COSMOGRAIL: the COSmological MOnitoring of GRAvItational Lenses. IX: Time delays, lens dynamics and baryonic fraction in HE 0435-1223

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Abstract: We present accurate time delays for the quadruply imaged quasar HE 0435-1223. The delays were measured from 575 independent photometric points obtained in the R-band between January 2004 and March 2010. With seven years of data, we clearly show that quasar image A is affected by strong microlensing variations and that the time delays are best expressed relative to quasar image B. We measured Δt_{BC} = 7.8 ± 0.8 days, Δt_{BD} = -6.5 ± 0.7 days and Δt_{CD} = -14.3 ± 0.8 days. We spacially deconvolved HST NICMOS2 F160W images to derive accurate astrometry of the quasar images and to infer the light profile of the lensing galaxy. We combined these images with a stellar population fitting of a deep VLT spectrum of the lensing galaxy to estimate the baryonic fraction, fb, in the Einstein radius. We measured fb = 0.65-0.10+0.13 if the lensing galaxy has a Salpeter IMF and fb = 0.45-0.07+0.04 if it has a Kroupa IMF. The spectrum also allowed us to estimate the velocity dispersion of the lensing galaxy, ap = 222 ± 34 km s^-1. We used fb and ap to constrain an analytical model of the lensing galaxy composed of an Hernquist plus generalized NFW profile. We solved the Jeans equations numerically for the model and explored the parameter space under the additional requirement that the model must predict the correct astrometry for the quasar images. Given the current error bars on fb and ap, we did not constrain H0 yet with high accuracy, i.e., we found a broad range of models with 2 < 1. However, narrowing this range is possible, provided a better velocity dispersion measurement becomes available. In addition, increasing the depth of the current HST imaging data of HE 0435-1223 will allow us to combine our constraints with lens reconstruction techniques that make use of the full Einstein ring that is visible in this object. Based on observations made with the 1.2 m Euler Swiss Telescope, the 1.5 m telescope of Maidanak Observatory in Uzbekistan, and with the 1.2 m Mercator Telescope, operated on the island of La Palma by the Flemish Community, at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. The NASA/ESA Hubble Space Telescope data was obtained from the data archive at the Space Telescope Science Institute, which is operated by AURA, the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS-5-26555. Light curves are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A+536/A53

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COSMOGRAIL: the COSmological MOonitoring of GRAvitational Lenses

IX. Time delays and N-body realisations of the lens in HE 0435-1223

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\textbf{ABSTRACT}

We present accurate time delays for the quadruply imaged quasar HE 0435-1223, from the COSMOGRAIL collaboration. A new way of turning the delays into $H_0$ is proposed, using N-body realisations of the lensing galaxy. The delays are measured from 575 independent photometric points obtained in the R-band between January 2004 and March 2010. With 6 years of data, we clearly show that quasar image A is affected by strong microlensing variations and that the time delays are best expressed relative to quasar image B. We measure $\Delta t_{\text{BA}} = 8.4 \pm 2.1$ days, $\Delta t_{\text{BC}} = 7.8 \pm 0.8$ days and $\Delta t_{\text{BD}} = -6.5 \pm 0.7$ days. HST NICMOS2 F160W images are spatially deconvolved in order to derive accurate astrometry of the quasar images and to infer the light profile of the lensing galaxy. In combination with deep VLT spectroscopy of the lens, the HST images are used to estimate the baryonic fraction, $f_b$, in the Einstein radius. We measure $f_b = 0.65^{+0.13}_{-0.10}$ if the lensing galaxy has a Kroupa IMF and $f_b = 0.45^{+0.08}_{-0.07}$ if it has a Salpeter IMF. N-body realisations of the lensing galaxy are used to infer its dark matter profile, given the measured rest-frame stellar velocity dispersion, $\sigma_{\text{ap}} = 222 \pm 34$ km s$^{-1}$ and the baryonic fraction. These dynamical models and baryonic fraction are also required to match the lensing observables. We find that only the lensing galaxies with Kroupa IMF match all the data simultaneously. Using the time delays to estimate the Hubble constant under this assumption leads to $H_0 = 62^{+4}_{-3}$ km s$^{-1}$ Mpc$^{-1}$. While the relatively small formal error bars reflect the high potential of the method to provide an accurate estimate of $H_0$, the value itself might be revised when new observational constraints are available, in particular a high precision velocity dispersion measurement (or velocity dispersion profile) of the lens and a measurement of the external shear, from integral-field spectroscopy and/or deep X-ray images.

\textbf{Key words.} Gravitational lensing: time delay – Cosmology: Hubble constant – Galaxies: quasar: individual (HE 0435-1223)

1. Introduction

Determining accurately the expansion rate of the Universe, $H_0$, is important to scale the extragalactic distance ladder and to measure $w(z)$, the redshift evolution of the dark energy equation of state parameter (e.g., [Friedman et al. 2008]).

Some of the most popular methods in use to measure $H_0$ have recently been reviewed ([Friedman & Madore 2010]). The huge observational and theoretical efforts invested in this work have led to about 10% random errors. However, all these methods rely at some level on each other and are all based on the same local standard candles. In addition, the accuracy required on $H_0$ to measure $w(z)$ and $H(z)$ is of the order of 1% rather than 10% ([Hu 2005]; [Riess et al. 2009]). It is therefore of interest (i) to explore methods that are fully independent of any standard candle and (ii) to combine the different methods to further reduce the current error bar on $H_0$.

Strong gravitational lensing of quasars and the so-called “time delay method” in multiply imaged quasars is independent
of the traditional standard candles (Refsdal 1964) and is based on well understood physics: general relativity. However, it requires to measure the time delays from long-term photometric monitoring of the many lensed quasars, which has long been a serious observational limitation. While the attempts to measure accurate time delays have been numerous, only a few have been measured with an accuracy close to the percent (e.g., Goicoechea 2002; Vuissoz et al. 2008). In addition, the lens model necessary to convert time delays into \( H_0 \) often remains poorly constrained and hampers to break the degeneracies between the properties of the lensing galaxy and \( H_0 \). In the recent years, successful attempts have been made to constrain as much as possible the lens model in order to minimise the effect of these degeneracies (Suyu et al. 2009, 2010).

