Mass discrepancy in galaxy clusters as a result of the offset between dark matter and baryon distributions

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ABSTRACT
Recent studies of lensing clusters reveal that it might be fairly common for a galaxy cluster that the X-ray centre has an obvious offset from its gravitational centre which is measured by strong lensing. We argue that if these offsets exist, then X-rays and lensing are indeed measuring different regions of a cluster, and may thus naturally result in a discrepancy in the measured gravitational masses by the two different methods. Here we investigate theoretically the dynamical effects of such lensing–X-ray offsets and compare with observational data. We find that for typical values, the offset alone can give rise to a factor of 2 difference between the lensing and X-ray-determined masses for the core regions of a cluster, suggesting that such ‘offset effect’ may play an important role and should not be ignored in our dynamical measurements of clusters.

Key words: gravitational lensing: strong – dark matter – X-rays: galaxies: clusters.

1 INTRODUCTION
Galaxy clusters, the largest gravitationally bound structures in the Universe, are ideal cosmological tools. Accurate measurements of their masses provide a crucial observational constraint on cosmological models. Several dynamical methods have been available to estimate cluster masses, such as (1) optical measurements of the velocity dispersions of cluster galaxies, (2) measurements of the X-ray-emitting gas and (3) gravitational lensing. Good agreements between these methods have been found on scales larger than cluster cores.

However, joint measurements of lensing and X-rays often identify large discrepancies in the gravitational masses within the central regions of clusters by the two methods, and the lensing mass has always been found to be two to four times higher than the X-ray-determined mass. This is the so-called mass discrepancy problem (Allen 1998; Wu 2000). Many plausible explanations have been suggested, e.g. the triaxiality of galaxy clusters (Morandi et al. 2010a,b), the oversimplification of the strong-lensing model for the central mass distributions of clusters (Bartelmann & Steinmetz 1996), the inappropriate application of the hydrostatic equilibrium hypothesis for the central regions of clusters (Wu 1994; Wu & Fang 1997) or the magnetic fields in clusters (Loeb & Waxman 1998). Recent studies of lensing clusters reveal that it might be fairly common for a galaxy cluster that the X-ray centre has an obvious offset from its gravitational centre which is measured by strong lensing. We argue that if these offsets exist, then X-rays and lensing are indeed measuring different regions of a cluster, and may thus naturally result in a discrepancy in the measured gravitational masses by the two different methods. Here we investigate theoretically the dynamical effects of such lensing–X-ray offsets and compare with observational data. We find that for typical values, the offset alone can give rise to a factor of 2 difference between the lensing and X-ray-determined masses for the core regions of a cluster, suggesting that such ‘offset effect’ may play an important role and should not be ignored in our dynamical measurements of clusters.

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If the X-ray centre of a cluster has an offset from its lensing (gravitational) centre, then the X-rays and lensing are indeed measuring different regions of the cluster. Given the same radius, the lensing is measuring the DM halo centred at the gravitational centre (shown by the long solid black circle in Fig. 1), while the X-rays are measuring the sphere of the halo that is offset from the true gravitational centre (shown by the red circle in Fig. 1). In this case, there will always be a natural discrepancy between the lensing and X-ray-measured masses – or specifically, the X-ray mass will always be lower than the lensing mass, just as the long-standing ‘mass discrepancy problem’ has indicated.

In this paper, we investigate the lensing–X-ray mass discrepancy caused by the offsets between DM and X-ray gas. To check our

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predictions, we compile a sample of 27 clusters with good lensing and X-ray measurements. We conclude that such ‘offset’ effect should not be ignored in our dynamical measurements of galaxy clusters. A flat ΛCDM cosmology is assumed throughout this paper, where Ωm = 0.3, ΩΛ = 0.7 and H0 = 70 km s⁻¹ Mpc⁻¹.

