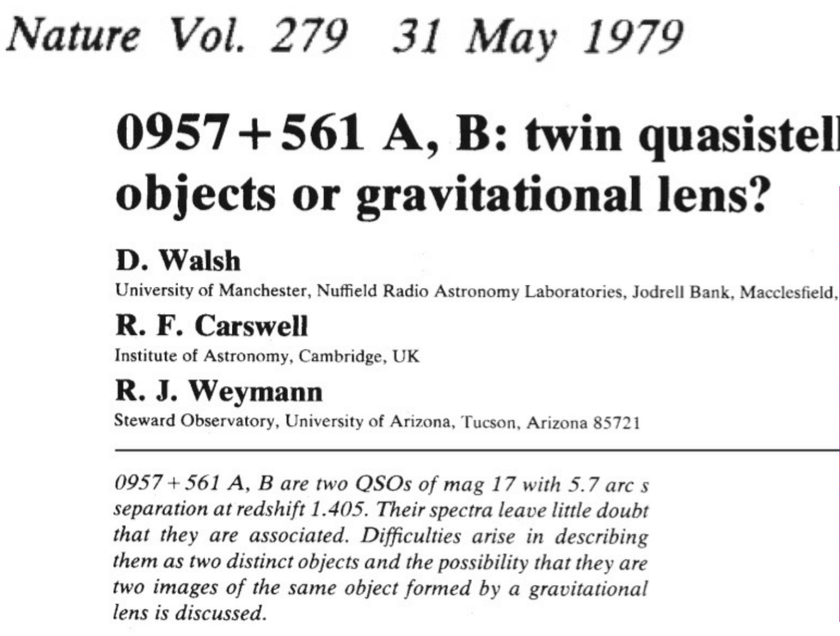
1979 Walsh, Carswell, Weymann:



Nature Vol. 279 31 May 1979 **381**

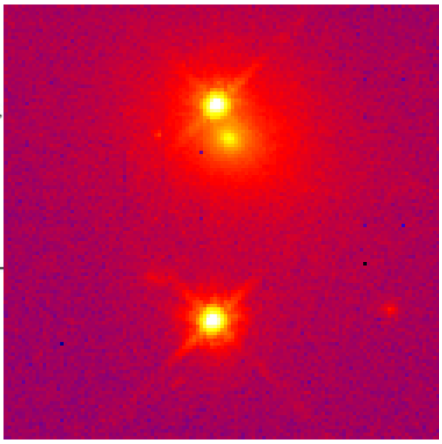
0957+561 A, B: twin quasistellar objects or gravitational lens?

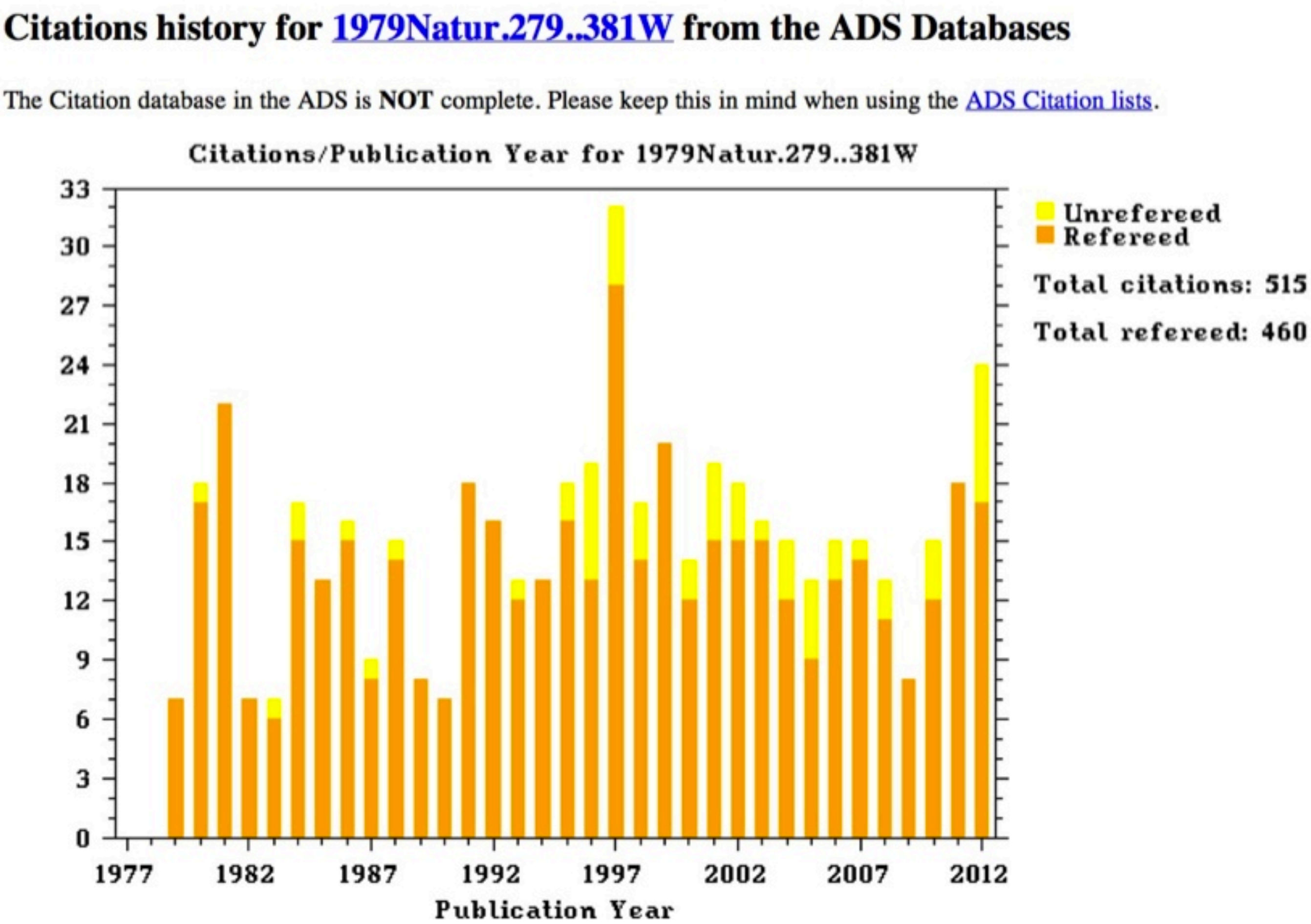
D. Walsh
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield,

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.





Citations history for 1979Natur.279..381W from the ADS Databases

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Total citations: 515

Total refereed: 460

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 (and small $\Delta\theta$!)
- 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 (November 2012):
> 300 "accepted" multiple quasars systems!

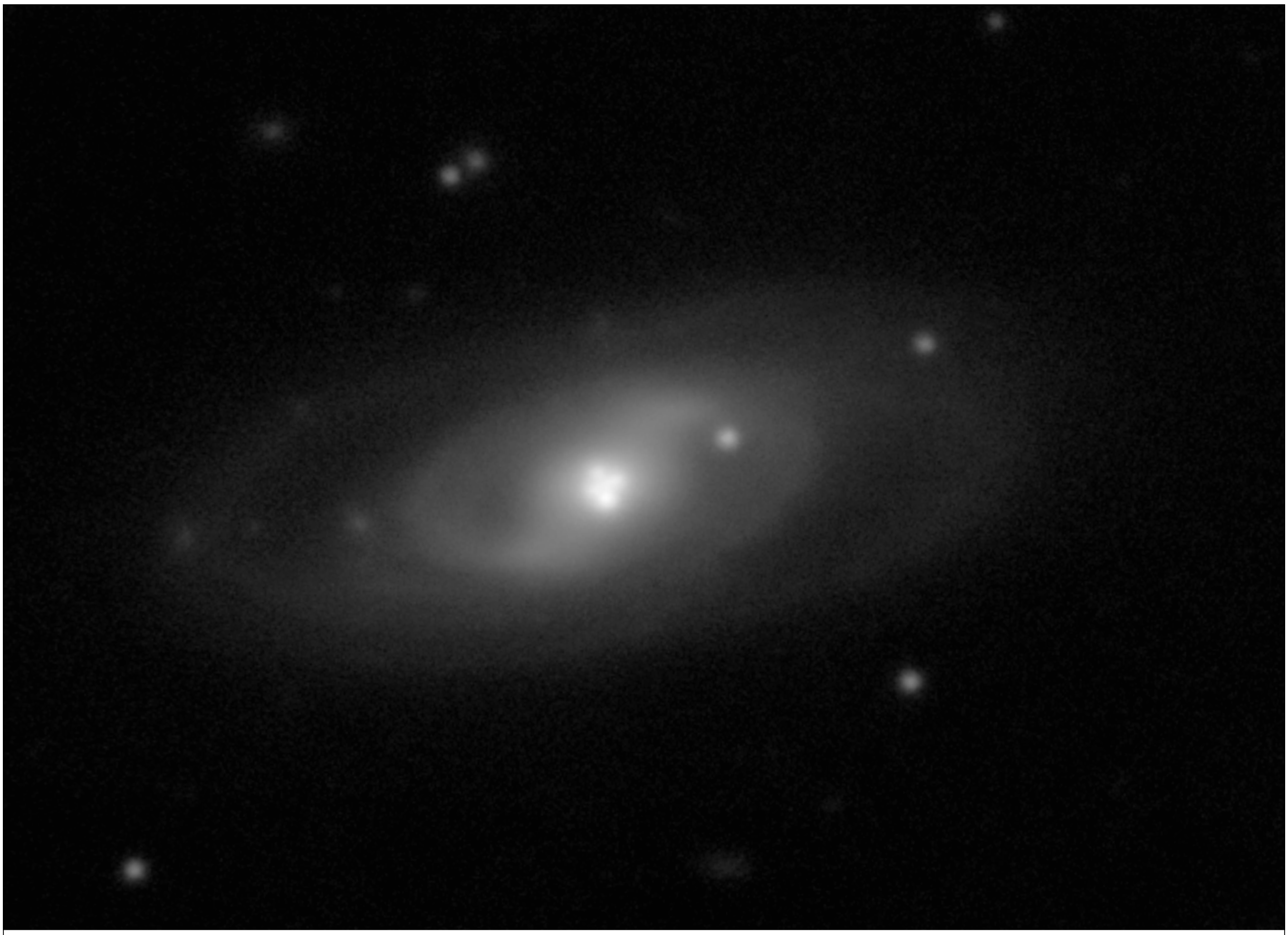
How to find gravitationally lensed quasars?

(... if you were to get a telescope and the task)

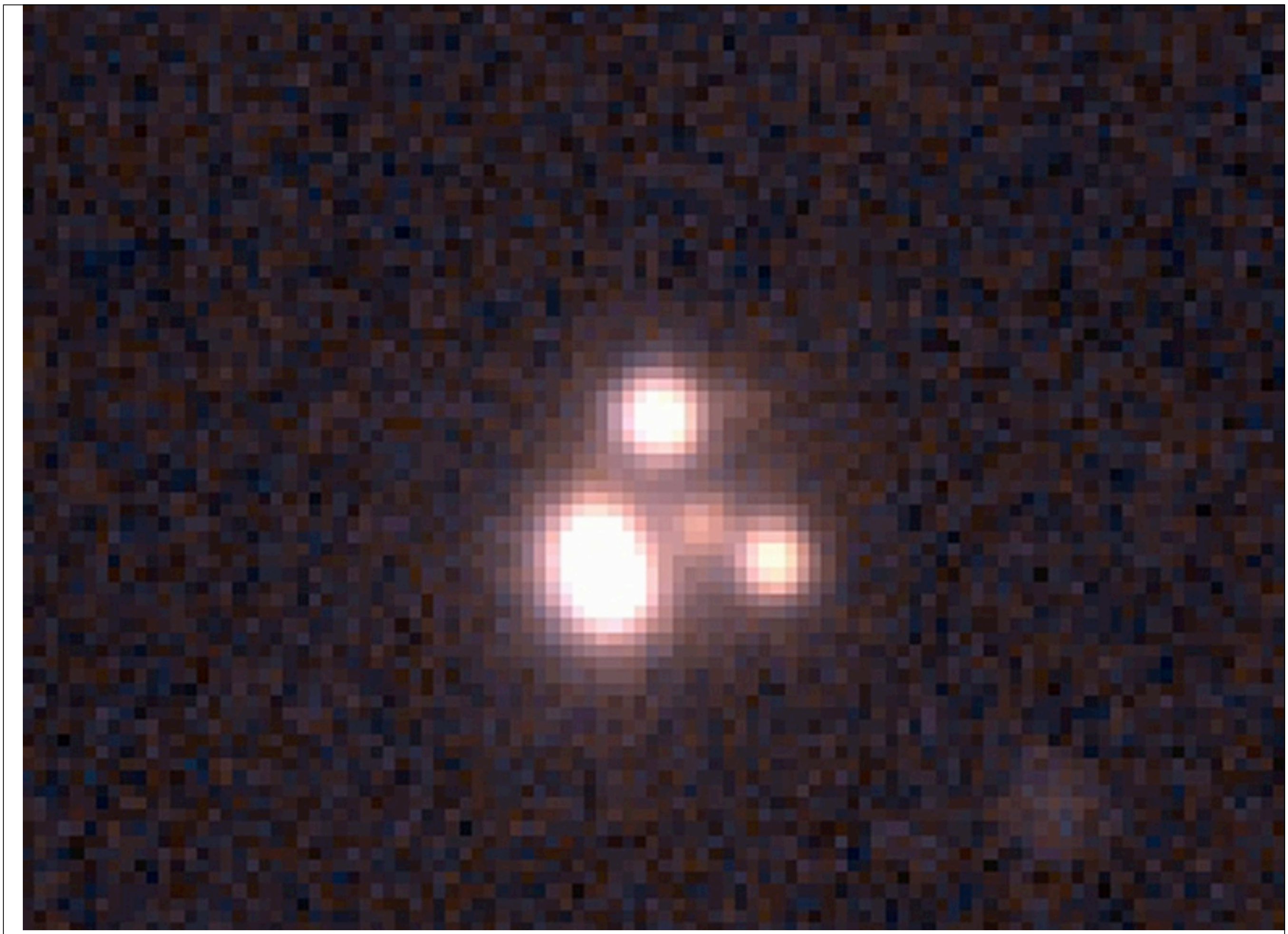
- high-resolution imaging of (sample of) bright quasars:
  - ideally: resolve two, three, four images
  - in practice often: “non-circular” point-spread function plus follow up
- spectroscopy of millions of galaxies:
  - search for super-posed spectra: galaxy spectrum plus (high-z) quasar spectrum
- be lucky:
  - serendipitous discovery

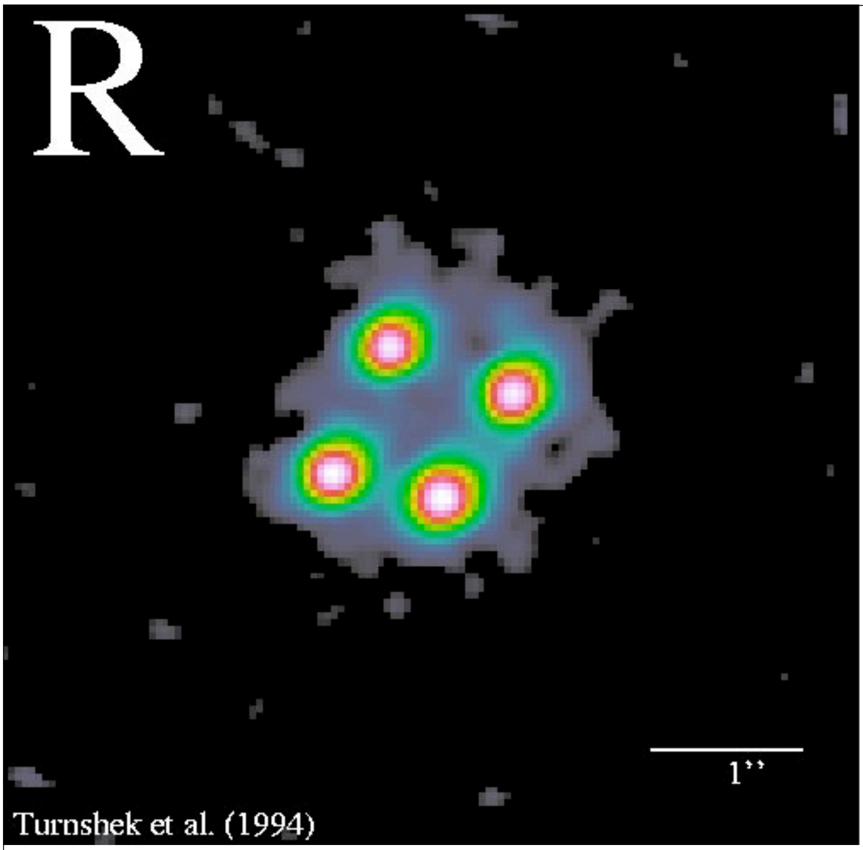
Occurance of multiply imaged quasars:

(1 in 100 to) 1 in 500

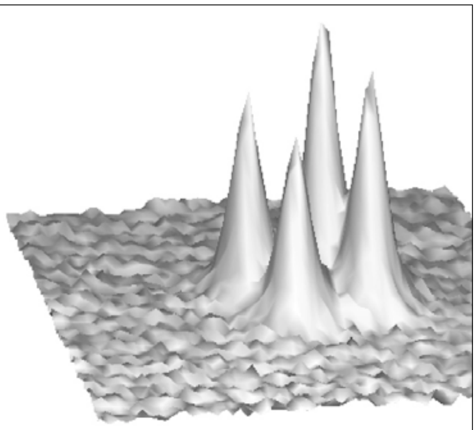


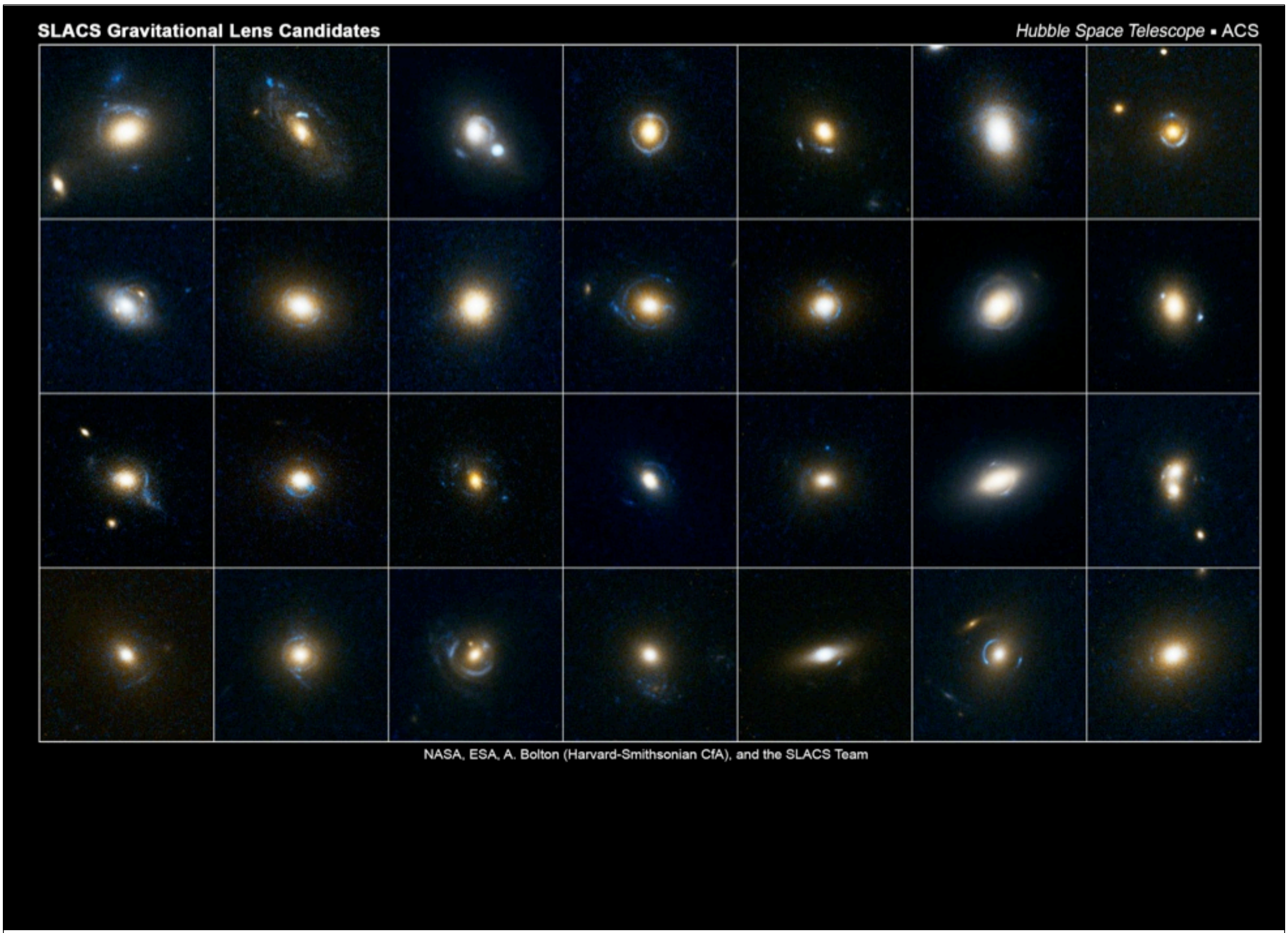
Gravitational Lens G2237+0305





Turnshek et al. (1994)





SLACS Gravitational Lens Candidates

NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

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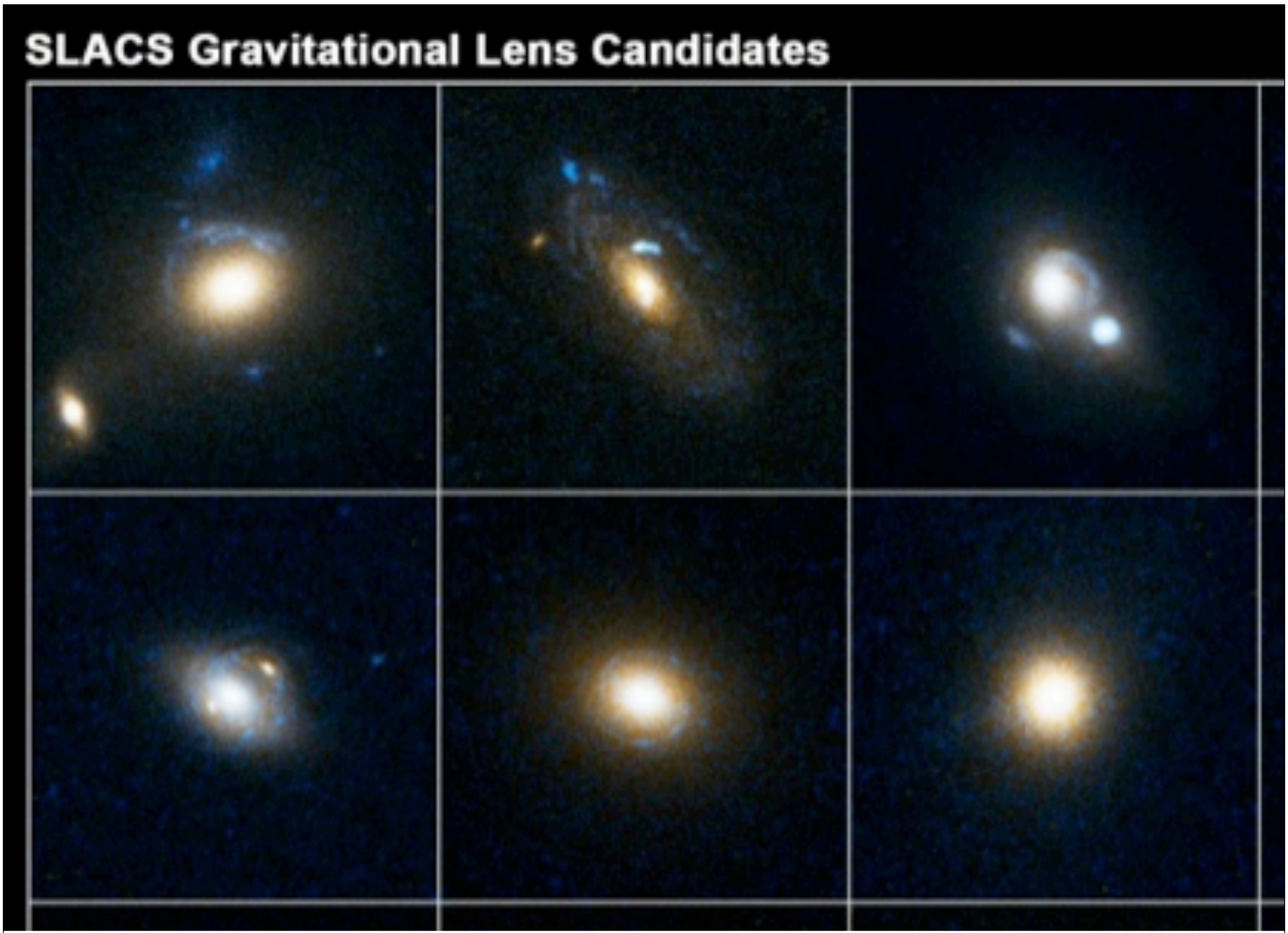
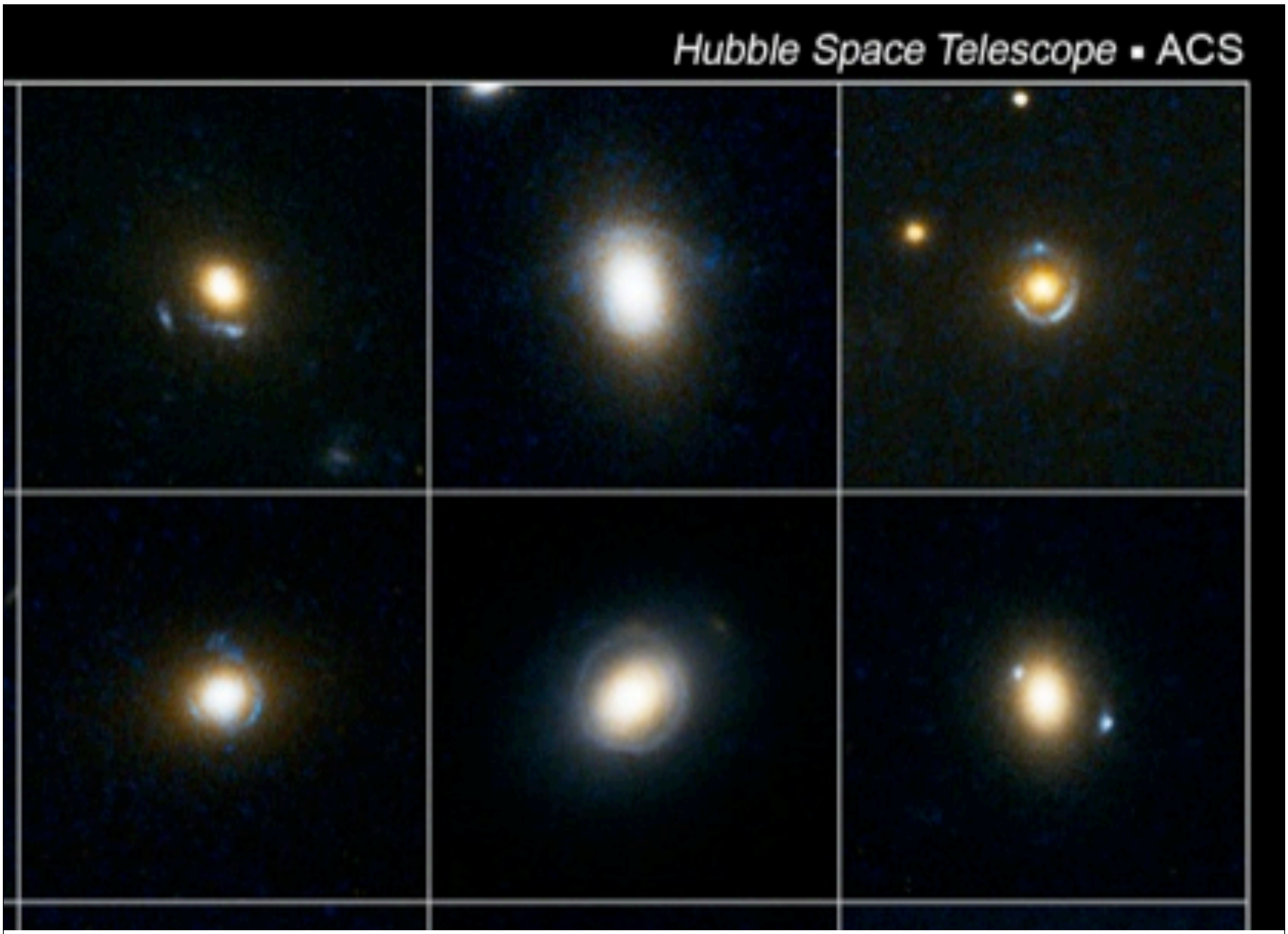
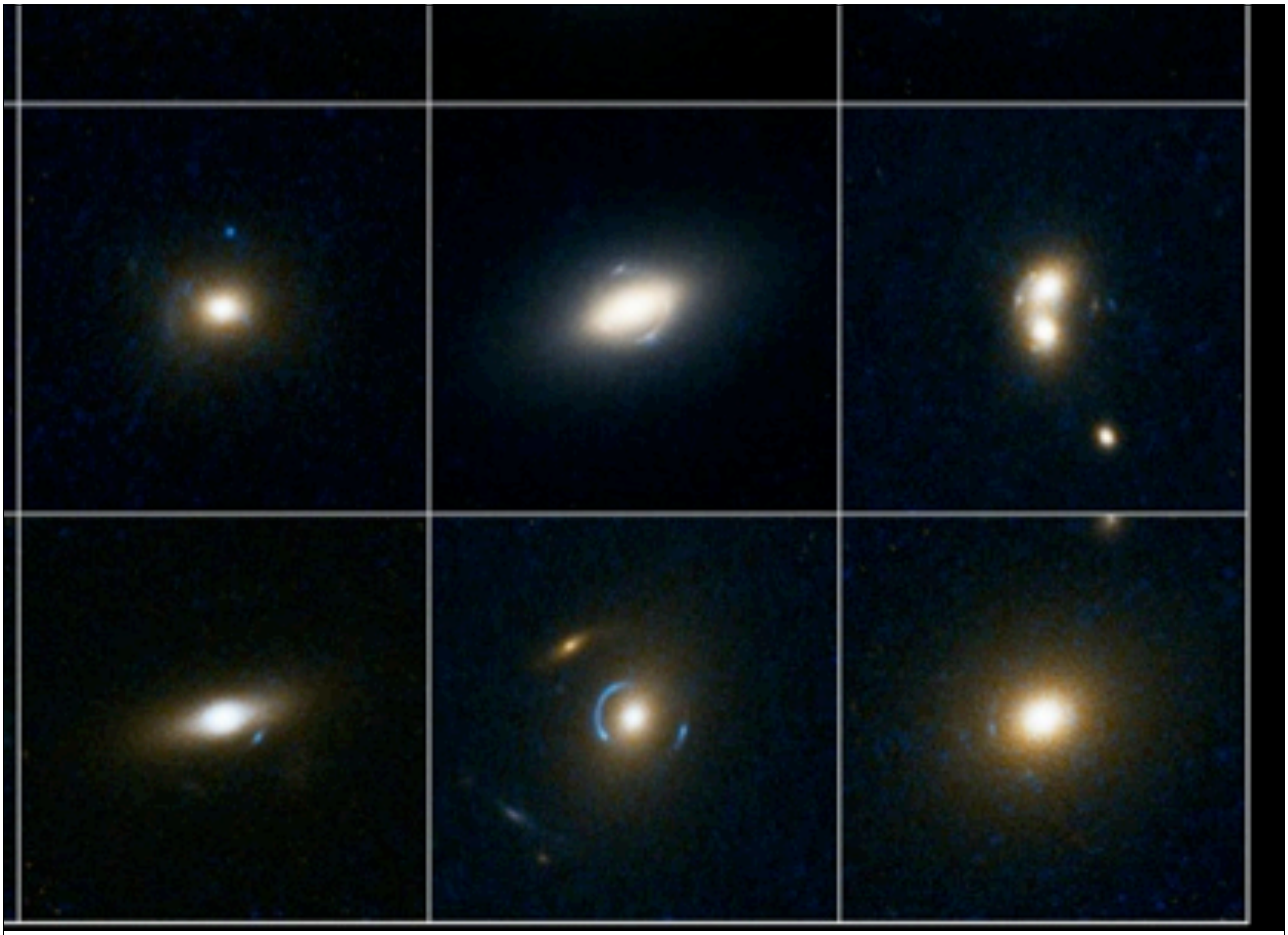
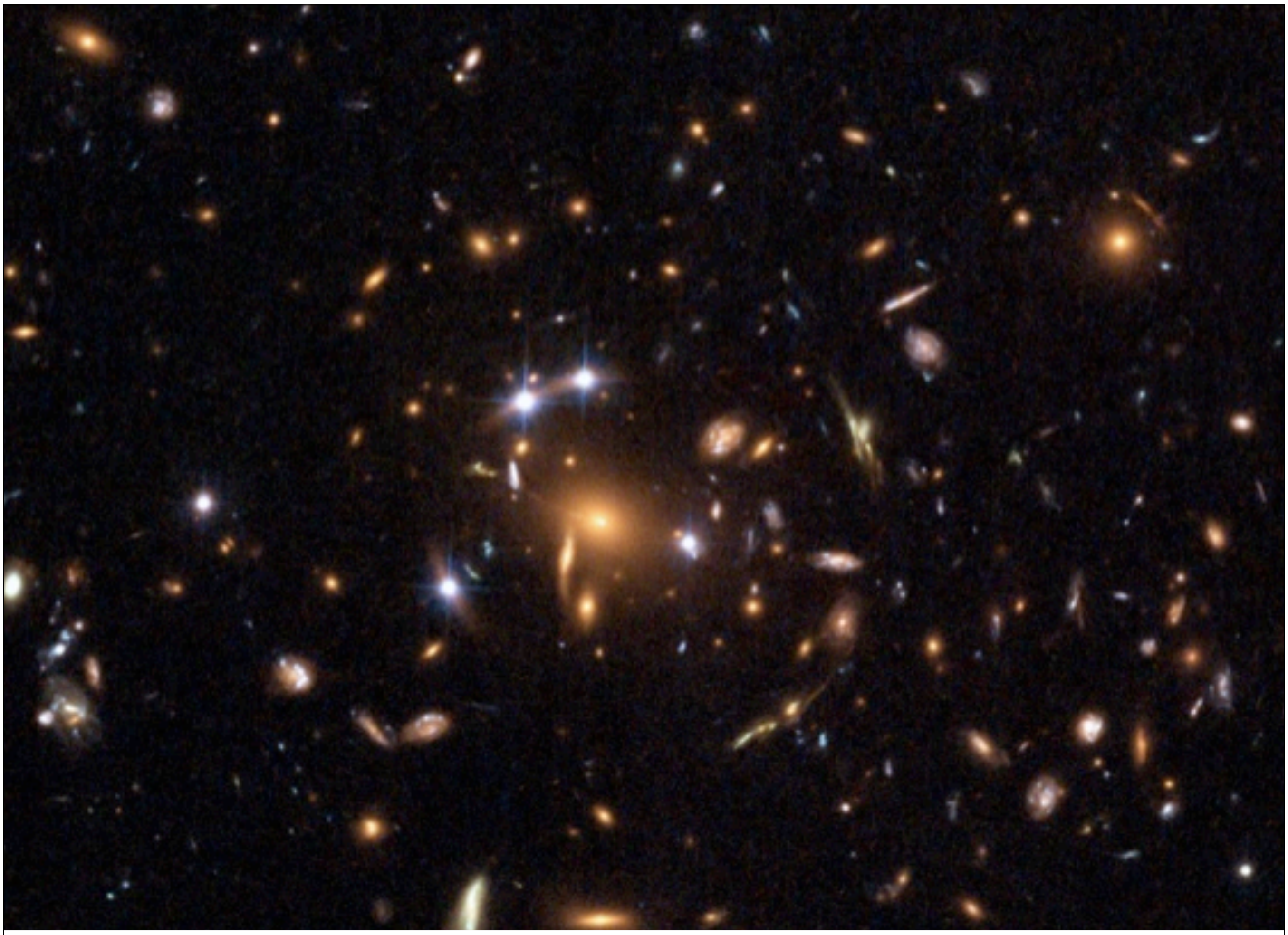


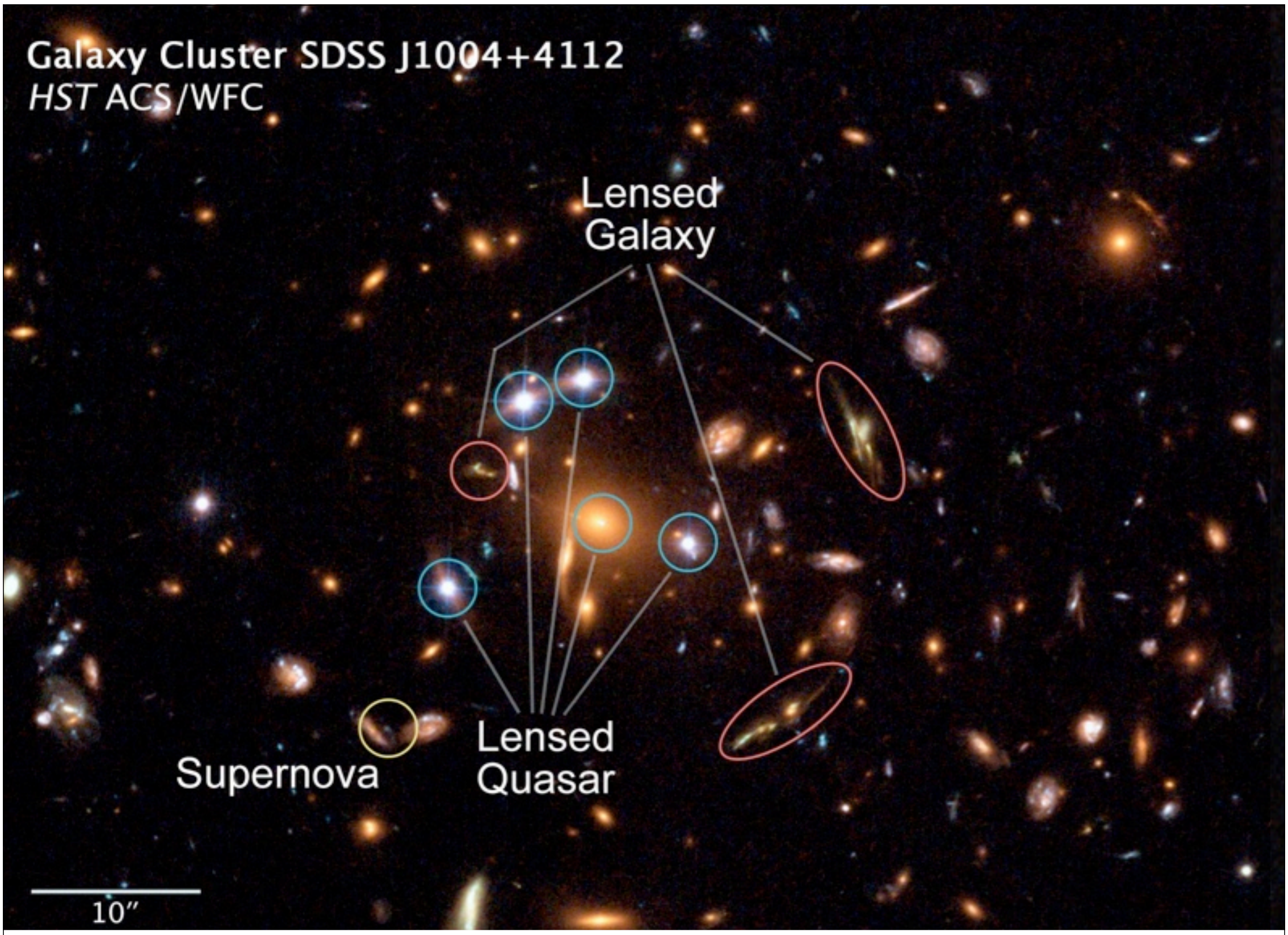
SLACS Gravitational Lens Candidates


Hubble Space Telescope ▪ ACS

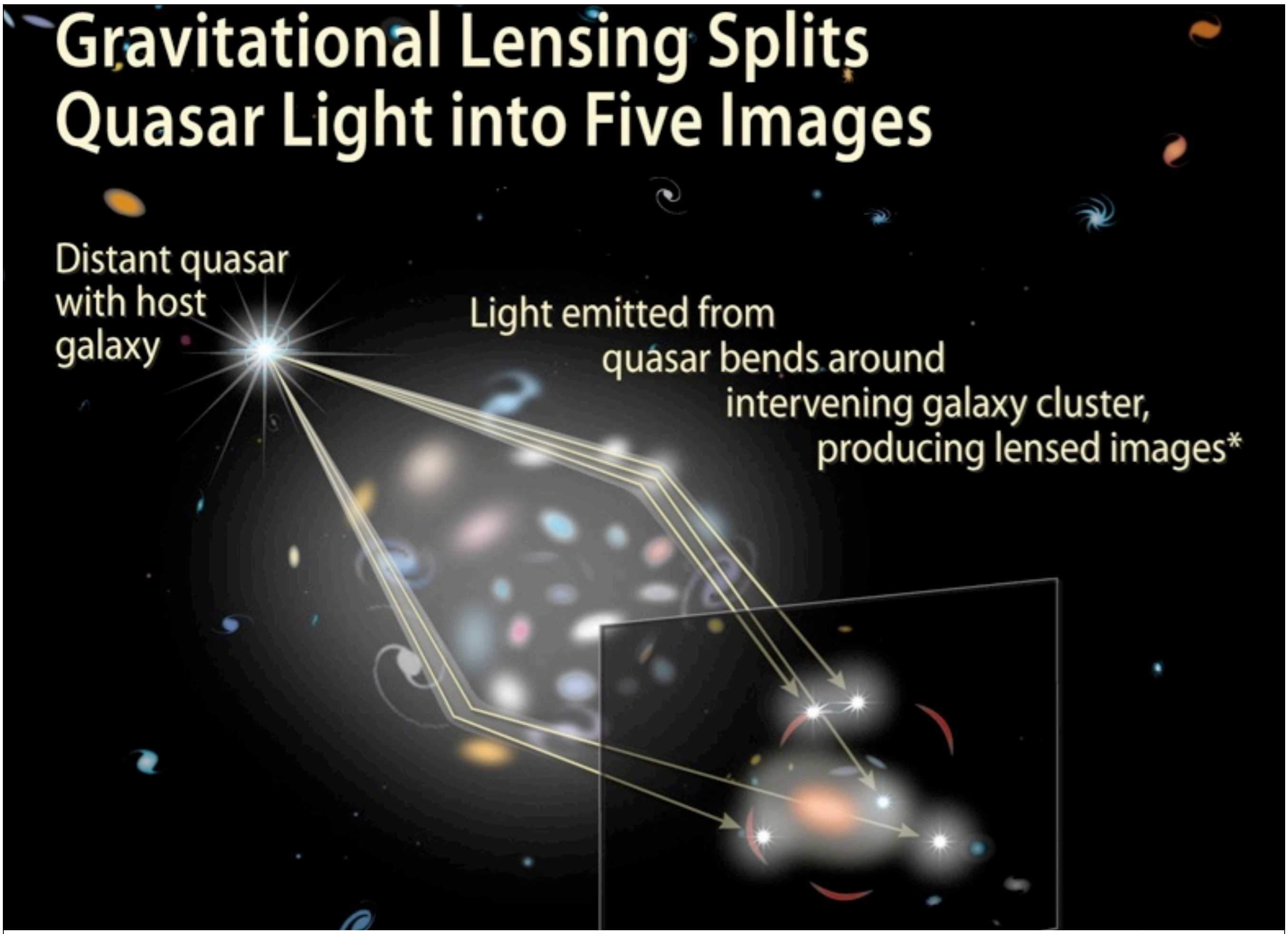




Galaxy Cluster SDSS J1004+4112
HST ACS/WFC



Gravitational Lensing Splits Quasar Light into Five Images



Distant quasar with host galaxy

Light emitted from quasar bends around intervening galaxy cluster, producing lensed images*

