Baryon Census in Hydrodynamical Simulations of Galaxy Clusters

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CosmoComp Meeting
Trieste, 4th-7th September 2012

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**

GENERAL PROPERTIES

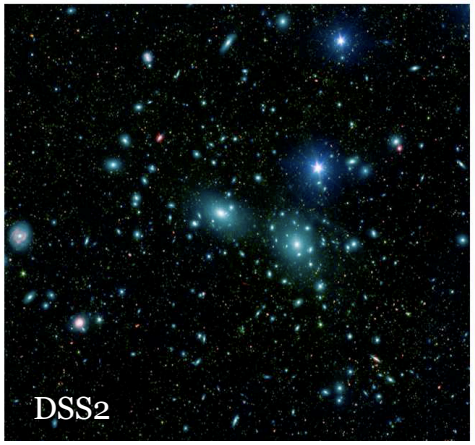
- Largest virialized structures in the Universe: $M \approx 10^{13}$-10^{15} $M_\odot$, $R \approx 1$-3 Mpc
- Composition: galaxies and stars (~5%), ICM (~15%), DM (~80%)
- Baryon budget: stars in galaxies + ICL + ICM
- Baryonic mass fractions:

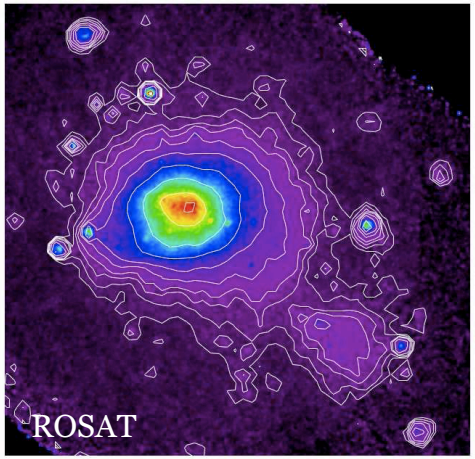
$$f_b = f_g + f_* \qquad f_* = \frac{M_*}{M_{tot}} \qquad f_g = \frac{M_g}{M_{tot}}$$

- Depletion factors:

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

- 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
    $\Rightarrow$ clean cluster surveys
  - X-ray observables $\Leftrightarrow$ M_{tot} $\Rightarrow$ hydro. simulations



