Modelling the Formation of the Intracluster Light in Semi-Analytic Models

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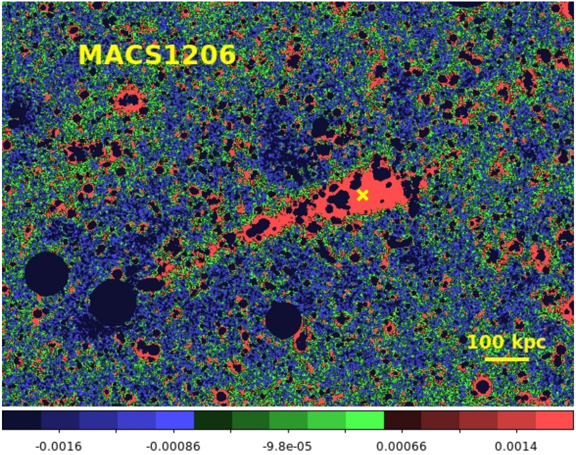
Outline

* First part:
    - Introduction to the Intra-Cluster Light (ICL)
    - What's a Semi-Analityc Model (SAM)?
    - Modelling stellar stripping in a SAM
    - ICL properties (model predictions)
    - Recent observations
    - Conclusions and future perspectives
* Second part:
    - How to improve the model
    - Very recent model results and observations
    - Conclusions

Intra-Cluster Light

ICL: diffuse component made of stars not bound to galaxies



Courtesy of V.Presotto (Presotto et al. 14)

Formation Channels

1) Disruption of dwarf galaxies (Purcell+07,Murante+07,Conroy+07)
2) Tidal stripping of intermediate/massive galaxies (Rudick+09,Watson & Conroy+13,Laporte+13,Contini+14)
3) Mergers between galaxies (Purcell+07,Murante+07,Conroy+07,Contini+14)
4) Pre-processing/accretion (Rudick+06,Sommer-Larsen 06, Contini+14)
5) In situ star formation (Puchwein+10), but observations say no! (Sand+11, Melnick+12)

Definitions

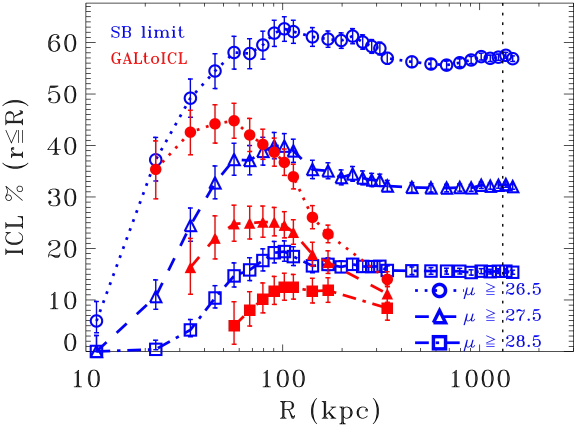
ICL should be the light after having removed the contribution of all galaxies that are cluster members, including the brightest cluster galaxy (BCG)

Observations	Isophotal cuts and/or two-dimensional profile fittings to model the surface brightness profile of brightest cluster galaxies (Zibetti+05, Gonzalez+05, Krick-Bernstein 07, Presotto+14, Montes+14)
Simulations	Binding energy definitions plus dynamical information (Murante+07,Puchwein+10,Rudick+11,Cui+14)
SAMs	By construction (Monaco+07, Somerville+08, Guo+12, Contini+14)

Are Surface Brightness Cuts Safe?

MACS1206 (CLASH survey), a massive cluster, $M_{200} = 1.4 \cdot 10^{15} M_{\odot}$ at $z \sim 0.44$

GOAL: Understanding possible systematics/bias using different ICL detection techniques



Presotto+14

- SBlimit method provides higher ICL fractions (larger effect at lower SB limit)
- GALtoICL method provides safer ICL detections almost free of contamination, but more time consuming

