Baryon Census in Hydrodynamical Simulations of Galaxy Clusters

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Outline

• Introduction
  • Galaxy clusters
  • Clusters as cosmological probes

• Cosmological simulations
  • DIANOGA cluster set

• Results  (Planelles et al. in prep.)
  • Baryon content of clusters
  • Cosmological implications: calibration of the baryonic bias

• Summary and discussion
• Largest virialized structures in the Universe: $M \approx 10^{13}-10^{15} M_{\odot}$, $R \approx 1-3$ Mpc
• Composition: galaxies and stars ($\sim 5\%$), ICM ($\sim 15\%$), DM ($\sim 80\%$)
• Baryon budget: stars in galaxies + ICL + ICM
• Baryonic mass fractions:

$$f_b = f_g + f_* \quad f_* = \frac{M_*}{M_{\text{tot}}} \quad f_g = \frac{M_g}{M_{\text{tot}}}$$

• Depletion factors:

$$Y_b = \frac{f_b}{\Omega_b/\Omega_m} \quad Y_* = \frac{f_*}{\Omega_b/\Omega_m} \quad Y_g = \frac{f_g}{\Omega_b/\Omega_m}$$

• Galaxy clusters at X-ray wavelengths:
  • Gravity squeezes gas, heating it to X-ray temperatures
  • Clusters only shine in X-rays if they are massive
    ⇒ clean cluster surveys
  • X-ray observables $\leftrightarrow M_{\text{tot}}$ $\Rightarrow$ hydro. simulations
Galaxy Clusters

ROLE OF CLUSTERS IN COSMOLOGY

• Cosmological probes:
  • Fair sample of the matter content of the Universe ⇒ $M_b/M_{tot} \sim \Omega_b/\Omega_m$ (White & Frenk 1991)
  • Constraints on cosmological parameters:
    • $f_b$ (X-ray) + $\Omega_bh^2$ (CMB/BBNS) + h ⇒ $\Omega_m$ (e.g., White & Frenk 1991)
    • Apparent z-evolution of $f_{\text{gas}}$ ⇒ geometry of the Universe (e.g., Allen et al. 2008)

• Challenges:
  • Observed $f_{\text{gas}}$ smaller than expected
  • Intriguing trend with cluster mass

• Possible explanations:
  • Physical processes which lower $f_b$
  • Undetected baryon components
  • Systematic underestimate of $\Omega_m$ by WMAP

[Graph showing $f_b$ vs. $M_{500}$ with data points and lines indicating trends.]
• Understanding the baryon mass fraction and its mass and $z$ dependence is crucial to understand astrophysics in galaxy clusters.

• **Our tools**: a set of hydrodynamical re-simulations of galaxy clusters, characterized by different physical processes, including AGN feedback.

• **Main objectives**:
  
  • **Baryon content**: to study how the fraction and spatial distribution of the baryons are affected by the physical conditions within clusters.

  • **Cosmological implications**: calibration of the different baryonic depletions as a function of redshift, radius and physics.
Cosmological Simulations

**DIANOGA CLUSTER SET**

- **General properties** (Bonafede et al. 2011)
  - Parallel Tree-PM SPH code **GADGET-3** (Springel 2005)
  - $\Lambda$CDM model: $\Omega_m = 0.24$, $\Omega_{\Lambda} = 0.76$, $\Omega_b = 0.04$, $h = 0.72$, $\sigma_8 = 0.8$, $n_s = 0.96$
  - Re-simulation of 29 Lagrangian regions centred around clusters with $M_{\text{vir}} \geq 10^{15}h^{-1}M_\odot$ (24) and $M_{\text{vir}} \approx (1-7) \times 10^{14}h^{-1}M_\odot$ (5)
  - Parent DM-only simulation: 1024$^3$ DM particles; $L_{\text{box}} = 1 \, h^{-1}\text{Gpc}$

- **Physics included**
  - **NR**: non-radiative run
  - **CSF**: cooling, SF, metals and SN feedback ($v_w = 500 \, \text{km s}^{-1}$)
  - **AGN**: cooling, SF, metals, SN ($v_w = 350 \, \text{km s}^{-1}$) and AGN feedback