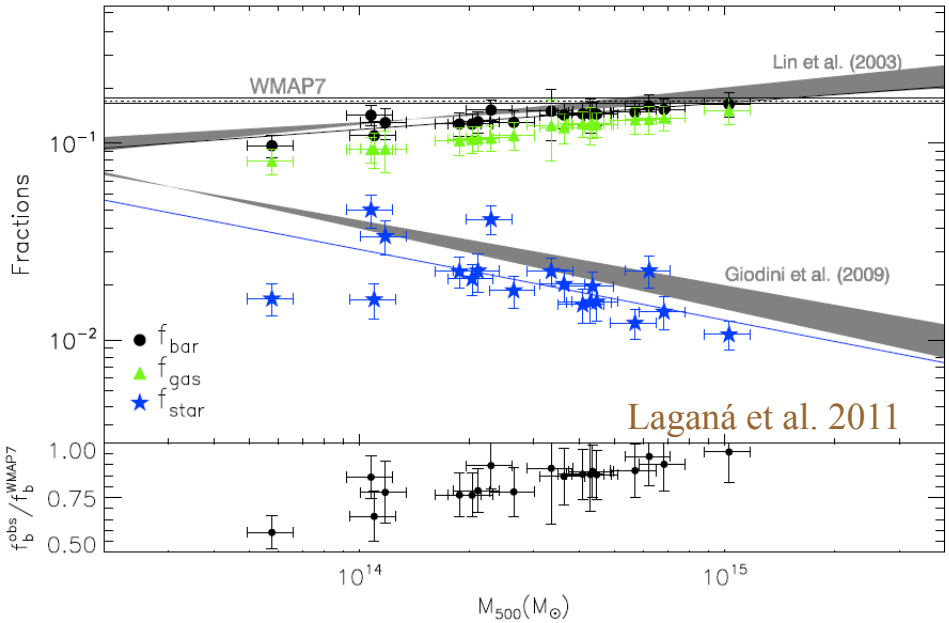


ROLE OF CLUSTERS IN COSMOLOGY

- 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) + $\Omega_b h^2$ (CMB/BBNS) + h ⇒ Ω_m (e.g., White & Frenk 1991)
    - Apparent z-evolution of f_{gas} ⇒ 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



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: calibration of the different baryonic depletions as a function of redshift, radius and physics.

DIANOGA CLUSTER SET

- General properties (Bonafede et al. 2011)
  - 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 $M_{vir} \geq 10^{15} h^{-1} M_\odot$ (24) and $M_{vir} \approx (1\text{-}7) \times 10^{14} h^{-1} M_\odot$ (5)
  - Parent DM-only simulation: 1024^3 DM particles; L_{box}=1 h^{-1}Gpc
- Physics included
  - *NR*: non-radiative run
  - *CSF*: cooling, SF, metals and SN feedback (v_w=500 km s^{-1})
  - *AGN*: cooling, SF, metals, SN (v_w=350 km s^{-1}) and AGN feedback
- The set of simulated clusters
  - Final sample: ≈160 clusters with $M_{vir} \geq 3\times10^{13} h^{-1} M_\odot$ (≈70 with $M_{vir} \geq 10^{14} h^{-1} M_\odot$)
  - Cluster identification: minimum potential of a FoF group + SO method

$$\boxed{M_\Delta = \Delta\, \rho_c(z)\, (4\,\pi/3) R_\Delta^3} \qquad (\Delta = 2500, 500, 200)$$

