Gravitational lens surveys with LOFAR

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Abstract

Deep surveys planned as a Key Science Project of LOFAR provide completely new opportunities for gravitational lens searches. For the first time do large-scale surveys reach the resolution required for a direct selection of lens candidates using morphological criteria. We briefly describe the strategies that we will use to exploit this potential. The long baselines of an international *E*-LOFAR are essential for this project.

Introduction

Gravitational lensing is the best method to determine the mass distribution of distant galaxies with high accuracy. With a large sample of lens systems at a range of redshifts, we can study not only the structure but also the evolution of galaxies. We identify three main topics, in which lensing can help to resolve controversial problems.

- Most galaxies at moderate redshifts seem to have very close to isothermal ($\rho \propto r^{-2}$) mass distributions. Why is this the case, and does it also hold for higher redshifts?
- How does the *central* density profile of galaxies look like? Do they have cores or cusps, how do masses of central black holes evolve?
- Are small sub-halos as abundant as predicted by the CDM structure formation scenario (see Fig. 1)?

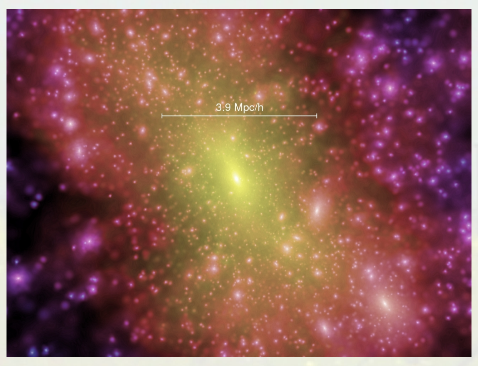

Fig. 1: Radio lenses with extended sources can be used to detect substructure in galaxies, which is expected from structure formation simulations (image from Springel et al., 2005). The statistics of substructure provides information about the properties of dark matter.

We can help answering these questions by modelling the mass distributions to fit for the structure of gravitationally lensed sources. In order to obtain information about the complete mass distribution, lensed *extended* sources like the ones shown in Fig. 2 should be used and modelled with LensClean (Wucknitz, 2004). There are several advantages in using radio observations. Most important is the wide range of resolutions that can be achieved with radio arrays. Another important advantage is that microlensing and propagation effects can usually be neglected at radio wavelengths. So far we know less than 50 radio lenses, whilst the number of optical lenses has grown well above that and is increasing further. We should catch up with them and take the lead again!

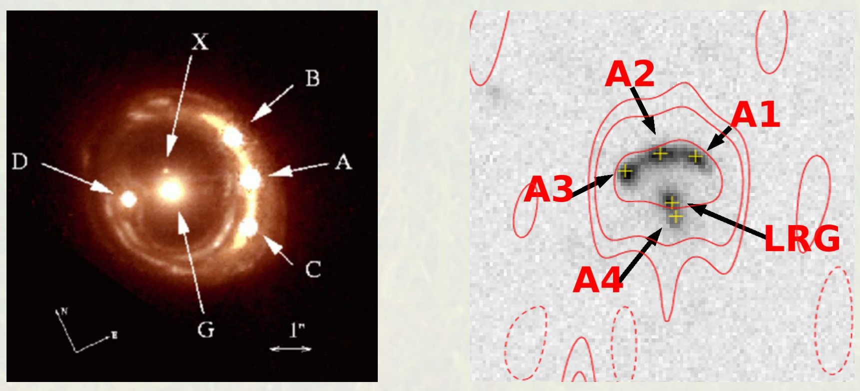

Fig. 2: Two examples from the bright end of typical lens systems expected to be found in LOFAR surveys. The fraction of star-burst galaxies (and other extended sources) will be higher than in the previous survey CLASS. Left: RXS J1131–1231 (HST image from Claeskens et al., 2006), a lensed star-forming galaxy at $z = 0.658$ with a quadruply imaged Seyfert core. Right: The "8 o'clock arc". At $z = 2.73$ this is the brightest known Lyman break galaxy (Allam et al., 2007). WSRT (4 h at 5 GHz) superimposed upon SDSS colour image. Deeper VLA-B observations are scheduled for November 2007.

New lens surveys

Source-targeted search

As shown in Tab. 1, LOFAR (see Fig. 3) not only probes a new frequency range but also new parameter space in terms of resolution and sensitivity of wide-area radio surveys. With these surveys, it is for the first time possible to identify lens systems directly from the source surveys using morphological criteria. In previous surveys, follow-up observations of complete source samples were necessary (Myers et al., 2003; Browne et al., 2003). This previous approach would be prohibitive for the extreme number of sources expected in LOFAR surveys.