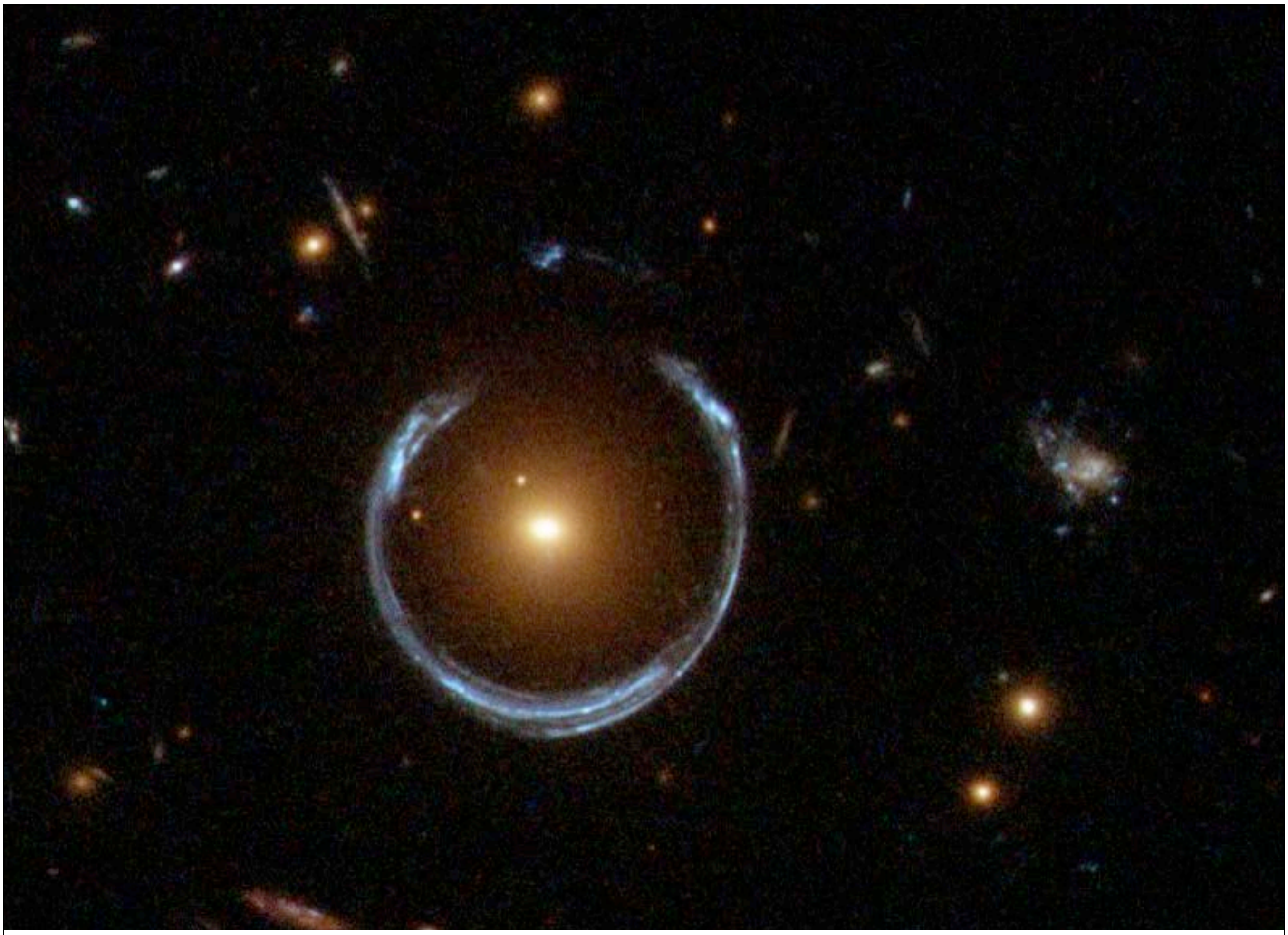
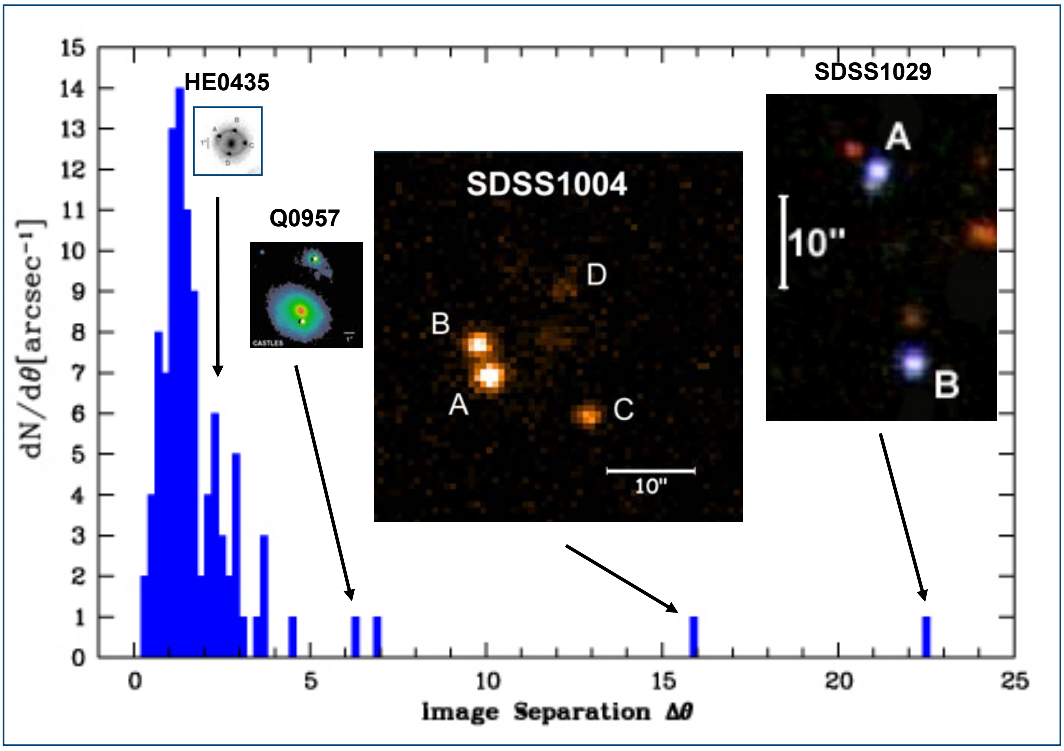


Image separations of known multiply imaged QSOs



(from Janine Fohlmeister)

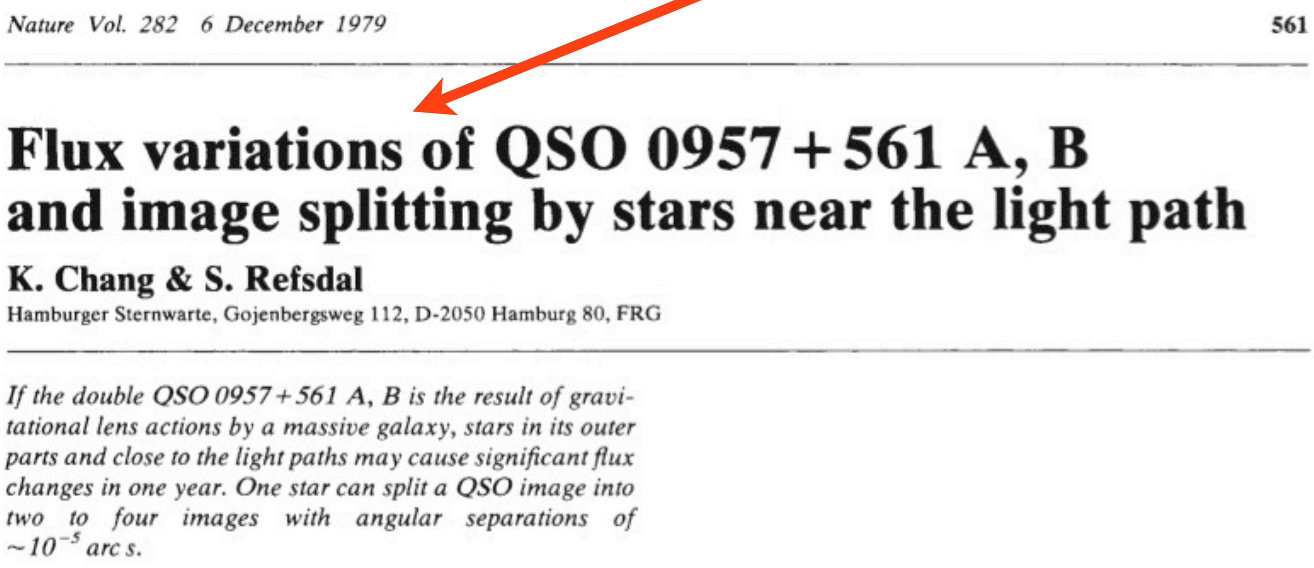
AGNs and Quasars

Joachim Wambsganss

2) Microlensing of Quasars: Size and Luminosity Profile

1979 Chang & Refsdal:

Quasar Microlensing



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

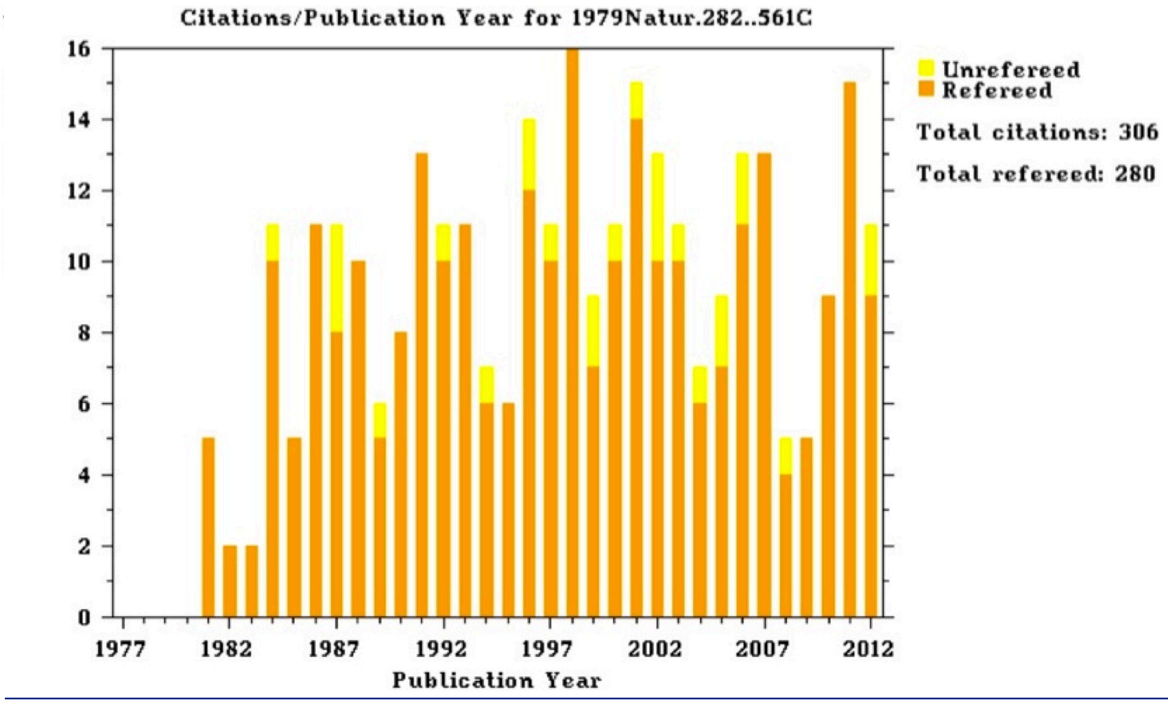
If the double QSO 0957+561 A, B is the result of gravitational lens actions by a massive galaxy, stars in its outer parts and close to the light paths may cause significant flux changes in one year. One star can split a QSO image into two to four images with angular separations of ~10^{-5} arc s.

1979 Chang & Refsdal:

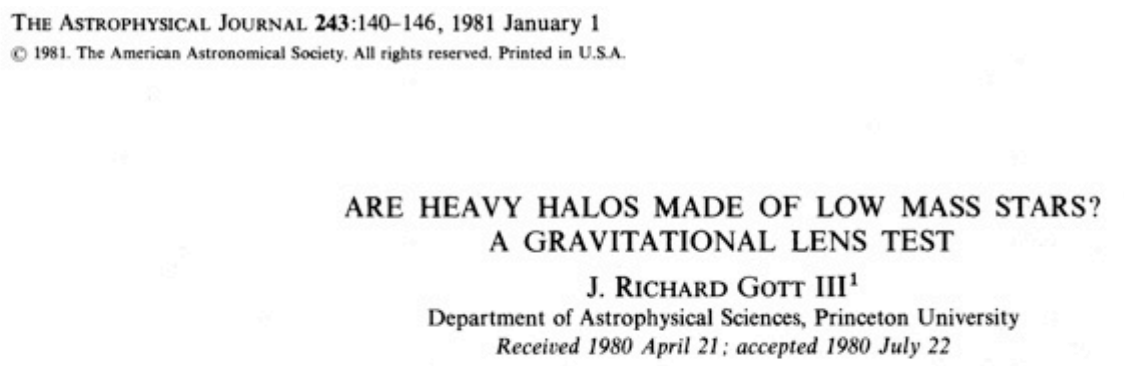
Quasar Microlensing

Citations history for 1979Natur.282..561C from the ADS Databases

The Citation database in the ADS is **NOT** complete. Please keep this in mind when using the ADS Citation lists.



1981 Gott:



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

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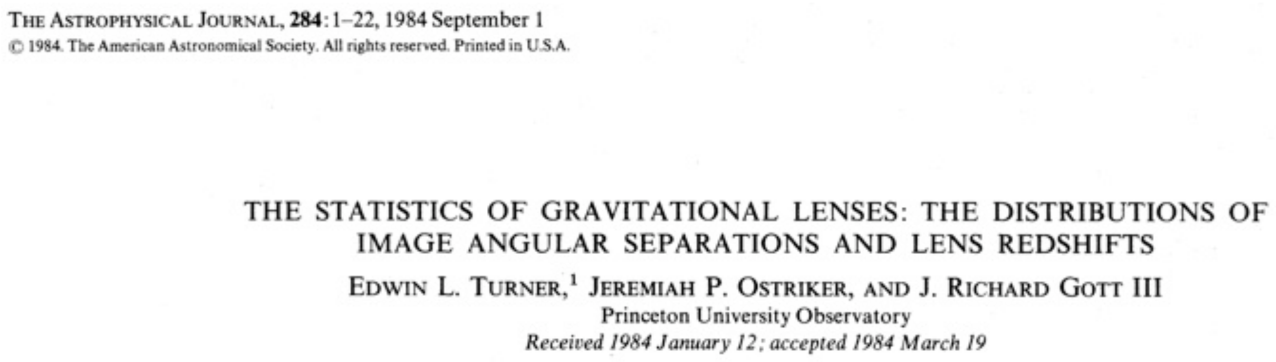
ARE HEAVY HALOS MADE OF LOW MASS STARS?
A GRAVITATIONAL LENS TEST

J. RICHARD GOTT III[1]

Department of Astrophysical Sciences, Princeton University

Received 1980 April 21; accepted 1980 July 22

1984 Turner, Ostriker, Gott:



THE ASTROPHYSICAL JOURNAL, **284**:1–22, 1984 September 1

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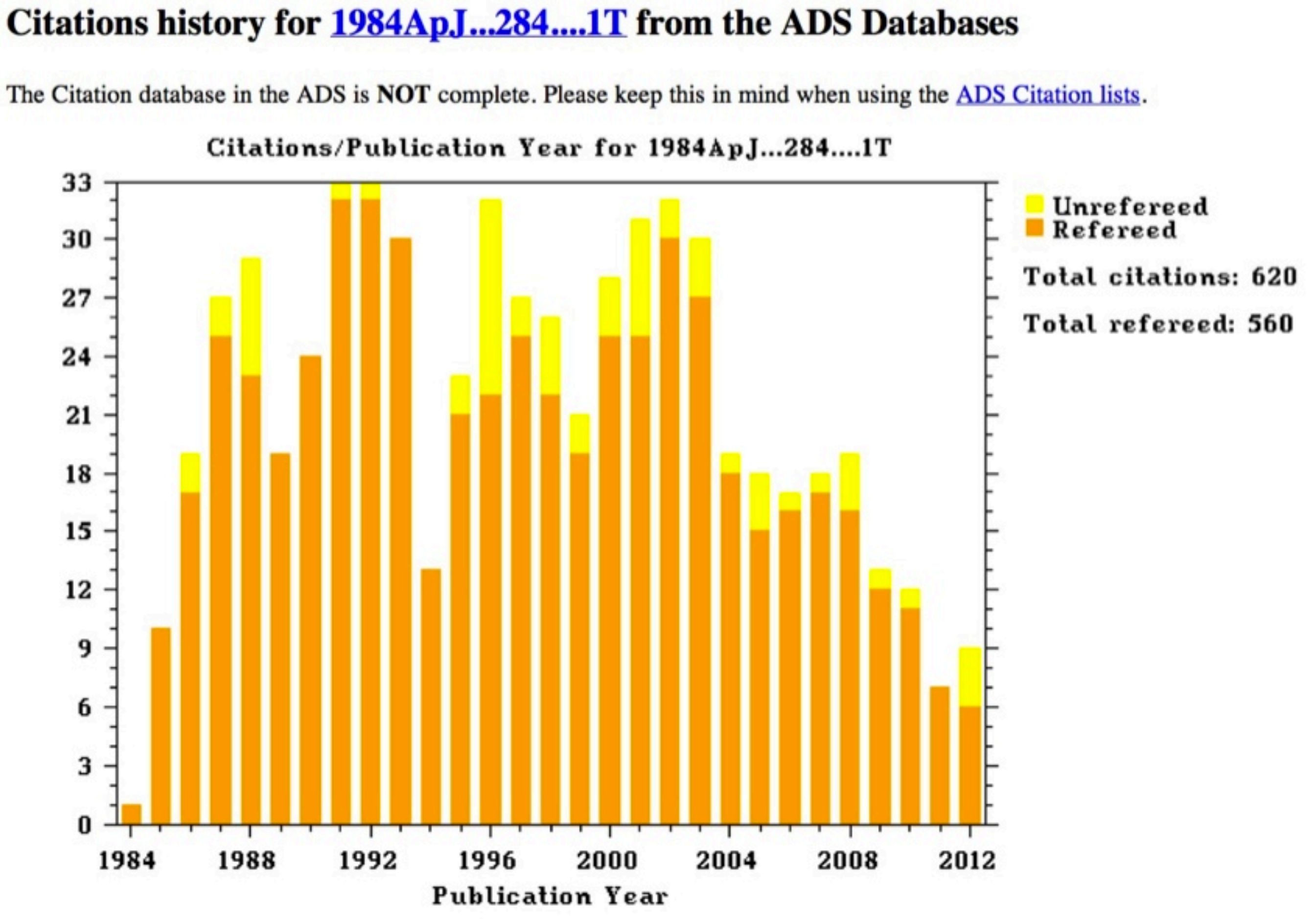
THE STATISTICS OF GRAVITATIONAL LENSES: THE DISTRIBUTIONS OF
IMAGE ANGULAR SEPARATIONS AND LENS REDSHIFTS

EDWIN L. TURNER,[1] JEREMIAH P. OSTRIKER, AND J. RICHARD GOTT III

Princeton University Observatory

Received 1984 January 12; accepted 1984 March 19

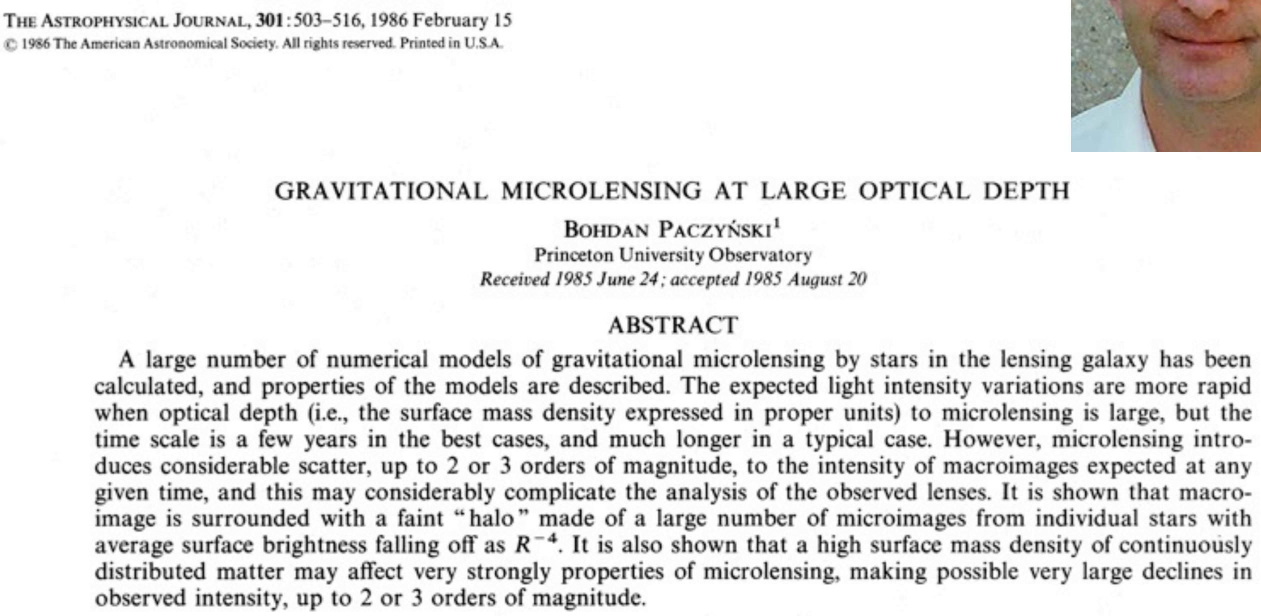


Citations history for 1984ApJ...284....1T from the ADS Databases

The Citation database in the ADS is **NOT** complete. Please keep this in mind when using the ADS Citation lists.

Paczyński
ApJ 301, 503 (1986)

Bohdan Paczyński
(1940 - 2007)



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

GRAVITATIONAL MICROLENSING AT LARGE OPTICAL DEPTH

BOHDAN PACZYŃSKI[1]
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. It is shown that macroimage is surrounded with a faint “halo” made of a large number of microimages from individual stars with average surface brightness falling off as R^{-4}. It is also shown that a high surface mass density of continuously distributed matter may affect very strongly properties of microlensing, making possible very large declines in observed intensity, up to 2 or 3 orders of magnitude.

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” ?

⇒ $10^{-6} < M/M_\odot < 10^3$

what is “compact” ?

⇒ (much) smaller than Einstein radius

what are the “distant sources”?

⇒ 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:

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

Quasar microlensing: Basics

Einstein radius: $\theta_E \approx 1.8\sqrt{\frac{M}{M_\odot}}$ microarcsec

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

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

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

(Pre-)History of quasar microlensing

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 !

⇒ 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:

⇒ microlensing is a **dynamic** phenomenon! It is observable:

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

Two regimes of **micro**lensing:

- 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

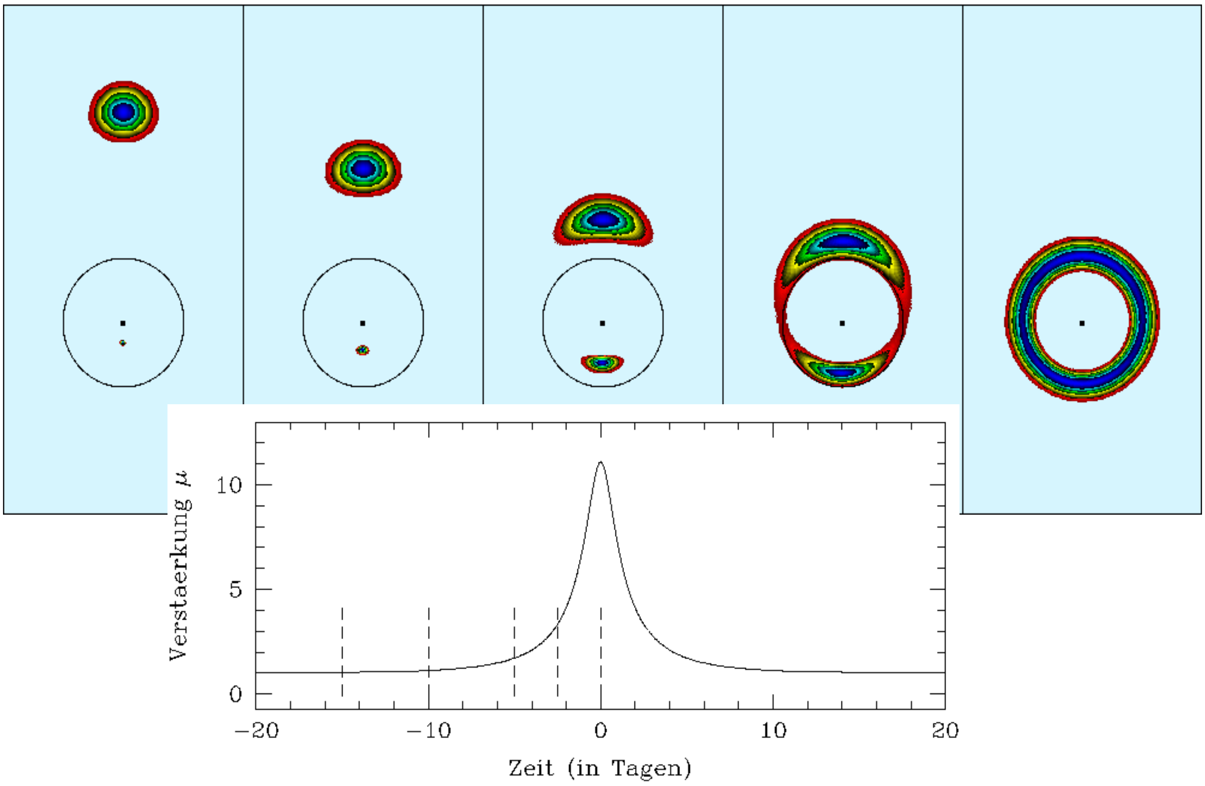
optical depth: ~1

far

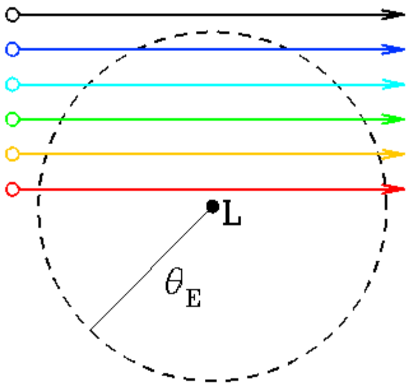
Gravitational microlensing:

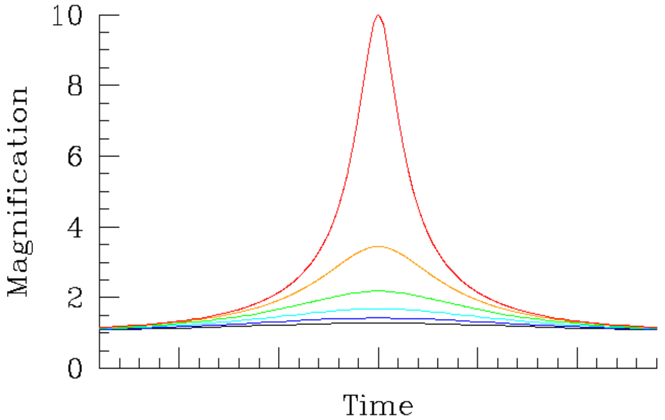
	stellar, Galactic, Local Group microlensing	quasar, extragalactic, cosmological microlensing
main lenses:	stellar mass objects in Milky Way, SMC, LMC, M31, halo	stellar mass objects in lensing galaxy
sources:	stars @ kpc/Mpc	quasars (SNe) @ Gpc
Einstein angle:	0.5 milliarcsec	1 **micro**arcsec
Einstein 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

Simulation: Point lens and extended source



Microlensing Lightcurve: Single Star as a Lens





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

(from Sackett 1999)

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

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

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

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

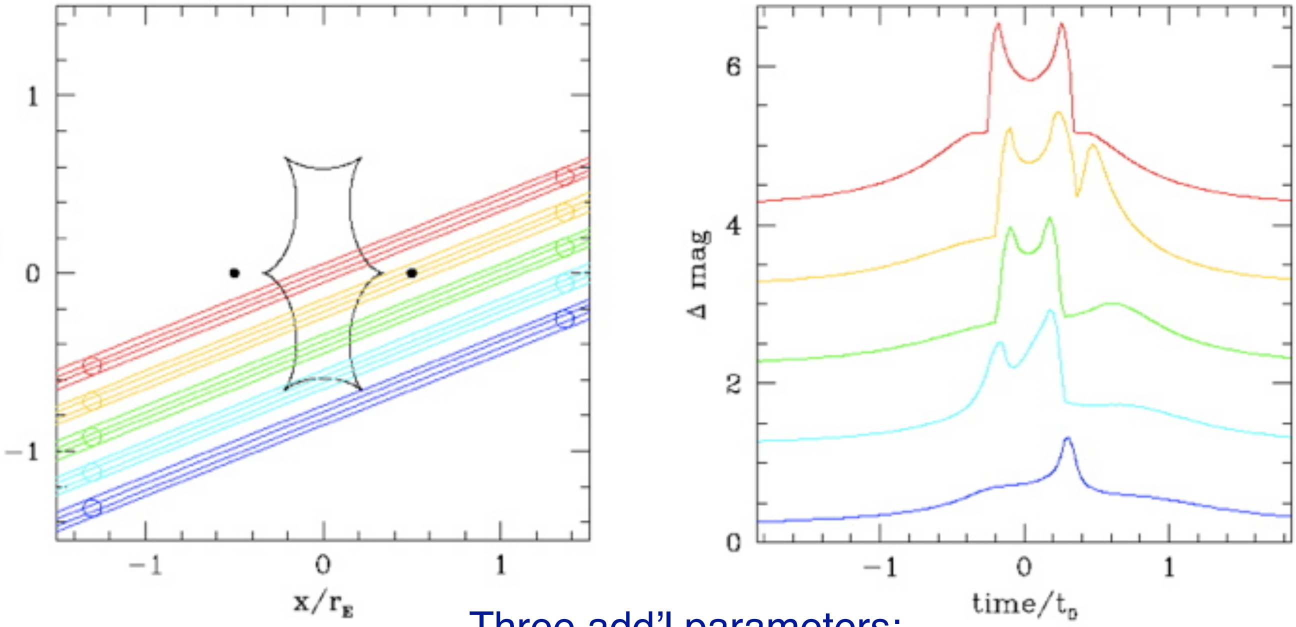
Microlensing by Planets (Mao & Paczynski 1991):

In Gravitational Lensing:

$2 \neq 1 + 1$

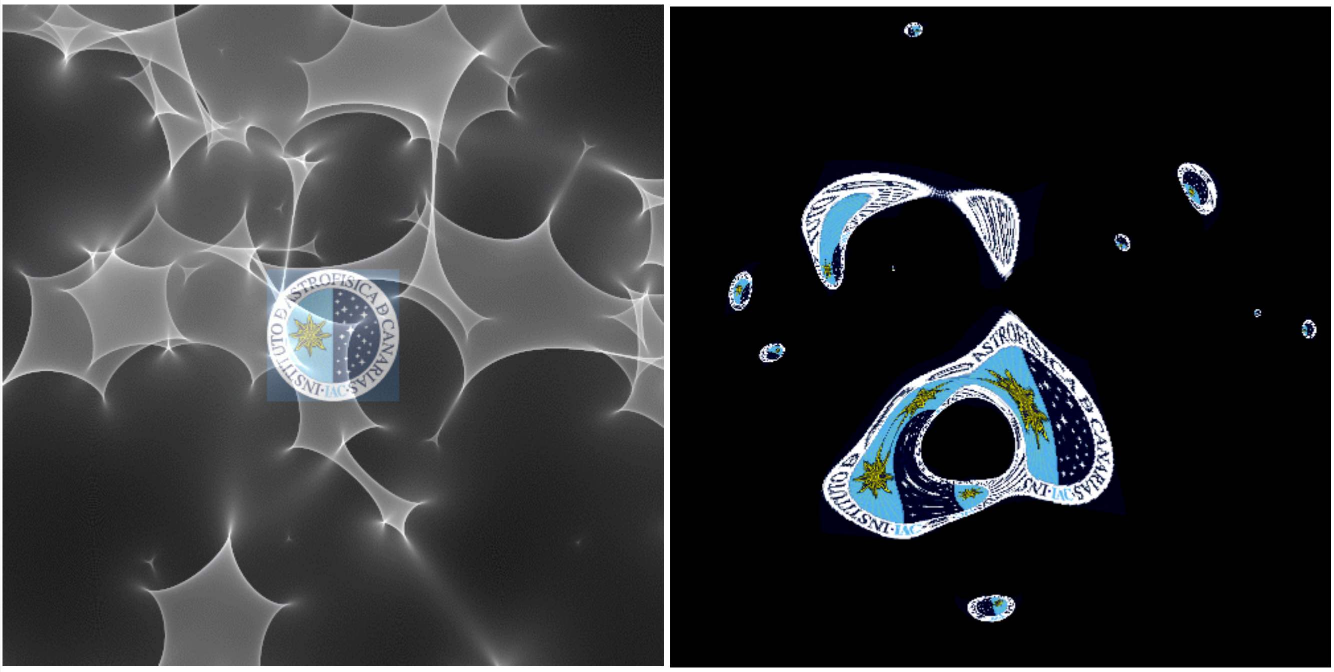
$2 \gg 1 + 1$

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

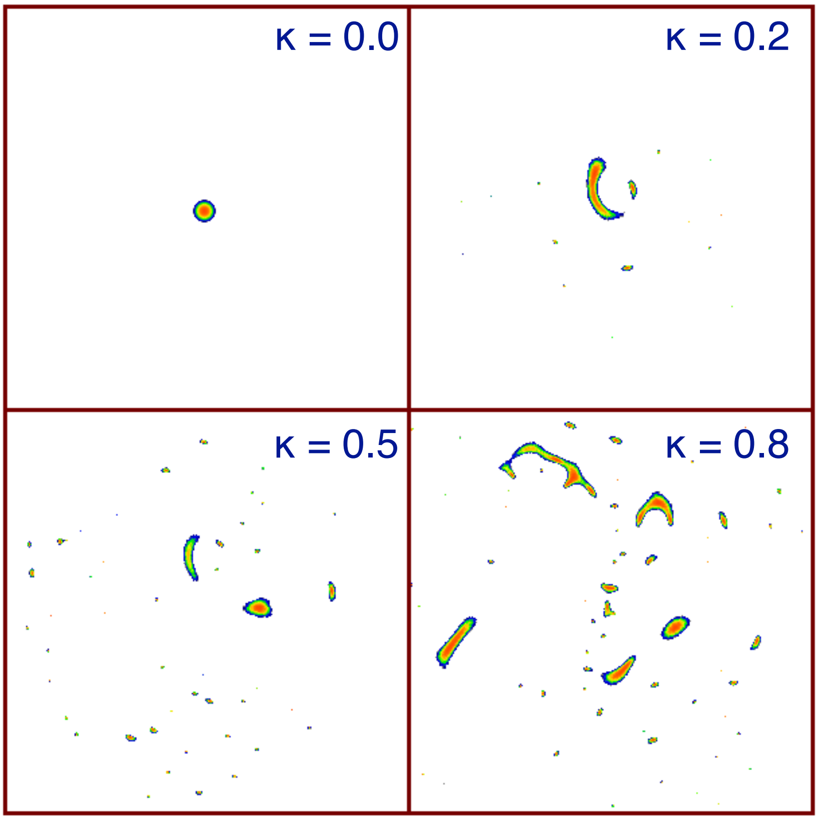


Three add'l parameters:
1) mass ratio q,
2) separation d,
3) angle Φ

Many Lenses: Quasar Microlensing



(Unresolvable) Image Configurations in Microlensing ...



... as a function of the surface mass density κ (“kappa”)

here: external shear γ (“gamma”) = 0

How to calculate quasar microlensing:

Two-dimensional lens equation (“macro lensing”):

$$\begin{pmatrix} x_{\text{source}} \\ y_{\text{source}} \end{pmatrix} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa-\gamma_1 \end{pmatrix} \begin{pmatrix} x_{\text{image}} \\ y_{\text{image}} \end{pmatrix}$$

Convergence κ corresponds to a certain value of surface mass density (constant sheet of matter)

Microlensing: Split up into many point lenses!

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

In lens equation: $$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

How to calculate quasar microlensing:

Consider the deflection of (very) many stars close to the light bundle of a quasar (macro) image with given values of convergence (kappa) and shear (gamma):

→ 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

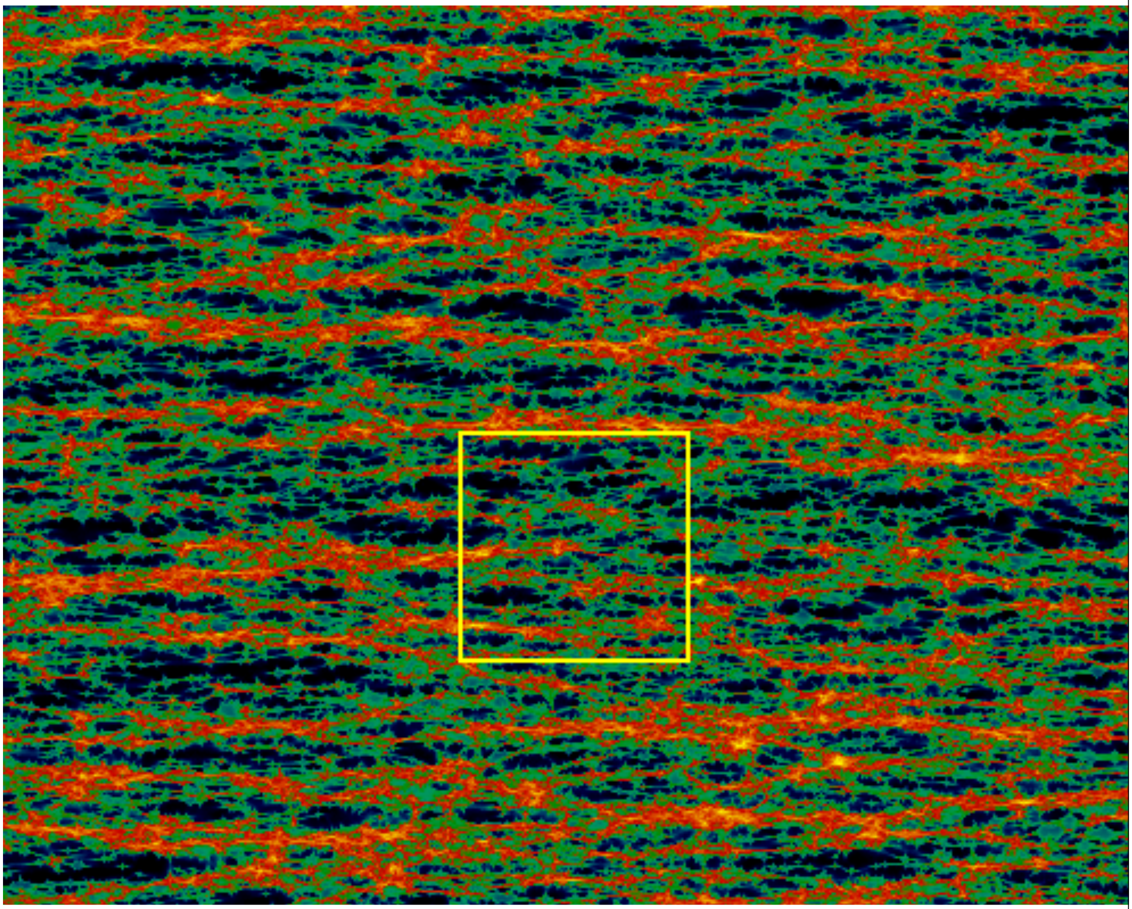
→ evaluate for linear track

→ obtain microlensed lightcurve

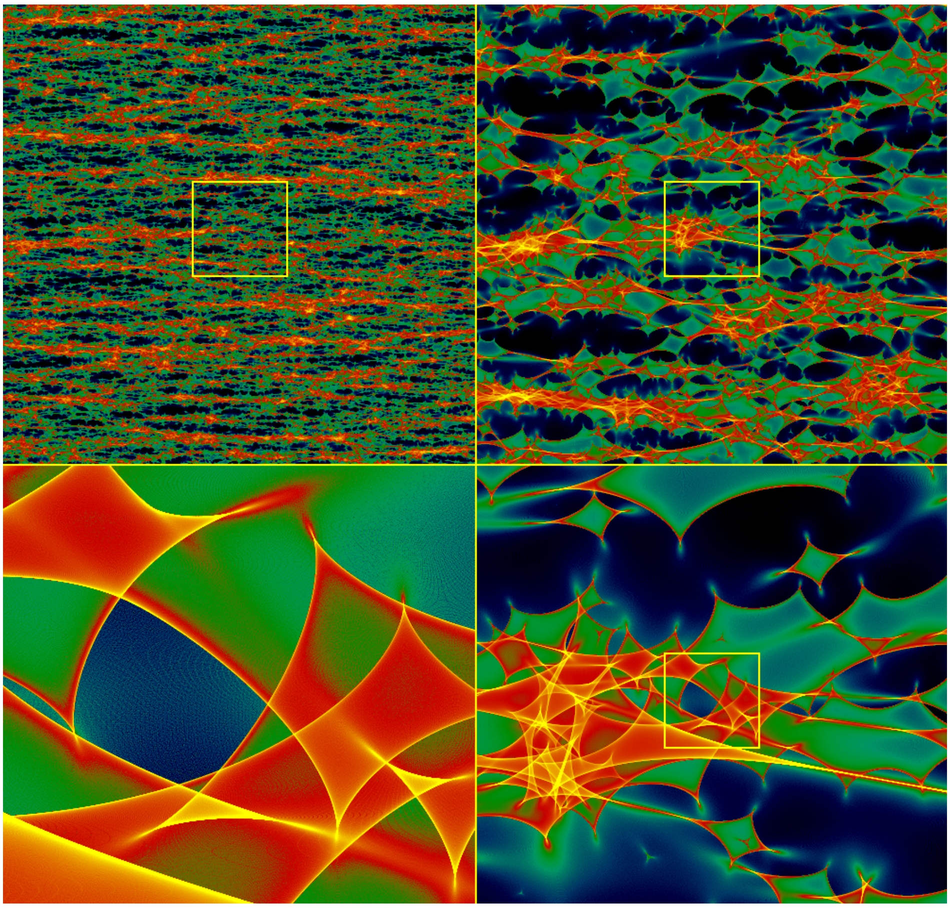
→ learn HOW to do it next week with Jorge Jimenez-Vicente!

