COSMOLOGY WITH CLUSTERS: FIRST RESULTS FROM HFF

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Collaborators

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• Massimo Meneghetti
Cosmology with cluster-lenses

Lensing tests of dark matter – comparison with LCDM simulations
Mass profiles of clusters: concentration
Substructure: abundance, profiles, spatial distribution
Density profiles of DM halos: inner and outer slopes
Shapes of dark matter halos
Higher order statistics: flexion, correlation function of substructure – pencil beam surveys, $P(k)$
Science by stacking

Lensing constraints on dark energy
Cosmography with strong lensing (CSL)
Triplet statistics

Lensing tests of the standard world model
Primordial Non-Gaussianity (Arc-statistics)
Growth of Structure and Structure Formation
FF CLUSTERS MACS0416 & Abell2744

Jauzac+ 2014a,b CATS
MAPPING SUBSTRUCTURE IN CLUSTER LENSES

\[ \Phi_{\text{cluster}} = \sum_i \Phi_{\text{smooth}} + \sum_n \Phi_{\text{perturbers}} \]

PN & Kneib 1997; PN+ 2005; 2009; 2011
Granularity of DM - substructure

dependence on the nature of DM

substructure is reduced – small halos are heated as they move through larger ones, and tend to dissolve and merge into the larger structure in all self-interacting dark matter models

\[
\frac{dn}{dm} \propto m^{-1.8}
\]

Comparison with LCDM simulations Millenium

Springel+ 05; PN, De Lucia & Springel 07; Gao & Theuns 2007; PN+2009
ILLUSTRIS

AREPO MOVING MESH CODE

DM ONLY RUN

FULL PHYSICS RUN

<table>
<thead>
<tr>
<th>name</th>
<th>volume</th>
<th>DM particles / hydro cells / MC tracers</th>
<th>$\epsilon_{\text{baryon}} / \epsilon_{\text{DM}}$</th>
<th>$m_{\text{baryon}} / m_{\text{DM}}$</th>
<th>$r_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illustris-1</td>
<td>106.5$^3$</td>
<td>$3 \times 1,820^3 \cong 18.1 \times 10^9$</td>
<td>710/1,420</td>
<td>12.6/62.6</td>
<td>48</td>
</tr>
<tr>
<td>Illustris-2</td>
<td>106.5$^3$</td>
<td>$3 \times 910^3 \cong 2.3 \times 10^9$</td>
<td>1,420/2,840</td>
<td>100.7/501.0</td>
<td>98</td>
</tr>
<tr>
<td>Illustris-3</td>
<td>106.5$^3$</td>
<td>$3 \times 455^3 \cong 0.3 \times 10^9$</td>
<td>2,840/5,680</td>
<td>805.2/4008.2</td>
<td>273</td>
</tr>
<tr>
<td>Illustris-Dark-1</td>
<td>106.5$^3$</td>
<td>$1 \times 1,820^3$</td>
<td>710/1,420</td>
<td>–/75.2</td>
<td>–</td>
</tr>
<tr>
<td>Illustris-Dark-2</td>
<td>106.5$^3$</td>
<td>$1 \times 910^3$</td>
<td>1,420/2,840</td>
<td>–/601.7</td>
<td>–</td>
</tr>
<tr>
<td>Illustris-Dark-3</td>
<td>106.5$^3$</td>
<td>$1 \times 455^3$</td>
<td>2,840/5,680</td>
<td>–/4813.3</td>
<td>–</td>
</tr>
</tbody>
</table>

The initial conditions assume a LCDM cosmology consistent with WMAP-9 measurements, from which a linear power spectrum is used to create a random realization in a periodic box with side length 75 Mpc/h = 106.5 Mpc, at a starting redshift of 127. A series of simulations are run at different resolutions, and a second set is run with only dark matter. The main simulation initially has $1820^3 = 6,028,168,000$ hydrodynamic cells, and the same number of DM particles and MC tracers (see table for more details, including mass resolutions and gravitational softening lengths). Evolving the main simulation to $z=0$ used 8,192 compute cores, a peak memory of 25 TB, and 19 million CPU hours.
Mapping substructure with the HST Frontier Fields

