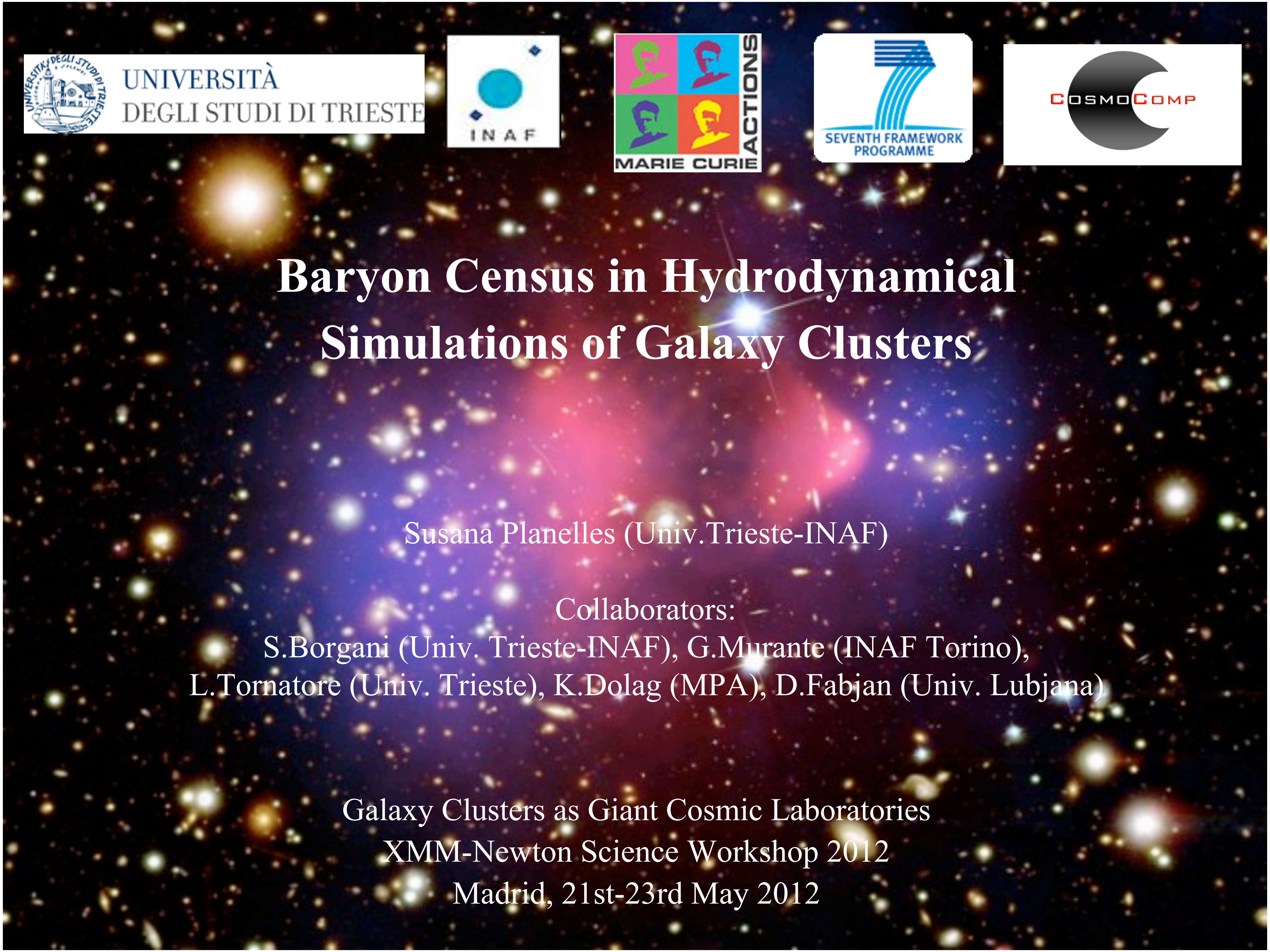

Baryon Census in Hydrodynamical Simulations of Galaxy Clusters

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Galaxy Clusters as Giant Cosmic Laboratories
XMM-Newton Science Workshop 2012
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Outline

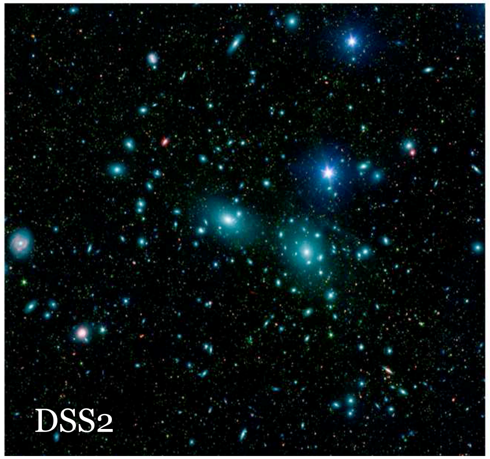
- **Introduction**
    - Galaxy clusters
    - Clusters as cosmological probes
- **Cosmological simulations**
    - DIANOGA cluster set (S. Borgani's talk)
- **Preliminary results**
    - Baryon content
    - Cosmological implications
- **Summary and future directions**

