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Simulation of Isolated Clusters to Investigate the Fate of Dwarf Galaxies and the Origin of Intracluster Stars

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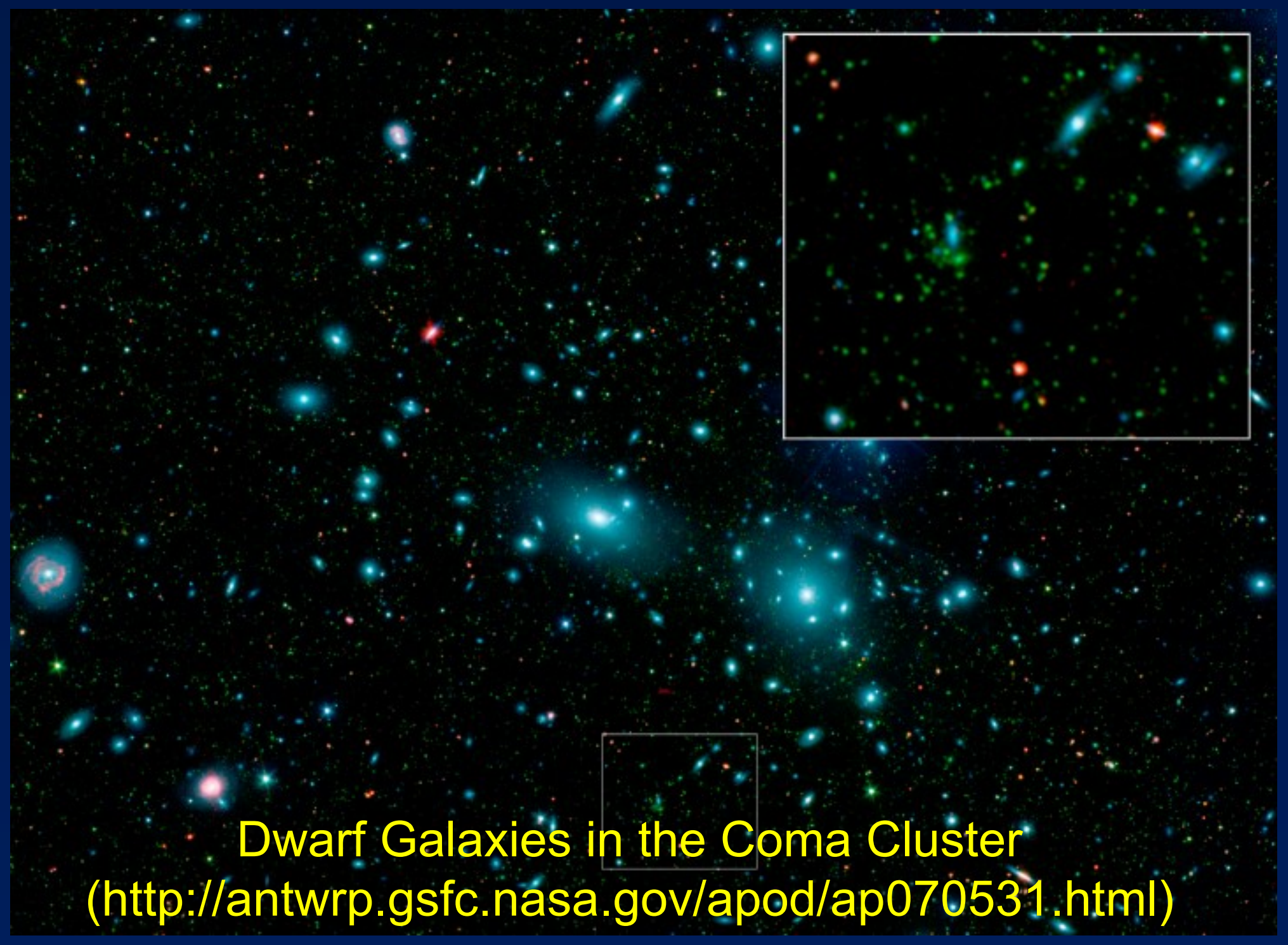


Dwarf Galaxies in the Coma Cluster
(http://antwrp.gsfc.nasa.gov/apod/ap070531.html)

Galactic Collision in Cluster Abell 1185
(http://antwrp.gsfc.nasa.gov/apod/ap051122.html)