COSMOGRAIL, the COSmological MONitoring of GRAvItational Lenses, aims both at measuring precise time delays for a large sample of strongly lensed quasars, and at obtaining and using all necessary observations to constrain the lens models. The present paper describes the COSMOGRAIL results for the quadruply imaged quasar HE 0435-1223, using deep VLT spectra, deconvolved HST images and N-body realisations of the lensing galaxy.

HE 0435-1223 (\( \alpha(2000) : 04\,h\,38\,min\,14.9\,sec; \delta(2000) = -12^\circ 17' 14''.4 \)) was discovered by Wisotzki et al. (2000) during the Hamburg/ESO Survey (HES) for bright quasars in the southern hemisphere. It was identified two years later as a quadruply imaged quasar by Wisotzki et al. (2002). The redshift of the source is \( z_{\text{QSO}} = 1.689 \) (Wisotzki et al. 2000) and the one of the lens is \( z_l = 0.4546 \pm 0.0002 \) (Morgan et al. 2005). The quasar shows evidence for intrinsic variability which makes it a good candidate for determining the time delays between the different images. The local environment of the lensing galaxy has been studied in detail by Morgan et al. (2005) using the Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) and by Momcheva (2009) who finds that the lensing galaxy lies in a group of at least 11 members. The velocity dispersion of the group is \( \sigma \sim 496 \text{ km s}^{-1} \).

Analytical lens models of HE 0435-1223 are given by Kochanek et al. (2006), who also measure time delays from 2 years of optical monitoring: \( \Delta t_{\text{AD}} = -14.37^{+0.32}_{-0.35} \) days, \( \Delta t_{\text{AB}} = -8.00^{+0.73}_{-0.82} \) days, and \( \Delta t_{\text{AC}} = -2.10^{+0.78}_{-0.71} \) days. For a fixed \( H_0 = 72 \pm 7 \text{ km s}^{-1}\text{Mpc}^{-1} \) they found that the lensing galaxy must have a rising rotation curve at the position of the lensed images and a non-constant mass-to-light ratio. Moreover, high dark matter surface densities are required in the lens halo. New monitoring data of Blackburne & Kochanek (2010) analysed using a physically motivated representation of microlensing give time delays compatible with those of Kochanek et al. (2006), although these authors do not provide their measured values.

Fig. 1. Part of the field of view of the 1.2 m Swiss Euler telescope, with HE 0435-1223 visible in the center. The 4 PSF stars and the reference stars used to carry out the flux calibration are indicated.
comes from the fact that we have to assemble data coming from the pipeline described in Vuissoz et al. (2007). The main challenge to collaboration are treated with the semi-automated reduction pipeline.

The data from the three telescopes used by the COSMOGRAIL collaboration are treated with the semi-automated reduction pipeline described in Vuissoz et al. (2007). The main challenge comes from the fact that we have to assemble data coming from different telescopes: each camera has a different size, resolution and orientation on the plane of the sky.

The pre-reduction for each observing epoch consists of flat-fielding using master sky flats. The Euler image with the best seeing is taken as the reference frame in order to register all the different frames. This reference frame was taken on the night of the 11th of November 2005 and has a seeing of 0.82. Several reference stars are then chosen in the field of view (Fig. 1) in order to compute the geometrical transformations between the images. This transformation involves a spatial scaling and a rotation. The reference stars are also used to compute the relative photometric scaling between the frames taken at different epochs. Eventually, the L.A. Cosmic algorithm (van Dokkum 2001) is applied separately to every frame in order to remove cosmic rays. All images are checked visually in order to make sure that no pixel has been removed inappropriately, especially in the frames with good seeing.

The photometric measurements are carried out using “deconvolution photometry” with the MCS deconvolution algorithm (Magain et al. 1998). This software has been successfully applied to a variety of astrophysical problems ranging from gravitationally lensed quasars (Burud et al. 2000, 2002), to the study of quasar host galaxies (Letawe et al. 2008), or to the search for extrasolar planets using the transit technique (Gillon et al. 2007a,b). Image deconvolution requires accurate knowledge of the instrumental and atmospheric Point Spread Function (PSF). The latter is computed for each frame from the 4 stars labeled PSF 1-4 in Fig. 1. These stars are from 0 to 1 magnitude brighter than the quasar images in HE 0435-1223 and are located within 2' from the center of the field, hence minimizing PSF distortions.

As it does not attempt to achieve an infinite gain spatial resolution, the MCS algorithm produces deconvolved images that are always compatible with the adopted pixel size. This avoids both the apparition of deconvolution artifacts and allows us to carry out accurate photometry all over the field of view. Moreover, the deconvolved image is computed as the sum of extended nu-

![Stacked R-band](image)
![Deconvolved](image)

**Fig. 2.** Result from the simultaneous deconvolution of the ground-based frames. G is the lensing galaxy and G22 is its closest neighbour on the plane of the sky. The grey scale in the deconvolved image is set to display all light level above $3 \times \sigma_{sky}$. The resolution of the deconvolved image is 0.34 Full-Width-Half-Maximum (FWHM).