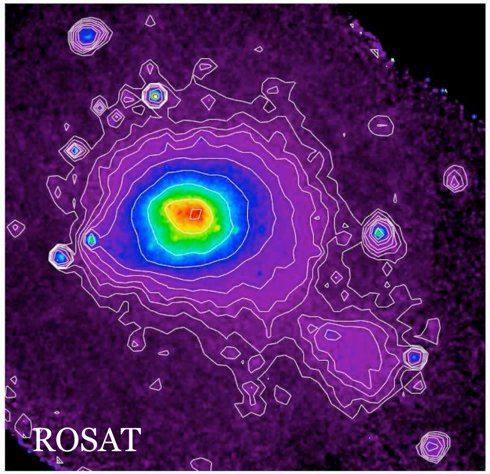
GENERAL PROPERTIES

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

$$\boxed{f_b = f_{st} + f_{gas} = f_{gas}(1+s)} \qquad s \equiv \frac{f_{st}}{f_{gas}}$$

$$f_{gas} = \frac{M_{gas}}{M_{tot}} \qquad f_{st} = \frac{M_{st}}{M_{tot}}$$





- 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

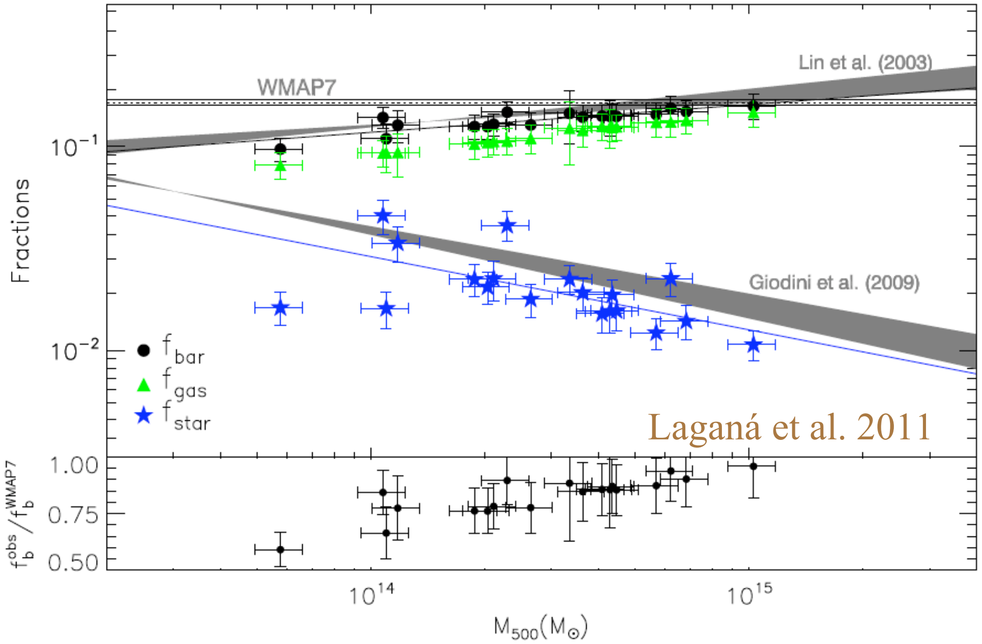
    ⇒ clean cluster surveys
  - X-ray observables ⇔ M_{tot} ⇒ hydro. simulations

ROLE OF CLUSTERS IN COSMOLOGY

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

- Challenges:
  - Observed f_{gas} smaller than expected
  - Intriguing trend with cluster mass

- Possible explanations:
  - Physical processes which lower f_b
  - Undetected baryon components
  - Systematic underestimate of Ω_m by WMAP



Laganá et al. 2011

PURPOSE OF THE PRESENT WORK

- 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: to analyse some implications for the constraints on cosmological parameters over a large redshift range ($z\leq1$).

