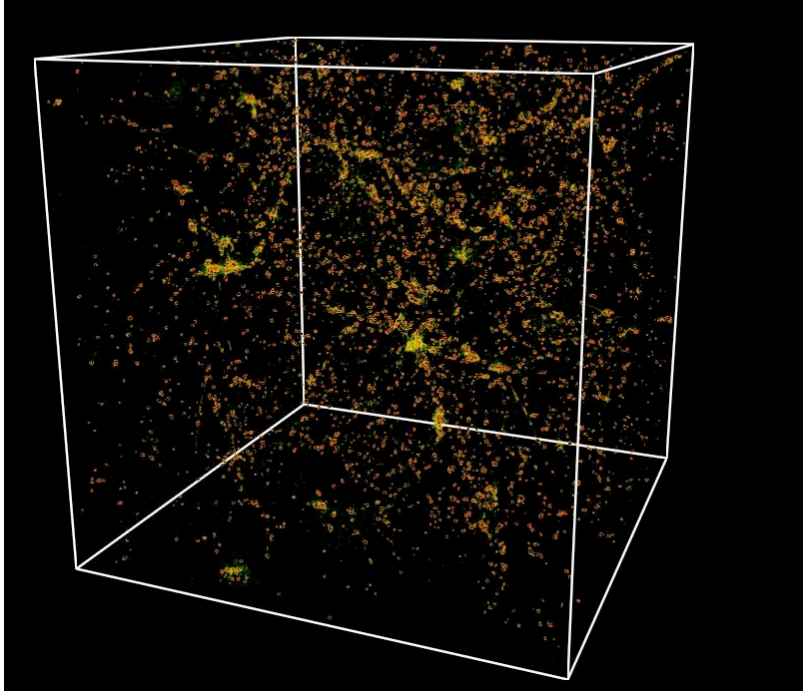
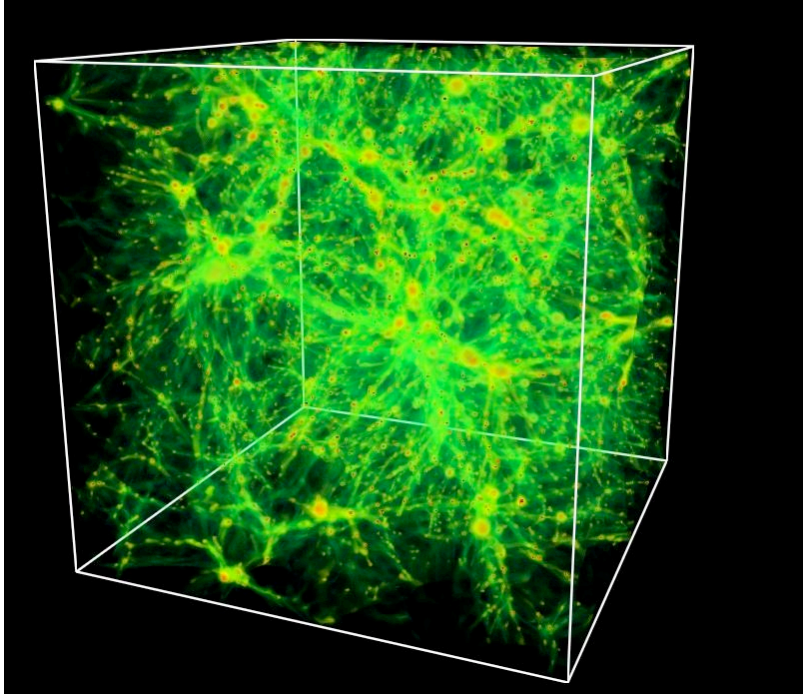




Massive Galaxies at z=1-3 in Cosmological Hydrodynamic Simulations

Ken Nagamine (UCSD) (http://cosmos.ucsd.edu/~nagamine/)

Collaborators:

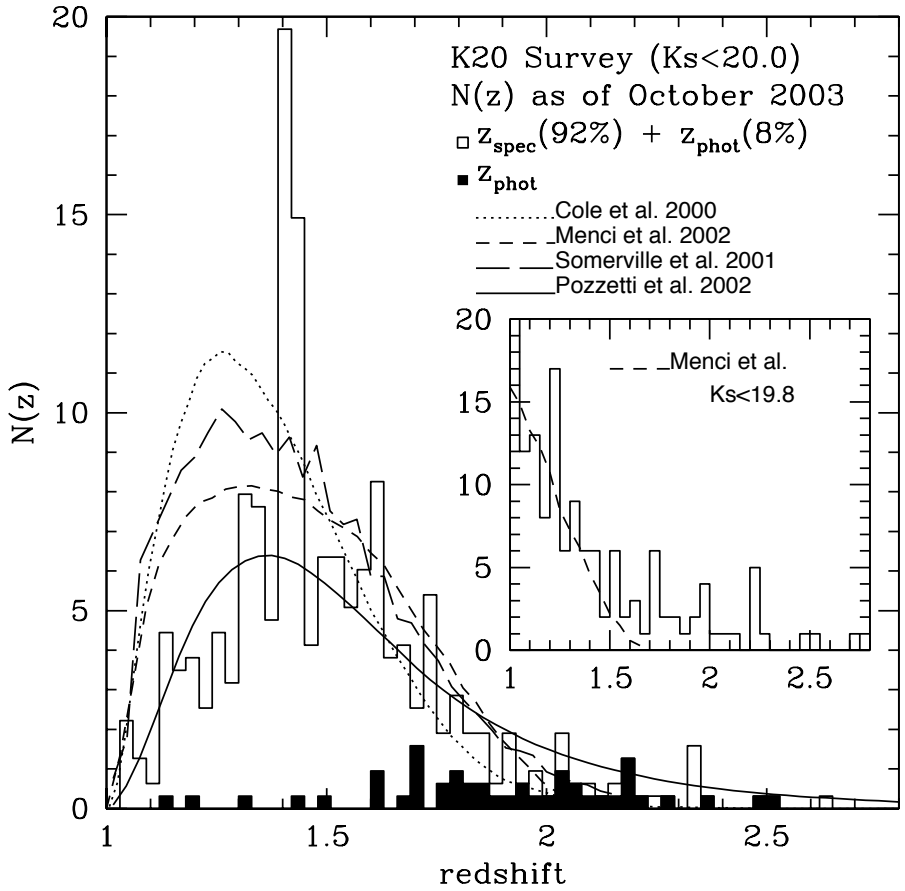
Renyue Cen (Princeton)
Jerry Ostriker (Princeton)

Lars Hernquist (Harvard)
Volker Springel (MPA)

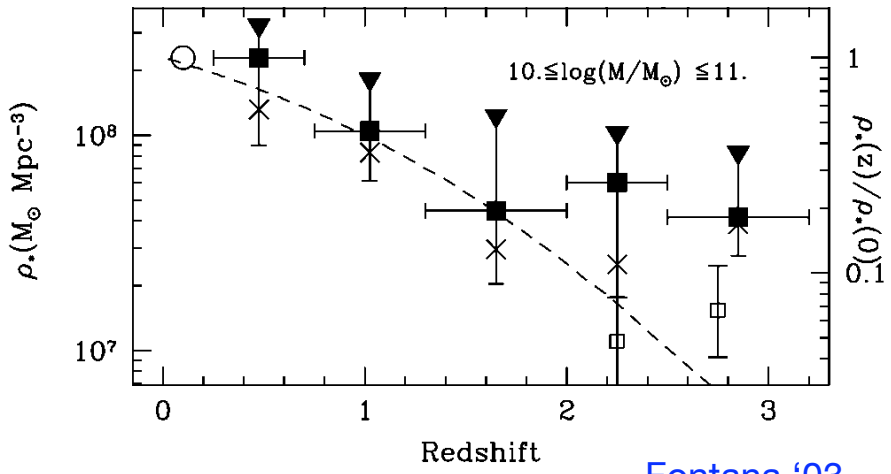
KN et al. '01a,b
KN 2002
KN et al. 2004a,b,c

Observation vs. Theory:

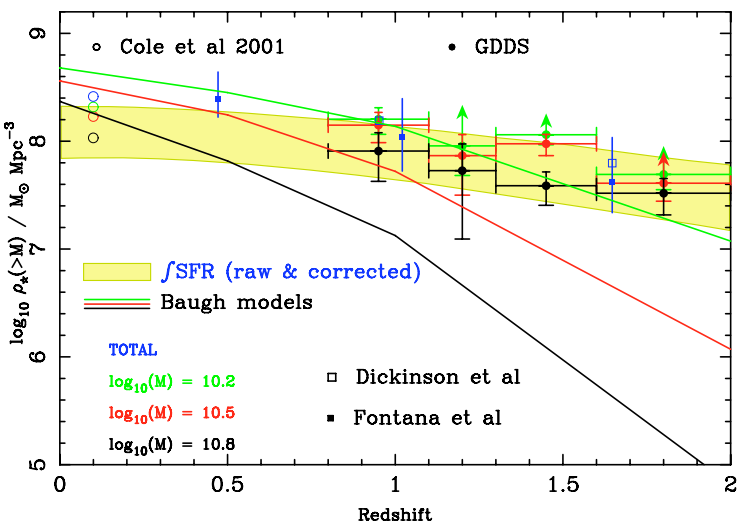
Is hierarchical model inconsistent w/ data?



Cimatti ‘04



Fontana ‘03

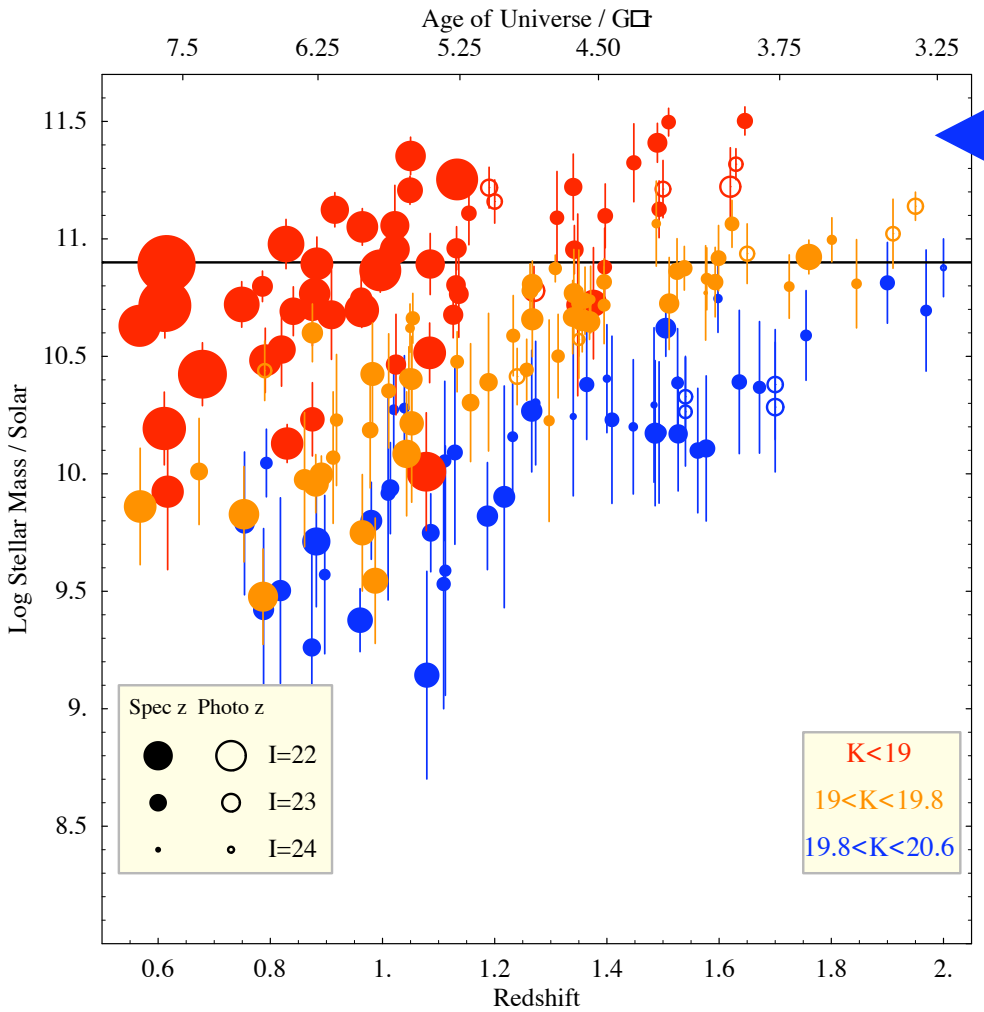


Glazebrook et al. ‘04

Lack of massive gals in hierarchical model?

(cf. Kauffmann & Charlot ‘98)

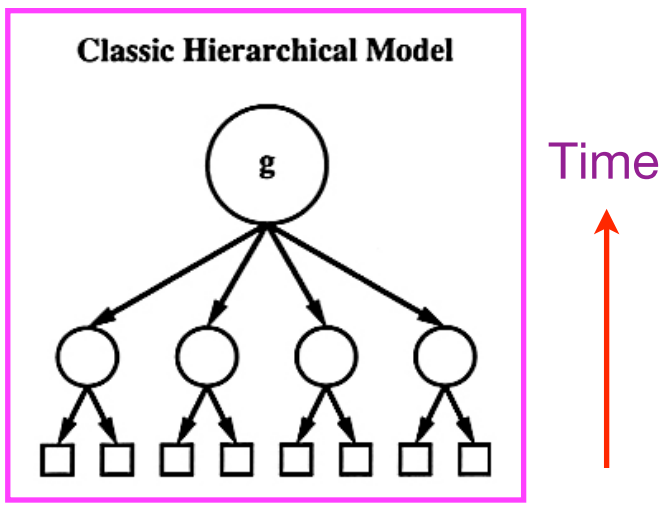
The “mass-scale problem”



$M_{star} > 10^{11} M_{\odot}$

Glazebrook et al. 2004

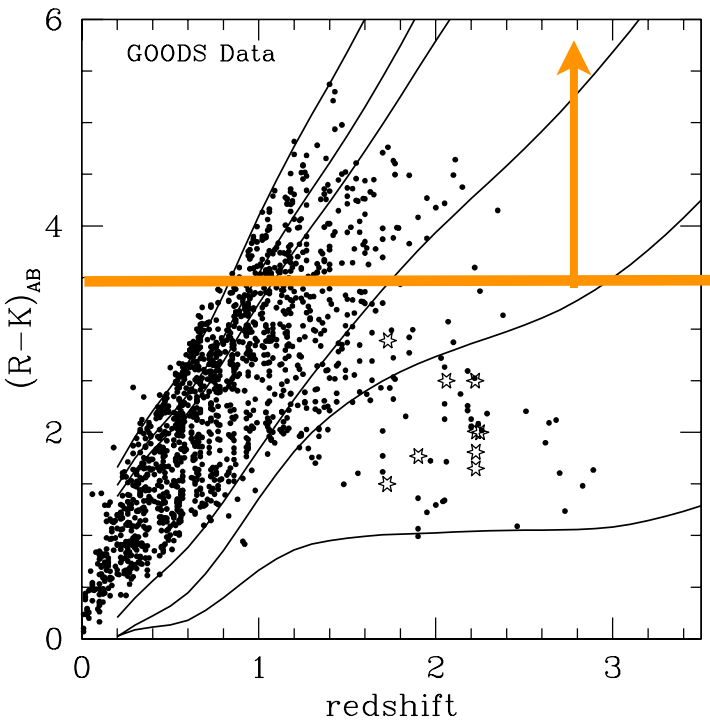
Do these massive galaxies exist in hydro simulations based on hierarchical CDM model?