2 MASS DISCREPANCY AS A RESULT OF THE DARK MATTER–BARYON OFFSET

We model our galaxy cluster with a fiducial model as follows: (1) the DM halo is modelled by the Navarro–Frenk–White (NFW) profile (Navarro, Frenk & White 1997) with concentration c = 4.32 and scaled radius rs = 516 kpc; (2) the gas distribution is modelled by a β model with β = 0.65, the cluster core radius rc = 200 kpc and the gas fraction fgas = 12 per cent and (3) the mass density of the brightest cluster galaxy (BCG) is described by a singular isothermal sphere (SIS) with a velocity dispersion of 300 km s⁻¹.

The projected mass within a sphere of radius Rx is

\[ m(R_x, d) = \int_0^{2\pi} \int_0^r \left[ \Sigma_{\text{NFW}}(R') \right. \right. \]
\[ + \Sigma_{\text{gas}}(R') \left. \right] R' \, dR' \, d\theta, \]

where \( R' = \sqrt{d^2 + R^2 + 2dR \cos \theta} \) is the 2D radius from the halo centre, \( R \) is the 2D radius from the X-ray gas centre, \( d \) is the 2D offset between the halo centre and X-ray centre and \( \Sigma_{\text{NFW}} \), \( \Sigma_{\text{gas}} \) and \( \Sigma_{\text{BCG}} \) are the projected mass densities of the DM halo, the gas and the BCG, respectively. For a given radius Rx, the gravitational mass measured by lensing \( m_{\text{lens}} \) can be given by \( m(R_x, 0) \) (as shown by the dark blue sphere in Fig. 1), while the projected mass measured by X-rays \( m_{\text{xray}} \) is described by \( m(R_x, d) \) (the mass within the red circle in Fig. 1). We now calculate the mass ratio \( m_{\text{lens}}/m_{\text{xray}} \) or, equivalently, \( m_{\text{gas}}/m_{\text{xray}} \).

Fig. 2 shows the mass ratio as a function of the 2D offset \( d \), for a typical rich cluster. The solid curves are the mass ratio with the fiducial model, the dashed and dotted curves are the mass ratio with the NFW concentration \( c = 4.04 \) and 5.13 (top left-hand panel), the cluster core radius \( r_c = 150 \) and 400 kpc (top right-hand panel), the β index \( \beta = 0.6 \) and 0.9 (bottom left-hand panel) and the gas fraction \( f_{\text{gas}} = 0.1 \) and 0.2, respectively. For these cases, the three curves from top to bottom are for the three measuring radii \( R_x = 50, 100, 200 \) kpc, respectively. From Fig. 2 we have the following conclusions.

1. The lensing-measured mass \( m_{\text{lens}} \) is always higher than the X-ray-measured mass \( m_{\text{xray}} \). For typical values of offset \( d = 100 \) kpc and \( R_x = 100 \) kpc, \( m_{\text{lens}}/m_{\text{xray}} \sim 2 \), comparable to the ratio found in early studies (Allen 1998; Wu 2000; Richard et al. 2010).

2. The ‘offset effect’ we are reporting here should contribute significantly to the long-standing ‘mass discrepancy problem’.

3. The ratio of \( m_{\text{lens}}/m_{\text{xray}} \) increases with offset \( d \).

4. \( m_{\text{lens}}/m_{\text{xray}} \) depends very strongly on \( R_x \). Here \( R_x \) acts like the arc radius \( r_{\text{arc}} \) in strong lensing, i.e. we only measure the enclosed mass within a small region of \( R \leq R_x \). When \( R_x \) is very small, the offset effect is most prominent and gives large \( m_{\text{lens}}/m_{\text{xray}} \). Increasing \( R_x \) will reduce \( m_{\text{lens}}/m_{\text{xray}} \). When \( R_x \) is very large (compared with \( d \)), the offset effect will be ‘smeared out’ and the \( m_{\text{lens}}/m_{\text{xray}} \) discrepancy introduced by the offset will vanish.