Cosmological Simulations

DIANOGA CLUSTER SET

- General properties (S. Borgani's talk)
  - Parallel Tree-PM SPH code GADGET-3 (Springel 2005)
  - ΛCDM model: Ω_m=0.24, Ω_Λ=0.76, Ω_b=0.04, h=0.72, σ_8=0.8, n_s=0.96
  - Re-simulation of 29 Lagrangian regions centred around clusters with $M_{vir} \geq 10^{15} M_\odot\, h^{-1}$ (24) and $M_{vir} \approx (1\text{-}7) \times 10^{14} M_\odot h^{-1}$ (5)
  - Parent DM-only simulation: 1024^3 DM particles; L_{box}=1 Gpc h^{-1}
- Physics included
  - *NR*: non-radiative run
  - *CSF-M-W*: cooling, SF, metals and SN feedback (v_w=500 km s^{-1})
  - *CSF-M-W-AGN*: cooling, SF, metals, SN feedback (v_w=350 km s^{-1}) and AGN feedback
- The set of simulated clusters
  - Final sample: 140 clusters with $M_{500} \geq 5 \times 10^{13} M_\odot h^{-1}$ (≈30 with $M_{vir} \geq 10^{15} M_\odot h^{-1}$)
  - Cluster identification: minimum potential + SO method

$$\boxed{M_\Delta = \Delta\, \rho_c(z)\, (4\,\pi/3) R_\Delta^3}$$

$(\Delta = 2500, 500, 200)$

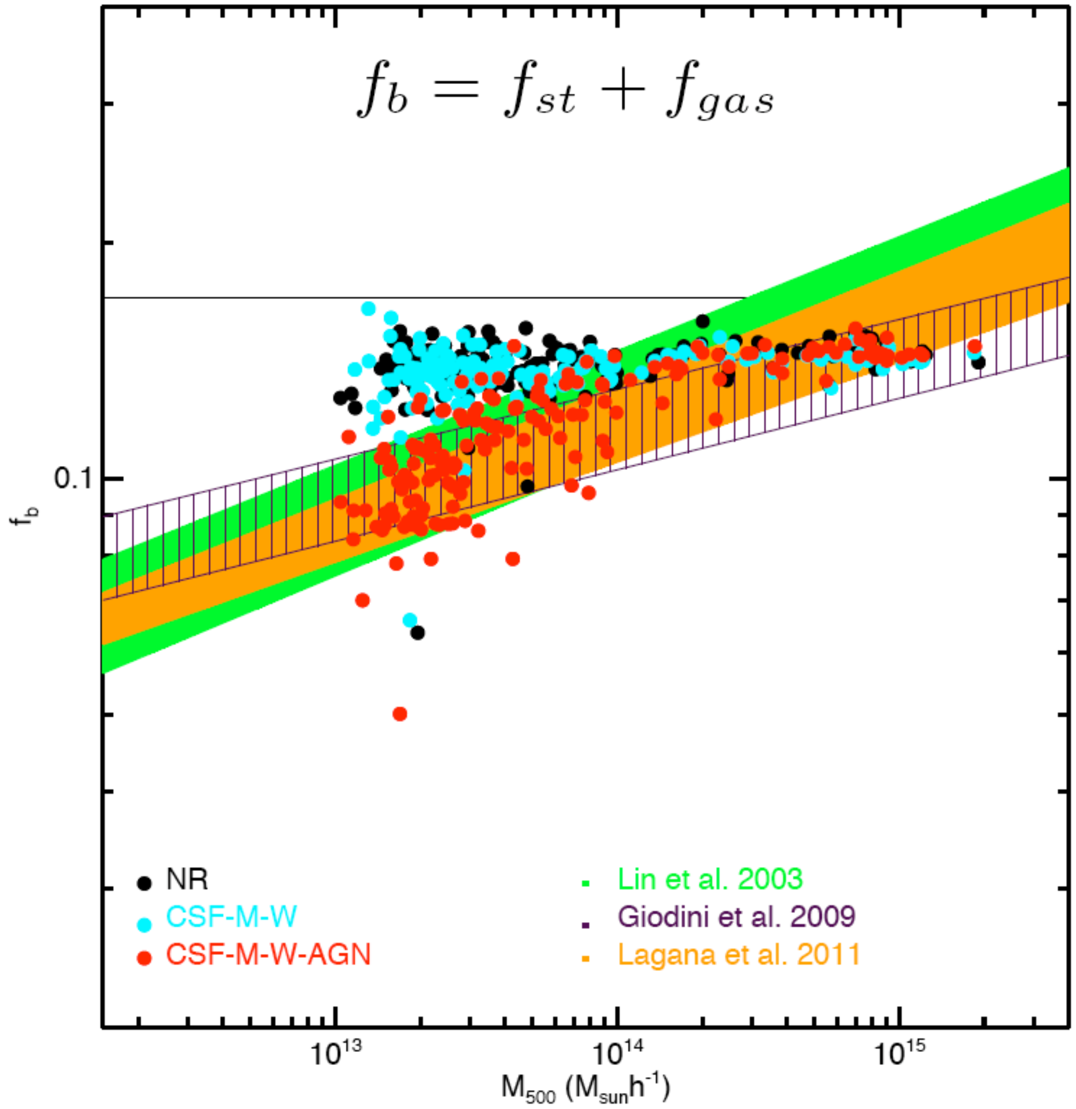
Baryon content

BARYON MASS FRACTION

- *NR & CSF-M-W* runs:
  - f_b appears flat as a function of M_{500}
  - f_b differs by ≤ 10% from the assumed cosmic fraction

