The University of Manchester
Jodrell Bank Observatory

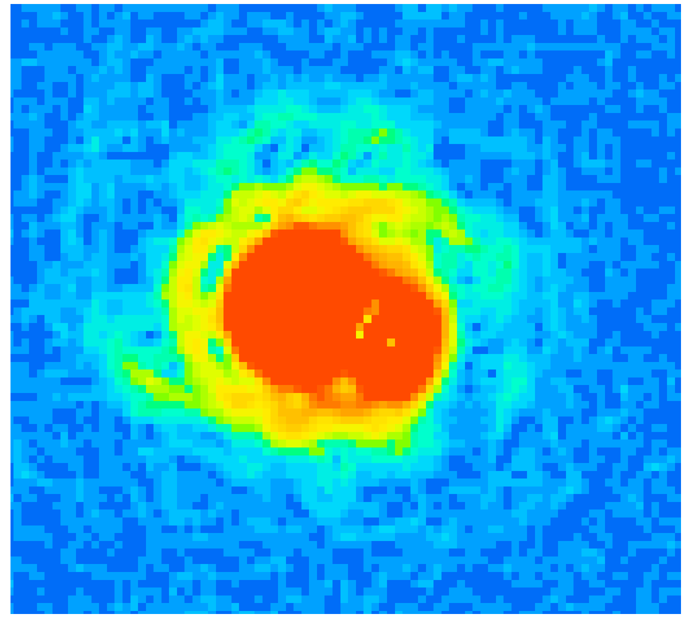
MANCHESTER 1824

Gravitational lensing by galaxies

$$\mathbf{A} = \partial \mathbf{y} / \partial \mathbf{x}$$

$$= \delta_{ij} - \begin{pmatrix} \frac{\partial^2 \psi}{\partial x_1^2} & \frac{\partial^2 \psi}{\partial x_1 \partial x_2} \\ \frac{\partial^2 \psi}{\partial x_2 \partial x_1} & \frac{\partial^2 \psi}{\partial x_2^2} \end{pmatrix}$$

$$= \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix}$$

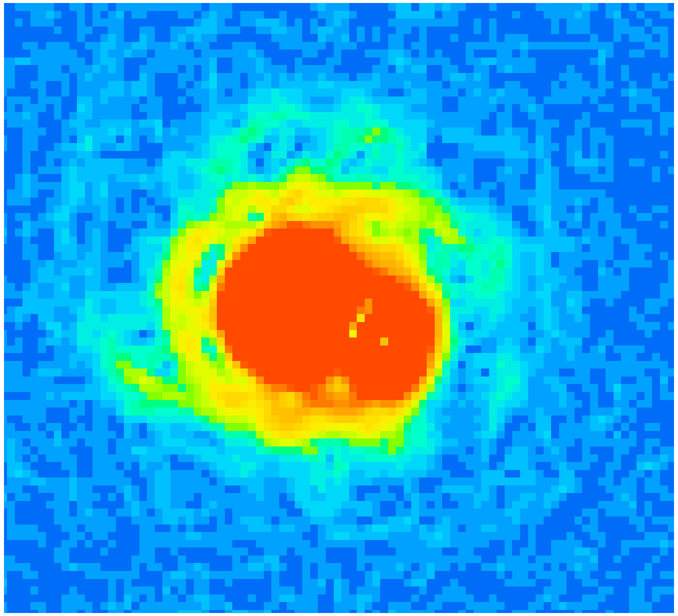


Neal Jackson, Jonathan Quinn, Philippa Hartley
Olaf Wucknitz, Dominique Sluse, Filomena Volino (JVLA)
and the E-MERLIN Lens Legacy Programme

The University of Manchester
Jodrell Bank Observatory

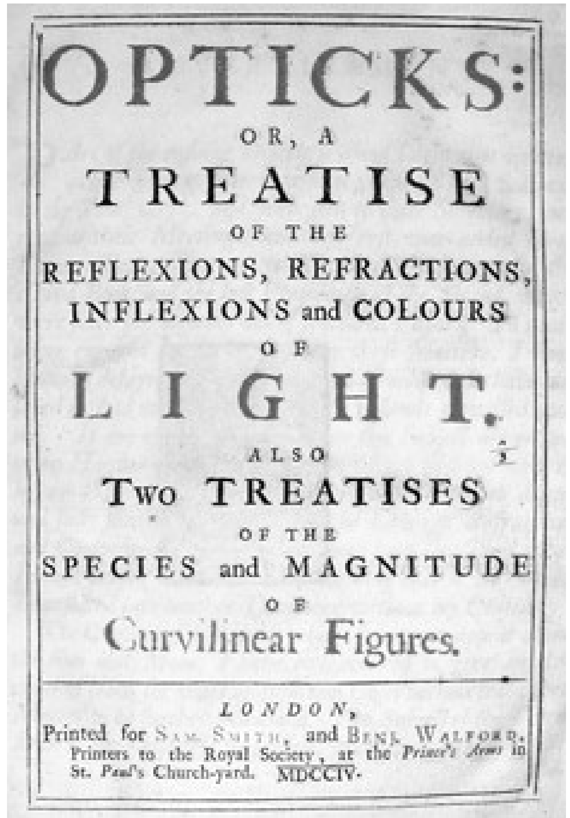
MANCHESTER
1824

Outline



1. Introduction and geometry
2. Why study lenses?
   - lensing galaxies
   - cosmography
   - magnifying lensed sources
3. The Future

The story starts with Newton…



OPTICKS:

OR, A

TREATISE

OF THE

REFLEXIONS, REFRACTIONS, INFLEXIONS and COLOURS

OF

LIGHT.

ALSO

Two TREATISES

OF THE

SPECIES and MAGNITUDE

OF

Curvilinear Figures.

LONDON,

Printed for SAM. SMITH, and BENJ. WALFORD, Printers to the Royal Society, at the Prince's Arms in St. Paul's Church-yard. MDCCIV.

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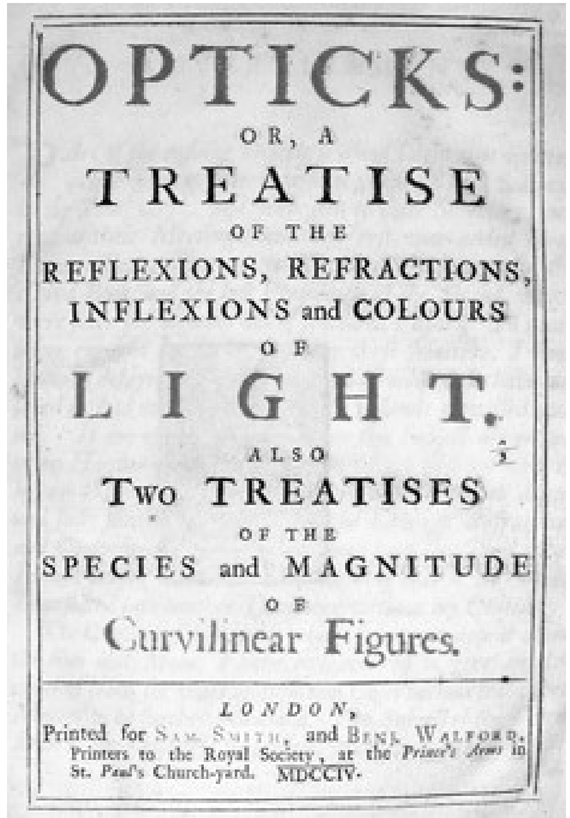

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LONDON,
Printed for SAM. SMITH, and BENJ. WALFORD,
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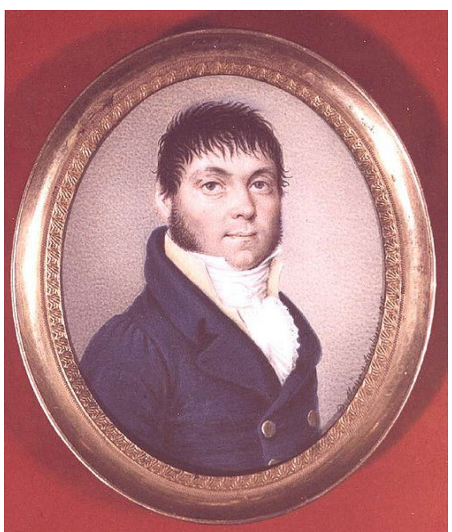
St. *Paul's* Church-yard. MDCCIV.

…or Jean-Paul Marat



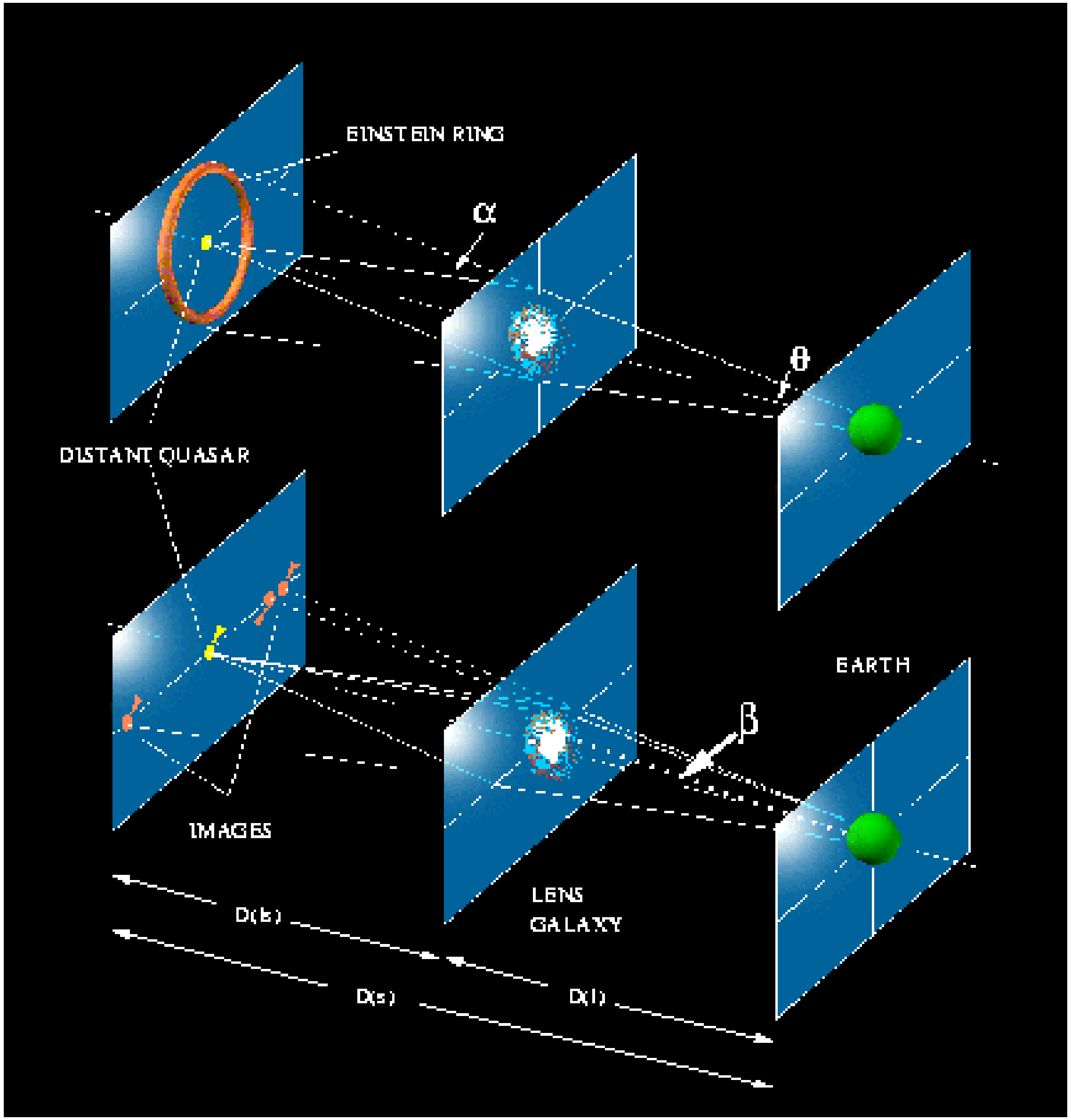
…or Johann Soldner

..but Einstein worked out the equation correctly

If M is the mass of the deflector and b the distance of approach of the light ray, then the deflection angle is given by…

$$\alpha = \frac{4GM}{bc^2}$$

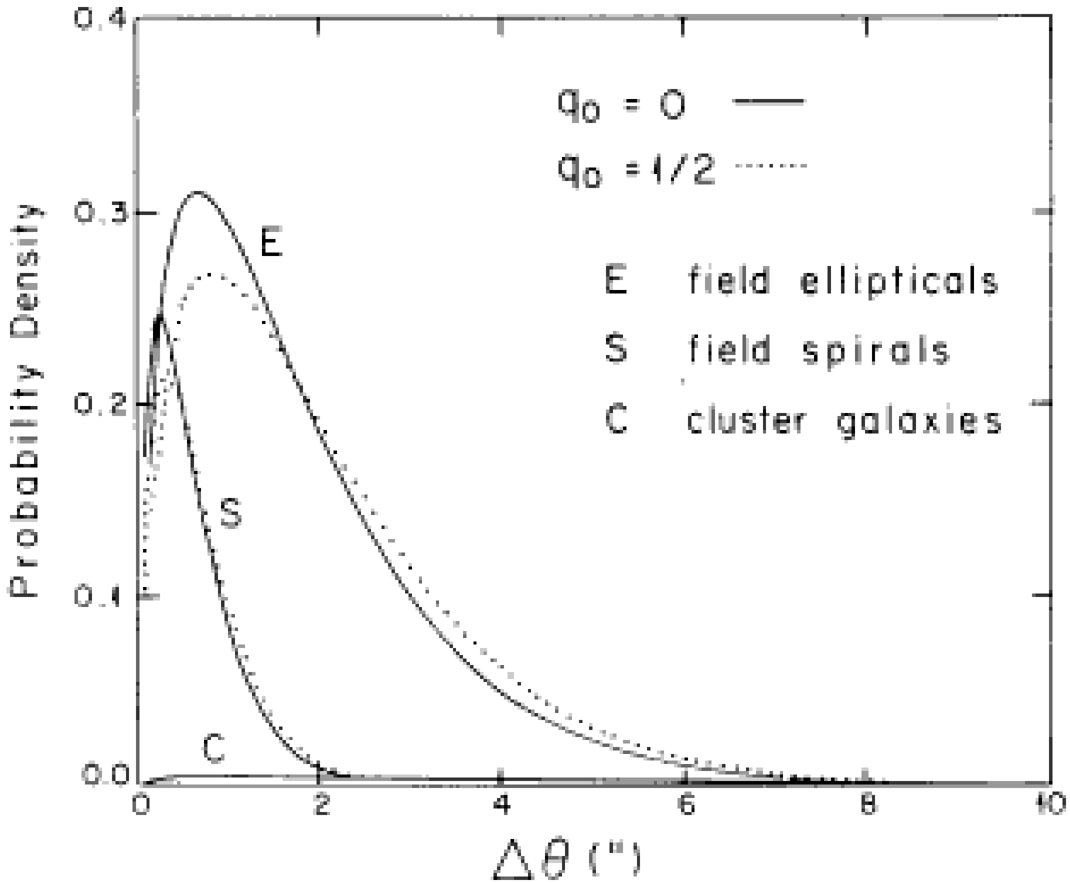
Basic principle



1 in 500 chance
Einstein radius ~0.7”
Exact alignment = ring
Usually 3 or 5 images
Central image very faint

First lens in 1979
~400 now known

Lens systems



Giant ellipticals statistically most likely

Turner, Ostriker & Gott 1984

Where do the images form?

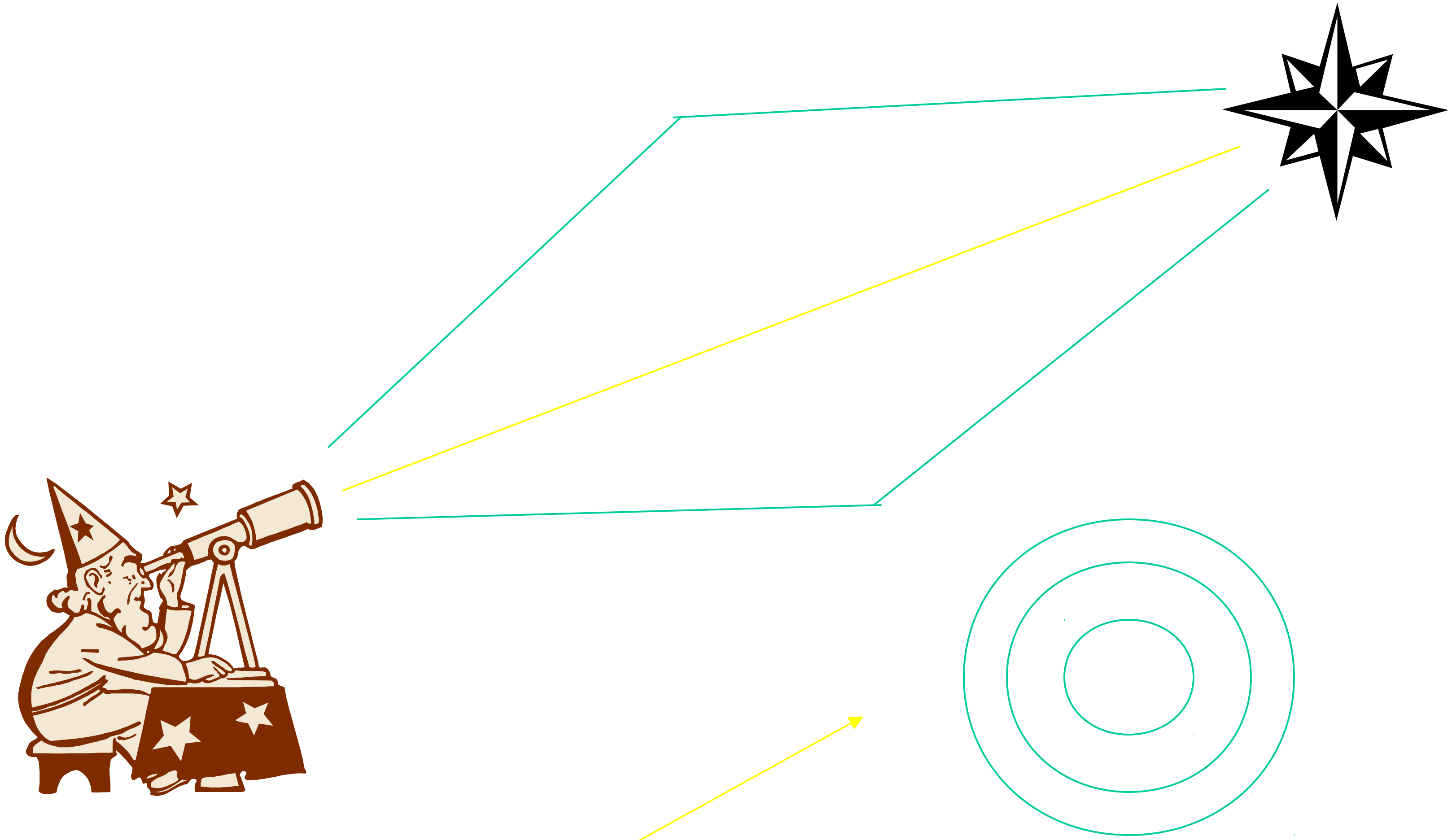
From all possible paths that it might take to get from one point to another, light takes the path which requires the shortest time.

(actually, shortest or longest)

…First we have an observation, then we have some numbers we can measure, then we have a law which summarises all the numbers. But the real *glory* of science is that *we can find a way of thinking* such that the law is *evident*

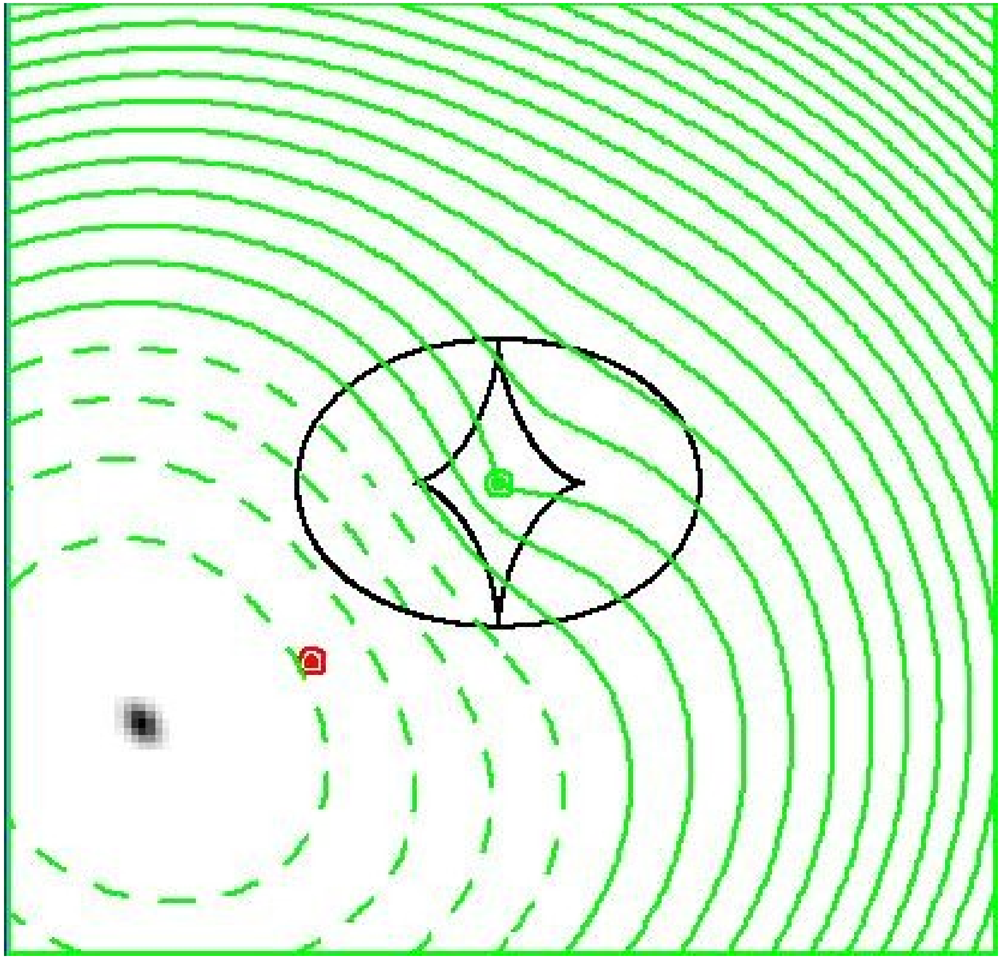
----- Richard Feynman

An example: a straight line is the shortest



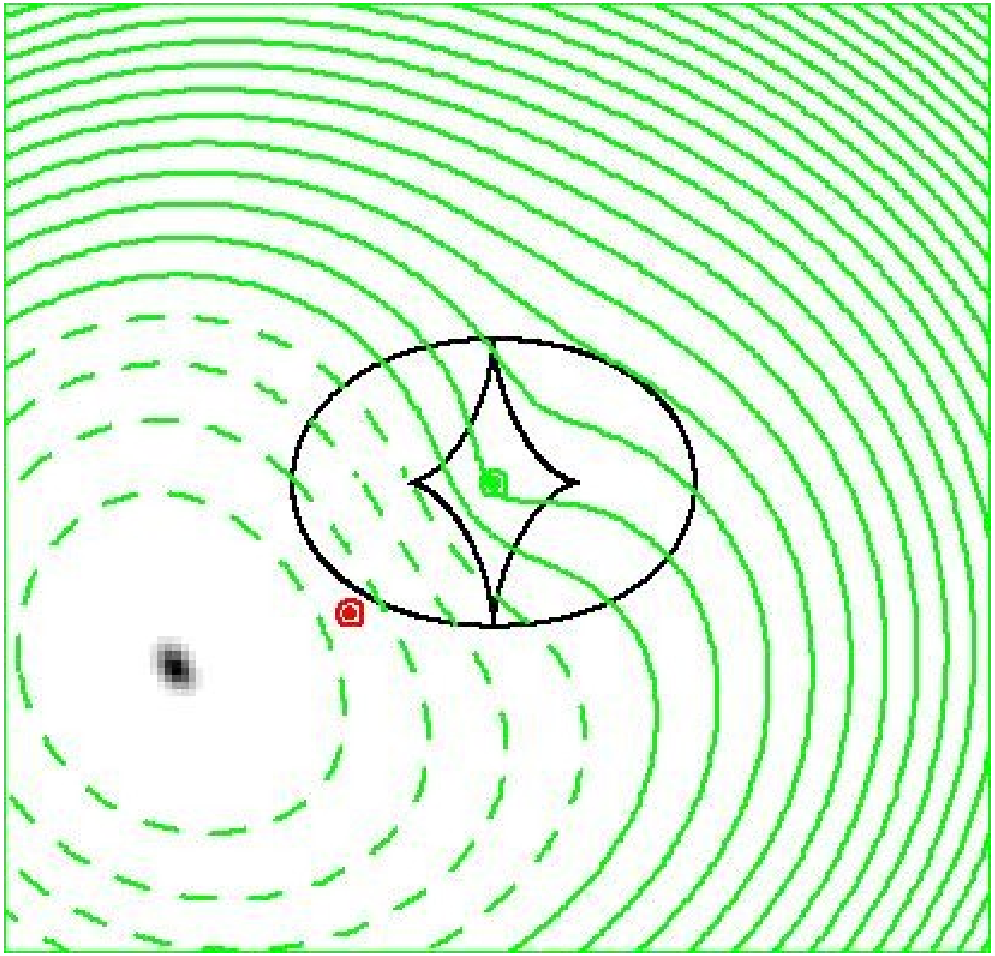
From observer's point of view, contours of constant time are concentric circles centred on light ray

Source (red spot) a large angle away from galaxy (green spot) seen in projection by the observer



