Gravitational Lenses and VLBI

Andy Biggs

biggs@jive.nl

Joint Institute for VLBI in Europe

Talk Outline

- Brief introduction to lensing
- Finding lenses
- Mass model constraints
- Lens substructure
- Propagation effects
- Future developments

What is gravitational lensing?

Chance alignment of *at least* two astronomical sources as seen from the Earth

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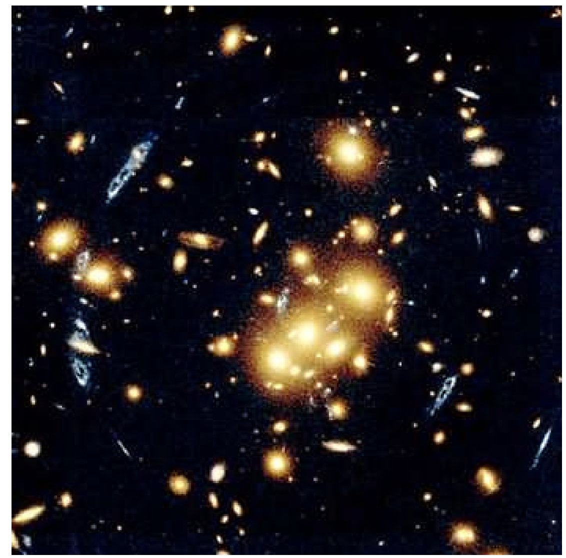

(APOD)

What is gravitational lensing?

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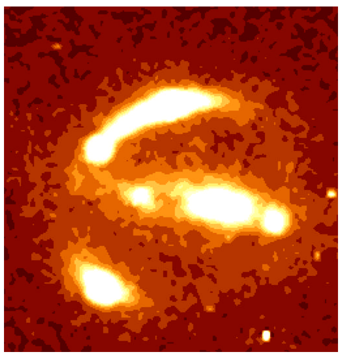
(APOD)

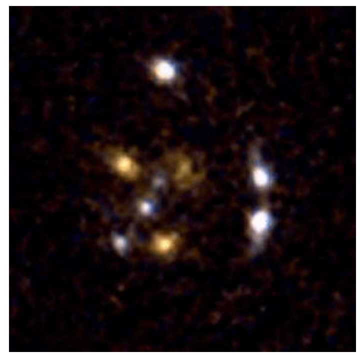
Sufficient alignment and mass in deflector produces multiple imaging

Lensing by galaxies

Galaxies and galaxy groups form $\geq$80 known lenses

Lensed source is usually a quasar





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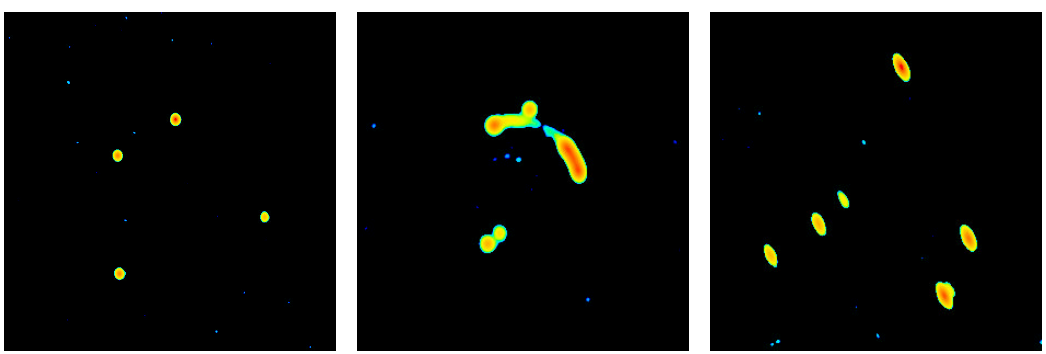

(CLASS and CASTLEs)

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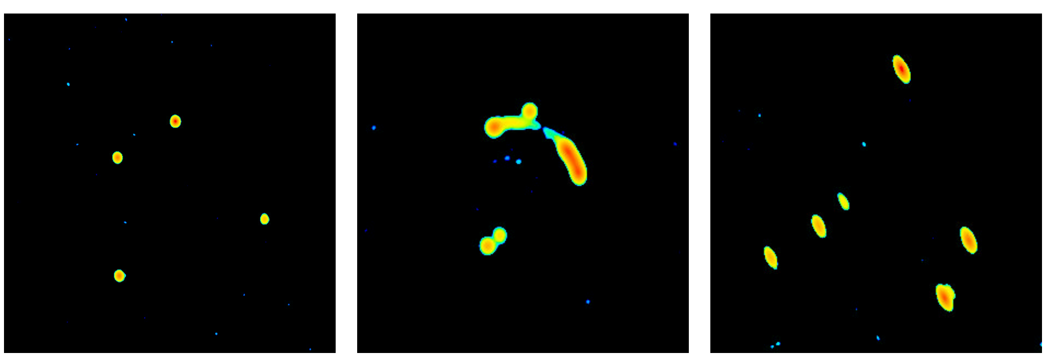

(CLASS and CASTLEs)

Uses include:

- Weighing galaxies
- Mass profiles of galaxies
- H_0 through time delay
- Lens statistics (Λ_0, Ω_0)
- Astrophysics of galaxies
- Gravitational telescopes

Why study lenses with VLBI?

Most radio lenses consist of unresolved components to linked arrays such as MERLIN and the VLA

VLBI techniques must be utilised in order to fully exploit gravitational lensing as...

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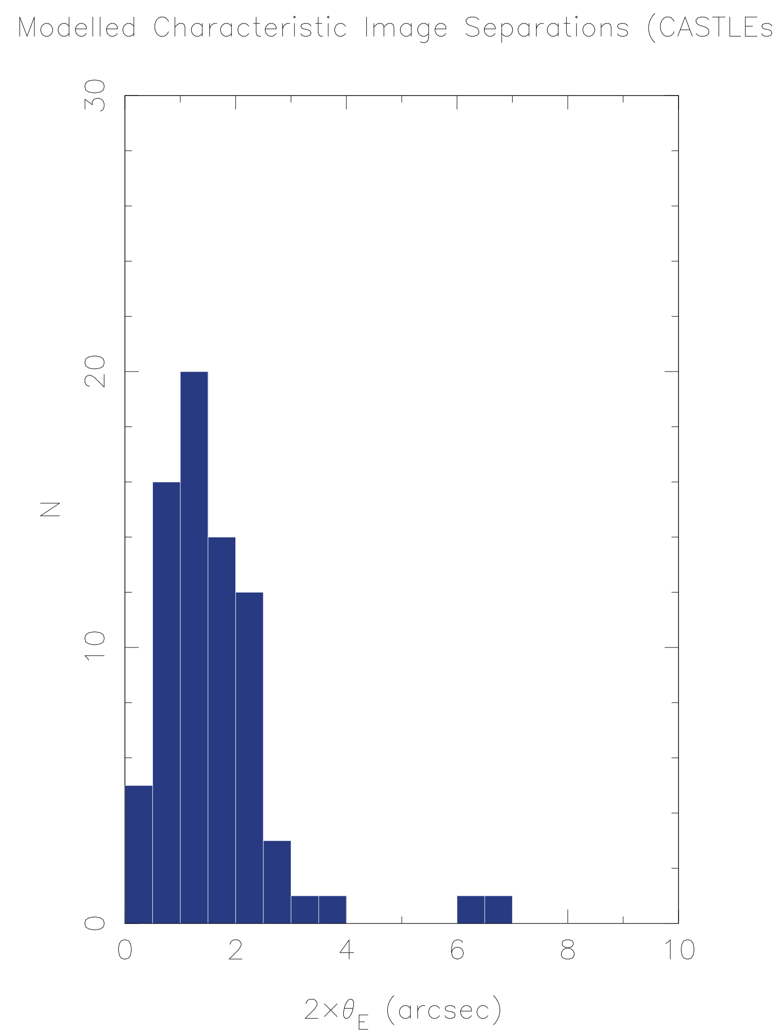
Most radio lenses consist of unresolved components to linked arrays such as MERLIN and the VLA

VLBI techniques must be utilised in order to fully exploit gravitational lensing as...

- Mas-scale structure provides powerful constraints on lens models...
- ...and aids in identifying lens systems
- Higher positional accuracy
- Sources can be studied at higher resolution
- Gas in high-redshift galaxies is probed on pc scales

Wide-field VLBI

Gravitational lens VLBI is inherently a wide-field discipline



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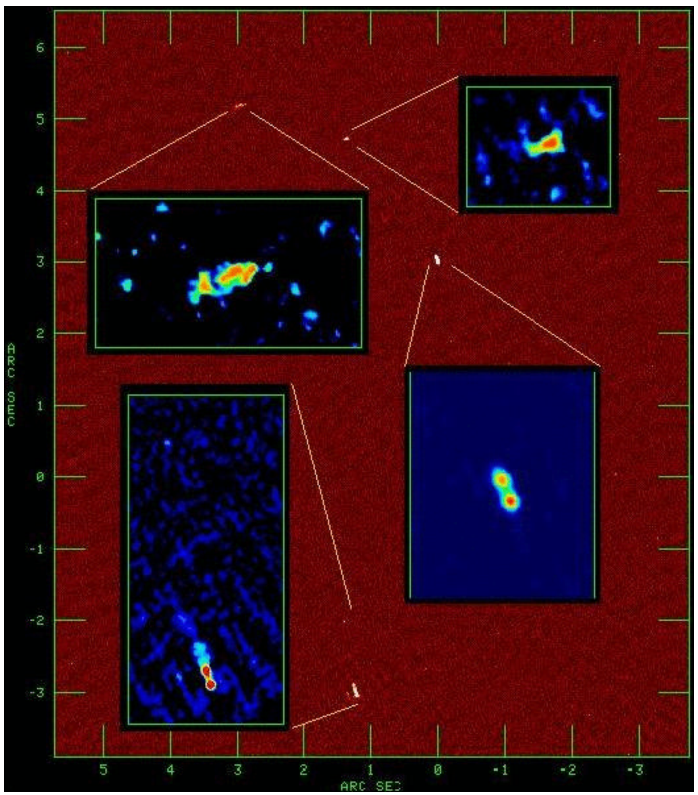
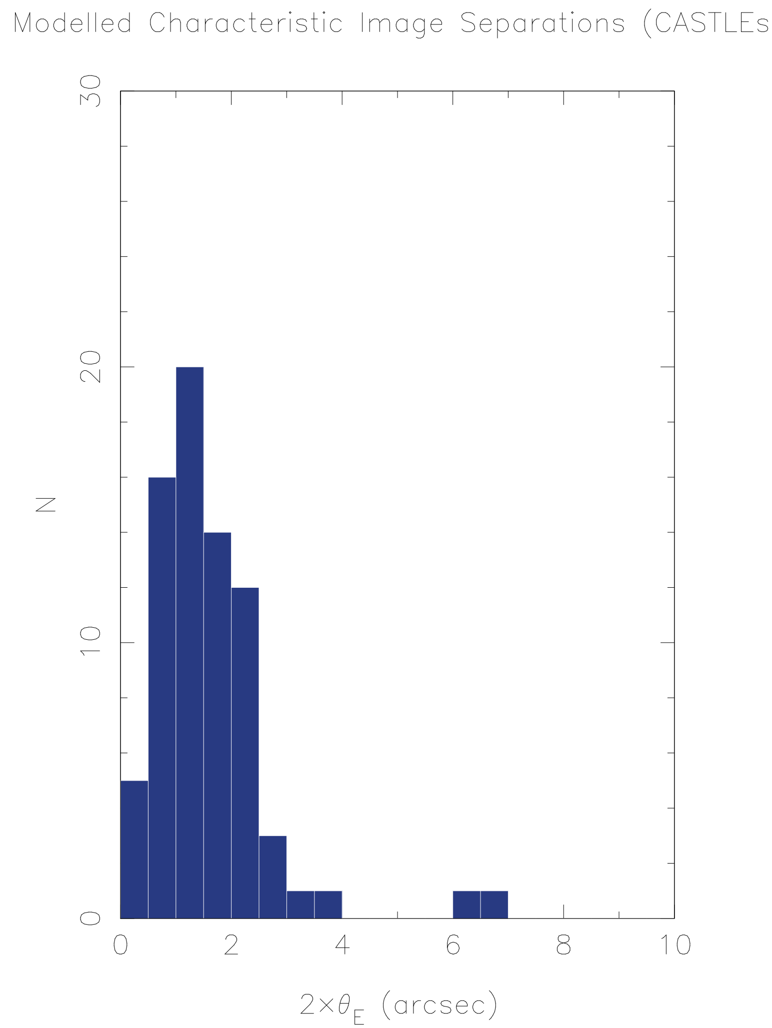
Gravitational lens VLBI is inherently a wide-field discipline

- Restricted time and frequency averaging
- Very large datasets!