5. The mass ratio is very sensitive to the NFW concentration, and it increases dramatically with \( c \).

6. The mass ratio increases with the core radius and decreases with \( \beta \) index and gas fraction. However, the mass ratio is not very sensitive to the gas model.

3 COMPARISON WITH OBSERVATIONAL DATA

To compare with our theoretical predictions, we compile a sample of 27 clusters with 48 arc-like images, which have both strong lensing and X-ray measurements. The clusters and their lensing and X-ray data are listed in Table 1. For the 22 arcs that have no redshift information, we estimate their lensing masses \( m_{\text{lens}} \) by assuming...
the mean redshifts of \( \langle z_d \rangle \) is 0.8 and 2.0, respectively. The X-ray data are taken from Tucker et al. (1998), Wu (2000), Bonamente et al. (2006) and references therein. The offsets between lensing and X-ray centres are taken from Shan et al. (2010). The clusters in our table are classified as relaxed (with cooling flow) and unrelaxed (which are dynamically immature), from their X-ray morphologies. The definition has been used in the literature by Allen (1998), Wu (2000), Baldi et al. (2007) and Dunn & Fabian (2008).

### Mass from strong lensing: assuming a spherical matter distribution

One can calculate the gravitational mass of a galaxy cluster projected within a radius of \( r_{\text{arc}} \) on the cluster plane as

\[
m_{\text{lens}}(r_{\text{arc}}) = 4\pi r_{\text{arc}}^2 \Sigma_{\text{crit}}.
\]

(1)

where \( \Sigma_{\text{crit}} = [c^2/(4\pi G)][D_l/(D_l D_{ls})] \) is the critical surface mass density, \( D_l, D_s \) and \( D_{ls} \) are the angular diameter distances to the cluster, to the background galaxy and from the cluster to the galaxy, respectively. The above equation is actually the lensing equation for a cluster lens of spherical mass distribution with a negligible small alignment parameter for the distant galaxy within \( r_{\text{arc}} \). The values of \( m_{\text{lens}} \) within the arc radius \( r_{\text{arc}} \) are listed in Table 1.

Allen (1998) pointed out that the use of more realistic, elliptical mass models can reduce the masses within the arc radii by up to 40 per cent, though a value of 20 per cent is more typical. However, such corrections are still not very significant compared with the large discrepancies between the lensing and X-ray-determined masses. We will discuss it in more detail in the next section.

### Mass from X-rays: assuming that the intracluster gas is isothermal and in hydrostatic equilibrium

The cluster mass \( m(r) \) enclosed within a radius \( r \) can be easily calculated from

\[
-\frac{Gm(r)}{r^2} = \frac{kT}{\mu m_p} \frac{d\ln n_{\text{gas}}(r)}{dr}.
\]

(2)

where \( T \) is the gas temperature, \( n_{\text{gas}} \) the gas number density, \( m_p \) the proton mass and \( \mu = 0.585 \) the mean molecular weight. Here we assume that the gas follows the conventional \( \beta \) model, i.e. \( n_{\text{gas}}(r) = n_{\text{gas}}(0)(1 + r^2/r_\beta^2)^{-3/2} \). In order to compare the mass measured by X-rays with the lensing result, we need to convert this \( m(r) \) (i.e. 3D) into the projected mass \( m_{\text{xray}} \) (see e.g. Wu 1994):

\[
m_{\text{xray}} = 1.13 \times 10^{13} \beta \mathcal{J} \left( \frac{R}{r_c} \right) \left( \frac{r_c}{0.1 \text{ Mpc}} \right) \left( \frac{kT}{1 \text{ keV}} \right) M_\odot,
\]

(3)

where

\[
\mathcal{J}(y) = \frac{\pi y^2}{2(1 + y^1/2)}.
\]

(4)

the mass ratios \( m_{\text{lens}}/m_{\text{xray}} \) are listed in Table 1.

