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Submm Galaxies: Testing Mass Assembly at the Upper End[1]

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ABSTRACT

From CO mm interferometry and near-IR integral field spectroscopy of submillimeter galaxies we test high-z mass assembly at the upper end of the galaxy mass function. We have carried out a 1Ms survey of mm CO line emission with the IRAM mm-interferometer in a sample of radio detected SCUBA sources. The CO survey quadruples the number of mm-confirmed redshifts of $z \sim 2.5$ submillimeter galaxies and shows that the median velocity dispersion of the galaxies is ~ 250 km/s. With the SPIFFI near-IR integral field spectrometer on the ESO VLT we have obtained J, H, and K-band spectroscopy of the $z = 2.5$ submillimeter galaxy SMM J14011+0252. The spatially resolved data show that the source is a super-solar metallicity starburst of age ≥ 100 Myr. Our IRAM and VLT data demonstrate that the most luminous members of the submm galaxy population are gas rich, massive ($\sim 10^{11}$ $M_\odot$) galaxies with intense starbursts. Submillimeter galaxies are much more massive than Lyman break galaxies, and more numerous at high redshift than predicted by current semi–analytic models of galaxy evolution.

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1. Introduction

Deep imaging in the rest-frame UV has constrained both the evolution of the cosmic star formation rate density (e.g., Madau et al. 1996) and its time integral, the growth of the cosmic stellar mass density (e.g., Dickinson et al. 2003). Short–wavelength studies give an incomplete picture, however, since an important population of high–redshift galaxies is heavily dust obscured. The strength of the extragalactic mid- and far-IR/submillimeter background indicates that about half of the cosmic energy density comes from dusty luminous and ultra-luminous infrared galaxies (LIRGs/ULIRGs: $L_{IR} \sim 10^{11.5}$ to $10^{13.5}$ $L_\odot$) at $z \gtrsim 1$ (Puget et al. 1996; Pei, Fall, & Hauser 1999). Because the brightest of these submillimeter galaxies (SMGs; see Blain et al. 2002 and references therein) tend to lack strong X–ray emission (Almaini et al. 2003), their large IR luminosities probably correspond to high star formation rates (Barger et al. 2000). Moreover, as the strikingly different appearances of the Hubble Deep Field at $0.83\,\mu$m (Williams et al. 1996) and $850\,\mu$m (Hughes et al. 1998) exemplify, SMGs are rarer and forming stars much more intensely than typical optically selected systems. Throughout the paper we assume a flat $\Omega_\Lambda = 0.7$ cosmology with $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2. IRAM mm-Observations

Since SMGs in most cases have relatively poorly known positions and frequently have only weak counterparts in the rest-frame UV and optical, redshifts and spectroscopic parameters have thus far been confirmed with CO interferometry for only two of the few hundred detected submm sources (Blain et al. 2002). Recently a subgroup of the authors have initiated a new program of obtaining spectroscopic redshifts with the Keck telescope for a number of sources detected with the SCUBA camera at 850μm, in most cases aided by more precise positions derived from deep 1.4 GHz VLA observations of the same fields (Chapman et al. 2003). Here we report the first results of the millimeter follow-up of these submm sources, undertaken with the IRAM Plateau de Bure mm-interferometer (PdBI). For this purpose, we observed in a sample of twelve SMGs with S(850(μm)$\geq$ 5 mJy) and reliable UV/optical spectroscopic redshifts the CO J$= 3-2$ and $4-3$ rotational transitions redshifted to the 3mm window, in the D and B/C configurations of the PdBI. Integration times per source varied between 13 and 30 hours for a total integration time of about 1Ms for the survey in the 2002/2003 observing season. We detected significant CO emission in 7 out of the 12 sources, thus approximately quadrupling the number of mm-confirmed redshifts of SMGs (Neri et al. 2003, Greve et al. 2004). Figure 1 shows the CO $3-2/4-3$ spectra for the seven new sources and for SMMJ02399-0136 ($z = 2.81$, Genzel et al. 2003). Figure 2 gives the CO line integrated maps superposed on rest-frame UV (I-band) and optical (K-band) images of three of the sources (Neri et al. 2003).

Our PdBI observations confirm the median $z \sim 2.4$ redshifts identified from rest-frame UV/optical spectroscopy (Chapman et al. 2003) although for several sources (e.g. SMM J09431+4700 in Fig.2) the UV redshift is inferred from a source that is physically distinct from the submillimeter source. SMGs very likely sample very dense environments, which may harbor additional, UV bright star forming galaxies.

