COSMOGRAIL: the COSmological MOnitoring of GRAvItational Lenses

Time delays and the Hubble constant

Bangalore - January 2007

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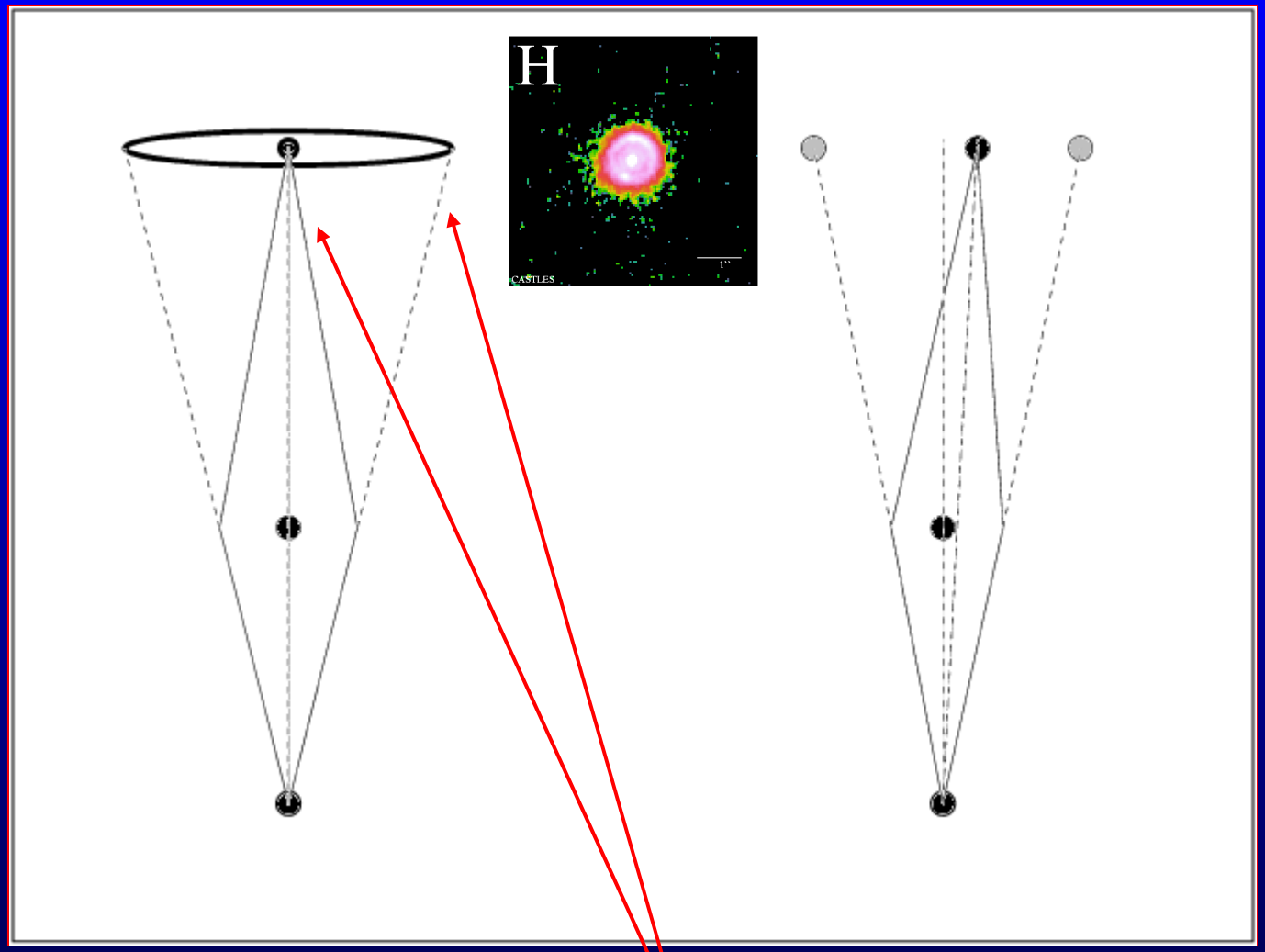
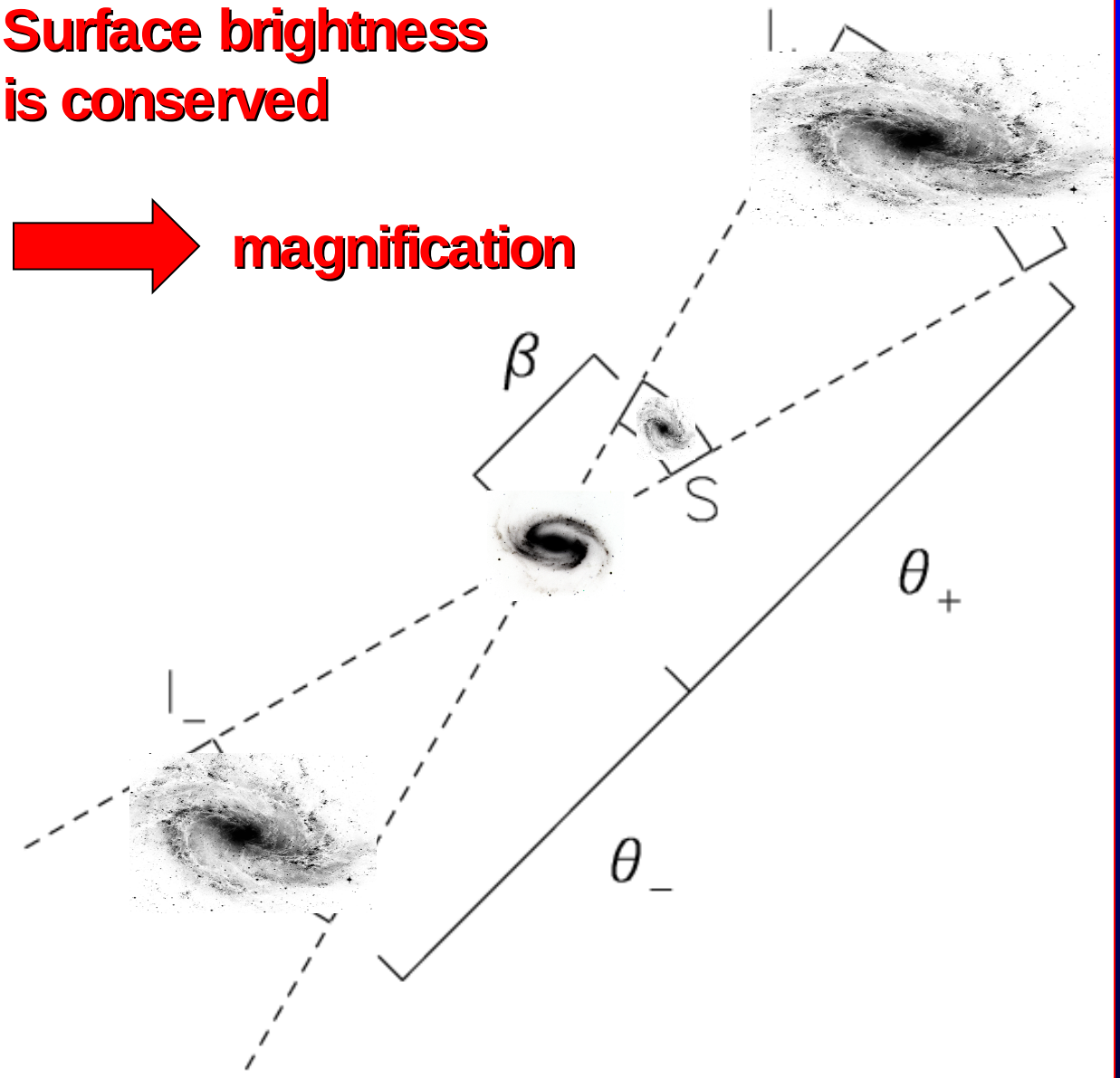
http://lastro.epfl.ch

Basics of gravitational lensing



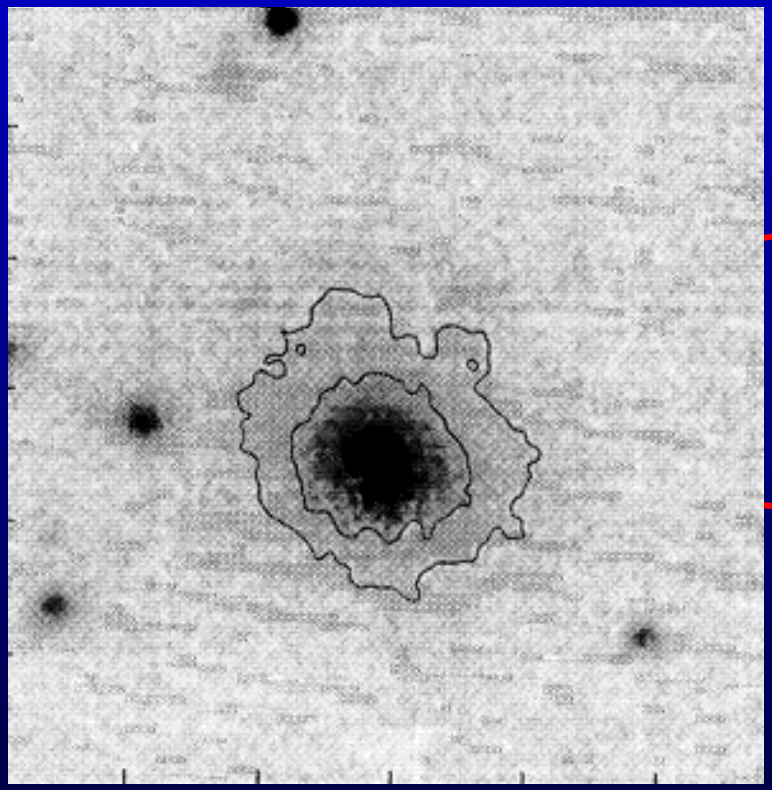
$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{ds}}{D_{od}D_{os}}}.$$

