# The Growth of Massive Galaxies in Cosmological Hydrodynamic Simulations

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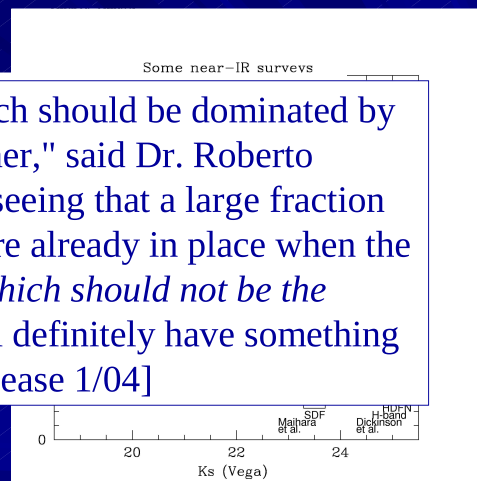
## Elements of Galaxy Formation Theory

- How does gas get *into* galaxies?
  - CDM + shock heating + cooling
    - ⇒ Classic overcooling problem
- How does gas get *out* of galaxies?
  - Feedback, winds, AGN, jets, etc.
- State of the Models: Progress on former, confusion on latter.
- Massive galaxy evolution provides a nice (and controversial) test.

# Observing Massive Galaxies: Near-Infrared Galaxy Surveys

- Near-infrared selection can trace optical light of stellar
- General result: Massive galaxies are in place at z~2: *Early epoch of stellar mass growth in the Universe.*




"Theory tells us that this epoch should be dominated by little galaxies crashing together," said Dr. Roberto Abraham [GDDS]. "We are seeing that a large fraction of the stars in the Universe are already in place when the Universe was quite young, *which should not be the case*… The theoreticians will definitely have something to gnaw on!" [AAS press release 1/04]

Cimatti 2004

# NIR Surveys vs SAMs

- Semi-analytic models give a wide range of predictions: Confusion.
- In simulations, the problem has always been *over*cooling, though reasonable feedback models can solve this.
- What do current simulations predict?