![Image](https://example.com/image.png)

Fig. 3 shows the relation between the mass ratios \( m_{\text{lens}}/m_{\text{xray}} \) and the (scaled) offsets for our sample of 27 clusters (48 arc images). It should be pointed out that the 27 clusters in our sample have quite different sizes and masses. This can be seen from the wide range of the cluster temperatures -- from 4 to 14 keV. Therefore, it is useful to compare the offsets of the clusters on the same scale. We realize that the \( M-T \) relation of clusters scales as \( M \sim T^{3/2} \) (e.g. Nevalainen, Markevitch & Forman 2000; Xu, Jin & Wu 2001), and that \( M \sim R^2 \), where \( R \) is the size of the cluster. Therefore, in Fig. 3, instead of using the physical offset \( d \), we use a scaled offset which is characterized by \( d_{\text{arc}}/D_{\text{arc}}^{1/2} \).

From Fig. 3, the mass ratios \( m_{\text{lens}}/m_{\text{xray}} \) exhibit large dispersions -- roughly ranging from 2 to 4. Many clusters have large error bars. It appears that relax clusters (marked by crosses) have smaller \( m_{\text{lens}}/m_{\text{xray}} \) ratios. The fact that \( m_{\text{lens}} > m_{\text{xray}} \) is consistent with our theoretical predictions, and the ratio of \( m_{\text{lens}}/m_{\text{xray}} \sim 2-4 \) is also roughly consistent with our predictions as plotted in Fig. 2.

However, no strong correlation has been found between the offset and mass discrepancies. We note that many clusters in the sample have very small offset values -- smaller than the errors in lensing and X-ray measurements which are typically a few arcseconds. So these offset values are robustly measured themselves, and we thus remove these data points and only focus on clusters with large offsets of \( d > 10 \text{ arcsec} \), as has been suggested in Shan et al. (2010). This leaves a subsample of only 24 arc images. The dashed line in Fig. 3 shows a \( \chi^2 = 40 \) this subsample, which satisfies \( m_{\text{lens}}/m_{\text{xray}} > 3.24 \left( d_{\text{arc}}/D_{\text{arc}}^{1/2} \right) \) with a reasonable \( \chi^2 = 0.75 \). We can find \( m_{\text{lens}}/m_{\text{xray}} \) increasing slightly with \( d \).

### 4 DISCUSSION AND CONCLUSIONS

As has been reported by Shan et al. (2010), it might be fairly common in galaxy clusters that the X-ray centre has an obvious offset from the gravitational centre. We have explored the dynamical consequences of this lensing–X-ray offset and tried to attribute such an effect to the long-standing 'mass discrepancy problem' in galaxy clusters. Our theoretical model predicts that such an offset effect will always result in a larger \( m_{\text{lens}} \) than \( m_{\text{xray}} \), with a typical mass ratio \( m_{\text{lens}}/m_{\text{xray}} \sim 2 \), which is consistent with observations.

To test our model, we have compiled a sample of 27 clusters and studied in detail their lensing and X-ray properties and obtained their lensing and X-ray masses, \( m_{\text{lens}} \) and \( m_{\text{xray}} \). The lack of strong correlation between \( m_{\text{lens}}/m_{\text{xray}} \) and the offset \( d \) suggests that the problem is more complicated. As we have found in Section 2, \( m_{\text{lens}}/m_{\text{xray}} \) is not only a function of \( d \), but also depends very strongly on \( R_e \) (or the arc radius \( r_{\text{arc}} \)). Apparently, each cluster in our sample has quite different \( r_{\text{arc}} \).

Probably, other mechanisms than the offset effect should play important roles, and the lensing–X-ray mass discrepancy may not be just from one mechanism, but a combination of many effects.

(1) The central regions of clusters may be still undergoing dynamical relaxation, and the X-ray gas may not be in good hydrostatic equilibrium. Therefore, large errors could be induced in the X-ray measurement of cluster cores, especially for unrelaxed clusters.