- **The set of simulated clusters**
  - Final sample: $\approx 160$ clusters with $M_{\text{vir}} \geq 3\times 10^{13}h^{-1}M_\odot$ ($\approx 70$ with $M_{\text{vir}} \geq 10^{14}h^{-1}M_\odot$)
  - Cluster identification: minimum potential of a FoF group + SO method

\[
M_\Delta = \Delta \rho_c(z) \left( \frac{4 \pi}{3} \right) R_\Delta^3 \quad (\Delta = 2500, 500, 200)
\]
• *NR & CSF* runs:
  • $f_b$ appears flat as a function of $M_{500}$
  • $f_b$ differs by $\leq 10\%$ from the assumed cosmic fraction
  
  (e.g., Kravstov et al. 2005, Ettori et al., 2006)

• *AGN* run:
  • Significant baryon depletion for $M_{500} \leq 10^{14}h^{-1}M_\odot$ (e.g., Puchwein et al. 2010)
  • $f_b$ is closer to the cosmic value for the most massive clusters
  • Good agreement with observations is only achieved for the AGN model

\[ f_b = f_g + f_* \]
**Baryon content**

**TOTAL STELLAR MASS FRACTION**

- **General behaviour:**
  - $f_\star$ decreases smoothly with increasing mass and flattens for $M_{500} \leq 10^{14}h^{-1}M_\odot$

- **CSF:**
  - $f_\star$ is quite large: $\sim$(30%-50%) $f_b$

- **AGN:**
  - $f_\star$ is lowered by $\sim 1/3$
  - Some caution when comparing observational and simulated samples

\[ f_\star = \frac{M_\star}{M_{tot}} \]
Baryon content

BCG + ICL STELLAR COMPONENT (see W. Cui’s talk)

- Relative increase of stars in ICL+BCG when AGN feedback is included (Puchwein et al. 2010)
- Decreasing trend of the ICL+BCG fraction with cluster mass (Gonzalez et al. 2007)
- ICL+BCG fraction larger than observations by Gonzalez et al. 2007
Baryon content

GAS MASS FRACTION

• NR run:
  • $f_g$ appears flat as a function of $M_{500}$
  • $f_g$ is larger than in the radiative runs
    (e.g. Kravtsov et al. 2005; Fabjan et al. 2010)

• Radiative runs:
  • $f_g$ increases as a function of mass
  • Similar values for poor clusters
  • Differential effect of AGN feedback
    in low- and high-mass halos in
    • removing baryons from the centre
    • suppressing star formation
  • Better agreement with observations
    when AGN feedback is included
Cosmological implications

CALIBRATION OF THE BARYONIC BIAS

- Basic idea:  (White & Frenk 1991)
  massive galaxy clusters ~ fair sample of matter content of the Universe $\Rightarrow Y_b = 1$
- "Baryonic bias": any deviation from $Y_b = 1$
- Why calibrating the baryonic bias?  (e.g., Allen at al. 2008)
  - $f_{\text{gas}}$ provides one of the best constraints on $\Omega_m$:
    \[
    \Omega_m = \frac{Y_b \Omega_b}{f_{\text{gas}}(1 + s)}
    \]
    $Y_b \rightarrow$ simulations  // $\Omega_b \rightarrow$ BBNS/CMB
    $f_{\text{gas}} \rightarrow$ observations  // $s \equiv \frac{f_{\text{st}}}{f_{\text{gas}}} \rightarrow$ statistical approach

- $f_{\text{gas}}(z) \propto d_{\text{ang}}(z, \Omega_m, \Omega_\Lambda, w) \Rightarrow$ geometry of the Universe  (e.g., Allen et al. 2008)
- Non-radiative simulations predict:  (e.g., Eke et al. 1998)
  - $Y_b = 0.83 \pm 0.04$ at $R_{2500}$
  - No redshift evolution for $z < 1$
- Objective: to test the robustness of the calibration through simulations of the baryonic bias
Cosmological implications

• Calibration of the baryonic bias
• Redshift evolution of the baryonic bias

REDSHIFT EVOLUTION OF THE BARYONIC BIAS

• Reduced sample: \( \sim 40 \) clusters with \( M_{500} \geq 2 \times 10^{14} h^{-1} M_\odot \) at \( z=0 \) and \( \sim 10 \) at \( z=1 \)