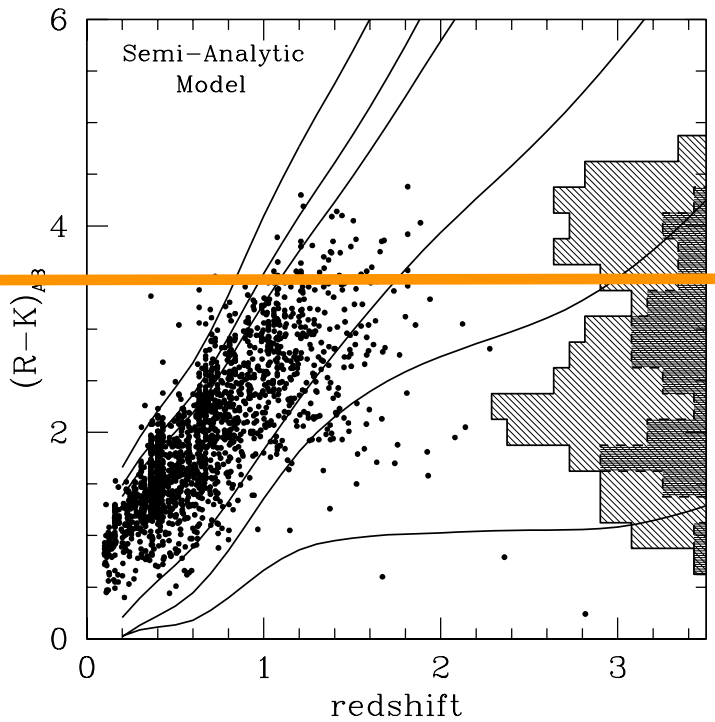
The “reddeness problem”

EROs (extremely red objects)

GOODS data



SA model

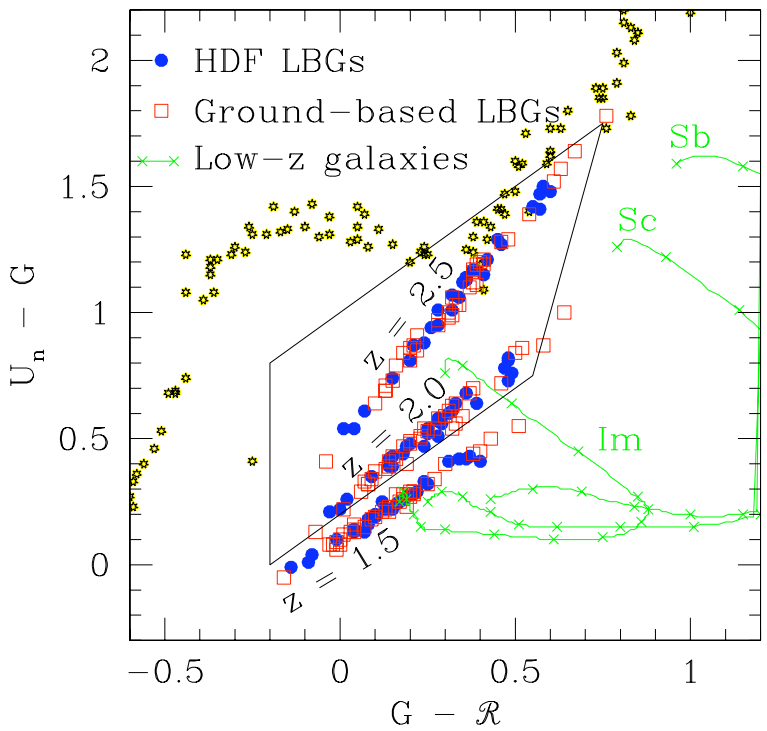


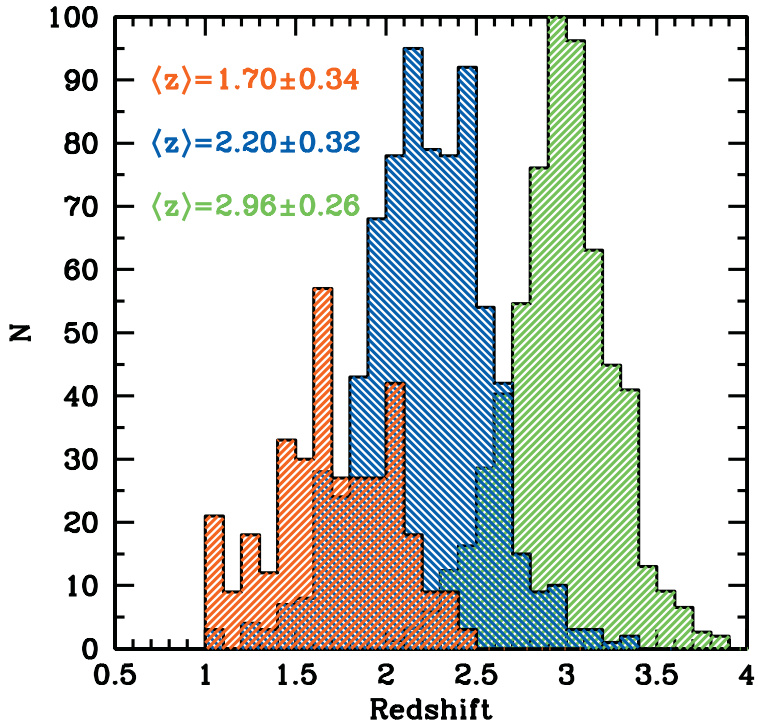
Not enough red massive gals in hierarchical model?

Somerville et al. ‘04

Color-color selection: z=1.5-2.5 galaxies

revealing the `redshift desert'





LBGs, SMGs, EROs, LAEs, QSOs, etc....
mounting evidence for high-z galaxy formation

Adelberger et al. (2004)
Steidel et al. (2004)

Cosmological Hydrodynamic Simulations

- TVD (Total Variation Diminishing method: TIGER, Cen & Ostriker)
  TVD for IGM and Galaxy Evolution and foRmation

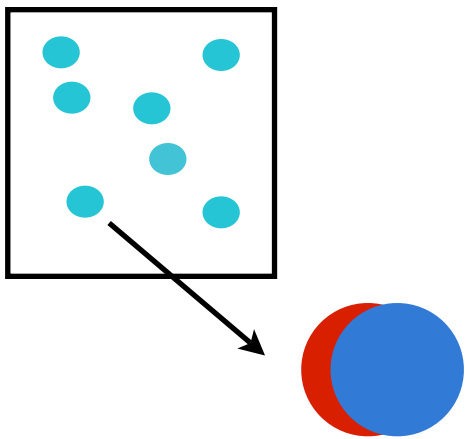
  - Eulerian, mesh based, PM gravity solver
  - shock capturing hydro
  - radiative cooling/heating, self-consistent UV background
  - star formation & SN, UV feedback
  - metals

$$\Delta m_* = c_* \frac{m_{gas}}{t_*} \Delta t$$

$$\Delta E_i = \epsilon_i \Delta m_* c^2$$

- SPH (Smoothed Particle Hydrodynamics: P-Gadget2, Springel & Hernquist)

  - Lagrangian, TreePM for gravity
  - new `entropy-conservative' formulation
  - sub-particle multiphase gas model
  - radiative cooling/heating, UV background
  - star formation & SN feedback
  - galactic wind model
  - metals



Simulation Parameters

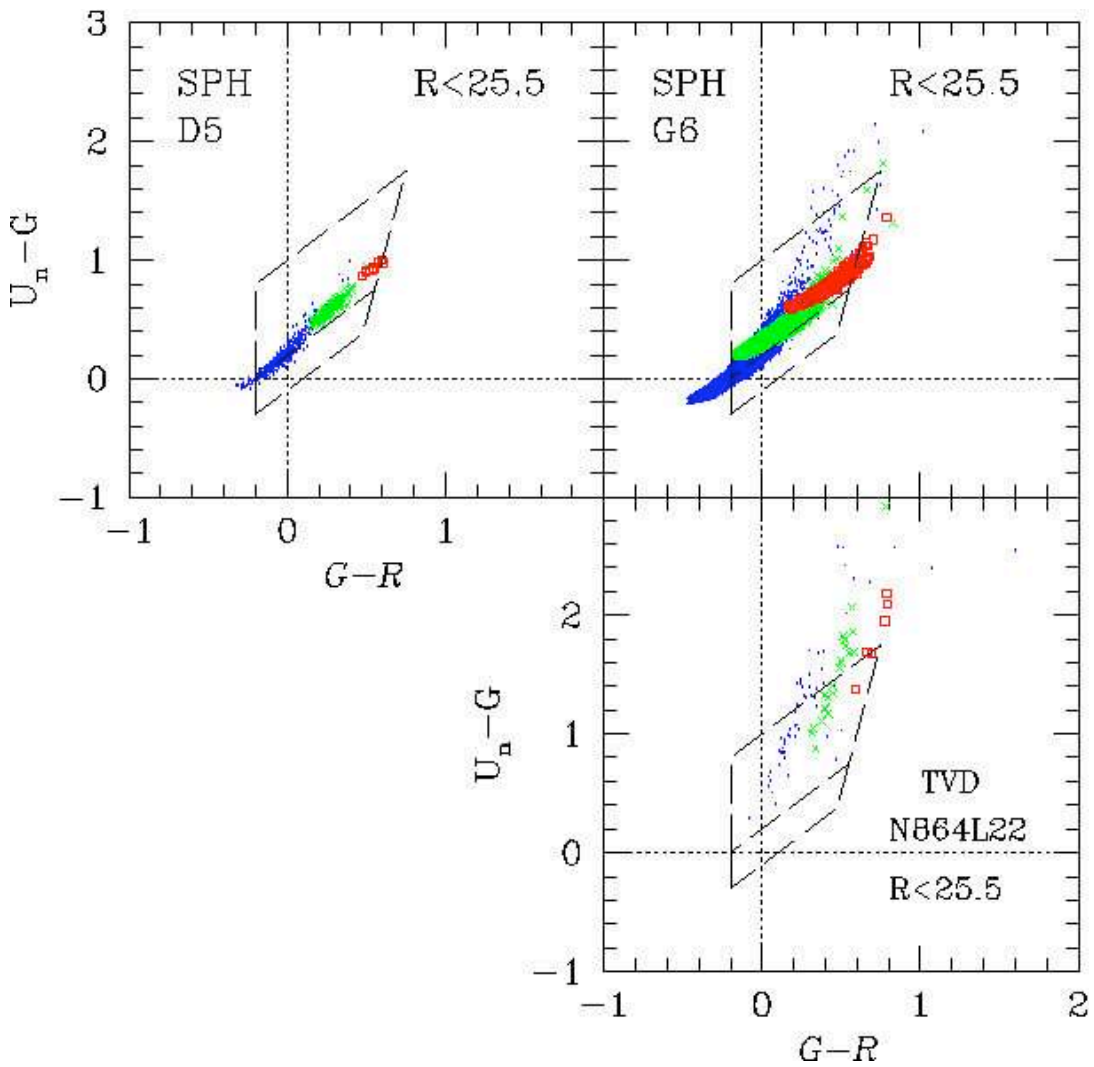
Table 1. Simulations

Run	$L_{\rm box}$ $[h^{-1}\,{\rm Mpc}]$	$N_{\rm mesh/ptcl}$	$m_{\rm DM}$ $[h^{-1}M_\odot]$	$m_{\rm gas}$ $[h^{-1}M_\odot]$	$\Delta\ell$ $[h^{-1}\,{\rm kpc}]$
TVD: N864L11[a]	11.0	864^3	1.1×10^6	2.7×10^4	12.7
TVD: N864L22[a]	22.0	864^3	8.9×10^6	2.2×10^5	25.5
TVD: N768L25[b]	25.0	768^3	2.0×10^7	3.4×10^5	32.6
SPH: Q5[c]	10.0	324^3	2.1×10^6	3.3×10^5	1.2
SPH: D5[c]	33.75	324^3	8.2×10^7	1.3×10^7	4.2
SPH: G6[c]	100.0	486^3	6.3×10^8	9.7×10^7	5.3

