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# Galaxy-dark matter offsets in galaxy clusters / groups of the Illustris simulation

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**ABSTRACT**

**Key words:** galaxy clusters, dark matter, something else

## 1 INTRODUCTION

## 2 DATA

### 2.1 Test data from Gaussian mixture(s)

In order to examine the performance of commonly used point-estimates of the distribution of the galaxy data, we test them on Gaussian mixtures with known mean and variance. Fig 1. one Normal mixture
Fig 2. one big normal mixture and one smaller normal mixture
Fig 3. bridged normal mixtures

### 2.2 Data from the Illustris simulation

#### *2.2.1 Properties of the galaxy clusters / groups*

Most important properties of the galaxy clusters that we examine in this study include, colors, magnitude, richness and non-relaxedness. We defined and examined these properties one by one. Fig 4. Relaxedness Fig 5.

Richness characterizes the number of galaxies in a given cluster. We provide several definitions of non-relaxedness to characterize whether the clusters underwent any recent merger activities. These definitions of non-relaxedness

#### *2.2.2 Volume Selection*

1. Rockstar halo finder 2. Light cone 3. spatial projections

#### *2.2.3 Data with and without noise*

#### *2.2.4 Galaxy Selection*

#### *2.2.5 Galaxy weights*

1. Mass-richness diagram - with different cuts

## 3 METHODS

### 3.1 Galaxy Centers

#### *3.1.1 Unweighted and weighted centroids*

We follow the usual definition of spatial centroid as

$$\vec{x} = \frac{1}{n}\sum_i \vec{x}_i. \quad (1)$$

While the weighted centroids are just:

$$\vec{x} = \frac{\sum_i w_i \vec{x}_i}{\sum_i \vec{x}_i}, \quad (2)$$

for each spatial dimension $x$ and the weights $w_i$ for the $i-th$ galaxy is described in section. This estimator is sensitive to merging activities.

#### *3.1.2 Cross-validated Kernel Density Estimation (KDE) and peak finder*

We employed a KDE algorithm to infer a smooth density distribution of the galaxies while using smoothed cross-validation to obtain the optimal smoothing bandwidth matrices ($H$). Specifically, we made use of the statistical package ks (Duong) in the R statistical computing environment (R Core Team 2014). Cross validation eliminates the free parameters in the KDE and minimizes the asymptotic mean-integrated squared error (AMISE). After obtaining the KDE estimate, we employed a finite differencing algorithm to find the local maxima. We sorted the local maxima according to the KDE density at the maxima locations and identified the dominant peak.

#### *3.1.3 Shrinking aperture*

#### *3.1.4 Brightest Cluster Galaxies (BCG)*

### 3.2 DM Centers

### 3.3 Finding offsets

We computed the offsets between the galaxy density peaks inferred from the cross-validated KDE and the

## 4 RESULTS

### 4.1 Benchmark results from Gaussian mixtures

(We expect some of the existing point-estimates are quite crappy e.g. the shrinking aperture method, and will not use them for the Illustris data)

### 4.2 Galaxy-DM Offset in Illustris

#### *4.2.1 Permutation tests for computing the P-value*

## 5 DISCUSSION

### 5.1 Comparison to other simulations

### 5.2 Comparison to other observational studies

### 5.3 Galaxy-DM Offset in Merging Galaxy Clusters

## 6 ACKNOWLEDGEMENTS

## APPENDIX A: KDE