Theorethical Models

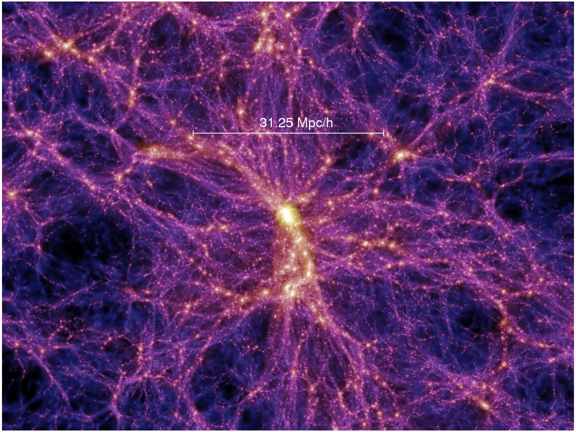
How does a Semi-analytic model work?

- Merger trees from N-body simulations
- Modelling the physics of baryons

Simulating Dark Matter Haloes

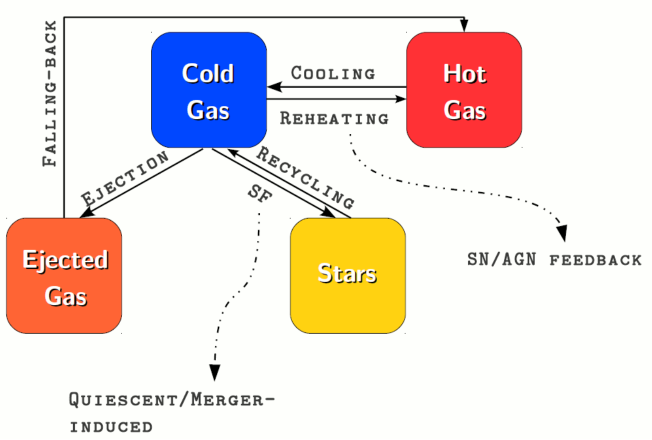
Large set of High Resolution Simulations:

- 27 simulations of very massive clusters, $\gtrsim 5 \cdot 10^{14}\,\mathrm{M}_\odot$
- ΛCDM cosmology
- Particle Mass $= 10^8\,\mathrm{h}^{-1}\mathrm{M}_\odot$
- R_{200} = radius that encloses a mean density of 200 times the critical density of the Universe at the redshift of interest
- M_{200} = mass within R_{200}.



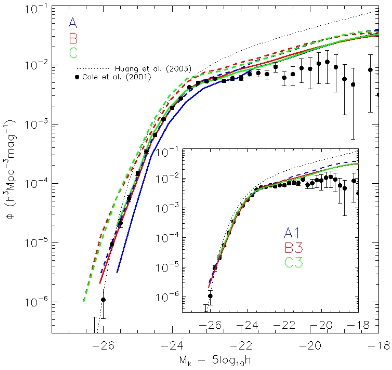
The Semi-Analytic Model of Galaxy Formation

Standard scenario of galaxy formation (White & Rees 1978)

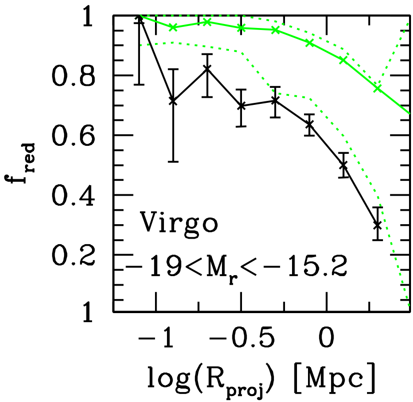


(De Lucia & Blaizot 07)

Open Problems



Wang et al. 08



Weinmann et al. 11

Models predict an excess of low-intermediate mass and red galaxies

Implementing Stellar Stripping

Model Disruption:

- we estimate the pericentric distance of any single satellite
- we compute the halo density within the pericenter and the galaxy density
- if $\rho_{halo} > \rho_{sat}$ we assume the satellite to be destroyed (Guo+12)

Model Tid. Radius:

- we estimate the tidal radius: $R_t = \left(\frac{M_{sat}}{3 \cdot M_{halo}}\right)^{1/3} \cdot D$ (Binney & Tremaine 08)
- if $R_t < R_{bulge}$ we assume the satellite to be destroyed
- we strip the stellar mass in the shell $R_t - 10 \cdot R_{sl}$ assuming an exponential profile for the disk