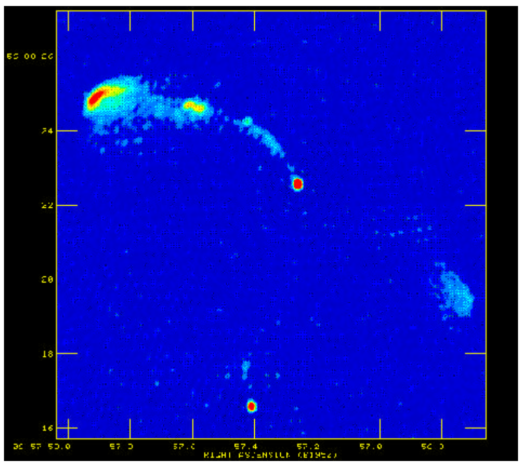
(Garrett et al. 94)



Finding lenses: An historical interlude...

The first VLBI observations of a gravitational lens (B0957+561) took place on 2 June 1979

Three telescopes recorded a single 2-MHz band (Mark II system)



(N. Jackson)

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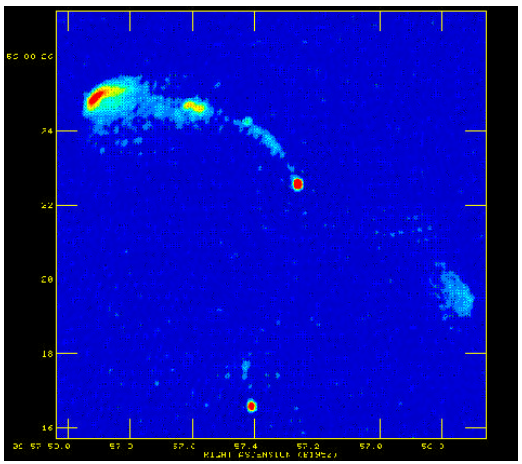
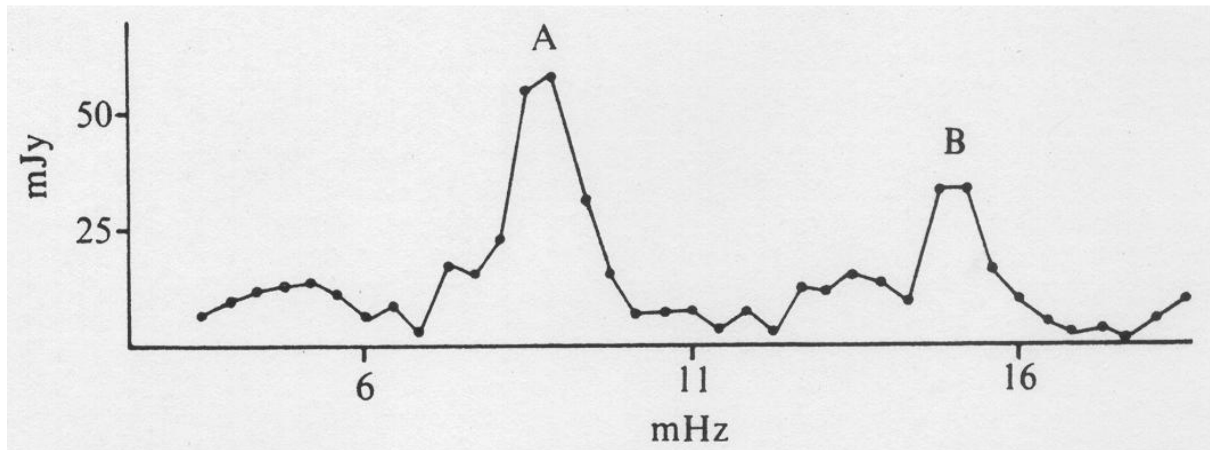


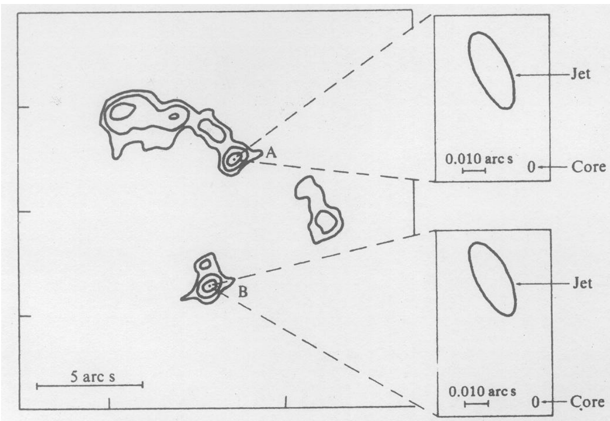


(N. Jackson) (Porcas et al. 79)

- Fringe rate spectrum showed two unresolved (< 20 mas) components
- Observations were consistent with the gravitational lens hypothesis

Finding lenses: resolving 0957+561

1980 (Porcas et al. 81)



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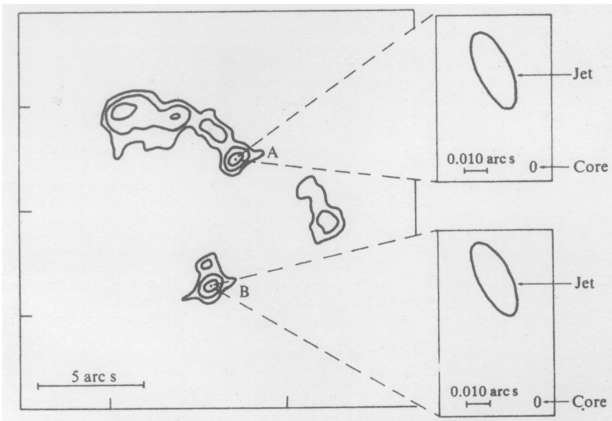
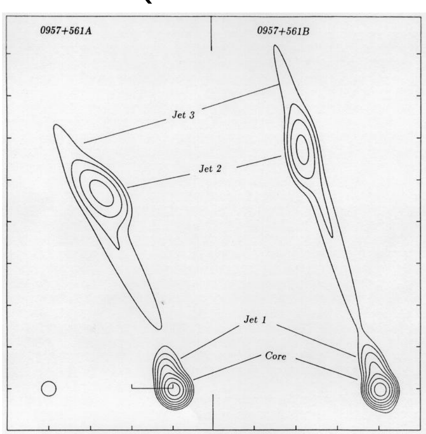


1981 (Gorenstein et al. 88)



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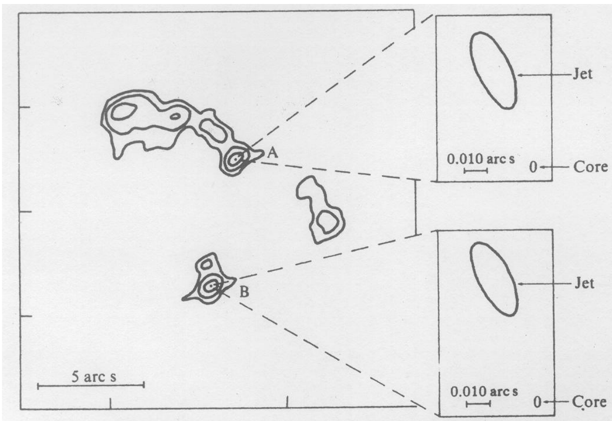

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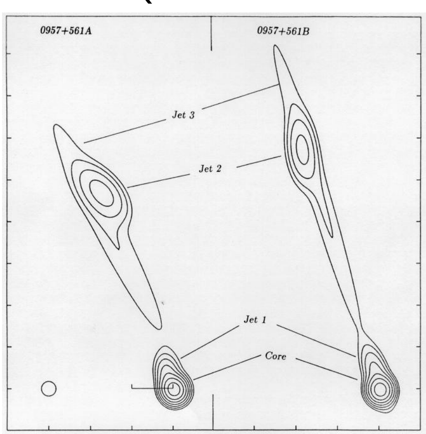
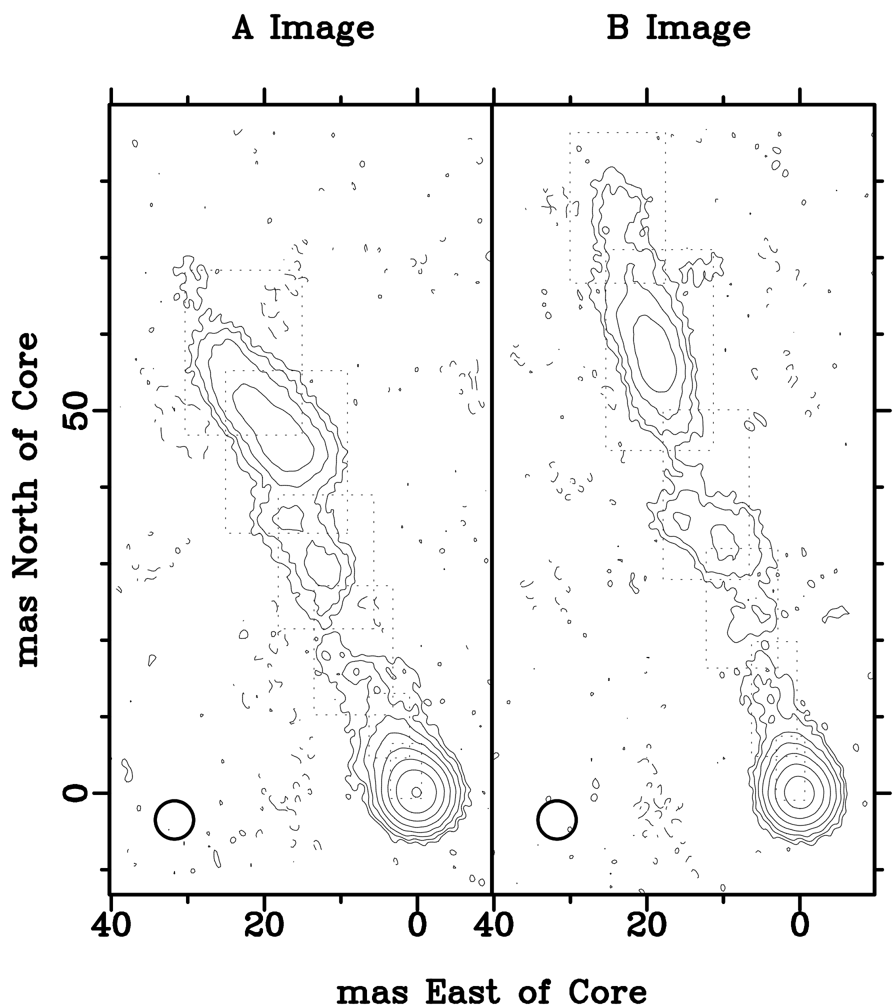


1992 (Campbell et al. 95)



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Radio surveys (e.g. JVAS/CLASS) have proved very efficient at discovering lens systems

- High resolution
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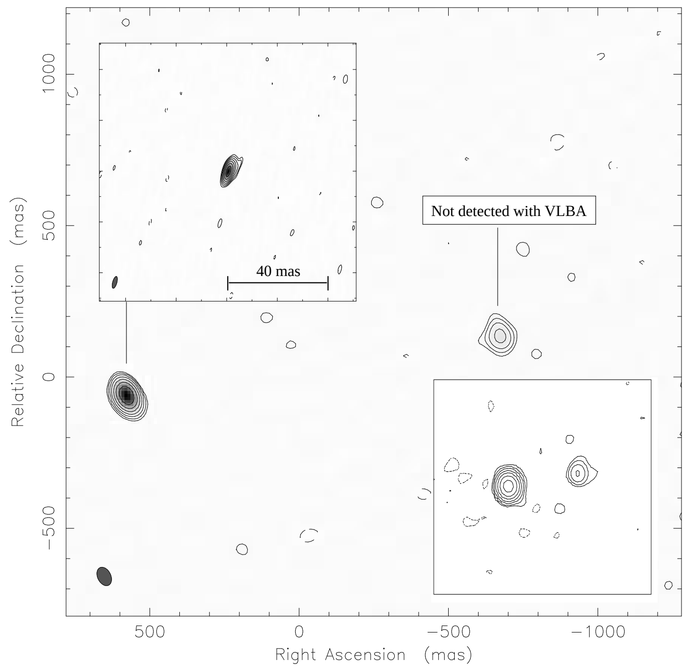
CLASS Methodology

Important lensing theorem: Surface brightness is preserved!