- Some dependence on physics within \( R_{2500} \)
- Redshift evolution:
  - Roughly constant up to \( z=1 \) (e.g., Eke et al. 1998, Kravstov et al. 2005)
  - \( Y_b(z) = Y_{0,b}(1 + \alpha Y_b z) \)

\[ Y_{0,b} = 0.83 \pm 0.06 \]
\[ -0.02 \leq \alpha_{Y_b} \leq 0.07 \]
• Cosmological simulations
  • Re-simulations of 29 Lagrangian regions using GADGET-3
  • Physics included: NR, CSF, AGN

• Baryon content
  • Consistency with observations in \( f_b = f(M_{500}) \) and \( f_g = f(M_{500}) \).
  • Additional caution must be taken when comparing \( f_* = f(M_{500}) \) with observations.
  • When AGN is included the total \( f_* \) decreases whereas stars in BCG+ICL increase.
  • In general: better agreement with observations when AGN feedback is included.

• Calibration of the baryonic bias
  • \( Y_b \approx \text{constant with } z \) but shows some dependence on physics within \( R_{2500} \)
  • We predict: \( Y_{0,b} = (0.83 \pm 0.06) \) with a range of evolution of \(-0.02 \leq \alpha_{Y_b} \leq 0.07\)
"I think you should be more explicit here in step two."

Thank you!
Cosmological implications

RADIAL AND MASS DEPENDENCE OF THE BARYONIC BIAS

• Within $R_{500}$:
  • Larger $Y_b$ with AGN feedback
  • $Y_g$ shows no flattening
  • A mass and model independent correction can be calibrated from simulations to infer $Y_b$ for massive clusters

• Within $R_{2500}$:
  • Steady increase with $M_{500}$
  • No fattening at high masses
  • Dependence on physics included
  • Additional care must be taken to calibrate $Y_b$
## Baryon content

### OBSERVATIONAL SAMPLES

<table>
<thead>
<tr>
<th>Sample</th>
<th>Best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lin et al. (2003)</td>
<td>$f_{b,500} = 0.148^{+0.005}<em>{-0.004} \left( \frac{M</em>{500}}{[3 \times 10^{14} M_\odot]} \right) (0.148 \pm 0.040)$</td>
</tr>
<tr>
<td>Giodini et al. (2009)</td>
<td>$f_{b,500} = (0.123 \pm 0.003) \left( \frac{M_{500}}{[2 \times 10^{14} M_\odot]} \right) (0.09 \pm 0.03)$</td>
</tr>
<tr>
<td>Laganá et al. (2011)</td>
<td>$f_{b,500} = 10^{-0.930 \pm 0.018} \left( \frac{M_{500}}{10^{14} M_\odot} \right) (0.136 \pm 0.028)$</td>
</tr>
<tr>
<td>Z11+S09, V06+APP07+S09</td>
<td>$f_{g,500} = 10^{-1.07 \pm 0.02} \left( \frac{M_{500}}{[10^{14} M_\odot]} \right) (0.30 \pm 0.07)$</td>
</tr>
<tr>
<td></td>
<td>$f_{g,500} (h/0.7)^{3/2} = (0.093 \pm 0.002) \left( \frac{M_{500}}{[2 \times 10^{14} M_\odot]} \right) (0.21 \pm 0.03)$</td>
</tr>
<tr>
<td>Lin et al. (2003)</td>
<td>$f_{*,500} = 0.0164^{+0.0010}<em>{-0.0009} \left( \frac{M</em>{500}}{[3 \times 10^{14} M_\odot]} \right) (0.26 \pm 0.09)$</td>
</tr>
<tr>
<td>Gonzalez et al. (2007)</td>
<td>$f_{*,500} = 10^{7.57 \pm 0.08} M_{500} (0.64 \pm 0.13)$</td>
</tr>
<tr>
<td>Laganá et al. (2011)</td>
<td>$f_{*,500} = 10^{-1.54 \pm 0.10} \left( \frac{M_{500}}{[10^{14.5} M_\odot]} \right) (0.36 \pm 0.17)$</td>
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