Model Cont. Stripping:

- we use a fitting formula set by simulations

$$M^*_{lost} = M^*_{accr} \exp\left[\left(\frac{-16}{1-\eta}\right)\left(\frac{M_{sub}}{M_{par}}\right)^{\frac{1}{2}}\left(1 - \frac{t}{t_m}\right)\right]$$

by computing all quantities at the time of accretion (Villalobos+12)

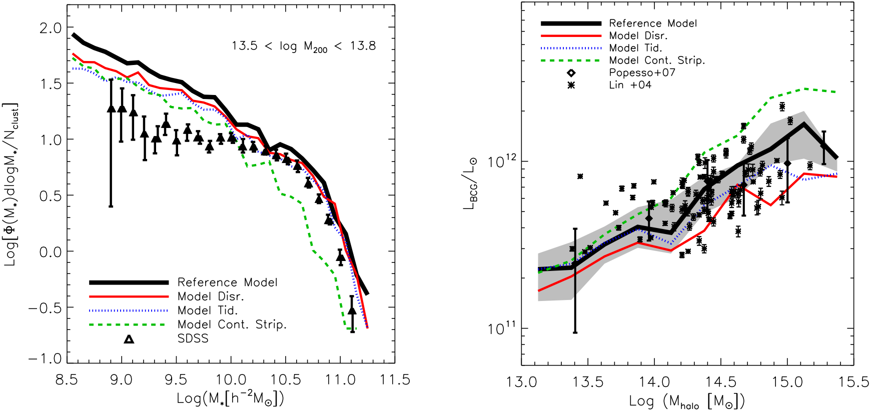
Mergers: 20% of the stellar mass of the merging satellite is added to the ICL component of the other galaxy

Main Points

1) Stellar Mass Function and BCG luminosity
2) ICL/ICL+BCG fraction from groups to clusters
3) Roles of concentration and formation time
4) Contribution to the ICL from different channels
5) BCG and ICL growth
6) ICL metallicity

Stellar Mass Function and BCG Luminosity

BCG sample: 341 Brightest Cluster Galaxies (BCGs) in haloes with mass in the range $10^{13} < \log M_{200}[h^{-1}M_{\odot}] < 10^{15.3}$

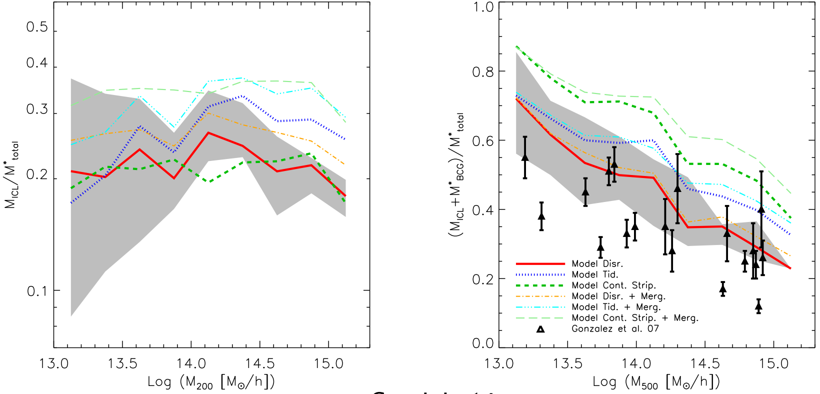


Contini+14

- Conditional Stellar Mass Function (CSMF) improved in the low-mass end
- Models Disruption and Tid. Radius reproduce the observed K-band luminosity
- Model Cont. Stripping predicts BCGs too bright on cluster scale (shorter merging times)

ICL Fraction in Clusters

$M^*_{tot} = M^*_{BCG} + M_{ICL} + M^*_{sat}$ within R_{500} (right panel) and within R_{200} (left panel)