(2) The spherical models are too simple to reflect the real mass distribution of clusters. The use of more realistic mass model could reduce the lens mass within the arc radius by up to 40 per cent, though values of \( \sim 20 \) per cent are more typical (Bartelmann 1995; Allen 1998).

(3) The presence of substructures may complicate our simple spherical lens model, and hence could be a main source of uncertainties in \( m_{\text{lens}} \). The absence of the secondary arc-like images in most arc-cluster systems may indicate the limitations of the spherical mass distribution in the central regions of clusters.

It should be noted that the mass ratios we obtained here are slightly higher than Allen (1998) and Wu (2000) because they unfortunately used a Hubble constant of \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \). The use of \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) here will of course make the mass discrepancy problem more pronounced.

It should be noted that the gas represents only a 10 per cent perturbation due to the small ratio of gas to DM in the central region; likewise the offset of the gas is only a small perturbation (less than 10 per cent) to the otherwise concentric matter density or potential. It is unlikely to create a factor of 2 difference in the lensing-derived enclosed masses within an arc.

To illustrate the lensing effect of the offset perturbation and triaxiality, we show the critical curves in Fig. 4. The solid curves indicate the critical curve of circular NFW plus \( \beta \) model without offset, the
| Cluster       | $z_{\text{cluster}}$ | Offset (arcsec) | $r_{\text{acc}}$ (Mpc) | $r_{\text{acc}}$ (×10^14 M⊙) | Ref. A | Ref. A′ | $kT$ (keV) | $\beta$ | $r_c$ (Mpc) | $m_{\text{acc}}$ (×10^14 M⊙) | $m_{\text{acc}}$ (×10^14 M⊙) | Class | Ref. B′ |
|--------------|----------------------|----------------|------------------------|------------------------------|--------|--------|------------|---------|-----------|-------------------------------|-------------------------------|-------|---------|
| 1E0657–56    | 0.296                | 47.4           | 209.2                  | 3.24                         | 0.25   | 4.37   | 3.4        | 14.1   | 0.62      | 0.36                          | 2.15                          | 2.03  | U 12    |
| A68          | 0.255                | 14.3           | 56.7                   | 1.60                         | 0.40   | 0.13   | 11         | 10.0   | 0.72      | 0.25                          | 1.61                          | 1.61  | U       |
|              | 1.60                 | 0.10           | 0.80                   | 2.63                         | 0.11   | 0.94   |            |         |           |                               |                               |       |         |
|              | –                    | 0.211          | 4.49(3.54)             | 0.86                         | 0.28   | 7.49   |            |         |           |                               |                               |       |         |
|              | –                    | 0.27           | 7.26(5.72)             | 1.27                         | 0.32   | 8.66   |            |         |           |                               |                               |       |         |
|              | –                    | 0.12           | 1.54(1.22)             |                               |        |        |            |         |           |                               |                               |       |         |
| A267         | 0.230                | 9.62           | 35.3                   | 0.12                         | 1.48   | 1.20   | 11         | 6.0    | 0.71      | 0.19                          | 0.39                          | 2.23  | U 2     |
| A370         | 0.375                | 19.9           | 102.7                  | 1.30                         | 0.41   | 13.1   | 7          | 7.13   | 0.95      | 0.56                          | 4.34                          | 3.57  | U 13    |
|              | 0.72                 | 0.19           | 4.09                   |                               |        |        |            |         |           |                               |                               |       |         |
| A697         | 0.282                | 3.07           | 13.1                   | 0.12                         | 1.51   | 1.15   | 10         | 9.9    | 0.61      | 0.24                          | 0.26                          | 5.53  | U 2     |
| A773         | 0.217                | 6.43           | 22.6                   | 0.65                         | 0.11   | 1.39   | 11         | 7.6    | 0.61      | 0.19                          | 0.37                          | 3.75  | U 2     |
