Substructure in lens galaxies: first constraints on the mass function

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How do we probe the small scales beyond the Local Universe and independently from baryons?

Using strong gravitational lensing!

Independent of the baryonic content
Independent of the dynamical state of the system
Only way to probe small satellites at high redshift
Substructure Effect

How do we recognise the effect of substructure?

Extended galaxy
Bayesian grid-based gravitational imaging
Potential corrections

\[ \psi(x, \eta) = \psi_s(x, \eta) + \delta \psi(x) \]

\( \psi_s(x, \eta) \) Families of (elliptical) parametric models

\( \delta \psi(x) \) Potential corrections, pixelized on a Cartesian grid. Signature for substructure or general features that are not part of the parametric model.

Conservation of surface brightness allows us to express the lens mapping as a set of linear equations:

Vegetti S., Koopmans L. V. E., 2009a
A Simulated Example


\[ \rho_{\text{sub}} \propto r^{-2} \left( r^2 + a^2 \right)^{-1} \]

\[ M_{\text{sub}} = 3.0 \times 10^9 M_\odot \]
Multiple Substructures

Blind test with simulated lens systems containing multiple massive substructures

Substructures are drawn randomly from a mass function.
Substructure Statistics
Statistics of Detection

Constraining the substructure mass fraction and mass function

\[ \frac{dN}{dm} \propto m^{-\alpha} \]

\[ \mathcal{L}(n_s, m | \alpha, f, p) = \frac{e^{-\mu(\alpha, f, < R)}}{n_s!} \mu(\alpha, f, < R)^{n_s} \prod_{i=1}^{n_s} P(m_i, R | p, \alpha) \]

\[ P(\alpha, f | \{n_s, m\}, p) = \frac{\mathcal{L}(\{n_s, m\} | \alpha, f, p) P(\alpha, f | p)}{P(\{n_s, m\} | p)} \]
Statistics of Detection

Constraining the substructure mass fraction and mass function

\[ P (\alpha, f \mid \{n_s, m\}, p) = \frac{\mathcal{L}(\{n_s, m\} \mid \alpha, f, p) P (\alpha, f \mid p)}{P (\{n_s, m\} \mid p)} \]

Results depend on:

- The mass function slope
- The mass fraction of substructure
- Number of galaxies in the survey
- Mass-detection threshold, i.e smallest mass you can detect
- Error on the substructure mass measurement/Prior on mass slope
Statistics of Detections: Changing the Mass Fraction

Vegetti S., Koopmans L. V. E. 2009b

Constraining the substructure mass fraction and mass function

Systems with 10 lenses
Statistics of Detections: Changing the Detection Limit

Systems with 10 lenses
Statistics of Detections: Changing Survey Parameters

$N_{\text{lens}} = 10$

$N_{\text{lens}} = 30$

$N_{\text{lens}} = 200$

$M_{\text{low}} = 0.3 \times 10^8$

$M_{\text{low}} = 1.0 \times 10^8$

$\sigma = \frac{M_{\text{low}}}{3}$
Summary:

- Substructure detection threshold $3 \times 10^8 M_\odot$, 30 lenses and true dark-matter mass fraction is 1.0%:
  
  \[ f < 1.0\% \text{ (95\% CL)} \]

- Substructure detection threshold $3 \times 10^8 M_\odot$, 200 lenses and true dark-matter mass fraction is 0.5%:
  
  \[ f = 0.5\pm0.1\% \text{ (68\% CL)} \]
  \[ \alpha = 1.90\pm0.2 \text{ (68\% CL).} \]

- Constraining the mass function slope requires a high number of detected substructures ~ 10.
J12602+514229

Power Law + density corrections
The SLACS Survey

SLACS:
- Lens selected
- Spectroscopy-selected
- Uniform lens-galaxy criteria: E/S0
- Emission-line selection
- Blue star-forming source provides good lens/source contrast
- State of the art: few $\times 10^5$ targets
- Lensing rate: $\sim 1/2000$
- Results: $\sim 100$ confirmed lenses