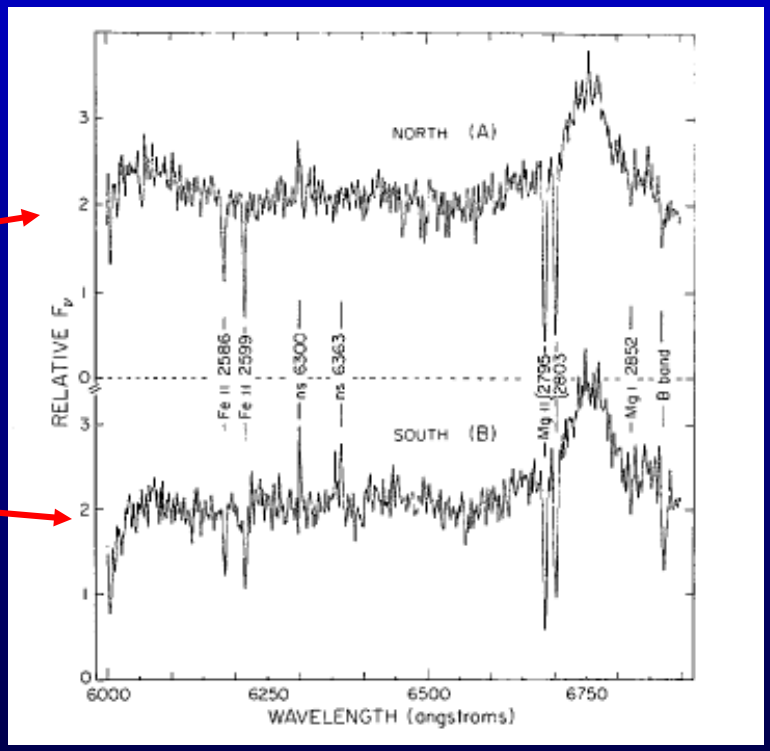
Surface brightness is conserved



The first discoveries and surveys

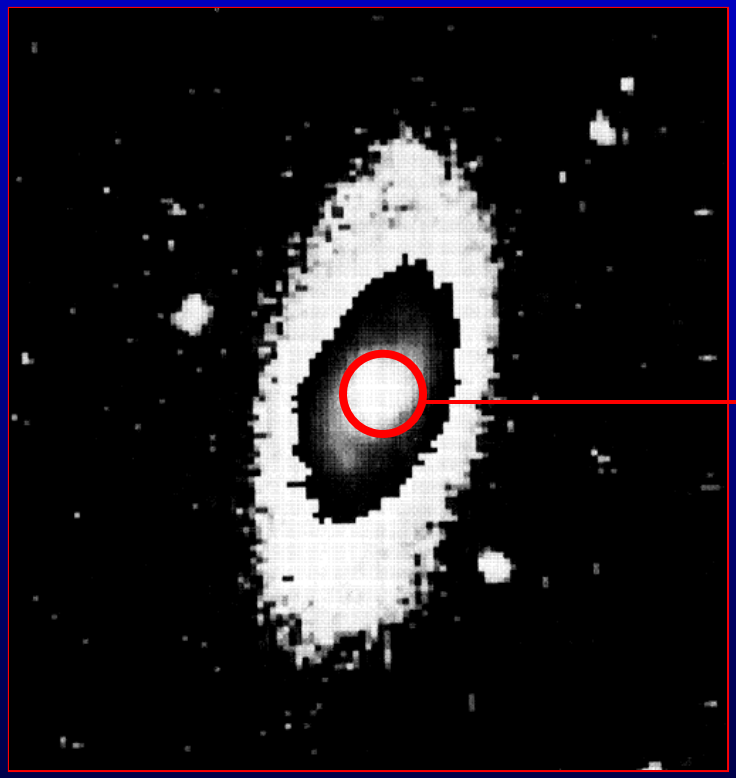
The first double: Q 0957+561

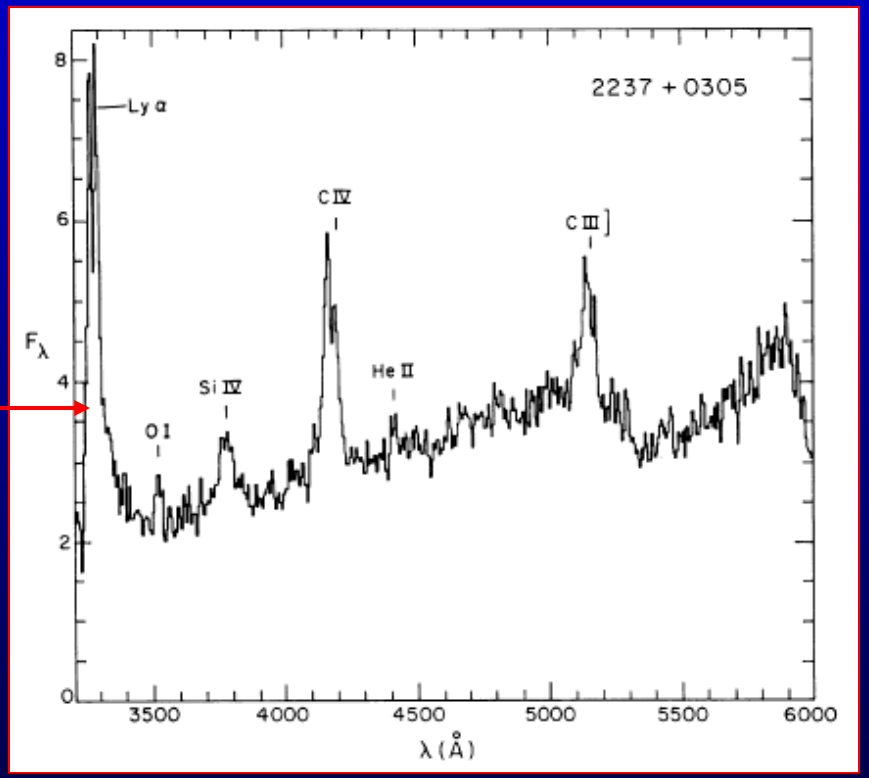




Walsh et al., 1979, Nature 279, 381
Weymann et al. 1979, ApJ 233, L43

Discovery of the Einstein cross



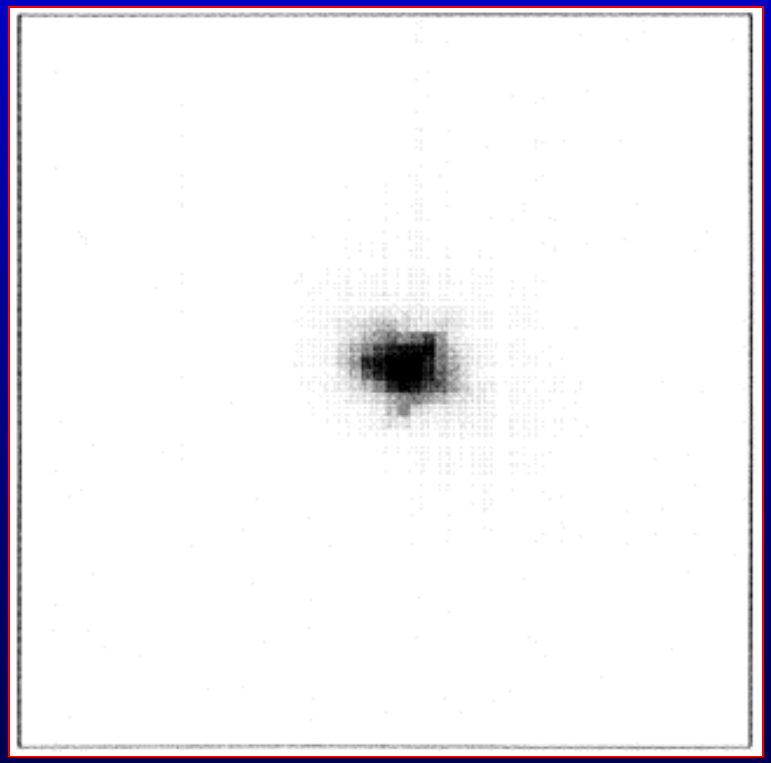


Huchra et al. 1985, AJ 90, 691

Discovery of the Einstein cross

- Almost perfect alignment with the the core of the galaxy

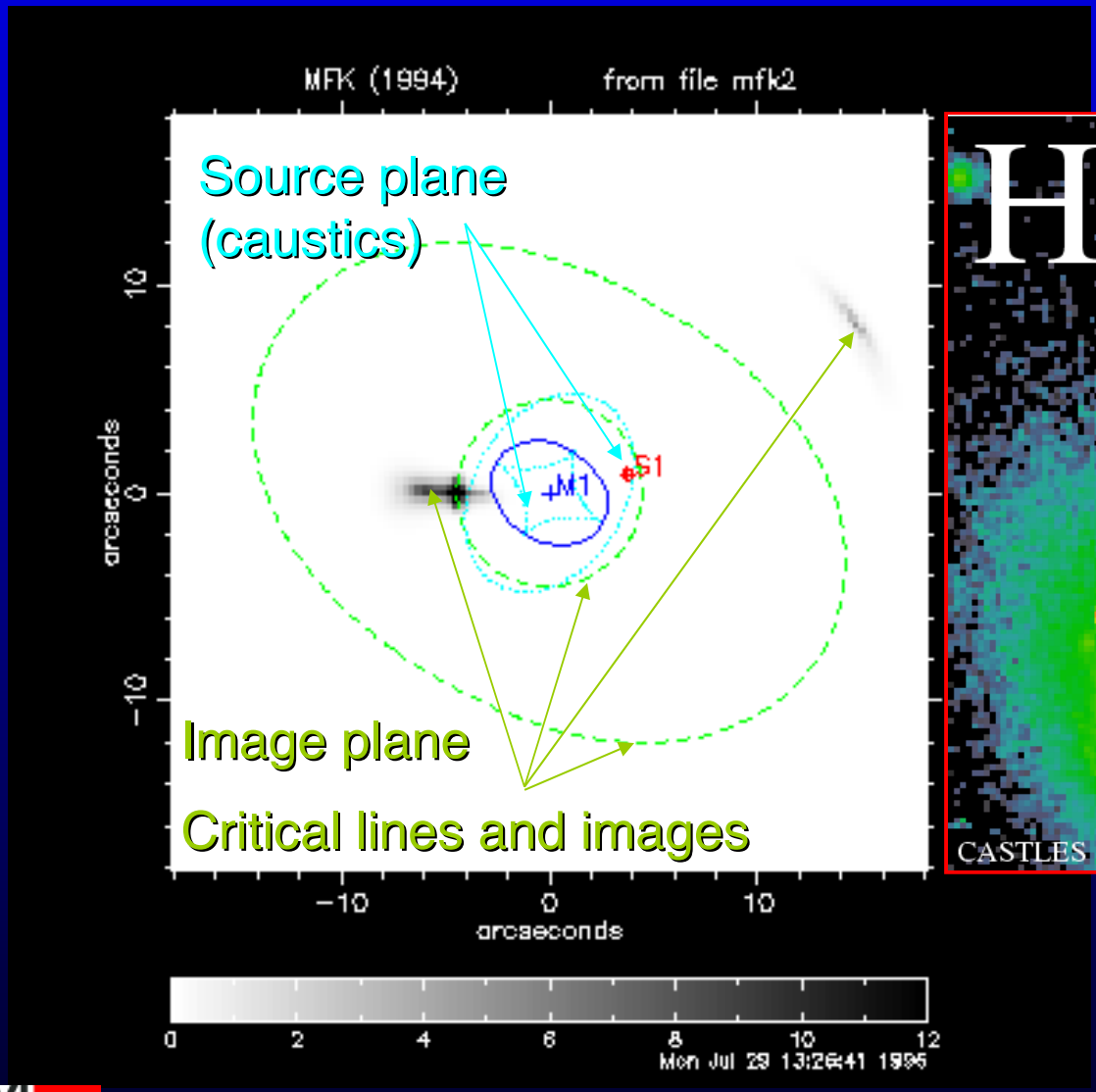
- Unusually bright nucleus

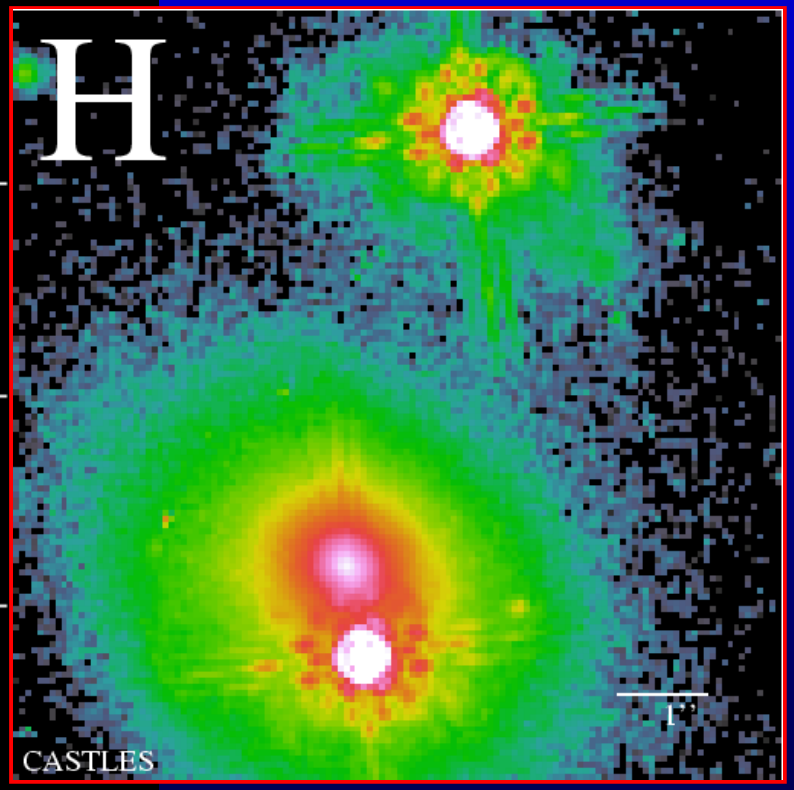


Schneider et al. 1988, AJ 95, 1619

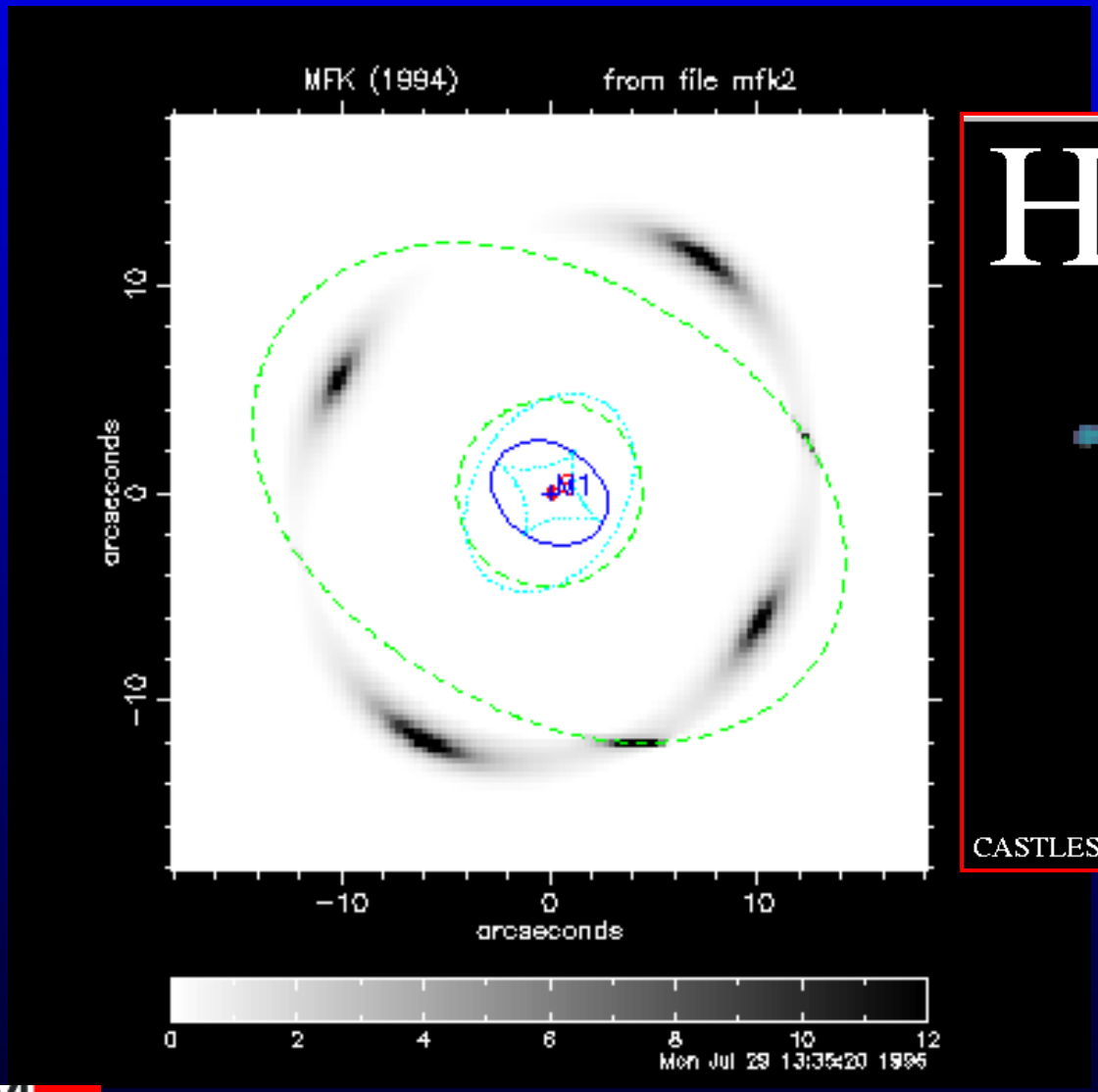
Image configurations

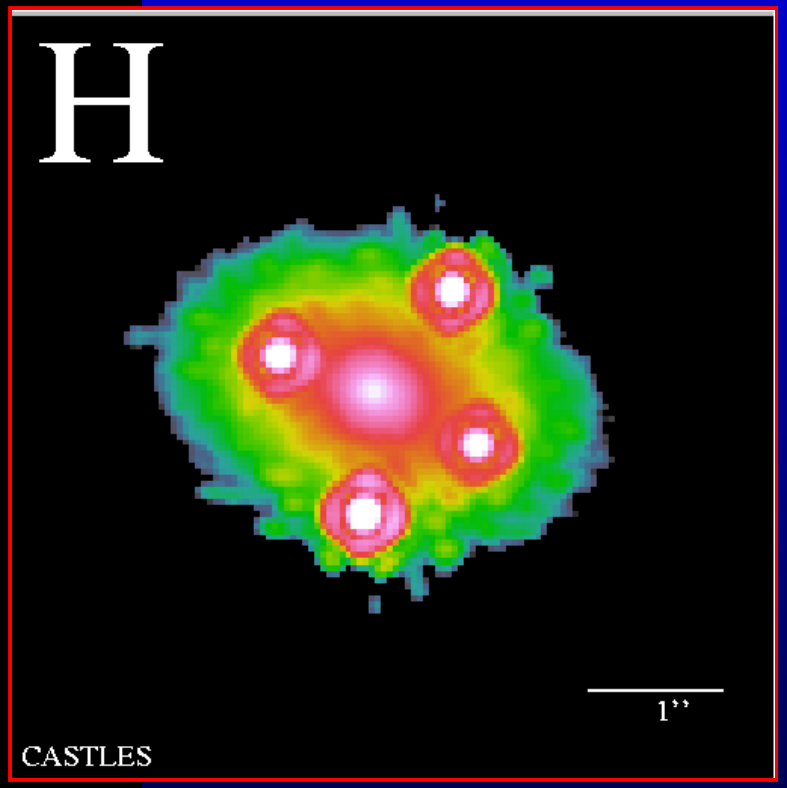
Double


MFK (1994)
from file mfk2
Source plane
(caustics)
M1
S1
Image plane
Critical lines and images
arcseconds
10
0
−10
−10
0
10
arcseconds
0
2
4
6
8
10
12
Mon Jul 29 13:26:41 1996