    (e.g., Kravstov et al. 2005, Ettori et al., 2006)

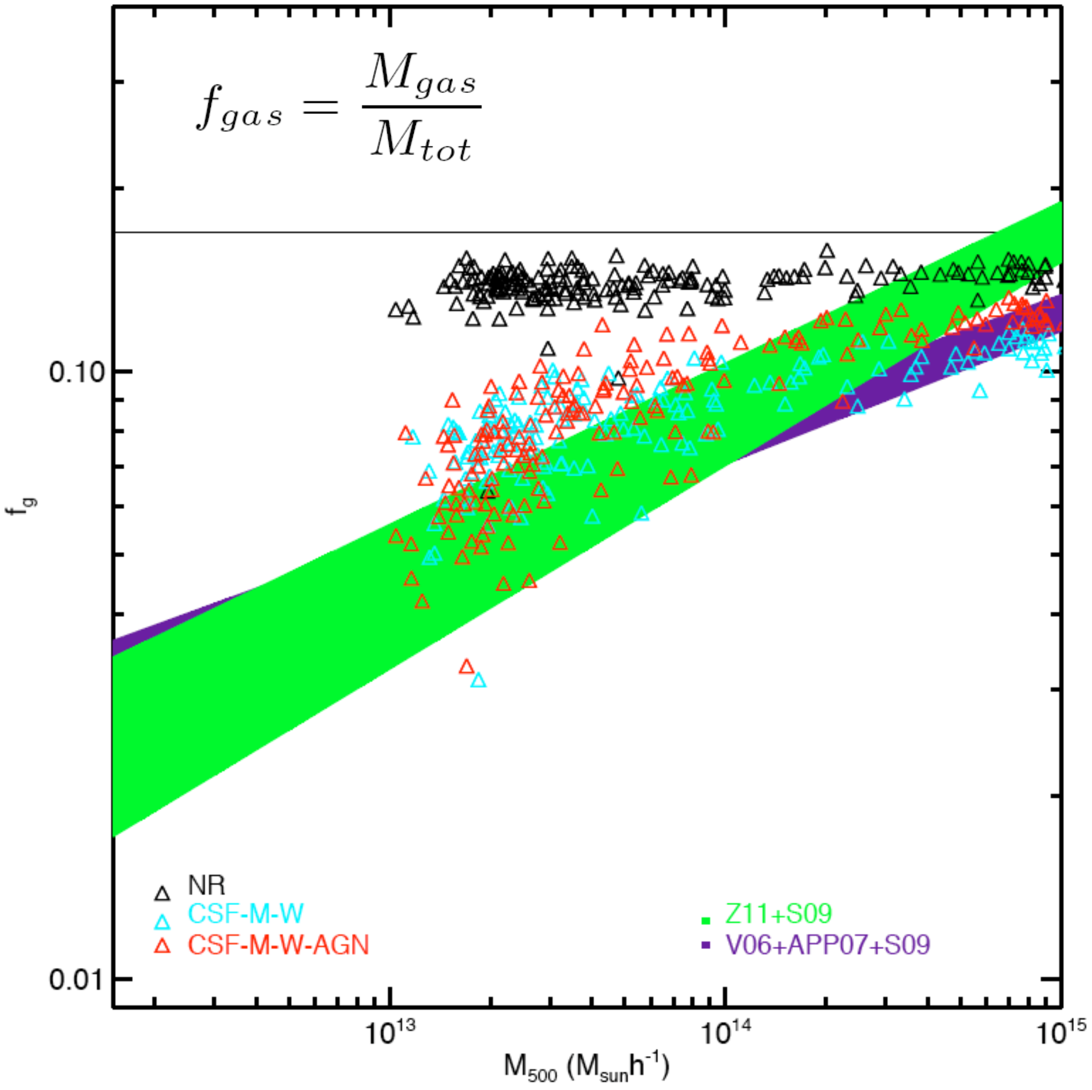
- *CSF-M-AGN* run:
  - Significant baryon depletion for $M_{500} \leq 10^{14} M_{\odot} h^{-1}$
  - f_b is closer to the cosmic value for the most massive clusters
  - Better agreement with observations when including AGN feedback



GAS MASS FRACTION

- *NR* run:
  - f_g appears flat as a function of M_{500}
  - f_g is larger than in the radiative runs