Abstract

Our main goal of this work is to compare the relative importance of destruction by tides, vs. destruction by mergers, in order to assess if tidal destruction of dwarf galaxies in clusters is a viable scenario for explaining the origin of intracluster stars. We have designed a simple algorithm for simulating the evolution of isolated clusters. The distribution of galaxies in the cluster is evolved using a direct gravitational *N*-body algorithm combined with a subgrid treatment of physical processes such as mergers, tidal disruption, and galaxy harassment. Using this algorithm, we have performed a total of 227 simulations. Our main results are (1) destruction of dwarf galaxies by mergers dominates over destruction by tides, and (2) the destruction of dwarf galaxies by tides is sufficient to explain the observed intracluster light in galaxy clusters.

Introduction

Dwarf Galaxies

- Low-mass (10^7–10^9 $M_\odot$), low surface brightness
- Most numerous galaxies in the Universe
- Observed in galaxy clusters

Intracluster Stars

- Diffuse light, outside galaxies, within cluster
- Observed in several clusters
- Origin & evolution not well constrained

Goals

- Investigate dominating destruction scenario of dwarf galaxies in clusters: mergers or tidal disruption
- Contribution of tidally destructed dwarf galaxies on the origin of intracluster stars

Procedures

- Numerical simulations of galaxy clusters
- Direct *N*-body computation of gravitational interactions using a particle-particle (*P–P*) algorithm
- Subgrid treatment of other physical mechanisms (merger, tidal disruption, accretion, etc.) of the galaxies

Our System

- Isolated galaxy cluster (after epoch of major merger)
- Background cluster halo of uncollapsed dark matter and intracluster gas – spherically symmetric, static (non-evolving density profile), stationary
- *N* galaxies – each a single particle having mass m_i, size (radius) s_i, internal energy U_i

$$U_i = -\zeta G m_i^2 / (2 s_i), \text{ with } \zeta = 1$$

- Galaxies orbit in the cluster potential and interact with each other

Cluster Halo Density

- Single β-model (isothermal) of gas [5], [8]

$$\rho_{gas}(r) = \rho_0 \left[1 + (r/r_c)^2\right]^{-3\beta/2}, \rho_{halo} = \rho_{gas}\Omega_M / \Omega_b$$

- NFW model of dark matter [7]

$$\rho_{DM}(r) = \frac{\rho_{crit}\delta_c}{(r/r_s)(1+r/r_s)^2}, \rho_{halo} = \rho_{DM}\Omega_M / (\Omega_M - \Omega_b)$$

- Background halo mass

$$M_{halo}(r) = \int_0^r 4\pi x^2 \rho_{halo}(x) dx$$

- Maximum halo radius

$$R_{halo}^{\max} = 5 \text{ Mpc}$$

Gravitational Interactions: The *P–P* Method

- Acceleration of galaxy *i*, a_i

$$a_i = -G \sum_{j=1, j\neq i}^{N} \frac{m_j(\vec{r}_i - \vec{r}_j)}{\left(\left|\vec{r}_i - \vec{r}_j\right|^2 + \varepsilon^2\right)^{3/2}} - \frac{G M_{halo}(r_i)\vec{r}_i}{\left(r_i^2 + \varepsilon^2\right)^{3/2}}$$

