Constraining Dark Matter Equation of State with CLASH Clusters

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The Equation of state

No direct observations of the EoS have been carried out to confirm the assumption of DM to be pressureless. Bharadwaj & Kar (2003) first proposed that combined measurements of rotation curves and gravitational lensing could be used to determine the equation of state of a galactic fluid.

Equation of State

\[ w = \frac{p_r + 2p_t}{c^2 3\rho} \]

Radial Pressure profile

\[ \frac{8\pi G}{c^4} p_t(r) = -\frac{2}{r^2} \left[ \frac{m(r)G}{c^2r} - r \tilde{\Phi}'(r) \left( 1 - \frac{2m(r)G}{c^2r} \right) \right] \]

Tangential Pressure profile

\[ \frac{8\pi G}{c^4} p_t(r) = -\frac{G}{c^2r^3} \left[ \frac{m'(r)r - m(r)}{c^2r^3} \right] \left[ 1 + r \tilde{\Phi}'(r) \right] + \cdots \]

\[ + \left[ 1 - \frac{2m(r)G}{c^2r} \right] \left[ \frac{\tilde{\Phi}'(r)}{r} + \tilde{\Phi}'(r)^2 + \tilde{\Phi}''(r) \right] \]

Density

\[ \int 4\pi \rho(r)r^2 = m(r) \]
Potentials and Mass profiles

**Kinematic approach**

- In the weak field approximation $\nabla^2 \Phi \approx -R_{tt}$

$$m_K(r) = \frac{r^2}{G} \Phi'_K \approx \frac{4\pi G}{c^2} \int (c^2 \rho + p_r + 2p_t) r^2 \, dr$$

- Using the Jeans equation

$$m_K(< r) = -\frac{r \sigma_r^2}{G} \left[ \frac{d \ln \rho_n}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

**Lensing approach**

- Apply Fermat’s principle to the time-like geodesics

$$\delta \int_{q_1}^{q_2} n(r) \left[ dr^2 + r^2 d\Omega^2 \right] = 0.$$ 

- Consider an effective refractive index

$$n(r) = 1 - \Phi(r) - \int \frac{m(r)}{r^2} \, dr + \mathcal{O} \left[ \left( \frac{2m}{r} \right)^2, \frac{2m}{r} \Phi, \Phi^2 \right].$$

$$\Phi(r) = \frac{G m_k}{r^2};$$

$$2 \Phi_{lens}(r) = \Phi(r) + \int \frac{m(r)}{r^2} \, dr$$

$$m(r) = 2m_{lens}(r) - m_k$$

Faber & Visser 2006, Lake 2004
The results of the methods described above show a good agreement between the measured profile and the real mass profile in the case of the simulated cluster, but it adopts an almost constant negative value for the real clusters of galaxies, however, consistent with the strong energy stress that a combination of several of them might be responsible for this apparent inconsistency.

It should be mentioned that the cluster of galaxies CL0024 experienced a merger along the l.o.s. (Czoske et al. 2002) approximately 2–3 Gyr ago. Nevertheless, the good agreement between the kine-matic mass profile computed and the Ota et al. (2004) hydrostatical mass profile computed and the Ota et al. (2004) hydrostatical mass profile computed is effective in estimating the mass profile in the outskirts, but it tends to explain the features we have shown (Serra 2008), although we have modified the NFW parameters of the lensing mass, according to the caustic effect data.

CL 0024
- low quality lensing data
- low member number
- kinematical evidence of merging

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As for the triaxiality of the halo, we have tested the lack of sphericity by computing the anisotropy parameter \( \beta \) instead of the constant zero value required by CDM. We have modified the NFW parameters of the lensing mass, according to the caustic effect data. Nevertheless, the good agreement between the kine-matic mass profile computed and the Ota et al. (2004) hydrostatical mass profile computed is effective in estimating the mass profile in the outskirts, but it tends to explain the features we have shown (Serra 2008), although we have modified the NFW parameters of the lensing mass, according to the caustic effect data.
Galaxy cluster MACS J1206-0847 (z = 0.44)

Properties of MACS 1206:
- Relaxed (X-ray, kinematics)
- No strong elongation bias (X-ray and lensing predictions on mass profiles agree)
- Concentric distribution of different mass components
- High quality lensing and dynamical data (~600 spect members)

MACS 1206 is ideally suitable for testing the Equation of State of cluster fluid

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Combining different mass profile determinations

- The best fit of the Caustic analysis agrees with the MAMPOSSt analysis within the 1σ error bars.
- The NFW model provides a good fit to the Caustic analysis.
- Combining the MAMPOSSt and Caustic analyses allows us to reach an accurate description of the mass profile.
- Error ellipses and confidence regions are consistent with the derived values.

**Projected mass profiles:**
- X-ray: Black dashed line
- Lensing (Weak + Strong): Pink dotted line
- Kinematic (NFW): Yellow line

**Graph:**
- The top panel shows the projected mass profiles $M_p(R)$ in $10^{14} M_\odot$.
- The bottom panel shows the ratio $M_{p,\text{kin}} / M_{p,\text{lensing}}$.
- The vertical line indicates $R = 0.5$ Mpc.

**References:**
- De Boni et al. (2013) for relaxed halos.
- Bhattacharya et al. (2013) for relaxed (resp. all) halos.
- Van Dokkum et al. (2013) for the passive population of cluster members.
- There is observational support that this assumption is verified (on a scale).
Constraining Dark Matter Equation of State

\[ w(r) = \frac{p_r(r) + 2p_t(r)}{3\rho(r)} \approx \frac{2}{3} \frac{m'_K(r) - m'_{lens}(r)}{2 m'_{lens}(r) - m'_K(r)} \]

Results obtained using different profiles for \( M_K \):

- **NFW** $\beta=O$ (blue curve)
- **NFW** $\beta=T$ (magenta curve)
- **NFW** $\beta=C$ (green curve)

Averaging over all radii

\[ w = -0.05 \pm 0.03 \text{ (stat)} \pm 0.1 \text{ (syst)} \]

for the NFW $\beta=O$ model.
Constraining Dark Matter Equation of State

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for the NFW \(\beta=O\) model.
Conclusions

- By using high quality kinematic and lensing mass analysis of MACS 1206 cluster we have obtained the most stringent constraint on DM EoS to date.

\[ w = -0.05 \pm 0.03 \text{ (stat)} \pm 0.1 \text{ (syst)} \]

- CLASH - VLT final sample will provide the mass estimates for 12 clusters allowing us to further reduce the uncertainties on the DM Equation of state and control the systematics.

- The possibility of non-negligible pressure fluid introduces a new free parameter into the analysis of combined kinematic and lensing observations.