SMGs are rich in molecular gas. Correcting for foreground lensing wherever appropriate (and known) and for the CO luminosity to gas mass conversion factor appropriate for $z \sim$0.1 ULIRGs the median gas mass of the eight SMGs in Fig.1 (plus the $z = 2.56$ galaxy SMM J14011+0252: Downes and Solomon 2003) is 2.2$\times$ 10^{10} $M_\odot$. This value is similar to the median molecular gas mass found in high-z QSOs and about three times greater than in local ULIRGs. The inferred median far-IR luminosity of the sample (again corrected for lensing) is about is 1.3$\times$ 10^{13} $L_\odot$, corresponding to a star formation rate of about 1100 $M_\odot$/yr.

Our most important finding is that the brightest SMGs (S(850(μm)$\geq$ 5 mJy), making up about 25 percent of the submillimeter background, have large dynamical masses. The median velocity dispersion of our sample is 255 (± 38) km/s. The ratio of the squares of the median velocity dispersions then implies that our SMGs have dynamical masses at least 13 (±4) times greater than the $z \sim 3$ Lyman break galaxy population (Shapley et al. 2001), and at least 5 (±1.5) times greater than the $z \sim 2$ population studied by Erb et al. (2003, see also this volume). These estimates are lower limits since the sizes of SMGs are $\sim$ 1", larger than those of Lyman break galaxies (LBGs, Genzel et al. 2003, Neri et al. 2003, Chapman et al. 2004). Assuming a rotating disk geometry at an inclination of 40 degrees, the median velocity dispersion corresponds to a dynamical mass of 1.1× 10^{11} $M_{\odot}$ within R = 4 kpc. Genzel et al. (2003) determine a total dynamical mass of 3× 10^{11} $M_{\odot}$ for SMM J02399-0136 from its spatially resolved rotation curve within R = 8 kpc, half of which is probably stellar. From an analysis of the near-IR light Shapley et al. (2001) estimate median stellar masses of 1.4× 10^{10} $M_{\odot}$ for the $z \sim 3$ Lyman break population, consistent with the mass ratio above. Dynamical and stellar masses of the SMGs in our sample thus are comparable to local m*-galaxies.

3. SPIFFI VLT Observations

We also conducted a detailed rest–frame optical case study of one of the brightest submillimeter galaxies, SMM J14011+0252 (hereafter J14011), a $z = 2.565$ SMG lying behind the $z = 0.25$ cluster A1835 (Ivison et al. 2001). For this study we used SPIFFI, the SPectrometer for Infrared Faint Field Imaging (Eisenhauer et al. 2003). In three SPIFFI VLT runs between February and April 2003, we observed J14011 in the J, H, and K-bands, with a FWHM spatial resolution of about 0.6" and spectral resolutions ranging from 125 to 200 km/s. SPIFFI obtains simultaneous spectra for 32×32 contiguous pixels (at $0.25''$ per pixel). The total on–source integration times were 60 minutes in J, 95 minutes in H, and 340 minutes in K. For details see Tecza et al. (2004).

Within the bright eastern "J1" component of J14011, the SPIFFI data reveal substantial spatial variation in Hα equivalent width: nebular line emission is extended over about 1" (lensing corrected) and is strongest away from the central continuum peak. The integrated spectrum of J1 (Figure 3) appears to exhibit a continuum break between the observed J and H bands. The feature's most likely origin is the Balmer break of a $\geq 100\,$Myr old stellar population at $z \simeq 2.565$. The J1 line fluxes allow us to measure the R_{23} estimator for its oxygen abundance. After correcting for $E(B-V) = 0.18$ inferred from the Balmer decrement, we derive an oxygen abundance of 8.96 ± 0.10 , or 1.9 times solar. The observed high [N II]/Hα ratio implies that J14011 cannot fall on the lower–metallicity branch of the [O/H] vs. R_{23} relation. In contrast to the high metallicities measured in high-z QSOs, this metallicity refers to the entire galaxy on scales of 10 kpc.