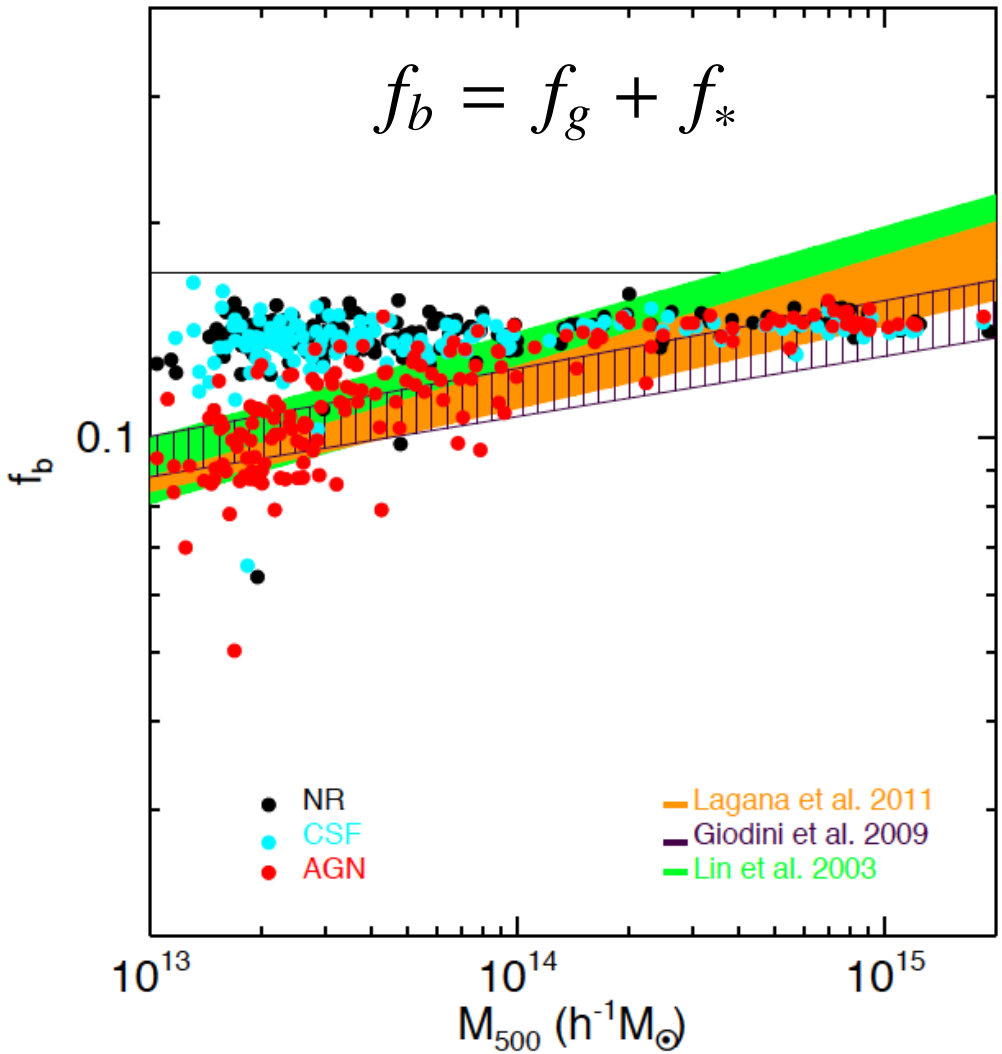
Baryon content

BARYON MASS FRACTION

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