Quasar microlensing: typical magnification patterns

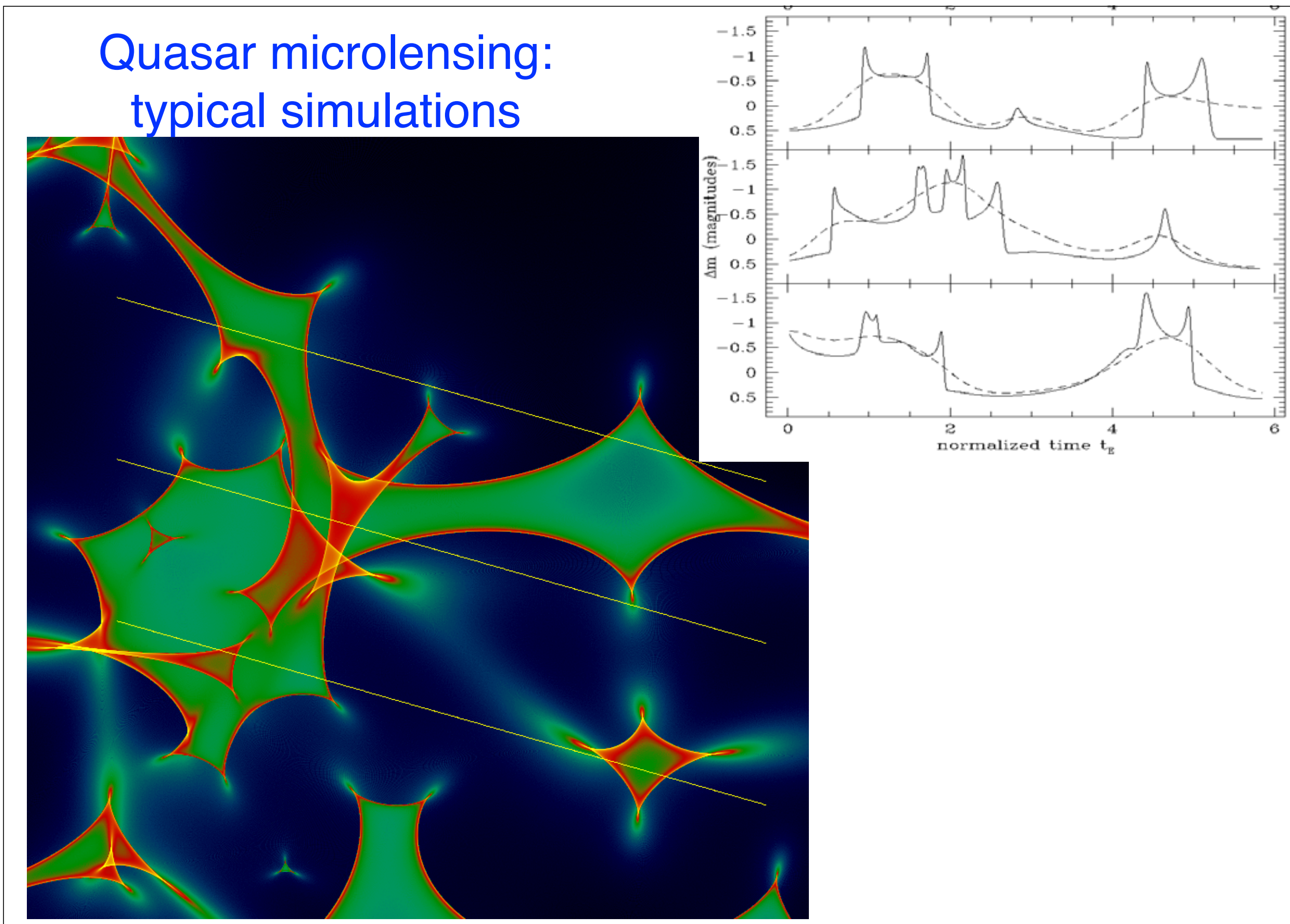
L = 100 R_E



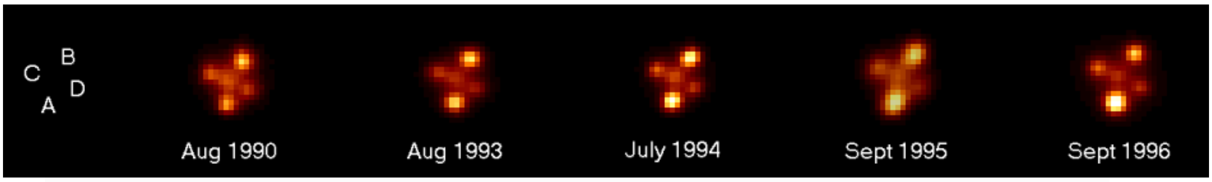
Quasar microlensing: typical magnification patterns



Quasar microlensing: typical simulations



Quasar Microlensing: Q2237+0305



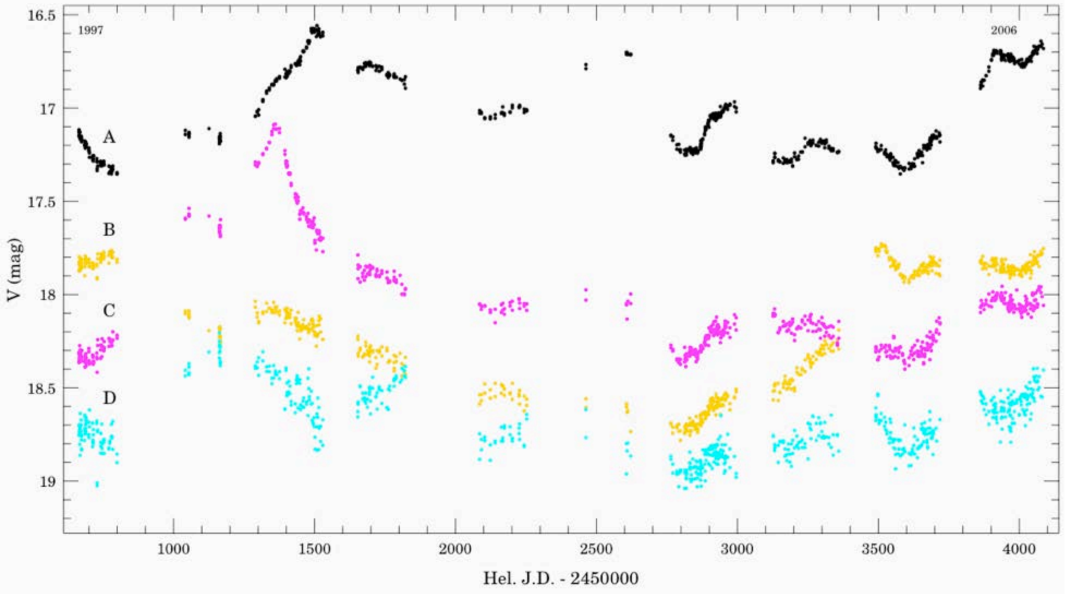


Fig. 4. OGLE light curve of the gravitational lens QSO 2237+0305 covering ten observing seasons 1997–2006.

Udalski et al. 2006 (OGLE)

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!

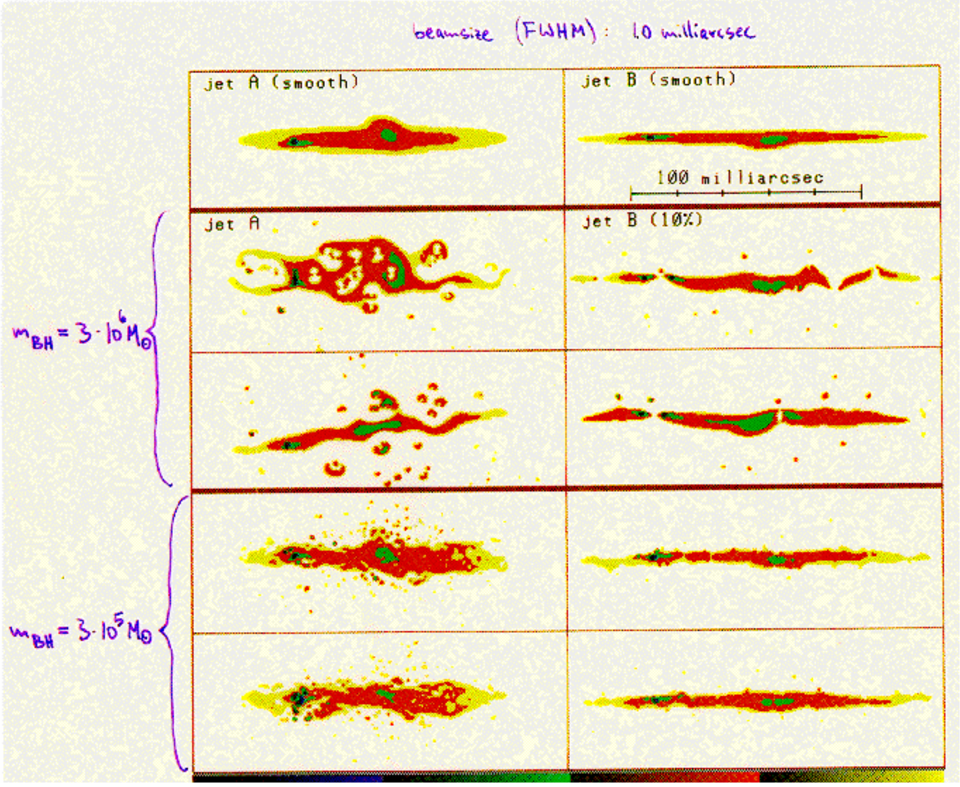
    ⇒ shift lightcurves in time (Δt) and magnitude (Δm) :

    obtain "difference" lightcurve:
    - if flat - no microlensing
    - if variable - microlensing

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

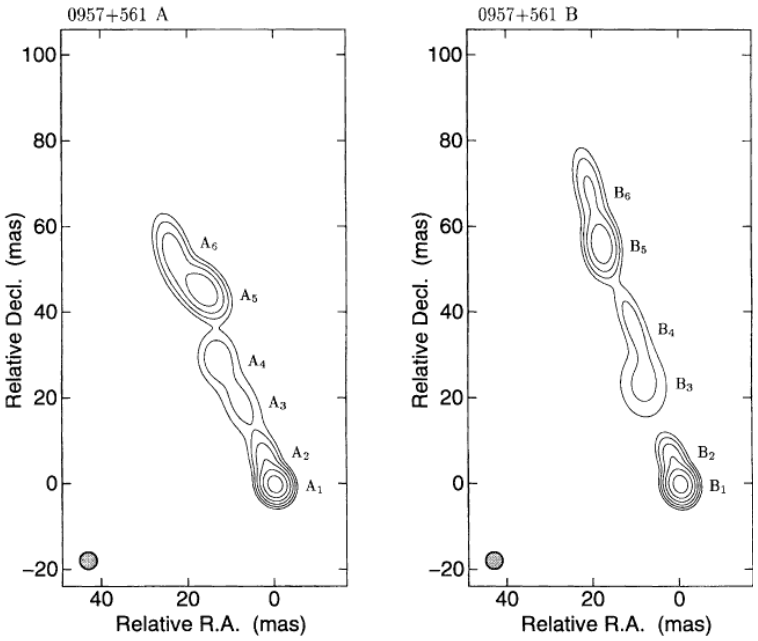
Millilensing: One million solar mass halo black holes?

VLBI test for million solar mass black holes in halo of G0957+561
(Wambsganss & Paczynski 1991): differential distortion of radio jets



Millilensing: One million solar mass halo black holes?

Global VLBI observations of the gravitational lens system 0957+561 A,B

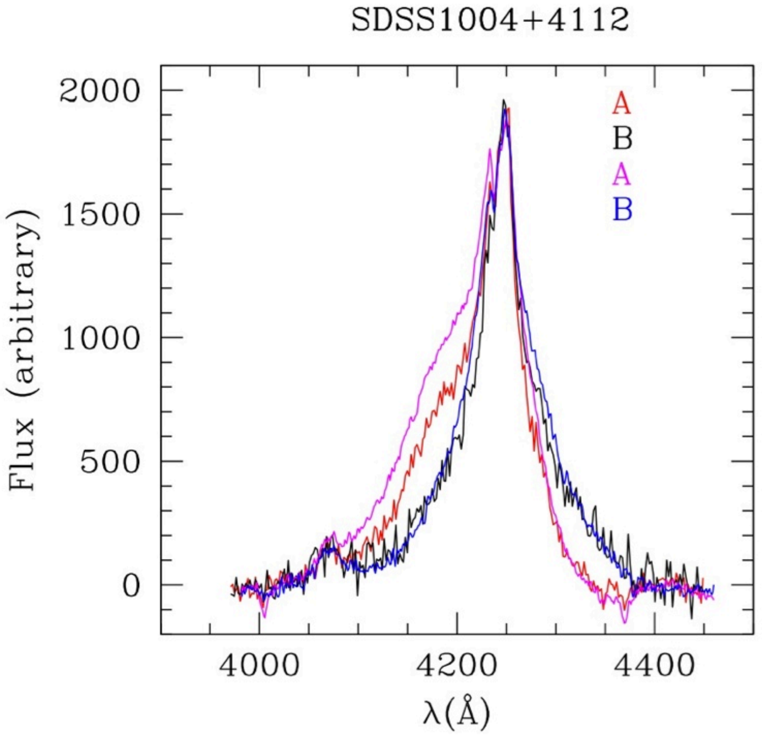


Garrett et al. (1994):

black holes with $M > 3 \times 10^6 M_M$ form less than
10% of the dark matter in the halo of G0957+561

Measuring Microlensing using Spectra of Multiply Lensed QSOs

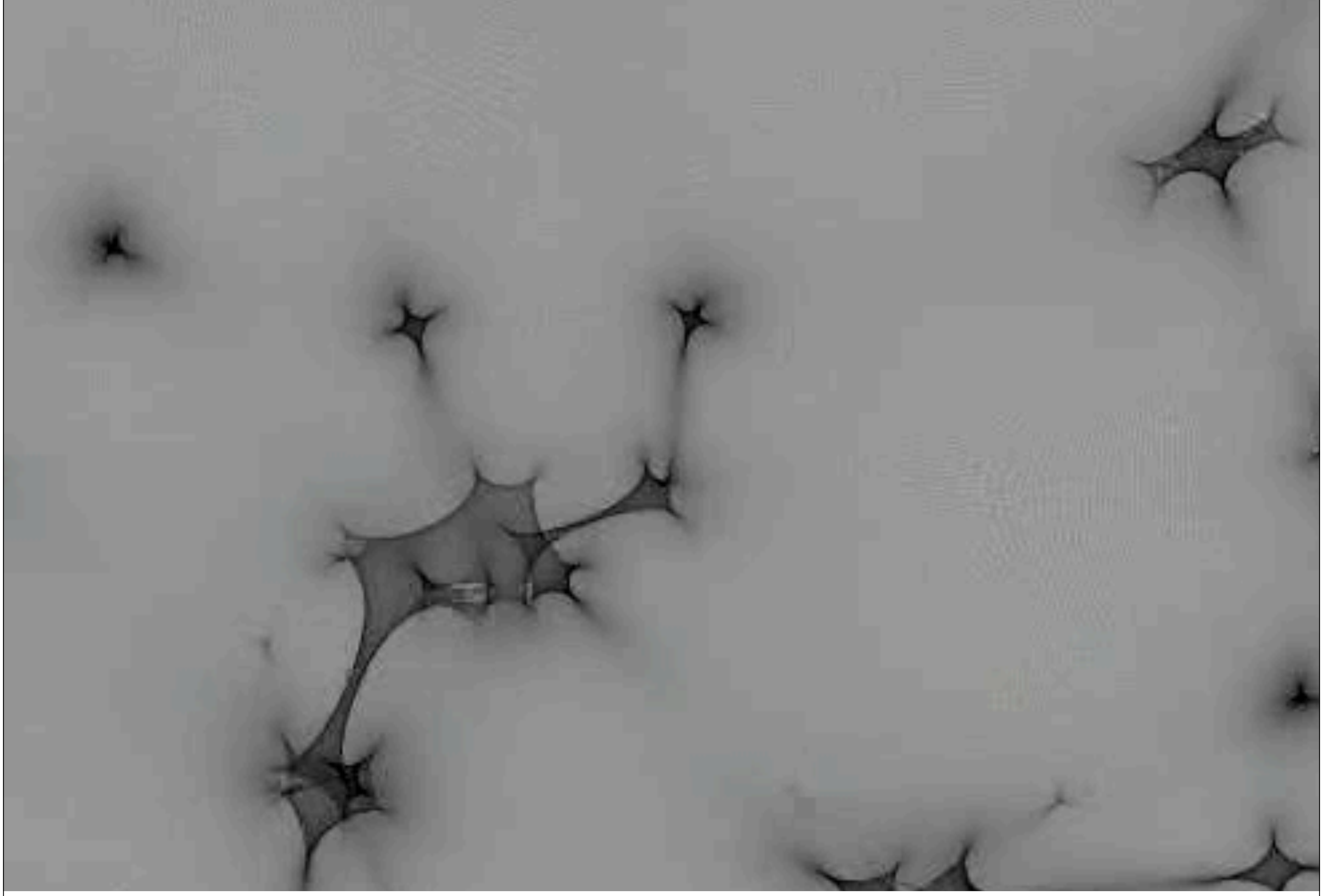
(Motta, Mediavilla, Falco & Munoz 2012)



→ **Next talk by Veronica Motta!**

Microlensing is a fantastic & fun tool:

kappa = 0.2 Wambsganss & Kundic (1995)



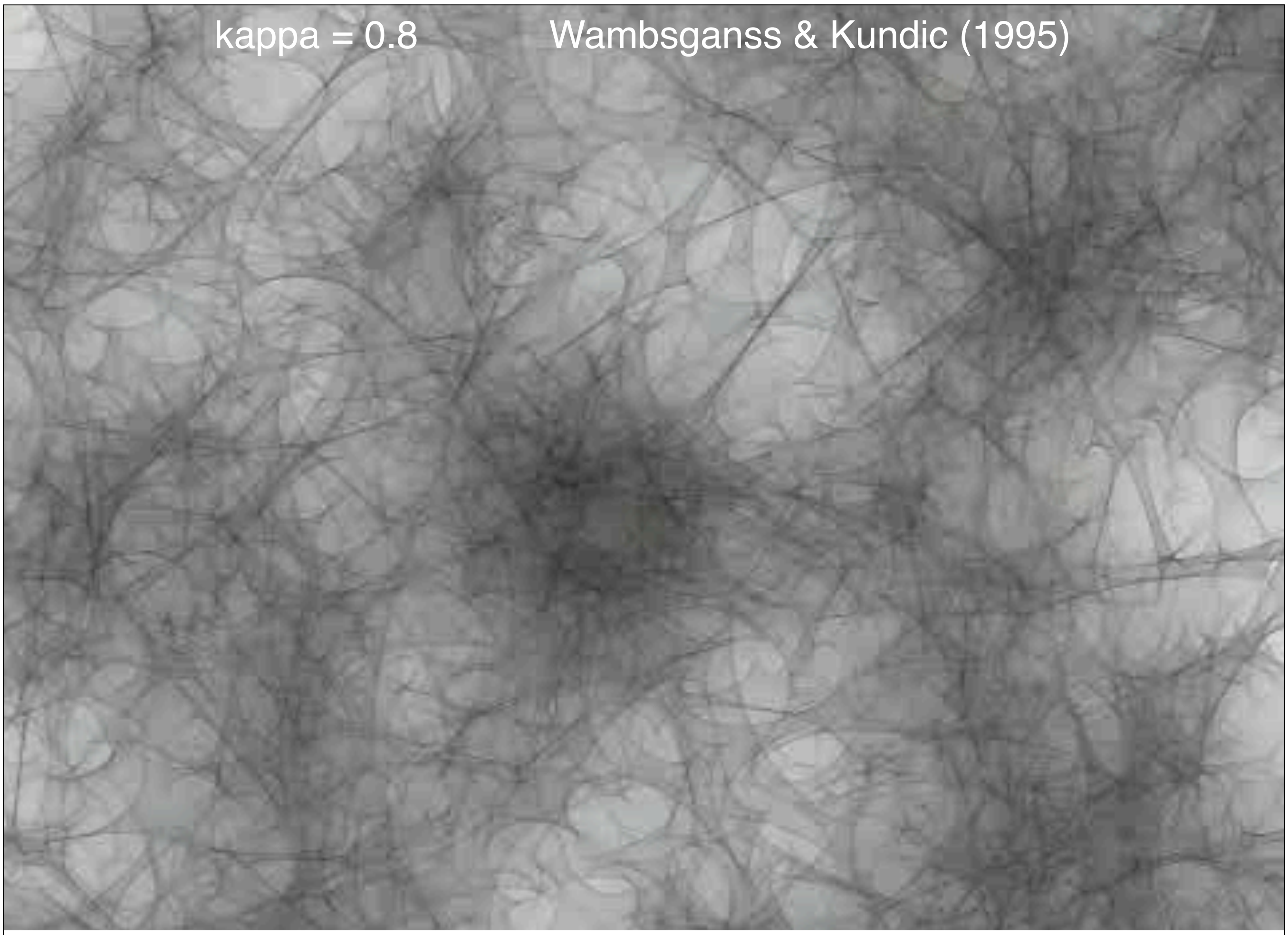
kappa = 0.5 Wambsganss & Kundic (1995)

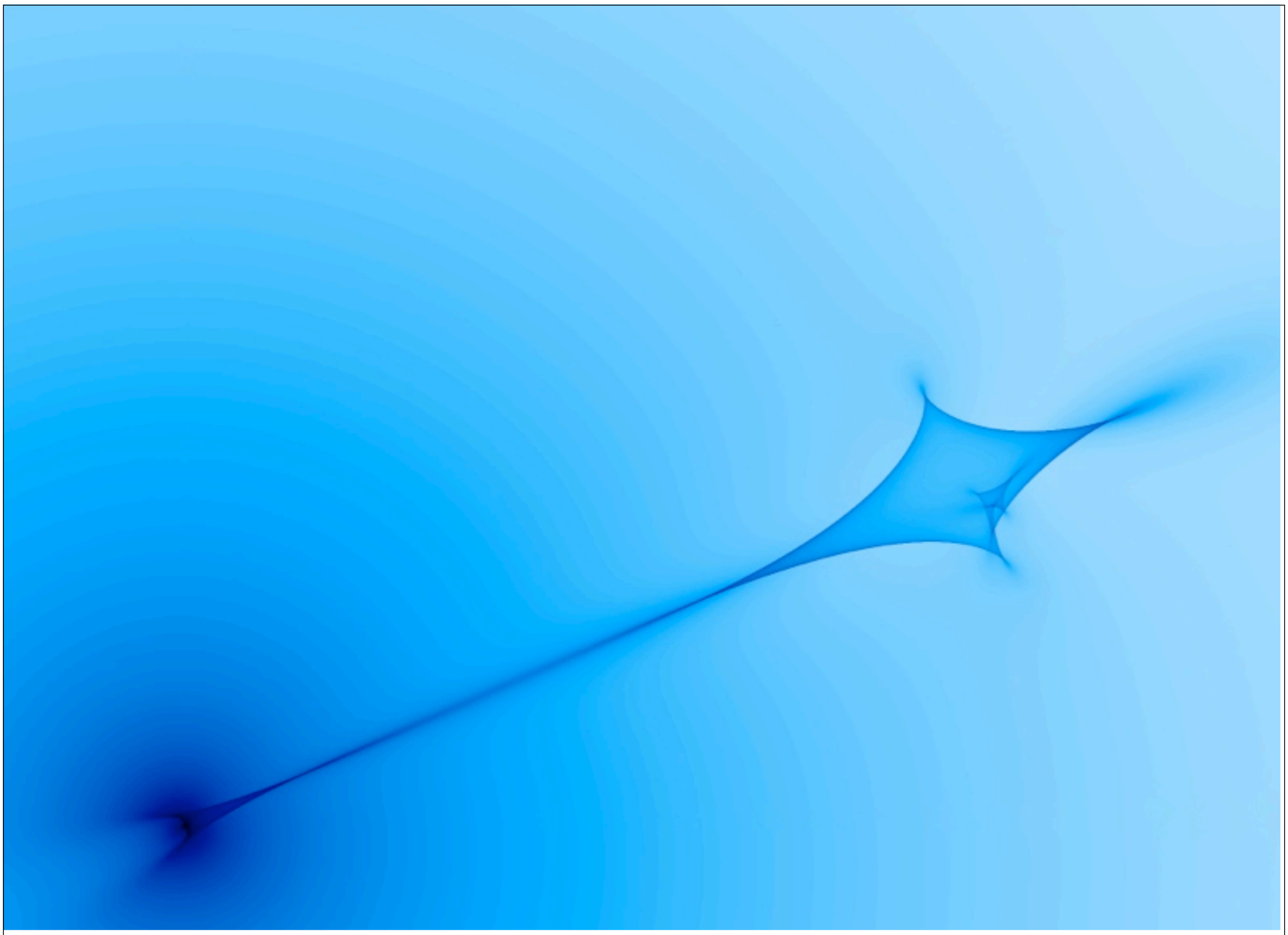
Gravitational Microlensing
due to moving stars

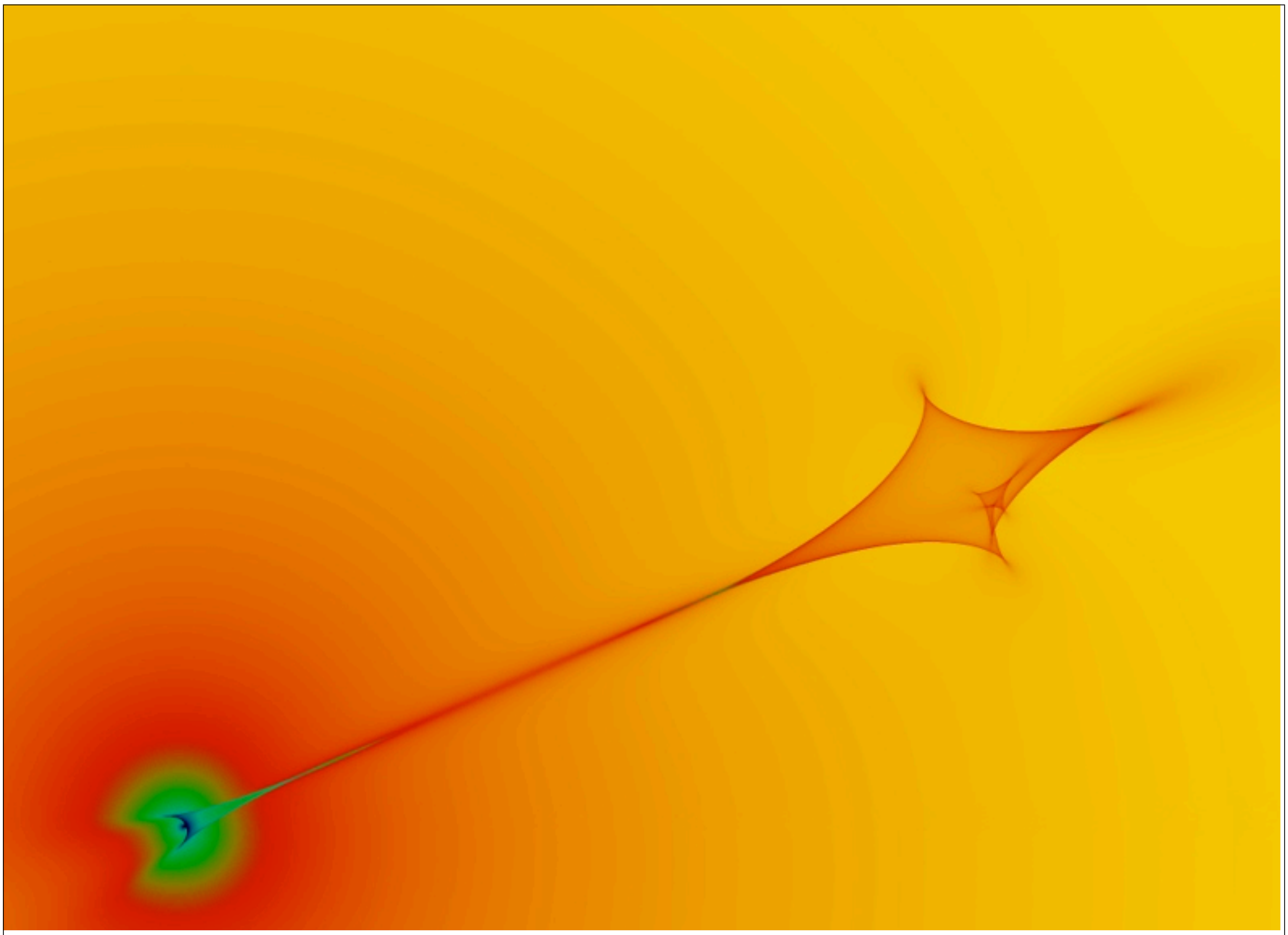
Joachim Wambsganss (1,2,3) and Tomislav Kundic (2

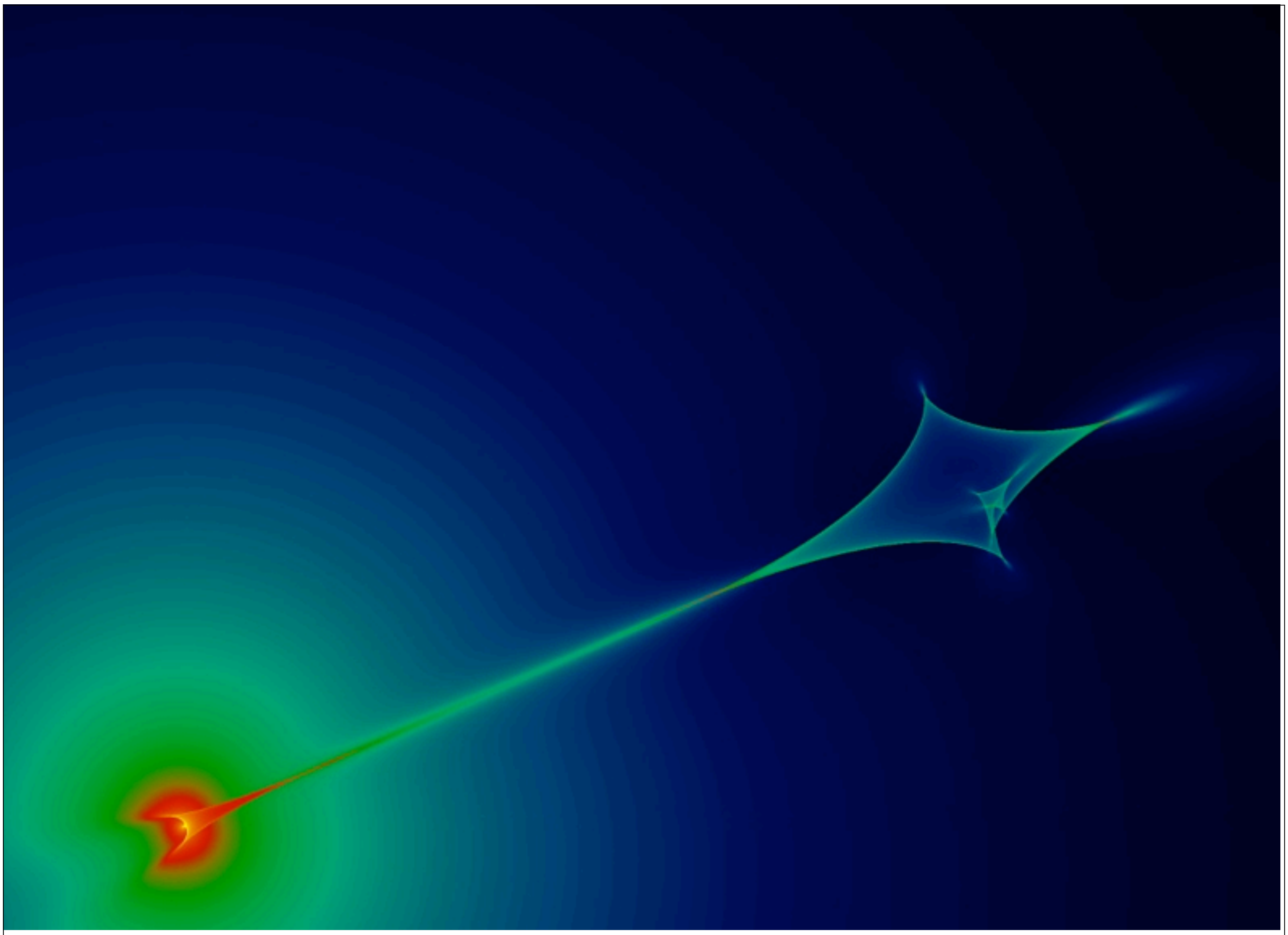
(1) Max-Planck-Institut fuer Astrophysik, Garching
(2) Princeton University
(3) now: Astrophysikalisches Institut Potsdam

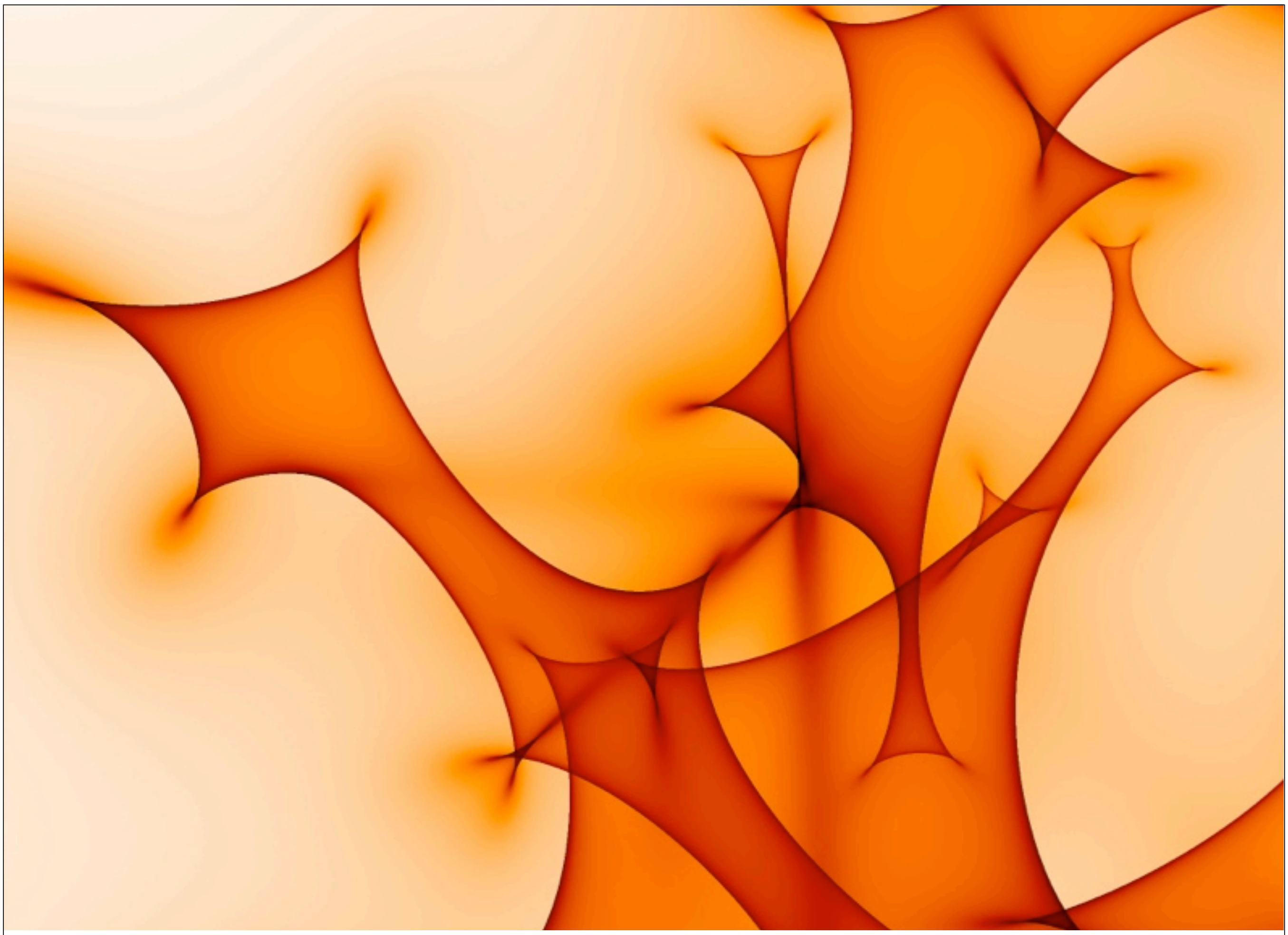
kappa = 0.8 Wambsganss & Kundic (1995)