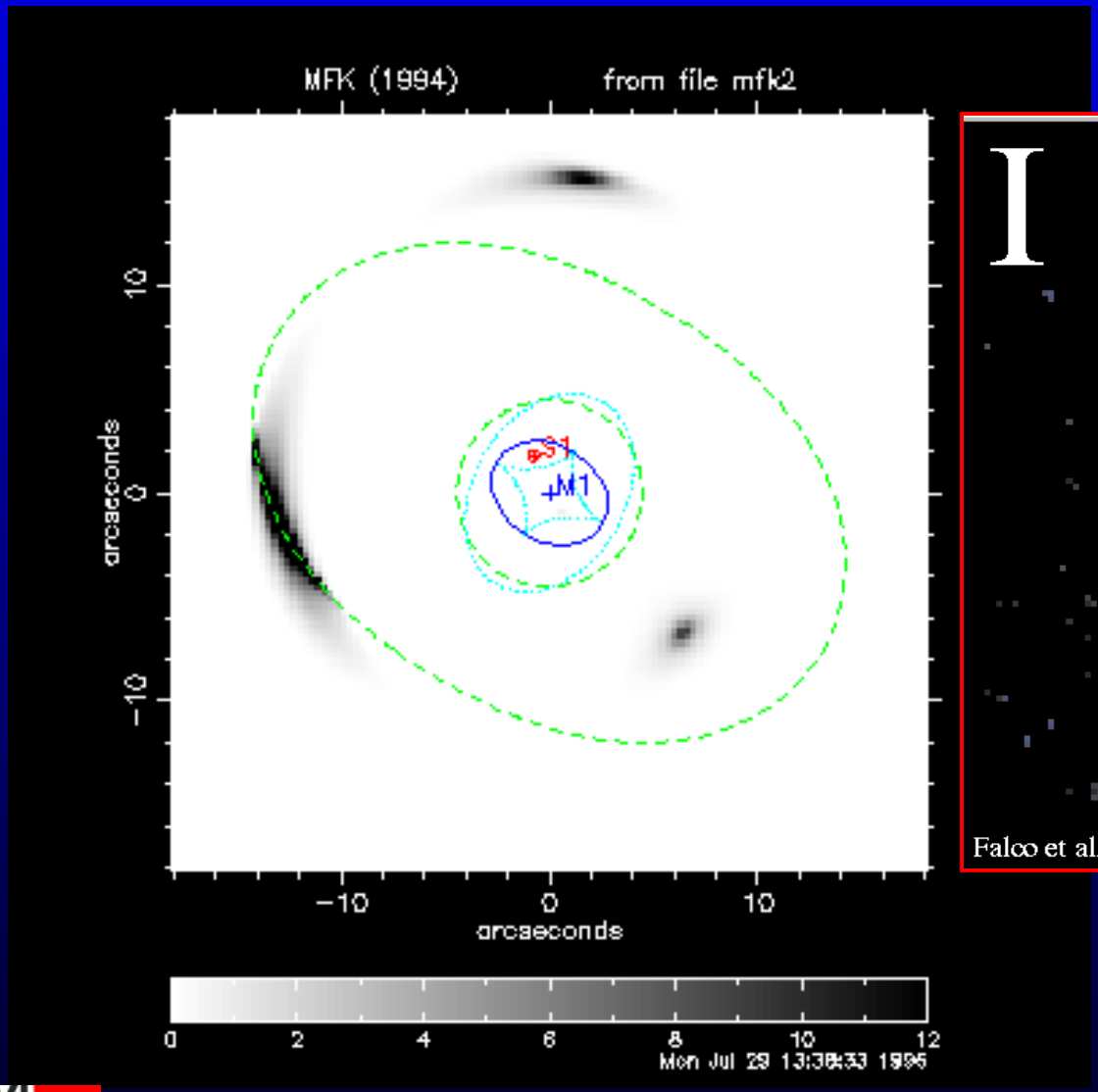

H
CASTLES

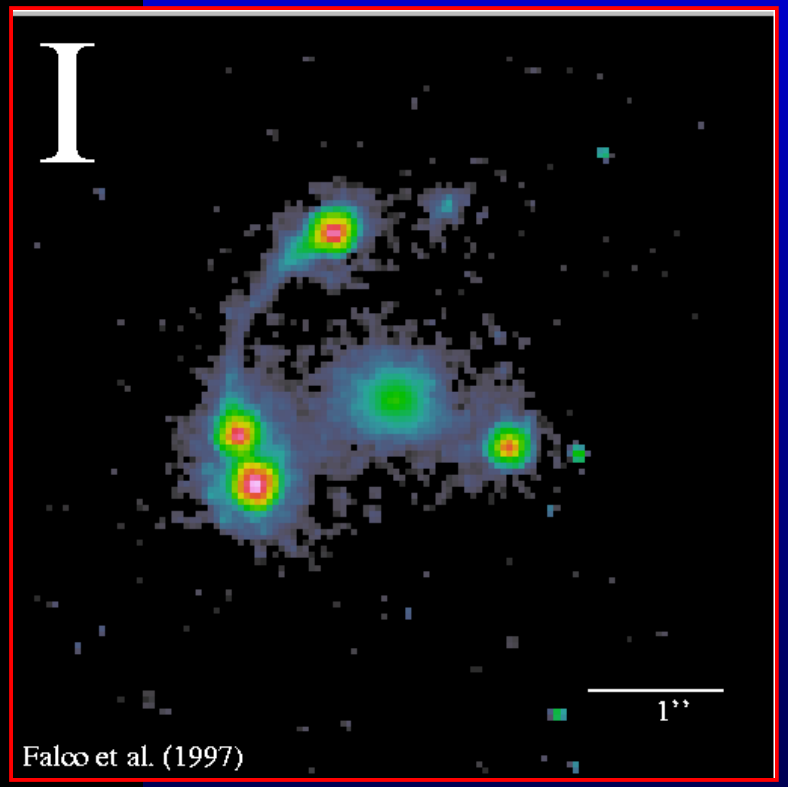
Symetric quadruple



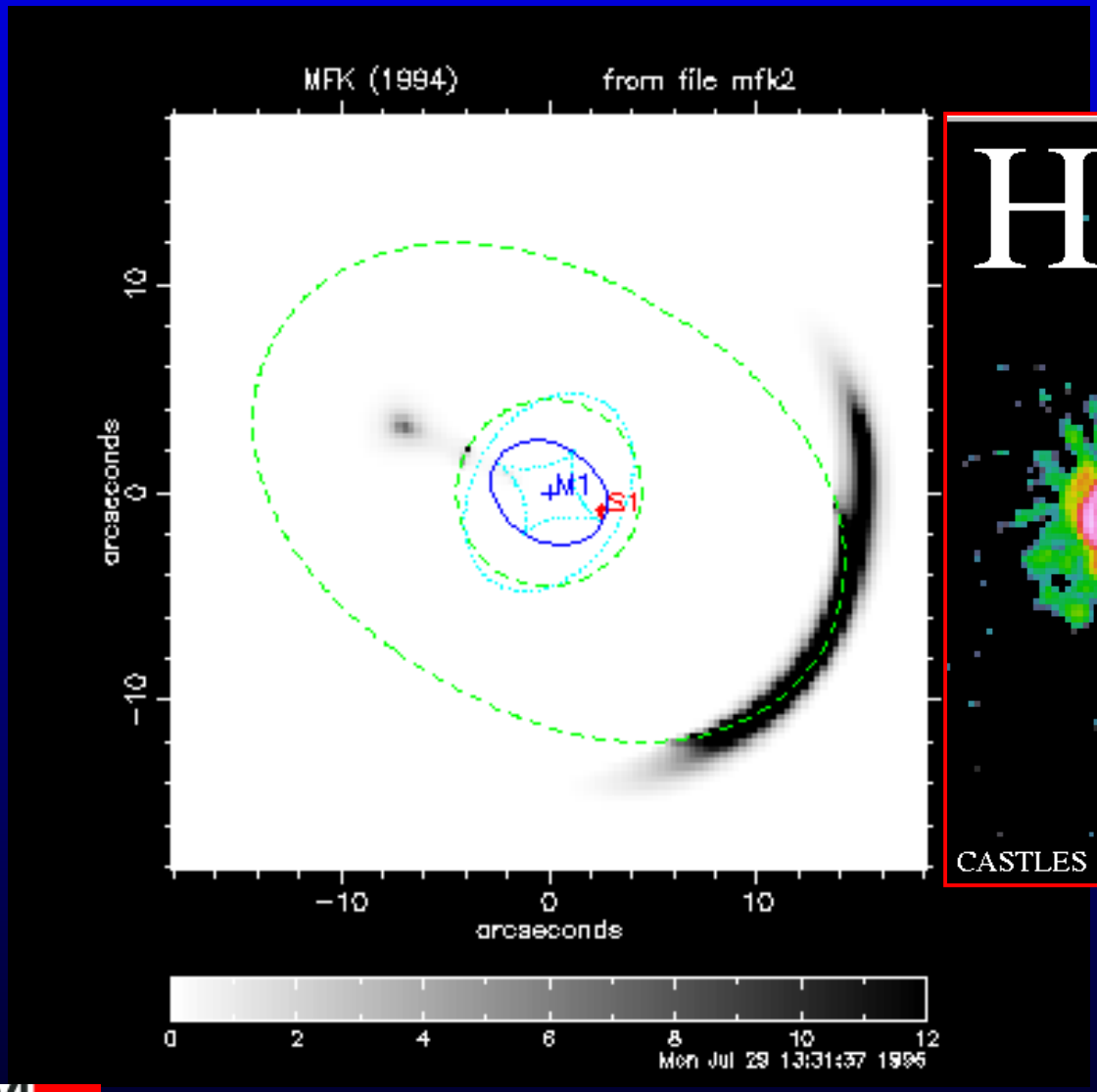


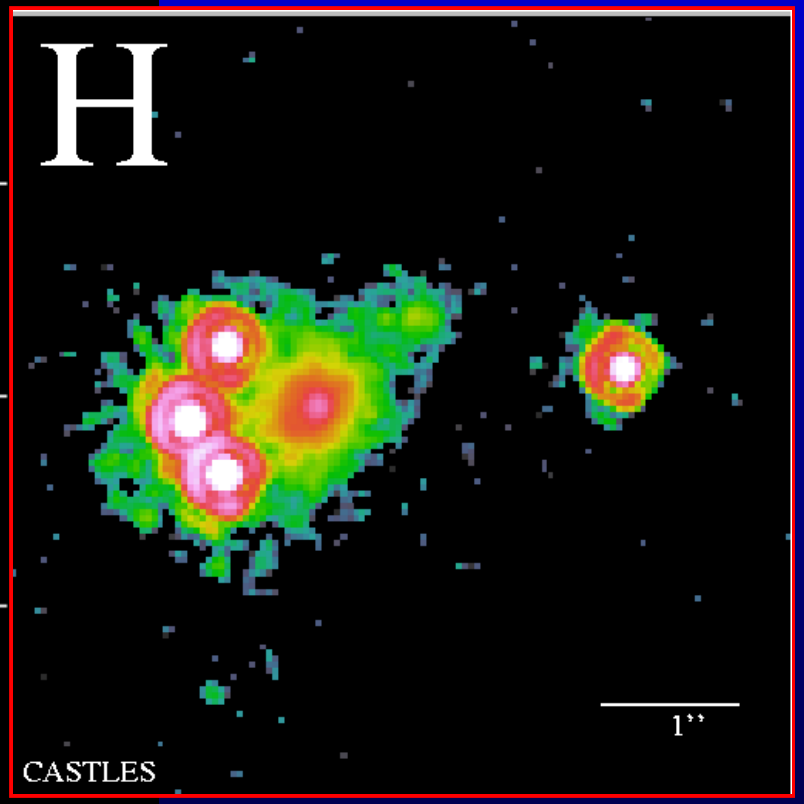
Asymmetric quadruple



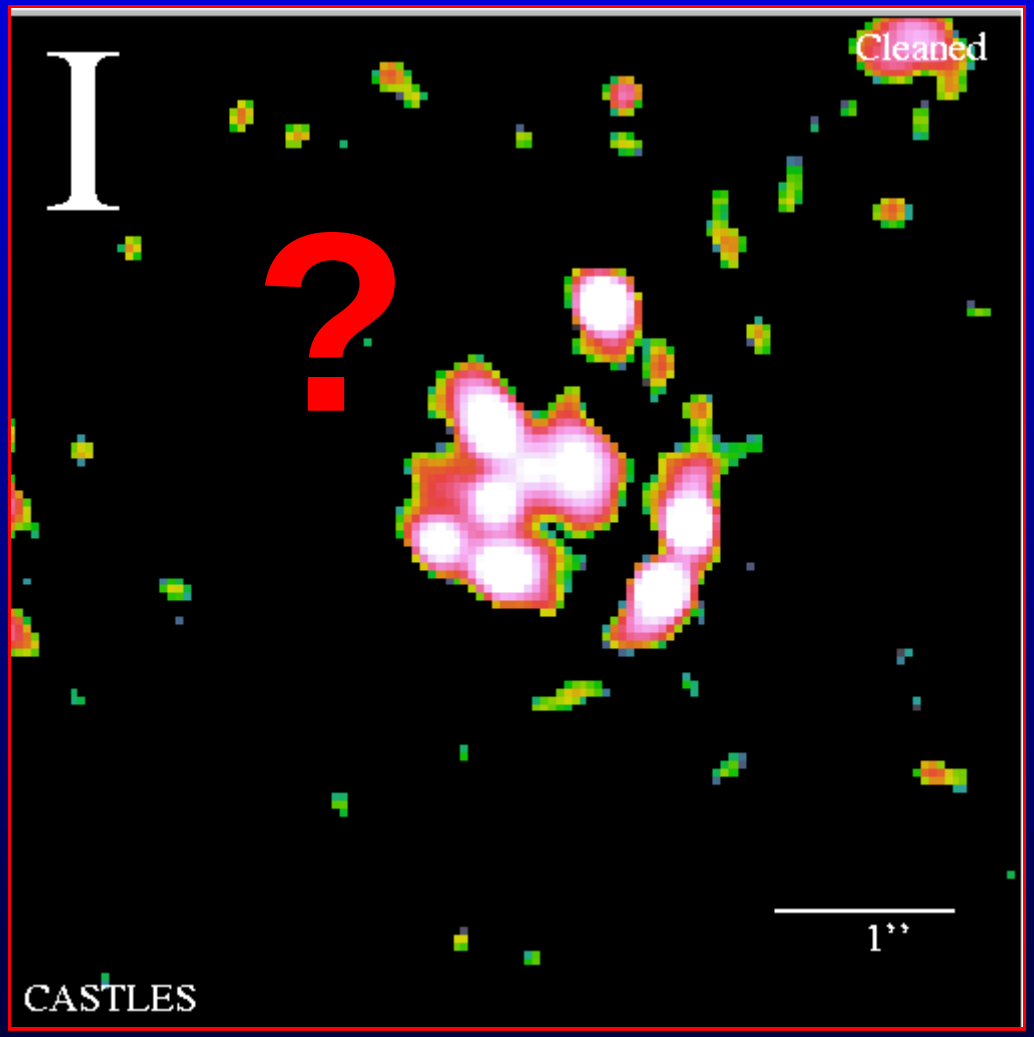


Long axis quadruple





Weird



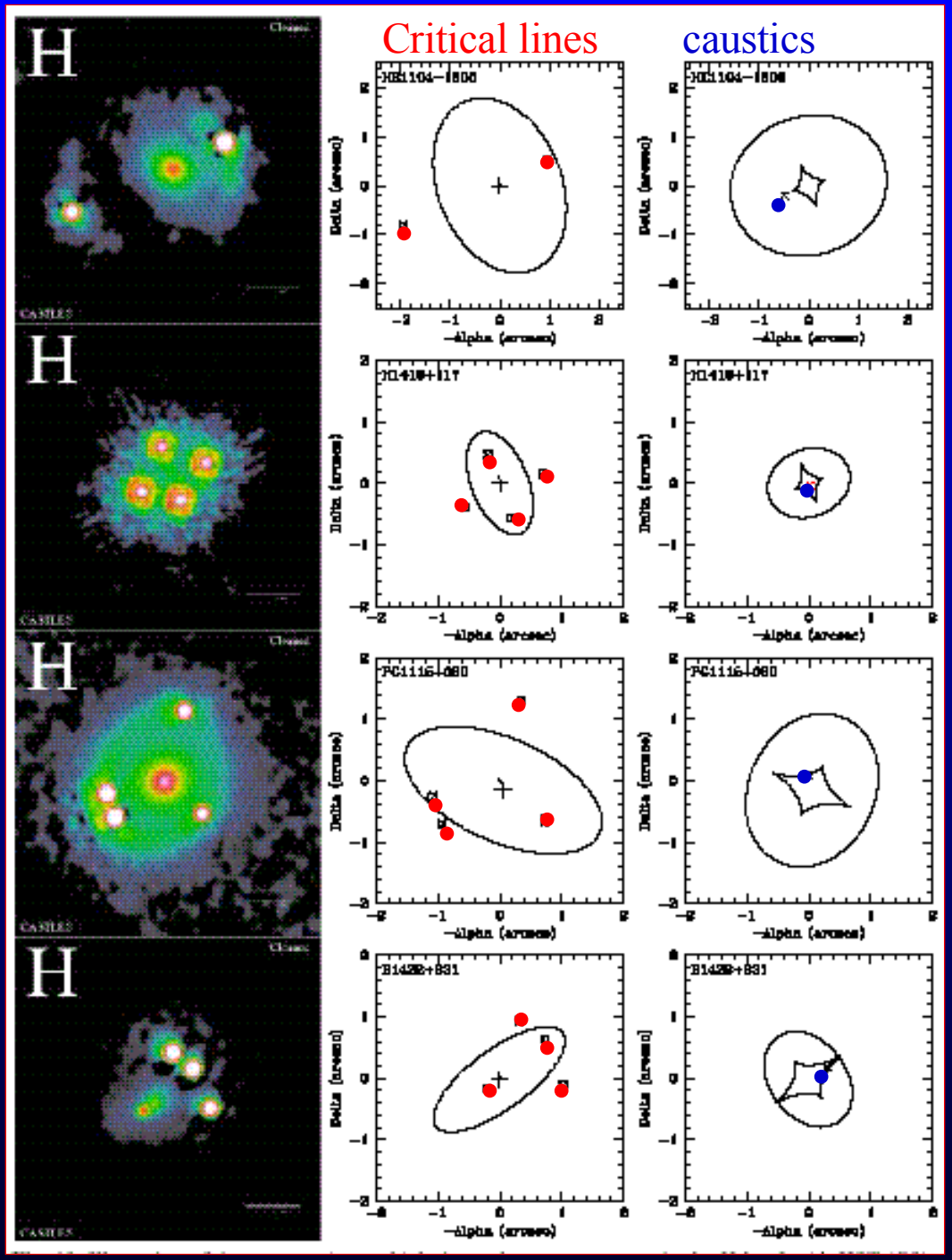
Rusin et al. 2001, ApJ 557, 594

HE1104-1805

H1413+117

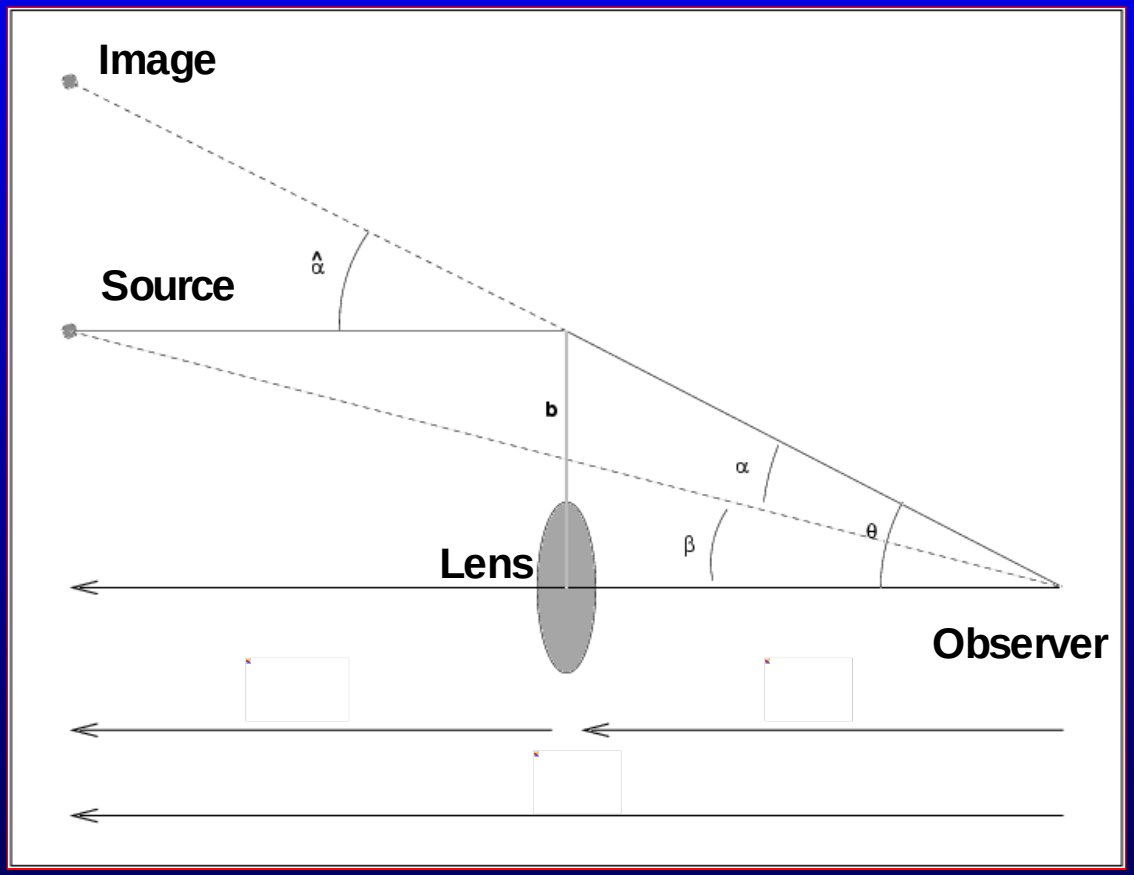
PG1115+080

B1422+231



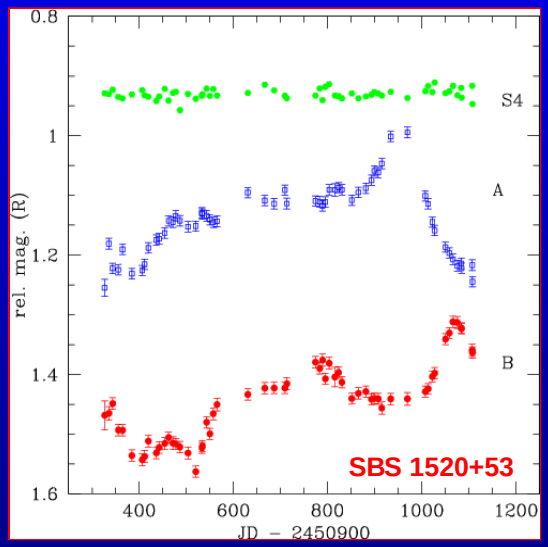
The time delay method

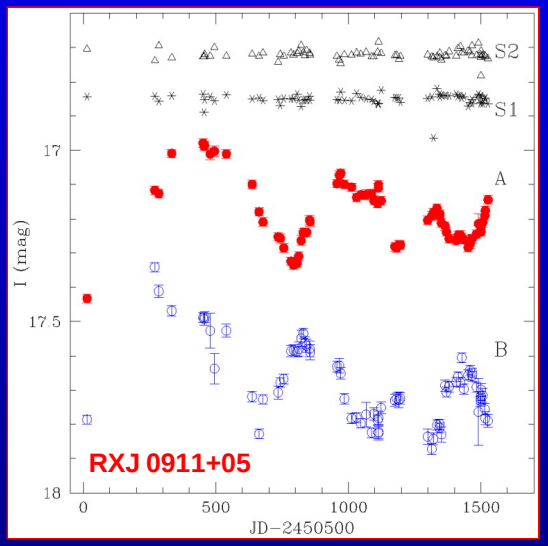
Lenses and the Hubble parameter H_0



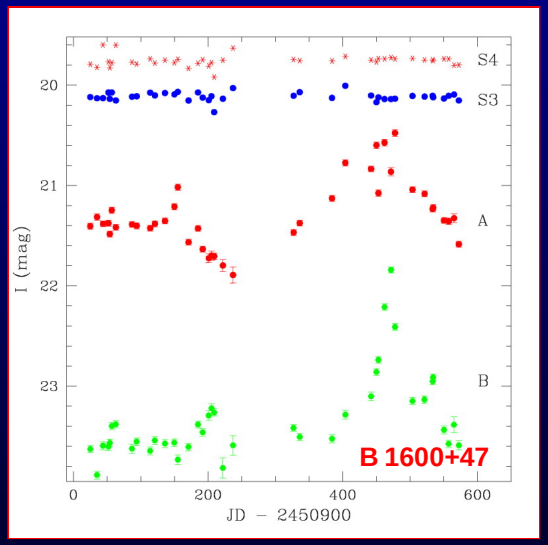
$$t(\vec{\theta}) = \frac{1}{2}(1+z_{\rm L})\frac{D_{\rm L}D_{\rm S}}{cD_{\rm LS}}(\vec{\theta}-\vec{\beta})^2 - (1+z_{\rm L})\frac{8\pi G}{c^3}\nabla^{-2}\Sigma(\vec{\theta}).$$

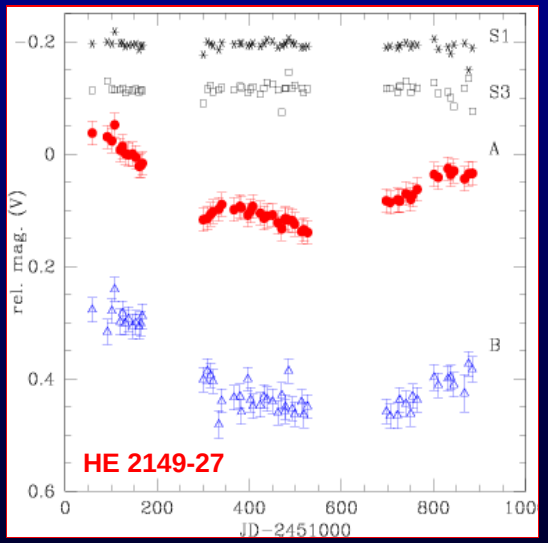
Examples of light curves





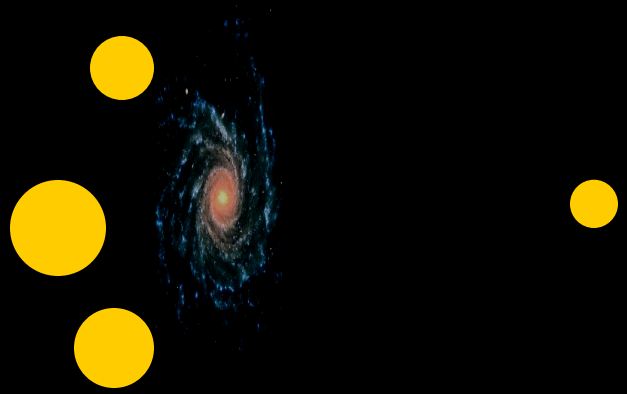
I. Burud, PhD, 2001 (NOT and ESO observations)



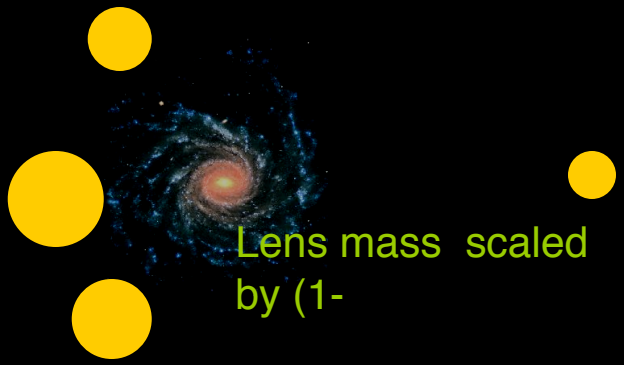


Intervening clusters and groups

Ellipticity-induced shear



External shear



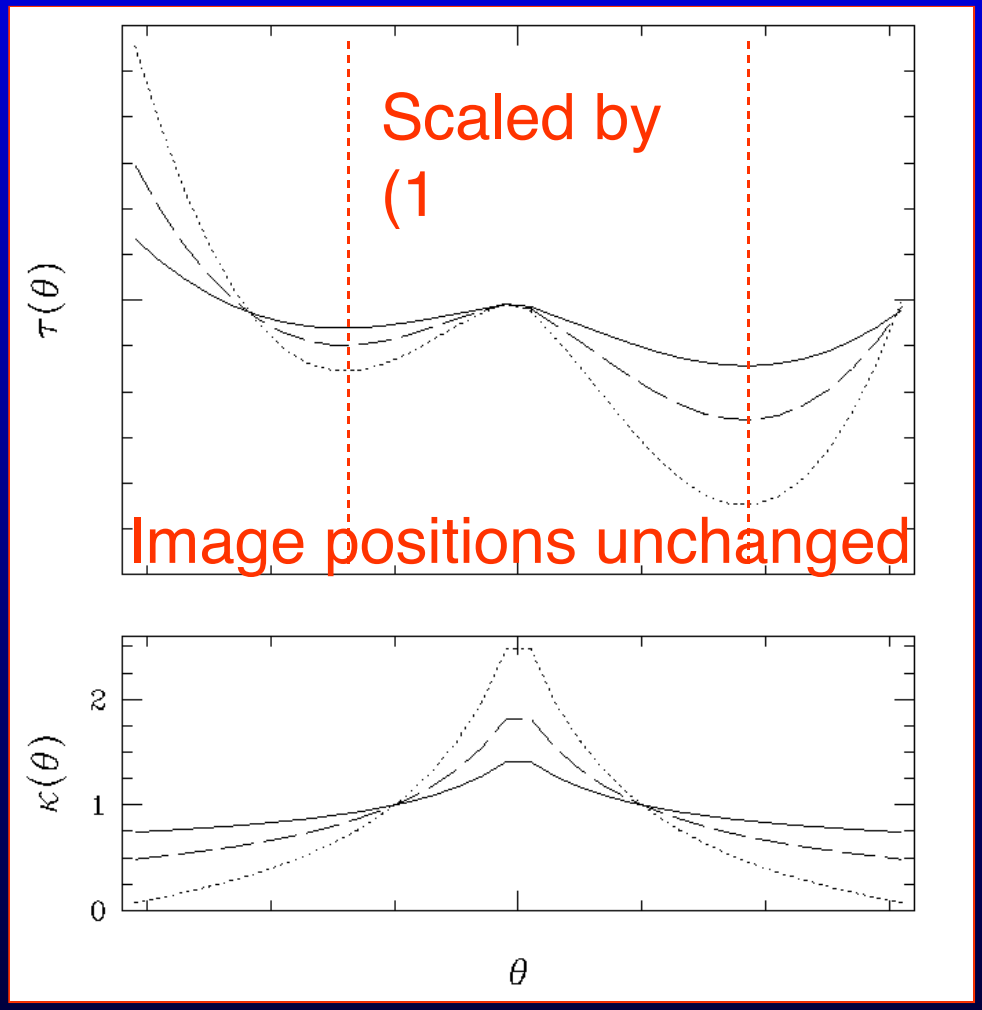
Lens mass scaled by (1-

Cluster:
mass sheet with convergence

Mass-sheet degeneracy

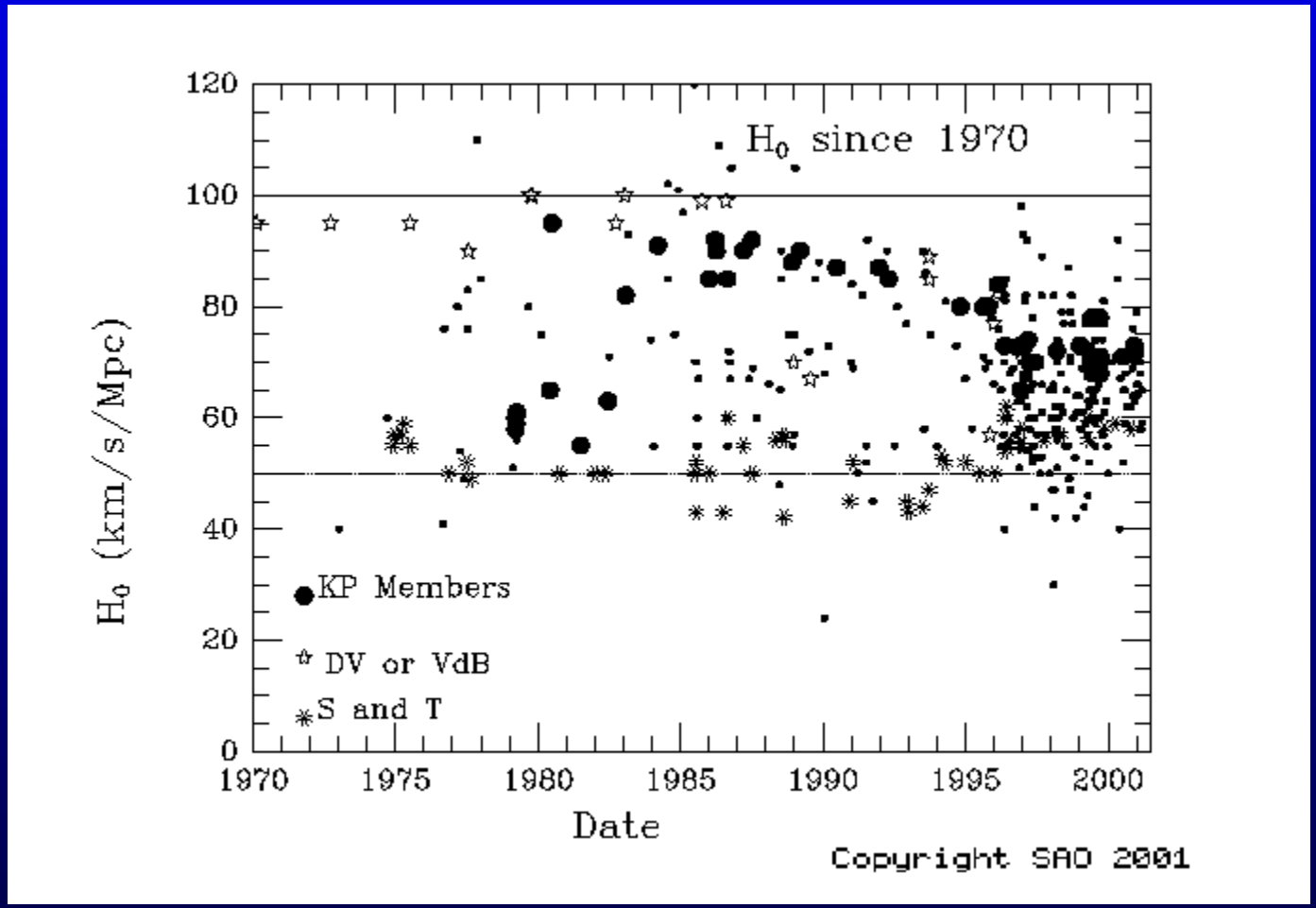
Arrival time surfaces

Normalized mass profile (convergence)