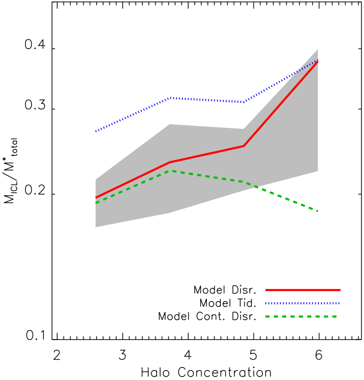


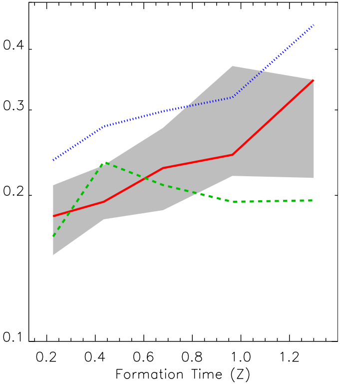
Contini+14

- Models predict a constant ICL fraction in clusters, in good agreement with observations (10% – 40%, e.g. Feldmeier+04, Zibetti 08, McGee & Balogh 10, Toledo+11)
- Model Cont. Stripping over-predicts the observed ICL+BCG fraction
- Mergers increase the ICL+BCG fraction (different merging history of BCGs)

Roles of halo concentration and formation time

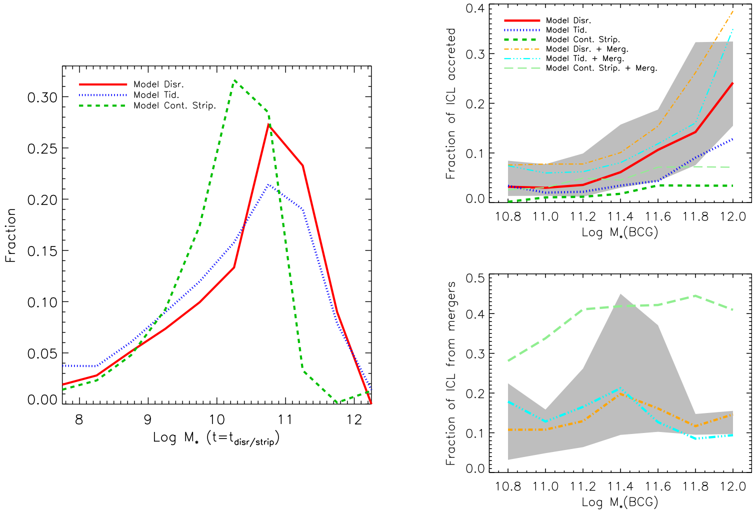
Halo sample: 53 haloes with $\mathrm{M_{200}[h^{-1}M_\odot]} > 10^{14}$.





More concentrated haloes are supposed to have a larger fraction of ICL, since tidal forces get stronger and galaxies are more easily disrupted

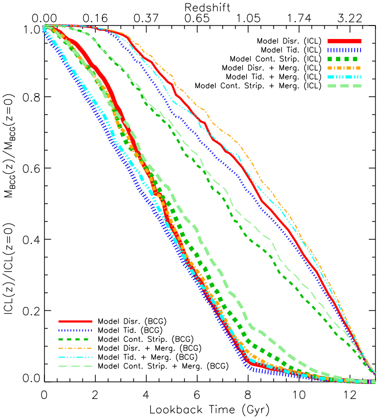
What Contributes Most to the ICL?



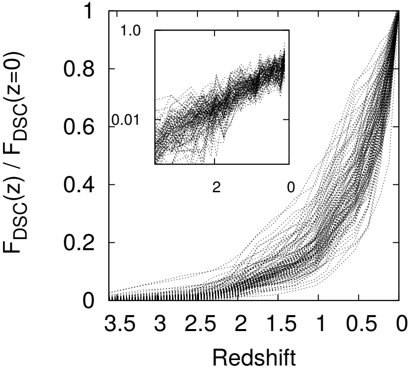
Contini+14

- Massive satellites contribute most to the ICL
- Massive BCGs accrete a significant amount of ICL
- Mergers play an important role mostly in Model Cont. Stripping

