Hot, massive, and awfully complicated
Measuring the mass of the merging cluster 1E0657-56 using strong and weak gravitational lensing

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4th Aug 2006
The world of clusters as viewed by...

Roger in 2006 in Leiden

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- Unique case of a major supersonic cluster merger occurring nearly in the plane of the sky ($i < 15^\circ$, Markevitch et al. 2002).
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0.5 Ms Chandra data

- Using the gas density jump at the shock they derived a shock Mach number of $3.2 \pm 0.8$, which corresponds to a subcluster velocity $4500 \pm 1100 - 800$ km s$^{-1}$.
- "How Rare is the Bullet Cluster?" (Hayashi and White 2006). Rare, but not exceptionally.
- The peak of the density of the cluster galaxies is offset from the X-ray halo at 3.4 $\sigma$ significance. ⇒ Where is the dark matter?
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⇒ Where is the dark matter?
The idea of combining weak and strong lensing not new (e.g. Natarajan and Kneib 1996; Abdelsalam et al. 1998; Kneib et al. 2003; Diego et al. 2005; Cacciato et al. 2005).

We combine strong and weak lensing constraints in a “non-parametric” fashion (parametrisation as general as possible).

Need to properly include weak lensing constraints in the vicinity where multiple images form (and the lens is not weak any longer).

Include redshift information for strong (and weak) lensing sources (helps breaking the mass-sheet degeneracy).

Bradač et al. (2006) and Bradač et al. (2005).
Strong and weak lensing united

- Following the idea of Bartelmann et al. (1996) we parametrise the lens by considering the values of the potential $\psi_k$ on a regular grid.
- The penalty function includes weak lensing (extended to the cluster centre), strong lensing and regularisation.

$$\chi^2(\psi_k) = \chi^2_\epsilon(\psi_k) + \chi^2_M(\psi_k) + \eta R(\psi_k).$$  \hspace{1cm} (1)

- Start from some trial solution, linearise and iteratively solve the equation

$$\frac{\partial}{\partial \psi_k} \chi^2(\psi_k) = 0. \hspace{1cm} (2)$$
Strong and weak lensing united

Data typical of ACS imaging we use
SW United and the bullet cluster

1. Identify arcs, model them separately, however only to determine redshifts.
2. Weak lensing data → measure ellipticities of background sources.
3. Combine both data sets in a reconstruction.
Strong lensing - “awfully complicated” bit

- Search for multiply imaged sources - conserved colours, surface brightness, morphology information, redshift information.
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- Multi-colour ACS data (F435W - 1 orbit, F606W - 2 orbits, F815W - 2 orbits) of the subclump region.
- Single-band ACS data (F606W - 2 orbits) of the main cluster region.
- Wealth of arc(lets). Difficult to model - no colour information for counter images for the main system, two dominant components.
- Shallow blue band.
- Only one arc system with a spectroscopically confirmed redshift.

Strong and weak lensing united for 1E0657-56, Leiden Aug 2006
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Strong lensing
The bullet cluster

Parametrised models

Strong lensing

Strong and weak lensing united for 1E0657-56

GL, Leiden Aug 2006
Strong and weak lensing united for 1E0657-56

GL, Leiden Aug 2006
Weak lensing data

- Weak lensing catalogs of ACS data.
- The PSF shape changes as a function of position, radius (see e.g. Heymans et al. 2005) and time. We therefore match the radius used to measure the stellar correction factors with that for the galaxies.
- PSF issues not crucial for a single cluster mass reconstruction.
- High density of background sources.
Mass distribution
Mass distribution

Weak and strong lensing data
Mass distribution

Chandra data + SWunited
Mass distribution - in numbers

- Only the combination of weak+strong lensing allow us to derive a high-resolution, absolutely calibrated mass map, with no assumptions on the physical properties of the underlying cluster potential.

- Projected, enclosed mass
  \[ M_{\text{main}}(< 250 \text{ kpc}) = (2.8 \pm 0.2) \times 10^{14} M_\odot \]
  \[ M_{\text{sub}}(< 250 \text{ kpc}) = (2.3 \pm 0.2) \times 10^{14} M_\odot \]

- Assuming an isothermal profile (do you actually believe this assumption?)
  \[ \sigma_{\text{main}} = (1400 \pm 100) \text{ km s}^{-1} \]
  \[ \sigma_{\text{sub}} = (1200 \pm 100) \text{ km s}^{-1} \]
Mass distribution - profile

- The integrated mass profile (fit $\kappa(r) \propto r^{-n}$, $n_{\text{main}} = 1.2$, and $n_{\text{sub}} = 0.9$):
Where have all the baryons gone?

10-σ and 6-σ significance
Dark matter properties

- Combining the Chandra data with lensing mass maps ⇒ place an upper bound on the dark matter self-interaction cross section \( \sigma/m < 1 \text{cm}^2 \text{g}^{-1} \) (Markevitch et al. 2004).
  
  ⇒ Significant offset between subcluster X-ray gas core and dark matter peak gives \( \frac{\sigma}{m} < 10 \text{ cm}^2 \text{g}^{-1} \).
  
  ⇒ Survival of the subcluster dark matter peak during interaction gives \( \frac{\sigma}{m} < 3 \text{ cm}^2 \text{g}^{-1} \).
  
  ⇒ No loss of mass from subcluster during interaction gives \( \frac{\sigma}{m} < 0.8 \text{ cm}^2 \text{g}^{-1} \).
Gas fractions
Dust bunny or high-z ($\gtrsim 6$) object?

Bright in IRAC (3.6µm blue, 4.5µm green, 8µm red) but detected at $< 3\sigma$ in I-band imaging.
Conclusions

- We have obtained tight constraints on mass-distribution in 1E0657–56 - most of the matter not where most of the baryons are!
- A unique cluster merger system - combining all possible data sets there is a lot to be learned - constraints on DM self interaction cross section, gas physics, cluster dynamics, merger history, ...
- Gravitational lensing is truly golden for this “golden lens”.
Conclusions

The double-black diamond of all clusters...
The evidence of MOND...

...at SFO airport...
Bibliography


