Galaxy formation: big and small

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Ben Moore (Zürich)
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1- Galaxy formation and feedback

2- AMR simulations of a dwarf galaxy with stellar feedback
   arxiv/1206.4895

3- AMR simulations of a massive elliptical with AGN feedback
   Davide Martizzi’s PhD work
Feedback processes in galaxy formation

Moster et al. (2010)
Stellar-to-halo mass ratio

Silk & Rees (1998)

Dekel & Silk (1986)

THE ORIGIN OF DWARF GALAXIES, COLD DARK MATTER, AND BIASED GALAXY FORMATION

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Simulated MW properties dominated by feedback

Scannapieco et al. (2012)
Stellar winds, supernovae remnants are highly turbulent environment, filled with cosmic rays and magnetic field. Thermal energy dissipates almost instantaneously through cooling. Non-thermal processes dissipate much more slowly.

Hanasz et al. 2009; Scannapieco & Brüggen 2010; Wadepuhl & Springel 2011 and others...

Here, we capture the non-thermal energy as:

\[
\rho \frac{D \epsilon_{\text{turb}}}{Dt} = \dot{E}_{\text{inj}} - \frac{\rho \epsilon_{\text{turb}}}{t_{\text{diss}}} \quad \epsilon_{\text{turb}} = \sigma_{\text{turb}}^2
\]

The total dynamical pressure is

\[
P_{\text{tot}} = P_{\text{thermal}} + P_{\text{turb}}
\]

Maximal feedback scenario:

\[
\dot{E}_{\text{inj}} = \dot{\rho} \cdot \eta_{\text{SN}} 10^{50} \text{ erg/M}_\odot \quad t_{\text{diss}} \sim 10 \text{ Myr}
\]

We mimic slow dissipation of non-thermal energy using delayed cooling for the thermal energy:

\[
\rho \frac{D \epsilon_{\text{thermal}}}{Dt} = \dot{E}_{\text{inj}} - P_{\text{thermal}} \nabla \cdot \mathbf{v} - n_{H\alpha}^2 \Lambda \quad \Lambda = 0 \text{ if } \sigma_{\text{turb}} > 10 \text{ km/s}
\]
High density threshold SF in dwarf galaxies

High-resolution SPH simulations with dense clumps and strong feedback result in very strong and very fast potential variations.

Read & Gilmore (2005); Mashchenko et al. (2008); Governato et al. (2010)

Irreversible «heating» of the dark matter cusp into a core.

Pontzen & Governato (2011)
Feedback in dwarf galaxies: a controlled experiment

We consider an equilibrium NFW halo (dark matter + 15% gas).

parameters: $N_{DM}=10^6$, $\Delta x=20$ pc, $V_{200}=35$ km/s, $M_{200}=10^{10}$ $M_\odot$

3 runs with the RAMSES code: 1- pure adiabatic hydrostatic case
2- pure cooling and star formation (no feedback) versus 3- stellar feedback

![Dark matter profiles](image)

**Adiabatic**

- $t=0$ Gyr
- $t=0.6$ Gyr
- $t=1.3$ Gyr
- $t=1.9$ Gyr

**Cooling and SF**

- $t=0$ Gyr with NFW
- $t=0.6$ Gyr
- $t=1.3$ Gyr
- $t=1.9$ Gyr

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Widely different galaxy properties

Cooling and SF

Feedback
Dark matter core out of an initially cuspy profile

Excellent fit with a pseudo-isothermal profile

$$\rho \propto \frac{1}{1 + (r/r_{\text{core}})^2}$$

Feedback

Dark matter profile
Fluctuations in the gravitational potential...

Star formation rate

Enclosed gas mass

r<1600 pc
r<800 pc
r<400 pc
r<200 pc
...lead to an irreversible flattening of the cusp
Comparison to WLM (Leaman et al. 2012)
A (cored ?) exponential profile

$R_d = 1 \text{ kpc}$

$R_d = 1.1 \text{ kpc}$
A thick rotating disc

![Graph showing rotation velocities and dispersions as a function of radius](image-url)
Mass profile of WLM

\[ M_c(< r) = V_c^2 r / G \]

- HI SIS fits
- Stellar SIS fit
- Stellar NFW fit

Inset: Guo et al. (2010) Eq. 3
Solution:

Early radiative stellar feedback with 10x the fiducial supernovae energy.