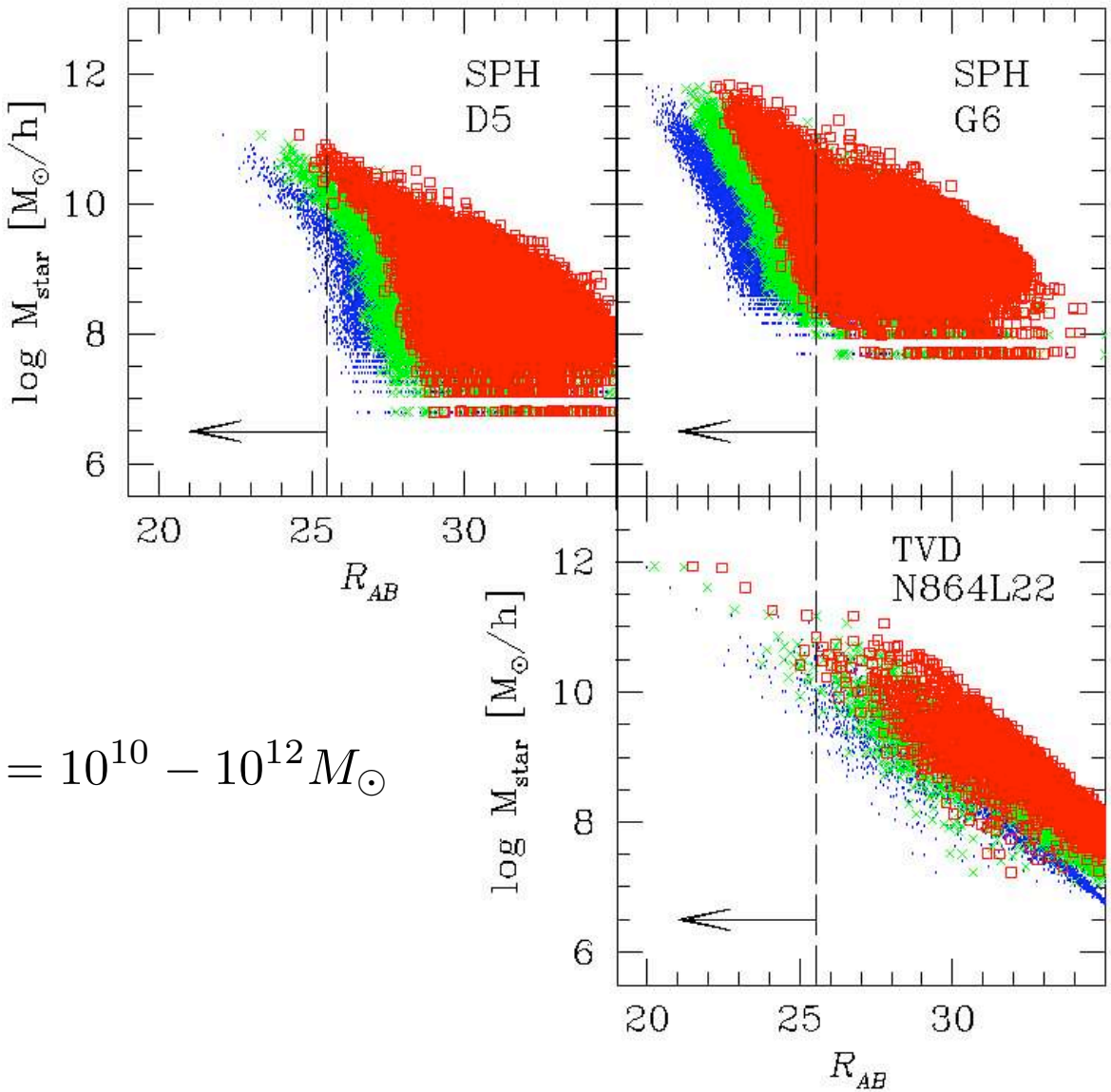
Color-color selection at z~2

Pop Synthesis model
Bruzual-Charlot (2003)
Chabrier IMF (~Kroupa)
[0, 100] Msun
6 metallicity
Un, G, R filters
E(B-V)=0, 0.15, 0.3
(cf. Shapley et al. 2001)

$m_\star, t_f, Z/Z_\odot$

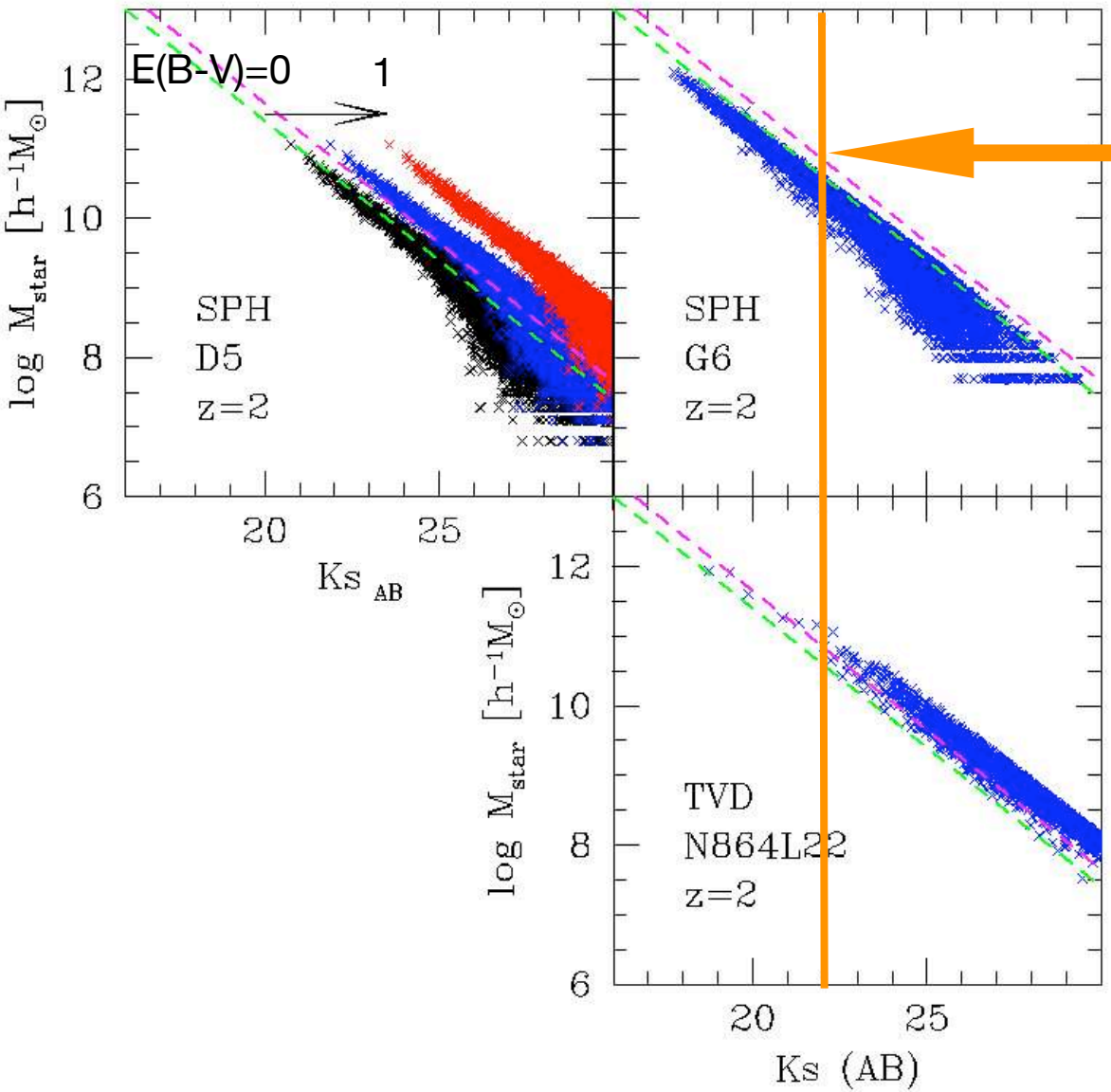


Stellar mass vs. R magnitude @ z=2



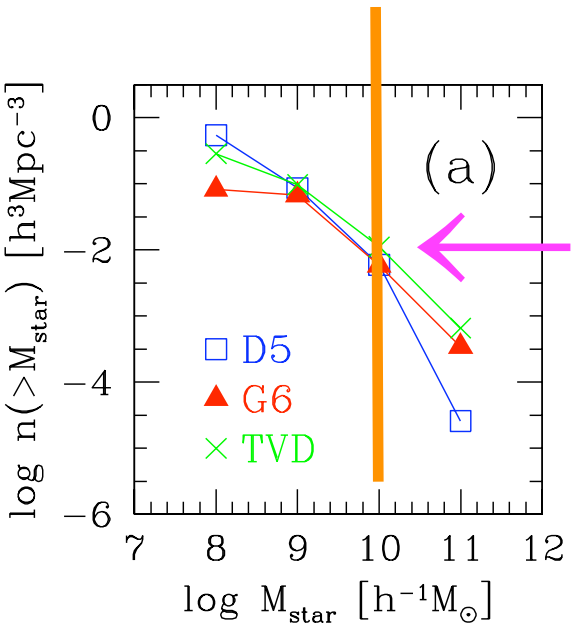
$$M_{\rm star} = 10^{10} - 10^{12} M_{\odot}$$