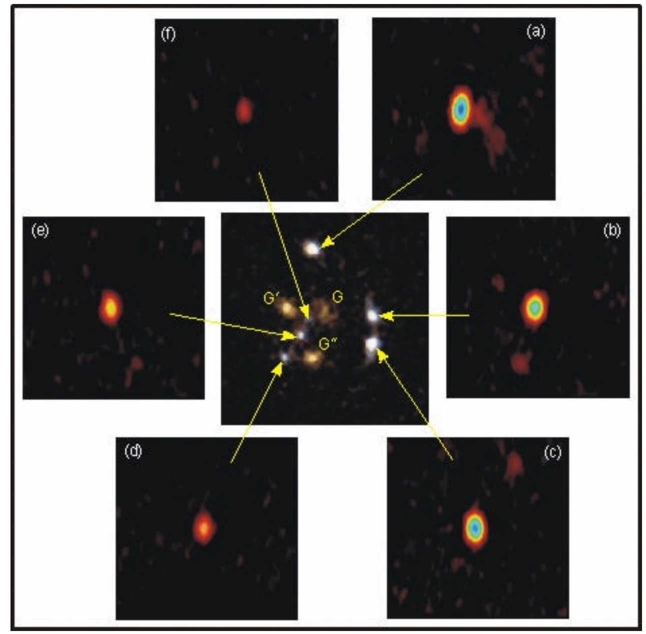
- Weaker images must be smaller
- Observe flat-spectrum sources (16,503) with the VLA at 8.4 GHz
- Follow-up candidates with MERLIN and VLBA (at 5 GHz)

Finding lenses: JVAS/CLASS



(Browne et al. 03)

J0722+195: REJECT!



(Rusin et al. 01)

B1359+154: 6-IMAGE LENS SYSTEM!

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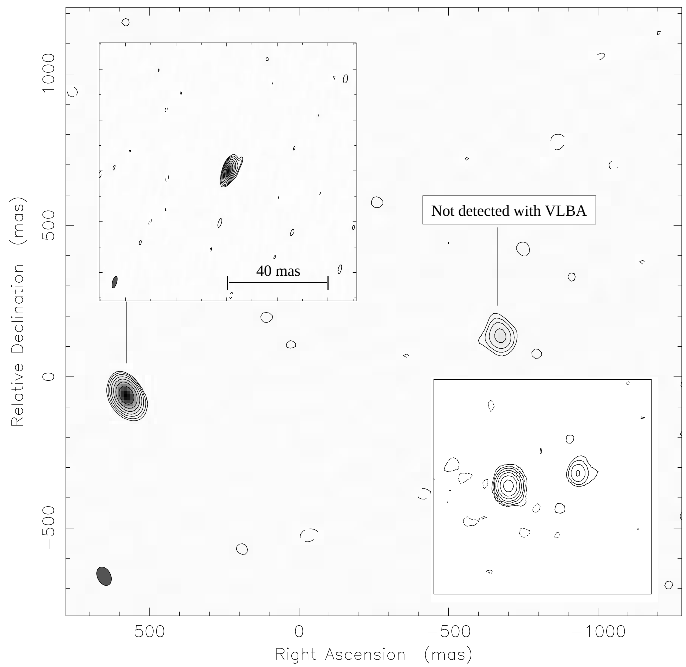

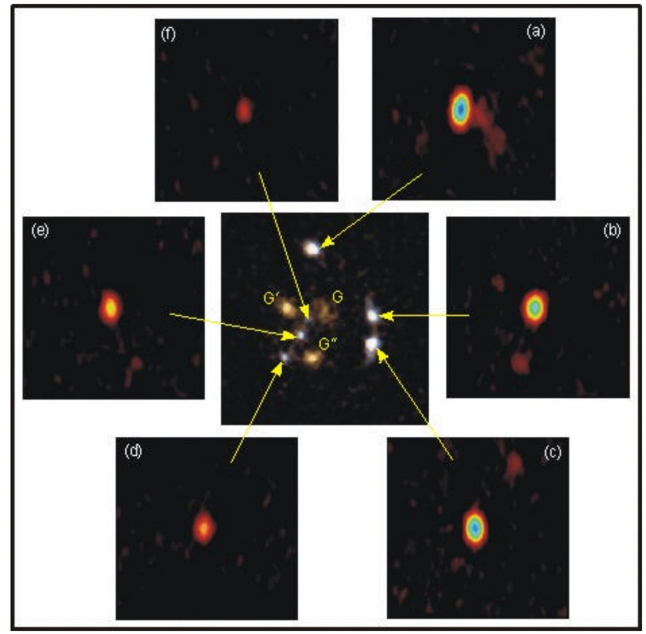

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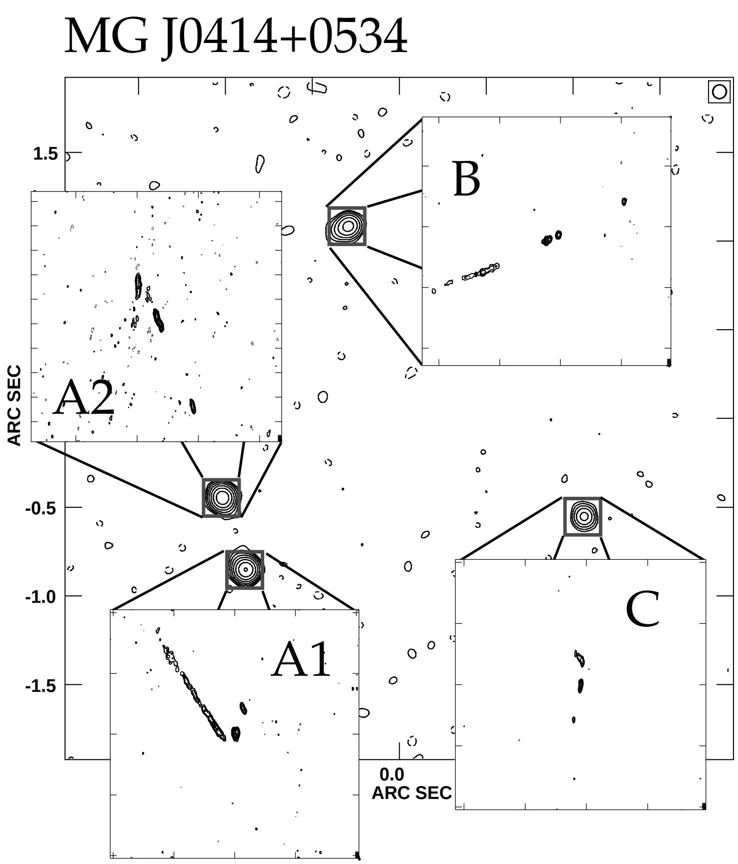
B1359+154: 6-IMAGE LENS SYSTEM!

Only one source that survived the radio tests was rejected with subsequent optical observations

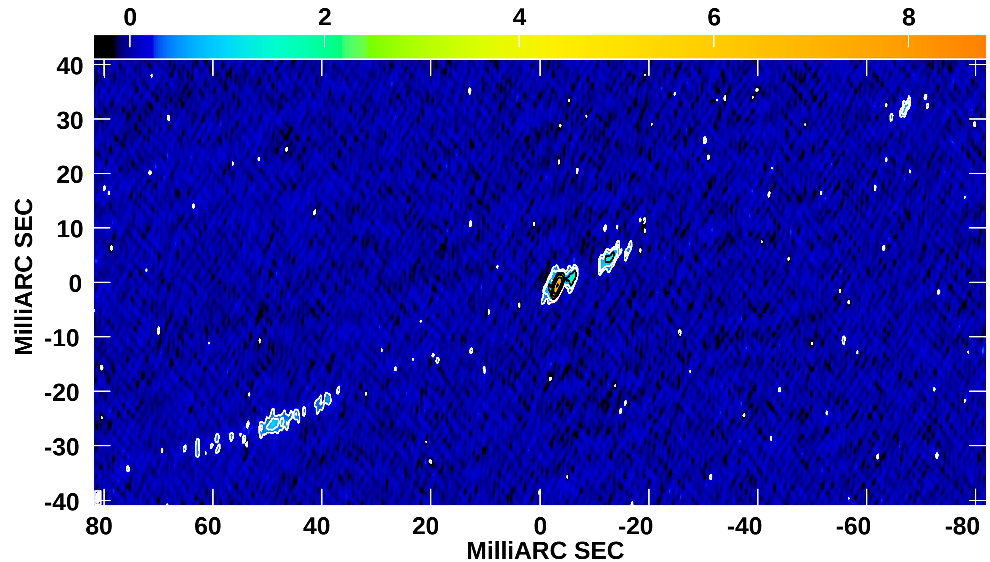
22 lens systems were identified in total

Constraining mass models

Many lens systems consist of multiple sub-components



(Trotter et al. 00)



(Ros et al. 00)

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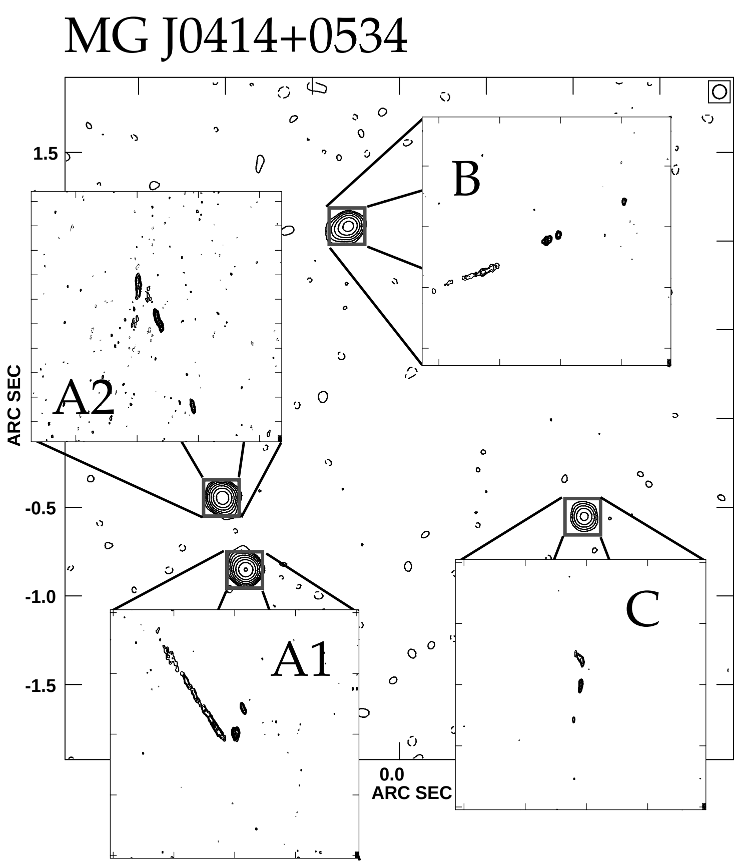

