Weak lensing by line-of-sight halos as the origin of flux-ratio anomalies in quadruply lensed QSOs

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Nano-Workshop at IAP
Outline

- Introduction
- Magnification perturbation
- Non-linear power spectrum
- Contribution to the flux ratios
- Summary
- Future work
Introduction
Missing Satellite Problem

Madau et al. 08
Suppression Mechanism

- Baryon physics (reionization, tidal disruption due to disk)
- New physics (warm dark matter, super WIMPs)
- Need to probe clustering property of halos with $M<10^9$ solar mass
Flux-ratio anomalies

- Positions can be well fit to the model.
- Flux-ratios fits are poor.

Cusp-caustic relation

\[
\frac{A + B + C}{|A| + |B| + |C|} = 0
\]

(Mao & Schneider ‘98
Metcalf & Madau ‘01,
Chiba ‘02 Dalal &
Kochanek ‘02)
Flux- ratio anomalies

- Predicted subhalos too low for anomalies
  (Maccio & Mirranda 2006, Amara et al. 2006;
   Xu et al. 2009, 2010; Chen 2009; Chen et al. 2011)

- Luminous satellites may contribute significantly
  (McKean et al. 2007, Shin & Evans 2008;
   MacLeod et al. 2009)

- Line-of-sight halos?
  (Chen et al. 2003, Metcalf 2005, Xu et al. 2011)
Flux-ratio anomalies

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Flux-ratio anomalies

Sub halos

QSO

ETG
Our work

- Semi-analytic estimate based on VERY high resolution N-body simulation fully incorporating clustering effects $>10^5$ solar mass halos
- Astrometric shifts taken into account
- New static rather than ‘classic’ cusp-caustic relations
- Only MIR lenses. Source sizes $\approx O[1 \text{ pc}]$
Magnification perturbation
Parity of lensed images
Arrival time surface

Blandford & Narayan 1986
Systematic (de)magnification

- - +
- -

demagnify
or magnify

++
magnify

---
demagnify

or

or
New statistic $\eta$

$A, C: \text{minima} \quad B: \text{saddle}, \quad \kappa_{\downarrow B} < 1$

$\delta_i^\mu \equiv \frac{\delta \mu_i}{\mu_i}$: magnification contrast

$\eta$: effective magnification perturbation

$$\eta^2(A, B, C) = \frac{1}{4} \left[ (\delta_A^\mu - \delta_B^\mu)^2 + (\delta_C^\mu - \delta_B^\mu)^2 \right].$$

$$\eta^2 \approx \frac{1}{4} \left[ \left( \frac{AB_0}{A_0B} - 1 \right)^2 + \left( \frac{CB_0}{C_0B} - 1 \right)^2 \right].$$
New statistic $\eta$

\[
\langle \eta^2 \rangle = \frac{1}{4} \left[ (J_A + J_B)\sigma^2_{\kappa}(0) - 2J_{AB}\xi_{\kappa}(\theta_{AB}) + (J_B + J_C)\sigma^2_{\kappa}(0) - 2J_{BC}\xi^2_{\kappa}(\theta_{BC}) \right],
\]

where

\[
J_i = \mu_i^2(4(1 - \kappa_i)^2 + 2\gamma_i^2),
\]

and

\[
J_{ij} = \mu_i\mu_j(4(1 - \kappa_i)(1 - \kappa_j) + 2\gamma_i\gamma_j),
\]

$\kappa$: background convergence  $\gamma$: background shear
Astrometric shifts

\[ \delta \theta \]

- Source plane: \( N + 1 \)
- Primary lens plane: \( N \), \( l + 1 \), \( l \), \( l - 1 \)
- Observer plane: \( 1 \), \( O \)

\[ \alpha_N, \alpha_{l+1}, \alpha_l, \alpha_{l-1} \]
Astrometric shifts

2-point correlation in shift of image separated by $\theta$

$$\xi_{\delta\theta}(\theta) \equiv \langle \delta\theta(0)\delta\theta(\theta) \rangle$$

Given by power spectrum $P(k)$

$$2\langle \delta\theta^2(0) \rangle - 2\langle \delta\theta(0)\delta\theta(\theta_{AB}) \rangle < \epsilon^2,$$

Given by accuracy in position of centroid $\epsilon$
Astrometric shifts

\[ k_{lens} \equiv \frac{2\pi}{L_{lens}} \text{ where } L_{lens} \sim 4r(z_L)\theta_E \]

Minimum wavelength given by the size of Einstein radius

\[ k_{lens} = \mathcal{O}[100-1000]h/\text{Mpc} \]
Astrometric shifts

\[ \frac{d}{d \ln k} (\Delta \theta(\theta; k))^2 \]

\( k \ h/\text{Mpc} \)