Jauzac+14 CATS

BEST FIT MODEL: d.o.f - 139, chi$^2$=2.04 and RMS = 0.69"

51 image families, 159 images, 2 large scale PIEMDs + 733 cluster galaxies
Comparison with Illustris LCDM clusters

The subhalo mass function
Comparison with Illustris LCDM clusters

The subhalo mass function
Comparison with Illustris LCDM clusters

The subhalo mass function
Comparison with Illustris LCDM clusters
Concentration-Mass Relation

Oguri+ 2011; Ishigaki+ 2014
Concentration-Mass Relation

\[ c_{\text{vir}} = \frac{14.5 \pm 6.4}{(1+z)} \left( \frac{M_{\text{vir}}}{1.3 \times 10^{13} \, h^{-1} M_\odot} \right)^{-0.15 \pm 0.13} \]

Bullock+ 2001
Hennawi+ 2007
Comerford & PN 2007
Einstein radii at multiple source redshifts

Ratio of the position of multiple images depends on mass distribution and cosmological parameters
\[ \theta = \beta + \alpha(\theta, \xi; M) \]
\[ \xi = \frac{D(0, z_1)D(z_1, z_s)}{D(0, z_s)} \equiv \frac{D_{01} D_{ls}}{D_{cs}} \]

For multiple images of the same source
\[ \beta_f = \theta_{f,i} - \nabla \varphi_M(\theta_{f,i}, \xi). \]

notation denotes the position of the \(i^{th}\) image of family \(f\)

Taking the ratio of 2 distinct families of multiple images
\[
\begin{pmatrix} D_{ls1} & D_{cs2} \\ D_{cs1} & D_{ls2} \end{pmatrix} \begin{pmatrix} \sum_{i=1}^{m} \nabla \phi_M(\theta_{1,i}) \\ \sum_{j=1}^{n} \nabla \phi_M(\theta_{2,j}) \end{pmatrix} = \begin{pmatrix} -m\beta_1 + \sum_{i=1}^{m} \theta_{1,i} \\ -n\beta_2 + \sum_{j=1}^{n} \theta_{2,j} \end{pmatrix}.
\]

\[ \Xi(z_1, z_{s1}, z_{s2}; \Omega_M, \Omega_X, w_X) = \frac{D(z_1, z_{s1}) D(0, z_{s2})}{D(0, z_{s1}) D(z_1, z_{s2})} \]

Gilmore & PN 08; D’Aloisio & PN 10
RESULTS FOR ABELL 1689

Mass model with 3 PIEMD potentials; 58 cluster galaxies
Bayesian optimization: 32 constraints, 21 free parameters;
RMS = 0.6 arcsec; 28 multiple images from 12 sources with
spec z, flat Universe prior

$0.1 \leq \Omega_M \leq 0.58; -1.57 \leq w_X \leq -0.85$

Broadhurst+ 05, Benitez+ 06; Halkola+ 06; Limousin+ 07
D’Aloisio & PN 10; Jullo & Kneib 09; Jullo+ 10
Cosmography with 100 multiple images

Optimized in the image plane with 242 image constraints (122 multiply imaged families)

\[ \Omega_M = 0.2395 \pm 0.0230 \]
\[ w_X = 0.9691 \pm 0.0348 \]
HFF COSMOGRAPHY

INPUTS NEEDED
Spectroscopic redshifts for as many multiple images
Central velocity dispersions for cluster galaxies
High fidelity mass models

KEY SYSTEMATICS
LOS SUBSTRUCTURE
Correlated LOS (infalling subclusters, filaments)
Uncorrelated LOS (primary contribution to the errors)

RELATING MASS TO LIGHT
Scatter in Scaling Relations

D’Aloisio & PN ’10, ’11, D’Aloisio, PN & Shapiro’14

MUSE Richard+ CATS, HST Grism GLASS