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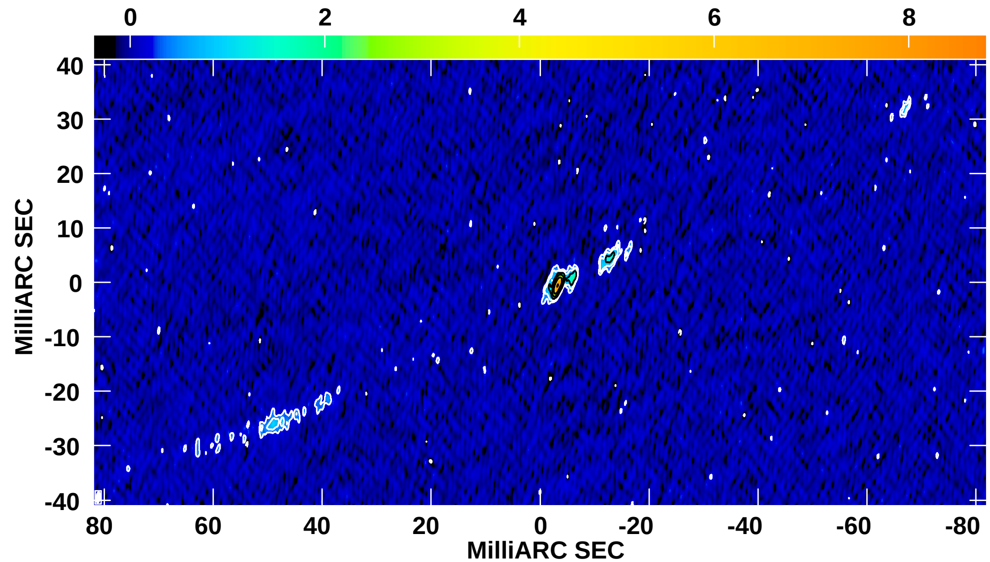

(Ros et al. 00)

- Parameterise with elliptical Gaussians
- Model has large number of d.o.f.
- LensClean should be possible

Radial mass profiles: JVAS B0218+357

Four-image lenses constrain the angular mass profile

Two-image systems better sample the radial mass profile

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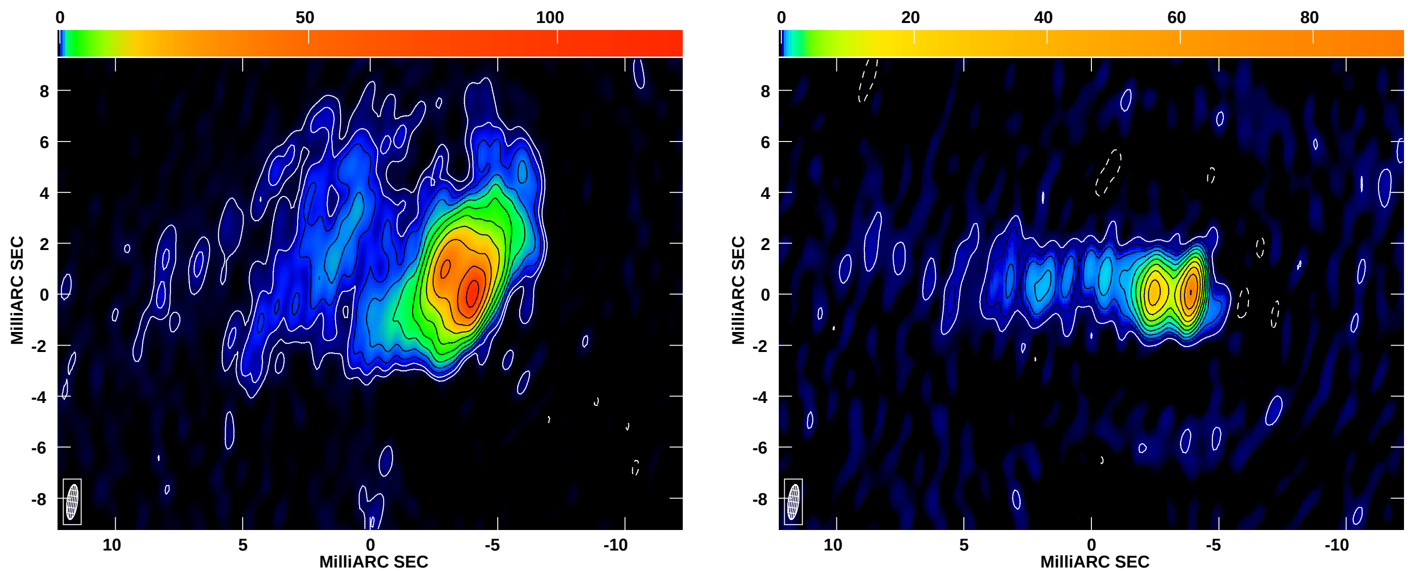

(Biggs et al. 03)

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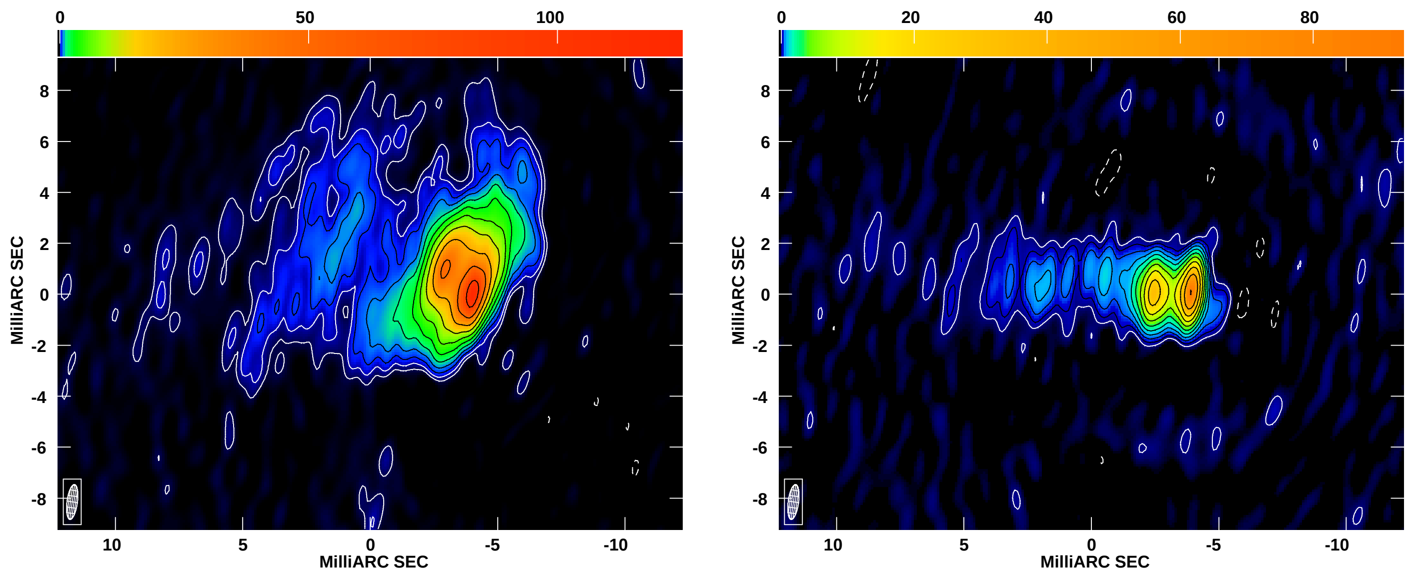
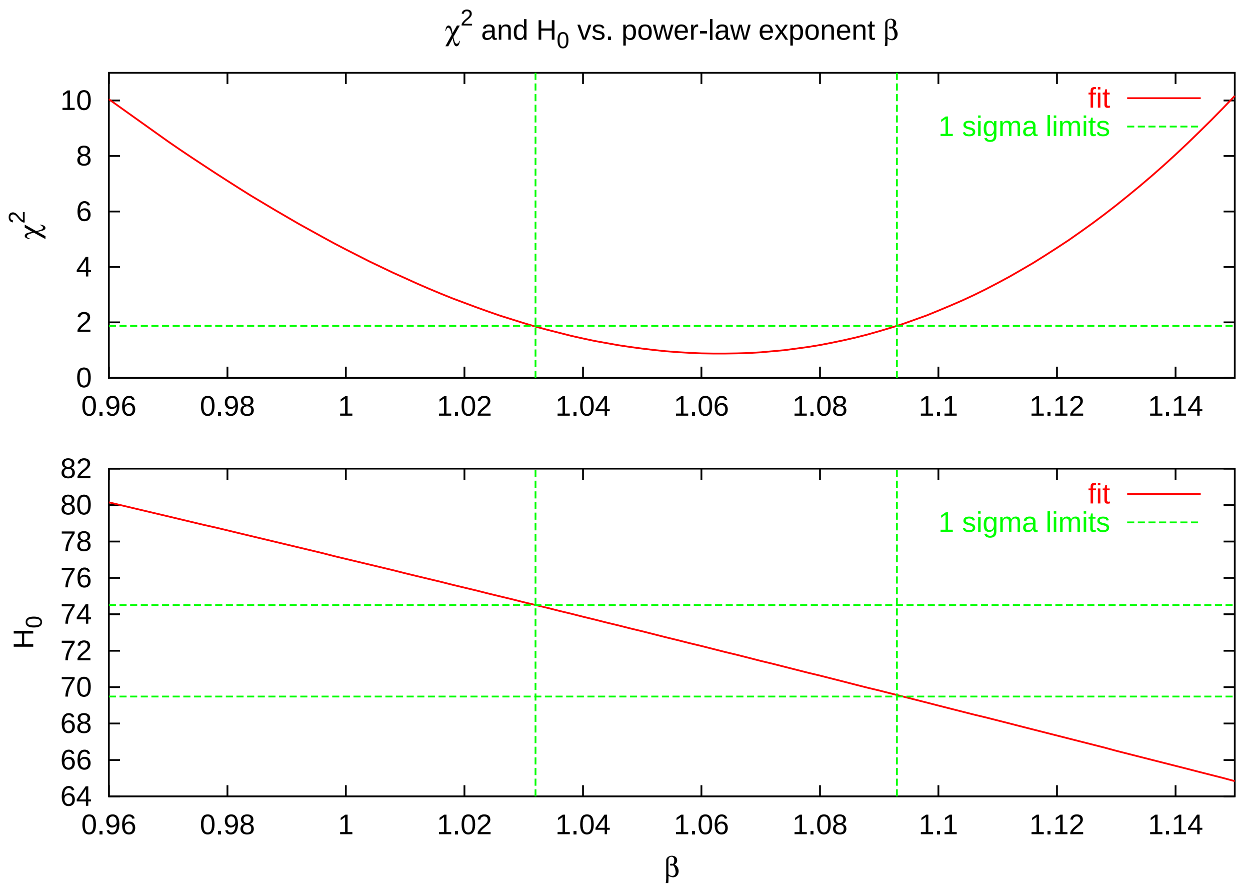


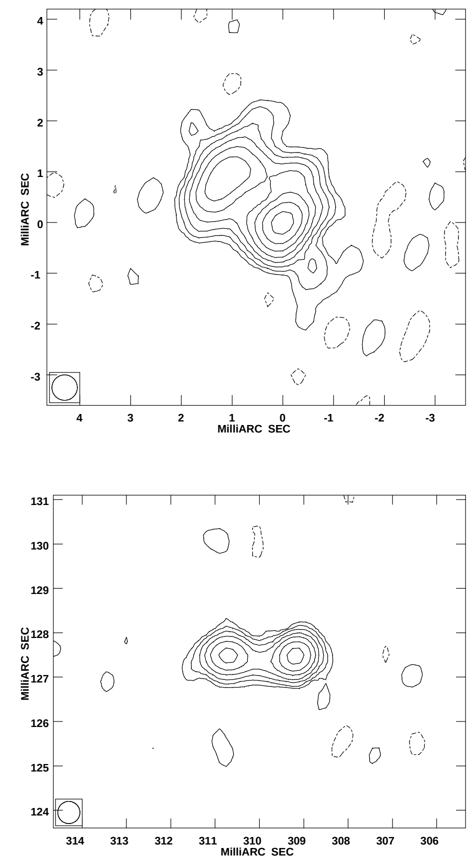
(Biggs et al. 03)

- Jet in image A is tangentially stretched by the lens potential
- Source has counterjet despite being a BL Lac
- No detection of third image or galaxy core

Radial mass profiles: JVAS B0218+357

Different lengths of jets in B0218+357 constrain the radial mass profile





(O. Wucknitz)

(Patnaik et al. 95)