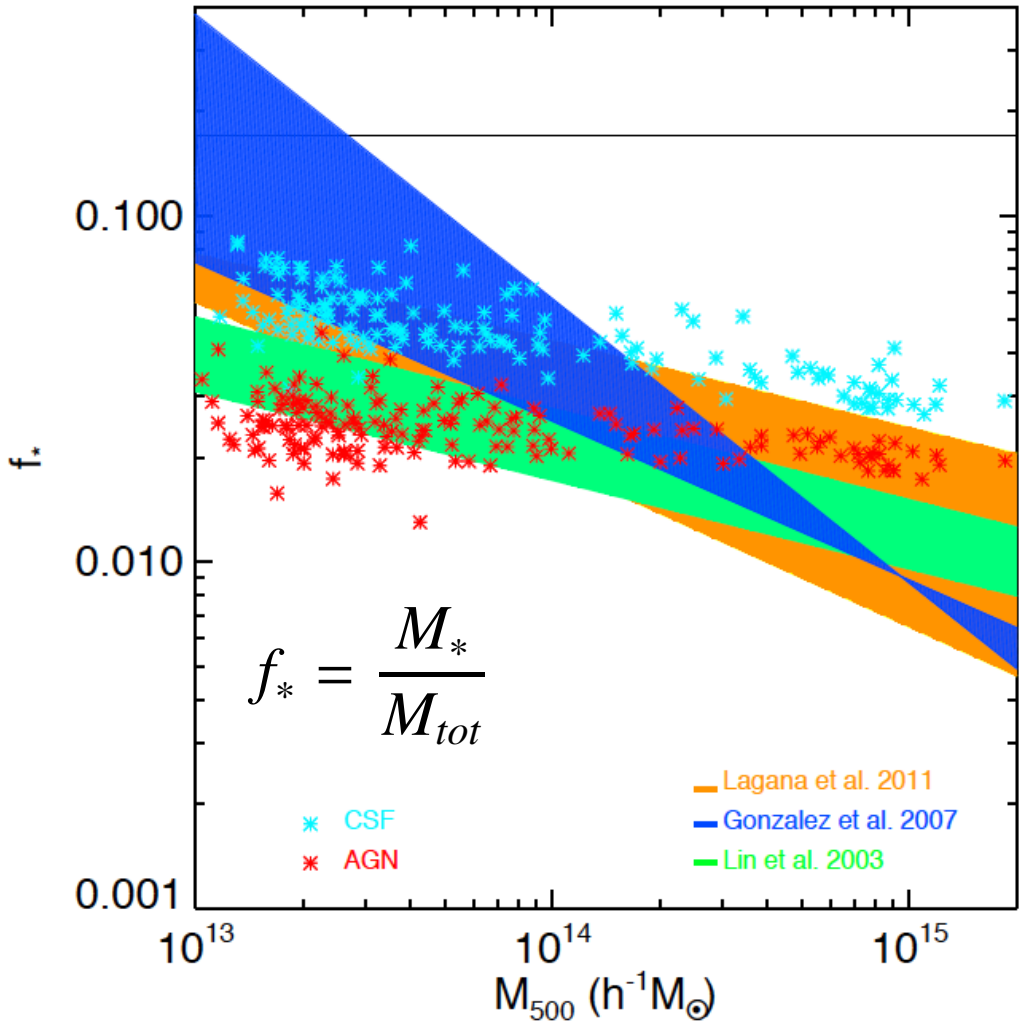
    (e.g., Kravstov et al. 2005, Ettori et al., 2006)