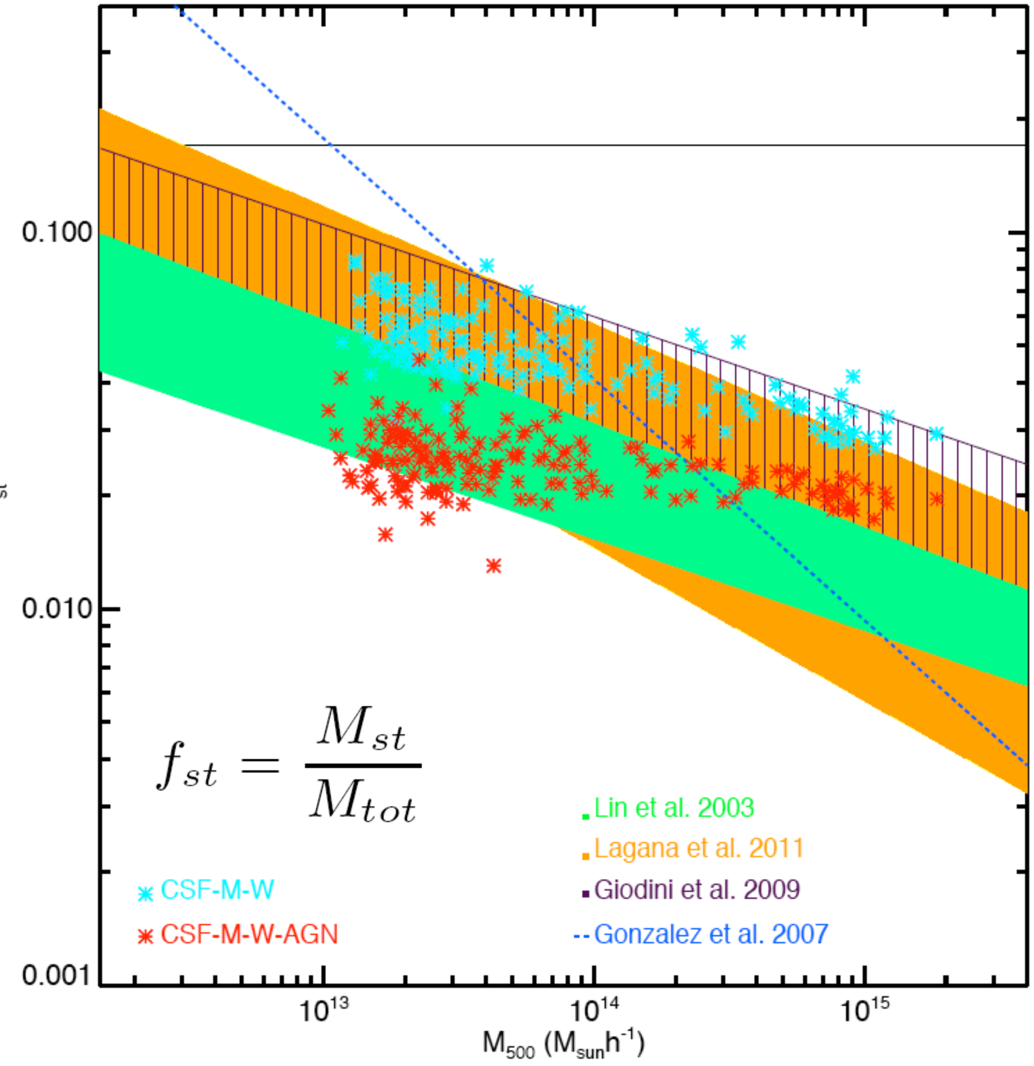
- Radiative runs:
  - f_g increases as a function of mass
  - AGN feedback significantly reduces:
    - f_g in poor clusters and groups
    - overcooling in the richest clusters
  - f_g is still smaller than the observed value



Baryon content

STELLAR MASS FRACTION

- General behaviour:
  - f_{st} decreases smoothly with increasing mass and flattens for $M_{500} \leq 10^{14} M_{\odot} h^{-1}$
- *CSF-M-W*:
  - f_{st} is quite large: ~(30%-50%) f_b
- *CSF-M-AGN*:
  - f_{st} is lowered by ~1/3 but still larger than observations by a factor 2-3
  - None of our simulations reproduce the observed strong trend of f_{st} with mass



Cosmological implications

INTRODUCTION

- Basic idea: galaxy clusters are so large that their matter content should provide a ~ fair sample of matter content of the Universe (White & Frenk 1991)
- Constraining Ω_m: (e.g., Allen at al. 2008)

