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QSO-Galaxy Association and Gravitational Lensing

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Abstract The amplification caused by gravitational light bending by compact objects in a foreground galaxy can affect the apparent number density of background QSOs, as well as their distribution in the fields of galactic halos. In this work we investigate the number enhancement of QSOs in the fields of galactic halos caused by point mass lensing effect and singular isothermal lensing effect, and apply the micro-lensing effect due to dark compact objects in the halo to NGC 3628. NGC 3628 is a well-studied nearby edge-on Sbc peculiar galaxy, where QSOs are shown to be concentrated around the galaxy with a density much higher than background. We show that if present understanding of the luminosity function of QSOs is right, such concentration could not be caused by gravitational lensing.

Key words: micro-lensing, QSOs, ULXs, black holes, Dark Matter, galactic halo, NGC 3628

1 INTRODUCTION

Ultra-Luminous X-ray sources (ULXs) have been found from several nearby spiral galaxies and they are commonly believed to be either stellar mass compact systems or intermediate-mass black holes (IMBHs) (see for example, Miller and Colbert 2004 and references therein). However, a considerable fraction of these ULXs have been identified as QSOs with high redshifts (Arp et al. 2002, 2004), and these QSOs are shown to be highly concentrated around these galaxies; it has been proposed that these ULXs are "local" QSOs physically associated with these galaxies, with high intrinsic redshifts in the process of being ejected from those galaxies (Burbidge et al. 2003a, 2003b). On the other hand, if these ULX-QSO associations are real and the QSOs are cosmologically distant objects, then there must exist a mechanism responsible for enhancing the apparent QSO number density and concentration towards the center of their foreground galaxies in flux limited observations.

The only possible mechanism to link nearby galaxies with high redshift QSOs and to boost the number density of QSOs in the fields of galaxies is gravitational lensing. In this paper we investigate on the question: What will happen to the number density enhancement, if these QSOs are magnified by gravitational lensing effect due to compact objects in galactic halos of their foreground galaxies? We find that the local fractional number density enhancement is

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insignificant unless that a considerable portion of dark matter in galactic halos are compact objects, by comparing micro-lenses and singular isothermal lenses with the same total mass as shown in Sect. 2.

In Sect. 3, we apply this micro-lensing effect to NGC 3628 which is a well-studied nearby edge-on Sbc peculiar galaxy and find that the concentration of QSOs in the fields of NGC 3628 could not be caused by gravitational lensing. Throughout this paper, we adopt a QSO luminosity function given by Ueda et al. (2003) with a 2−10 keV flux limit of 3×10^{-14} erg cm^{-2} s^{-1} and isotropic QSO luminosity lower limit of 10^{44} erg s^{-1}.

2 QSO DISTRIBUTION IN THE FIELDS OF GALACTIC HALOS

For a given total mass, galaxies at different distances will show different gravitational lensing effects and therefore the QSO distribution in the fields of galactic halos will be different.

2.1 Micro-lenses vs smooth lenses

For nearby galaxies, a halo with micro-lenses will amplify the background QSOs much more effectively than a halo with the same amount of mass but distributed smoothly, e.g., in the form of WIMPs. We first compare an extreme example of lensing in which all the mass in the galaxy is either in the form of a point mass (i.e., micro-lens) or a smoothly distributed mass (i.e., singular isothermal lens). For a galaxy with mass M and typical size L, the Einstein radius r_{Ep} for the micro-lens is given by:

$$r_{\rm Ep} = \left(\frac{4GMD}{c^2}\right)^{1/2}, \qquad (1)$$

where $D = \frac{D_{\rm l} D_{\rm ls}}{D_{\rm s}}$, and $D_{\rm l}, D_{\rm s}, D_{\rm ls}$ are angular distances between the lens (foreground galaxy) and observer, the source (background QSO) and observer, QSO and galaxy, respectively.