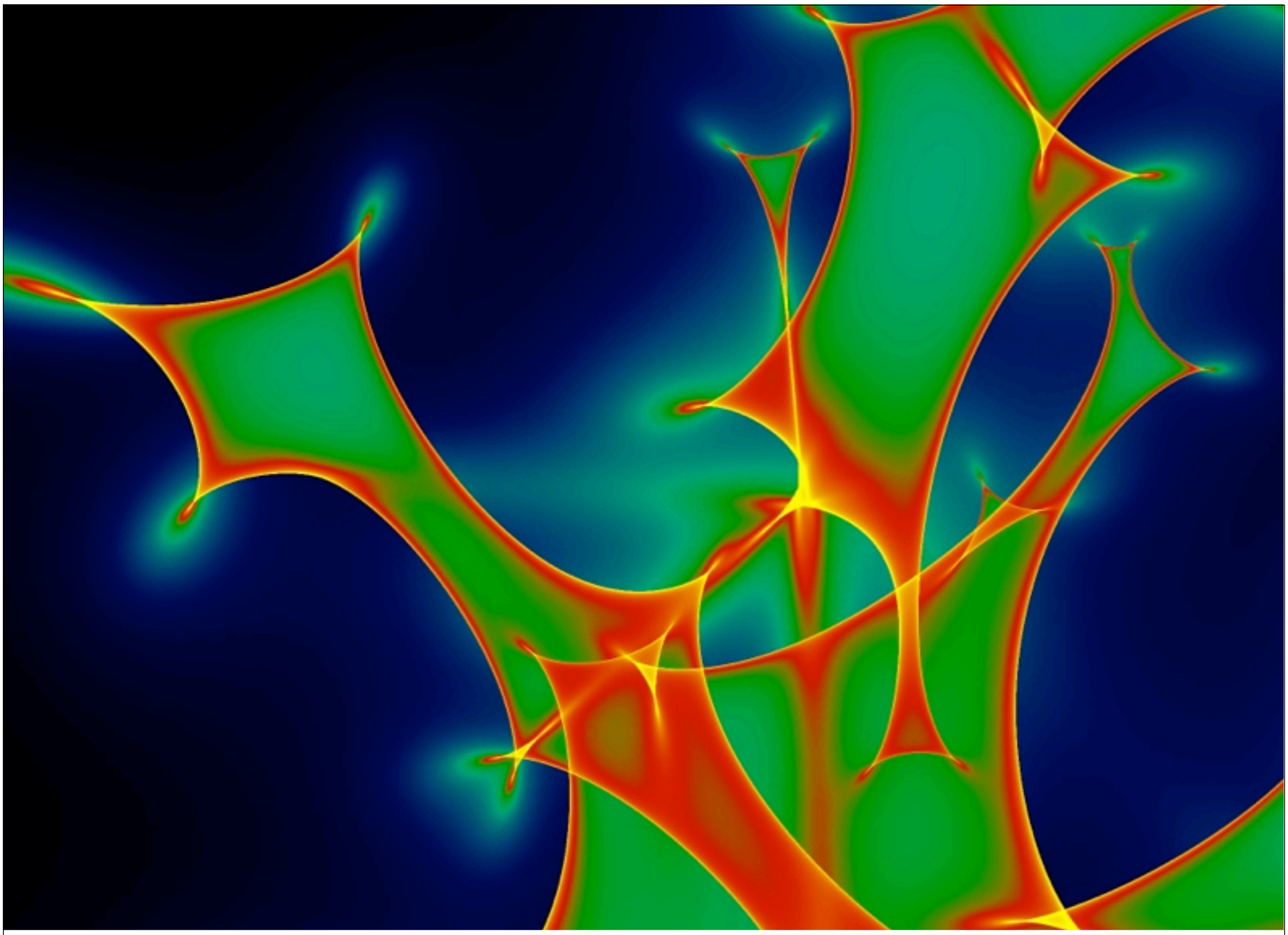


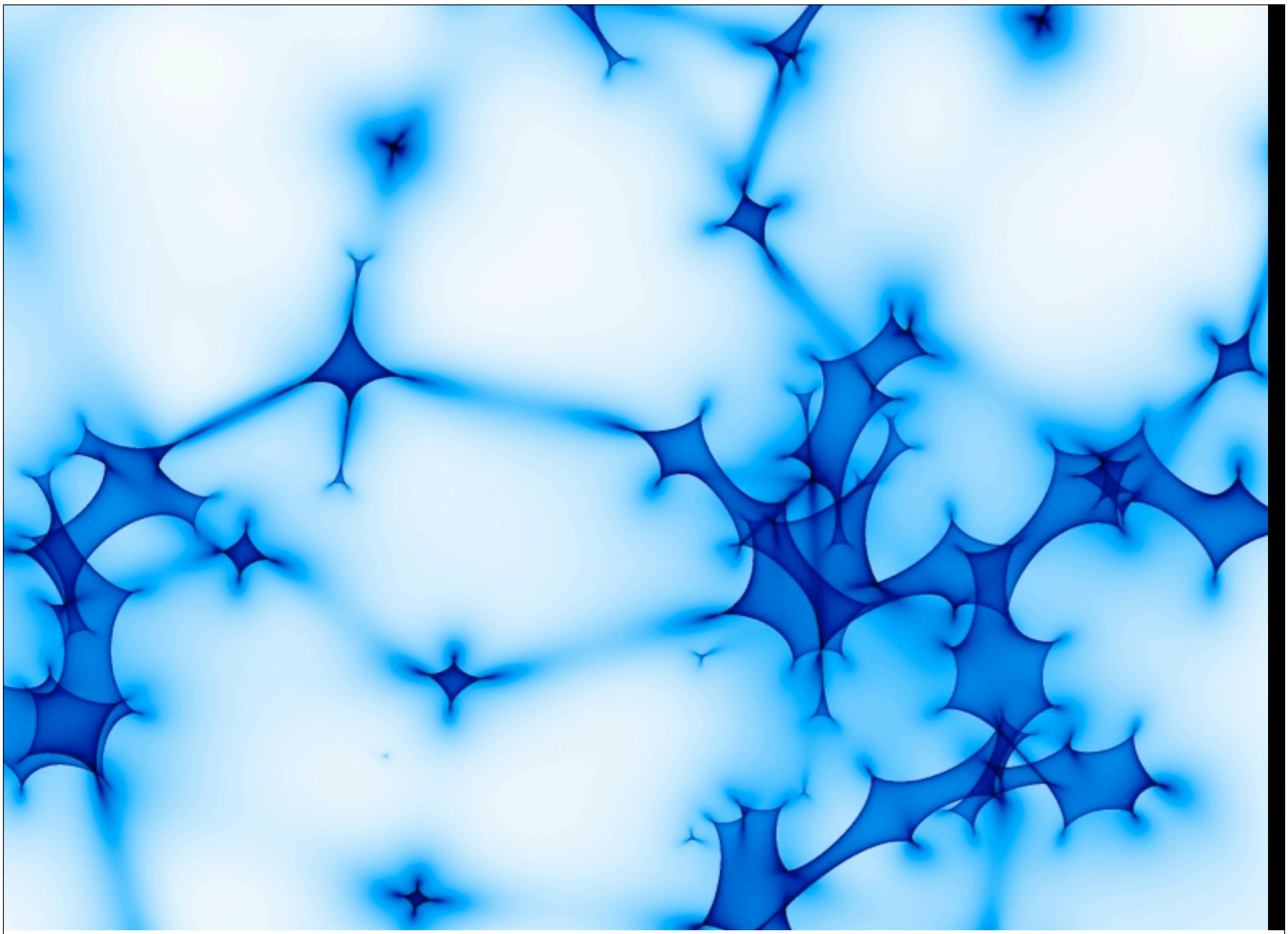


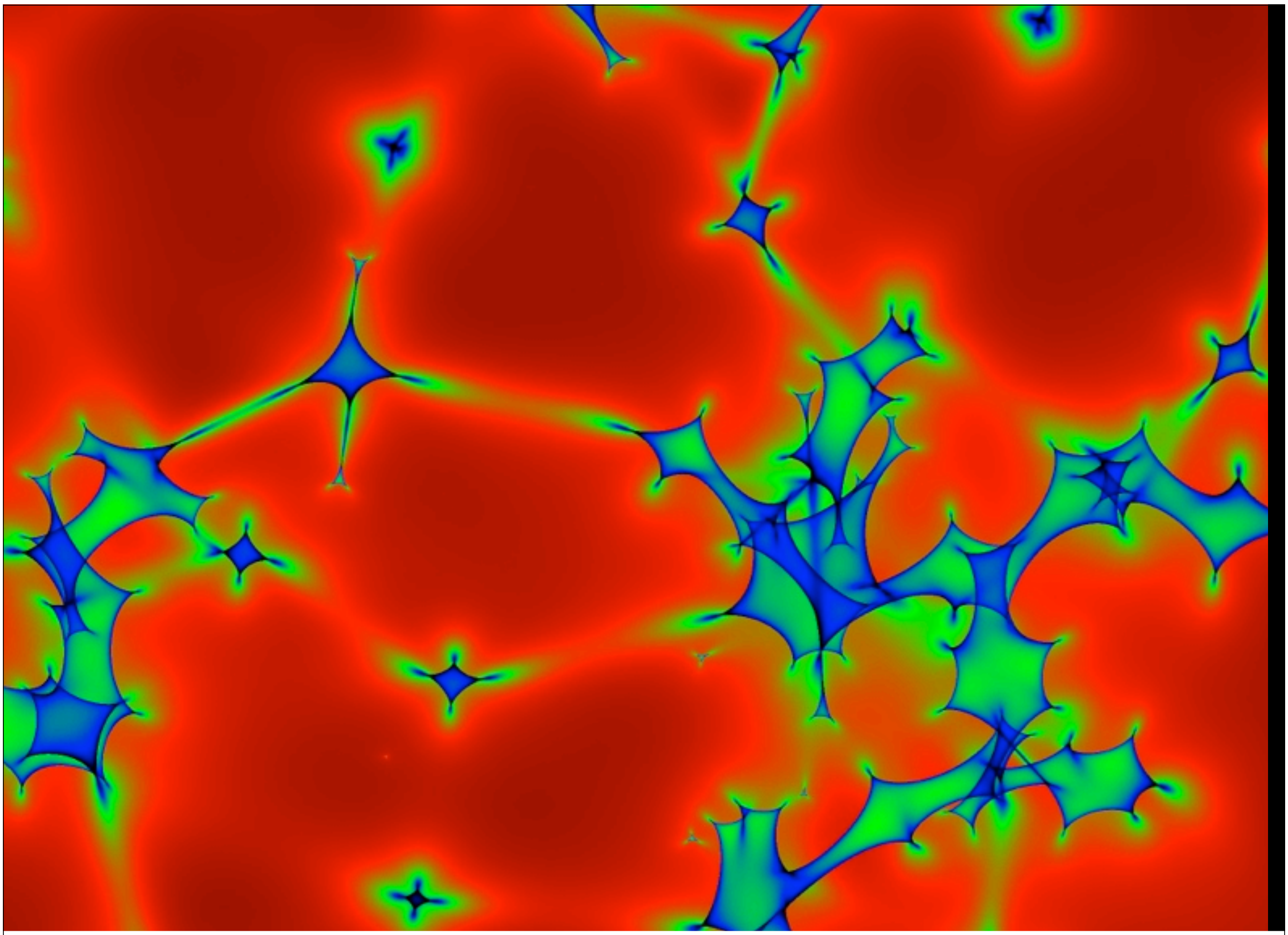


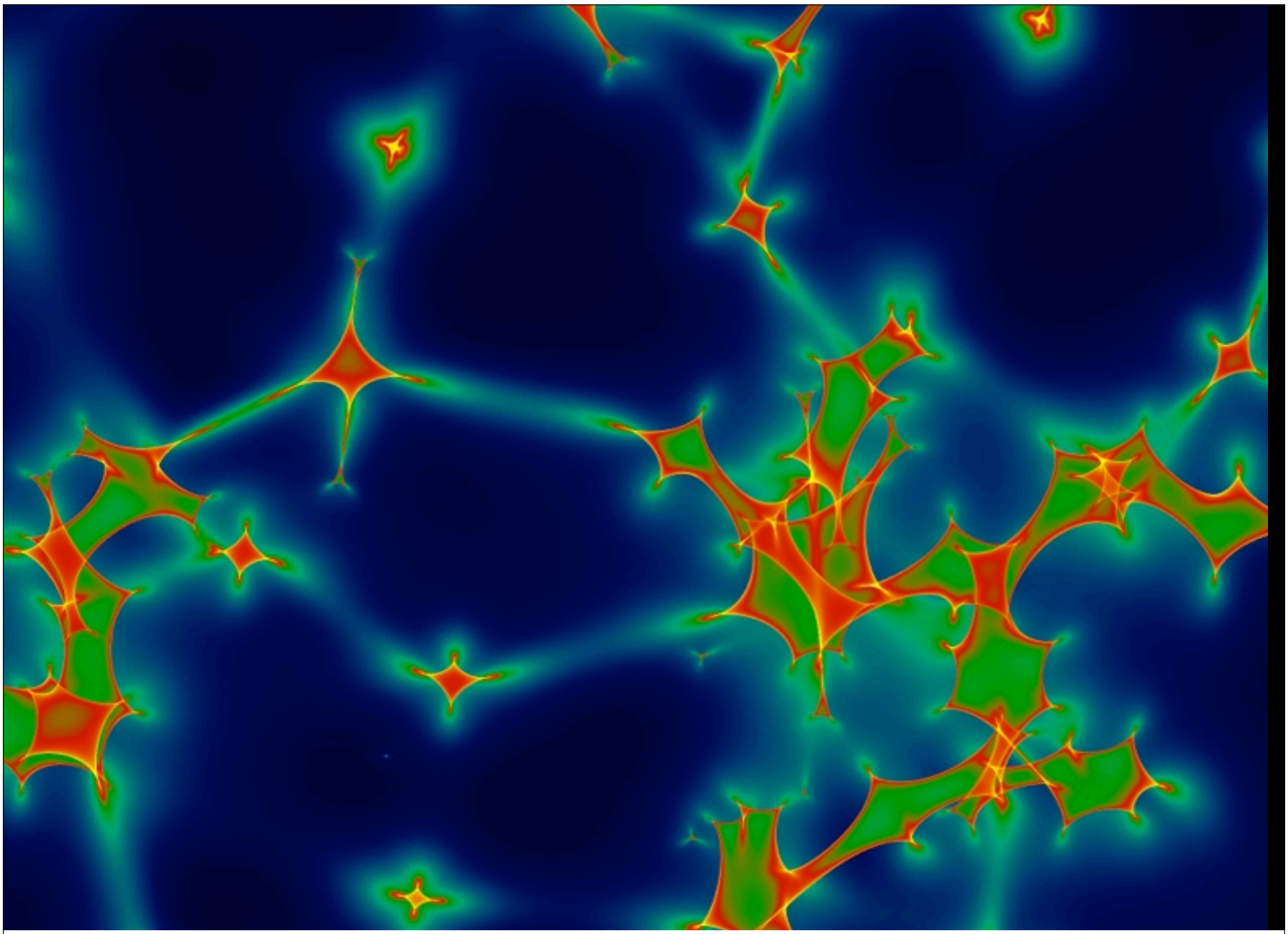


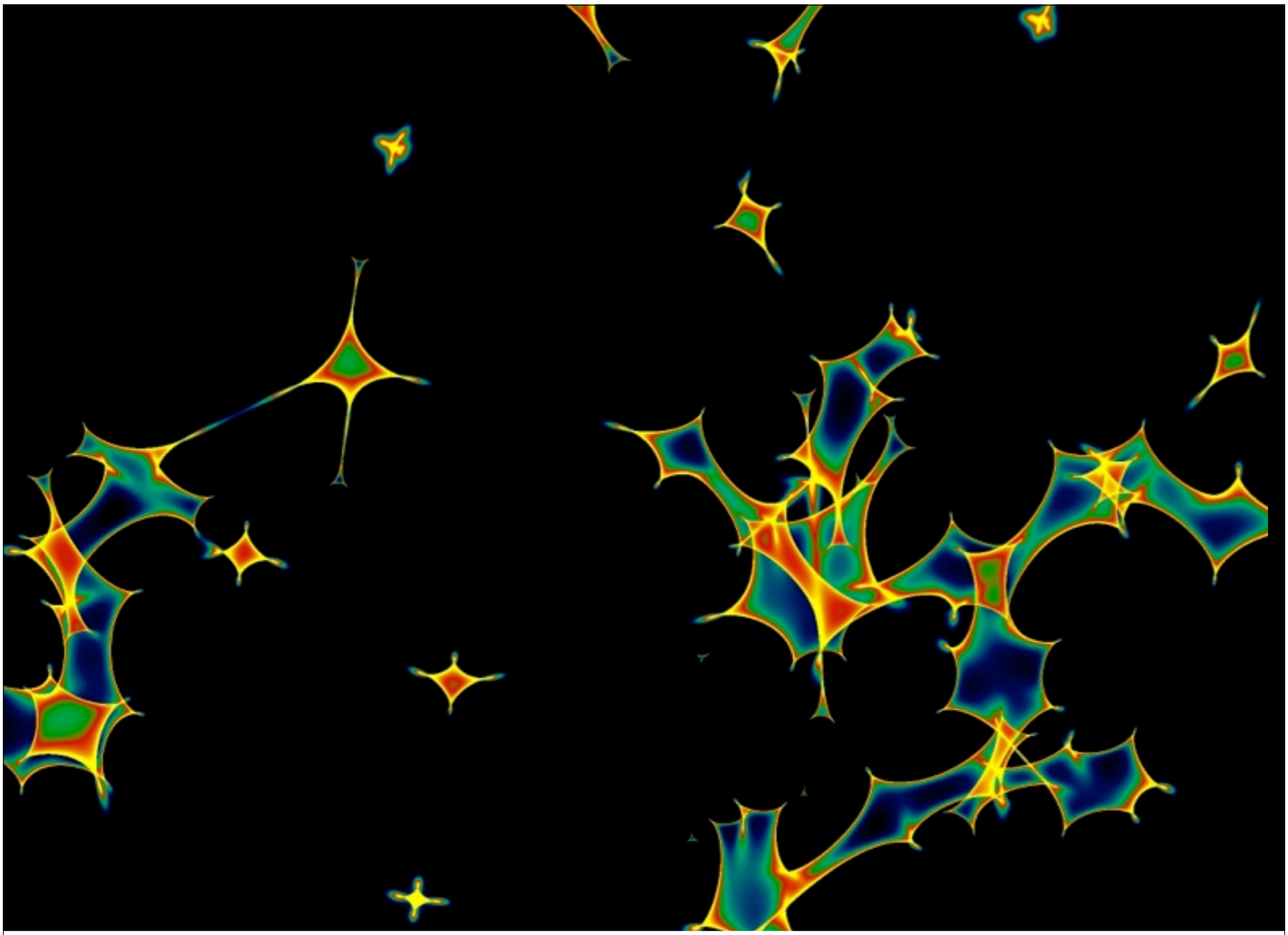


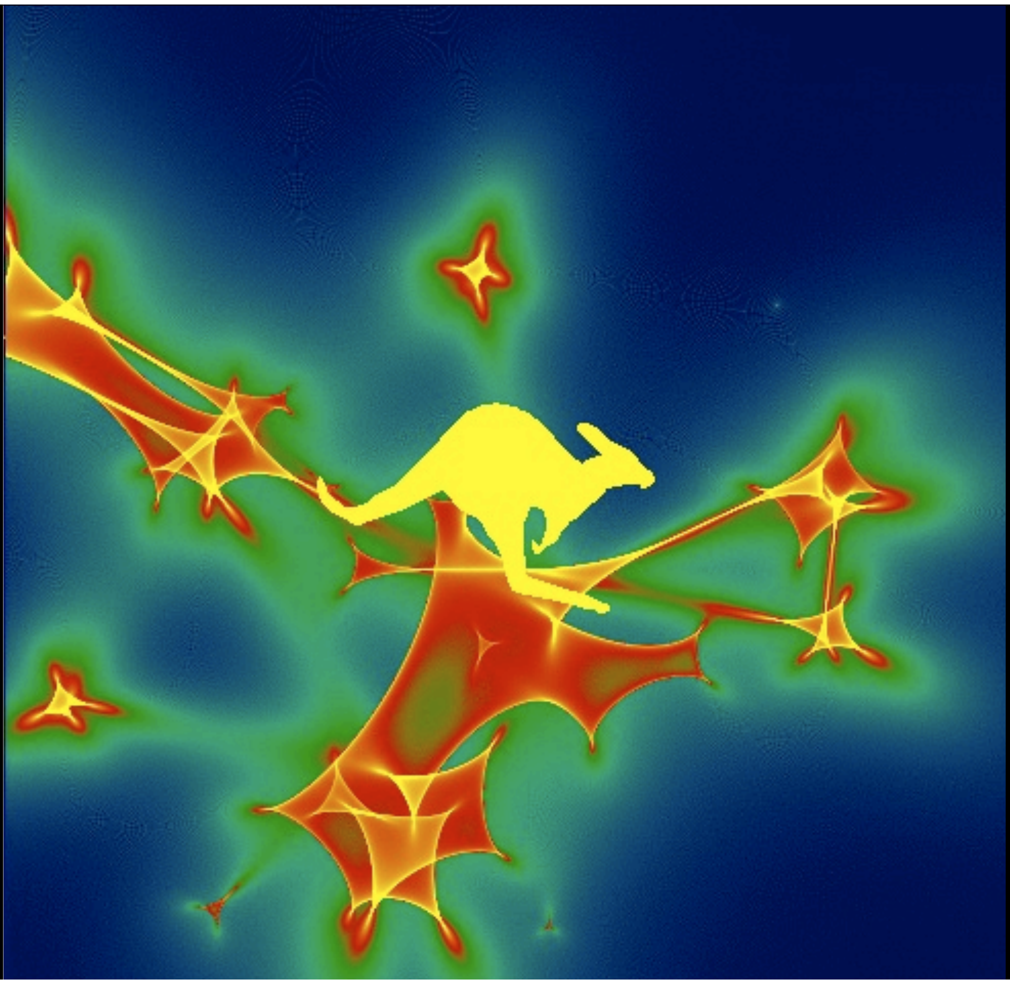












AGNs and Quasars

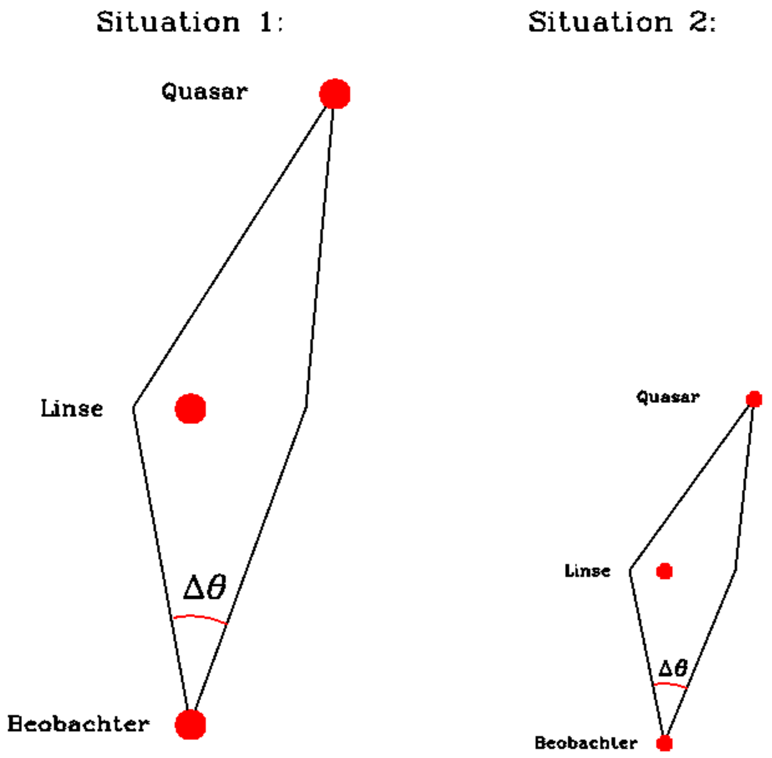
Joachim Wambsganss

3) Multiply Imaged Quasars: Time Delays and Hubble Constant

Time Delays and Hubble Constant

- Q0957+561: Kundic et al. (1997)
- Sample of 16 systems: Oguri (2007)
- J1004+4112: Fohlmeister et al. (2006, 2008)
- SDSS J1029+2623: Fohlmeister et al. (2012)
- RX J1131-1231: COSMOGRAIL, Tewes et al. (2012), Suyu et al. (2012)
- HE 0435-1223: COSMOGRAIL, Tewes et al. (2011)
- ... and a curiosity:
  Three quasars acting as lenses, Courbin et al. (2011)

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

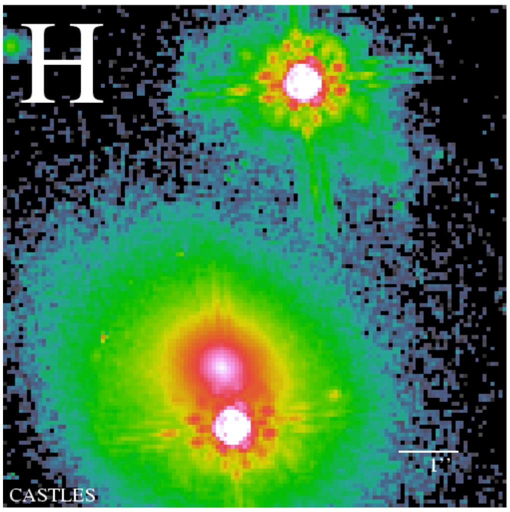


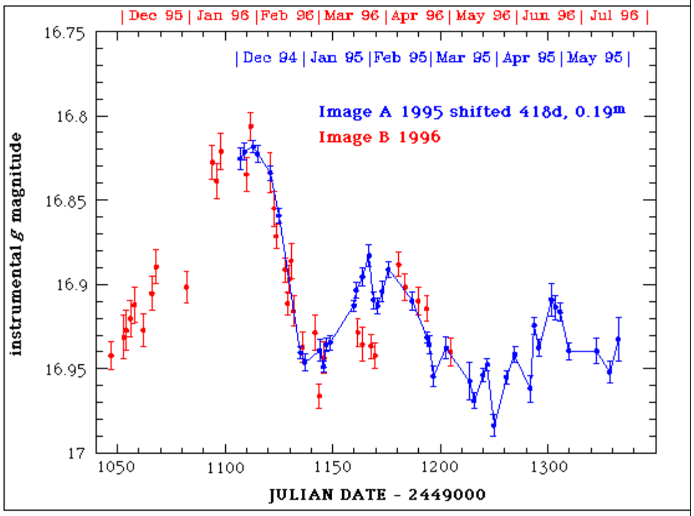
$$\Delta t_{AB} \propto D_{\Delta t}\ \phi_{lens}$$

$$\propto H_0^{-1}\ \phi_{lens}$$

(cf. Suyu talk)

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):

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

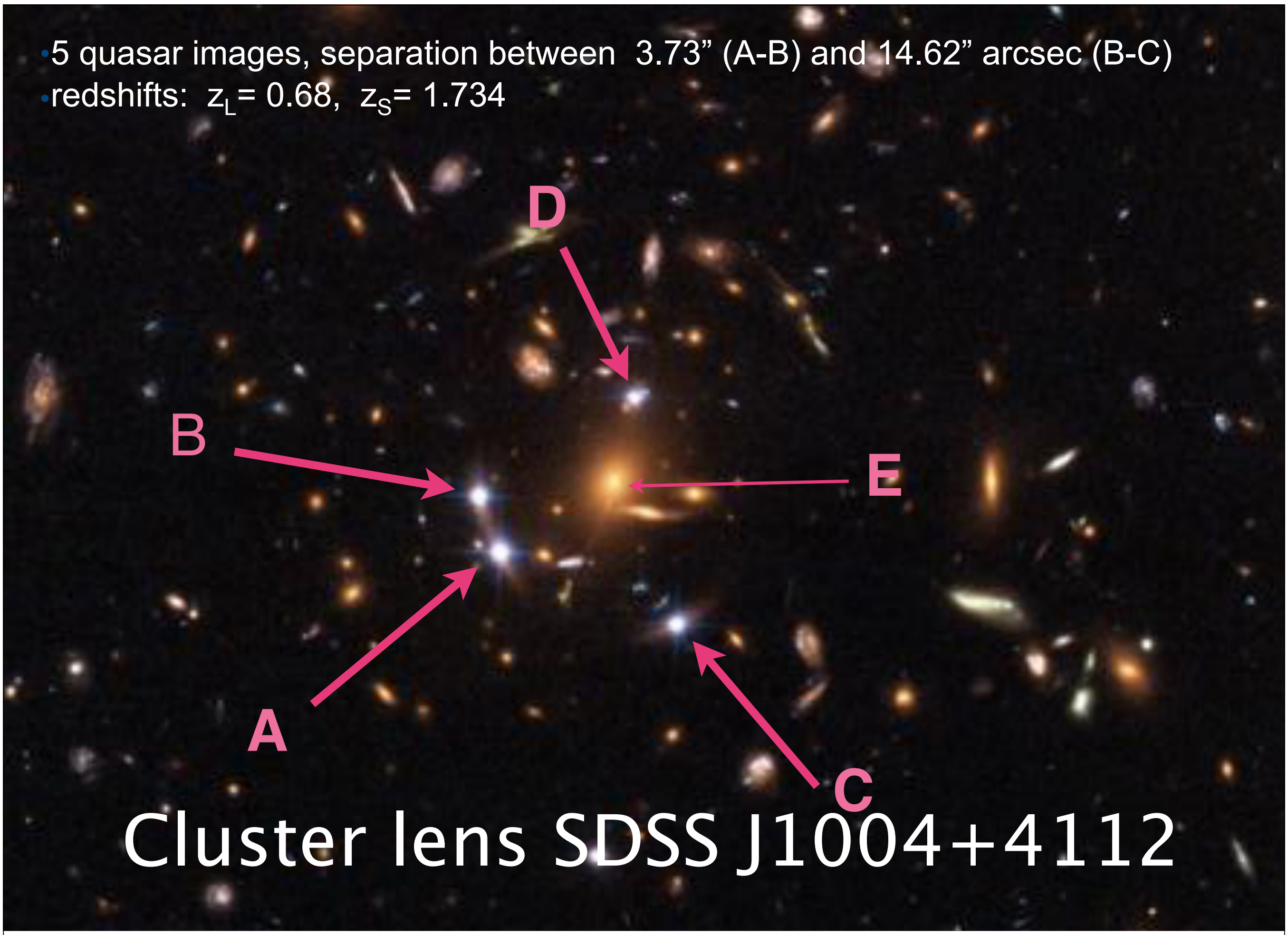
Ensemble of 16 multiple quasars: Time Delay & Hubble constant

May 2007: Oguri, ApJ 660, 1

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

...

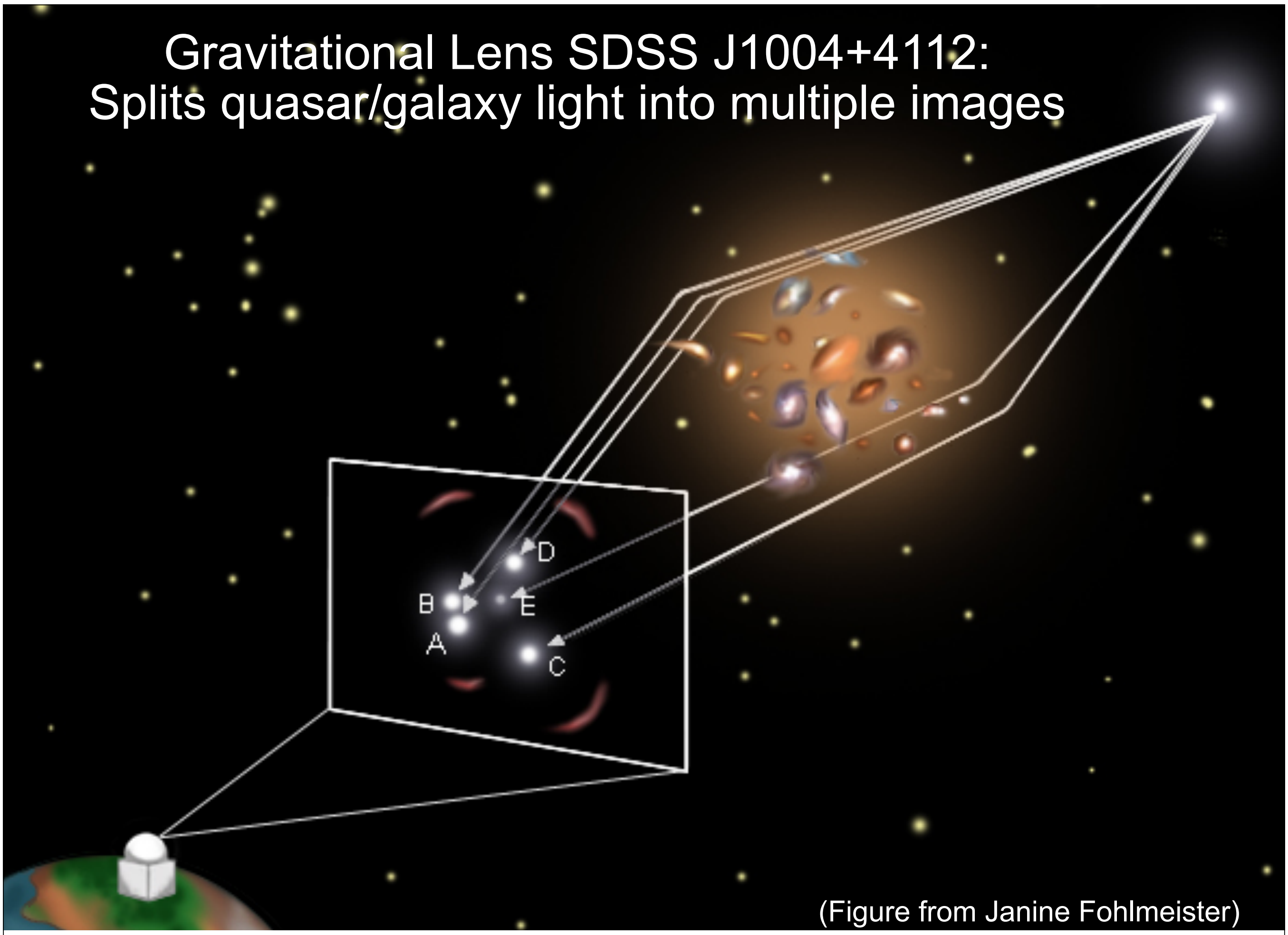
After including rough estimates of important systematic errors, we find $H_0 = (68 \pm 6$ [stat.] ± 8 [syst.]) km/s/Mpc.”



- 5 quasar images, separation between 3.73” (A-B) and 14.62” arcsec (B-C)
- redshifts: $z_L = 0.68$, $z_S = 1.734$

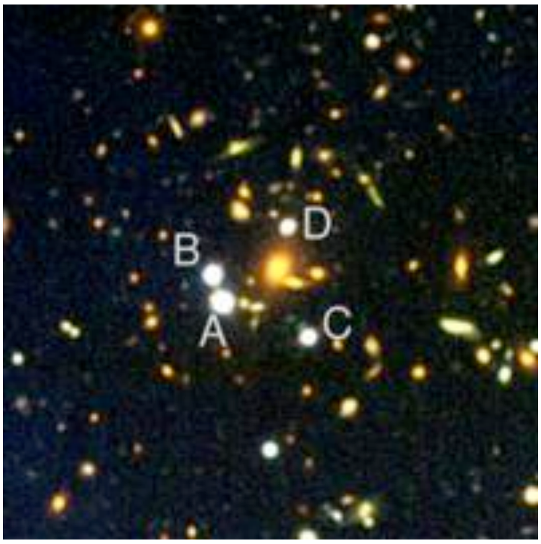
Cluster lens SDSS J1004+4112

Gravitational Lens SDSS J1004+4112: Splits quasar/galaxy light into multiple images



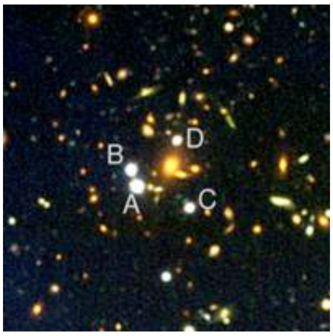
(Figure from Janine Fohlmeister)

Characteristics of SDSS J1004+4112



- Sloan lens, discovered by Inada et al. (2003)
- wide image separation between 3.73" (A-B) and 14.62" arcsec (B-C)
- lens: galaxy cluster $z_L = 0.68$, $z_S = 1.734$
- 4 bright images with r-band magnitude ~19
- faint fifth image near bright cluster galaxy (Sharon et al. 2005)
- Lensed arcs from high redshift background galaxies (Inada et al. 2005)

Time delay predictions for SDSS J1004+4112



- time ordering C-B-A-D or D-A-B-C
- longest delay between C-D (months-years)
- shortest between A-B (days-months)
- $dt_{CD}/dt_{BA} = 143 \pm 16$

- **$dt_{BA} < 30$ days, $dt_{CA} \sim 400$ days, $dt_{AD} \sim 600$ days**

Oguri et al. 2004, Williams & Saha 2004, Kawano & Oguri 2006

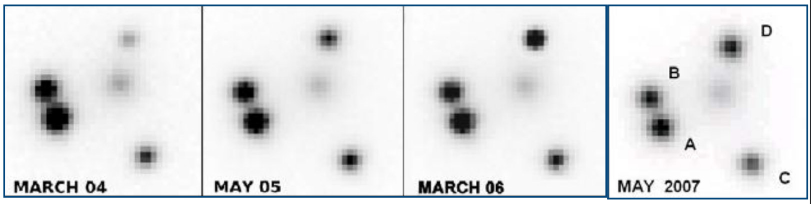
Monitoring of SDSS J1004+4112

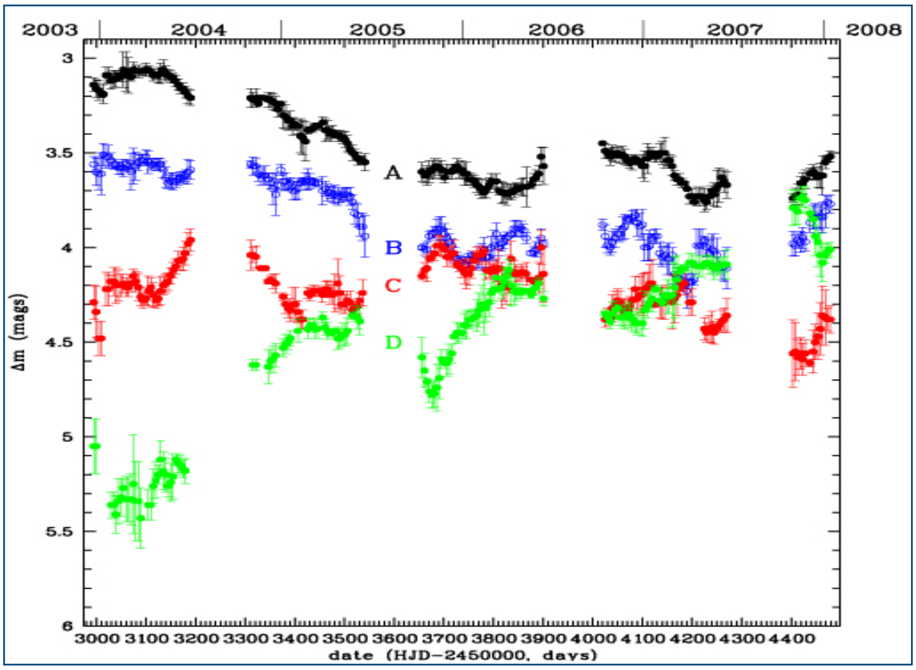
Janine Fohlmeister, Emilio Falco, Chris Kochanek & J.W.