BCG and ICL growth



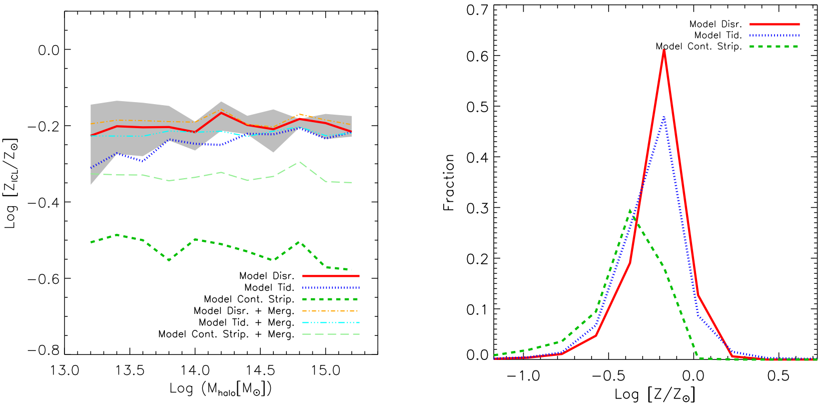
Contini+14



Murante+07

- Most of the ICL (about 80 per cent) forms after $z \sim 1$ (in agreement with simulations, Murante+07)
- BCGs grow much faster than the ICL before $z \sim 1$ (in agreement with observations, e.g. Burke+15)

ICL Metallicity



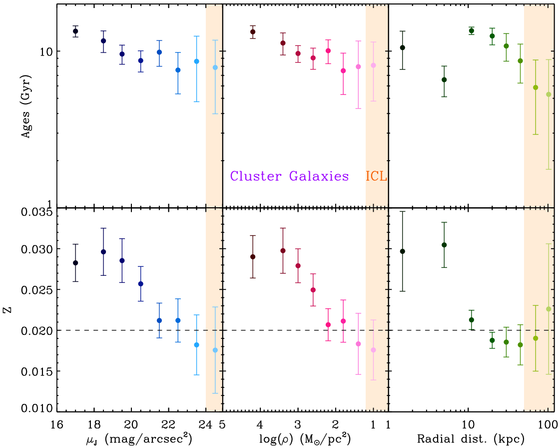
Contini+14

- Models predict sub-solar metallicity, in agreement with observations (Virgo, William+07 A2744, Montes & Trujillo 14 CLASH, DeMaio+15)
- Metallicity distributions cover a wide range

Updates from Observations

Abell Cluster 2744, a rich cluster at $z \sim 0.3$ with virial mass $\sim 7 \cdot 10^{15} M_{\odot}$ and virial radius $\sim 3.7\ Mpc$, undergoing a major merger

GOAL: characterize age and metallicity of the ICL in A2744



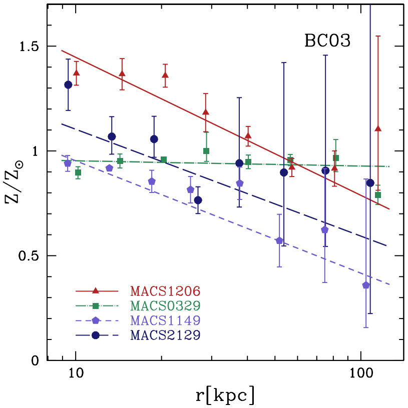
Montes & Trujillo 14

- The ICL is the result of the disruption of infalling galaxies with mass around $3 \cdot 10^{10} M_{\odot}$
- The ICL metallicity is $Z = 0.018 \pm 0.007$ and age around $6 \pm 3\ Gyr$
- Fraction of stellar mass in ICL at least 6%
- The ICL has been formed recently, $z < 1$

Updates from Observations II

DeMaio+15

Sample: 4 clusters from CLASH survey at $0.44 < z < 0.57$, with mass range $[0.6-2.6] \cdot 10^{15} M_{\odot}$



- Negative metallicity gradients, from supersolar in the inner regions (BCG dominated), to subsolar at larger radii (ICL dominated)
- Tidal stripping of L* galaxies and/or disruption of dwarf as the main mechanism/s of ICL formation
- The little evolution of the faint-end slope of the luminosity function rules out disruption of dwarfs as the main mechanism
- Results disfavour significant contribution to the ICL by major mergers with the BCG

Conclusions (First Part)