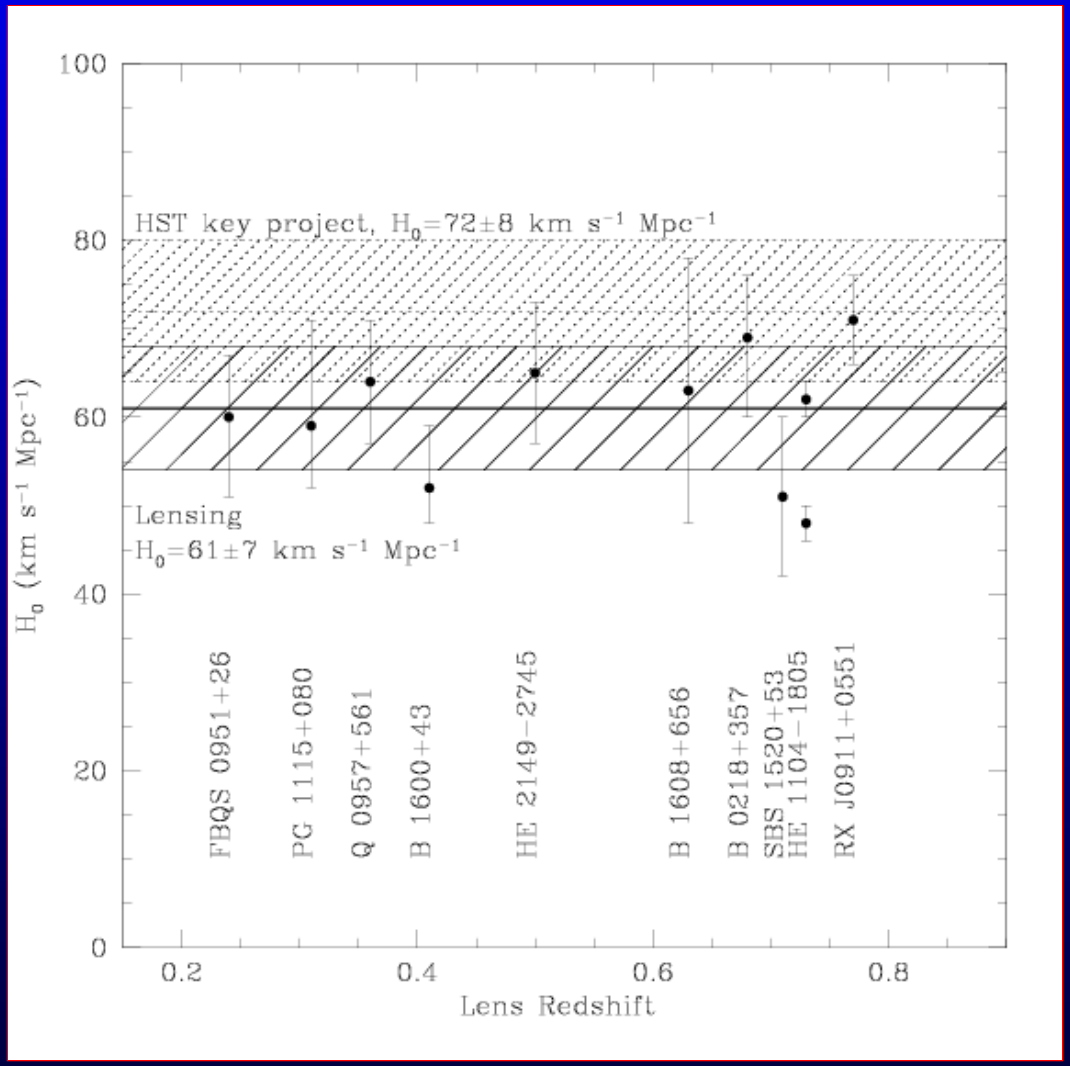
Saha, 2000, AJ 120, 1654

Lenses and the Hubble parameter H_0



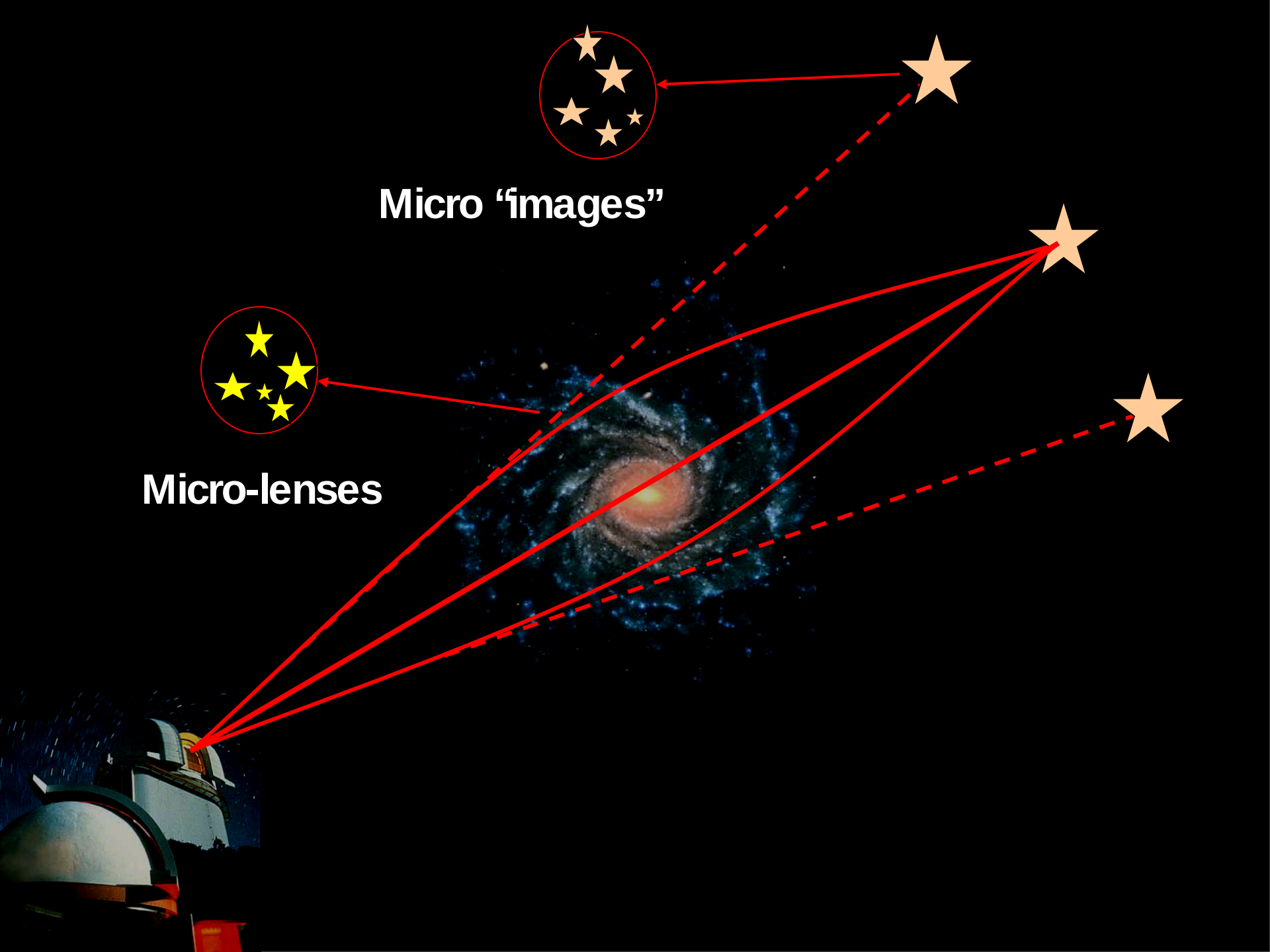
http://cfa-www.harvard.edu/~huchra

Lenses and the Hubble parameter H_0

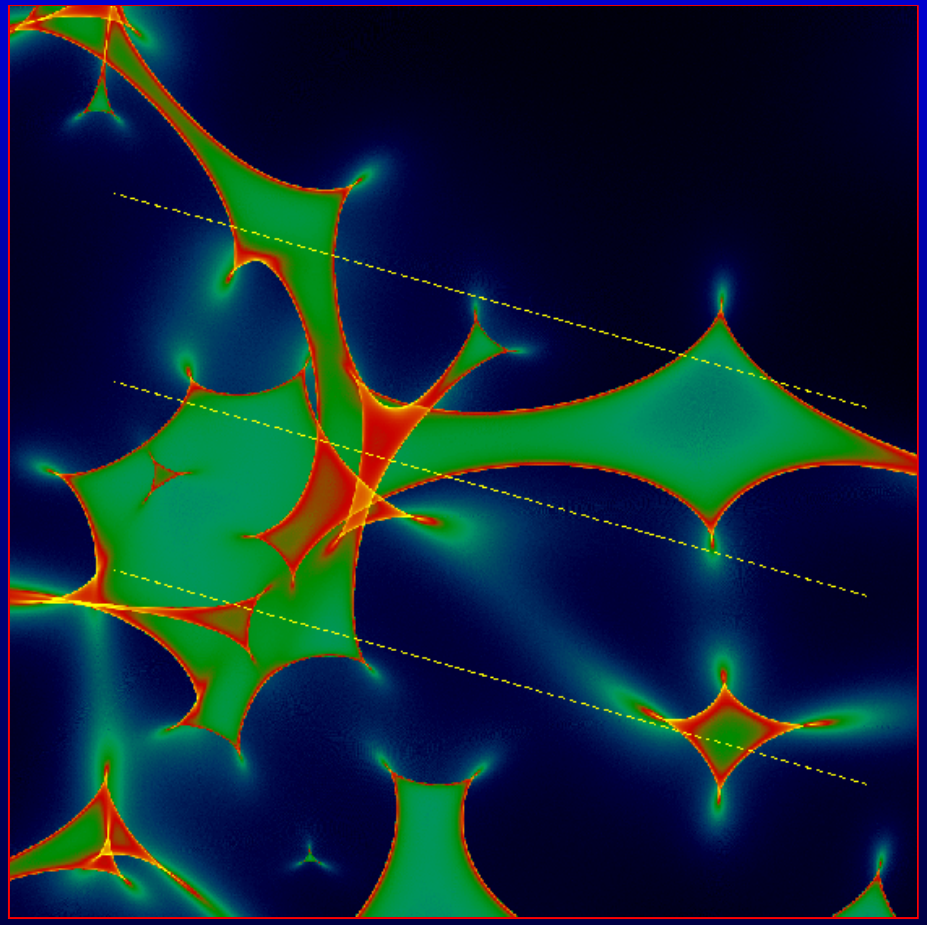


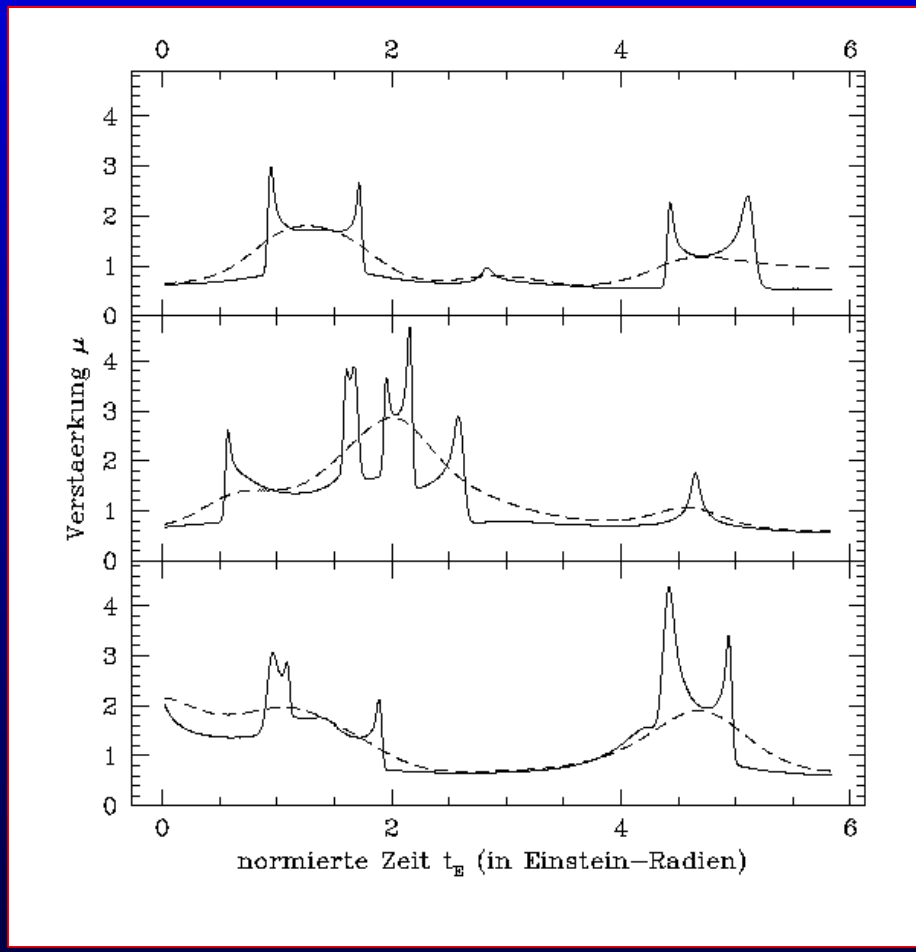
Courbin (astro-ph/0304497), updated 2006

A word about microlensing

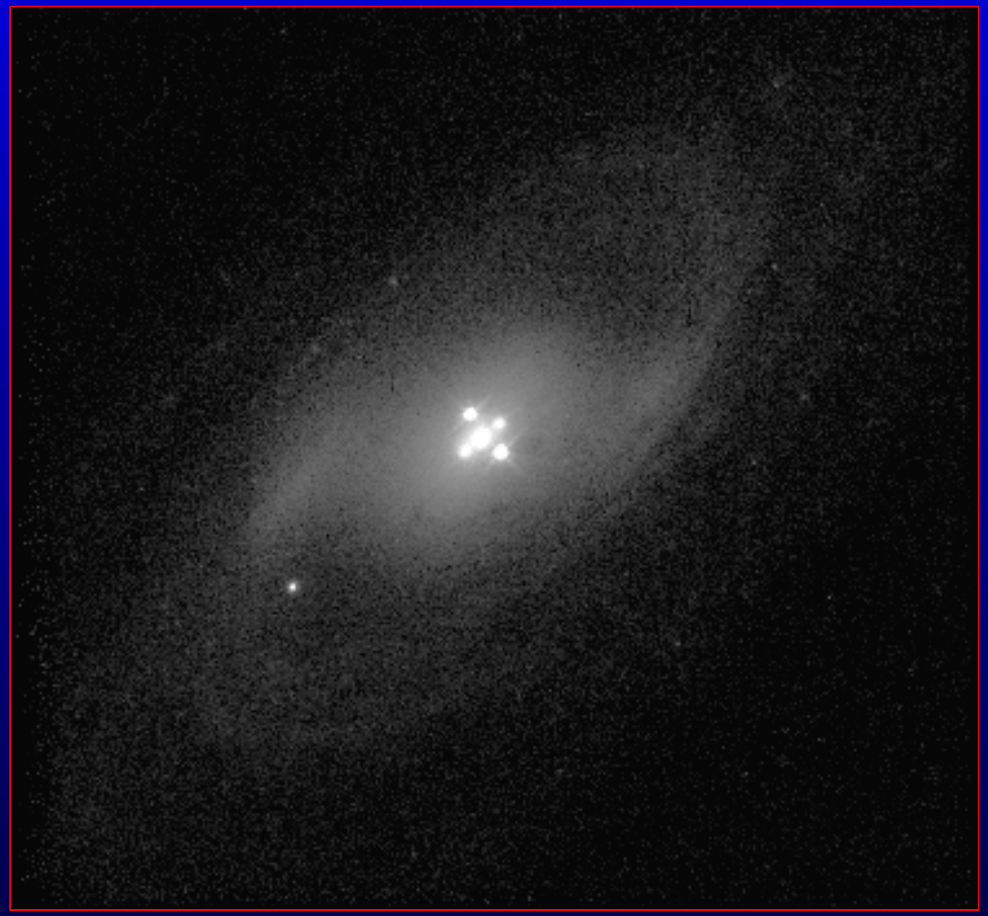

Micro “images”
Micro-lenses

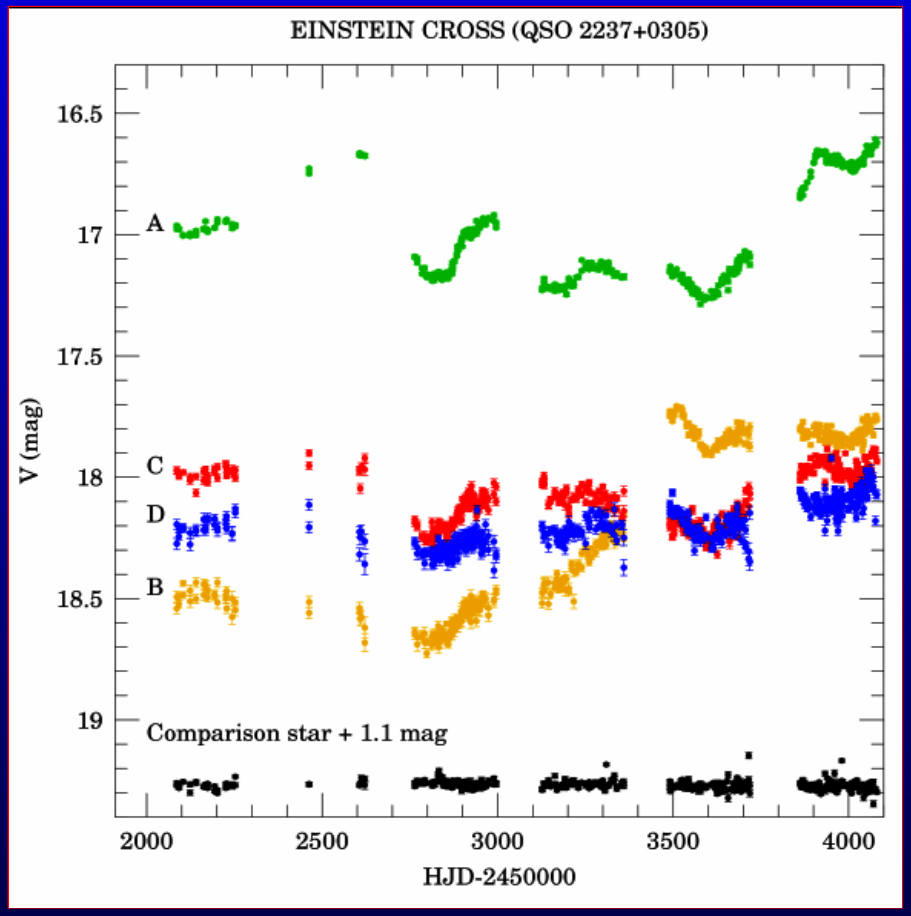
Microlenses





Microlenses

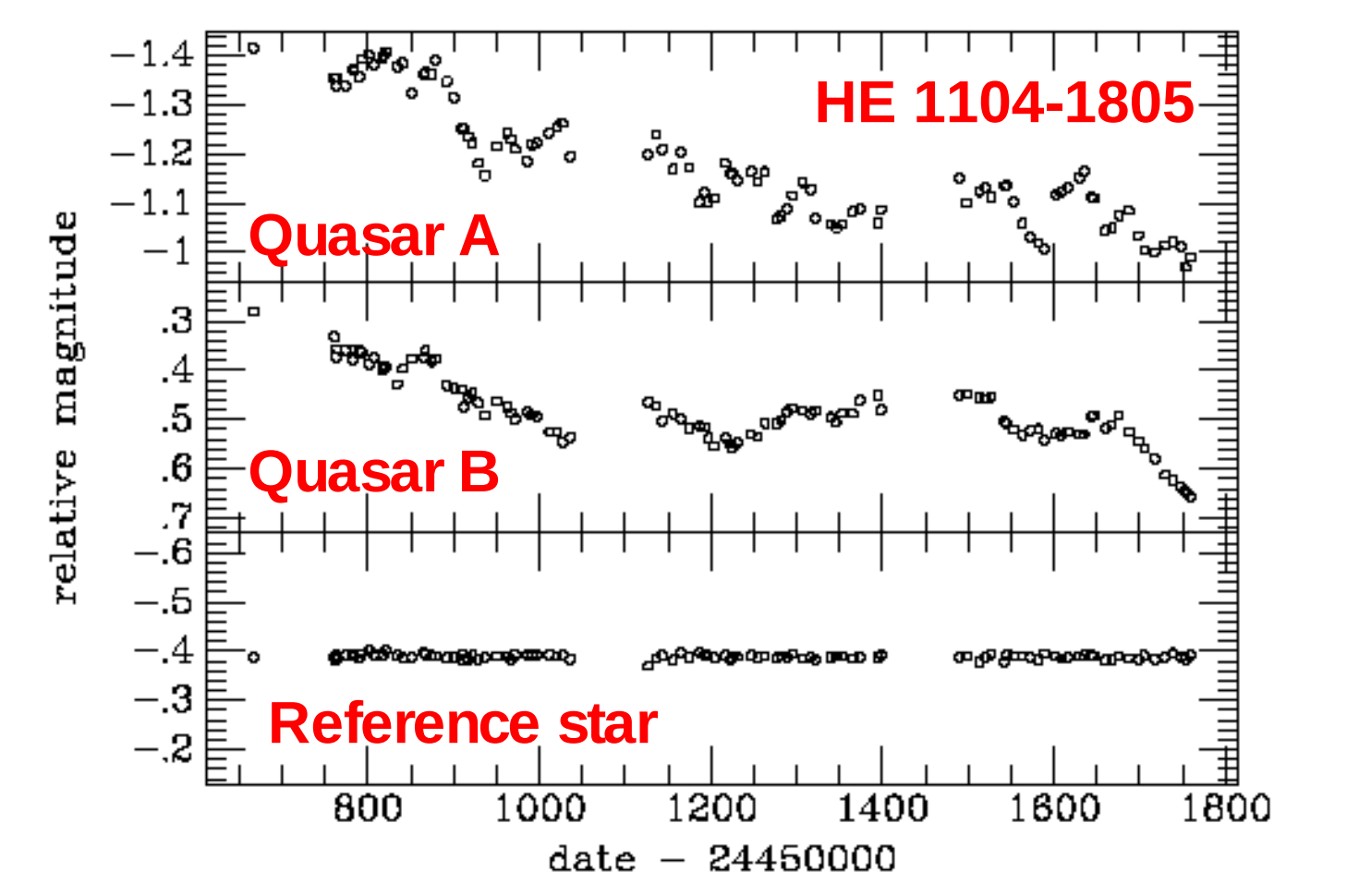




Wozniak et al. 2000, ApJ 529, 88

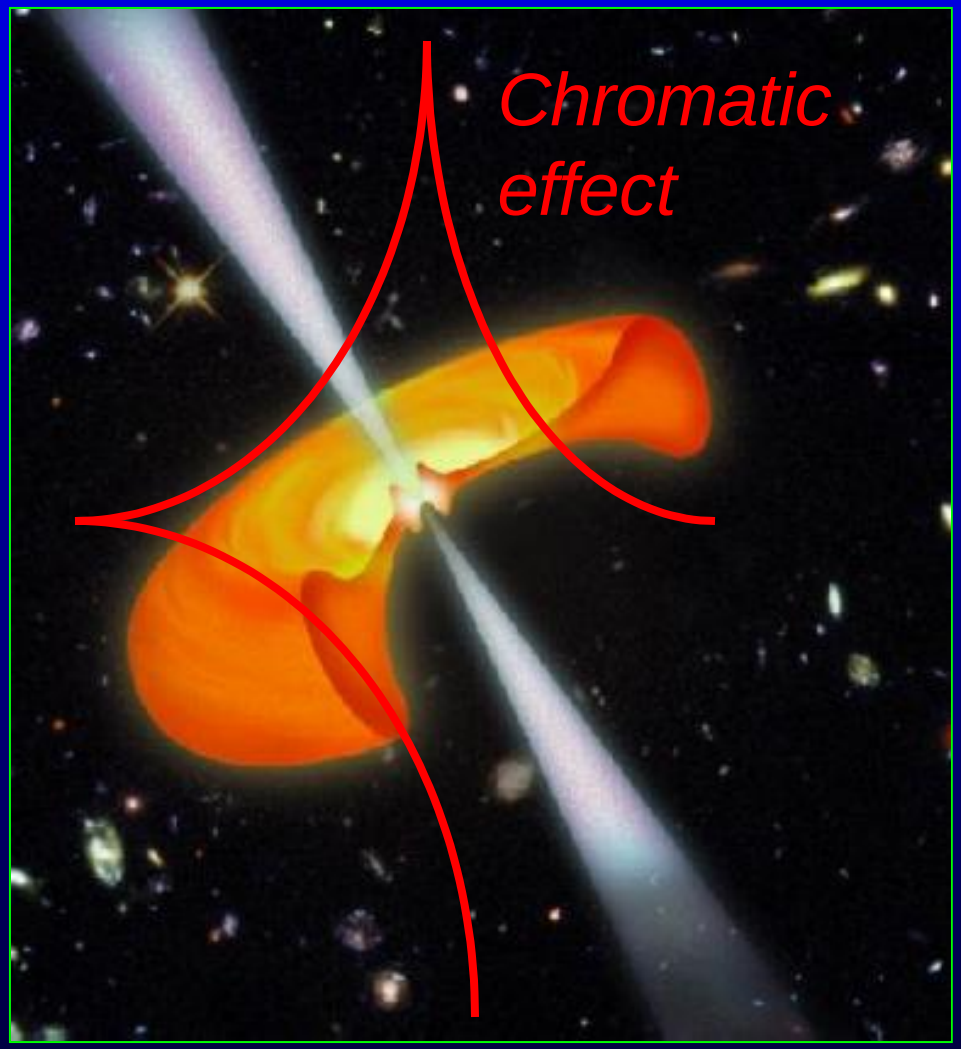
Updated 2006

Microlenses



Schechter et al. 2003 ApJ 584, 657

Microlenses



Do we need to measure H_0 ?