For a singular isothermal lens, its properties are characterized by a one-component velocity distribution $\sigma_{\|}$. The density and mass within a radius r are,

$$\rho(r) = \frac{\sigma_{\|}^2}{2\pi G}\frac{1}{r^2}, \qquad M(r) = \frac{2\sigma_{\|}^2 r}{G}\,, \qquad (2)$$

and the Einstein radius r_{Ei} is given by,

$$r_{\rm Ei} = \frac{4\pi\sigma_{\|}^2 D}{c^2} = \frac{2\pi GDM}{Lc^2} = \frac{\pi}{2}\frac{r_{\rm Ep}^2}{L}\,. \qquad (3)$$

We re-write the above equation as,

$$\frac{\pi}{2} r_{\rm Ep}^2 = r_{\rm Ei} L\,. \qquad (4)$$

It is clear that $r_{\rm Ei} < r_{\rm Ep}$ for $D \leq 2 \times 10^3$ Mpc ($z \leq 0.4$) for a $10^{12}\,M_{\odot}$ galaxy with a radius of 20 kpc. Since in the low-optical-depth limit and in the condition of point lens approximation, the amplification of background QSO caused by micro-lenses depends on the total solid angle of Einstein rings and consequently depends on the total mass of micro-lenses, the micro-lensing induced QSO number enhancement is independent of the mass function of micro-lenses and widely-distributed micro-lenses would behave the same way as a single object with a given total mass. Therefore we can conclude that micro-lenses are more effective than smoothly distributed singular isothermal lenses for nearby galaxies. It is thus possible to use background QSO distribution in the fields of galactic halos of nearby galaxies to distinguish between dark matter halos made of smoothly distributed matter such as WIMPs from those made of point mass lenses.

2.2 QSO number enhancement in the fields of galaxies

In the low optical depth regime, the micro-lensing induced QSO number enhancement in the fields of galaxies is independent of the mass function and spatial distribution of micro-lenses, and only relies on the total mass of dark matter micro-lenses M and redshifts z of galaxies (e.g., Paczynski 1986b). Figure 1 shows the net number enhancement δN of QSOs in the field of a galaxy within a radius 20 kpc as a function of redshift of the galaxy due to micro-lensing of point lens dark matter. For an observed QSO number N, the statistical uncertainty σ is $\sigma = \sqrt{N}$. This should be compared with the net number enhancement caused by micro-lensing: $\frac{\delta N}{\sigma} = \frac{\delta N}{\sqrt{N}}$, which is shown in Fig. 2. We see that:

(1) The three curves, corresponding to different total masses of micro-lenses in the galaxy, are very different. Therefore if a considerable portion of halo dark matter is in the form of micro-lenses, statistics of background QSO distribution in the fields of galactic halos can be used to determine the total mass of micro-lenses.

(2) Though the net number enhancement in nearby galaxies is far more than distant galaxies because they cover larger sky areas, the statistical value $\frac{\delta N}{\sqrt{N}}$ is relatively flat as a function of the redshifts of foreground galaxies. This tells us that number counts of background QSOs in spatially resolved fields of foreground galaxies are sensitive to the galaxy distances and thus may be used to study the cosmological parameters such as dark energy, but the simple QSO-galaxy correlation is insensitive to galaxy distances. We will return to the issue of QSO-galaxy correlation in the last part of the paper.

3 APPLICATION TO NGC 3628

NGC 3628 is a well-studied nearby edge-on Sbc peculiar galaxy in the Leo Triplet. Dahlem et al. (1996) have listed many X-ray sources in the ROSAT-detected hot gaseous halo of NGC 3628, and they found this number density is higher than background with a 1.5σ deviation. They also pointed out that most of these X-ray sources in the halo of NGC 3628 are probably background AGNs. Recently, Arp et al. (2002) identified several confirmed and probable QSOs in the halo of NGC 3628 and they found these QSOs are highly concentrated around NGC 3628. Confirmed X-ray QSOs from Weedman (1985), Dahlem et al. (1996) and Arp et al. (2002) are listed in Table 1.

Table 1 Confirmed X-ray QSOs near NGC 3628. These are taken from the whole-sky X-ray/radio/optical verlays catalogue by Flesch, which is accessible at ftp://quasars.org/quasars.

