Modelling galaxy cluster evolution

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The standard model reproduces:
- the linear initial conditions
- IGM structure during galaxy formation
- large-scale structure today

Simulation of the standard model gives *precise* predictions for the:
- abundance
- internal structure
- assembly history
- spatial/peculiar velocity distributions
- merger rates of DM halos at all redshifts

How do galaxies form and evolve within this frame?

How do cluster environments affect galaxy formation and evolution?
Direct simulation of cluster/galaxy formation

- $M_{\text{tot}}^{(\text{Coma})} \sim 10^3 M_{\text{tot}}^{(\text{Milky Way})}$
  
  Simulating formation of Coma's galaxy population is $\sim 1000$ times harder than simulating the formation of the Milky Way

- The problem is made even harder by the strong effects of
  -- the intergalactic medium
  -- tidal stripping
  -- galaxy collisions and mergers
  -- AGN feedback
“Coma” $\log(M) = 15.2$

Dolag, Murante, Borgani (2010)

Simulations include cooling, star-formation, strong galactic winds, but no AGN effects

Of the “Coma” stars
42% are ICL
23% are the cD
35% are other galaxies

“Virgo” $\log(M) = 14.3$
Dolag, Murante, Borgani (2010)

\[ \log(M_*) \sim -1.6 \]

Dolag et al. (2009)

\[ \alpha \sim -1.6 \]
Puchwein et al. (2010)

“Virgo” model including AGN feedback.

Baryon content
70% of cosmic mean

60% of baryons in stars

65% of stars in the ICL

50% of galaxy stars in the cD
AGN feedback reduces cD luminosities to almost the observed values

The stellar fractions in the ICL exceed even the largest quoted observational values
The semi-analytic programme

- Follow the DM distribution with high-resolution simulations identify dark halos and subhalos at all times and build merger trees to describe their growth and internal structure.

- Treat baryonic physics within each DM object using simple physical models for processes such as:
  - gas cooling onto central galaxies
  - star formation within these central galaxies
  - central black hole growth
  - generation of winds through stellar and AGN feedback
  - production, expulsion and mixing of nucleosynthesis products

- Determine the efficiencies of these processes observationally by comparison of model output with appropriate data.
Millennium Run
2005

simulated the
formation/evolution of
$2 \times 10^7$ galaxies
simulated the formation/evolution of $2 \times 10^7$ galaxies from $z=10$ to $z=0$
393 papers making direct use of data from the MS (27-6-2011)
Most by authors unassociated with the consortium
Most based on the galaxy catalogues, particularly mock surveys
Limitations of the Millennium Simulation

• Limited modeling of *structure* of galaxies, gas components..

• Limited volume – too small for BAO work, precision cosmology

• Limited resolution – too poor to model formation of dwarfs

• No convergence tests – are galaxy results numerically converged?

• Only one (“wrong”) cosmology

• Users unable to test dependences on parameters/assumptions
Millennium-II (2008)

- Same cosmology
- Same N
- 1/5 linear size
- Same outputs/post-processing

Resolution tests of MS results and extension to smaller scales
Next generation galaxy formation models based on the MS and the MS-II jointly

Qi Guo et al 2011

• Implement modelling simultaneously on MS and MS-II

• Test convergence of galaxy properties near resolution limit of MS

• Extend to properties of dwarf galaxies

• Improve/extend treatments of “troublesome” astrophysics

• Adjust parameters to fit new, more precise data

• Test against clustering and redshift evolution
The stellar mass function of galaxies

Guo et al 2011

Note that the simulated mass function fits the data over 5 dex!
Scaling relations

Stellar mass – disk size

Stellar mass – bulge size

Stellar mass – gas metallicity

Tully-Fisher

SDSS

Tremonti

Tully-Fisher

Lee

Blanton/Geha

Springob
Mass-dependent galaxy clustering

Guo et al 2011

Note agreement of MS and MS-II

small scales too high

? disruption too inefficient?

σ₈ too big?

large scales good

MS-II

MS

SDSS/DR7
Evolution of stellar mass function

Lower mass galaxies $\log M_* < 10.5$ form too early.

Efficiency of star-formation is too high in lower mass objects at high $z$?

Guo et al 2011
$0.018 < z < 0.028$

SDSS data
Coma cluster with $R_{200}$

SDSS data

$0.018 < z < 0.028$
$h^{-1}\ \text{Mpc}$

MS cluster halos only
MS cluster galaxies in subhalos
Projected galaxy number density profiles of clusters

log $M_{\text{gal}} > 10.0$

14.0 < log $M_{\text{clus}} < 14.3$

Note: good agreement of MS with MS-II is only when orphans are included

Orphan treatment is physically consistent and needed to fit SDSS

Disruption efficiency too low near centre?
• Halos in simulations do not correspond to galaxies
  -- many galaxies are satellites within big halos

• Subhalos also do not correspond perfectly to galaxies
  -- the subhalos of many galaxies are prematurely destroyed
  -- this has both numerical and physical origins

• DM simulations alone, even at high resolution, cannot faithfully predict the galaxy distribution

![Graph showing galaxy, subhalo, and halo merger rates](image)
Stellar mass function of the most massive MS-II cluster