Fig. 3: A small part of the low-band antenna fields in the LOFAR core near Exloo (Netherlands). Photo taken in April 2007.

The expected lensing rates for this source population is 1:2000, leading to potential numbers of 400 000 and 15 000 lenses in the LOFAR surveys at 120 and 200 MHz, respectively. Because of sensitivity and resolution limitations, we will be able to identify only a small fraction of these lenses. At 200 MHz, 900 lenses are a more realistic number, for which we probably have to follow-up around 10 000 candidates with the EVLA and/or *e*-MERLIN. At 120 MHz, longer baselines will be needed to detect more than just the systems with the largest image separations (see Fig. 4).

A good fraction of the LOFAR sources will be star-bursts galaxies, and the majority will have extensions and structures exactly on the scale that is needed for accuracte lens models. We can thus build the perfect sample for the study of the structure and evolution of galaxies.

survey array	frequency rms/flux limit	area definition	number of sources density	resolution (400 km)
LOFAR-120	120 MHz 14/43 μJy	half-sky	860×10^6 42 000/ deg^2	1.″3
LOFAR-200	200 MHz 4.7/14 μJy	250 deg^2	30×10^6 120 000/ deg^2	0.″8
FIRST, VLA B	1.4 GHz 0.15/1 mJy	galactic caps 9 033 deg^2	811 000 90/ deg^2	5″
NVSS VLA D/DnC	1.4 GHz 0.45/2.5 mJy	$\delta > -40°$	1.8×10^6 53/ deg^2	45″
WENSS+WISH WSRT	330 MHz 4/18 mJy	$\delta > +30°$ $-26° < \delta < -9°$	230 000 22/ deg^2	$\geq$ 60″
VLSS VLA BnA/B	74 MHz 0.1/0.5 Jy	$\delta > -30°$	~90 000 3/ deg^2	80″

Tab. 1: Comparison of two planned LOFAR surveys (pre-descope planning, 400 km baseline) with the most relevant existing radio surveys.

Lens-targeted search

There are more efficient ways of finding lens systems than to scan through a whole LOFAR catalog of hundreds of millions of sources. Luckily our colleagues from the optical community are providing large catalogues of medium-redshift galaxies which are potential lenses. By cross-correlating these galaxy catalogues with the LOFAR source catalogues, we can establish a large sample of lens systems with well-defined selection criteria for the lens galaxies. Combining the *Luminous Red Galaxies* (LRG) from the SDSS with the 120 MHz LOFAR survey, we expect to find about 500 lenses in 5000 candidates. With upcoming larger galaxy surveys, this number can be significantly increased.

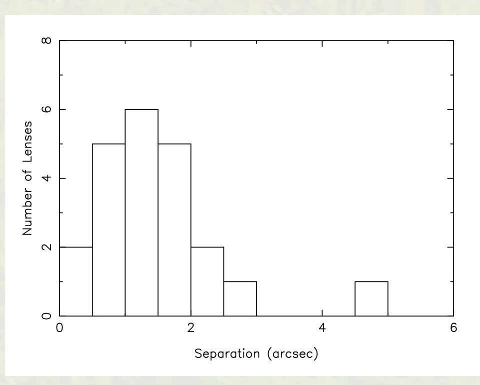

Fig. 4: Histogram of image-separations in CLASS (Browne et al., 2003). The majority of lenses would be only marginally resolved by a 400 km LOFAR. This means that we are in a regime where even small improvements of the resolution result in a significant gain for lens surveys.

Limitations

Even with additional stations in neighbouring countries, the resolution of LOFAR will be sufficient to securely identify only lenses with relatively large separations. Fig. 5 shows the dirty beams expected for three different international *E*-LOFAR arrays. We see that a good number of international stations is not only required for the resolution but also for good mapping properties, which is confirmed by simulations of an unlensed radio source and a lensed star-burst galaxy shown in Fig. 6.

