Testing LCDM Predictions with Cluster Lensing in the ELT Era

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Galaxy clusters

- Largest self-gravitating objects formed in the universe
- Dominated by dark matter (DM)
- Can be observed with various ways:
  - Optical/NIR
  - X-ray
  - Radio (Sunyaev-Zel’dovich effects)
  - Gravitational lensing
Clusters as DM probes

• Standard paradigm for structure formation
  – Collisionless, cold DM (CDM)

• Clusters offer fundamental tests of assumed DM properties:
  – DM density profile shape, $\rho(r)$
  – Concentration-mass relation
  – Phase-space distribution of DM
  – Triaxial halo shape
  – DM offset
  – Substructure distribution

Diemer & Kravtsov 14

Bullet Cluster (Clowe+04)
Ensemble cluster mass profile from lensing

- Combining strong and weak lensing allows measurements of cluster total mass profiles over a wide dynamic range ($R_{\text{min}} = 40 \text{kpc}/h$).

- The stacked ensemble profile is well described by cuspy, outward steepening density profiles as predicted for CDM-dominated halos.

- Halo concentration in good agreement with recent LCDM simulations
Possible science cases for ELTs

1. **Cluster DM peculiar velocity from lensing**
   - High velocity precision spectroscopy (sub km/s) of background galaxies/QSOs strongly lensed by clusters

2. **Splashback features in phase space**
   - Spectroscopic survey of member galaxies in targeted clusters: e.g., massive clusters with high mass accretion rates (MAR)

3. **Granularity of galaxy-scale DM halos: CDM vs. ψDM**
   - High precision, high resolution photometry of QSO-galaxy strong lensing systems (lensing flux anomalies) with AO narrow-band imaging
(1) Cluster dark-matter peculiar velocity from the moving lens effect

Abundance of Bullet clusters

Pairwise velocity (extreme event) statistics of colliding clusters are sensitive to cosmology.

Juropa Hubble Volume simulation at $z=0.3$ (Watson+14)

Cluster collision in the sky plane

4.2σ kSZE toward B (3500km/s) in MACS0717 at $z=0.55$ (Sayers+13)

Inference of DM velocity requires hydrodynamical interpretation of gastrophysics in complex mergers
Moving lens effect (Birkinshaw & Gull 83)

Lensing-analog of the Rees-Sciama 68 effect

\[
\left( \frac{\Delta \nu}{\nu} \right) = -2 \int \dot{\Phi} dt
\]

Change of potential along photon path due to tangential lens motion

\[
\Delta_{\nu} \equiv \left( \frac{\Delta \nu}{\nu} \right)_{BG83} = -2 \int \mathbf{V}_\perp \cdot \nabla \perp \Phi dt \approx \mathbf{V}_\perp \cdot \hat{\alpha}
\]

Observable pairwise frequency shift between multiply lensed images

\[
(\Delta_{\nu})_{\text{pair}} = |\Delta_{\nu,1} - \Delta_{\nu,2}| \approx 2V_\perp \theta_E = 3 \times 10^{-6} \left( \frac{V_\perp}{3000 \text{km/s}} \right) \left( \frac{\theta_E}{30''} \right)
\]

\sim 1\text{km/s} \text{ velocity shift}
Total frequency shift

\[
\Delta_v(\theta_I) = \left[ \beta_L^T \mathcal{F}_L - \frac{D_{LS}}{D_{OS}} \beta_O^T - \frac{D_{OL}}{D_{OS}} \frac{1 + z_L}{1 + z_S} \beta_S^T \right] \cdot \alpha,
\]

with \( \beta_T = \frac{V}{c} \)

Observer and source motions are down-weighted by geometric factors (~10m/s)

Current best velocity centroid precision ~ 1km/s with X-Shooter on 8m VLT for lensed star-forming galaxies (Christensen+10)

Uncertainty in tangential velocity using \( N \) line features per source

\[
\frac{\sigma(\beta_T)}{\beta_T} = \frac{1}{\sqrt{N}} \frac{\sigma(\Delta_v)}{\Delta_v}
\]
Simulated DM flow centered on the Bullet

FLASH (DM+gas) AMR simulation of the Bullet Cluster (Molnar+13)

\[ \mathbf{v}_\perp(\theta) \]

\[ \left( \frac{\Delta v}{v} \right) = \mathbf{v}_\perp \cdot \mathbf{\hat{a}} \]

Largest pairwise shift of \(~0.5\text{km/s}\) expected for the Bullet Cluster
(2) Splashback features in phase space

In collaboration with Teppei Okumura (ASIAA), Takahiro Nishimichi (IPMU), Ken Osato (Univ of Tokyo), Benedikt Diemer (CfA)
Splashback radius, $R_{sp}$: Physical halo boundary