- Softening length, ε < initial radius of smallest galaxy

Calculate

- Number fractions of mergers and tidal disruptions of galaxies

$$f_{destroyed}^{mergers} = \frac{N_{merge} + N_{accr}}{N_{destroyed}},$$

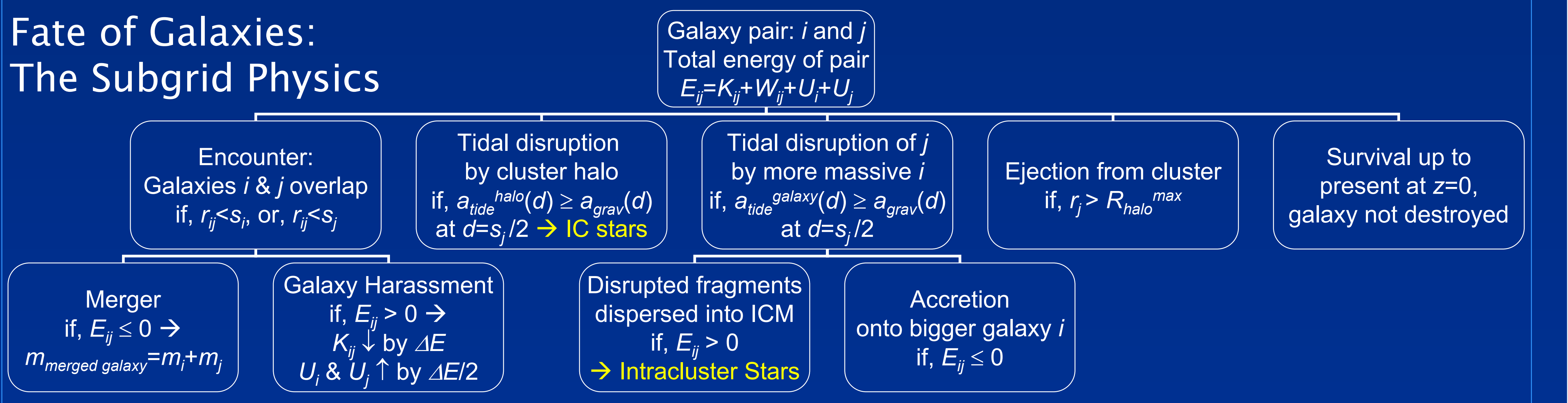
$$f_{destroyed}^{tides} = \frac{N_{tides}^{gal} + N_{tides}^{halo}}{N_{destroyed}},$$

$$N_{destroyed} = N_{merge} + N_{tides}^{gal} + N_{accr} + N_{tides}^{halo}.$$

- Galactic mass fraction contributed to the ICM as intracluster stars, f_{ICS}

$$f_{ICS} = \frac{M_{tides}^{gal} + M_{tides}^{halo}}{M_{total} - M_{eject}}$$

Fate of Galaxies: The Subgrid Physics



Galaxy pair: *i* and *j*
Total energy of pair
$E_{ij}=K_{ij}+W_{ij}+U_i+U_j$

Encounter:
Galaxies *i* & *j* overlap
if, $r_{ij}<s_i$, or, $r_{ij}<s_j$

Merger
if, $E_{ij} \leq 0$ →
$m_{merged\ galaxy}=m_i+m_j$

Galaxy Harassment
if, $E_{ij} > 0$ →
K_{ij} ↓ by ΔE
U_i & U_j ↑ by $\Delta E/2$

Tidal disruption
by cluster halo
if, $a_{tide}^{halo}(d) \geq a_{grav}(d)$
at $d=s_j/2$ → IC stars

Tidal disruption of *j*
by more massive *i*
if, $a_{tide}^{galaxy}(d) \geq a_{grav}(d)$
at $d=s_j/2$

Disrupted fragments
dispersed into ICM
if, $E_{ij} > 0$
→ Intracluster Stars

Accretion
onto bigger galaxy *i*
if, $E_{ij} \leq 0$

Ejection from cluster
if, $r_j > R_{halo}^{max}$

Survival up to
present at *z*=0,
galaxy not destroyed

Galaxy Initial Conditions

- Mass *m* from Schechter luminosity function [10]
  - Mass-to-light ratio = 193 *h* $M_\odot/L_\odot$ [2]
  - α = –1.28 [6]

$$\phi(L)dL = \phi^*\left(\frac{L}{L^*}\right)^{\alpha} e^{-L/L^*} \frac{dL}{L^*}$$