Guo et al 2011

\[ M_{\text{tot}} = 6 \times 10^{14} M_\odot \]

shape is very similar to the field stellar mass f'n

low mass slope is \( \alpha \sim 1.35 \)

see T. Lisker's talk
Massive E's form stars early but assemble late. Assembly is later in lower mass clusters.
Formation of a brightest cluster galaxy

De Lucia & Blaizot 2007
Suppression of star formation within rich clusters

Fraction of actively star-forming galaxies (i.e. $M_*>M_*/10^{11}$ yr) relative to the value “in the field”

SDSS data taken from Weinmann et al (2008)

Model data for 1000 clusters in the MS with $M_{\text{tot}}>2\times10^{14}$ $M_\odot$

black line DLB07
red line Guo et al (2011)

Suppression of star-formation still too efficient?
Diffuse intracluster light in groups and clusters

Guo et al 2011

Fraction of all stars within $R_{200}$ in the ICL

Fraction of cD+ICL stars in the ICL

Disruption producing ICL too inefficiently?

see talks by G. De Lucia and M. Arnaboldi
The Millennium Run Observatory
(Overzier, Lemson, et al. in prep.)

- Lightcones can now be pointed at arbitrary objects at any z (e.g. CLUSTERS)

- Sky-projected angular size, inclination & PA (from z, radius, ang. mom., and l.o.s.)

- IGM absorption: corrected observed-frame magnitudes (important for high-z)

- Telescope Simulator: Realistic simulated images (with proper PSF, rms, pix scale, ...)
(modified version of Skymaker (Bertin 2007) plus custom code)

- Choice of spectral synthesis models (e.g., BC03 vs. M05)

- Scalable cosmology (e.g., WMAP 1 vs. WMAP 7)

- Open-access database implementation (expected late 2011)
Inserting the Disks...
Inserting the Bulges...
Putting it all together...


```
M_{200} = 4 \times 10^{15} M_{\odot}

z = 0.02

1^\circ \times 1^\circ

SDSS g, r, I

54 sec/filter
```

“Coma”
“Coma”

\[ M_{200} = 4 \times 10^{15} M_\odot \]

\[ z = 0.41 \]

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000sec/filter
“Coma”

\[ M_{200} = 4 \times 10^{15} M_\odot \]

\[ z = 0.41 \]

\[ 3.4' \times 3.4' \]

HST/ACS
F475W, F625W, F850LP

10,000 sec/filter
C10024
Harsono & De Propris
2007

z = 0.40

3.4' x 3.4'

HST/ACS
“Coma”

$M_{200} = 4 \times 10^{15} M_\odot$

$z = 0.83$

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000 sec/filter
“Coma”

$M_{200} = 4 \times 10^{15} M_\odot$

$z = 0.83$

$3.4' \times 3.4'$

HST/ACS
F475W, F625W, F850LP

10,000 sec/filter
MS1054

Blakeslee et al 2006

$z = 0.83$

$3.4' \times 3.4'$

HST/ACS
“Coma”

$M_{200} = 4 \times 10^{15} M_\odot$

$z = 1.50$

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000 sec/filter
“Coma”

\[ M_{200} = 4 \times 10^{15} M_\odot \]

\[ z = 1.50 \]

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000 sec/filter
RCDS1252

Demarco et al 2007

$z = 1.24$

$3.4' \times 3.4'$

HST/ACS
Virgo

$M_{200} = 2 \times 10^{14} M_\odot$

$z = 0.005$

$4^\circ \times 4^\circ$

SDSS g, r, I

54 sec/filter
Virgo

$M_{200} = 2 \times 10^{14} M_{\odot}$

$z = 0.41$

$3.4' \times 3.4'$

HST/ACS
F475W, F625W, F850LP

10,000 sec/filter
“Virgo”

$M_{200} = 2 \times 10^{14} M_\odot$

$z = 0.41$

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000 sec/filter
“Virgo”

\[ M_{200} = 2 \times 10^{14} M_\odot \]

\[ z = 0.83 \]

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000sec/filter
“Virgo”

$M_{200} = 2 \times 10^{14} M_\odot$

$z = 0.83$

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000 sec/filter
“Virgo”

$M_{200} = 2 \times 10^{14} M_\odot$

$z = 1.08$

$3.4' \times 3.4'$

HST/ACS
F475W, F625W, F850LP

10,000 sec/filter
“Virgo”

$M_{200} = 2 \times 10^{14} M_\odot$

$z = 1.08$

3.4' x 3.4'

HST/ACS
F475W, F625W, F850LP

10,000 sec/filter
Concluding remarks

- New techniques enable simulation of the full galaxy population within the current standard $\Lambda$CDM paradigm

- Comparison with observed populations produces measurements of the efficiency and mass/redshift/Z dependences of e.g.
  - sequestration of baryons in galaxies
  - driving of winds
  - quiescent vs merger driven growth of galaxies/BH's
  - galaxy disruption
  - enrichment of the ICM/IGM

- When comparing with nearby clusters and their high-z analogues, current models appear
  - too efficient at making stars at early times in lower mass halos
  - too efficient at suppressing star formation after satellite infall
  - too inefficient at disrupting galaxies to make the ICL