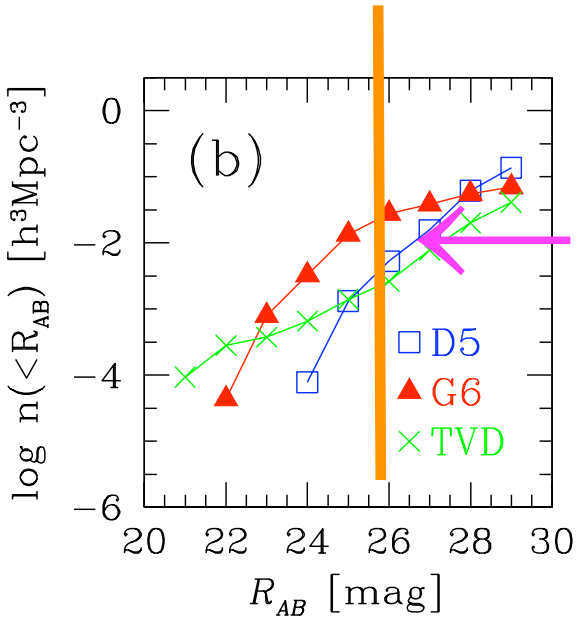
Near-IR: K-band vs. Mstar



Fontana et al. ‘04
Daddi et al. ‘04

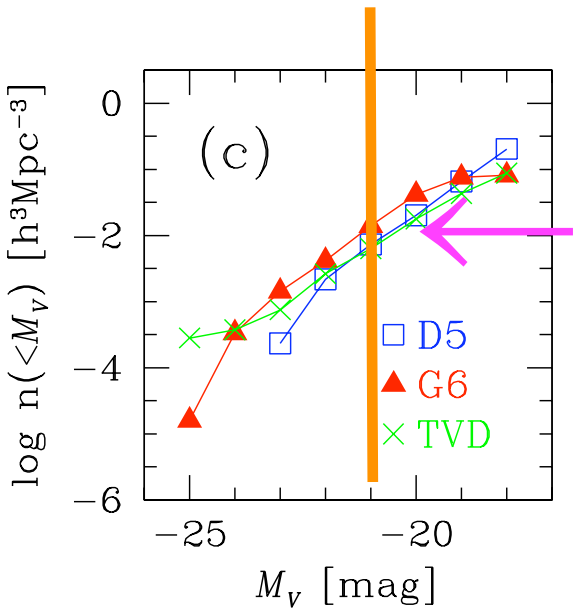
Number density of galaxies @ z=2



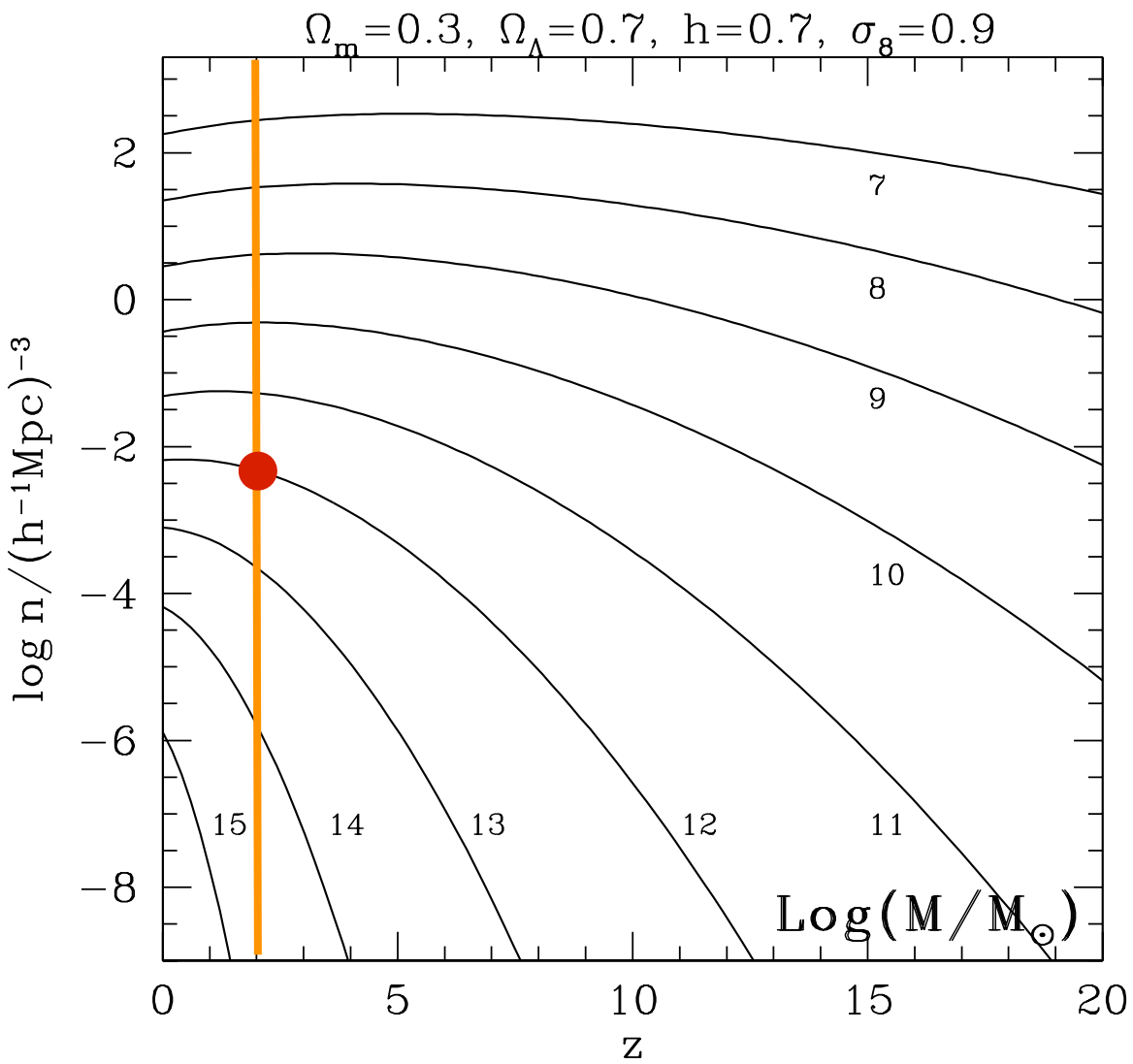


$$n \sim 1 \times 10^{-2}\ h^3\mathrm{Mpc}^{-3}$$

above obs limit

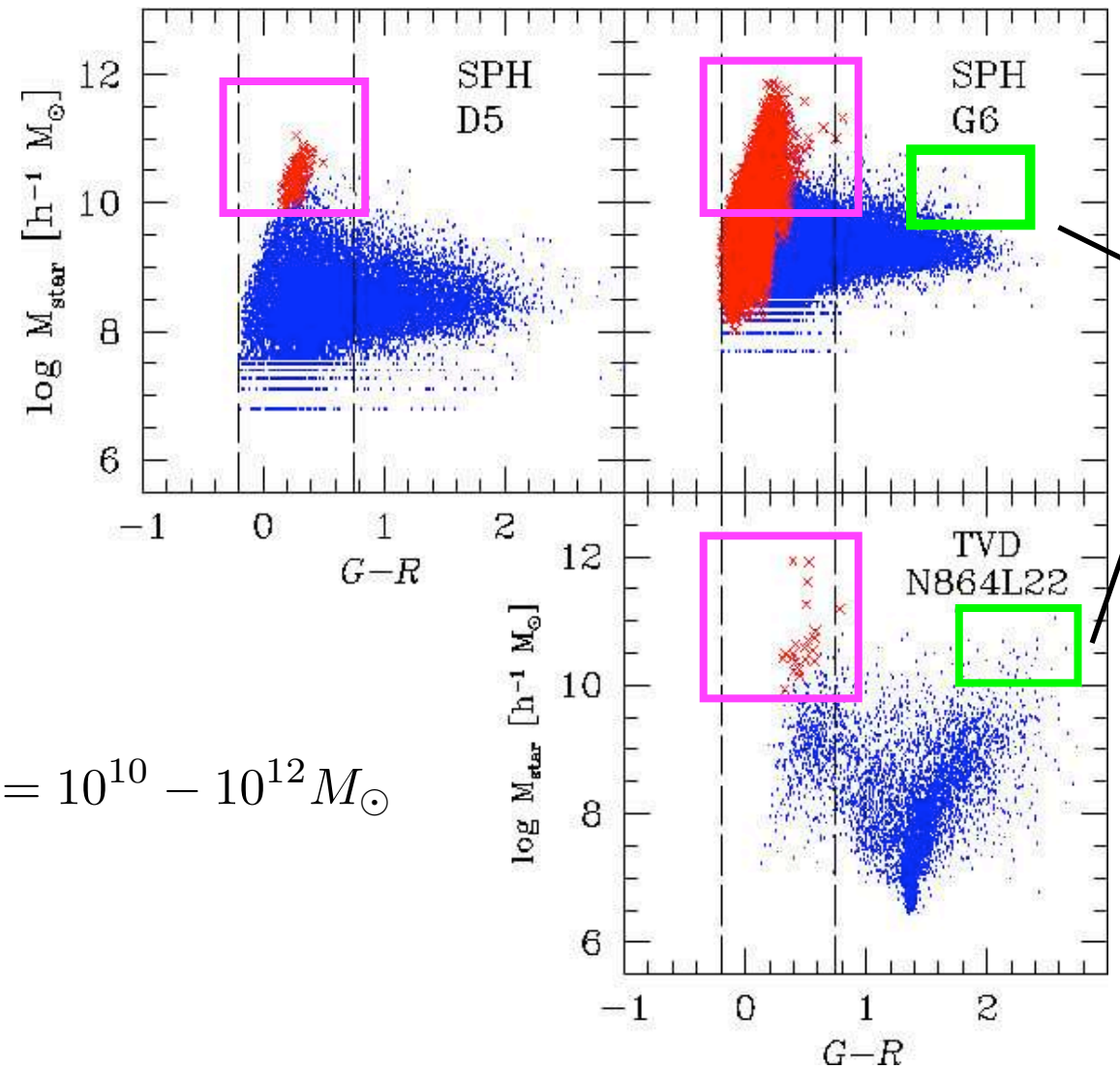


Number density of DM halos $> \log(M/M_\odot)$



Mo & White ‘02

G-R vs. Mstar

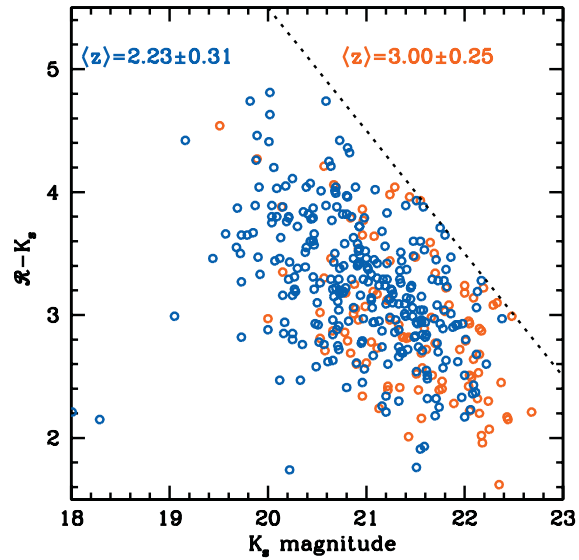


redder passive system

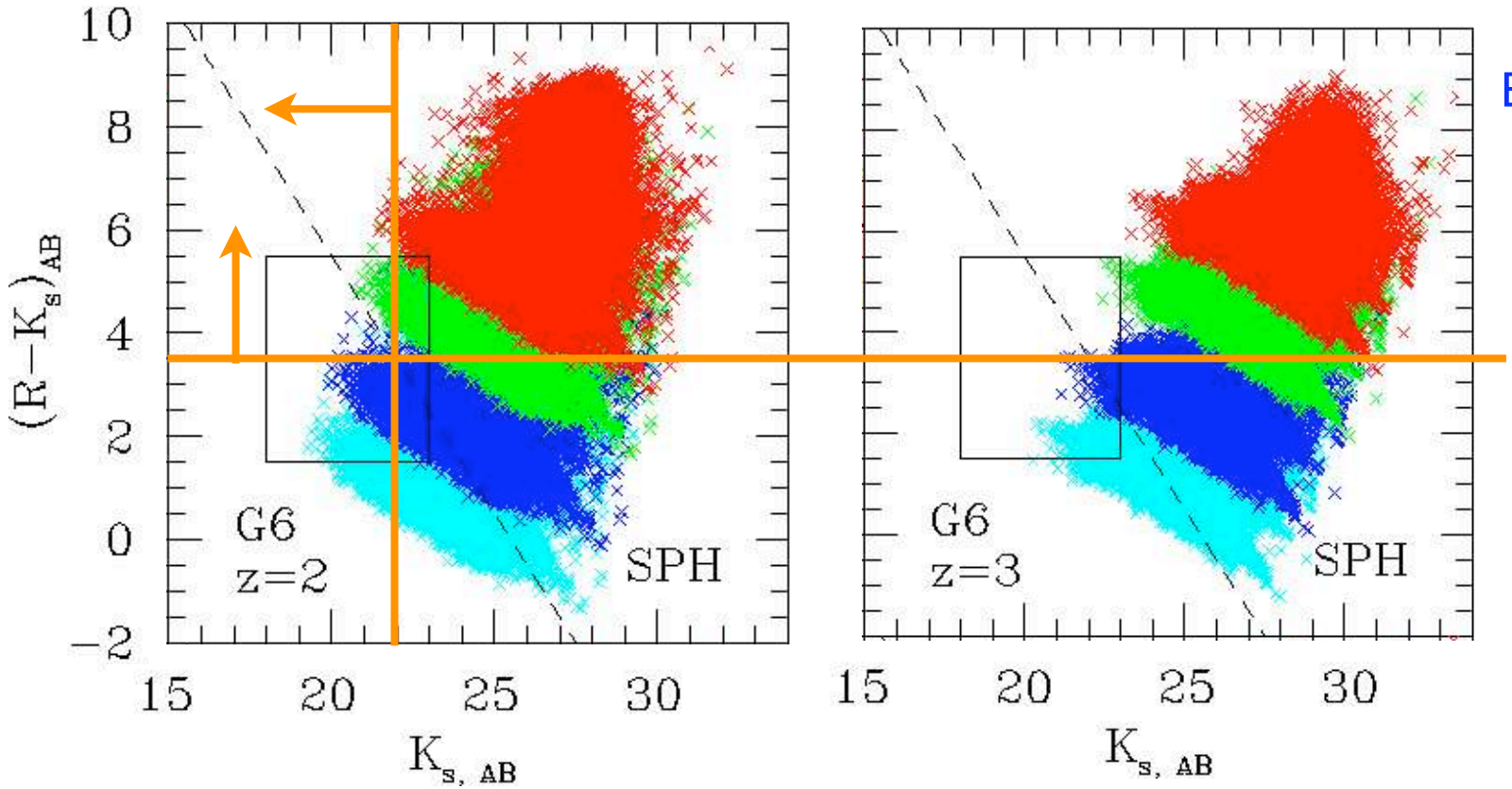
$$M_{\rm star} = 10^{10} - 10^{12} M_{\odot}$$

R-Ks vs. Ks

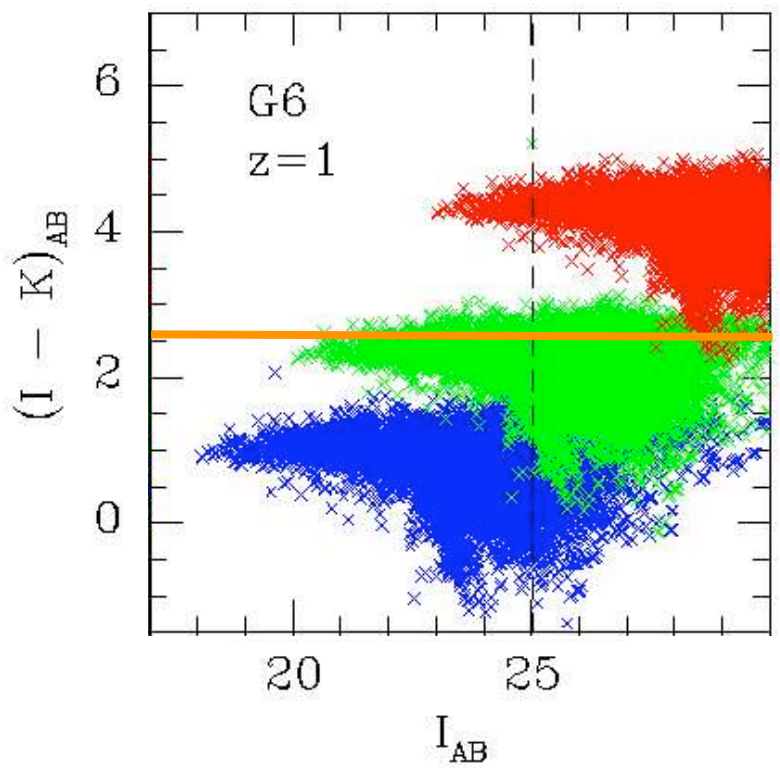
EROs: $(R-K)_{AB}>3.5$

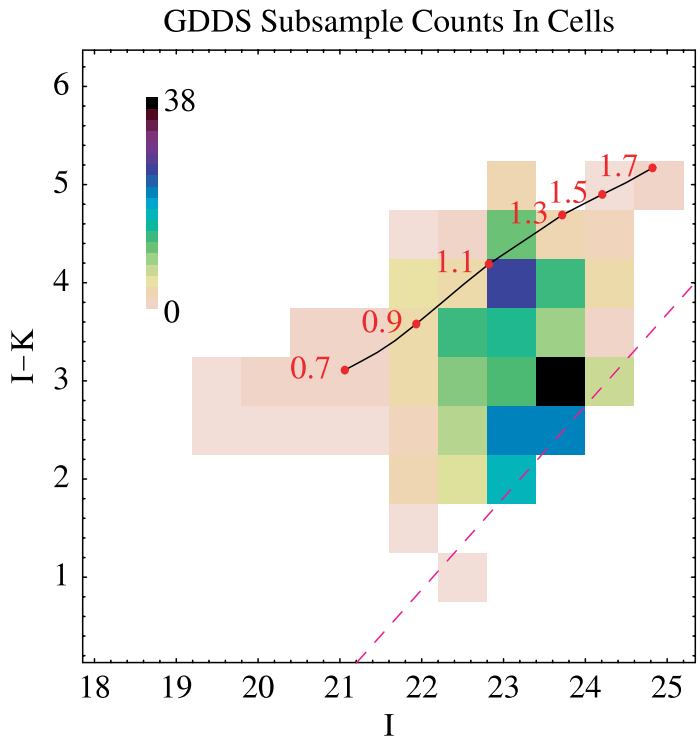


Steidel et al. '04



I-K vs. I @ z=1





$(I-K)_{vega}>4$ suggests $E(B-V) \geq 0.4$

$(I-K)_{AB}>2.6$

`BzK' = (B-z) - (z-K)

SPH G6 run:

K<20

$3.6 \times 10^{-4} h^3 \mathrm{Mpc}^{-3}$

K<20 & z-K>2.5

$1.9 \times 10^{-4} h^3 \mathrm{Mpc}^{-3}$

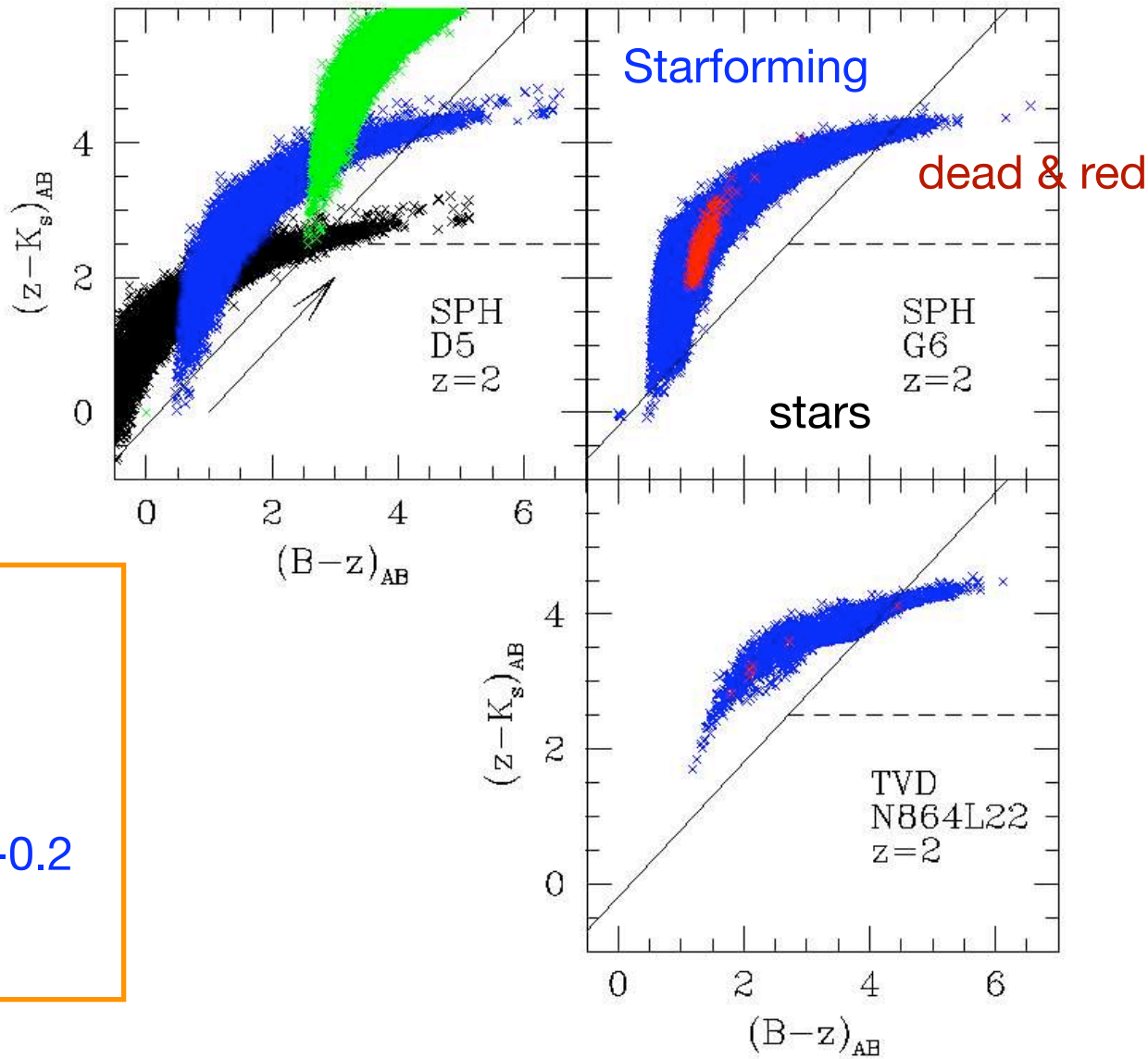
TVD run:

K<20 & z-K>2.5

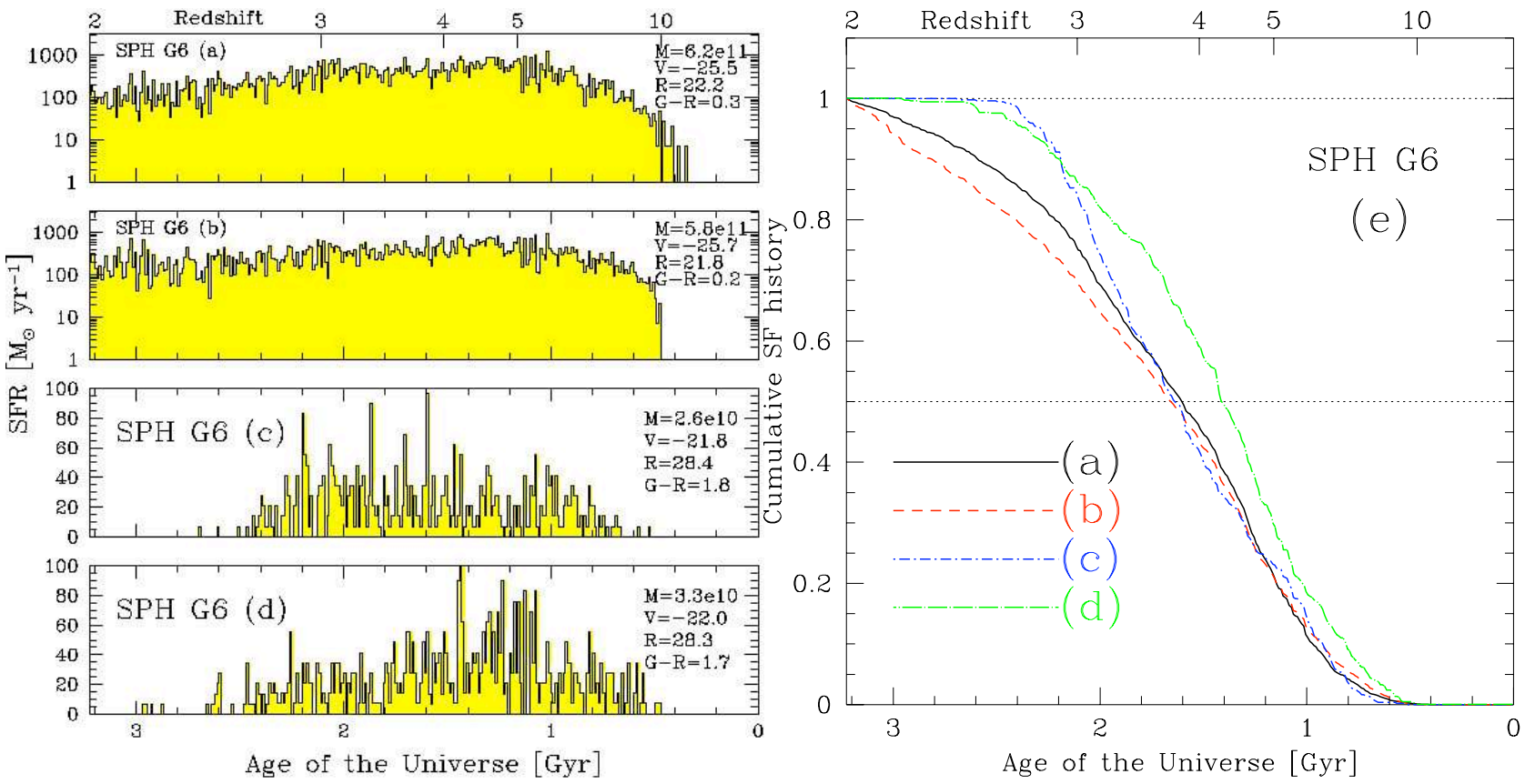
$5.6 \times 10^{-4} h^3 \mathrm{Mpc}^{-3}$

K<20 & z-K>2.5 & BzK>-0.2

$1.0 \times 10^{-4} h^3 \mathrm{Mpc}^{-3}$



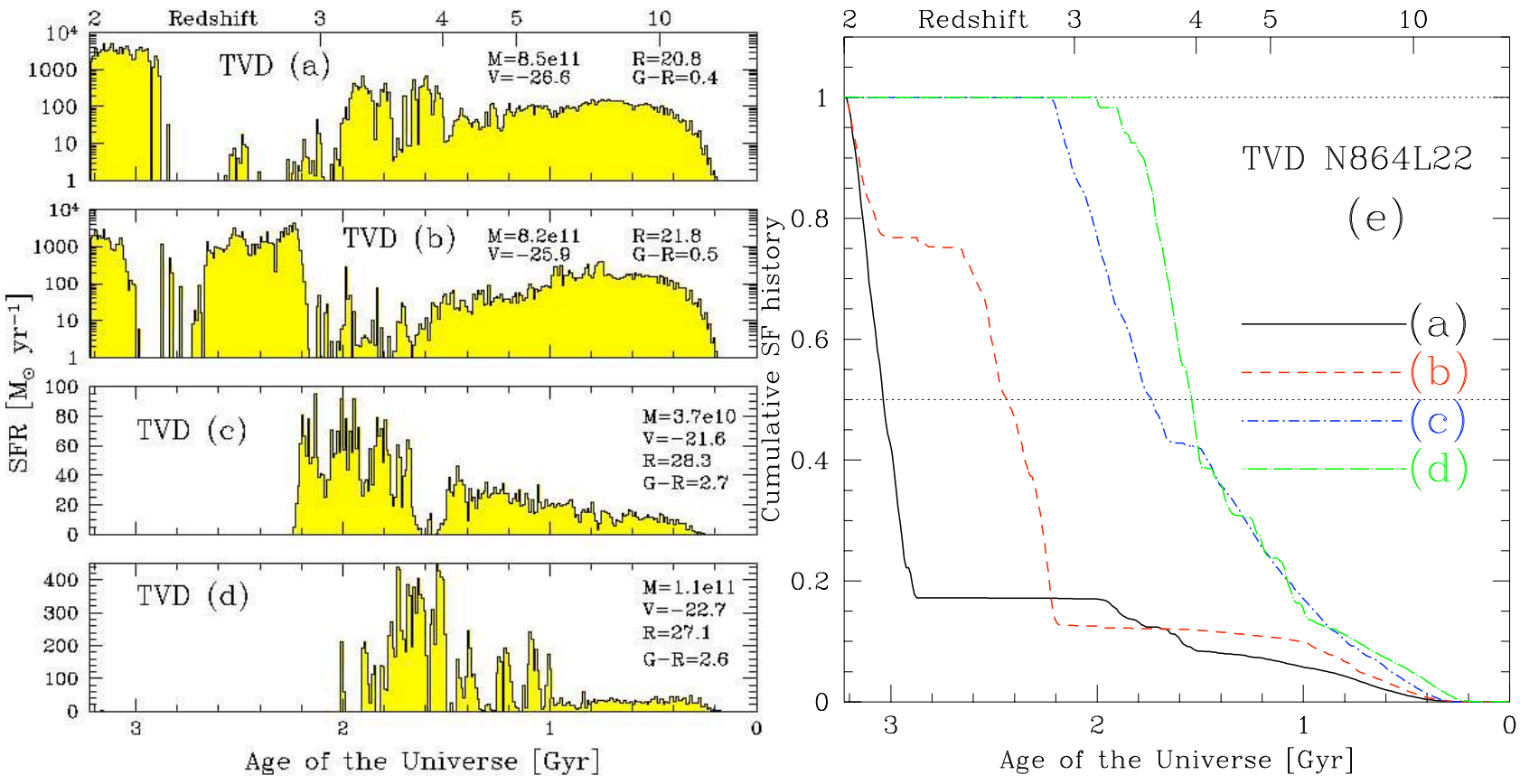
Star formation histories: SPH G6 run



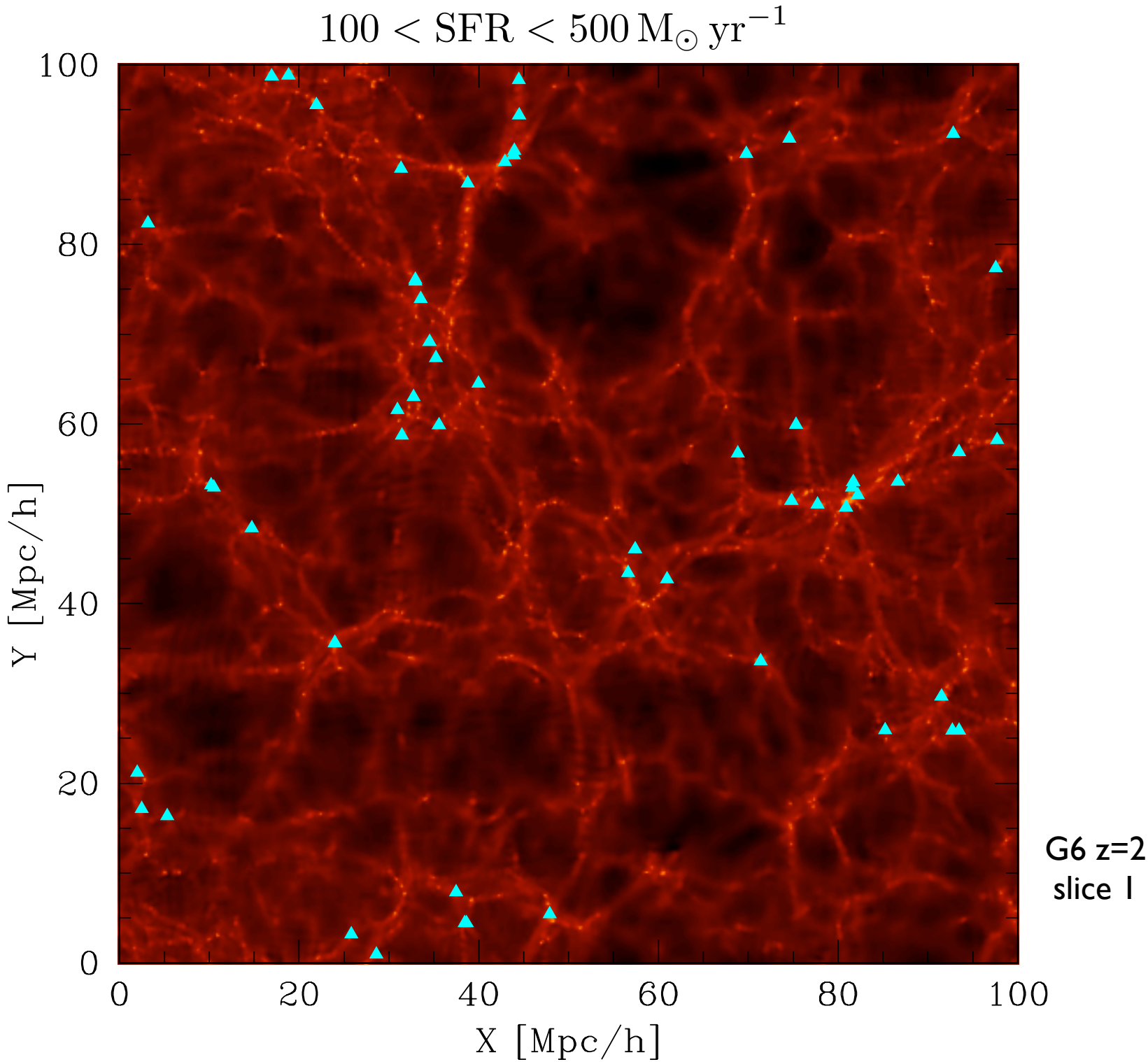
continuous $(40\,M_\odot\,\mathrm{yr}^{-1} \times 3\,\mathrm{Gyr} \sim 10^{11}\,M_\odot)$