- 6 telescopes: FLWO 1.2m
  APO 3.5m
  MDM 2.4 & 1.3m
  Palomar Observatory 1.5m
  Wise Observatory 1.0m
  WIYN 3.5m
- 4.5 observing seasons separated by ~100 day gaps
- average sampling three times per week
- 3 times 300 s exposures per night
- R / r filter
- photometry via psf fitting using 5 reference stars in the field

570 epochs between December 2003 and January 2008

Light Curves of SDSS J1004+4112



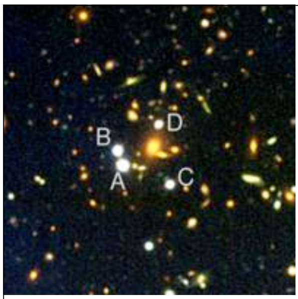


5 years of data, 570 epochs:

Image **A**, **B** faded by ~ 1mag

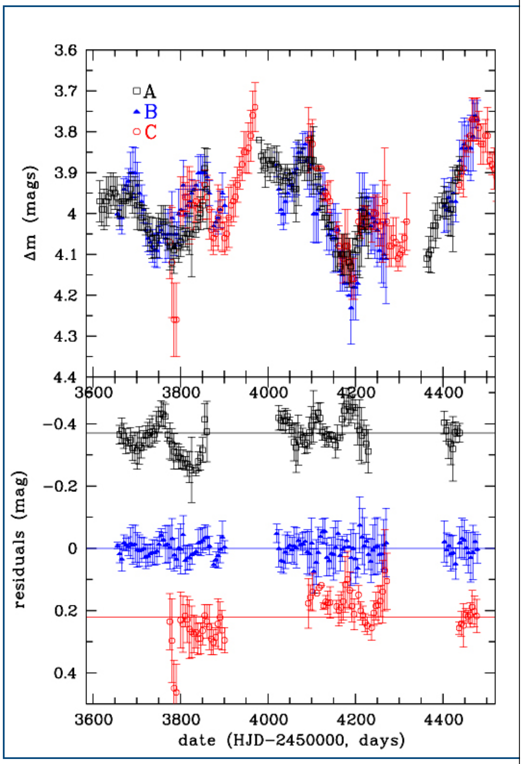
C relatively constant

D brightened by ~ 1.7mag



Measured Time Delays

SDSS J1004+4112



- Time Ordering **C-B-A-D**
- Close image pair **A & B**:

Δt_{BA} = (**40.6** ± 1.8) days

- Wide image pair **C & A**:

Δt_{CA} = (**821.6** ± 2.1) days

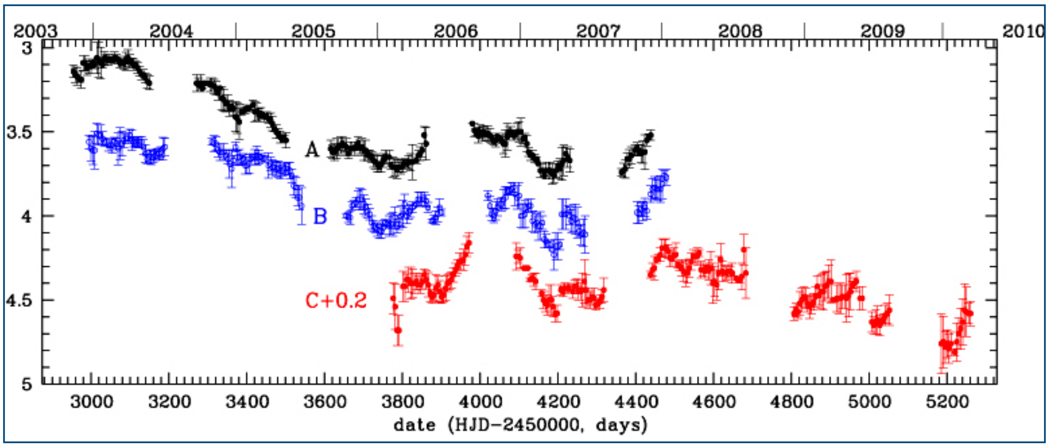
- Lower limit for **A & D** :

Δt_{AD} > **1250** days

Fohlmeister et al., ApJ 662, 62 (2007) & ApJ 676, 761 (2008)

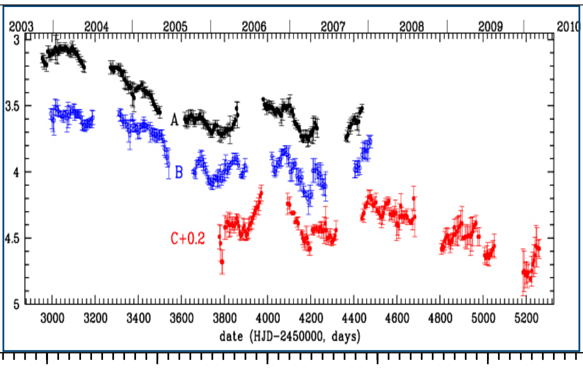
“Forecast” for SDSS J1004+4112

- C leading A & B by 2.3 years
- sharp variations in C re-observable in A & B
- plan: intensive monitoring of A & B for reverberation mapping and microlensing studies
- good mass model of galaxy cluster needed for Hubble constant

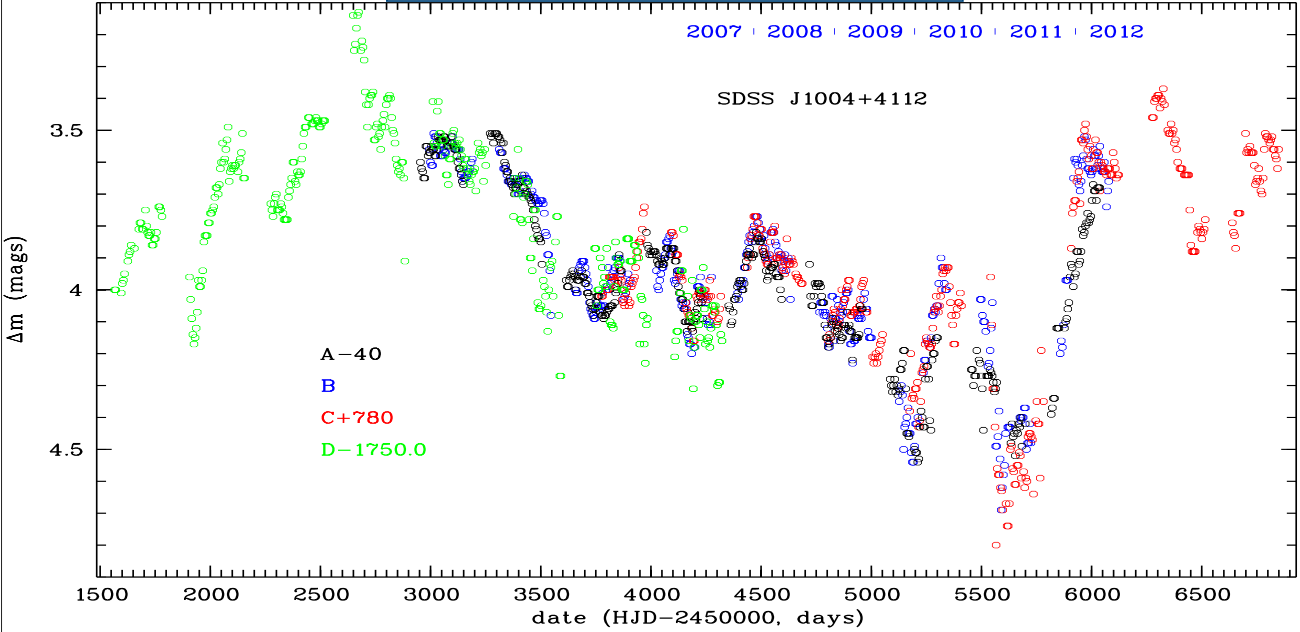


Fohlmeister et al., ApJ 662, 62 (2007) & ApJ 676, 761 (2008)

“Forecast” for SDSS J1004+4112

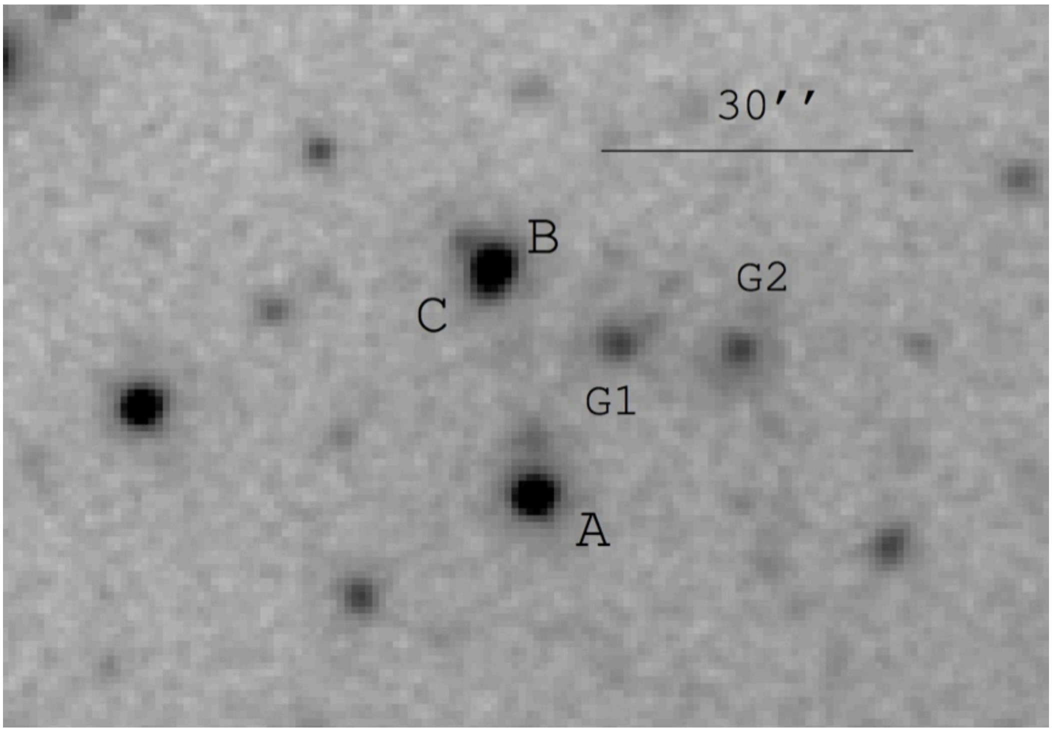


Fohlmeister et al.
(work in progress)



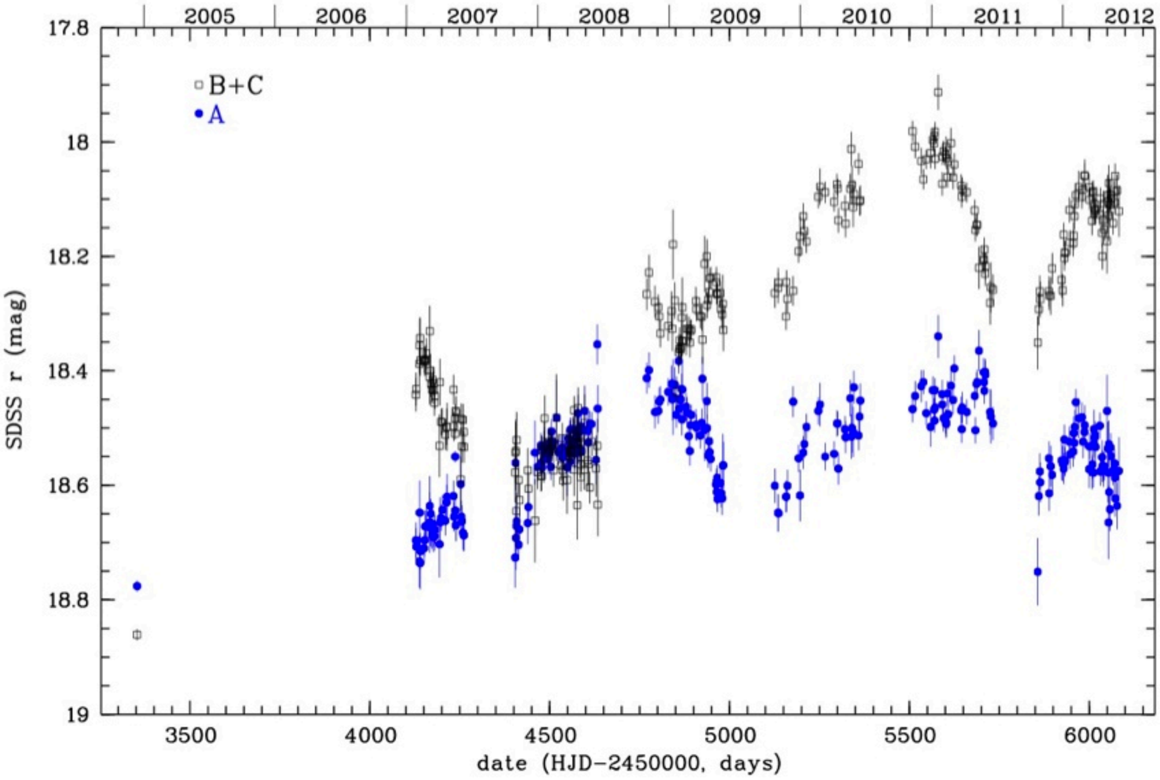
Time delay in **largest separation multiple quasar**: SDSS J1029+2623, Δθ = 22.6”

Fohlmeister, Kochanek, Falco, Wambsganss & Dai (2012)



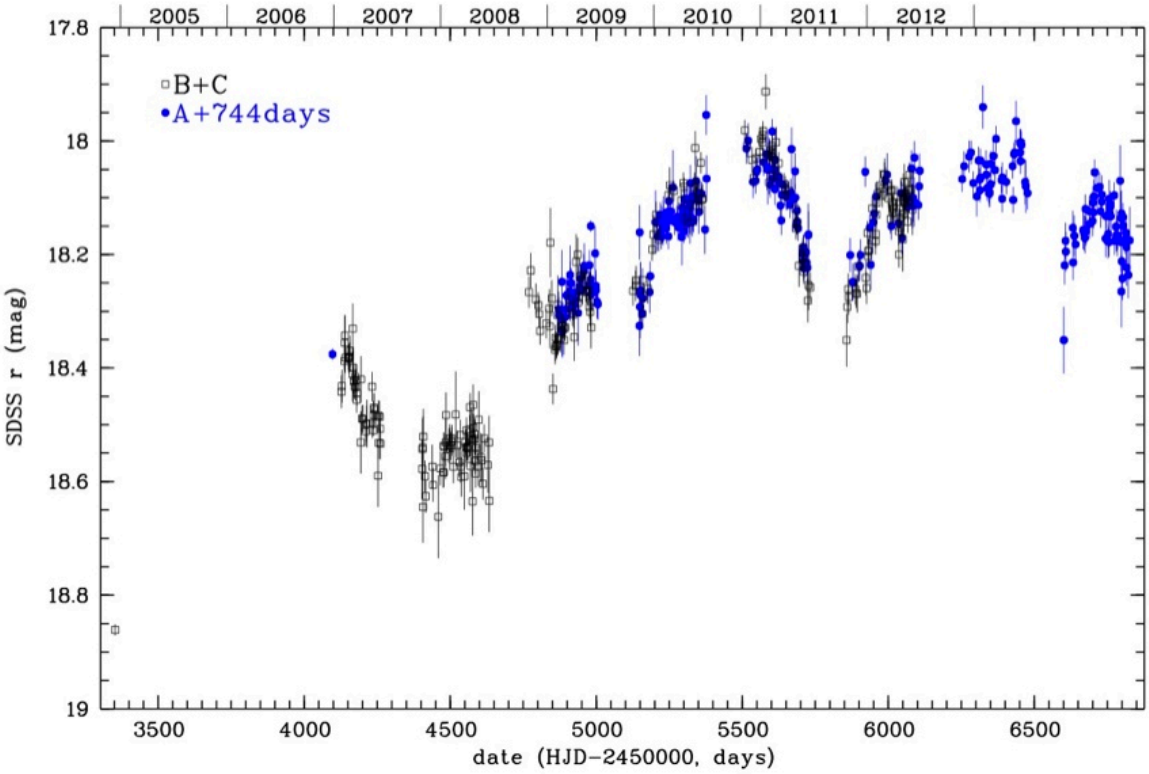
Time delay in **largest separation multiple quasar**: SDSS J1029+2623, Δθ = 22.6”

Fohlmeister, Kochanek, Falco, Wambsganss & Dai (2012)



Time delay in **largest separation multiple quasar**: SDSS J1029+2623, $\Delta\theta = 22.6''$

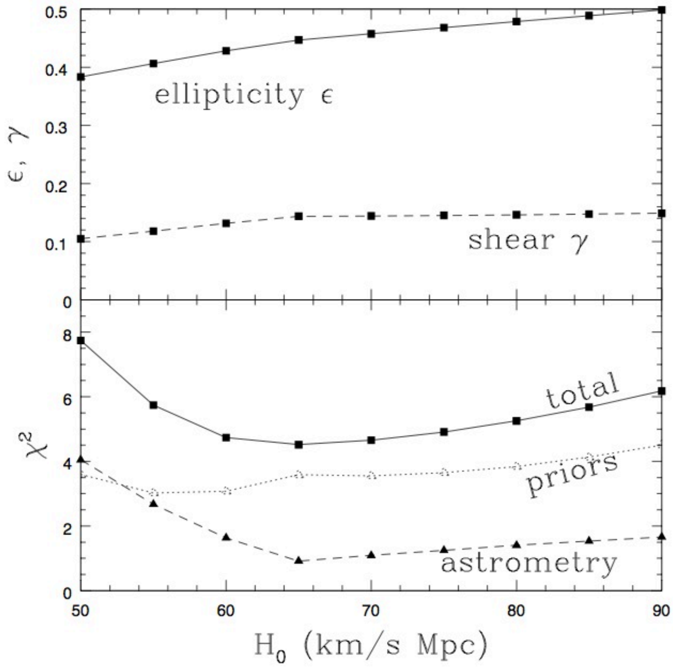
Fohlmeister, Kochanek, Falco, Wambsganss & Dai (2012)



Time delay in **largest separation multiple quasar**: SDSS J1029+2623, $\Delta\theta = 22.6''$

Fohlmeister, Kochanek, Falco, Wambsganss & Dai (2012)

(Weak) Constraints on Hubble constant H_0:



Time delay in **largest separation multiple quasar**: SDSS J1029+2623, $\Delta\theta = 22.6''$

Fohlmeister, Kochanek, Falco, Wambsganss & Dai (2012)

- 279 epochs of optical monitoring spanning 5.4 years (01/2007 - 06/2012)
- Image A leads image B by Δt_{AB} = (744 ± 10) days
- in fact: triple system, but B and C very close, not separable, all models $\Delta t_{BC} \lesssim 3$ days, therefore no effect
- no good limits on Hubble constant H_0: not enough constraints

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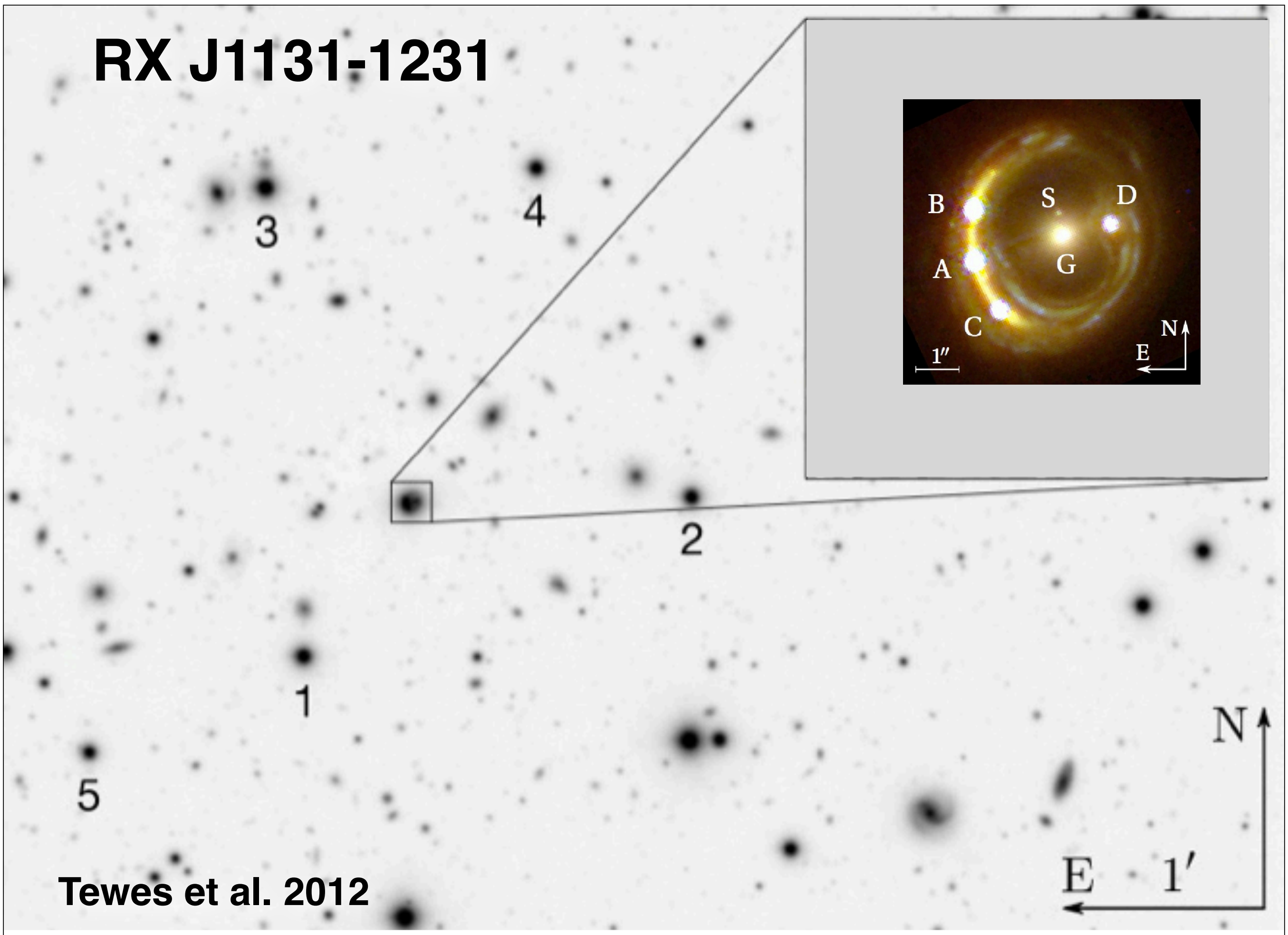
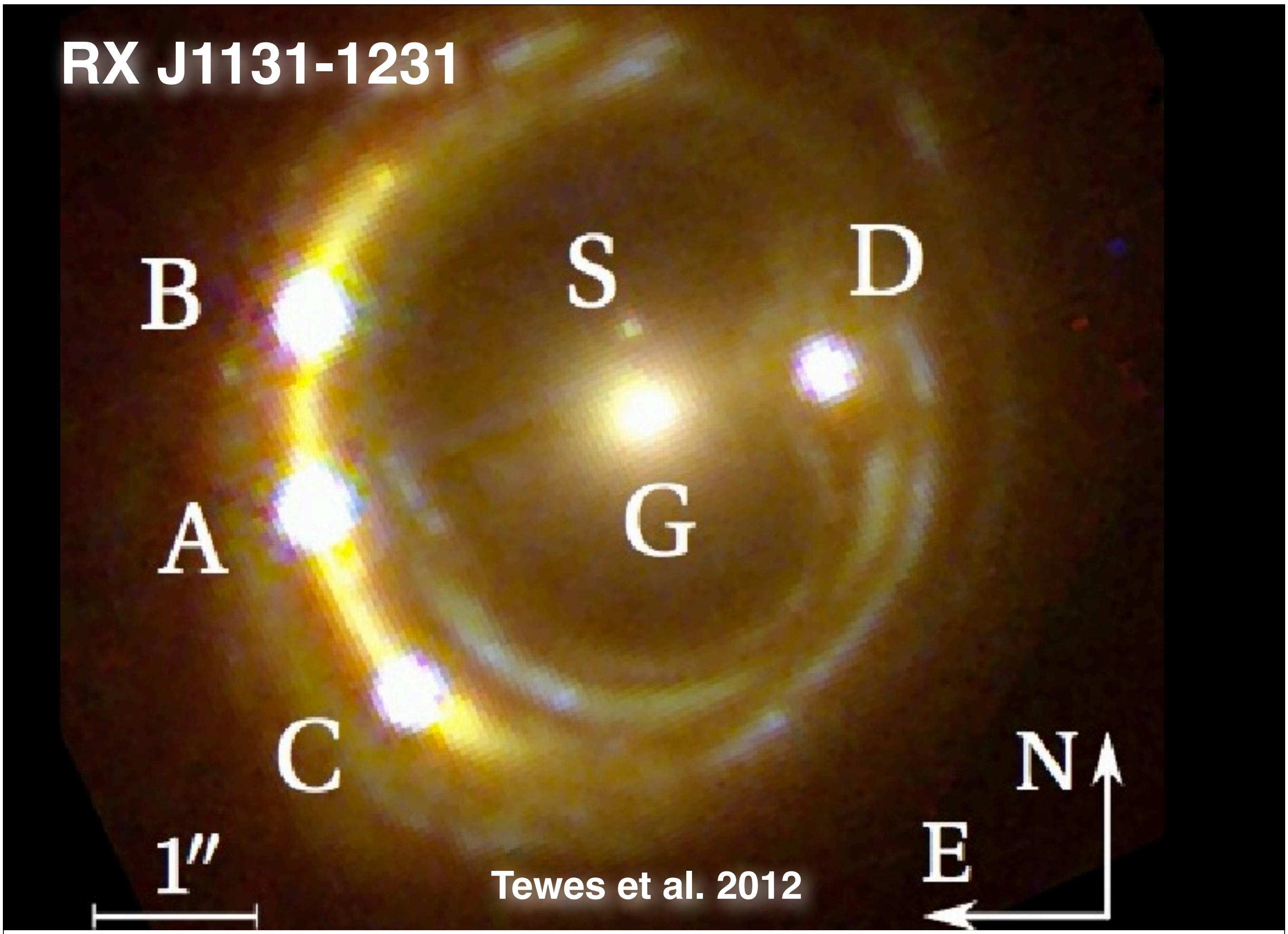
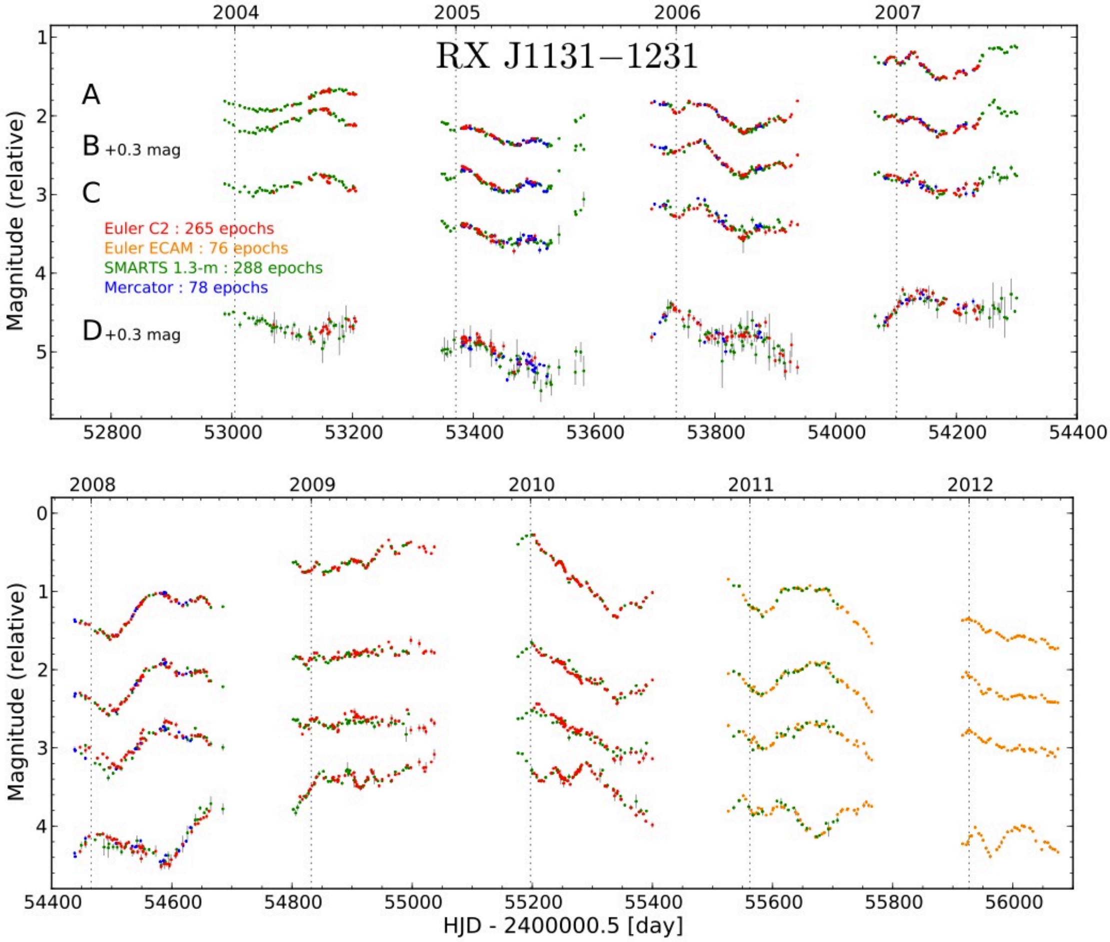
RX J1131-1231

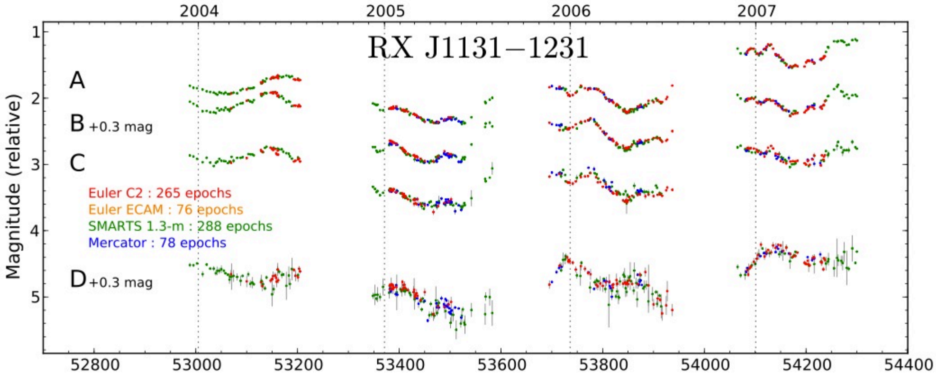


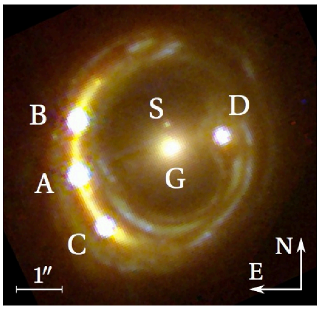
Tewes et al. 2012





Tewes et al. 2012 (Cosmograil)





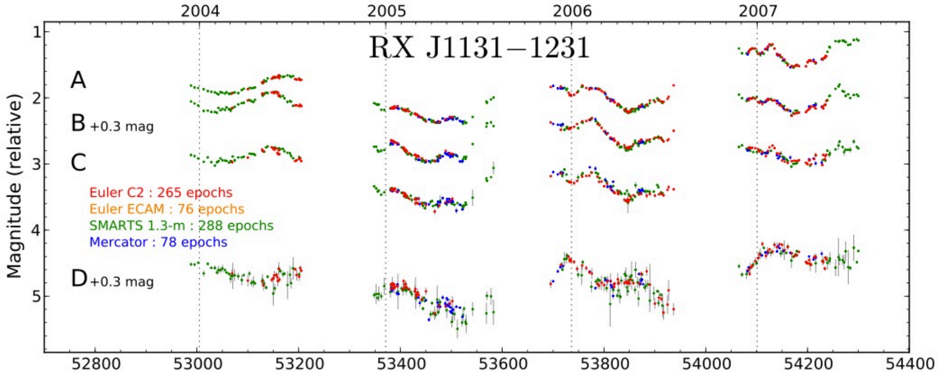
Tewes et al. (2012): Time delays of RX J1131-1231

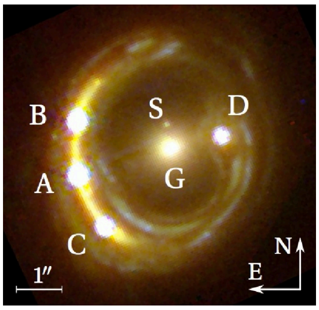
Δt_{1131} (D vs. A/B/C) = (91 ± 1.5) days

Suyu et al. (2012): Hubble constant H_0 from RX J1131-1231:

Time delay Δt_{1131} (D vs. A/B/C) = (91 ± 1.5) days
plus
Velocity dispersion measurement (323 ± 20) km/s
plus
line-of-sight measurement of add’l matter:

H_0 = (78.7 ± 4.5) km/s/Mpc (5.5% uncertainty)





Suyu et al. (2012):
Joint constraints from RX J1131-1231, B1608+666 and WMAP7:

For flat wCDM:

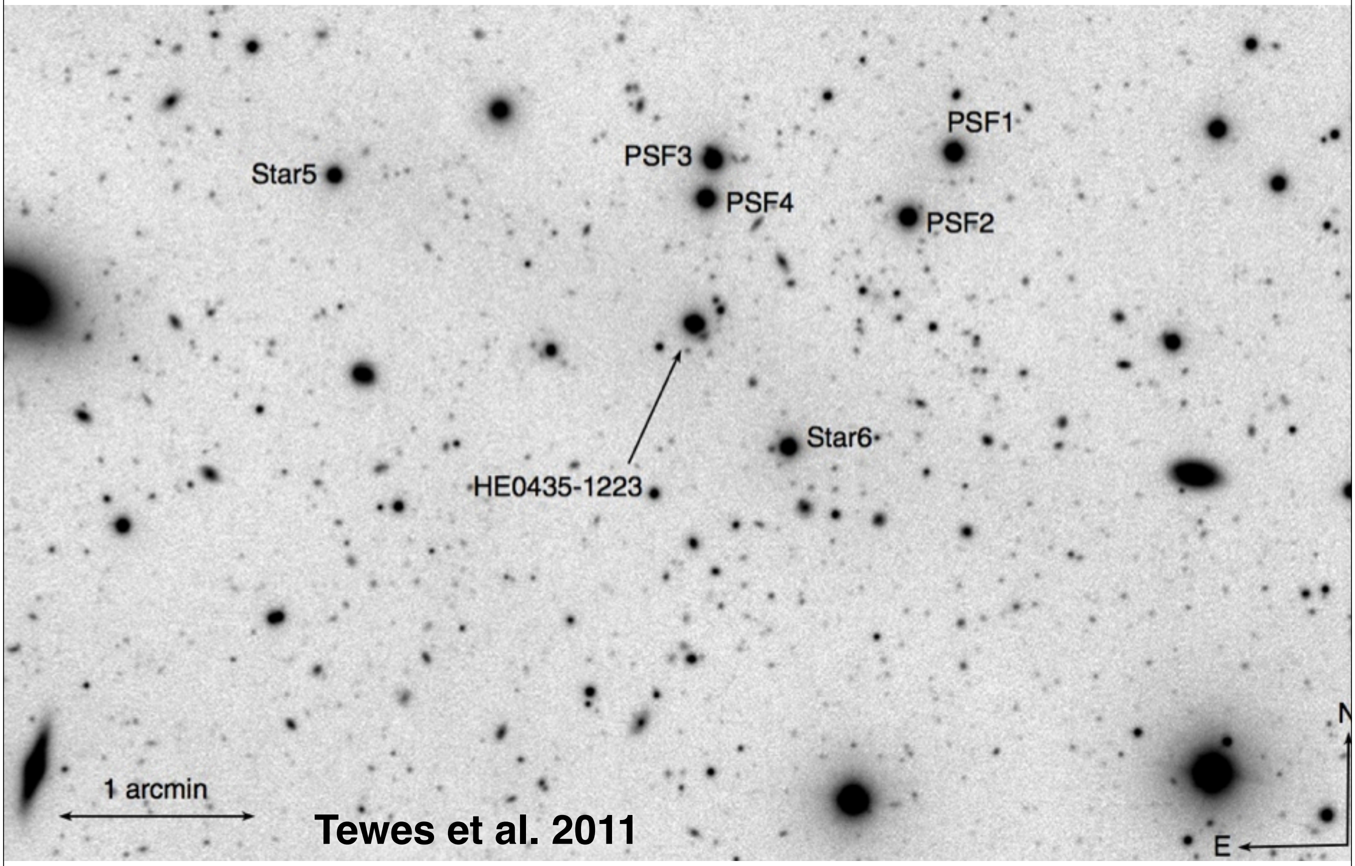
$H_0 = (75.2 \pm 4.5)$ km/s/Mpc $\Omega_{DE} = 0.76 \pm 0.03$ $w = -1.14^{+0.17}_{-0.20}$

For open ΛCDM:

$H_0 = (73.1 \pm 3.6)$ km/s/Mpc $\Omega_\Lambda = 0.75 \pm 0.02$

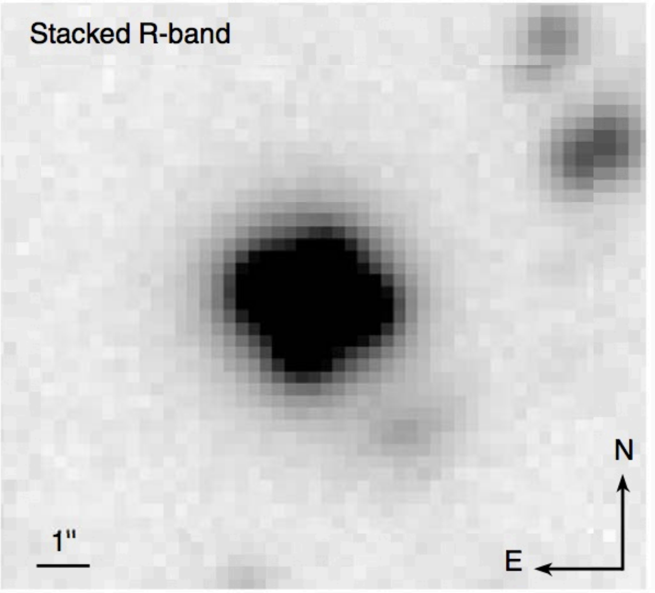
Overall accuracy similar to BAO measurements (Baryonic Acoustic Oscillation)