### Table 1. Summary of the optical monitoring data.

| Telescope          | Camera  | FoV     | Pixel | Period of observation | #obs. | Exp. time | Seeing | Sampling |
|--------------------|---------|---------|-------|-----------------------|-------|-----------|--------|----------|
| Euler C2           | 11' x 11' | 0.344   |       | Jan 2004 - Mar 2010   | 301   | 5 x 360s  | 1'.37  | 6 days   |
| Mercator MEROPE    | 6.5' x 6.5' | 0.190   |       | Sep 2004 - Dec 2008   | 104   | 5 x 360s  | 1'.59  | 11 days  |
| Maidanak SITE      | 8.9' x 3.5' | 0.266   |       | Oct 2004 - Jul 2006   | 26    | 10 x 180s | 1'.31  | 16 days  |
| Maidanak SI        | 18.1' x 18.1' | 0.266   |       | Aug 2006 - Jan 2007   | 8     | 6 x 300s  | 1'.31  | 16 days  |
| SMARTS ANDICAM     | 10' x 10'  | 0.300   |       | Aug 2003 - Apr 2005   | 136   | 3 x 300s  | 1'.80  | 4 days   |
| **TOTAL**          |         |         |       | Aug 2003 - Mar 2010   | 575   | 242.3 h   |        | 3.2 days |

2. Photometric monitoring

#### 2.1. Optical imaging

HE 0435-1223 was monitored during 7 years, from January 2004 to March 2010, through the R-band filter, using three different telescopes: the Swiss 1.2m Euler telescope located on the ESO La Silla site (Chile), the Belgian-Swiss 1.2m Mercator telescope located at the Roque de Los Muchachos Observatory, La Palma, Canary Island (Spain), and the 1.5m telescope located at the Maidanak Observatory (Uzbekistan). In addition we also use 136 epochs from the 2-year long monitoring of Kochanek et al. (2006), from August 2003 to April 2005, obtained with the ANDICAM camera mounted on the 1.3m Small and Moderate Aperture Research Telescope System (SMARTS) located at the Cerro Tololo Inter-American Observatory (CTIO) in Chile. A summary of the observations is given in Table 1. Note that for the SMARTS data, we use the published photometry, i.e., we do not reprocess the original FITS files using our own photometric pipeline.

#### 2.2. Image processing and deconvolution photometry

The data from the three telescopes used by the COSMOGRAIL collaboration are treated with the semi-automated reduction pipeline described in Vuissoz et al. (2007). The main challenge comes from the fact that we have to assemble data coming from different telescopes: each camera has a different size, resolution and orientation on the plane of the sky.

The photometric measurements are carried out using “deconvolution photometry” with the MCS deconvolution algorithm (Magain et al. 1998). This software has been successfully applied to a variety of astrophysical problems ranging from gravitationally lensed quasars (Burud et al. 2000, 2002), to the study of quasar host galaxies (Letawe et al. 2008), or to the search for extrasolar planets using the transit technique (Gillon et al. 2007a,b). Image deconvolution requires accurate knowledge of the instrumental and atmospheric Point Spread Function (PSF). The latter is computed for each frame from the 4 stars labeled PSF 1-4 in Fig. 1. These stars are from 0 to 1 magnitude brighter than the quasar images in HE 0435-1223 and are located within 2' from the center of the field, hence minimizing PSF distortions.

As it does not attempt to achieve an infinite gain spatial resolution, the MCS algorithm produces deconvolved images that are always compatible with the adopted pixel size. This avoids both the apparition of deconvolution artifacts and allows us to carry out accurate photometry all over the field of view. Moreover, the deconvolved image is computed as the sum of extended nu-
Fig. 3. R-band light curves of the four lensed images of HE 0435-1223 from December 2003 to April 2010. The magnitudes are given in relative units as a function of the Heliocentric Julian Day (HJD), along with their total 1σ error bars. The colour code indicates the telescope used to obtain each data point.
We use deep near-IR HST images of HE 0435-1223 in order to derive the best possible relative astrometry between the quasar images and the lensing galaxy in order to constrain the light distribution in the lensing galaxy. The data are part of the CASTLES project (Cfa-Arizona Space Telescope LEns Survey) and were acquired in October 2004 (PI: C.S. Kochanek) with the camera 2 of NICMOS, the Near-Infrared Camera and Multi-Object Spectrometer. They consist in four dithered frames taken through the F160W filter (H-band) in the MULTIACCUM mode with 19 samples and calibrated by CALNICA, the HST image

Table 3. Shape parameters for the lensing galaxy in HE 0435-1223. The position angle (PA) is measured positive East of North. The 1σ error bars (internal errors) are given in paren

Table 4. Relative astrometry of HE 0435-1223, as derived from the simultaneous deconvolution of all NIC2 frames. The 1σ error bars are the internal errors after deconvolution. We also measure the apparent magnitudes in the Vega system. For comparison, we show the results from Morgan et al. (2005) using HST/ACS images and from Kochanek et al. (2006) using HST/NIC2 images. The right ascension α and the declination δ are given in arcseconds relative to component A.

| ID   | This work | Morgan et al. (2005) | Kochanek et al. (2006) |
|------|-----------|----------------------|------------------------|
| A    | 0.        | 0.                   | 0.                     |
| B    | -1.4743 ± 0.0004 | +0.5518 ± 0.0006 | +0.5532 ± 0.0002 | +0.553 ± 0.001 |
| C    | -2.4664 ± 0.0003 | -0.6022 ± 0.0013 | -0.6033 ± 0.0002 | -0.603 ± 0.004 |
| D    | -0.9378 ± 0.0005 | -1.6100 ± 0.0006 | -1.6147 ± 0.0002 | -1.614 ± 0.001 |
| G    | -1.1706 ± 0.0030 | -0.5665 ± 0.0004 | -0.5723 ± 0.0002 | -0.573 ± 0.002 |

With the MCS software, dithered images of a given target can be “simultaneously deconvolved” and combined into a single deep and sharp frame that matches the whole dataset at once, given the PSFs and the noise maps of the individual frames. In doing this, the intensities of the point sources are allowed to vary from one frame to the next while the smooth background, which includes the lensing galaxy, is kept constant in all the frames. The result of the process is shown in Fig. 2, where the point sources are labeled as in Wisotzki et al. (2002). Prior information on the object to be deconvoluted can be used in order to achieve the best possible results. In the case of HE 0435-1223 the relative positions of the point sources are fixed to the HST astrometry obtained in Sect. 3.