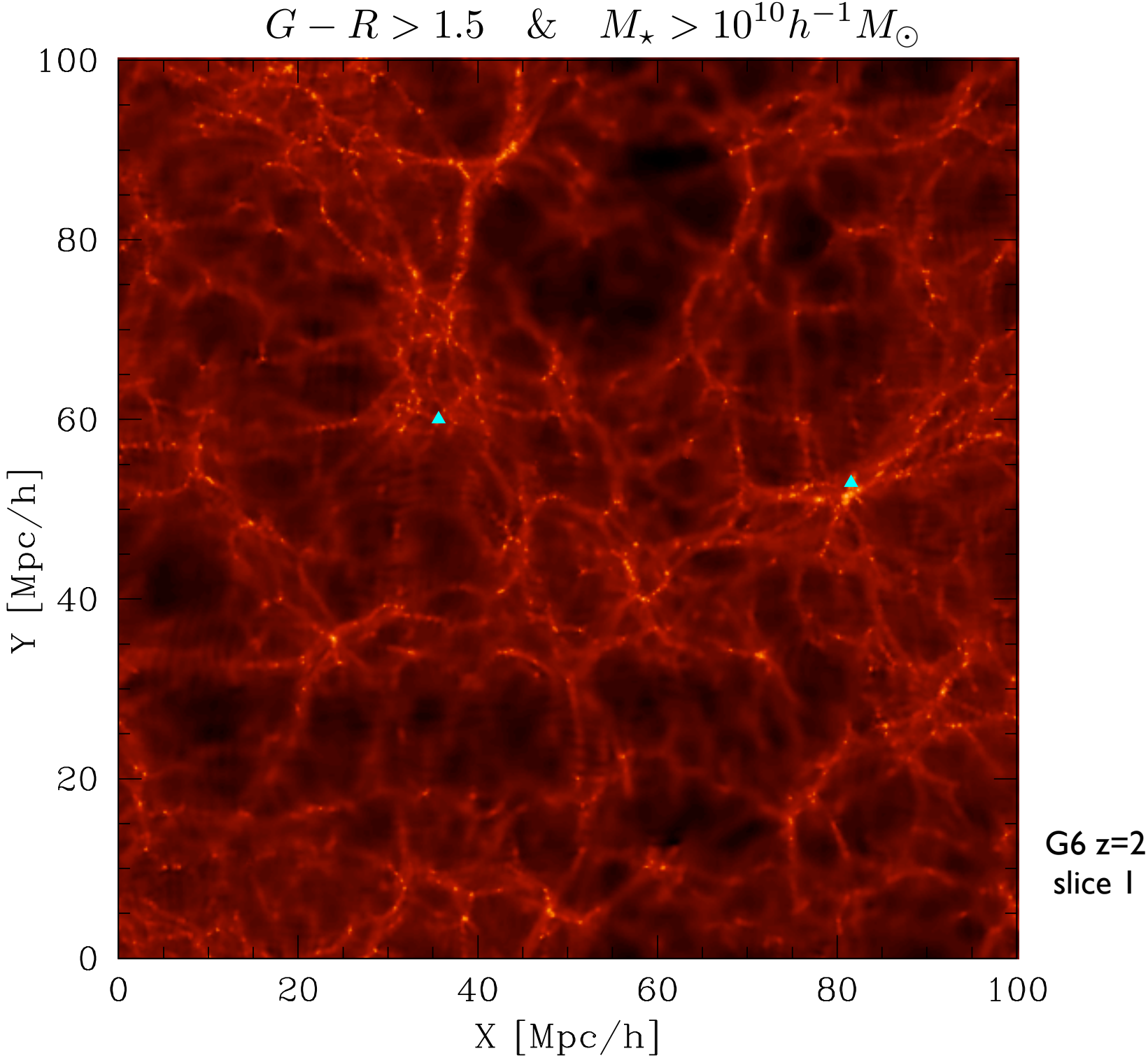
+ starbursts (up to $1000\,M_\odot\,\mathrm{yr}^{-1}$)

Star formation histories: TVD

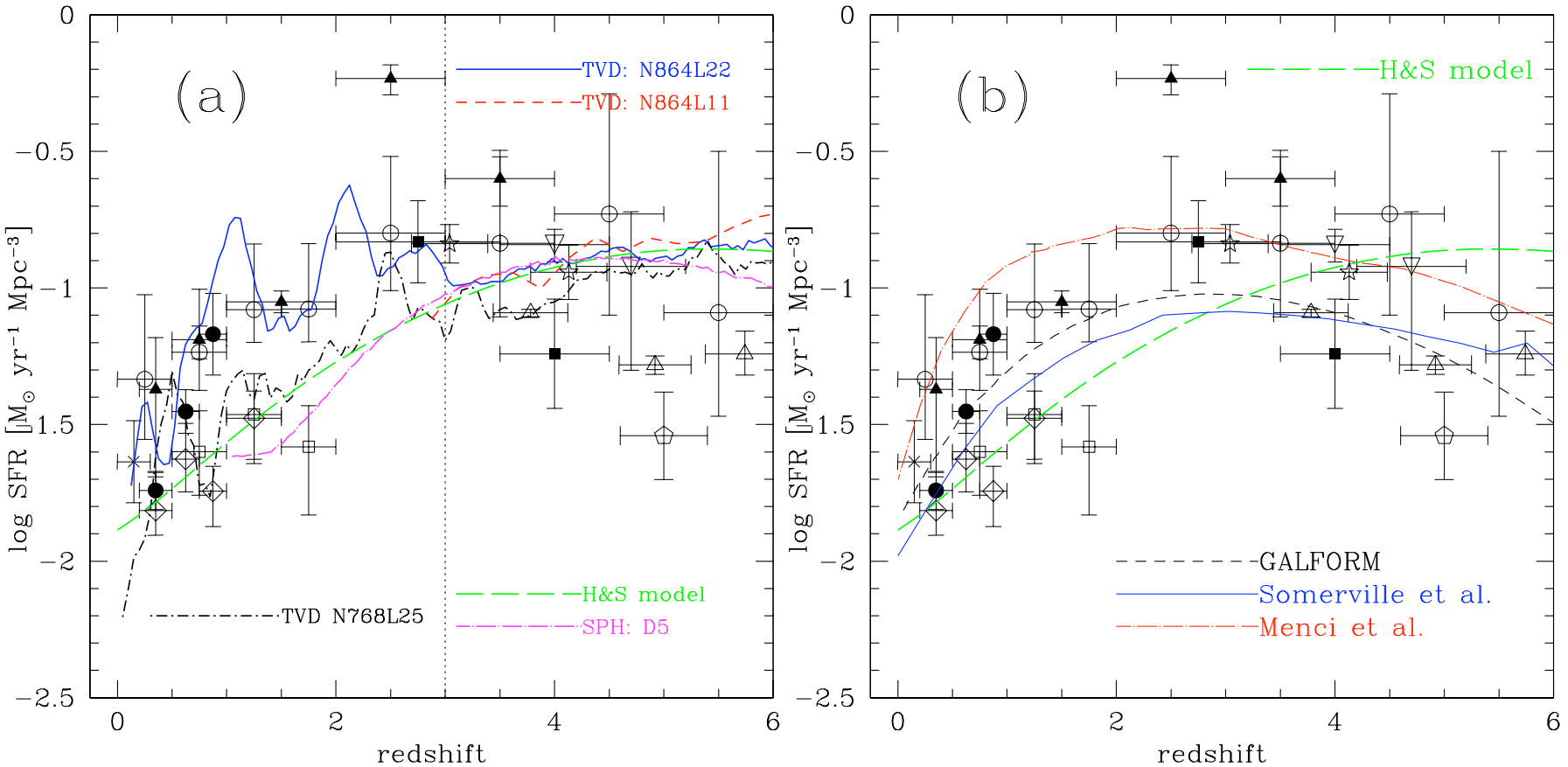


Sporadic starbursts up to $1000\,M_\odot\,\mathrm{yr}^{-1}$


$100 < \mathrm{SFR} < 500\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$
100
80
60
40
20
0
Y [Mpc/h]
0
20
40
60
80
100
X [Mpc/h]
G6 z=2
slice 1


$G - R > 1.5$ & $M_\star > 10^{10} h^{-1} M_\odot$
100
80
60
40
20
0
Y [Mpc/h]
0
20
40
60
80
100
X [Mpc/h]
G6 z=2
slice 1

Cosmic Star Formation History



SFR peak at z≥5

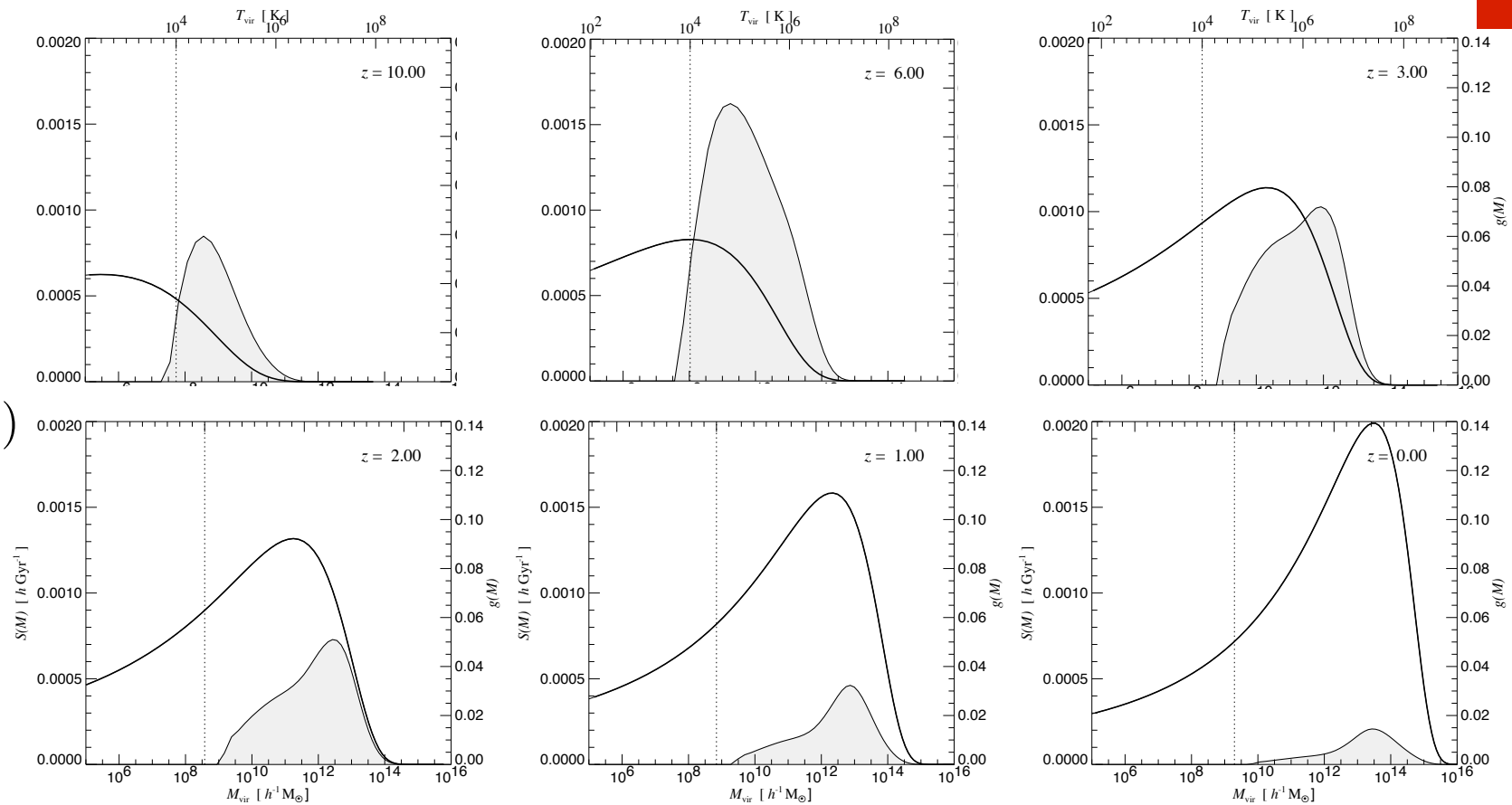
suppression of high-z SF in SA models

Is there a missing galaxy problem at high-z?