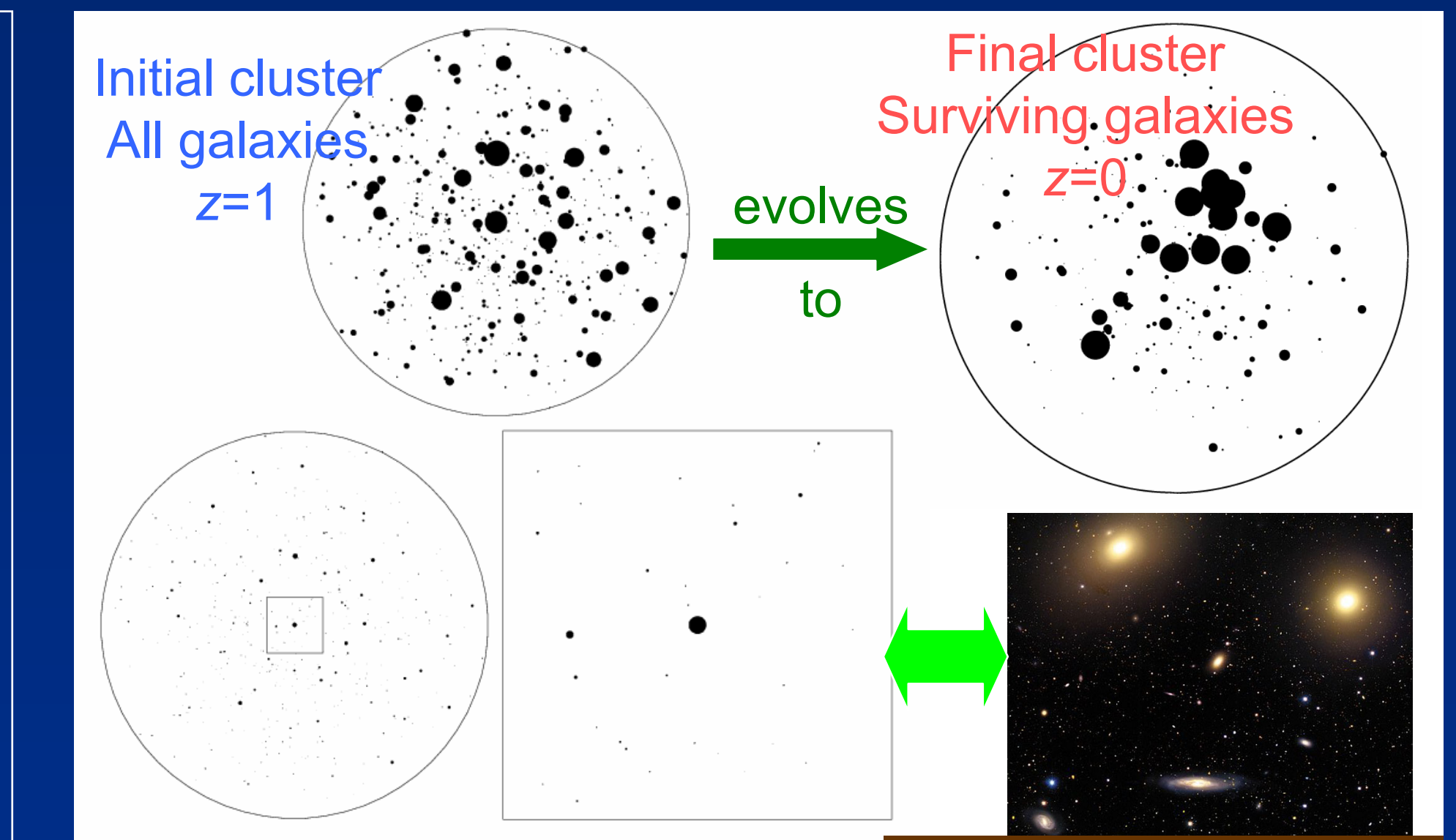
- Size $s = r_{200}$, the virial radius at epoch of formation, from linear spherical collapse model
- Position
  - Radial number density, $\nu(r) \sim \rho_{halo}(r)$ [4]
  - Spherical coordinates (θ, φ) randomly
  - Most massive galaxies near cluster center
- Velocity
  - Magnitude – within 10% of circular velocity
  - Directions – randomly

cD Galaxy [11]

- At cluster center with L_{cD} = 10 L^*

Simulations

- ΛCDM cosmological model
- Evolve a cluster from *z*=1 to *z*=0, & track galaxy outcomes



Center of the Virgo Cluster
(http://antwrp.gsfc.nasa.gov/apod/ap050213.html)

Fig. 1. — Run A12: Virgo-like cluster.
Top left – Initial conditions at *z*=1. Solid circles are the virial radii of galaxies. Large circle is the maximum distance from cluster center.
Lower left – Same as top, with galaxy sizes rescaled to optical diameter of real galaxies.
Bottom middle – Enlargement of the central (0.6 Mpc)^2 of simulated cluster.
Bottom right – Image of Virgo cluster.
Top right – Galaxies surviving in simulation at *z*=0. Far fewer dwarf galaxies than at *z*=1.