Bolton A. S. et al. 2006
Two concentric ring-like structures

Dark-matter fraction: $f(<R_{eff}) = 73\% \pm 9\%$

Expected number of mass substructure from CDM paradigm within $\Delta R = R_{ein} \pm 0.3$

$$\mu(\alpha = 1.90, f = 0.3\%, R \in \Delta R) = 6.46 \pm 0.95$$

If $f \sim 5\%$ (Dalal & Kochanek 2002), the expectation values for mass substructure is $\sim 50$ substructures
Single Power-Law model + Potential Corrections

Results are stable against changes in the PSF, lens galaxy subtraction, number of pixels, pixel scale and rotations

\[ \int k(r) \, dr = 0 \]
**J0946+1066 - Double ring**

Power-Law smooth model + Power-Law substructure

\[ \Delta \log E = -128.0 \]

\[ M_{\text{sub}} = (3.51 \pm 0.15) \times 10^9 M_\odot \]

\[ r_t = 1.1 \text{ kpc} \]

\[ \Delta \log E = -128.0 \]

equivalent to a \(~16\sigma\) detection

\[ M_{3D}(< 0.3) = 5.83 \times 10^8 M_\odot \]
Work in Progress
The SHARP survey
The Goals:

- search for evidence of mass substructure in cosmologically distant galaxies
- built up information on the substructure mass function and the dark matter mass fraction in substructure
- compare with prediction from simulations

The Tools:

- gravitational lensing imaging technique
- high angular resolution imaging
First Applications to SHARP
Radio Source at $z_s = 2.059$ with a Infrared Einstein ring lensed by an early-type galaxy at $z_l = 0.881$. 

Lagattuta et al. 2012
Vegetti et al. 2012

AO

HST + Merlin

King et al. 1998
$B1938+666$  

Keck K-band  

$M \approx 1.7 \times 10^8 M_\odot$
B1938+666

Keck H-band

\[ M \approx 1.7 \times 10^8 M_\odot \]
B1938+666

HST

\[ M \approx 1.7 \times 10^8 M_\odot \]
B1938+666

Substructure as a truncated pseudo Jaffe

\[ M_{\text{sub}} = (1.9 \pm 0.1) \times 10^8 M_\odot \]

\[ M(< 0.6) = (1.15 \pm 0.06) \times 10^8 M_\odot \]

\[ M(< 0.3) = (7.24 \pm 0.6) \times 10^7 M_\odot \]

Substructure as SIS

\[ M(< 0.3) = 3.4 \times 10^7 M_\odot \]

\[ \sigma_v \approx 16 \text{ km s}^{-1} \]

\[ V_{\text{max}} \approx 27 \text{ km s}^{-1} \]

\[ \Delta \log E = 65.0 \quad 12 \sigma \text{ detection} \]
Substructure mass function
\( B1938+666 + \text{double ring} \)

\[
P(\alpha, f \mid \{n_s, m\}, p) = \frac{\mathcal{L}(\{n_s, m\} \mid \alpha, f, p) P(\alpha, f \mid p)}{P(\{n_s, m\} \mid p)}
\]

Within the inner 5 kpc

\[
f = 3.33^{+3.64}_{-1.81} \%
\]

\[
\alpha = 1.06^{+0.56}_{-0.44}
\]

\[
f = 1.21^{+0.6}_{-0.6} \%
\]

\[
\alpha = 1.87^{+0.08}_{-0.04}
\]

\( f_{CDM} \approx 0.1\% \quad \alpha_{CDM} = 1.9 \)
The major source of systematic error is de-projection of the substructure position within the host galaxy.

De-projection yields a systematic uncertainty on the total mass of 0.3 dex at the 68 per cent confidence level.

Probability of $M$ under the assumption that the satellites follow the host galaxy mass distribution.

Contamination from LOS interlopers is also possible:

Chen et al. 2009: 1-10 \%
Conclusions

- Surface brightness anomalies can be used to find low mass galaxies at high $z$.
- Simulations show that with HST quality data, 10 systems are sufficient to constrain the mass function.
- Using high resolution adaptive optics data and the gravitational imaging technique we discovered an analogue of the Fornax satellite at redshift about 1.
- The first constraints on the mass function are consistent with prediction from CDM (large errors ....)
- LOS contamination is not necessarily bad.