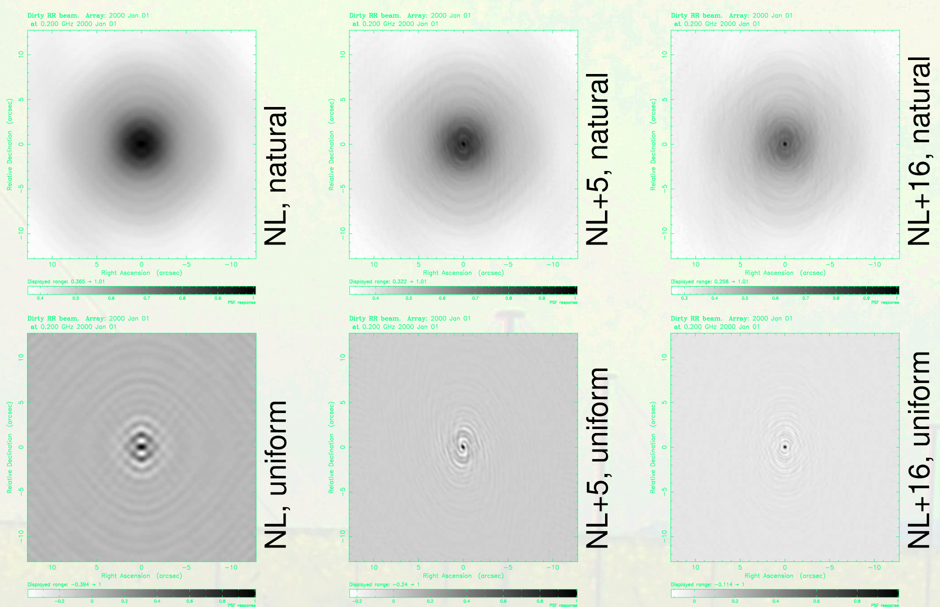

Fig. 5: Simulated dirty beams (long track, natural and uniform weighting) for a LOFAR consisting of (a) only Dutch stations, (b) NL plus 3 in Germany, (c) NL plus 7 in Germany, 4 in the UK, 2 in France and one each in Italy, Sweden and Poland.

The recently announced de-scope of LOFAR will modify the expectations for the lens surveys. Very roughly, a drop in sensitivity by a factor of 2 will lead to a reduction in the number of lenses by the same factor. Realistic expectations will depend on the adapted survey strategy and the number of international stations. We mostly need the sensitivity on long baselines, so that the reduction of the Dutch LOFAR can be compensated by more international stations. This would at the same time make calibration easier and improve the mapping quality.

More international stations are thus highly welcome!

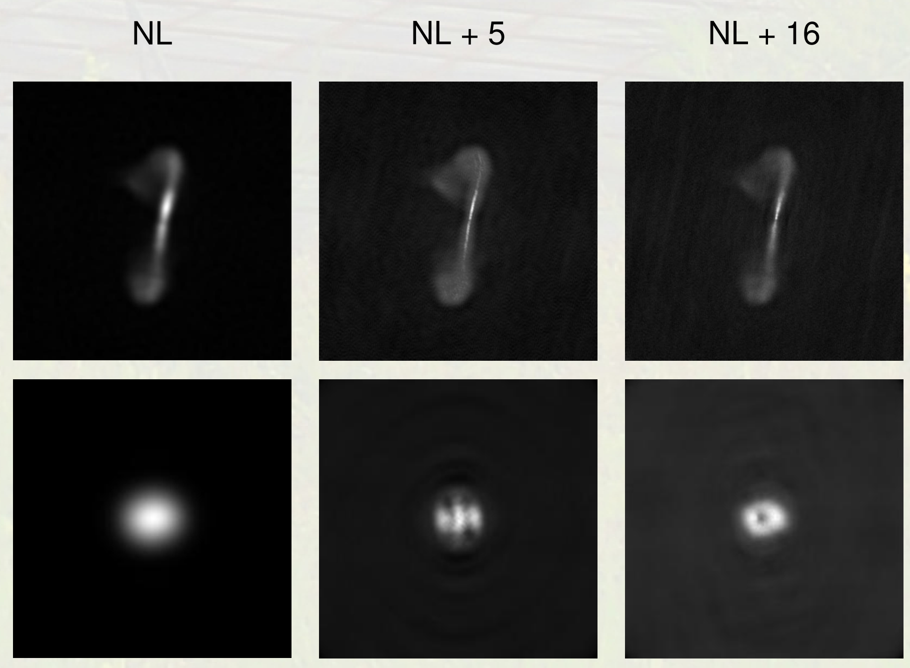

Fig. 6: Simulated Clean maps of an unlensed FRI radio source (top) and (with different scale) a lensed star-burst galaxy (bottom). The full international array is needed to properly resolve and map the lensed source.

Acknowledgments

This work is supported by the EC FP6 Marie Curie Research Training Network Programme, Contract No. MRTN-CT-2004-505183 "ANGLES", and by the Emmy-Noether-Programme of the 'Deutsche Forschungsgemeinschaft', reference WU 588/1-1.

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