Gravitational Lensing and Dark Matter

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Jan. 30, 2014 (W3-2)
1. Strong Lensing & Dark Matter

2. Joint Weak & Strong Lensing Analyses
   - The Bullet (and similar) Cluster
   - Testing CDM Halo Profiles

3. Reminders
To first order, we can approximate the mass inside a gravitationally lensed area or ring as

$$M(\theta < \theta_{\text{ring}}) = \pi \theta_{\text{ring}}^2 D_{\text{OL}}^2 \Sigma_{\text{crit}}$$  \hspace{1cm} (1)$$

- For known clusters, this approximation is only accurate to within $20 - 40\%$, but it yields mass to light ratios of around $100 - 300$.
- This is still strong evidence that these clusters are dark matter dominated.
Strong Lensing Conclusions

- Despite the limitations of strong lensing we discussed last time, several significant conclusions can be drawn from it.
- The mass-to-light ratio inside of arcs and rings is $10^{-20}$ for galaxies and $100^{-300}$ for galaxy clusters.
- The mass-to-light ratio of galaxies increases with mass as well as radius.
- Galaxies seem to be baryon-dominated in their innermost regions.
- The total mass (dark and baryon) profiles of galaxies is very well modeled by an isothermal profile (i.e. $\rho(r) \propto r^{-2}$). For clusters, the situation is less clear, as we will see.
Weak & Strong Lensing Analyses

- Strong lensing provides highly detailed information about mass distributions where it occurs, but it is relatively rare.
- Weak lensing provides less detailed information but is applicable to all galaxy clusters.
- The most powerful and famous results regarding dark matter have been obtained by using both lensing regimes to determine the mass profiles of clusters from the innermost sections to the periphery.
What do you know about the bullet cluster?
Joint Weak & Strong Lensing Analyses

The Bullet (and similar) Cluster

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Gravitational Lensing & DM

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Figure: Left: color image from the Magellan images of the merging cluster 1E0657−558, with the white bar indicating 200 kpc at the distance of the cluster. Right: is a 500 ks Chandra image of the cluster. Shown in green contours in both panels are the weak lensing $\kappa$ reconstruction with the outer contour level at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the $\kappa$ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels (astro-ph/0608407).
Top: Central region of Abell 520, with the diffuse Chandra X-ray emission (red), lensing mass density (blue), and galaxies confirmed to be part of the cluster marked with an X.

Bottom Left: Visible light distribution together with lensing contours

Bottom Right: Same as left but with X-ray contours.

Both clusters show a similar pattern: the hot X-ray emitting gas was stripped out of the clusters by the collision, but the mass (as traced by gravitational lensing) is aligned with the galaxies.

Since there is far more mass that light (and X-ray emissions) in these clusters, the dark matter appears to have followed the galaxies.

This is powerful evidence of the existence of dark matter and one of its properties: collisionlessness. In particle physics terms, this means a zero (or very small) cross-section $\sigma$. 
Conclusions

- Like the other clusters, the mass-to-light ratio is \( \sim 200 \), although the ratio in the “dark core” (peak 3) is \( \sim 700 \).
- Unlike the other clusters, the mass seems to be concentrated in a dark core that is aligned with the X-ray emitting gas but devoid of galaxies.

Possible Explanations

- This cluster was produced by a multiple merger resulting in a more complex structure.
- Dark matter does experience collisions.
Cross-sections

Galaxies and stars can be treated as collisionless on these scales because their separation is so large compared to their size. Since the mass moves with the galaxies and stars, except for Abell 520, several groups have calculated upper limits on the self-interaction cross-section of dark matter. In the case of Abell 520, the authors calculate a cross-section with uncertainties.

<table>
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<tr>
<th>$\sigma/m$ ($\text{cm}^2\text{g}^{-1}$)</th>
<th>Reference</th>
<th>Cluster/Galaxy</th>
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<tr>
<td>$&lt; 1.25$</td>
<td>arXiv:0704.0261</td>
<td>1E0656-56</td>
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<td>$&lt; 4$</td>
<td>arXiv:0806.0261</td>
<td>MACS J0025.4-1222</td>
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<td>$3.8 \pm 1.1$</td>
<td>arXiv:0706.3048</td>
<td>Abell 520</td>
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<td>$&lt; 0.02$</td>
<td>arXiv:astro-ph/0002050</td>
<td>MS2137-23</td>
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<td>$&lt; 0.1$</td>
<td>arXiv:astro-ph/0011405</td>
<td>MS2137-23</td>
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Dark Matter Halo Mass Profiles

- We can use the information gained from gravitational lensing and velocity distributions to determine the mass distributions (or profiles) of dark matter in halos.
- Numerical simulations based on our understanding of dark matter make predictions about the shapes and parameters of these distributions.
- Comparing the simulated distributions to the data can support or refute our hypotheses about dark matter.
- The mass profiles obtained from several clusters do not produce particularly consistent results.
Navarro, Frenk, and White (NFW) profile

The NFW profile is the most popular mass profile. It occurs in many numerical simulations and is parameterized as a density $\rho$ varying with radius $r$ of the halo:

$$
\rho(r) = \frac{200}{3} \frac{c_{200}^3}{\ln(1 + c_{200}) - c_{200}/(1 + c_{200})} \frac{\rho_{\text{crit}}(z)}{(r/r_s)(1 + r/r_s)^2}
$$

- $\rho_{\text{crit}}(z)$ is the critical density of the Universe at redshift $z$
- $c_{200} = r_{200}/r_s$ is the “concentration parameter”
- $r_{200}$ is the radius at which the halo density is $200\rho_{\text{crit}}(z)$
- $r_s$ is a scale radius that varies from halo to halo
- $M_{200}$ is also seen; it represents the mass within $r_{200}$

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Figure: In cluster Cl0024+1654, an NFW profile is the most likely fit, with the parameters shown above (Astrophys. J. 598 (2003) 804).
Figure: In a collection of galaxies imaged with the Hubble Telescope, the joint dark and luminous mass profile is well fitted by an isothermal profile $\rho(r) \propto r^{-2}$, while the NFW is only a good fit for the calculated dark matter component (astro-ph/0701589).
Figure: In cluster Abell 1689, a power law with exponent $-3.16$ is the best fit, with an NFW profile also doing well. An isothermal profile $\rho(r) \propto r^{-2}$ is ruled out. (Astrophys.J. 619 (2005) L143, astro-ph/0412192)
Discussion

- Gravitational weak and strong lensing provides powerful evidence of mass that is not luminous.
- The exact nature and distribution of dark matter are not yet fully understood on the scale of galactic clusters.
- The distribution of dark matter may not be consistent from cluster to cluster.
- These are unsolved problems that physicists and astrophysicists are currently pursuing.
Reminders

- All midterm presentation topics have been chosen.
  - Doug Tiedt: MaCHOs (Feb. 27)
  - Dan Rederth: Sterile Neutrinos
  - Tyler Bogwardt: Modified Gravity
  - Hari Chapagain: Axions
- Choose your topic for final presentation on or before Feb. 20
- Since we have no USD students, for most of the rest of the semester we will be in CB 110, except February 27 and April 3, when we will be back in CB 108.