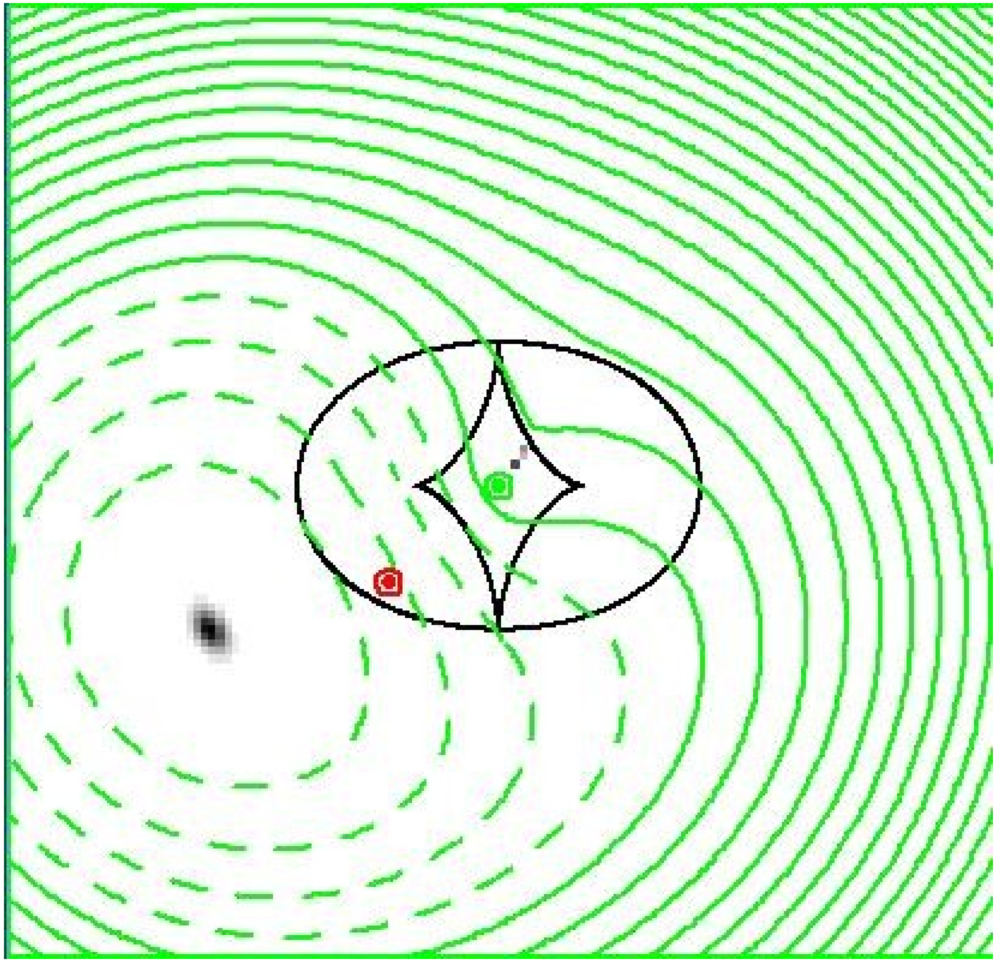
Only one path of shortest time (contours represent time of path)

Lines of sight get closer…



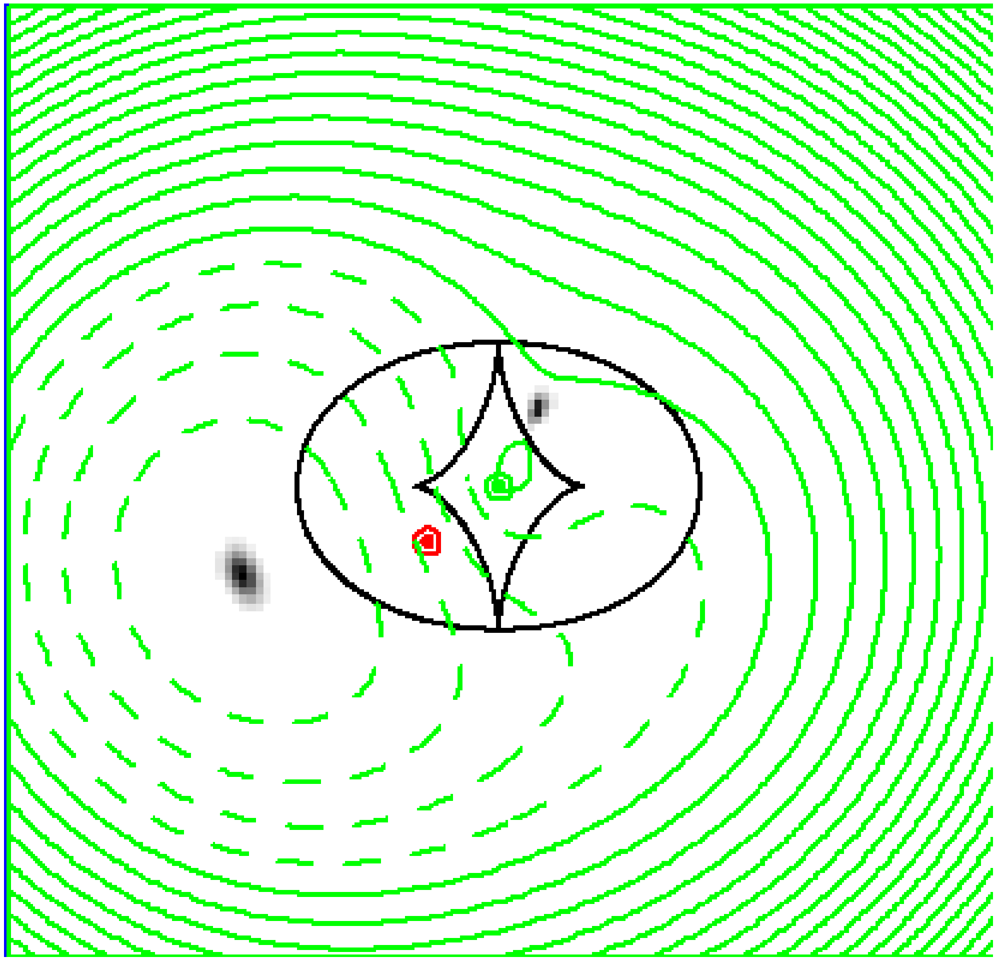
still only one image, until…

Source crosses a critical line…



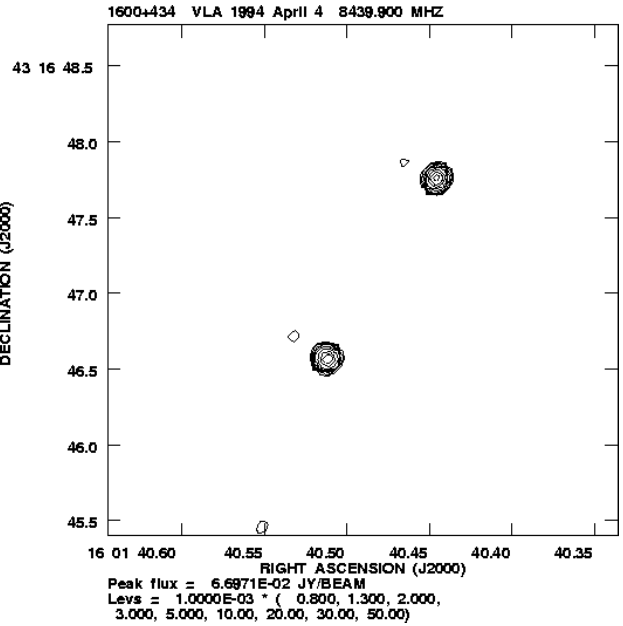
…and another image appears where contours pucker

Closer still…

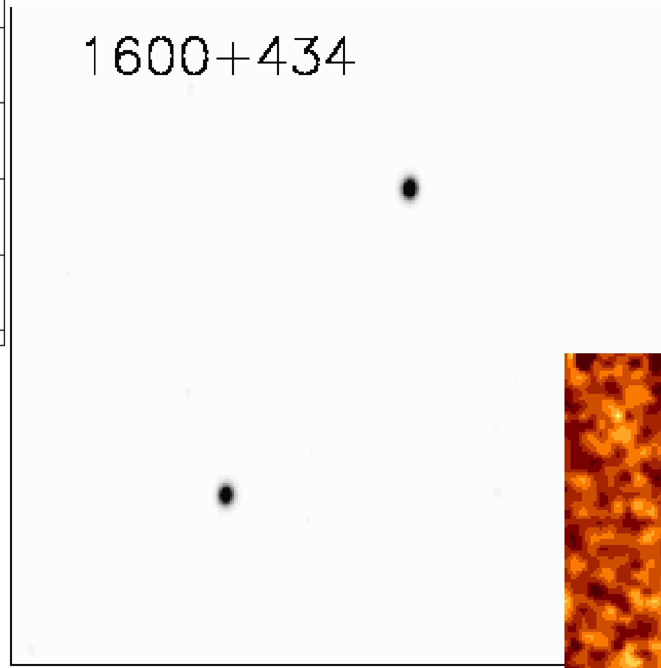


second image gets stronger…

CLASS B1600+434

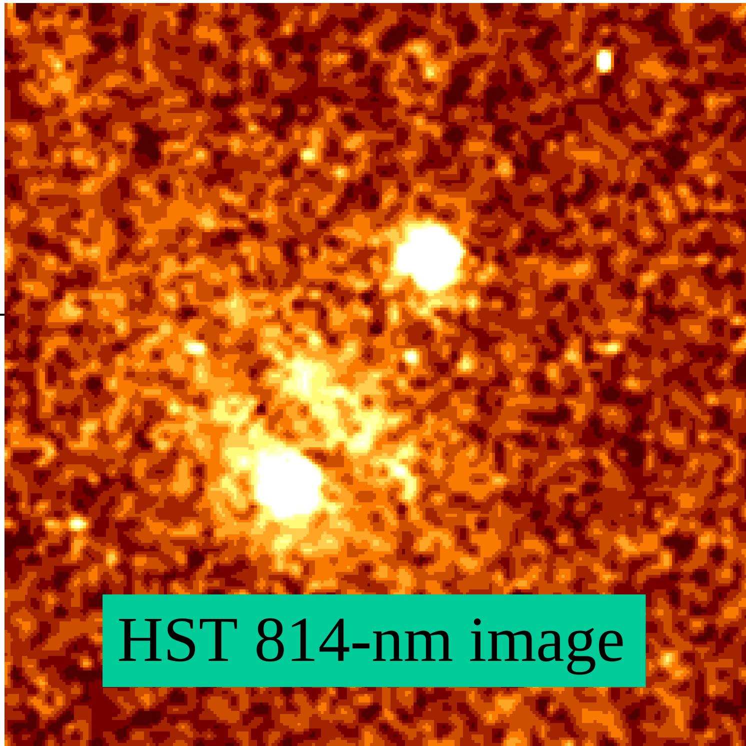


Initial VLA image
(220mas resolution)

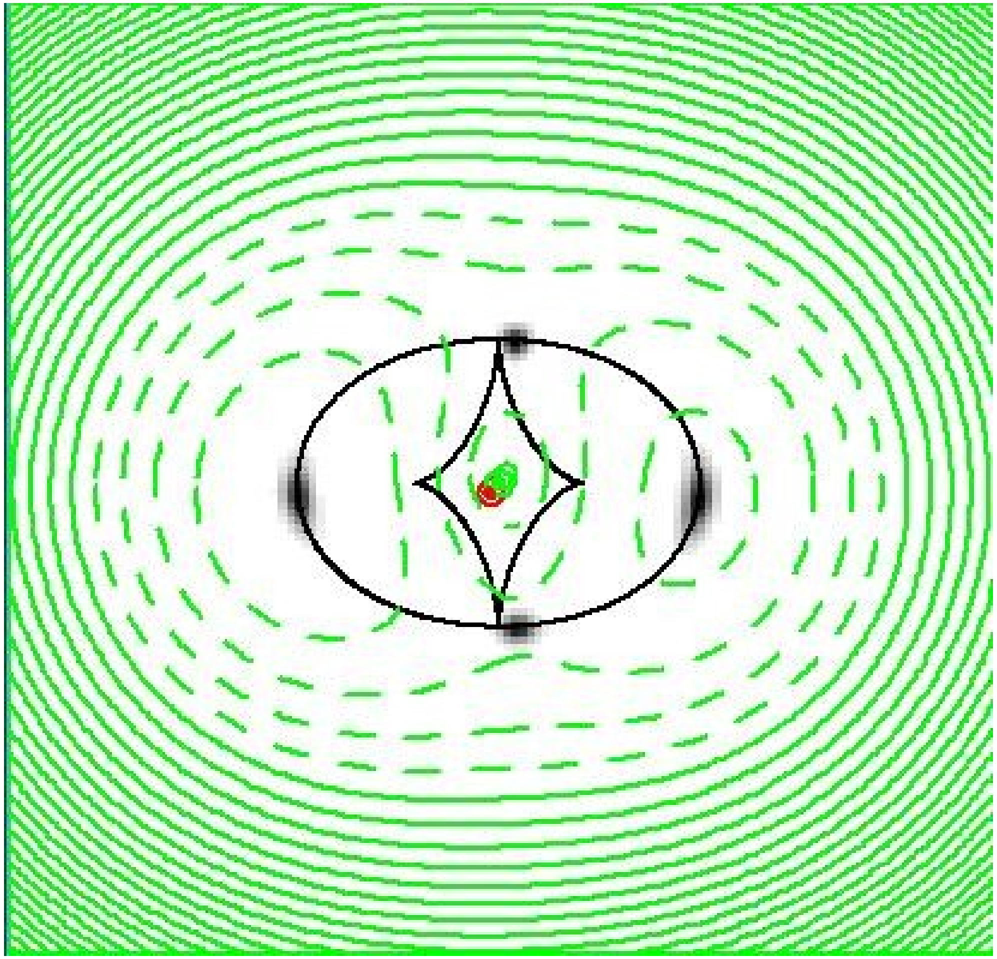


MERLIN image
(50 mas at 5GHz)

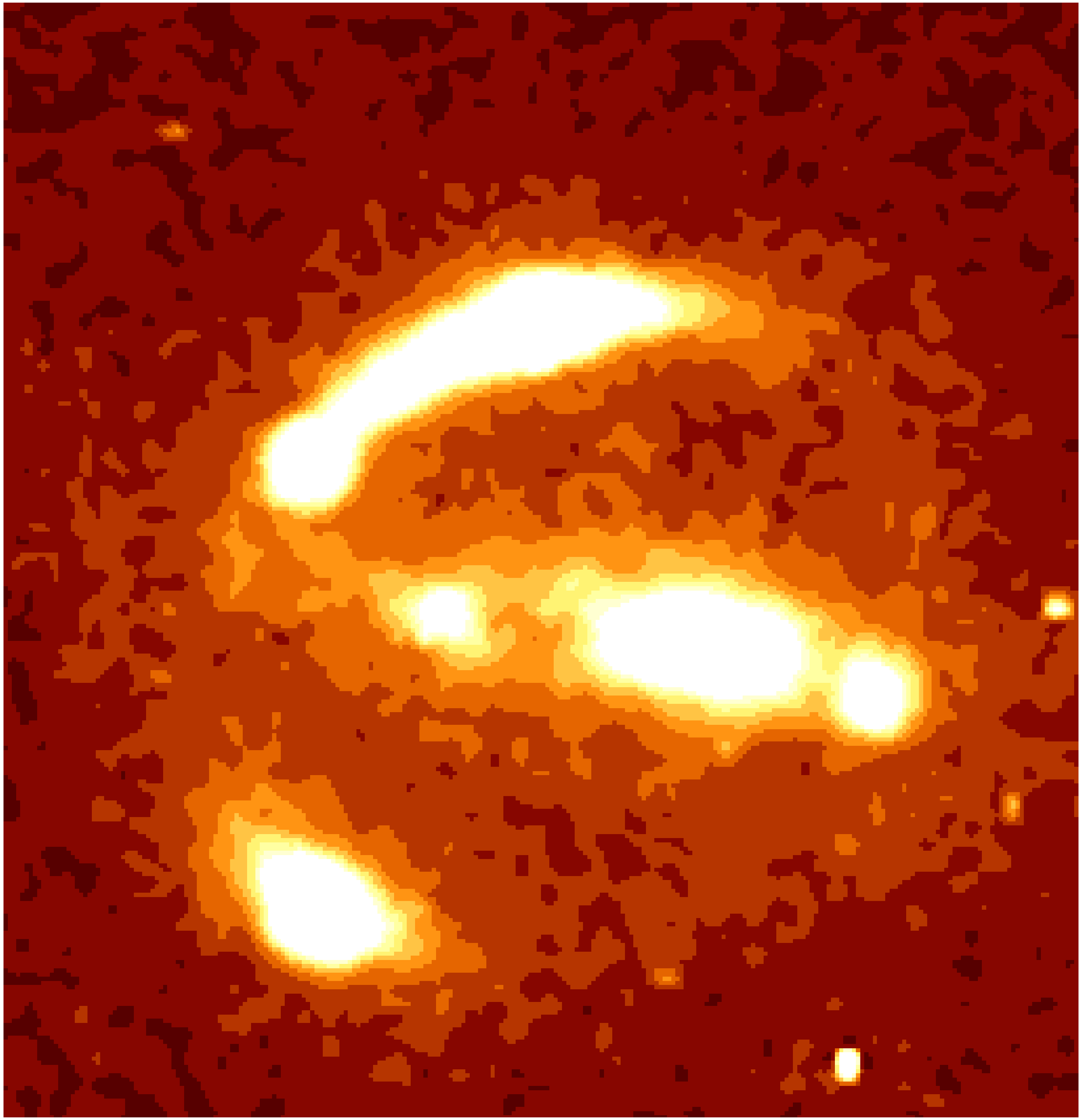
VLBA 1mas:
2 point sources

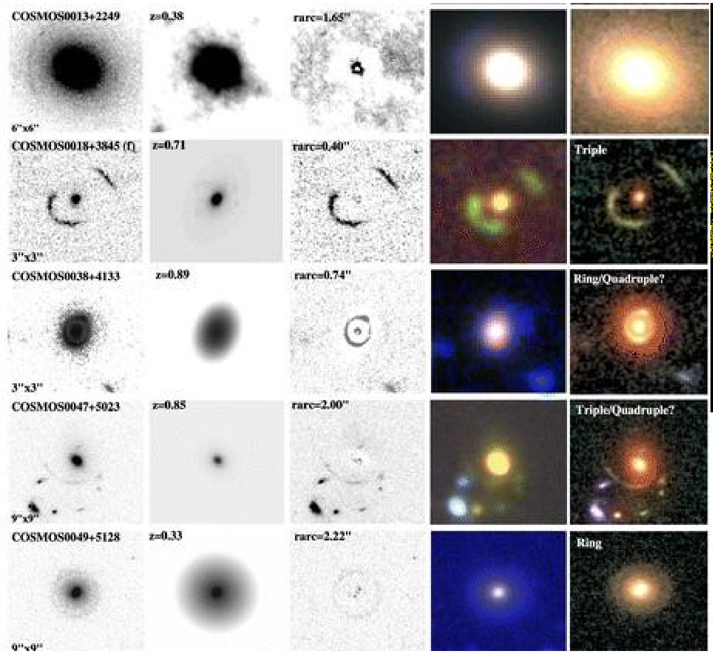


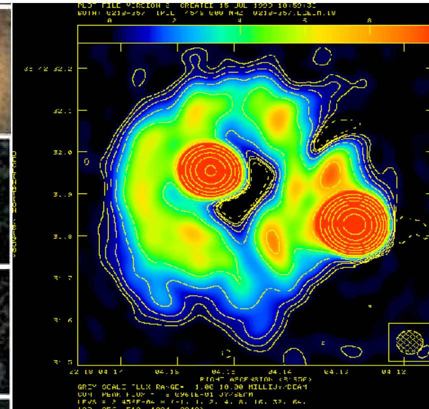
Crossing of second critical line

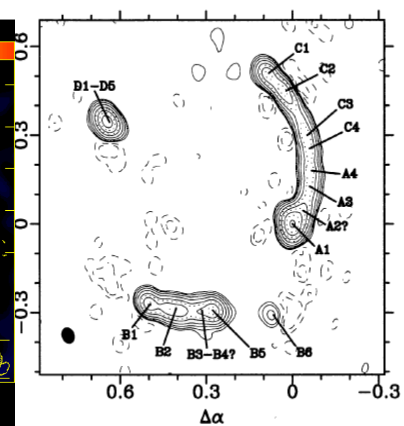


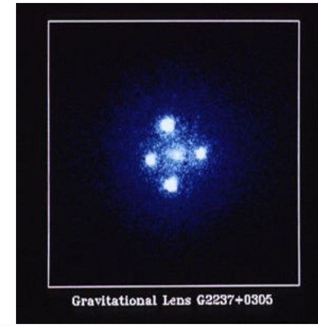
…two more images appear, again at flat points in the surface defined by the contours

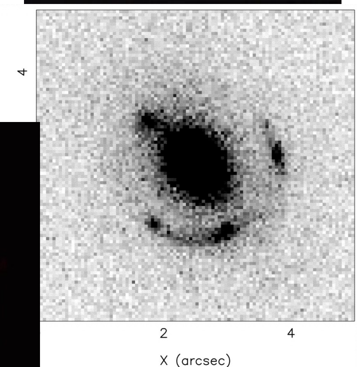


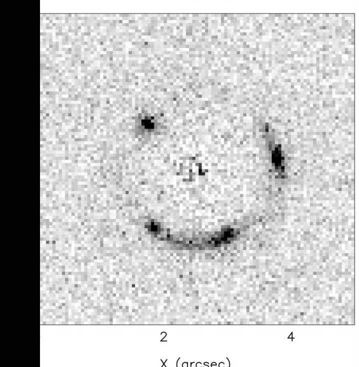


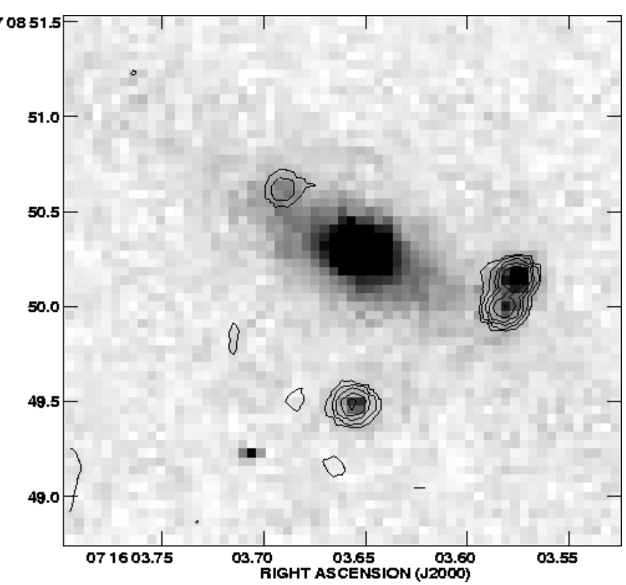


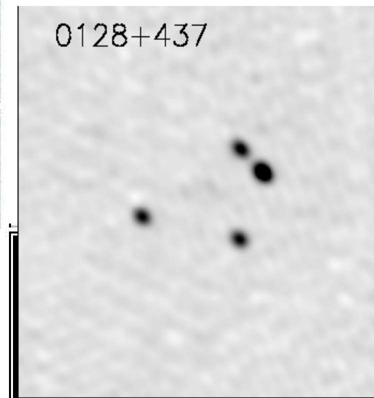


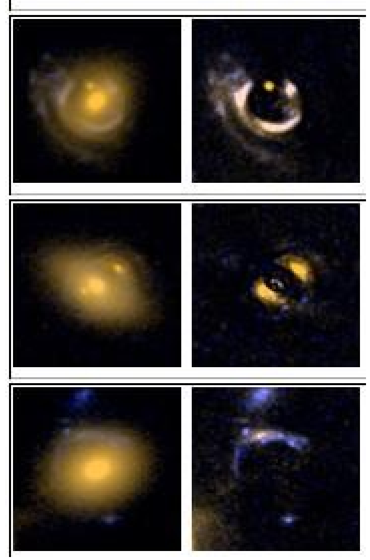


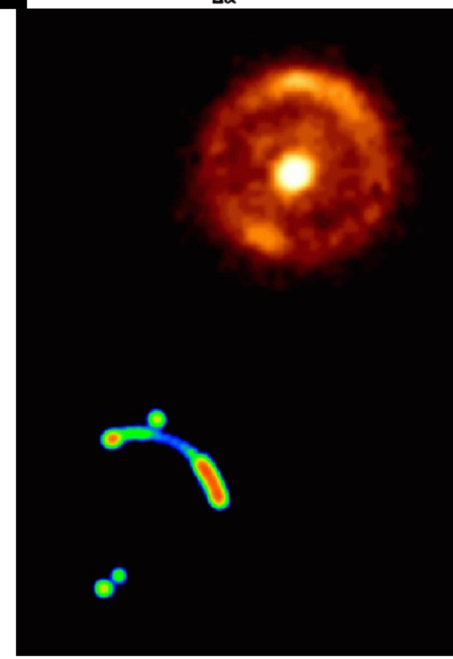






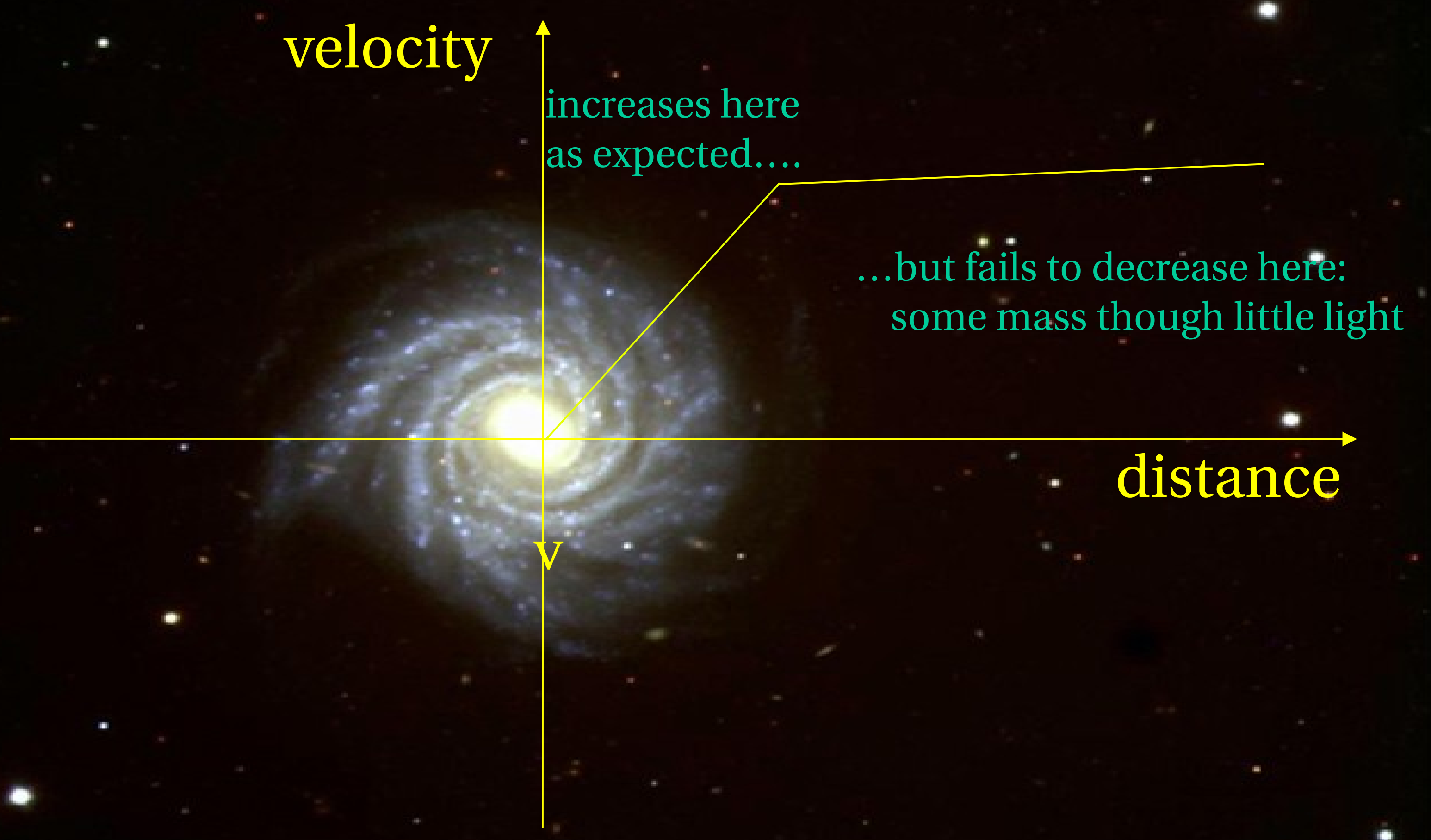






Faure+2008; King+1998; Dye&Warren 2005; Jackson 1998; Biggs+ 2004; Lehar+2000; Bolton+ 2006; Phillips+ 2001; Bolton+2008