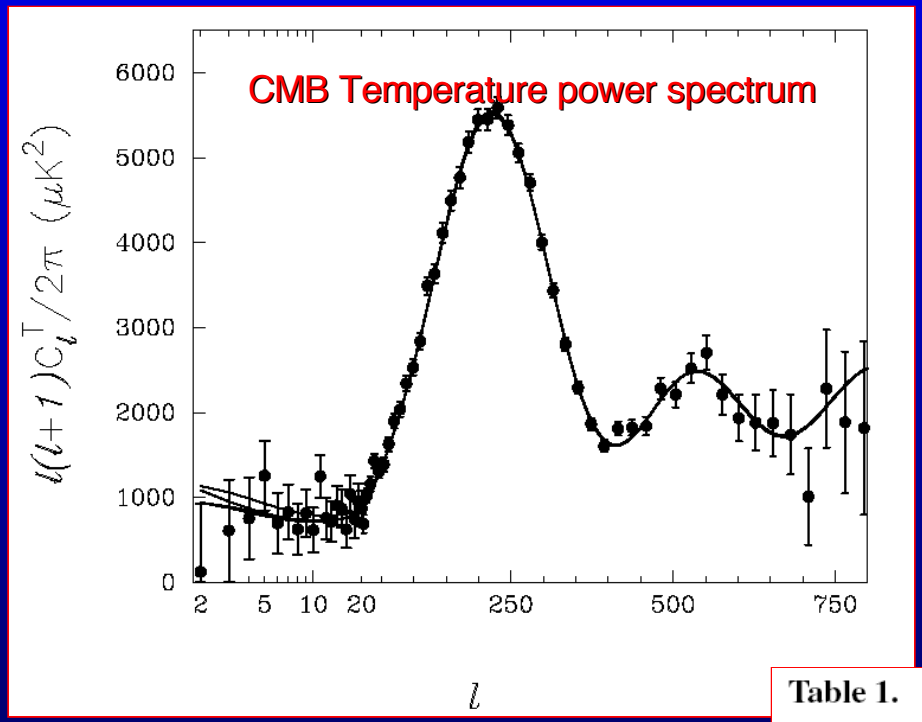
H_0: most "popular" methods

1- Cepheids
- Local measurement
- Period-luminosity relation depends on metallicity
- Blends of photometrically variable objects
- Depends on a standard candle

2- Supernovae
- Constrain well ($_m$,) but not H_0
- Depends on a standard candle

3- Cosmic Microwave Background (CMB)
- Does not constraint H_0 on its own
- Sensitive to removal of low frequencies
- Assumes perfectly flat Universe

H_0: most "popular" methods



H_0 = 72 if the Universe is exactly flat.

H_0 = anything between 55 and 72
if the Universe is not exactly flat.

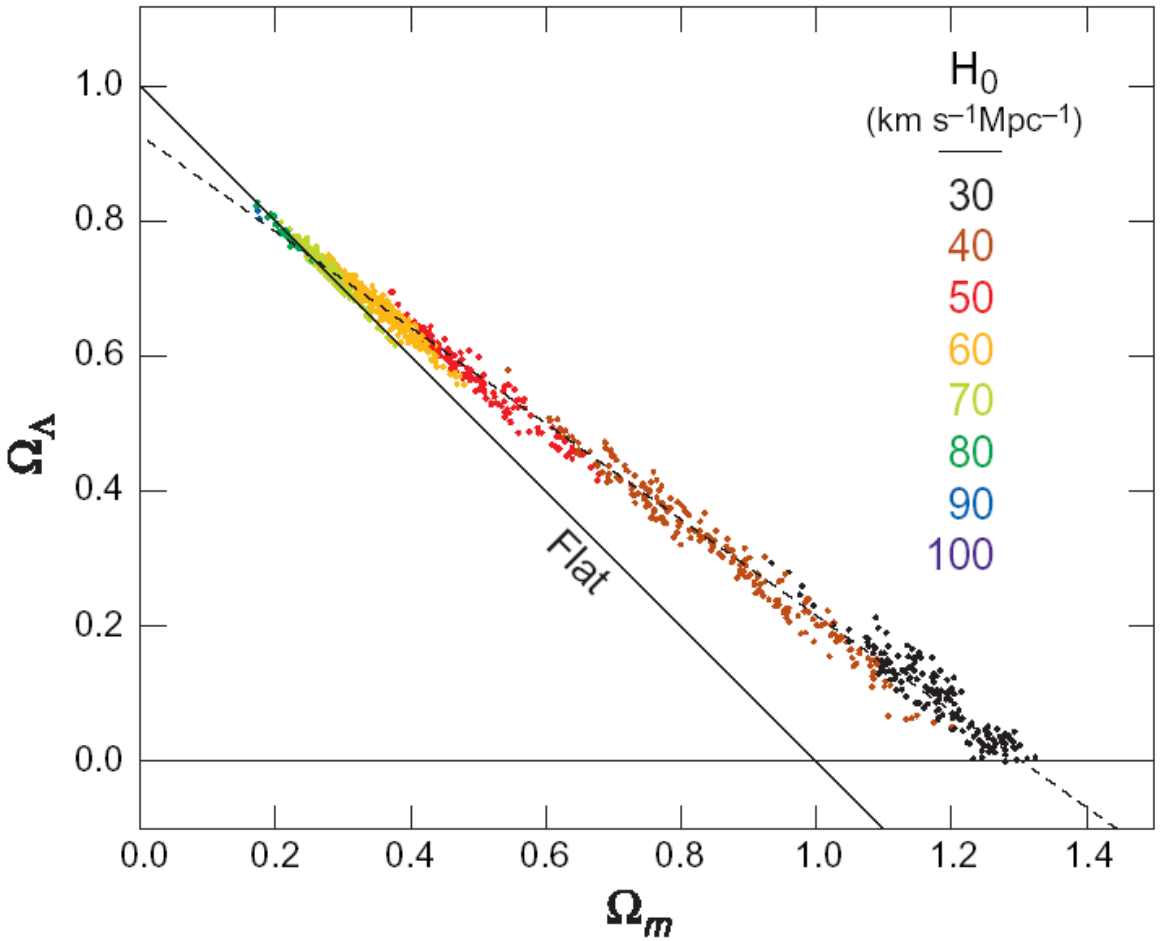
(Efstathiou, 2003, MNRAS 343, L95)

Table 1. Parameters for degenerate models.

Ω_k	Ω_b	Ω_c	Ω_Λ	h
0.00	0.0463	0.2237	0.73	0.720
−0.05	0.0806	0.3894	0.58	0.546
−0.10	0.1114	0.5386	0.45	0.446
−0.20	0.1714	0.8286	0.20	0.374

Total Baryons CDM Vacuum H_0

WMAP and H_0



If the Universe is exactly flat then WMAP constrains H_0

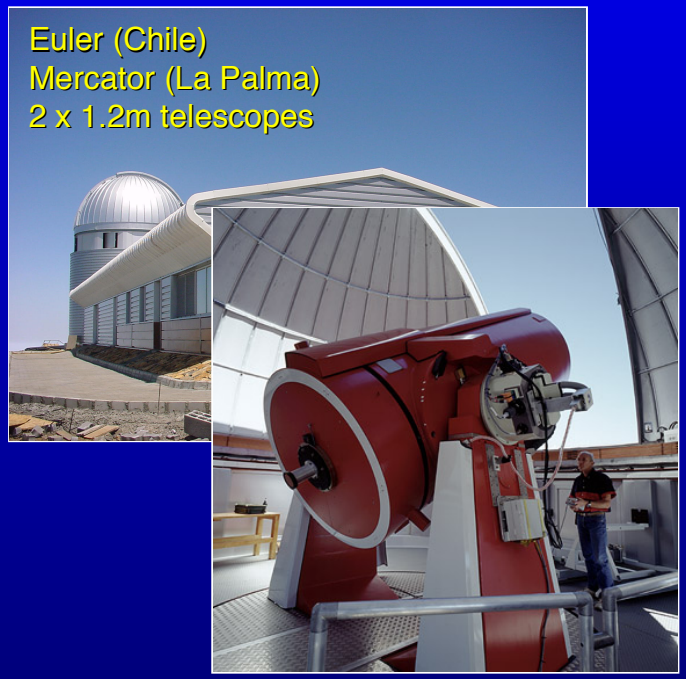
WMAP alone is not incompatible with =0 (Spergel et al. 2006)

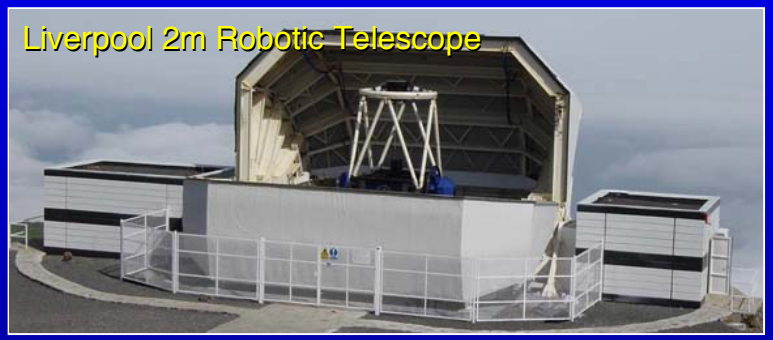
COSMOGRAIL

Main goals of the project

- To measure time delays with ~ 1-2% accuracy in order to determine H_0
- To follow long- and short-term microlensing
- To give alert for spectrophotometric monitoring
- To provide deep high-resolution images of lenses potentially useful to determine H_0
- To measure missing lens redshifts and velocity dispersions

Teams and telescopes





Swiss node:

C. Vuissoz
A. Eigenbrod
G. Meylan
F. Courbin
D. Sluse
P. Saha

Belgian node:

P. Magain
L. Le Guillou
H. Van Winckel
C. Waelkens

British node:

S. Warren
S. Dye

Uzbek node:

M. Ibrahimov
I. Asfandiyarov
D. Sharapov

Indian node:

T. Prabhu
D. Sahu
Stalin

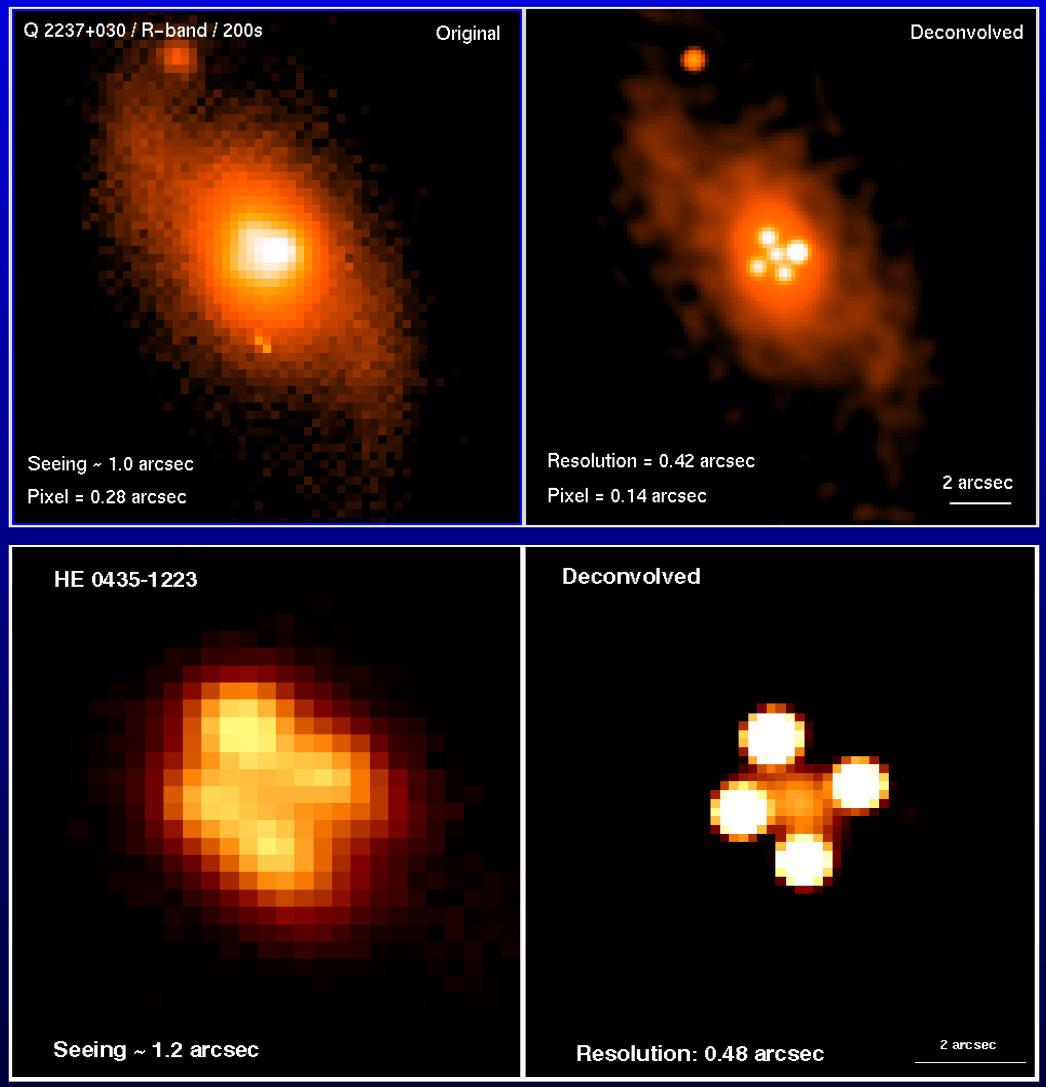
Examples of images of lensed quasars at Euler

Target S/N: 100-200 per quasar image

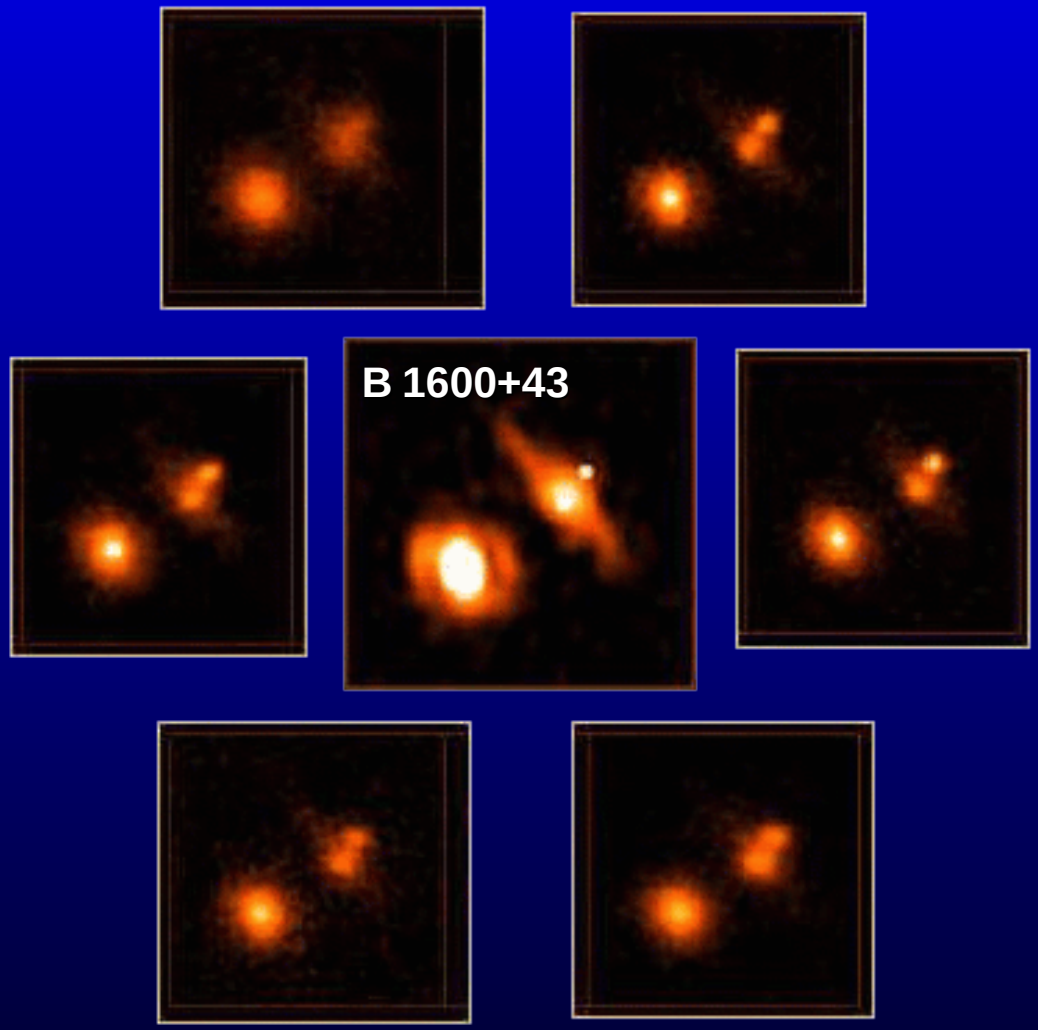
Temporal sampling adapted to each target

R-band (for a start)

Data analyzed using deconvolution photometry and the MCS algorithm. (Magain et al. 1998, ApJ 494, 472)

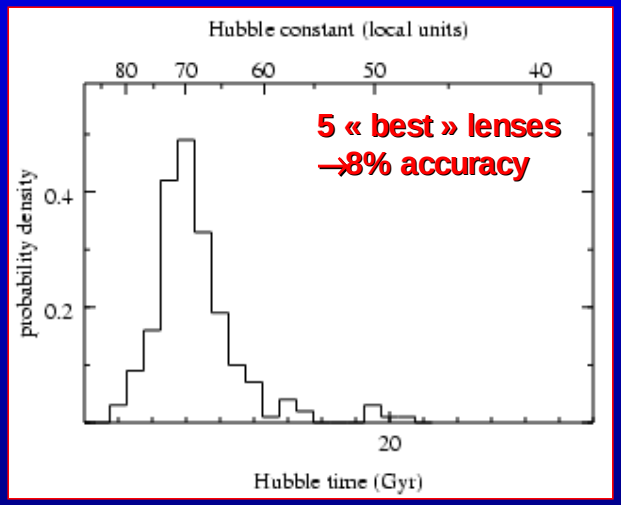


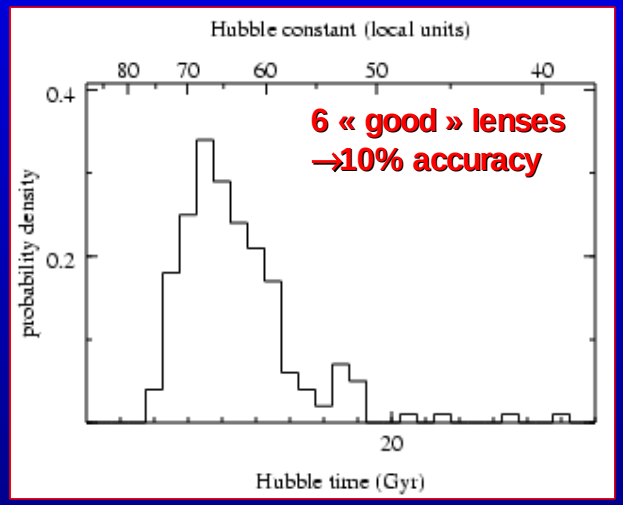
Example of simultaneous deconvolution

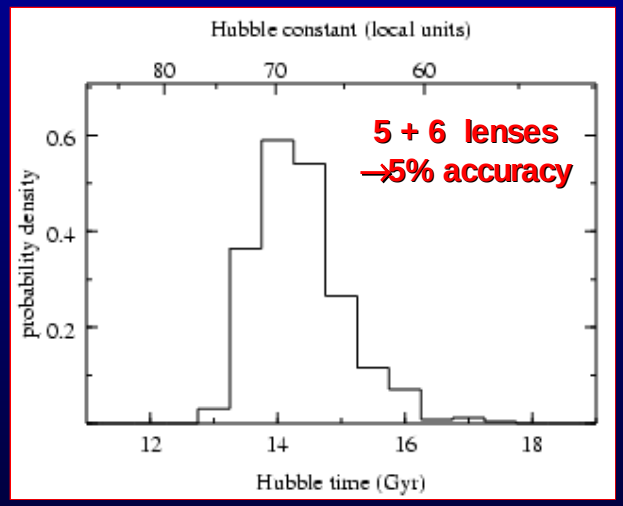


Expectations

Expected accuracy on H_0



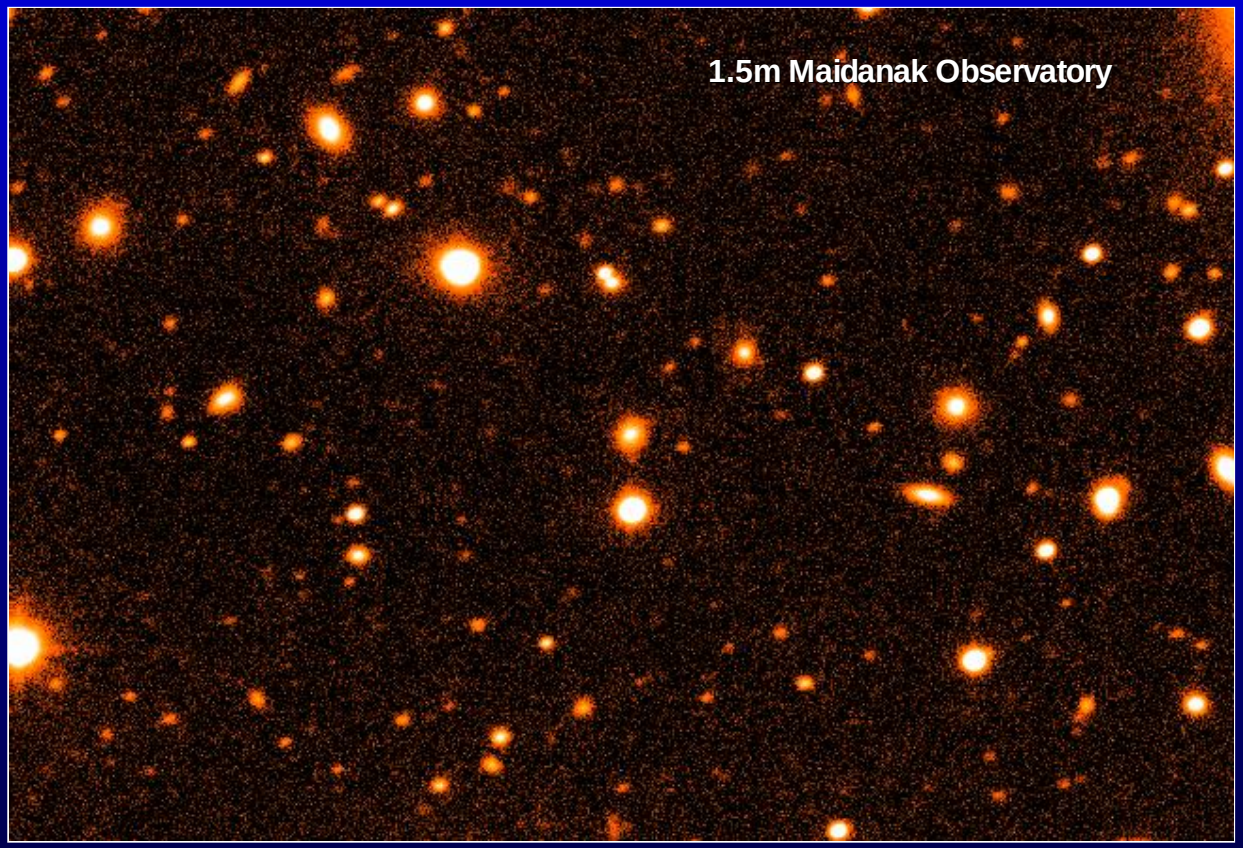




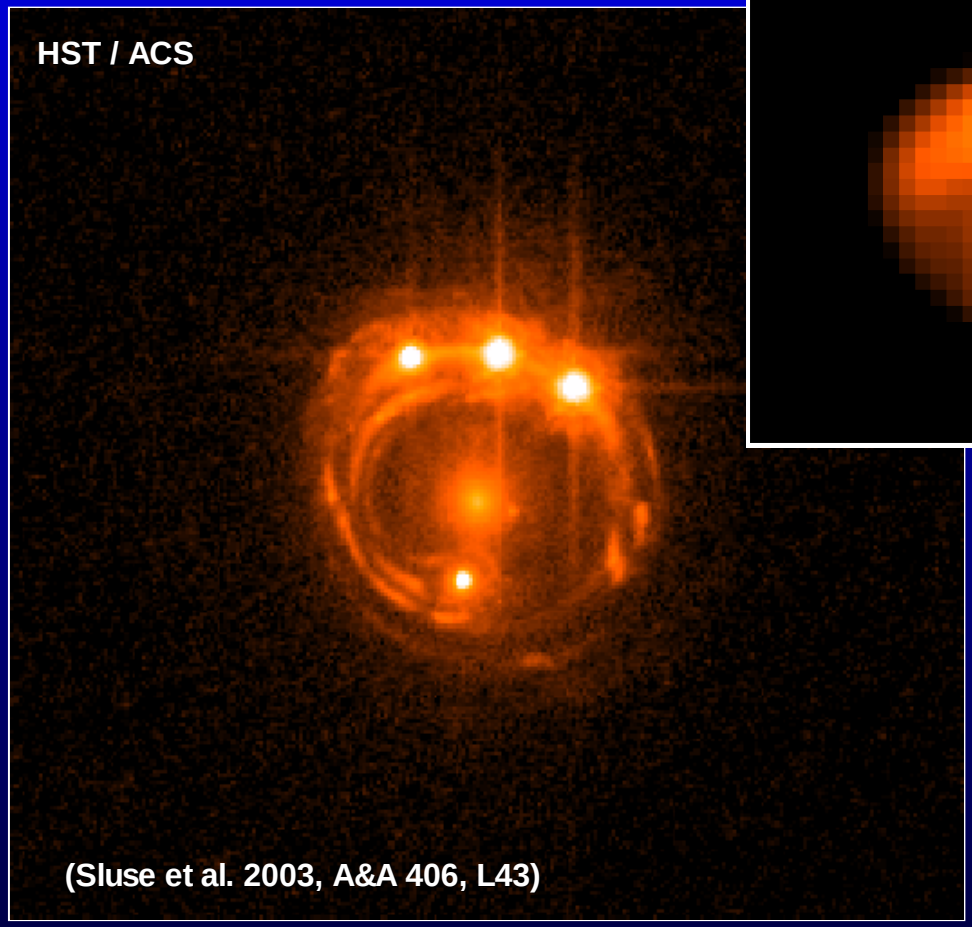
(cosmograil IV: Saha et al. 2005, A&A 450, 461)