- $r > R_{sp}$: infall region
- $r < R_{sp}$: multi-stream intra-halo region

Splashback radius depends on MAR, halo peak height, cosmology ($\Omega_m$)

**Slow accreting halos**

$R_{sp} > r_{200m}$

**Fast accreting halos**

$R_{sp} \sim r_{200m}$

*N-body simulations from S. More, Diemer, & Kravtsov 2015*
Splashback feature in real space

DM density steepening relative to Einasto/NFW

\[ R_{sp} \sim r_{200m} \] for high-mass forming halos

\[ \nu > 3.5, \text{ scaled by } R_{200m} \]

Halo edge, \( R_{sp} \)

\[ \gamma = \frac{d \log \rho}{d \log r} \]

\( z = 0 \)
- Einasto fit
\( z = 0.25 \)
\( z = 0.5 \)
\( z = 1 \)
\( z = 2 \)
\( z = 4 \)
\( z = 6 \)

\( \text{Einasto fit} \)

N-body simulations from Diemer & Kravtsov 2014 (DK14)
Cluster outskirts: DM vs. hot gas

Ensemble cluster halos from cosmological hydro simulations (*Omega*500, Lau+15)

Accretion shock radius, $<R_{\text{shock}}/r_{200m}> \sim 1.6$

DM splashback steepening

Gas density steepening

Collisional gas accretes slower than DM due to shocks and ram pressure, leading to 10% departures in gas/DM density ratio from the cosmic mean value

Lau et al. 2015
Splashback in SDSS cluster satellite galaxies

Projected galaxy distribution around SDSS/DR8 redMaPPer clusters (S. More+16)

![Cluster-satellite density correlation](image1)

- Steepest slope found at significantly smaller radius than predicted $R_{sp}/r_{200m} \approx 1.1$
- Projection effects in cluster membership identification (Zu+16; Busch & White 17)

Cluster-satellite density correlation

Logarithmic slope

\[
R_{sp}/r_{200m} = 0.84 \pm 0.03 \text{ at } M_{200m} = 1.9 \times 10^{14} M_{\odot}/h \quad (z = 0.24)
\]  
CLASH cluster lensing constraints on $R_{sp}$

Simultaneous model fit to “scaled” $\Sigma$ profiles of 16 X-ray-selected CLASH clusters

$R_{sp} / r_{200m} > 0.89 \, (1\sigma)$ at $M_{200m} = 1.3 \times 10^{15} M_{\odot} / h \quad (z = 0.34)$

Density steepening: Observations vs. simulations

![Graph showing density steepening comparison between observations and simulations. The graph plots $R_{sp}$ vs. peak height $\nu_{200m}$. The CLASH mass range is indicated by a blue arrow. The legend includes simulations from More et al. 2015, CLASH lensing from this work, and stacked galaxy surface density from More et al. 2016. The reference is Umetsu & Diemer 17, ApJ, 836, 231.]
Splashback feature in real & velocity space

Intrinsic Alignments and Splashback Radius of Dark Matter Halos from Cosmic Density and Velocity Fields

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We investigate the effects of intrinsic alignments (IA) of dark-matter halo shapes on cosmic density and velocity fields from cluster to cosmic scales beyond 100 $h^{-1}$ Mpc. Besides the density correlation function binned by the halo orientation angle which was used in the literature, we introduce, for the first time, the corresponding two velocity statistics, the angle-binned pairwise infall momentum and momentum correlation function. Using large-volume, high-resolution $N$-body simulations, we measure the alignment statistics of density and velocity, both in real and redshift space. We find that the alignment signal is not amplified by redshift-space distortions at linear scales. Behaviors of IA in the velocity statistics are similar to those in the density statistics, except that the halo orientations are aligned with the velocity field up to a scale larger than those with the density field, $x > 100 h^{-1}$ Mpc. On halo scales, $x \sim R_{200m} \sim 1 h^{-1}$ Mpc, we detect a sharp steepening in the momentum correlation associated with the physical halo boundary, or the splashback feature, which is found more prominent than in the density correlation. Our results indicate that observations of IA with the velocity field can provide additional information on cosmological models from large scales and on physical sizes of halos from small scales.

arXiv:1706.08860
Cluster-satellite correlations in simulations

\[ \xi_{gc}(x) := \left\langle \delta_g(r_1) \delta_c(r_2) \right\rangle \]

\[ \psi_{gc}(x) := \left\langle [1 + \delta_g(r_1)] [1 + \delta_c(r_2)] v^x_g(r_1) v^x_c(r_2) \right\rangle \quad \text{with } x = r_2 - r_1 \]

- Steepening in momentum correlation (slope \( \sim -5 \)) more prominent than in density correlation (slope \( \sim -4 \))
- Need high-resolution kSZE to measure \( \psi_{gc} \)