HE 0435-1223



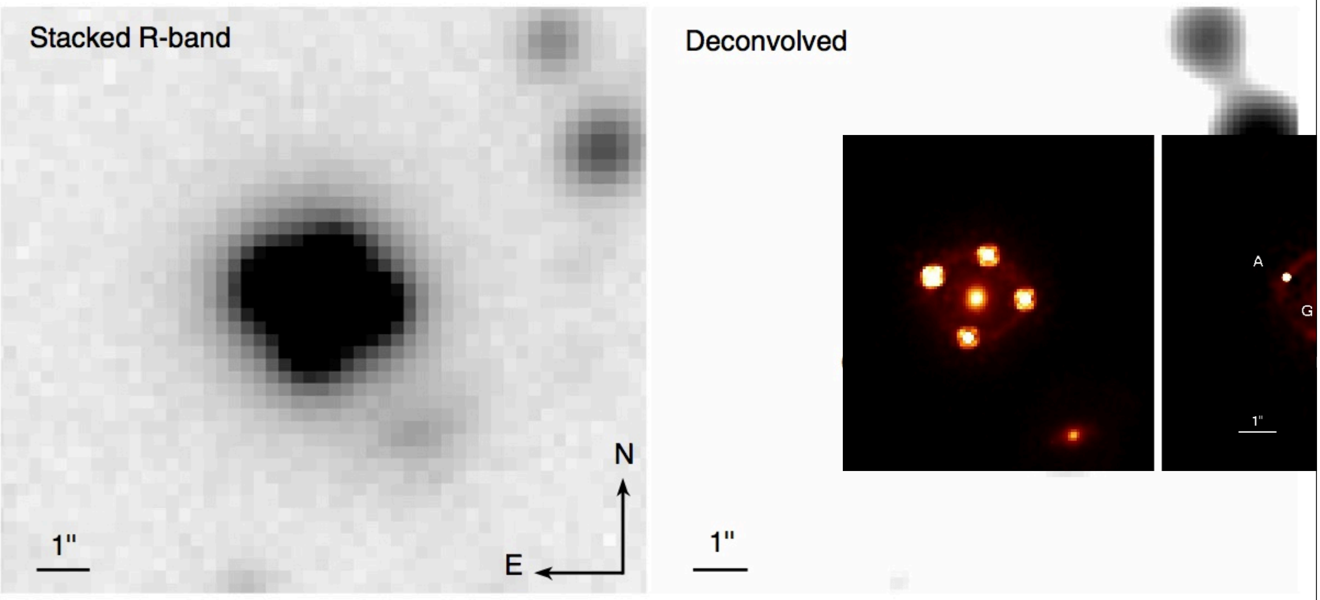
Tewes et al. 2011

HE 0435-1223



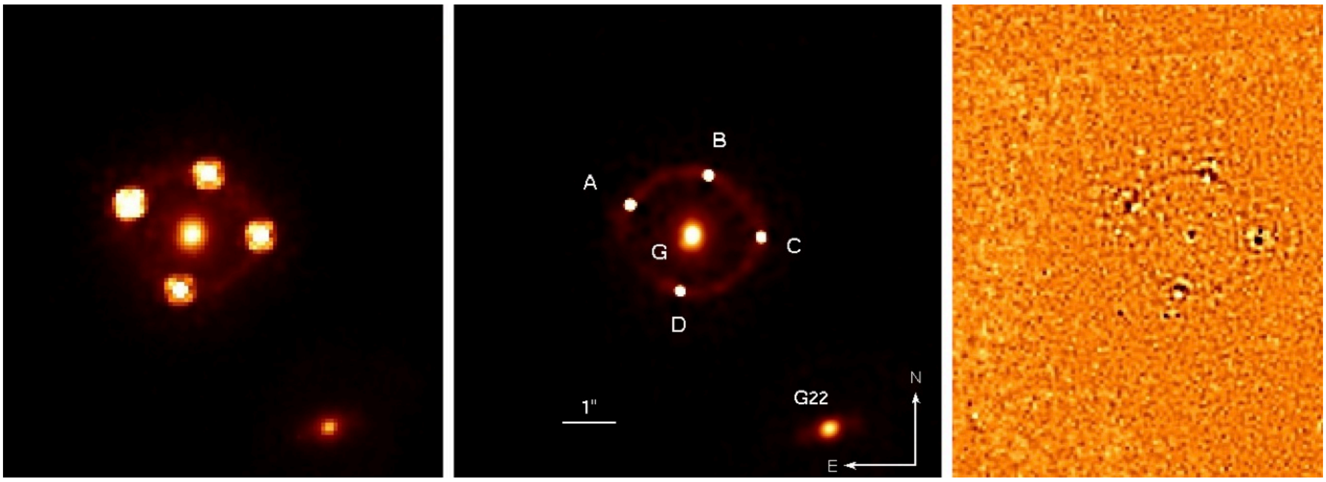
Tewes et al. 2011

HE 0435-1223



Tewes et al. 2011

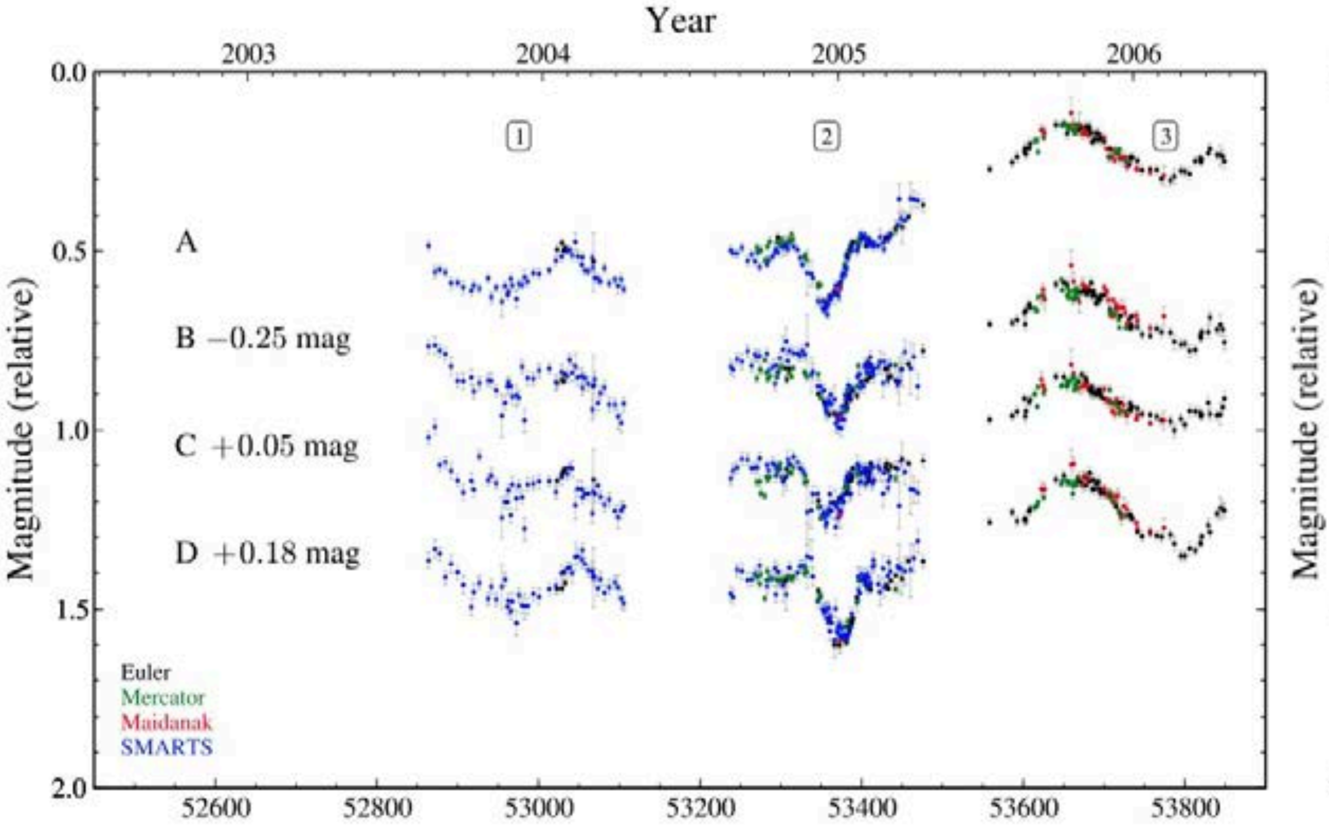
HE 0435-1223



Tewes et al. 2011

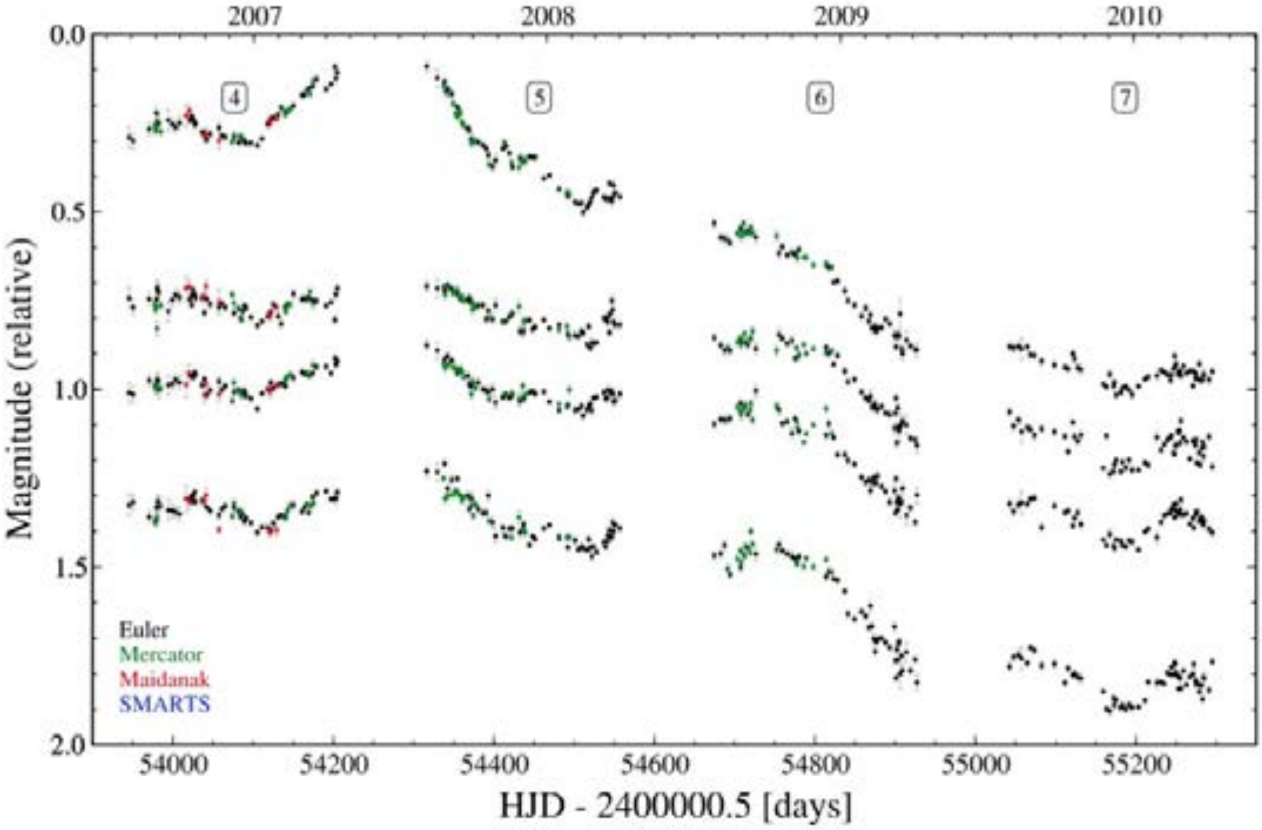
HE 0435-1223

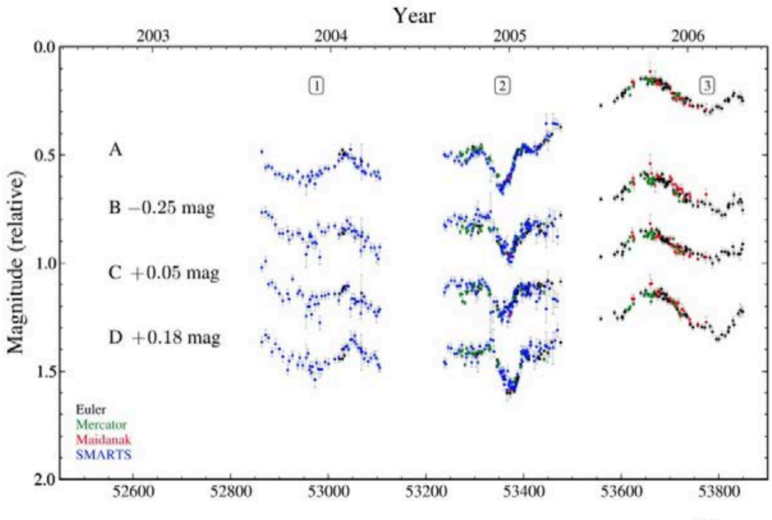
Tewes et al. 2011



HE 0435-1223

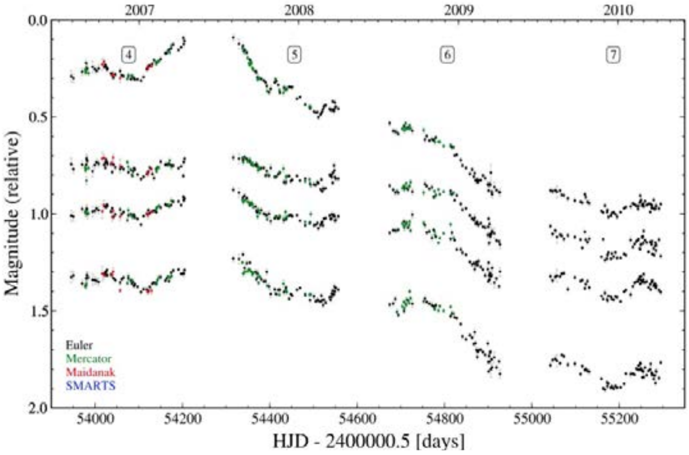
Tewes et al. 2011





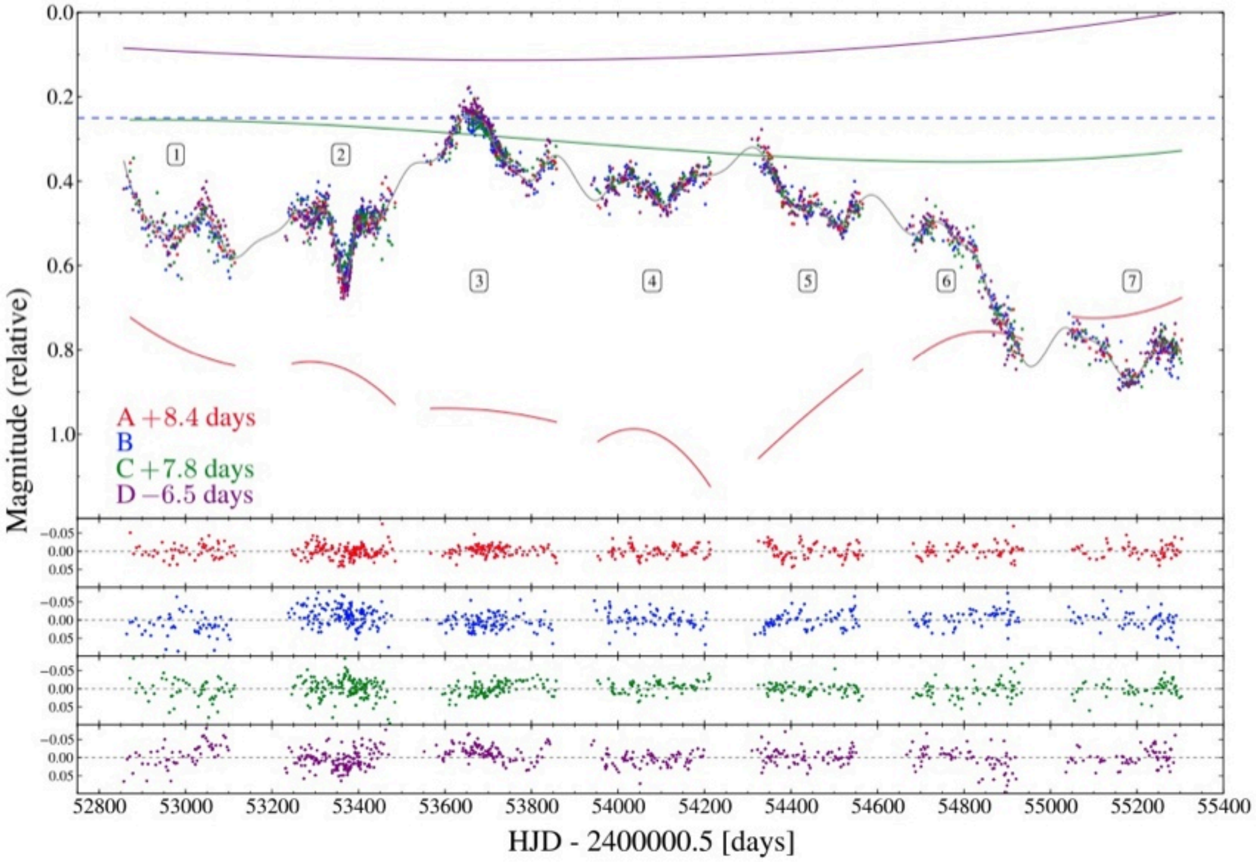
HE 0435-1223

Tewes et al. 2011

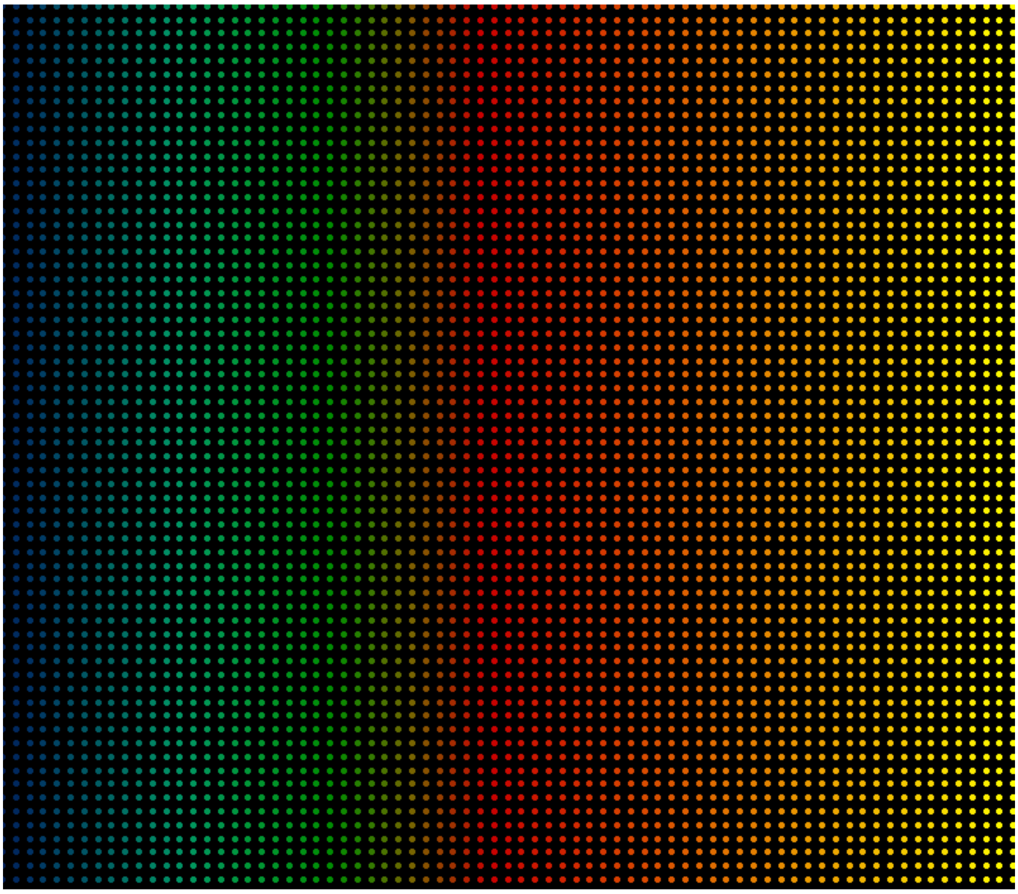


Tewes et al. 2011

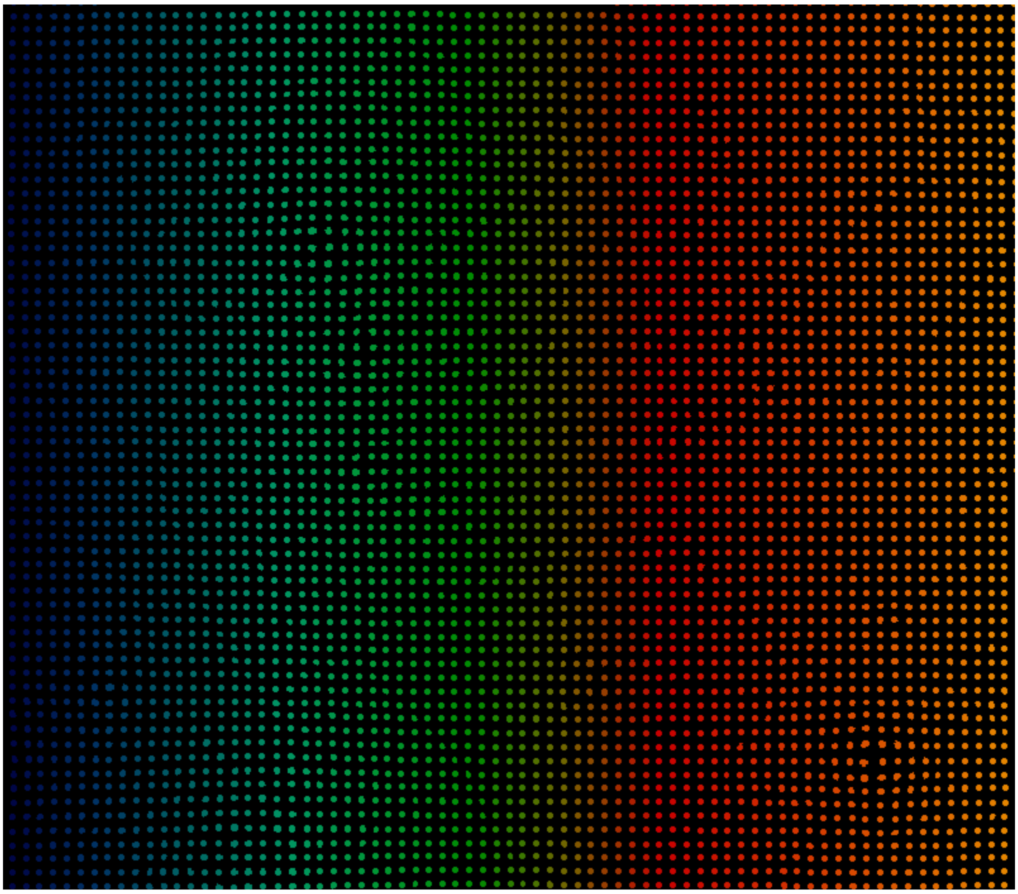
HE 0435-1223



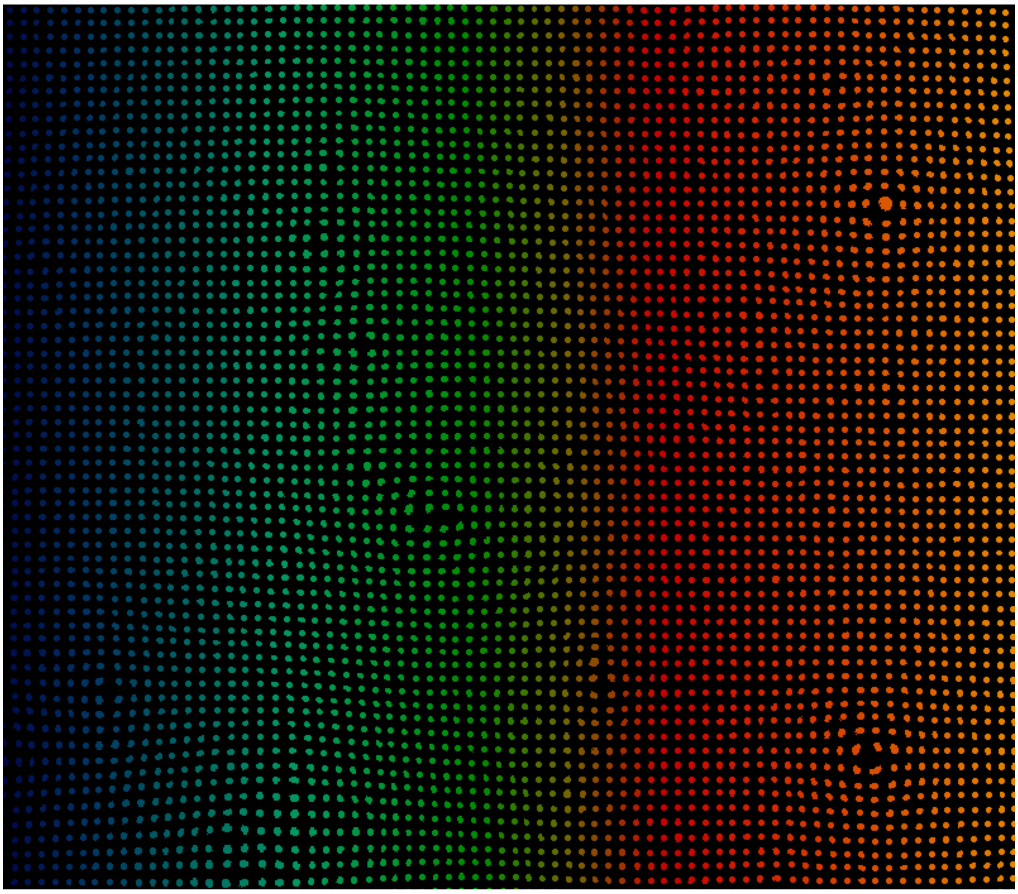
Examples for lensed structures with increasing z:



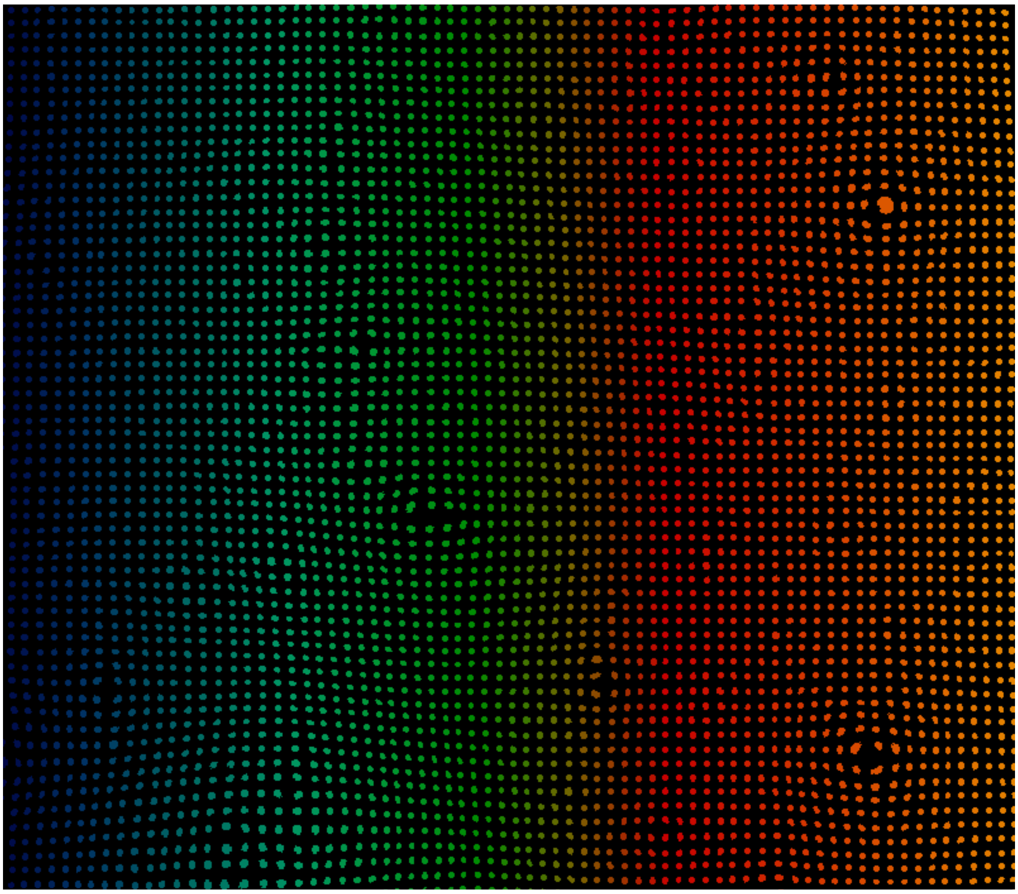
Examples for lensed structures with: $z_S = 0.5$



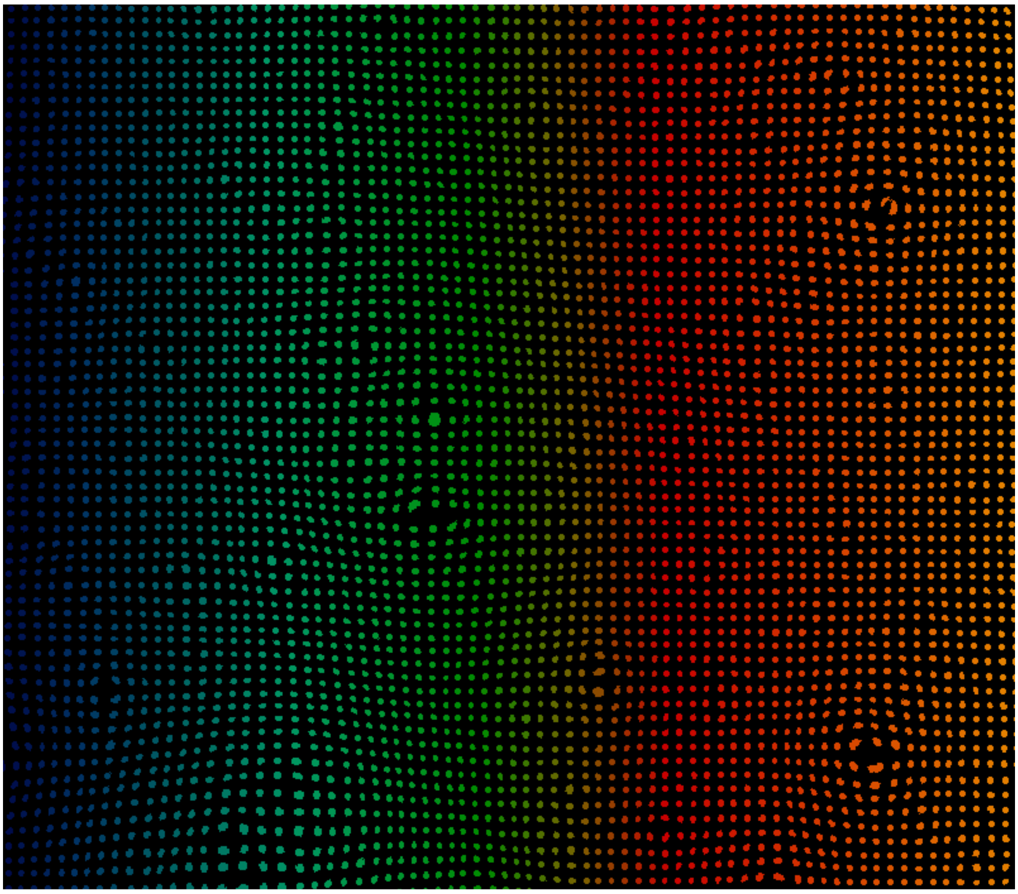
Examples for lensed structures with: $z_S = 1.1$



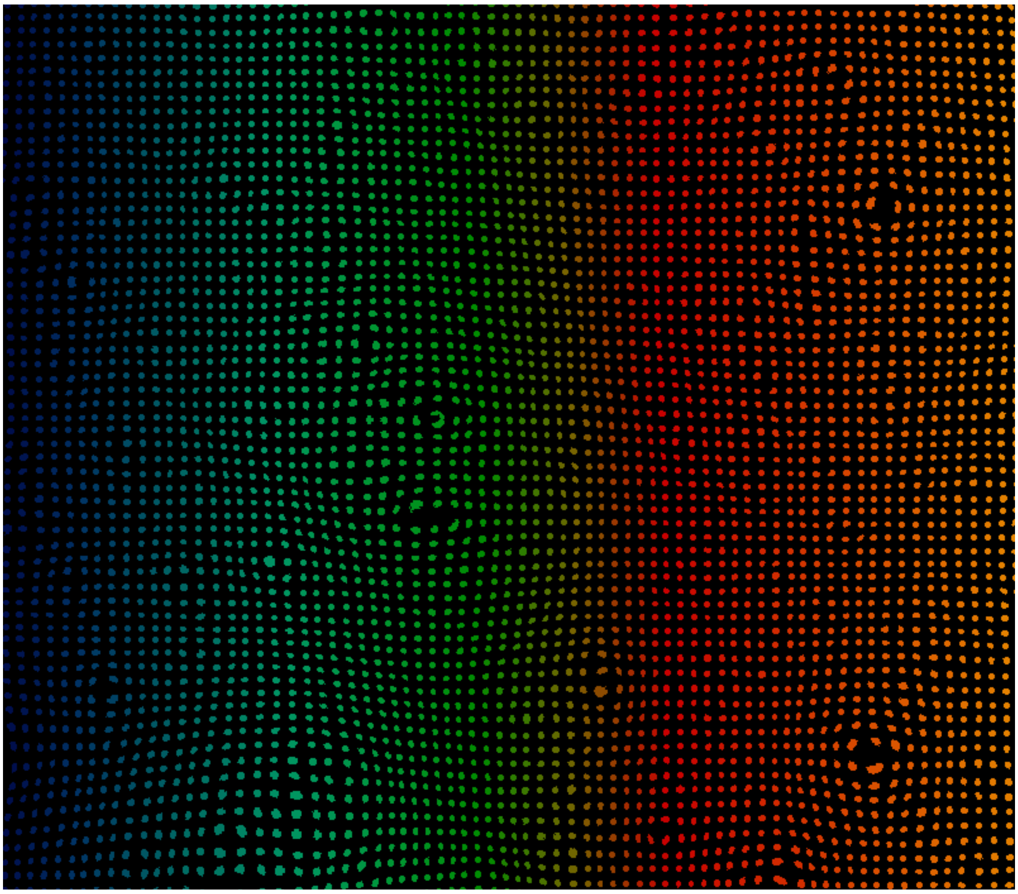
Examples for lensed structures with: $z_S = 1.5$



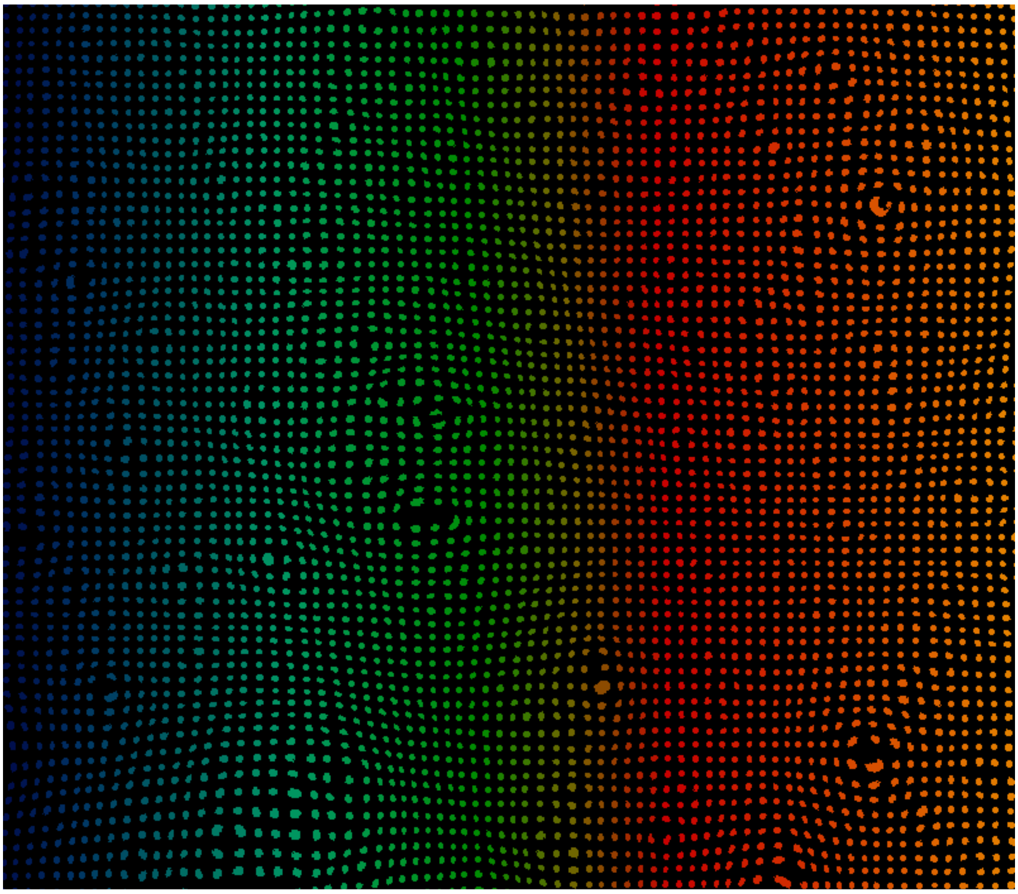
Examples for lensed structures with: $z_S = 2.5$

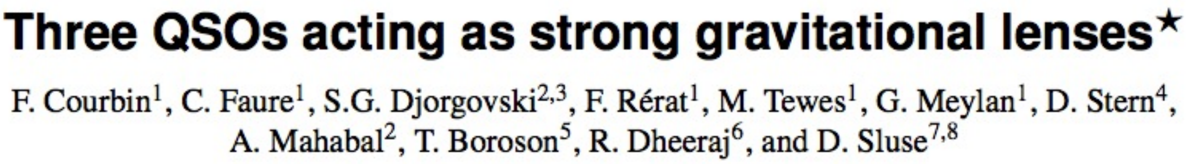


Examples for lensed structures with: $z_s = 3.8$



Examples for lensed structures with: $z_s = 5.4$





Three QSOs acting as strong gravitational lenses★

F. Courbin[1], C. Faure[1], S.G. Djorgovski[2,3], F. Rérat[1], M. Tewes[1], G. Meylan[1], D. Stern[4], A. Mahabal[2], T. Boroson[5], R. Dheeraj[6], and D. Sluse[7,8]

Searching through 23,000 SDSS spectra:

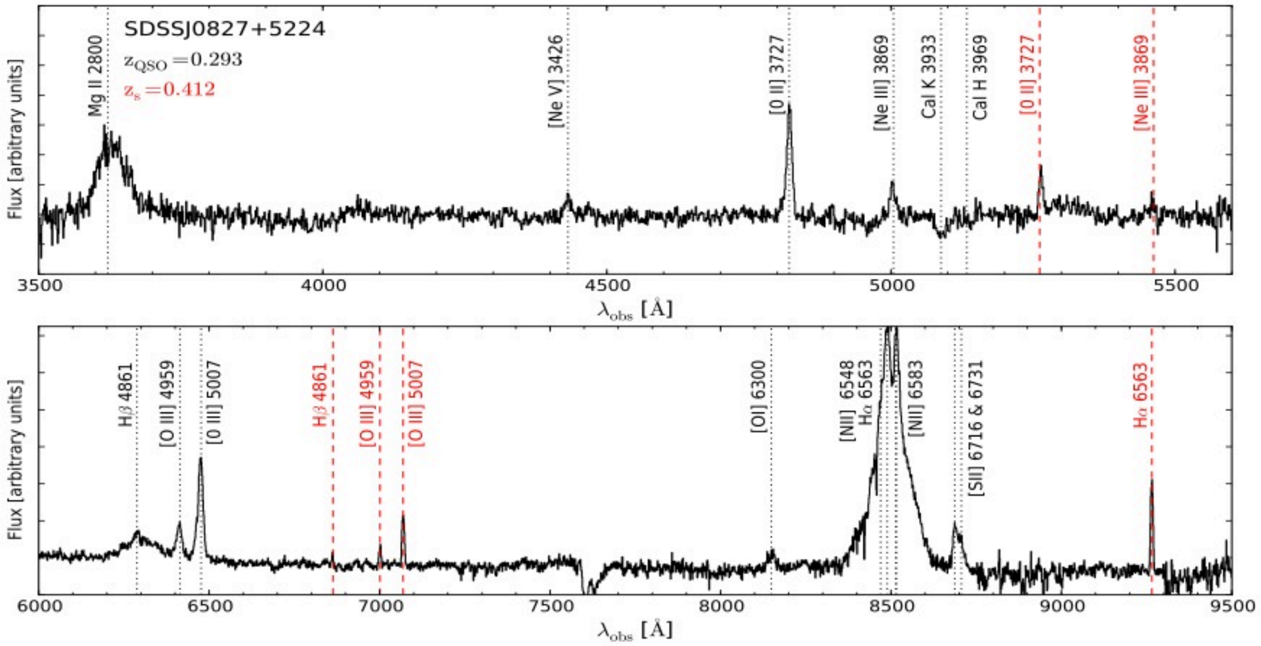
Looking for spectra with ≥ 4 emission lines at a
redshift different from the foreground quasar

Confirming with Keck spectra and imaging:

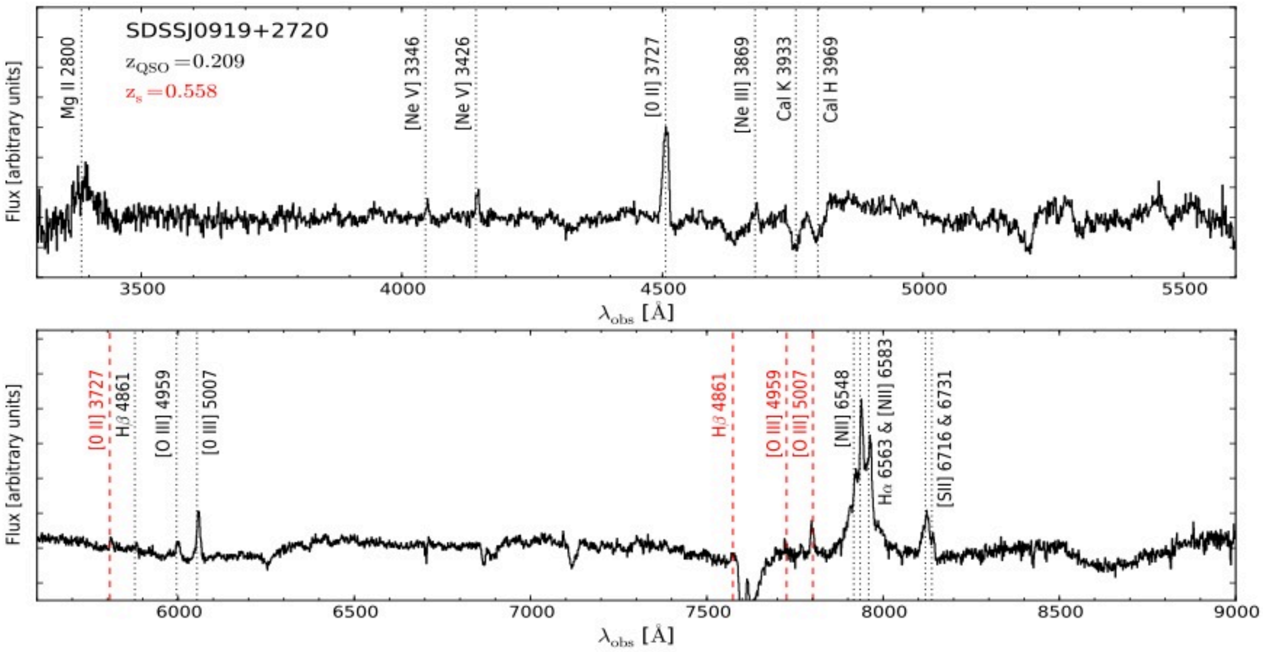
SDSS J0827+5224:	$z_{QSO} = 0.293$	$z_S = 0.412$
SDSS J0919+2720:	$z_{QSO} = 0.209$	$z_S = 0.558$
SDSS J1005+4016:	$z_{QSO} = 0.230$	$z_S = 0.441$

(Velocity dispersions between 210 and 285 km/s)

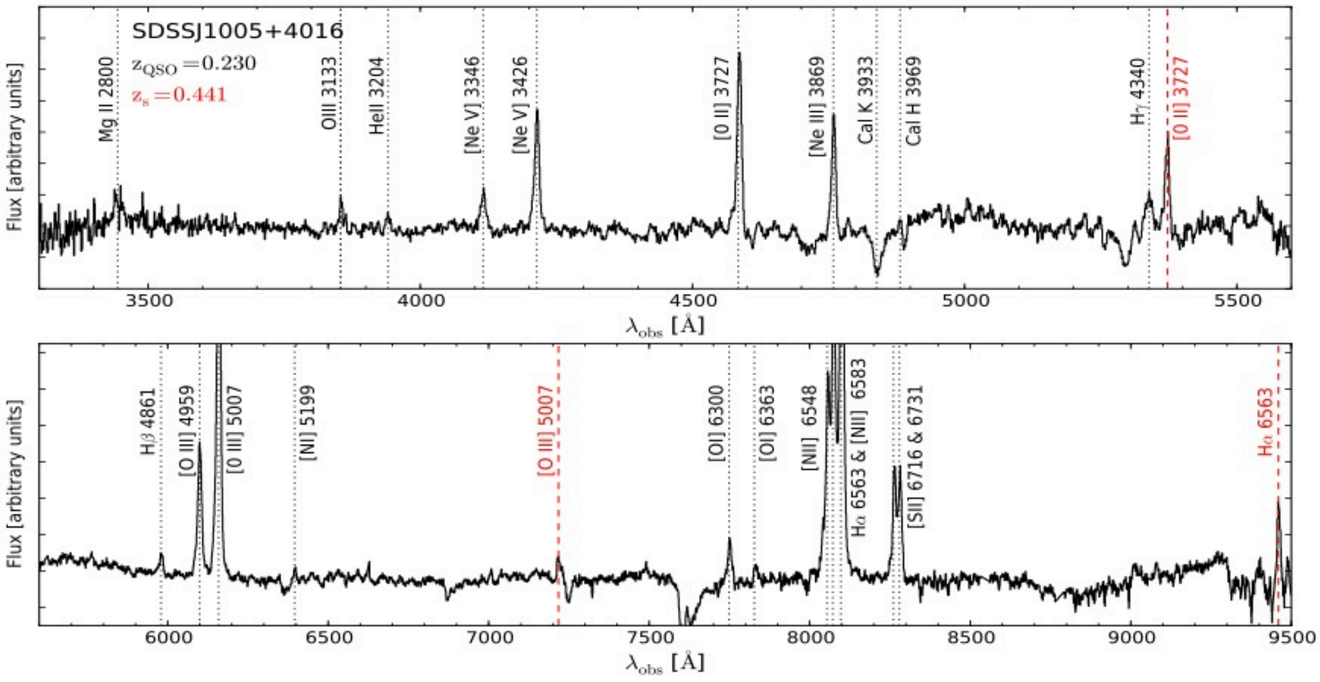
QSOs acting as strong lenses: SDSS J0827+5224 (Courbin et al. 2012)

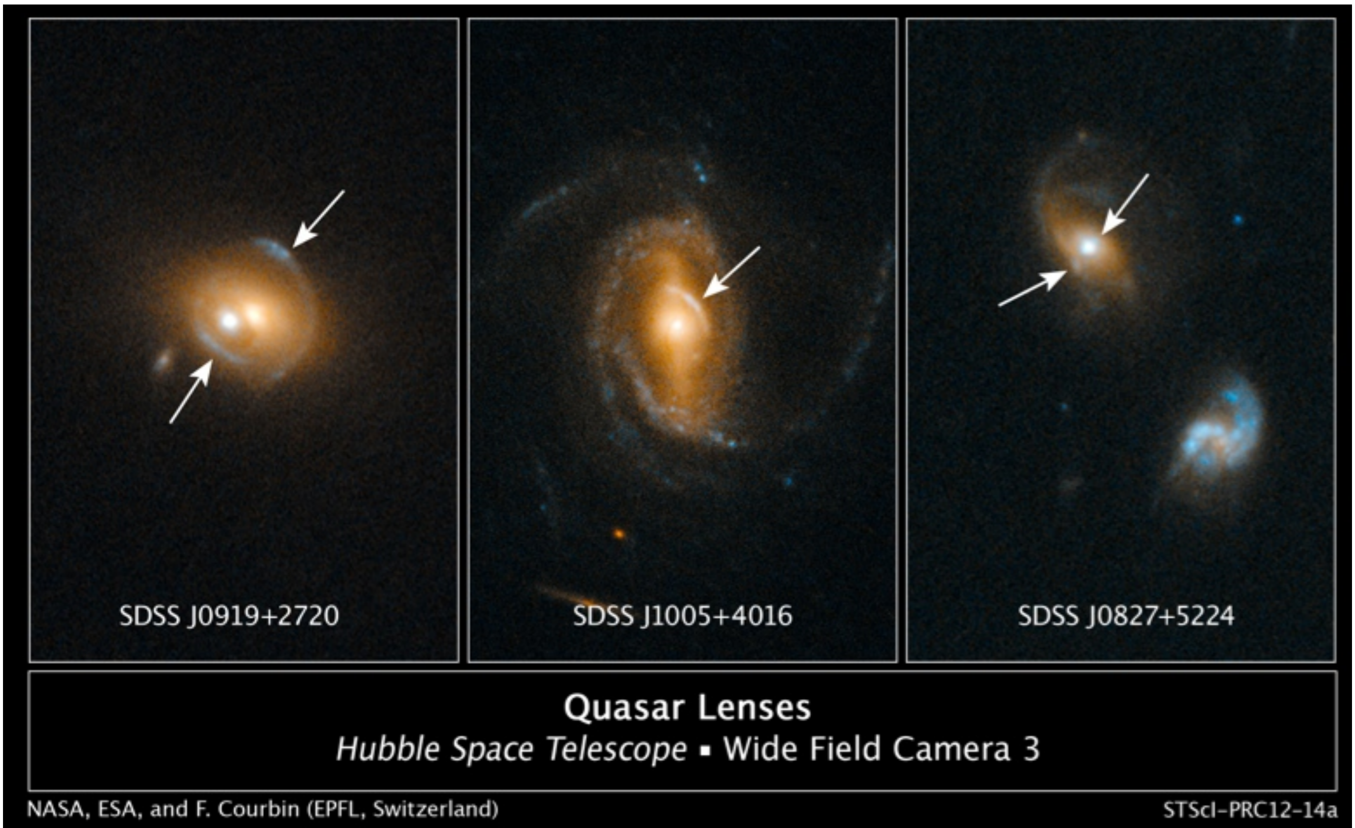


QSOs acting as strong lenses: SDSS J0919+2720
(Courbin et al. 2012)



QSOs acting as strong lenses: SDSS J1005+4016
(Courbin et al. 2012)