$$f_b = Y_b \frac{\Omega_b}{\Omega_m}$$

$$s \equiv \frac{f_{st}}{f_{gas}}$$

$$\Rightarrow \boxed{\Omega_m = \frac{Y_b \Omega_b}{f_{gas}(1+s)}}$$

Y_b → simulations
Ω_b → BBNS/CMB
f_{gas} → observations
s → statistical approach

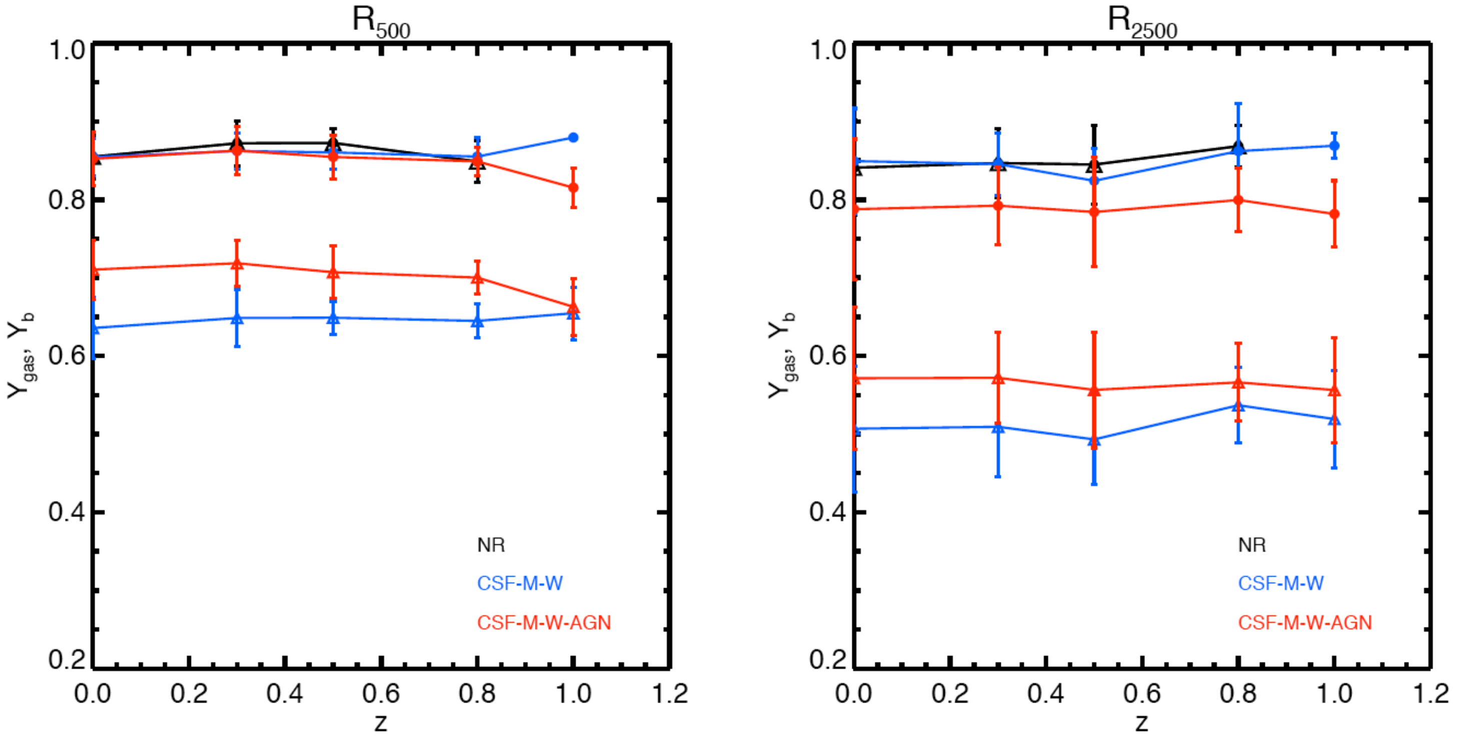
- Main assumptions: 1) Y_b does not evolve with z
  2) The ratio $s=f_{st}/f_{gas}$ holds constant at any radius and z
- Main advantages:
  - This test can be performed with a small statistics
  - Relative insensitivity to cluster selection

Cosmological implications

BARYONIC BIAS

- Reduced sample: the hottest ($T_{sl} \geq 4$ keV) and most X-ray luminous galaxy clusters

- Results on Y_b:



- Within R_{500}:
  $Y_b \approx (0.86 \pm 0.03)$
  $Y_b \approx (0.85 \pm 0.02)$
  $Y_b \approx (0.85 \pm 0.03)$

- Within R_{2500}:
  $Y_b \approx (0.84 \pm 0.06)$
  $Y_b \approx (0.85 \pm 0.07)$
  $Y_b \approx (0.79 \pm 0.09)$

- Roughly constant up to z=1 (e.g., Eke et al. 1998, Kravstov et al. 2005)
- Dependence on physics within R_{2500}

Cosmological implications

DEVIATIONS FROM THE MODEL

- Main assumptions: 1) Y_b does not evolve with z
  2) The ratio $s=f_{st}/f_{gas}$ holds constant at any radius and z