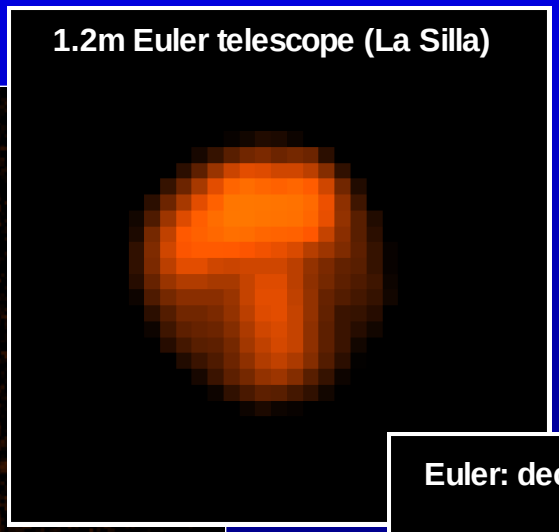
First light curve

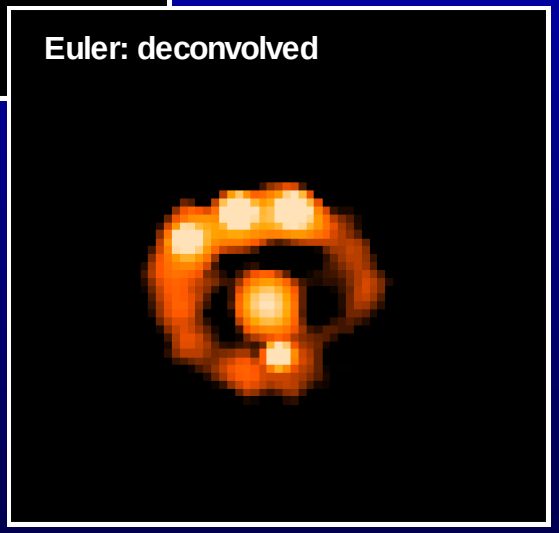
The quadruple RX J1131-123



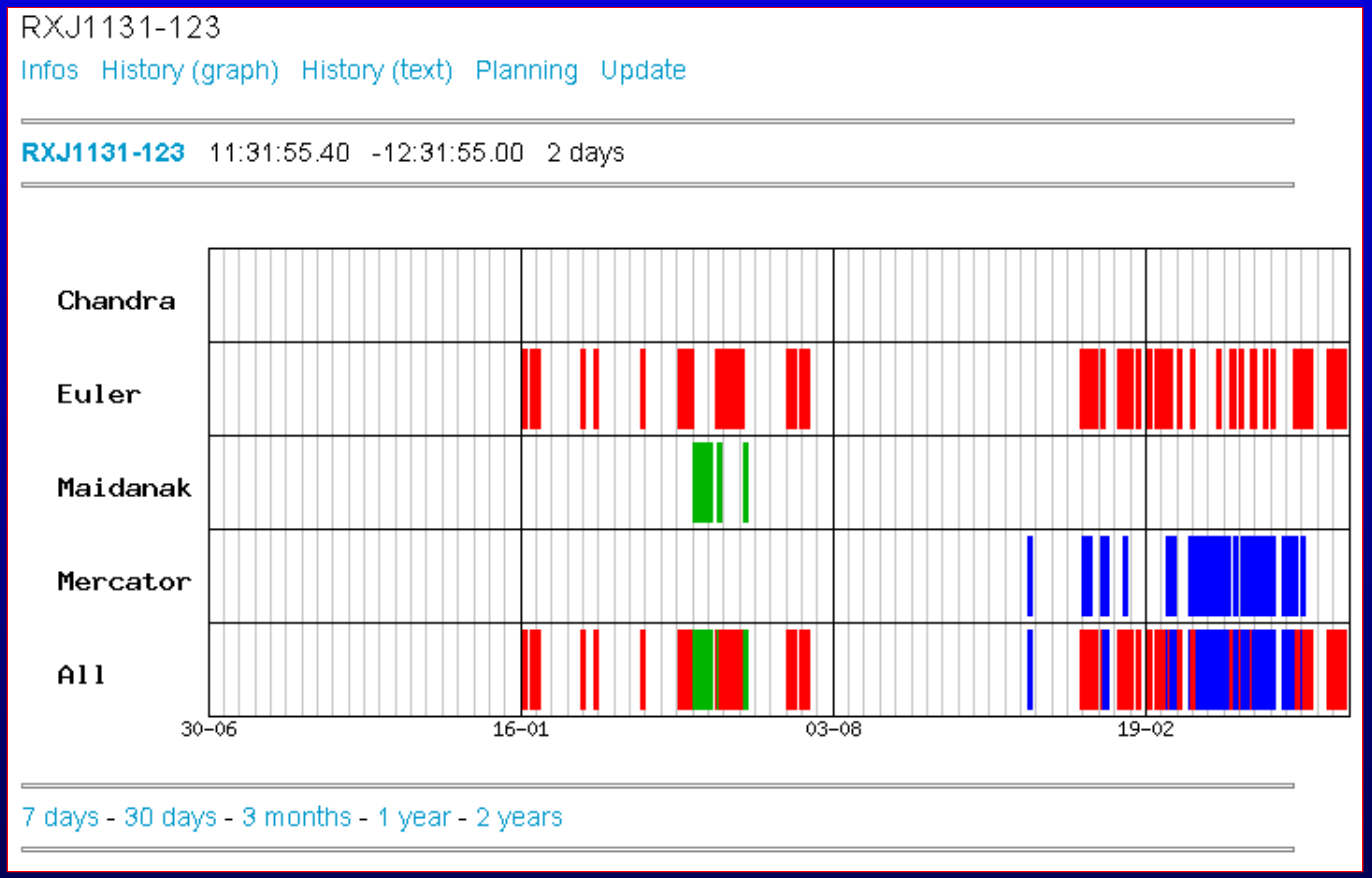
The quadruple RX J1131-123





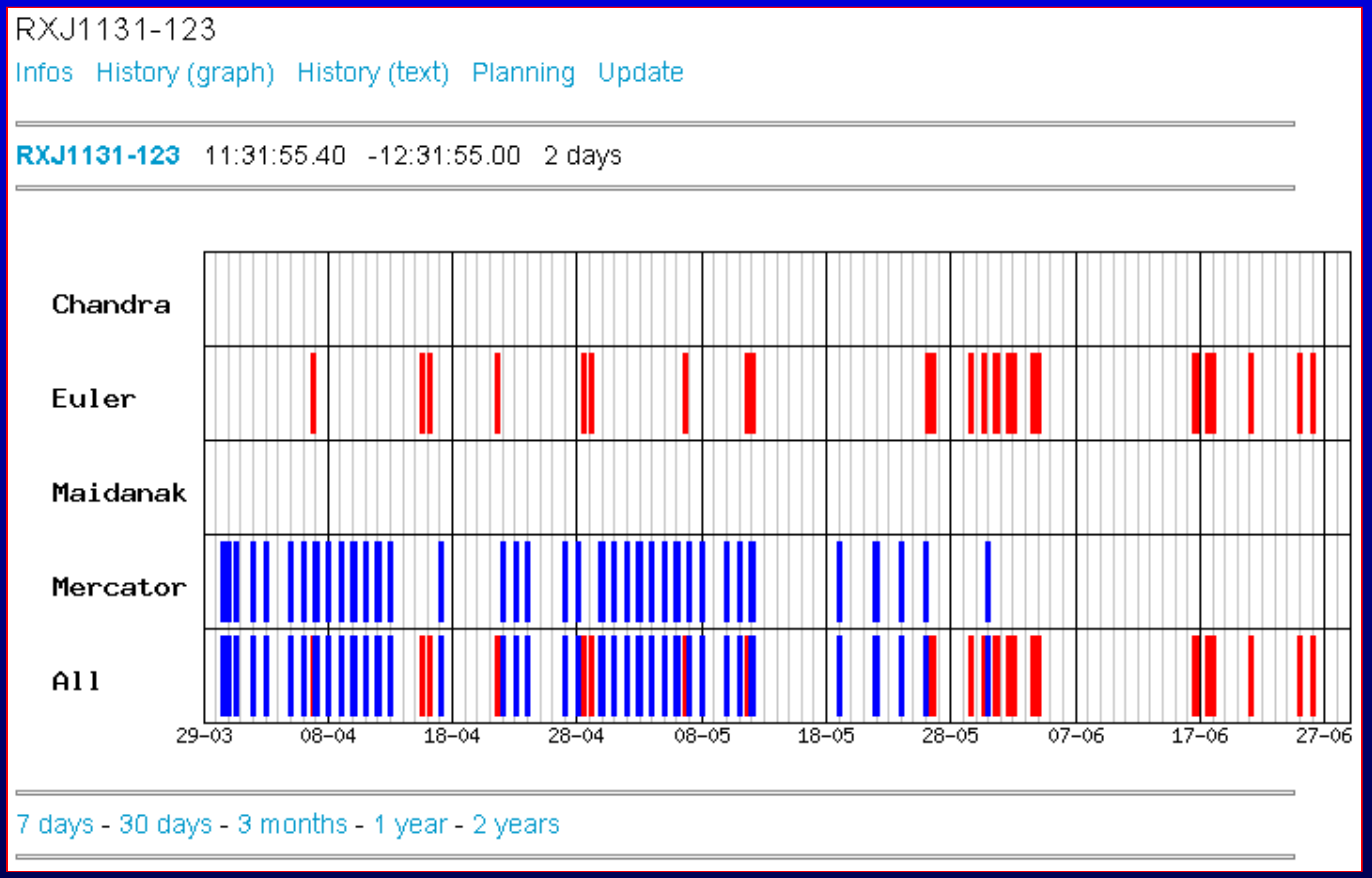


The quadruple RX J1131-123



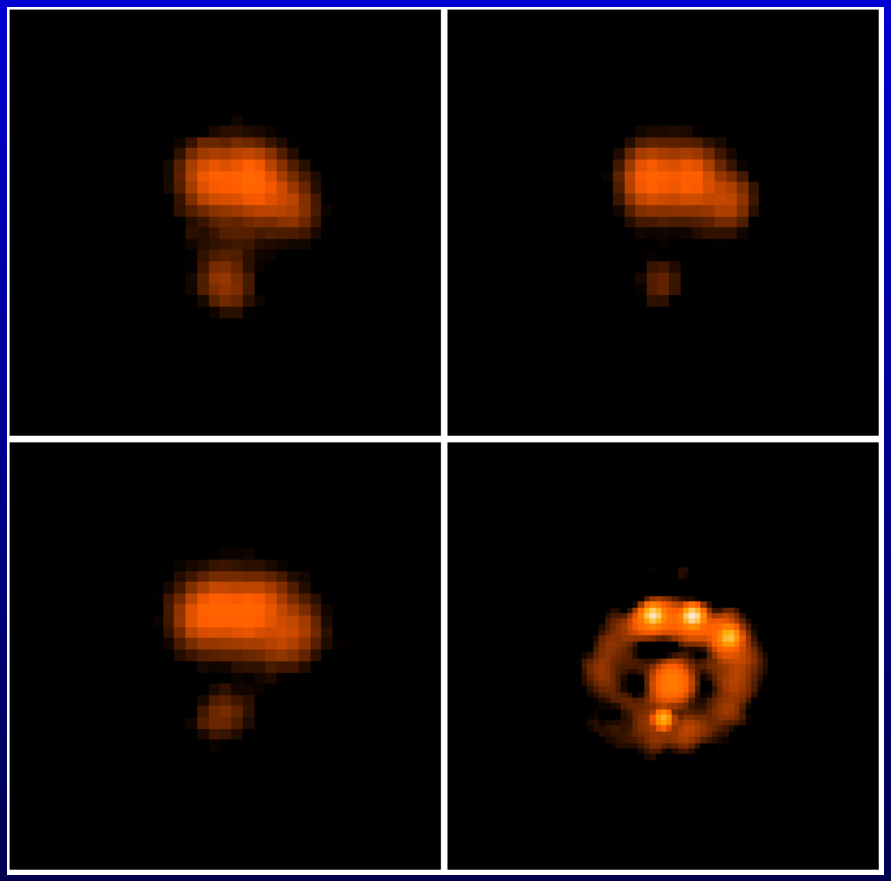
Automated log of the observations (Le Guillou & Vuissoz)

The quadruple RX J1131-123

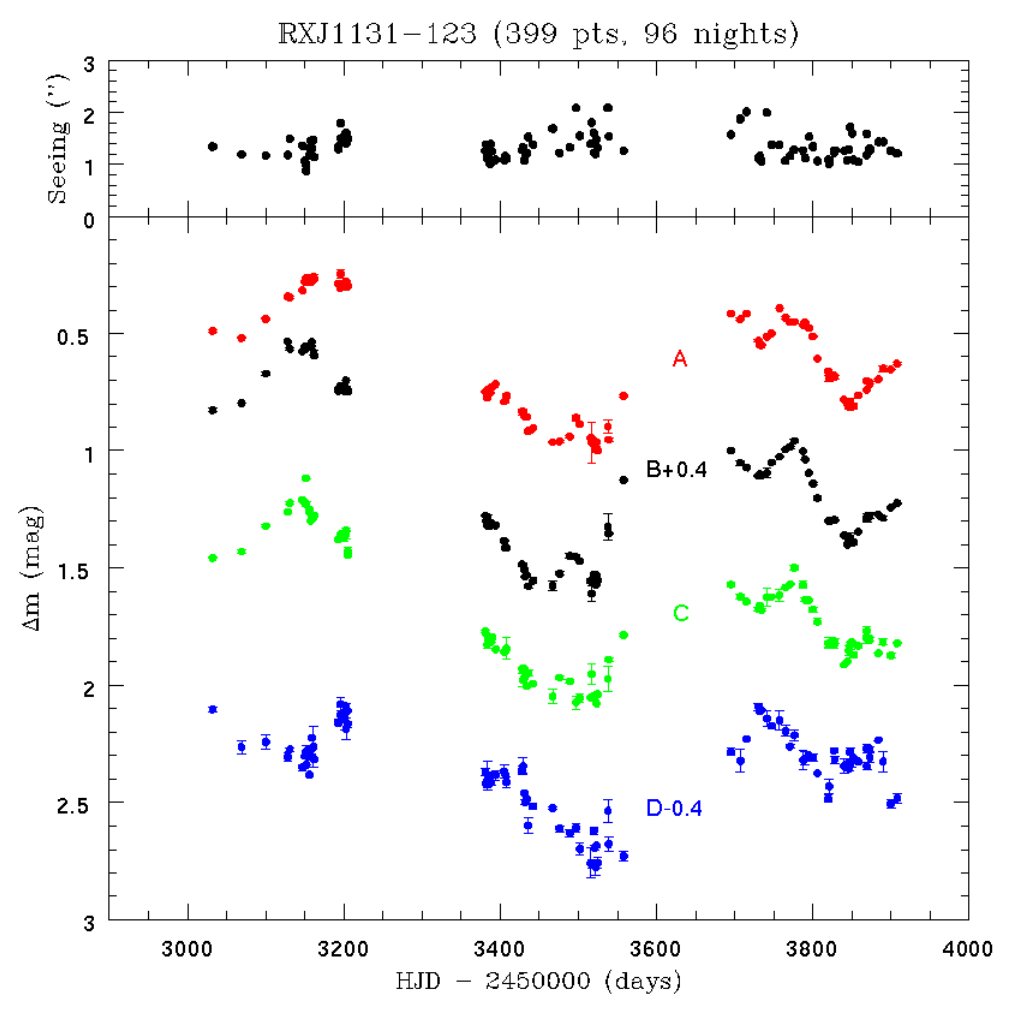


Automated log of the observations (Le Guillou & Vuissoz)

The quadruple RX J1131-123



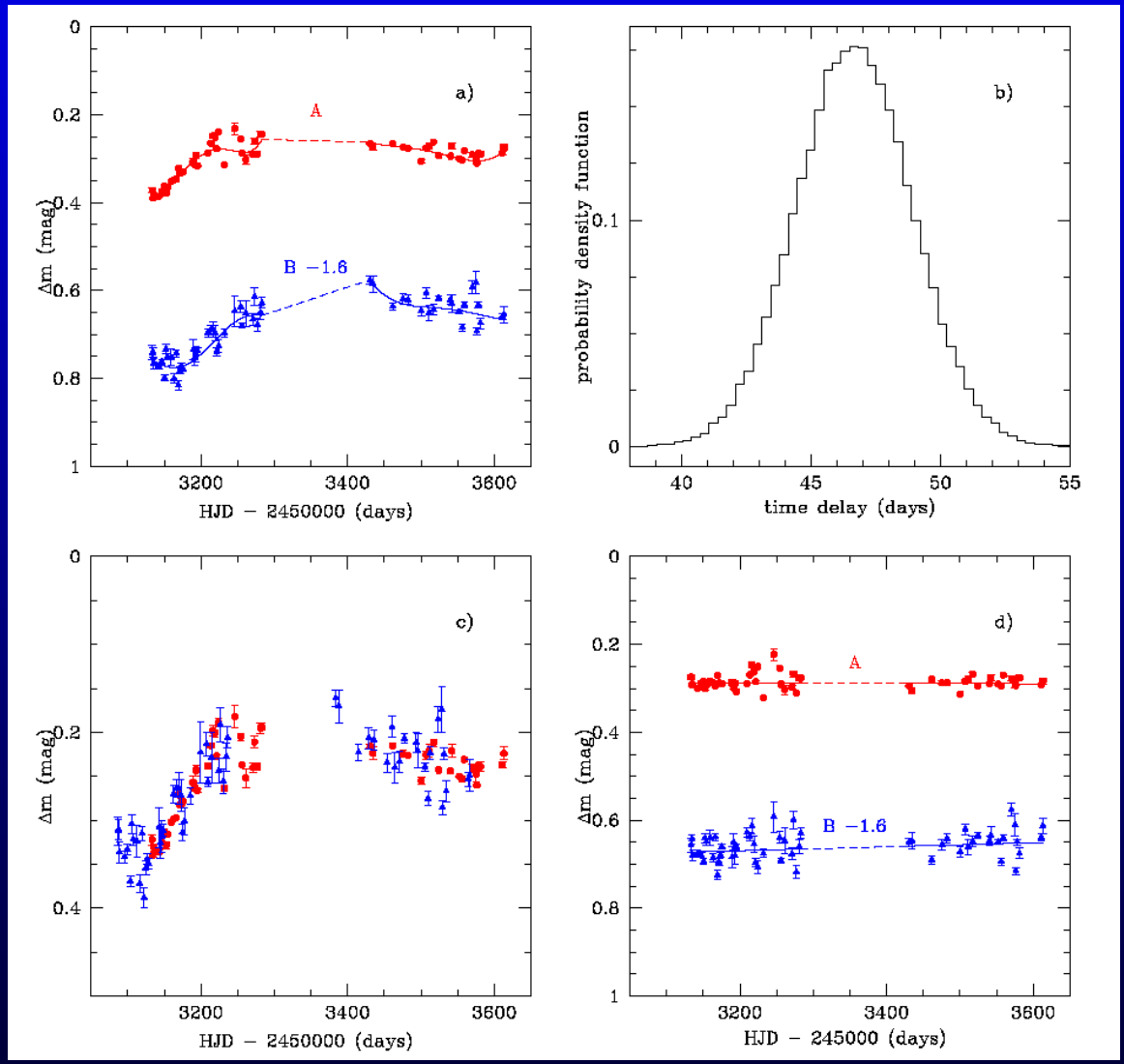
The quadruple RX J1131-123



First COSMOGRAIL time delay

A new double: SDSS 1650+42

Polynomial fitting of the light curves and cross-correlation techniques



Vuissoz et al. 2006, (astro-ph/0606317)