Okumura+17, arXiv:1706.08860


**Satellite velocity dispersion**

\[
\sigma_{v,gc} := \langle [1 + \delta_g (\mathbf{r}_1)][1 + \delta_c (\mathbf{r}_2)][v_g^z (\mathbf{r}_1) - v_c^z (\mathbf{r}_2)]^2 \rangle
\]

Accessible in principle from spectroscopic observations in projection

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Figure courtesy of Teppei Okumura

Okumura+17, arXiv:1706.08860
Stacked infall patterns in projected phase space

Stacked ensembles of 58 X-ray-selected clusters at 0.1<z<0.3 (Hectspec Cluster Survey with MMT) by Rines+13

Dynamical caustic: escape velocity

Projected radius, $R_p$ [Mpc/h]

Line-of-sight velocity, $v$ [$10^3$ km/s]

$\rho(r)$ ($h^2 M_\odot Mpc^{-3}$)

Rines et al. 2013
Halo edge in Superlens A1689

Phase-space identification of cluster edge radius, ~2.1Mpc/h, thanks to high density contrast of the superrich cluster A1689

Joint observations of splashback and accretion shock features?

Collisionless splashback features (~ $R_{sp}$)
- Steepening in satellite density
- Steepening in lensing signal
- Steepening in velocity caustic (+$\sigma_v$)

Accretion shock features (~ $R_{shock}$)
- Maximum peak in gas entropy @ $R_{shock}$
- Steepening in gas density

Theoretical requirements
- Quantitative understanding of splashback feature in phase space (e.g., Okumura+17)
- Establish the relation between DM and gas features from simulations (e.g., Lau+15, Diemer+17)
(3) Granularity of galaxy-scale dark matter halos: CDM vs. \( \psi \)DM


Hsi-Yu Schive (U of Illinois)
James Chan (NTU)
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Quantum fluid $\psi$DM in nonlinear regime: Numerical challenges

de Broglie $\lambda \sim kpc$ for astrophysical Bose-Einstein condensates with $m_B \sim 10^{-22}eV$

$\rightarrow$ Ultra-high resolution ($\lambda \propto 1/v$, 200km/s $\rightarrow$ 100pc) and extremely small time-step ($\Delta t \propto \Delta x^2$) are required!!
$\psi_{\text{DM}}$ vs. CDM: large scale features

$\psi_{\text{DM}}$ on AMR grid (GAMER)  
Particle CDM (GADGET-2)

Large scale structures indistinguishable from collisionless CDM

Schive, Chiueh, & Broadhurst 14
Nonlinear structure of wavelike $\psi$DM halos: Density granules and solitonic core
Granularity of ψDM halos

The halo density field is 100% modulated with ψDM, which is the most obvious difference from particle CDM and WDM

\[ M_{\text{halo}} \sim 1.6e11 M_{\text{sun}}, \; z=0.3 \]
\[ M_{DM}/M_* \sim 0.93 \text{ within } R_{\text{Ein}} \sim 0.9\text{kpc} \; (z_s=3) \]

Soliton core size ~ Halo granule size

The halo granule scale is set by the halo mass:

\[ \frac{M_{\text{core}}}{M_{\text{halo}}} \propto a^{-1/2} M_{\text{halo}}^{-2/3} \]

(Schive+14, PRL, 113, 261302)

- \[ M_{\text{core}} \sim 5x10^8 M_{\text{sun}}, \; r_{\text{core}} \sim 160\text{pc} \text{ for a Milky-Way-sized halo} \]
- Quantum effects less important for high-mass halos (e.g., clusters)
Predictions: Flux anomalies due to $\psi$DM halo granules

Lensing flux anomalies common for quasars strongly lensed by galaxies: $\mu_1+\mu_3-|\mu_2|$ should =0, but usually 10-50% residual

Caustic structure more complex in $\psi$DM – changing image brightness and positions on scale of ~0.1—1 kpc

High angular resolution, narrow-line imaging of QSOs with ELTs to avoid micro lensing

Figure courtesy of J. Chan, H.-Y. Schive, T. Chiueh
Summary

1. **Cluster DM peculiar velocity from the moving lens effect**
   - High velocity precision spectroscopy (sub km/s) of background galaxies/QSOs strongly lensed by clusters

2. **Splashback features in phase space**
   - Spectroscopic survey of cluster outskirts for splashback features in phase space, together with joint lensing and X-ray observations

3. **Granularity of galaxy-scale DM halos: $\psi$DM vs. CDM**
   - High precision, high resolution photometry of QSO-galaxy strong lensing systems with AO narrow-band imaging to test wavelike $\psi$DM vs. CDM