Fig. 3 shows the deconvolution light curves obtained for each quasar image of HE 0435-1223, where the 1σ error bars account both for the statistical and systematic errors. The statistical part of the error is taken as the dispersion between the photometric points taken during each night. The systematic errors are estimated by carrying out the simultaneous deconvolution of reference stars in the vicinity of HE 0435-1223.

Finally, a small scaling factor is applied to the light curves of all telescopes, including the published light curves of Kochanek et al. (2006), in order to match the Euler photometry. These shifts are all smaller than 0.03 mag.

3. HST NICMOS2 imaging

We use deep near-IR HST images of HE 0435-1223 in order to derive the best possible relative astrometry between the quasar images and the lensing galaxy and in order to constrain the light distribution in the lensing galaxy. The data are part of the CASTLES project (Cfa-Arizona Space Telescope LEns Survey) and were acquired in October 2004 (PI: C.S. Kochanek) with the camera 2 of NICMOS, the Near-Infrared Camera and Multi-Object Spectrometer. They consist in four dithered frames taken through the F160W filter (H-band) in the MULTIACCUM mode with 19 samples and calibrated by CALNICA, the HST image
reduction pipeline. The total exposure time amounts to approximately 44 minutes and the pixel scale is 0′′.075652.

The MCS deconvolution algorithm is used to combine the four NIC2 frames into a deep sharp IR image. We follow the iterative technique described in Chantry et al. (2010) and Chantry & Magain (2007) which allows us to build a PSF in the absence of a stellar image in the field of view. The method can be summarised as follows. First, we estimate the PSF using Tiny timer software (Krist & Hook 2004) and we carry out the simultaneous deconvolution of the 4 F160W frames using a modified version of the MCS software (Magain et al. 2007). This produces a first approximation of the extended channel of the deconvolved image, i.e., the lensing galaxy and the lensed quasar host galaxy. We reconvolve the latter by the PSF and we subtract it from the original data. A new estimate of the PSF is built on the new image, that now contains only the quasar images. The process is repeated until the residual image is satisfactory (see Chantry et al. 2010, for more details). Fig. 4 shows the result. In this image the pixel size is half of that of the original data and the resolution FWHM is 0′′.075, unveiling an almost full Einstein ring.

In the finally deconvolved image, the lensing galaxy is modelled analytically rather than numerically in order to minimised the number of degrees of freedom. We find that the best-fit profile is an elliptical de Vaucouleurs, which is not surprising: the spectrum obtained by Eisenhauer et al. (2006), displays the characteristics of an S0 galaxy. The shape parameters of the lensing galaxy are summarised in Table 3 and the astrometry of the quasar images is given in Table 2. The astrometry is corrected from the known distortions of the NIC2 camera, as well as from the difference of pixel scale between the x and y directions. Based on our previous work using deconvolution of NICMOS images (Chantry & Magain 2007), we estimate that the total error bars, accounting for residual correction of the distortions amounts to 2 milliarcseconds. Our results agree well with previous measurements from HST/ACS (Morgan et al. 2005) or HST/NIC2 imaging (Kochanek et al. 2006), also shown for comparison in Table 2.

4. Time delay measurement

Our method to measure the time delays is based on the deconvolution technique of Pelt et al. (1996): the light curves are shifted in time and in magnitude to minimise a global dispersion function. This is done by adding low order polynomials to either the full curves or on specific observing seasons. Pelt et al. (1996) defines several dispersion statistics between pairs of light curves. We implement a dispersion estimate similar to (see eq. 8 of Pelt et al. 1996), but that performs a linear interpolation between points over a maximum range of 30 days. In the case of four light curves, we define a total dispersion which is the sum of the dispersions computed using the 12 possible permutations of two curves among four. This avoids the arbitrary choice of a reference light curve. The photometric error bars are taken into account to weigh the influence of the data points in the dispersion. We then minimise the total dispersion by modifying the time delays and the microlensing polynomials. Simulated light curves that mimic the observed photometric variations are eventually used to estimate the robustness of the method.

The error bars on the time delays are calculated using Monte Carlo simulations, i.e., redistributing the magnitudes of the data points according to their photometric error bars. The width of the resulting time-delay distributions gives us the 1σ error bars.

Due to microlensing, we do not have access to the intrinsic variations of the source quasar. We represent microlensing in 3 of the light curves as a relative variation with respect to the fourth light curve, taken as a reference. We test in turn each of the 4 light curves as a reference and we keep the one that minimises the residual microlensing variations to be modeled in the 3 other ones. This is best verified with component B as a reference.

With B as a reference light curve, we note that microlensing in C and D remains smooth and can therefore be modeled with a low order polynomial drawn over the full length of the monitoring. However, A contains higher frequency variations that need to be accounted for in each season individually, as illustrated in Fig. 5. In doing this, we obtain an almost perfect fit to the light curves, as shown in the residual signal in Fig. 5.

We test the robustness of the method in several ways. First, we model the microlensing variations using polynomial fits of different orders. Second we fit these polynomials either across each individual season or across groups of seasons. Finally, we mask the seasons with the worst residual signal (Fig. 5). All these changes have negligible impact on the time delay measurements. We note that this is not the case when considering only 2 or 3 seasons of data, hence showing the importance of a long-term monitoring with good temporal sampling.

Our results are summarised in Table 4 and compared with the previous measurements of Kochanek et al. (2006) who use pure polynomial fit to the light curves and 2 seasons of monitoring. Using the same data but with our modified dispersion technique, we obtain very similar time delays as Kochanek et al. (2006), but larger error bars. We prefer keeping a minimum possible number of degrees of freedom (e.g. in the polynomial order used to represent microlensing), in accordance with “Occam’s razor” principle, even to the cost of apparently larger formal error bars.