For a closed–box model with solar yield, this metallicity corresponds to a gas/baryonic mass fraction of $\exp{(-Z/Z_{\odot})} \simeq 0.16$. From its intrinsic (corrected for a foreground lensing magnification of 5) gas mass of $\simeq 1.3 \times 10^{10} M_{\odot}$ we therefore infer a total baryonic mass $\simeq 8 \times 10^{10} M_{\odot}$ and stellar mass $\simeq 7 \times 10^{10} M_{\odot}$. This last value is also empirically supported by the location of J14011 in the local mass–metallicity relation. Adopting the recent version of that relation in Tremonti et al. (2004) we infer from the measured metallicity a stellar mass of $\sim 7 \times 10^{10}$ $M_{\odot}$. From the closed–box model with constant star formation and the current star formation rate (380 $M_{\odot}$/yr) we infer the overall duration of the star forming activity in J14011 to be $t_{\rm SF} \simeq 220\,$Myr. This age is entirely consistent with the strength of the Balmer break seen in Fig.3. As a further consistency check, we can estimate a dynamical mass for J14011 from the $\sim 2.2''$ and $\sim 180\,{\rm km\,s^{-1}}$ separations between J1 and J2, assuming these orbit around a common center. For a predominantly north–south lensing shear, the result is $\sim 3.4 \times 10^{10} \csc^2 i \, M_{\odot}$, consistent with the a moderately low inclination also inferred from the morphology of Hα.

4. SMGs and mass assembly

Our VLT/IRAM data on metallicity and on gas/dynamical masses make a compelling case that the most luminous SMGs (S(850(μm)$\sim$5 to 10 mJy) have dynamical and - within the factor 2 uncertainties of the present estimates - also stellar masses of $\sim 10^{11}\,M_{\odot}$. This stellar component has plausibly formed in the current starburst activity of duration $\sim 10^{2}$ Myrs. How does the inferred co-moving volume density of SMGs compare to theoretical models of galaxy formation ?

From the observed surface density of SMGs with $S_{850} > 5\,$mJy (Smail et al. 2002) we infer that radio detected SMGs with baryonic masses $\geq 10^{11}\,M_{\odot}$ in the range $1.8 \leq z \leq 3.5$ have a comoving number density of $1.6^{+1.0}_{-0.6} \times 10^{-5}\,\mathrm{Mpc}^{-3}$ (Tecza et al. 2004). This density needs to be corrected upward to account for sources that are in this mass bin but no longer luminous enough to have been detected at $850\,\mu$m. Relative to the 1.8 Gyr elapsed over the range $1.8 \leq z \leq 3.5$ the $\sim$60 to 10^{2} Myr gas exhaustion time of SMGs implies a correction factor of about 20 to 30. Figure 4 plots this prediction, together with the comoving number densities of galaxies with stellar masses above the $10^{11}\,M_{\odot}$ threshold at $z \sim 0$ (Cole et al. 2001) and $z \sim 1$ (Drory et al. 2003). Also plotted are the predictions of semi–analytic models, one of which is taken from Kauffmann et al. (1999) and the other an update of Baugh et al. (2003). Since all theoretical and observational values assume the same cosmology and a consistent (either Miller–Scalo or $1 - 100\,M_{\odot}$ Salpeter) IMF, we are secure in concluding that the models underpredict the number densities of massive galaxies at $z \sim 2.5$ (Tecza et al. 2004). Couching Fig.4 in terms of *mass* emphasizes that the observed surface densities of SMGs cannot be explained using a very flat IMF alone. We also note that the models contain sufficiently many dark halos of total mass $\geq 10^{11}\,(\Omega_{\mathrm{M}}/\Omega_{\mathrm{b}})\,M_{\odot}$ to account for the observed comoving number densities of massive SMGs, provided all of their baryons can be rapidly assembled into galaxies. SMGs thus provide a powerful "mass assembly" test at the upper end of the mass function of galaxies (Genzel et al. 2003).

Our correction of the observed number density of SMGs to account for their less dust–luminous descendants raises the question of what types of galaxies SMGs can plausibly evolve into. Although LBGs are clearly excluded due to their smaller masses, an intriguing alternative is the newly identified population whose red $J-K$ colors can stem from a strong Balmer break at $z \sim 2.5$ (Franx et al. 2003). These galaxies appear to be strongly clustered (Daddi et al. 2003) and– assuming a uniform distribution in the redshift range $2 \leq z \leq 3.5$ (van Dokkum et al. 2003)– have a comoving number density $\sim 1.8 \times 10^{-4}\,\mathrm{Mpc}^{-3}$. Relatively few sources with red $J-K$ colors are also luminous (sub)millimeter emitters, indicating that the two populations have little direct overlap. With three examples in the HDF–S having (for a Miller–Scalo IMF) stellar masses $(0.6 - 1.4) \times 10^{11}\,M_{\odot}$ (Saracco et al. 2004), it would seem plausible that the more luminous objects with red $J-K$ colors at this epoch could have passed through an SMG phase at higher redshift.