- *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



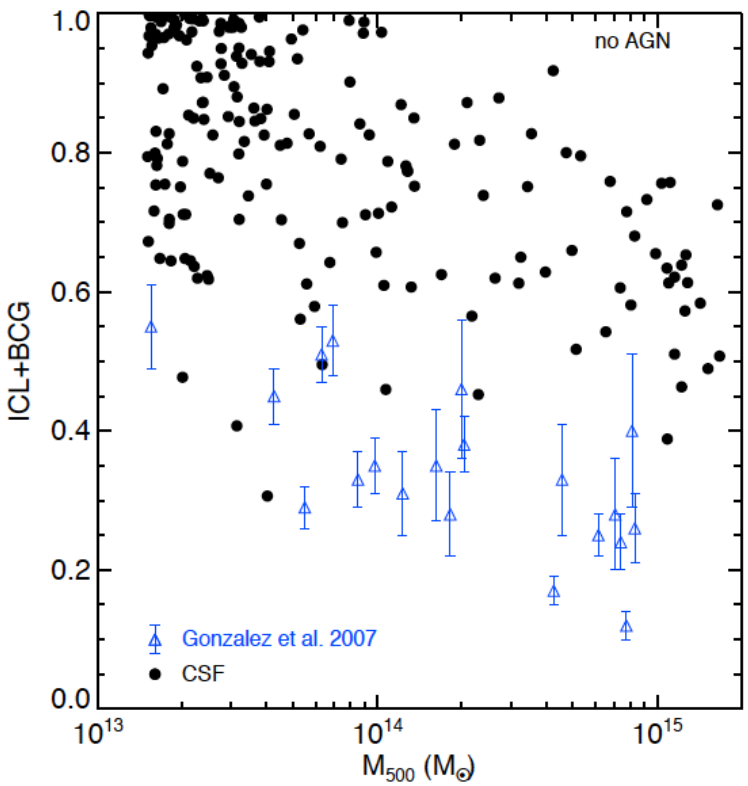
TOTAL STELLAR MASS FRACTION

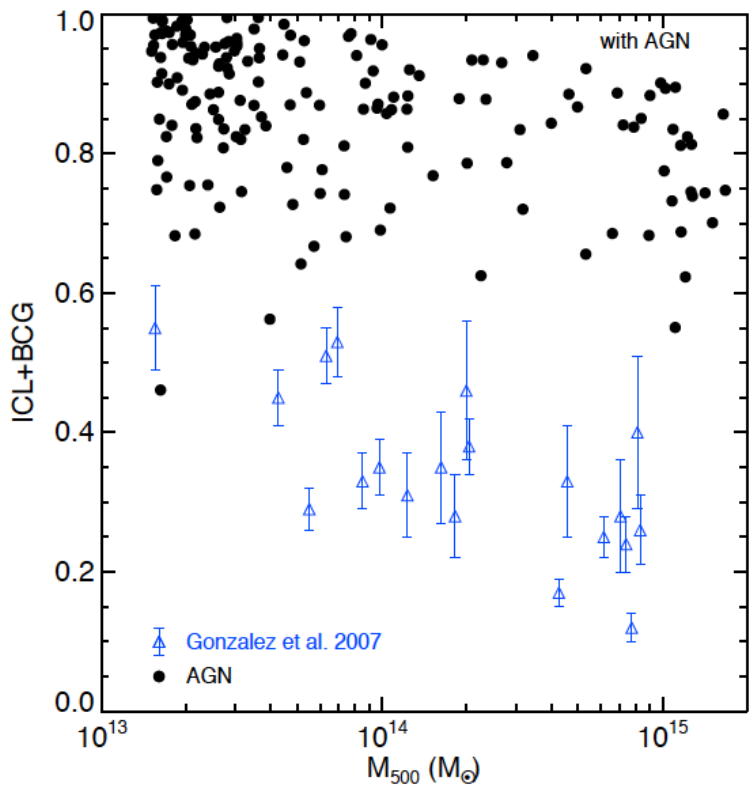
- General behaviour:
  - f_* decreases smoothly with increasing mass and flattens for $M_{500} \leq 10^{14} h^{-1} M_\odot$
- *CSF*:
  - f_* is quite large: ~(30%-50%) f_b
- *AGN*:
  - f_* is lowered by ~1/3
  - Some caution when comparing observational and simulated samples