Steepening of the Schechter Function with Redshift

- Numerical fit to the distribution of galaxy masses
- Series A & B:

$$\alpha = -1.28 \text{ at } z = 1 \xrightarrow{\text{evolves to}} \alpha = -1.20 \text{ at } z = 0$$

- Observations of nearby clusters give α= –1.28 → this α is only valid for clusters at *z*=0
- Series C:

$$\alpha = -1.36 \text{ at } z = 1 \xrightarrow{\text{evolves to}} \alpha = -1.28 \text{ at } z = 0$$

- Consistent with observations [9]

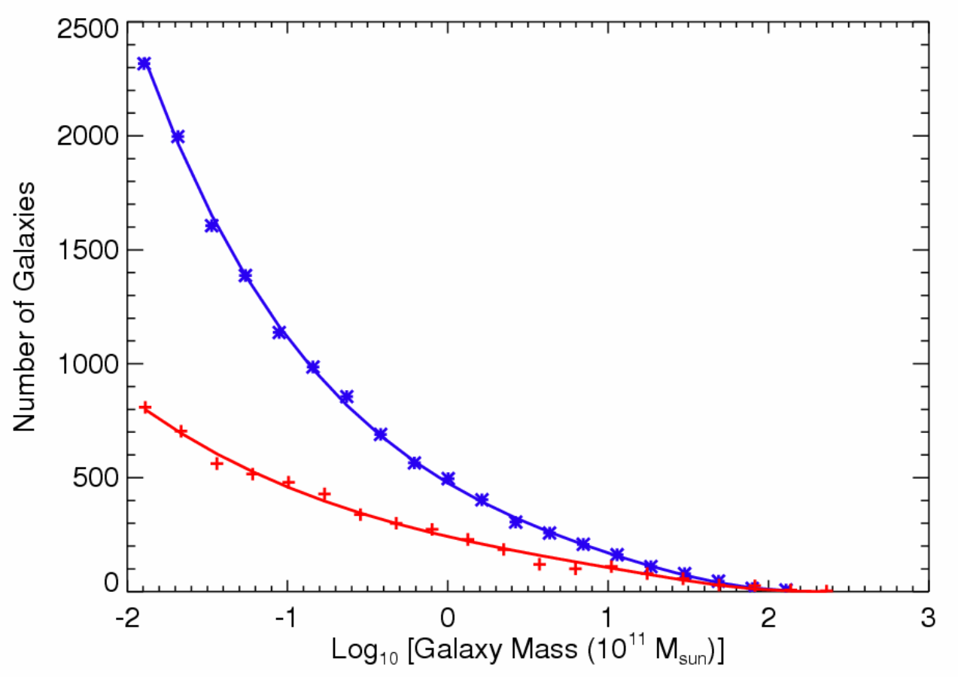


Fig. 2. — In series C, initial 13628 galaxies at *z*=1 (asterisks), and surviving 5356 galaxies at *z*=0 (plus signs). Best-fit Schechter distribution functions are with α=–1.36 at *z*=1 (upper blue curve), and α=–1.27 at *z*=0 (lower red curve).