2. Why study lenses?



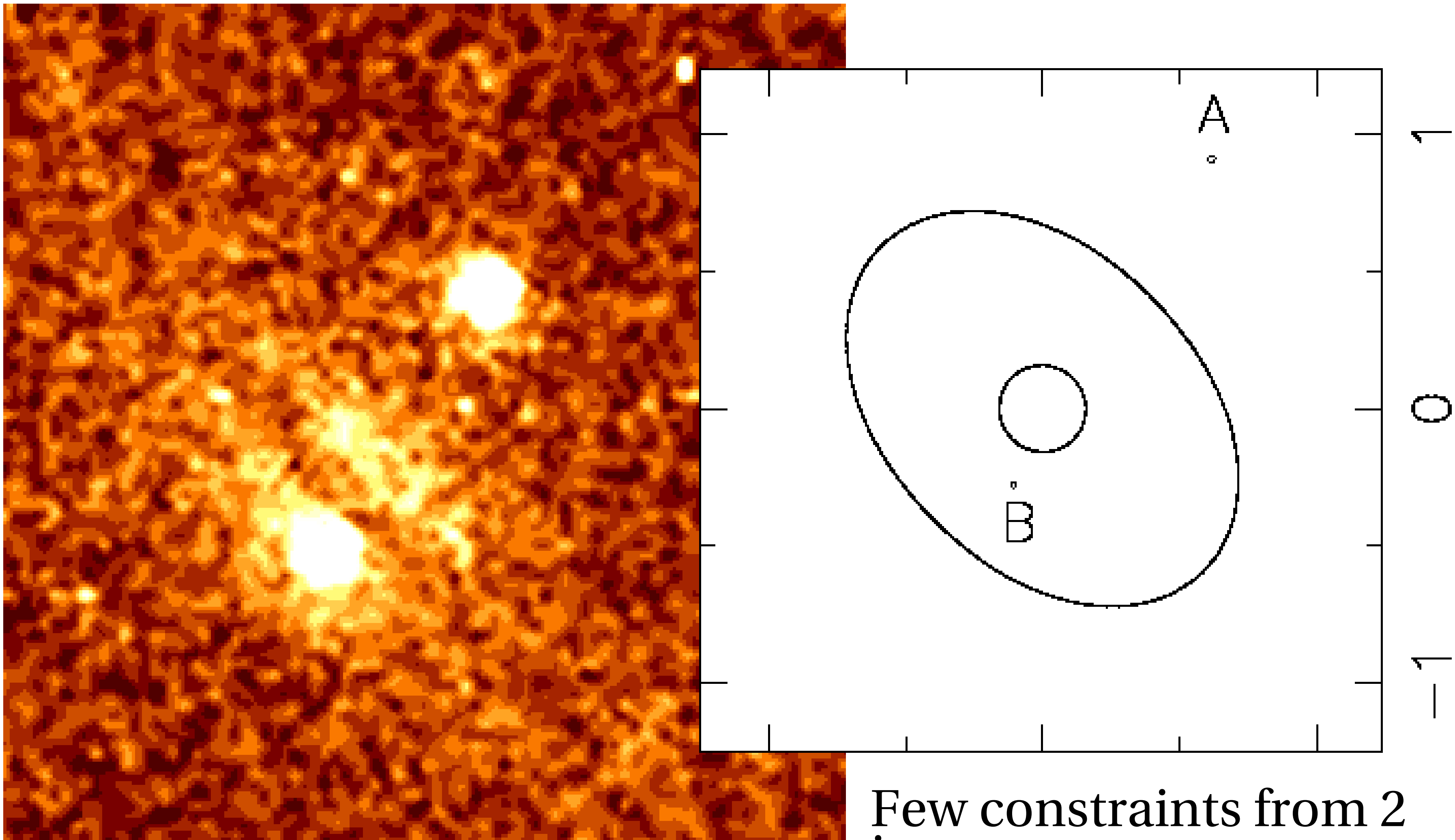
Dark matter revealed by spectroscopy in nearby galaxies
Distant galaxies, lensing gives a probe of all gravitating matter

Studying lensed structure tells you about

- overall mass profile (and evolution)
- CDM substructure in galaxies
- central regions of galaxies (within 100pc of SMBH)
- propagation effects in galaxies (two lines of sight with same object at end)

(Image positions constrain 1st derivative of potential
Fluxes constrain 2nd derivative)

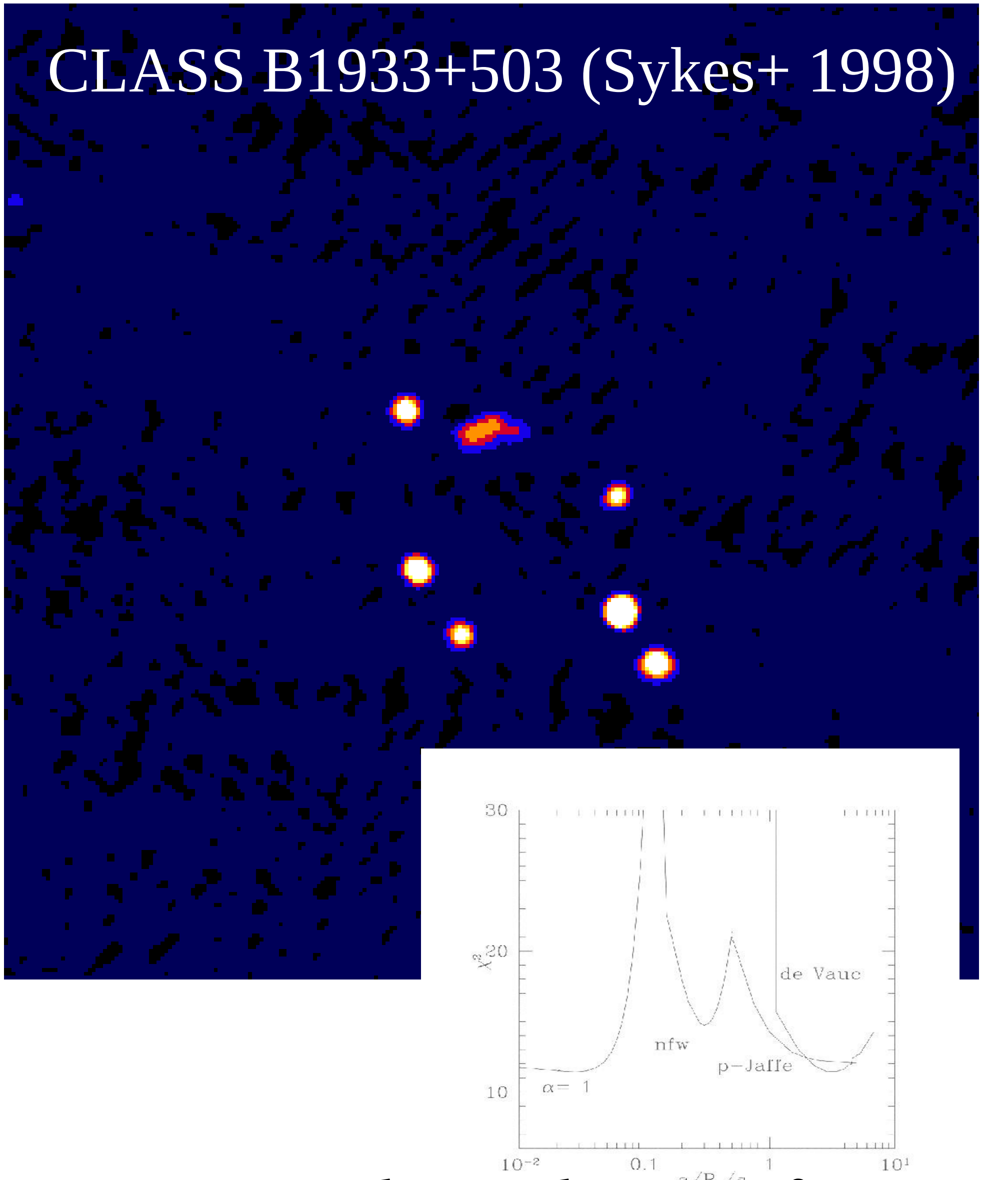
But you only get constraints where there are images…

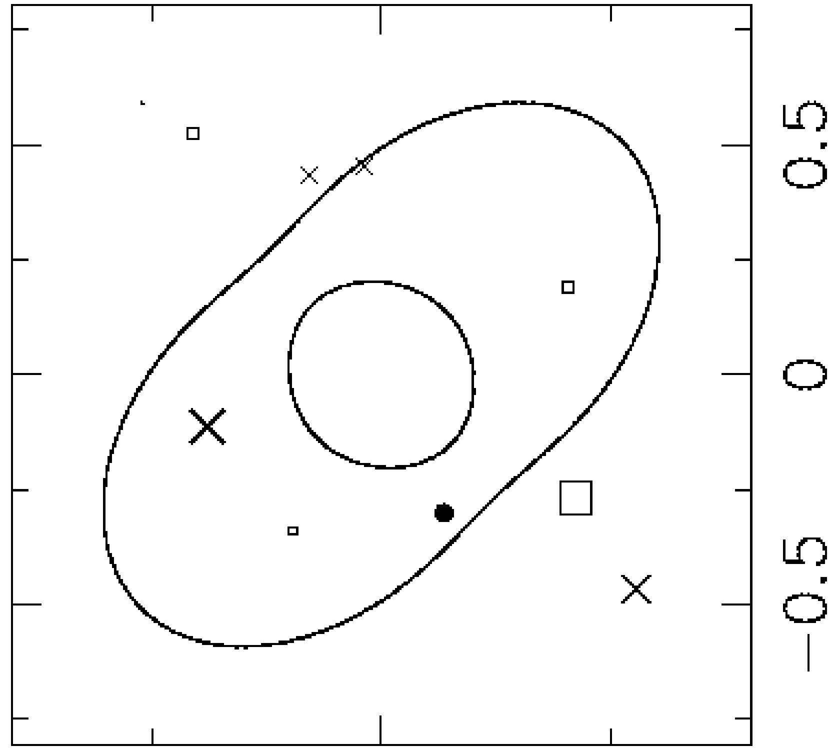


Few constraints from 2 images,
-1 degrees of freedom!

CLASS B1600+434 (Jackson et al. 1995)
HST/WFPC2 image

…so find some with more images…

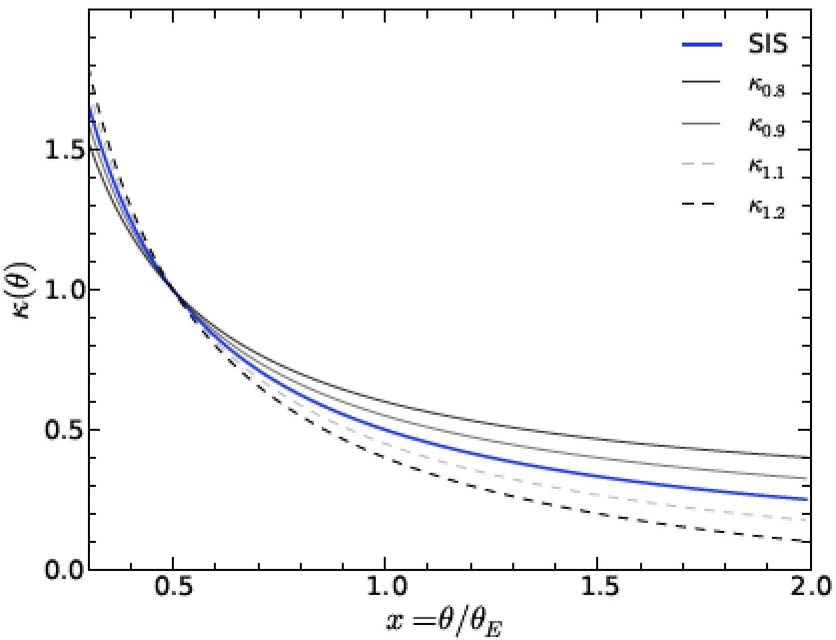




Galaxy model: mass, radial mass profile, ellipticity, and orientation (lots of constraints)

Cohn et al. 2001 – fit power-law mass distribution

...and worry to an appropriate extent about model degeneracies...

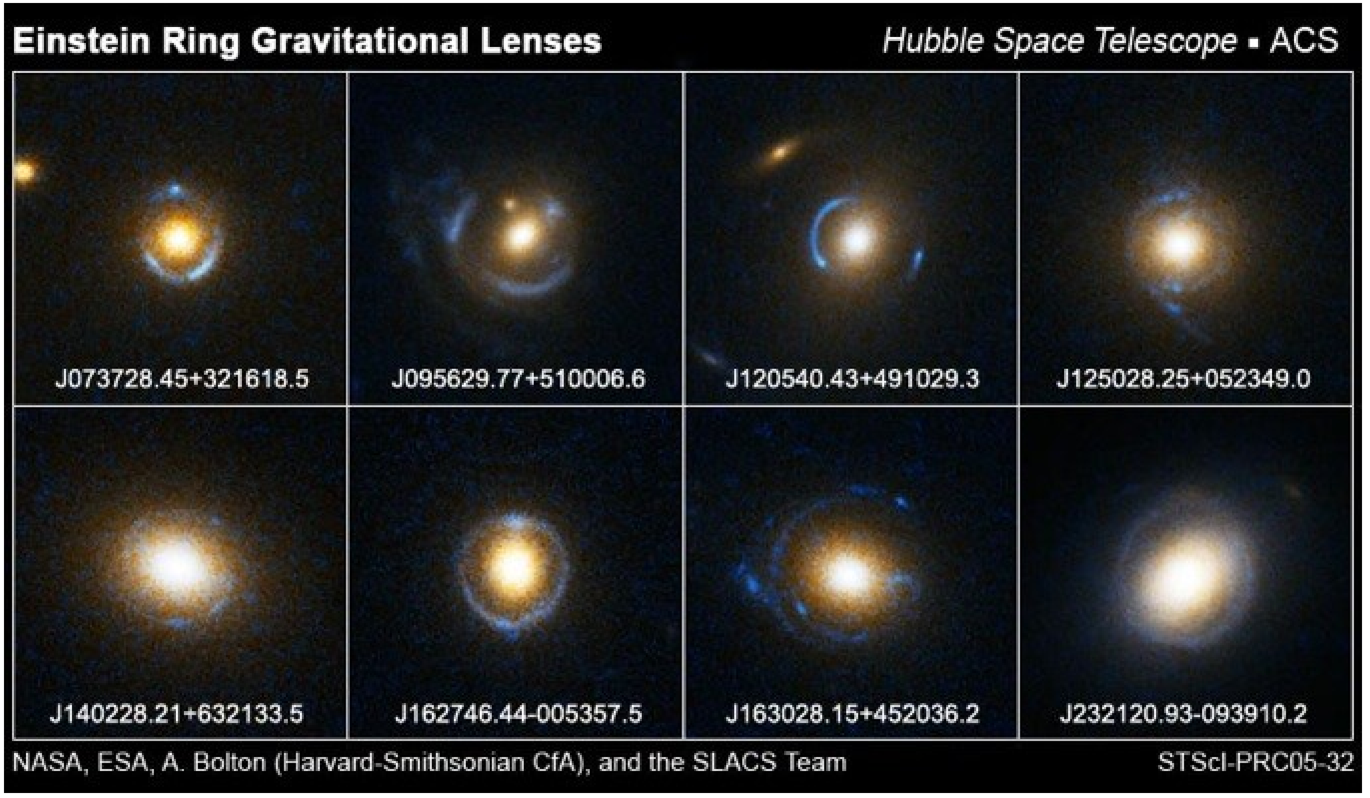


"mass sheet degeneracy" - e.g. Falco+ 1995, Schneider&Sluse 2013 (this figure)

Any lensed observables reproduced with a range of profiles – break degeneracy by:

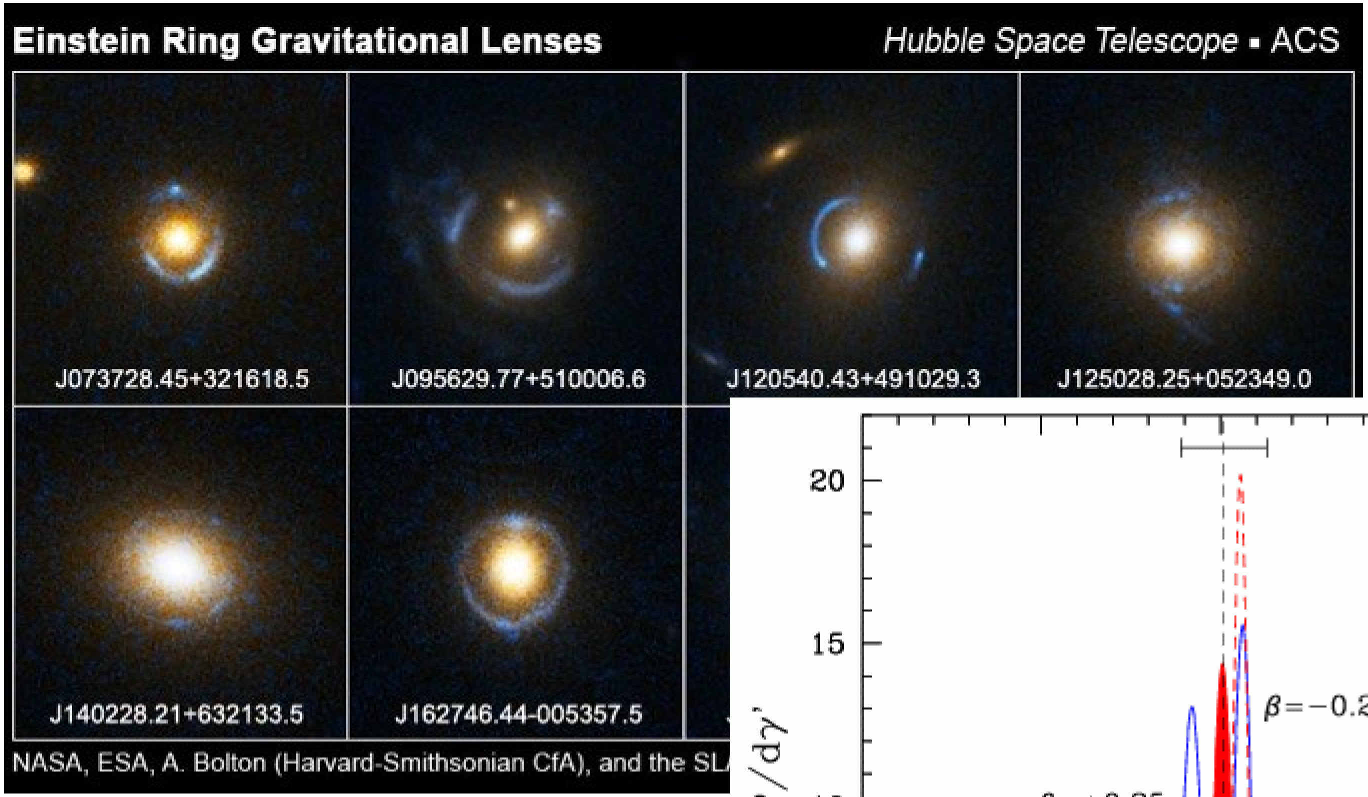
- assuming particular type of profile (e.g. power law)
- supplying other dynamical information (e.g. stellar velocity dispersion)
- multiple sources (breaks degeneracy entirely)

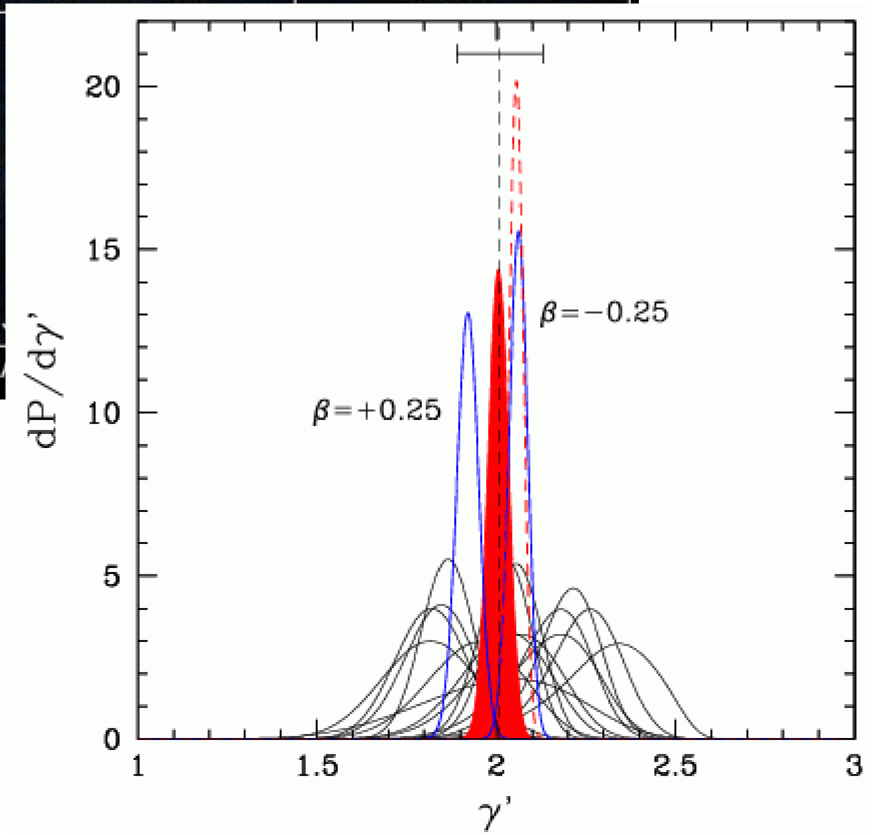
...or better still, find something with extended sources...



SLACS project (Bolton+ 2006,2008, Koopmans+ 2006)

...or better still, find something with extended sources...