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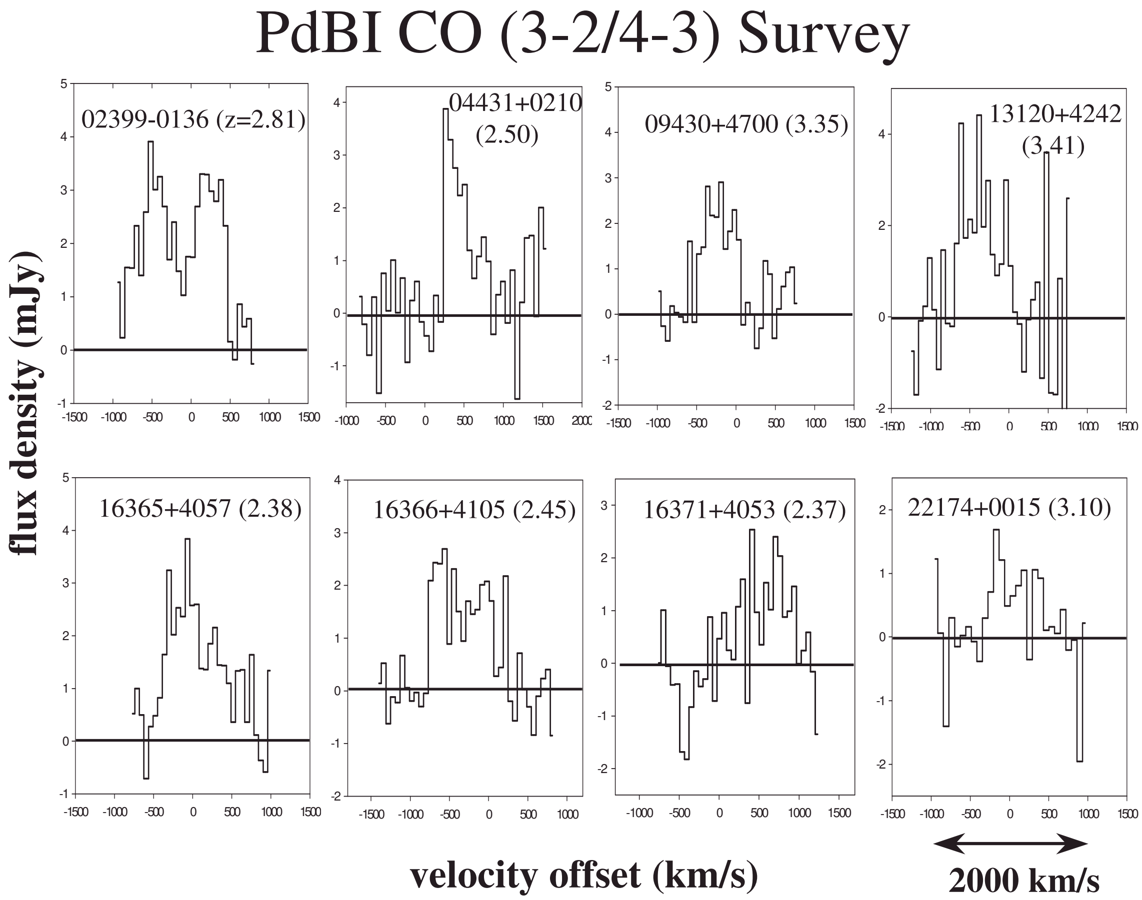

Fig. 1.— Integrated mm CO spectra of the PdBI survey sources, plus SMMJ 02399-0136 (Genzel et al. 2003). Source names and their redshifts are listed in the insets. Flux density and velocity scale is the same for all sources (adapted from Greve et al. 2004).