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

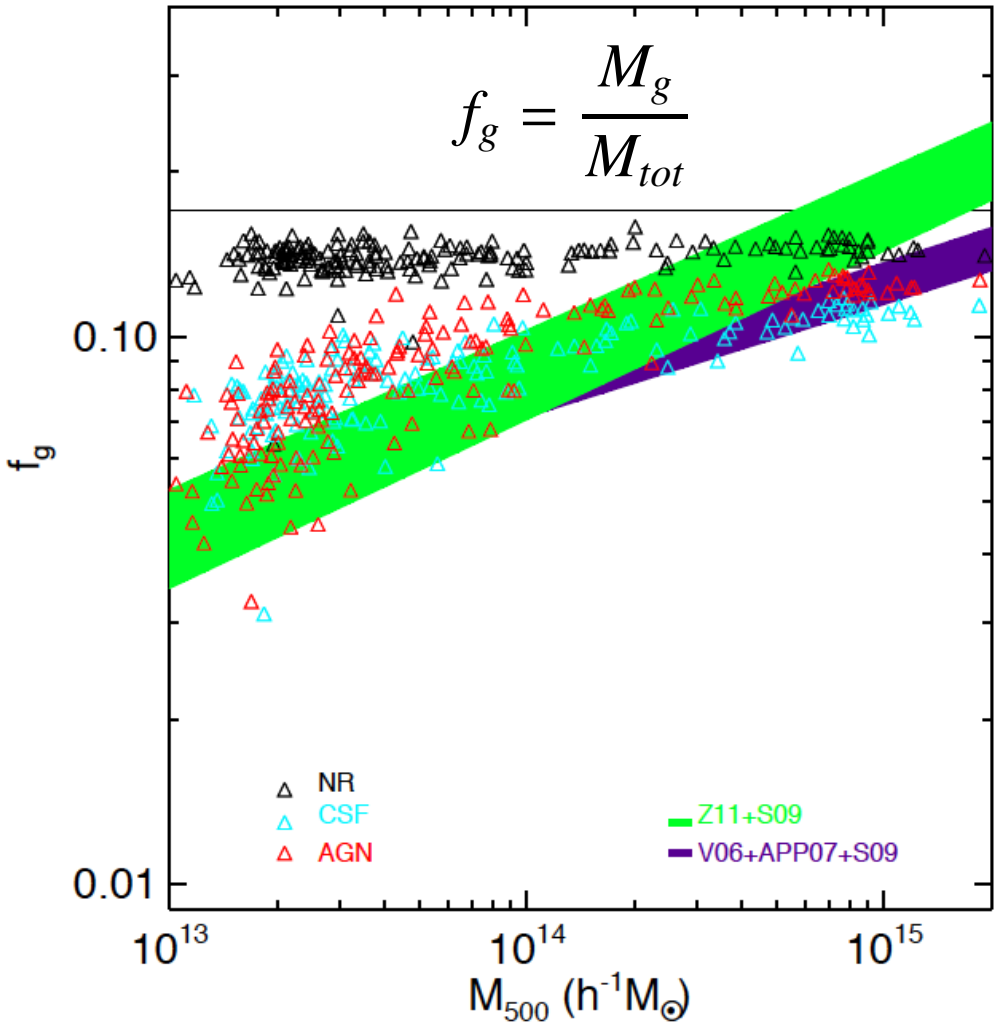
Baryon content

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



CALIBRATION OF THE BARYONIC BIAS

- Basic idea: (White & Frenk 1991)

  massive galaxy clusters ~ fair sample of matter content of the Universe ➔ Y_b=1
- "Baryonic bias": any deviation from Y_b=1
- Why calibrating the baryonic bias? (e.g., Allen at al. 2008)
  - f_{gas} provides one of the best constraints on Ω_m:

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

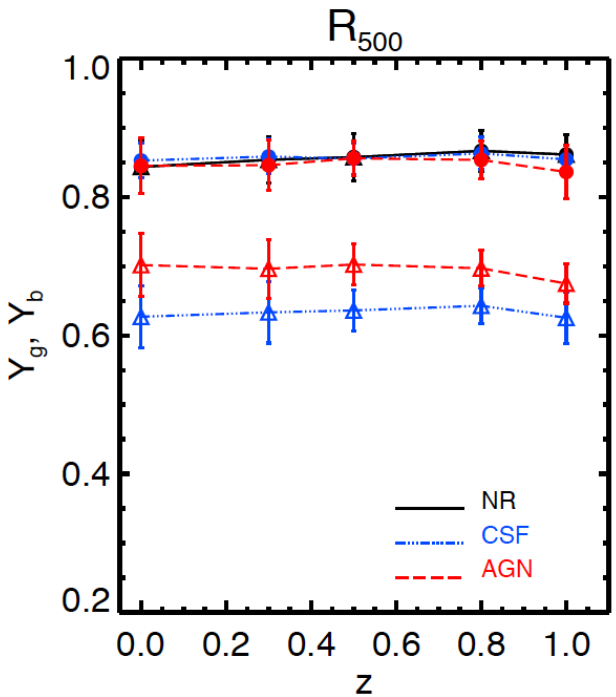
Y_b → simulations // Ω_b → BBNS/CMB

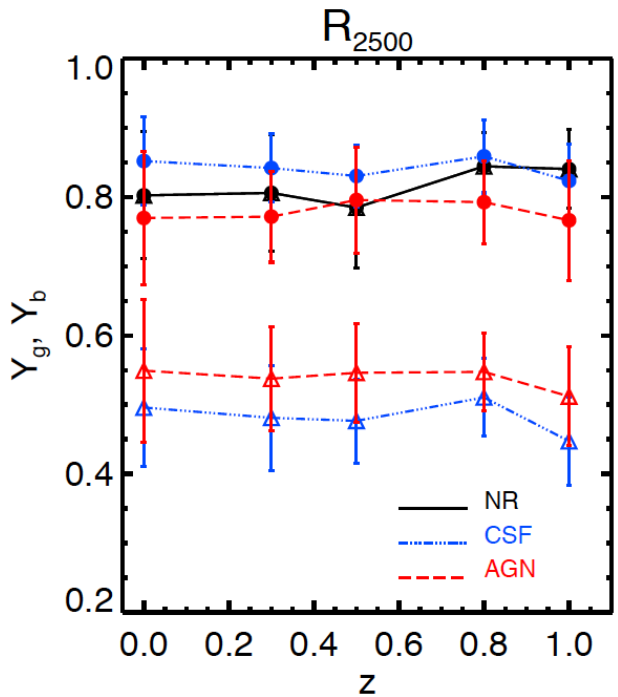
f_{gas} → observations // $s \equiv \frac{f_{st}}{f_{gas}}$ → statistical approach