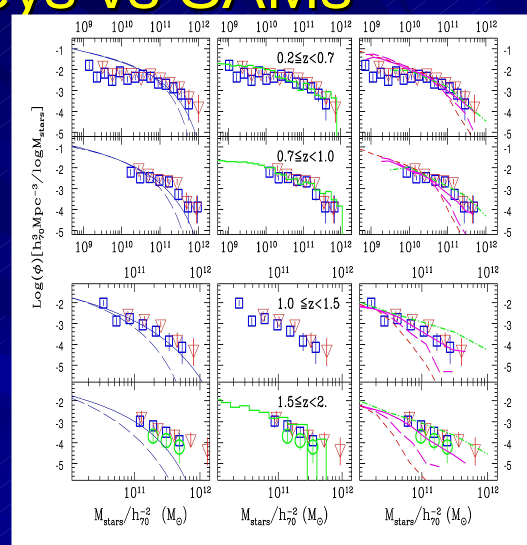


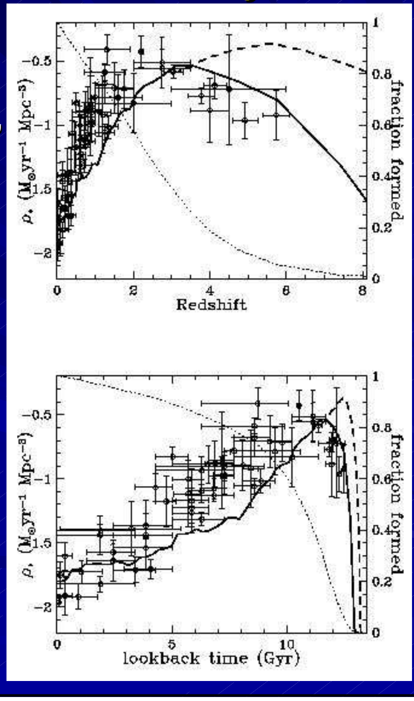

Fig. 9. Observed Galaxy Stellar Mass Functions in the K20 sample, compared with theoretical rendition in a Λ-CDM hierarchical Universe, divided according to the IMF adopted in the models. *Left panel:* Salpeter (1955), *Central panel:* Gould et al. (1996), *Right panel:* Kennicutt (1983). In the central and right panels the observed GSMFs have been scaled to the corresponding IMF as described in the text. The theoretical models are: *left panel:* Menci et al. (2002) (dashed line) and Menci et al. (2004) (solid line); *central panel:* Nagamine et al. (2001); *right panel:* Cole et al. (2000) (short-dashed); Somerville et al. (2004a) (S04 and S04b, thick solid and dashed lines); Granato et al. (2004) (dot-dashed). See text for full details. All the model predictions are evaluated at the central redshift of each bin, with the exception of the Nagamine et al. (2001) case which is computed at z = 0.5, 1 and 2.

# Gadget2 Hydro Simulations

- Entropy-conservative SPH + Tree-PM (Springel & Hernquist).
- H&He cooling, $J_\nu$, star formation according to Kennicut Law.
- Multi-phase subgrid ISM model, based on McKee & Ostriker.
- Supernova feedback:
  - Thermal, added to hot ISM phase.
  - Superwind, randomly expels gas from galaxies.
- Wind speed (constant) chosen to roughly reproduce observed $\Omega_*$ today; reduces stellar mass by factor of ≈2-3.
- G6 model:
  - $2\text{x}486^3$ particles: $m_{bary}=1.3\text{x}10^8\ M_\odot$.
  - 100 Mpc/h box size, 2 kpc/h resolution
  - $\Lambda$CDM: $\Omega=0.3$, $H_0=70$, $n=1$, $\sigma_8=0.9$, $\Omega_b=0.04$
- Galaxies found using SKID, spectra from integrating SF histories of individual galaxies using BC03 models, assuming $Z_\odot$, Salpeter IMF, E(B-V)=0.1; all parameters constant with redshift.

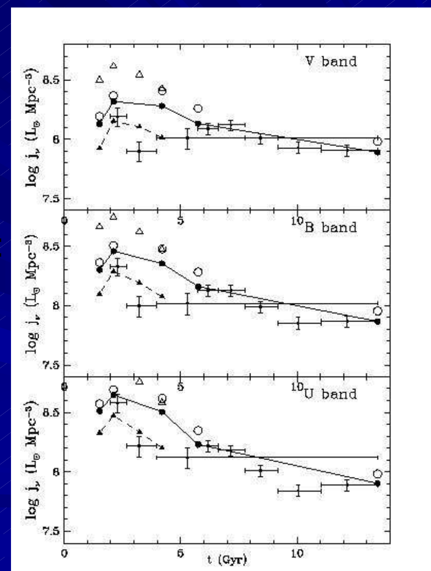
# Global Star Formation History

- G6 run underpredicts SFR at z<2, and overpredicts(?) at z>3: Early star formation.
- 50% of baryons in stars at z=2.1 (3.1 Gyr).
- Total stellar mass in G6 run today: 6.3% of $\Omega_b$.
- Low due to limited resolution. G6 *under*estimates early star formation: Dashed line shows Q5 (10 Mpc/h vol, 200X mass res).



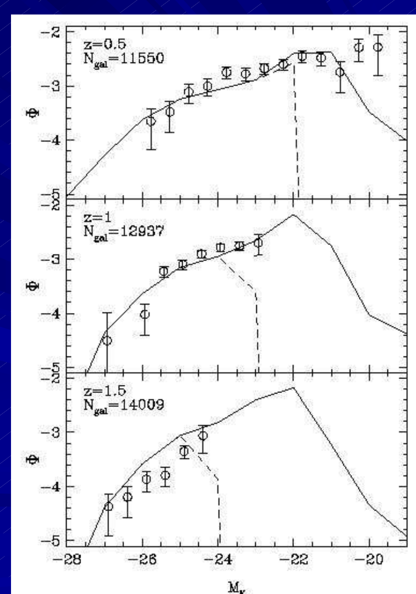
## Global Luminosity Density Evolution

- Rudnick et al (2004): SDSS + Combo-17 + FIRES, selecting massive galaxies to z~3.
- Rest-frame V, B, U luminosities broadly match @ z~0, and show expected increase from z = 0→3:
  - U, G6: 5.5x, Obs: 4.9±1.0.
  - B, G6: 3.8x, Obs: 2.9±0.6.
  - V, G6: 2.6x, Obs: 1.9±0.4.
- At z~3, G6 shows over-abundance of stellar mass (V), relative to SFR (U).
- Overall broad agreement.