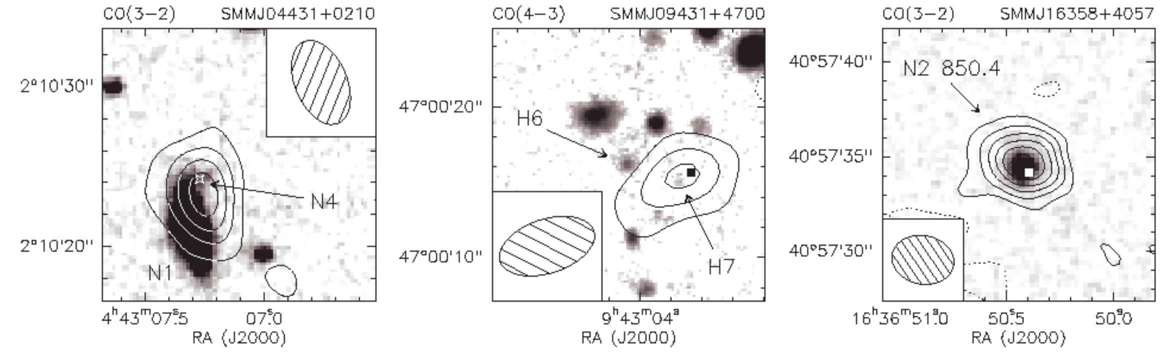

Fig. 2.— Velocity integrated, natural weighted CO maps of three of the SCUBA sources studied with the PdBI interferometer, superposed on greyscale images of the optical emission. The FWHM interferometer beams are shown as hatched ellipses. The three underlying images are in the K-band (left and right panel) and in the I-band (center panel). The asterisk in the left image is the position of the ERO N4 (uncertainty $\pm 0.5''$ – see text), the filled squares (black and light) are the millimeter continuum positions (center and right). The edge on spiral galaxy $2''$ SE of the CO source is the source N1 in the foreground cluster at redshift $z = 0.18$. In the middle panel, denoted by arrows, the positions of the two radio sources H6 and H7. The stronger optical and radio source H6 is a narrow line Seyfert galaxy at redshift $z = 3.349$ (Lyα). CO 4-3 emission from N2 850.4 remains largely unresolved (adapted from Neri et al. 2003).

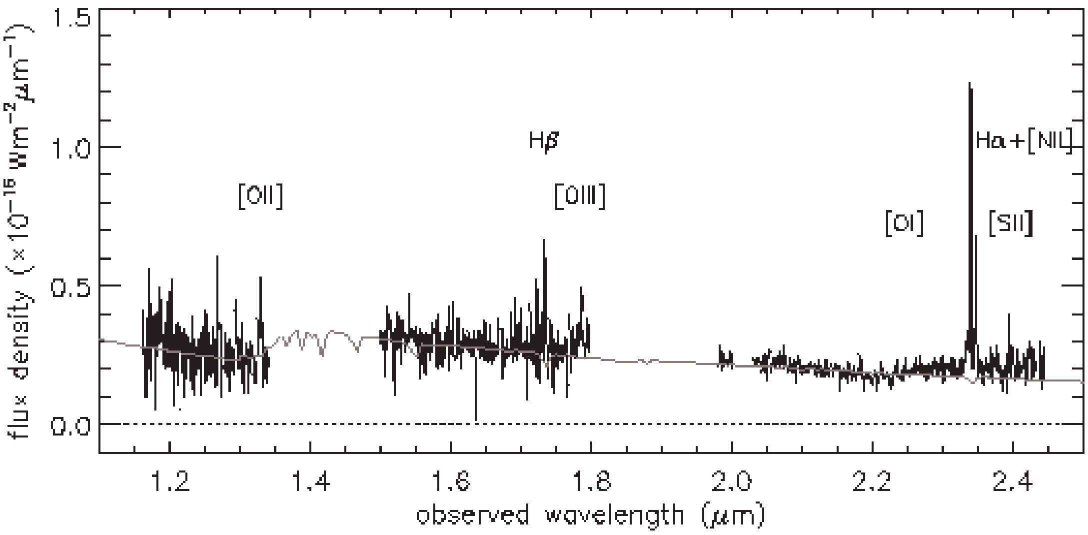

Fig. 3.— J, H, and K spectra of J14011 extracted from a $2'' \times 1.5''$ aperture. Superposed is the model STARS spectrum for a 200 Myr old continuous star formation episode, assuming solar metallicity, a $1 - 100\,M_{\odot}$ Salpeter IMF, and extinction $A_V = 0.7$ (adapted from Tecza et al. 2004).