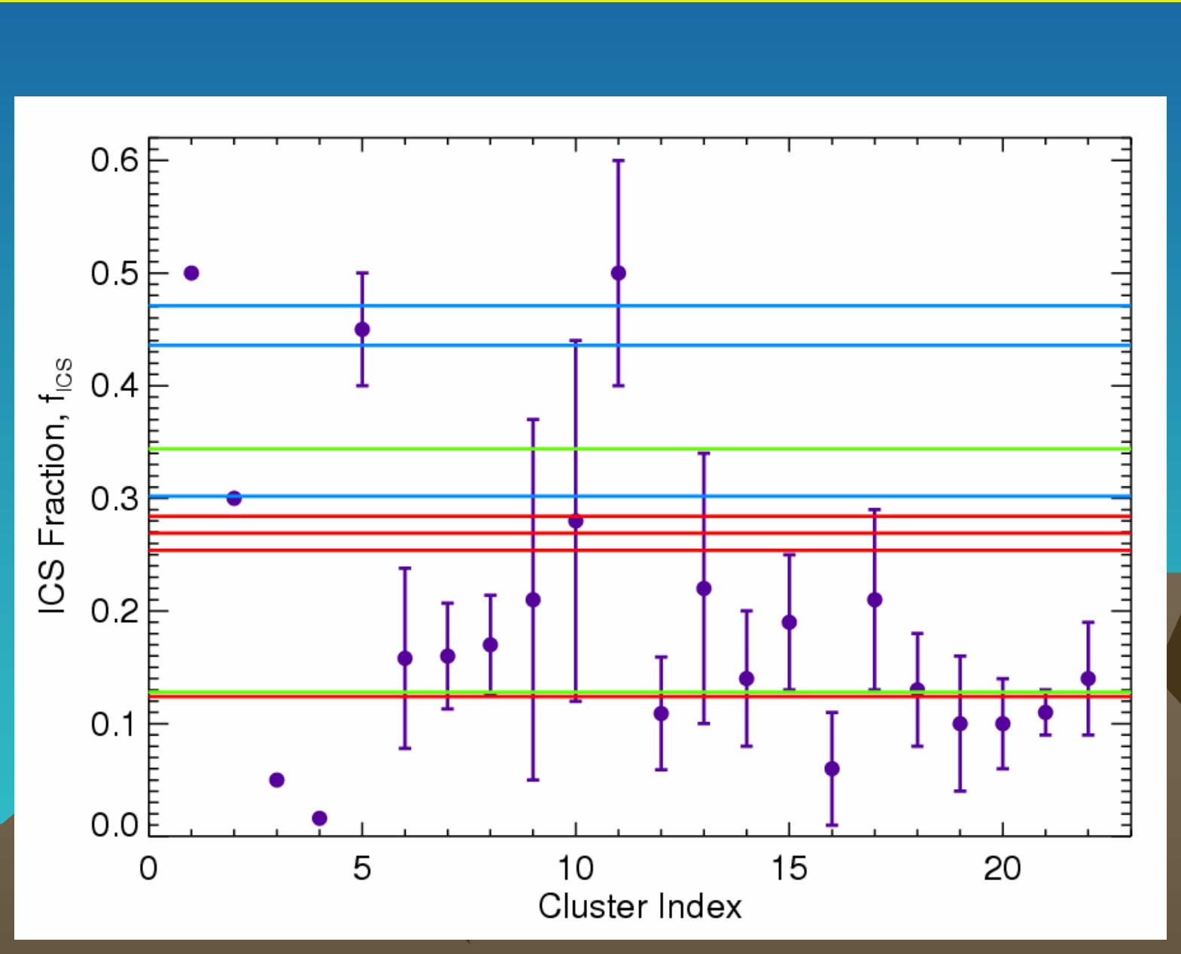


Fig. 5. — Fraction of intracluster stars. Horizontal lines show average f_{ICS} from our simulations, in red: Virgo-like cluster (series A-D), green: Perseus-like cluster (series E-F), blue: NFW model cluster (series G-I). Symbols and error bars show observational measurements of ICL fraction in clusters, as tabulated in Table 13 of Barai et al. (2007).

Table 1. Series of Simulations

Series	Runs	α_{start}	profile	β	ρ_0, ρ_s [g cm^{-3}]	c	r_c, r_s [kpc]	cD	Harassment	$\overline{f_{ICS}}$	$\sigma_{f_{ICS}}$
A	16	−1.28	β-Virgo	0.33	8.14×10^{-26}	…	3	×	×	0.254	0.093
B	17	−1.28	β-Virgo	0.33	8.14×10^{-26}	…	3	×	√	0.269	0.081
C	17	−1.36	β-Virgo	0.33	8.14×10^{-26}	…	3	×	√	0.284	0.090
D	16	−1.36	β-Virgo	0.33	8.14×10^{-26}	…	3	√	√	0.124	0.036
E	16	−1.36	β-Perseus	0.53	7.27×10^{-26}	…	28	×	√	0.344	0.093
F	16	−1.36	β-Perseus	0.53	7.27×10^{-26}	…	28	√	√	0.128	0.031
G	10	−1.28	NFW	…	2.35×10^{-25}	5	200	×	√	0.436	0.117
H	14	−1.31	NFW	…	2.35×10^{-25}	5	200	×	√	0.471	0.129
I	10	−1.31	NFW	…	2.35×10^{-25}	5	200	√	√	0.302	0.044

Table 2. Parameter variations of β-model. 5 runs done in each series, including galaxy harassment, and no cD galaxy. Schechter function α_{start}= –1.36.