* ICL fractions in good agreement with observations and not significantly dependent on the halo mass
* Massive galaxies are the major contributors to the ICL component (70% from galaxies $\gtrsim 10^{10.5}\,\mathrm{M}_\odot$)
* Mergers contribute most in Model Cont. Stripping (30% of the total ICL)
* Pre-processing/accretion important for the largest BCGs (from 20% to 40%)
* ICL forms relatively late. About 80% of the ICL forms after redshift $z \sim 1$
* Models predict sub-solar ICL metallicity

Future Perspectives

* A better description of the merger channel. The fraction of stripped stars might be a function of some properties of the merging satellites, such as stellar mass or orbital parameters
* Metallicity gradient in satellite galaxies
* Investigate deeper BCGs and ICL growths
* Investigate colors and metallicity of the ICL

Very Recent Model Results

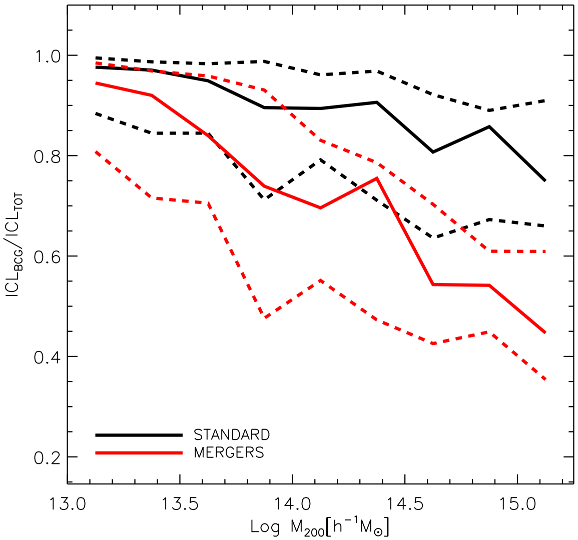
Two models for the formation of the ICL:

(1) Standard Model: stellar stripping and merger channels
(2) Mergers Model: contribution to the ICL from mergers only

(1) Formally identical to Model Tid. Radius (stellar stripping + 20% from merging satellites)

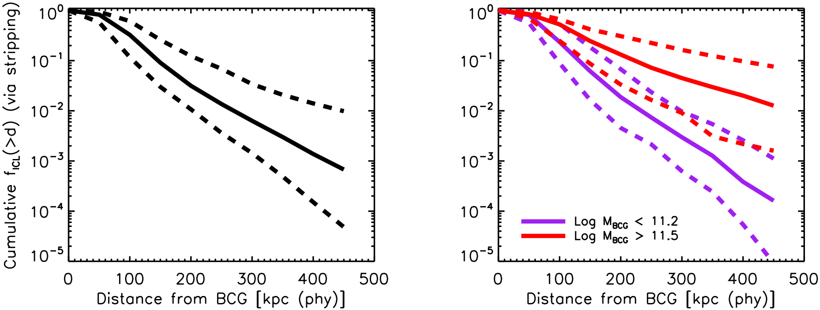
(2) 50% contribution from satellites and no stellar stripping

Mergers vs Stellar Stripping



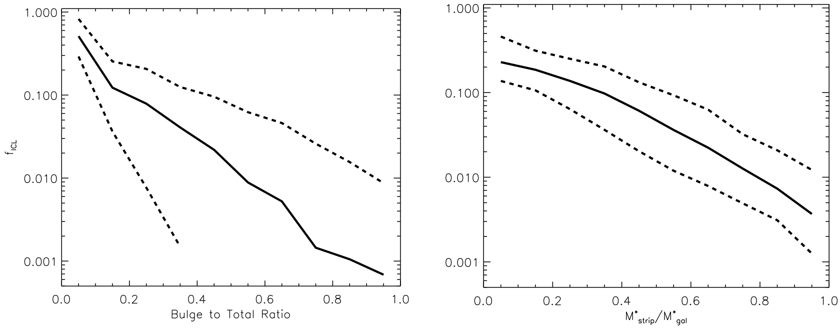
ICL observations on galaxy clusters can constrain models!