Nagamine, Cen, Hernquist, Ostriker, Springel (2004)

Star formation rate function

$S(M,z)$



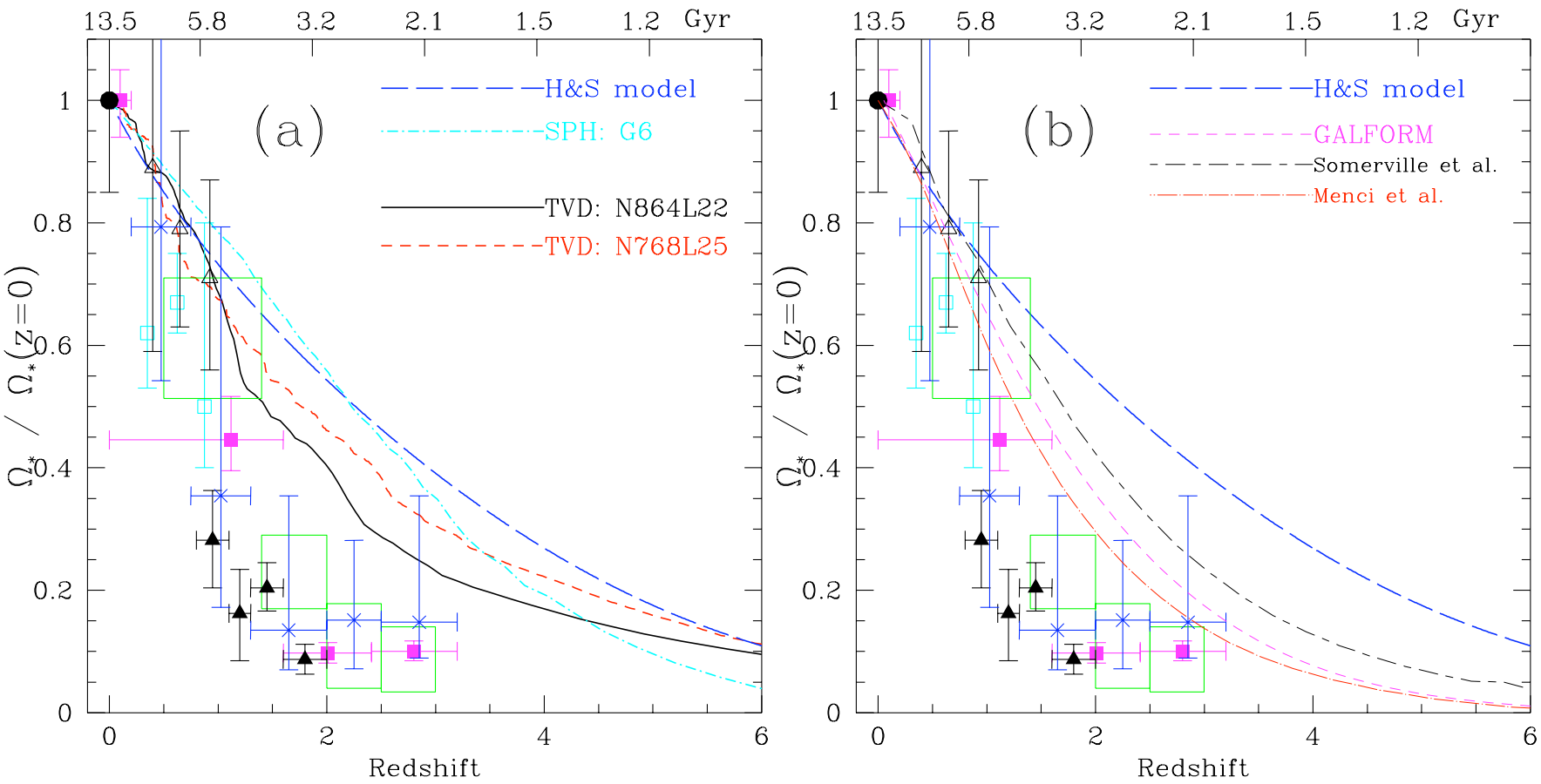
$M_{\rm vir}\ [h^{-1}M_\odot]$

Springel & Hernquist (2003)

$$\dot{\rho}_* = \bar{\rho} \int s(M,z)\, g(M,z)\, d\log M, \qquad S(M,z) \equiv s(M,z)\, g(M,z)$$

$$s(M,z) = \dot{M}_* / \langle M \rangle \qquad g(M) = \frac{dF}{d\log M}$$

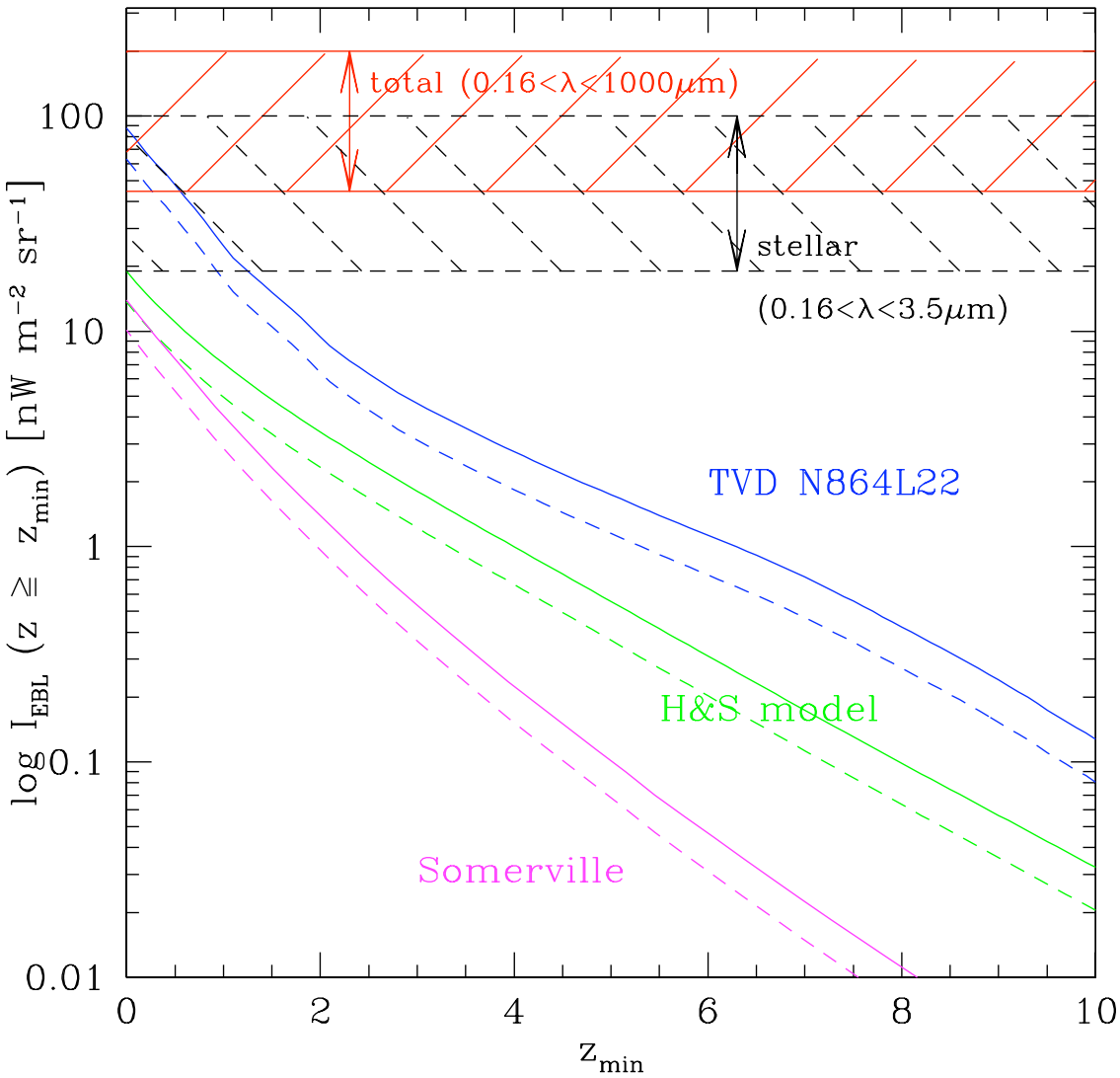
Stellar Mass Density $\Omega_*(z)$



$70, 50, 30, 10\%$ by $z = 1, 2, 3, 5$

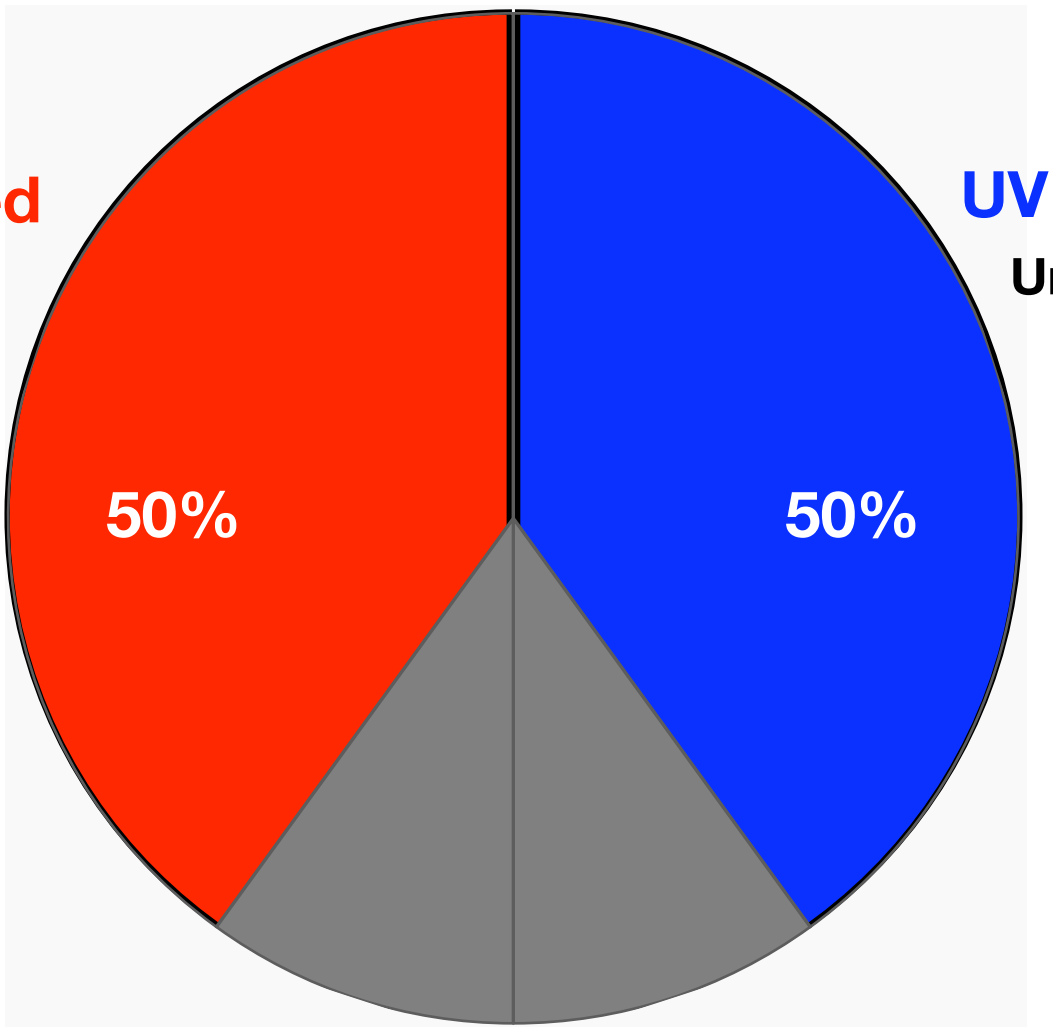
Is there a missing galaxy problem at high-z?
Nagamine, Cen, Hernquist, Ostriker, Springel (2004)

Extragalactic Background Light



Unified view of massive galaxies at z=2

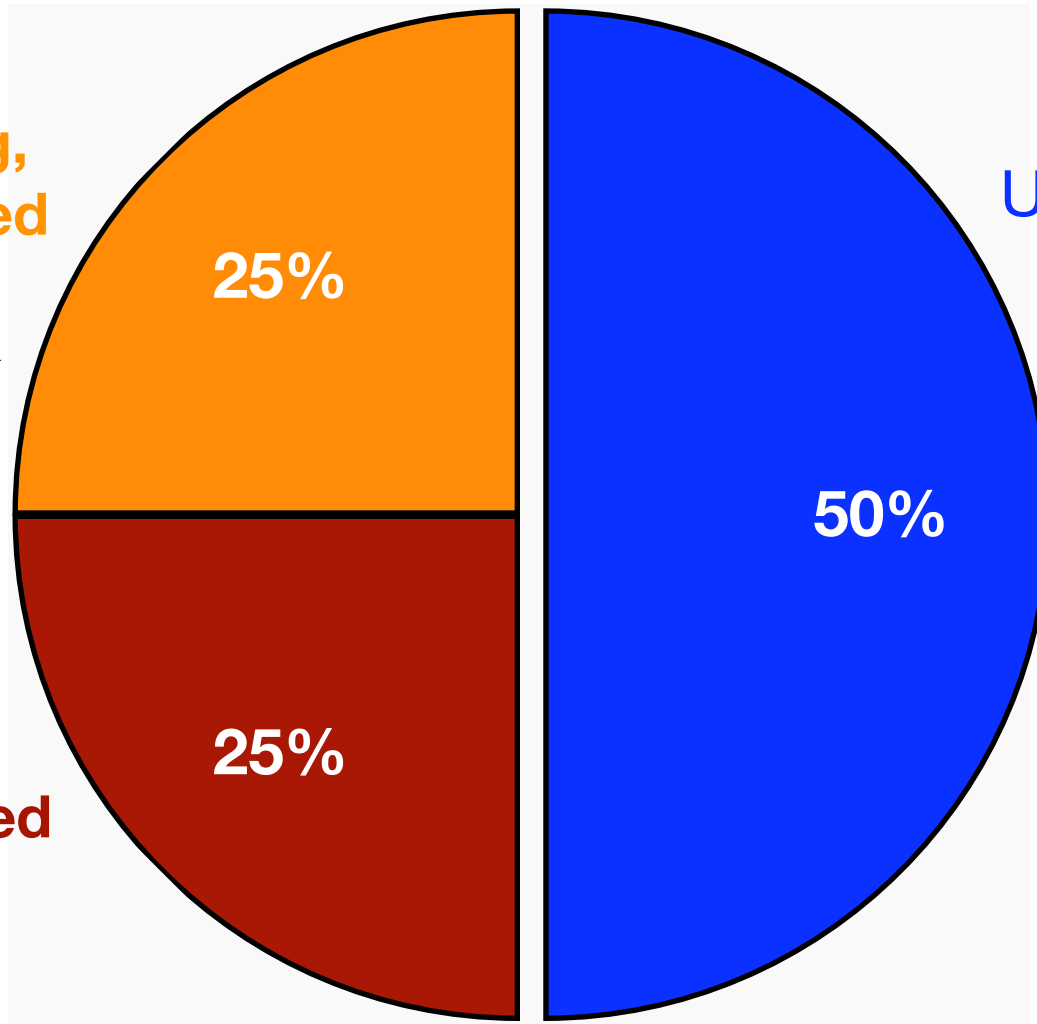
Total $n(>10^{10}h^{-1}M_{\odot}) \sim 1 \times 10^{-2}h^{3}\mathrm{Mpc}^{-3}$



some overlap

Unified view of massive galaxies at z=2

Total $n(>10^{10}h^{-1}M_{\odot}) \sim 1 \times 10^{-2}h^{3}\mathrm{Mpc}^{-3}$



star-forming, dust reddened

E(B-V)~0.4

$\mathrm{SFR} \sim 200 M_{\odot}\mathrm{yr}^{-1}$

IR selected

really dead & red

E(B-V)~0.1 ?