SLACS project (Bolton+ 2006,2008, Koopmans+ 2006)

Use simultaneous lens modelling + stellar dynamics

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(Image positions constrain 1st derivative of potential
Fluxes constrain 2nd derivative)

CDM substructure

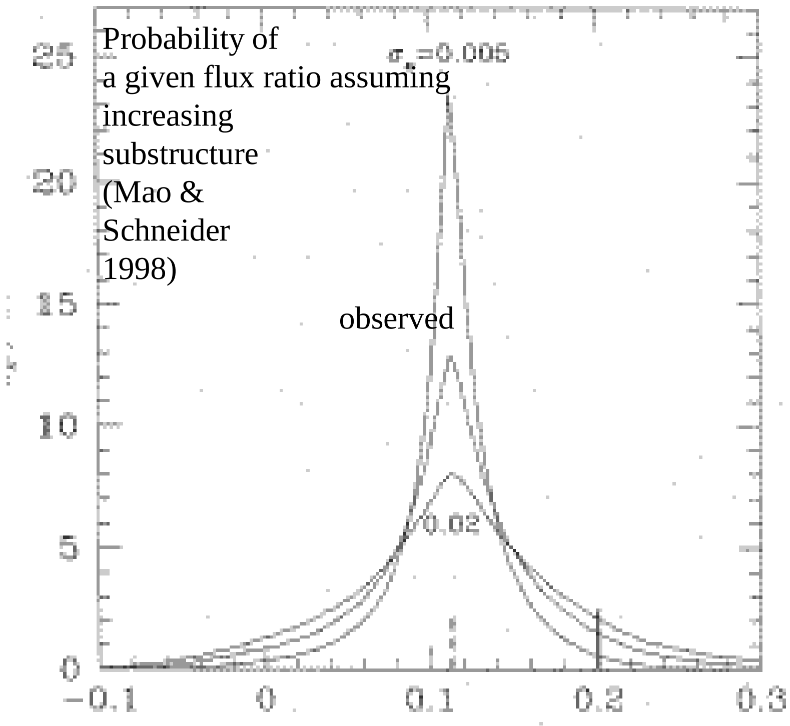
Strong prediction of CDM
Occurs on scales to subgalactic

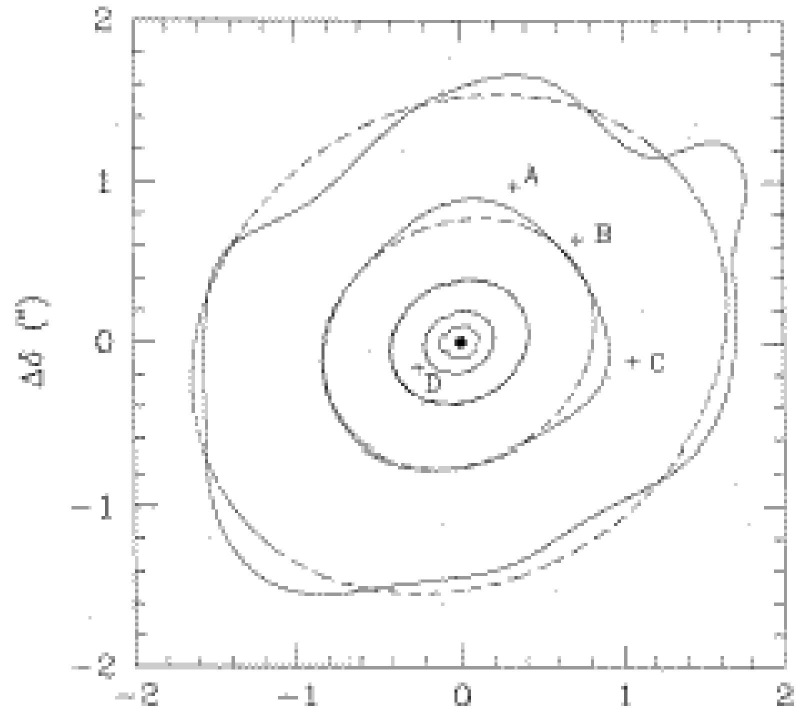
Galaxy halo DM simulation
(Moore et al. 1999)

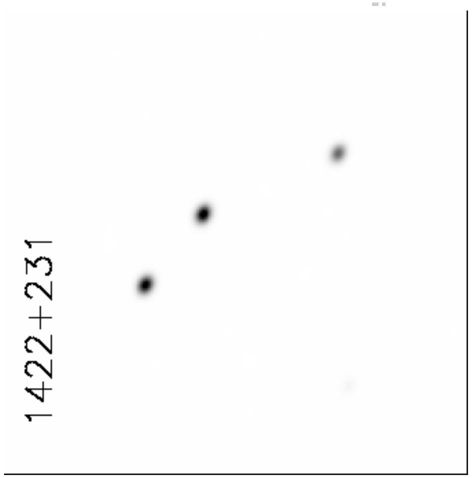
Small print:

* You can get rid of substructure
* These simulations don't have baryons
* Baryons might preserve substructure
* Hence lots of slop in predictions

Substructure in 1422+231



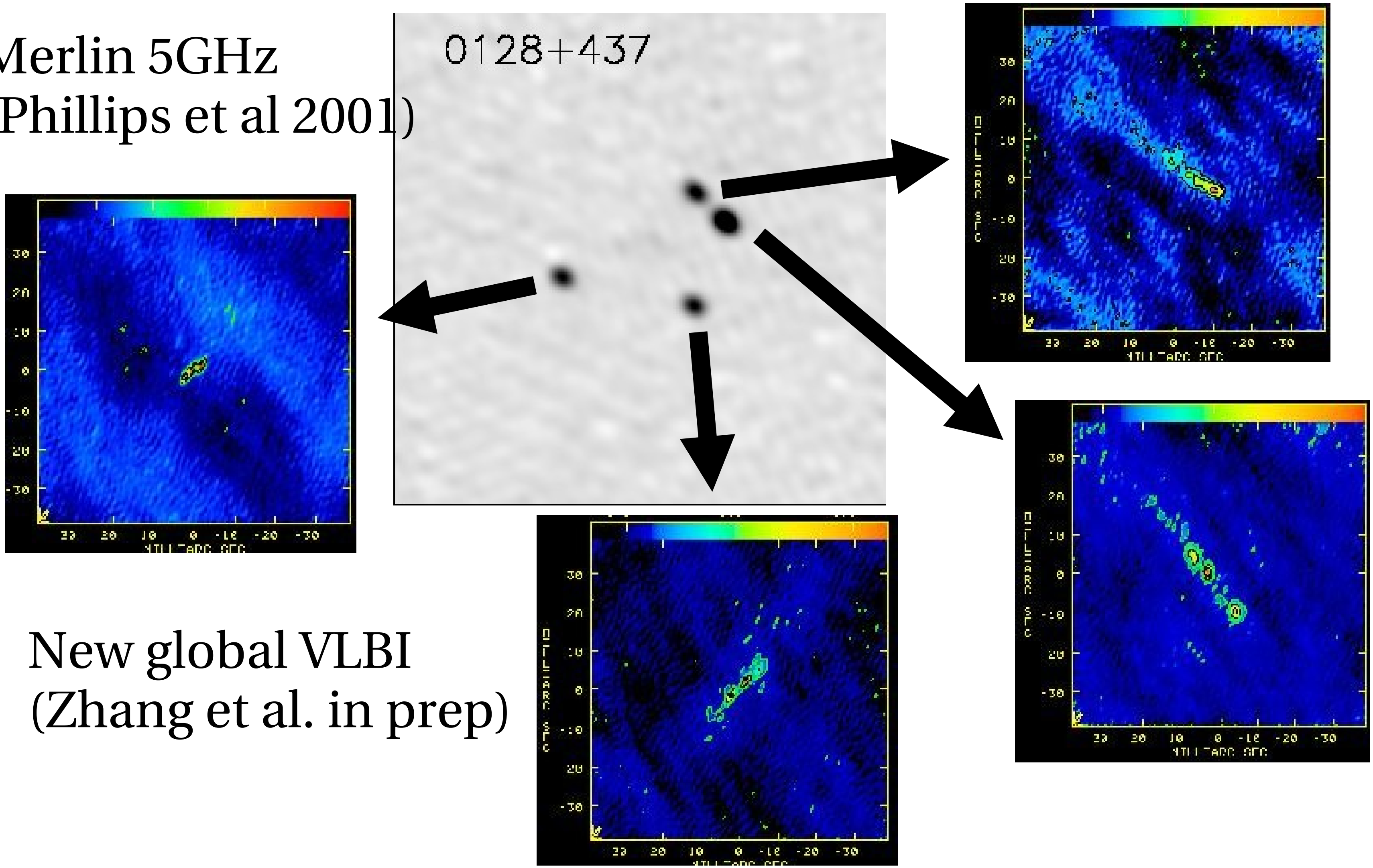




Difficult to reproduce observed flux ratios with any smooth model: requires substructure. Predicted by CDM but detailed sub-galactic estimates dodgy.

The case of CLASS0128+437

Merlin 5GHz
(Phillips et al 2001)



New global VLBI
(Zhang et al. in prep)

Statistical evidence

Dalal & Kochanek 2002
Kochanek & Dalal 2004

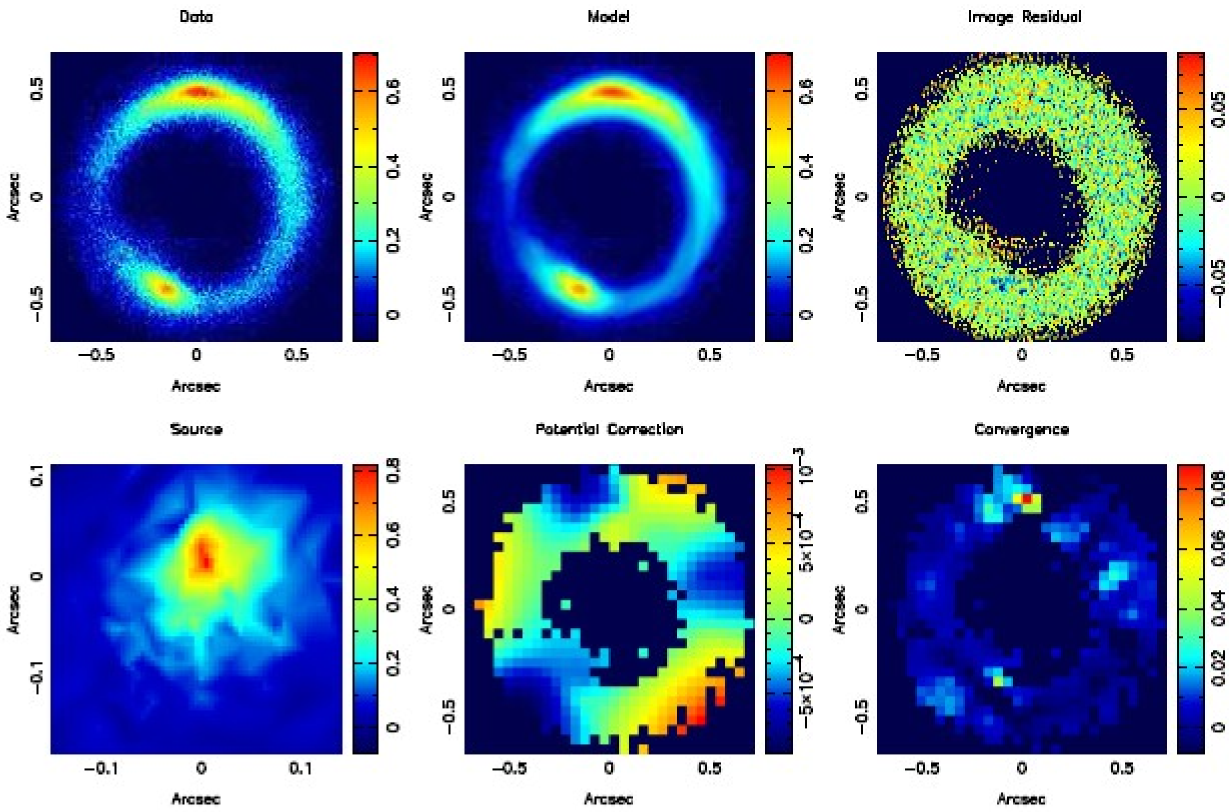
Studied the then available 7 radio 4-image lenses

Found 0.6%-6% of mass in substructures

Given where the lensing constraints are, this may be TOO MUCH

Likely to be a problem for WDM (Miranda & Maccio)

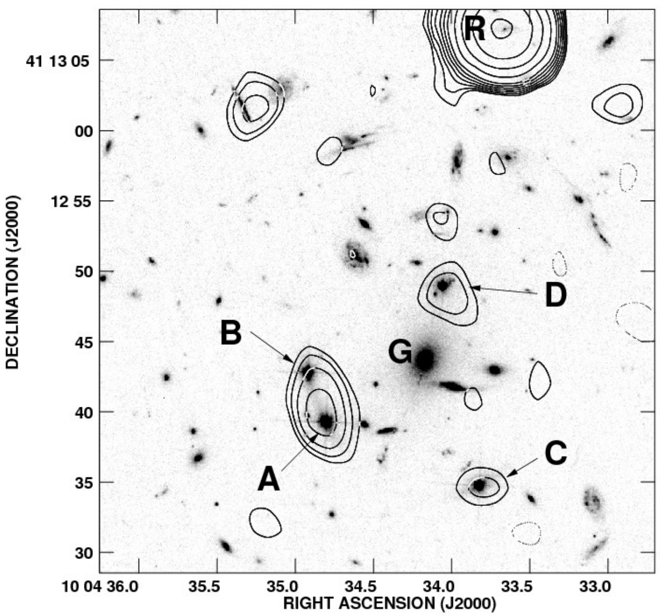
Direct mapping of substructure (Vegetti et al. 2012)



- tend to see larger substructures

Point-source substructure lenses: 7 so far – few % substructure (Dalal & Kochanek analysis, 2002)

- need free from microlensing
- radio/submm lenses ideal – submm will follow

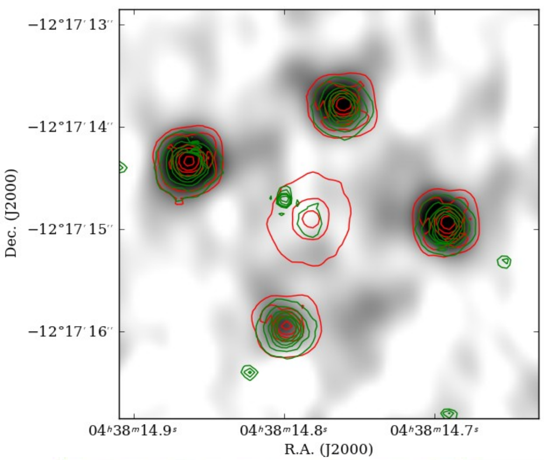


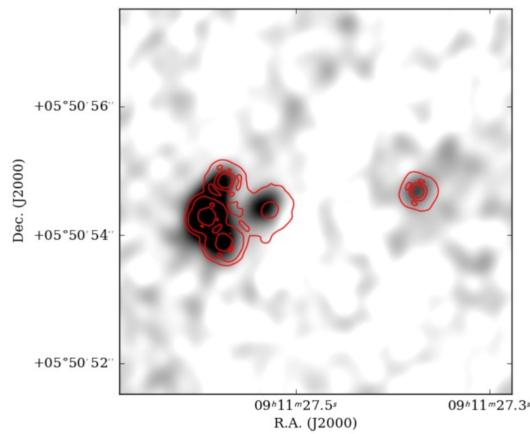
Jackson 2011, JVLA
(components ~20 microJy)

Alternative: make radio maps of radio-”quiet” lenses

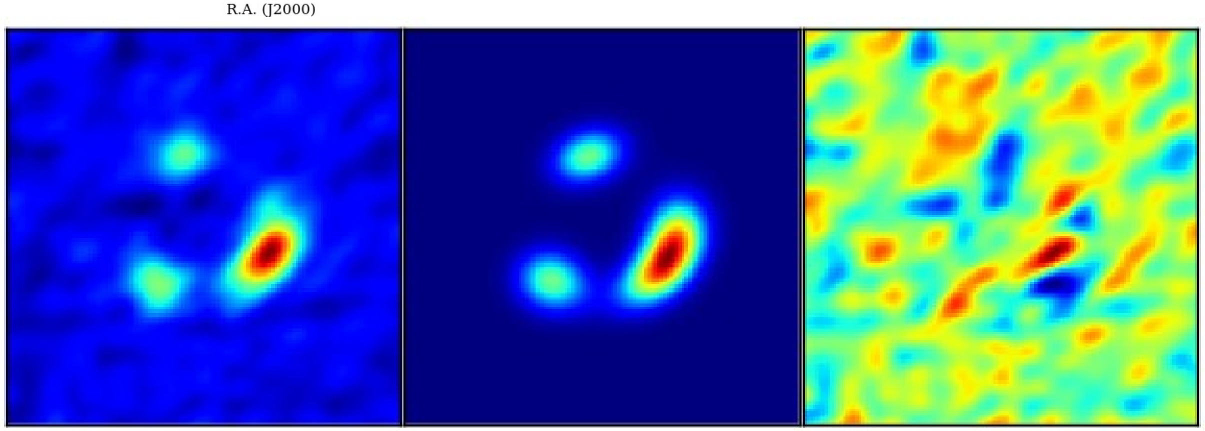
Point-source substructure lenses: 7 so far – few % substructure (Dalal & Kochanek analysis, 2002)

- need free from microlensing
- radio/submm lenses ideal – submm will follow





Preliminary maps from JVLA imaging programme



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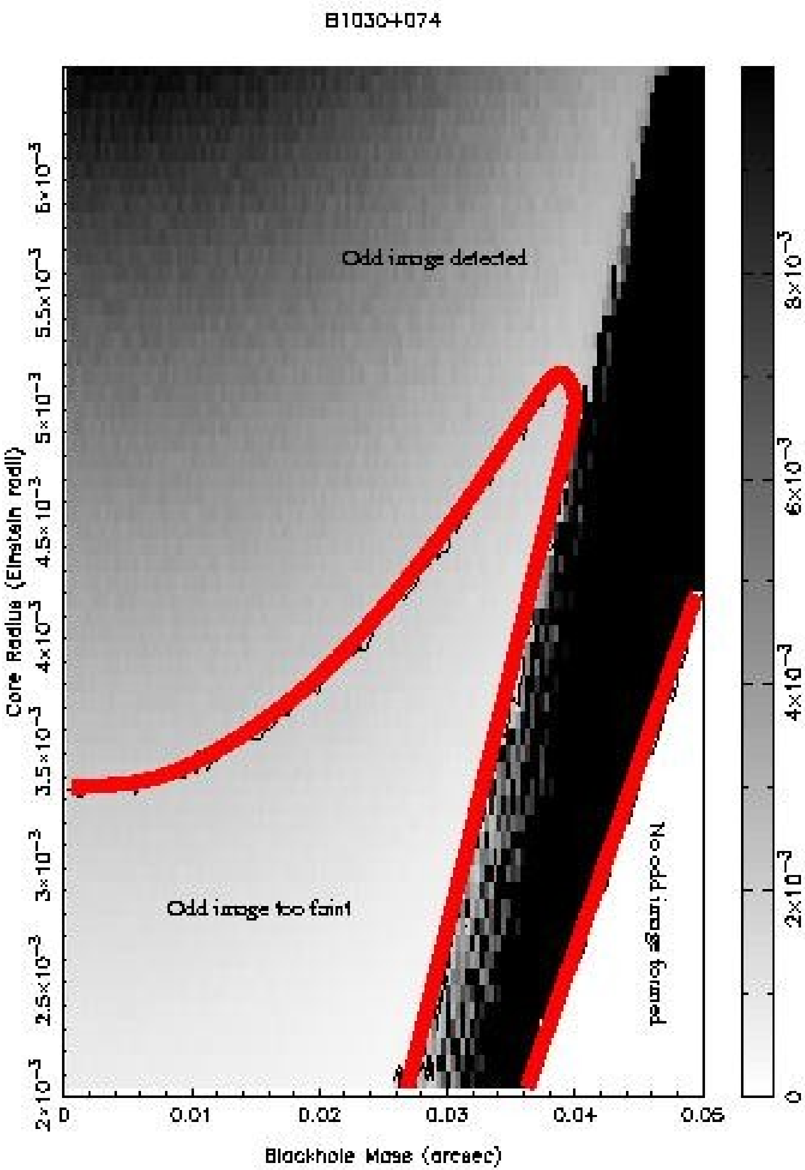
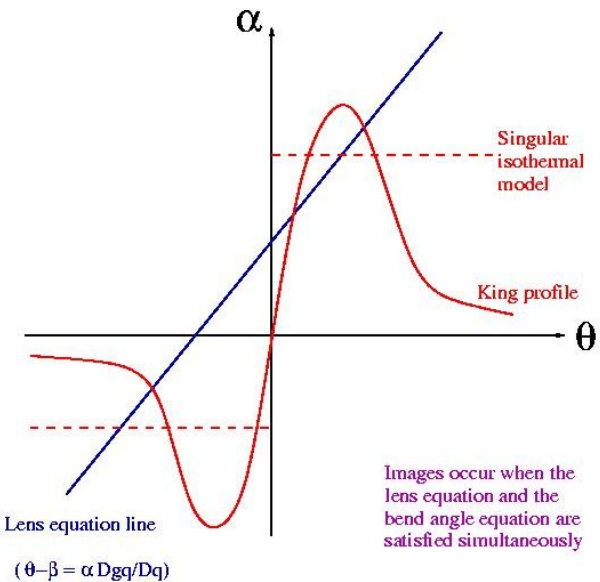
(Image positions constrain 1^{st} derivative of potential
Fluxes constrain 2^{nd} derivative)

Cores of galaxies

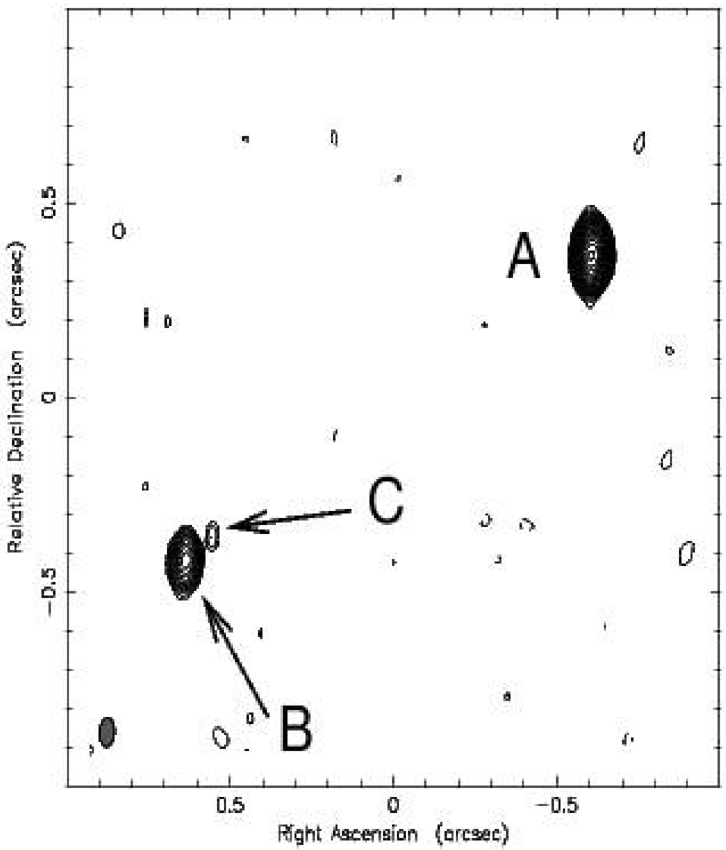
Norbury 2002 (1030+074); Zhang et al. 2007

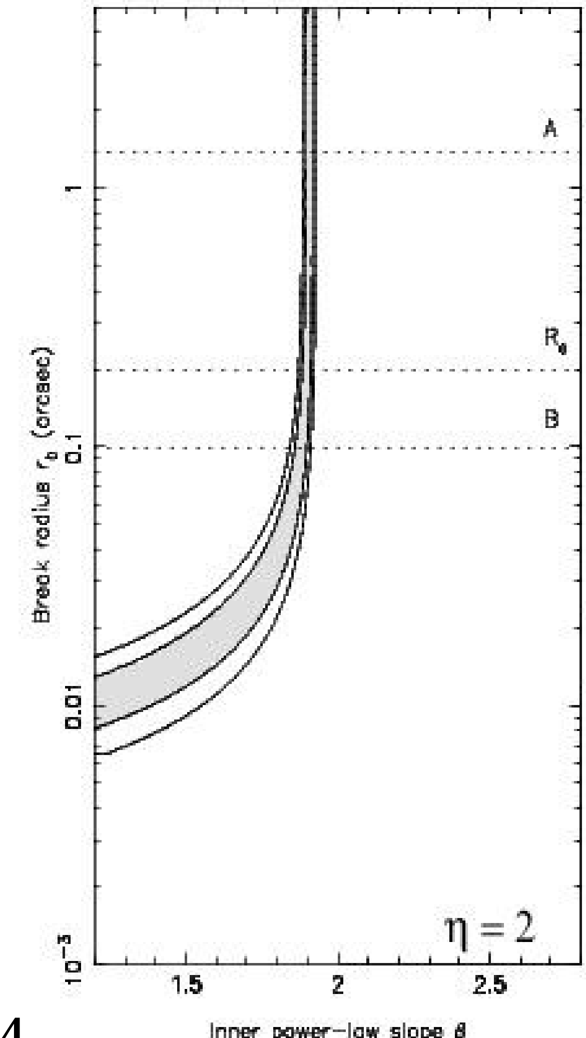


Softer core – brighter odd image



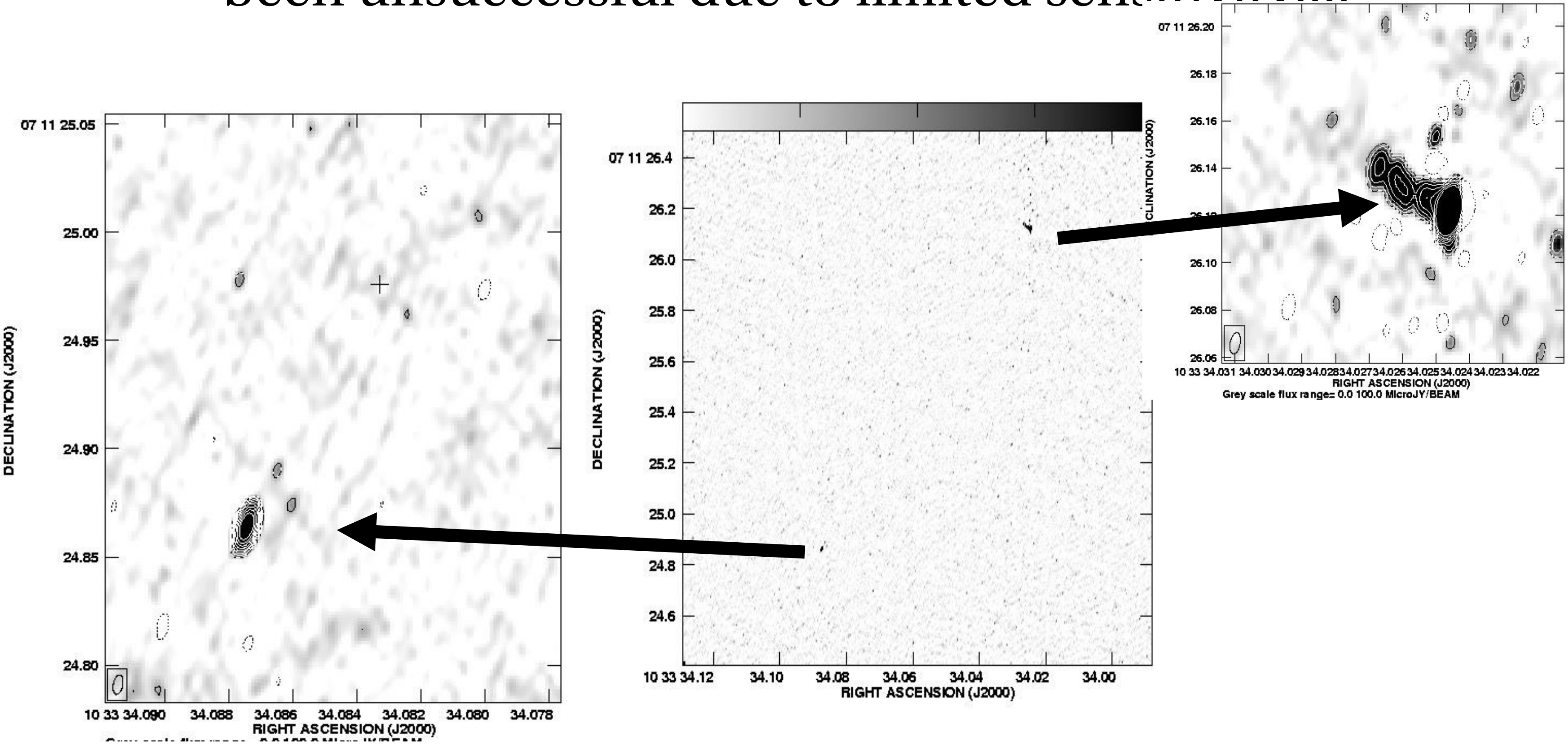
Studies of the central <100pc: core images





PMN1632-0033:
Winn, Rusin & Kochanek 2003, 2004

Further attempts to detect in galaxy-only lenses have been unsuccessful due to limited sensitivity...