We also note that Kochanek et al. (2006) give their time delays with respect to A, which, with 7 seasons of data, turns out to be the most affected by microlensing. As a consequence the error bars on these time delays are dominated by residual microlensing rather than by statistical errors. The time delays used in the rest of our analysis are therefore measured relative to B.

Finally, we use the mean values of our microlensing corrections to estimate the macrolensing R-band flux ratios between the four quasar images, assuming that no long-term microlensing affects the data. We find that the mean of the data is 0.62 ± 0.04, and which is well compatible with the ratios measured at 7 wavelengths by Mosquera et al. (2010). However, these authors report significant wavelength dependence of the image flux ratios, which leads us not to use flux ratios as a constraint in the lens models.

5. Constraints on the lensing galaxy

The goal of the present work is to constrain as much as possible the model of the lensing galaxy in HE 0435-1223. In order to do so, we use deep optical spectra of the lensing galaxy to measure the stellar mass-to-light ratio and the stellar velocity dispersion. We use these data to interpret numerical N-body simulations of the lensing galaxy.
Fig. 5. The lightcurves obtained with all 4 telescopes and shifted by time delays of $\Delta t_{BA} = 8.4$ days, $\Delta t_{BC} = 7.8$ days and $\Delta t_{BD} = -6.5$ days. The relative microlensing representations applied on curves A, C and D are shown as continuous curves, with respect to the dashed blue line (see text). A fifth order polynomial is used over the 7 seasons to model microlensing on the quasar images C and D, while 7 independent third order polynomials are used for image A. The lower panels show residuals obtained by subtracting a simultaneous spline fit (grey) from the light curves.

Table 4. Time delays for HE 0435-1223, with the same arrival order convention as Kochanek et al. (2006), i.e., D arrives last.

| Data            | Method       | $\Delta t_{AB}$ | $\Delta t_{AC}$ | $\Delta t_{AD}$ | $\Delta t_{BC}$ | $\Delta t_{BD}$ | $\Delta t_{CD}$ |
|-----------------|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| SMARTS (2 seasons) | Kochanek (2006) | $-8.0 \pm 0.8$  | $-2.1 \pm 0.8$  | $-14.4 \pm 0.8$ | -                | -                | -                |
| SMARTS (2 seasons) | dispersion   | $-8.8 \pm 2.4$  | $-2.0 \pm 2.7$  | $-14.7 \pm 2.0$ | $6.8 \pm 2.7$  | $-5.9 \pm 1.7$  | $-12.7 \pm 2.5$ |
| COSMOGRAIL (7 seasons) | dispersion | $-8.4 \pm 2.1$  | $-0.6 \pm 2.3$  | $-14.9 \pm 2.1$ | $7.8 \pm 0.8$  | $-6.5 \pm 0.7$  | $-14.3 \pm 0.8$ |

5.1. Stellar population and velocity dispersion of the lensing galaxy

A deep VLT spectrum of the lensing galaxy is available from Eigebrodt et al. (2006). While the spectrum was originally used to measure the redshift of the galaxy, it turns out to be deep enough to measure its stellar mass-to-light ratio as well as its velocity dispersion.

We perform the spectral fit using the PEGASE-HR Single Stellar Population models (SSP, Le Borgne et al. 2004). The models are built using the Elodie.3.1 (Prugniel & Soubiran 2001; Prugniel et al. 2007) spectral library and the Kroupa (Kroupa 2001) and Salpeter (Salpeter 1955) Initial Mass Functions (IMF). We obtain SSP-equivalent ages and metallicities of $\sim 3$ Gyr and $\sim 0.0$ dex respectively. The corresponding rest-frame B-band stellar mass-to-light ratio is $M_*/L_B = 3.2^{+0.3}_{-0.2}$ using a Kroupa IMF and $M_*/L_B = 4.6^{+0.9}_{-0.7}$ using a Salpeter IMF.
Table 5. Model parameters used in the N-body simulations. For the variables used as parameters the ranges of values used are given between brackets.

| Parameter | Value |
|-----------|-------|
| $R_{\text{eff}}$ | 8.44 kpc |
| $R_\kappa$ | 6.66 kpc |
| $f_b$ | baryonic fraction in the Einstein radius [0.05 – 0.5] |
| $r_\star$ | 5.3 kpc |
| $M_\star, M_b f_b/(1 - f_b)$ | stellar component scaling radius |
| $r_{\text{max}}$ | stellar truncation radius |
| $\gamma_{DM}$ | parameter |
| $\gamma_{DM}$ | dark matter inner slope [0 – 2] |
| $r_h$ | dark matter scaling radius [1, 2, 4, 8] $\times R_\kappa$ |
| $M_h$ | dark matter total mass [4.8 $\times 10^{11}$ – 9.1 $\times 10^{12}] M_\odot$ |
| $r_{h, \text{max}}$ | dark matter truncation radius |

To compute the physical velocity dispersion we subtract quadratically the instrumental broadening from the measured profile, neglecting the dispersion of the models since they are based on high resolution templates. The instrumental broadening is measured both from the PSF stars used to carry out the spatial deblending of the spectrum (Eigenbrod et al. 2006) and from the lamp spectra. We obtain the rest-frame physical stellar velocity dispersion of the lensing galaxy: $\sigma_{ap} = 222 \pm 34$ km s$^{-1}$ in an aperture of 1″, i.e., 5.7 kpc.

5.2. N-body modeling of the lensing galaxy

Most of the uncertainty on $H_0$ from the time delay technique comes from the so-called “mass-sheet degeneracy”, i.e., the degeneracy between $H_0$ and the slope of the total mass density of the lensing galaxy. In this section, we use N-body simulations to model the lensing galaxy and to minimise the range of possible mass slopes that fit equally well the lensing constraints. These N-body models must account for the observed stellar mass-to-light ratio of the lensing galaxy, and for its velocity dispersion. In addition, they are required to be dynamically stable.