Brook et al. 2012

Another solution:

Lower the SF efficiency by 10 (low metallicity induces low H2 formation efficiency?)

Krumholz & Dekel 2011

AND use a top-heavy IMF (boost the mass fraction in massive star by 10)

Marks et al. 2012
Constraints from abundance matching

- AM (Moster et al. 2010)
- 20% SFE

- dwarf (this work)
- ERIS (Guedes et al. 2011)
- dwarf (Governato et al. 2010)
- MW1 (Agertz et al. 2010)
- MW2 (Aquarius)
- MW2+AGN
- group (Feldmann et al. 2010)
- cluster (Teyssier et al. 2010)
- cluster+AGN
Numerical implementation in cosmological simulations: Di Matteo et al. 2005, Sijacki et al. 2007; Booth & Schaye 2010 and many others...

In high density regions with stellar 3D velocity dispersion > 100 km/s, we create a seed BH of mass $10^5 \, M_{\odot}$.

Accretion is governed by 2 regimes:

**Bondi-Hoyle regime**

$$\dot{M}_{BH} = \alpha_{boost} \frac{4\pi G^2 M_{BH}^2 \rho}{(c_s^2 + u^2)^{3/2}}$$

**Eddington-limited**

$$\dot{M}_{ED} = \frac{4\pi G M_{BH} m_p}{\epsilon_r \sigma_T c}$$

Feedback performed using a thermal dump

$$\Delta E = \epsilon_c \epsilon_r \dot{M}_{acc} c^2 \Delta t.$$  

with following trick to avoid overcooling:

$$E_{AGN} > \frac{3}{2} m_{gas} k_B T_{min} \quad T_{min} = 10^7 \, K$$

Free parameter $\epsilon_c$ calibrated on the M-$\sigma$ relation.
AGN feedback modifies the BCG properties

Booth & Schaye 10; Teyssier+10; Sembolini+11; Dubois+10,11; Martizzi+11
A dichotomy in the structure of elliptical galaxies

Faber et al. 1997

Faber et al. 1997
A stellar cusp in low mass elliptical galaxies

«Extra light» elliptical: light excess, high ellipticity, fast rotator

Kormendy et al. 2009
A stellar core in massive elliptical galaxies

«Cored» elliptical: light deficit, low ellipticity, slow rotator

Kormendy et al. 2009

core size ~ 0.5 kpc

core size ~ 3 kpc
Kinematic properties of the BCG

\[ \sigma \text{ in M87} \]

SAURON

HyperLeda

Martizzi et al. 2011
Structural properties of the BCG

core size $\sim 6$ kpc

Martizzi et al. 2011
Large mass deficit in the core

From the Sersic fit, we infer a mass deficit $M_{\text{def}}=10^{11} \, M_{\odot}$ or $M_{\text{def}}/M_{\bullet}=20$.

Kormendy et al. 2009
Martizzi et al. 2011
Origin of stellar and dark matter cores in clusters

$M_{\text{def}}/M \approx 1$ to $5$

Goerdt et al. 2010
Kulkarni & Loeb 2011

$\Delta \Phi/\Phi = 100%$

Martizzi et al. 2012

Pontzen & Governato 2011
Conclusion

A new stellar feedback scheme in RAMSES based on non-thermal processes and implemented as a delayed-cooling scheme.

Dwarf \((10^{10} \, \text{M}_{\text{sol}})\) cooling halo simulations give rise to a cusp-core dark matter profile transition, due to large potential fluctuations within the core.

Kinematic analysis reveals a thick, rotating, exponential disk, in striking agreement with the observed, quasi-isolated dwarf WLM.

Still too many baryons in stars: even stronger feedback required, or non-standard SF efficiencies with a top-heavy IMF (low Z regime ?).

The Booth & Schaye AGN feedback model has been implemented in RAMSES and used in a \(10^{14} \, \text{M}_{\text{sol}}\) halo cosmological simulation.

This brings the massive central galaxy properties in agreement with observations (no more overcooling).

Kinematics analysis reveals a massive, slowly rotating elliptical galaxy with a cored Sersic profile.

AGN feedback (high z) and SMBH scouring (low z) give rise to the formation of a dark matter and a stellar core (or broken power law) of similar sizes.