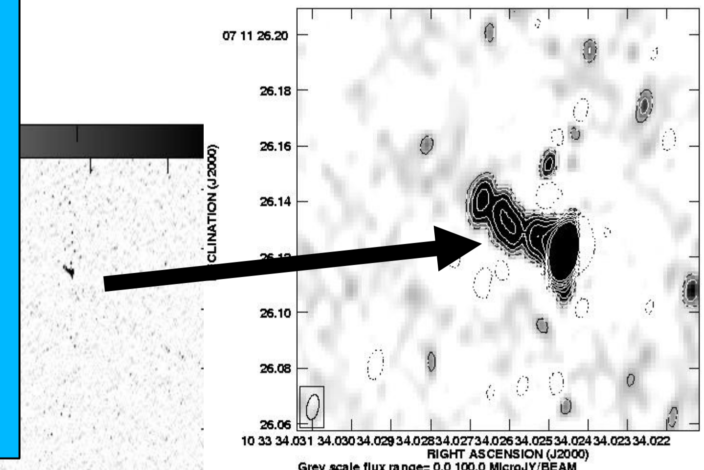


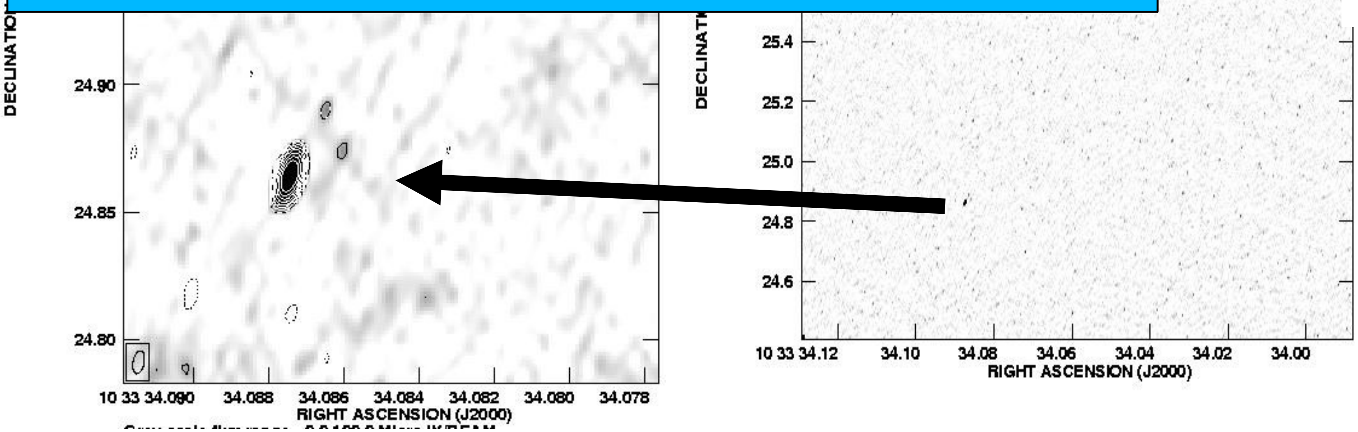
Recent HSA (VLA+GB+VLBA+Arecibo) observations of CLASS B1030+074 (Zhang et al. 2007)

(Lack of) central image constrains the steepness of the central part of the potential.

Steeper central profile or large BH gives weaker central image

Interesting constraints await e-Merlin





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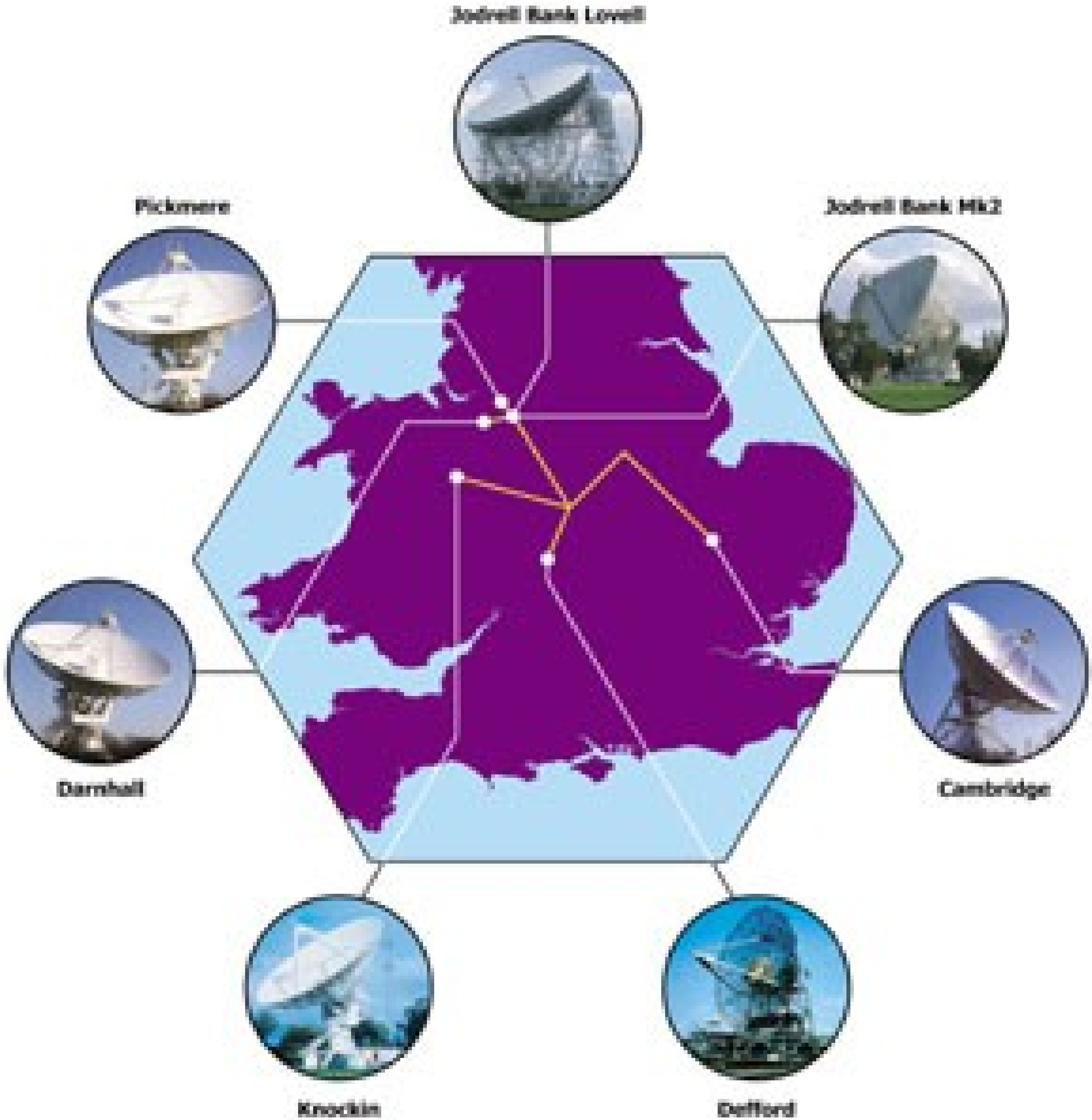
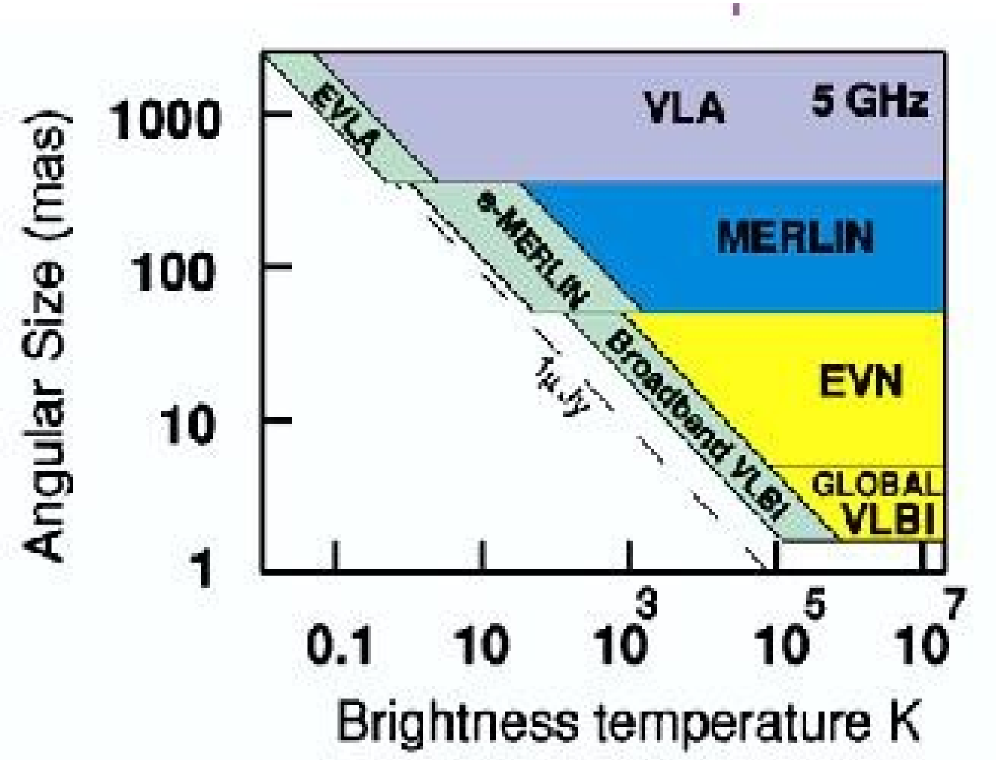
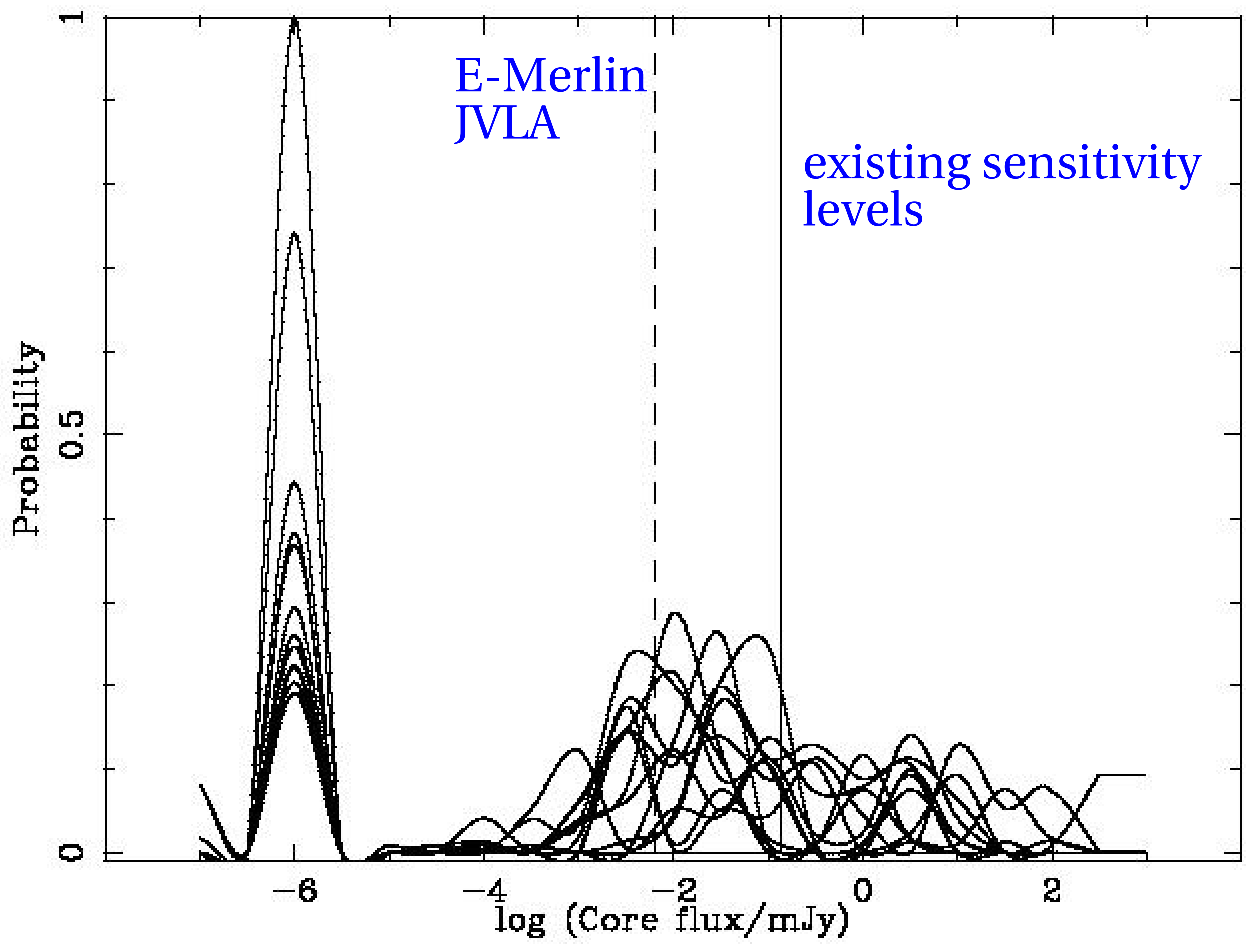

Jodrell Bank Lovell
Pickmere
Jodrell Bank Mk2
Darnhall
Cambridge
Knockin
Defford

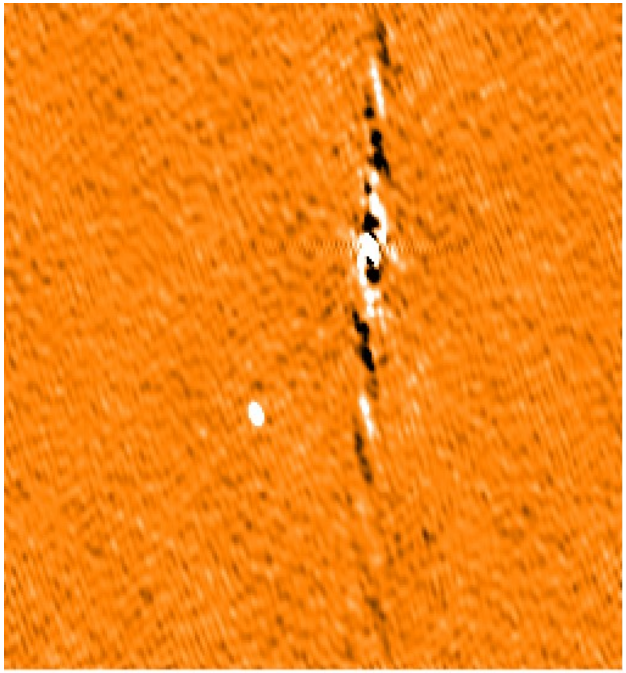
Band	Frequency (GHz)	Current sensitivity (μJy)	*e*-MERLIN sensitivity (μJy)	Brightness (K)	Resolution (arcsec)
UHF	0.327 or 0.408	700	200	7020	0.5
L	1.0 – 2.0	35	4.0	140	0.14
C	4.0 – 8.0	50	1.4	47	0.04
X	8.0-12.0	N/A	1.4	47	0.02
U	12.0-18.0	N/A	3.0	104	0.013
K	18.0-26.0	400	11.3	390	0.008



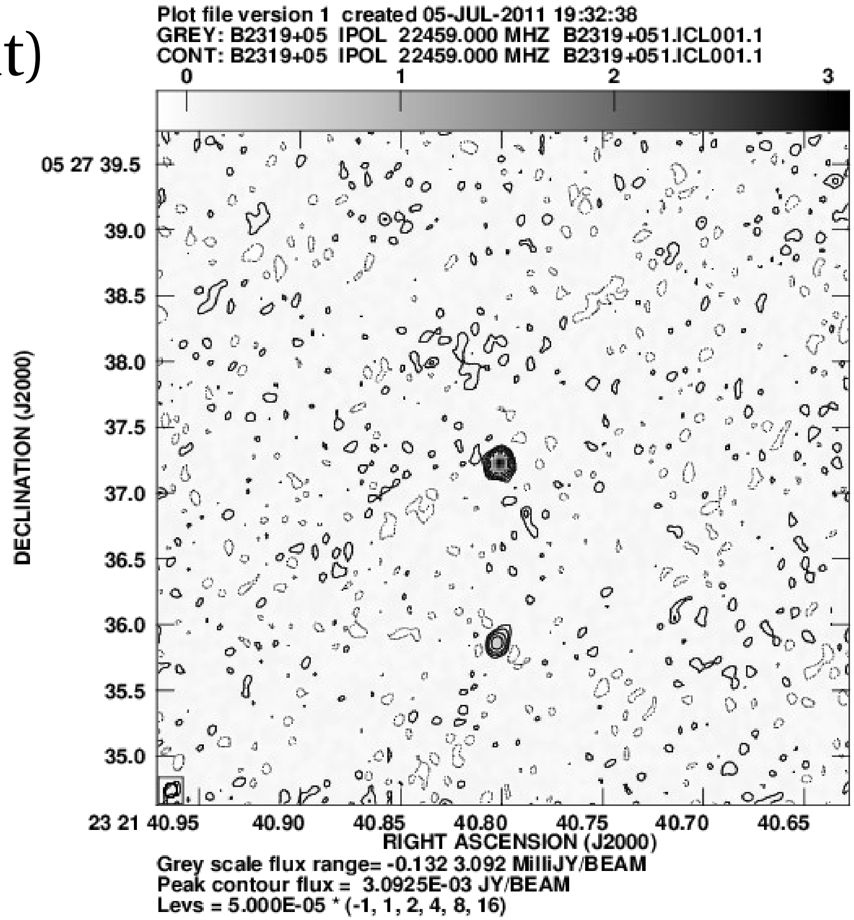


Currently: 1 radio lens/30; for standard BH and cusp parameters, should detect many more! (Keeton 2003)
-> determine these parameters

1030+074 (eMerlin, high burnout)



Starlink GAIA::Skycat 1030_im.fits
1033+0710:33:34.056 7:11:25.47 J2000
njj Jan 05, 2014 at 17:46:47



Again, preliminary results! No 3rd images in rms 20microJy (eMERLIN), ~5microJy (JVLA, new image by J. Quinn)

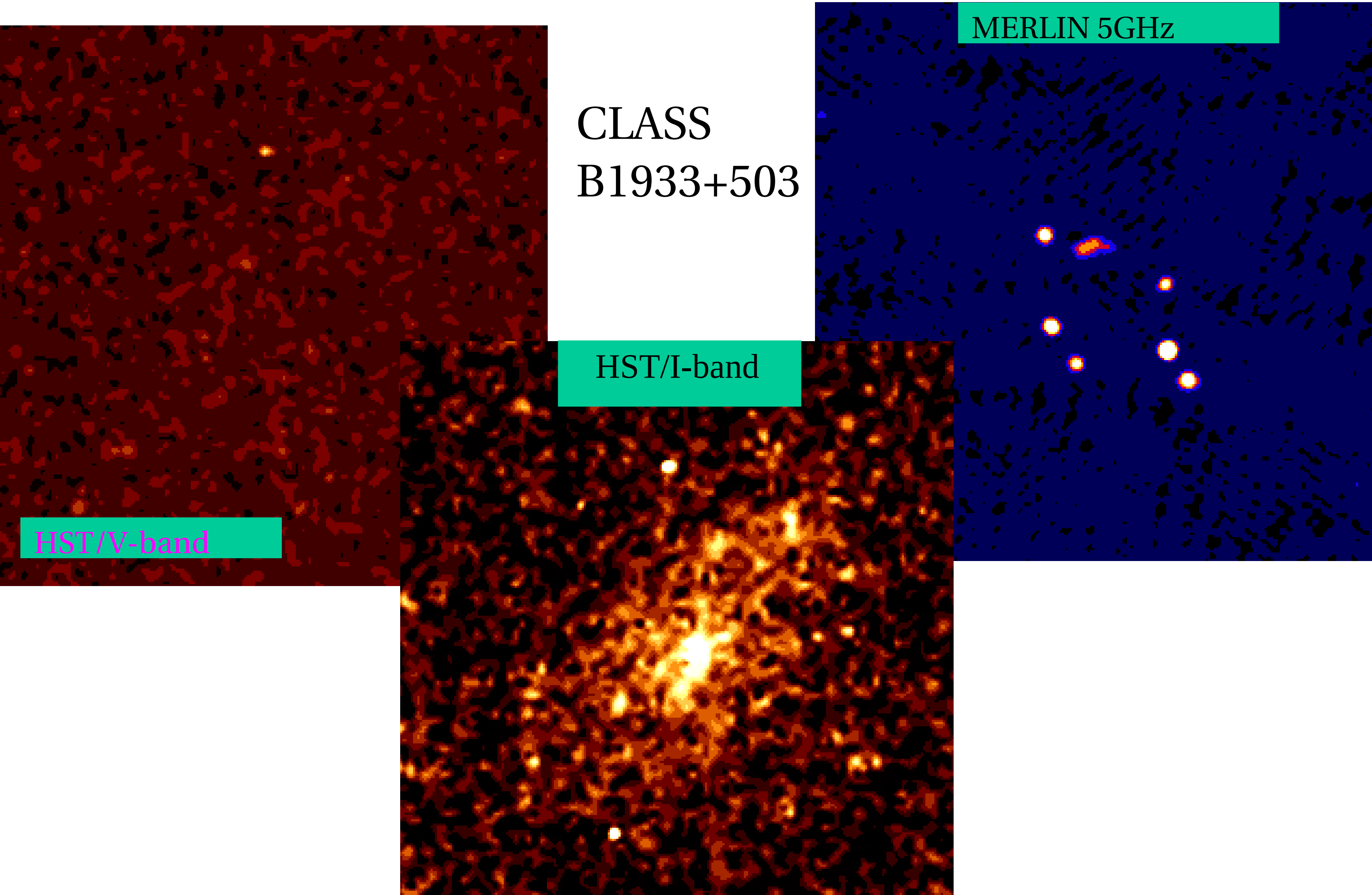
Studying lensed structure tells you about

- overall mass profile (and evolution)
- CDM substructure in galaxies
- central regions of galaxies (within 100pc of SMBH)
- propagation effects in galaxies (two lines of sight with same object at end) (LOFAR)

(Image positions constrain 1st derivative of potential
Fluxes constrain 2nd derivative)