Gravitational telescopes: MG 2016+122

Extremely high magnifications are possible at points where images merge

Sources here can be studied in unprecedented detail

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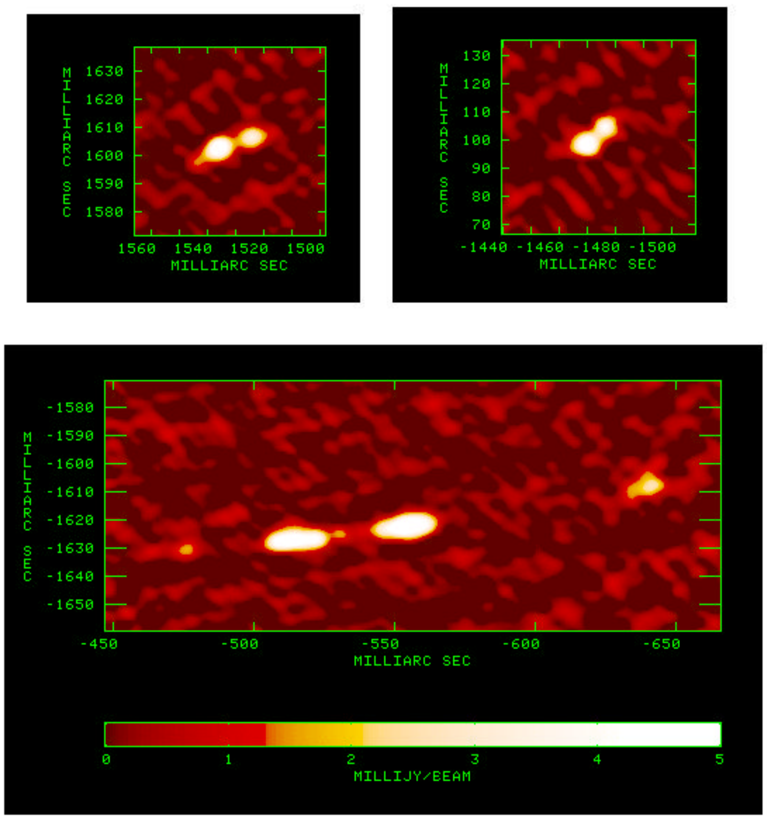

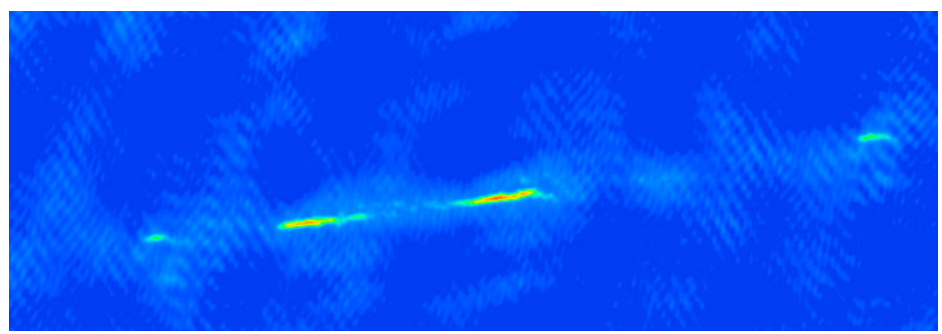

(Koopmans et al. 02)

(Porcas et al. 02)

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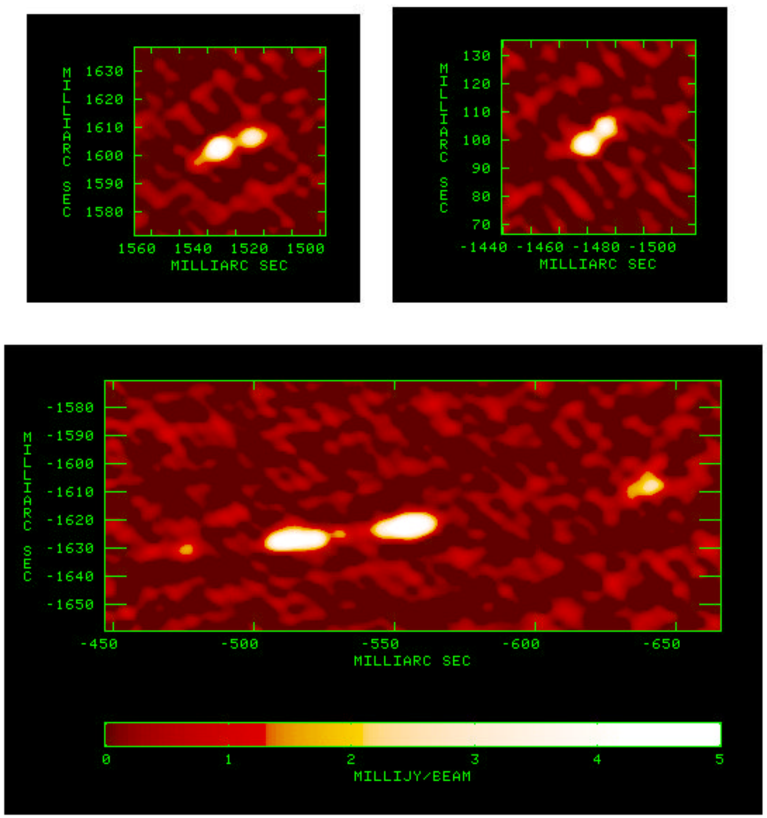
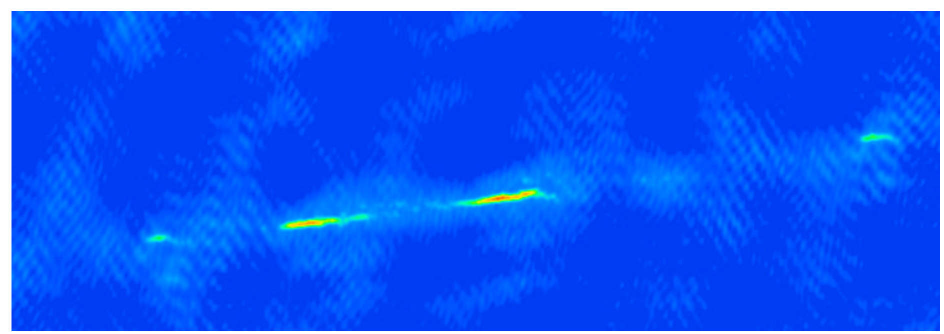


- Image C extremely elongated
- Magnification possibly ∼300 (!)
- Believed to be counterjet
- Not resolved in images A and B



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Lens substructure

Do galaxies contain enough satellite halos according to e.g. CDM?

Lensing can infer presence of perturbing masses within galaxy halos

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- On VLA/MERLIN scales use flux ratios
- VLBI can directly compare multiply-imaged jets

(Wambsganss & Paczyński 92)

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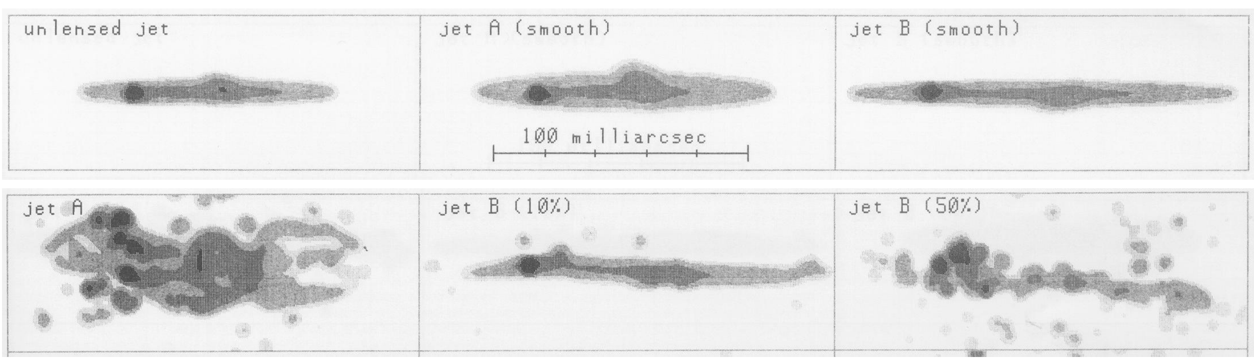

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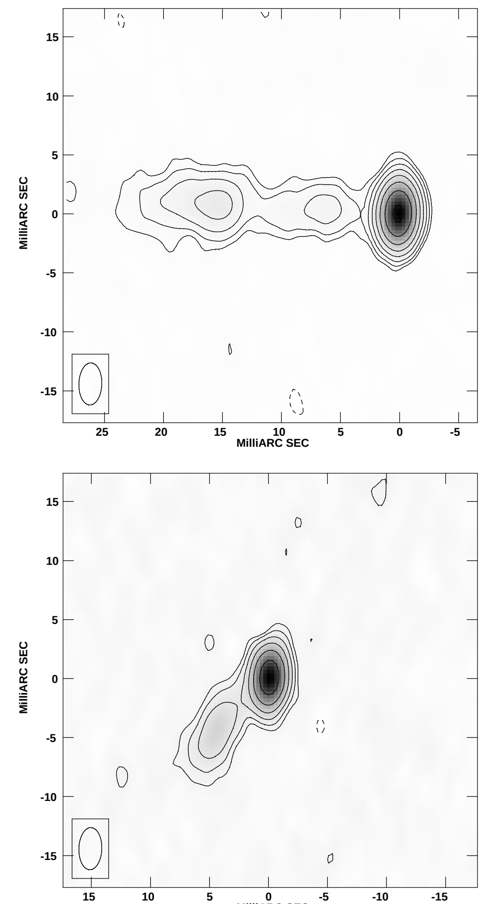

- CLASS B1152+199 is a possible candidate

(Rusin et al. 02, Metcalf et al. 02)

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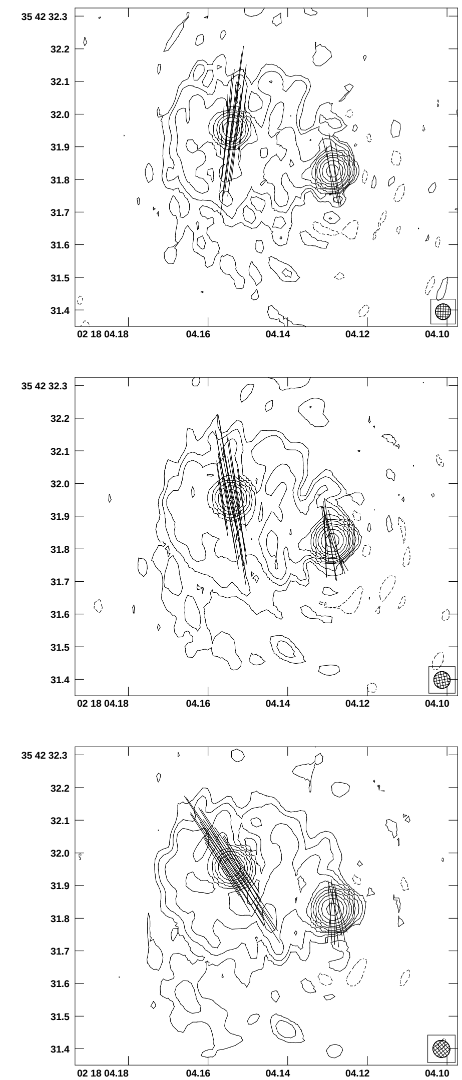
Astrophysical propagation effects

Astrophysical propagation effects observed in lens systems include:

- Faraday rotation
- Depolarization
- Scatter-broadening
- Atomic, molecular and free-free absorption



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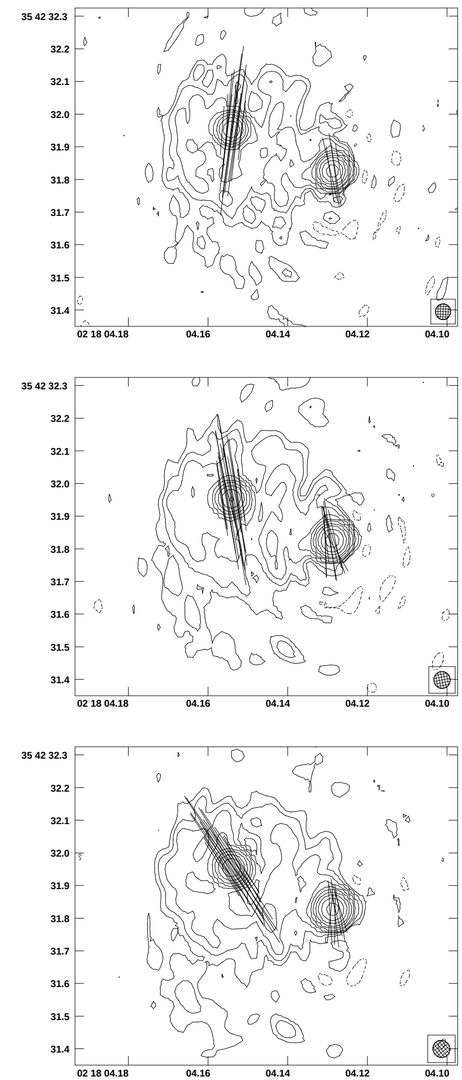
VLBI polarization observations provide:

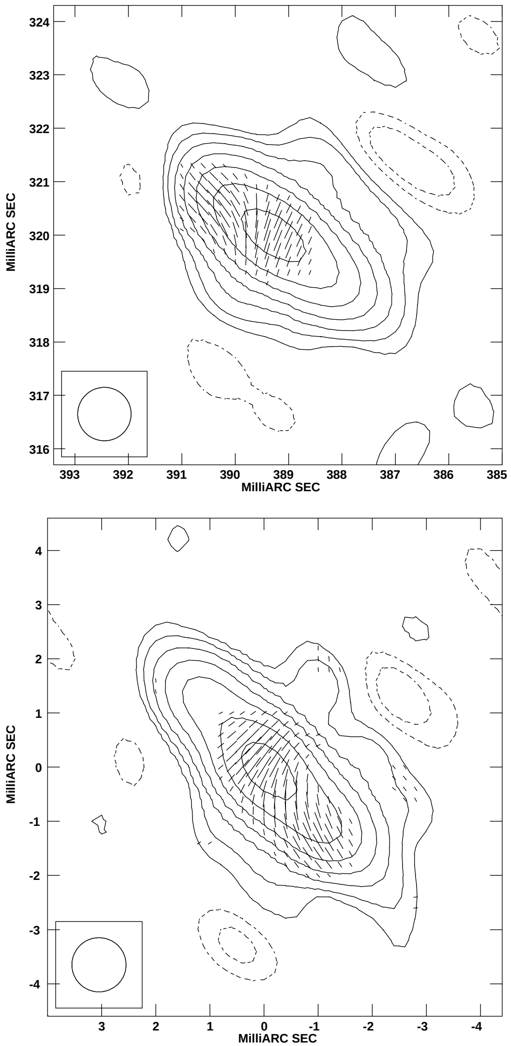
- Independent mass model constraints (but few lenses are polarized)

All VLBI observations can:

- Probe ISM of lensing galaxies on pc scales



Polarization observations

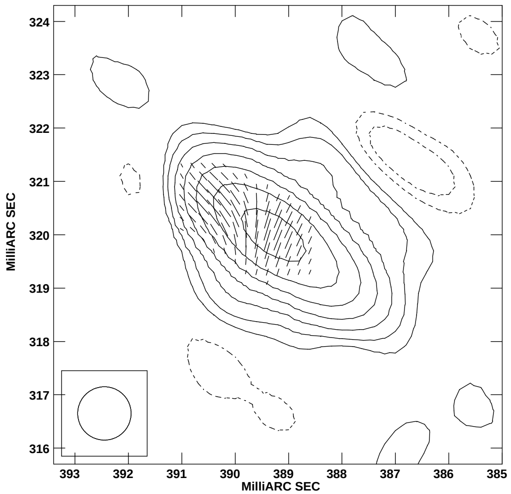


VLBI moderately resolves JVAS B1422+231

Polarization distribution is much more revealing

(Patnaik et al. 99)

Polarization observations



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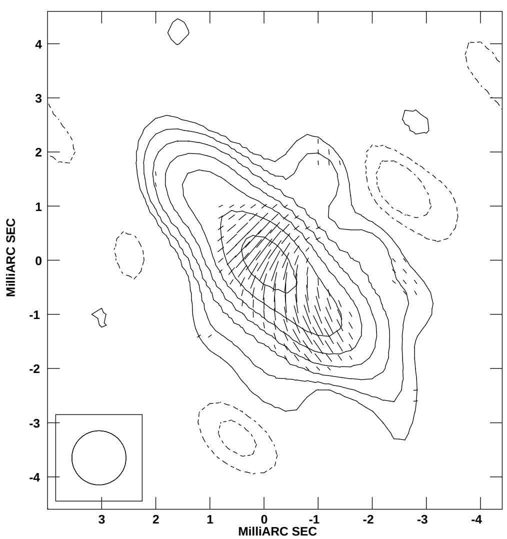
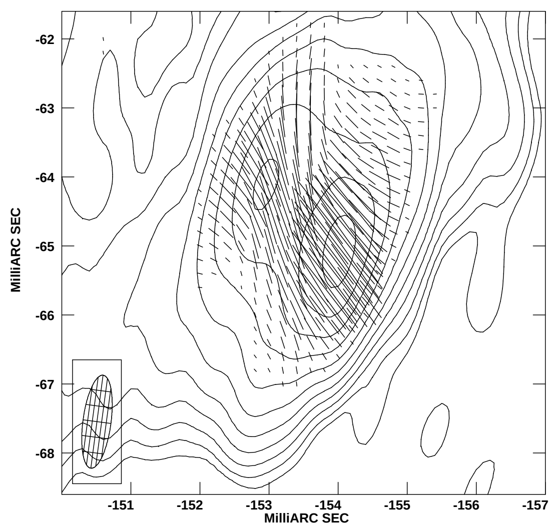
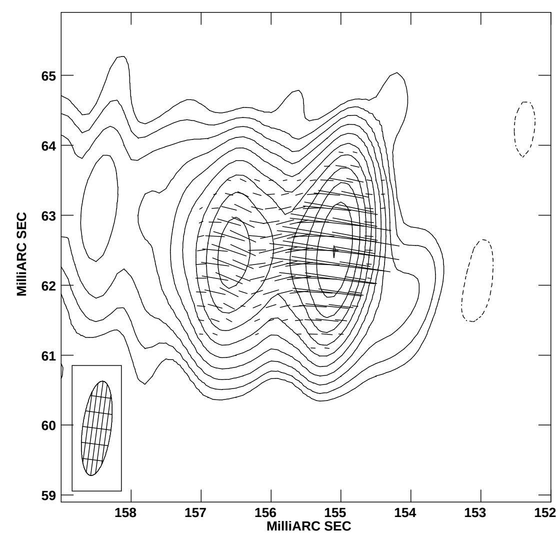
B0218+357 stretched as in total intensity

Anomolous region detected in image A



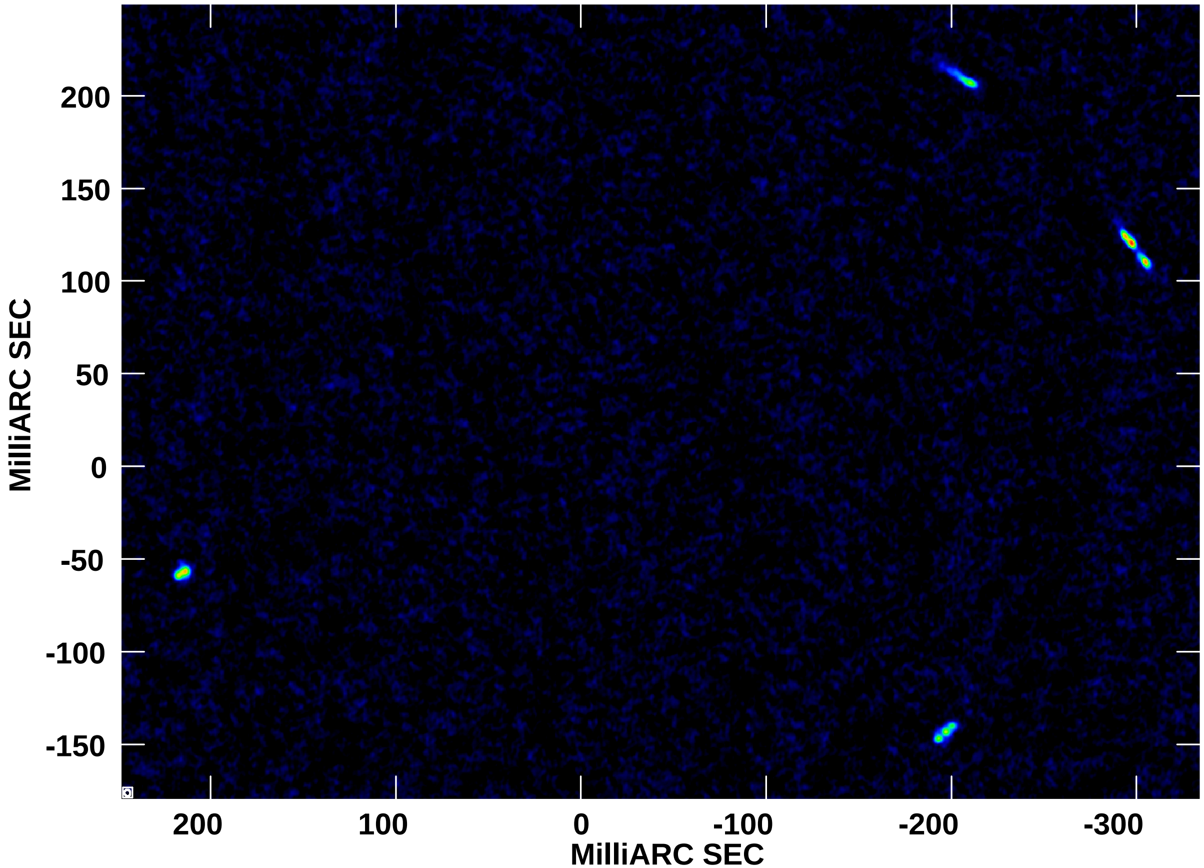




(Patnaik et al. 99)

(Biggs et al. 03)

Scatter-broadening: CLASS B0128+437



(Biggs et al., submitted)

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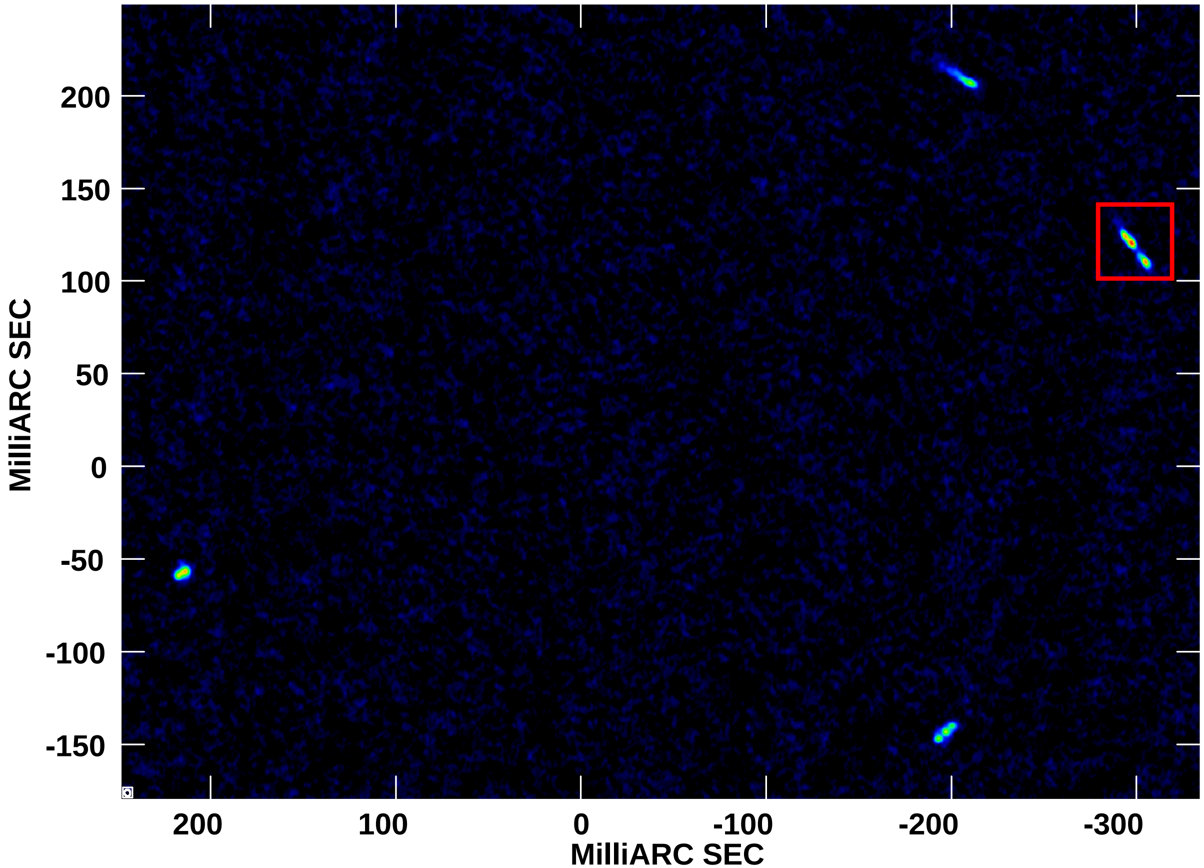