In the N-body realisation, we model the lens galaxy mass distribution by two spherical components: one for the luminous part of the galaxy, the stars, and the other one for the dark matter halo. The assumption of spherical symmetry is sufficient for our purpose, as illustrated by the study of MG 2016+112 by Koopmans & Treu (2002) where the authors introduce an anisotropy parameter and show that it has almost no influence on the inferred mass slope.

The luminous component is modeled by a Hernquist profile (Hernquist 1990):

$$\rho_\star(r) = \frac{\rho_\star(0)}{(r/r_\star)(1 + r/r_\star)^3}$$

where $\rho_\star(0)$ is the central density and $r_\star$ is a scaling radius chosen so that the integrated mass in a cylinder of radius $R_{\text{eff}}$ (effective radius) is equal to half the total stellar mass $M_\star$. The profile has a maximum radius of $r_{\text{max}} = 20 r_\star$. The dark matter halo is modeled as a generalised Navarro, Frenk & White (NFW) profile (Navarro et al. 1997):

$$\rho_h(r) = \frac{\rho_h(0)}{(r/r_s)[1 + (r/r_s)^2]^{(3 - \gamma_{DM})/2}}$$

where $\gamma_{DM}$ is the inner slope of the profile, $r_s$ is the scaling radius and $\rho_h(0)$ is the central mass density. For $\gamma_{DM} = 1$ the model follows closely the standard NFW profile. The total mass of the dark matter halo, $M_h$, is given in the truncation radius $r_{h, \text{max}} = 10 r_s$.

Following the usual convention, the dark matter total mass and the stellar total mass are related by the baryonic fraction $f_b$:

$$f_b = \frac{M_\star}{M_h + M_\star}$$

Note that the N-body realisations of the lensing galaxy allow us to compute $f_b$ in any aperture. We choose to compute it in the Einstein radius, which is where we also have the best estimate of the total mass. The velocity dispersion of the stellar component is computed by solving the second moment of the Jeans equation in spherical coordinates (Binney & Merrifield 1998). The velocity dispersion is then:

$$\sigma_\star^2(r) = \frac{1}{\rho_\star(r)} \int_0^\infty dr' \rho_\star(r') \partial_r \Phi(r')$$

where $\Phi(r')$ is the total gravitational potential. Equation (4) is solved numerically as follows. First, the density of each mass component (stars and dark halo) is sampled by N particles, using a Monte-Carlo method. Second, the potential is computed using a treecode method (Barnes & Hut 1986). For self-consistency, the density is taken from the N-body representation, by binning the particles in spherical shells. Then, a velocity following a Gaussian distribution of variance $\sigma_\star(r)$ is allocated to each particle at a distance $r$ from the galaxy center. Finally, the velocity dispersion is computed numerically, by integrating all the particle velocities in an aperture that matches exactly the slit used to carry out the observations.

The advantages of N-body models are multiple. They allow us: (i) to compute velocity dispersions for any combination of density profiles, even non-parametric ones, (ii) to account for the truncation radius of the halo, (iii) to test the dynamical equilibrium of the system by evolving the model with time. Computing the velocity dispersion as well as the total mass in a cylinder along the line of sight of the observer is then straightforward.

In the N-body simulations, we fix the effective radius to the one observed for the lensing galaxy, i.e., $R_{\text{eff}} = 8.44$ kpc. The remaining parameter space to explore is composed of the halo scale radius, $r_s$, the total halo mass $M_h$, the slope of the profile, $\gamma_{DM}$, and the baryonic fraction, $f_b$, within the Einstein radius.

Using our HST photometry, we measure the total rest-frame B-band galaxy luminosity, by converting its total H-band magnitude, $m_{B_{\text{H-band}}} = 16.20$, using a $k$-correction of 1.148, and a galactic extinction $A_B = 0.059$ (Schlegel et al. 1998). The observed rest-frame B-band luminosity is then $L_B = 1.04 \times 10^{11} L_{B,\odot}$. For every galaxy model we can therefore compute

1 A galactic extinction calculator is available at this address: http://nedwww.ipac.caltech.edu/forms/calculator.html
Fig. 6. Results of the N-body realisations for 6 values of $r_s$, the scale radius of the dark matter halo of the lensing galaxy. Each plot shows the $\chi^2_{NB}$ value of the model (Sect. 5.2) as a function of the stellar mass for 960 000 simulated galaxies. From top to bottom and from left to right the values for the dark matter scale radius are $r_s = 0.5 \times R_E$, $1 \times R_E$, $2 \times R_E$, $4 \times R_E$, $8 \times R_E$, and $16 \times R_E$. The colour code shows the slope, $\gamma_{DM}$, of the dark matter halo. The models with the smallest possible $\chi^2_{NB}$ are obtained for $r_s = 4 \times R_E$. 
the total stellar mass-to-light ratio, \( M_*/L_B \), as well as the baryonic fraction that we can compare with the observed ones.

In order to estimate the baryonic fraction from the VLT spectra, we need to assume an IMF. For a Salpeter IMF we measure \( f_b = 0.65^{+0.13}_{-0.16} \) while for a Kroupa IMF we measure \( f_b = 0.45^{+0.04}_{-0.07} \).

We compare the model properties to the data by computing a \( \chi^2_{NB} \) for each galaxy model. This \( \chi^2_{NB} \) includes the measured lens velocity dispersion and the total mass in the Einstein radius. The latter is \( M(< R_E) = (3.16 \pm 0.31) \times 10^{11} M_\odot \), where \( R_E = 6.66 \) kpc. We allow for a 10% error on the total mass in the Einstein radius in order to account for the weak dependence of this mass upon the choice of a lens model.

5.3. Constraints from the N-body simulations

Some of the parameters describing the N-body simulations are well constrained by the HST observations presented in Sect. 3. The others must be explored within realistic ranges, as summarised in Table 3.