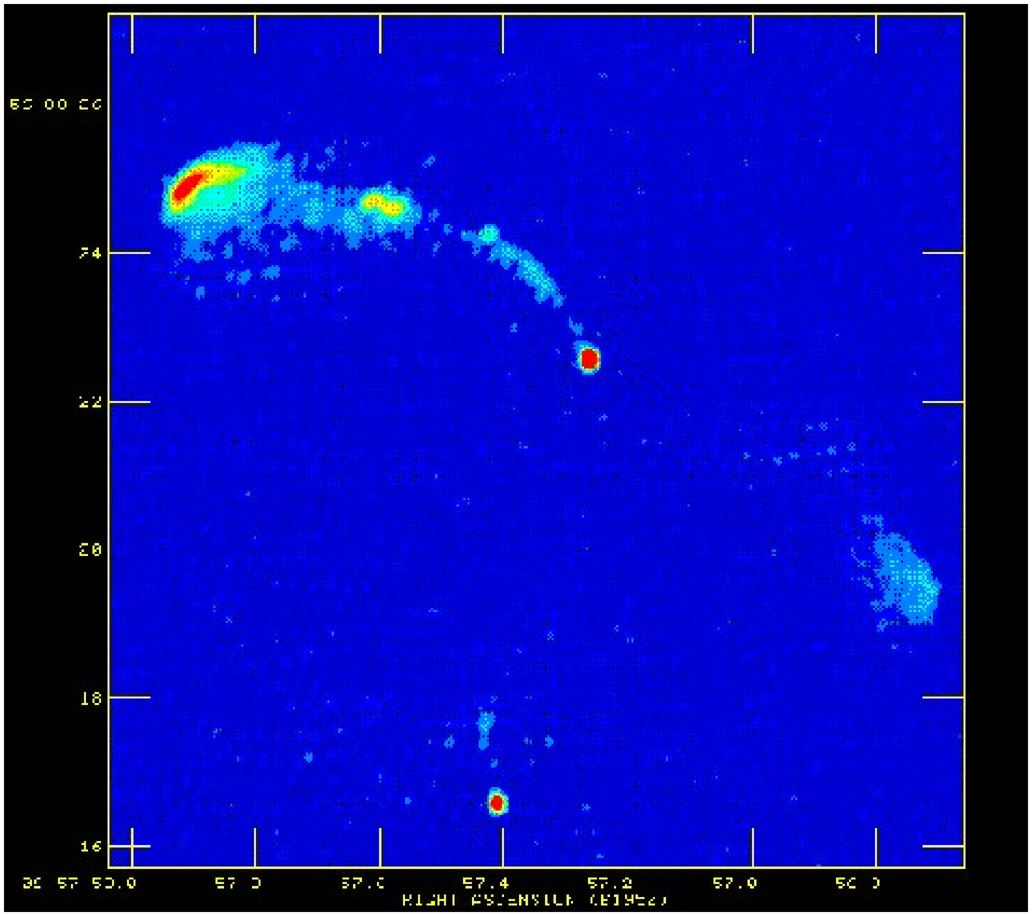
Effects of obscuration…

CLASS
B1933+503

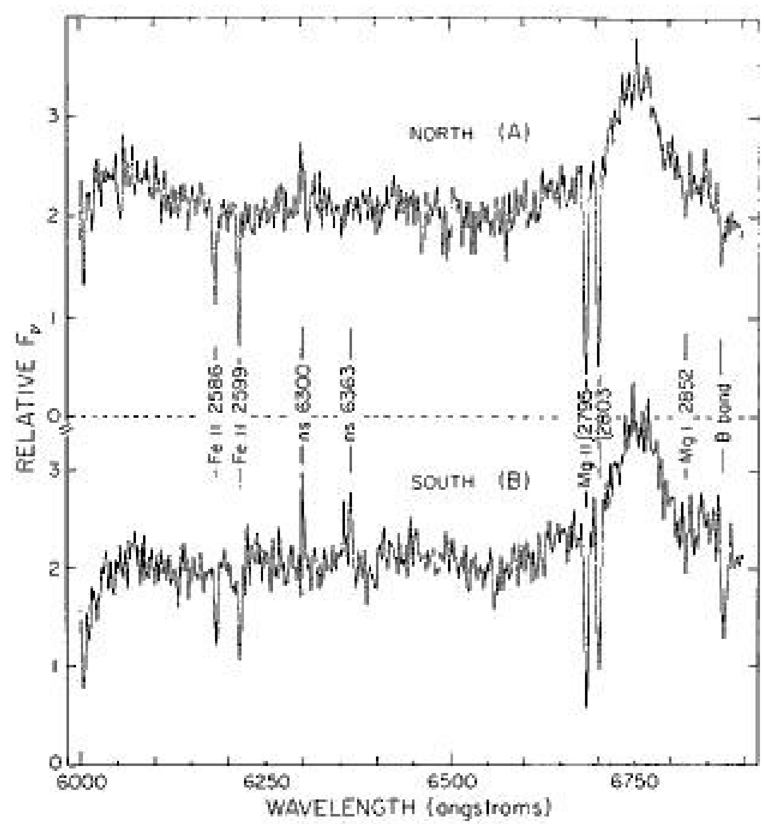


0957+561: the first lens system

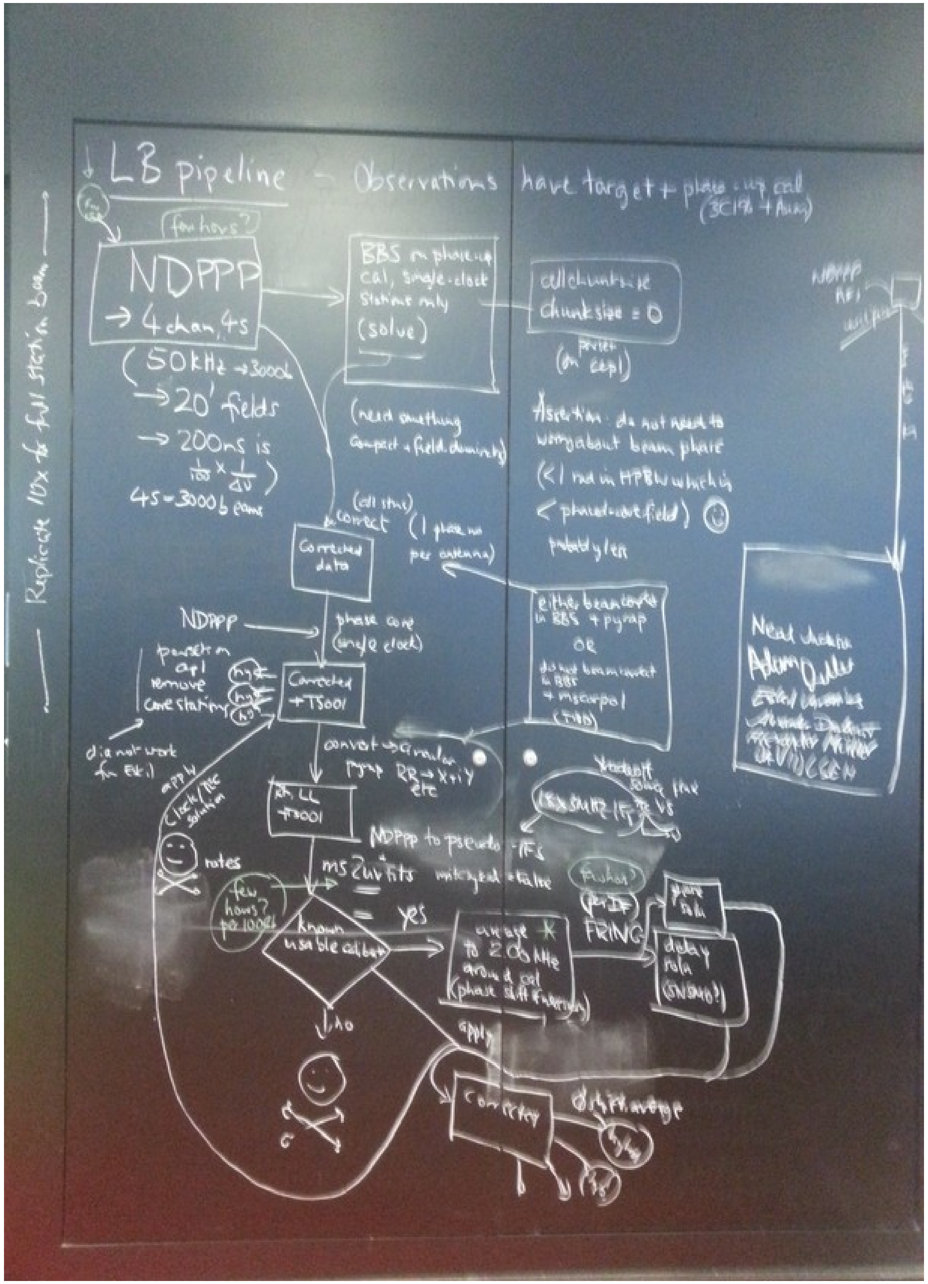
Walsh, Carswell & Weymann 1979



Merlin 5 GHz



Optical (Weymann et al.)



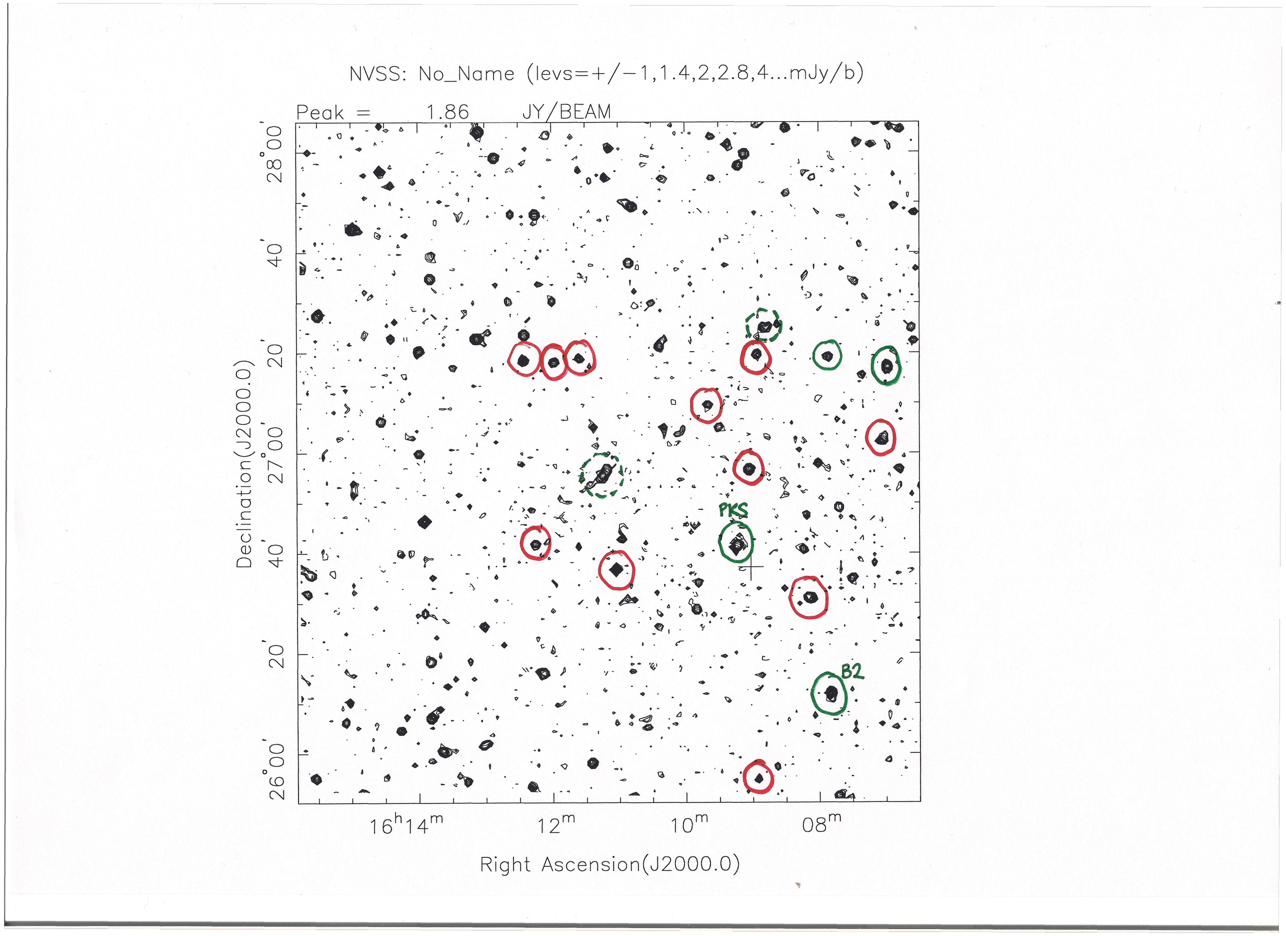
Gravitational lenses

- 3 lenses awarded for cycle 0, 1 for cycle1
- Data taken
- Analysis status: first one analysed (0957+561), 30 subband image produced
- Trying to install LofIm in Manchester

- Long baseline data analysis- general status
- Analysis process for 0957+561
- General remarks and intended progress

General remarks on the functioning of the pipeline

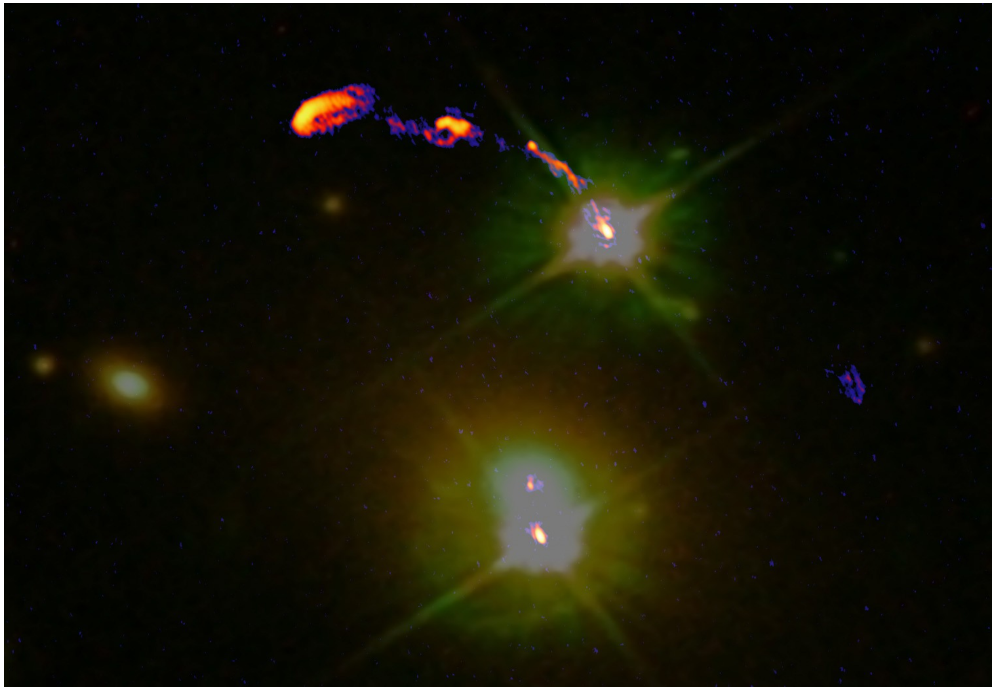
Tested on MSSS data of H242+27 field (has bright calibrator in the middle)



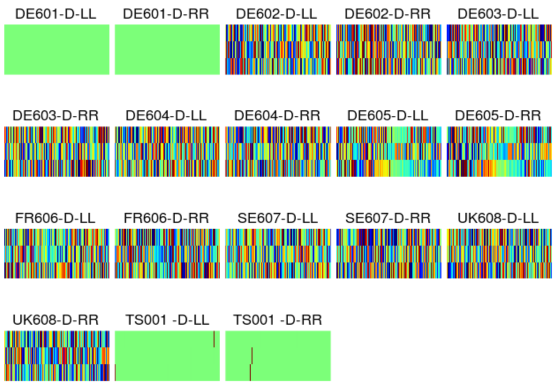
Bottom line: reasonable number of sources per field found, but transferring phase from one to another is hard (could not transfer PKS -> B2 source and map it)

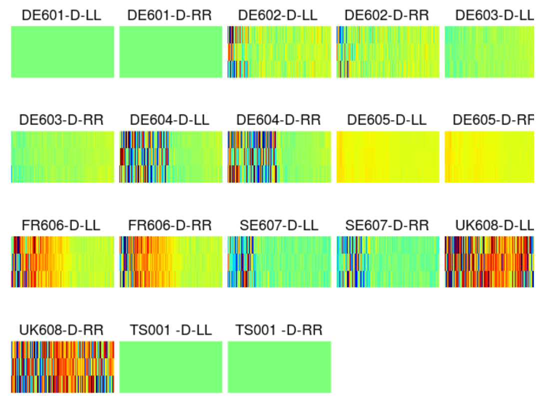
Analysis of the 0957+561 data

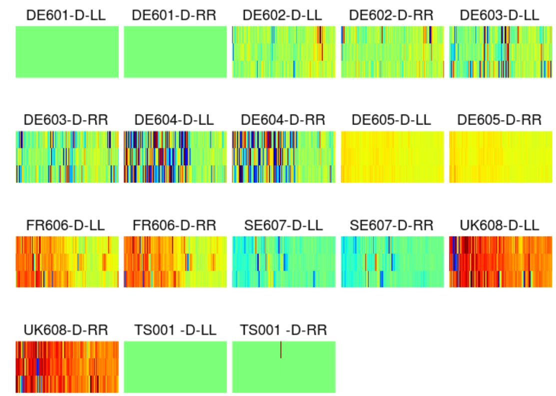
- 30 subbands used
- Core stations phased into TS001 superterp station using locapi.py script
- Conversion to circular using MSCORPOL
- Formed into 3 Ifs of 10 channels each and read into AIPS
- Fringe fitted and calibrated/imaged by hand, either
  * without using a model
  * using a model from e-MERLIN:



Collapse data around three points: Q0957+561, nearby calibrator (0954+556) and a piece of blank sky:



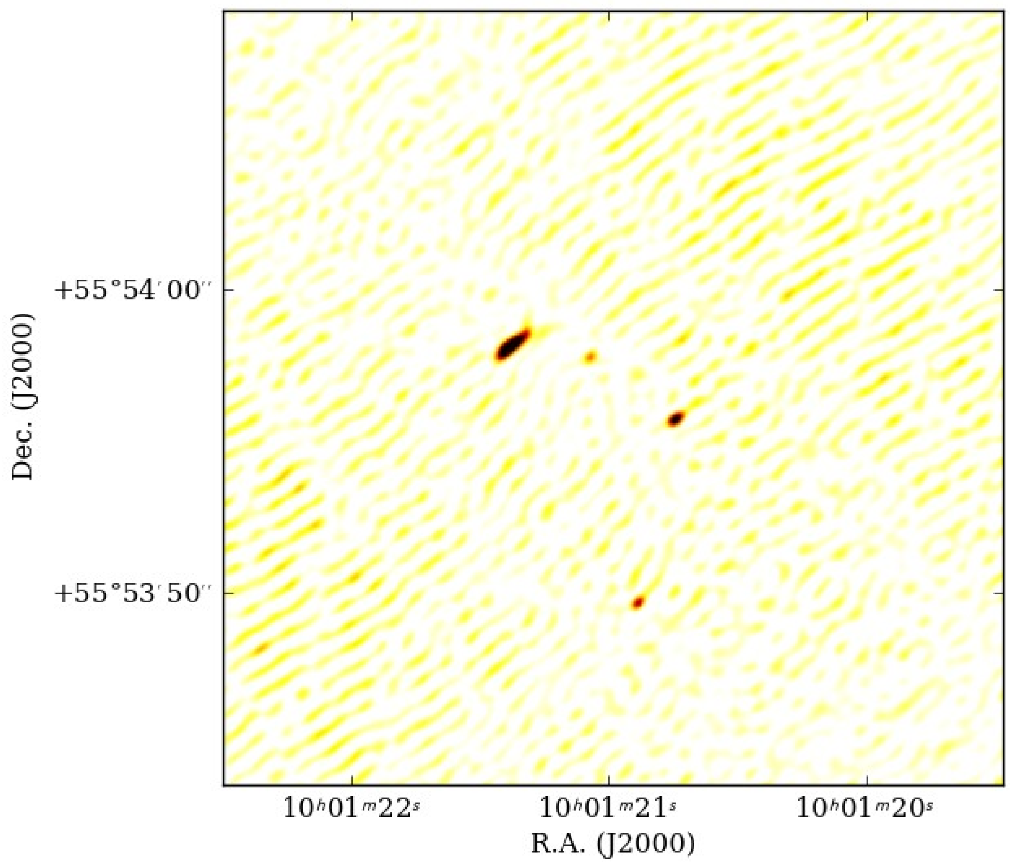




Left to right: blank sky, phase calibrator, target

Comments; 1) obviously working!; 2) UK608 very intermittent;

3) coherence seems to come and go on longest baselines (may need to edit a little)



LOFAR 150MHz image

Flux ratio A/B ~ 1.8 – different from higher frequencies (~1.4) – scattering/propagation

The future – very large lens surveys

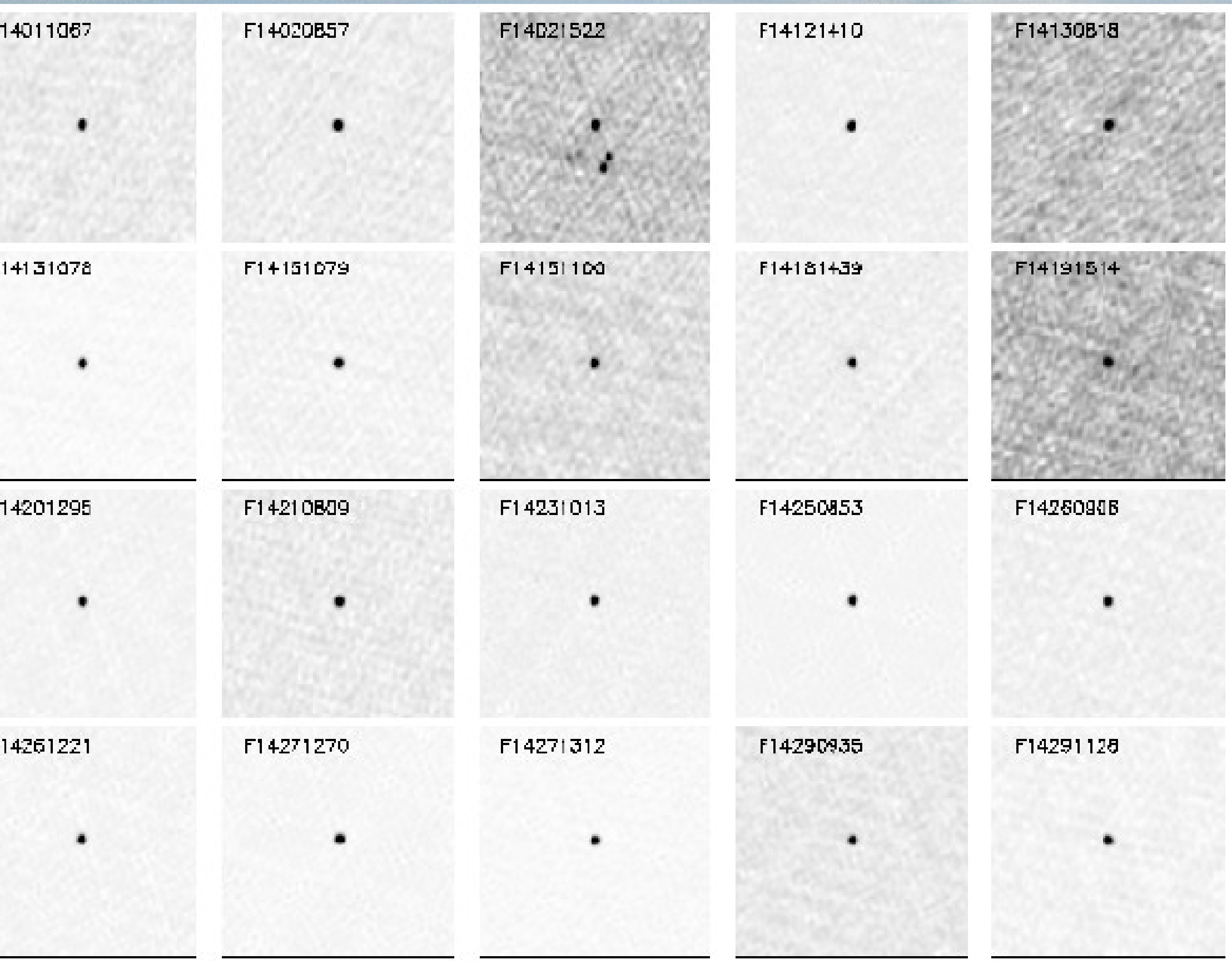
-samples of a few hundred -> tens of thousands in 10 yr

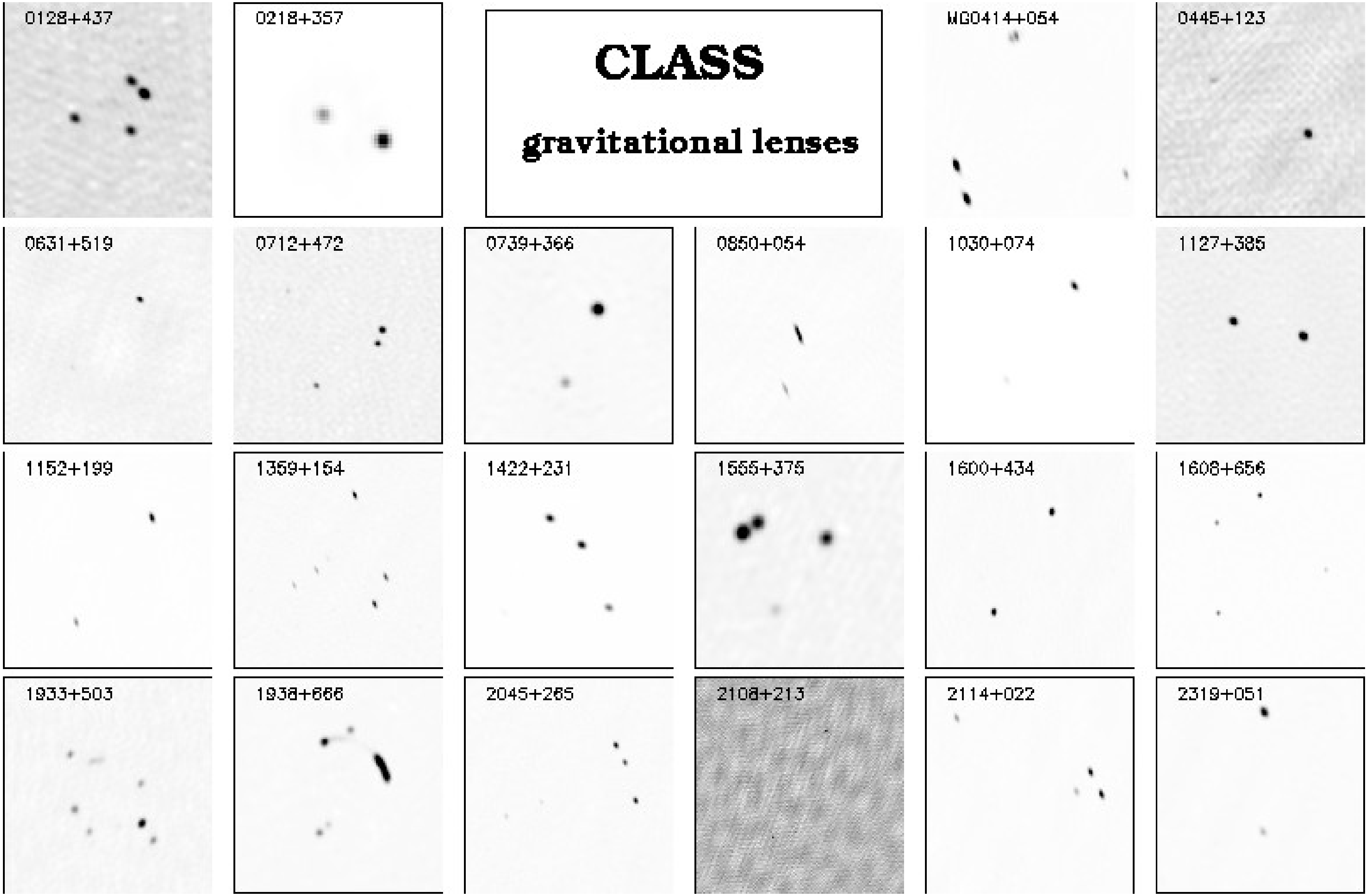
LOFAR?
LSST
Euclid
SKA

But finding them is difficult

Few lines of sight have galaxies in the way
Difficult to find enough distant background objects
Difficult to distinguish lensing from intrinsic structure
Difficult to get high enough (better than 1” resolution)

The discovery process

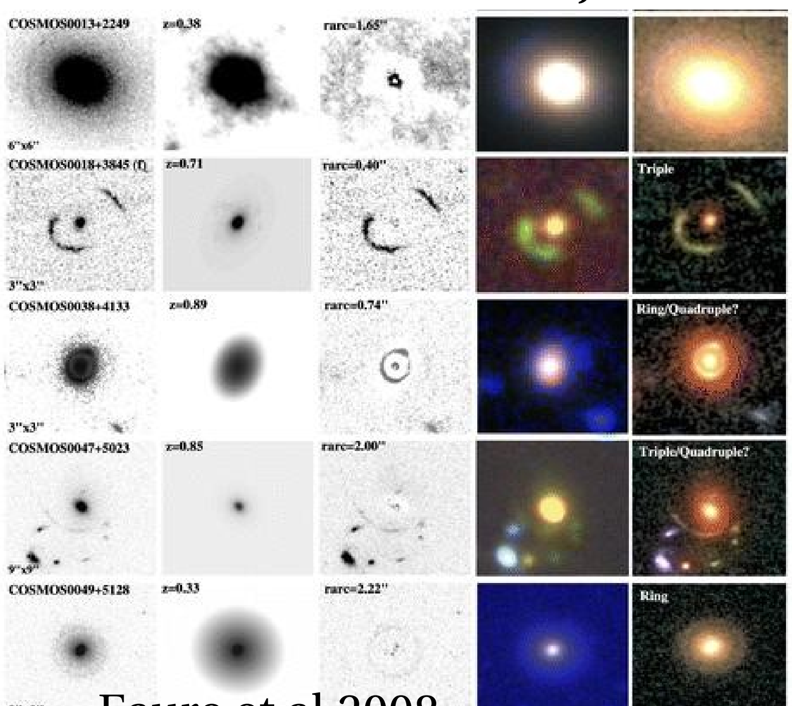



CLASS
gravitational lenses
0128+437
0218+357
MG0414+054
0445+123
0631+519
0712+472
0739+366
0850+054
1030+074
1127+385
1152+199
1359+154
1422+231
1555+375
1600+434
1608+656
1933+503
1938+666
2045+265
2108+213
2114+022
2319+051

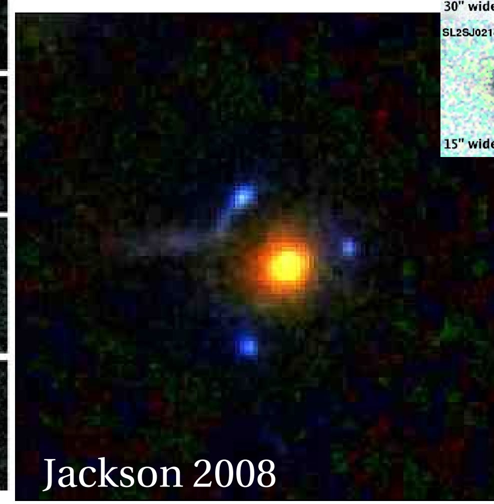
Discovery of new lenses:

short-term: efficient use of existing surveys (SL2S, COSMOS,UKIDSS/MUSCLES….)