A new double: SDSS 1650+42

Best estimate of the time delay:

$\Delta t = 49.5 \pm 1.9$ days (~4%)

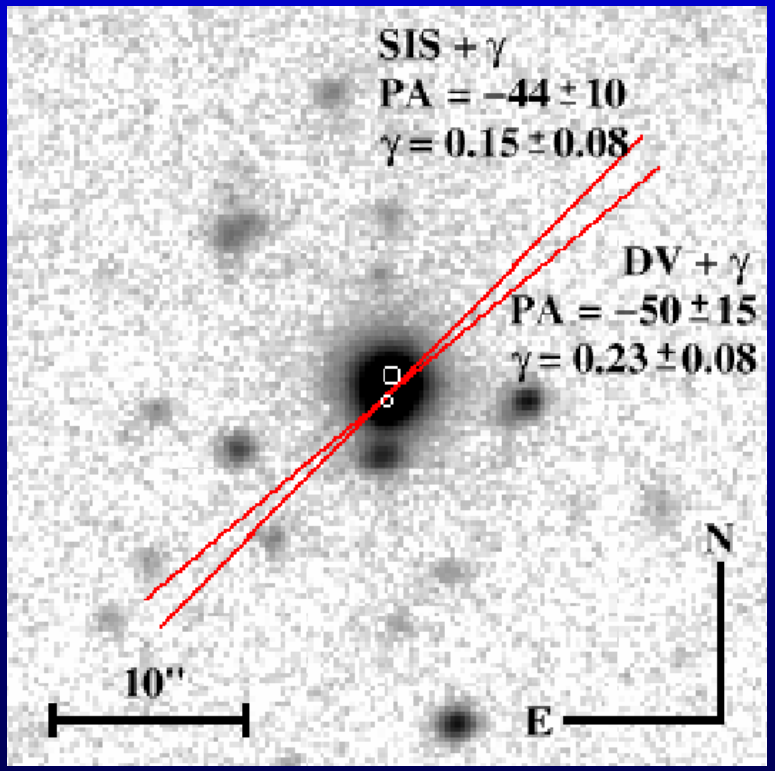
$H_0 = 80.8$ (+7)(-3) (de Vaucouleurs)

$H_0 = 51.7$ (+4)(-3) (SIS)

No obvious galaxy in the direction of the shear

Microlensing is negligible

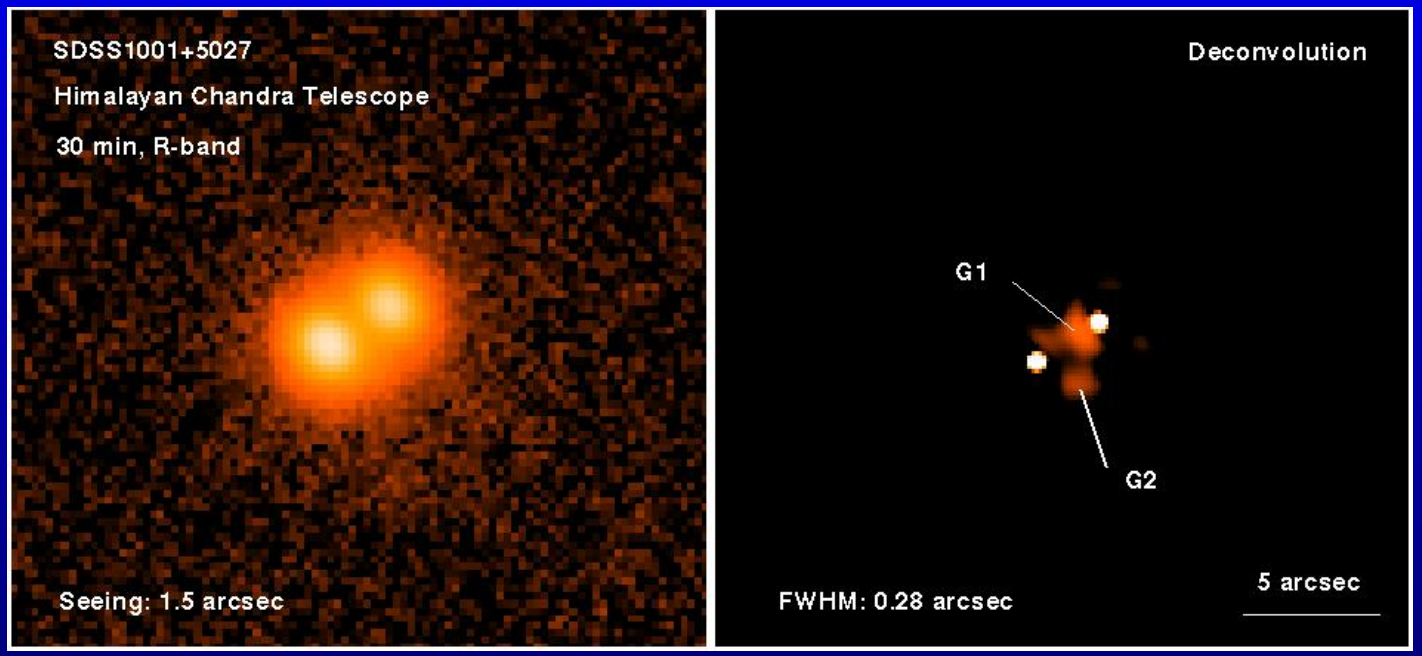
A/B = 6.2 corrected for the time delay

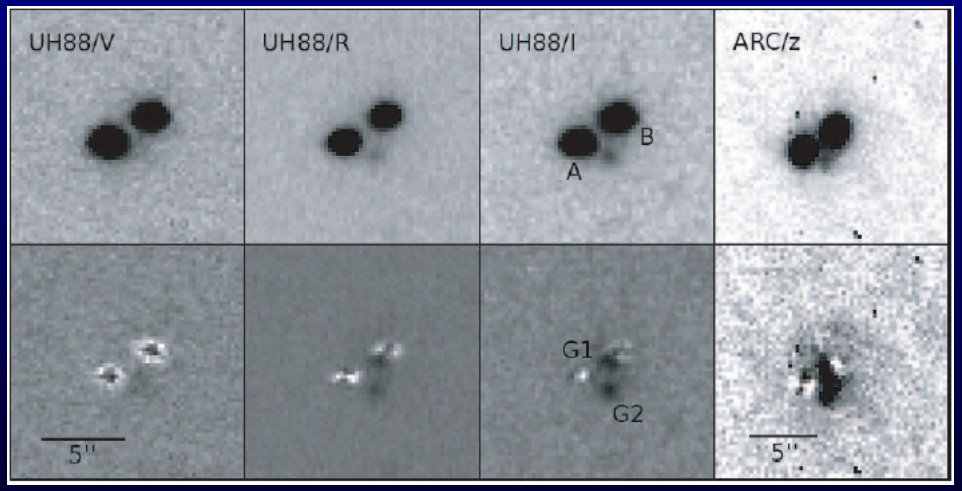


Vuissoz et al. 2006, (astro-ph/0606317)

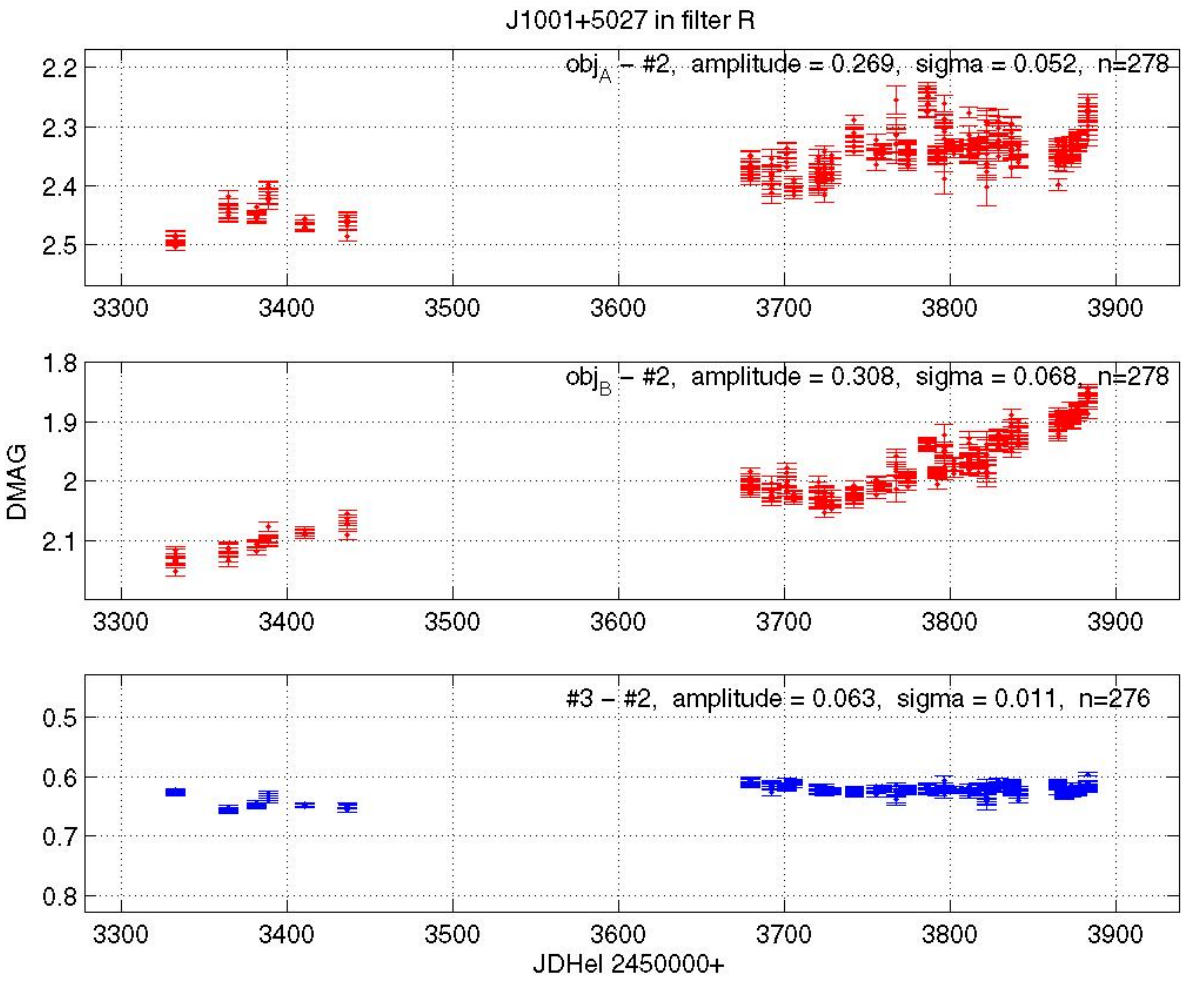
Results from the HCT, India

SDSS 1001+51


SDSS1001+5027
Himalayan Chandra Telescope
30 min, R-band
Seeing: 1.5 arcsec
Deconvolution
G1
G2
FWHM: 0.28 arcsec
5 arcsec


UH88/V
UH88/R
UH88/I
ARC/z
A
B
G1
G2
5''
5''

SDSS 1001+51

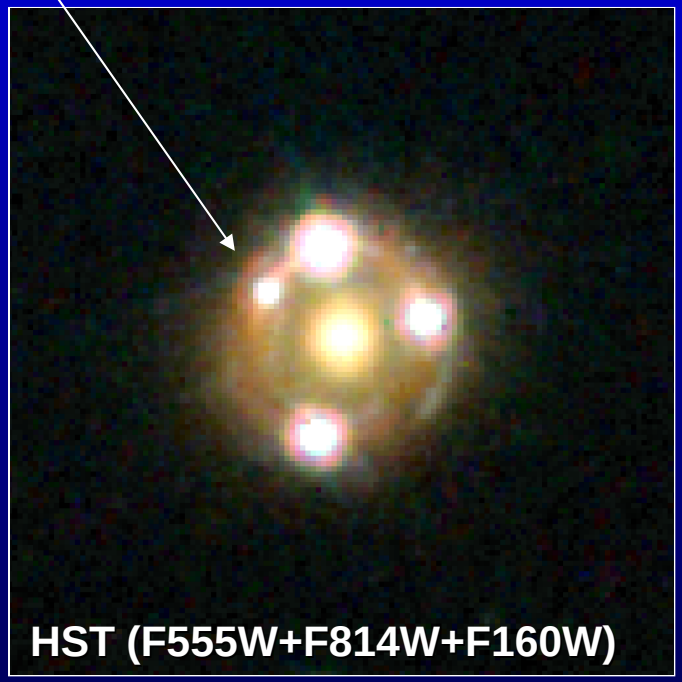


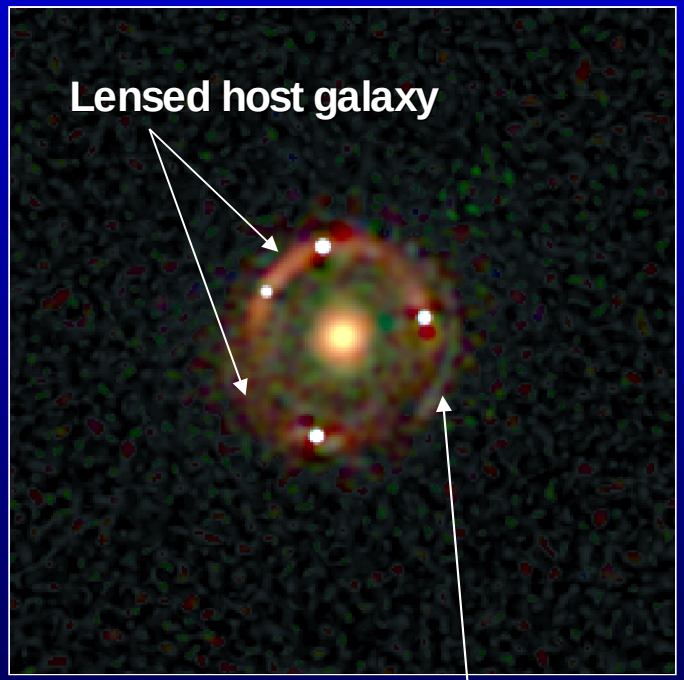
Maidanak observatory

Detailed follow-up at the VLT and the HST

An unusual quadruple: SDSS J0924+02

De-magnified image D

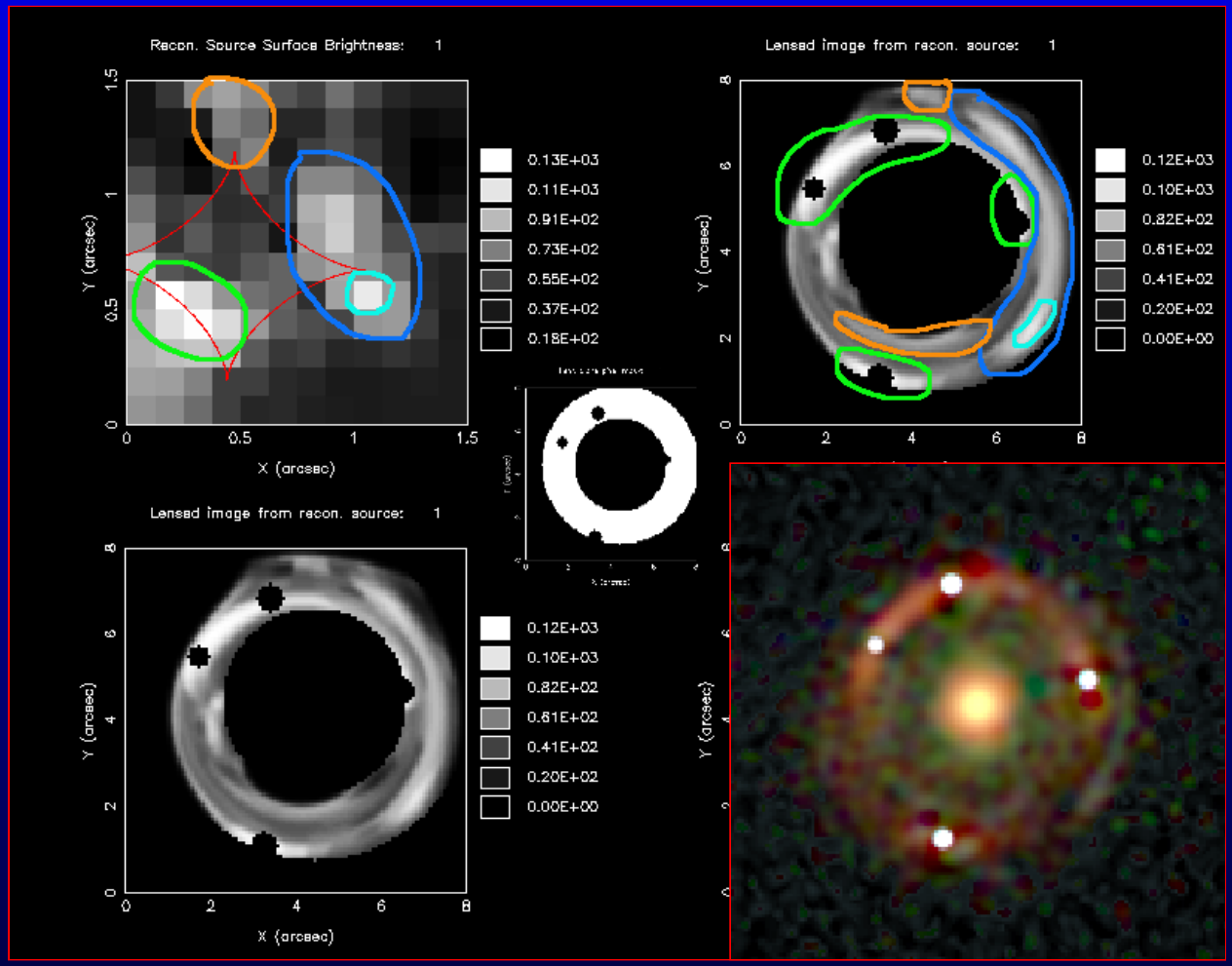




Bluer arcs : Lower redshift galaxy ?
Star forming region of the host ?

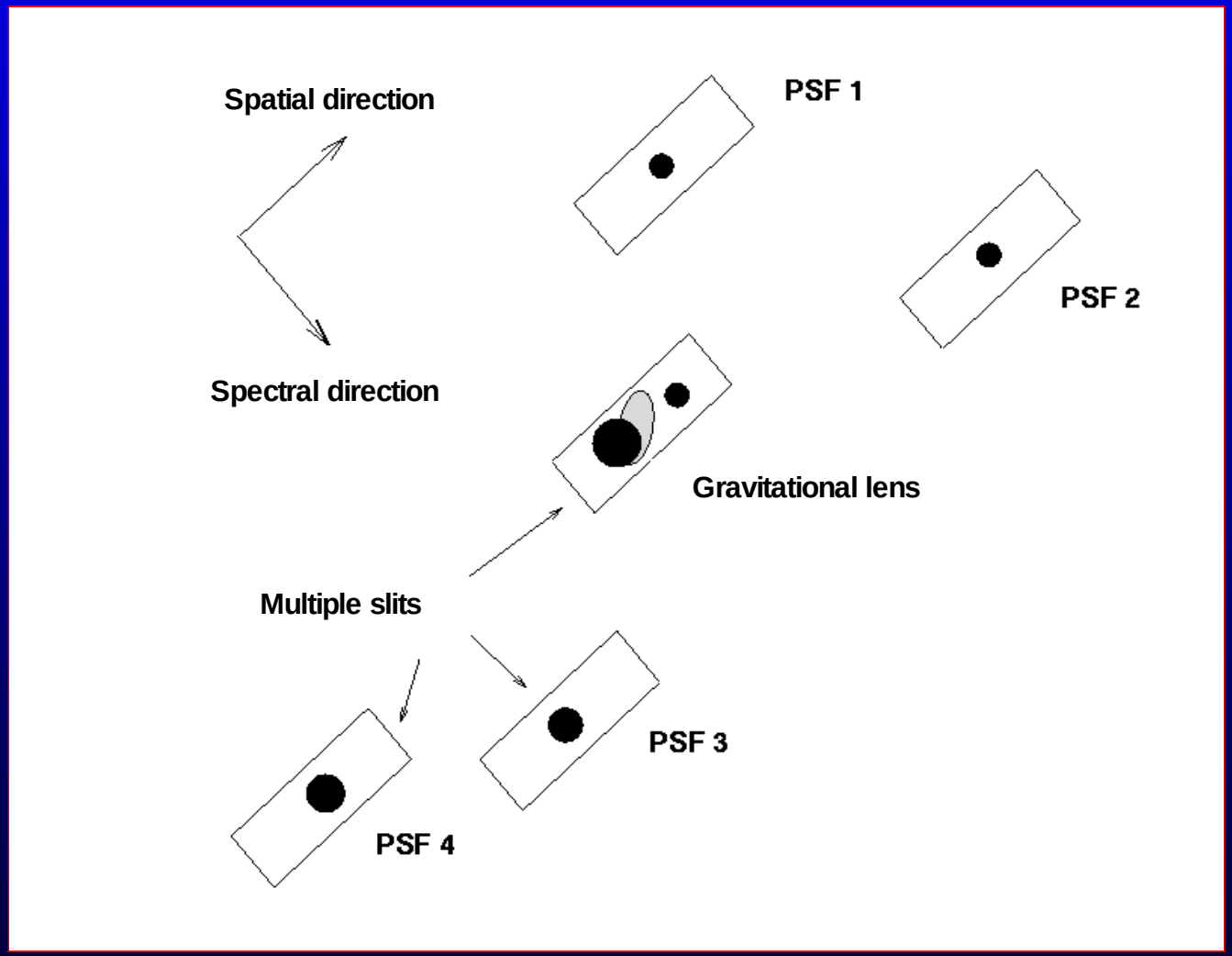
(Eigenbrod et al. 2005, A&A 451, 747)