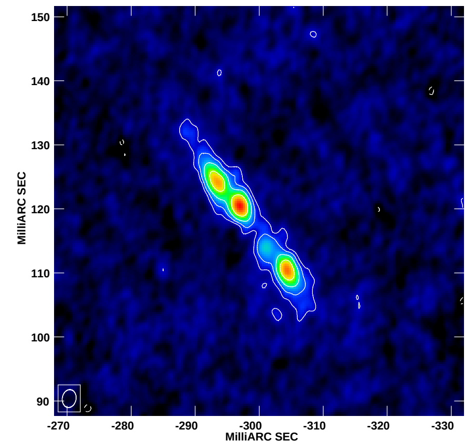

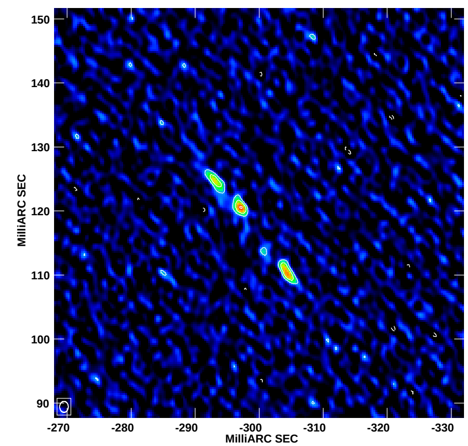

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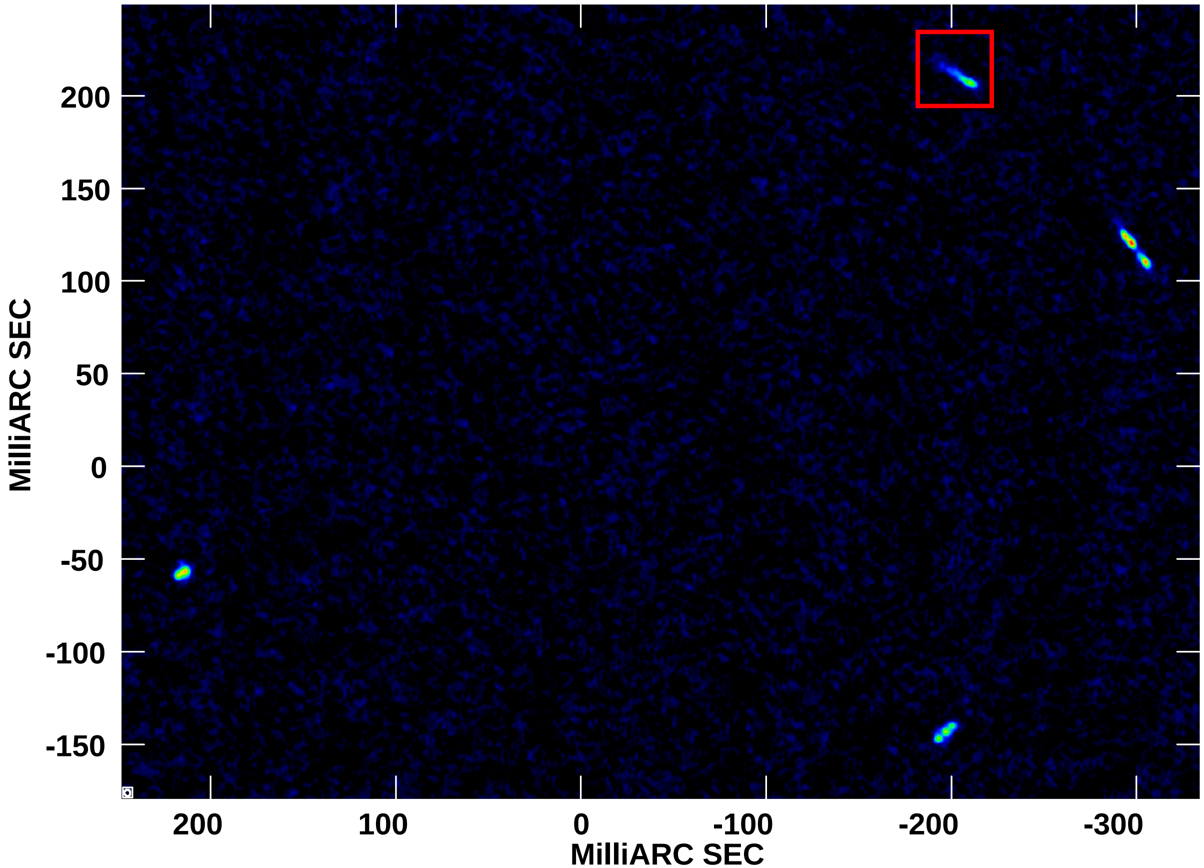

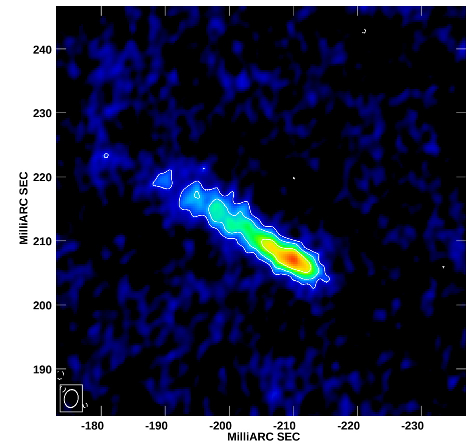

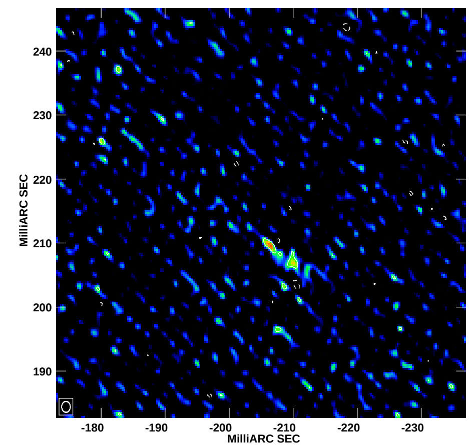

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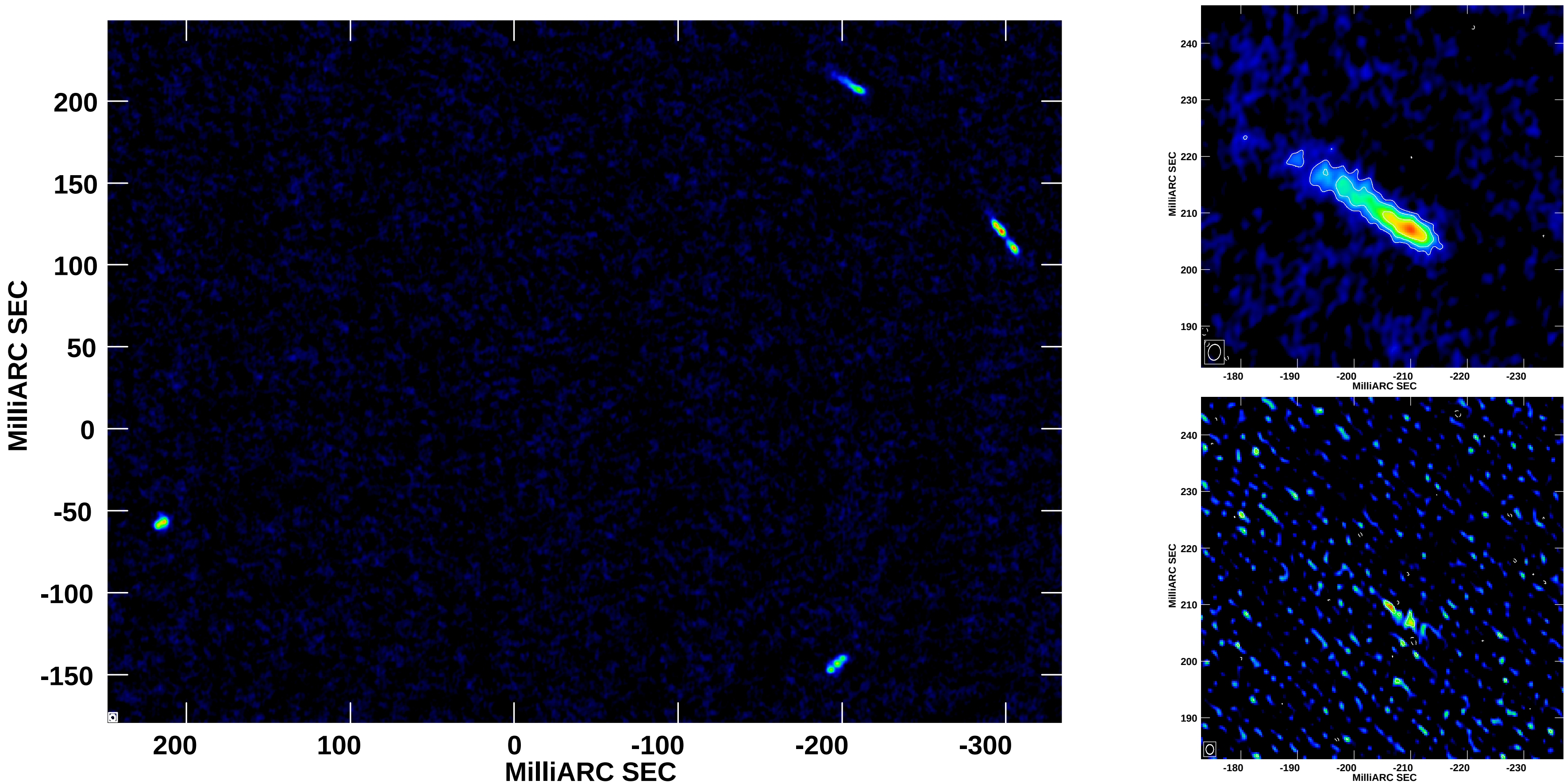
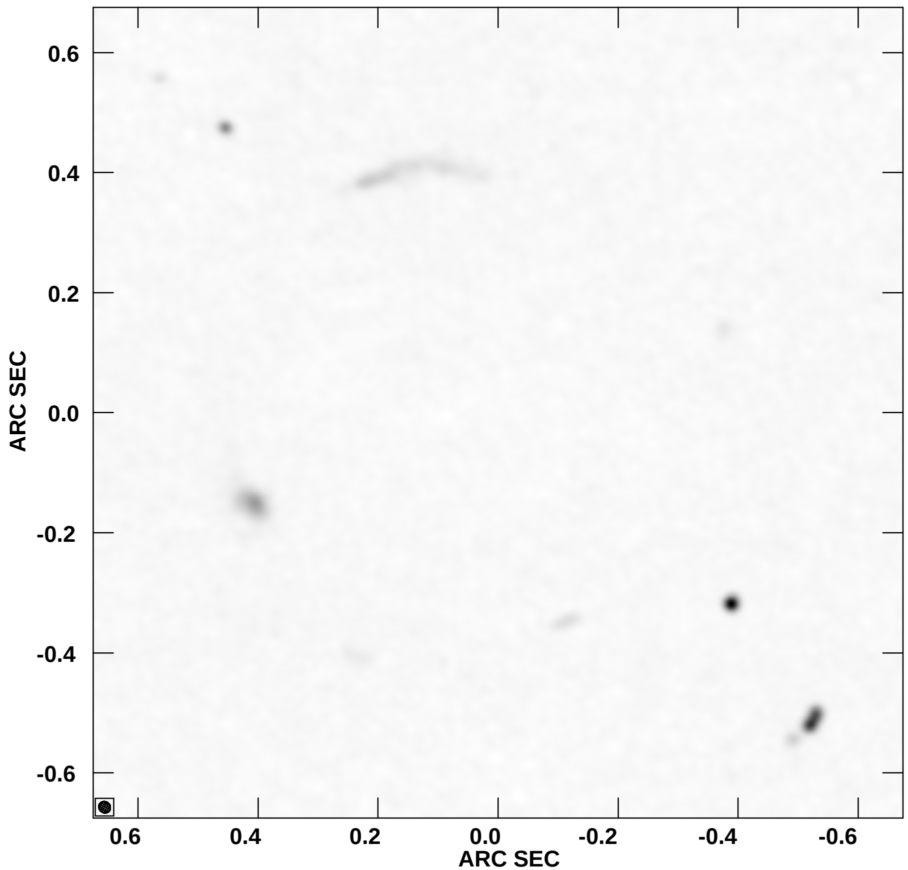