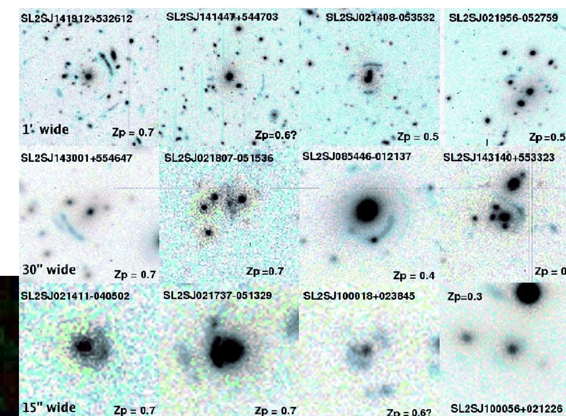
long-term: big new instruments (e.g. LSST, JDEM, SKA…)



Faure et al.2008



Jackson 2008



Cabanac et al. 2008

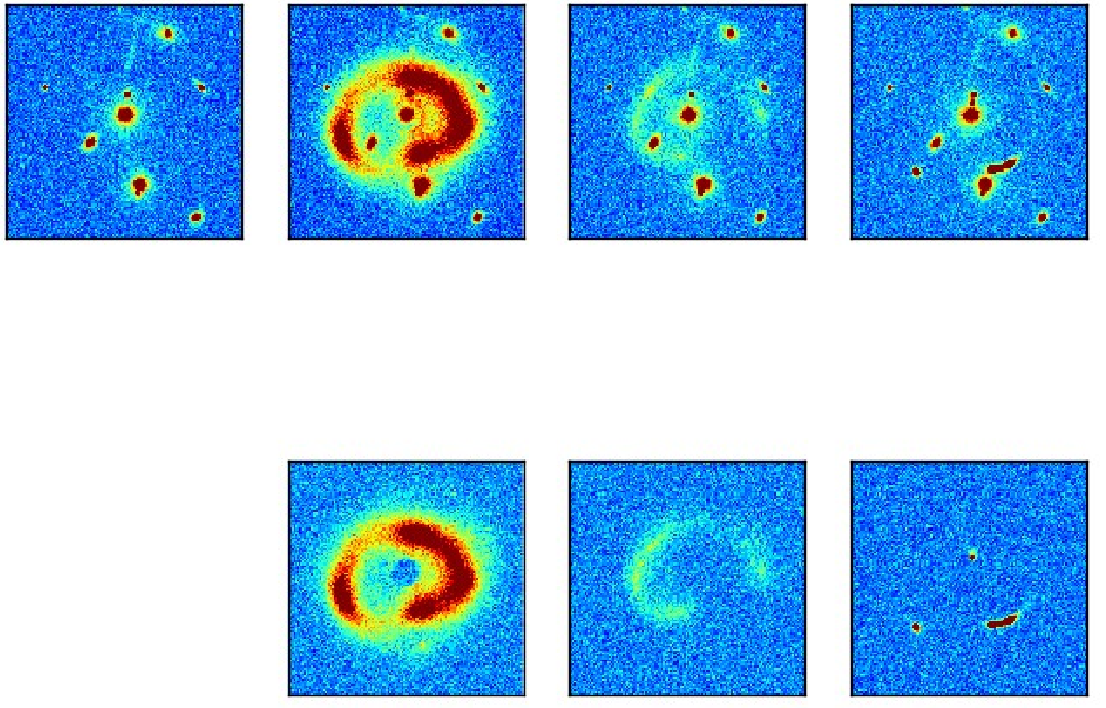
Euclid will find ~10 billion objects!

1 in 1000 will be lensed....

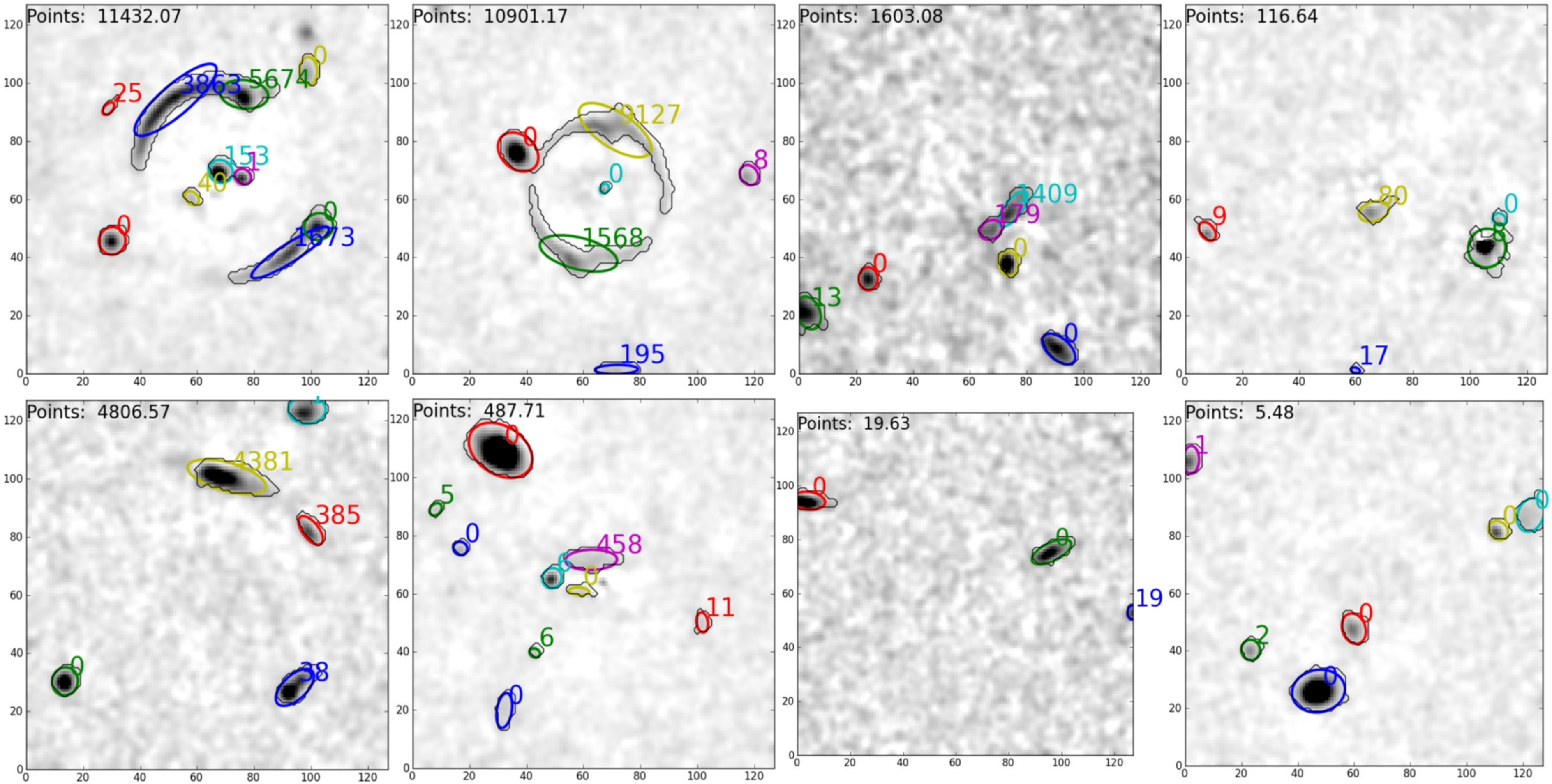
But cannot look through by eye (not enough graduate students)

Need algorithms that give low rate of false positives...

Try out on some simulated "Euclid lenses"



Award points for elliptical objects at similar radius from a galaxy



Simple algorithms have problems with false positives and false negatives – investigating more sophisticated algorithms, machine learning...

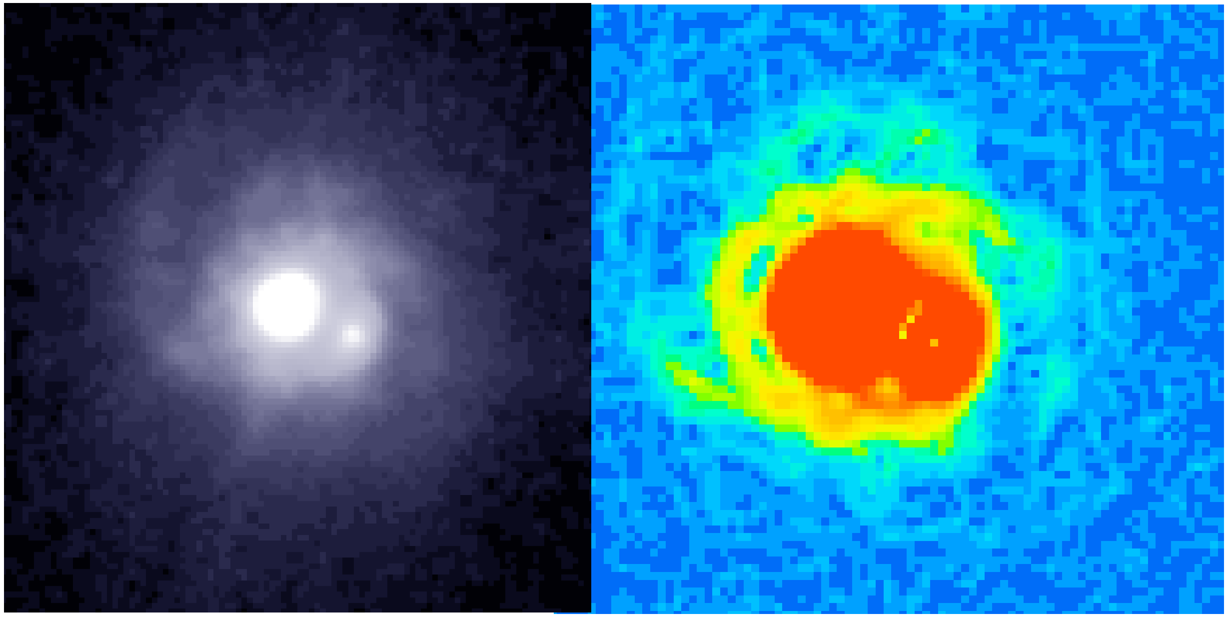
Summary

Lenses are useful for
- studies of the galaxies (overall mass distribution, CDM substructure, central regions, propagation)
- studies of the sources (magnified)
- cosmography (Hubble constant, dark energy)

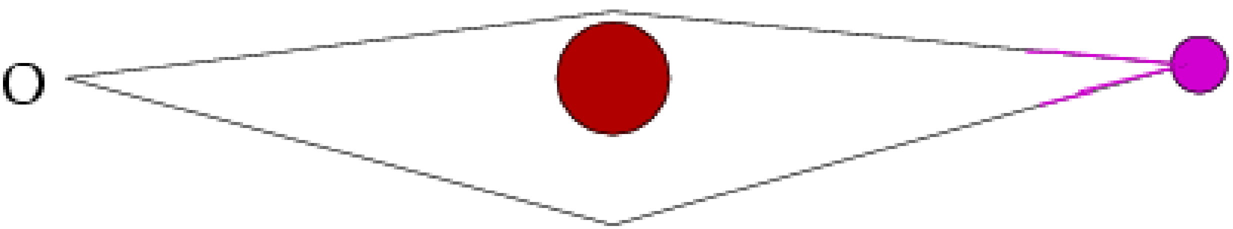
We want more and will get more, but
- selection not trivial in very large datasets
- huge potential for getting mass distributions in galaxies, galaxy evolution, and cosmography

The University of Manchester
Jodrell Bank Observatory

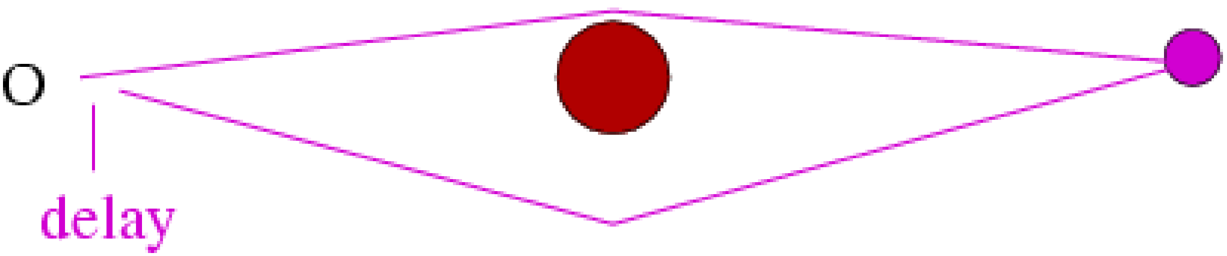
Applications of galaxy lensing: IV. The Hubble constant



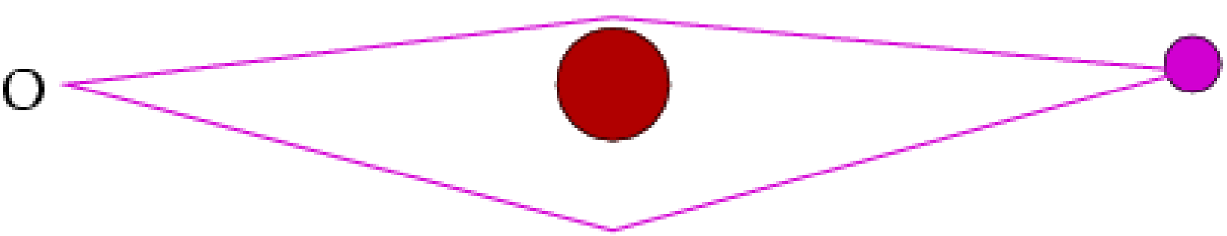
Principle of the method



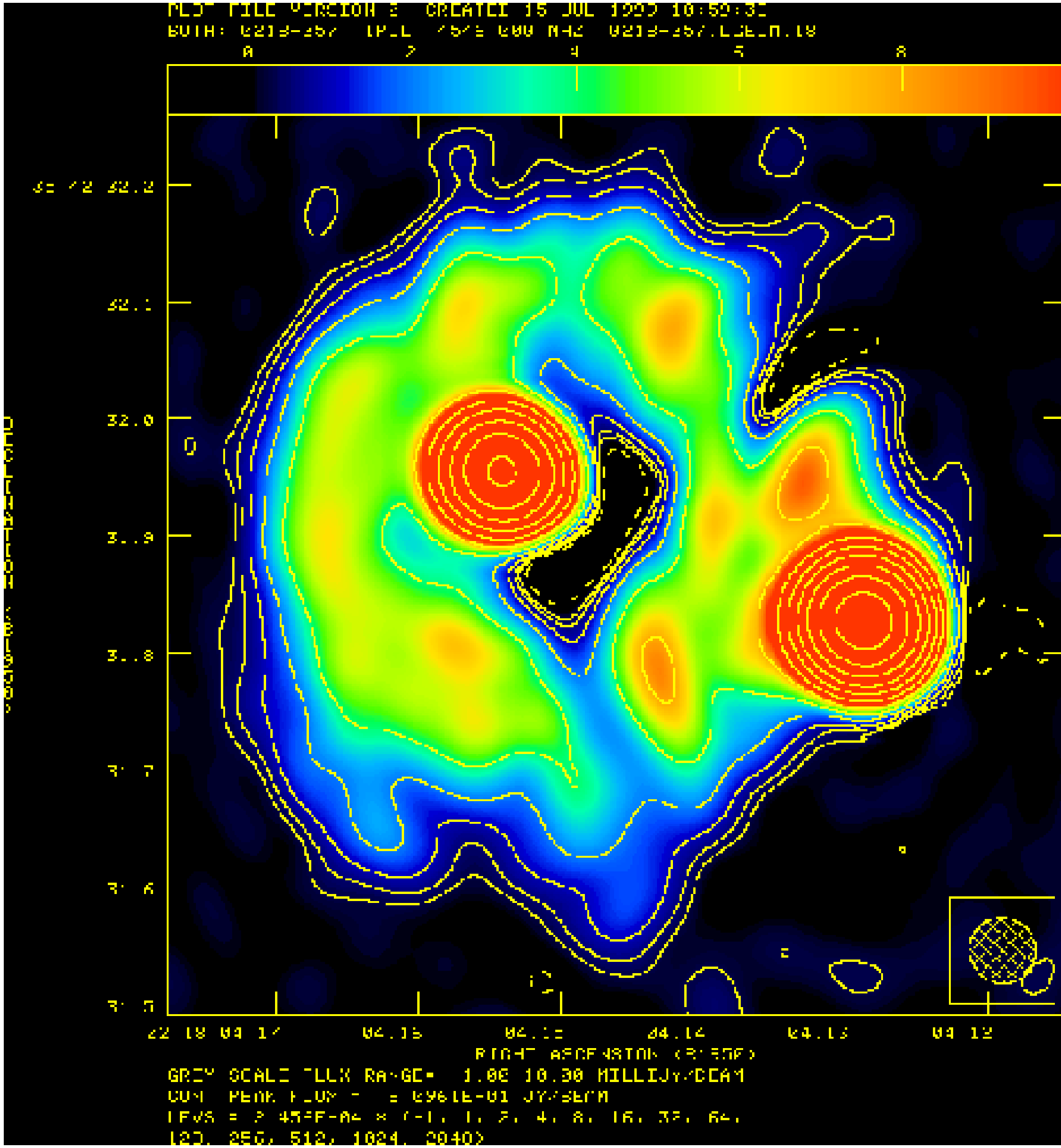
Source brightens



Brightening arrives along shorter light path first

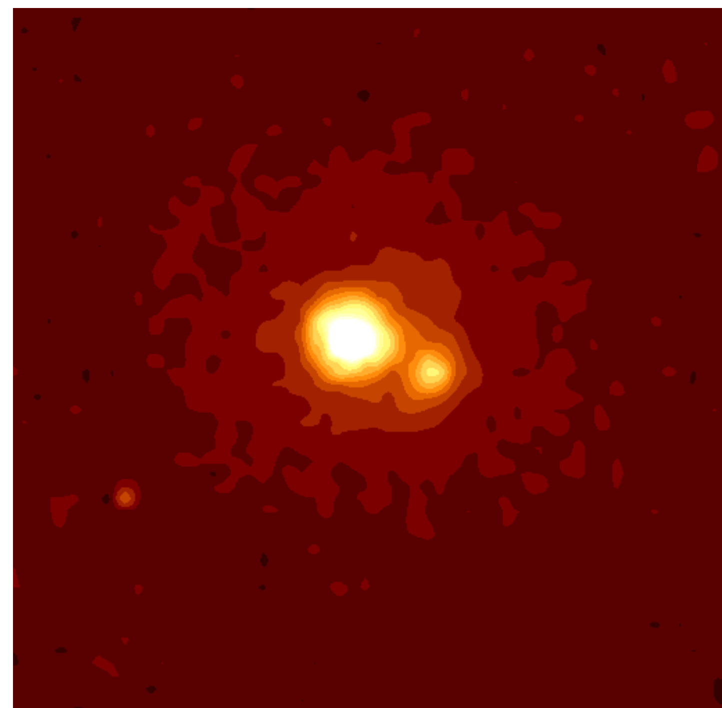


Delay gives an absolute value of a distance (difference in light paths)

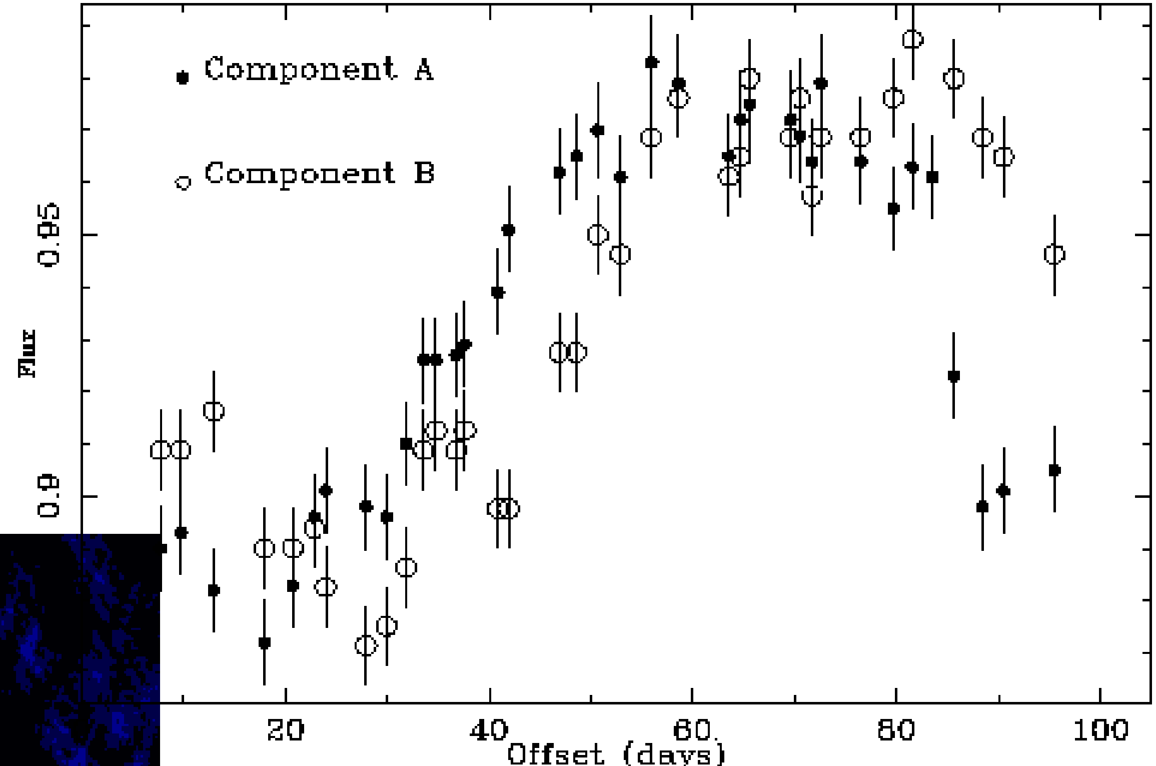


Radio (MERLIN): 2 images of point source, plus Einstein ring from extended source