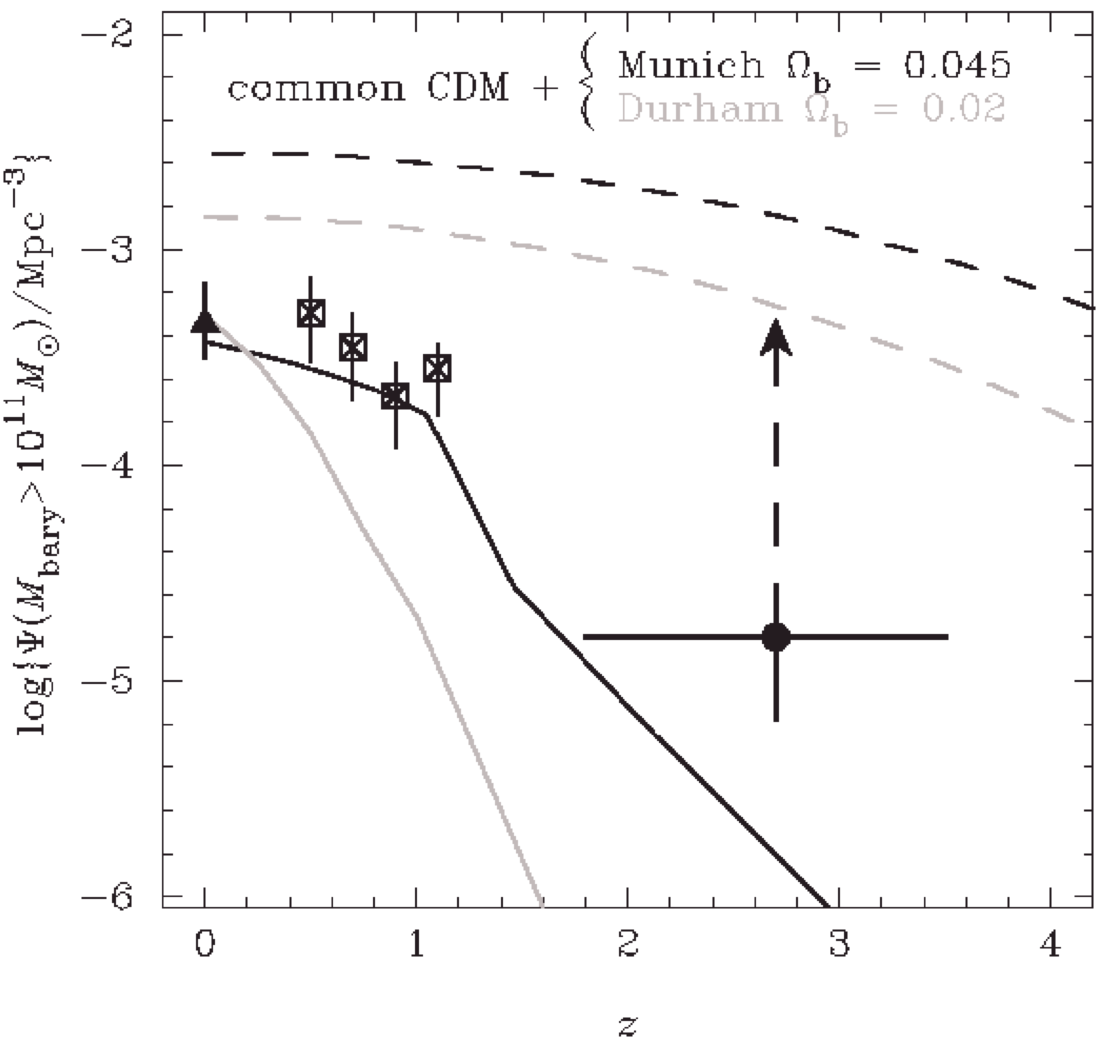

Fig. 4.— Comoving number densities of galaxies with baryonic masses $\geq 10^{11}\,M_\odot$ as a function of redshift. Triangle and open squares show densities of massive stellar systems at $z = 0$ (Cole et al. 2001) and $z \sim 1$ (Drory et al. 2003); circle shows density for massive SMGs at $z \sim 2.7$, with a factor of 30 correction for burst lifetime. Solid curves show the predictions of semi–analytic modelling by the "Munich" group (Kauffmann et al. 1999) and the "Durham" group (an updated version of Baugh et al. 2003); dashed curves show the corresponding number densities of halos with *available* baryonic masses $\geq 10^{11}\,M_\odot$. The two models use the same halo simulations but assume different Ω_b (adapted from Tecza et al. 2004).