|              | 0.40                 | 0.21           | 7.08                   |                               |        |        |            |         |           |                               |                               |       |         |
|              | –                    | 0.25           | 6.50(5.36)             |                               |        |        |            |         |           |                               |                               |       |         |
|              | –                    | 0.23           | 5.41(4.45)             |                               |        |        |            |         |           |                               |                               |       |         |
|              | 1.11                 | 0.213          | 4.34                   |                               |        |        |            |         |           |                               |                               |       |         |
|              | 0.40                 | 0.16           | 4.14                   |                               |        |        |            |         |           |                               |                               |       |         |
|              | –                    | 0.04           | 0.18(0.15)             |                               |        |        |            |         |           |                               |                               |       |         |
|              | 0.49                 | 0.23           | 7.42                   |                               |        |        |            |         |           |                               |                               |       |         |
| A963         | 0.206                | 7.10           | 24.0                   | 0.057                        | 0.35   | 0.29   | 11         | 6.13   | 0.51      | 0.11                          | 0.14                          | 2.41  | R 13    |
|              | 0.71                 | 0.09           | 0.87                   |                               |        |        |            |         |           |                               |                               |       |         |
| A1689        | 0.183                | 0.60           | 1.85                   | 0.20                         | 4.5(3.8) | 8      | 9.02      | 0.65   | 0.65      | 1.44                          | 1.68                          | 2.68  | R 13    |
| A1835        | 0.252                | 1.61           | 6.33                   | 0.17                         | 2.82   | 2.23   | 11         | 9.8   | 0.65      | 0.08                          | 1.73                          | 2.68  | R 13    |
| A1914        | 0.171                | 11.3           | 32.9                   | 0.10                         | 1.16   | 1(1.01) | 10         | 9.9   | 0.90      | 0.20                          | 0.70                          | 1.67  | U 2     |
| A2204        | 0.151                | 1.20           | 3.15                   | 0.025                        | 0.08   | 0.07   | 10         | 6.5   | 0.48      | 0.02                          | 0.11                          | 0.71  | R 2     |
|              | –                    | 0.01           | 0.013(0.012)           |                               |        |        |            |         |           |                               |                               |       |         |
| A2163        | 0.203                | 44.0           | 146.9                  | 0.73                         | 0.07   | 0.58   | 1          | 14.6   | 0.62      | 0.33                          | 0.23                          | 2.39  | U 13    |
| A2218        | 0.176                | 19.1           | 56.9                   | 1.03                         | 0.28   | 8.60   | 11         | 7.1    | 0.65      | 0.25                          | 1.67                          | 5.07  | U 13    |
|              | 0.70                 | 0.09           | 0.89                   |                               |        |        |            |         |           |                               |                               |       |         |
|              | 2.52                 | 0.09           | 0.82                   |                               |        |        |            |         |           |                               |                               |       |         |
| Cluster   | $\bar{z}_{\text{cluster}}$ | Offset (arcsec) | $z_{\text{arc}}$ | $r_{\text{arc}}$ (Mpc) | $m_{\text{los}}$ ($\times 10^{14}$ M$_\odot$) | Ref. | $kT$ (keV) | $\beta$ | $r_c$ (Mpc) | $m_{\text{Xray}}$ ($\times 10^{14}$ M$_\odot$) | $m_{\text{los}}/m_{\text{Xray}}$ | Class | Ref.  |