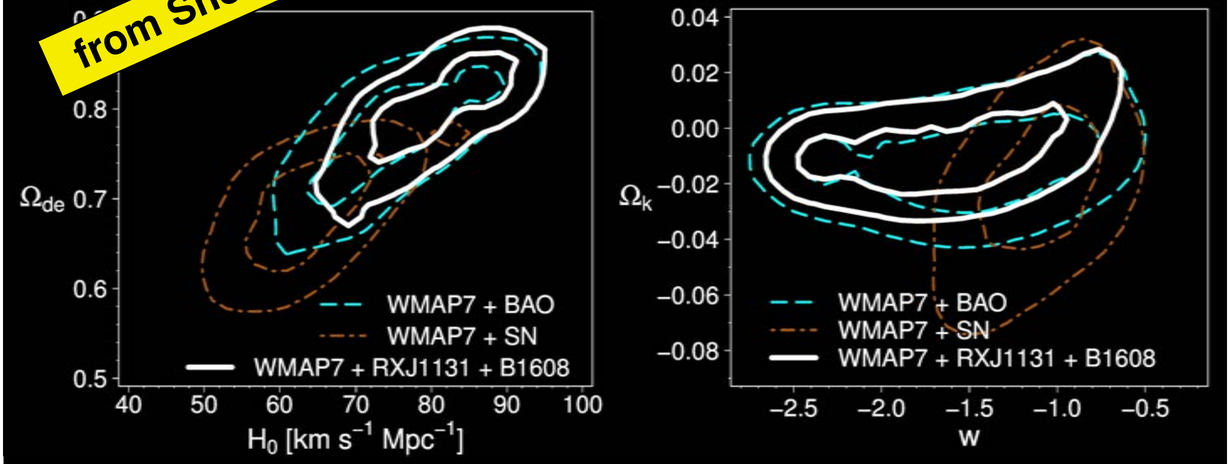
Velocity dispersions between 210 and 285 km/s

Cosmologic robe Comparison I

from Sherry Suyu's 4th talk:

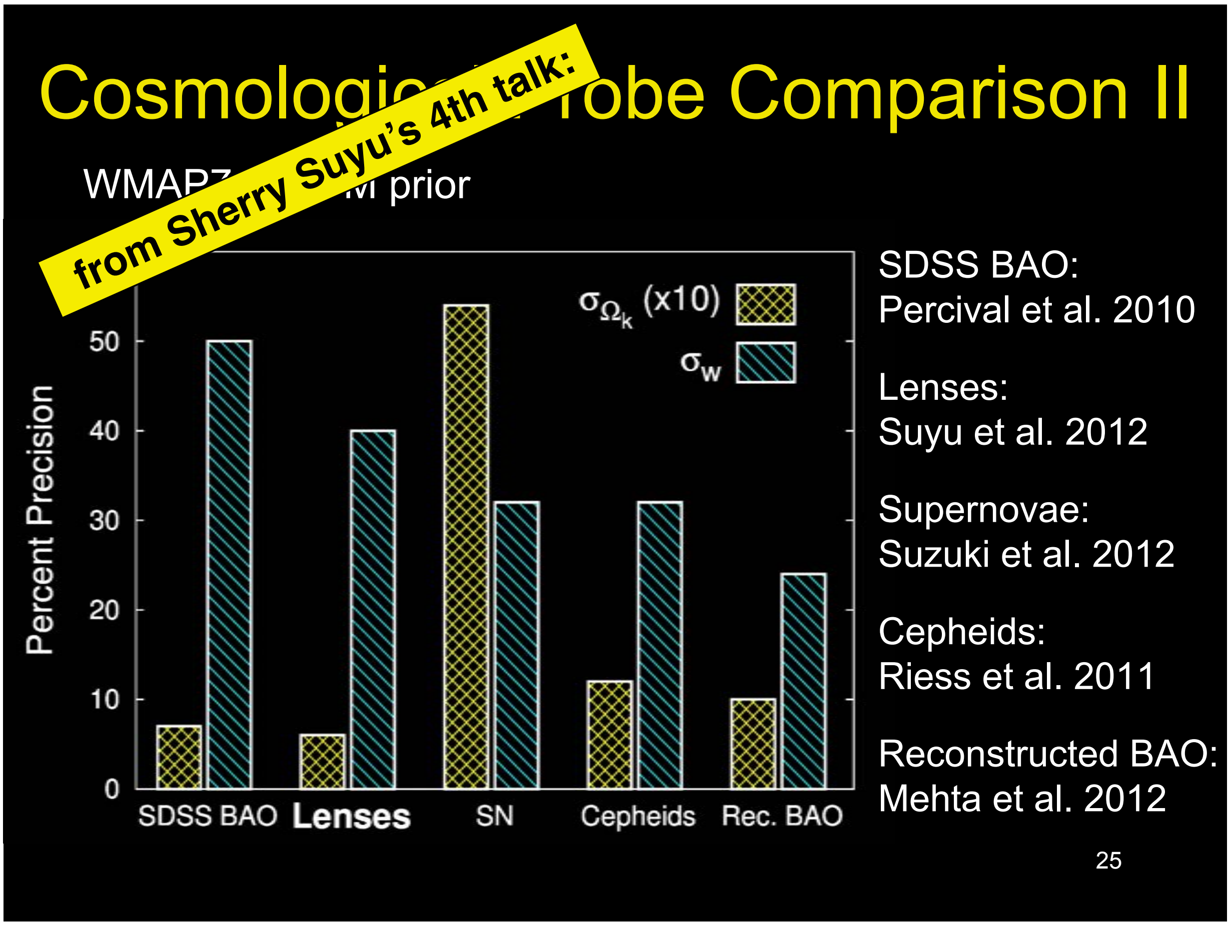
WMAP7 M prior

[Suyu et al. 2012]



- contour orientations are different: complementarity b/w probes
- contour sizes are similar: lensing is a competitive probe

24



Cosmologic robe Comparison II

from Sherry Suyu's 4th talk:

WMAP7 M prior

SDSS BAO:
Percival et al. 2010

Lenses:
Suyu et al. 2012

Supernovae:
Suzuki et al. 2012

Cepheids:
Riess et al. 2011

Reconstructed BAO:
Mehta et al. 2012

AGNs and Quasars

Joachim Wambsganss

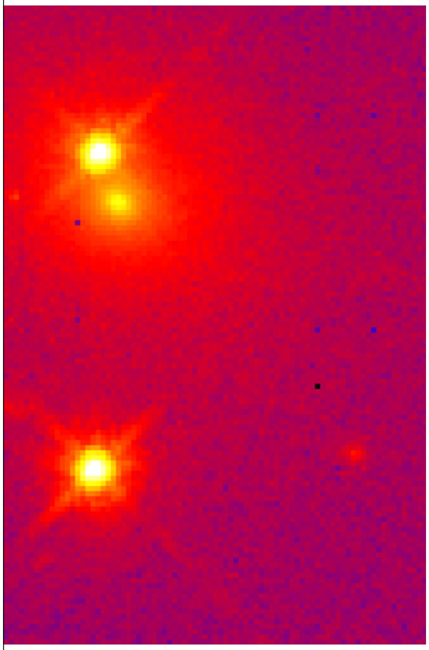
4) Microlensing of Quasars: (No) Machos, Smooth Dark Matter and more

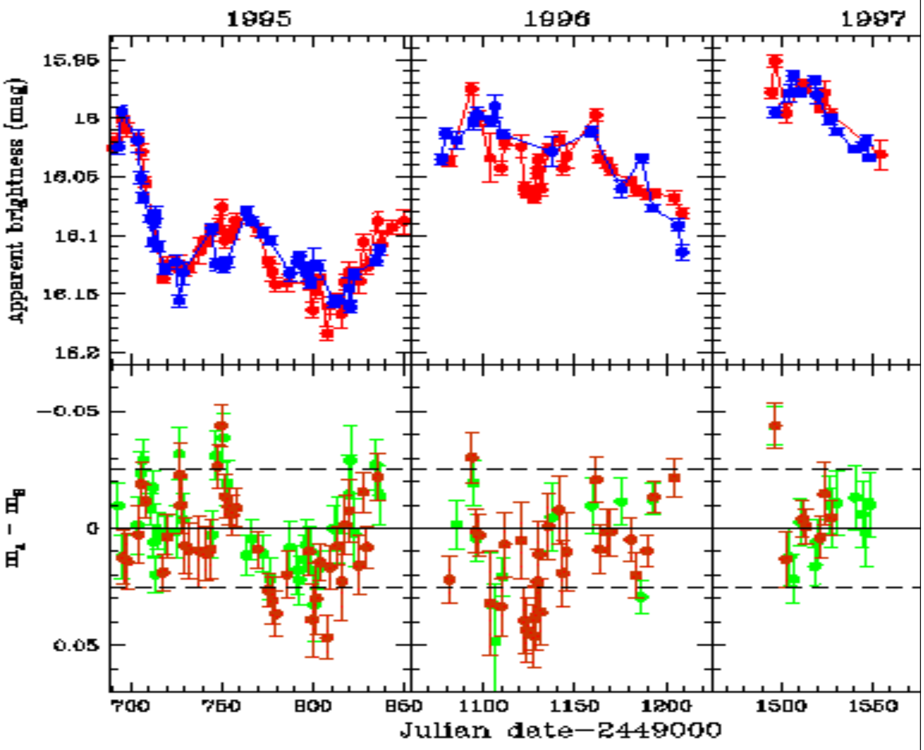
XXIV Canary Islands Winter School of Astrophysics
Astrophysical Applications of Gravitational Lensing
Puerto de La Cruz, Tenerife, Spain, 4th-16th November 2012

Nine Applications of Quasar Microlensing

- Q0957+56: no Machos
- Q2237+0305: limits on transverse velocity
- Odd images
- Size is everything
- Various “suppressed saddlepoints”: smooth dark matter
- Dark Matter fraction via microlensing
- Measuring the accretion disk profile
- Astrometric microlensing
- Microlensing of Broad Line Region

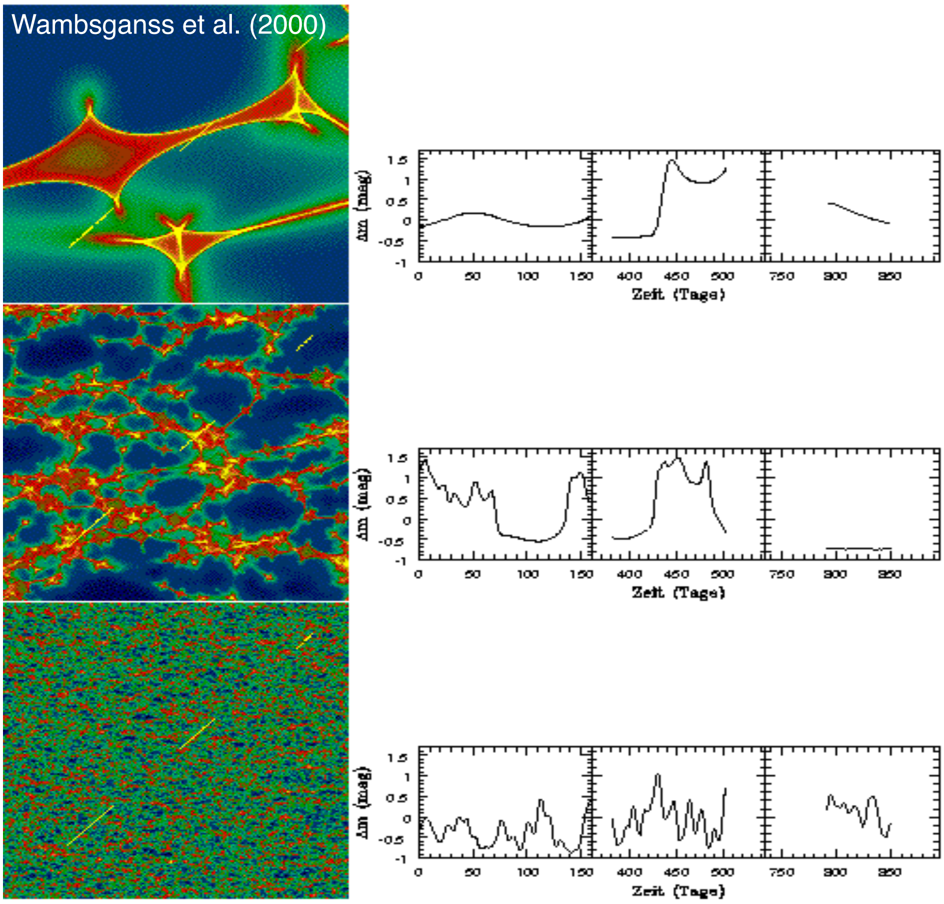
Quasar Microlensing? Q0957+561





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

Quasar Microlensing Simulation: Q0957+561



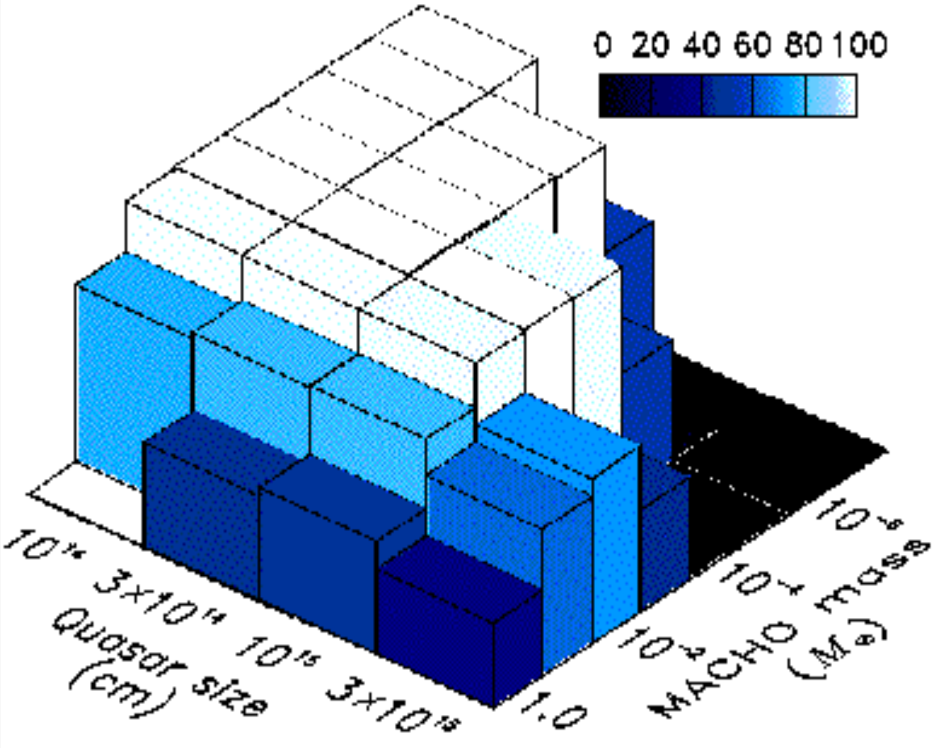
Wambsganss et al. (2000)

$10^{-1} M_\odot$

$10^{-3} M_\odot$

$10^{-5} M_\odot$

Quasar Microlensing Results: Q0957+561



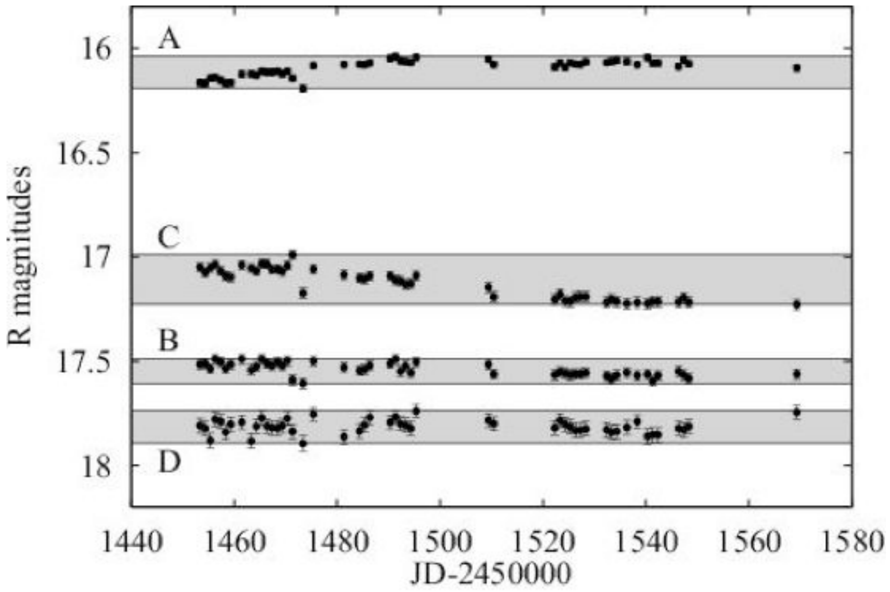
Halo of lensing galaxy cannot consist entirely of compact objects (MACHOs) in certain mass ranges
(Wambsganss et al. 2000)

More systems,
longer baseline
⇒ better constraints!

Quasar Microlensing: Q2237+0305

Monitoring campaign: 6 months in 2000

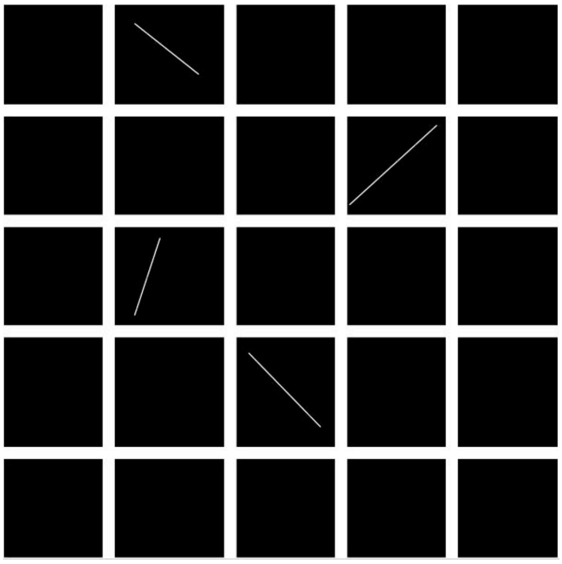
GLITP - Gravitational Lens International Time Project

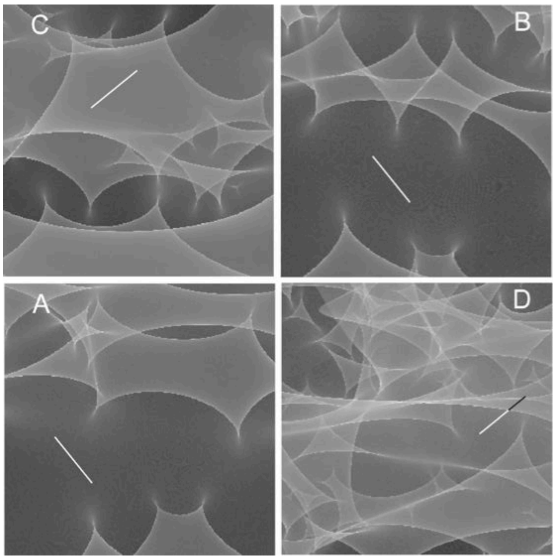


Quasar Microlensing: Q2237+0305

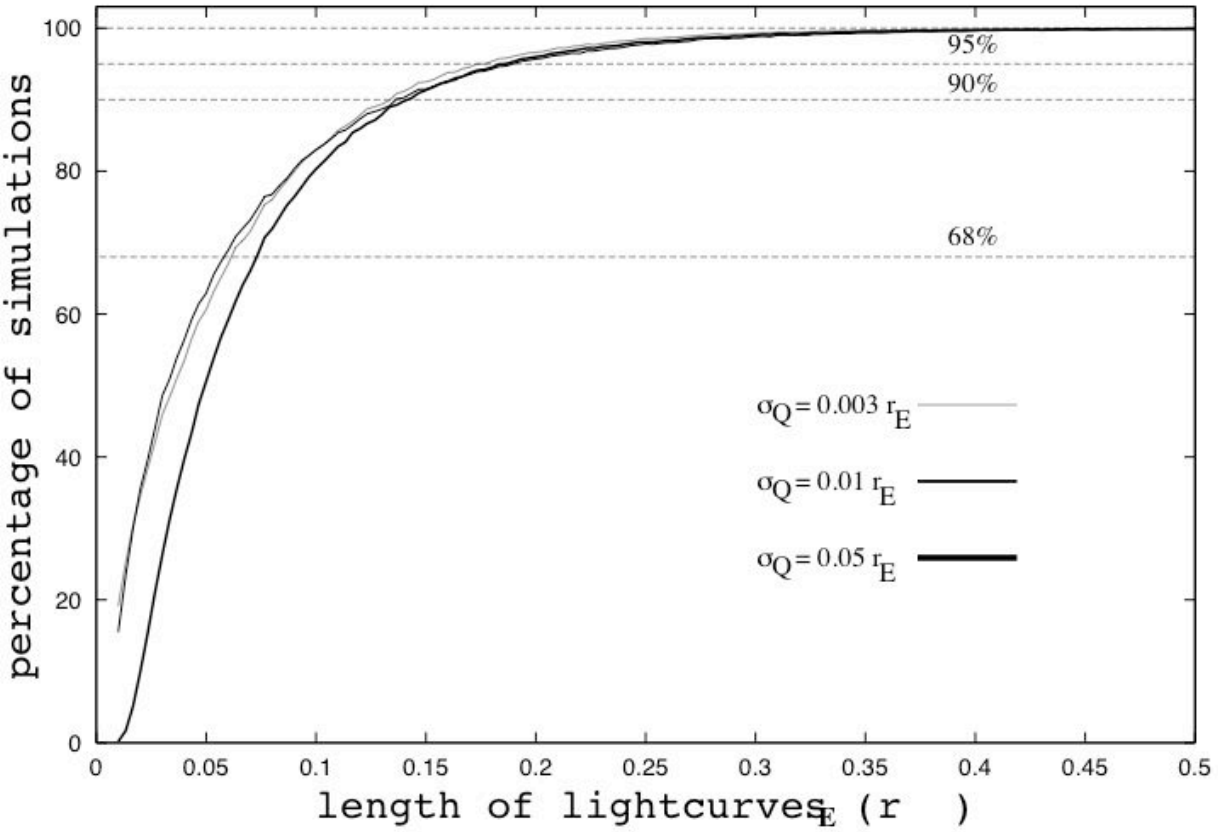
Limits on transverse velocity of lensing galaxy:

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

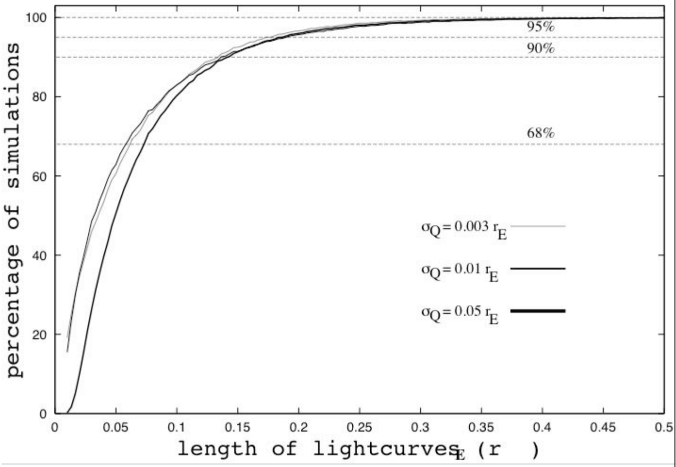




Quasar Microlensing: Q2237+0305



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

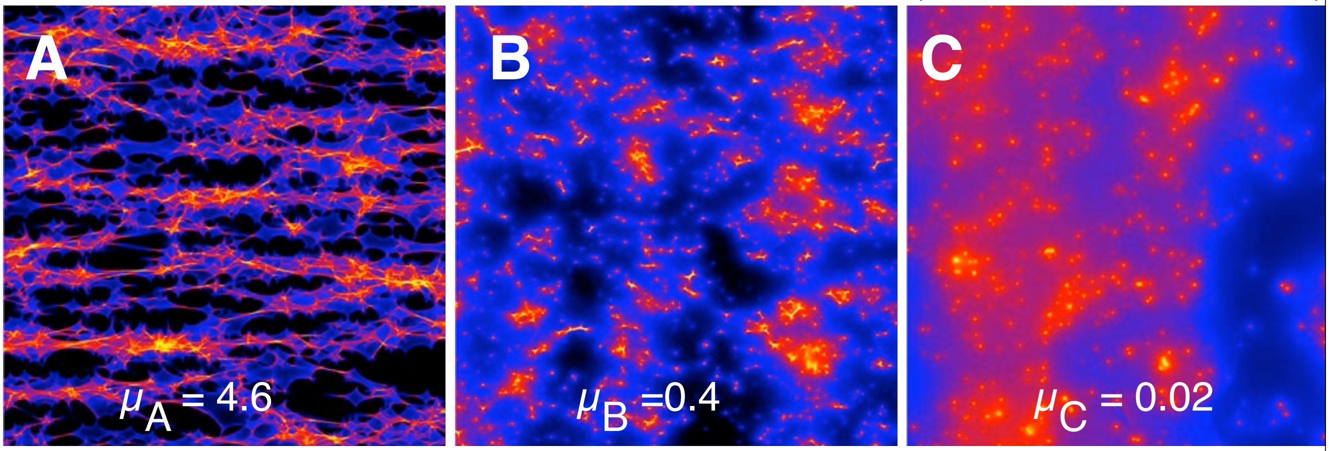
$M = 0.1\ M_\odot$:

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

Gil-Merino,
Wambsganss
et al. (2005)

“Odd Images”: Microlensing Magnification Maps for PMN J1632-0033

(Winn et al. 2002, 2003, 2004)



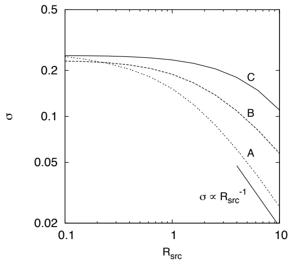
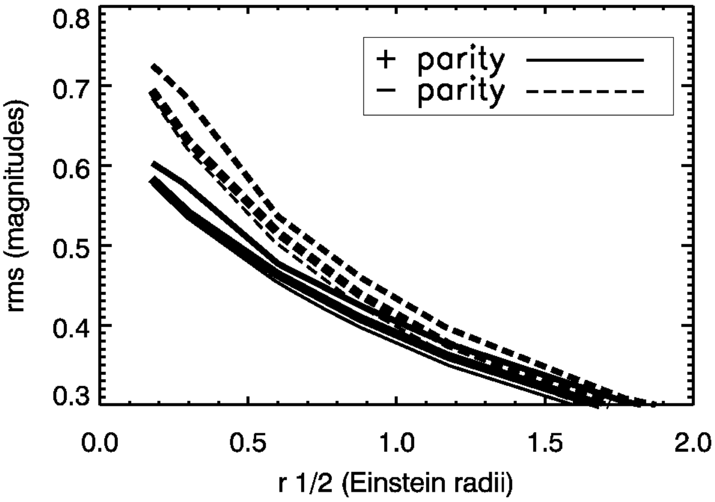


Figure 7. Magnification dispersion as a function of source size, for the three images, assuming $f = 100\%$ of the mass in stars.

Dobler, Keeton & Wambsganss (2007)

“Size is everything”:

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

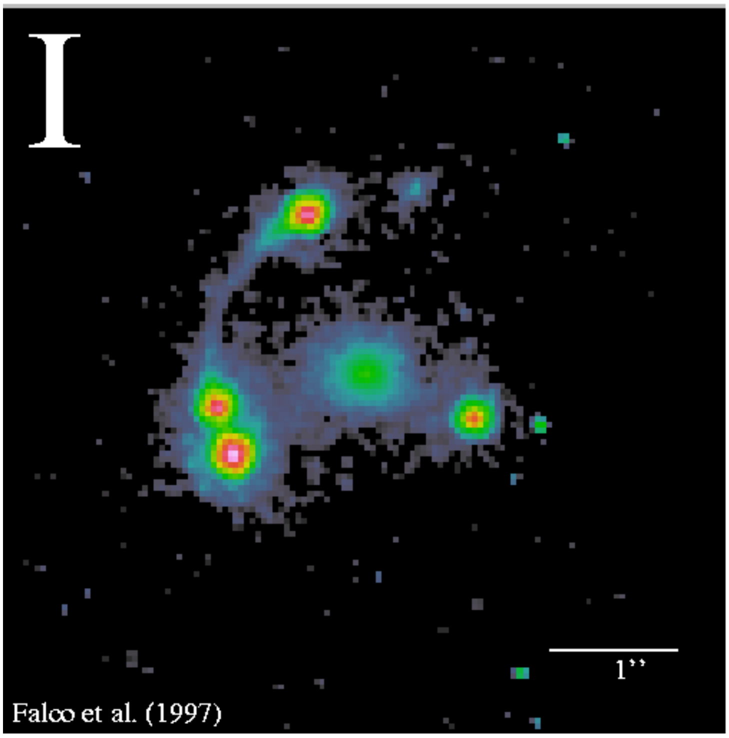


for circular disk models:

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



Falco et al. (1997)

CASTLES

MG0414+0534:

close pairs of bright images:

should be about equal in brightness

they are not!

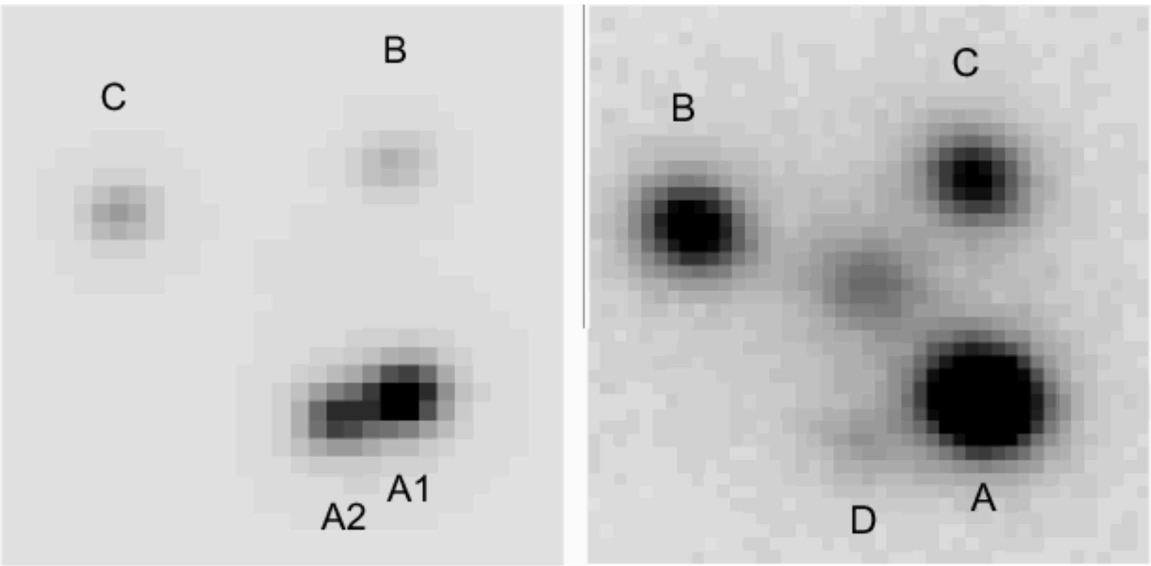
saddle point image demagnified!

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", $\Delta m = 0.5$ mag
(Weymann et al. 1980)

SDSS0924+0219:
0.66", $\Delta m = 2.5$ 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

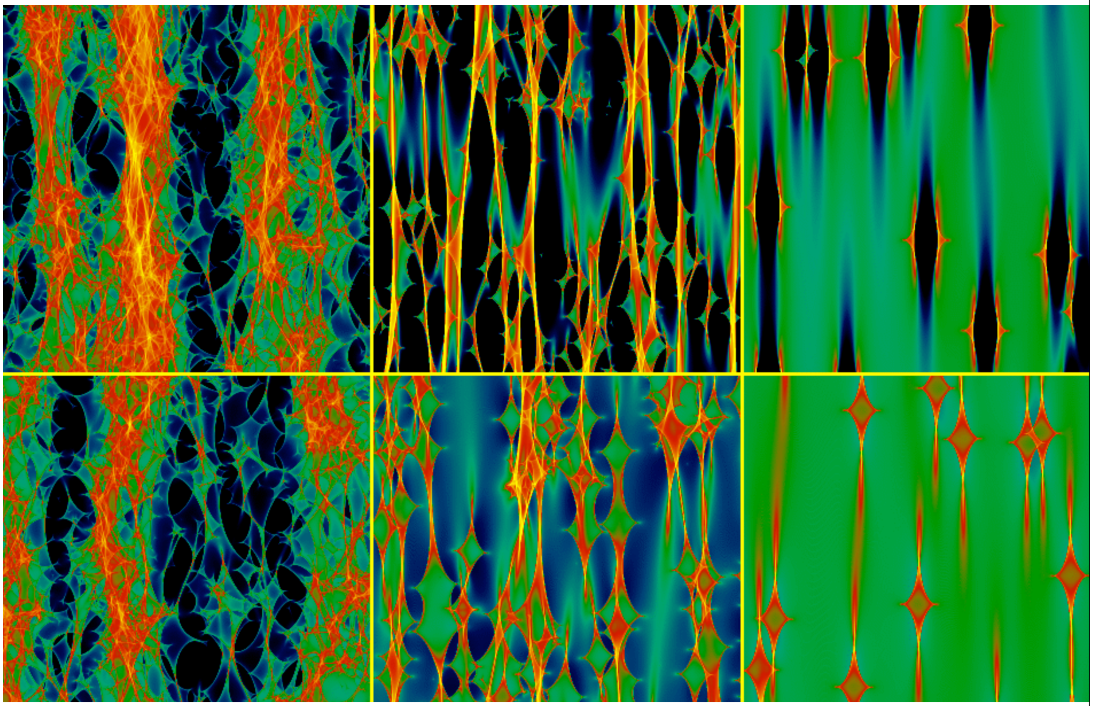
κ_{smooth} = 0%

= 85%

= 98%

saddle point image:

minimum image:

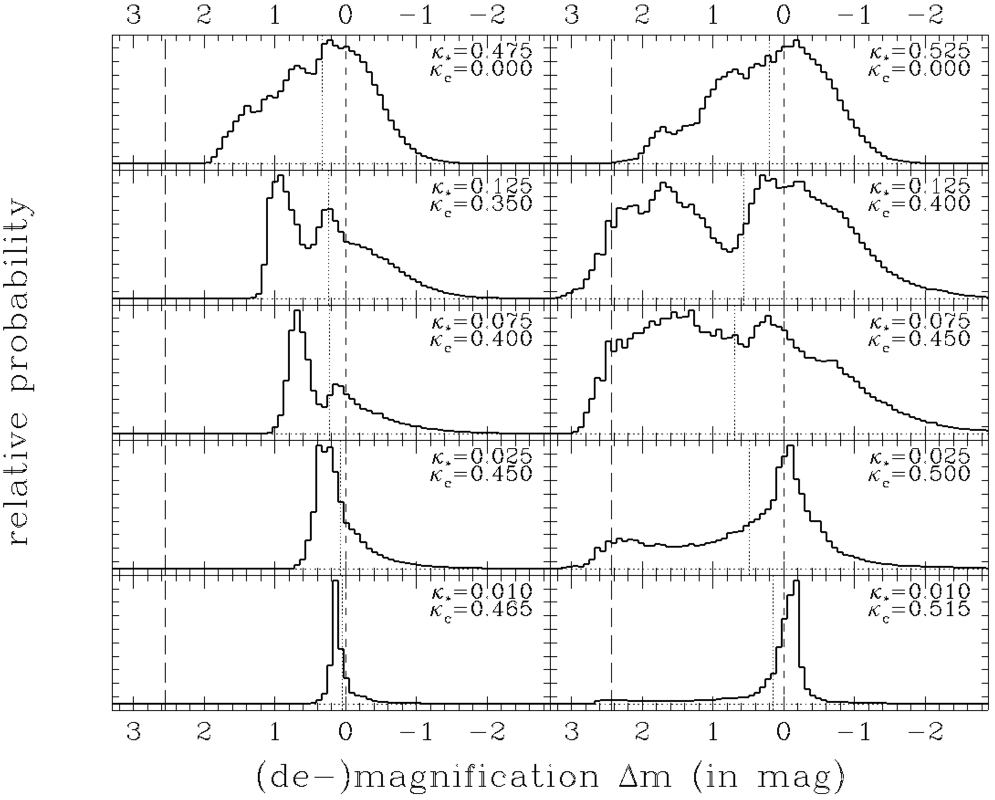


Quasar Microlensing at high magnification: suppressed saddlepoints and the role of dark matter (Schechter & Wambsganss 2002)

minimum:

saddle:

κ_{tot} = const in columns

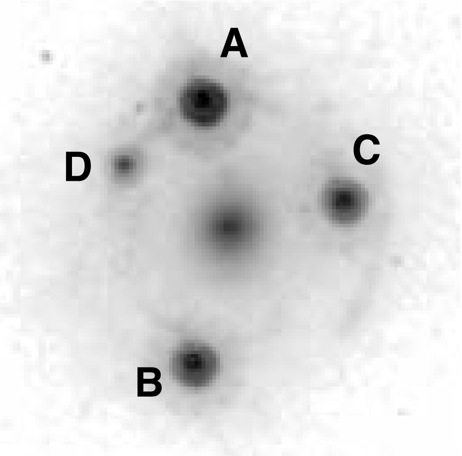


κ_{smooth} = 0%

= 85%

= 98%

“Most anomalous lensed quasar”: SDSS J0924+0219

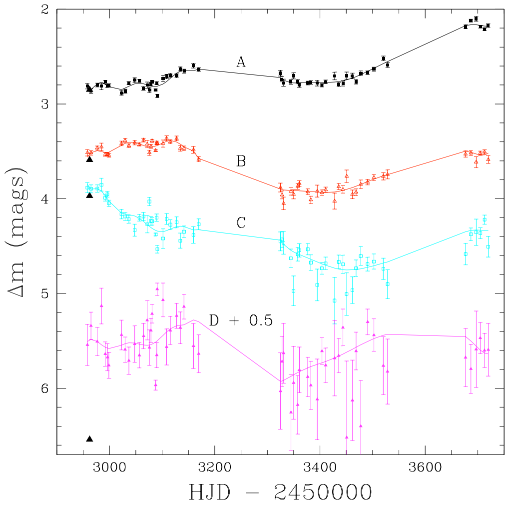


Keeton et al. (2006):

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

variability detected ⇒ microlensing!
⇒ $R_{BLR} \le 0.4\ R_E$

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



Morgan et al. (2006):

more variability ⇒ microlensing!

predictions: images C & D brighten

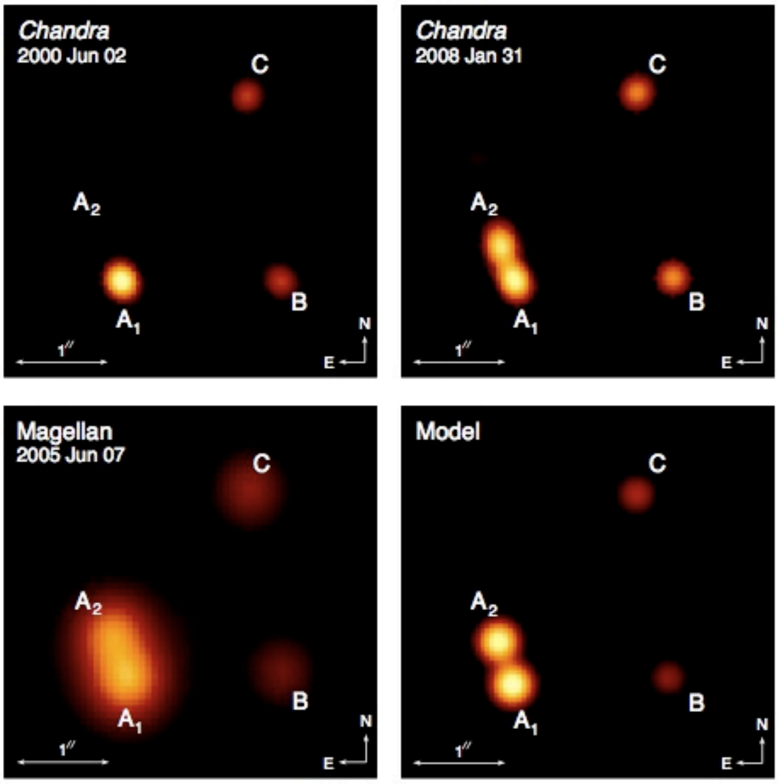
Keeton et al. (2006) & Morgan et al. (2006):
microlensing can explain the flux ratio anomaly

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

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

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

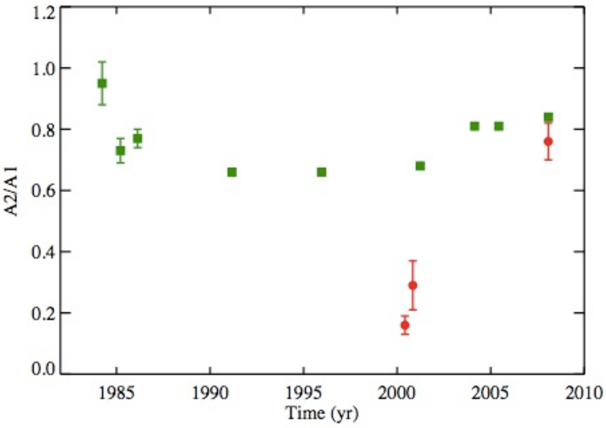
based on analyses of the X-ray fluxes of individual images in 2000 and 2008:



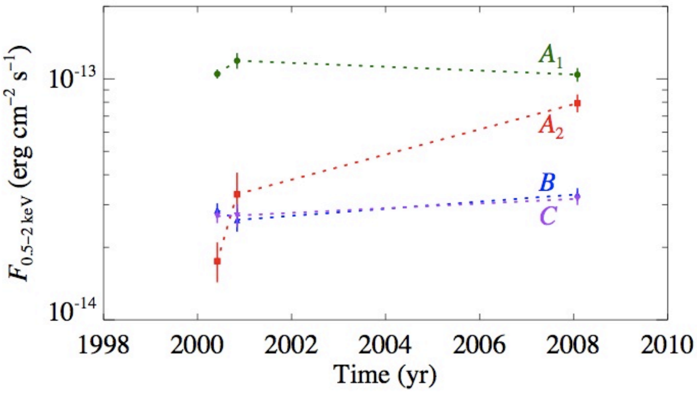
Pooley, Rappaport, Blackburne, Schechter, Schwab, Wambsganss (2009)