Since the number of parameters to explore is large we cannot realistically explore all of them. We therefore choose to fix the scale radius, \( r_s \), of the dark matter halo. In order to make our choice in an objective way, we build N-body models for a set of 6 different values of the scale radius, \( r_s = 0.5x \), 1x, 2x, 4x, 8x, and 16x\( R_E \). For each one we compute 960 000 galaxy models as well as their \( \chi^2_{NB} \) as defined in Sect. 5.2.

The results are displayed in Fig. 6 where the best \( \chi^2_{NB} \) are obtained for \( r_s = 4 \times R_E \), i.e., the fourth panel of the Figure. For this fixed value of \( r_s \) we explore all other model parameters, i.e., \( M_*, \gamma_{DM}, M_b \). The results are summarised in Fig. 7 which gives, for each model, the theoretical total \( M_*/L_B \) and compares it with the observed one for a range of realistic baryonic fractions measured in the Einstein radius.

It is clear from Fig. 7 that for a given IMF and baryonic fraction, fixing \( M_*/L_B \) constrains well the dark matter slope, \( \gamma_{DM} \), which is the goal of the N-body simulations. This turns out to be particularly important since we do not know a priori whether the lens is the central galaxy of a group or a satellite (Momcheva et al. 2009) and since the dark matter slope, \( \gamma_{DM} \), depends on the environment of the galaxy (e.g., Limousin et al. 2009, 2007; Dobke et al. 2007). We use this constraint in the following Section in combination with lens models in order to measure \( H_0 \) from our new time delay measurements.

6. Lens modeling

We now use the results of the previous sections to constrain the lens models for HE 0435-1223. Three modeling tools are used: (i) non-parametric modeling using a pixelated representation of the lensing galaxy (Williams & Saha 2000), (ii) semi-linear lens inversion (Warren & Dye 2003), (iii) fully parametric models, as implemented by (Keeton 2004) as the gravlens software. The two former tools are used to derive the large-scale shape (ellipticity, position angle) of the lensing galaxy. We use the gravlens software in combination with N-body galaxy simulations in order to compute \( H_0 \) under the requirement that the models with the best \( \chi^2_{NB} \) also account well for the configuration of the quasar images.

6.1. Non-parametric modeling

The fully non-parametric lens models of Williams & Saha (2000) offer an easy way to explore the parameter space. In these models, the lensing galaxy is pixelated and no prior information is used on its shape. The data to be fitted include the time delays (relative to B) and the astrometry of Table 2. The model can also account for intervening galaxies along the line of sight. Galaxies G12, G19, G22 of Morgan et al. (2005) are therefore included explicitly in the potential well. Since they are angularly far away from HE 0435-1223 we represent them as point masses.

The resulting lensing galaxy is shown in Fig. 5 showing that the PA of the light and of the mass distributions follow well each other. The best models have a formal velocity dispersion (Leiet 2009) of about 220 km s\(^{-1}\). In addition, little external shear is required to fit the data. Using exclusively the lensing data, the inferred values for \( H_0 \) span a broad range, between 66 and 88 (1σ). This illustrates well the need for external constraints on the lensing galaxy, in addition to the lensing observables taken alone.

6.2. Semi-linear lens modeling

We apply the semi-linear inversion method of Warren & Dye (2003) to the deconvolved, point source subtracted ring image. The method exploits the extra constraints provided by the extended ring image, rather than just those provided by the four point source positions. At the heart of the method lies an efficient matrix inversion which solves for the source surface brightness distribution that gives the best fit to the observed lensed image for a given lens model. This linear step is carried out per trial lens image. The fully constrained system of linear equations is solved for the entire model of the lensing galaxy. We use the gravlens software in combination with N-body galaxy simulations in order to compute \( H_0 \) under the requirement that the models with the best \( \chi^2_{NB} \) also account well for the configuration of the quasar images.

For the observed ring in HE 0435-1223, we try two different smooth single component lens models: a singular isothermal ellipsoid (SIE) and a NFW profile (Navarro et al. 1996). This al-
Table 6. Minimised semi-linear lens model parameters (Sect. 6.2) and corresponding \( \chi^2 \). The NFW normalisation, \( \kappa_0 \), is expressed in arbitrary units. Model parameters are described in the text.

| Model          | \( \chi^2_{\text{min}} \) | NDOF | Minimised parameters |
|----------------|-----------------|------|---------------------|
| SIE            | 4724            | 4421 | \( \sigma_r = 252 \text{ km/s}, (x, y) = (0.04', -0.04'), \theta = -28', l = 1.49 \) |
| SIE+shear      | 4431            | 4419 | \( \sigma_r = 249 \text{ km/s}, (x, y) = (0.02', -0.04'), \theta = -33', l = 1.13, \gamma = 0.068, \theta_r = -24' \) |
| NFW            | 4699            | 4421 | \( \kappa_0 = 100.0, (x, y) = (0.06', -0.05'), \theta = -32', l = 1.18 \) |
| NFW+shear      | 4423            | 4419 | \( \kappa_0 = 98.6, (x, y) = (0.08', -0.06'), \theta = -33', l = 1.06, \gamma = 0.059, \theta_r = -18' \) |

![Fig. 8. Non-parametric model of the lensing galaxy. The large tick marks are 1' long. Note the good agreement between the PA of the model, PA = ± 170° and the PA measured in the HST images.](image)

![Fig. 9. Semi-linear reconstruction of the deconvolved HST image of Fig. 4 using the best fit NFW+shear lens model. Top Left: Observed masked image (original orientation). Top right: Reconstructed source showing image caustic. Bottom left: Image of reconstructed source. Bottom right: Significance of residuals = (observed image - model image)/error. Note that the orientation is the one from the original NICMOS frames, i.e., rotated by -175.5° with respect to the North. This is to avoid any interpolation before applying the method.](image)

6.3. Parametric modeling

The parametric models as implemented by Keeton (2004) are our main tool to explore the details of the mass distribution in HE 0435-1223 and to convert the time delays into \( H_0 \). We adopt a total potential well composed of the main lensing galaxy, the nearby galaxy G22 (see Morgan et al. 2005) plus an external shear.