|-----------|-----------------------------|----------------|------------------|------------------------|---------------------------------|------|-------------|--------|-------------|---------------------------------|-----------------------------|-------|-------|
| A2219$^a$ | 0.228                       | 11.3           | 41.2             | -                      | 0.09                            | 0.79 (0.64)$^b$ | 11   | 12.4$^{+0.5}_{-0.5}$ | 0.40$^{+0.07}_{-0.07}$ | 0.16$^{+0.08}_{-0.08}$ | 0.38$^{+0.21}_{-0.21}$ | 2.19$^{+1.17}_{-1.17}$ | 1.78$^{+0.95}_{-0.99}$ | U     | 13    |
| A2259     | 0.164                       | 16.3           | 45.9             | 1.48                   | 0.04                            | 0.13                        | 10   | 5.6$^{+0.3}_{-0.3}$   | 0.58$^{+0.02}_{-0.02}$ | 0.14$^{+0.01}_{-0.01}$ | 0.06$^{+0.0089}_{-0.0089}$ | 2.71$^{+0.38}_{-0.38}$ | U     | 2     |
| A2261$^a$ | 0.224                       | 1.31           | 4.72             | -                      | 0.12                            | 1.49 (1.22)$^b$ | 10   | 7.2$^{+0.4}_{-0.4}$   | 0.56$^{+0.01}_{-0.01}$ | 0.08$^{+0.004}_{-0.004}$ | 0.71$^{+0.056}_{-0.056}$ | 2.15$^{+0.17}_{-0.17}$ | 1.73$^{+0.14}_{-0.14}$ | R     | 2     |
| A2390     | 0.228                       | 6.00           | 21.9             | 0.91                   | 0.20                            | 3.8                        | 10   | 11.1$^{+1.0}_{-1.0}$  | 0.59$^{+0.02}_{-0.02}$ | 0.16$^{+0.01}_{-0.01}$ | 1.79$^{+0.26}_{-0.26}$ | 2.22$^{+0.32}_{-0.32}$ | U     | 13    |
| CL0024    | 0.395                       | 13.2           | 70.4             | 1.68                   | 0.26                            | 4.7                        | 6    | 5.7$^{+3.9}_{-2.1}$   | 0.48$^{+0.08}_{-0.05}$ | 0.08$^{+0.05}_{-0.03}$ | 1.19$^{+1.22}_{-0.56}$ | 4.03$^{+1.44}_{-1.91}$ | U     | 13    |
| MS0440    | 0.190                       | 1.50           | 4.89             | 0.53                   | 0.10                            | 1.23                        | 5.10 | 5.3$^{+2.7}_{-0.85}$  | 0.45$^{+0.03}_{-0.03}$ | 0.03$^{+0.01}_{-0.01}$ | 0.40$^{+0.15}_{-0.12}$ | 3.20$^{+1.19}_{-0.94}$ | U     | 13    |
| MS0451    | 0.550                       | 12.1           | 76.8             | -                      | 0.23                            | 7.6 (3.5)$^b$            | 10   | 10.1$^{+1.55}_{-1.26}$ | 0.68$^{+0.13}_{-0.09}$ | 0.31$^{+0.09}_{-0.06}$ | 1.64$^{+0.85}_{-0.61}$ | 4.81$^{+2.49}_{-1.79}$ | (2.11$^{+0.96}_{-0.78}$) | U     | 13    |
| MS1008    | 0.360                       | 5.43           | 27.3             | -                      | 0.30                            | 9.2 (6.2)$^b$            | 1    | 7.29$^{+2.45}_{-1.32}$ | 0.63$^{+0.11}_{-0.07}$ | 0.23$^{+0.07}_{-0.05}$ | 1.89$^{+1.15}_{-0.73}$ | 4.84$^{+2.95}_{-1.89}$ | (3.29$^{+2.13}_{-1.28}$) | R     | 13    |
| MS1358    | 0.329                       | 2.79           | 13.2             | 4.92                   | 0.14                            | 1.24                        | 10   | 7.5$^{+4.3}_{-4.3}$   | 0.47$^{+0.02}_{-0.02}$ | 0.05$^{+0.02}_{-0.02}$ | 0.82$^{+0.53}_{-0.51}$ | 1.54$^{+0.99}_{-0.97}$ | R     | 13    |
| MS1455    | 0.258                       | 2.77           | 11.1             | -                      | 0.11                            | 1.22 (0.96)$^b$           | 9.10 | 5.45$^{+0.29}_{-0.28}$ | 0.64$^{+0.04}_{-0.04}$ | 0.07$^{+0.01}_{-0.01}$ | 0.57$^{+0.077}_{-0.067}$ | 2.14$^{+0.29}_{-0.25}$ | (1.68$^{+0.23}_{-0.20}$) | U     | 13    |
| MS2053    | 0.580                       | 10.5           | 69.1             | 3.15                   | 0.16                            | 1.41                        | 10   | 4.7$^{+0.4}_{-0.4}$   | 0.64$^{+0.04}_{-0.03}$ | 0.16$^{+0.02}_{-0.01}$ | 0.60$^{+0.13}_{-0.094}$ | 2.47$^{+0.54}_{-0.39}$ | U     | 2     |
| MS2137    | 0.313                       | 5.70           | 26.1             | -                      | 0.10                            | 0.99 (0.72)$^b$          | 9.10 | 4.37$^{+0.38}_{-0.72}$ | 0.63$^{+0.04}_{-0.03}$ | 0.06$^{+0.01}_{-0.01}$ | 0.44$^{+0.067}_{-0.049}$ | 2.20$^{+0.34}_{-0.48}$ | (1.65$^{+0.25}_{-0.35}$) | R     | 13    |
| PKS0745   | 0.103                       | 6.82           | 12.9             | 0.43                   | 0.05                            | 0.42                        | 10   | 8.7$^{+1.6}_{-1.6}$   | 0.59$^{+0.01}_{-0.01}$ | 0.06$^{+0.01}_{-0.01}$ | 0.29$^{+0.075}_{-0.061}$ | 1.55$^{+0.40}_{-0.33}$ | R     | 13    |
| RXJ1347   | 0.451                       | 2.81           | 16.2             | 0.81                   | 0.28                            | 8.9                         | 1    | 11.3$^{+0.10}_{-0.02}$ | 0.57$^{+0.04}_{-0.04}$ | 0.07$^{+0.01}_{-0.01}$ | 3.07$^{+0.54}_{-0.35}$ | 2.90$^{+0.51}_{-0.33}$ | R     | 13    |