Series	β	ρ_0 [g cm^{-3}]	r_c [kpc]	$\overline{f_{ICS}}$	$\sigma_{f_{ICS}}$
Bb1	0.3	1.0×10^{-26}	50	0.315	0.082
Bb2	0.4	1.0×10^{-26}	50	0.227	0.061
Bb3	0.5	1.0×10^{-26}	50	0.140	0.100
Bb4	0.6	1.0×10^{-26}	50	0.060	0.049
Bb5	0.8	1.0×10^{-26}	50	0.046	0.035
Bb6	1.0	1.0×10^{-26}	50	0.050	0.023
Br1	0.5	1.0×10^{-26}	10	0.045	0.038
Br2	0.5	1.0×10^{-26}	100	0.252	0.077
Br3	0.5	1.0×10^{-26}	200	0.356	0.062
Br4	0.5	1.0×10^{-26}	300	0.413	0.072
Br5	0.5	1.0×10^{-26}	400	0.426	0.077
Br6	0.5	1.0×10^{-26}	500	0.451	0.079

Table 3. Parameter variations of NFW-model. 5 runs done in each series, with galaxy harassment, and no cD galaxy. Schechter function α_{start}= –1.31.

Series	c	r_s [kpc]	$\overline{f_{ICS}}$	$\sigma_{f_{ICS}}$
Nr1	4.5	10	0.214	0.112
Nr2	4.5	50	0.097	0.109
Nr3	4.5	100	0.230	0.077
Nr4	4.5	200	0.443	0.110
Nr5	4.5	300	0.667	0.054
Nc1	4	100	0.196	0.109
Nc2	6	100	0.278	0.105

Pros.

- Simple: a single particle represents one galaxy
- Easy distinction & quantification of the fate of galaxies
- Direct *P–P* (the simplest *N*-body) algorithm
- Requires less computational resources
- Performed 227 simulations – robust results covering substantial parameter space

Cons.

- Adopted prescription of galaxy harassment and associated energy dissipation might be speculative
- Assumed: Isolated clusters in equilibrium – no cluster merger, no cluster accretion

Future work

- Brito et al. (2008): Simulation of a cosmological volume containing many galaxy clusters, forming and evolving

Conclusions

(1) Destruction of dwarf galaxies by mergers dominates over destruction by tides, for most of the investigated parameters. For the NFW and the β- models, the two destruction mechanisms become comparable, and tides outnumber mergers eventually, when their scale/core radius approaches or exceeds ~200-300 kpc.

(2) The galactic mass imparted to the ICM by tidal destruction of dwarf galaxies is sufficient to account for the observed fraction of ICL. $f_{ICS} = 4.5\% - 66.7\% \,(\text{most within } 10\% - 45\%)$

(3) ICS fraction increases with the mass of the cluster halo.

(4) In the NFW model halo, a large number of galaxies are destroyed by the tidal field of the cluster halo.

→ Cluster halo is probably not stationary.

→ Possible solution to the cusp crisis of cold dark matter halos. The central cuspy region of the cluster dark matter halo could have inelastic encounters with the member galaxies, which could inject energy into the halo and erase the cusp.