The main galaxy is composed of a projected Hernquist + cuspy halo model identical to those used for the N-body simulations (eqs. 1 & 2). The angular scaling parameters are expressed in arcsec and the surface mass density is normalised by the critical surface density. For the Hernquist profile, we fix the ellipticity and PA of the lensing galaxy to the observed ones.

We then estimate how well each of the N-body realisations of the galaxy reproduces the observed image configuration and the time delays. In doing this, we allow only the shear (\( \gamma, \theta_r \)), the Einstein radius of G22 and \( H_0 \) to vary. The potential well of G22 is assumed to lie at its observed position and is modeled as a Singular Isothermal Sphere (SIS). We assume a conservative value of \( R_E(G22) \leq 0.4' \), following the results of Morgan et al. (2005) who find \( R_E(G22) = 0.18' \).
Fig. 10. Distribution of our N-body models as a function of the dark matter slope and $H_0$. The colour code represents $\chi^2_{NB}$. The results are shown for a Salpeter IMF in the left panel and for a Kroupa IMF in the right panel. The contours give the iso-$\chi^2$ limits, i.e., $\Delta \chi^2 = 0.25, 0.5, 1.0$. The lensing $\chi^2$ itself is not included in the Figure. However, it is systematically lower for galaxies with Kroupa IMFs than for galaxies with Salpeter IMFs.

7. Towards $H_0$ from HE 0435-1223

We show in Fig. 10 a summary of our results, where the value of $H_0$ is given for each of the N-body realization, as a function of the dark matter slope, $\gamma_{\text{DM}}$. The colour code in the figure corresponds to the value of $\chi^2_{\text{NB}}$, where the baryonic fraction is now included in the $\chi^2$ calculation. As the baryonic fraction depends on the choice of an IMF we show our results for the two most common IMFs in use in stellar population modeling, the Salpeter and the Kroupa IMFs.

The points define a $\chi^2_{\text{NB}}$ surface with a clear valley which minimum gives the best dark matter slopes for each IMF. These are $\gamma_{\text{DM}}(\text{Sal}) = 1.15$ and $\gamma_{\text{DM}}(\text{Kro}) = 1.54$ for the Salpeter and the Kroupa IMFs respectively. The corresponding best-fit values for $H_0$ are $H_0=64$ km s$^{-1}$ Mpc$^{-1}$ and $H_0=62$ km s$^{-1}$ Mpc$^{-1}$, respectively for a Salpeter and Kroupa IMF. Importantly, the best lensing $\chi^2_{\text{NB}}$ are systematically obtained for the lensing galaxies with Kroupa IMFs. The present lensing and dynamical work therefore favours a lensing galaxy with a Kroupa IMF, as also found by Cappellari et al. (2006) from 3D spectroscopy of early-type galaxies and by Ferreras et al. (2008) using the SLACS sample of strong lenses (Bolton et al. 2008).

Our final estimate of $H_0$, given the current data on HE 0435-1223, is therefore the one obtained with a Kroupa IMF, i.e., $H_0=62^{+6}_{-4}$ km s$^{-1}$ Mpc$^{-1}$. This is significantly lower than the current estimates from other methods. Aside from the possibility that this might be the true value for $H_0$, the difference with popular estimates can be attributed (i) to our current large error bars on the lens velocity dispersion and (ii) to the lack of observational constraints on the external shear and convergence due to the galaxies close to the line of sight.

The first source of uncertainty can be reduced by obtaining a deep and high resolution spectrum of the lensing galaxy. This is observationally easy with good ground based data and spectra deconvolution (Courbin et al. 2000). More difficult, but possible, is to use the lens velocity dispersion profile which is a direct prediction of the N-body simulations and which is measurable with deep HST spectra.

A second observational improvement will be to estimate the effect of the lens environment on the overall potential well. The parametric models presented here have an external shear with a PA of the order of $-15^\circ$, consistent with the non-parametric models, and amplitudes in the range $0.06 < \gamma < 0.08$. The corresponding range of values for $H_0$ is large, as shown in Fig. 10. The effect of this second source of degeneracy (e.g., Wucknitz 2002) will be more difficult to minimise, especially since HE 0435-1223 is in a group of galaxies (Momcheva 2009). The unknown convergence, $\kappa$, associated with the group leads to an overestimate of $H_0$ by a factor $(1-\kappa)^{-1}$, meaning that $H_0$ would decrease further if we have underestimated the convergence due to the group. This statement should, however, be considered with care because the effect of the group is poorly approximated by a simple convergence term. Explicit modeling of the group halo is likely needed to properly account for the modifications induced on the main lens potential. Deep X-ray observations may turn out to be very useful to determine the mass and the center of the group with respect to HE 0435-1223.

To conclude, we have introduced a new way to interpret time delays in lensed quasars, based on N-body realisations of the lensing galaxy. This allows us to minimise at least one of the two main sources of degeneracy between the lens models and $H_0$. These models also give constraints on the stellar populations of the lensing galaxy, by showing that only a lens with a Kroupa IMF fit the lensing constraints in HE 0435-1223. The contribution of the errors in the time delays on the total error budget is made negligible, which is the main goal of COSMogrAIL. In order to make further progress with HE 0435-1223, the focus must now be put on a detailed study of its immediate environment and on the dynamics of the main lensing galaxy.

We believe that the methodology adopted here shows that strong gravitational lensing is a competitive way to measure $H_0$ with high accuracy, complementary with other methods, as also shown by Suyu et al. (2009, 2010). The cost in terms of follow-
up observations is modest compared with all other existing methods to measure $H_0$.

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