An unusual quadruple: SDSS J0924+02

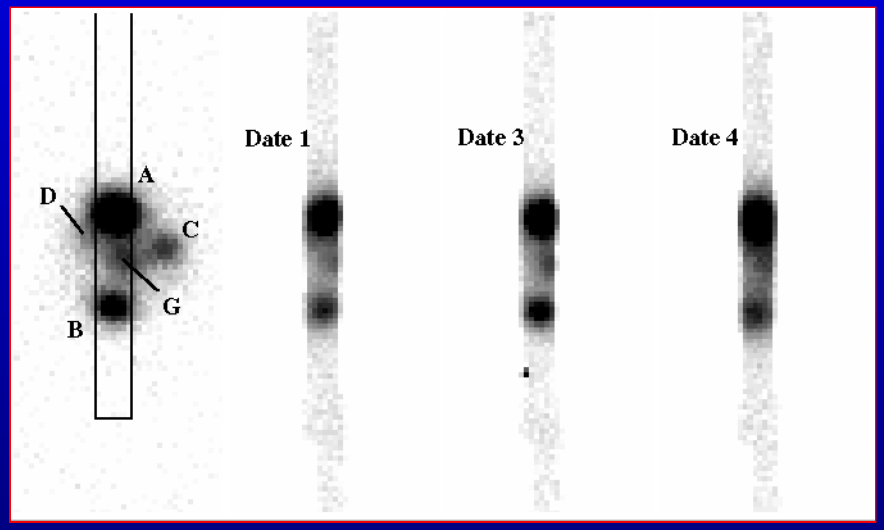


Modeling using Warren & Dye, 2003 ApJ 590, 673

Spatial deconvolution of spectra

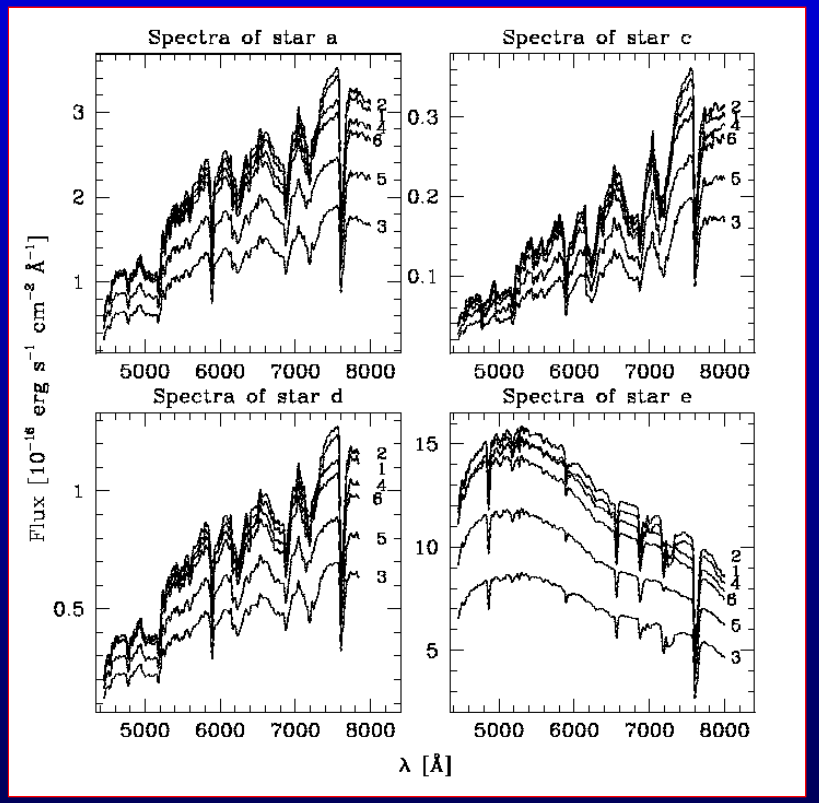


An unusual quadruple: SDSS J0924+02



VLT Multi-Object-Spectroscopy :

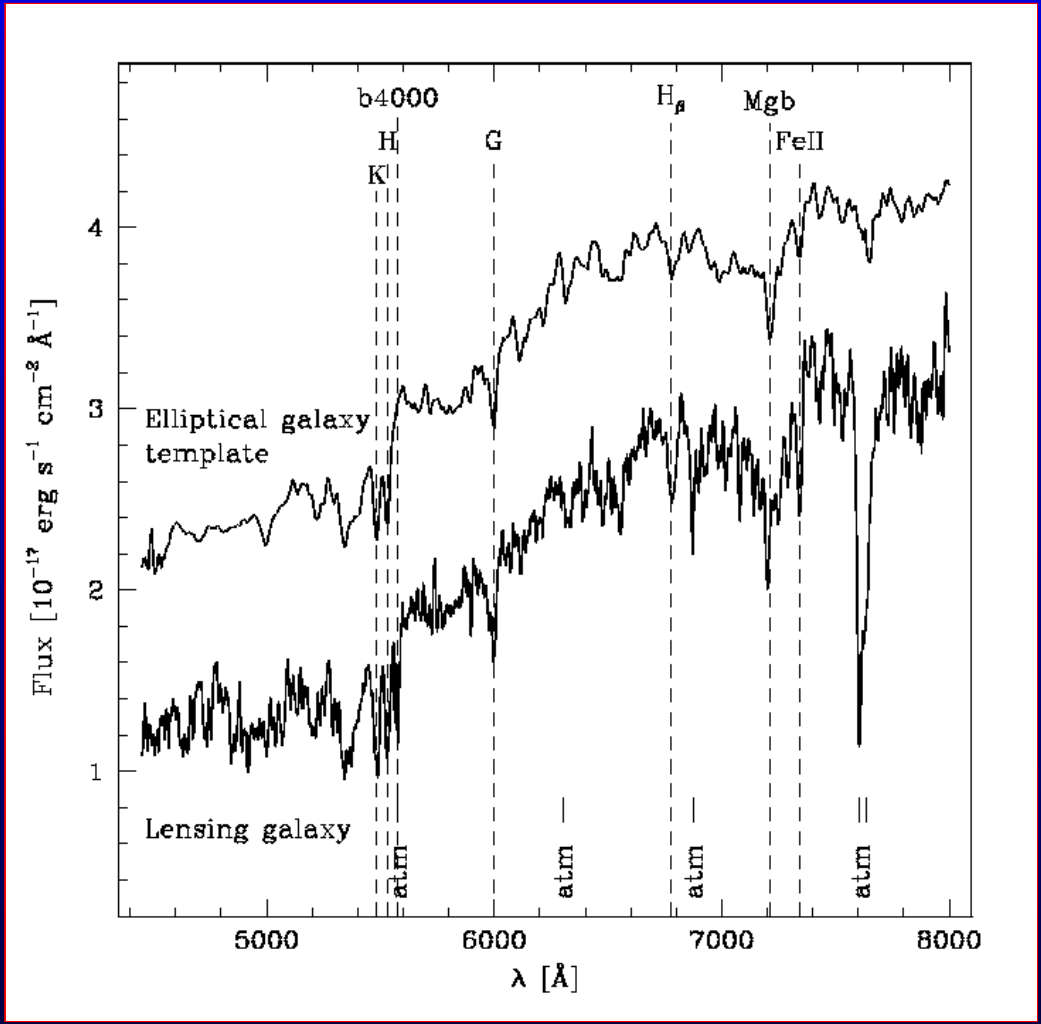
- Redshift of the lens (3h of exposure)
- Temporal variations (microlensing)



Reference stars :

- PSF
- Flux calibration

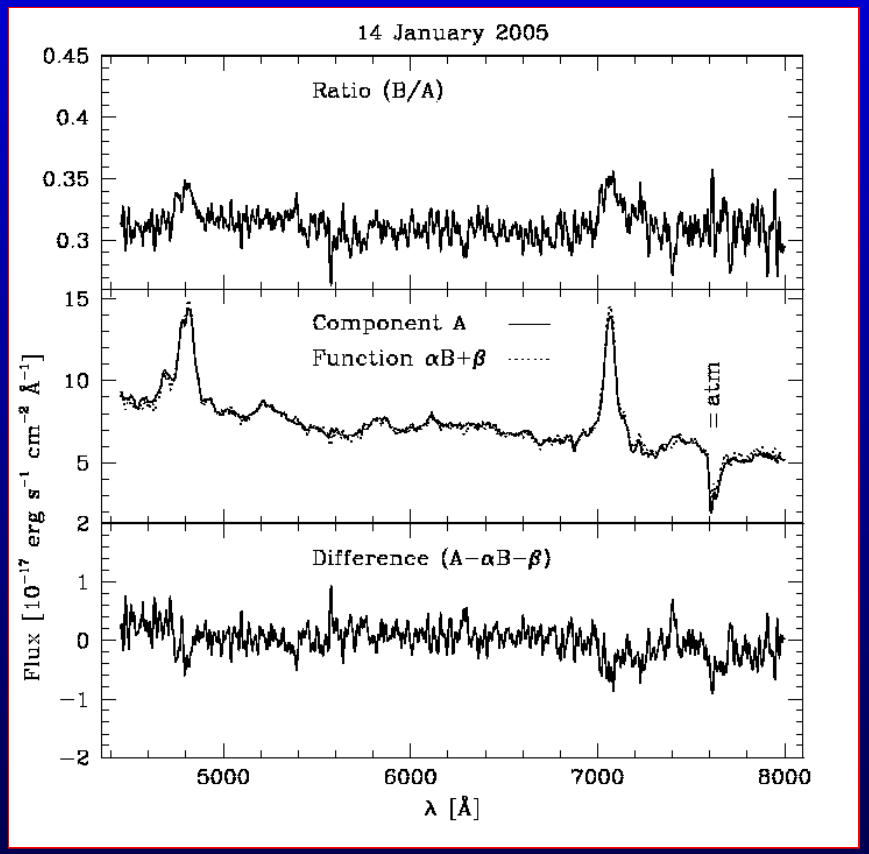
An unusual quadruple: SDSS J0924+02

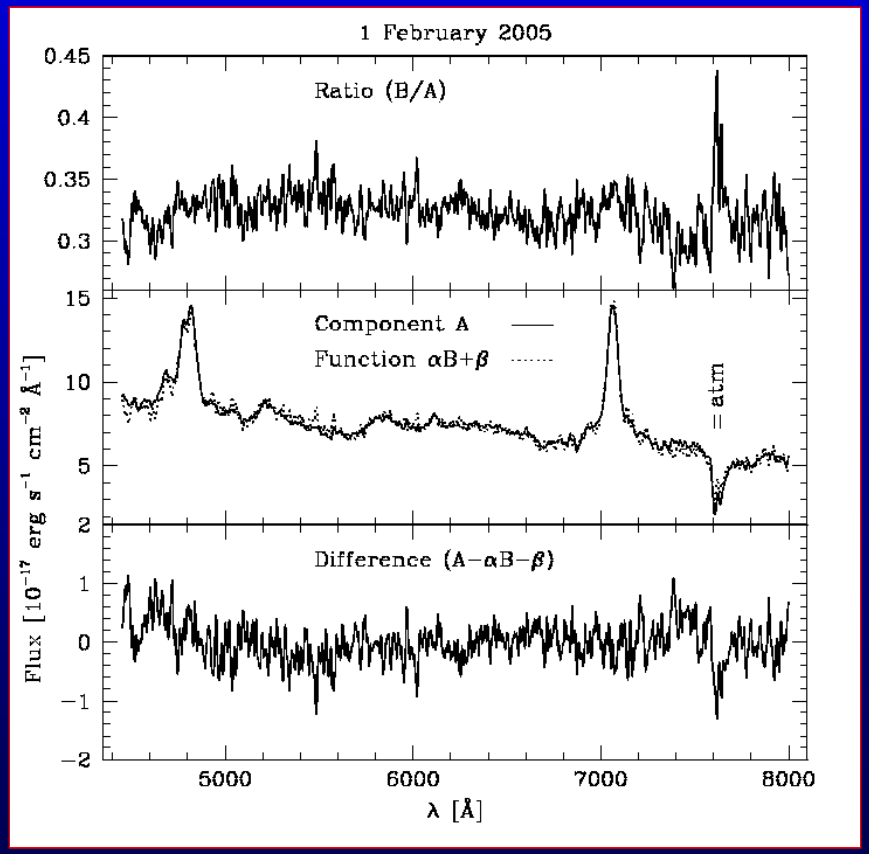


COSMOGRAIL publications so far

- Eigenbrod et al. 2005, A&A 436, 25
- Eigenbrod et al. 2006, A&A 451, 747
- Eigenbrod et al. 2006, A&A 451, 759
- Saha et al. 2006, A&A 450, 461
- Vuissoz et al. 2007, in press in A&A (astro-ph/0606317)
- Eigenbrod et al. 2007, accepted by A&A (astro-ph/0612419)

An unusual quadruple: SDSS J0924+02

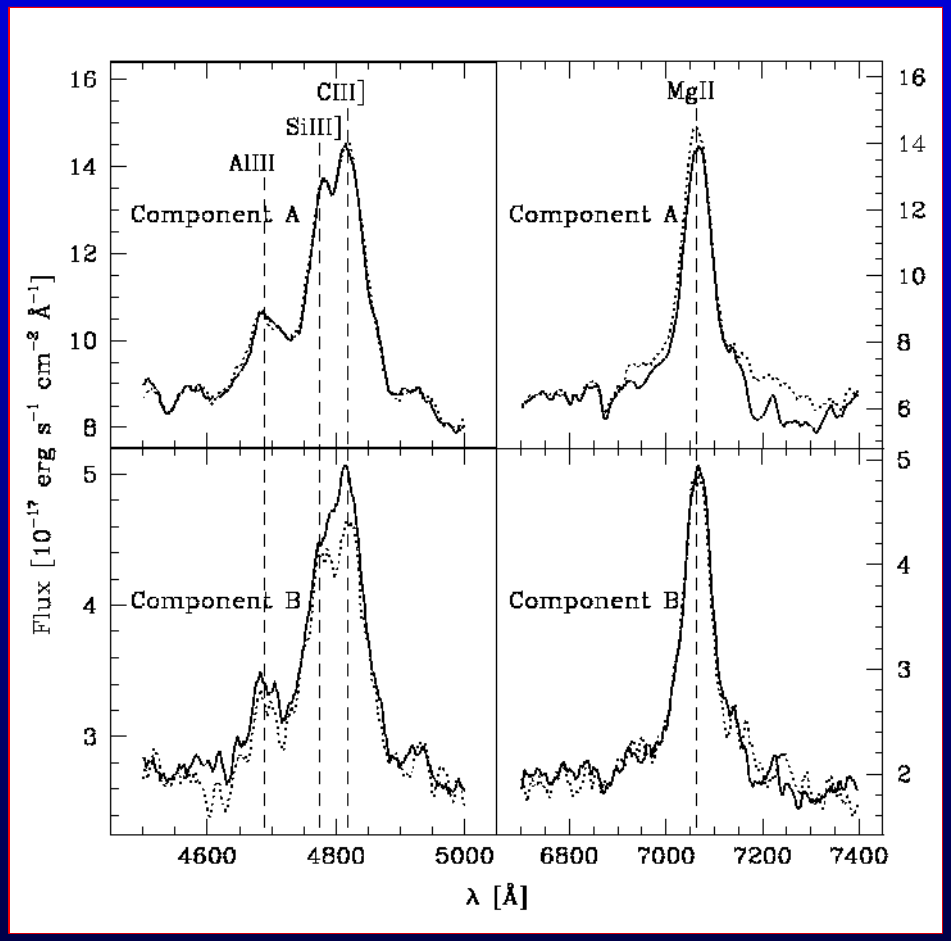




α = 2.80

α = 2.86

An unusual quadruple: SDSS J0924+02



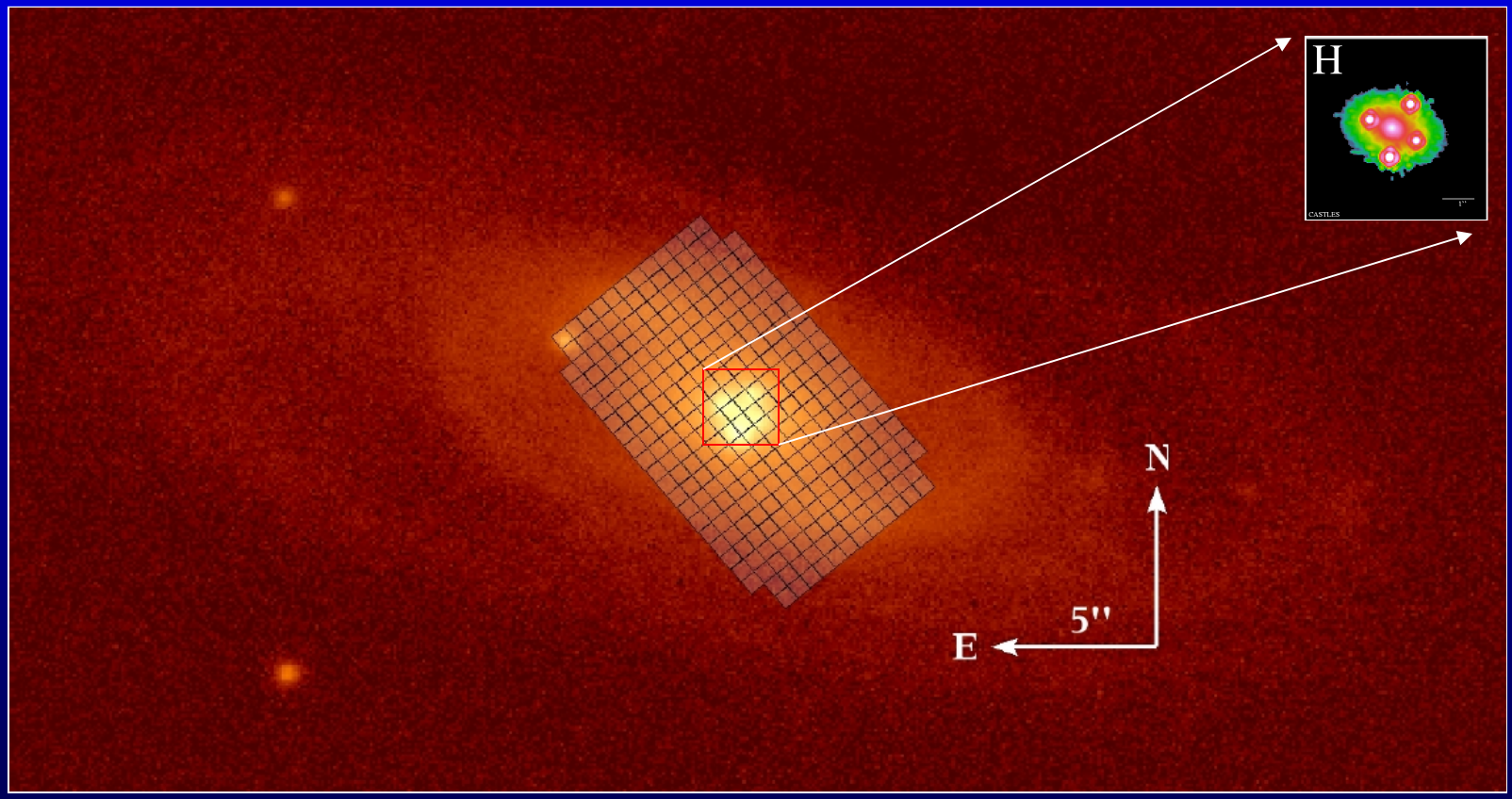
Component B varies first (solid curve: first epoch)

→Expected time delay = time interval between observations (15 days)

The solid curves in the lower panels should match the dotted curves in the upper panels

→The variations are due to microlensing

Integral field spectroscopy of lens galaxies

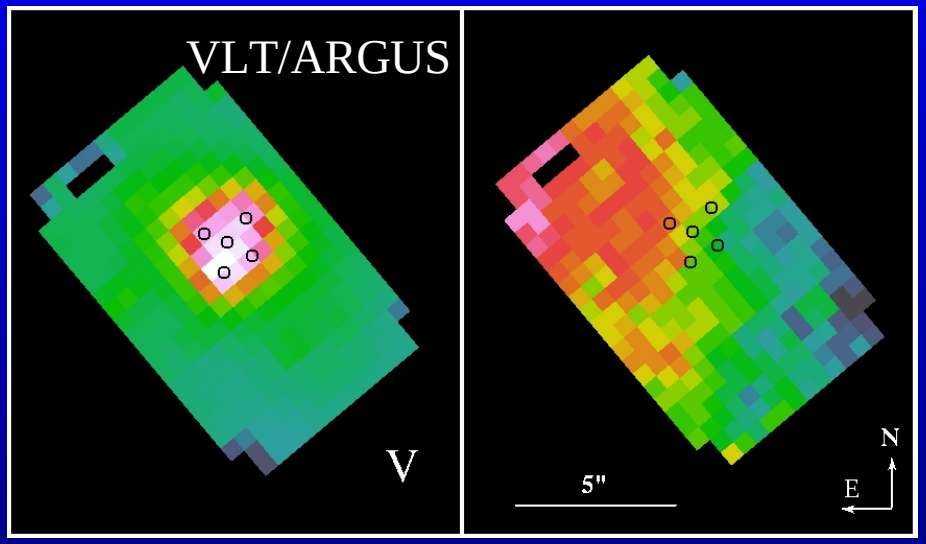


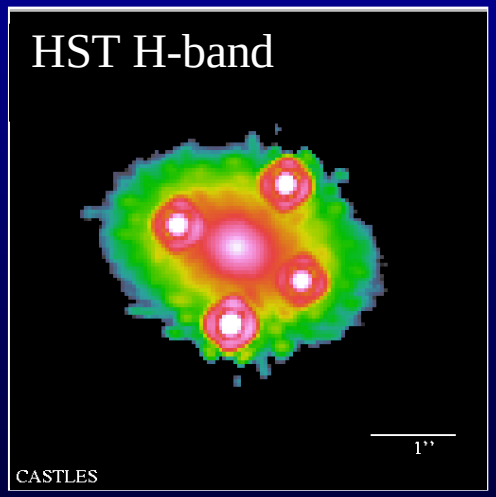
VLT FLAMES/ARGUS field of view in the Einstein Cross

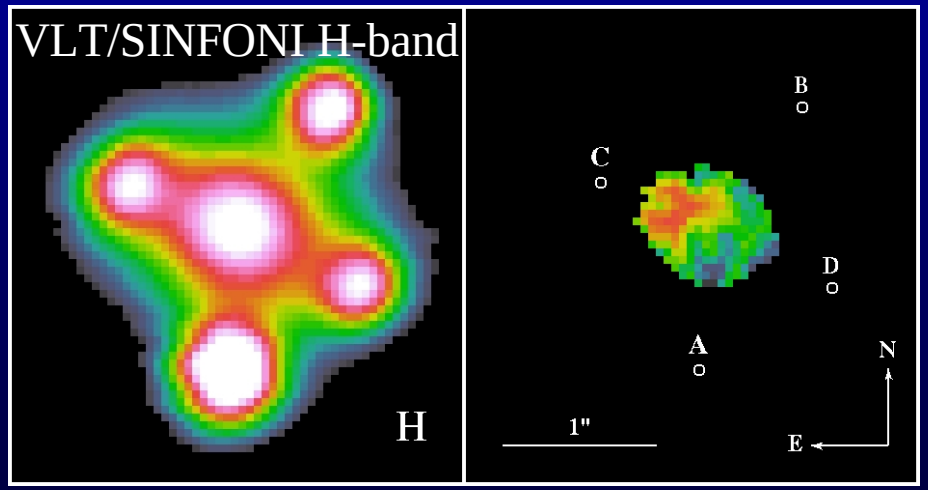
Integral field spectroscopy of lens galaxies

Lensing vs. Dynamics

Lensing *using* dynamics







3 arcsec !

Adaptive optics

Summary

- H_0 still is not known with an accuracy any better than 10%
- International monitoring campaign with **5** medium-size telescopes.
- Target accuracy 1-2% can be reached on individual time delays even in presence of microlensing.
- Residual microlensing of 1% has no effect on the time delay measurement.
- Below 5% accuracy on H_0 using only the COSMOGRAIL time delays
- Follow-up of microlensing events and use of Einstein rings to constraint the lens models.

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