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

Optical (green) and X-ray (red) flux ratio between images A1 and A2 vs. time:



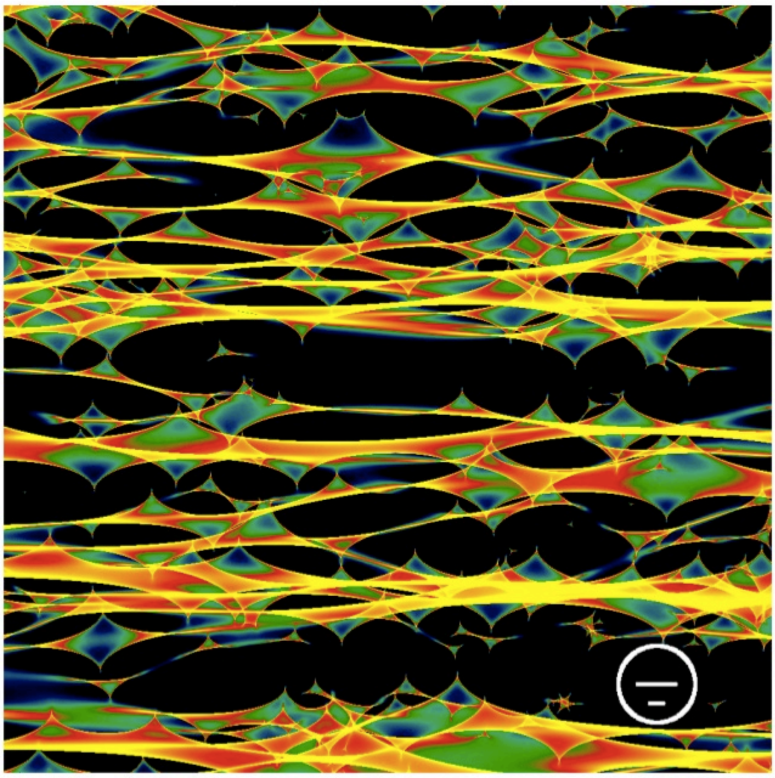
X-ray fluxes vs. time for individual images in PG 1115+080:



Pooley, Rappaport, Blackburne, Schechter, Schwab, Wambsganss (2009)

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

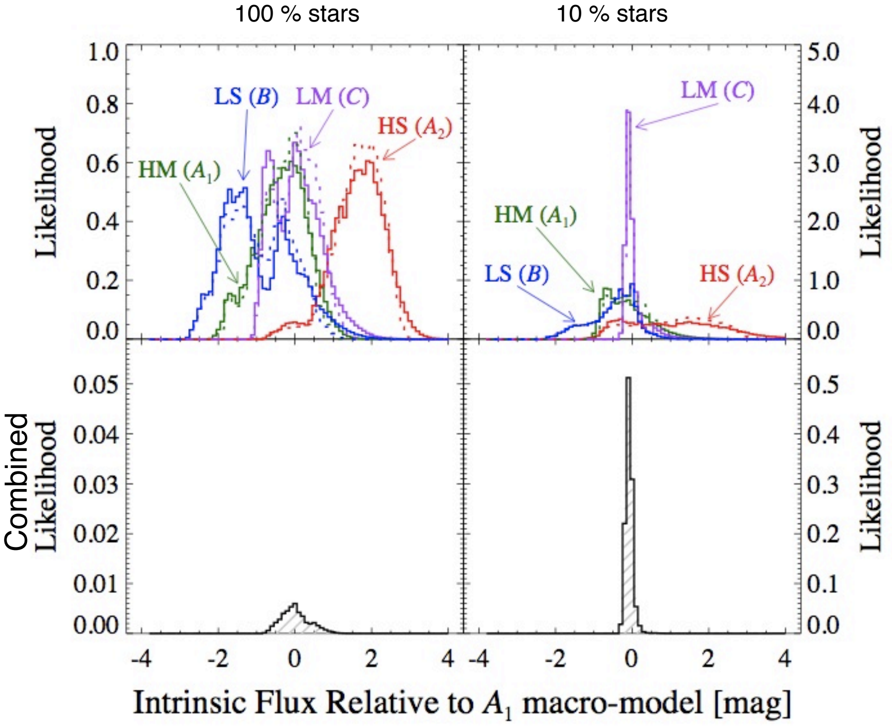
Microlensing magnification map for image A_2



Pooley, Rappaport, Blackburne, Schechter, Schwab, Wambsganss (2009)

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

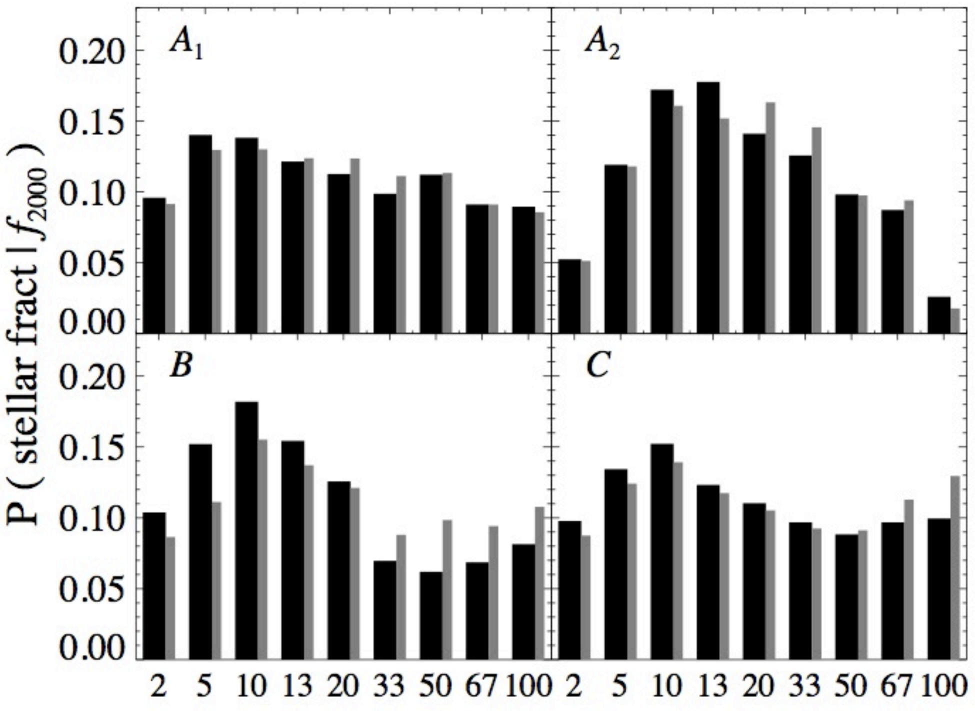
Bayesian analysis: likelihood to observe (microlensed) intensity O, given intrinsic (macrolensed) intensity I



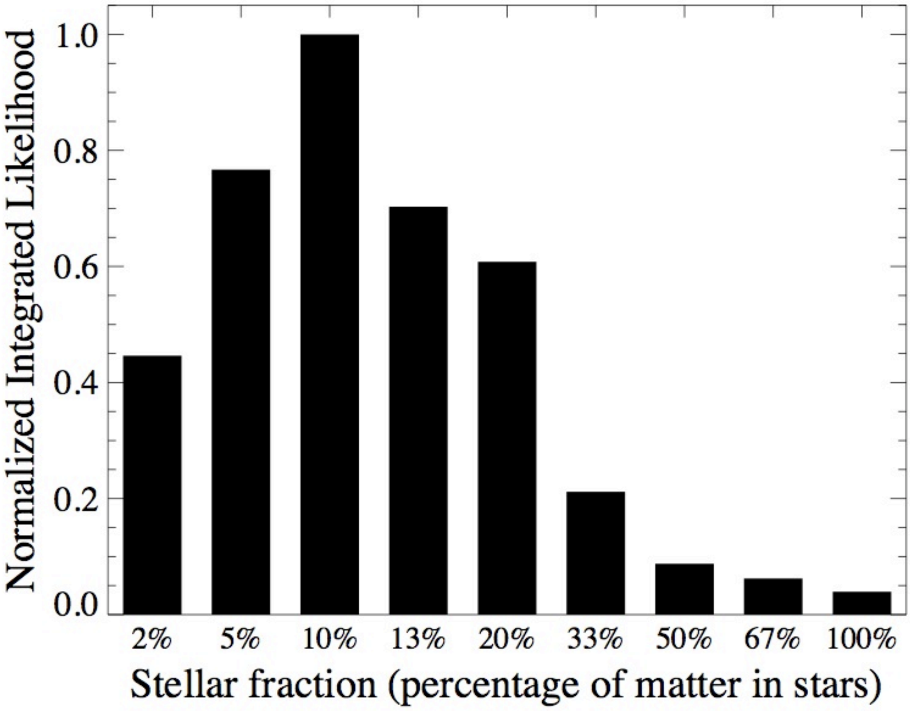
Pooley, Rappaport, Blackburne, Schechter, Schwab, Wambsganss (arXiv:0808.3299)

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

(Pooley, Rappaport, Blackburne, Schechter, Schwab, Wambsganss 2009)



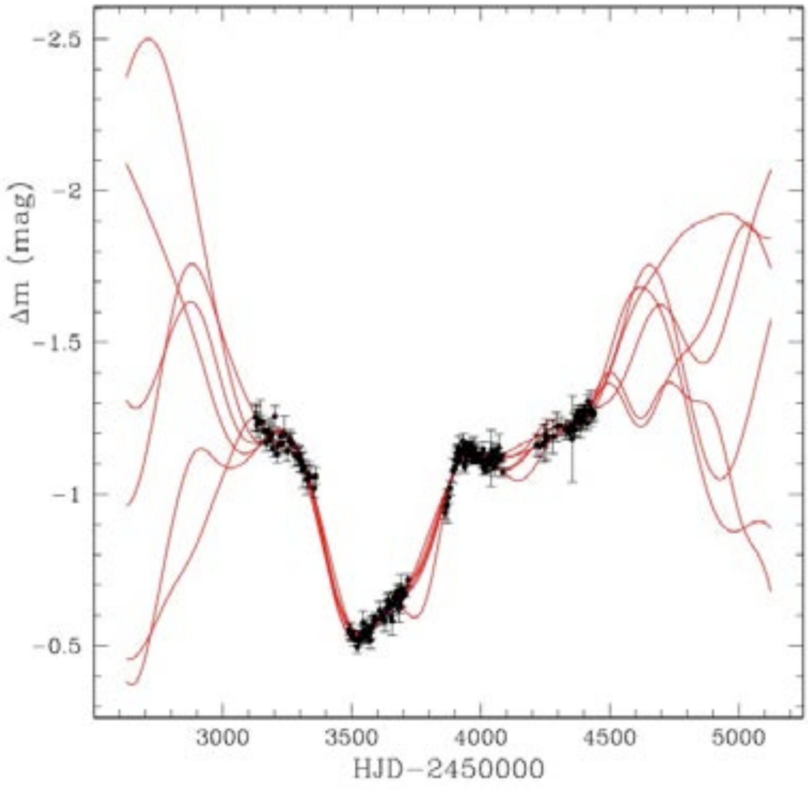
The Dark-Matter Fraction in the Elliptical Galaxy Lensing the Quasar PG 1115+080



Pooley, Rappaport, Blackburne, Schechter, Schwab, Wambsganss (arXiv:0808.3299)

Accretion disk profile from quasar microlensing

(Eigenbrod et al. 2008)

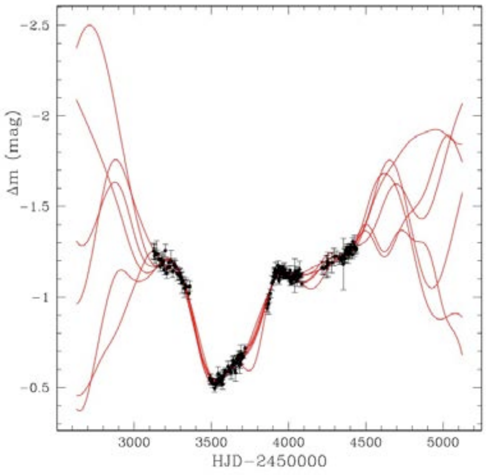


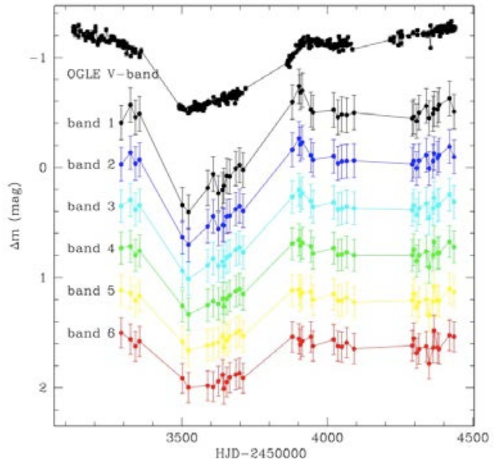
Q2237+0305:
$\Delta m = m_A - m_B$

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,





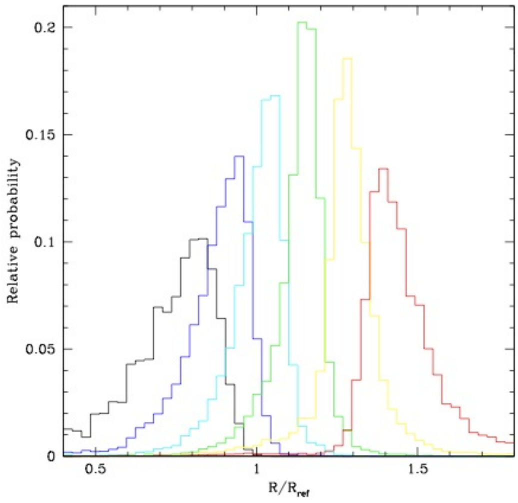
OGLE V-band data, fitted with different microlensing lightcurves

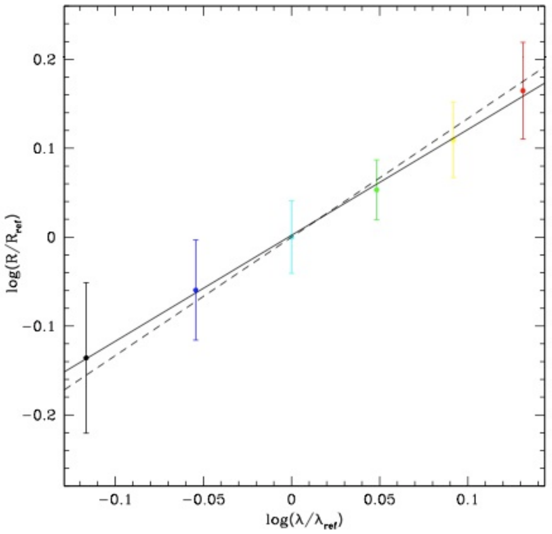
our spectroscopic data, reproduced as 6 “filters”:
39 epochs of spectrophotometric monitoring

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: $R \propto \lambda^{\zeta} \rightarrow \zeta = 1.2 \pm 0.3$

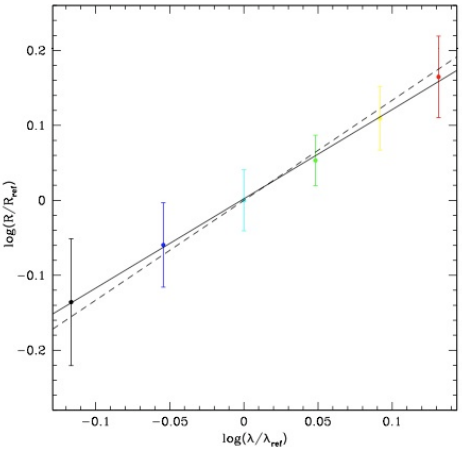
Accretion disk profile from quasar microlensing

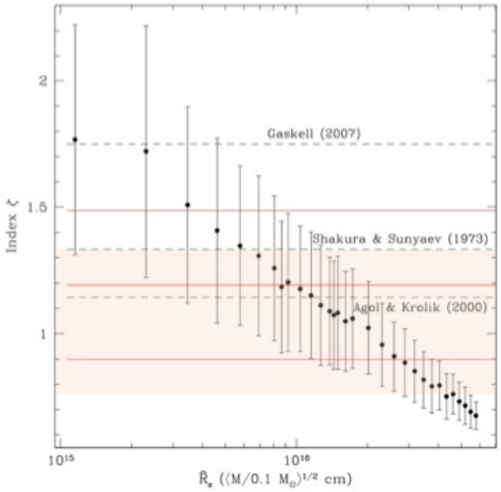
(Eigenbrod et al. 2008)

- we study: accretion disk profile: $T \propto R^{-\zeta}$

- we find: source responsible for the UV/optical continuum has an energy profile well reproduced by a power-law $R \propto \lambda^{\zeta}$ with $\zeta = 1.2 \pm 0.3$

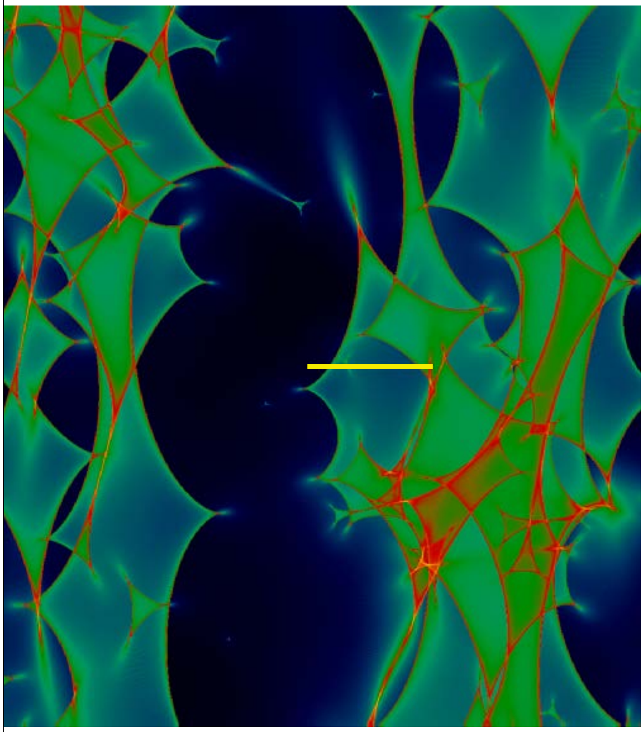
- absolute scale with velocity prior:

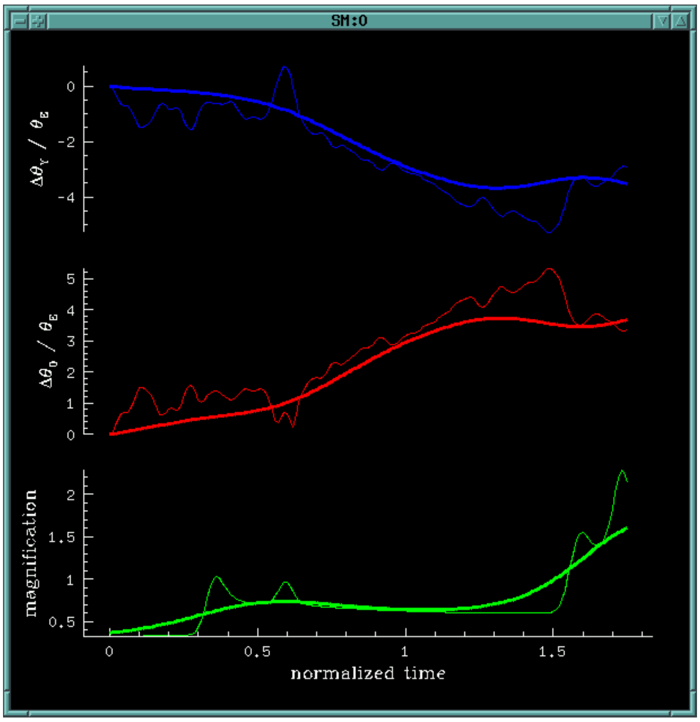




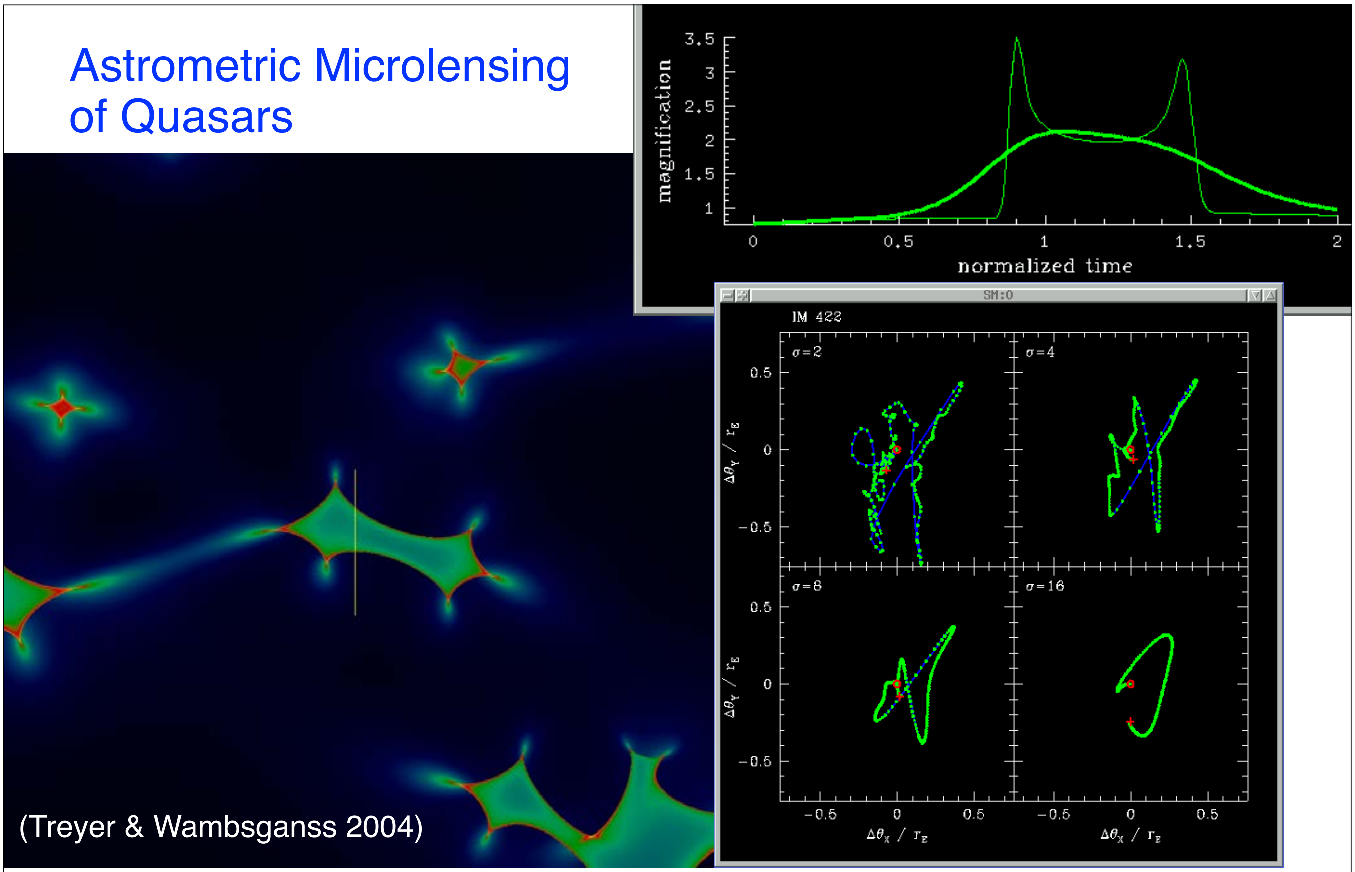
Astrometric microlensing of quasars

(Treyer & Wambsganss 2004)





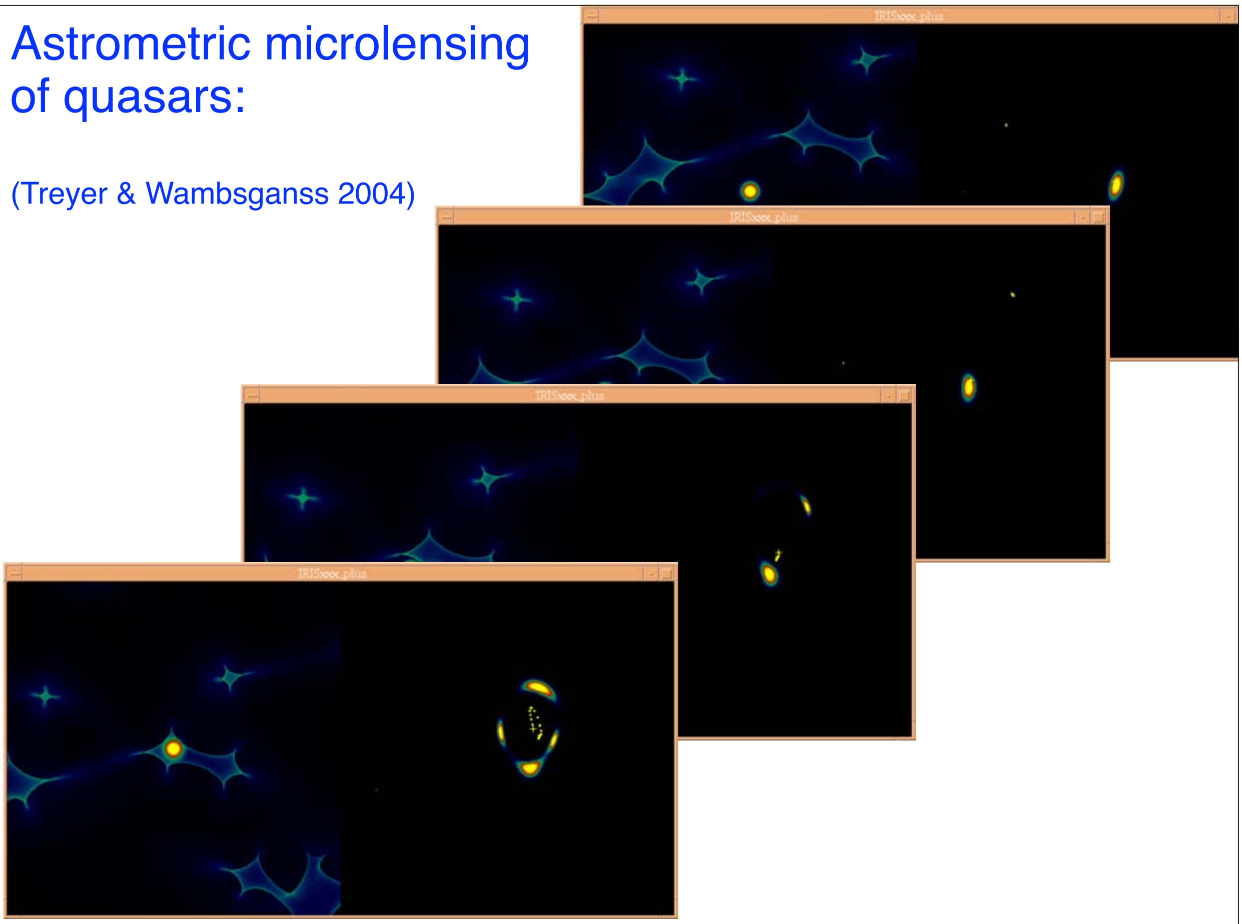
Astrometric Microlensing of Quasars



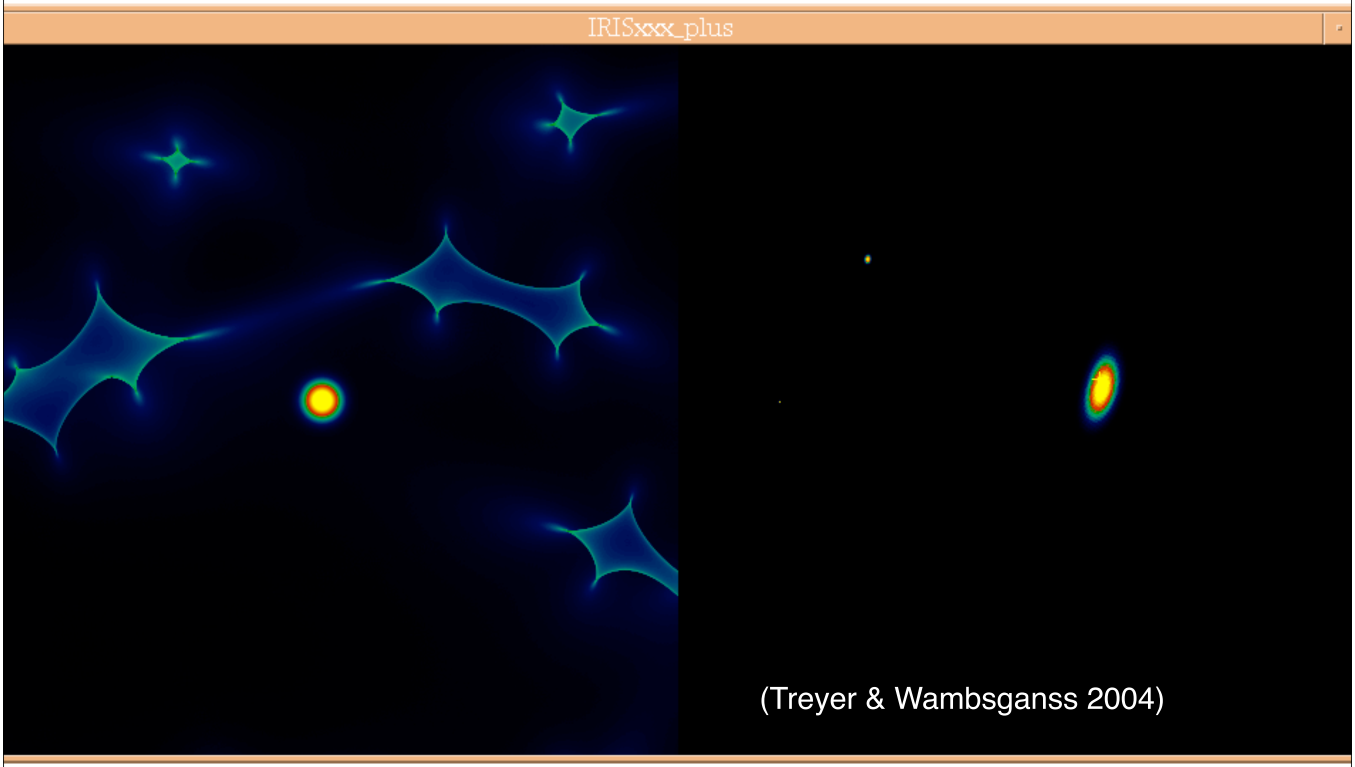
(Treyer & Wambsganss 2004)

Astrometric microlensing of quasars:

(Treyer & Wambsganss 2004)



Astrometric microlensing of quasars

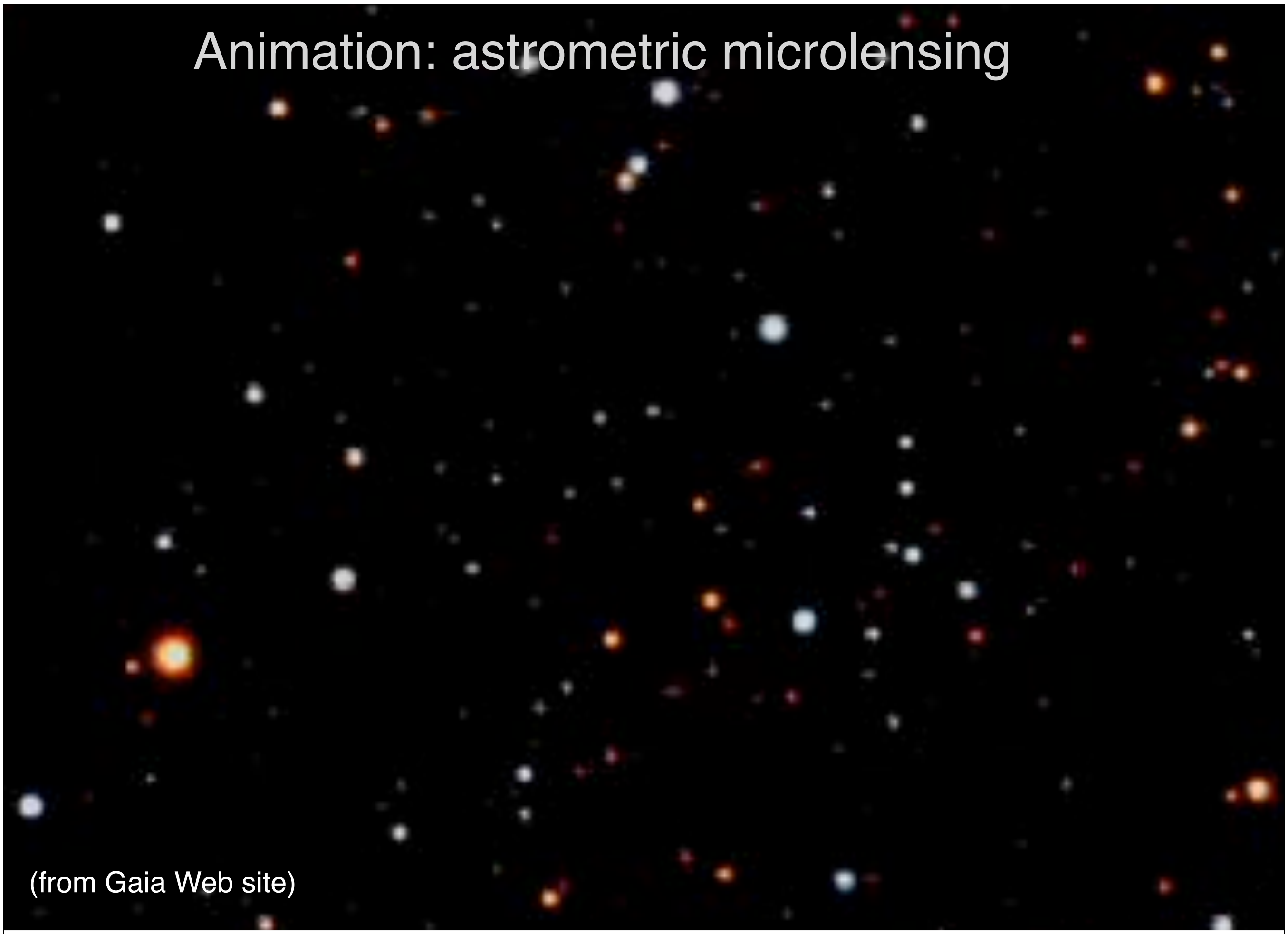


(Treyer & Wambsganss 2004)

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!
- effect on surface mass density/external shear:
    - strongest for "interesting cases" with kappa = gamma = 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 microarcseconds
- exciting opportunity for detection:
    - SIM, Gaia, VLTI or other high angular resolution instrument in next few years ...

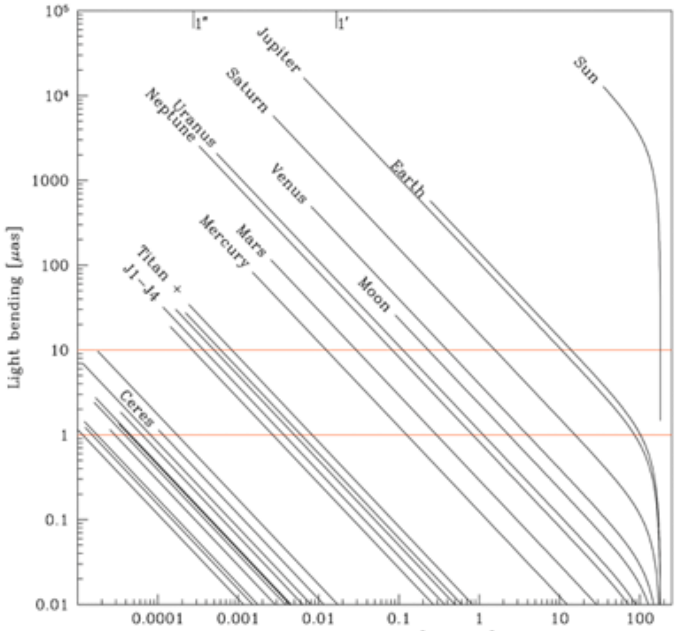
Animation: astrometric microlensing



(from Gaia Web site)

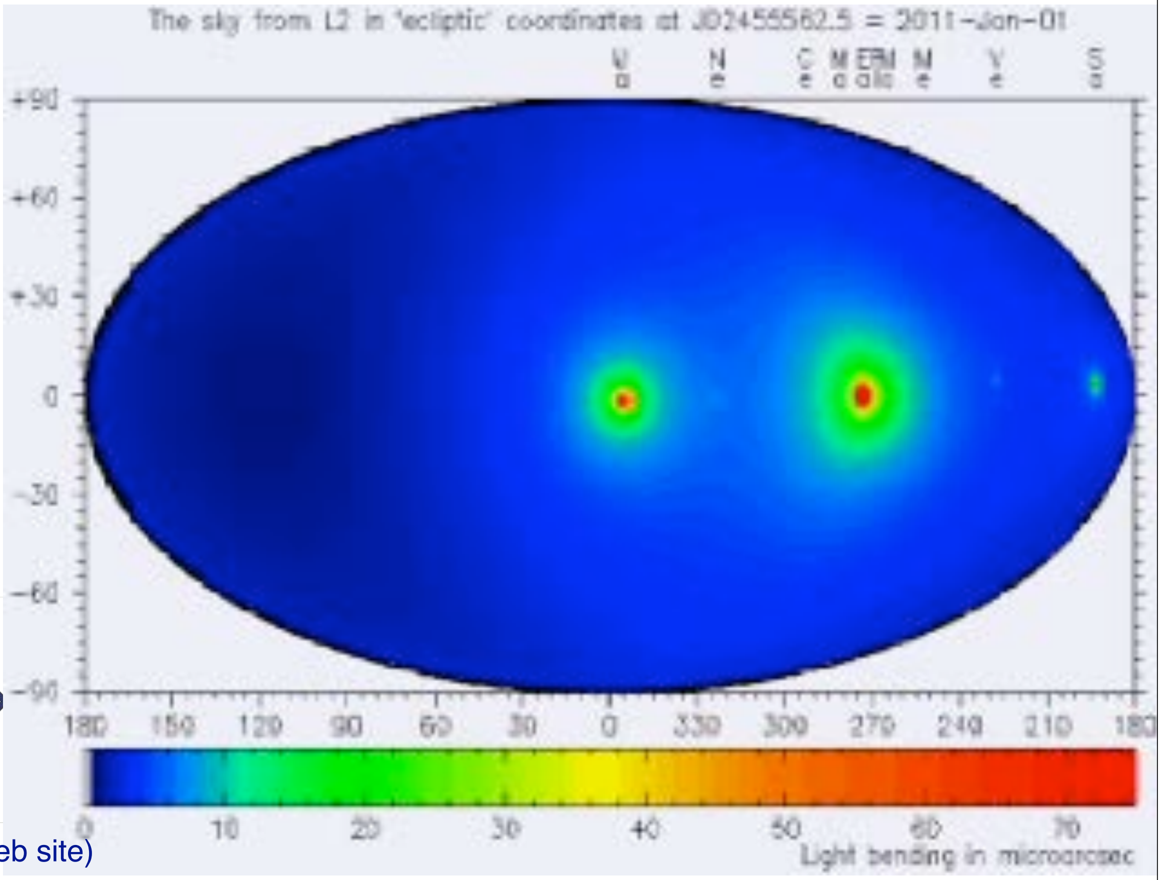
The **Future** of Astrometric Microlensing: Gaia

Deflection angle by solar system objects as function of angular separation



(from Gaia Web site)

The **Future** of Astrometric Microlensing: Gaia



(from Gaia Web site)

Microlensing of the broad line region in 17 lensed quasars

D. Sluse[1,2], D. Hutsemékers[3], F. Courbin[4], G. Meylan[4], and J. Wambsganss[1]

Microlensing effects depend on source size:
compact continuum region (accretion disk) best suited!

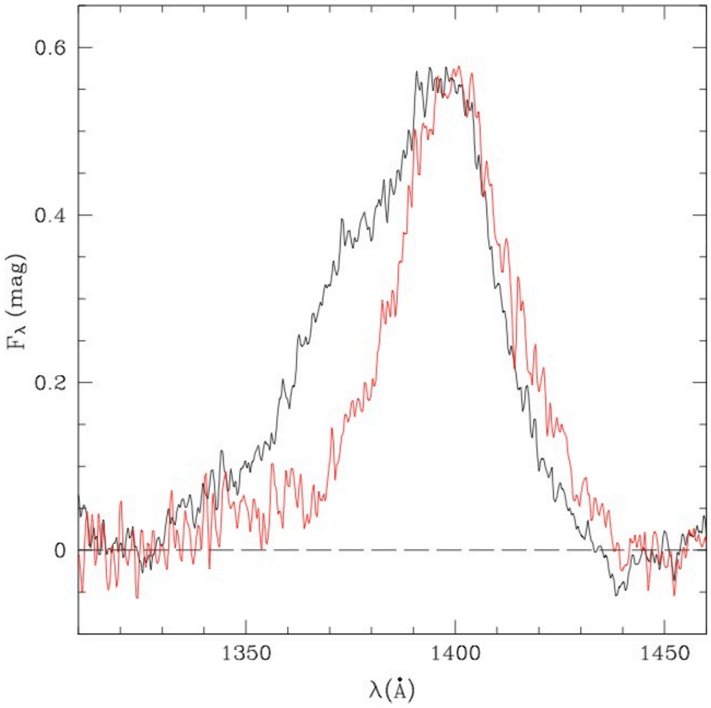
What about the (large) broad line region?
Schneider & Wambsganss (1990): should be detectable via
change of line shapes over time or between images

Sluse et al. (2012): Detection of BLR microlensing

14 (out of 17): Microlensing of continuum region
12 (out of those 14): Microlensing of BLR, line shapes
significantly different

Microlensing of Quasar Broad Emission Lines: Constraints on Broad Line Region Size

Guerras, Mediavilla, Jimenez-Vicente, Kochanek, Munoz, Falco, Motta (2012)



→ Next talk by Veronica Motta!