Optical (HST): images + lens galaxy

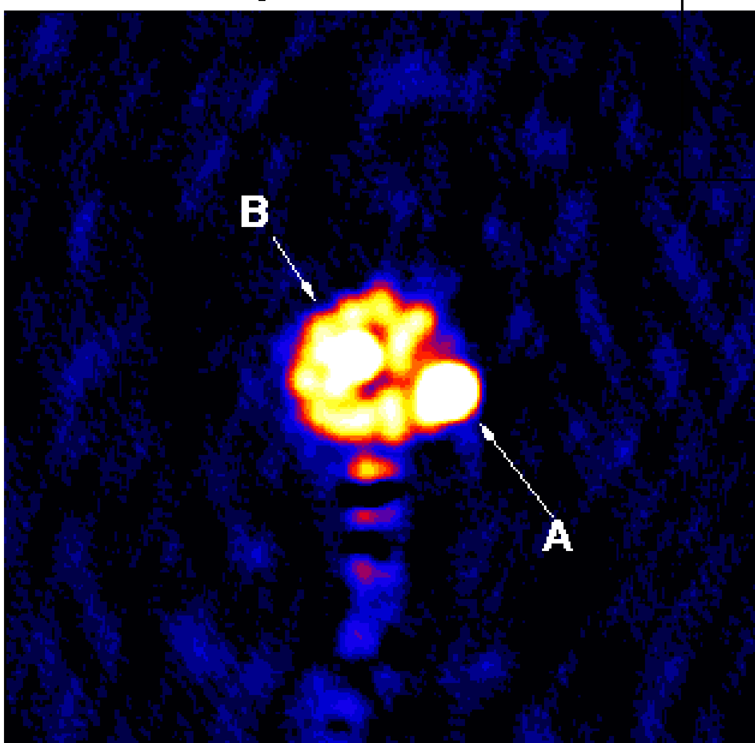


The gravitational lens JVAS0218+357



Radio light curves

Radio map

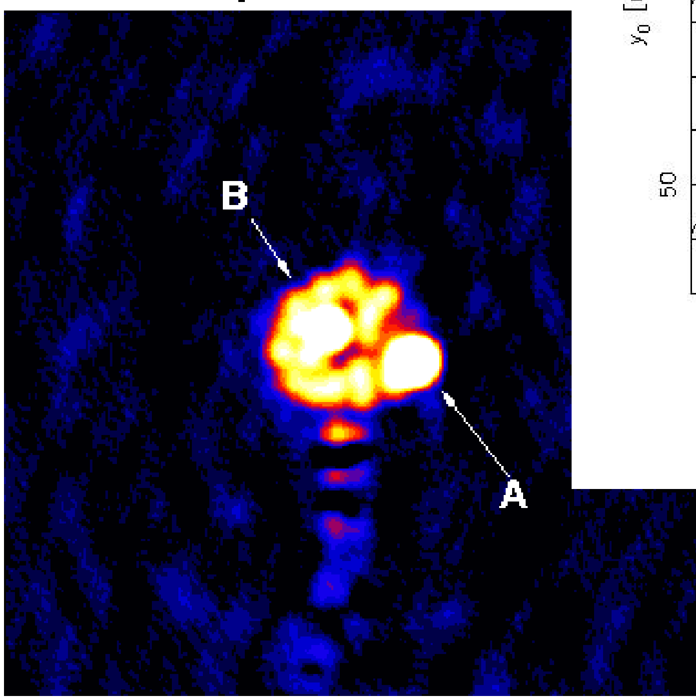


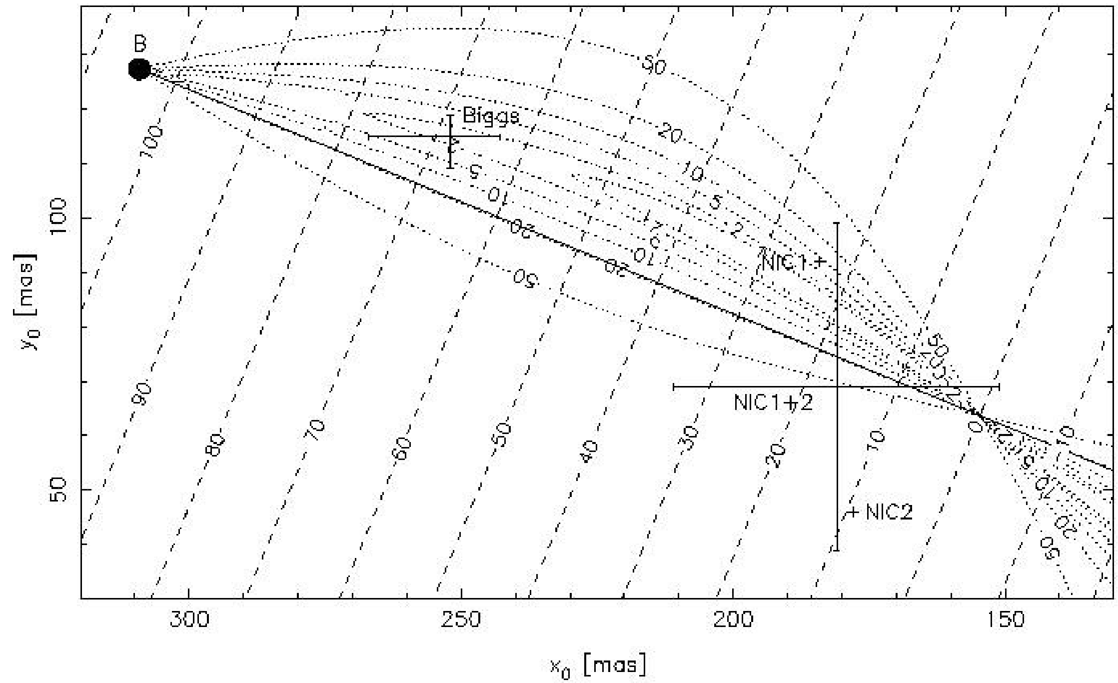
Time delay = 10.5+/-0.4 days
Hubble constant estimate:
69 km/s/Mpc (+13/-19, 95%)

Time delay+mass model = H_0

The gravitational lens JVAS0218+357

Radio map





But critically dependent on galaxy position…

Time delay = 10.5+/-0.4 days
Hubble constant estimate:
69 km/s/Mpc (+13/-19, 95%)

Current status

CLASS 0218+357	10.5 ± 0.2	Biggs et al. 1999
HE 0435−1223	$14.4^{+0.8}_{-0.9}$ (AD)	Kochanek et al. 2006
SBS 0909+532	45^{+1}_{-11} (2σ)	Ullan et al. 2006
RX 0911+0551	146 ± 4	Hjorth et al. 2002
FBQ 0951+2635	16 ± 2	Jakobssen et al. 2005
Q 0957+561	417 ± 3	Kundic et al. 1997
SDSS 1004+4112	38.4 ± 2.0 (AB)	Fohlmeister et al. 2006
HE 1104−185	161 ± 7	Ofek & Maoz 2003
PG 1115+080	23.7 ± 3.4 (AC)	Schechter et al. 1997
RX 1131−1231	$12.0^{+1.5}_{-1.3}$ (AB)	Morgan et al. 2006
CLASS 1422+231	8.2 ± 2.0 (BC)	Patnaik & Narasimha 2001
SBS 1520+530	130 ± 3	Burud et al. 2002
CLASS 1600+434	51 ± 4	Burud et al. 2000
	47^{+5}_{-6}	Koopmans et al. 2000
CLASS 1608+656	31 ± 7 (AB)	Fassnacht et al. 2002
	36 ± 7 (BC)	
	76 ± 9 (BD)	
SDSS 1650+4251	49.5 ± 1.9	Vuissoz et al. 2006
PKS 1830−211	26^{+4}_{-5}	Lovell et al. 1998
HE 2149−2745	103 ± 12	Burud et al. 2002
Q 2237+0305	$2.7h^{+0.5h}_{-0.9h}$	Dai et al. 2003

Now 18 with time delays (cf. 11 in 2004)

Remove anything with uncertain time delay
Remove anything with large cluster contribution
Rem
Rem
Rem

NB: words like
dodgy"
e

Carefully studied lenses with good constraints give low 70s (see e.g. Wucknitz et al. 2004, Suyu et al. 2010)

Using a known H0 breaks nearly all the degeneracies for an immediate mass model

0957
0909
(1004)
0911

With few exceptions, convergence around 50-60 (problem pointed out by Kochanek 2002) – systematically non-isothermal OR H_0=50 OR CDM is wrong

Summary

-200 lenses so far
-Can give good mass models, especially with known Hubble constant
- Otherwise unobtainable constraints on dark matter substructure and central potentials

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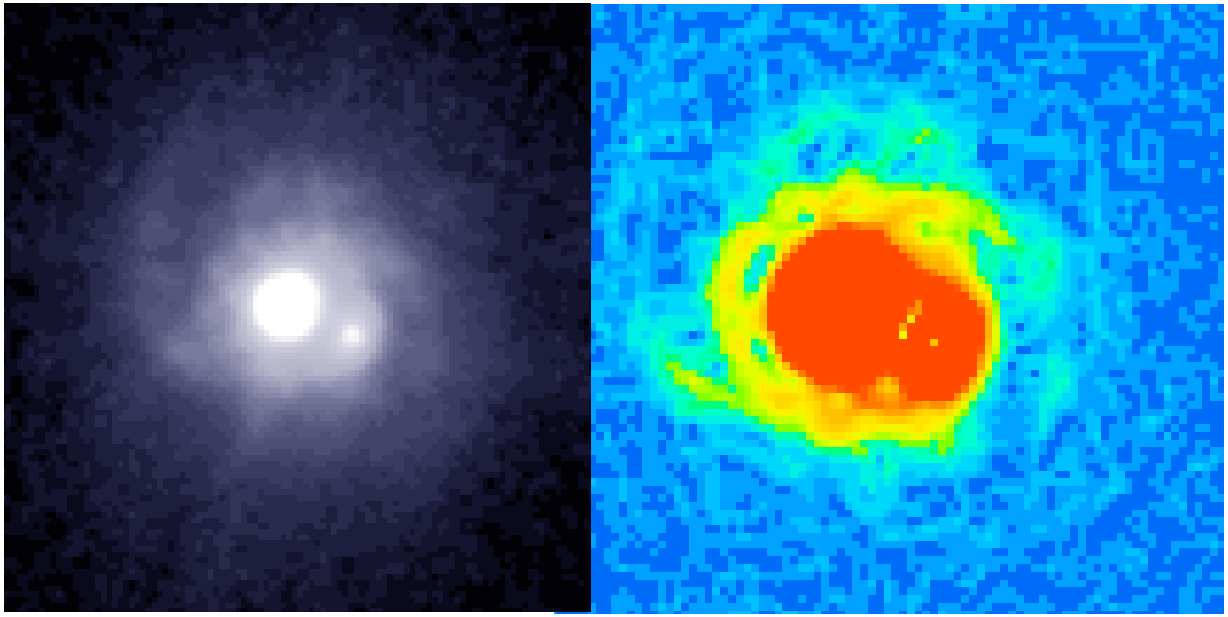
Jodrell Bank
Observatory

MANCHESTER
1824

Future lens surveys



The basic problem

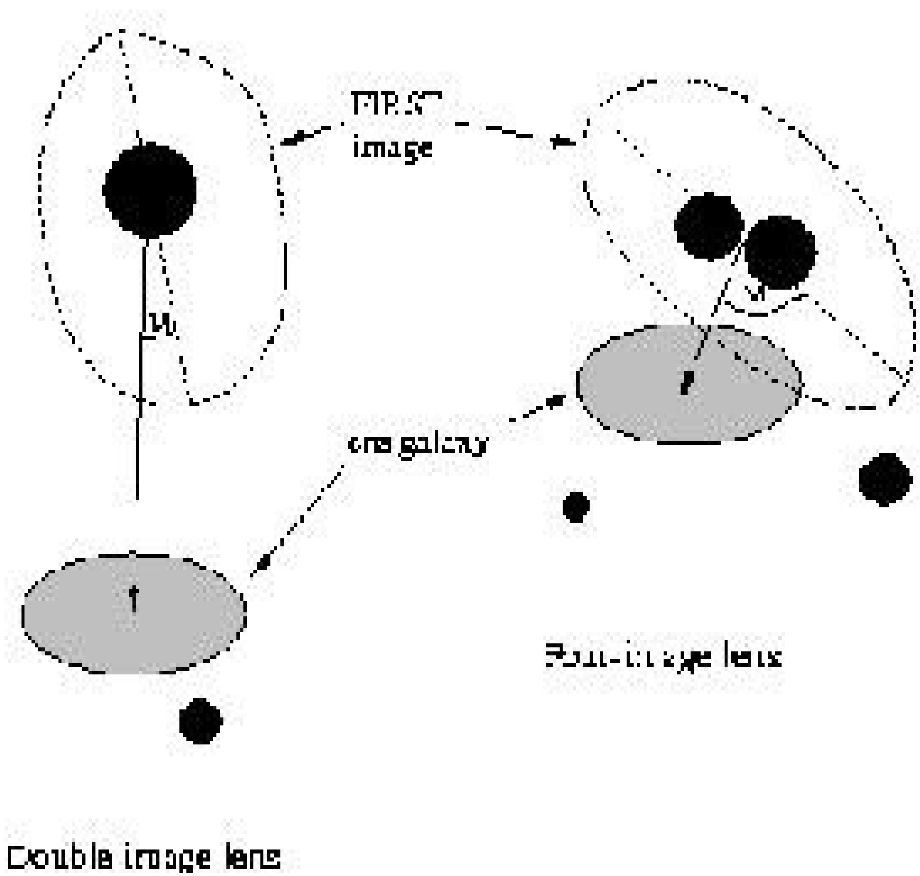
To be interesting, surveys should be 10 times as big.

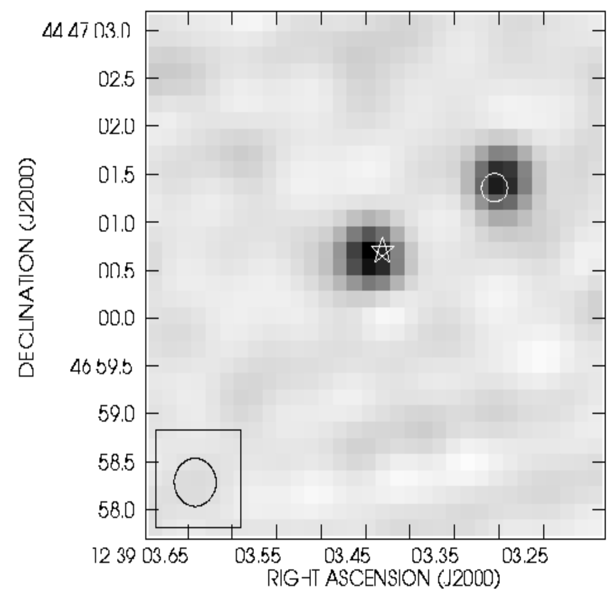
All bright sources have been done, so the survey will have to be 10 times as big AND 10 times as faint.

EVLA/eMerlin sensitivity takes care of 10 times as faint, but for 10 times as big you need 10 times more efficient.

CLASS and after

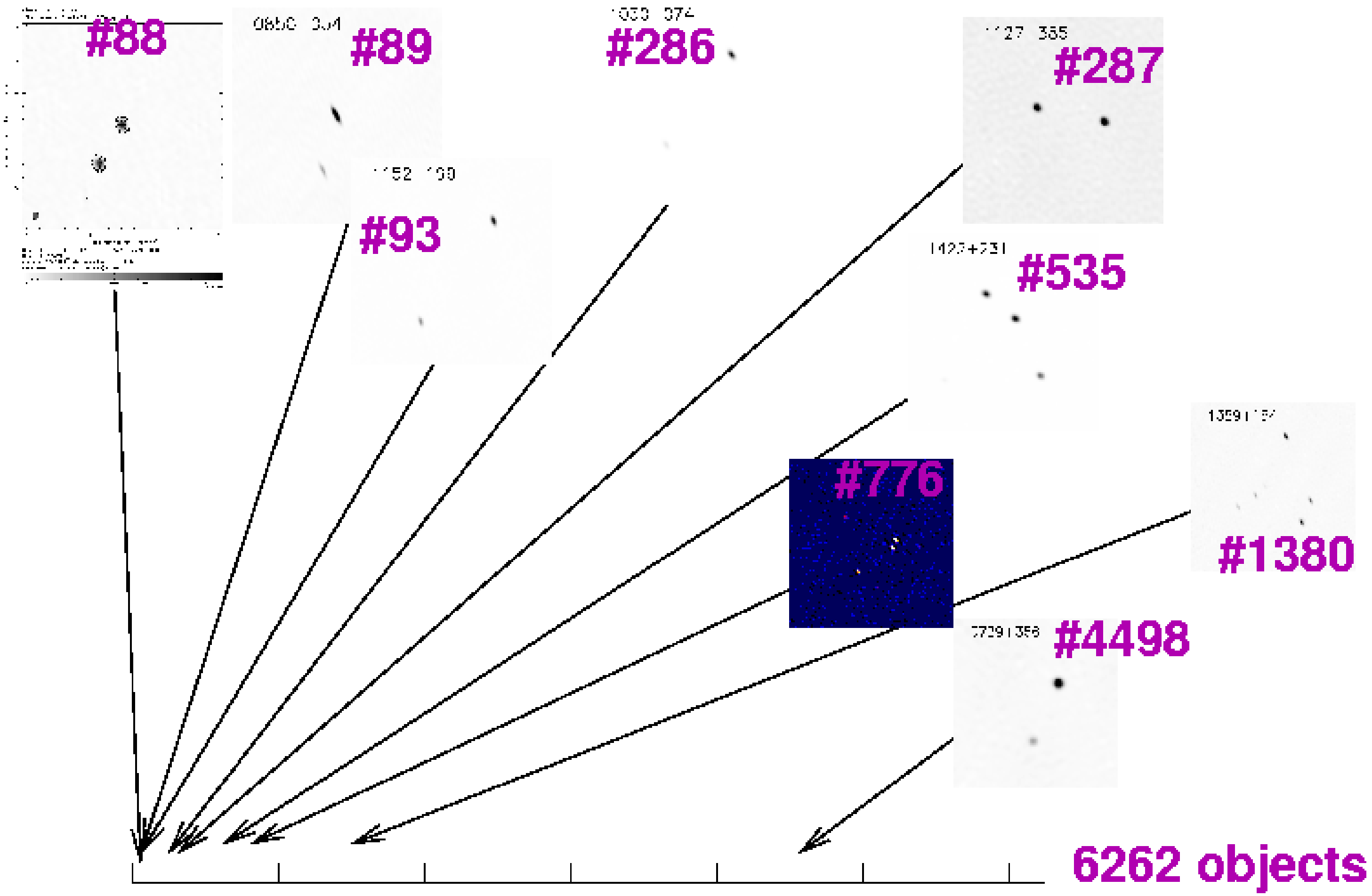
"Efficient" surveys





Jackson & Browne, astro-ph/0609818

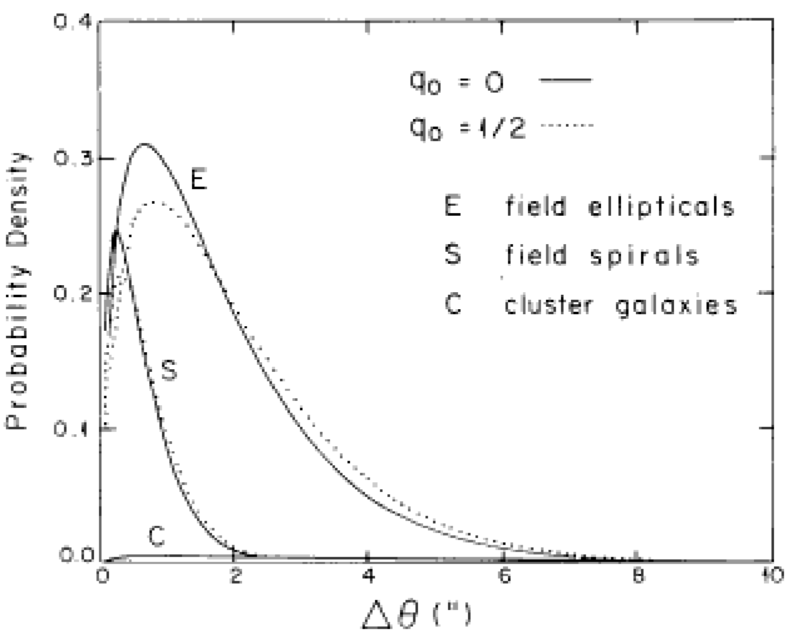
CLASS and after



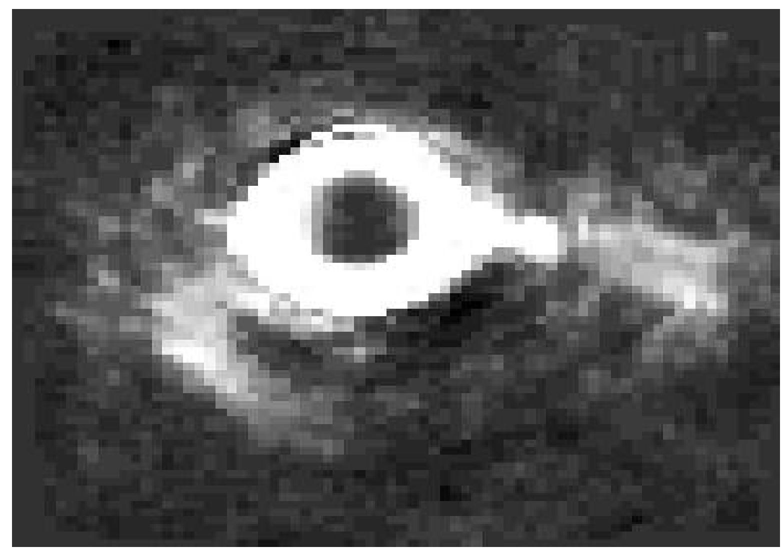
* Using sub-resolution information in FIRST could have discovered 50% of CLASS lenses in 5% of the time
* Using FIRST and SDSS information together could discover 50% of lenses in 1% of the time; further studies planned...

Why try and find 10000 lenses?

- Cosmology (H_0, [illegible]) – will be known
- Mass models – still interesting
  - rare lenses (spirals)
  - statistics across range of Hubble type and r(E)/mass
  - complex systems and good constraints
  - substructure and complex lens models



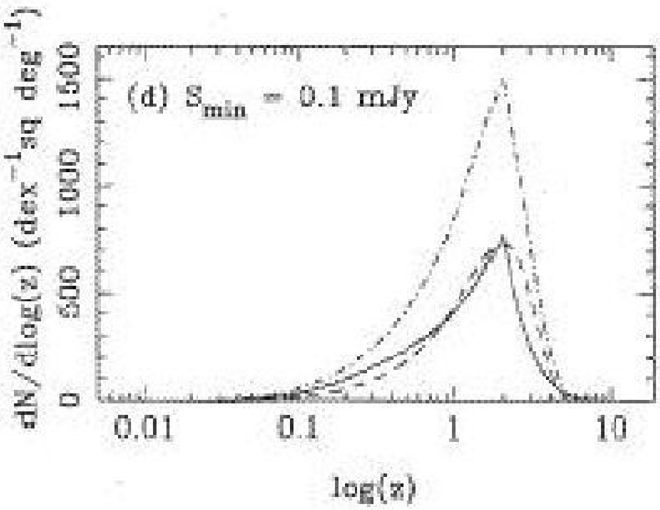
Turner, Ostriker & Gott 1984



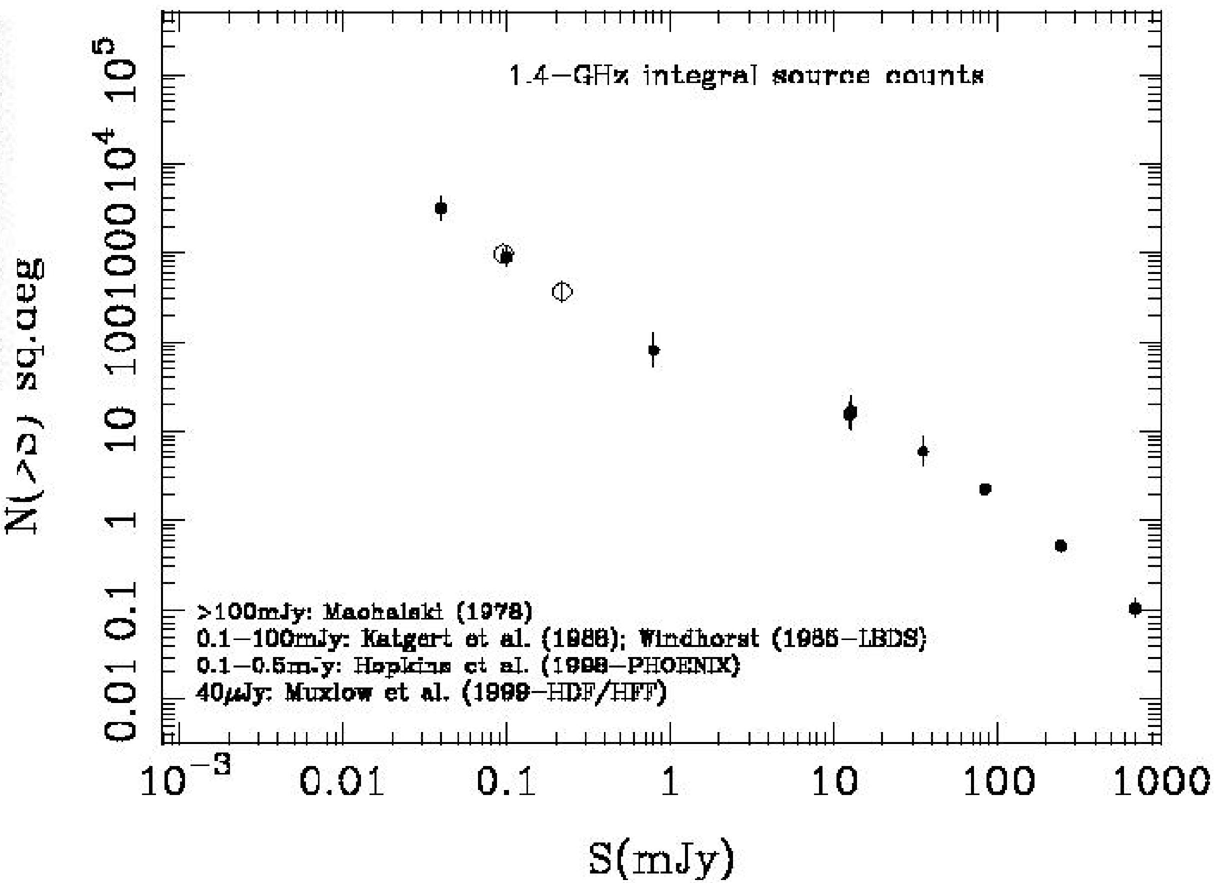
Muxlow et al. 1999 (lensed)

Basic parameters of a SKA survey

- Few months integration
- 10000 square degrees at a few square degrees FOV, <1 ⌙ Jy RMS
- A few billion sources, 1 million lens systems?



Hopkins et al. 1998



Potential problems

- Low source redshifts (are there any lenses?)
  probably OK, starbursts at z approaching 1
- Completeness (can they be found reliably?)
  difficult to get complete for cosmological statistics
  could just use quads (requires assumptions)
- Redshifts and identifications (can they be studied?)
  NGST…
- Will we know all the answers already?
  cosmological parameters – maybe
  mass distributions of high-z galaxies – no
  how structure forms – probably not
- What is needed from SKA?
  resolution, resolution, resolution – 50mas or better
  reasonable (x10 range of frequencies)