- \( \theta = 1.5 \) arcsec
- \( \theta = 1.0 \) arcsec
- \( \theta = 0.5 \) arcsec
Astrometric shifts

- Super cluster
- Cluster
- Galaxy
- Satellite
- Mini-halo

External shear

SIE, SIS

Perturbation
Constrained convergence power

- Accuracy in lensed images and lens = maximum contribution

- Size of the Einstein ring
  (absorbed into background shear)

- These two give the largest scale of modes $k < k_{\text{min}}$ that can affect the flux-ratios
New statistic $\eta$

$$\xi_\kappa(\theta) \equiv \langle \delta_\kappa(0) \delta_\kappa(\theta) \rangle$$

$$= \frac{9 H_0^4 \Omega_m^2}{4c^4} \int_0^{r_S} dr r^2 \left( \frac{r - r_S}{r_S} \right)^2 [1 + z(r)]^2$$

$$\times \int_0^\infty \frac{dk}{2\pi} k W(k; k_{cut}(r; \epsilon)) P_\delta(k; r) J_0(g(r)k\theta),$$
Constrained convergence power

\[
\sigma_k(0) \quad k_{\text{min}} = 20 \, h/\text{Mpc} \quad k_{\text{min}} = 100 \, h/\text{Mpc} \quad k_{\text{min}} = 500 \, h/\text{Mpc}
\]

\[
z_s \quad k_{\text{max}} = 1000 \, h/\text{Mpc}^{-1}
\]
Non-linear power spectrum
Non-linear power spectrum

\[ \Delta^2(k) \]

- \( z = 0, 0.35, 1, 2.2 \)
- Halo - fit by our work
- Halo - fit by Smith et al. 2003

- Shot noise

- \( k_{Nyq} \)
Non-linear power spectrum

\[ \Delta^2(k) \]

\[ k_{\text{Nyq}} \]

Halo – fit by our work

Halo – fit by Smith et al. 2003

shot noise
Contribution to the flux ratios
MIR QSO-galaxy quads

- 6 samples: 5 continuum 1 line [OIII]

- SIE-ES model possibly with SIS for a luminous satellite (gravlens by Keeton)

- Astrometric shifts given by position errors (CASTLES) in lensed images and lens & size of critical curves -> minimum wavelength.
Source size estimated from dust reverberation method $\sim 1\text{-}3\text{pc} \gg$ Einstein radius of stars (by Chiba et al. 2005 & Minezaki et al. 2009)
# MIR quadruple lenses

## Table 1. Observed MIR Flux Ratios

<table>
<thead>
<tr>
<th>Lens</th>
<th>$z_L$</th>
<th>$z_S$</th>
<th>$N$</th>
<th>Flux Ratio</th>
<th>$\langle e \rangle$ (&quot;)</th>
<th>$\langle \theta \rangle$ (&quot;)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXJ1131-1231(*)</td>
<td>0.295</td>
<td>0.658</td>
<td>3</td>
<td>A/B = 1.63$^{+0.04}<em>{-0.02}$, C/B = 1.19$^{+0.03}</em>{-0.12}$</td>
<td>0.017</td>
<td>1.9</td>
<td>1, 2</td>
</tr>
<tr>
<td>Q2237+0305</td>
<td>0.04</td>
<td>1.695</td>
<td>4</td>
<td>B/A = 0.84$^{±0.05}$, C/A = 0.46$^{±0.02}$, D/A = 0.87$^{±0.05}$</td>
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<td>0.9</td>
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<tr>
<td>PG1115+080</td>
<td>0.31</td>
<td>1.72</td>
<td>2</td>
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<td>H1413+117</td>
<td>1.88(++)</td>
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Note: (*) [OIII] line flux ratios. (++) The lens redshift $z_L$ is obtained from a best-fit model using the observed positions of the images and the primary lens, the flux ratios, and the time-delays between the images assuming $H_0 = 70$ km/s/Mpc.
# MIR quadruple lenses

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Result I

![Graph showing the relationship between $\eta$ and $z_s$ for different $k_{\text{max}}$ values. The graph includes data points for $k_{\text{max}} = 320h/$Mpc (circles), $k_{\text{max}} = 1000h/$Mpc (squares), and $k_{\text{max}} = 10000h/$Mpc (triangles).]
Clustering line-of-sight halos with $M=10^3-7$ solar mass can explain the observed anomalous flux ratios without any substructures inside a lensing galaxy.

The estimated amplitudes of convergence perturbation increase with the source redshift as predicted by theoretical models.

Unique probe into mini-halos $M<10^6$ solar mass.
Future work

- Consistency check using light-ray tracing simulations
- Minimum change in astrometric shift for lensed image & lens.
- Check of SIE+ES, luminous group/satellite galaxies
- Extention to radio lenses incorporating finite source-size effects