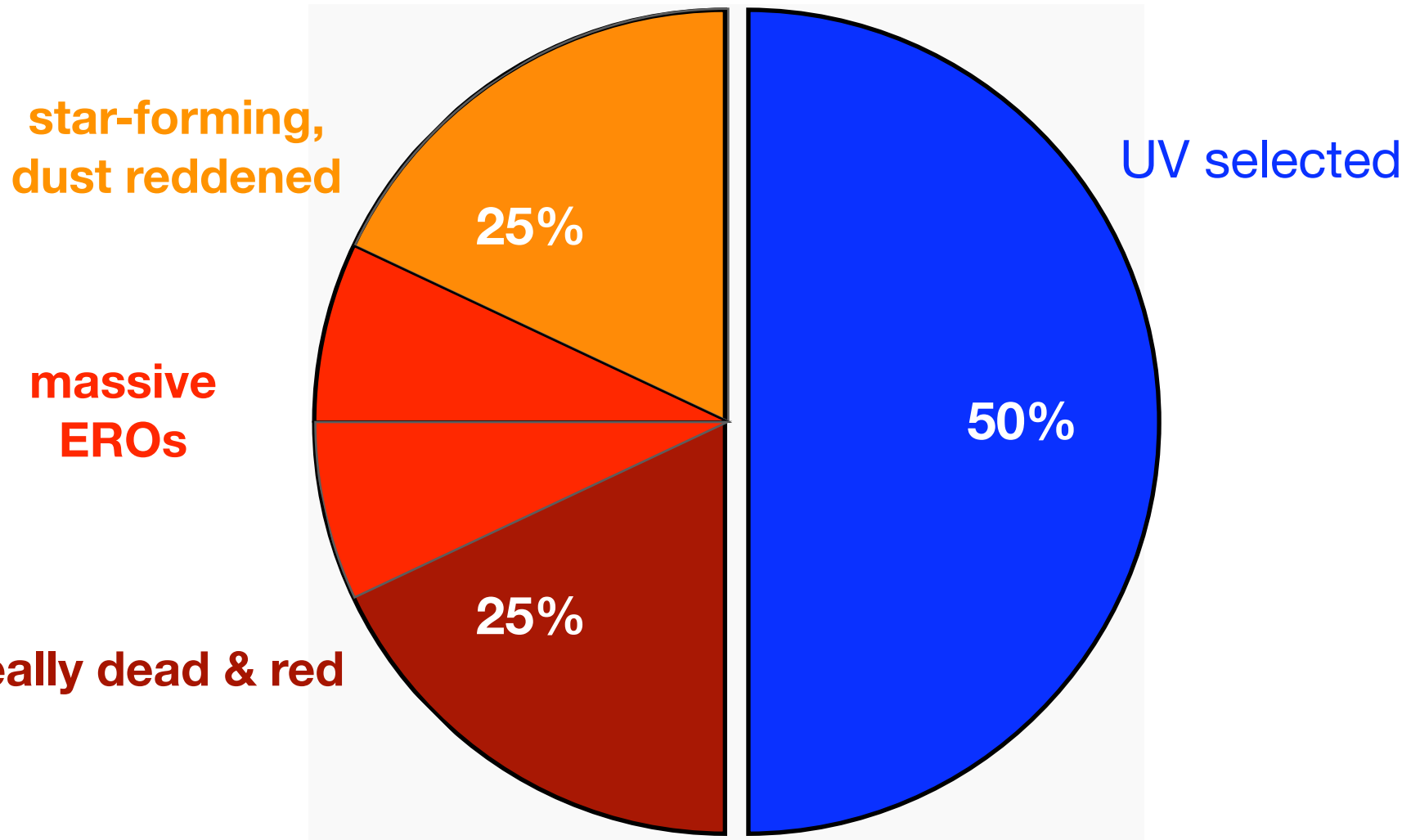
UV selected

E(B-V)~0.15

$\mathrm{SFR} \sim 50 M_{\odot}\mathrm{yr}^{-1}$

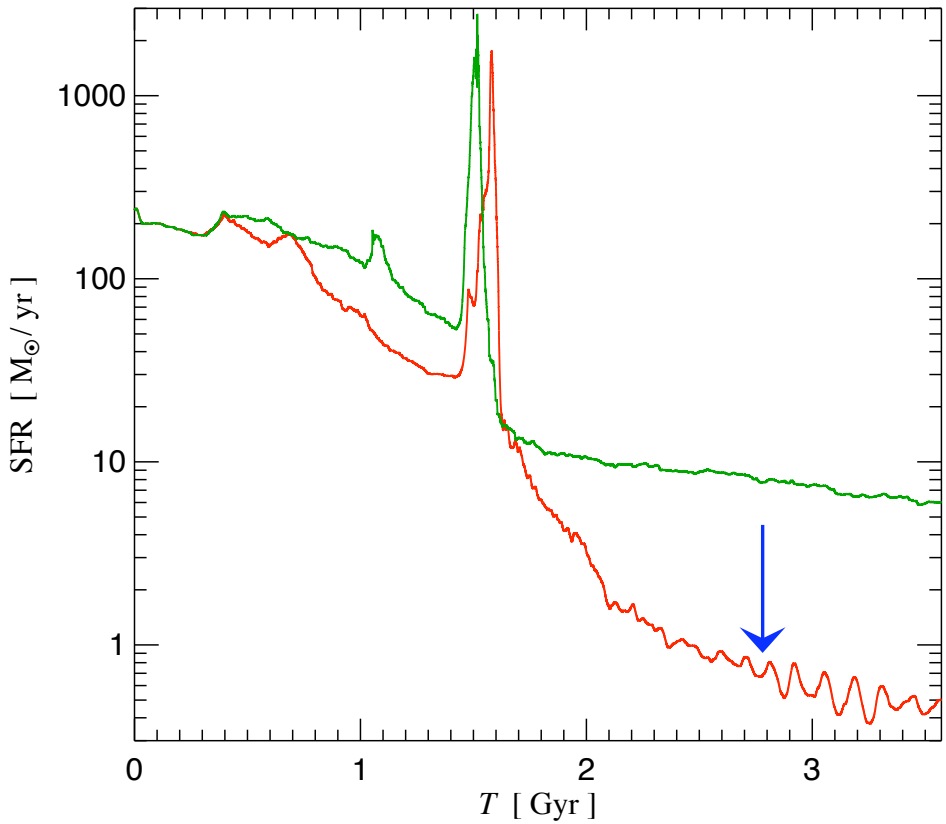
Unified view of massive galaxies at z=2

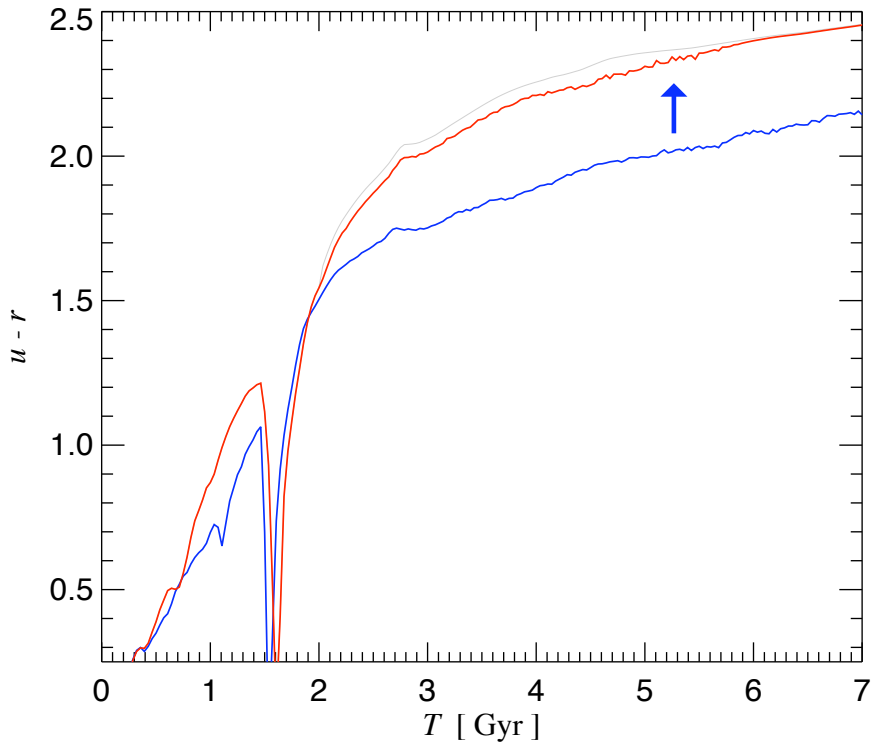
Total $n(>10^{10}h^{-1}M_{\odot}) \sim 1 \times 10^{-2}h^{3}\mathrm{Mpc}^{-3}$



Effect of AGN feedback

BH sink particle + energy feedback





Springel, Di Matteo, Hernquist ‘04

Summary

♠ Un,G,R selected UV bright galaxies @ z=2-3 ⇔

massive galaxies in massive DM halos

stellar mass $M_{\rm star} \sim 10^{10} M_\odot$ (z~3), $10^{11} M_\odot$ (z~2) → clustering OK.
colors (median E(B-V) ~ 0.15)
number density: total $n(> 10^{10} M_\odot) \sim 10^{-2}\, h^3\, {\rm Mpc}^{-3}$

perhaps ~1/2 UV, ~1/2 IR selected

(cf. Erb et al.)

♠ IR selected bright galaxies:

larger median E(B-V) ~0.4 (but EROs?)
BzK selection → relatively red, star-forming galaxies
$n(> 10^{11} M_\odot, 100 M_\odot {\rm yr}^{-1}) \sim 10^{-4} {\rm Mpc}^{-3}$

(cf. Daddi et al. 04)

♠ SF history:

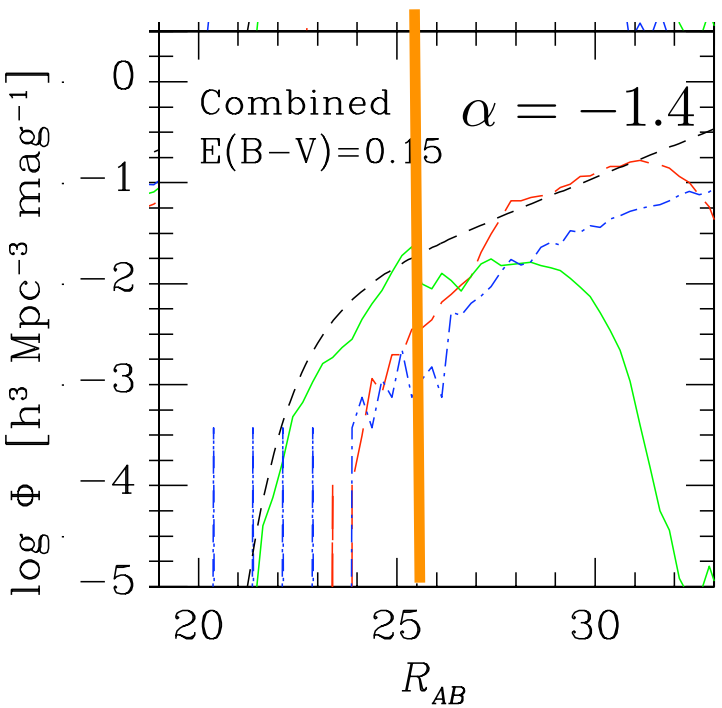
- bursts + continuous $(40\,M_\odot\,\mathrm{yr}^{-1} \times 3\,\mathrm{Gyr} \sim 10^{11}\,M_\odot)$
- SFR up to $1000\,M_\odot\,\mathrm{yr}^{-1}$
- peak of the Madau plot at $z \geq 5$ → GRBs w/ Swift
- high-z SF seems to be too suppressed in SA models

♣ Future work:

- more on IR selected sample: Spitzer, K21, etc. ...dust...
  (are EROs dusty starbursts or really dead&old? 50-50%?)
- SFR Intensity, b-param, SFR correlations
- bimodal color distribution, downsizing, etc.
- feedback --- SN, AGN, UV ---> faint & bright-end of LF

Luminosity Functions: z=2

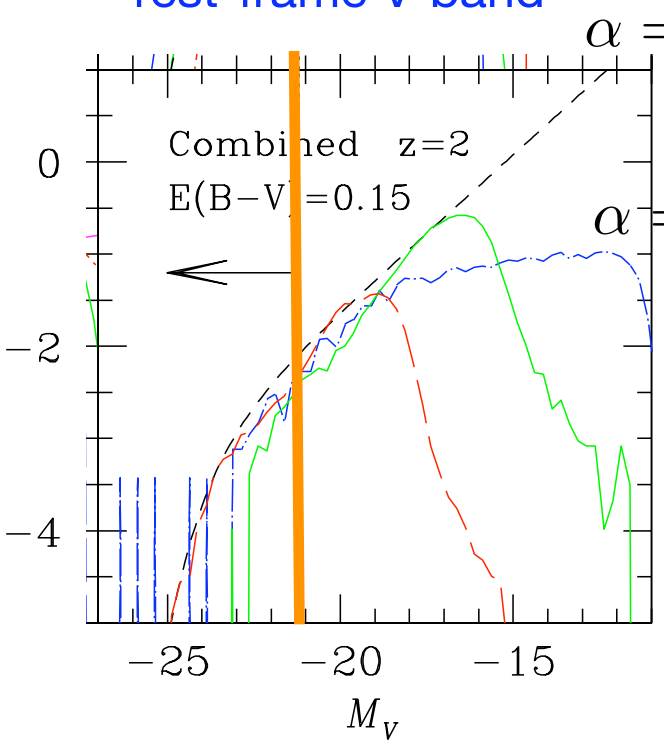
obs-frame R-band



$M_R^* = 23.2$

$\Phi^* = 1 \times 10^{-2}$

rest-frame V-band



$M_V^* = -23.4$

~ 0.5 mag brighter than z=3

~ 50% of stars could be missed