(Biggs et al., submitted)

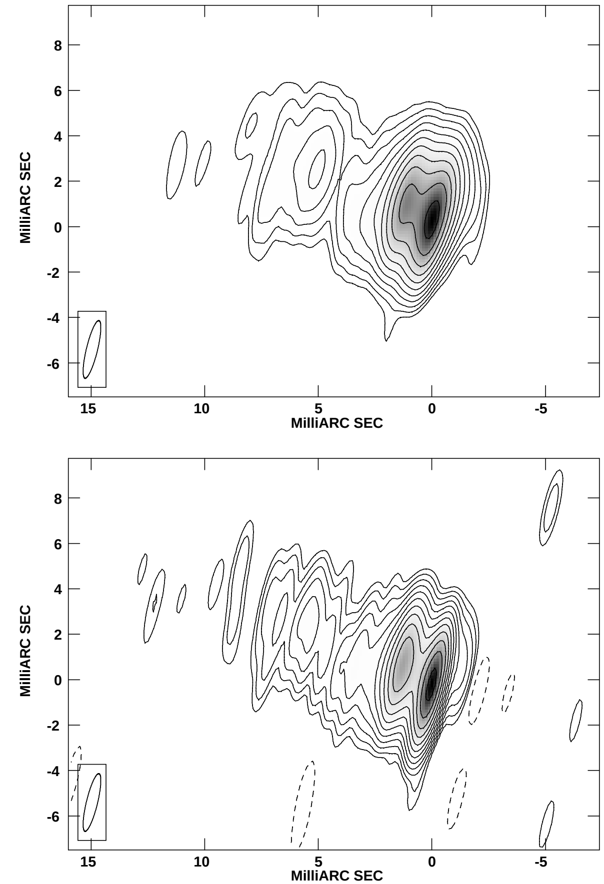
- Data indicate that image B is significantly more extended

More scatter-broadening

CLASS B1933+503



JVAS 0218+357



(Marlow et al. 98)

(Biggs et al. 03)

- Also PKS 1830-211, CLASS 1600+434 & PMN J0134-0931

Absorption line studies

Two of the four known high-redshift molecular absorption systems are lens systems (PKS 1830-211 and B0218+357)

HI absorption has been seen with VLBI in these systems

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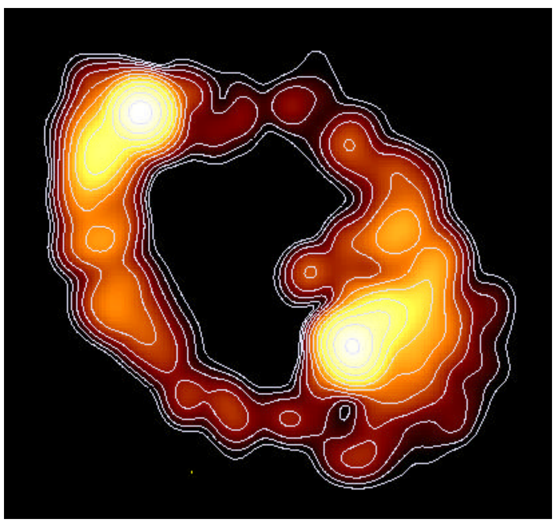
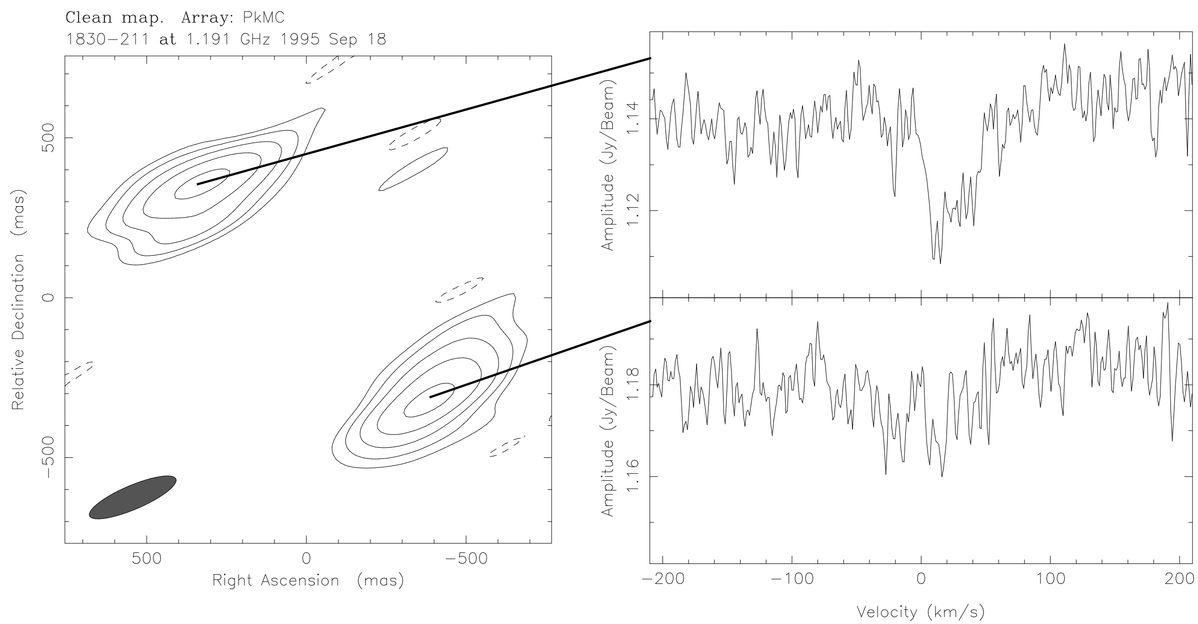
PKS 1830-211



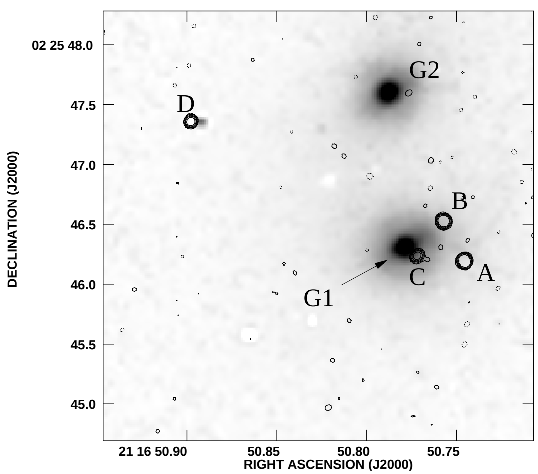


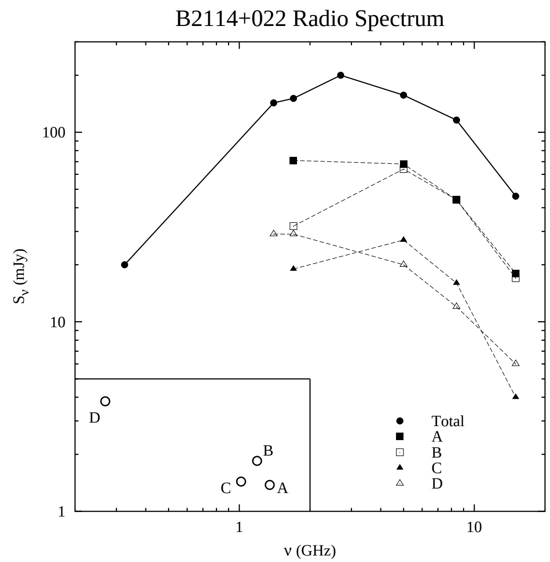
(Lovell et al. 96)

JVAS B2114+022: free-free absorption?

Four compact components detected with MERLIN/VLA

Two have flat radio spectra whilst the other two turnover at $\sim$5 GHz





(Augusto et al. 01)

JVAS B2114+022: free-free absorption?

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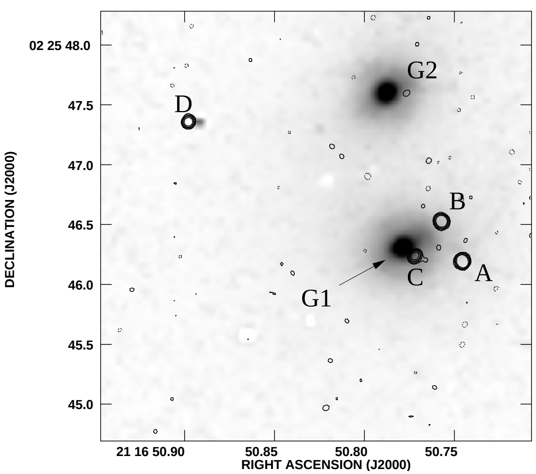

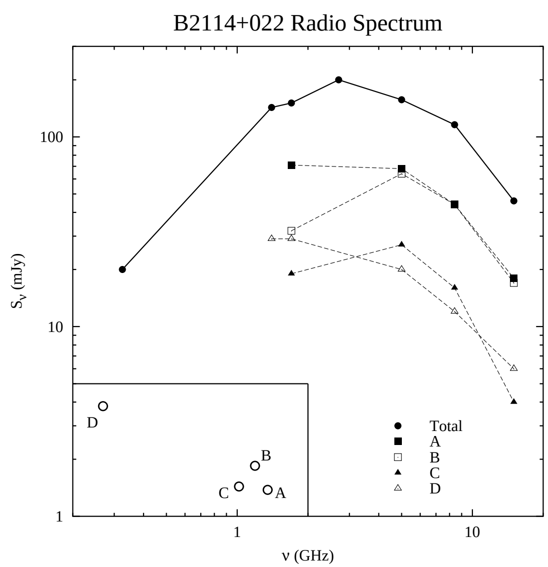

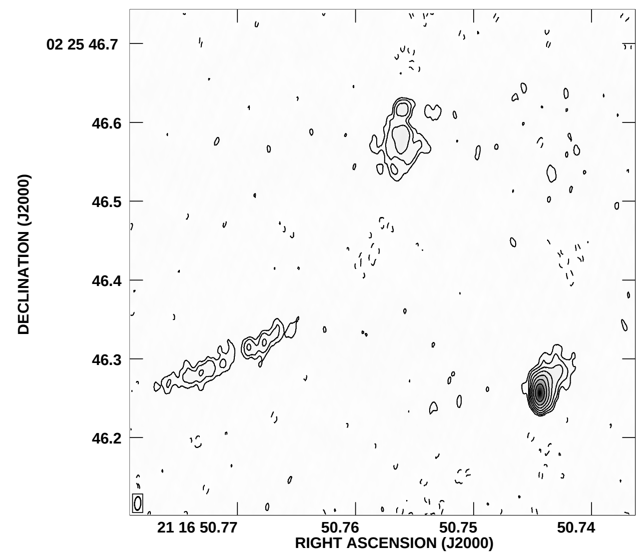

(Augusto et al. 01)

- VLBA observations reveal that peaked components are extended
- Galaxy G1 has a M82-esque spectrum

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The future

VLBI sensitivity is increasing rapidly e.g. MK5 @ 1 Gb s^{-1}

- More jet structure imaged
- More polarized emission detected
- VLBI structure found in future generation of fainter systems
- VLBI maps of Einstein rings?
- Odd images detected in more systems?
- Motion of jet sub-components?

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VLBI field of view is shortly going to explode!

- EVN PCInt project will result in mapping of full primary beam
- VLBI lens surveys will become much more efficient
- Lenses with separations < 0.3 arcsec