- However, these assumptions are not completely valid in our simulated dataset!
  ⇒ we evaluate how Ω_m changes due to the variation of Y_b ($\equiv D_b$) and s ($\equiv D_{st}$) as a function of R_Δ, z, and physics:

$$\boxed{D_b \equiv \frac{\Omega'_\mathrm{m} - \Omega_\mathrm{m}}{\Omega_\mathrm{m}} = \frac{\Delta\Omega_\mathrm{m}}{\Omega_\mathrm{m}} = \frac{Y_\mathrm{b}(< R_\Delta, z = z_o)}{Y_\mathrm{b}(< R_\Delta, z = 0)} - 1}$$

$$\boxed{D_{st} \equiv \frac{\Omega'_\mathrm{m} - \Omega_\mathrm{m}}{\Omega_\mathrm{m}} = \frac{\Delta\Omega_\mathrm{m}}{\Omega_\mathrm{m}} = \frac{1 + s(< R_\Delta, z = 0)}{1 + s(< R_\Delta, z = z_o)} - 1}$$

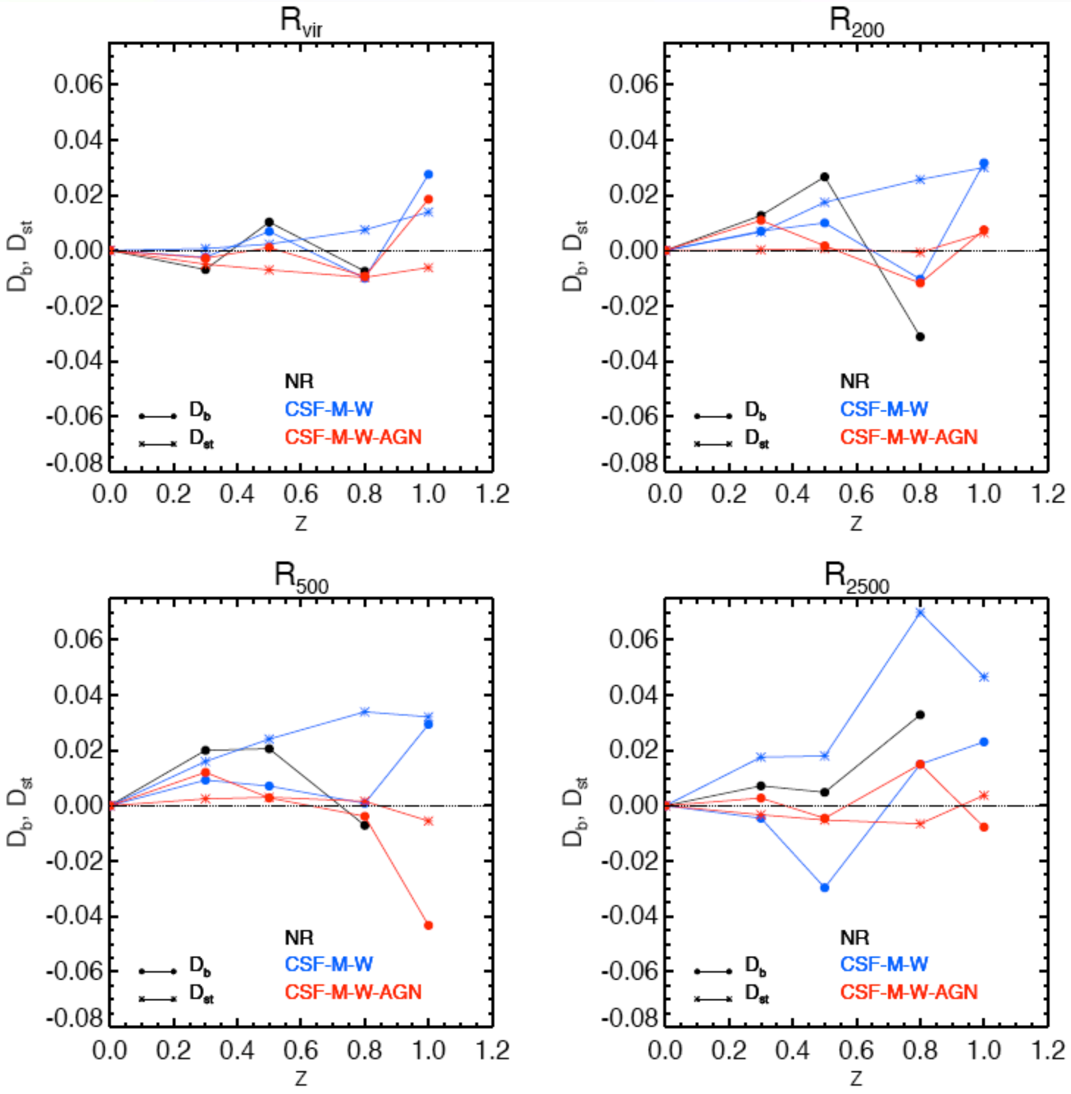
(Ettori et al. 2006)

$$R_\Delta = (R_{vir}, R_{200}, R_{500}, R_{2500}) \qquad z_0 = (0.3, 0.5, 0.8, 1)$$