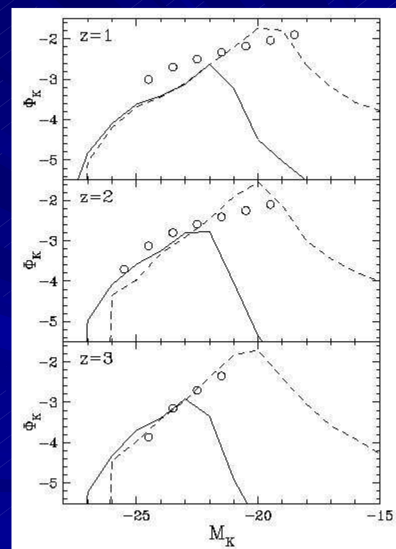

## Rest-frame K-band LF Evolution: K20

- K20 Survey (Cimatti et al 03): points with errors.
- Good agreement at all redshifts (up to resolution limit of G6),
- Hint of excess at z=1.5, but within cosmic variance.
- Note: Excess at bright end not apparent here, but seen at log Φ<-5 vs. e.g. 2MASS.
- CDM models predict early star formation in massive galaxies, and many such objects out to z~2:
  No "massive galaxies problem".



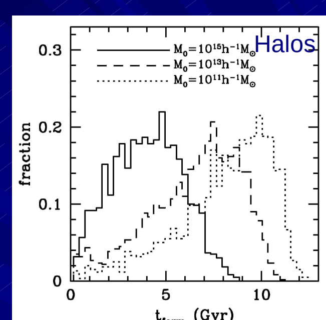
## Rest-frame K-band LF Evolution: SDF

- Subaru Deep Field Survey (Kashikawa et al 2003): 3.74□', spectroscopic survey to $K'_{vega}$=23.7 with Subaru.
- G6 (solid line) LF mainly agrees at all redshifts for *bright end*.
- Go fainter with D5 simulation (dashed line), showing good overlap with G6 run but probing ~2.5 mags fainter.
- D5 shows a hint of too steep faint end.

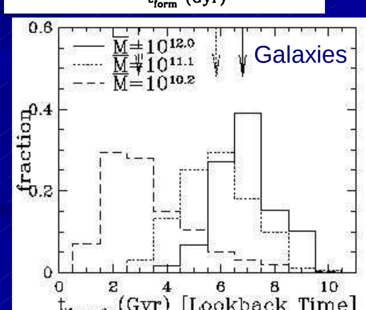



## Downsizing in Simulations

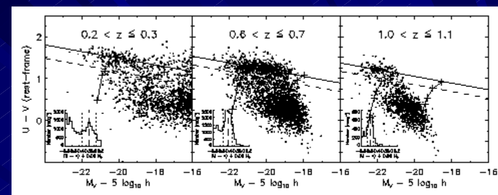
- Hierarchical models predict big *halos* form late, but *galaxy* formation not simply related.
- Hierarchical means big halos form *late*, but collapse *early*.
- Star formation begins on collapse, so halo and star formation times are *anti-correlated*.
- This is sometimes called "downsizing" or "anti-hierarchical" behavior, but is actually a natural prediction of CDM.
- Nevertheless, still require increased efficiency of SF at early times – happens naturally in simulations, as we shall see.