  - $f_{gas}(z) \propto d_{ang}(z, \Omega_m, \Omega_\Lambda, w) \Rightarrow$ geometry of the Universe (e.g., Allen et al. 2008)
- Non-radiative simulations predict: (e.g., Eke et al. 1998)
  - Y_b=0.83±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

REDSHIFT EVOLUTION OF THE BARYONIC BIAS

- Reduced sample: ~ 40 clusters with $M_{500} \geq 2\times10^{14} h^{-1} M_{\odot}$ at z=0 and ~10 at z=1





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

- Within R_{2500}:
  $Y_b \approx (0.79 \pm 0.07)$
  $Y_b \approx (0.85 \pm 0.05)$
  $Y_b \approx (0.78 \pm 0.07)$

- 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)
  - $Y_b(z)=Y_{0,b}(1+\alpha_{Yb} z)$

$$Y_{0,b}=0.83\pm0.06$$

$$-0.02 \leq \alpha_{Yb} \leq 0.07$$

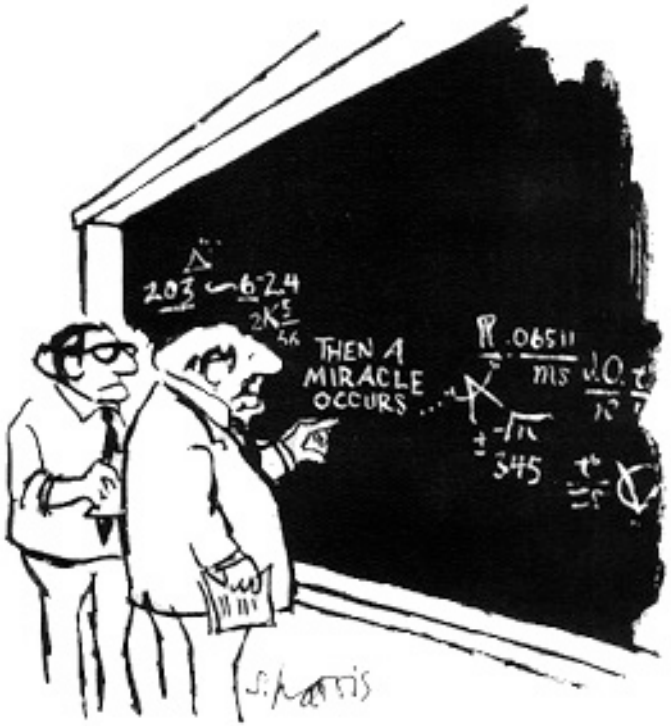
Conclusions

SUMMARY

- 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
  - $Y_b \approx$constant with z but shows some dependence on physics within R_{2500}
  - We predict: $Y_{0.b}=(0.83\pm0.06)$ with a range of evolution of $-0.02\leq\alpha_{Yb}\leq0.07$