Cosmological implications

DEVIATIONS FROM THE MODEL

- *NR runs*
  - Correction to Ω_m due to the variation of Y_b with z and overdensity
- Radiative runs
  - $\Delta\Omega_m/\Omega_m$ has two contributions due to the variation with z of Y_b and s
- Different physical models ⇒different z-dependent corrections to Ω_m



Conclusions

SUMMARY AND FUTURE DIRECTIONS

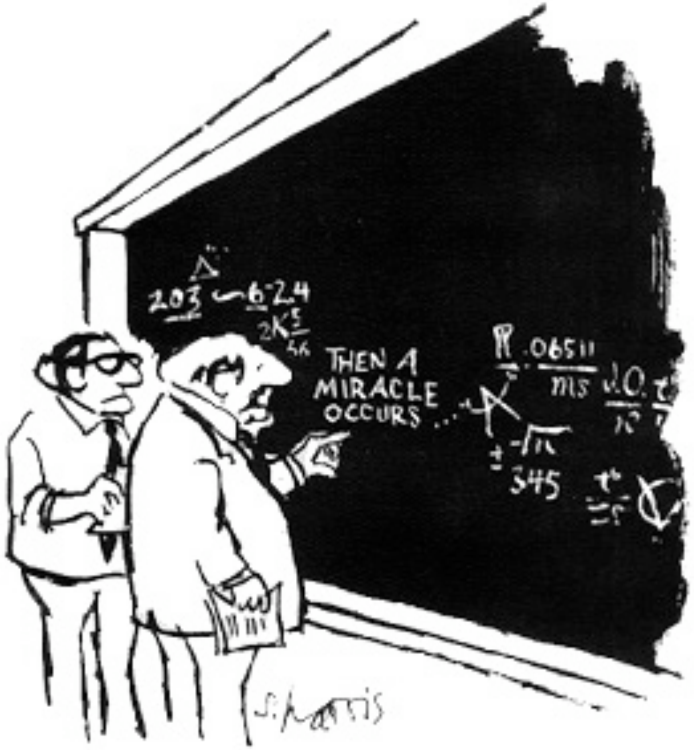
- Main conclusions
  - Consistency with observations in $f_b=f(M_{500})$ and $f_g=f(M_{500})$.
  - None of our simulations is able to reproduce the observed $f_{st}=f(M_{500})$.

    However,

    better agreement with observations when AGN feedback is included.
  - $Y_b \approx$constant with z but shows some dependence on physics within R_{2500}

- Future directions
  - Analyse in detail the different stellar components (ICL+BCG+satellites)
  - Constraints on Ω_m-Ω_Λ using $f_{gas}(z) \propto d_{ang}(z, \Omega_m, \Omega_\Lambda, w)$

Thank you!



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

Baryon content

OBSERVATIONAL SAMPLES

Sample	Best fit
Lin et al. (2003)	$f_{\mathrm{b},500} = 0.148^{+0.005}_{-0.004}(M_{500}/[3\times10^{14}\mathrm{M}_\odot])^{(0.148\pm0.040)}$
Giodini et al. (2009)	$f_{\mathrm{b},500} = (0.123\pm0.003)(M_{500}/[2\times10^{14}\mathrm{M}_\odot])^{(0.09\pm0.03)}$
Laganá et al. (2011)	$f_{\mathrm{b},500} = 10^{(-0.930\pm0.018)}(M_{500}/10^{14}\mathrm{M}_\odot)^{(0.136\pm0.028)}$
Z11+S09	$f_{\mathrm{g},500} = 10^{-(1.07\pm0.02)}(M_{500}/[10^{14}\mathrm{M}_\odot])^{(0.30\pm0.07)}$
V06+APP07+S09	$f_{\mathrm{g},500}(h/0.7)^{3/2} = (0.093\pm0.002)(M_{500}/[2\times10^{14}\mathrm{M}_\odot])^{(0.21\pm0.03)}$
Lin et al. (2003)	$f_{\mathrm{st},500} = 0.0164^{+0.0010}_{-0.0090}(M_{500}/[3\times10^{14}\mathrm{M}_\odot])^{-(0.26\pm0.09)}$
Gonzalez et al. (2007)	$f_{\mathrm{st},500} = 10^{7.57\pm0.08)}\,M_{500}{}^{-(0.64\pm0.13)}$
Giodini et al. (2009)	$f_{\mathrm{st},500} = (0.050\pm0.001)(M_{500}/[5\times10^{13}\mathrm{M}_\odot])^{(-0.26\pm0.09)}$
Laganá et al. (2011)	$f_{\mathrm{st},500} = 10^{(-1.54\pm0.10)}(M_{500}/[10^{14.5}\mathrm{M}_\odot])^{(-0.36\pm0.17)}$

Baryon content

INTRACLUSTER LIGHT