$^a$Multiple-arc system.

$^b$Arc-like image is assumed at $z_s = 0.8$ ($z_s = 2$).

$^c$R: relaxed; U: unrelaxed.

$^d$References: (1) Allen (1998); (2) Bonamente et al. (2006); (3) Bradac et al. (2006); (4) Clowe et al. (2006); (5) Gioia et al. (1998); (6) Jee et al. (2007); (7) Kneib et al. (1993); (8) Limousin et al. (2007); (9) Newbury & Fahlman (1999); (10) Sand et al. (2005); (11) Smith et al. (2005); (12) Tucker et al. (1998); (13) Wu (2000).
The ratio of lensing and X-ray-determined masses for our sample of 27 clusters (48 arc images). The x-label shows the scaled offset between DM and baryons. The squares denote unrelaxed clusters, and crosses denote the relaxed clusters. The dashed line shows a $\chi^2$ fit satisfying $m_{lens}/m_{xray} \sim 3.24 \left( \frac{d}{100 \text{ kpc}} \right)^{0.20}$ with $\chi^2 = 0.75$ for the clusters with offset larger than 10 arcsec.

The dotted curves indicate the critical curve of elliptical NFW plus $\beta$ model with offset $d = 10$ arcsec. The square and cross denote the centre of DM and the X-ray gas, respectively. For the NFW profile, $c = 4.3$, $r_s = 516$ kpc; and for the $\beta$ model, $\beta = 0.65$, $r_c = 150$ kpc. The ellipticity and position angle are $e = 0.15$ and $\theta = 30^\circ$. The lens and source redshifts are $z_l = 0.3$ and $z_s = 1$.

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