No	Survey ID	RA(J2000)	Dec	Redshift	Count rate
1	Wee 48	11 19 46.9	13 37 59	2.06	2RXP 6 cts h^{-1}
2	Wee 51	11 20 11.9	13 31 23	2.15	1RXH 5 cts h^{-1}
3	1WGAJ1120.2+1332	11 20 14.7	13 32 28	0.995	1RXH 3 cts h^{-1}
4	1WGAJ1120.4+1340	11 20 26.2	13 40 24	0.981	1RXH 9 cts h^{-1}
5	1WGAJ1120.6+1336	11 20 39.9	13 36 20	0.408	1RXH 3 cts h^{-1}
6	Wee 52	11 20 41.6	13 35 51	2.43	1RXH 3 cts h^{-1}
7	Wee 55	11 21 06.1	13 38 25	1.94	2RXP 22 cts h^{-1}

The number density of QSOs in the fields of NGC 3628 is shown in Fig. 3, which is about three time the number density of background. Figure 4 shows the variation of net enhancement factor q of QSO number with a magnification M for several observational flux limit f_0, which

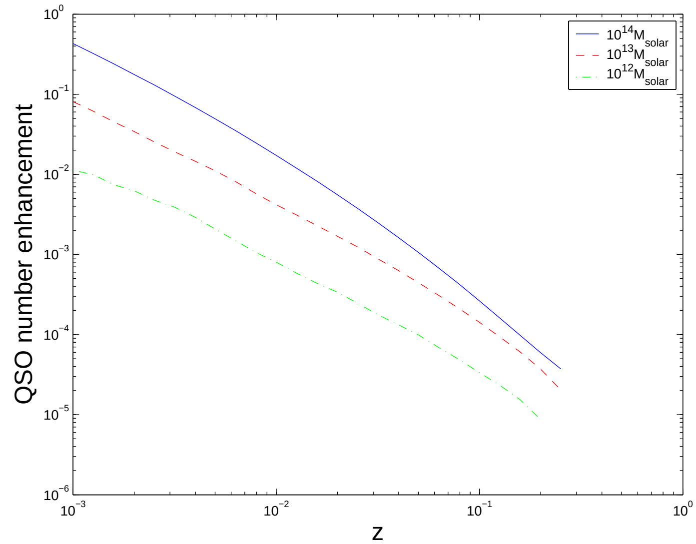

Fig. 1 Micro-lensing induced QSO number enhancement in the field of a galaxy within a radius 20 kpc at different redshifts, and the three curves denote different total masses of micro-lenses in the galaxy as $10^{14}M_\odot$, $10^{13}M_\odot$, and $10^{12}M_\odot$ respectively.

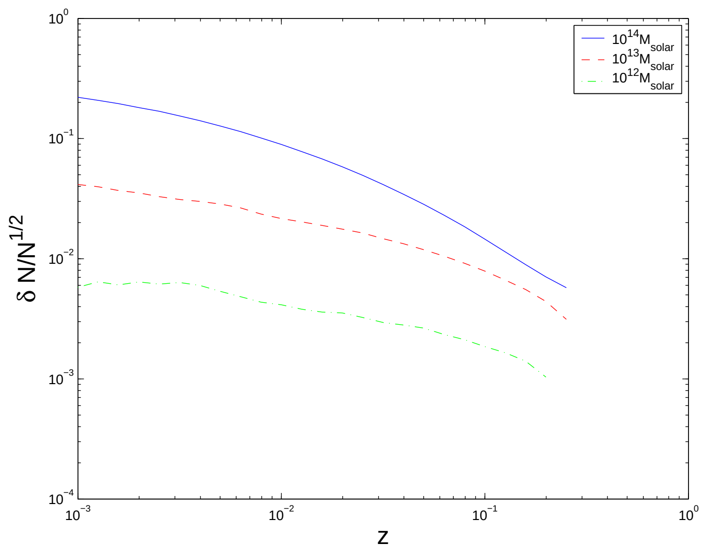

Fig. 2 Micro-lensing induced QSO number enhancement over statistical uncertainty. Parameters are the same as in Fig. 1.