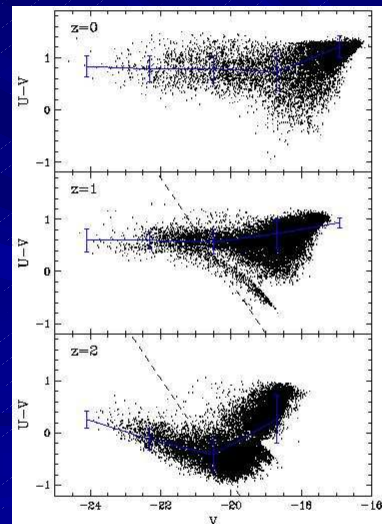

Van den Bosch etal 04



## Evolution of Color-Magnitude Relation



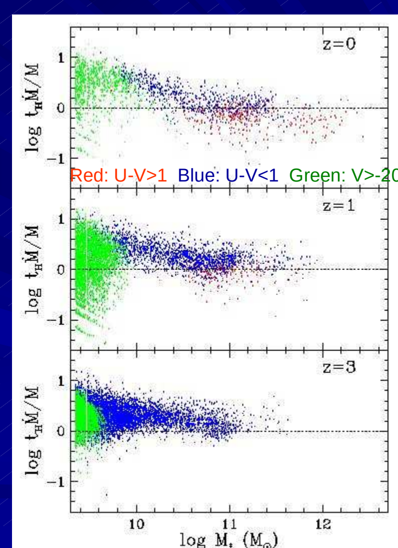

Bell et al 2003




- Combo-17 (Bell et al 03): Red sequence persists to z~1, with mild evolution.
- G6 (with $M_*$-Z relation applied): “Red sequence” too shallow, too blue.
- No color gap between early & late-types.
- Color evolution broadly consistent.
- Star formation not shutting off enough in massive galaxies: Downsizing is not fast enough.

## Birthrates of Simulated Galaxies

- Birthrate = $t_{Hubble}$xSFR/$M_*$
- Small galaxies show a range of birthrates (depends on environment: Berlind et al).
- Trend to lower birthrates in larger galaxies – good.
- Massive galaxies still show significant birthrates at z=0 – bad.
- Need truncated SFR in massive galaxies: AGN? (Springel etal 04)



## Merging vs. Smooth Accretion

- Galaxies obtain most of their mass by smooth accretion, not merging.
- Globally, SFR follows smooth accretion rate.
- Smooth accretion rate above fixed mass resolution high at early times (efficient “cold mode”), low at late times (inefficient “hot mode”).

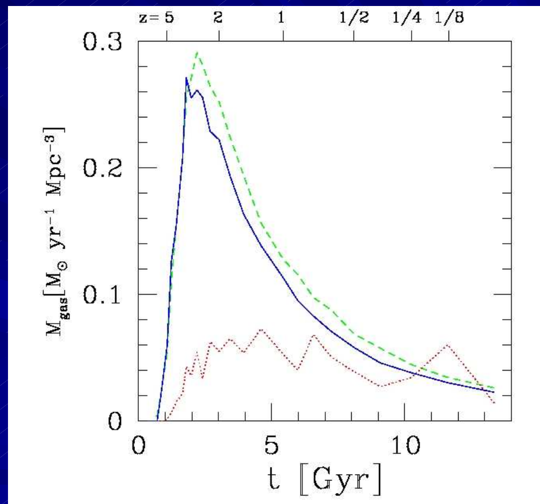



Fig. 14. Star formation rate per unit volume (dashed line) for all resolved galaxies in the simulation compared to smooth gas accretion (solid line) and merger accretion rates (dotted line). The merger mass accretion rates include the accretion of stars.

## Conclusions

- Simulations naturally produce early stellar mass growth in massive galaxies, consistent with expectation from hierarchical structure formation.
- Current simulations do not adequately truncate SF in massive systems, resulting in color-magnitude relations inconsistent with observations.
- Cold mode accretion is more efficient than hot mode, and the transition to hot mode is responsible for downsizing (at least partly).
- Bimodality in accretion does NOT fully explain observed bimodality in colors, gas content, $M_*$-Z, etc.
- Galaxies grow mainly by smoothly accreting gas until z~2, after which merging growth become comparable.