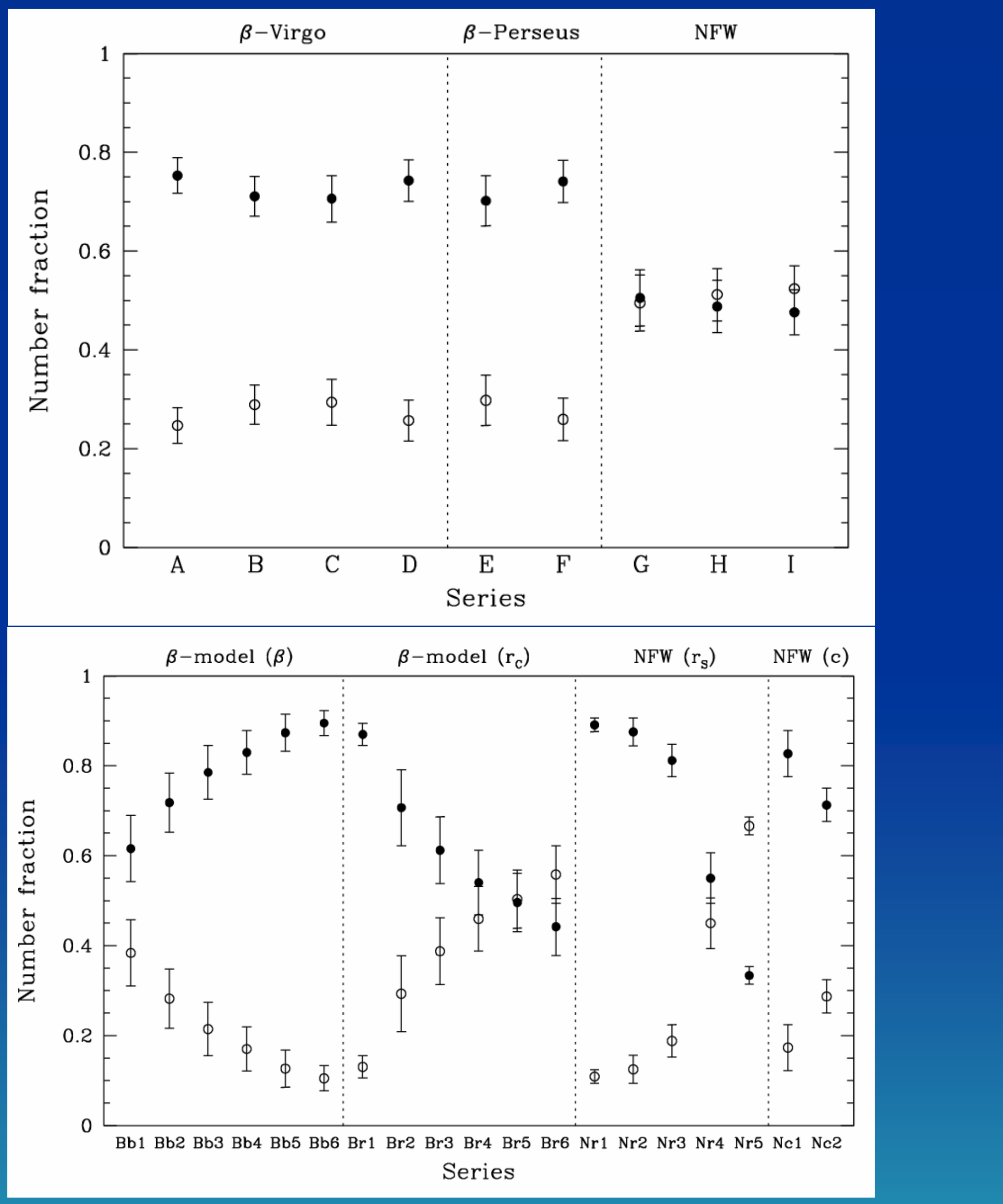


Fig. 3. & Fig. 4. — Fractional number of galaxies destroyed by mergers, $f^{mergers}_{destroyed}$ (filled circles), and that destroyed by tides, $f^{tides}_{destroyed}$ (open circles), averaged over all runs within each series. Error bars show the standard deviation.

References

[1] Barai, P., Brito, W. & Martel, H. 2007, submitted to ApJ, arXiv:0707.1533
[2] Brainerd, T. G. & Specian, M. A. 2003, ApJ, 593, L7
[3] Brito, W., Martel, H. & Barai, P. 2008, in preparation
[4] Carlberg, R. G. et al. 1997, ApJ, 485, L13
[5] Cavaliere, A. & Fusco-Femiano, R. 1976, A&A, 49, 137
[6] De Propris, R. et al. 2003, MNRAS, 342, 725
[7] Navarro, J. F., Frenk, C. S. & White, S. D. M. 1997, ApJ, 490, 493
[8] Piffaretti, R. & Kaastra, J. S. 2006, A&A, 453, 423
[9] Ryan, R. E. Jr. et al. 2007, ApJ, in press (astro-ph/0703743)
[10] Schechter, P. 1976, ApJ, 203, 297
[11] Schombert, J. M. 1988, ApJ, 328, 475