is given by:

$$q(M, f_0) = \frac{1}{M} \frac{N(> f_0/M)}{N(> f_0)} \,. \tag{5}$$

For NGC 3628, the flux limit is about $3 \times 10^{14}\,\mathrm{erg\,s^{-1}}$, and the net enhancement factor is about 3. Therefore, if present understanding of luminosity function of QSO is right, such concentration cannot be the result of gravitational lensing. However, as pointed out by Narayan

(1989), since the net enhancement of a given flux limit is dominated by those QSOs with flux larger than f_0/M and less than f_0, if the QSO counts are steeper at faint magnitudes than present understanding, higher concentration could be caused by gravitational lensing.

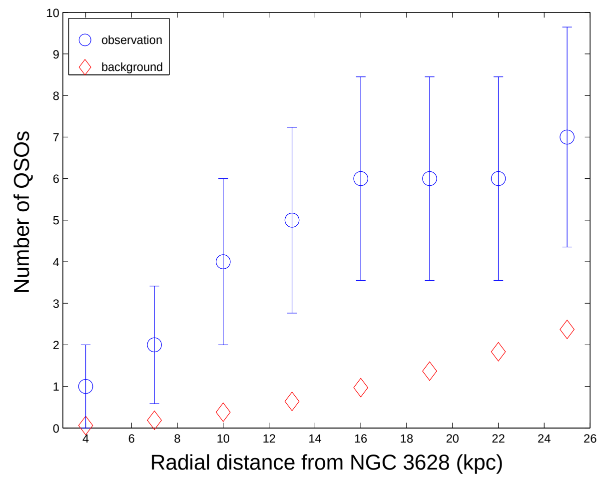

Fig. 3 The number of confirmed X-ray selected QSOs within a radial distance from NGC 3628 (circles), compared with the expected number of X-ray selected background QSOs (diamonds).

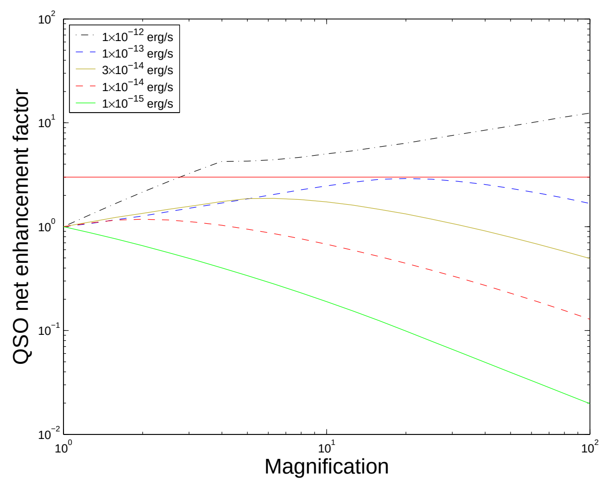

Fig. 4 Variation of QSO number density enhancement with magnification, for five limiting fluxes. The red solid line represents the enhancement factor of 3 observed in NGC 3628.

4 CONCLUSIONS AND DISCUSSIONS

We have reached the following conclusions in this paper:

1. From eqn. (4), micro-lensing (e.g. from black holes) in nearby foreground galaxies may enhance the number of background QSOs in flux limited detection much more effectively than lensing effects caused by smooth lenses (e.g. WIMPs).

2. From Fig. 1, the QSO number enhancement is sensitive to the distance of the foreground galaxy, and thus may be used as a distance measure of galaxies.

3. The observed QSO excess in NGC 3628 cannot be caused by gravitational lensing, unless the QSO counts are steeper at faint magnitudes than present understanding.

However, the following point is worth further discussions. For point mass lenses, since the area within the Einstein radius is proportional to the total mass, amplification is independent of the mass function of lenses when the optical depth is low. However, as pointed out by Paczynski (1986a), a point source approximation is not suitable for micro-lensing on objects with low mass such as less massive than Jupiter, when the projection of the QSO onto the sky is larger than the Einstein rings of point mass lenses. Therefore if lenses consist of very low mass objects, micro-lensing effect will be less important.

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