Contribution from Stellar Stripping I



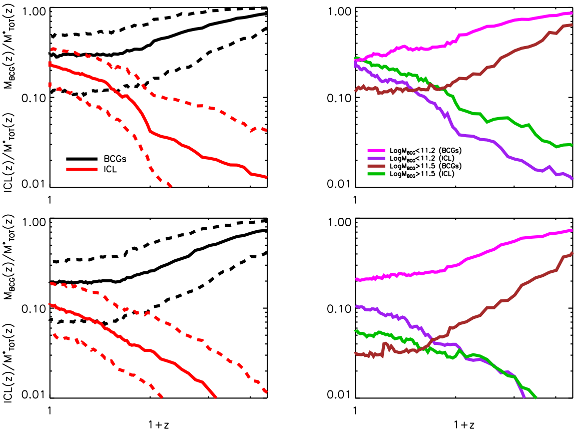
- 90% of the ICL (from the stripping channel) comes from stripping events within 150 kpc
- Stellar stripping depends on the concentration of the halo on which the BCG resides

Contribution from Stellar Stripping II



- Disk-like galaxies ($B/T < 0.4$) are those which contribute most to the ICL (∼75%)
- A large number of small/intermediate stripping events (mass fractions below 0.3) account for most of the ICL from stripping (∼83%) within 100 kpc

BCG and ICL growth



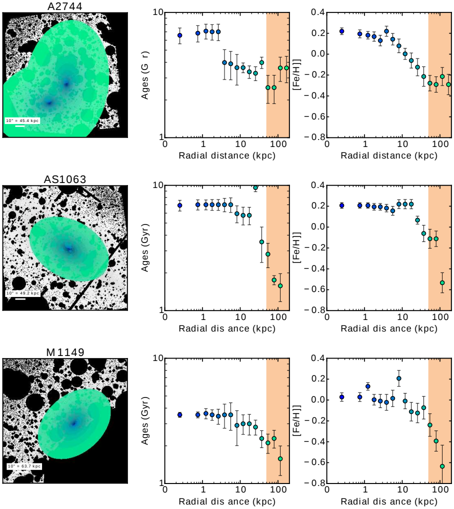
- Both models predict a decreasing fraction for BCGs and an increasing fraction for the ICL (hierarchical growth of structures)
- Less and more massive BCGs show different fractions, being lower for more massive BCGs (M^*_{tot} higher in more massive haloes)

How to Improve the Model

* The current STANDARD model assumes no metallicity gradient in satellite galaxies, at odds with observations (i.e. Toledo+11)
* No model prediction on ICL colors so far!

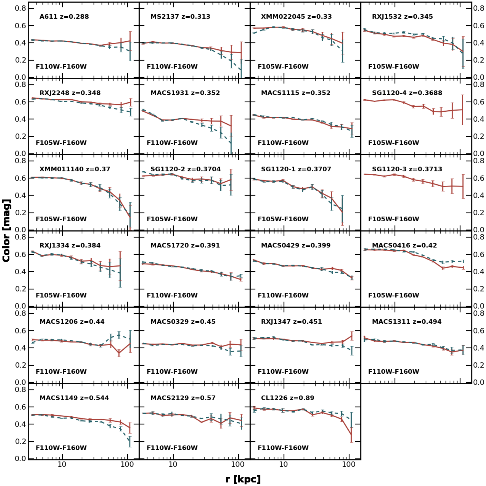
...but observations made a good step forward

New Observations: Metallicity Gradient



Montes & Trujillo 18: negative metallicity gradient and sub-solar ICL metallicity

New Observations: Color Gradient



DeMaio+18: negative color gradients of BCG+ICL

How to Improve the Model II

How to distribute metals in satellite galaxies?