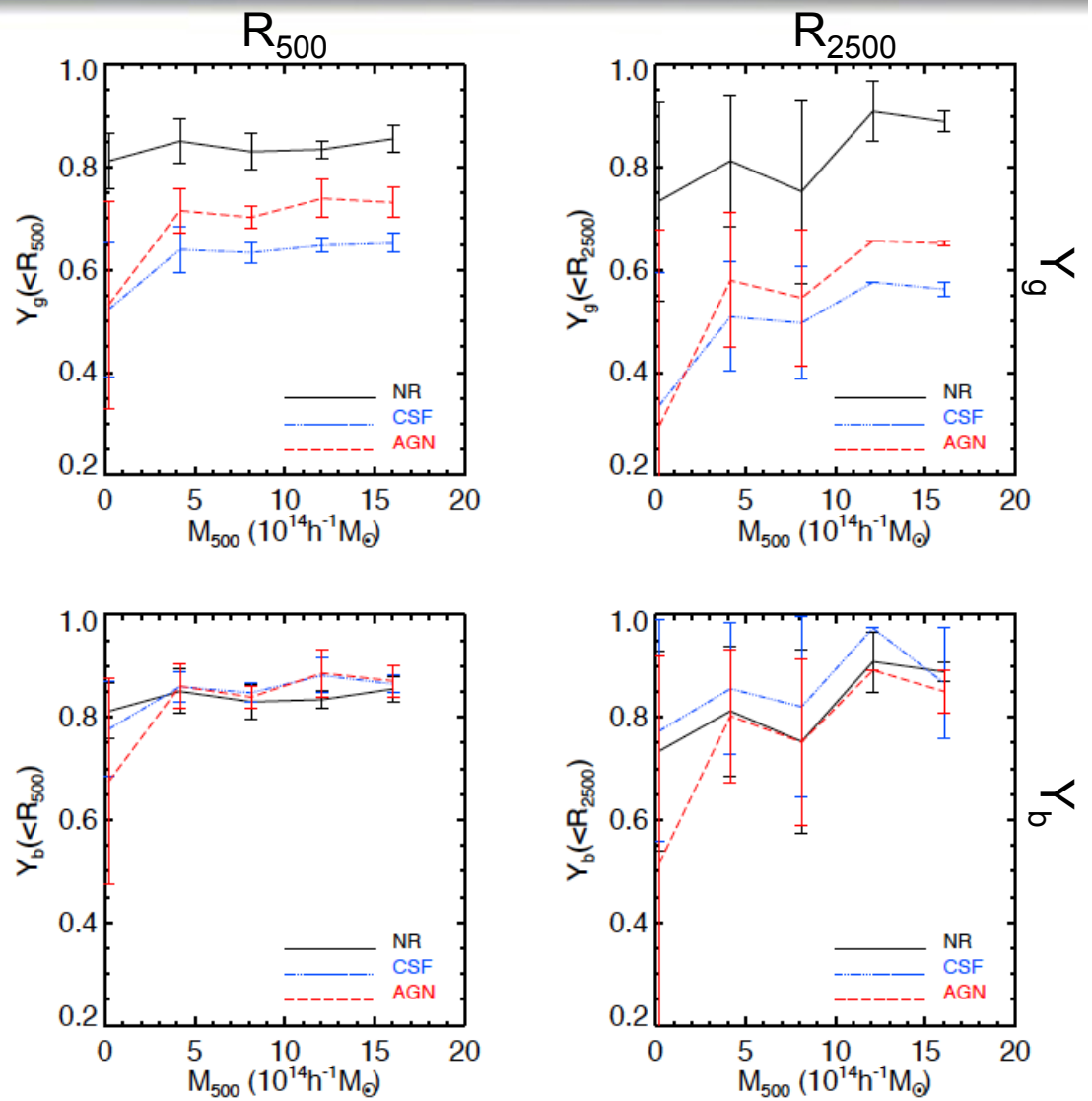
"I think you should be more explicit here in step two."

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

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)	$f_{*,500} = 0.0164^{+0.0010}_{-0.0090}(M_{500}/[3\times10^{14}\mathrm{M}_\odot])^{-(0.26\pm0.09)}$
Gonzalez et al. (2007)	$f_{*,500} = 10^{(7.57\pm0.08)}M_{500}{}^{-(0.64\pm0.13)}$
Laganá et al. (2011)	$f_{*,500} = 10^{(-1.54\pm0.10)}(M_{500}/[10^{14.5}\mathrm{M}_\odot])^{(-0.36\pm0.17)}$