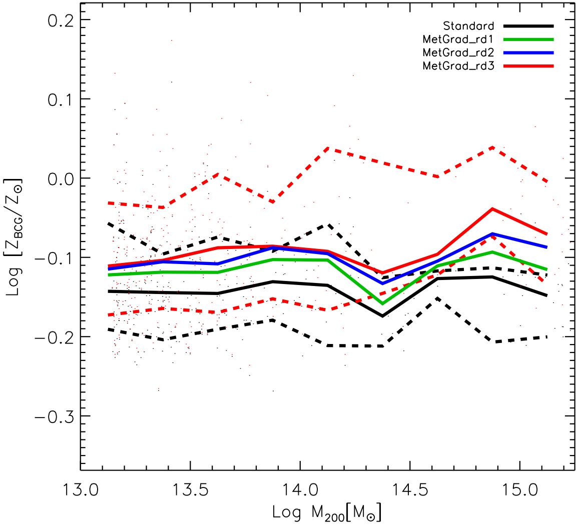
Let's assume an exponential profile for the disk such as:

$$M_{disk}(< R) = M_{disk}\left[1 - \left(1 + \frac{R}{R_d}\right)\exp^{(-R/R_d)}\right]$$

where R_d is the scale length of the disk, such that:

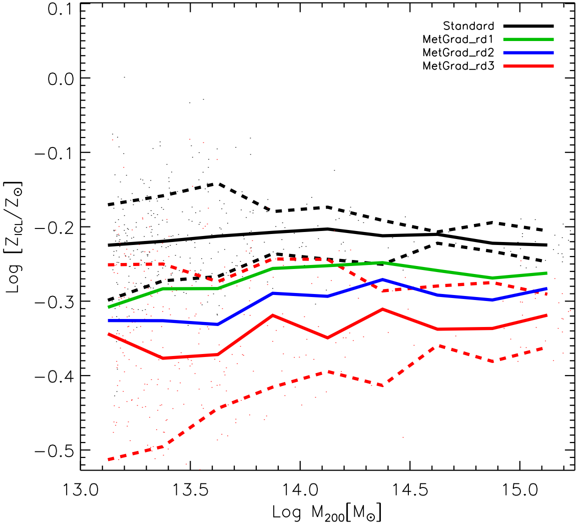
- $R_d = R_D$ for the stellar mass in the disk
- $R_d = f \cdot R_D$ for the metals in the disk, with $f < 1$

Preliminary Results: BCG metallicity



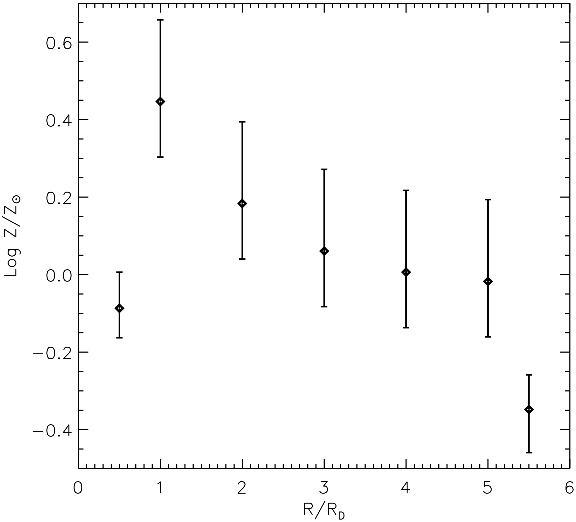
The metallicity of BCGs increases with decreasing f

Preliminary Results: ICL metallicity



The metallicity of the ICL decreases with decreasing *f*

Preliminary Results: BCG+ICL metallicity gradient

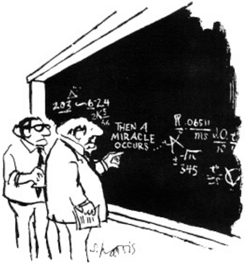


Negative metallicity gradient: super-solar in the disc and sub-solar in the ICL region (in agreement with observations)

Conclusions (Second Part)

* The total ICL (rather than that associated with the BCG) on cluster scale can constrain models
* 90% of the ICL generated from stripping comes from stripping events in the innermost regions (150 kpc):
  - Disk-like galaxies are the major contributors ($\sim$90%)
  - It is generated by small/intermediate stripping events
* A negative metallicity gradient in satellites is favoured in order to reproduce the negative metallicity gradient of the BCG+ICL system (super-solar in the inner region and sub-solar in the ICL dominated region)

Thank you!



"I think you should be more explicit here in step two."